2020

PRCI Research Exchange Meeting

Presentations

March 2-3, 2020

Pipeline Research Council International
LEADING PIPELINE RESEARCH

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PRCI 2020 Research Exchange
Turning Research into Operational Excellence

TUESDAY, MARCH 3, 2020			
8:00 to 9:30 AM	**Opening Plenary Session | Emerald Ballroom, Second Floor** **Welcome, Keynote, and Awards**		
9:30 to 10:00 AM	**Networking Break | Ballroom Foyer, Second Floor** **Visit with Exhibitors**		
	Track One: Corrosion **Topaz Room, Second Floor**	**Track Two: Data Mining & Machine Learning** **Crystal Ballroom I, Second Floor**	**Track Three: Materials & Integrity** **Emerald Ballroom, Second Floor**
10:00 AM	*Assessment of SCC Clusters with Intelligent Interaction Rules* : Bo Wang, CRES	*A Digital Alternative to In-Line Inspection:* Christopher De Leon and Michael Smith, ROSEN	*Optimization of Steel Alloy Design for Critical Welded Pipeline Structures* : Maina Portell Garcia & Frank Barbaro, University of Wollongong
10:30 AM	*Improved Failure Pressure Estimates of SCC Colonies from ILI and Field Data* : Bruce Nestleroth, Kiefner	*Using Machine Learning to Enhance Pipeline Reliability Assessment* : Daryl Bandstra, Integral Engineering & Mari Shironishi, SoCal Gas	*Mechanical Damage Management* : Aaron Dinovitzer, BMT
11:00 AM		*Hybrid Physics-Informed, Data-driven Analytics for Natural Gas Pipeline Condition Diagnostics and Integrity Prognostics:* Kayte Denslow, Pacific Northwest Laboratory	*Example of Use of PRCI Research in Mechanical Damage as Data for University Research and Improve of Company Standards* : Husain Al-Muslim, Saudi Aramco
11:30 AM			
12:00 to 1:00 PM	**Conference Luncheon | Pool Deck, Third Floor**		
	Track One: Corrosion **Topaz Room, Second Floor**	**Track Two: Composites** **Crystal Ballroom I, Second Floor**	**Track Three: Integrity** **Emerald Ballroom, Second Floor**
1:00 PM	*Psqr Model and Its Safe Implementation - With Data Driven Demonstrated Improvement in Performance and Effectivenes* Presented by: Shahani Kariyawasam, TC Energy	*Composites Workshop* : Chris Alexander, ADV Integrity	*Full-scale Fatigue Testing of Crack-in-Dent and Framework Development for Life Prediction:* Ming Gao and Ravi Krishnamurthy, Blade Energy
1:30 PM			*Improved ERW Fatigue Life Estimation:* Aaron Dinovitzer, BMT
2:00 PM			*Innovation in Reliability Based Pipeline Integrity Methods: Making the Best Information Accessible for Everyday Operations & for Informing Major Decisions* : Aidan Charlton, Penspen
2:30 PM			*Methodology for Assessing Seam Weld Anomalies Using In-Line Inspection Data* : Samarth Tandon, Blade Energy
3:00 to 3:30 PM	**Networking Break | Ballroom Foyer, Second Floor** Visit with Exhibitors		
3:30 to 5:00 PM	**Emerging Fuels Forum | Emerald Ballroom, Second Floor** *Future Fuels CRS* : David Norman, FFCRC; *Emerging Fields Agenda within GERG:* Robert Judd, GERG; and *PRCI Emerging Fuels Strategic Research Priorities:* Francois Rongere, PG&E and Amelie Louvat, GRTgaz		
5:00 to 6:30 PM	**Cocktail Reception | Pool Deck, Third Floor** Join PRCI for an evening of drinks, hor d'oeuvres and networking		

PRCI 2020 Research Exchange
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WEDNESDAY, MARCH 4, 2020			
	Track One: Corrosion **Topaz Room, Second Floor**	**Track Two: Welding** **Crystal Ballroom I, Second Floor**	**Track Three: Integrity** **Emerald Ballroom, Second Floor**
8:00 AM	*Measuring the Accuracy of Instant OFF Potentials:* Kalen Jensen, ATCO	*Support for Standardization of Weld Test Method* : Sanjay Tiku, BMT	*Ensuring the Permanency of Pipeline Composite Repair Systems:* Colton Sheets, Stress Engineering
8:30 AM	*Optimization of Pipeline Reconditioning:* Husain Al-Muslim, Saudi Aramco	*Vintage Girth Weld Management: A Pragmatic Application of PRCI and UKOPA Research:* Kalen Jensen, ATCO	*Status of Efforts on Hydrotest Optimization of Older Liquid Pipelines* : Gery Wilkows, EMC
9:00 AM	*Quantification of ILI Sizing Performance for Severe Corrosion Anomalies:* Smitha Koduru, C-FER Technology	*Weld Hydrogen Cracking Susceptibility* : Aaron Dinovitzer, BMT	*Tripartite Project on Delayed Failure* : Brian Leis, BN Leis, Consultant, Inc.
9:30 AM		*Welding Options and Specifications for Strain-Resistant Girth Welds:* Yong-Yi Wang, CRES	*Validating Computed Tomography Using Crack-like Features in Full-scale Pipe Samples:* Chris Alexander, ADV Integrity
10:00 to 10:30 AM	**Networking Break | Ballroom Foyer, Second Floor** **Visit with Exhibitors**		
	Track One: Welding Workshop **Topaz Room, Second Floor**	**Track Two: Materials** **Crystal Ballroom I, Second Floor**	**Track Three: Geohazard** **Emerald Ballroom, Second Floor**
10:30 AM	*Workshop: Recommendations of Improved Linepipe Specificaitons and Girth Weldig Procedure for Girth Weld Strain Capacity:* Yong-Yi Wang, Center for Reliable Energy Systems	*Tracking and Traceability Marking Standard for Natural Gas Transmission Components* : Shannon Katcher, Gas Technology Institute	*Correlation of Single-Run ILI IMU Bending Strain Features to Geohazard Locations* : Bailey Theriault, Golder
11:00 AM		*Transition Temperature Behavior of New Line-Pipe Steels:* Mo Uddin, EMC	*Developing a Representative Soil Response Model* : Ryan Phillips, C-Core
11:30 AM			
12:00 to 1:00 PM	**Conference Luncheon | Pool Deck, Third Floor**		
	Track One: Inspection **Topaz Room, Second Floor**	**Track Two: Design** **Crystal Ballroom I, Second Floor**	**Track Three: Geohazard** **Emerald Ballroom, Second Floor**
1:30 PM	*Guidelines for Integrity Assessment of Difficult to Inspect Pipelines* : Ben Mittelstadt, Dynamic Risk	*Assessment of Pressure Isolation Tools for Onshore Pipelines via Full-scale Testing and Finite Element Modeling* : Chris Alexander, ADV Integrity	*InSAR Monitoring of Pipeline Geohazards in Vegetated and Very Large Non-Vegetated Areas* : Kris Covey, 3v Geomatics
2:00 PM	*In-line Inspection Crack Tool Reliability and Performance Evaluation:* Smitha Koduru, C-FER Technology	*Guidelines for the Determination of Pipeline Lowering-in Stresses and Mitigative Strategies for Construction* : Banglin Liu, CRES	*Life-Cycle Management of Geohazards for Pipelines* : Yong-Yi Wang, CRES
2:30 PM	*Representing MFL Performance under Casings to Improve ILI based Decision Making* : Dongliang Lu, TC Energy		
3:00 to 3:30 PM	**Networking Break | Ballroom Foyer, Second Floor** **Visit with Exhibitors**		

PRCI 2020 Research Exchange
Turning Research into Operational Excellence

WEDNESDAY, MARCH 4, 2020			
	Track One: Operations **Topaz Room, Second Floor**	**Track Two: Design** **Crystal Ballroom I, Second Floor**	**Track Three: Geohazard** **Emerald Ballroom, Second Floor**
3:30 PM	*Guidelines to Calculate Erosional Velocity for Liquid Hydrocarbon Transmission Pipelines:* Jose Vera, DNV GL	*Risk Consistent Safety Class System and Hoop Stress Factors for Pipeline Design:* Maher Nessim, C-FER Technology	*Monitoring Integrity, Geohazards, and Leaks at River Crossings* : Nick Tzonev, Syscor
4:00 PM	*Overpressure Protection From Wildfire and Expanded Fire Study at Compressor Stations and Tank Terminals* : Perry Krebes, TC Energy	Tensile Strain Capacity of Vintage Girth Welds: Banglin Liu, CRES	*Significance of Ground Movement on Pipeline Integrity* : Aaron Dinovitzer, BMT
4:30 PM	*Methane Emissions Solutions for the Pipeline Transmission Industry* : Brian Weeks, Gas Technology Institute		*Structured Response Plan after a Ground Movement Event* : Yong-Yi Wang, CRES

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- **Hand Sanitizer and Tissues are Available at the Registration Desk**

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  - Cover your mouth and nose with a flexed elbow or tissue (not your hands) when you cough or sneeze
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  - Discard a used tissue immediately into a closed trash can, and wash your hands with an alcohol-based sanitizer and/or soap and water right away

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- Tran Mah-Paulson, TD Williamson
- David Xu, PG&E
- Kalen Jensen, ATCO
- Angela McPherson, TC Energy
- Shenwei Zhang, TC Energy
- Dave Johnson, Energy Transfer
- Muhammad Saleem, TC Energy
- Husain Al-Muslim, Saudi Aramco
- Hemanth Satish, TC Energy



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(Name of Individual)

For attendance at

2012 PRCI Research Exchange Meeting

(Title of Technical Session/Event)

On

February 7-9, 2012 / Phoenix, Arizona USA for 18.0 PDH

(Date and Location) (No. of Hours/PDH)

Cliff Johnson, President

Pipeline Research Council International

February 9, 2012

Date

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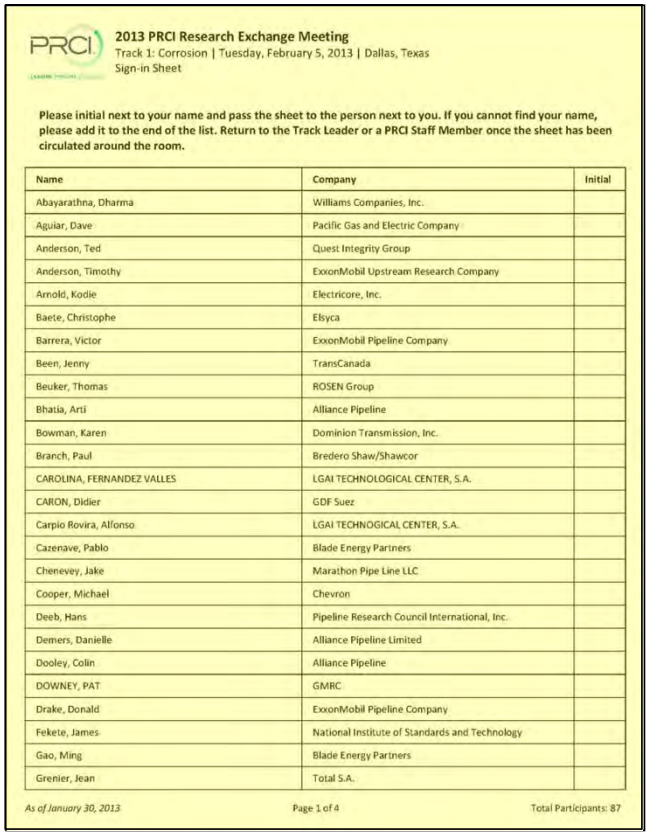

2013 PRCI Research Exchange Meeting
Track 1: Corrosion | Tuesday, February 5, 2013 | Dallas, Texas
Sign-in Sheet

Please initial next to your name and pass the sheet to the person next to you. If you cannot find your name, please add it to the end of the list. Return to the Track Leader or a PRCI Staff Member once the sheet has been circulated around the room.

Name	Company	Initial
Abayarathna, Dharma	Williams Companies, Inc.	
Aguiar, Dave	Pacific Gas and Electric Company	
Anderson, Ted	Quest Integrity Group	
Anderson, Timothy	ExxonMobil Upstream Research Company	
Arnold, Kodie	Electricore, Inc.	
Baete, Christophe	Elsyca	
Barrera, Victor	ExxonMobil Pipeline Company	
Been, Jenny	TransCanada	
Beuker, Thomas	ROSEN Group	
Bhatia, Arti	Alliance Pipeline	
Bowman, Karen	Dominion Transmission, Inc.	
Branch, Paul	Bredero Shaw/Shawcor	
CAROLINA, FERNANDEZ VALLES	LGAI TECHNOLOGICAL CENTER, S.A.	
CARON, Didier	GDF Suez	
Carpio Rovira, Alfonso	LGAI TECHNOGICAL CENTER, S.A.	
Cazenave, Pablo	Blade Energy Partners	
Chenevey, Jake	Marathon Pipe Line LLC	
Cooper, Michael	Chevron	
Deeb, Hans	Pipeline Research Council International, Inc.	
Demers, Danielle	Alliance Pipeline Limited	
Dooley, Colin	Alliance Pipeline	
DOWNEY, PAT	GMRC	
Drake, Donald	ExxonMobil Pipeline Company	
Fekete, James	National Institute of Standards and Technology	
Gao, Ming	Blade Energy Partners	
Grenier, Jean	Total S.A.	

As of January 30, 2013 Page 1 of 4 Total Participants: 87

2019 Year in Review



Learn About PRCI's Accomplishments in the Last Year!

Don't Forget Your Copy!

Click here to view the fully digital version of the 2019 Year in Review

Save the Date! Upcoming Meetings



Spring 2020 Joint Meeting of the PRCI Measurement & Pipeline Technical Committees

June 9-11, 2020 | Denver



Fall 2020 Joint Compressor & Pump Station, Measurement, & Pipeline Technical Committee Meetings

October 20-22, 2020 | Dallas



2021 PRCI Research Exchange Meeting & Winter Technical Committee Meetings

March 2-5, 2021 | Houston

Please Contact Tami Pizani if Your Company is Interested in Sponsoring any of These Meetings!

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Welcome to the 2020 Research Exchange!

Cliff Johnson, President

March 3-4, 2020
San Diego, California

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Safety Moment



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Our Mission



To collaboratively deliver relevant and innovative applied research to continually improve the global energy pipeline systems.

Welcome to the 14th Annual Research Exchange!

- Report Important Research Results and Outcomes for Completed Work
- Focus on How to Use the Results
- Tuesday Evening Networking Reception in the Discovery Center



Housekeeping

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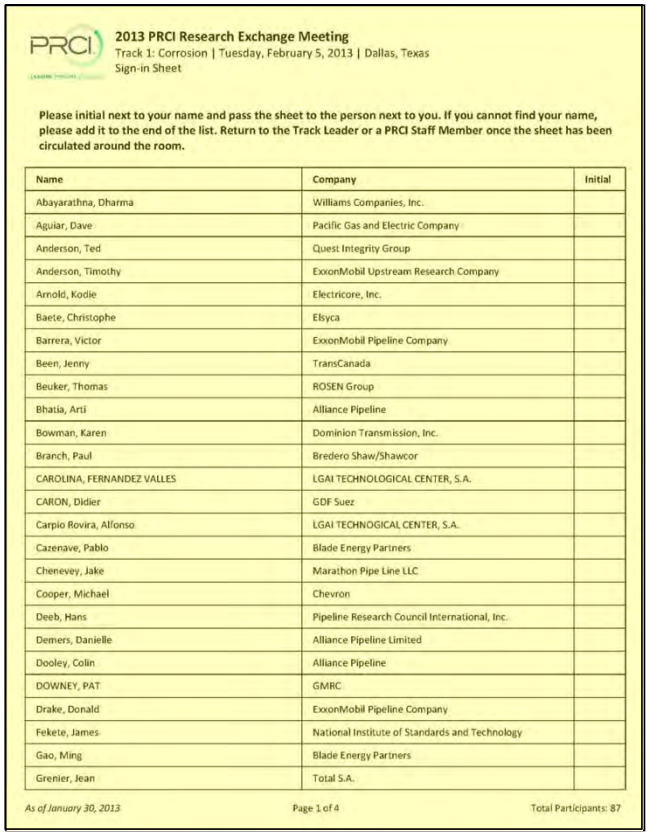

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Distinguished Service Award

For Distinguished Service to the Energy Pipeline Industry through a Sustained Commitment to PRCI and Noteworthy Contributions to the Achievement of its Mission, Goals, and Programs



David McQuilling

Distinguished Service Award

For Distinguished Service to the Energy Pipeline Industry through a Sustained Commitment to PRCI and Noteworthy Contributions to the Achievement of its Mission, Goals, and Programs



Natalie Tessel

Distinguished Researcher Award

For Dedicated and Distinguished Service and Scientific Achievements that have Enhanced the Integrity, Reliability and Environmental Performance of Energy Pipelines Around the World



Aaron Dinovitzer

Distinguished Researcher Award

For Dedicated and Distinguished Service and Scientific Achievements that have Enhanced the Integrity, Reliability and Environmental Performance of Energy Pipelines Around the World



Patrick Vieth

In-Kind Support Award

For Companies that have Provided Significant Contributions and Support for Furthering PRCI Research

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Other Award Recipients in June 2020

Distinguished Service Award



Kerry Checkwitch

In-kind Support Award

EMERSON

Distinguished Researcher Award



Terry Grimley

SICK
Sensor Intelligence.

Keynote Speaker



Dr. Scott W. Tinker

Director, Bureau of Economic Geology

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"If the world was perfect, it wouldn't be."

…Yogi Berra

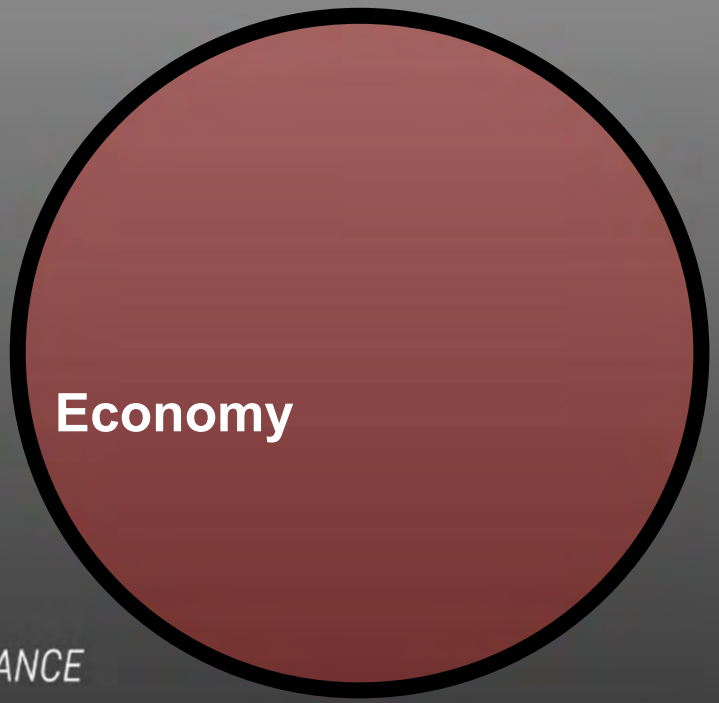


Tinker 2020

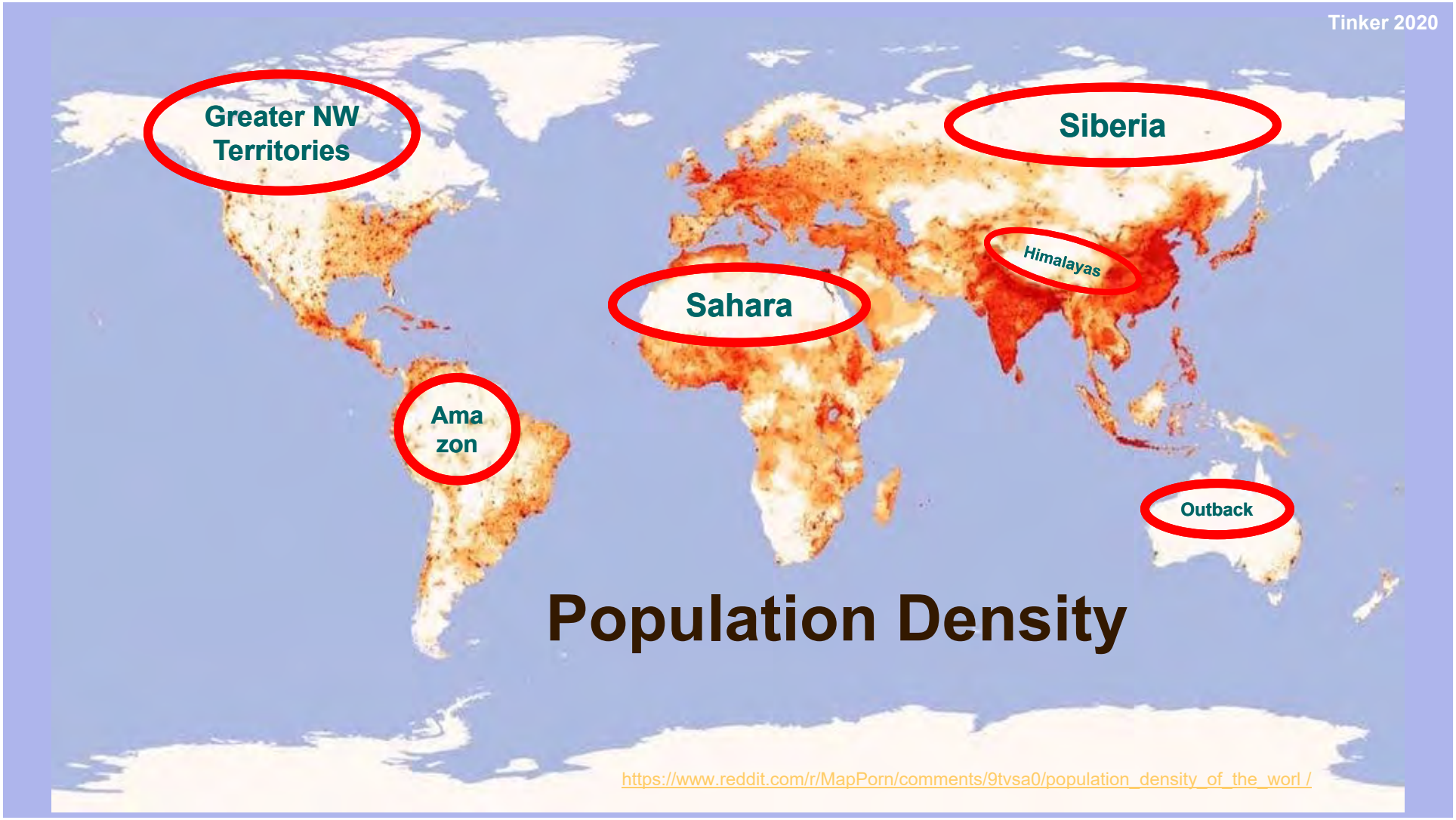
Climate Change
Education
Energy
Gender Equality
Healthcare
Housing
Hunger
Immigration
Land, Air, Water
Population
War



SW
EN

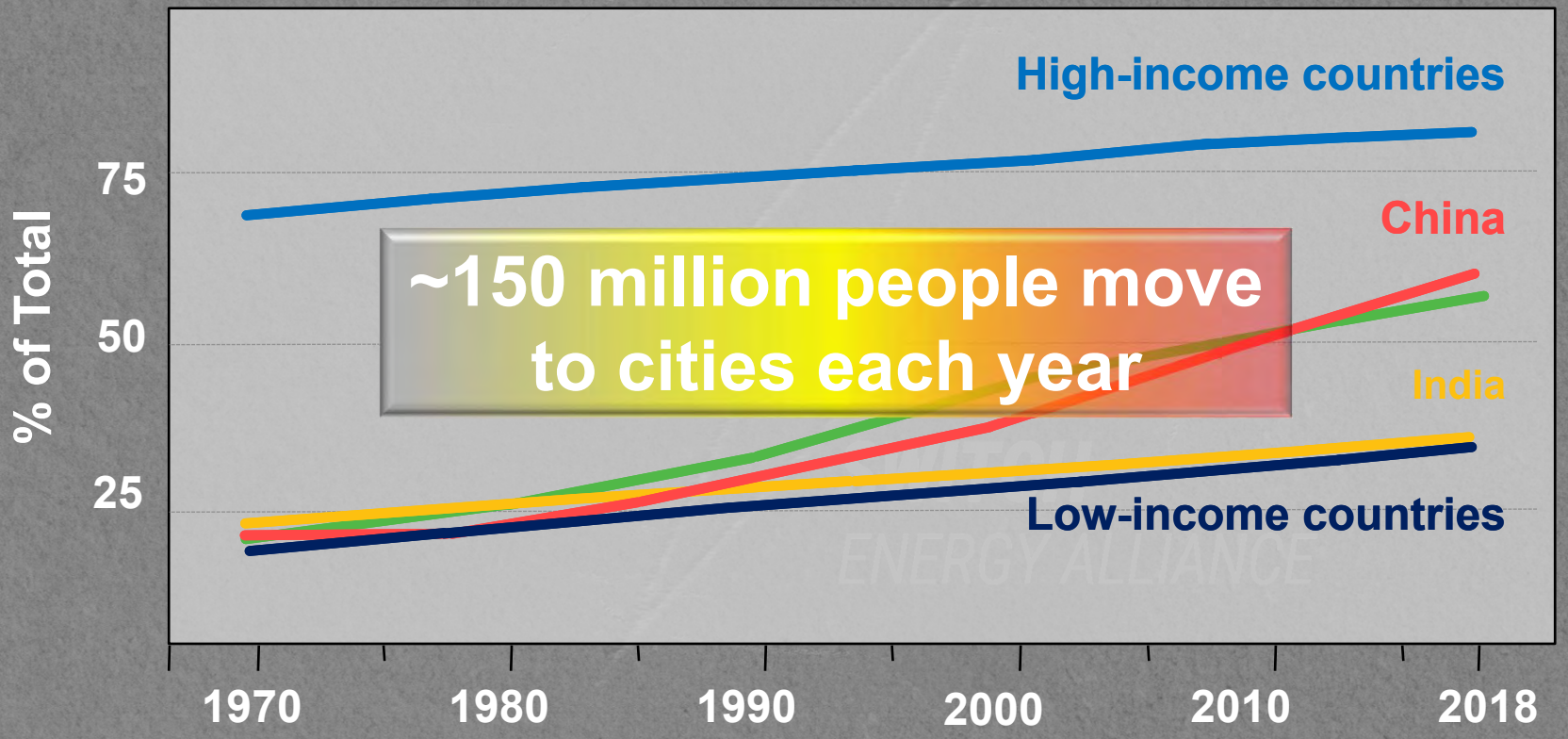


SWITCH
ENERGY ALLIANCE


Tinker 2020
Greater NW Territories
Siberia
Himalayas
Sahara
Ama zon
Outback
Population Density
https://www.reddit.com/r/MapPorn/comments/9tvsa0/population_density_of_the_worl /

Tinker 2020

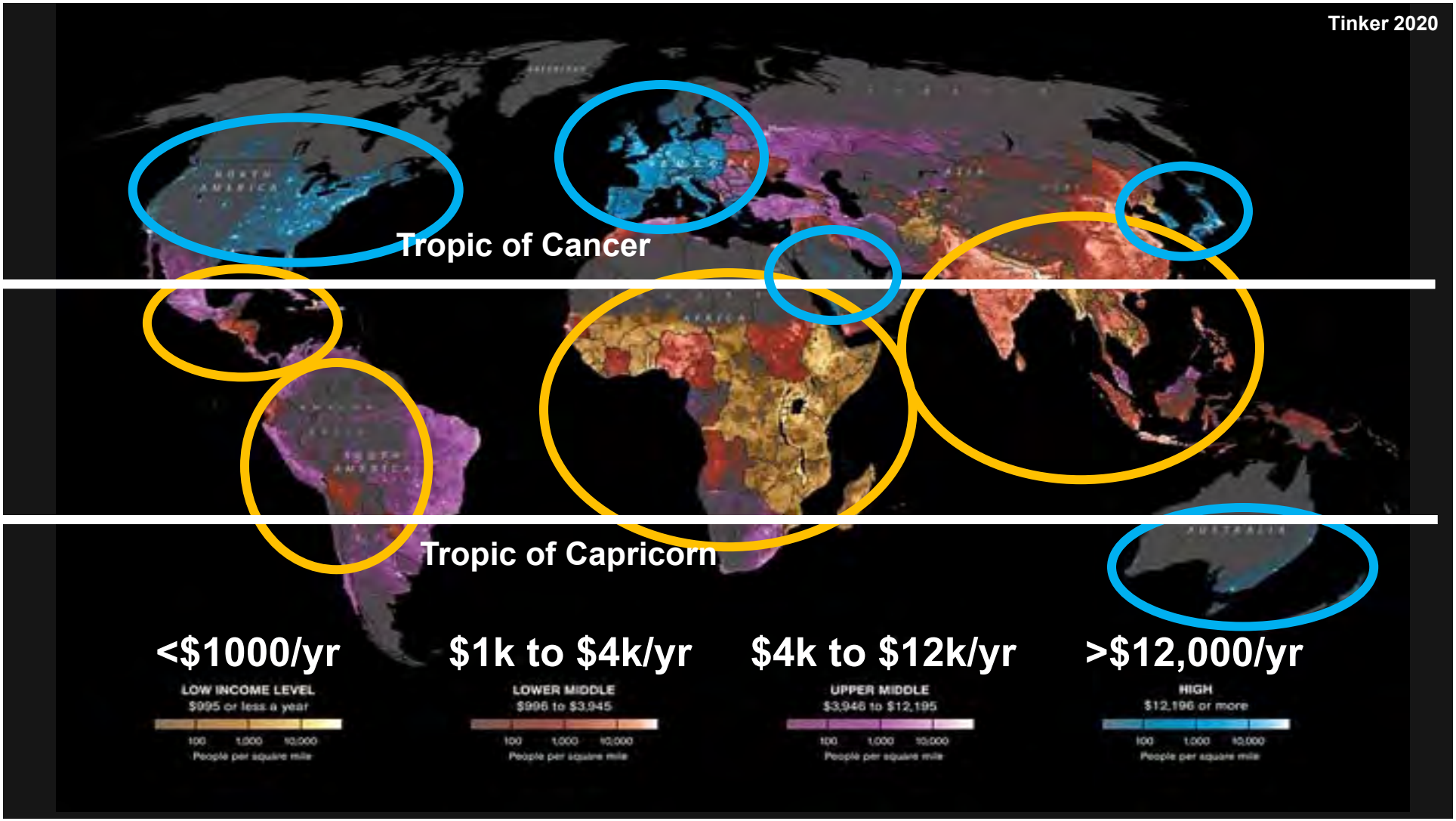
Urban Population

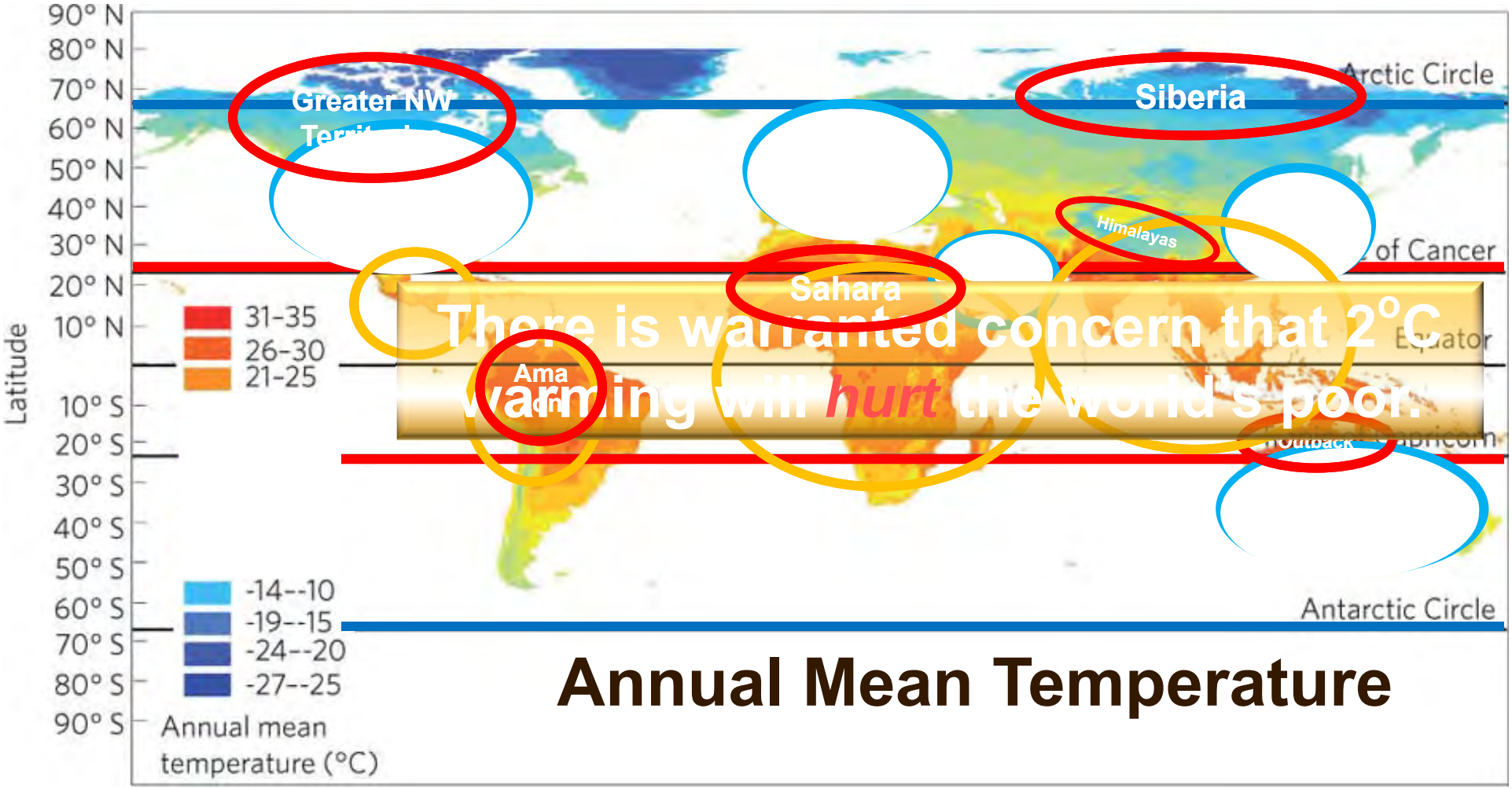


Source: World Bank, The Economist, November 16, 2019

QAe8430


Tinker 2020
Centralized Grid


Tinker 2020
Tropic of Cancer
Tropic of Capricorn
<$1000/yr
LOW INCOME LEVEL
$995 or less a year
100 1,000 10,000
People per square mile
$1k to $4k/yr
LOWER MIDDLE
$996 to $3,945
100 1,000 10,000
People per square mile
$4k to $12k/yr
UPPER MIDDLE
$3,946 to $12,195
100 1,000 10,000
People per square mile
>$12,000/yr
HIGH
$12,196 or more
100 1,000 10,000
People per square mile


90° N
80° N
70° N
60° N
50° N
40° N
30° N
20° N
10° N
10° S
20° S
30° S
40° S
50° S
60° S
70° S
80° S
90° S
Latitude
Greater NW
Siberia
Arctic Circle
Himalayas
of Cancer
Sahara
Ama
Equator
Outback
Antarctic Circle
31–35
26–30
21–25
-14--10
-19--15
-24--20
-27--25
Annual mean
temperature (°C)
There is warranted concern that 2°C
warming will hurt the world's poor.
Annual Mean Temperature

Energy will *help* the world's poor, just as it helps the world's rich.




What does
“little to no energy”
mean?
SWITCH
ENERGY ALLIANCE
Bureau of
Economic
Geology

THERE ARE 3 KINDS OF PEOPLE
IN THE WORLD.

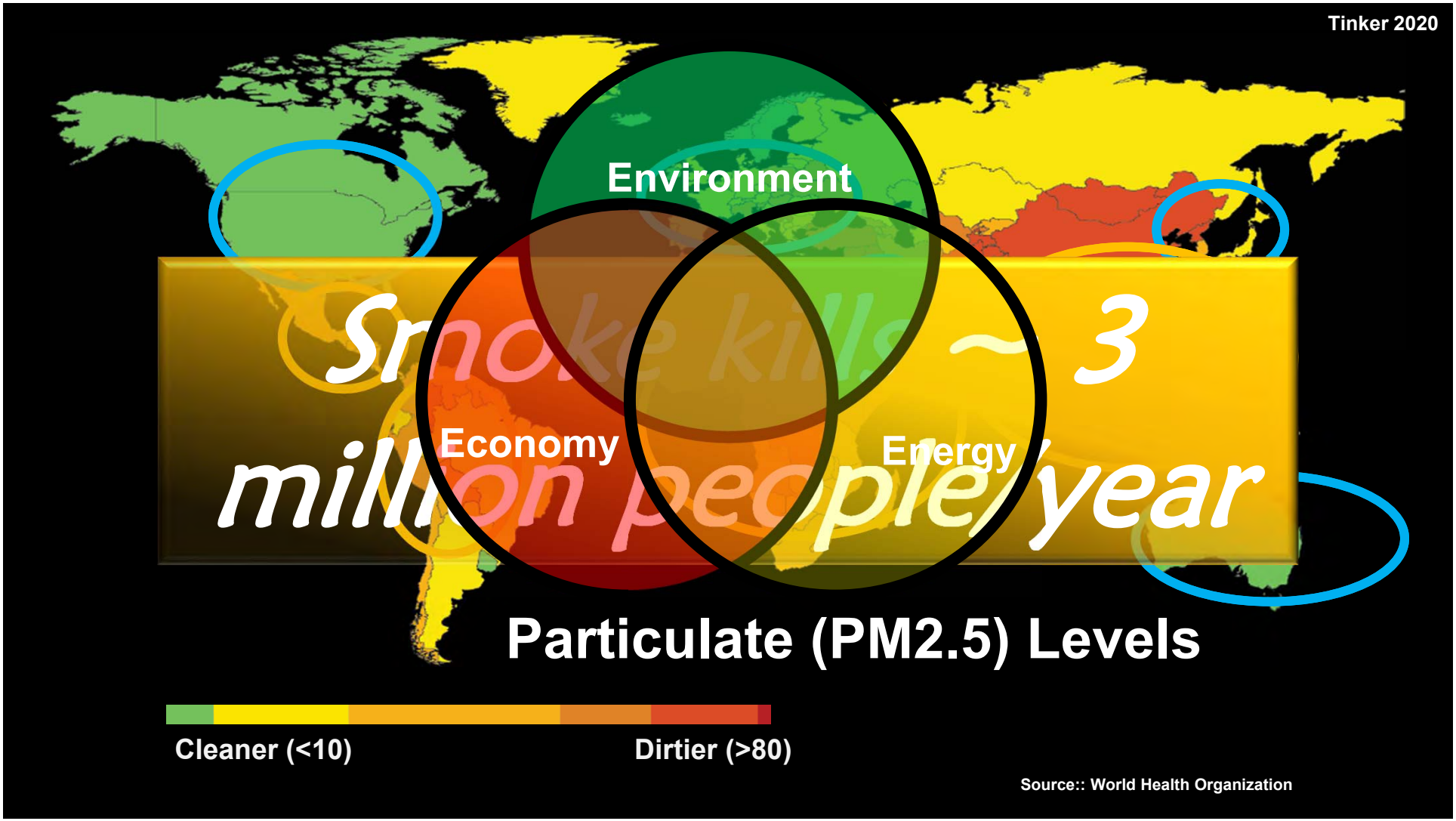
THOSE WHO ARE GOOD AT MATH,
AND THOSE WHO AREN'T.

Electricity and Clean Cooking



n People

Source: **World Energy Outlook, 2017, EIA**


Tinker 2020
Environment
Economy
Energy
Smoke kills ~ 3
million people/year
Particulate (PM2.5) Levels
Cleaner (<10)
Dirtier (>80)
Source:: World Health Organization

Economic Poverty and Energy Poverty

Tinker 2020

Circles sized by total population

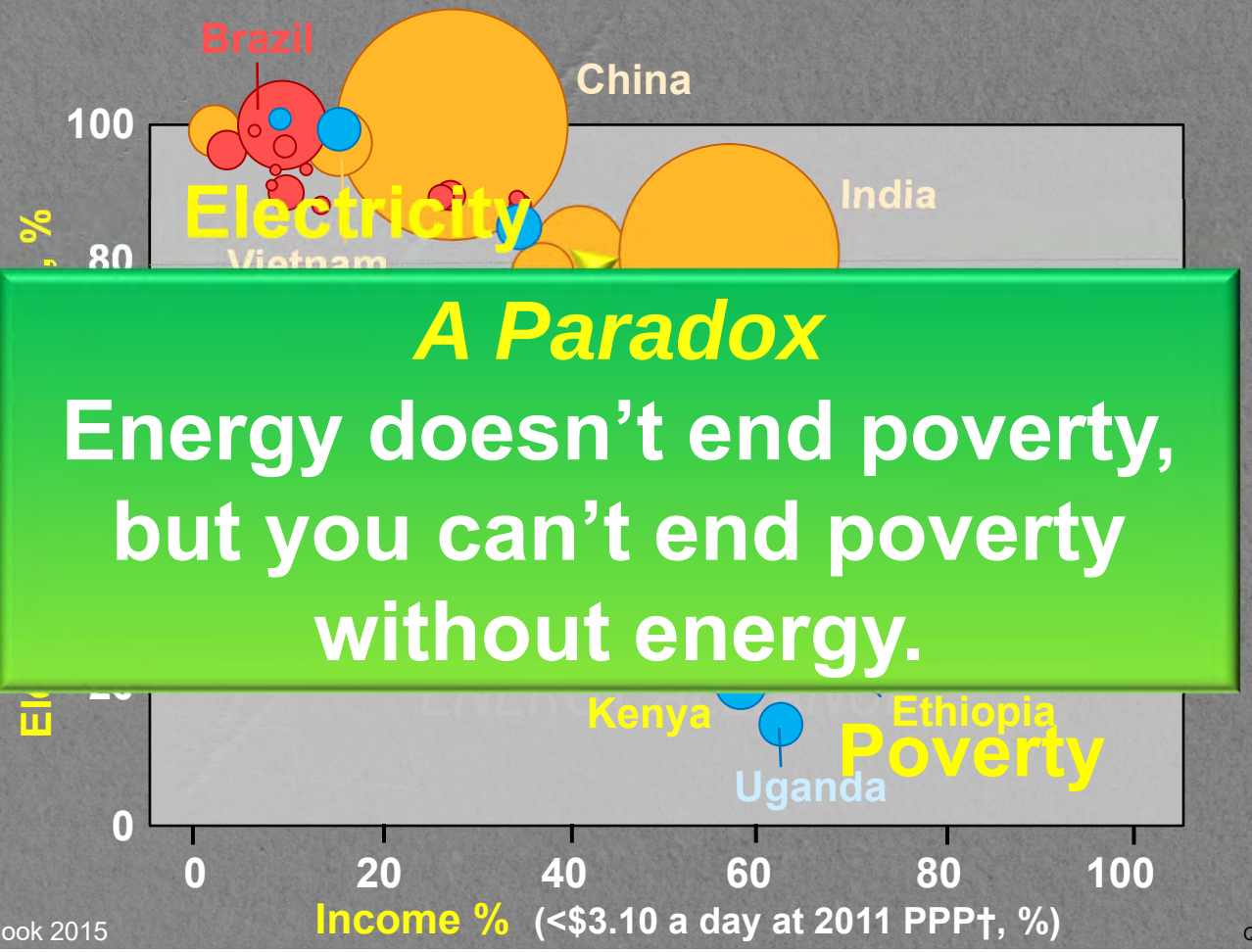
Africa

Asia

Latin America

* Bangladesh uses 2005 PPP and $2 a day poverty line

† Purchasing power parity

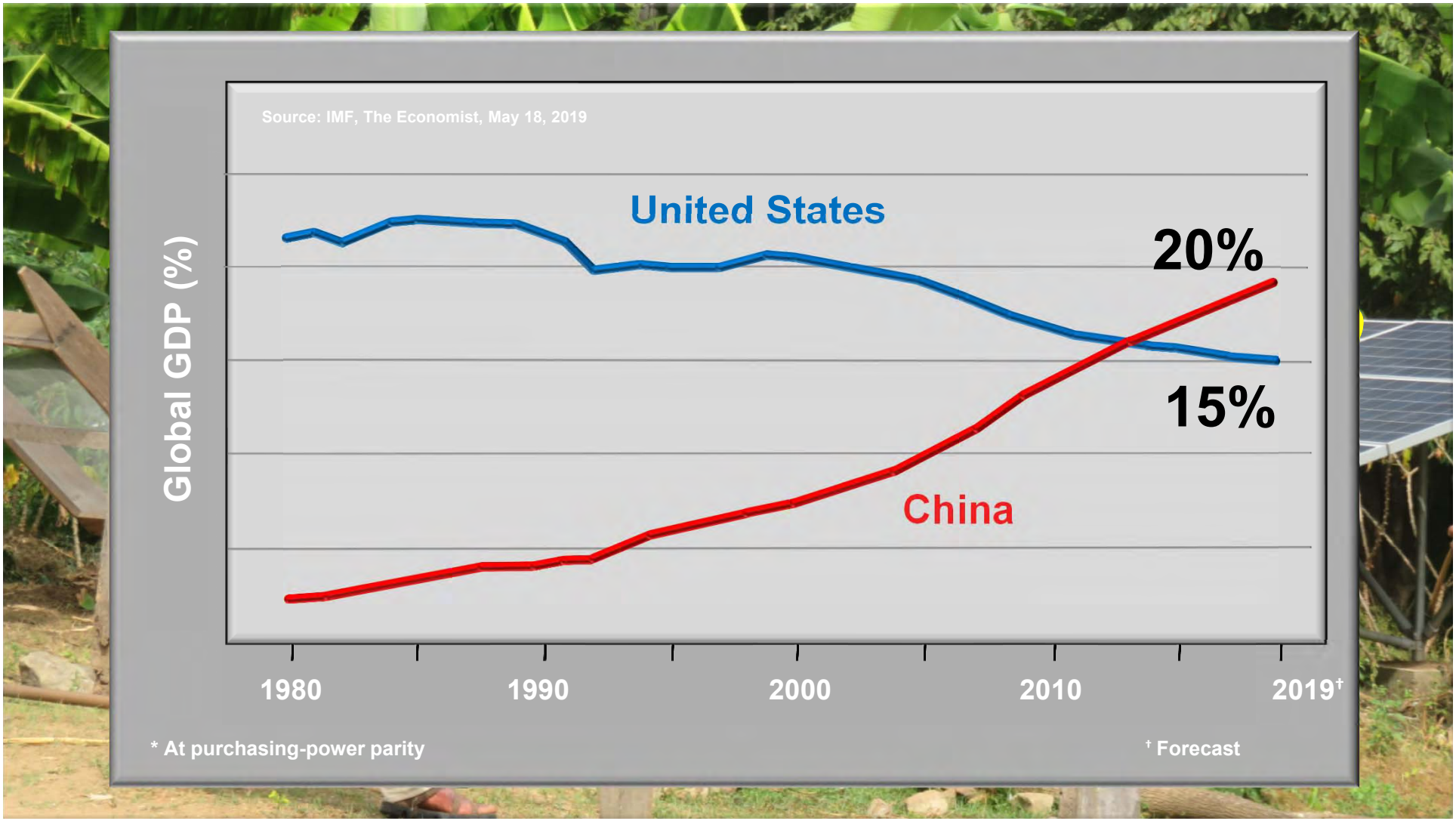


A Paradox

Energy doesn't end poverty, but you can't end poverty without energy.

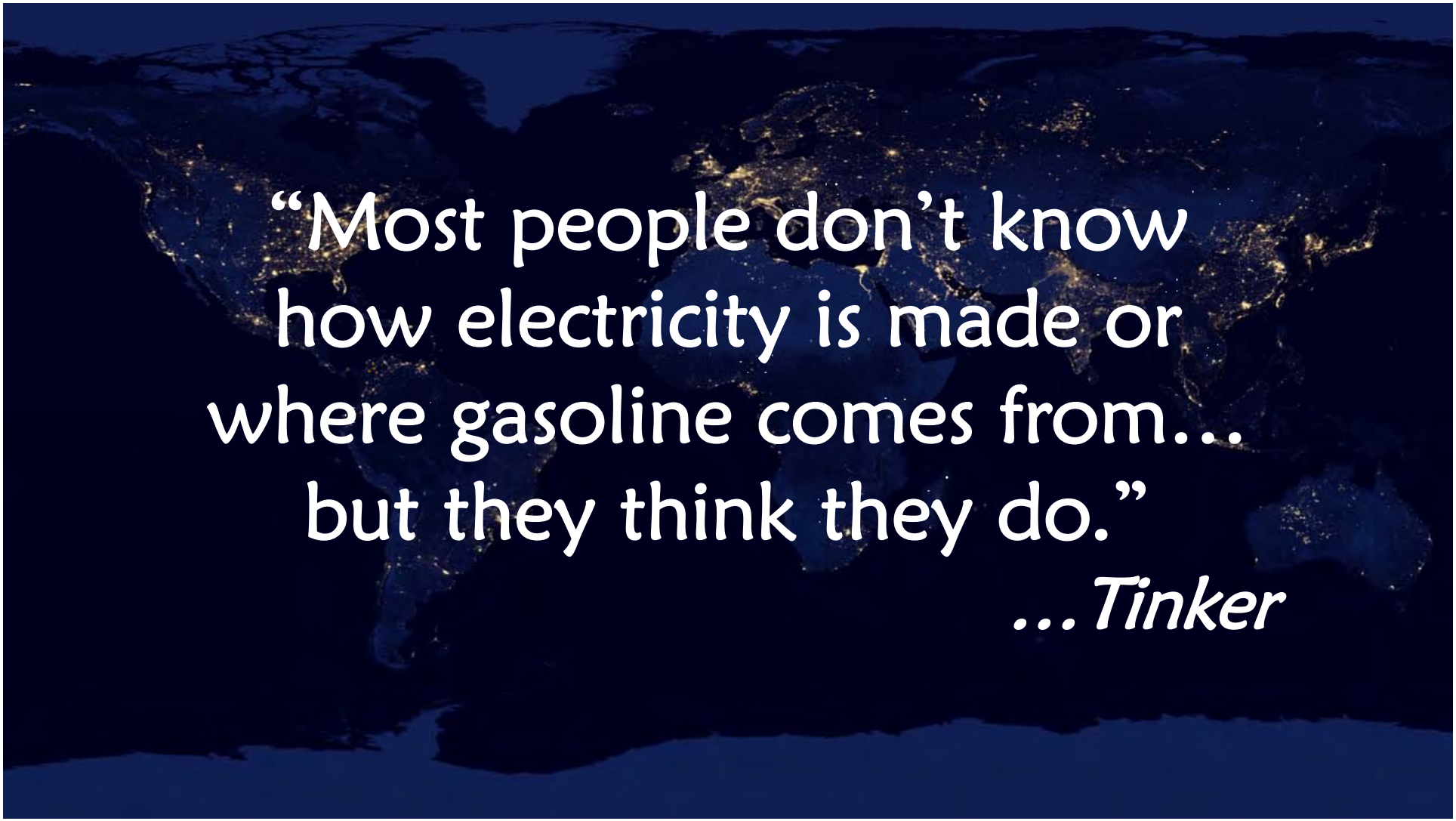
Sources: World Bank; IEA; World Energy Outlook 2015

QAe5021

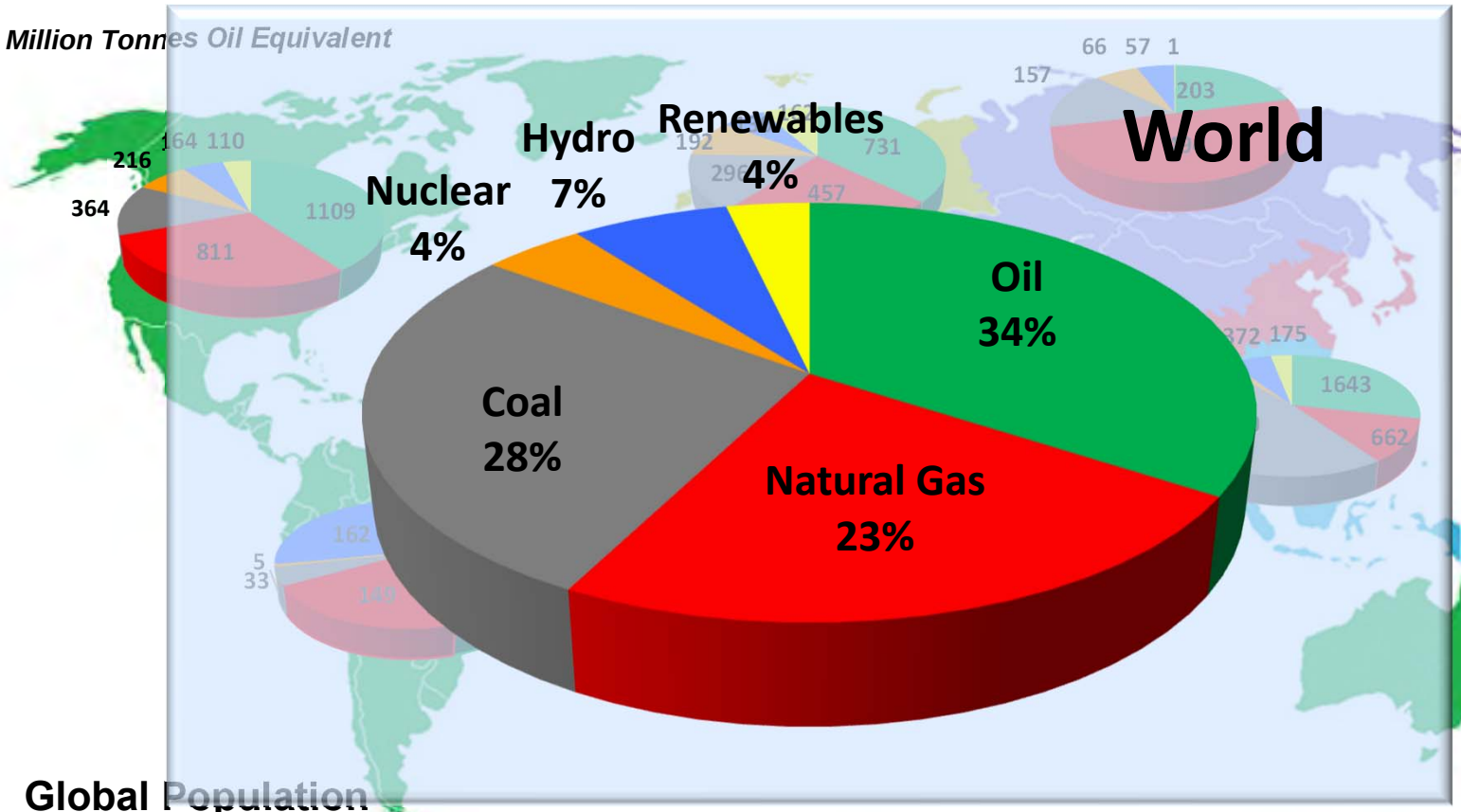

Source: IMF, The Economist, May 18, 2019
Global GDP (%)
United States
20%
15%
China
1980
1990
2000
2010
2019†
* At purchasing-power parity
† Forecast



SWITCH
ENERGY ALLIANCE


"Most people don't know
how electricity is made or
where gasoline comes from...
but they think they do."
...Tinker

The Global Energy Mix



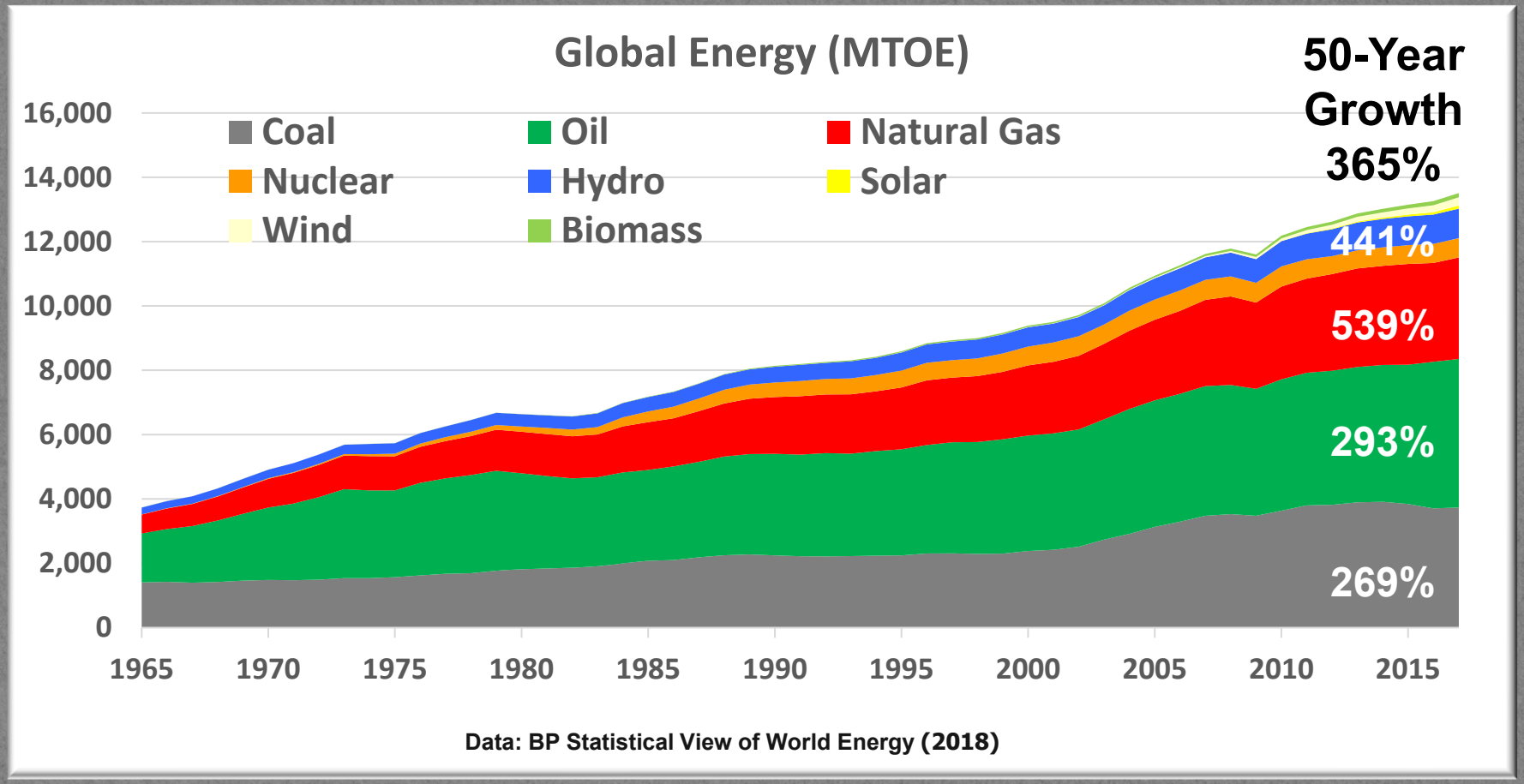
Global Population

Each color on the map represents ~ 1 billion people

Data: BP Statistical View of World Energy (2018)

Tinker 2020

Global Energy Consumption Mix



Data: BP Statistical View of World Energy (2018)

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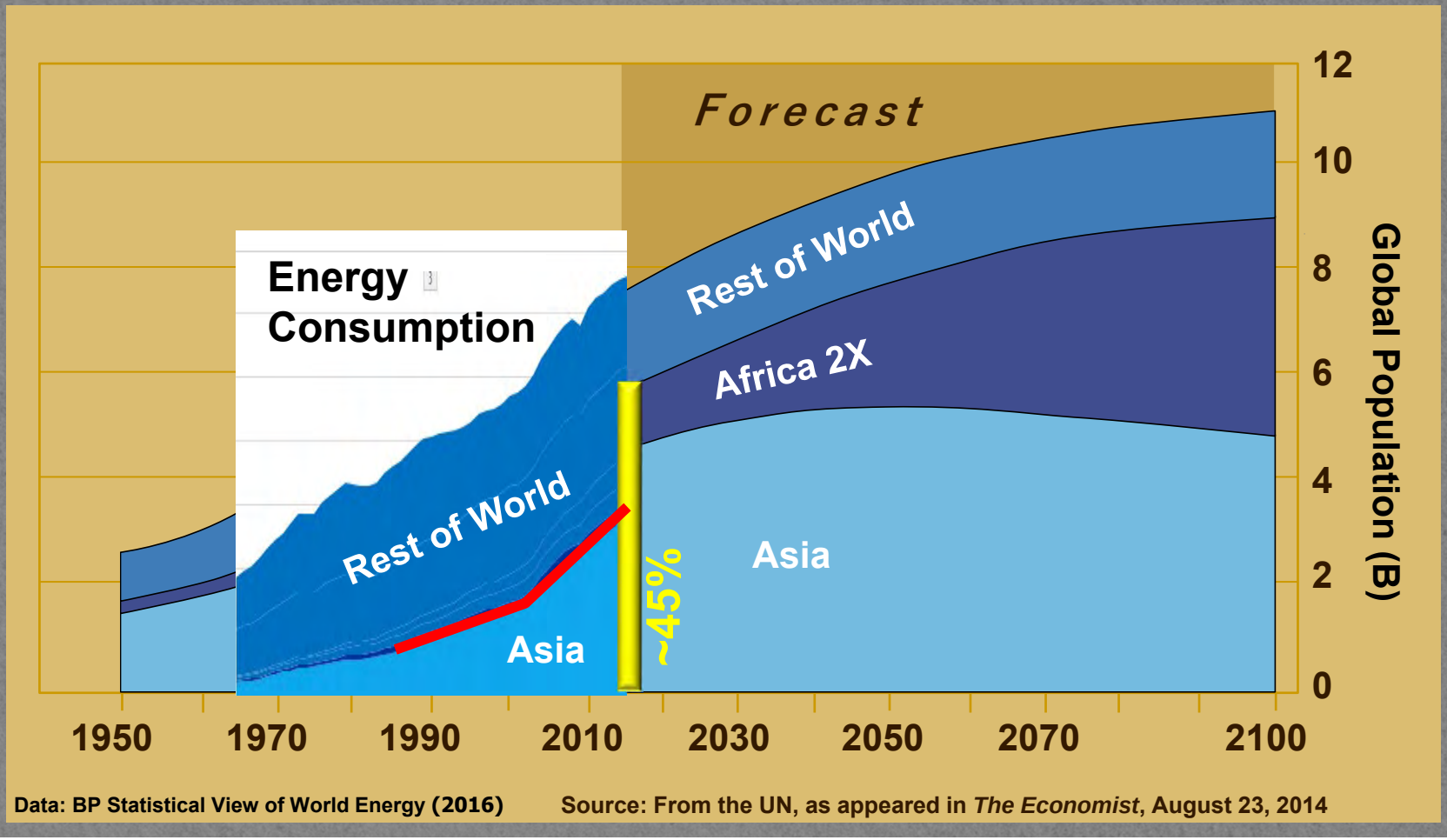
Population and Energy



Data: BP Statistical View of World Energy (2016)

Source: From the UN, as appeared in *The Economist*, August 23, 2014

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P y



rld could
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12
10
0

1950
1970
19
70
2100

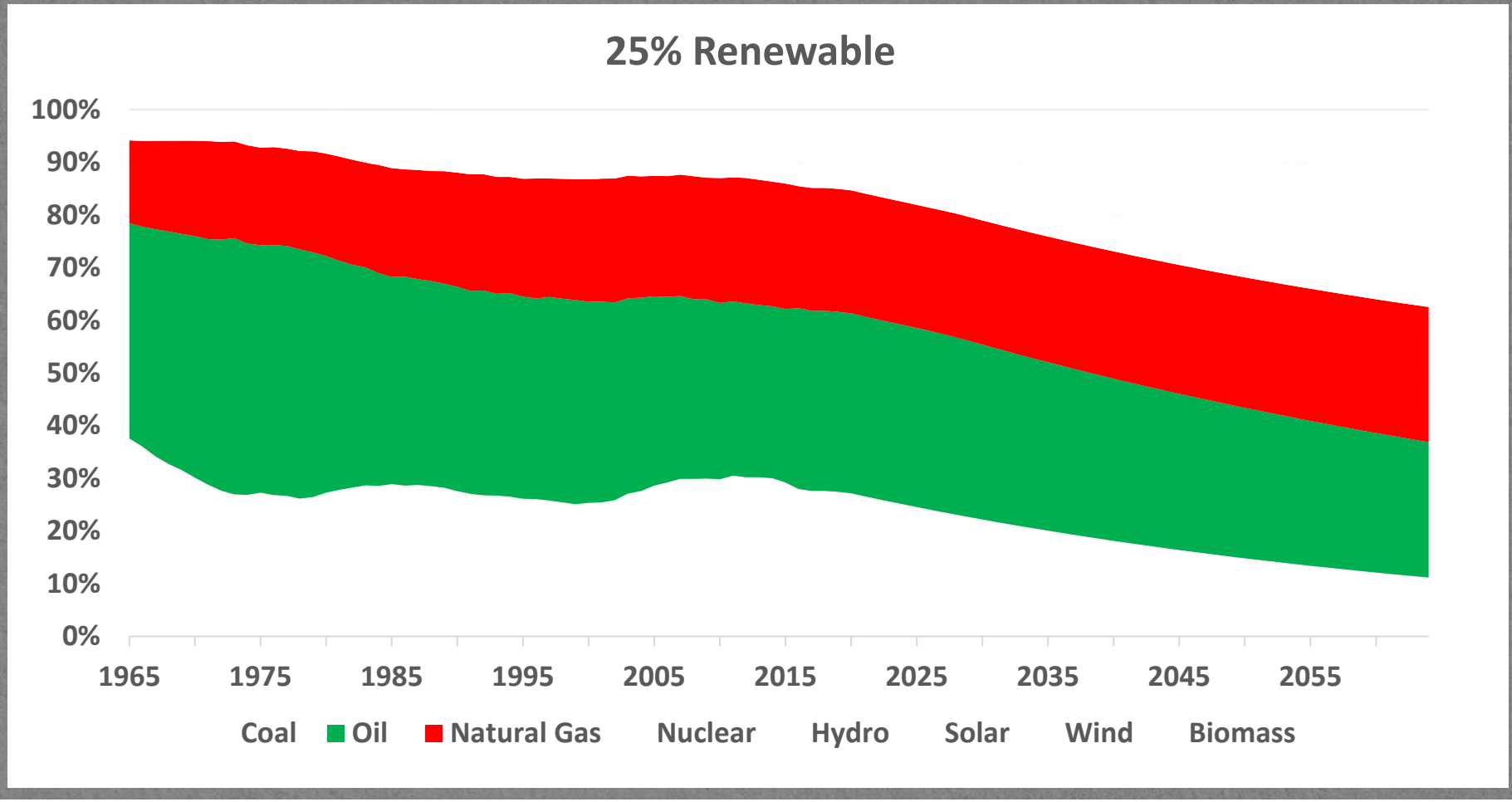
Data: BP Statistical View of World E

e Economist, August 23, 2014

Data: BP Statistical View of World Energy (2018)

Global Energy 2065

Tinker 2020




(inlc. Permian WCA&WCB)
Gas Tcf
Oil Bbbl
Original In-Place 5300 1800
Tech. Recoverable 1100 145
Production to date 75 10
For presentation or publication, reference: Bureau of Economic Geology Shale Resource and Production Project
http://www.beg.utexas.edu/research/programs/shale
Bakken/Three Forks
~18,000
~100,000
Recovery to date of just 3% of the natural gas and 2% of the oil leaves a tremendous remaining resource.
~35,000
Eagle Ford
~16,500
~90,000
2010
2011
2012
2013
2014
2015
2016
Google Earth

Moving the "Cloud"



Global data centers use about 3% of total electricity.

Source: Gadgets 360
https://gadgets.ndtv.com/internet/news/aws-snowmobile-will-move-your-data-to-the-cloud-in-a-huge-truck-1632542

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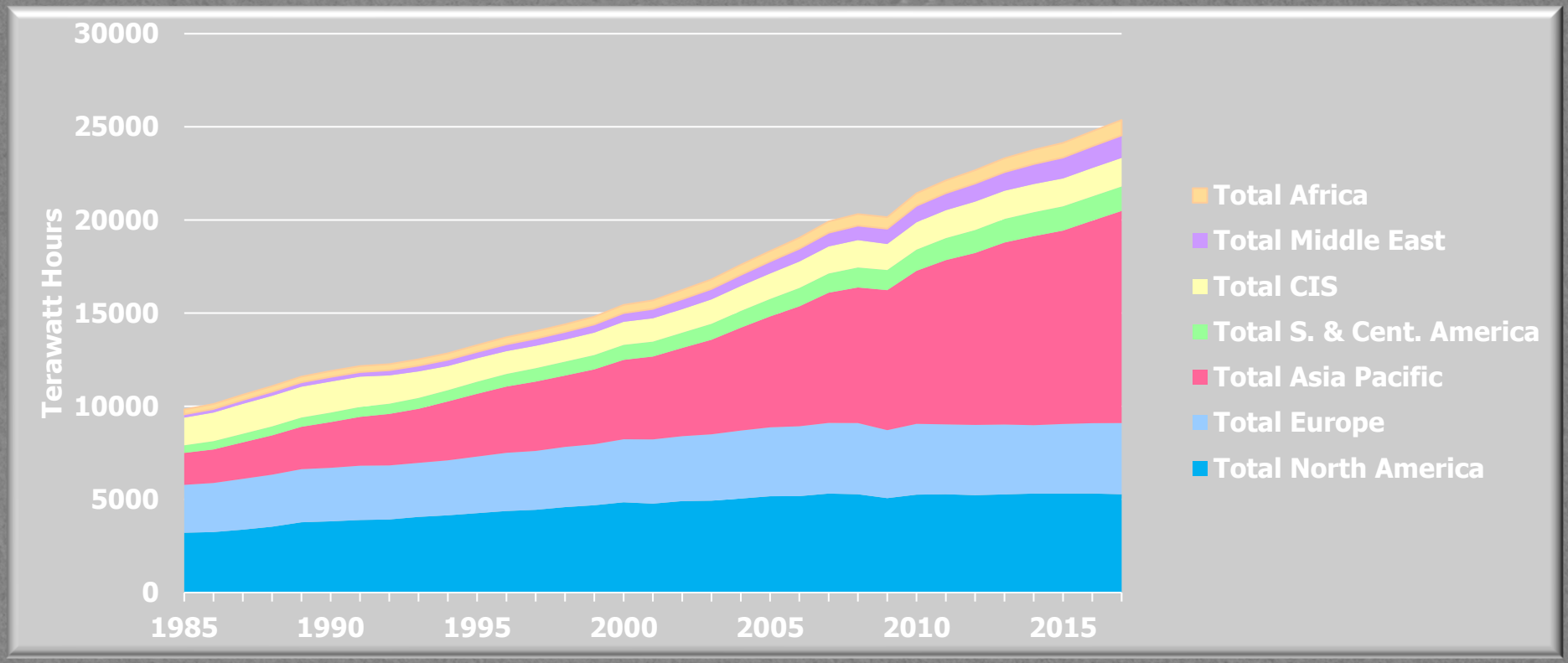
Global Electricity Generation

By Region



Source: **2018 BP Statistical Review**

QAe6822

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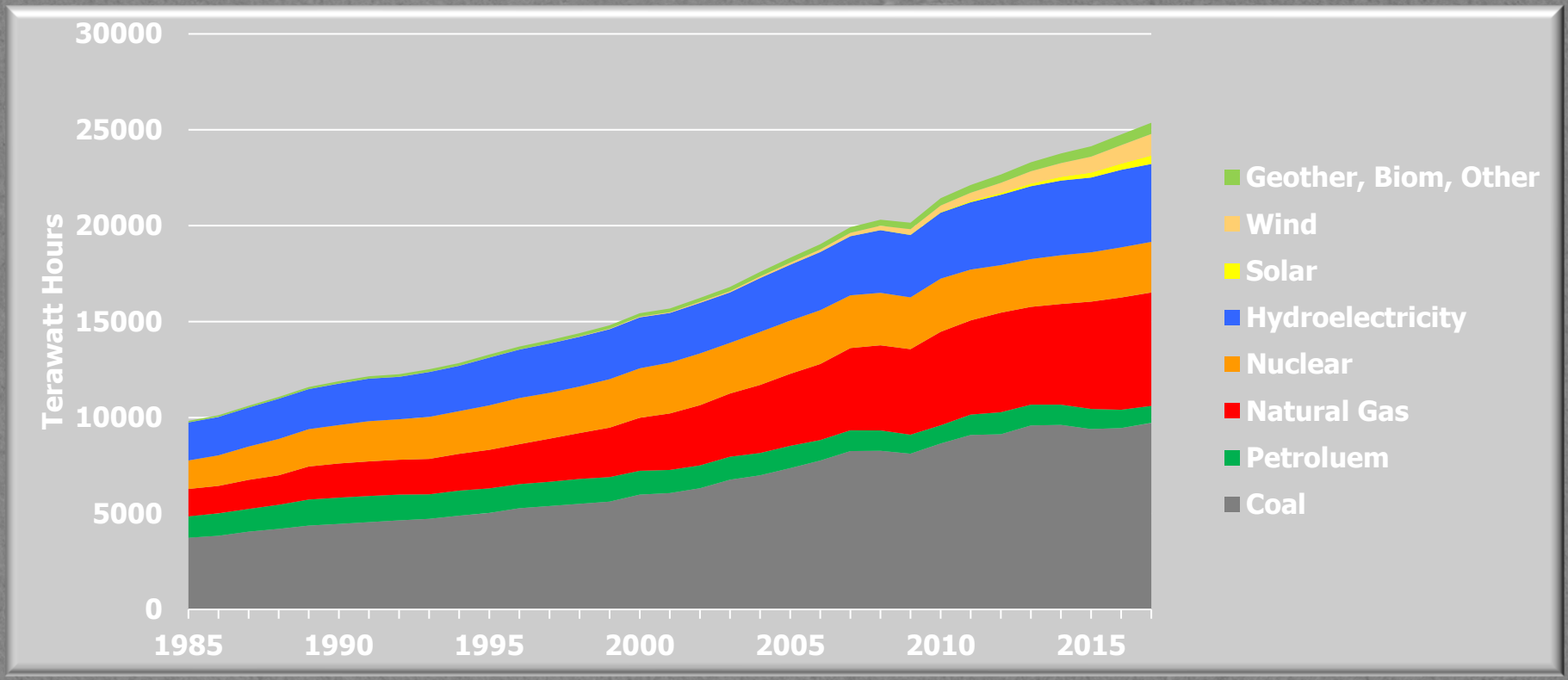
Global Electricity Generation

By Source



Source: 2018 BP Statistical Review

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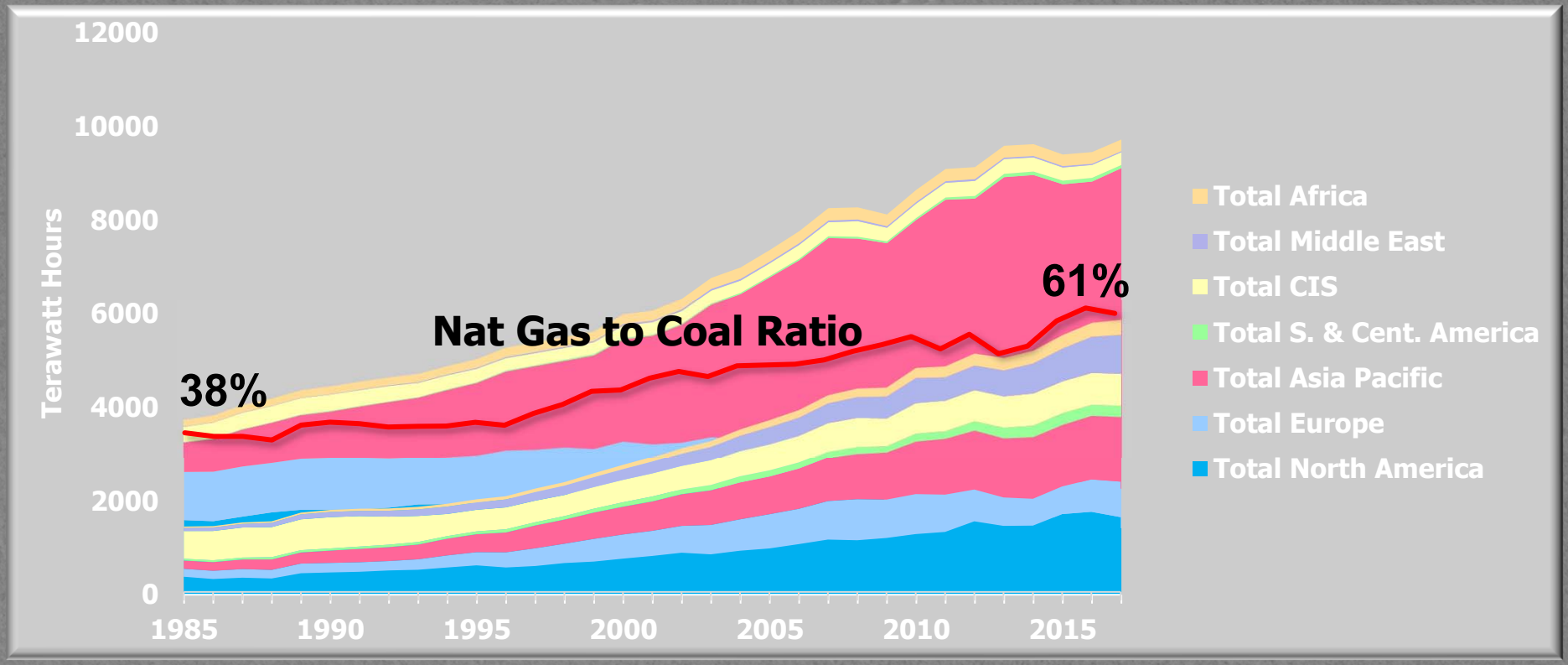
Global Electricity Generation

Coal v. Natural Gas



Source: 2018 BP Statistical Review

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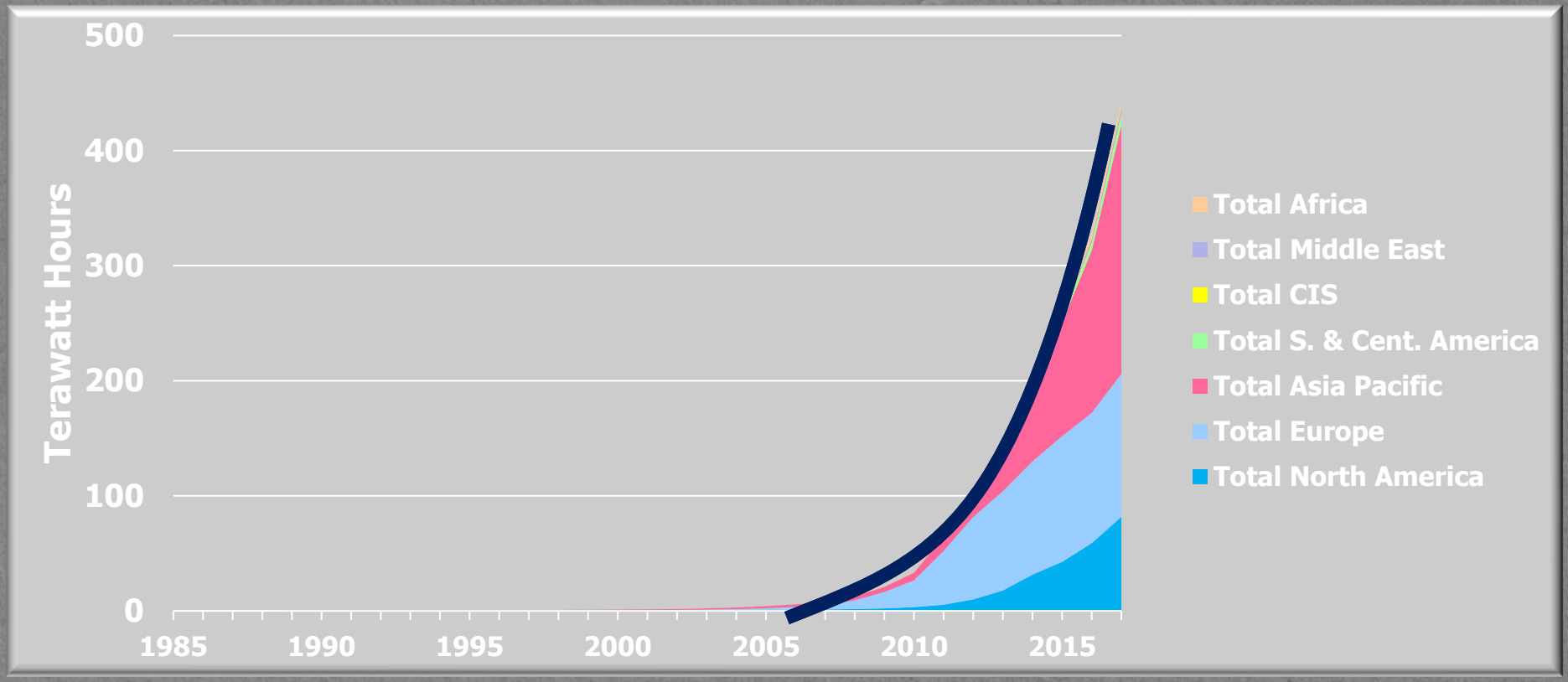
Global Solar Photovoltaic Electricity

Generation

Tinker 2020



Source: 2018 BP Statistical Review

QAe6821

Tinker 2019

U.S. New Capacity

Residential Solar Panels

MW, quarterly

~2200 MW/yr New Capacity

~ 30% Capacity Factor

~ 700 MW Generation

< 1 Nuclear Reactor

Source: The Economist, Wood Mackenzie Power & Renewables

QAe7585a

Tinker 2019

Nuclear Power Reactors

Potential Output (Gross Gw)



Source: World Nuclear Association

QAe8502

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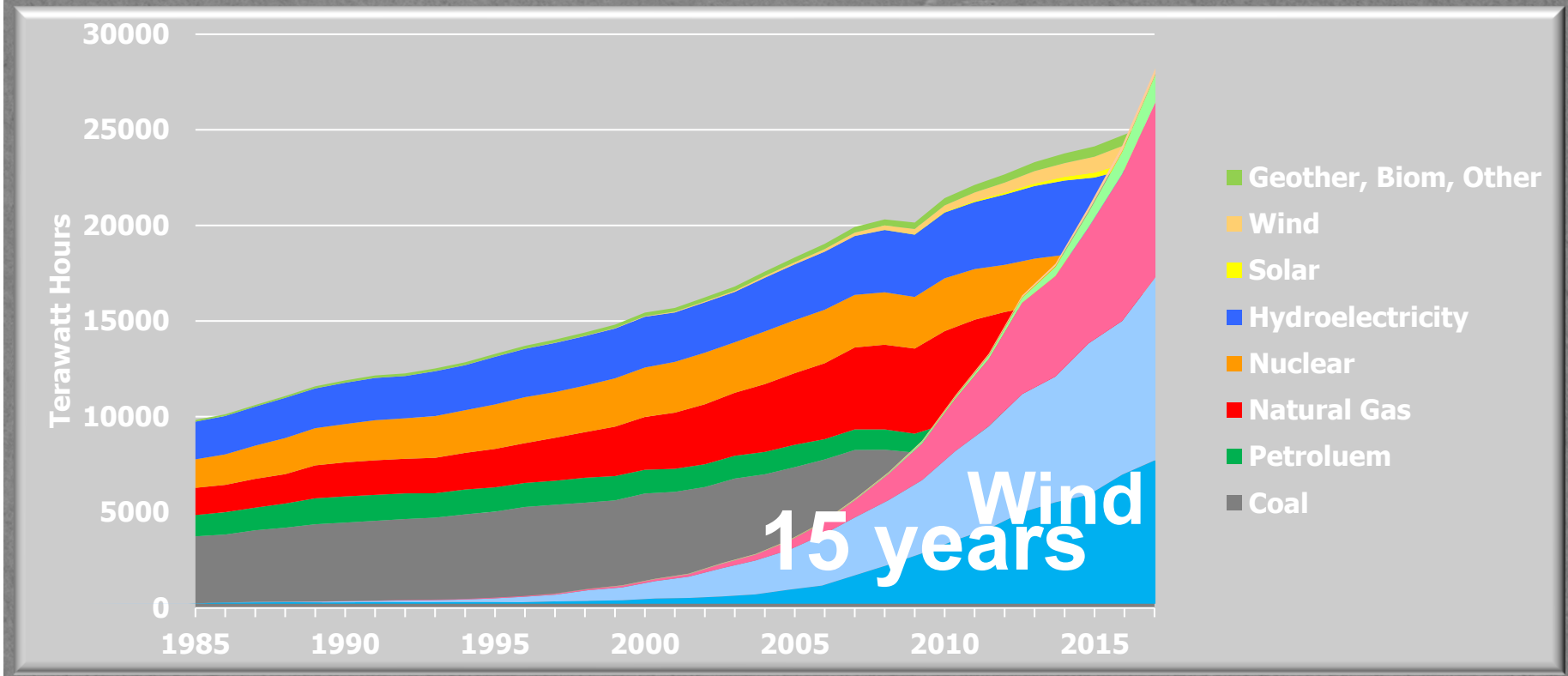
Global Electricity Generation
By Source



Source: 2018 BP Statistical Review

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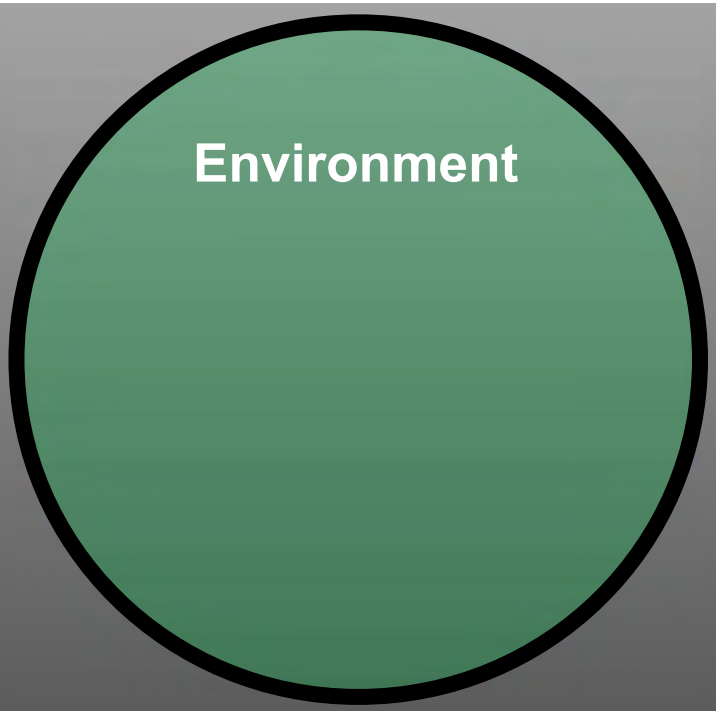

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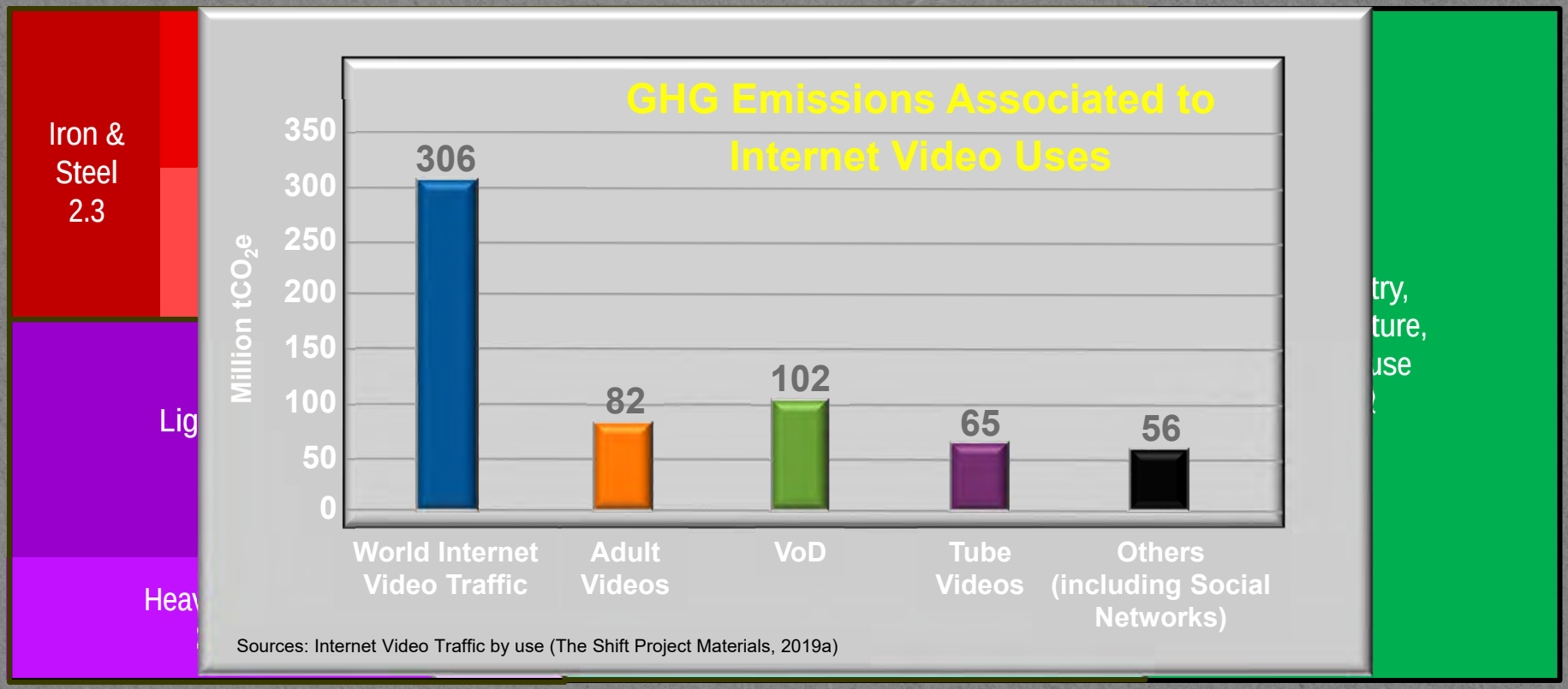
It is the mark of an educated mind to be able to entertain a thought without accepting it.

…Aristotle

Tinker 2020

Global Anthropogenic CO_2 Emissions

2014, Total 48 Billion Tonnes



Data: International Energy Agency

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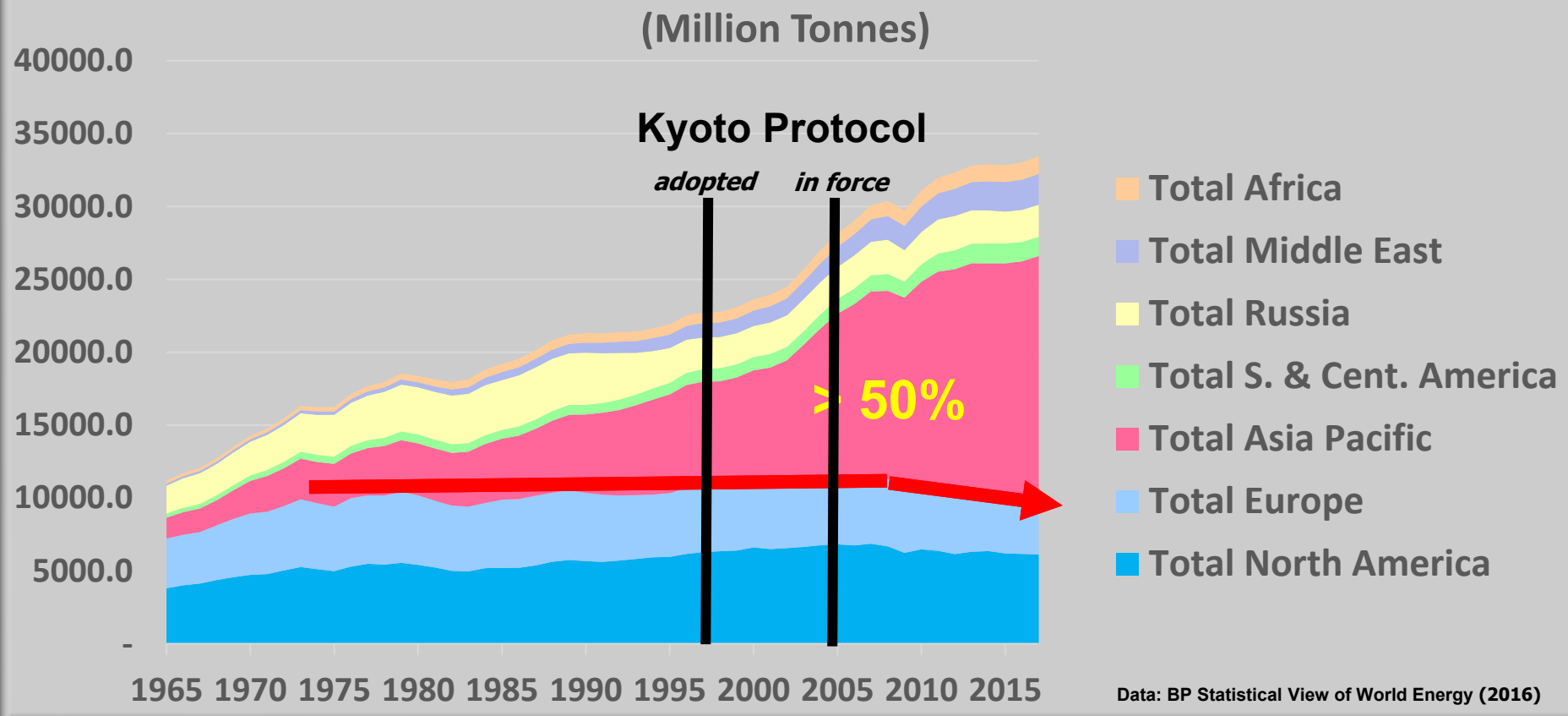
CO_2 Emissions



Data: BP Statistical View of World Energy (2016)

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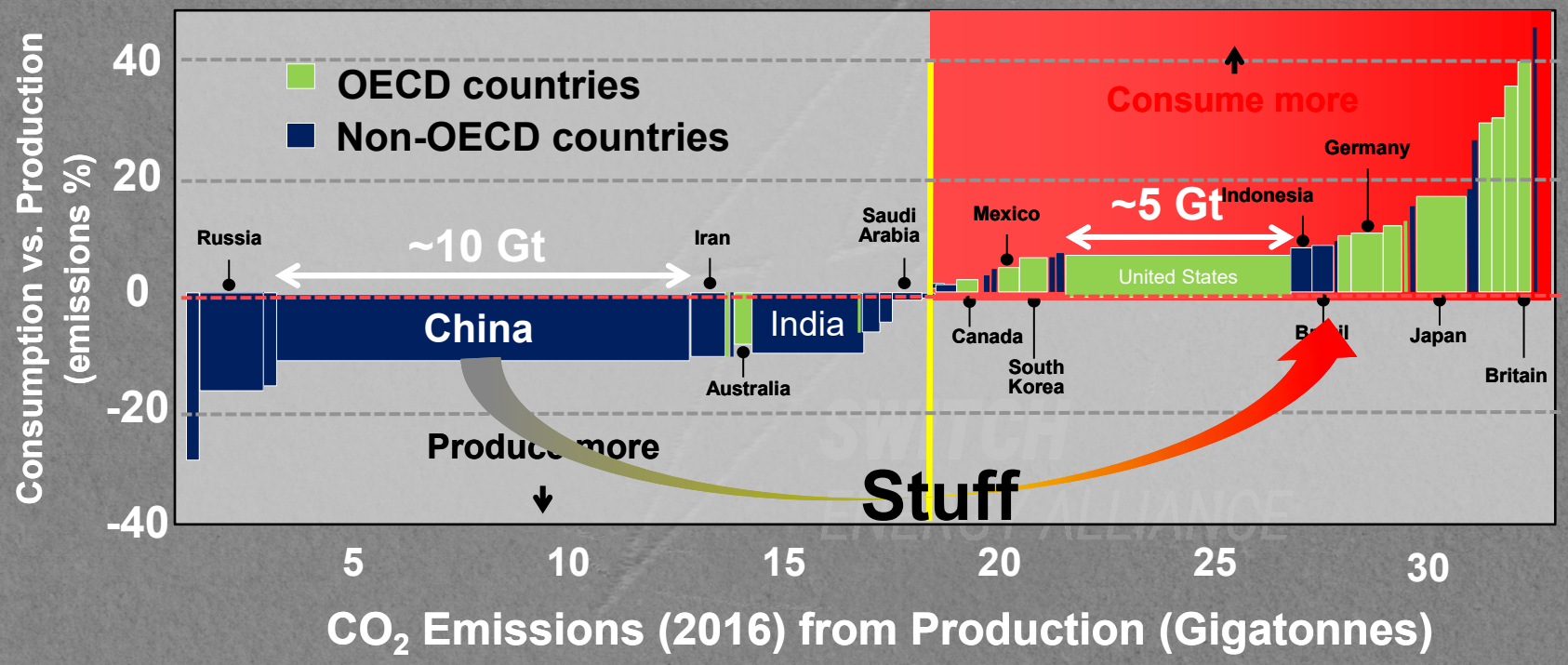
CO_2 Emissions

Consumption vs. Production



Source: Global Carbon Project; World Bank; The Economist, October 19, 2019

QAe8430

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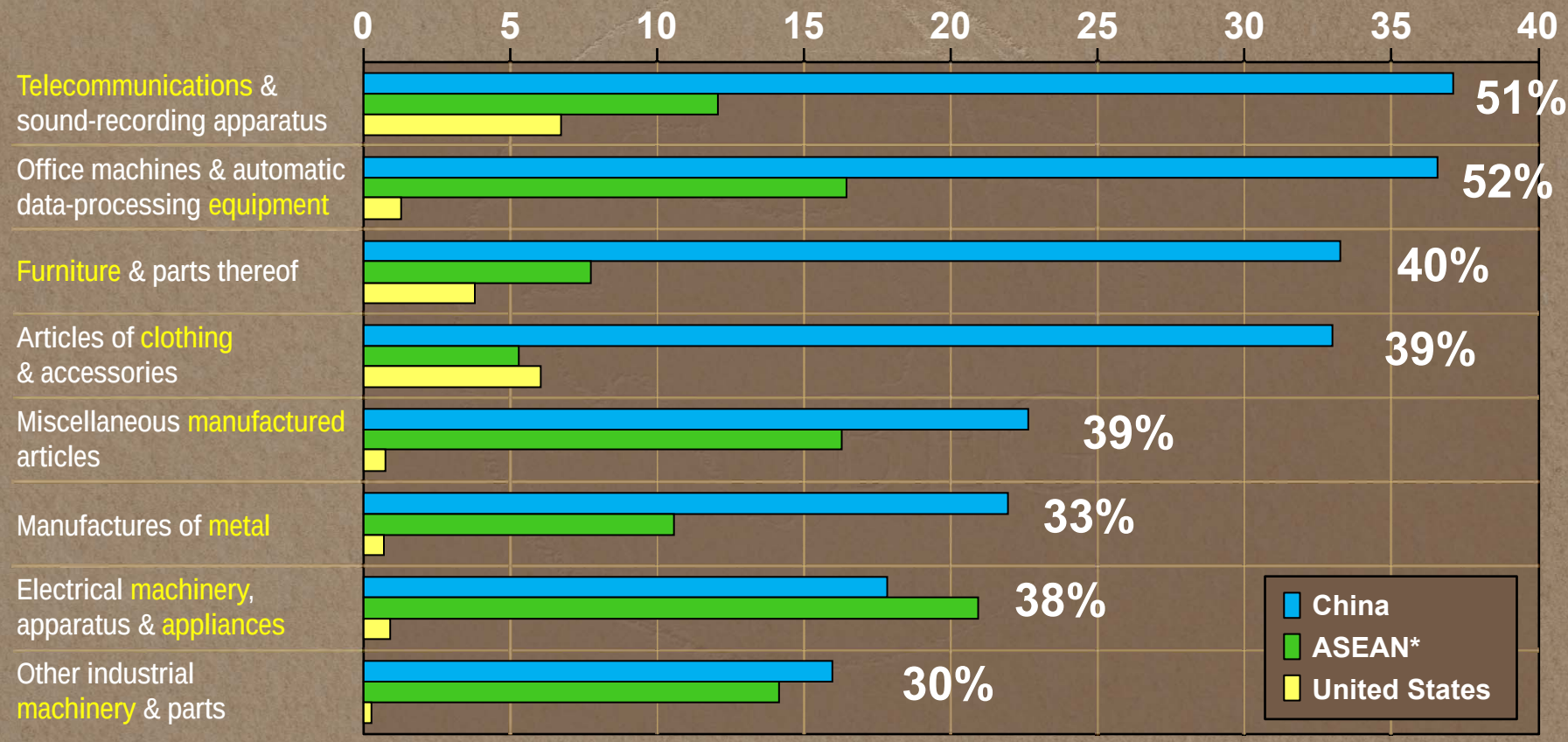
Global Market Share of Selected Industries

(2018, %)



Source: Natixis; UNCTAD

*Indonesia, Thailand, Singapore, Malaysia, Philippines, Vietnam, Cambodia, Brunei, Myanmar (Burma), Laos

QAe8502(a)

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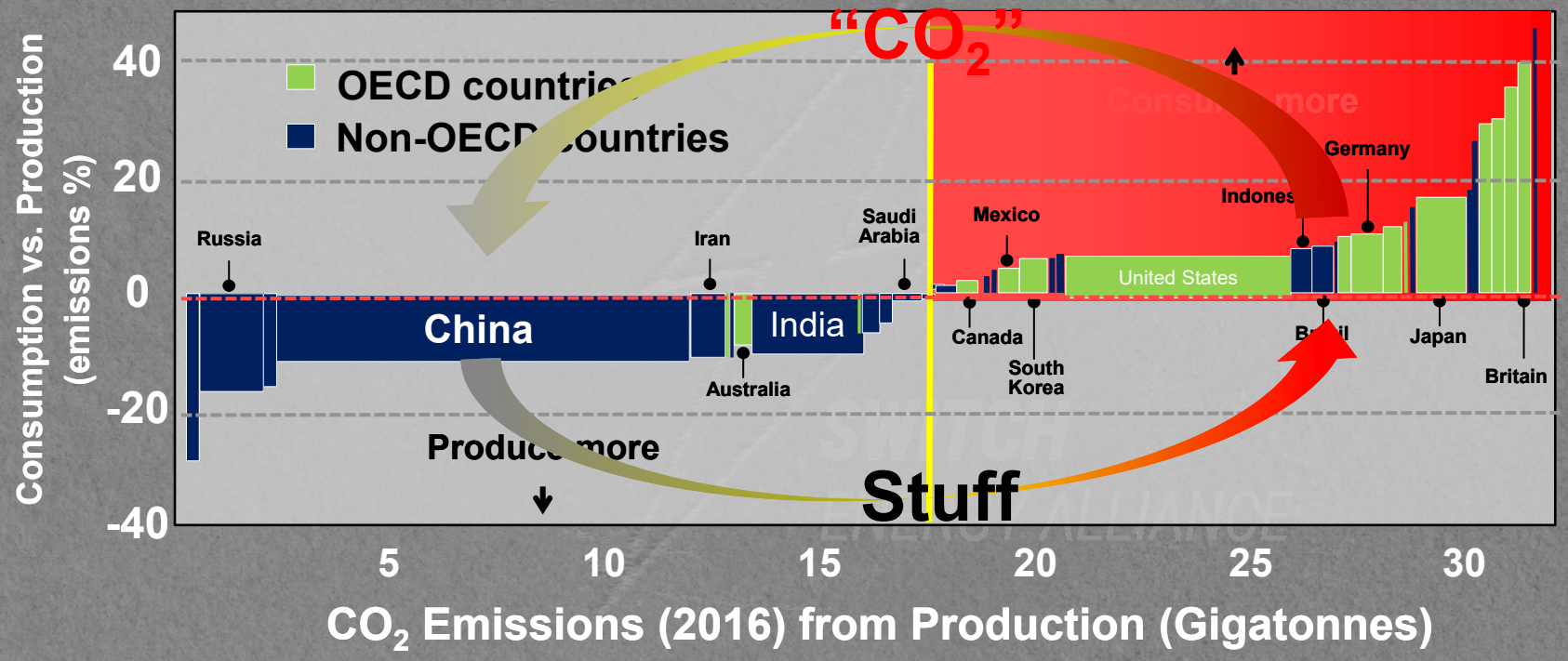
CO_2 Emissions

Consumption vs. Production



Source: Global Carbon Project; World Bank; The Economist, October 19, 2019

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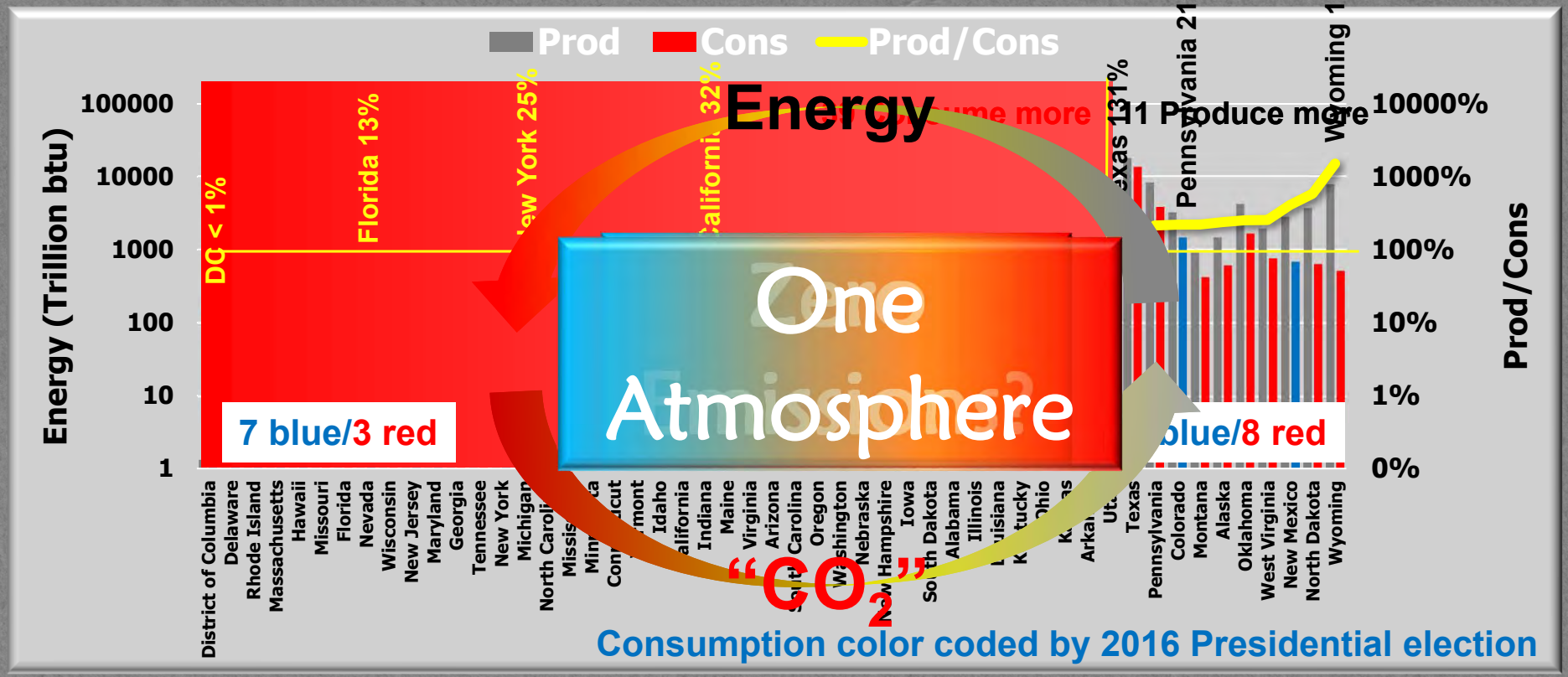
U.S. States Total Energy

Production and Consumption



Consumption color coded by 2016 Presidential election

Data Source: U.S. EIA https://www.eia.gov/state/rankings/ https://www.eia.gov/state/seds/seds-data-complete.php

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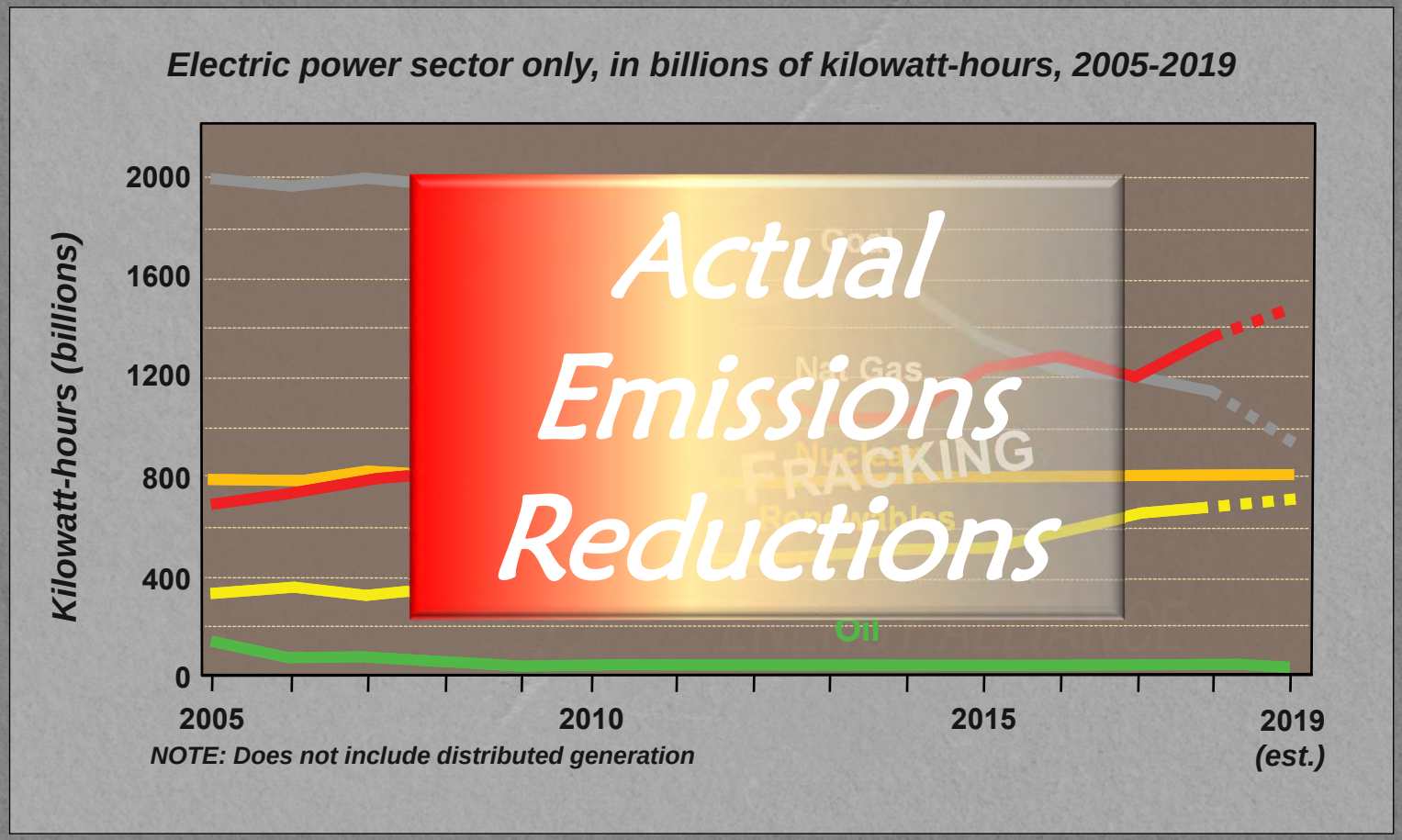
U. S. Power Generation by Energy Source



Source:
Rhodium Climate Service, *Inside Climate News*, Nicholas Kusnetz, January 9, 2020

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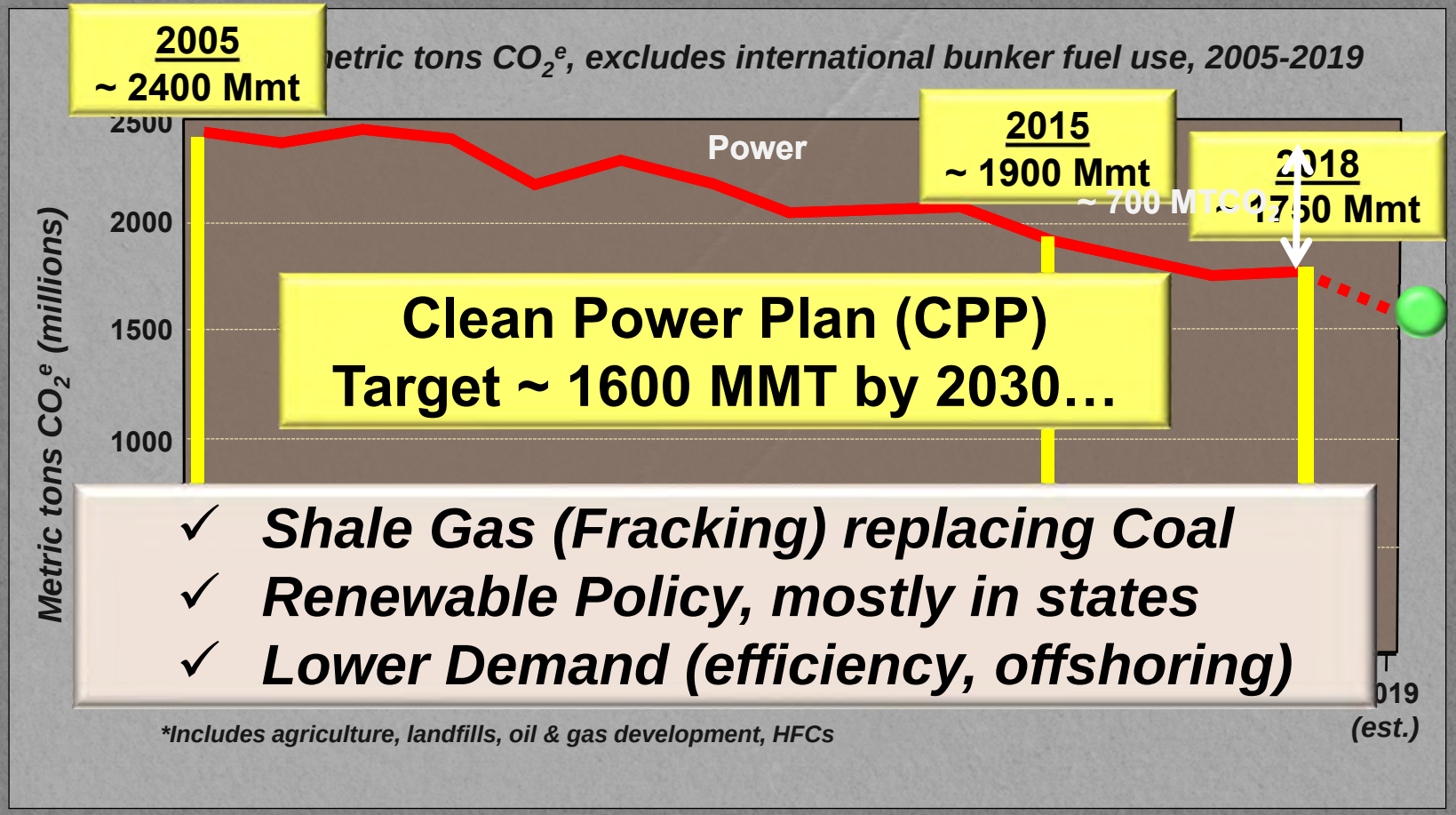
U. S. Net Greenhouse Gas Emissions by Sector



Source:
Rhodium Climate Service, *Inside Climate News*, Nicholas Kusnetz, January 9, 2020 . BP Data

QAe8429

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Nat Gas Twh

2000
1800
1600
1400
1200
1000
800
600
400
200
0

201
Coal/Gas
8X Gas

19
Coal/G

2017
Coal/Gas ~ 5X
10X Coal Twh

fic

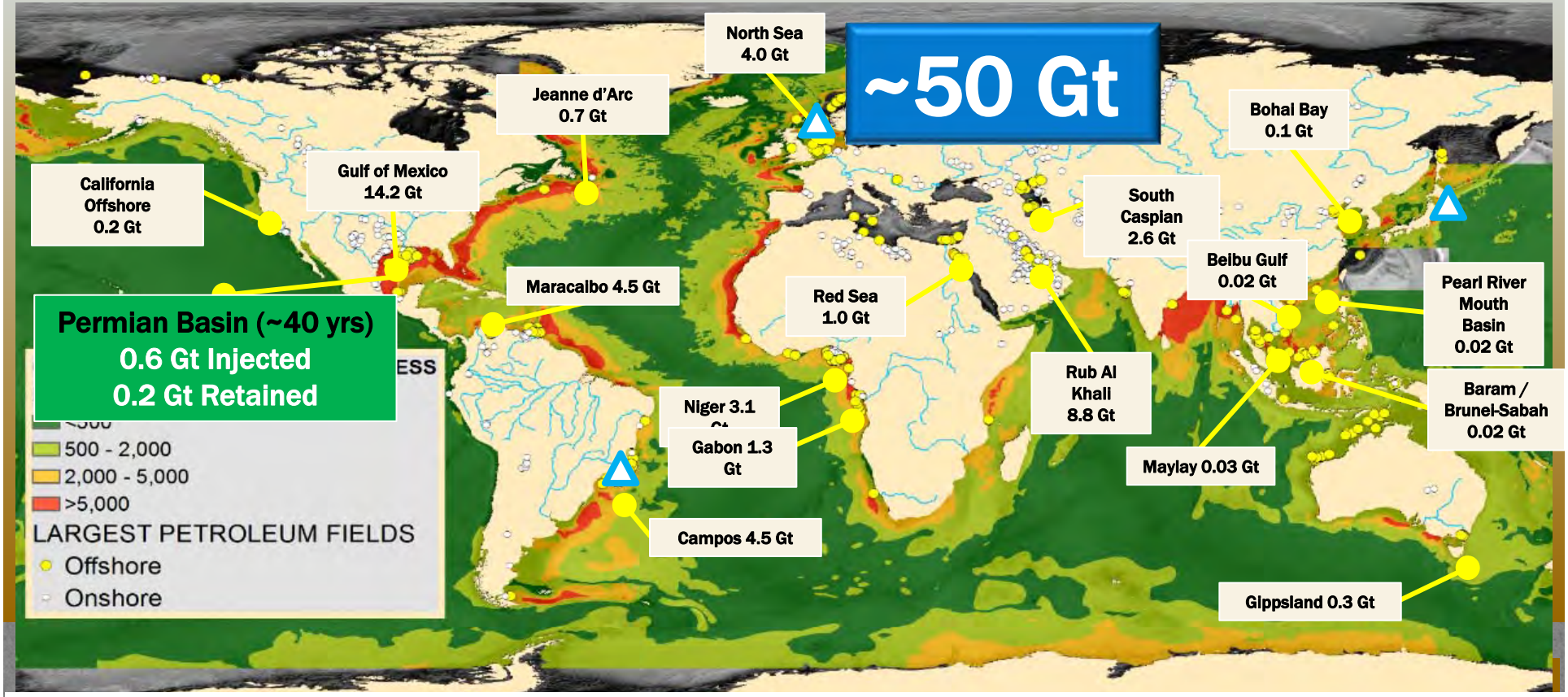
0
7000
8000

Data Source: BP Stats Rev

QAe6822

Source: BEG Gulf Coast Carbon Center

Offshore Margins and Potential Use of CO_2 for EOR



EOR Source: ISO/TC265 Carbon Dioxide Capture, Transportation and Geological Storage – Carbon Dioxide Storage using Enhanced Oil Recovery (CO2-EOR): Cyphers, Koperna, and Godec

CO_2 Emissions Reduction at Scale

- Coal to Gas (CCUS)
- Efficiency
- Nuclear
- Geothermal and Hydro
- Distributed Renewables

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Bureau of Economic Geology



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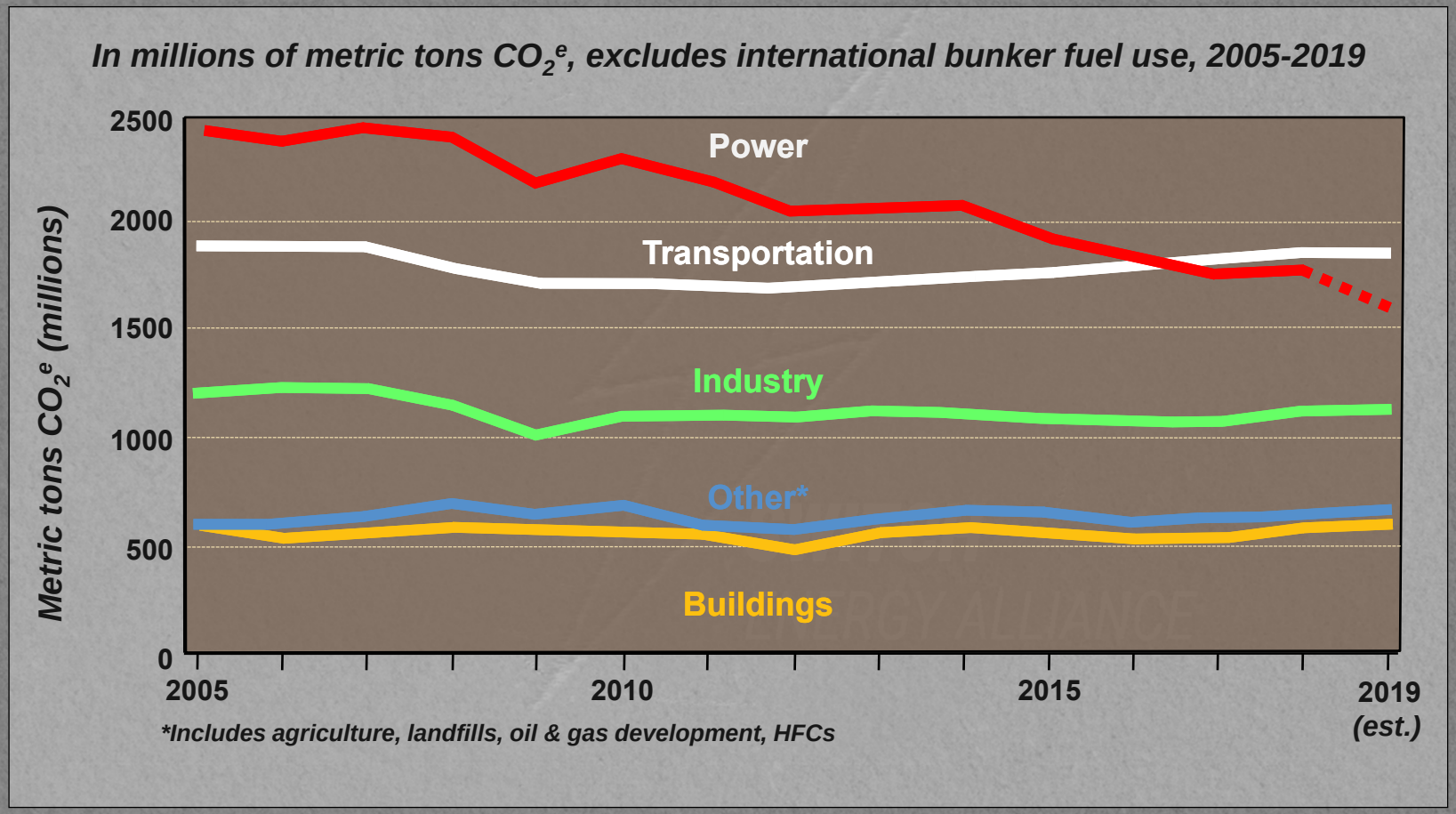
U. S. Net Greenhouse Gas Emissions by Sector



Source:
Rhodium Climate Service, *Inside Climate News*, Nicholas Kusnetz, January 9, 2020 . BP Data

QAe8429


Electrons!
...Diesel!
NULLARBOR

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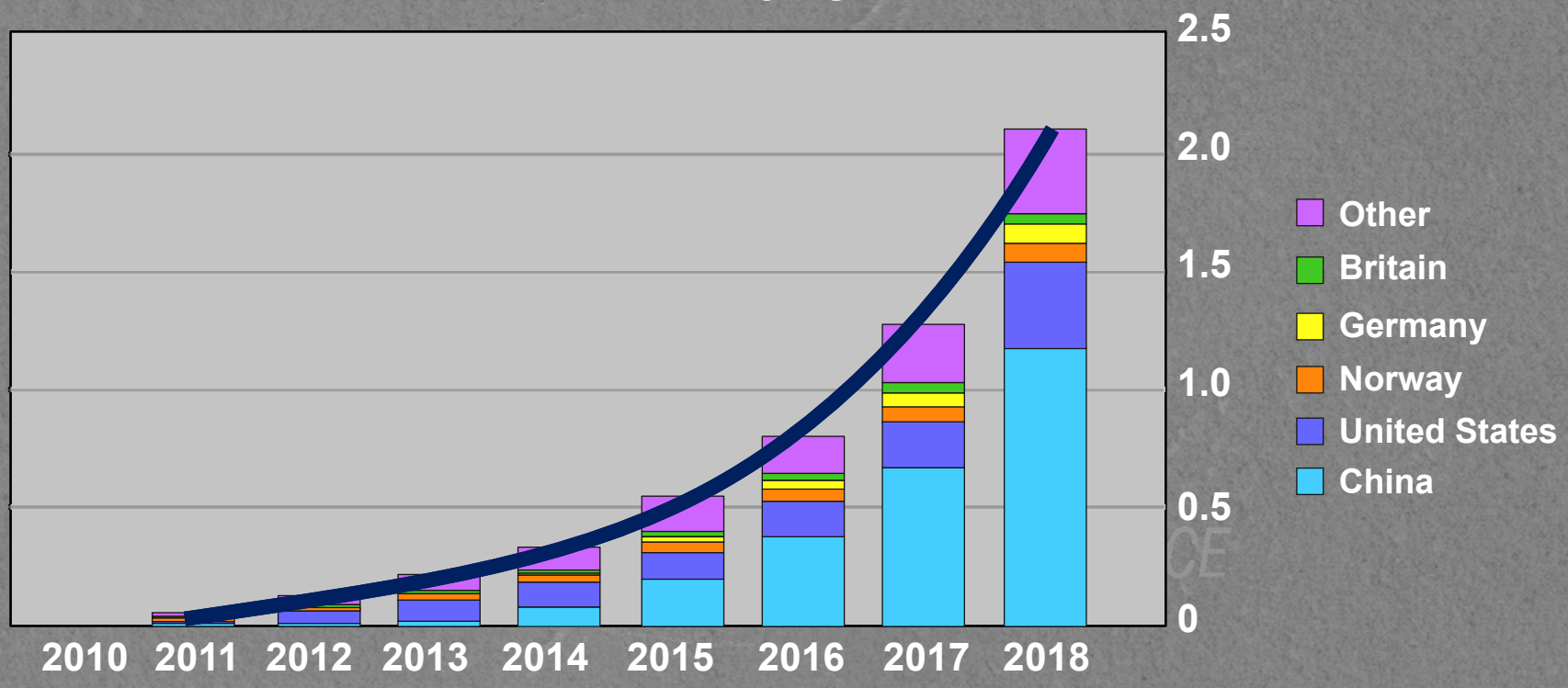
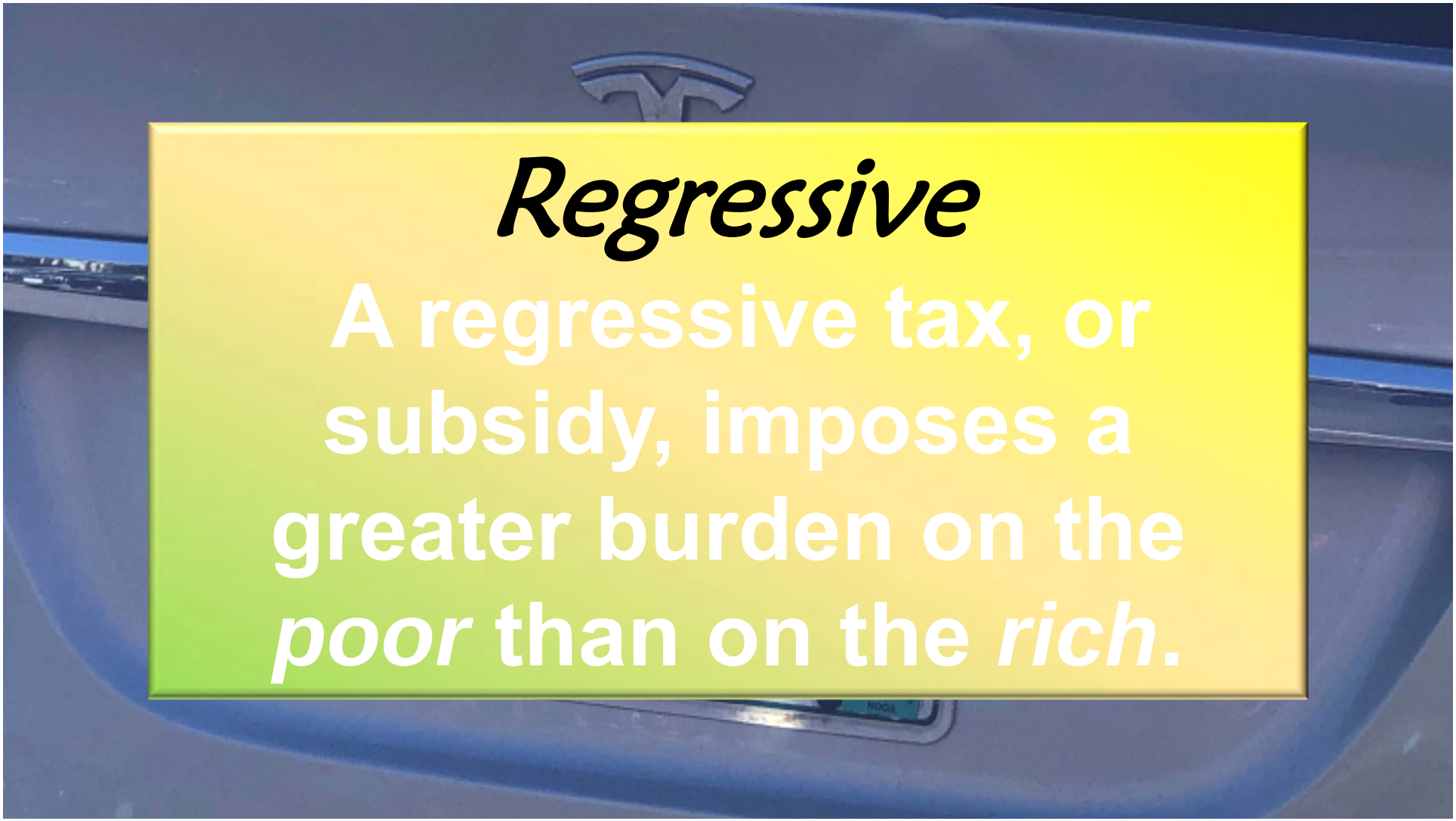
Global Electric-Vehicle Deliveries



Sources: The Economist, EV volumes; Bloomberg NEF

QAe7584e


Regressive
A regressive tax, or subsidy, imposes a greater burden on the *poor* than on the *rich*.

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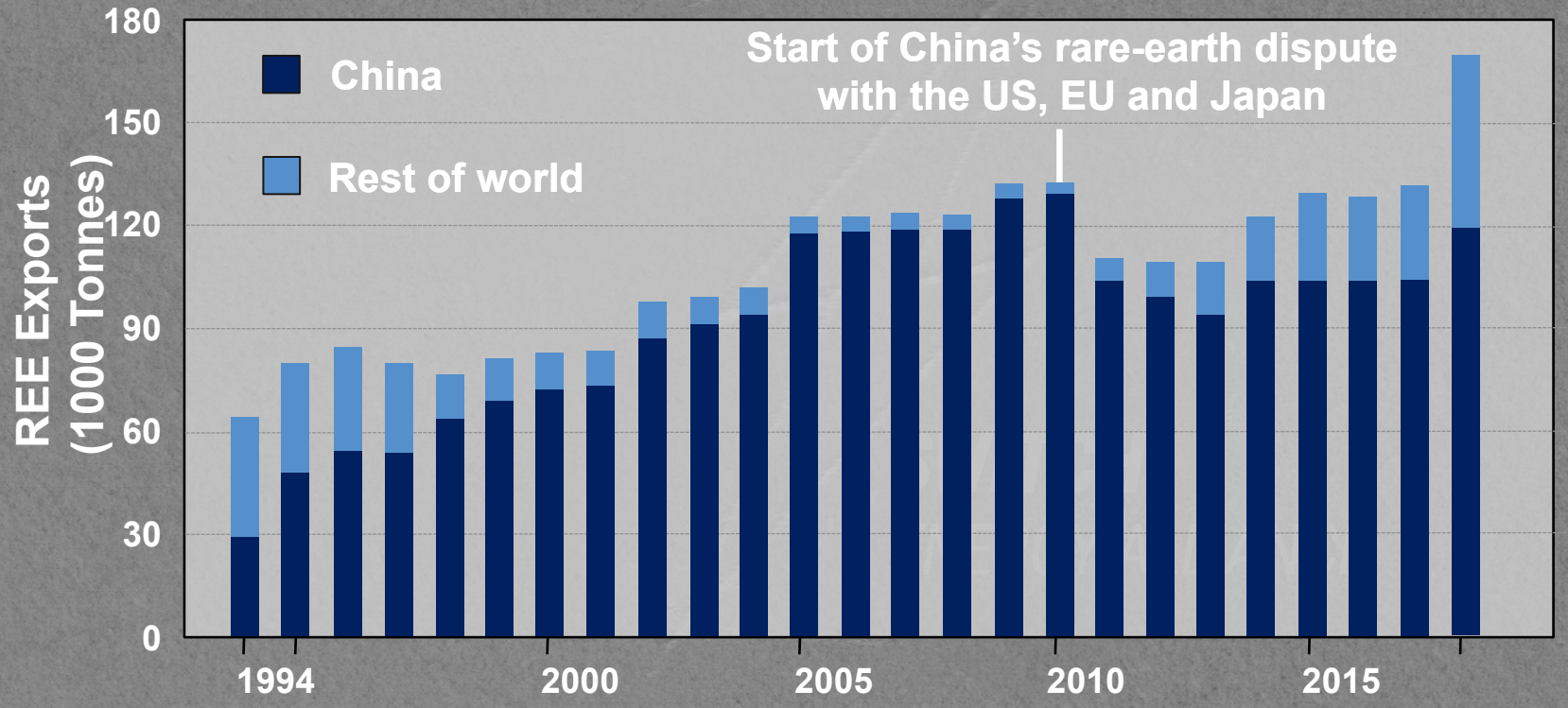
Rare-Earth Exports



Source: Wind Info, The Economist, June 15, 2019

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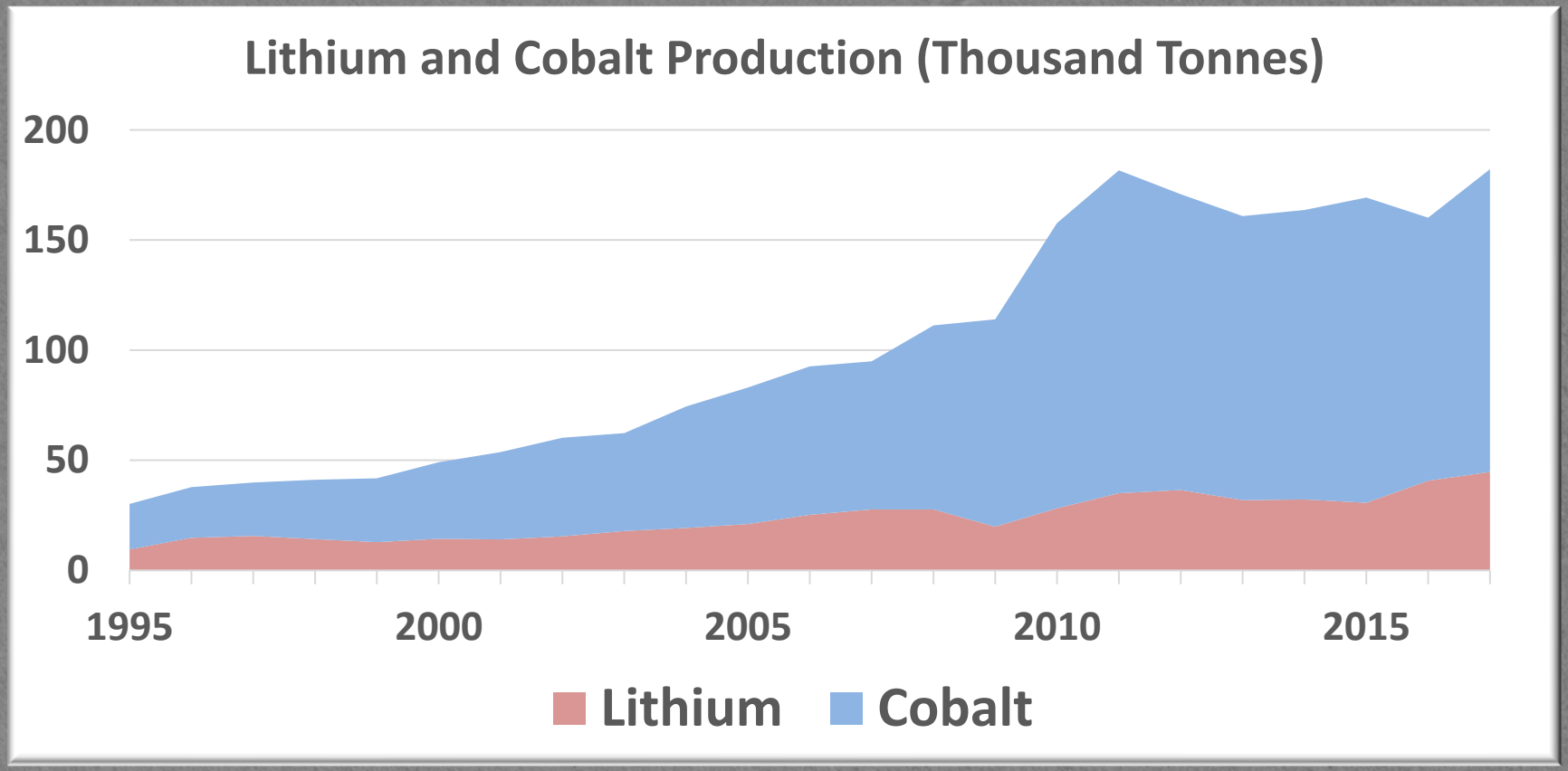
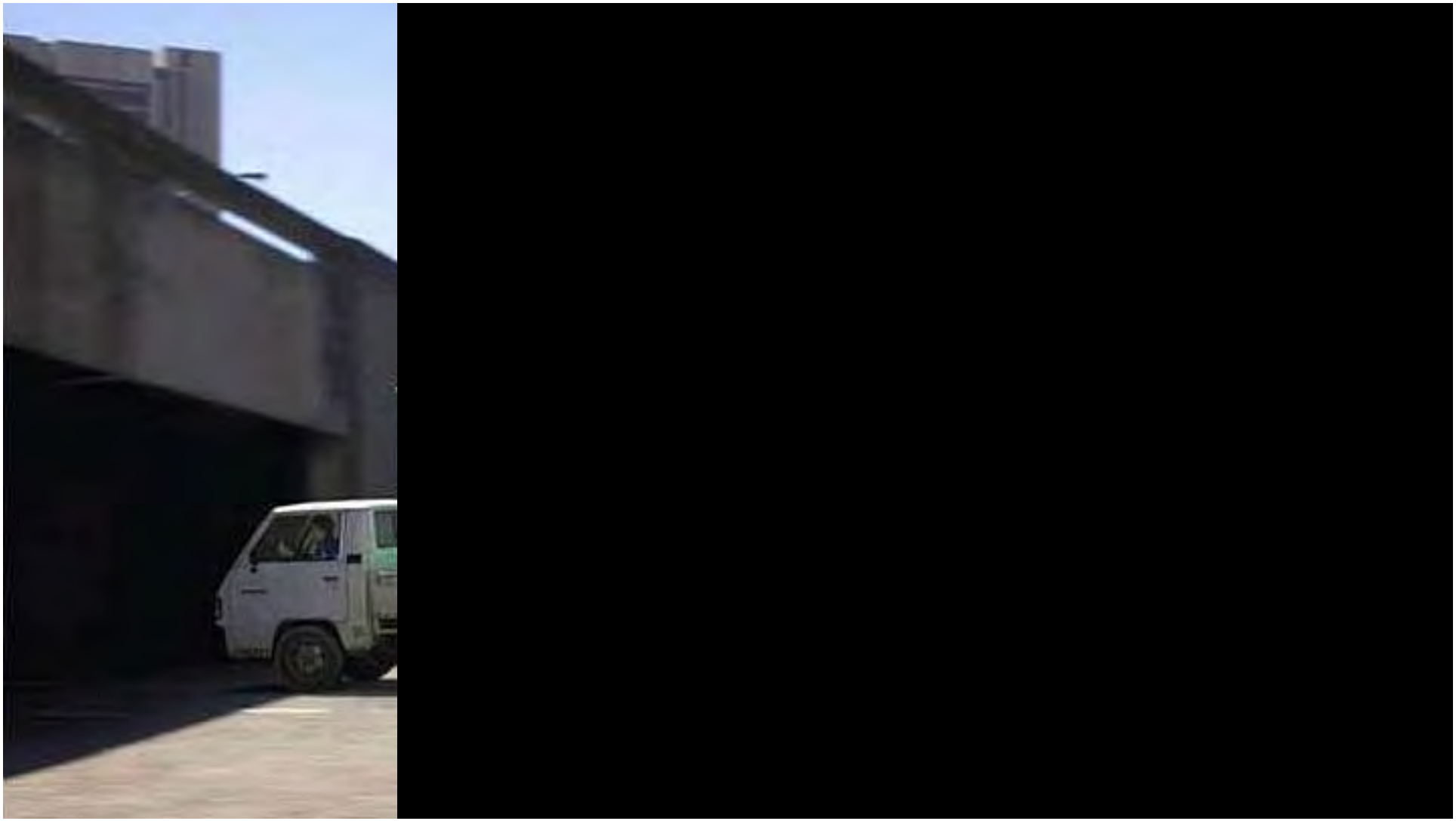
Battery Mining



Data: BP Statistical View of World Energy (2018)

Are solar and wind "clean" and fossil fuels "dirty?"


ARMY

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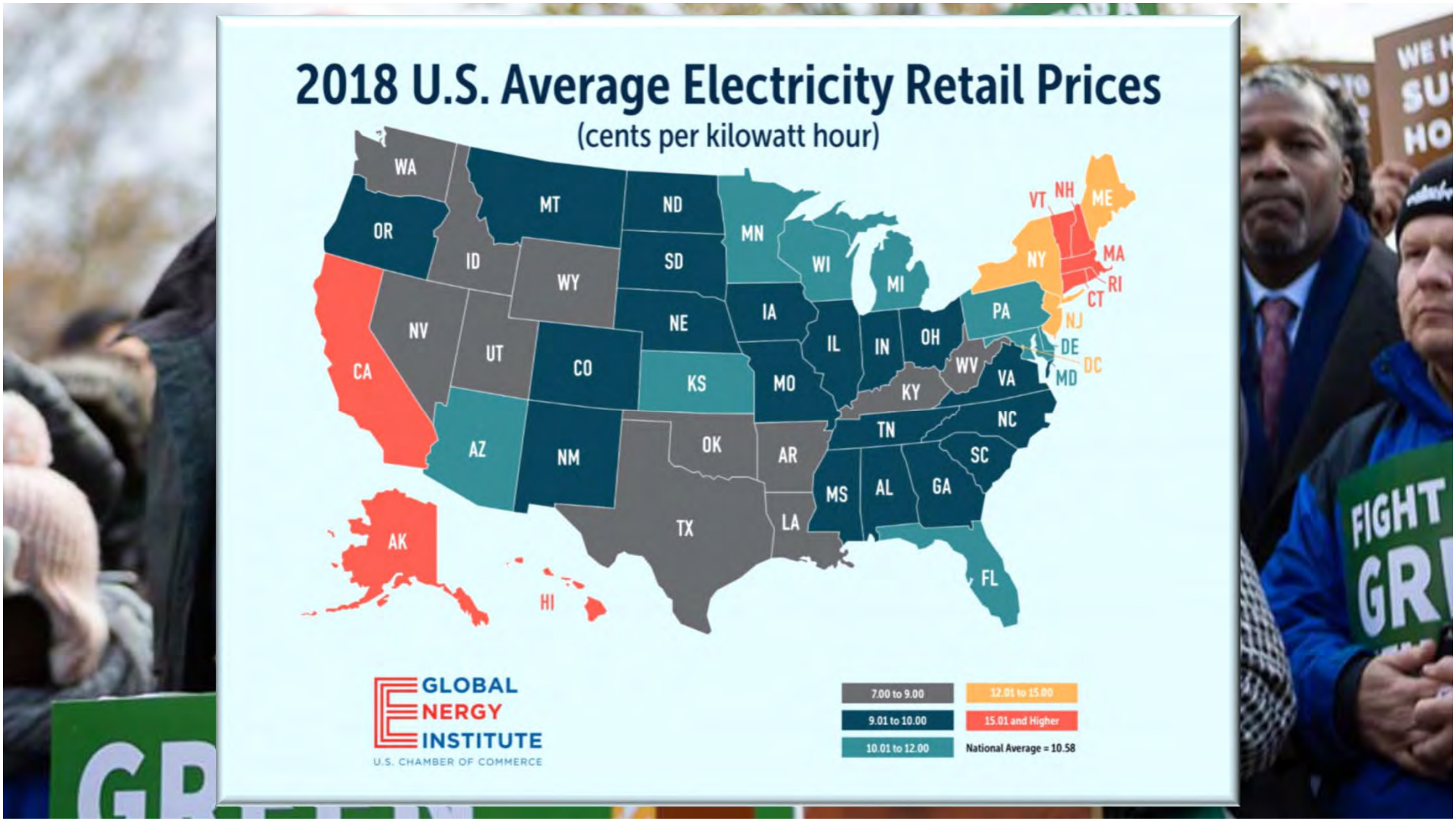
2018 U.S. Average Electricity Retail Prices
(cents per kilowatt hour)
WA
OR
CA
ID
NV
MT
WY
UT
AZ
CO
NM
ND
SD
NE
KS
OK
TX
MN
IA
MO
AR
LA
WI
IL
MS
MI
IN
KY
TN
AL
OH
WV
GA
FL
SC
NC
VA
PA
NY
VT
NH
ME
MA
RI
CT
NJ
DE
MD
DC
AK
HI
GLOBAL ENERGY INSTITUTE
U.S. CHAMBER OF COMMERCE
7.00 to 9.00
9.01 to 10.00
10.01 to 12.00
12.01 to 15.00
15.01 and Higher
National Average = 10.58


Tinker 2020
Hunger, Clothing,
Shelter, Clean Water
Immigration
and Migration
Environmental
Changes the World!
Population
Growth
Rights and Empowerment
of Women
Education and
Health Care

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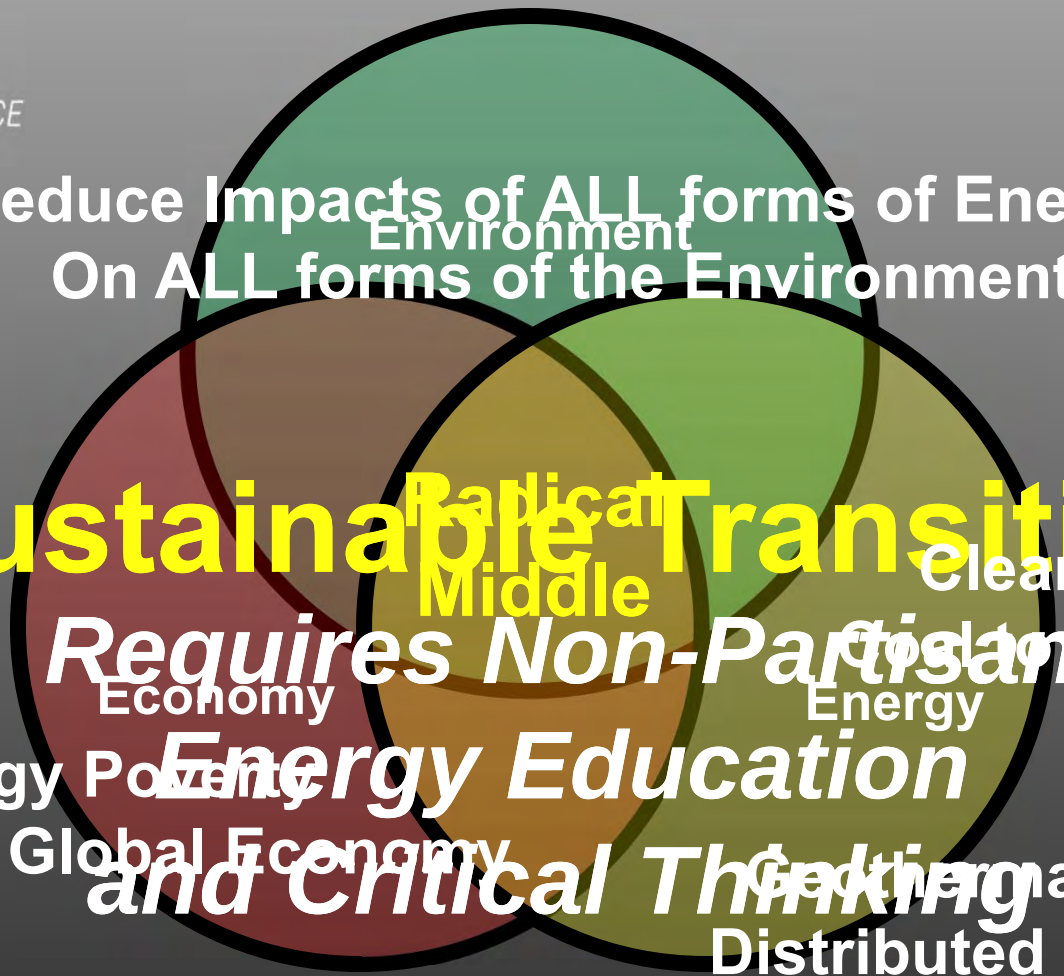

Reduce Impacts of ALL forms of Energy
On ALL forms of the Environment

Sustainable Transition

Radical
Middle

Requires Non-Partisan
Energy Education
and Critical Thinking

End Energy Poverty
Underpin Global Economy

Clean Up Fossils
Gas (CCUS)
Efficiency
Nuclear
Geothermal and Hydro
Distributed Renewables

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Inspire an Energy Educated Future

Switch Energy Alliance

Join us in the Radical Middle

https://Switchon.org

- Follow Scott on Instagram @doctinker
- Download Slide Decks
- Watch the films
- Create educational materials

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For financial interests of Scott Tinker see

http://www.beg.utexas.edu/people/scott-tinker

BACK TO AGENDA

FUTURE FUELS CRC

Update from Australia

Emerging Fuels Forum

PRCI – Research Exchange Meeting
San Diego, U.S.A – 3rd March 2020

David Norman - CEO

Overview

'what is being done in Australia & at the FFCRC'

1. Introduction to Future Fuels CRC
2. Australia's Activity in Emerging Fuels
3. Current Australian Projects and R & D
4. The National Hydrogen Strategy
5. Challenges and near term needs
6. Opportunities for International Collaboration
7. Questions and Discussion

1. - Introduction to Future Fuels CRC

Future Fuels Cooperative Research Centre (FFCRC) was established in late 2018 to bring together:

- Industry-Led & Outcomes Focused Applied Research
- 75+ Organisations - Collaborative partnership
  - (TSO, DSO, owners\suppliers\users – across the value chain)
- Researchers who can deliver applied research
- Commonwealth & other Government participants
- International collaborations

These partners:

- Bring funding and in-kind support (~$12 m/year over a 7 year period)
- Long term – until 2025 - 7 year period
- Evolved / expanded from the Energy Pipelines CRC

A unique collaboration



Australian Government
Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program

























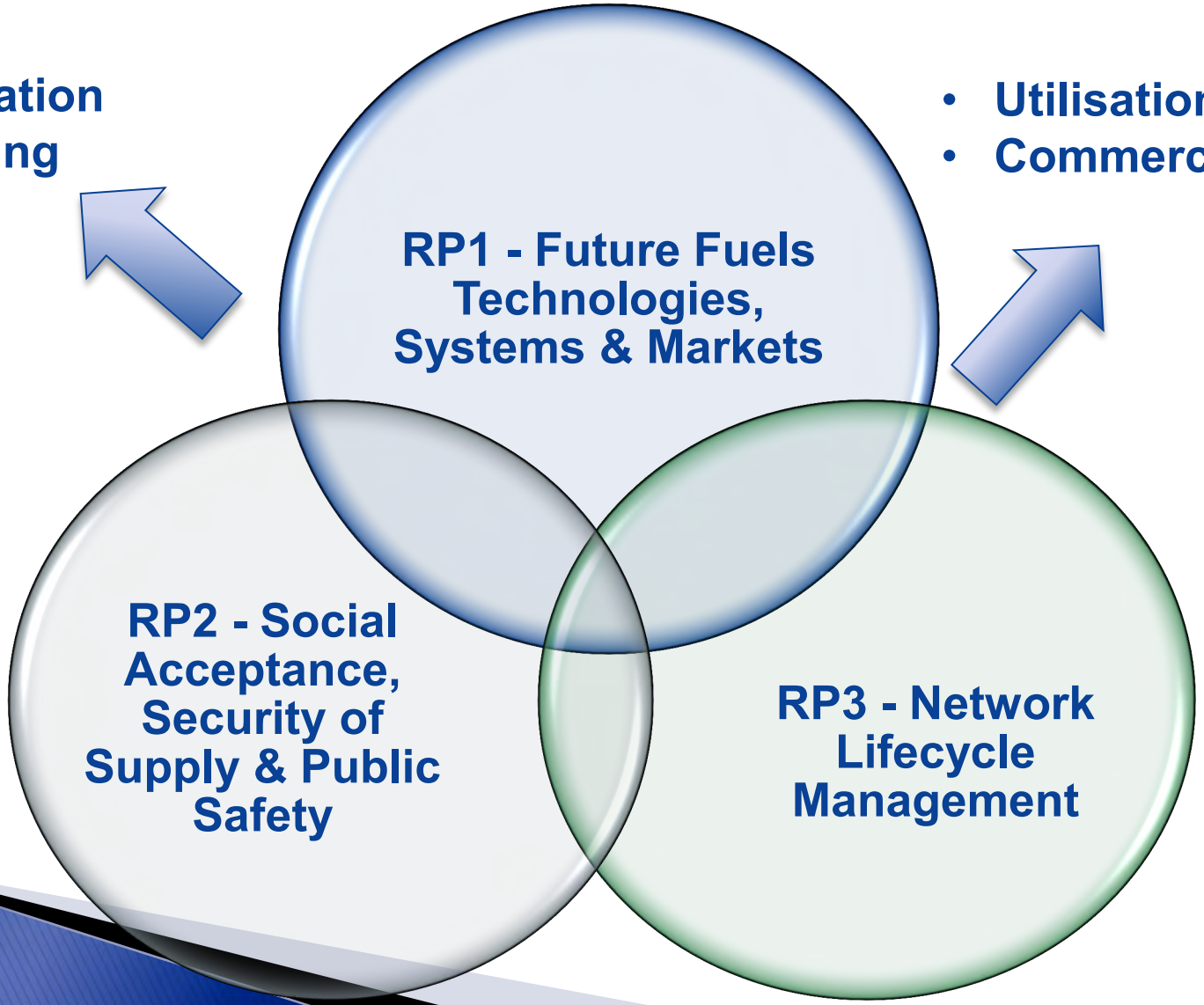
UNIVERSITY
OF WOLLONGONG
AUSTRALIA



Industry-led research addressing major infrastructure and logistical issues

- Education
- Training

- Utilisation
- Commercialisation





Future Fuels CRC contribution has started

- 42 research projects already approved
- A$12 m cash committed to research (total investment scaled through in-kind investment – A$30 m)
- First 31 PhD's projects approved

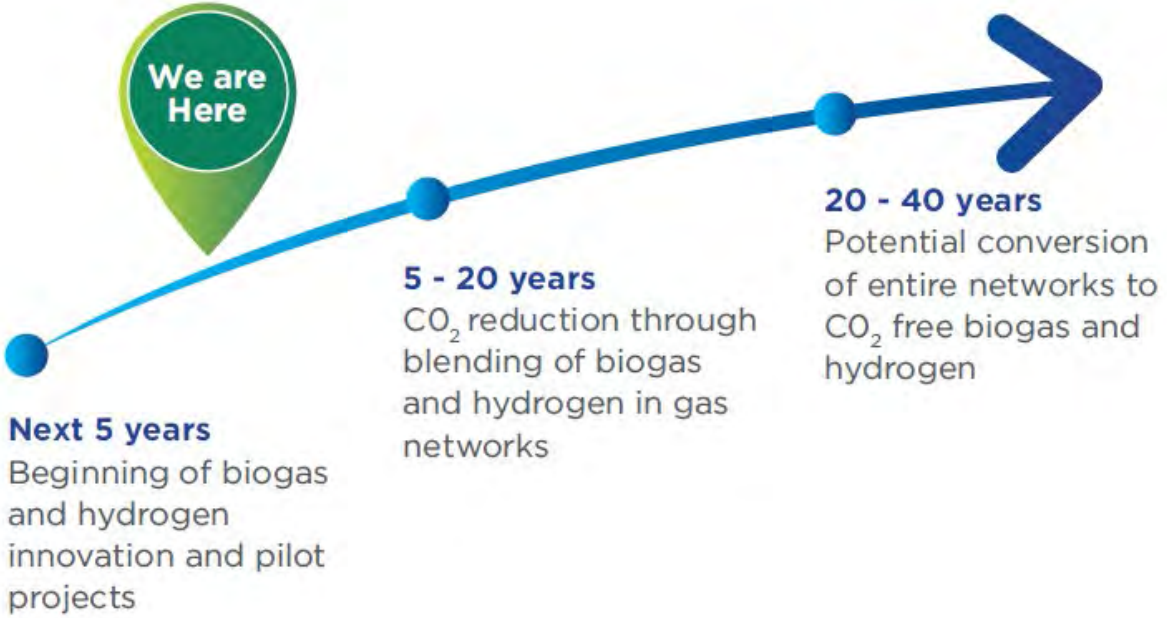


2. Overview of Australia's Activity in Emerging Fuels



Gas Industry Activity – since 2017





Hydrogen innovation networks led activity



- Projects across the country, three injecting in networks
- >$180 million invested
- Four electrolysers producing 2 MW of renewable hydrogen production capacity

ATCO

Project	Location	Page
Clean Energy Innovation Hub	Jandakot, WA	6

Australian Gas Infrastructure Group

Project	Location	Page
Hydrogen Park SA	Tonsley, Adelaide, SA	7

evoenergy

Project	Location	Page
Hydrogen Test Facility	Fyshwick, ACT	8

Jemena

Project	Location	Page
Western Sydney Green Gas Project	Western Sydney, NSW	9

FUTURE FUELS CRC

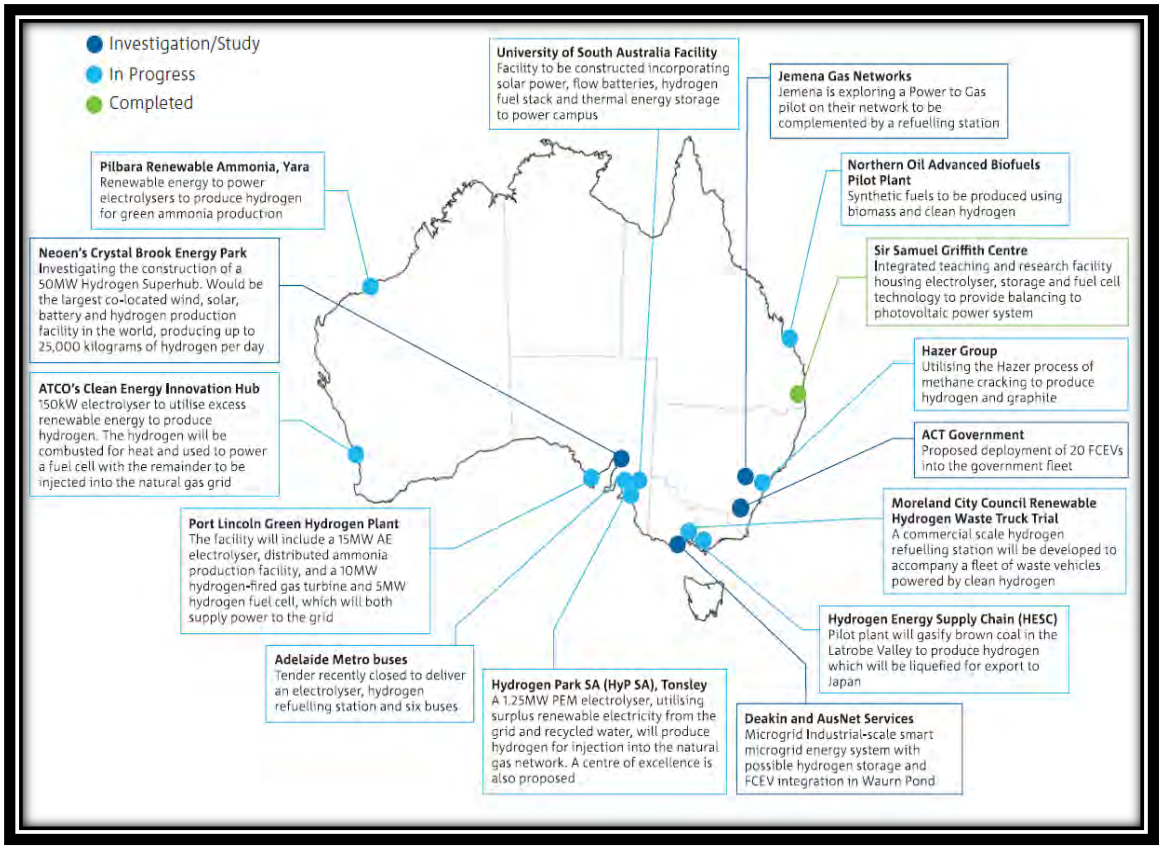
Project	Location	Page
Future Fuels Cooperative Research Centre	National	10

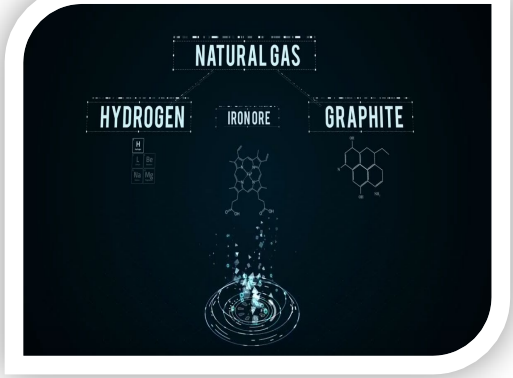
Woodside **MONASH University**

Project	Location	Page
Woodside Monash Energy Partnership	Monash University, Vic	12

Network injection · Renewable · Appliance trial · Engagement · R&D · Regulation · FCAS · Export · Mobility (Vehicles)

3. - National Activity / Projects – Jan 2020



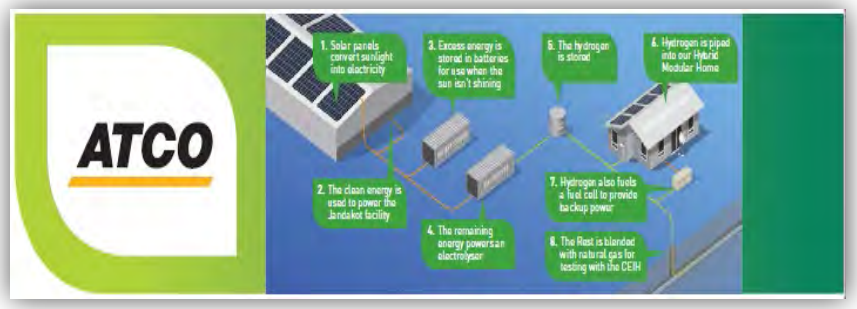




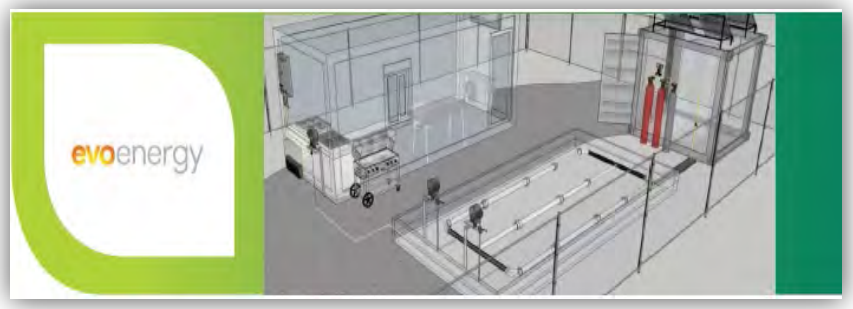


- AGIG AHC SA and HyP-Qld
- Yara/ENGIE Green H2 Feasibility Study

Hydrogen Innovation Projects - operational



- Clean Energy Innovation Hub
- Purpose:
  - Renewable hydrogen
  - Stored for electricity supply backup
  - Appliances in hybrid home
  - 260 kW electrolyser
- Location: Western Australia



- Hydrogen Test Facility
- Purpose:
  - Test pipelines, joints and other components on 100 per cent hydrogen and blends
  - Test appliances
  - Produce renewable hydrogen
  - Train plumbing students
- Location: ACT

Hydrogen Innovation Projects – under construction



- Hydrogen Park - SA
- Purpose:
  - Produce renewable hydrogen
  - Community engagement
  - Appliance testing
  - Blending into network (up to 5 percent) to around 700 homes
- 1.25 MW electrolyser
- Injection to commence mid 2020
- Location: South Australia



- Western Sydney Green Gas Project
- Purpose:
  - Produce renewable hydrogen
  - Hydrogen storage
  - Blending into network
  - Hydrogen for mobility
- 500 kW electrolyser can produce enough hydrogen for 250 homes, can scale up across network
- Location: New South Wales

Hydrogen Innovation Projects - Research



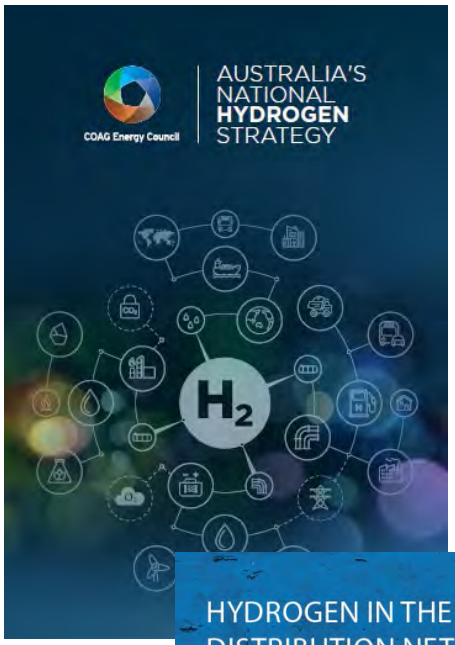
- Future Fuels Cooperative Research Centre
- Purpose:
  - Provide enabling research and development to transition energy infrastructure to a low-carbon economy using fuels such as hydrogen and biogas
  - $ 92 million over 7 years
  - Future fuels technologies, systems & markets
  - Social acceptance, security of supply & public safety
  - Network lifecycle management
- Location: National

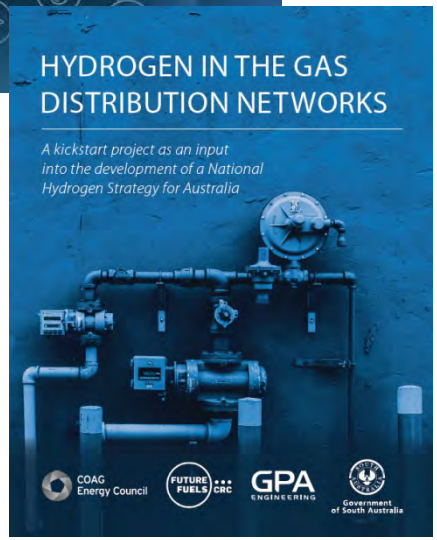


- Woodside Monash Energy Partnership
- Purpose:
  - $40 million joint investment
  - $16.5 million towards the construction of the new technology and design building
- Location: Victoria

4. - National Hydrogen Strategy

- COAG Energy Council Hydrogen Working Groups
  1. Hydrogen Exports
  2. Hydrogen in Gas Networks
  3. Hydrogen for Transport
  4. Hydrogen and Electricity Systems
  5. Hydrogen for Industrial Users
  6. Cross-cutting issues

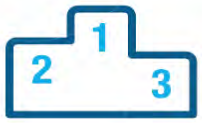




- Future Fuels CRC involved in WG on H2 in Gas Networks.
- Co-chaired Kickstart Project.
- Strategy released 22 November
- https://www.industry.gov.au/about-us/what-we-do/coag-energy-council-hydrogen-working-group

National Hydrogen Strategy

- Australia can make hydrogen our next energy export.
- Potential for thousands of new jobs and billions of dollars in economic growth between now and 2050.
- Measures of success:



AUSTRALIA
is one of the top three exporters of hydrogen to Asian markets



AUSTRALIA
has an excellent hydrogen-related safety track record



HYDROGEN
is providing economic benefits and jobs in Australia



AUSTRALIA
has a robust, internationally accepted, provenance certification scheme in place

National Hydrogen Strategy – Two phases

FOUNDATIONS AND DEMONSTRATIONS → TO 2025

- Advance priority pilots, trials and demonstration projects
- Build demonstration scale hydrogen hubs
- Assess supply chain infrastructure needs
- Develop supply chains for prospective hydrogen hubs

Supply chain infrastructure includes powerlines, pipelines, storage tanks, refuelling stations, ports, roads and railway lines and any other facilities needed for hydrogen supply.

FROM 2025 → LARGE-SCALE MARKET ACTIVATION

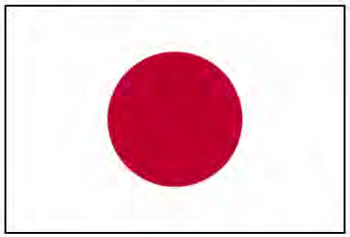
- Scale up projects to support export and domestic needs
- Build and maintain robust and sustainable export and domestic markets and supply chains

National Hydrogen Strategy – Actions

- $70m from ARENA - hydrogen electrolyser projects
- $300m from the Clean Energy Finance Corporation
  - to support emerging hydrogen industry projects
- 57 joint actions to achieve the vision, some examples:
  - Supporting research, pilots, and demonstrations along the supply chain
  - Using clean hydrogen in Australian gas networks
  - Assessing our hydrogen infrastructure needs
  - Skills and training for the hydrogen economy
- Future Fuels CRC support hydrogen mission with a strong focus on R&D supporting gas pipeline/network businesses
- National Energy Resources Australia (NERA) will support SMEs to take advantage of opportunities in the hydrogen
- CSIRO accountable for hydrogen mission that brings together Industry, government and to deliver R&D

Interest in Emerging Fuels - Why Now?

1 Countries are making commitments to use hydrogen to decarbonise their economies





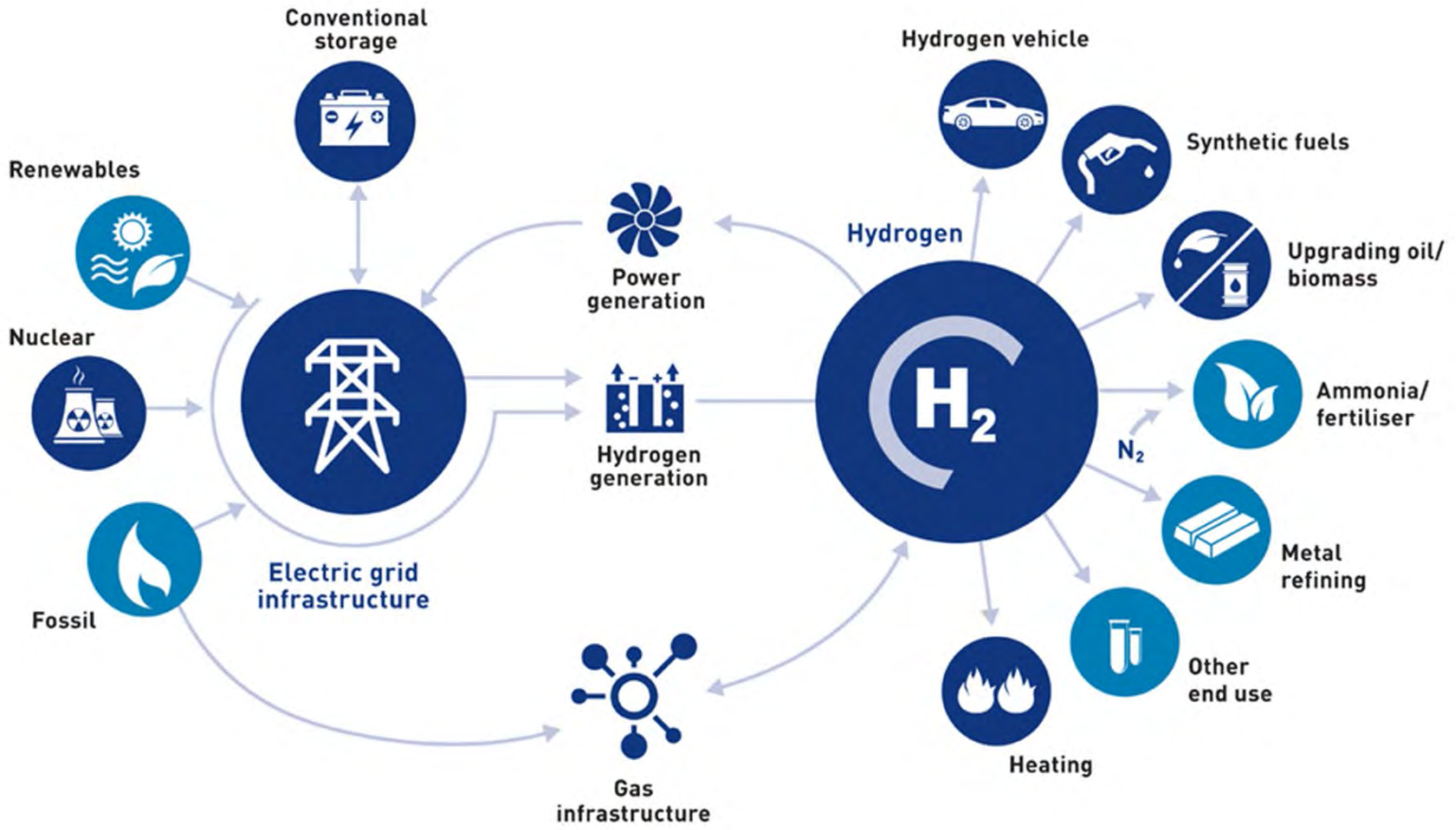
2 The cost of producing clean hydrogen is falling rapidly



3 The cost of using hydrogen is falling



Why the Interest in Hydrogen?



Source: US Department of Energy, "H2@SCALE"

Hydrogen 101



Most common substance in the universe



No greenhouse emissions



Produced from many energy sources



Can be made cleanly using water



Higher energy density than batteries when compressed



Can be stored as a liquid or gas



Can be stored, transported & exported

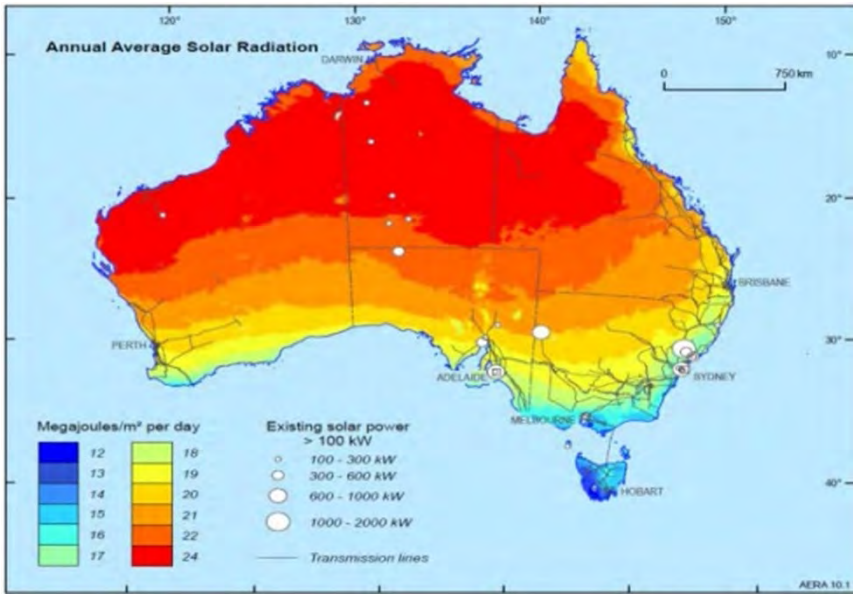


No more or less safe than petrol or diesel fuels



Can provide energy to all parts of the economy

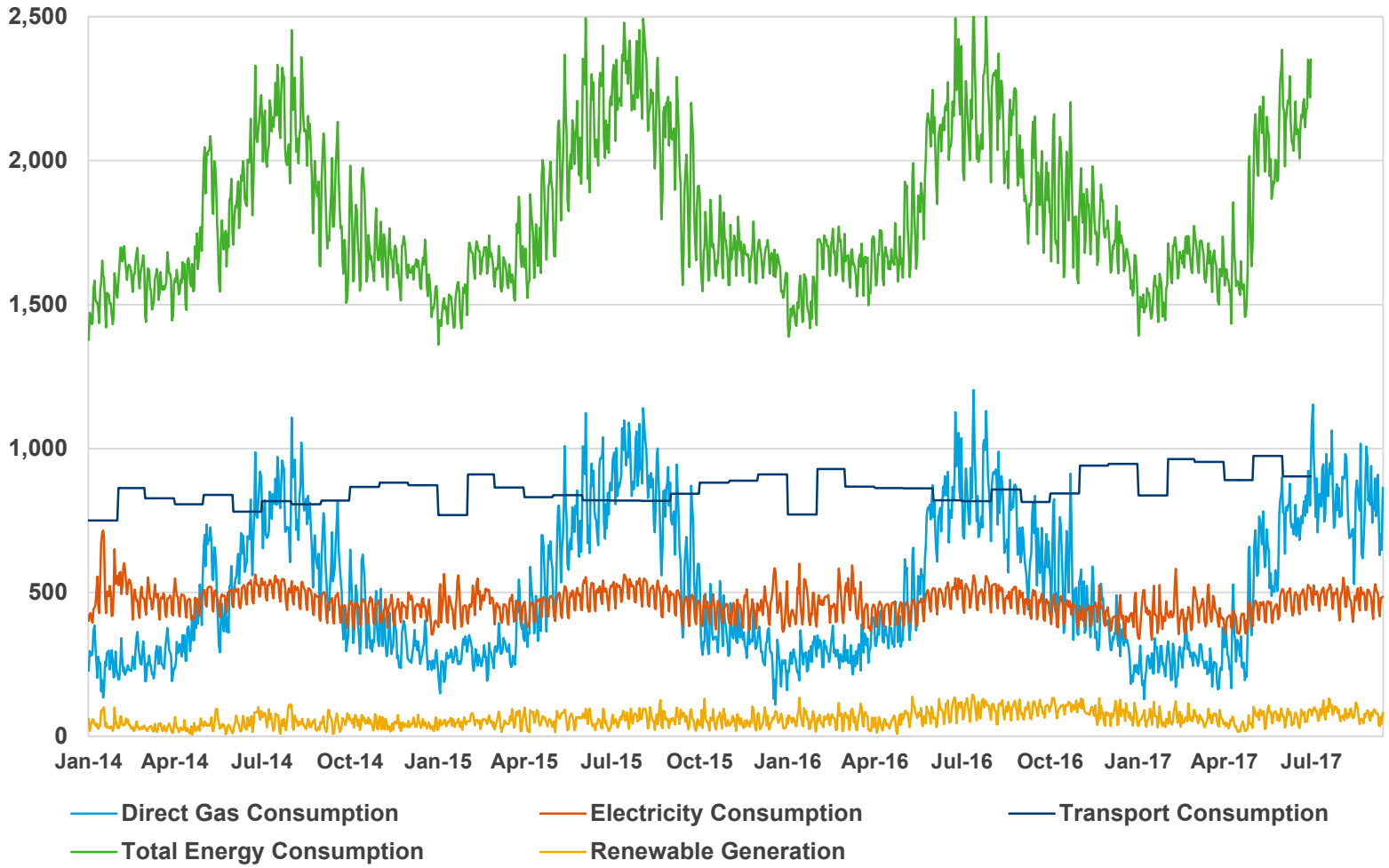
Why Interest in Australia?







5 - National Challenge – Electricity Sector ~ 25% of the task



The decarbonisation challenge is huge - Gas and electricity networks are both part of the solution

Challenges and Opportunities

- The move to a low carbon energy is gaining momentum.
- Non-electric use is currently much greater than electric.
- Electrification cannot provide the complete solution.
- Significant infrastructure is in place for non-electric energy .
- The infrastructure cost for electrification is significant
- The gas industry has this opportunity to transition its significant installed energy infrastructure to carry new fuels
- Tackle Difficult sectors including Transportation, Industrial Use and Heating loads.
- Costs / Economics yet to be proven – but next stage is scale-up dependent, not waiting for this to happen. H2 <$2.
- Emerging Fuels / Future fuels? Hydrogen, derivatives e.g. Ammonia & Methanol, Biogas > Bio Methane, Synthetic Methane, Syngas

Initial Areas for Deeper Collaboration:

- Integrated Systems Thinking:
- H2 in High Pressure High Strength Steels
  - Both H2 blending at low rates and repurposing of lines to 100% H2
- H2 Storage – key to exports, energy storage and the value proposal
- Experience with Pilot Programs and Demonstrations
- Appliances and End-Use
  - Initial low blend capability, 10% 20%, x%
  - 100% H2 capability suitable for natural gas and blends
- Transition Planning and Pathways - for least cost, inconvenience
- Regulatory Changes
- Safety / Social Acceptance

International Collaboration

- PRCI
  - World leader on steel pipelines research
- EPRG
  - GasUnie H2 transport in existing pipeline
- GERG (European Gas Research Group)
  - Knowledge exchange
- Gas Technology Institute (GTI)
  - Knowledge exchange
- UK – IGEM, OIES, SGI, BEIS, UK HSE,
- Energy Systems Catapult
- Germany, France, Japan, Korea



Summary of Drivers and Interest in H2

- Global and national momentum in hydrogen is building due to technological advancements and growing demand.
- Paris / Net-Zero – solutions needed beyond ‘electrify everything’
- Australia has identified competitive advantages in producing renewable / low carbon hydrogen and is well placed to become a hydrogen export superpower servicing Asia
- This is a time for great international collaboration

Conclusion

- There is a call to action – for the global gas community
  - Grow your hydrogen literacy and
  - Understand the opportunities, challenges and current next needs!
  - Ultimately leads to possible deep linkage of clean intermittent electricity (electrons) and renewable gas (molecules)
  - In medium term also provides a pathway for most cost effective production means to be SMR & CCS
  - Hydrogen in gas networks is part of a wider potential
  - Transport - Fuel Cell electric vehicles/buses/trucks/trains
  - Heavy Industry / Heating Loads
  - Exports - Hydrogen production and handling for export

Questions and Discussion

Further Information

- www.futurefuelscrc.com
- Key contacts:
  - david.norman@futurefuelscrc.com
  - klaas.vanalphen@futurefuelscrc.com

FUTURE FUELS CRC

Enabling the decarbonisation of Australia's energy networks



Australian Government

Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program

BACK TO AGENDA



GERG

THE EUROPEAN GAS RESEARCH GROUP

PRCI REX 2020

Emerging Fuels Forum, March 3rd 2020

Robert Judd, GERG Secretary General

This presentation..

- Who are GERG
- Gas industry Research Priorities in light of EU policy
- Examples of current activities in emerging fuels
- Where next and how?

Our Association

GERG
THE EUROPEAN GAS RESEARCH GROUP

The European gas industry collaborative R&D group

Our members


DGC
Danish Gas Technology Centre
DNV·GL
enagas
ENGIE
e·on
GASSCO
gasunie
GAZ system
GRTgaz
İGDAŞ
"Sky Friendly"
Italgas
kiwa
nationalgrid
nedgia
Grupo Naturgy
nortegas
Open Grid Europe
The Gas Wheel
PGNiG
Shell
snam
storengy
Synergrid
TERĒGA

Friends of GERG



How we work


Establish Industry R&I Priorities
Facilitate Projects
Work With Partners
European Initiatives
EU Engage-ment
GERG
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GERG HIPS Project

HIPS (**Hydrogen in Pipeline Systems**):
a benchmark in understanding the impact of hydrogen in gas networks

State of the art analysis (performance, lifetime and safety):

- ***gas transport and storage***
- ***gas distribution and utilisation***



The new realities for Innovation

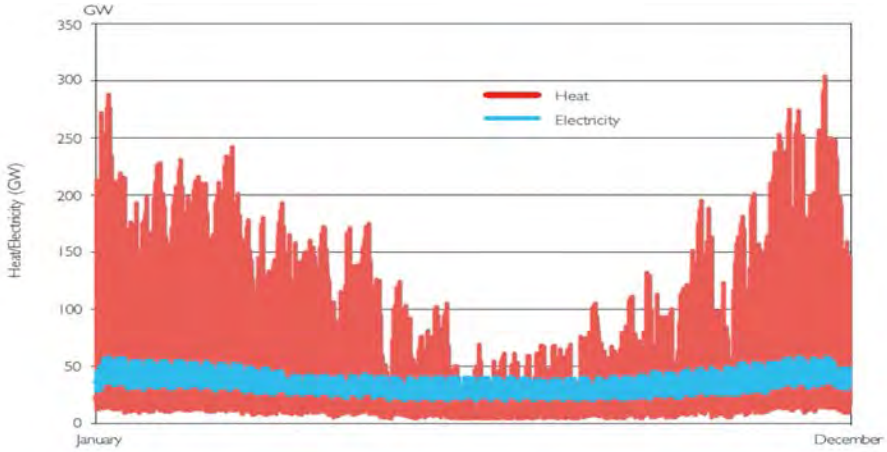
- Industry change dominated by externalities
- Political pressures on gas industry position
- Energy System model – Sector Integration
- Government stakeholders decide policy
- More 3rd Party input
- Regulation - 3rd Energy Package, the Green Deal
- Innovation for survival
- New industry transformation

Where are we now?

- Mature natural gas grids carry much more energy than electricity grids, and extra capacity is already available.
- In some EU countries the gas network carries three times as much energy as the electricity grid, comparable with energy consumed by road transport.
- End use of gas can be over 90% efficient with low transmission losses.
- Renewable electricity generation is often exceeding electricity network capacity.
- Curtailment of renewables leads to penalties for transmission system operators.
- The electricity transmission network has limited capability for storage. Flexibility and grid balancing comes at a price.

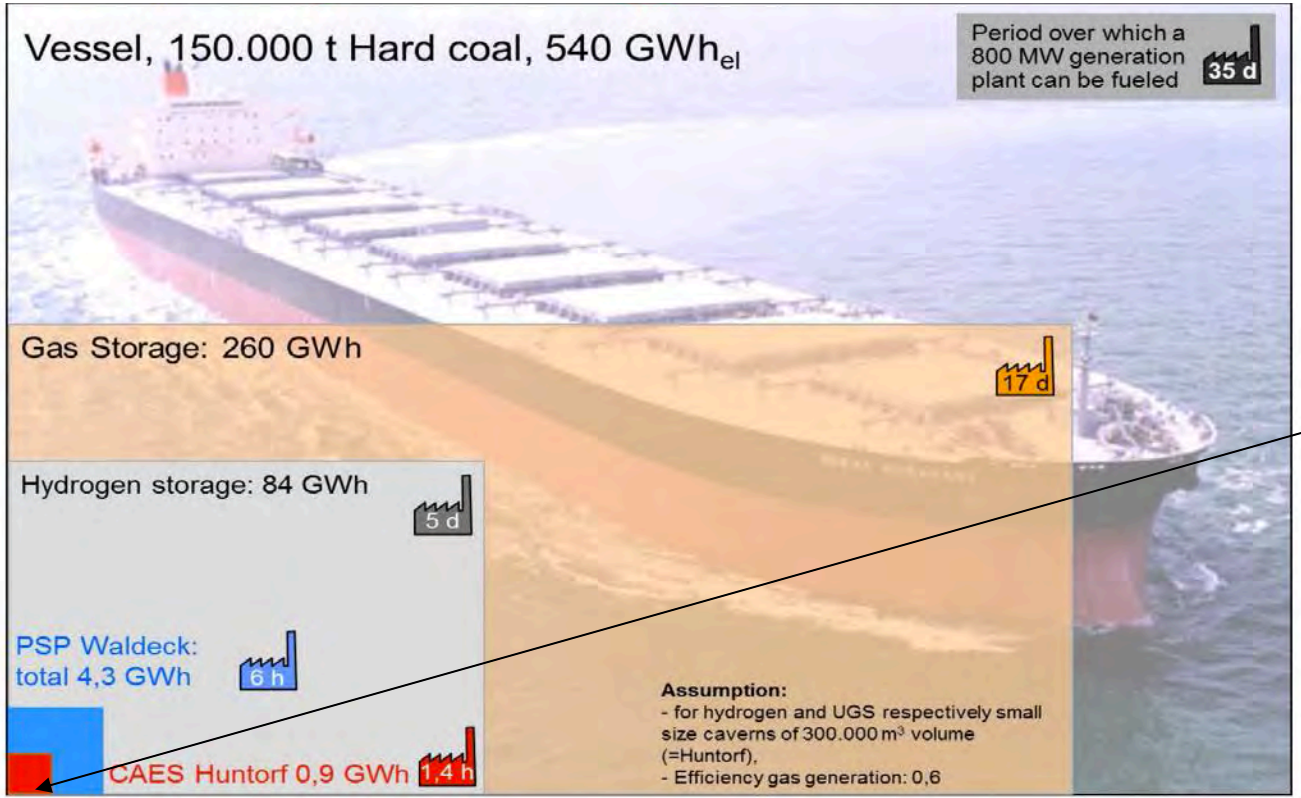
UK heat and Electricity

Gas demand versus Electricity system capacity



Numerous recent analyses confirm the benefits of the use of existing gas infrastructure to enable decarbonisation over a pure electrification approach.

Comparing Energy Content





A Tesla Mega battery = 800MW plant for 12 minutes

Where do we want to be?

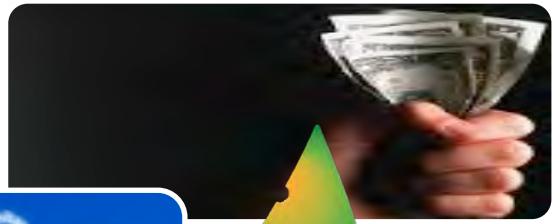
- An **efficient use** of all energy resources
- **Maximised efficiency** of renewables
- A **flexible, secure, competitive** energy supply system
- A **low carbon** energy system
- An **integrated SMART Energy System**
- **Minimum cost** for the the energy transition

The European balancing act

- Secure?
- Affordable?
- Sustainable?











Europe's Green Deal 2020

A roadmap to 2050

Achieving the current 2030 climate and energy targets is estimated to require €260 billion of additional annual investment, representing about 1.5% of 2018 GDP.

2030 – 50-55% reduction
2050 – net zero

The Green Deal - Innovation

- **Innovation, including funding, for areas including decarbonised gas:**
- *"The transition to climate neutrality also requires smart infrastructure. Increased cross-border and regional cooperation will help achieve the benefits of the clean energy transition at affordable prices. The regulatory framework for energy infrastructure will need to be reviewed to ensure consistency with the climate neutrality objective. This framework should foster the deployment of innovative technologies and infrastructure, such as **smart grids, hydrogen networks or carbon capture, storage and utilisation, energy storage, also enabling sector integration.**"*

- *the decarbonisation of the gas sector will be facilitated,*

*including via enhancing support for the development of **decarbonised gases,***

via a forward-looking design for a competitive decarbonised gas market,

and by addressing the issue of energy-related methane emissions.

*Partnerships with industry and Member States will support research and innovation on transport, including batteries, **clean hydrogen**, low-carbon steel making, circular bio-based sectors and the built environment."*

Horizon Europe will be structured to meet the objectives of the Green Deal

Or according to Hydrogen Europe…

The European Green Deal is essentially another name for the hydrogen revolution

News | Tuesday, February 25, 2020



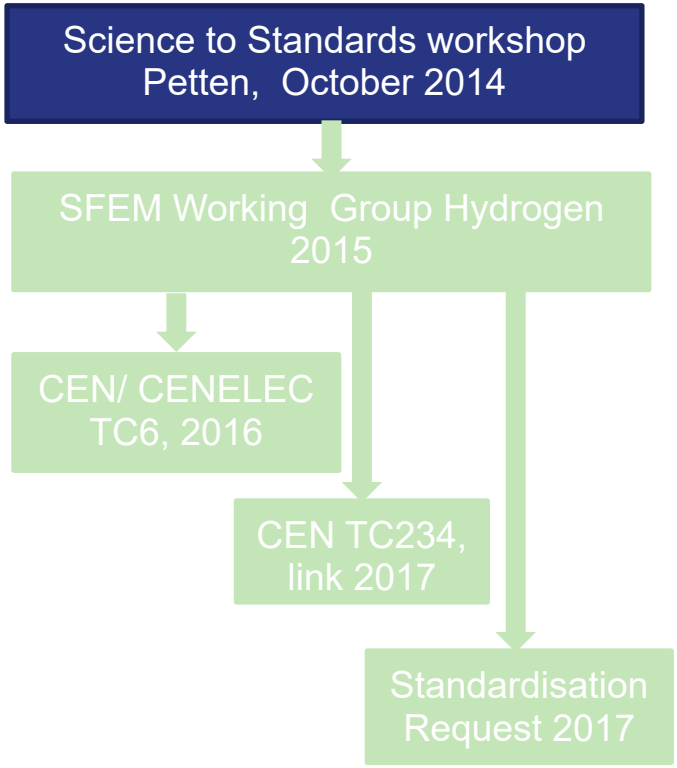
A+ A-

As Neil deGrasse Tyson once said, "Give a kid a book, and you change the world." This was certainly the case for Jorgo Chatzimarkakis, Secretary General of Hydrogen Europe, whose fiery commitment to clean hydrogen power was first sparked by a book he read as a child at school. Galvanized even further by the shock of the Chernobyl nuclear disaster, Jorgo went on to champion the production of hydrogen from solar power in the Sahara Desert as a university student, before laying the foundation for the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) as a member of the European Parliament. In his current role at the head of Hydrogen Europe, Jorgo seeks to accelerate the energy transition through what he sees as a versatile and game-changing energy vector: hydrogen fuel cells.



But it has taken us some time to reach this point…

A strategic vision for European standards



"Maintaining stability of the electricity grid with increasing amounts of intermittent renewable energy sources in the generation mix requires capabilities for energy storage throughout the power chain, next to dispatchable power and demand-side management.

The increasing needs for high-capacity, long-duration (seasonal) energy storage can only be met through chemical storage of high energy density gases, among which hydrogen can play a powerful role.

In this context, admixture of renewable hydrogen to the natural gas grid presents considerable advantages"

Science into Standards Workshop – CEN EC Initiative

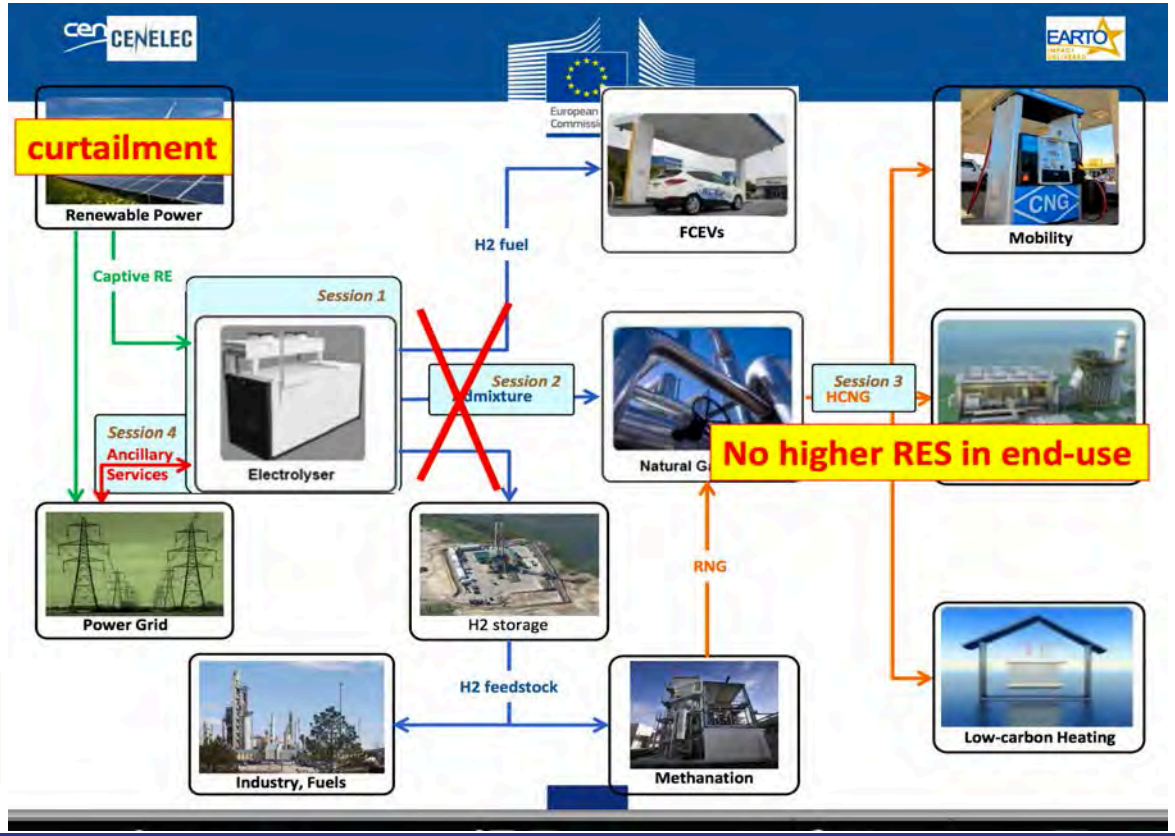
Science to Standards workshop
Petten, October 2014

SFEM Working Group Hydrogen 2015

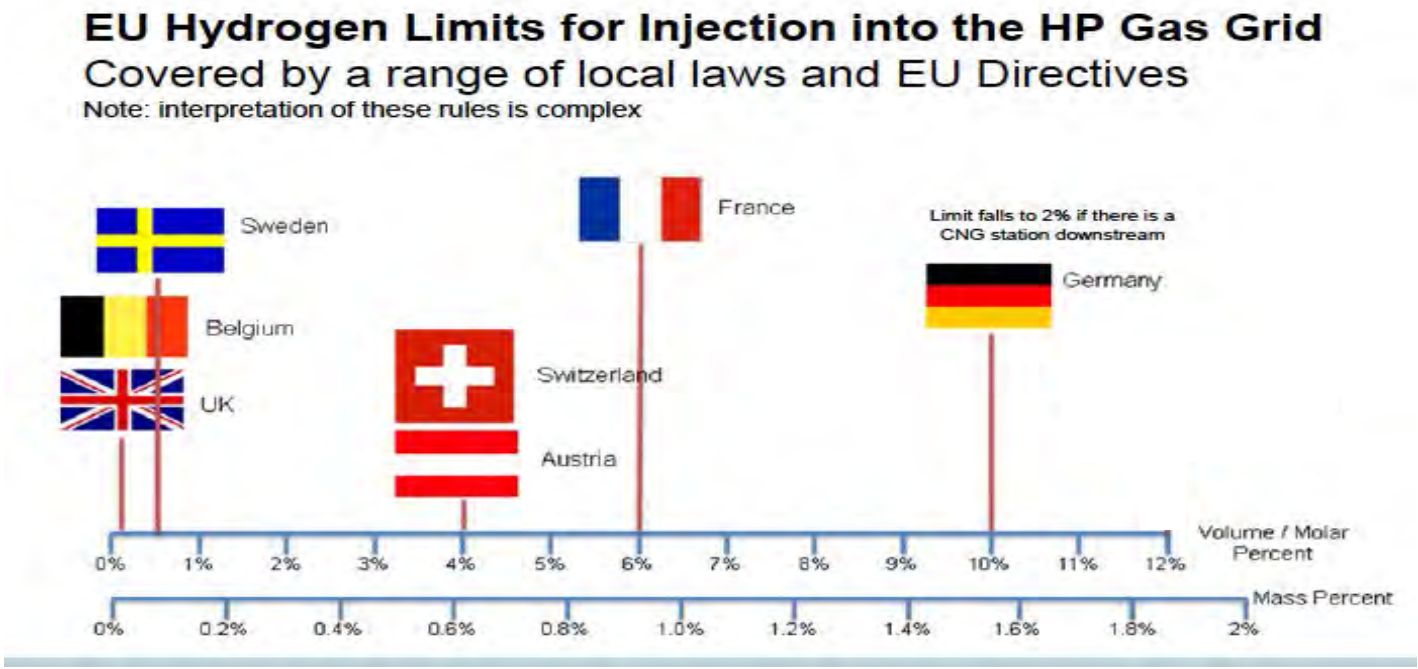
CEN/ CENELEC TC6, 2016

CEN TC234, link 2017

Standardisation Request 2017



Regulatory?



Source: ITM Power

Hydrogen Working group – a CEN / EC initiative

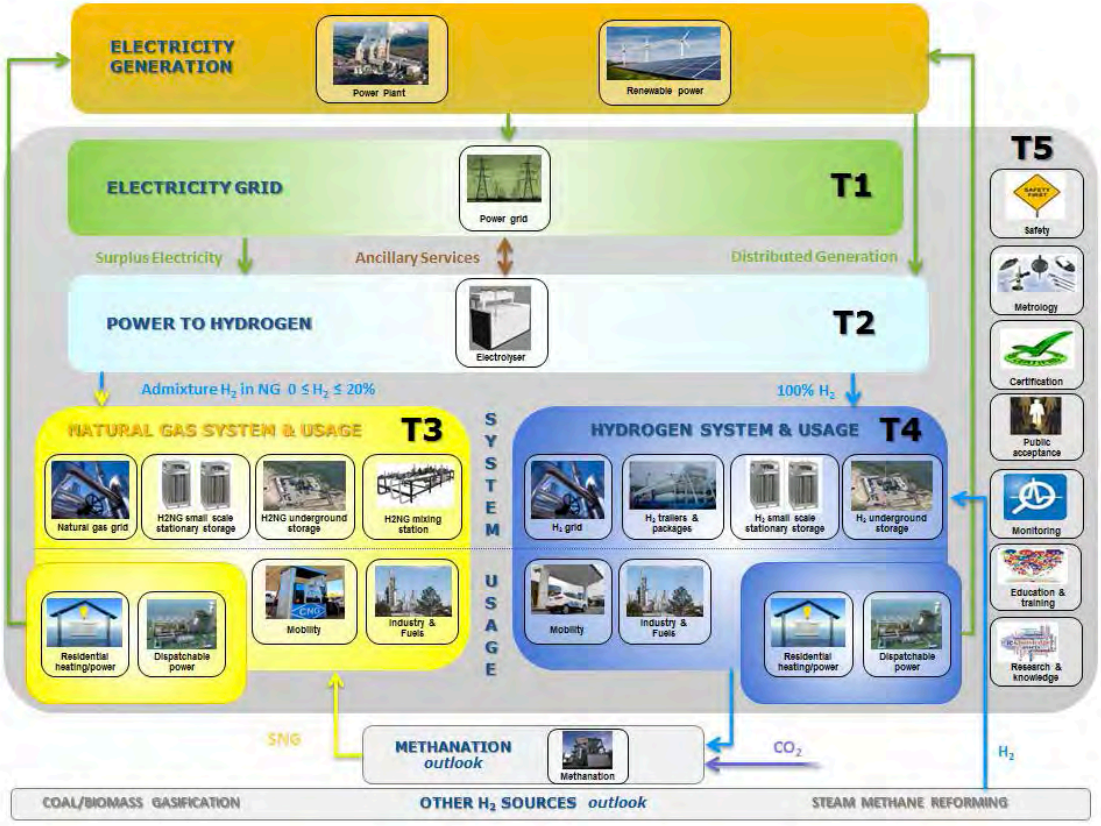
Science to Standards workshop
Petten, October 2014

SFEM Working Group Hydrogen
2015 -2019

CEN/ CENELEC
TC6, 2016

CEN TC234,
link 2017

Standardisation
Request 2017



SFEM WG Hydrogen Roadmaps

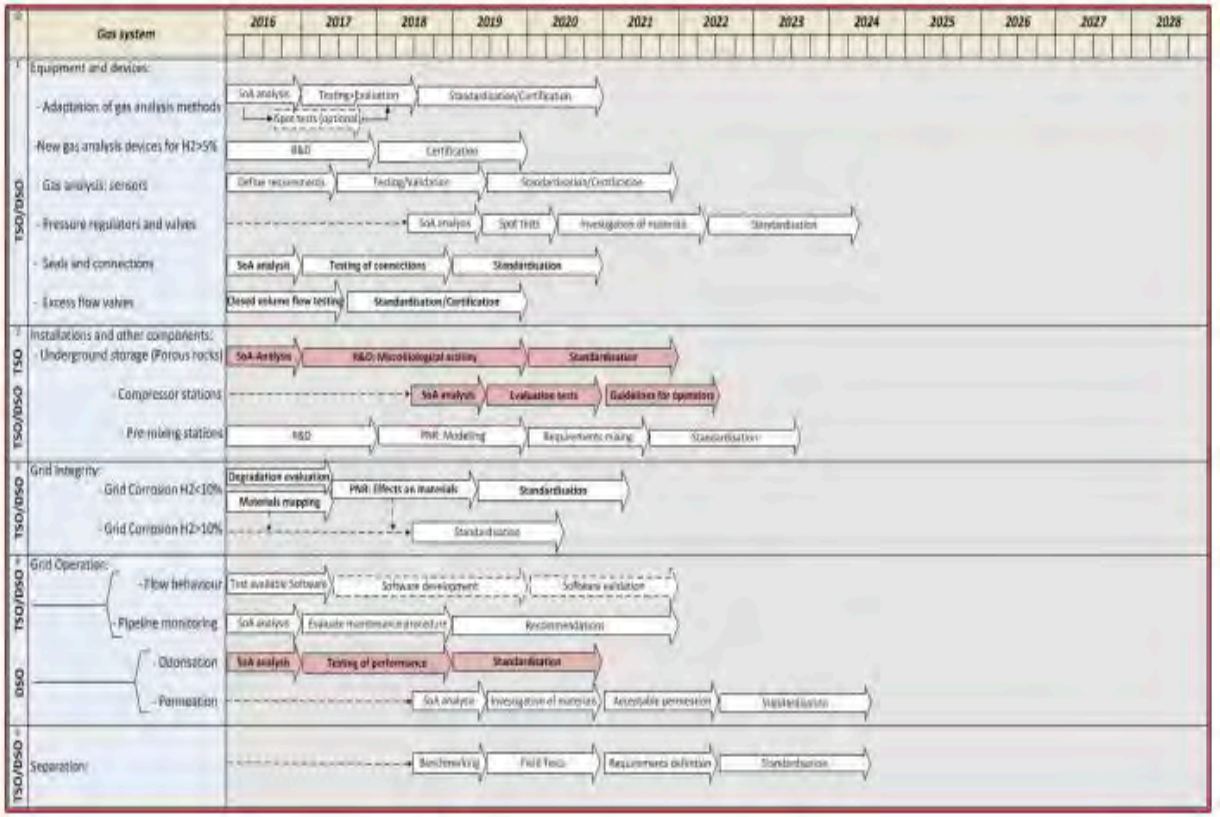
Science to Standards workshop
Petten, October 2014

SFEM Working Group Hydrogen
2015-2019

CEN/ CENELEC
TC6, 2016

CEN TC234,
link 2017

Standardisation
Request 2017



GERG Strategic alignment

GERG - Current Strategic Priorities



- Removing the barriers to the injection of **biomethane** in our gas networks – first step to decarbonise gas networks
- Further **Decarbonisation** of the gas networks through introduction of hydrogen
- Understanding and quantifying downstream **methane emissions** from the networks to better target reductions







GERG Biomethane project – Biomethane trace components and their potential impact on European gas industry

Biomethane trace components and their potential impact on European gas industry

Towards the removing of technical barriers to biomethane injection into the natural gas grids

A multi-phase project aiming to revise the standards limits regarding trace component in biomethane



Phase 1

January 2018

GERG gas industry priorities: Status review and gap analysis:

- Siloxanes
- Corrosive components
- Micro-organisms

Phase 2a:

Combination of GERG priorities & CEN immediate priorities:

- Status review and gap analysis
  - Sulfur
  - Oxygen
  - Health impact assessment
- Experimental program: impact of siloxane on:
  - Industrial boilers
  - Heavy duty vehicles performance

SA/CEN/RESEARCH/475/2017-07

Phases 2b & 2c

November 2019

Follow up from Phases 1 & 2a + new proposals

WP1: Experimental program on siloxanes impacts

- Boilers: cycling mode (start and stop)
- Engines: test on switching type oxygen sensors

WP2: Experimental program on the impact of sulfur on vehicles After Treatment System (Catalysts)

WP3: Experimental program on the impact of oxygen and corrosive components on gas facilities:

- Gas grid
- Underground Gas Storage

WP4: Improve knowledge on biomethane

- Biomethane quality database
- BioSNG & bioLNG quality data
- Odor masking impacts
- Terpenes impacts

GERG Hydrogen Projects

Overview of GERG Hydrogen activities

Network adaptation and hydrogen – the networks of the future are the networks of today



NaturalHy (GasUnie)

HIPS (E.ON)

Domhydro (KIWA)

HIPS NET (DBI)

European Power to Gas Platform (DNV GL)

Hyready (DNV GL, DBI)

THyGA (Engie)



ELEGANCy

SFEM Working Group Hydrogen

CENELEC

Fundamental Research

Gap analysis, applications, roadmaps

Standards

GERG HIPS Project

HIPS (**Hydrogen in Pipeline Systems**):
a benchmark in understanding the impact of hydrogen in gas networks

State of the art analysis (performance, lifetime and safety):

- ***gas transport and storage***
- ***gas distribution and utilisation***



Project THyGA

The main goal of the European Commission supported project is to enable the wide adoption of H2NG (hydrogen in natural gas) blends by closing knowledge gaps regarding technical impacts on residential and commercial gas appliances.

- Screening and segmenting the portfolio of appliance technologies in the domestic and commercial sectors and assessing the impact of hydrogen admixtures.
- • Testing up to 100 residential gas appliances to provide a generic protocol that can be adapted for virtually any appliance.
- • Developing a validated certification protocol for different levels of H2 in natural gas
- • Making recommendations for manufacturers and decision makers



BDR THERMEA GROUP · cea · DGC Danish Gas Technology Centre · DVGW · Electrolux · ENGIE · gas.be · GERG THE EUROPEAN GAS RESEARCH GROUP · gwi

THyGA has been awarded backing from the EU's Research and Innovation programme Horizon 2020 under its Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

Hydeploy

HyDeploy | HyDeploy II:

HyDeploy:

- Up to 20% injection
- Closed gas network
- Exemption approved by HSE
- Installation 2019
- Trials 2020

HyDeploy II:

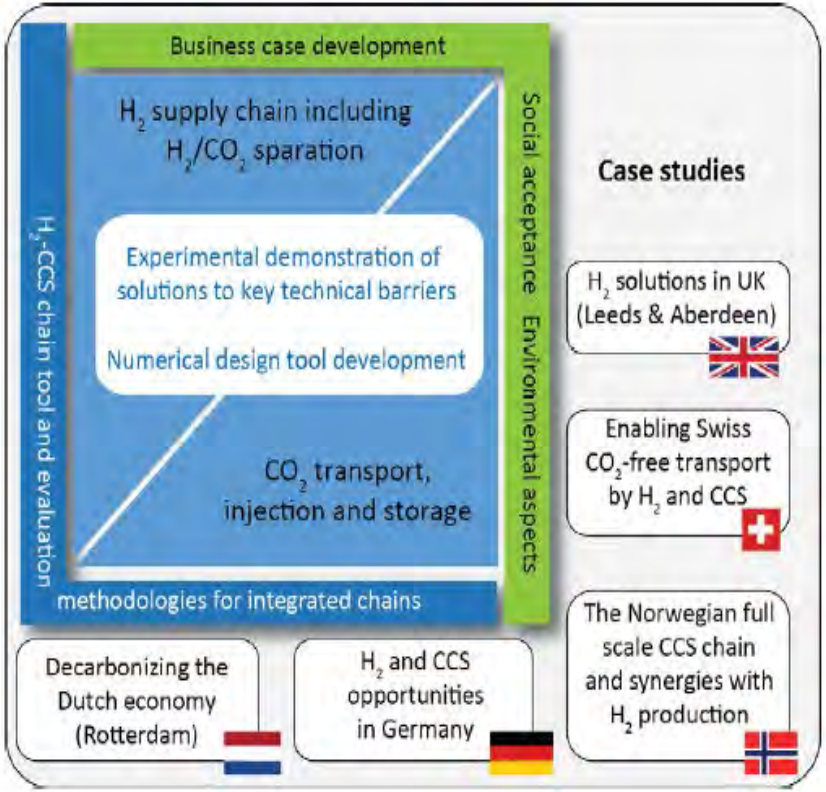
- Two trials on the open network
- Trials 2021 to 2023

Gas Grid Injection ofgem



GERG is on the Advisory Board of Hydeploy

Elegancy – €16M Project in H2020



- ELEGANCY – led by Sintef – GERG partners include Shell, OGE, Gassco, Imperial College, GERG
- **5 Case Studies**:
- The **Netherlands**: decarbonizing industry by a comprehensive H2-CCUS value chain.
- **Switzerland**: decarbonizing road transport, accelerating its CCS/geothermal roadmap
- The **UK**: switching large cities to a 100% H2 network,
- **Germany**: accelerating the decarbonization of gas infrastructure via a H2-CCS chain
- **Norway**: developing an optimal infrastructure investment scenario for H2 export and utilization.

CEN H2NG PNR Gap analysis 2020

- A European-scale GAP analysis to collate the current status of knowledge on H2 in gas networks
- Priorities set by the industry through consultation with CEN working groups
- Aligned with roadmap to standardization being developed by CEN and the European Commission
- Strong industry buy-in

	Priority / topic area	Expected Lead Organisation
1	Safety	DNVGL
2	Gas Quality	GRT Gaz
3	Underground storage	DBI
4	Power Generation and Engines	DNVGL
5	Industry	Engie
6	Steel Pipes	GRT Gaz
7	Network Equipment	DBI
8	End use commercial and domestic	DGC
	Project administration on behalf of CEN	DIN
	Integration coordination, interfaces and transverse subject management	GERG

Priority No 6

Steel Pipes

Steel pipelines at over 10% Hydrogen, corrosion and integrity, welding and embrittlement. Specific requirements for 100% hydrogen.

Partners

GRTGaz, DNVGL, DBI, Kiwa, RISE, Fluxys, Enagas, Gaz System, National Grid, Gasunie, Storengy

Proposed Aggregated Budget

Approx. 100k€

Objectives

- Obj 1: To identify safe operating conditions for H2 and H2NG pipelines (pressure, cathodic protection, etc.)
- Obj 2: To evaluate solutions to eliminate or mitigate the adverse effects of hydrogen

Issues to be addressed

- 1: Pipe materials properties are known to be affected by hydrogen (yield, toughness, fatigue behavior, sensibility to environmental assisted cracking) depending on operating conditions
- 2: Possible negative effect on corrosion protections
- 3: Applicability of existing defect assessment approaches

Expected outcomes and benefits

- Gaps to be filled for safe operating conditions
- Draft guidelines for NG to H2 conversion

Why GERG?

- R&D is essential to the gas industry to meet our commitments to:
  - customers
  - the environment
  - the position of gas in the future market



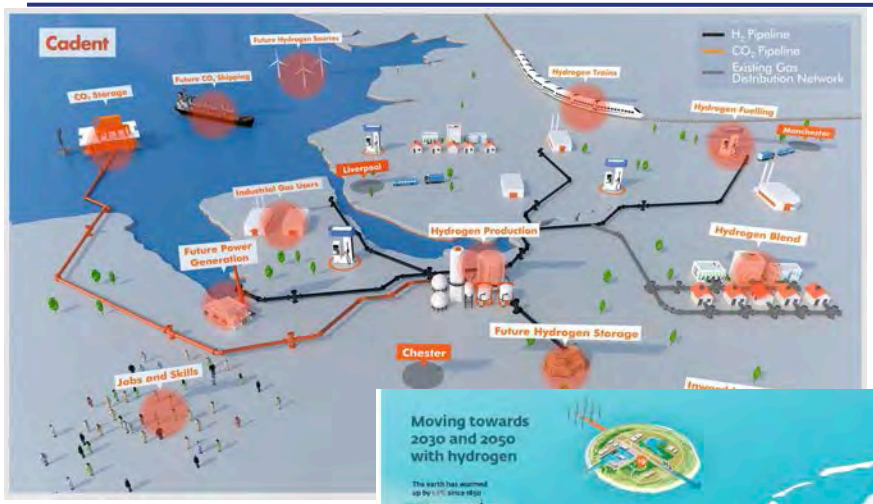
- Collaborative R&D and partnership is vital, as it enables:
  - shared costs, shared expertise
  - high acceptance of results
  - Breaking down of silos and development of a sector integrated future

The GERG collaborative model is becoming even more important
We are making concerted efforts to strengthen our cooperation outside Europe

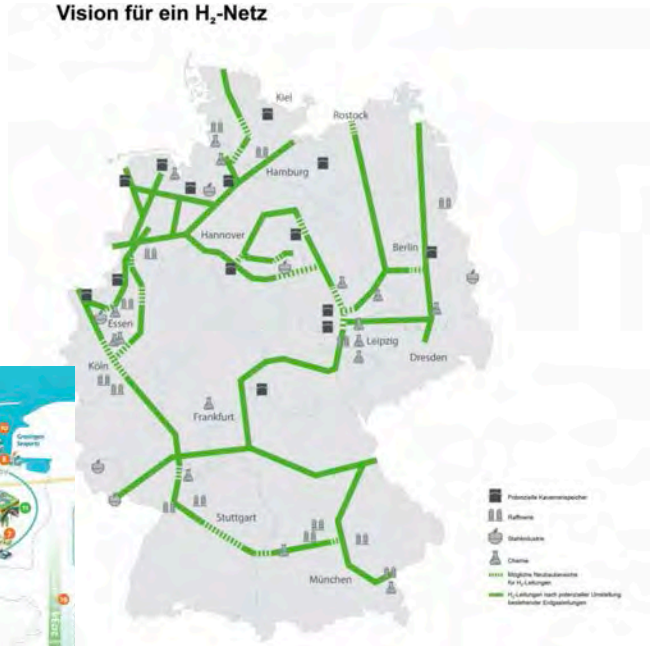
The UK Hydrogen Taskforce



Examples of EU National Approaches







Thank you for listening !

robertjudd@gerg.eu

GERG

THE EUROPEAN GAS RESEARCH GROUP

BACK TO AGENDA

PRCI 2020 Research Exchange

PRESENTATION OF THE PRCI ROADMPAS FOR EMERGING FUELS

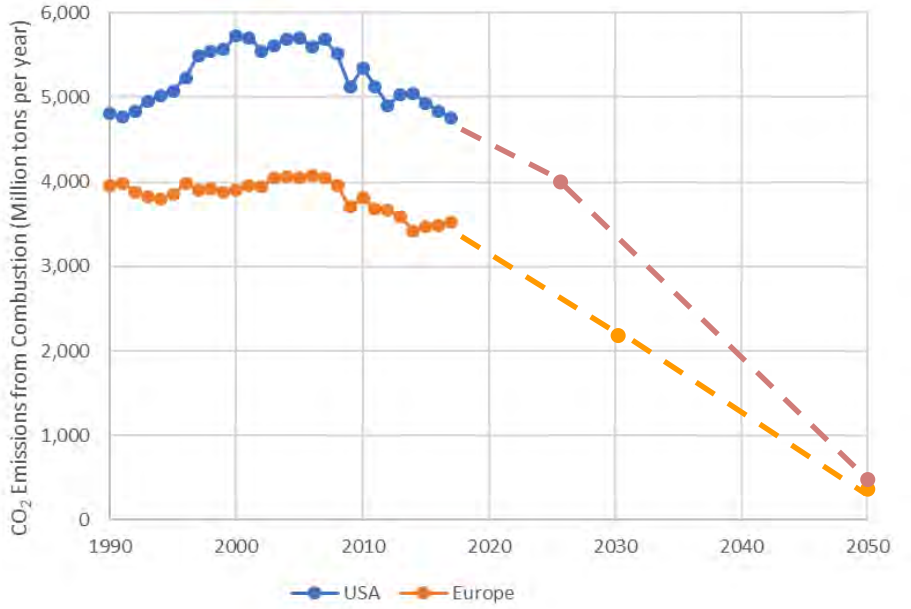
- François Rongère, PG&E
- Amélie Louvat, GRTgaz

LEADING PIPELINE RESEARCH

Background

- Greenhouse gas emission reduction is the main international drivers which guides Emerging fuels development → ex.: Paris Agreement and AB32 mandates
- Emerging fuels will play a significant role in reaching greenhouse gas emission reduction objectives in the world.

Historical CO_2 emissions and 2015 commitments



Impact to the industry

- **PRCI has the ambition to extend its R&D leadership within the pipeline industry including renewable gas transportation. To this end, PRCI must contribute to the optimization of transport costs of RNG, biogas and H2 through innovative solutions**

- **The Research Objective is:**
  - Ensuring the capability of injecting and transmitting renewable gas, including safe, reliable, and cost-effective operation of existing pipeline systems
- **The Target Program Outcomes are:**
  - Identify conditions and develop the tools & technologies to ensure the capability of injecting and transmitting RNG, and H2 and H2 – Natural Gas Blends, including a safe, reliable and cost-effective operation of existing pipeline systems

- **Proposal to establish a first version of the PRCI Emerging fuels Roadmap**

RNG ROADMAP

Definitions

- **BioGas:** Raw gas producted by the anaerobic digestion of waste (from Dairies, Landfills and Waste Water Treatment Plants). It contains 40% to 60% of methane and about the same amount of CO_2 as well as trace compounds such as H_2S, H_2O, NH_3, Siloxanes, etc. depending on the feedstock.
- **SynGas:** Gas produced by Gasification of woody biomass. It contains various concentrations of H_2, CO H_2O and CH_4 as well as long chains of hydrocarbons depending on the gasification process. Trace compounds such as H_2S are also present.
- **Biomethane:** Upgraded biogas to fulfill gas grid specifications to be safely injected in pipelines
- **Renewable Natural Gas (RNG):** Upgraded syngas through a process of methanation. It and can be safely injected in pipelines. It may also include Biomethane.
- **Renewable methane:** Definition sometime used to cover Biomethane and RNG
- **Synthetic Biomethane:** Sometime used to designate methane produced from H_2 and CO_2

Biomethane injection

- **European goals = 10% of renewable gases in 2030 - Well established in Europe [1]**
  - 621 units in Europe (end of 2018)
  - Annual production = 22 TWh or 75 bcf (2018)
  - Significant growth: +9% number of injection units per year
    - Germany: 216 units, 10 TWh/year
    - Denmark: 32 units, 1.75 TWh/year
    - Netherlands: 40 units, 1.1 TWh/year
    - UK: 88 units, 4.13 TWh/year
    - France: 115 units, 1.2 TWh/year (2019)



- **USA – injection of biomethane started in the USA and Canada, mainly driven by the California LCFS (Low Carbon Fuel Standard) incentive program [2]**

[1] Data: Biomethane European Benchmark – France Biomethane with Sia Partners – December 2019 https://france-biomethane.fr/
[2] https://ww3.arb.ca.gov/fuels/lcfs/lcfs.htm

RNG Production















gasunie ECN DAHLMAN

NETHERLANDS
AMBIGO Project (Alkmaaar) -
Energy Research Center of the Netherland (ECN) plans to built a 2,8 $MW_{biomethane}$ plant in 2018
ENGIE will be a partner and the EPC of the project

SWEDEN
BIO2G Project – EON project in Sweden – 200 MWbiomethane

Göteborg Energi

SWEDEN Goteborg Energi/ EOn
GoBiGas project : 20 MW biomethane large scale demonstration plant. (COD in 2013)- Repotec. Cooperation Haldor Topsöe in methanation
(Phase 2: Industrial plant of 100 MW biomethane).

USA
Pacific National Laboratory:
FICFB gasification + méthanation :
Pilot plant of 1 MW – expecting industrialize the technology by 2018

Updraft Nexterra, Tolko (CA), boiler, 12 MWth_biomass
Balfour Beaty will be the EPC

UK nationalgrid
GO GREEN GAS Project
National Grid
1 $MW_{biomethane}$ methanation pilot plant with connecte to an industrial waste gasification unit

FRANCE
GAYA PROJECT gaya
600 $kW_{biomass}$ gasification pilot plant with methanation – R&D project – FICFB technology – innovative methanation

repotec
AUSTRIA
Repotec indirect gasifier, Gussing 2 MWe
Ortner indirect gasifier, Villach 3.7 MWe
Ortner indirect gasifier, Oberwart 2.8 MWe
1 MW methanation pilot plant from CTU-PSI
(operational)

Projects

Available



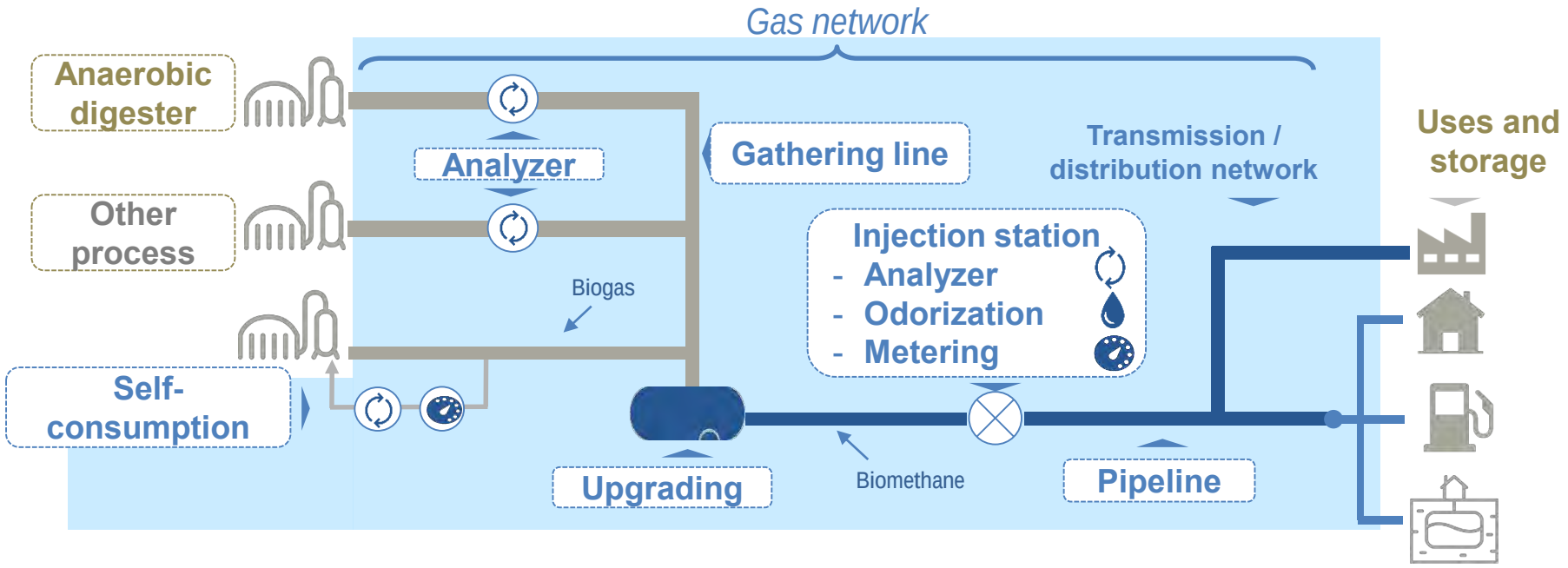
Source: O. Guerrini “Gasification technologies and their contribution to Biomethane development” EBA Workshop –General Assembly February2017

ENGIE

REX2020 PRCI RESEARCH EXCHANGE

Scope of work

PRCI has the ambition to extend its R&D leadership within the piping industry up to renewable gas transportation. To this end, PRCI must contribute to the optimization of transport costs of these RNG and also support the development of biogas transport thanks to innovative solutions.



Key objectives

Be prepared to transport RNG at best cost while managing impacts.
Help to reduce RNG total price with adapted R&D on midstream activities.

— RNG

Optimization at best cost the key elements of the chain value

Public acceptance, RNG knowledge
- Standardization
- RNG compounds

Injection
- Analyzer
- Odorization
- Metering
- Global system

Transport / Distribution
- Impacts on existing grid
- Safety

— Biogas

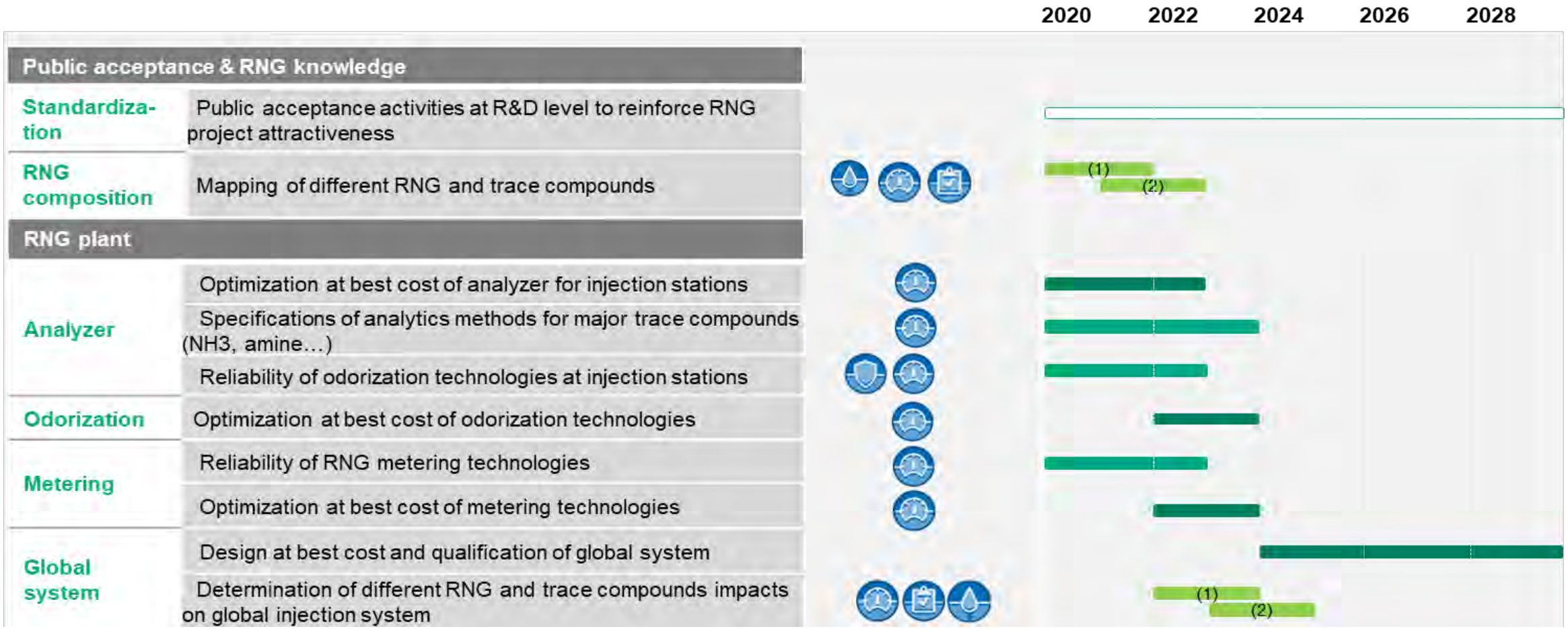
Support chain value perspectives with R&D effort

Public acceptance, biogas knowledge
- Standardization
- Biogas compounds
- Gathering line

Self- consumption
- Analysis
- Metering

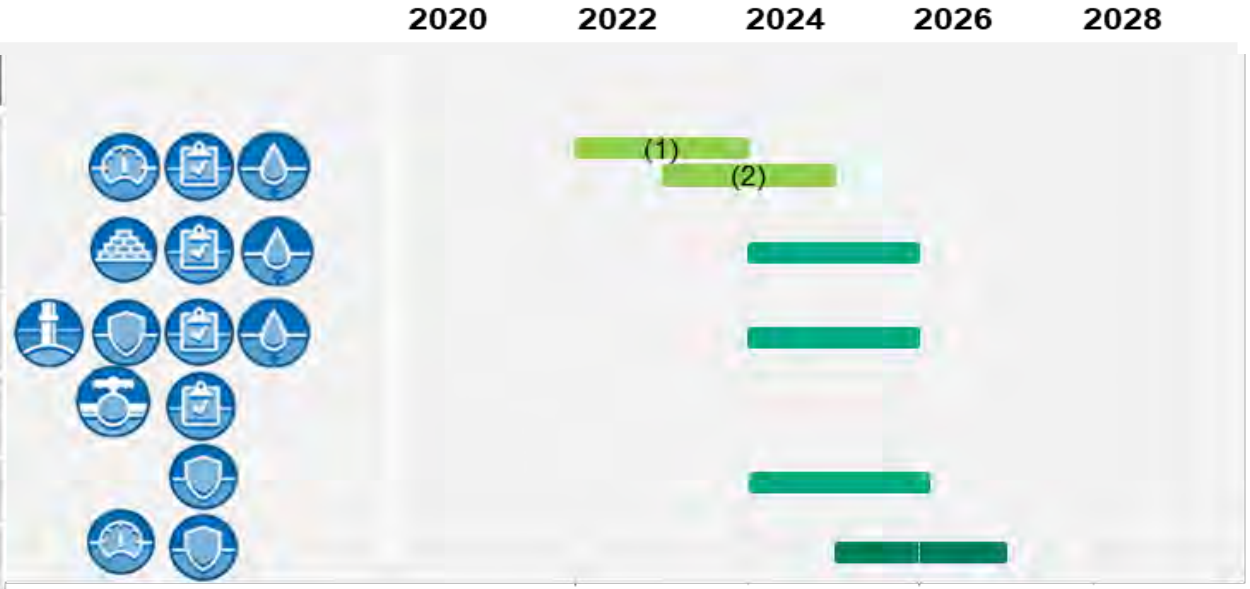
Transport / Distribution
- Analysis
- Upgrading
- Pipelines
- Safety

RNG Roadmap


2020
2022
2024
2026
2028
Public acceptance & RNG knowledge
Standardiza-tion
Public acceptance activities at R&D level to reinforce RNG project attractiveness
RNG composition
Mapping of different RNG and trace compounds
(1)
(2)
RNG plant
Analyzer
Optimization at best cost of analyzer for injection stations
Specifications of analytics methods for major trace compounds (NH3, amine…)
Reliability of odorization technologies at injection stations
Odorization
Optimization at best cost of odorization technologies
Metering
Reliability of RNG metering technologies
Optimization at best cost of metering technologies
Global system
Design at best cost and qualification of global system
Determination of different RNG and trace compounds impacts on global injection system
(1)
(2)

RNG Roadmap

Transport, distribution and storage	
Grid impact (corrosion)	Determination of different RNG and trace compounds impacts on the grid
Pipeline	Research on material suitable to trace compounds (e.g PE)
Storage	Check and prevent impact for all RNG compounds on natural storage area
Reverse flow	Design at best cost gas reverse flow system from distribution to transmission
Safety	Development of optimal solutions for gas leak detection
	Qualification of the odorization



PRCI commitees to involve

- Underground storage
- Design, materials & construction
- Compressor & pump station
- Corrosion
- Measurement
- Integrity & inspection
- Surveillance, operation & monitoring

R&D level

- Knowledge (~ TRL* 1-4)
- Development (~ TRL 5-7)
- Industrilization (~TRL 8-9)

(1) RNG from agricultural feedstocks
(2) RNG from no agricultural feedstocks

**TRL: Technology readiness level*

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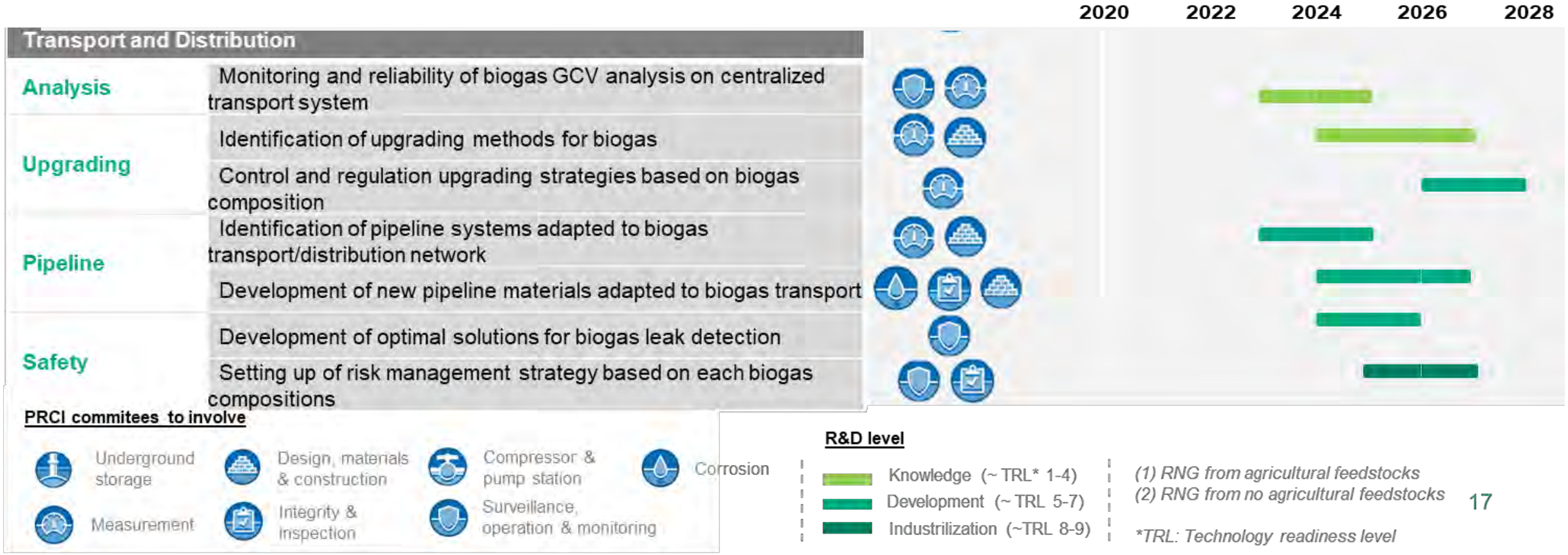
REX2020 PRCI RESEARCH EXCHANGE

Biogas Roadmap

		2020	2022	2024	2026	2028
Pulic acceptance & biogas knowledge						
Standardization	Lobbying activities at R&D level to reinforce biogas project attractiveness					
	Support of self injection set up and normalization					
	Support of "centralized transport system" set up and normalization					
Biogas composition	Mapping of different biogas and theirs compounds					
	Mapping of analytics chains to set up, associated to these biogas					
Gathering line	SOTA of gathering line for biogas					
	Identification of key technical and economical factors to develop safe transport					
Self consumption						
Analysis	Identification of a continuous control system (biogas composition)					
	Identification of biogas GCV analysis system					
Metering	Identification of biogas GCV measurement system					
	Identification of biogas other metering methods					

Biogas Roadmap

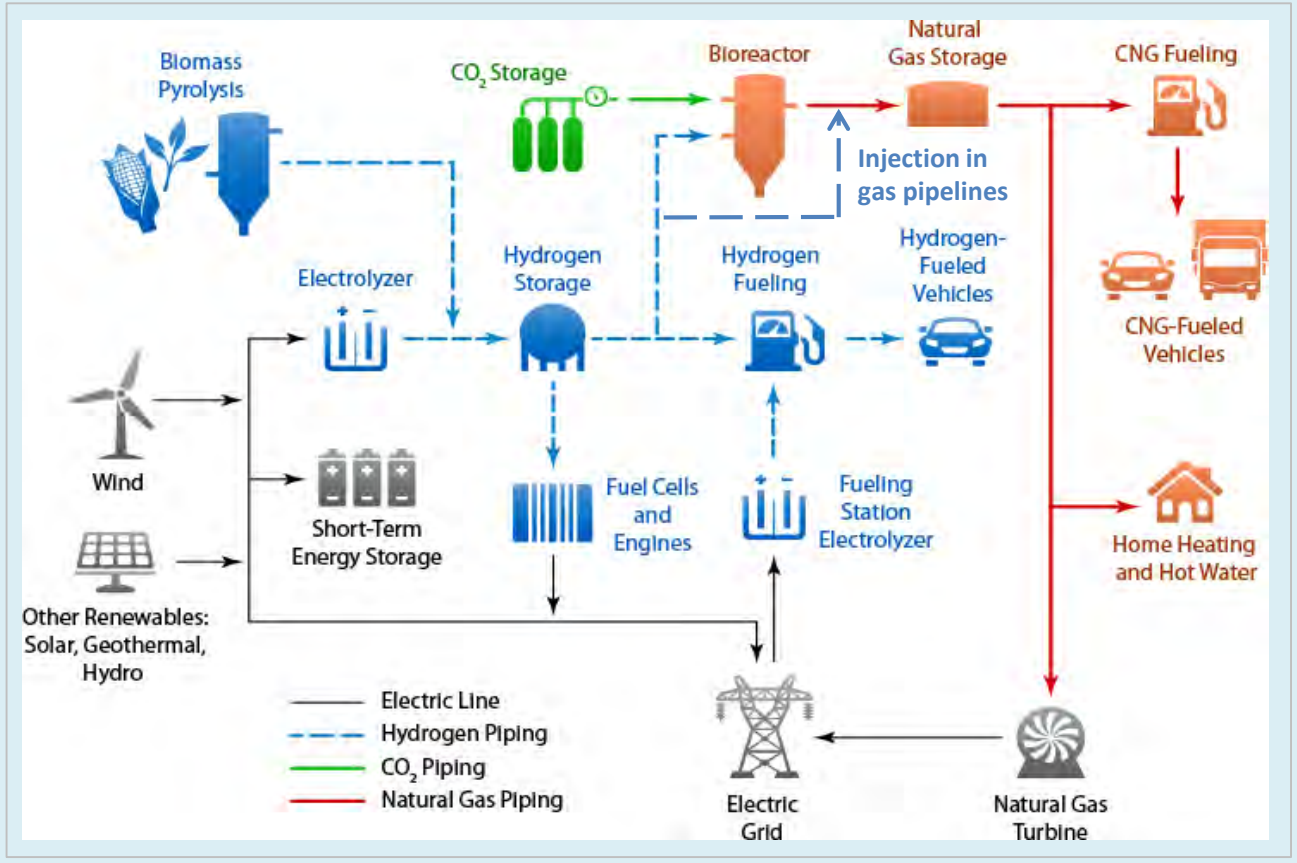


HYDROGEN ROADMAP

Business Drivers

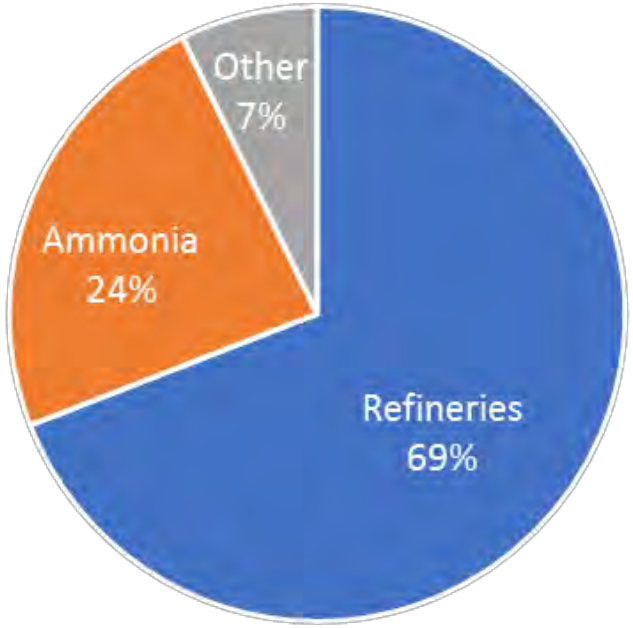
Production | Transportation | Demand

To achieve a sustainable use of natural and renewable resources and provide clean air to people through a low-carbon energy system

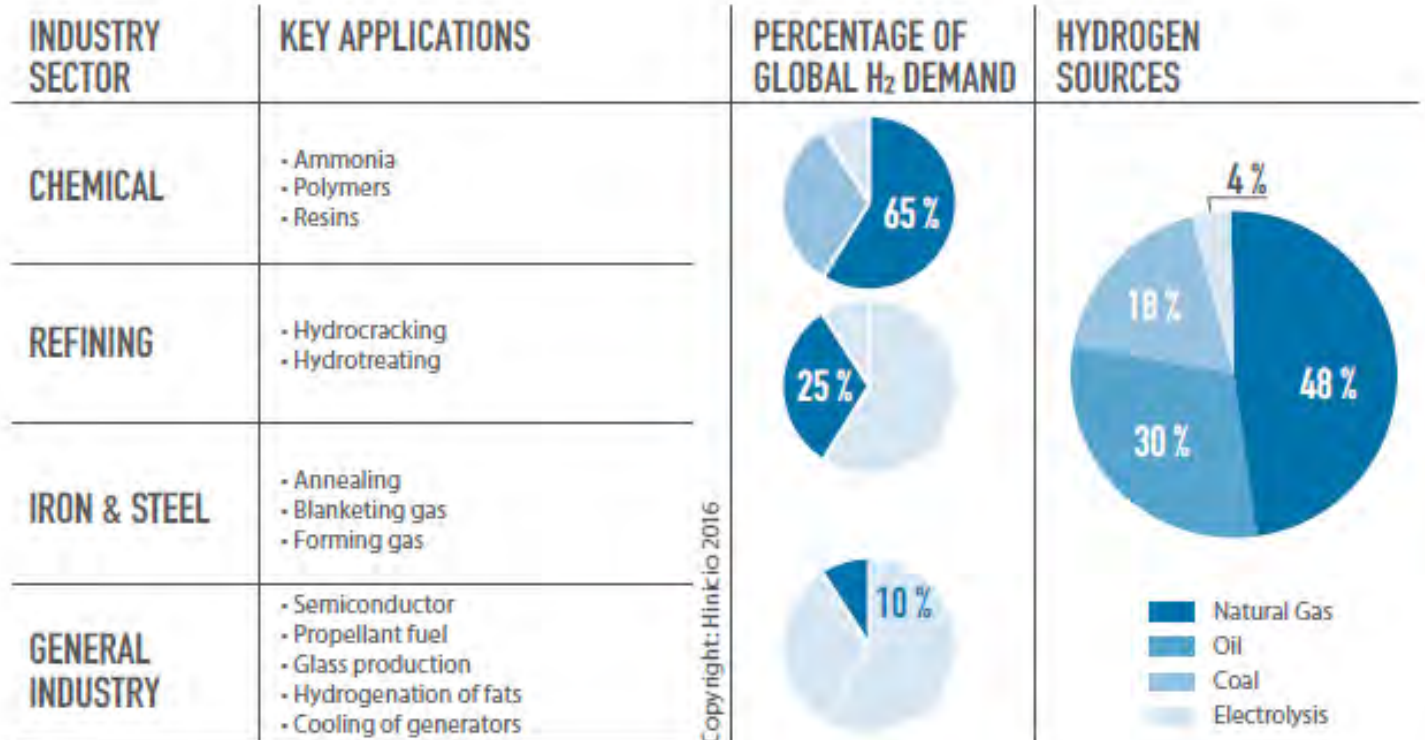


Current Hydrogen Production and Applications

- **Current production of hydrogen in the USA: 10 MMT/year, Worldwide: 65 MMT/year**



US Hydrogen Production and Use (2016)



World Hydrogen Production and Use (2016)

Sources: Fred Joseck et al. "Current U.S. Hydrogen Production" DOE May 2016
J. Adolf et al "Shell Hydrogen Study. Energy of the future?" Shell 2017
IRENA "Hydrogen from Renewable Power" IRENA September 2018

Pipeline Transportation

- **More than 2,800 miles of Hydrogen pipelines in the world today**



Source: J. Adolf et al "Shell Hydrogen Study. Energy of the future?" Shell 2017

Hydrogen Advancing Worldwide

North America	• HYREADY JIP • US UCI campus hydrogen microgrid • Hydrogen Canada Strategic Research Network (H2CAN) • National Fuel Cell Research Center (NFCRC)
Europe	• UK Leeds City Gate project • NaturalHy project (Europe/GERG) • East Germany Hydrogen Power Storage & Solutions (HYPOS) • Dunkirk GRHYD demo of hydrogen injection (Engie Consortium) • Jupiter 1000 (GRTGaz Consortium) • GERG admissible hydrogen concentrations in natural gas systems
Asia	• Japan Fukushima Hydrogen Energy Research Field (FH2R) • Chinese Academy of Sciences hydrogen fuel cell production • South Korea Hydrogen Energy Network (HyNet)
Australia	• Australian Association for Hydrogen Energy

High Level Objectives

- Identify conditions and provide tools to ensure safe hydrogen injection and transportation in existing and new natural gas pipeline infrastructure
- Develop tools to monitor, measure, and manage integrity
- Explore the requirements for 100% hydrogen dedicated networks.
- Identify new method of separating methane and hydrogen from the blended pipeline gas
- Develop products that fill out the downstream market demand for hydrogen in a safe and flexible way
- Get around the thermodynamic inefficiency of generating hydrogen

Subjects of interest but considered outside of the scope of PRCI

Infrastructures for hydrogen transportation

Hydrogen/Natural Gas Pipelines | Hydrogen Pipelines | Hydrogen Trucking

Measurement TC
Gas quality and gas metering of H2/NG mixtures

Compressor & Pump Stations CAPSTC
Compatibility of existing rotating equipment

Underground Storage TC
Impact on reservoir caprock storage

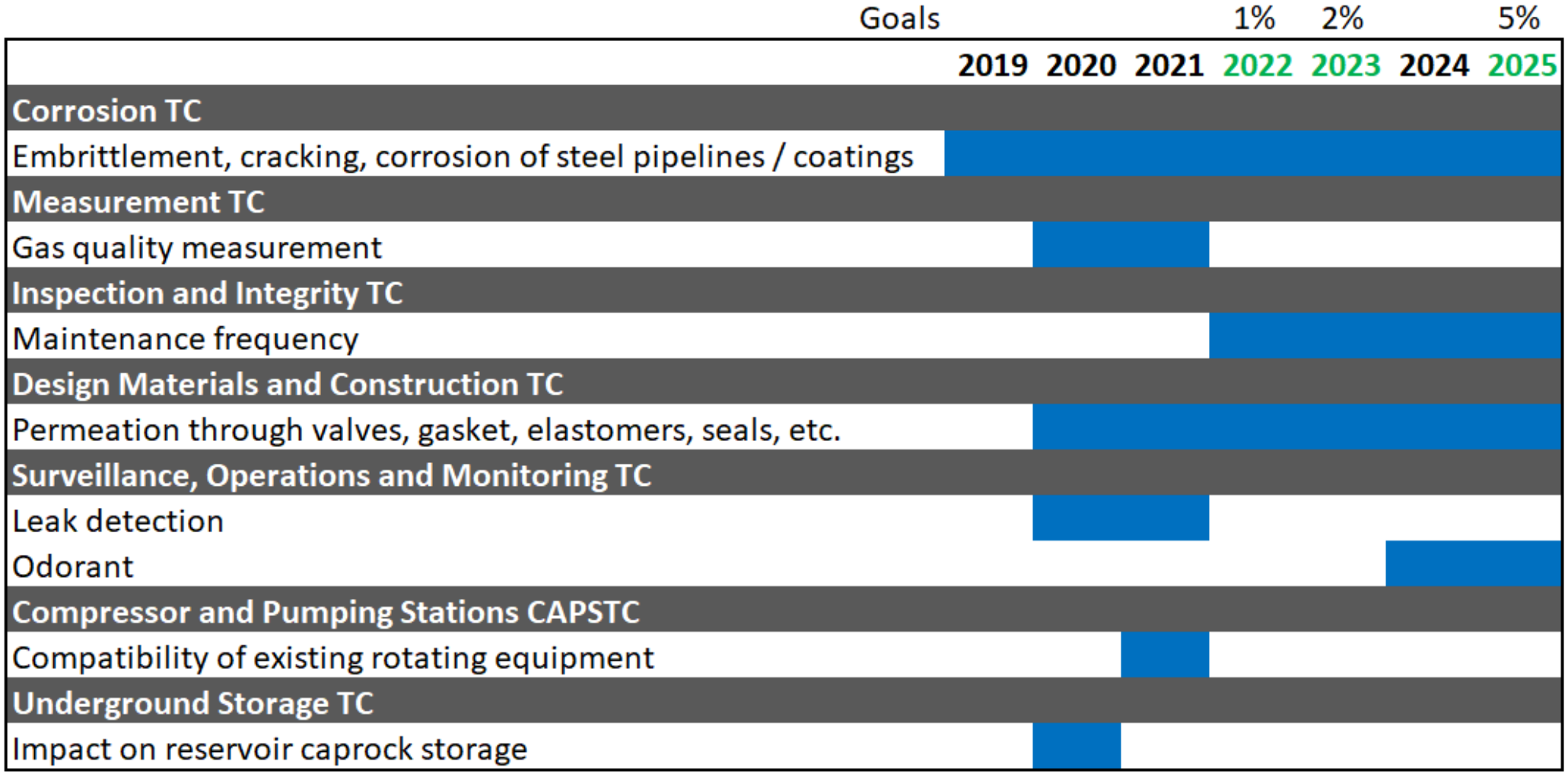
Corrosion TC
Embrittlement, cracking and corrosion of steel pipelines and coatings

Design Materials & Construction TC
Permeation through polyethylene, valves, gasket, elastomers, seals, etc.

Surveillance, Operations & Monitoring TC
Leak detection, odorant, safety zones

Inspection & Integrity TC
Maintenance frequency, impact on pipeline energy storage capacity

PRCI Hydrogen Roadmap (up to 5%)



NEXT STEPS

SOTA and Gap Analysis Objectives

- **Main objectives:**
  - To establish two in-depth state of the art reviews including gap analysis, one for RNG and another one for H_2.

- **These two studies must include at least the following issues:**
  - Mapping of current RNG and H_2 projects (mainly focused on filed project and lab studies)
  - SOTA of knowledge which allow ensuring RNG transport in gas network and the possible injection of up to 20% H_2 in the grid and the transport of pure H2
  - Gap Analysis
  - PRCI priority R&D topics
  - Options for coordinating with other international R&D organizations on these topics

- **Timeframe to complete:** February-July 2020 (presentation of the results at the EA meeting in September)
- **Co-leaders for this project:** GRTgaz (RNG) and PG&E (hydrogen)

Scope of Work

- **RNG:**
  - It is considered that RNG injection in the existing network can range from 0% to 100%
  - 6 technical topics:

TS1: RNG Composition & Analyzer

TS2: Global system, odorization & metering

TS3: Grid impact & pipeline

TS4: Safety (leak detection)

TS5: Storage

TS6: RNG Reverse flow & Gathering line for biogas

- **Hydrogen:**
  - Existing network: 0% - 10% H_2 injection
  - Existing network: 10% - 30%H_2 injection
  - Existing network: 100% H_2 injection
  - New network: 100% H_2 injection
  - 7 technical topics:

TS1: Integrity & inspection, corrosion & coating

TS2: Safety (odorization), maintenance, injection & blending

TS3: Metering (GCV, debit) leak detection and gas quality

TS4: Network equipment

TS5: Network management and compression

TS6: Separation and protection of sensitive customers

TS7: Storage

Coordination and Leverage of Other Initiatives

- **HYREADY:**
  - Engineering guidelines to support operations for H_2/natural gas mixtures with acceptable consequences.
  - 4 active Work Packages:
    - *Transmission Pipelines*
    - *Distribution Pipelines*
    - *Gas Interchangeability*
    - *Compressor Stations*
- **CEN-GERG:**
  - Shortlist of potential priority R&D subject areas to reduce barriers to injection of hydrogen in the natural gas grid, including issues relating to end use.
  - 8 priorities:
    - *Safety*
    - *Gas Quality*
    - *Underground storage*
    - *Power Generation*
    - *Industry*
    - *Steel Pipes*
    - *Grid devices*
    - *End use equipment*



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THANK YOU

BACK TO AGENDA

PRCI 2020 Research Exchange

Assessment of SCC Clusters with Intelligent Interaction Rules

SIA-1-5 / PR-350-144502

Bo Wang (presenter), Banglin Liu and Yong-Yi Wang
Center for Reliable Energy Systems (CRES)

San Diego, CA
March 3, 2020

LEADING PIPELINE RESEARCH

Overview of the Work

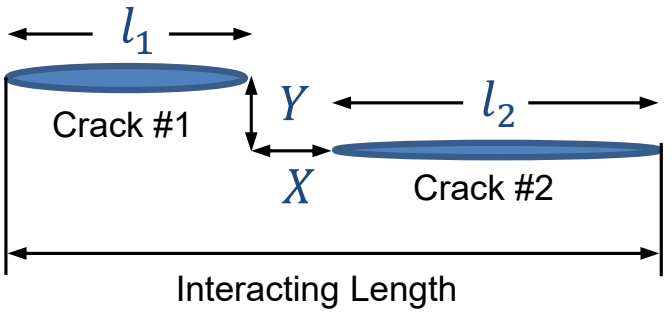
- **Incentives**
  - Stress Corrosion Cracking (SCC) often occurs in clusters and flaw interaction needs to be considered when predicting the burst pressure.
  - Existing flaw interaction rules could produce overly conservative burst pressure predictions which can lead to unnecessary hydrotests or repairs.
- **Objectives**
  - Develop intelligent flaw interaction rules to facilitate the integrity assessment of SCC clusters
  - Influence standards/codes by providing scientific basis for interaction rules
- **Work performed**
  - Development of intelligent flaw interaction rules (termed PRCI/CRES SIA-1-5 rules) through FEA
  - Evaluation of the PRCI/CRES SIA-1-5 rules through full-scale burst tests

Existing Flaw Interaction Rules – CEPA Rules

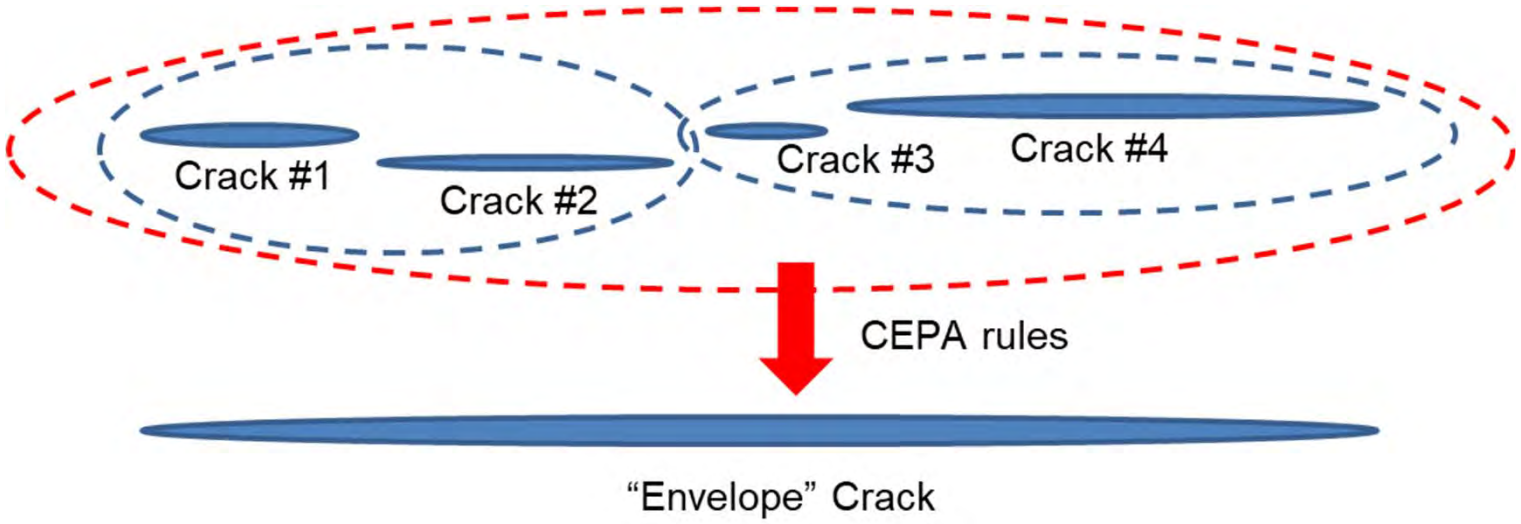
- **Two cracks are interacting if**

$$Y \leq \frac{0.14(l_1+l_2)}{2} \text{ and } X \leq \frac{0.25(l_1+l_2)}{2}$$

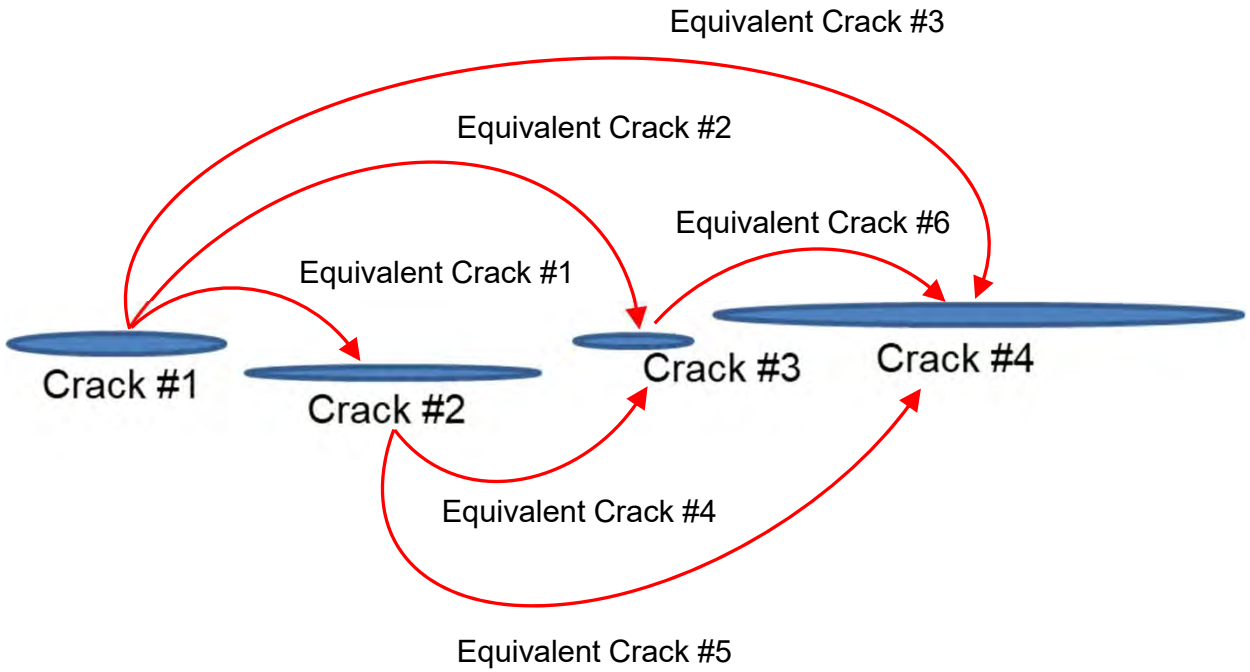
- **If interacting, a cumulative interacting length (i.e., the sum of individual crack length and their spacing) and the max depth in the colony were used to predict burst pressure.**
- **No depth information is considered.**



Application of CEPA Rules to Multiple Cracks



Application of PRCI/CRES SIA-1-5 Rules to Multiple Cracks



Full-Scale Burst Tests – Overview

- **Testing sections with SCC clusters**
  - Four testing sections
    - *Two are 20” OD and 0.25” WT, X60, DSAW*
    - *Two are 18” OD and 0.25” WT, X60, Spiral*
  - SCC clusters
    - *Characterized by NDT (MPI, PAUT, IWEX, Eddy Current Array)*
- **Instrumented with a camera mounting and recording system to record**
  - Crack opening
  - Pipe burst failure



Burst Location

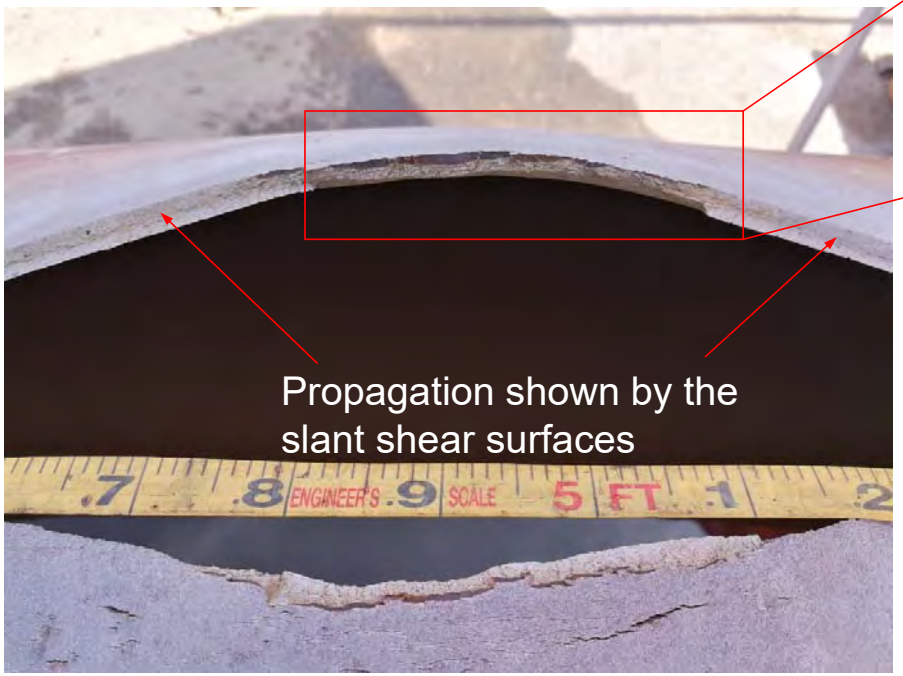
- Good agreement between the predicted and actual burst location



Full-Scale Burst Test Video – Burst1



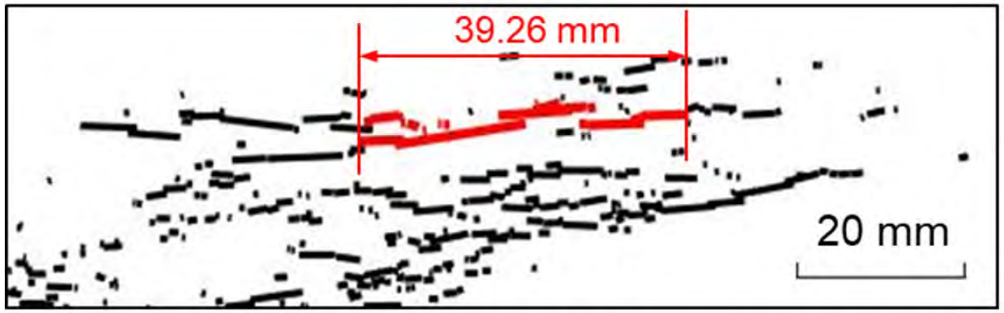
Fracture Surface – Burst1





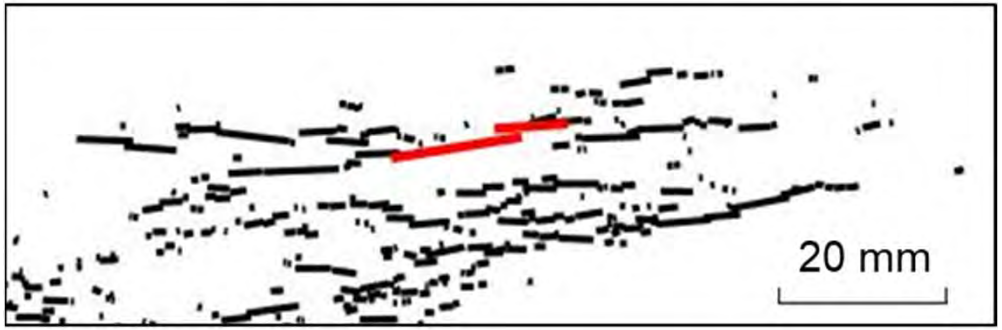
Comparison of Equivalent Crack Size – Burst1

CEPA rules



Equivalent crack: 39.26 mm long, 3.00 mm deep (PAUT)

PRCI/CRES SIA-1-5 rules



Equivalent crack: 16.48 mm long, 3.63 mm deep

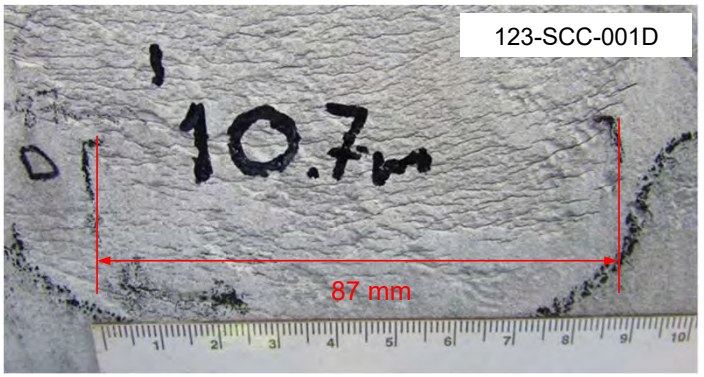
Burst Pressure Prediction – Key Components

- **Equivalent crack size**
  - Crack information (crack length, depth, and spacing)
  - Flaw interaction rules
- **Pipe material properties from small-scale tests**
  - Tensile (YS, UTS)
  - Charpy impact energy
- **Fracture mechanics model**
  - Modified Ln-sec method

Equivalent Crack Size Determination Method 1

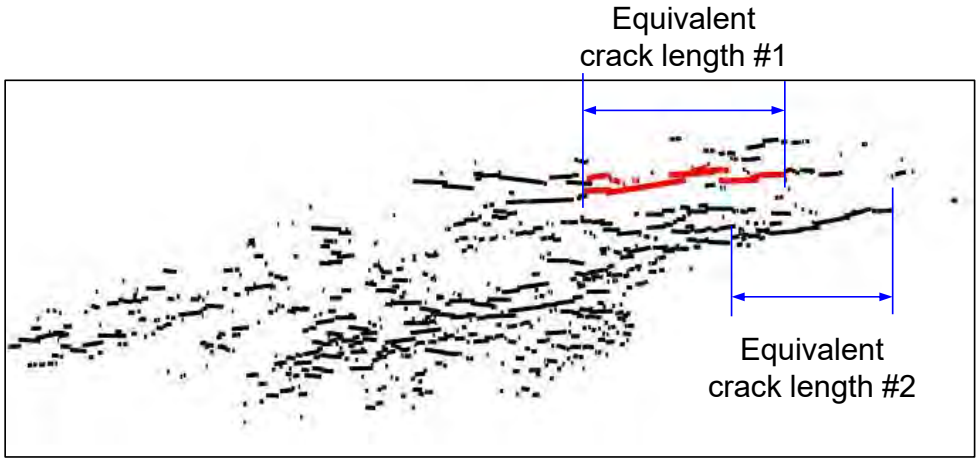
- **Field MPI + PAUT**
  - Input
    - *Field MPI photo*
    - *Depth from PAUT*
      - Maximum depth
  - Output
    - *Equivalent crack length*
      - From field technician output (supposedly using 1 mm x 1 mm interaction rules)
    - *Crack depth*
      - Maximum depth from PAUT

Field MPI photo



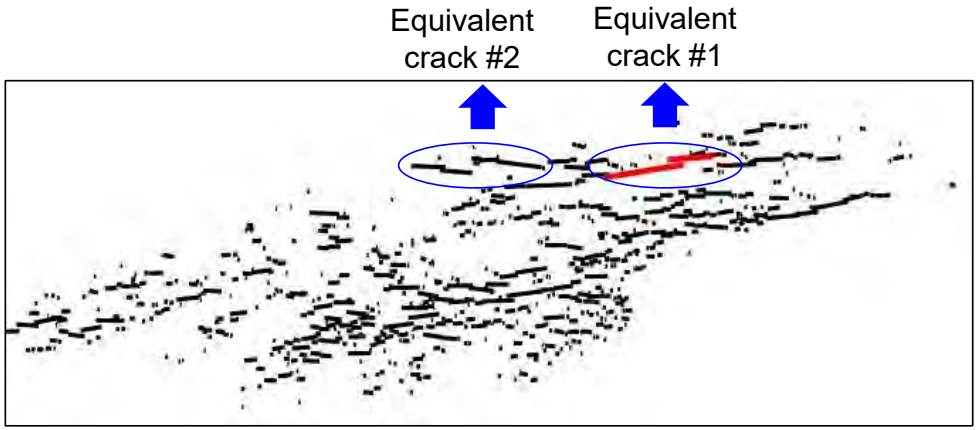
Equivalent Crack Size Determination Method 2

- **Computer Image-Processed MPI + PAUT**
  - Input
    - *Field MPI photo*
    - *Depth from PAUT: depth profile along pipe longitudinal direction*
  - Output
    - *Equivalent crack size from CEPA rules*



Equivalent Crack Size Determination Method 2 – Cont.

- **Computer Image-Processed MPI + PAUT**
  - Input
    - *Field MPI photo*
    - *Depth from PAUT: depth profile along pipe longitudinal direction*
  - Output
    - *Equivalent crack size from PRCI/CRES SIA-1-5 rules*



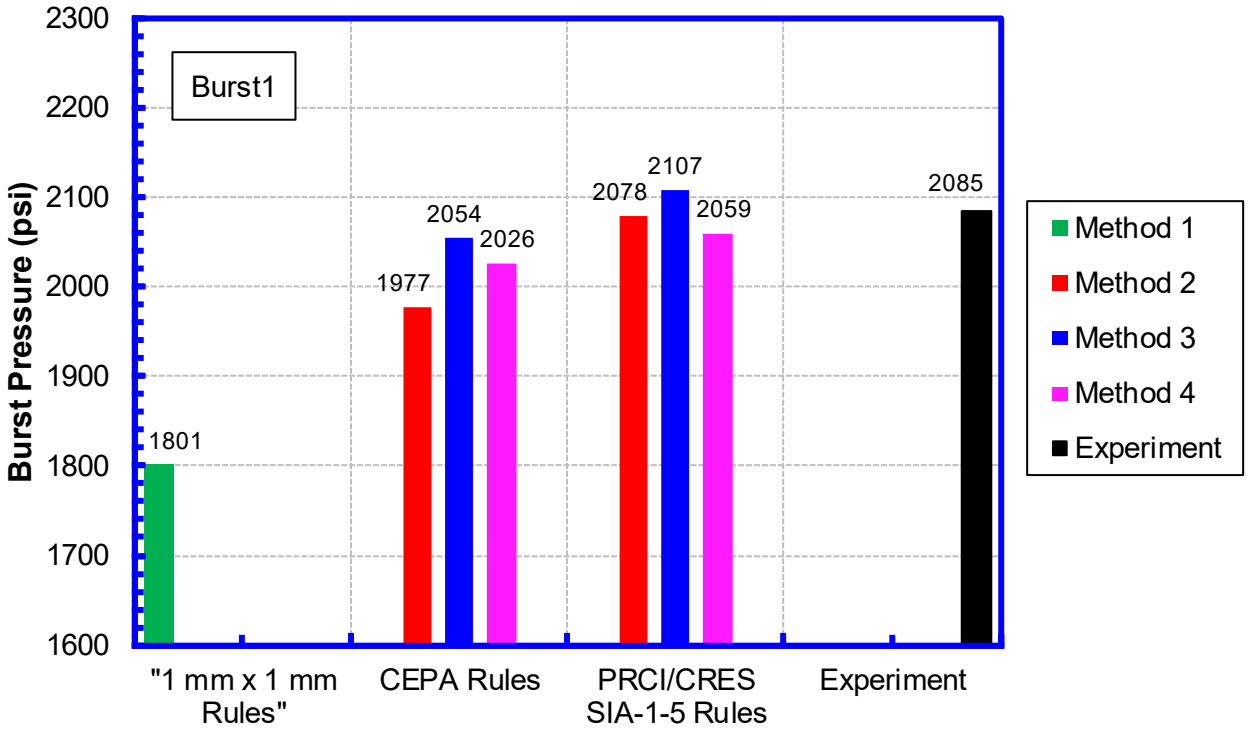
Equivalent Crack Size Determination Method 3

- **Computer Image-Processed MPI + ECA (Eddy Current Array)**
  - Input
    - *Field MPI photo*
    - *Depth from ECA*
      - Max depth within 0.5” x 0.5” grid
      - For each grid, assign max depth to all cracks within the grid
      - Depth discrimination in both longitudinal and hoop direction
  - Output
    - *The same as Method 2 except that the depth information is from ECA*

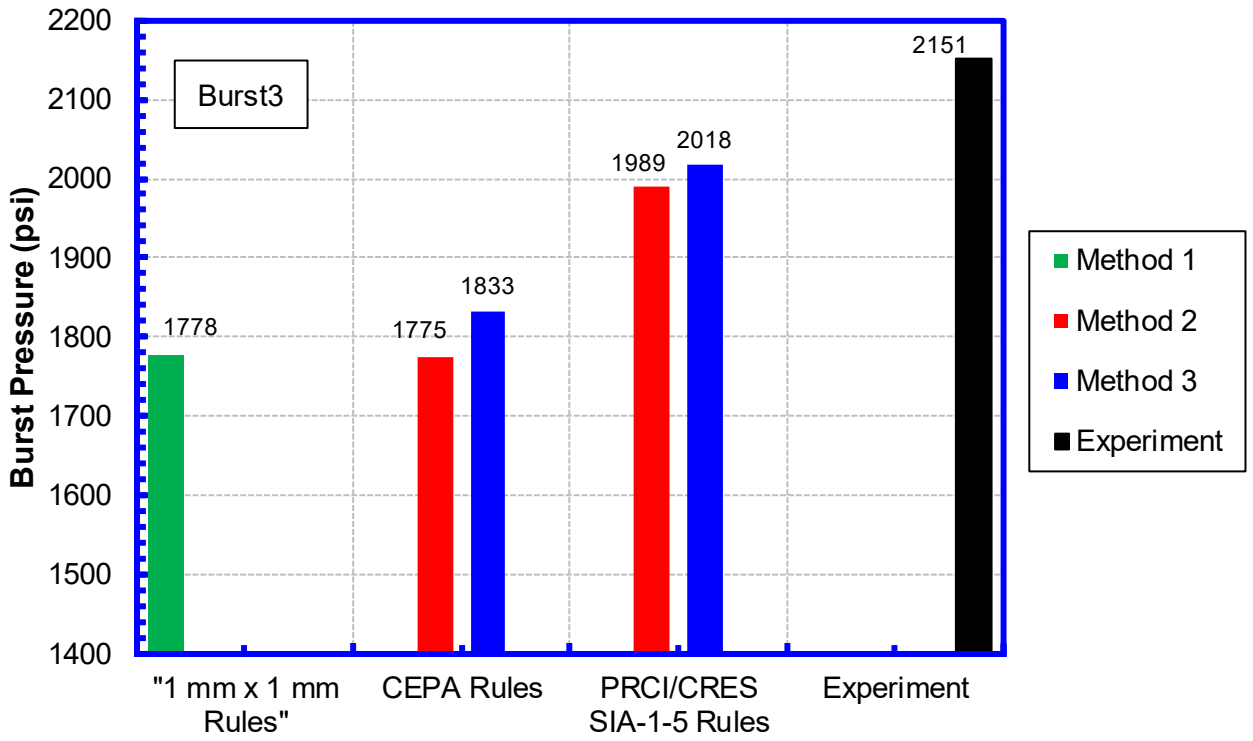
Equivalent Crack Size Determination Method 4

- **IWEX**
  - Input
    - *Identified individual cracks, including crack start and end point*
    - *Depth of identified individual cracks*
  - Output
    - *Same to Method 2, except for the following two steps:*
      - Determine the crack length and spacing from IWEX output of crack start and end point
      - Take the individual crack depth from IWEX output directly

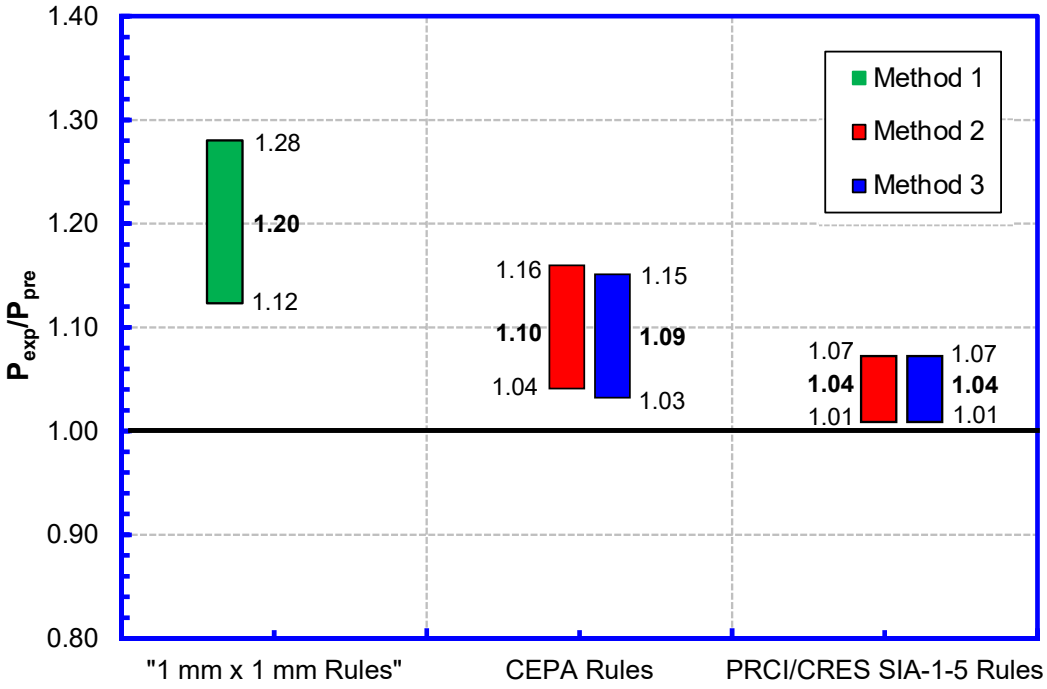
Comparison of Burst Pressure – Burst1



Comparison of Burst Pressure – Burst3



Assessment of Flaw Interaction Rules



Everything else being equal, the PRCI/CRES SIA-1-5 rules provide the most accurate and precise burst pressure prediction, with a mean actual-to-predicted burst pressure ratio of 1.04 and a standard deviation of 0.03.

Current Applications of PRCI/CRES SIA-1-5 Rules

- **Assess severity of SCC cluster and predict burst pressure using crack information from**
  - Existing in-ditch NDT methods
    - *Length and spacing: MPI*
    - *Depth: shear wave UT, PAUT, TOFD*
  - Advanced in-ditch NDT methods
    - *Eddy Current Array*
    - *IWEX*
    - *XCT*
- **Separate the effects of various factors contributing to the conservatism of burst pressure prediction**
  - Material properties (YS, UTS, and fracture toughness)
  - Flaw dimensions (length, depth)
  - Interaction rules (existing rules, PRCI/CRES SIA-1-5 rules)
  - Fracture mechanics models (Modified Ln-sec, API 579 FAD, CorLAS®, PRCI MAT-8-1, PAFFC)

Summary of Key Findings

- **PRCI/CRES SIA-1-5 rules**
  - Capture the fundamentals of flaw interaction by representing the impact of interaction via equivalent cracks
  - Improve the burst pressure prediction
- **Future applications**
  - ILI + PRCI/CRES SIA-1-5 Rules → Assessment results
  - Incorporate the rules into standards, codes, and guidance documents
    - *ASME B31.8S*
    - *API 579-1 / ASME FFS-1*
    - *CEPA SCC Recommended Practices*

Thank You

- Q & A

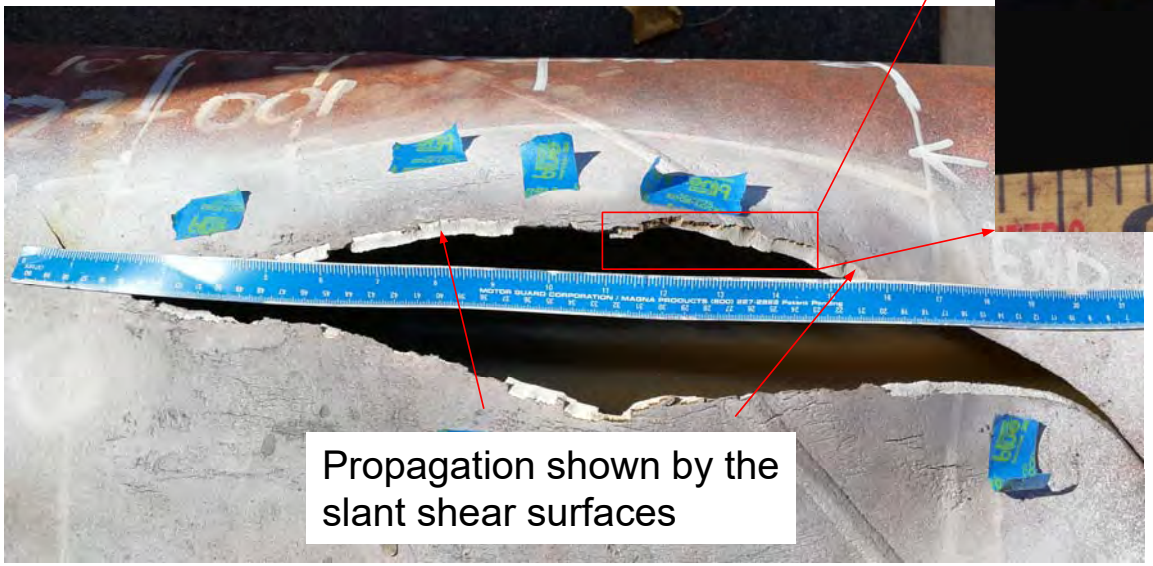
Full-Scale Burst Test Video – Burst3



Fracture Surface – Burst3

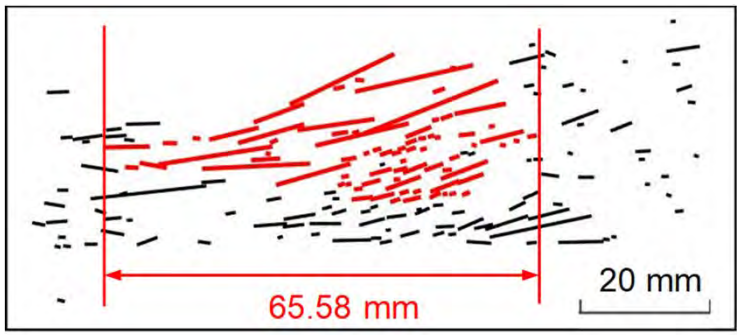
Large crack (23 mm long, 2.47 mm deep)





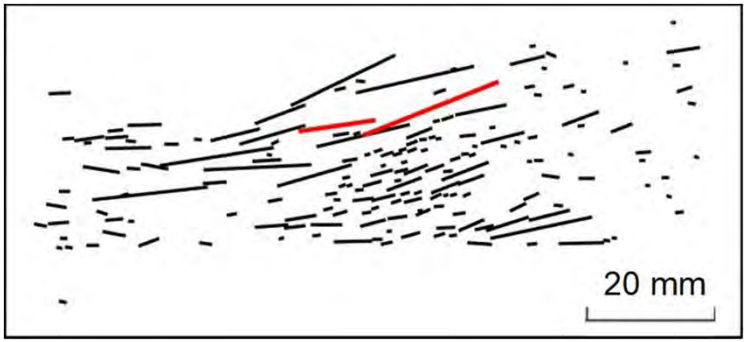
Comparison of Equivalent Crack Size – Burst3

CEPA rules



Equivalent crack:
65.58 mm long,
2.80 mm deep
(PAUT)

PRCI/CRES SIA-1-5 rules



Equivalent crack:
21.97 mm long,
3.37 mm deep

BACK TO AGENDA

PRCI 2020 Research Exchange

Improved Failure Pressure Estimates of SCC Colonies from ILI and Field Data

NDE-4-10 / PR-366-173814

Bruce Nestleroth, Kiefner - Presenter
Ben Hanson, Kinder Morgan
Domenico Bellistri, Applus
Thomas Walther, Rosen
Bo Wang, Center for Reliable Energy Systems (CRES)

LEADING PIPELINE RESEARCH

Project Objective

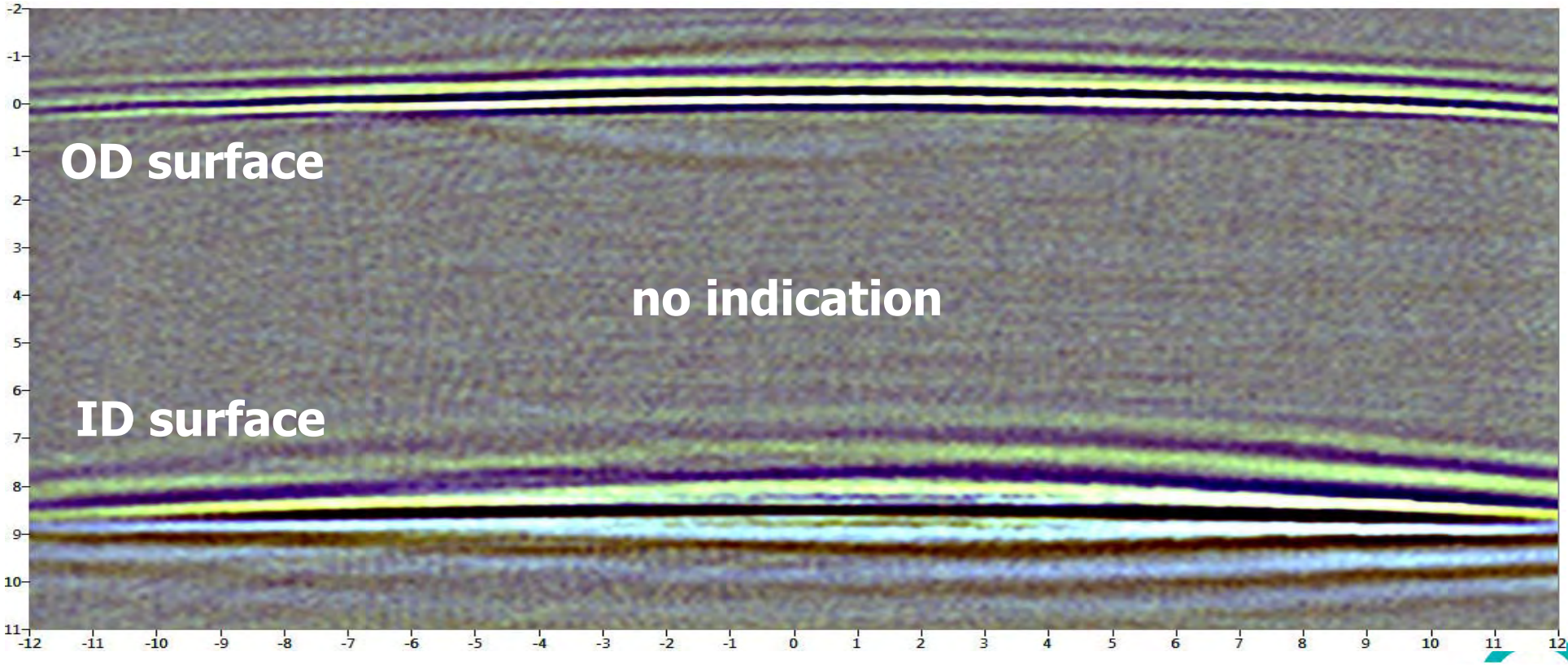
- **Provide operators a more effective and efficient means for calculating remaining life for Stress Corrosion Crack (SCC) colonies from in-line inspection data**
- **Intermediate objectives**
  - Develop ultrasonic imaging processes and procedures for gathering accurate in-ditch measurements of length separation and depth for SCC
  - Establish methodology to facilitate comparisons between ultrasonic imaging and in-line inspection (ILI) data for natural gas pipelines
  - Develop methodology to improve failure pressure estimates of SCC colonies using in-ditch data
  - Validate by means of burst tests to evaluate the performance of the model that predicts failure pressure based on ultrasonic imaging measurements

Summary of Results – Presentation Outline

1. **IWEX can provide accurate results**
   - Initial comparison showed improvements and adjustments needed
   - Good correlation between length and depth XCT and IWEX results
   - For 3 destructive tests, depth sizing agreed within 0.2 mm (0.008 inch)
2. **IWEX and EMAT data from same pipes compared well**
3. **IWEX can provide data for traditional (NACE/CEPA/ASME) and recently developed intelligent interaction criteria (PRCI SIA-1-5)**
4. **For the PRCI SIA-1-5 intelligent interaction criteria using IWEX data, the comparison between experimentally determined and predicted failure pressures were excellent**
   - Just a 3% average overestimation of predicted values
   - A tight error distribution with a 3% standard deviation

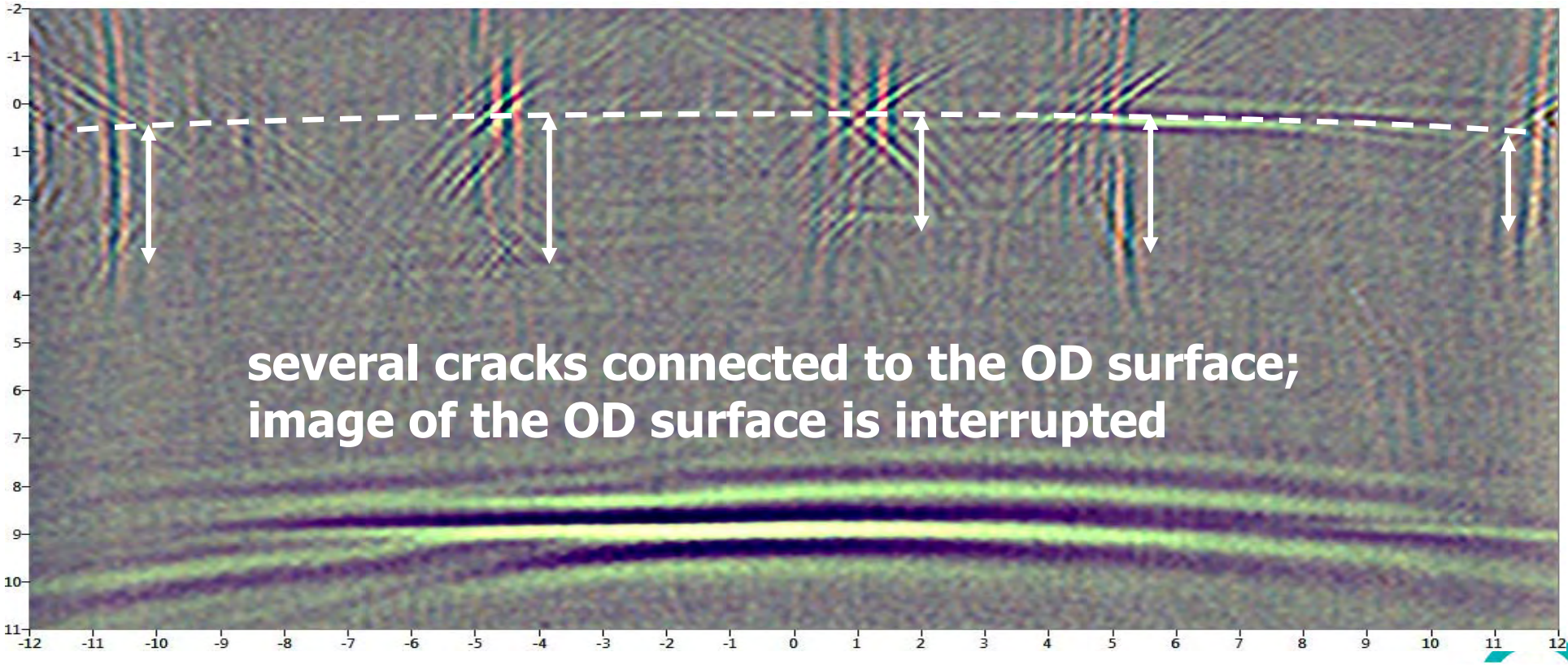
Comparison of IWEX Ultrasonic Images to X-ray Computed Tomography (XCT) Images

IWEX SCC Example: No Indication



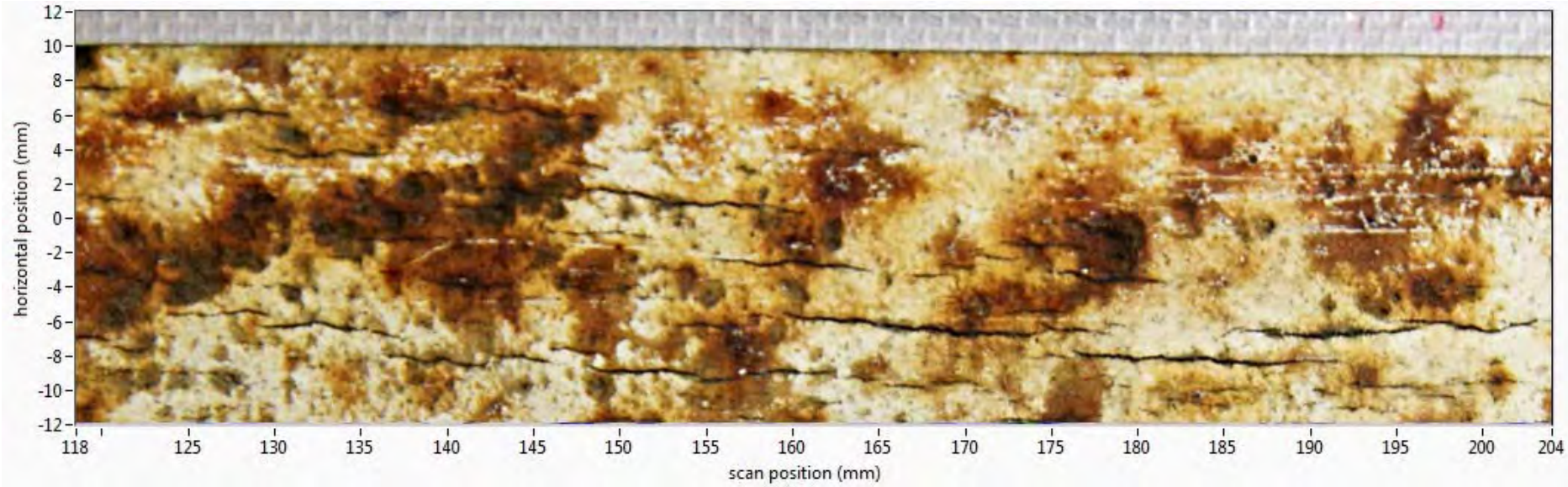
(all dimensions in millimeters)

IWEX Image: Several SCC Cracks



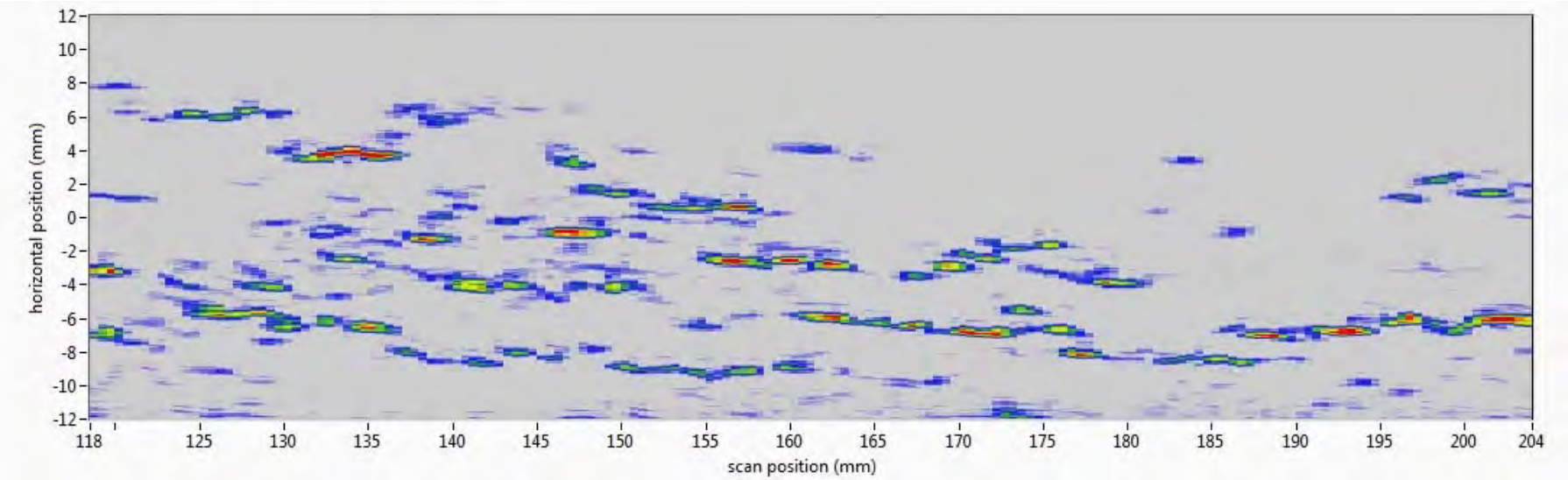
(all dimensions in millimeters)

C-scan View of SCC



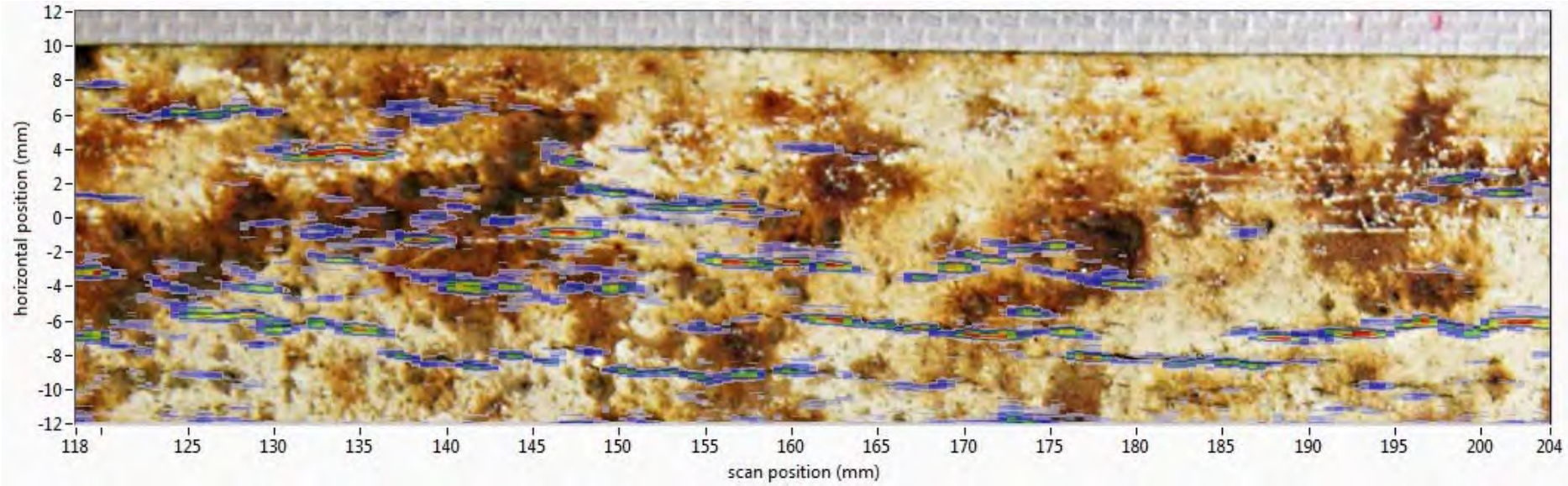
Photograph of the sample with MPI

SCC Defect



Removal of corner reflections for the C-scan

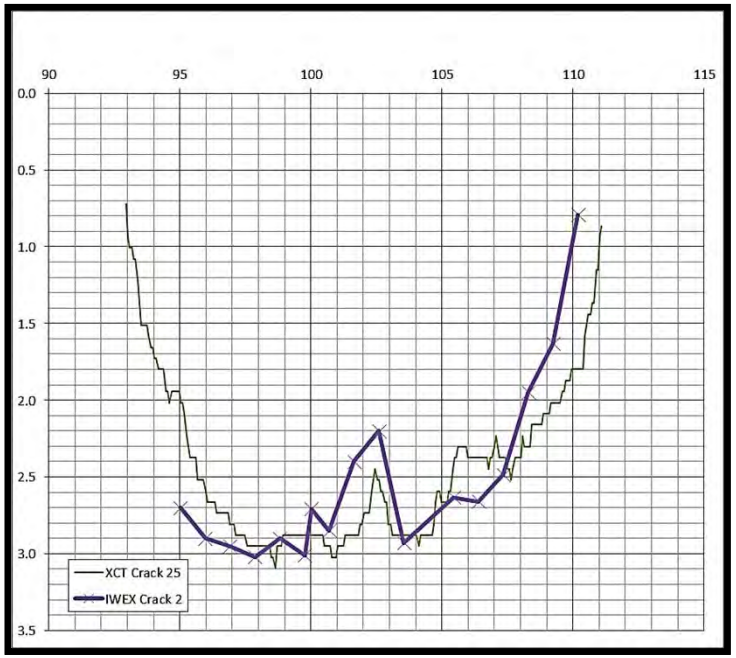
C-scan View of SCC



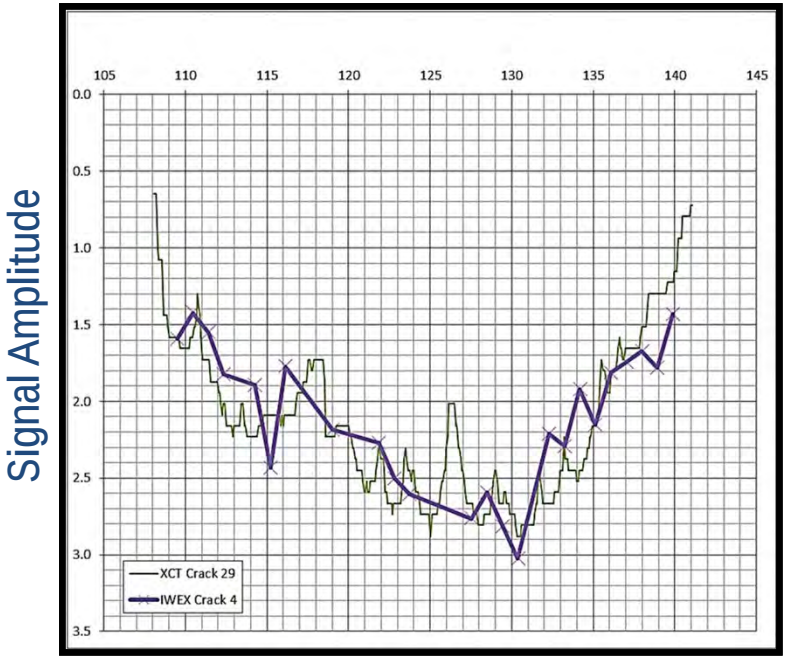
IWEX data superimposed on photograph

Comparison of XCT and IWEX for Isolated Cracks

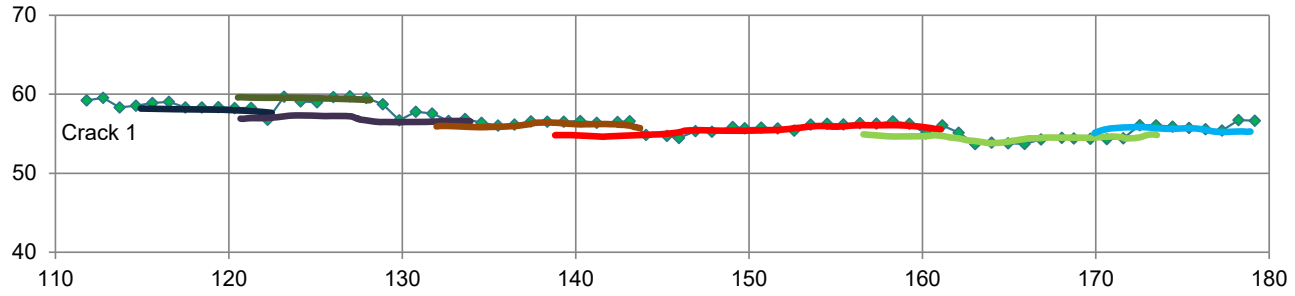
Crack 2

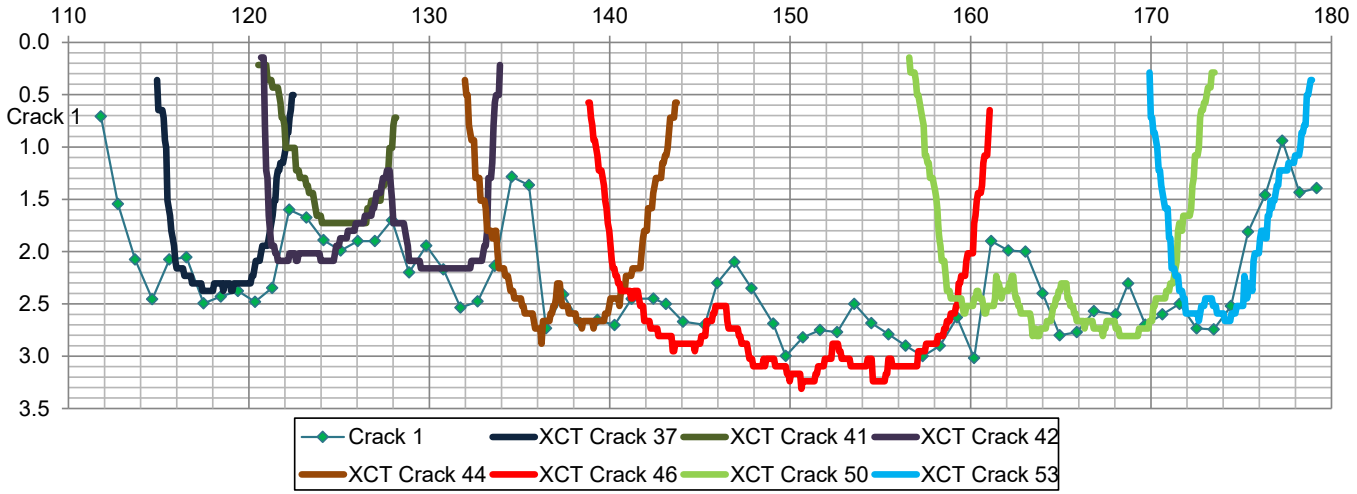


Crack 4



Comparison of XCT and IWEX for Interacting Cracks

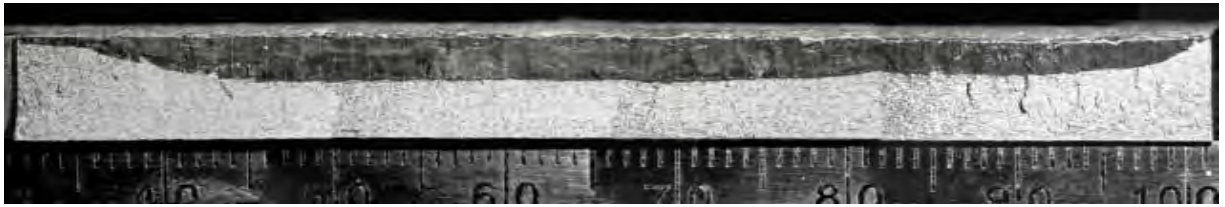


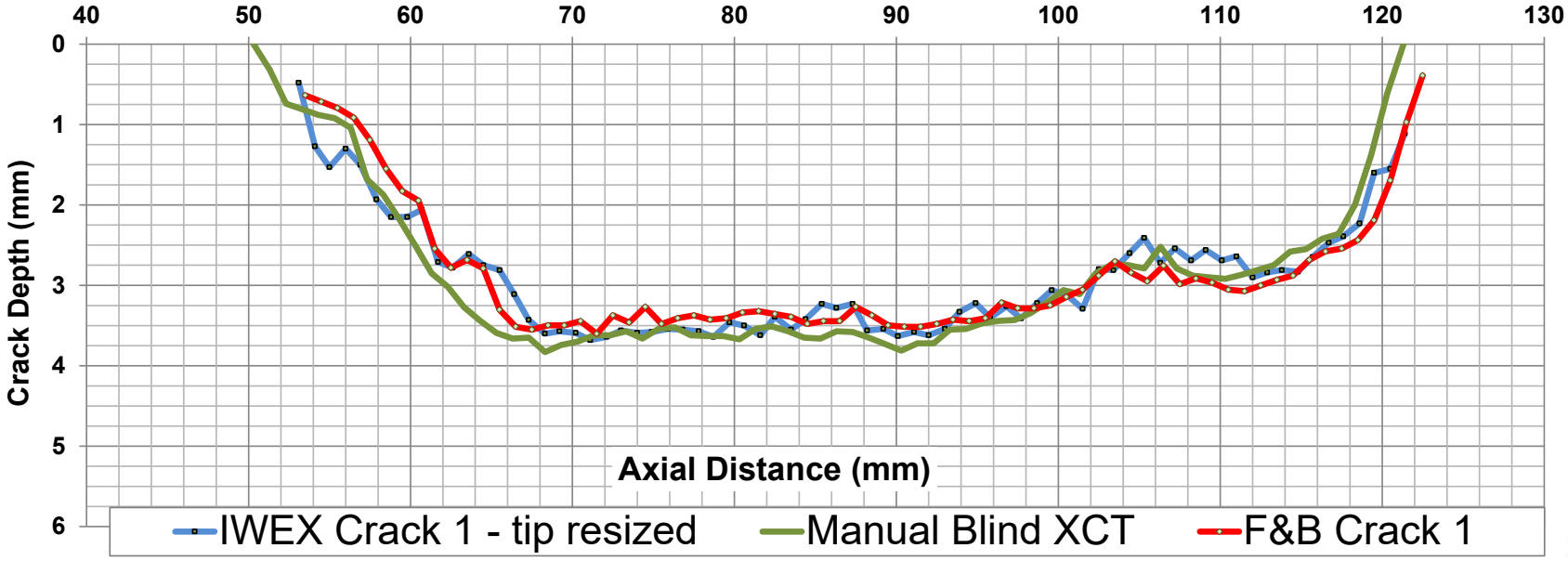


REX2020
PRCI RESEARCH EXCHANGE

ɔ, CA

IWEX and XCT Results versus Metallography





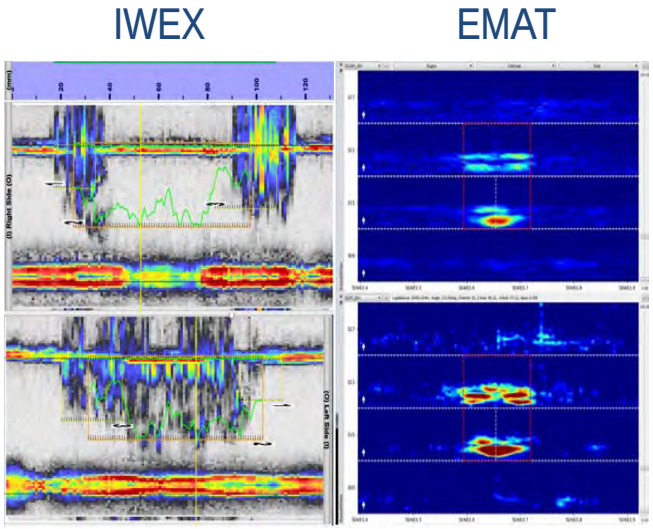
NDE Field Data Collection and Comparison to EMAT ILI

EMAT Task Objectives

- **Improve the understanding of EMAT data with regard to profiles and discrimination of individual crack features within an SCC colony**
  - Currently, EMAT reports 1 crack depth and 1 crack length for isolated features or groups of features.
  - These dimensions reflect the overall signal length and only the deepest crack location within the feature.
- **NDE 4-10 sought to determine whether a detailed comparison between EMAT and IWEX data could identify EMAT signal characteristics that might be used to support the development of crack profiles using EMAT technology**

2.4 Perform Comparisons - Background

- **To compare IWEX and EMAT results, the differences must be well understood:**
  - **Resolution & operational boundaries**
    - ILI measures anomalies from inside at gas flow speeds.
    - Factors such as cleanliness and flow rate influence the data recorded.
    - IWEX operates at lower speeds from the pipe OD with the coating removed.
  - **Sampling rate and resolution**
    - » *ILI tools and NDE tools have different sampling rates and overall resolution*



- **Due to the technology differences between ILI and IWEX, the ILI recorded data/signal shows less detail and does not allow for discrimination of the individual flaws the same way that IWEX does.**
- **A single reflection in EMAT may be caused by multiple individual flaws which can be more easily distinguished in the IWEX data.**

Correlation between EMAT and IWEX

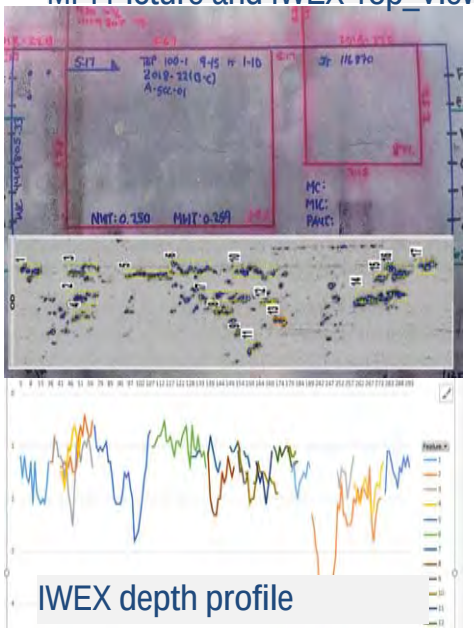
Workflow and Requirements

ROSEN
empowered by technology

- **Even with the differences in sampling and resolution between the techniques, it is possible to compare the measurements. It requires data exchange among Operator, ILI company, and field inspectors.**
  - MPI Picture from field
  - IWEX Top View
  - Spreadsheet with feature id, X, Y position and associated depth value

→Based on data provided, ROSEN can correlate the EMAT data to the IWEX data

MPI Picture and IWEX Top_View



IWEX depth profile

Input Data → Processed EMAT Data → Correlation of EMAT to IWEX → Identifying effective crack elements causing signal in EMAT data → Depth Comparison

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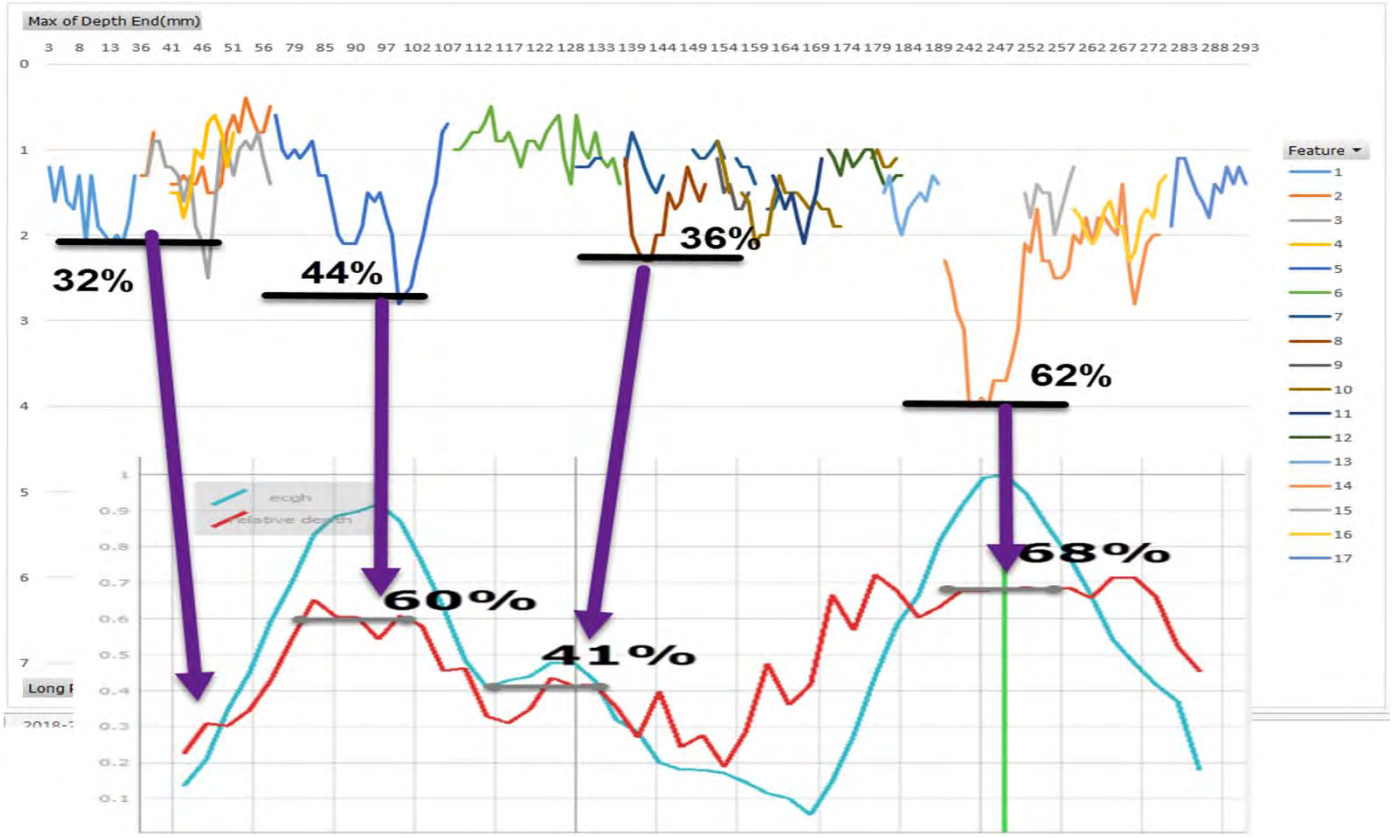
PRCI RESEARCH EXCHANGE

IWEX and EMAT Measurements

IWEX

EMAT



REX2020
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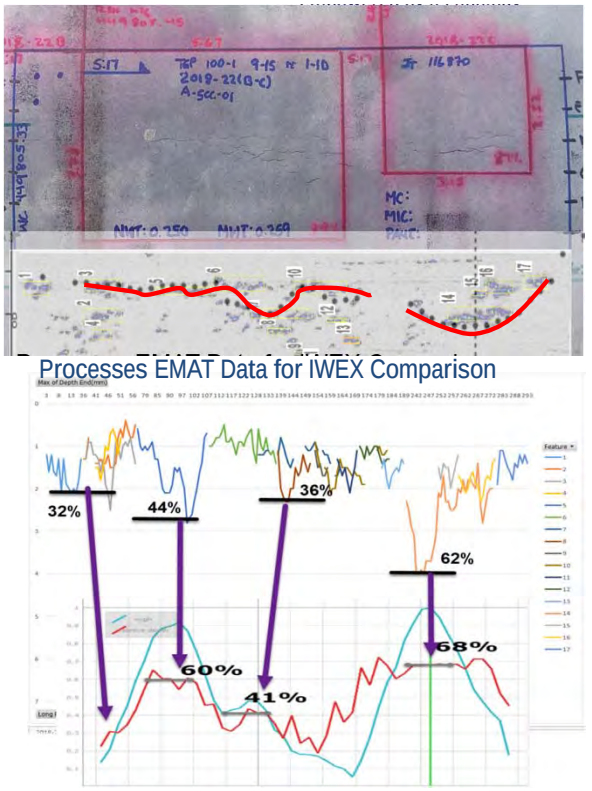
Correlation

- Additional information needs to be extracted from the EMAT data in order to correlate IWEX and EMAT.
- This information allows a comparison to the IWEX Top View
- Based on this correlation, the “effective crack elements” which causes the EMAT signal response can be identified
- Once the crack elements are identified, the EMAT depth can be compared to the crack profile recorded by IWEX
- Due to different resolutions, depth values may differ between IWEX and EMAT; therefore the length of a single flaw needs to be considered during the comparison



Correlation (Blind)

Sample ID	EMAT Length [mm]	EMAT Depth [%nwt]	IWEX Length [mm]	IWEX Depth [%nwt]	Depth Delta
2018-01	282	35/50/48/35/35	280	27/44/48/50/34	8/6/0/15/1
2018-06	62	55	53	62	8
2108-18	42	40	122	35	5
2018-19	128	45/35/60	101	47/47/47	2/8/13
2018-20	167.9	71	197	62	9
2018-21(A-C)	78/29	30/50	102	25/42	5/8
2018-21D	42	71	52	45	26
2018-21E	40	50	37	42	8
2018-21F	64	60	41	49	11
2018-21G	55	40	84	30/35	5
2018-22(B-C)	78/52	60/41/68		44/33/65	16/8/3
2018-22F	45	73	41	50	23
2018-22N	44	46	63	49	3

EMAT Summary / Results

- **In total 14 comparisons between IWEX and EMAT were performed**
- **5 samples provide the ability to derive multiple depth values**
- The remaining 9 indications are short in length and only one depth value can be derived from EMAT
- This study indicates that EMAT is usually more conservative in the depth sizing
- Length sizing for shorter flaws is quite consistent between IWEX and EMAT

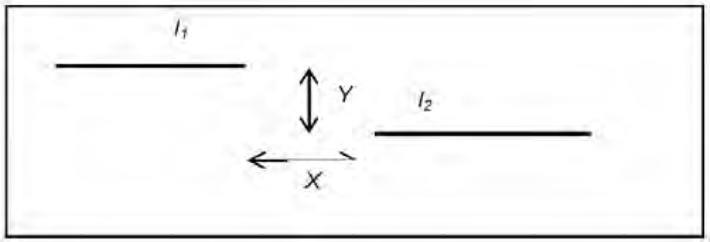
➢ The higher degree of conservatism in EMAT data needs further review

➢ Comparison in length for larger fields needs further improvement

Comparison to Burst Tests

Interaction Rules

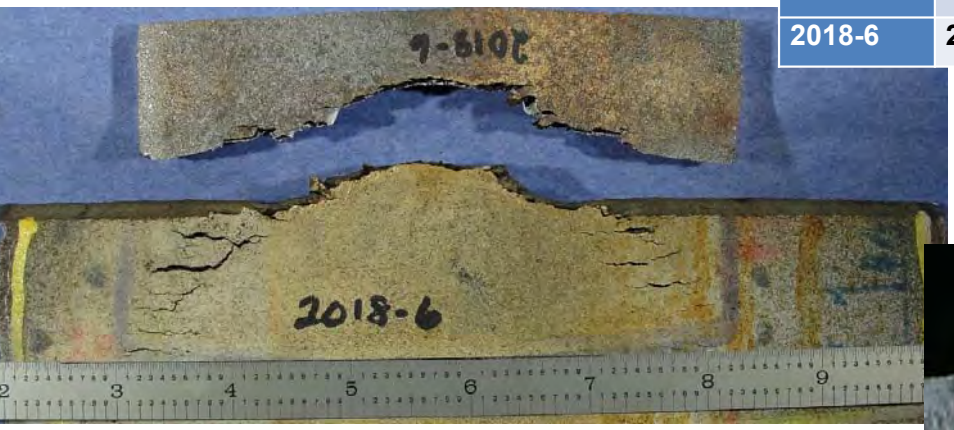
- **When there is more than 1 crack, it must be determined whether the stress combines to create a more significant crack**
- **Standards described in CEPA, NACE, and ASME commonly used:**
  - Depth not considered, just an MPI image
  - Circumferentially within 14% of their average length or
  - Axially within 25% of their average length.
- **API 579-1 also has interaction criteria for many crack configurations in pipes:**
  - Depth is considered, specifically in the axial separation. ≤ ½ max depth
  - Circumferential separation, the threshold in API 579 is a fixed 13 mm (0.5 inch)
- **New rules**
  - PRCI Project SIA-1-5, titled *Intelligent Flaw Interaction Rules*



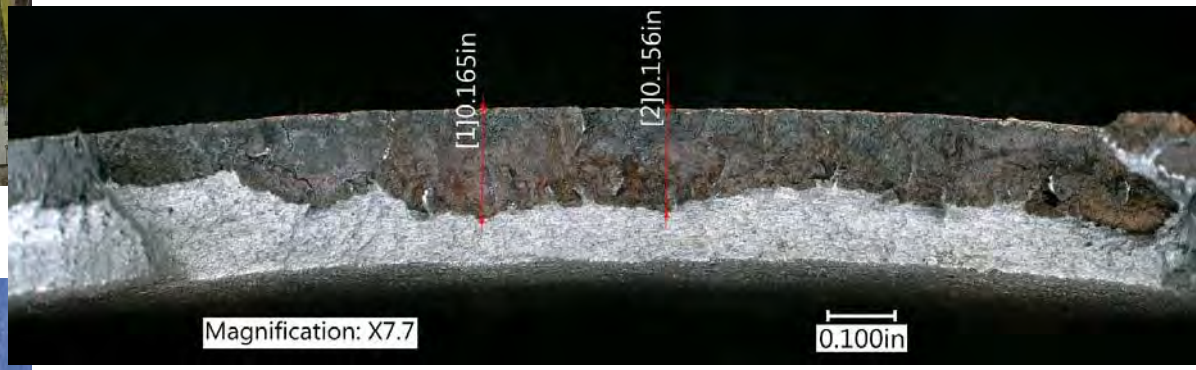
Pipe Specimen 2018-6

- Burst Pressure 1399 psi

	D	SMYS	Wall	100%		72%		Predicted P_f		
	inch	ksi	inch	kPa	PSI	kPa	PSI	kPa	PSI	% Ys
2018-6	24	50	0.250	7184	1042	5171	750	6824	990	95.0%



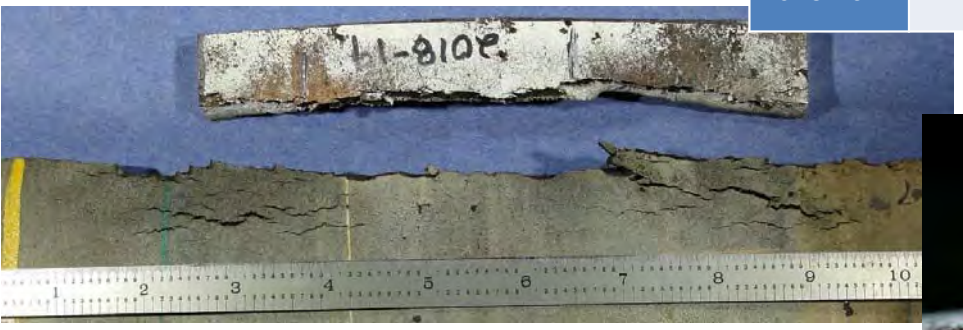


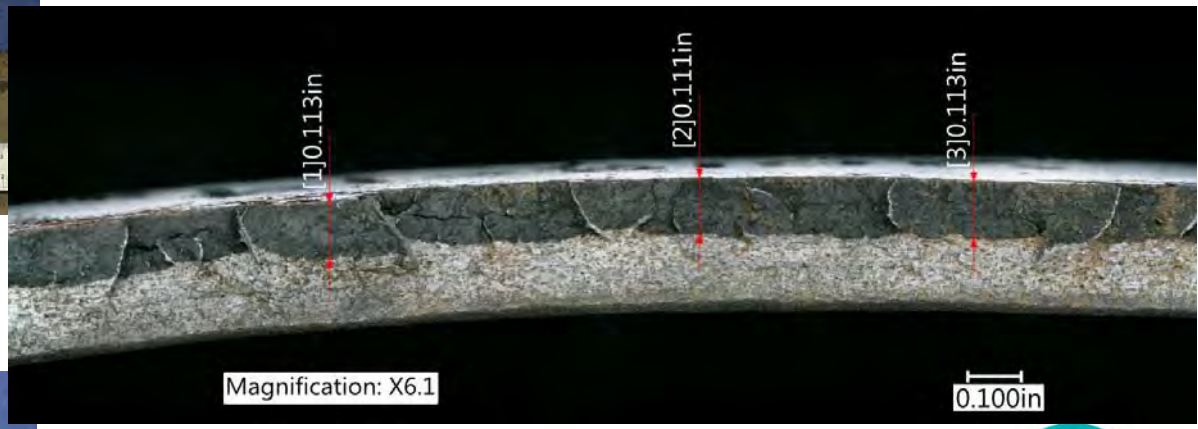


Pipe Sample 2018-19

- Burst Pressure 1441 psi

	D	SMYS	Wall	100%		72%		Predicted P_f		
	inch	ksi	inch	kPa	PSI	kPa	PSI	kPa	PSI	% Ys
2018-19	24	50	0.250	7182	1042	5171	750	6989	1014	97.3%





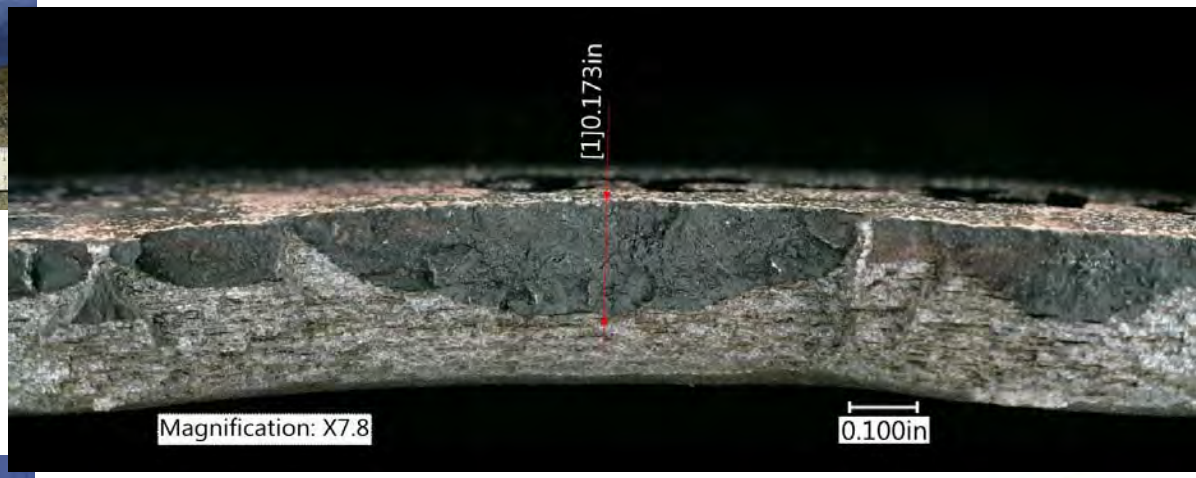


Pipe Sample 2018-20

- Burst Pressure 1349 psi
  - Yielded about 1200 psi

	D	SMYS	Wall	100%		72%		Predicted P_f		
	inch	ksi	inch	kPa	PSI	kPa	PSI	kPa	PSI	% Ys
2018-20	24	50	0.281	8073	1171	5171	843	7605	1103	94.2%

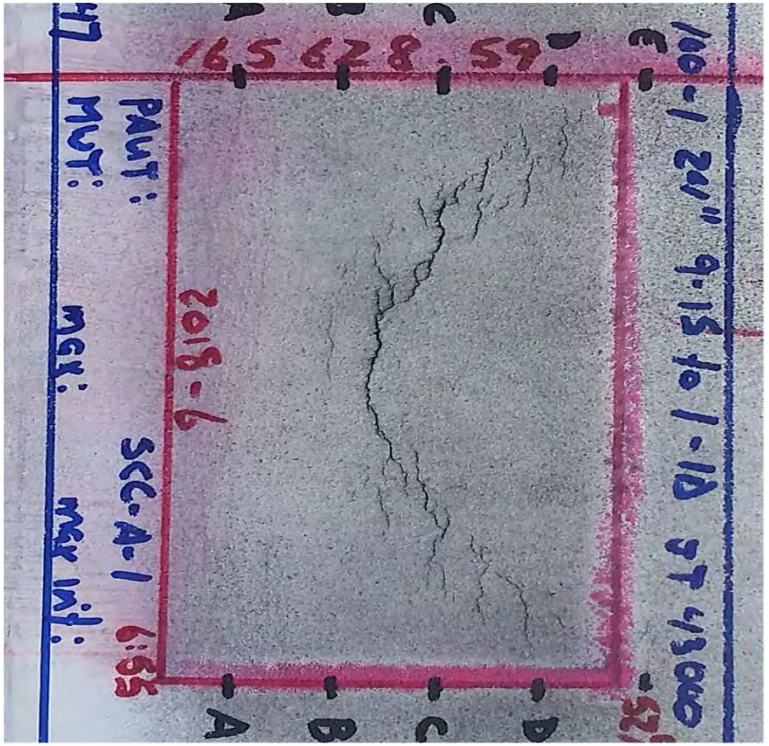




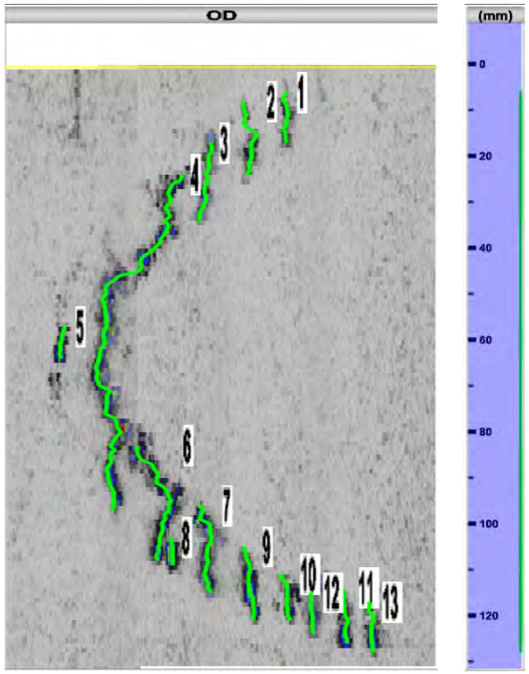


IWEX Reassessment isolating Cracks for SIA-1-5 Assessment

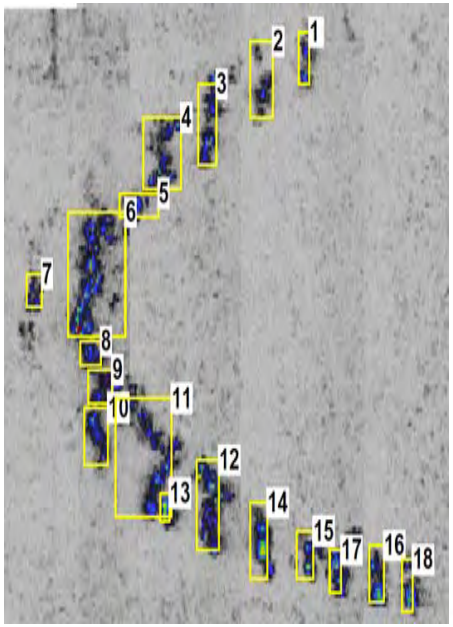
MPI Image



Initial IWEX Crack Clustering



IWEX Crack Clustering For SIA 1-5 Analysis



SIA-1-5 Equivalent and IWEX Length and Depth

Pipe ID	IWEX depth		Total length of all cracks in colony	Interacting length using NACE/CEPA	PRCI/CRES SIA-1-5 Predictions			Fracture Measurements	
					Equivalent Length	Equivalent Depth		Depth	
	mm	% WT	mm	mm	mm	mm	% WT	mm	% WT
2018-1	4.6	45	280	280	84	4.4	43	-	-
2018-6	3.9	61	122	53	25	4.4	70	4.3	66
2018-19	2.7	43	123	50	14	3.6	56	2.9	45
2018-20	4.4	62	197	176	40	3.4	48	4.4	69

SIA 1-5 Predicted and Actual Failure Pressures

Pipe ID	Failure Pressure				% Error		
	All cracks	NACE / CEPA	SIA-1-5	Actual	All cracks	NACE /CEPA	SIA-1-5
2018-1	1318	1318	2014	2178*	39%	39%	8%
2018-6	913	1226	1363	1399	22%	8%	2%
2018-19	1100	1322	1408	1441	16%	5%	2%
2018-20	762	796	1367	1349	27%	25%	-1%

Conclusions

- Pressure tests show that in the interaction rules developed on PRCI SIA1-5 can be used with IWEX data to produce accurate burst pressure estimates
- IWEX ultrasonic imaging compares well to the results from X-ray CT images.
- While EMAT and IWEX differences in sampling and resolution do not facilitate direct comparison, it is possible to establish parameters for burst pressure calculations.
- Emerging full matrix capture NDE methods and intelligent interaction criteria can be used to improve crack ILI.

Recommendations

It is recommended that a technology transfer task be considered to implement this process to improve failure predictions.

- Provide Rosen failure pressures calculated using intelligent interaction criteria (PRCI SIA-1-5) from all SCC colonies that have been examined by IWEX and EMAT data to develop less conservative failure pressure estimates.
- Engage other EMAT ILI vendors to develop a similar process for correlating EMAT and IWEX data and establish less conservative failure pressure estimates.
- Engage suppliers of full matrix capture technology to provide a similar capability as IWEX for ultrasonic imaging of SCC colonies.

Acknowledgments

Sincere thanks to :

- Kinder Morgan for access to the SCC samples and XCT data used in this project. In particular, thanks to Ben Hanson and Munendra Tomar for their insight into improving the interpretation and understanding of the XCT data.
- ROSEN for the EMAT results and, in particular, Thomas Walther, for the preparation of materials for presentations and reports.
- The PRCI members and staff for facilitating the cooperation with PRCI project SIA-1-5 Intelligent Flaw Interaction Rules.

BACK TO AGENDA

PRCI 2020 Research Exchange

Measuring the Accuracy of Instant Off Potentials

Are we interpreting cathodic protection data correctly?

- **Prepared by Peter Haas, P. Eng.**
- **Presented by Kalen Jensen, P. Eng.**

ATCO

Edmonton Alberta Canada

LEADING PIPELINE RESEARCH

Introduction

- Instant OFF Potential (IOP) measurements are used to eliminate “IR Drop Errors” when testing cathodic protection levels on pipelines

- The measured potential an be expressed as the sum of the potential at the metal/electrolyte (the ‘polarized potential’) plus the IR drop, or

$$V_M = V_P + IR$$

- Hypothetically, when the CP current is switched off, the current in the system is reduced to zero and the measured potential is representative of the polarized potential, or

$$V_M = V_P$$

Assumptions

- IOP hypothesis includes the following assumptions:

  1) The current flowing in the system equals zero when the CP power source is switched off

  2) The surface does not depolarize within the time required to measure IOP (0.5 seconds)

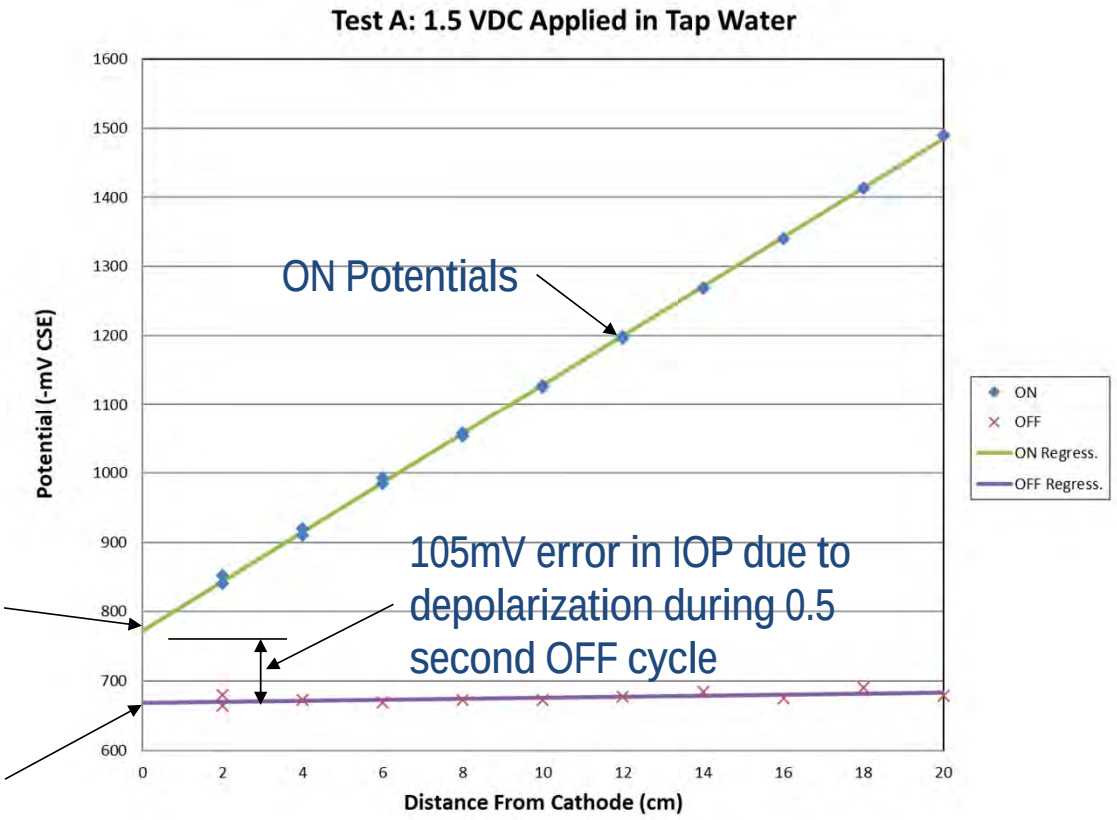
- Little or no data is available to demonstrate that IOP measurements are representative of the potential that exists on pipelines at the metal/electrolyte interface under normal operating conditions

- Electrolyte IR drop was measured in the laboratory to test assumption #2.

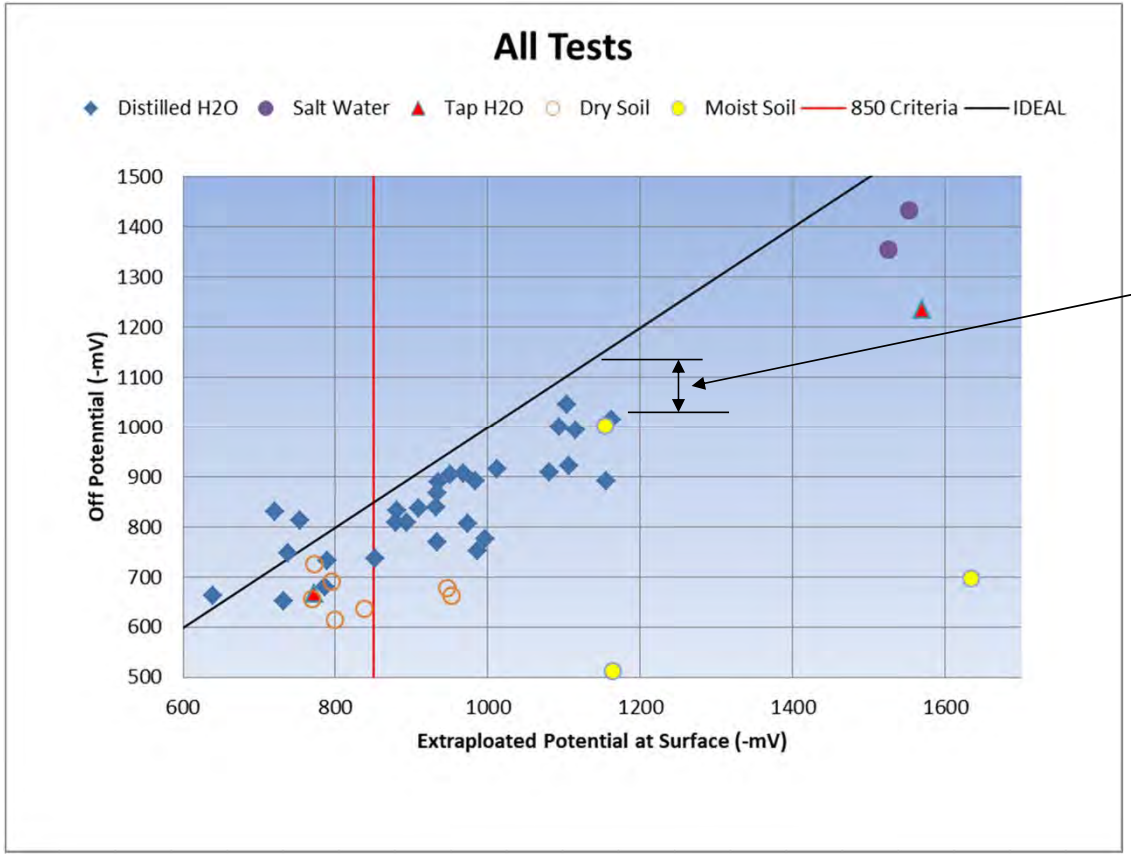
Test Apparatus



Typical Test Result

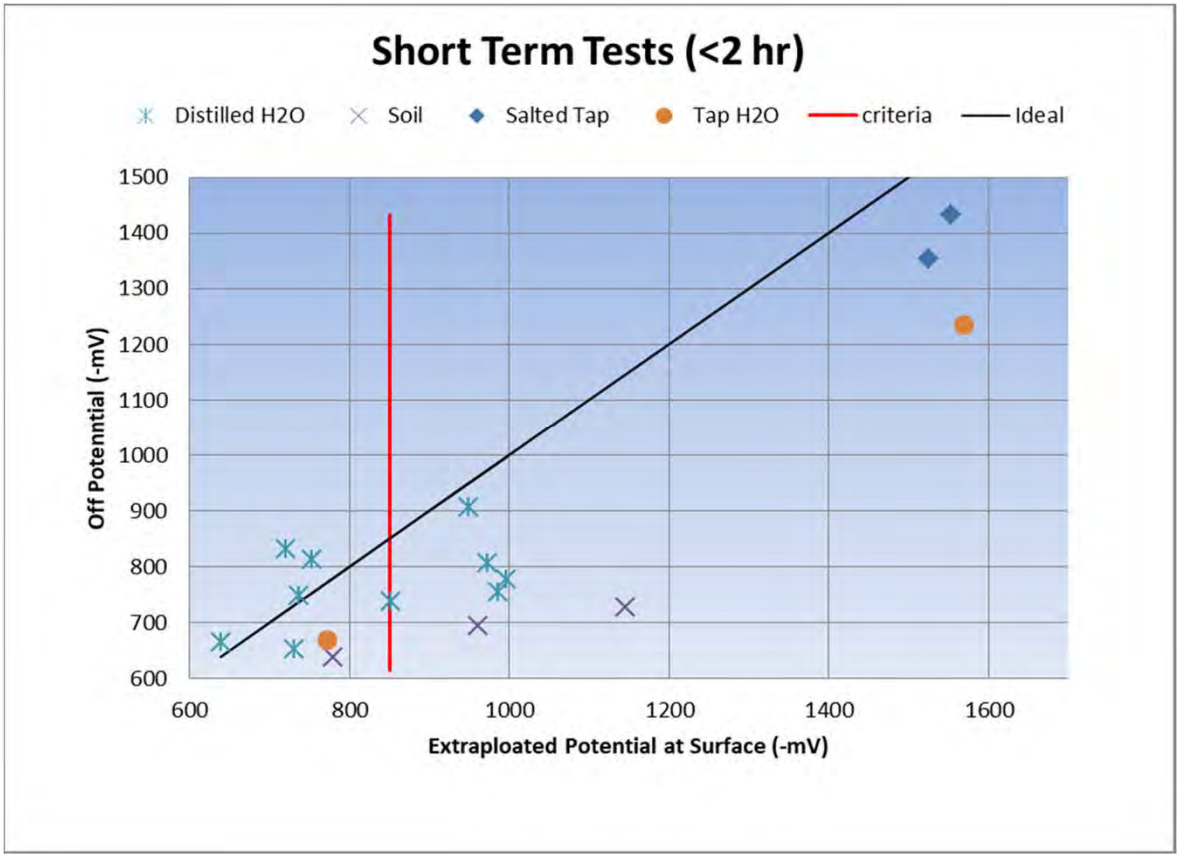


Test Result Summary (55 Tests)

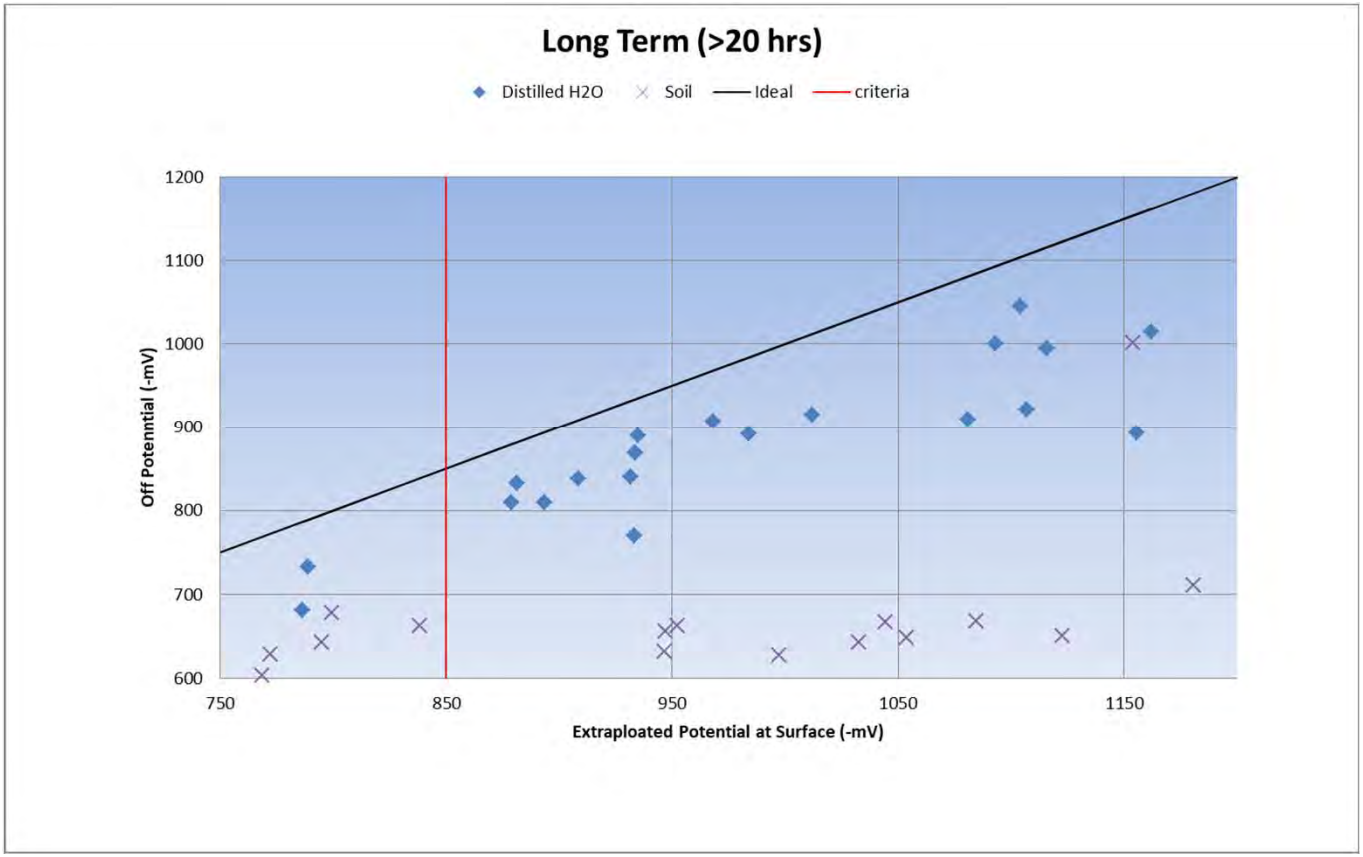


Error in OFF potential is given by vertical distance from any point to IDEAL line

Tests in Oxygenated Electrolytes



Tests in Oxygen Depleted Electrolytes



Chemical Hypothesis

- **Two Cathode Reactions Considered**
  - **1) $O_2+2H_2O+4e^- > 4OH^-$ (Oxygen reduction)**
    - *Reaction rate limited by oxygen diffusion (slow reaction)*
    - *Controls potential at low levels of CP*
  - **2) $2H_2O+2e^- > H_2 + 2OH^-$ (Hydrogen evolution)**
    - *Only requires water and high potential (Fast reaction)*
    - *Dominant reaction at higher potentials*
- **IOP thought to be reasonably accurate when potential controlled by Oxygen reaction**
- **Activation polarization associated with hydrogen reaction.**
- **IOP thought to capture concentration polarization but not activation polarization**
- **IOP generally limited to equilibrium potential for hydrogen reaction (approx. -1.1 V_{CSE})**

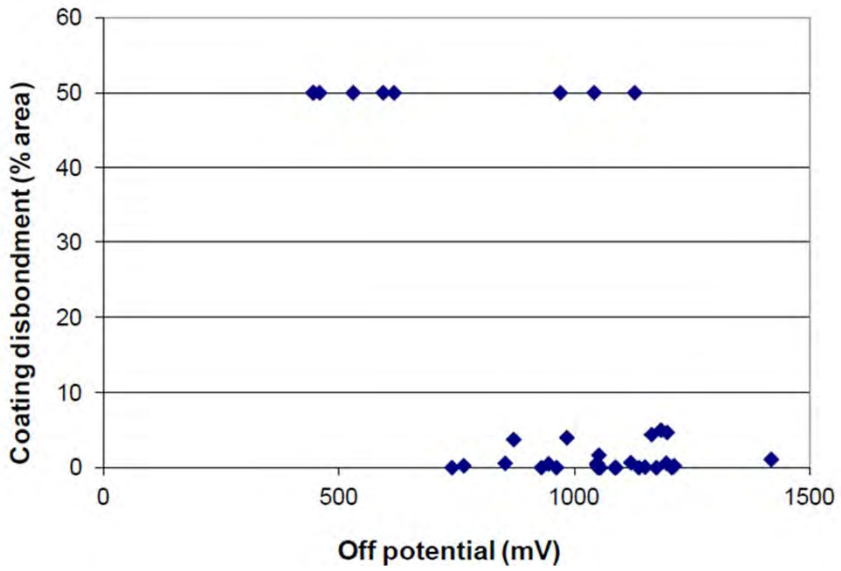
Observations and Conclusion

- **Test Results:**
  - IOP measurements may be accurate if:
    - *the electrolyte contains dissolved oxygen*

    AND
    - *the potential is more positive than -800mV (CSE)*
  - IOP measurements underestimated polarization levels at the metal/electrolyte interface by an average of 25% in all other test conditions
  - The IOP error increases with increasing potentials
- **Conclusions**
  - IOPs are not accurate for the conditions that typically exist on underground pipelines
  - IOPs generally underestimate pipeline potentials
  - Reliance on IOP may lead to excessive cathodic protection levels on pipelines
  - Corrosion research (based on IOP measurements) may have incorrect conclusions

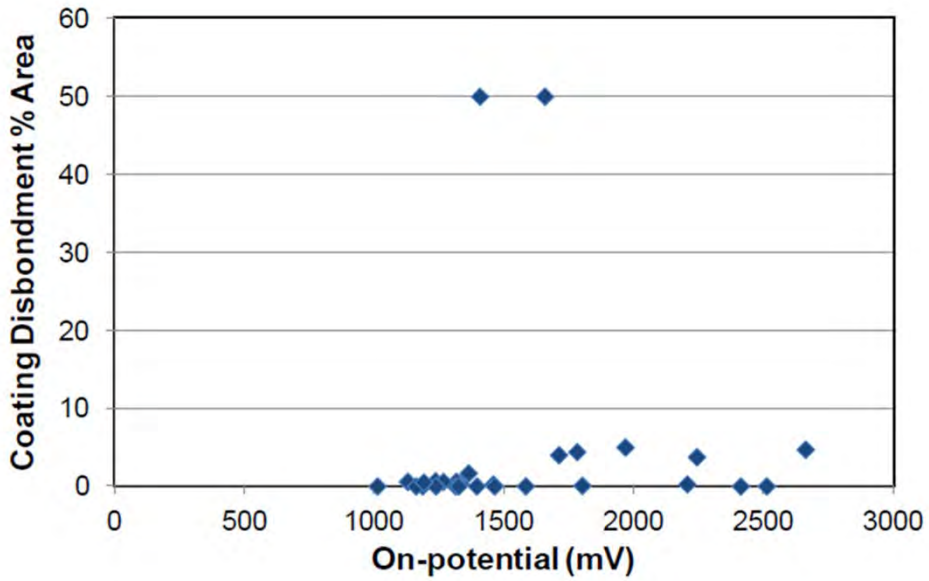
Example 1: PRCI "State-of-the-Art Review of the Performance of FBE Pipeline Coatings" (PR-377-113602-R01)

Conclusion Given By PRCI: "There is no evidence that high CP levels lead to a greater amount of coating disbondment"



Example 1 (cont'd): PRCI "State-of-the-Art Review of the Performance of FBE Pipeline Coatings" (PR-377-113602-R01)

- **Observation: 100% of coating disbondments occurred on pipelines with ON potentials in excess of 1200 –mV. Zero cases of disbondment occurred on pipelines with ON potentials below 1200 –mV.**



(b) As a function of the on-potential.

Example 1: Discussion and Conclusions

- Observation of ON potential data shows clear correlation between high CP levels and coating disbondment
- ON potentials in excess of 1200 –mV may lead to disbondment of FBE coatings
- IOP may not accurately describe potentials at pipeline surface, particularly at higher levels of protection
- Consideration of ON potentials is required for valid interpretation of potential data

Considerations for Cathodic Protection Operators

- **IOP measurements should not be considered as an accurate measure of cathodic protection levels**
- **IOP values tend to underestimate the level of cathodic polarization**
- **Reliance on IOP data may lead to:**
  - increased CP current requirements and equipment costs
  - increased anode and power consumption
  - increased interference effects
  - increased internal corrosion at pipeline insulators
  - possible increase in coating damage
  - possible increase in cracking of sensitive materials
  - poor correlation between models and measured values

Recommendations

- **Since IOP measurements have been shown to be inaccurate, it is difficult to justify synchronized interruption of all CP systems during for CP surveys (except where potential shift criteria are used).**

- **Consider eliminating requirements for synchronization to reduce cost of equipment and time required for testing**

- **Recommend interrupting only 1 or 2 rectifiers in area of influence to:**
  - Positively identify test stations
  - Indicate if interference effects exist on foreign structures
  - Identify continuity and isolation issues
  - Delineate current distribution

Recommendations

- Since it is shown that depolarization occurs very quickly:
  - Consider ON potential values, ON-OFF shifts and IOPs for valid interpretation of CP data
  - Upper limit for pipeline potential must be based on ON potential measurements (Suggest maximum ON value of 1.2 -VDC (CSE) where possible)

IR Drop Considerations

- To compensate for IR Drop error in ON potentials:
  - Recommend calculating electrolyte IR drop based on estimated current density and soil resistivity
  - Periodic close interval potential survey is required to validate assumption of uniform current distribution

Future Work

- Critically review and revise NACE SP-0169 cathodic protection criteria

- Critically review, and revisit if necessary, corrosion research conclusions based on IOP measurements including:
  - Coating disbondment
  - SCC
  - Interference
  - Modelling CP potential and current distribution

Thank You

Questions?

BACK TO AGENDA

PRCI 2020 Research Exchange

Optimization of Pipeline Reconditioning

- Nasser Al-Qahtani
- Saudi Aramco

- Mar 4, 2020

LEADING PIPELINE RESEARCH

Outline

- Objectives
- Introduction
- Integrity Process
- Monitoring the Bottom-Line
- Data Integration Way Forward
- Understanding the business value
- Conclusions

Non-Business Use

Objectives

- Achieve locational accuracy of pipeline assets.
- Improve accuracy of company data integration processes.
- Improve risk Assessments
- Identify Pipeline modifications that that weren't (or weren't properly) as-built.

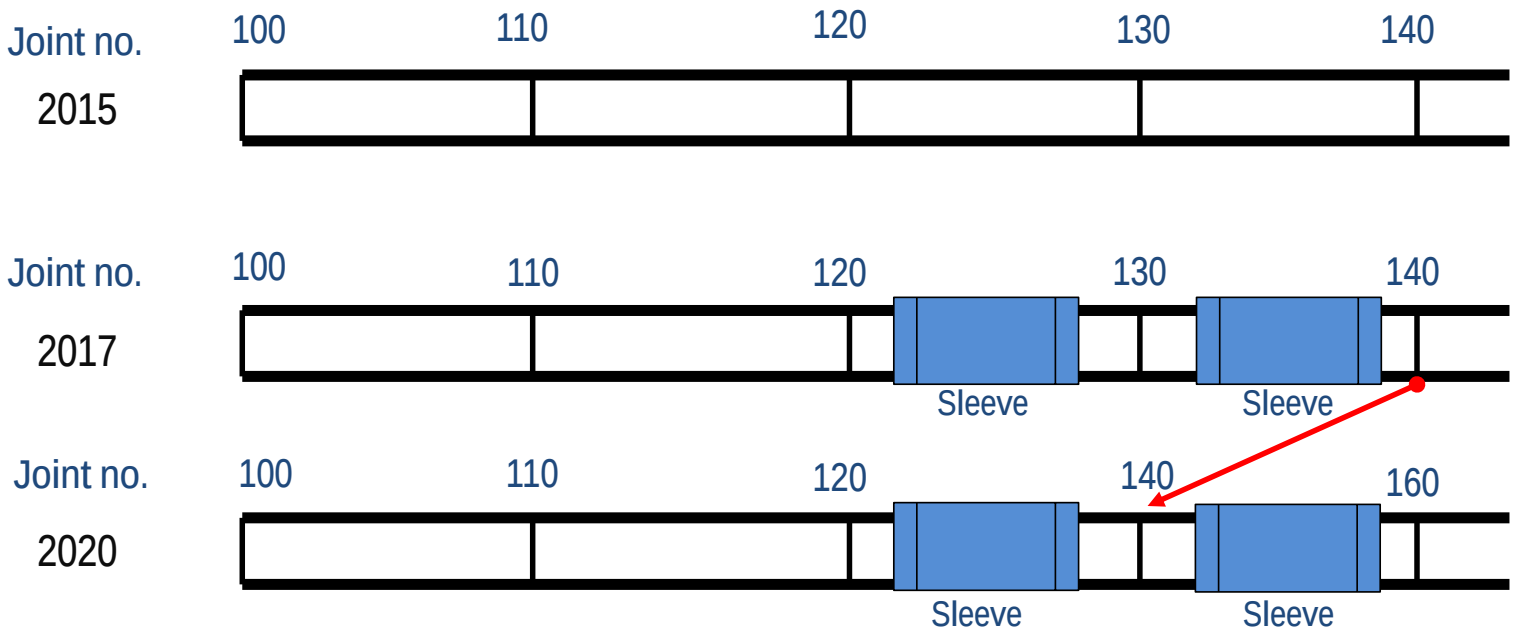
Non-Business Use

Introduction

- **Expectations of oil and gas industry demand better:**
  - Threat assessment
  - Risk analysis
  - Integrity decision making
- **Meeting these expectations requires comprehensive and complex integration of many disparate sets of data – the majority of which is spatial.**
- **Ever increasing levels of accuracy are needed to fuel these needs.**

Non-Business Use

Current Problem



Non-Business Use

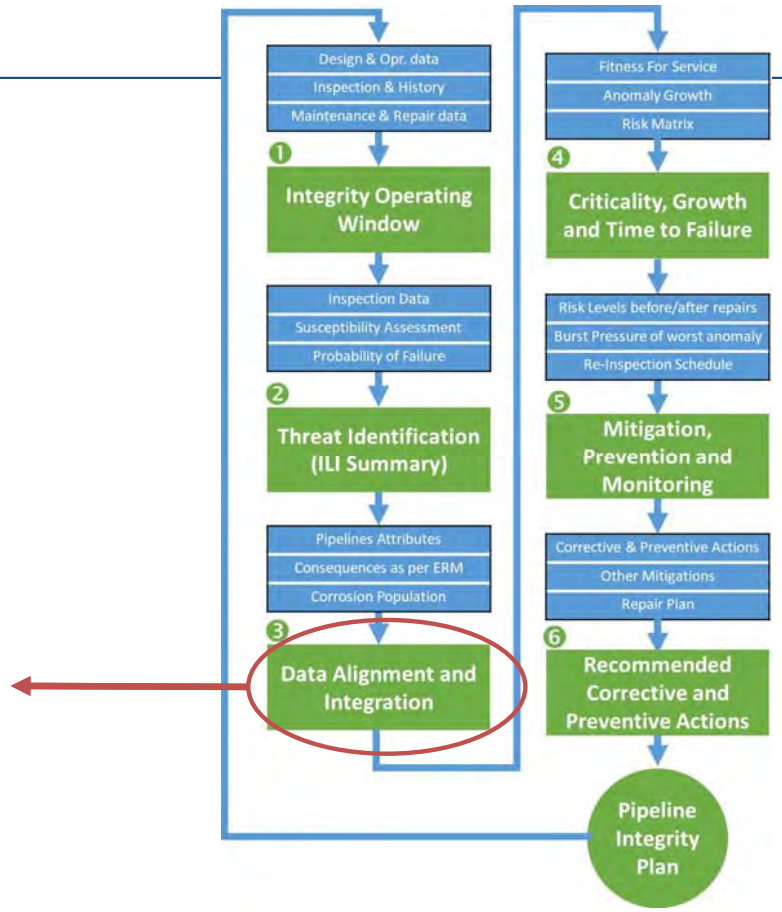
Integrity Process

Pipeline Integrity Plans (PIP's)

Considers a number of threats:

- Internal corrosion
- External corrosion
- Environmental-assisted cracking and pressure induced cracking.

Data alignment and integration is the key to prioritizing maintenance and repair by integrating survey data with other important information.



Non-Business Use

Integrity Process

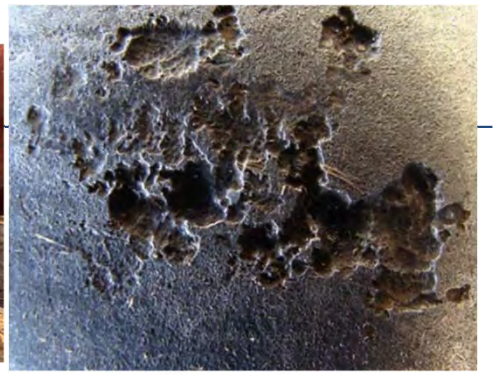
By doing this, operator can begin answering regulatory and risk related questions such as:

- Which anomalies fall under immediate repair vs. 60-day or 180-day?
- Where do we have predicted metal loss greater than 50 percent at foreign line crossings?
- Which dents on the top of the pipe are in areas that could affect a high consequence area?
- Which dents lie on the bottom of a pipe exhibiting metal loss?

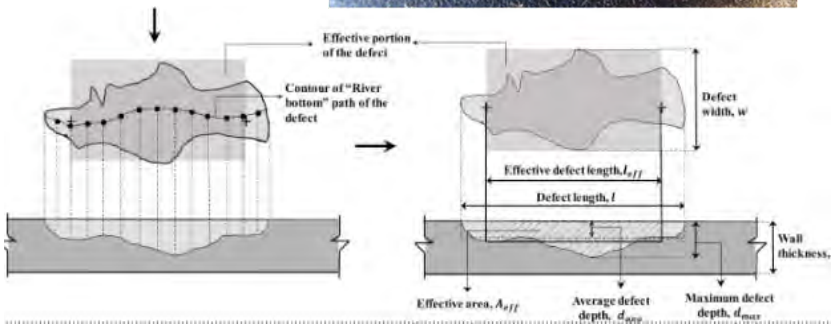
Non-Business Use

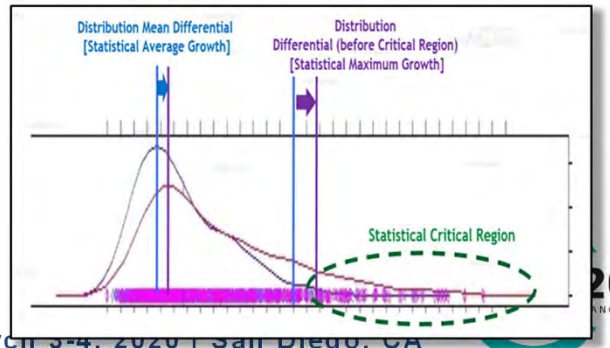
Use of PRCI work





- **Evaluating remaining strength of corroded pipelines**
  - ASME B31G/MB31G/RSTRENG (PR-3-805)
- **Establish corrosion growth rate**:
  - PRCI PR-331-063525 Comparing Successive ILI Runs to Establish Corrosion Growth Rates.
- **Reliability-Based Guidelines for Rehabilitation of Corroded Pipelines**
  - EC-1-8 for Reliability Based Corrosion Management
- **Benefit:**
  - Help to reduce pipelines repair workload 40-60% ($ 4 MM annual)





Non-Business Use

Integrity Process

Corrosion Rate Growth Calculation





CORROSION GROWTH RATE CALCULATION USING DISTRIBUTIONS

Method
Applicability

- Calculation using the differential of ILI reported depths between two (2) ILIs (ILI Anomaly Input & Input Previous tab)
- This method is used only for corrosion growth rates not exceeding NACE SP-0502 (0.46 millimiters/year)
- Corrosion growth rates exceeding NACE SP-0502 are recommended to be refined by using the PRCI Individual and Segmentation Corrosion Growth Rate

Calculate Average and Upper Growth Rates
Identifying Outliers (Potential "Fast Runners")

Latest ILI Distribution	15-Feb-2017	Previous ILI Distribution	30-Aug-2009
EXTERNAL CORROSION			
Mean	1.30298	Mean	1.12768
Standard Error	0.11528	Standard Error	0.14041
Median	1.2334	Median	0.9691
Mode	1.2334	Mode	0.881
Standard Deviation	0.58235	Standard Deviation	0.31396
Sample Variance	0.14619	Sample Variance	0.09857
Kurtosis	4.31593	Kurtosis	-1.11786
Skewness	1.92324	Skewness	0.93462
Range	1.405	Range	0.7048
Minimum	0.881	Minimum	0.881
Maximum	2.286	Maximum	1.5858
Sum	14.3328	Sum	5.6384
Count	11	Count	5
Confidence Level(95.0%)	26%	Confidence Level(95.0%)	39%

EXTERNAL CORROSION	80% CI	95% CI
Average Growth Rate (mm/year):	0.02191	
Latest ILI Depth at PDF80&95%	1.7924	2.0524
Previous ILI Depth at PDF80&95%	1.52955	1.74305
High Growth Rate (mm/year) at PDF80&95%	0.26285	0.3095

Localized Growth Rate: Scenarios for Fast Runners	mm/year	95% CI
#1: Growth Rate using Last ILI and fast 5 years of localized growth	0.35848	0.41048
#2: Growth Rate using Last ILI and fast 10 years of localized growth	0.17924	0.20524
#3: Growth Rate using Last ILI and half life years (18) of localized	0.19916	0.22804

EXTERNAL OUTLIERS (Anomalies for Investigation)		#N/UMs Means No Outliers		
Description	%Data	Anoms lg (mm) at %:	Quarter	
Anomaly size (mm) at Quarter1	25%	1.1013	1	
Anomaly size (mm) at Quarter2	50%	1.2334	2	
Anomaly size (mm) at Quarter3	75%	1.3215	3	Metal Loss
Anomaly size Start of Mild Outliers		1.65		19%
Anomaly size Start of Extreme Outliers		1.98	Check ILI	22%
Count of External Anomalies		11		

Ref: Engineering Statistics Handbook at http://www.itl.nist.gov/div898/handbook/prc/section1/

INTERNAL CORROSION	Column1
Mean	1.02093
Standard Error	0.01242
Median	0.9691
Mode	0.881
Standard Deviation	0.17604
Sample Variance	0.03099
Kurtosis	6.07775
Skewness	1.89938
Range	1.1453
Minimum	0.881
Maximum	2.0263
Sum	205.207
Count	201
Confidence Level(95.0%)	0.02449

INTERNAL CORROSION	80% CI	95% CI
Average Growth Rate (mm/year):	0.00302	
Latest ILI Depth at PDF80&95%	1.24627	1.36598
Previous ILI Depth at PDF80&95%	1.21774	1.33515
High Growth Rate (mm/year) at PDF80&95%	0.00853	0.00936

Localized Growth Rate: Scenarios for Fast Runners	mm/year	95% CI
#1: Growth Rate using Last ILI and fast 5 years of localized growth	0.24925	0.2732
#2: Growth Rate using Last ILI and fast 10 years of localized growth	0.12463	0.1366
#3: Growth Rate using Last ILI and half life years (18) of localized	0.13847	0.15178

INTERNAL OUTLIERS (Anomalies for Investigation)		#N/UMs Means No Outliers		
Description	%Data	Anoms lg (mm)	Quarter	
Anomaly size (mm) at Quarter1	25%	0.881	1	
Anomaly size (mm) at Quarter2	50%	0.9691	2	
Anomaly size (mm) at Quarter3	75%	1.059	3	Metal Loss
Anomaly size Start of Mild Outliers		1.58		15%
Anomaly size Start of Extreme Outliers		1.98	Check ILI	18%
Count of Internal Anomalies		201		

Ref: Engineering Statistics Handbook at http://www.itl.nist.gov/div898/handbook/prc/section1/prc16.htm

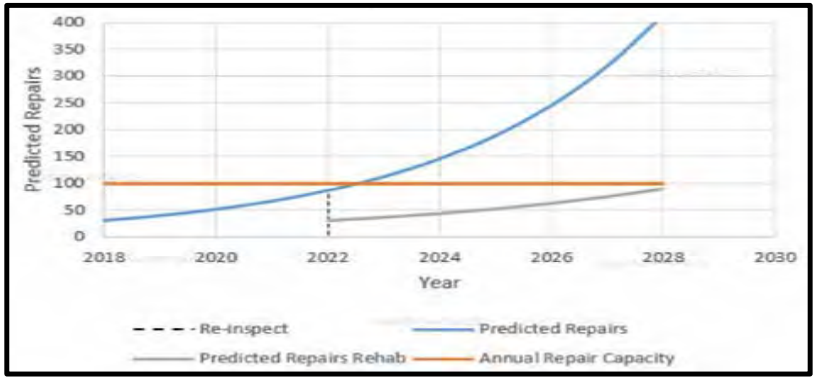
Boxplot (with an interquartile range) and a 95 probability density function (pdf) of a Normal N(0,σ²) Population

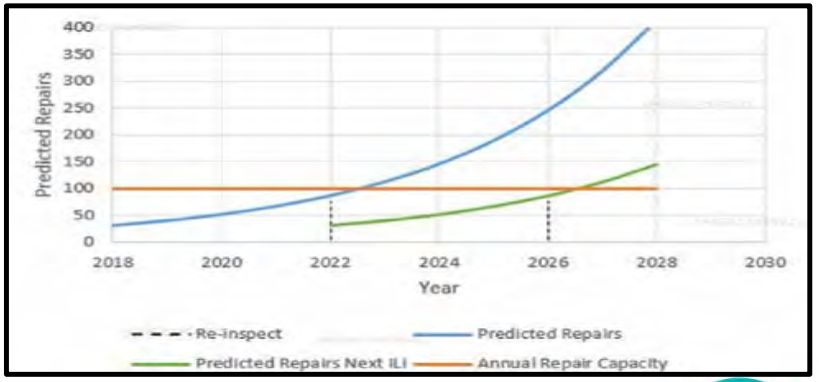
1_IOW | ILI Anomaly Input | ILI Anomaly Input_Previous | CGR Level 1 | PoF | Anomaly Density | Regressions | PBurst | PoF Forecast Chart | Codes | CP_Soil Data | Ext. Alignment_1 (%) | Ext. Alignment_2 (...

Non-Business Use

Monitoring the Bottom-Line

- A methodology for reliability-based management of Corrosion integrity has been developed for use by pipeline engineers to prioritize and schedule inspection, remediation and maintenance activities based on the information obtained from in-line inspection.
- The development approach involved adapting and extending the existing Reliability-based Design and Assessment process to address issues of key importance with respect to corrosion integrity management including defect-specific probability estimation, the treatment of inspection-related uncertainties, appropriate measures of reliability, reliability assessment criteria and the optimization of inspection and repair timing.





Non-Business Use

Data Integration Way Forward

- **There are five levels of data integration. first three level may assist in identifying clusters of anomalous readings and 3D visualization but it does not provide needed basis for data analyses while level four and five supports more precise risk assessment.**

- Levels of data integration:

1. Data remains unaligned.
2. Reconfigured odometer readings to provide approximate pipeline stationing.
3. Aligning data relative to aerial photography.
4. Alignment relative to an enterprise facility database.
5. Alignment relative to other in-line surveys.

Non-Business Use

Data Integration Way Forward

first three level may assist in identifying clusters of anomalous readings and 3D visualization but it does not provide needed basis for data analyses.

Implementation of the fifth level will result in:

- Correction of valve location
- Identifying missing sleeve
- Correction of casing ends
- Correction or Identification of Pipe Type

Non-Business Use

Understanding the business value

- **The result of the alignment process :**
- Provides a better understanding of where pipeline conditions are changing.
- Reduce their risk without significant additional investment
- Free up their integrity engineers to focus on high-value engineering tasks.

Non-Business Use

Conclusion

- **The consistency of the pipeline linear stationing must be maintained as:**
  - It is important for data upload and migration of pipeline systems.
  - Improve Data quality and refine its pipeline data assets.
  - Improve Data quality and refine its pipeline data assets.
  - Increased effectiveness of the process.
  - Eliminate error sources.

Non-Business Use

QUESTIONS?

Non-Business Use

THANKS

Non-Business Use

BACK TO AGENDA

PRCI 2020 Research Exchange

Quantification of ILI Sizing Performance for Severe Corrosion Anomalies

PRCI Project EC 4-6A

Presenter: Smitha Koduru, C-FER Technologies

Project Team Leaders:
Terry Huang, TC Energy
Travis Sera, Southern California Gas Company
Jeff Sutherland, Baker Hughes

LEADING PIPELINE RESEARCH

Introduction

- **Background:**
  - PRCI Project EC 4-6, *Improving Corrosion ILI Sizing Models for Long Complex Corrosion Anomalies,* focused on ILI performance in the presence of complex corrosion.
  - Complex corrosion identified based on high resolution laser scans
  - Data set consisted of 14 high resolution laser scans representative of complex corrosion – too small to quantify sizing errors with confidence

- **EC 4-6A Project Objectives:**
  - Develop criteria to identify severe corrosion anomalies from ILI data
  - Quantify ILI sizing errors for severe external corrosion as a function of feature morphology and dimensions

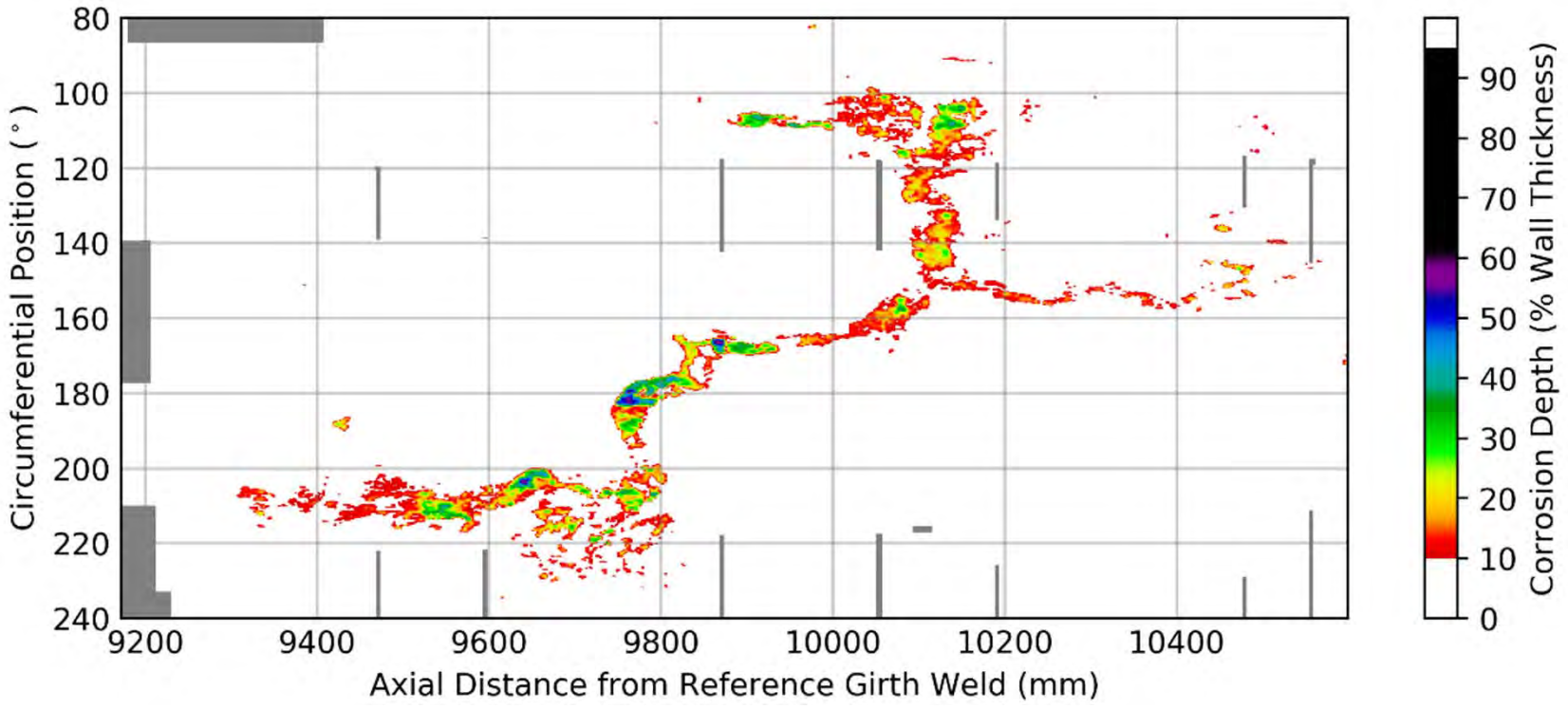
Project Tasks

- **Data Collection and Validation:**
  - Collection of high resolution laser scan data and associated ILI data sets
  - Validation of the data collection against correctness, completeness and consistency
  - Storage in secure database
- **Severe Anomaly Identification**
  - Severe anomaly definition
  - Severity characterization using corrosion attributes such as orientation, density of features, depth gradient
- **ILI Sizing Error Modeling**
  - Quantification of ILI sizing errors
  - Sizing error modeling for correction of depth and length sizing, and validation of the model
- **Project Management and Reporting**

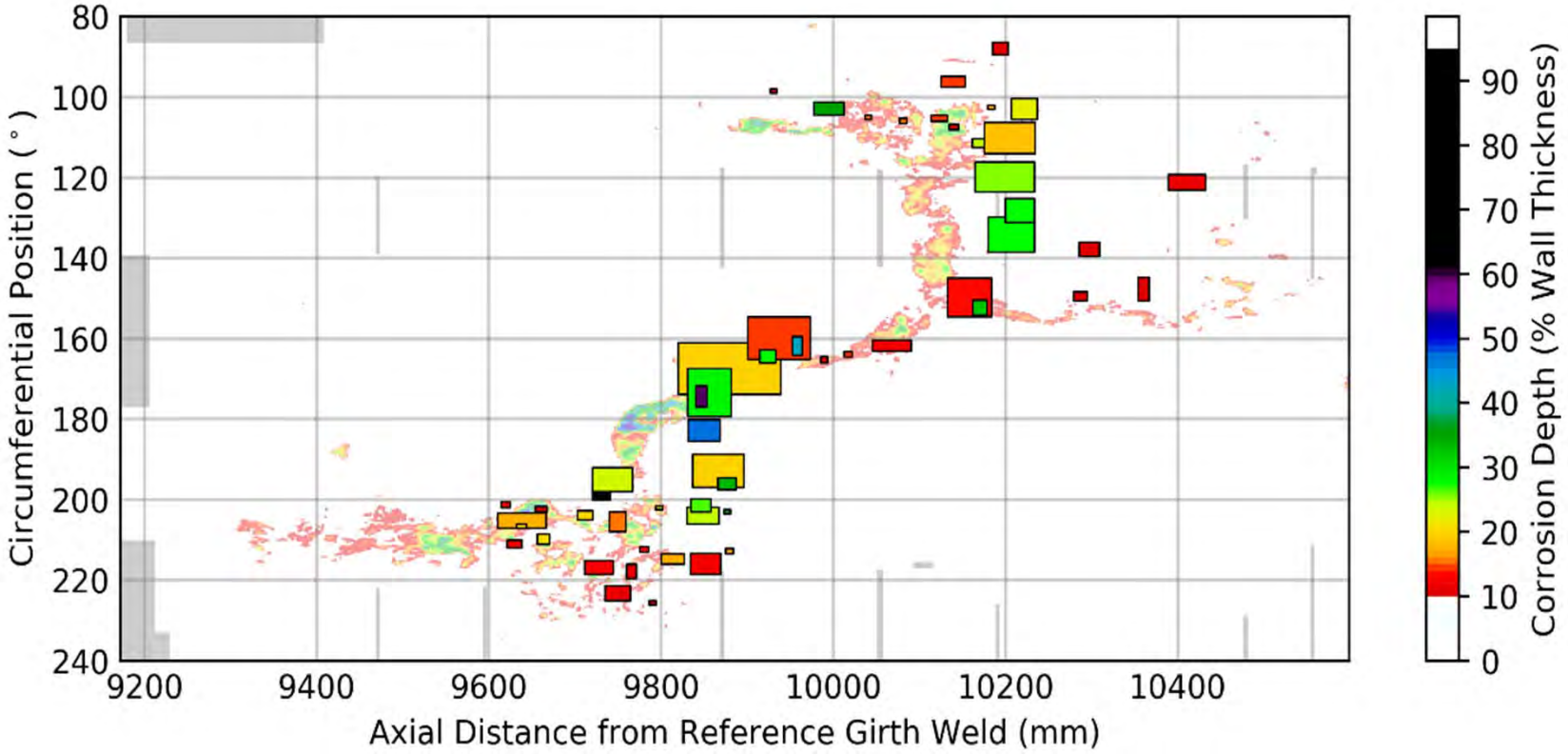
Project Outcomes

- A secure SQL database with 121 high-resolution LS and associated ILI datasets.
- Cluster length, average depth and maximum depth threshold criteria were developed to identify severe corrosion clusters.
- 22 out of 28 ILI runs in the dataset meet the typical depth sizing specifications of +/- 10%WT tolerance.
- Correction models for maximum depth and length were developed and validated
- Applying sizing corrections was shown to reduce the error in estimated burst pressure capacity for severe clusters.

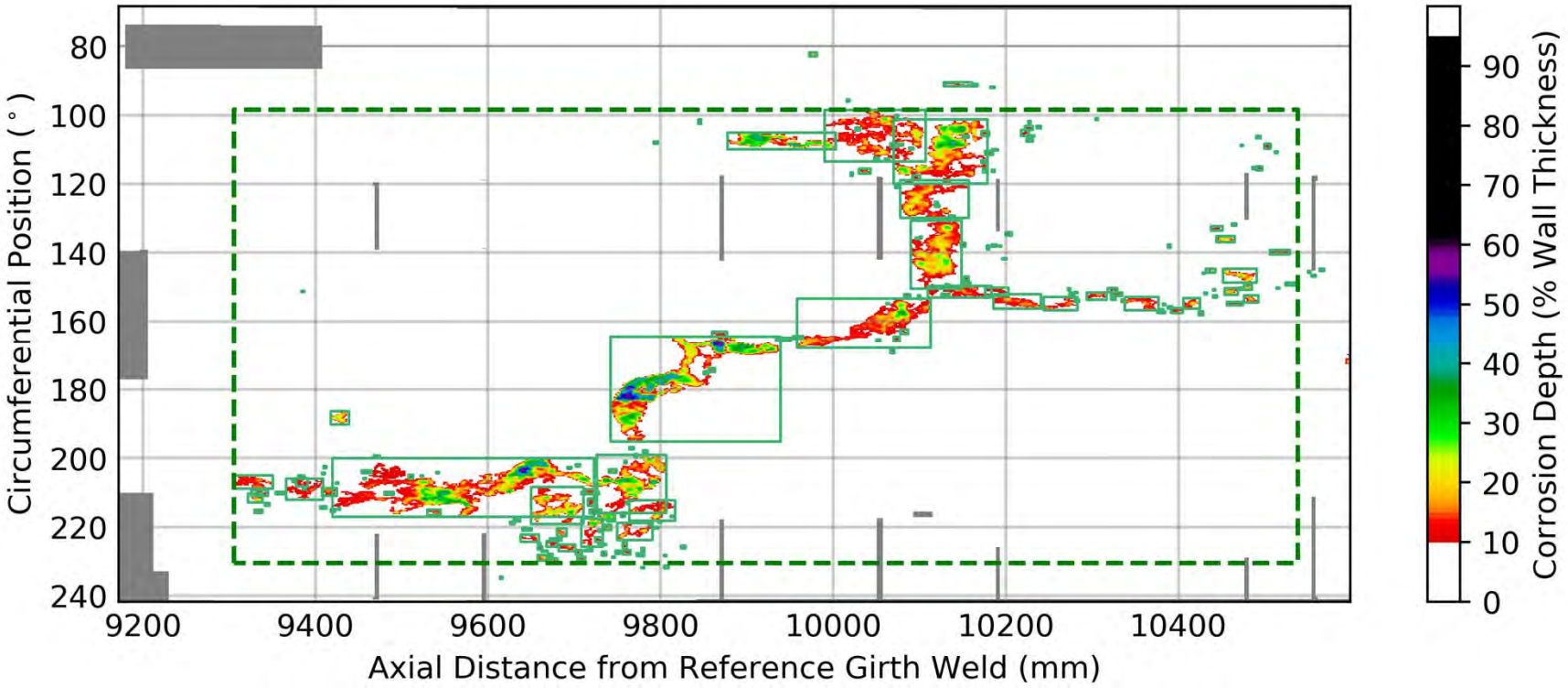
Data – High Resolution Laser Scan



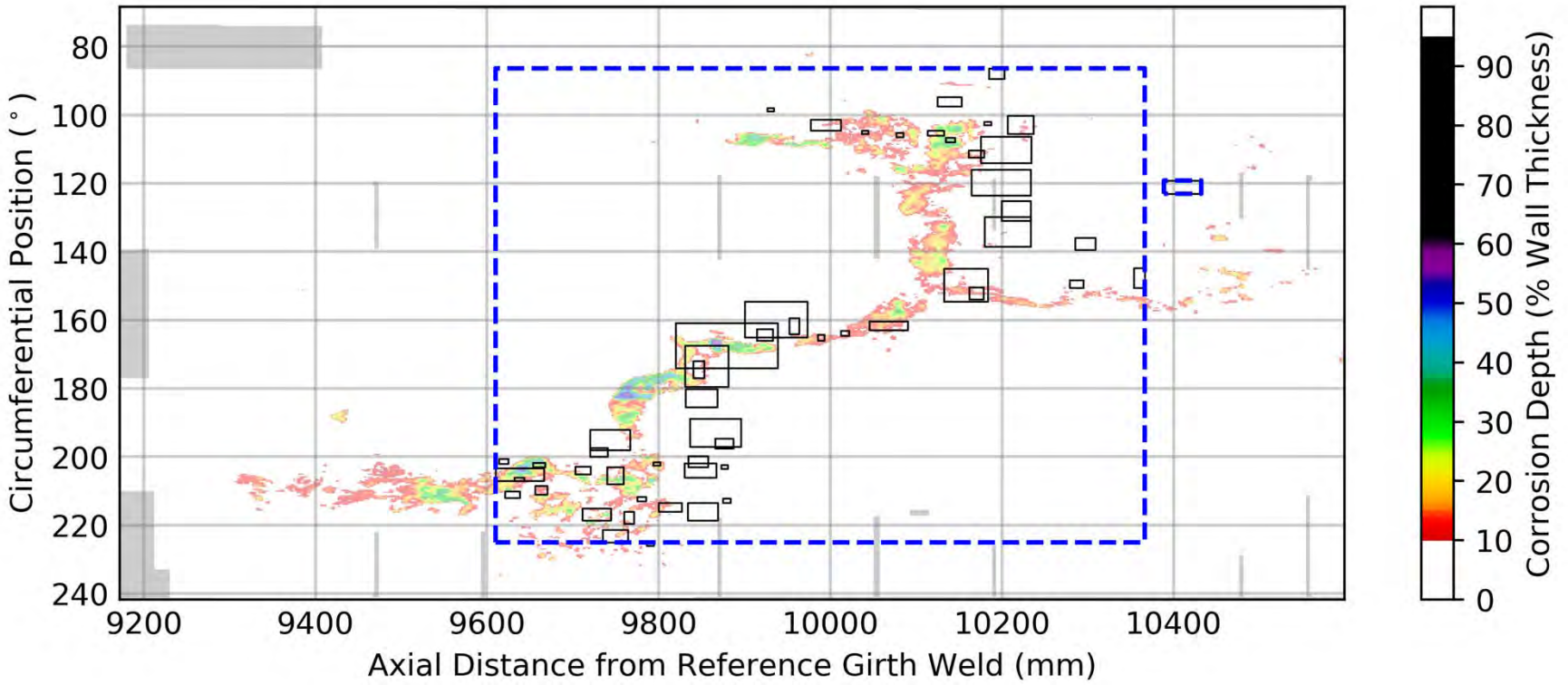
Data – Inline Inspection



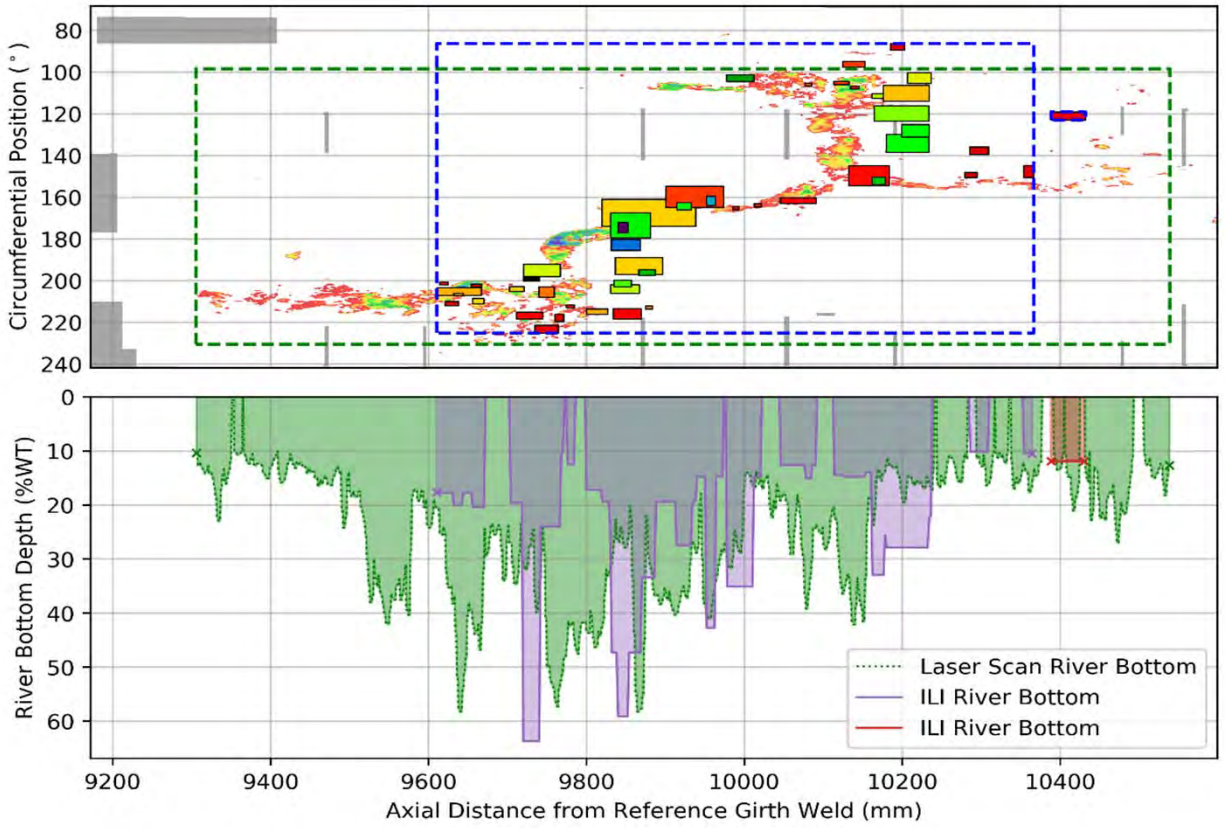
Data Processing – Laser Scans



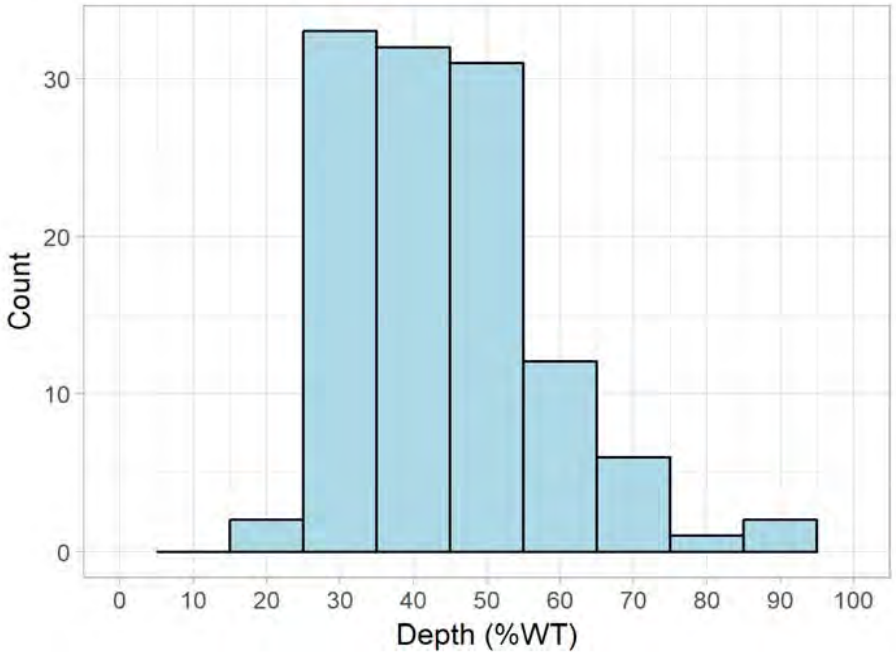
Data Processing – ILI Anomalies

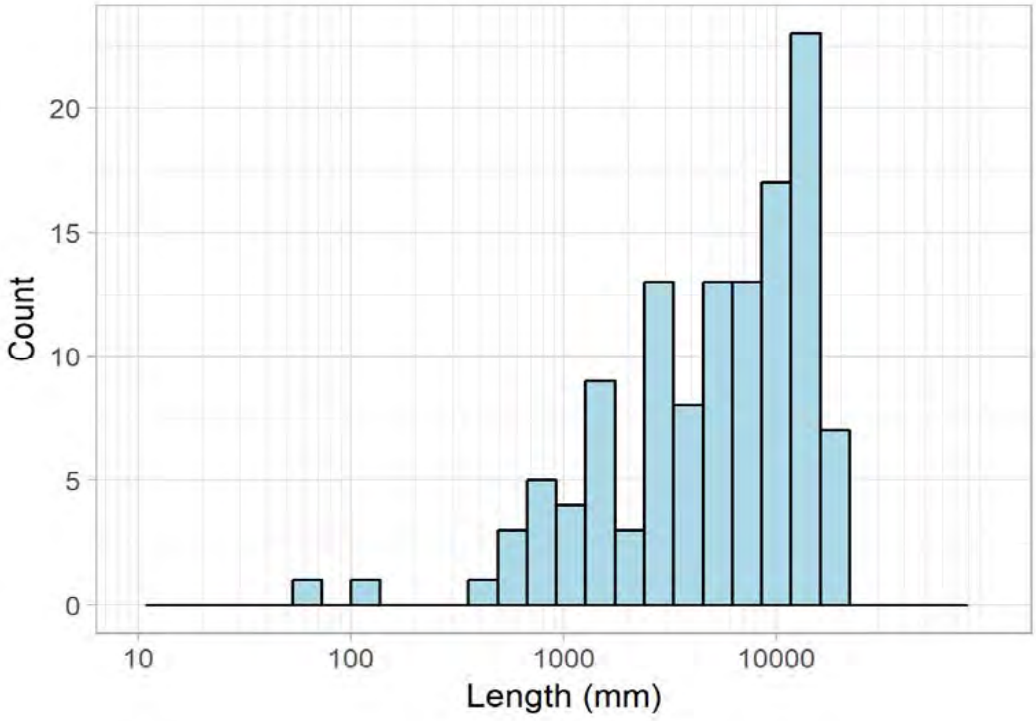


Data Processing – River Bottom Profiles



Data Summary – Laser Scans



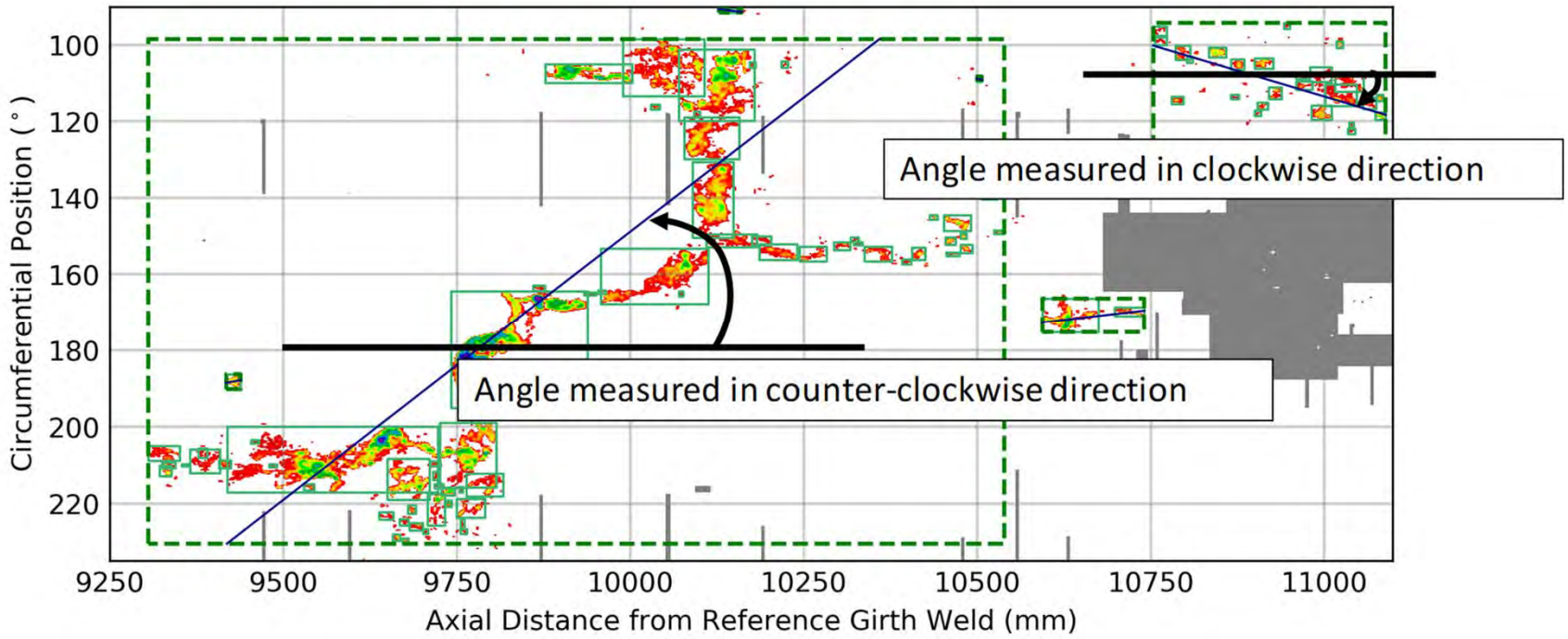


Severity Criteria Development

- **Severe Corrosion:**
  - Clustering of anomalies by 6t interaction distance – axially and circumferentially
  - Burst pressure capacity assessed by Effective Area method < 100% SMYS

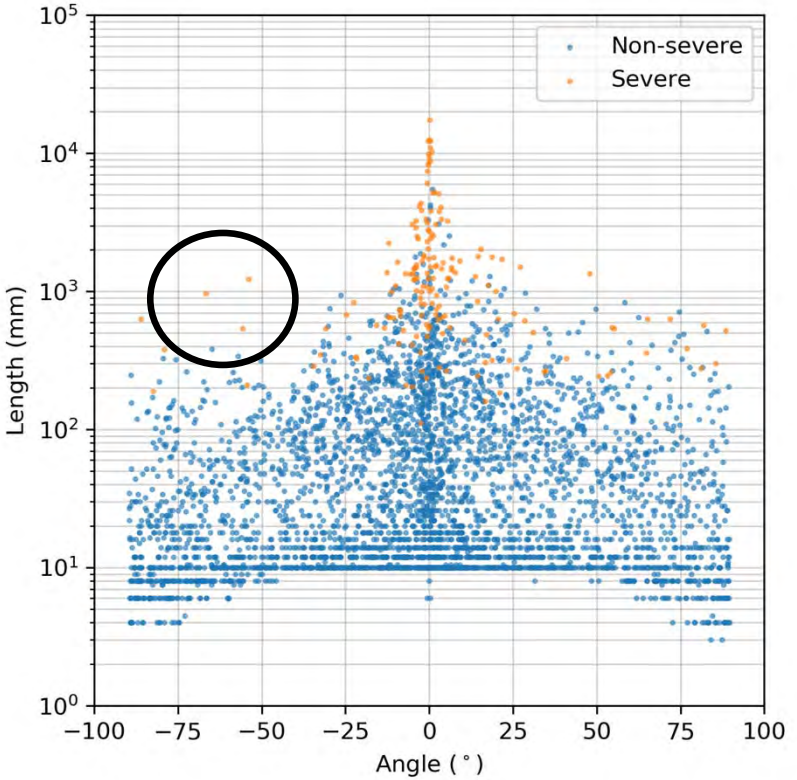
- **Cluster Attributes:**
  - Maximum depth: Maximum depth of a cluster
  - Length: Maximum length of the cluster
  - Average depth: Average of depths in a river bottom profiles
  - Density: Density of features within a corrosion cluster
  - Angle: Angle between the primary orientation of the corrosion cluster and the pipe longitudinal axis
  - Gradient: Ratio of maximum depth to length
  - Profile factor: Ratio of average depth to maximum length

Cluster Attributes

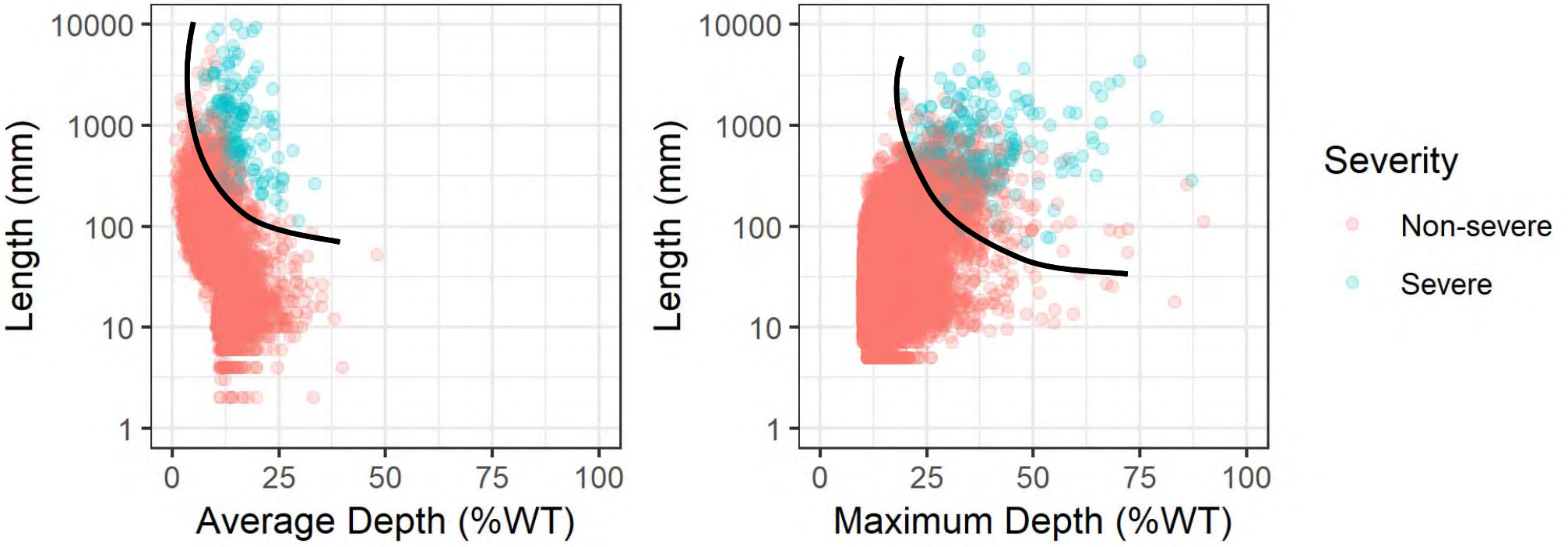


Exploratory Data Analysis

- **Relationships between all cluster attributes explored to identify "severe" clusters**
- **Most influential cluster attributes are related to burst pressure models**
- **Primary cluster attributes:**
  - Length
  - Average depth
  - Maximum depth



Severity Criteria Selection



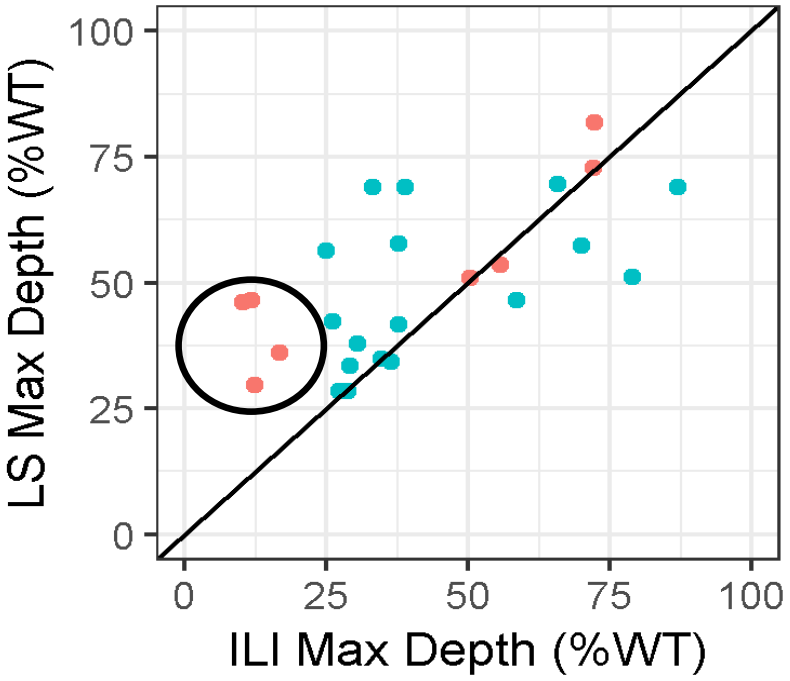
Severity Criteria

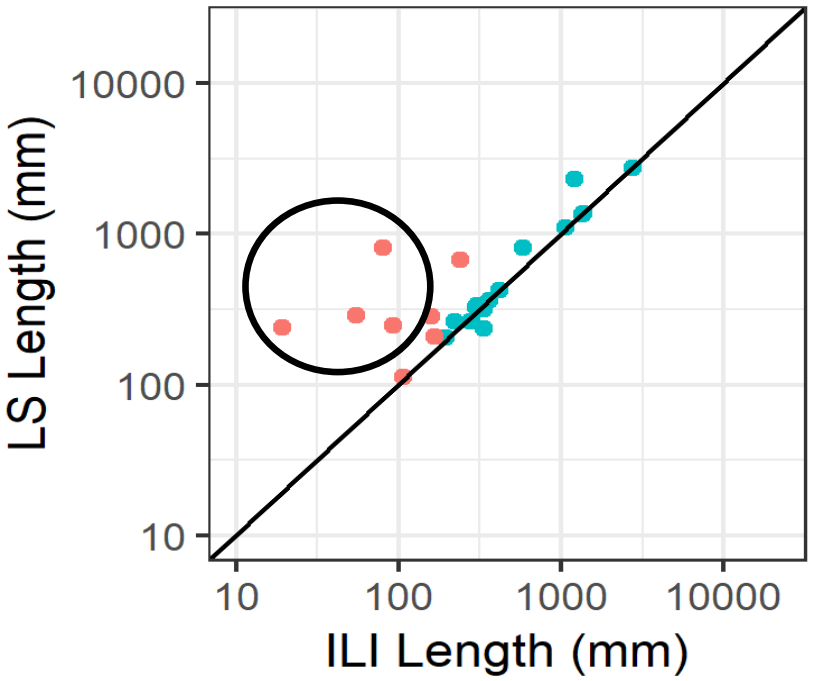
- ***Length*: Corrosion cluster length greater than 200 mm (7.87 in).**
- ***Average Depth*: Average depth greater than 10%WT**
- ***Maximum Depth*: Maximum depth greater than 25%WT**

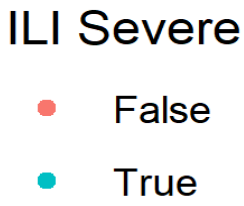
- **Selected for balance between**
  - True positive rate (TPR): Ratio of correctly identified severe clusters to the total number of severe clusters – 88%
  - False discovery rate (FDR): Ratio of non-severe clusters incorrectly identified as severe to the total number of severe clusters – 38%

- **High TPR reduces the likelihood of severe clusters being misclassified as non-severe**
- **Low FDR reduces the likelihood of non-severe clusters being misclassified as severe**

Severe Cluster Identification – Validation







Validated for 25 ILI-LS matched severe clusters considering ILI depth and length sizing tolerances

ILI Depth Sizing Performance by ILI Run

ILI run date	Number of One ILI to One LS matched clusters	% of clusters within 10%WT	95% confidence interval	
			Lower bound	Upper bound
2013	66	94%	85%	98%
2013	26	96%	81%	99%
2014	44	59%	44%	72%
2014	29	41%	25%	59%
2016	58	86%	75%	93%
2016	46	80%	67%	89%
2017	87	75%	65%	83%
2017	65	71%	59%	80%
2017	48	88%	75%	94%
2017	28	86%	68%	94%

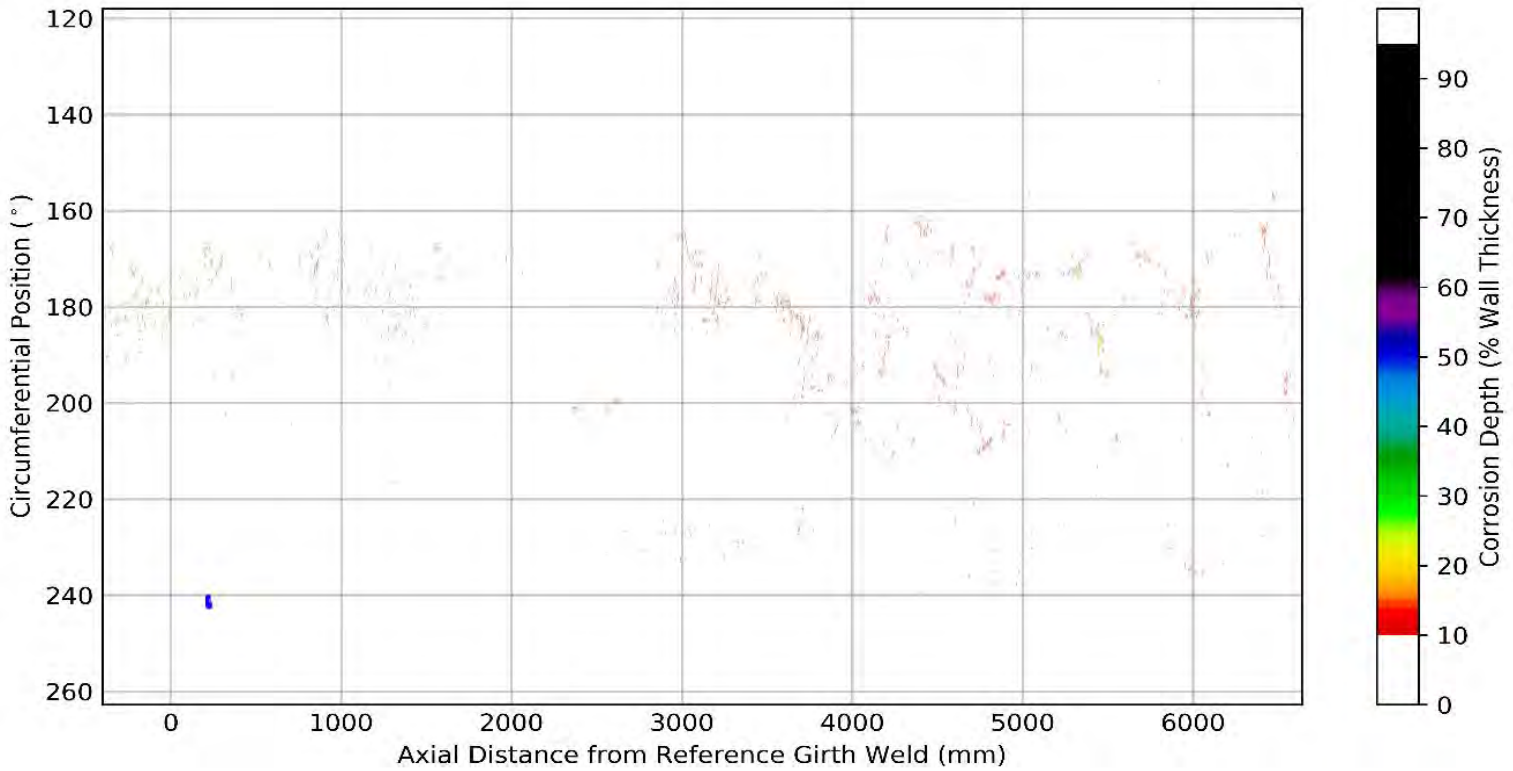
10 out of 28 ILI runs listed that have more than 15 one-to-one matched clusters
Corrosion growth could affect sizing error quantification for ILI runs earlier than 2017

ILI Sizing Performance - Severe Corrosion

- **Only 25 one-to-one matched severe corrosion clusters with 6t x 6t interaction distance**
- **"Scan-wide" clusters matched based on the entire laser scan area**
  - 121 laser scans matched all ILI anomalies within the scanned area

ILI run date	Number of scan-wide clusters	% within 10%WT tolerance	% within 15%WT tolerance	%within 20%WT tolerance
2013	32	84%	94%	97%
2014	17	41%	59%	65%
2015	2	100%	100%	100%
2016	18	28%	44%	44%
2017	51	75%	82%	90%
2018	1	0%	100%	100%

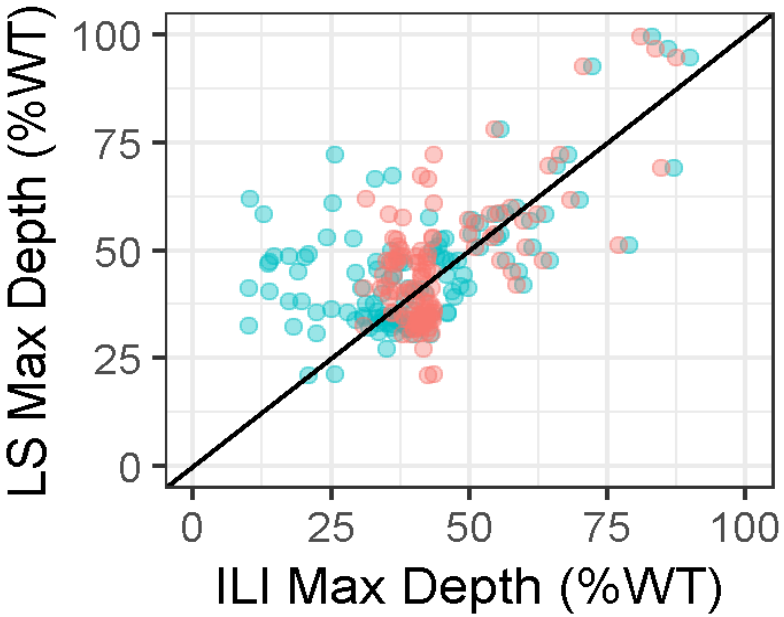
ILI Sizing Performance - Outliers

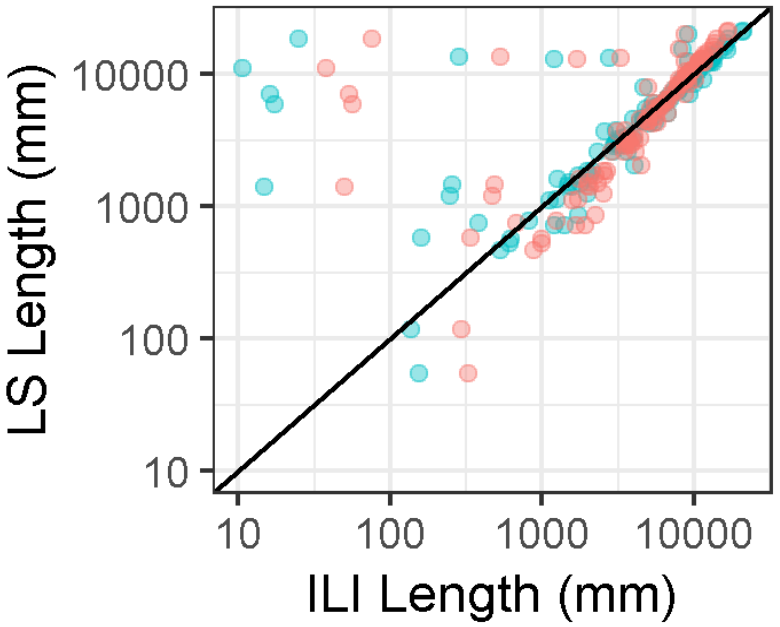


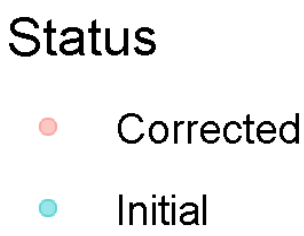
ILI Sizing Correction Models

- **Maximum depth sizing:**
  - Maximum ILI depth > 50% WT
    - *Likely sizing error less than 50% WT for under-calls*
    - $D_{ILI_{corrected}} = m_D \cdot D_{ILI_{raw}} + b_D$
  - Maximum ILI depth < 50% WT
    - *Likely sizing error greater than 50% WT for under-calls*
    - *Nonlinear correction model needed for large corrections of under-calls*
    - $D_{ILI_{corrected}} = D_{ILI_{raw}} \cdot \exp(m_D \cdot D_{ILI_{raw}} + b_D)$
- **Length sizing:**
  - Linear model for length converted to log-scale in base 10
  - $L_{ILI_{corrected}} = m_L \cdot L_{ILI_{raw}} + b_L$

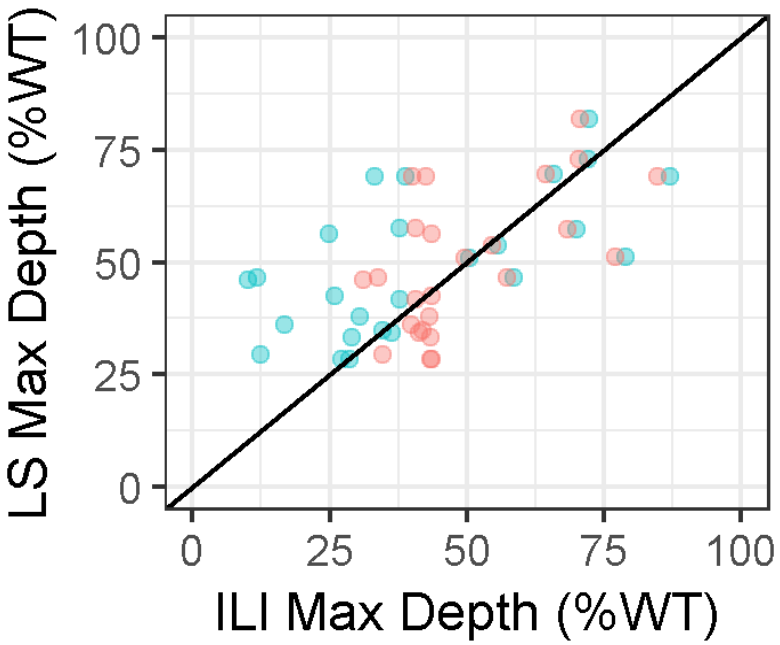
Sizing Correction – Scan Wide Clusters

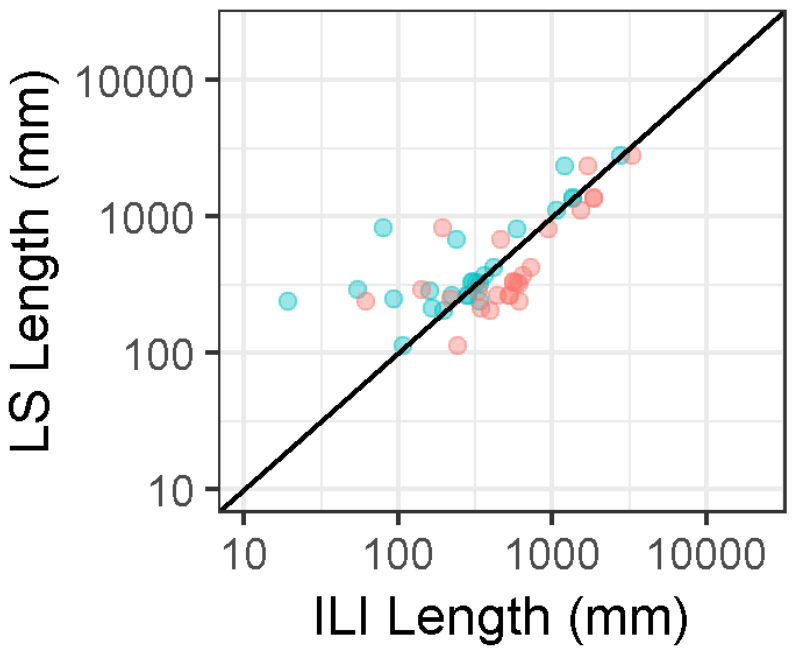






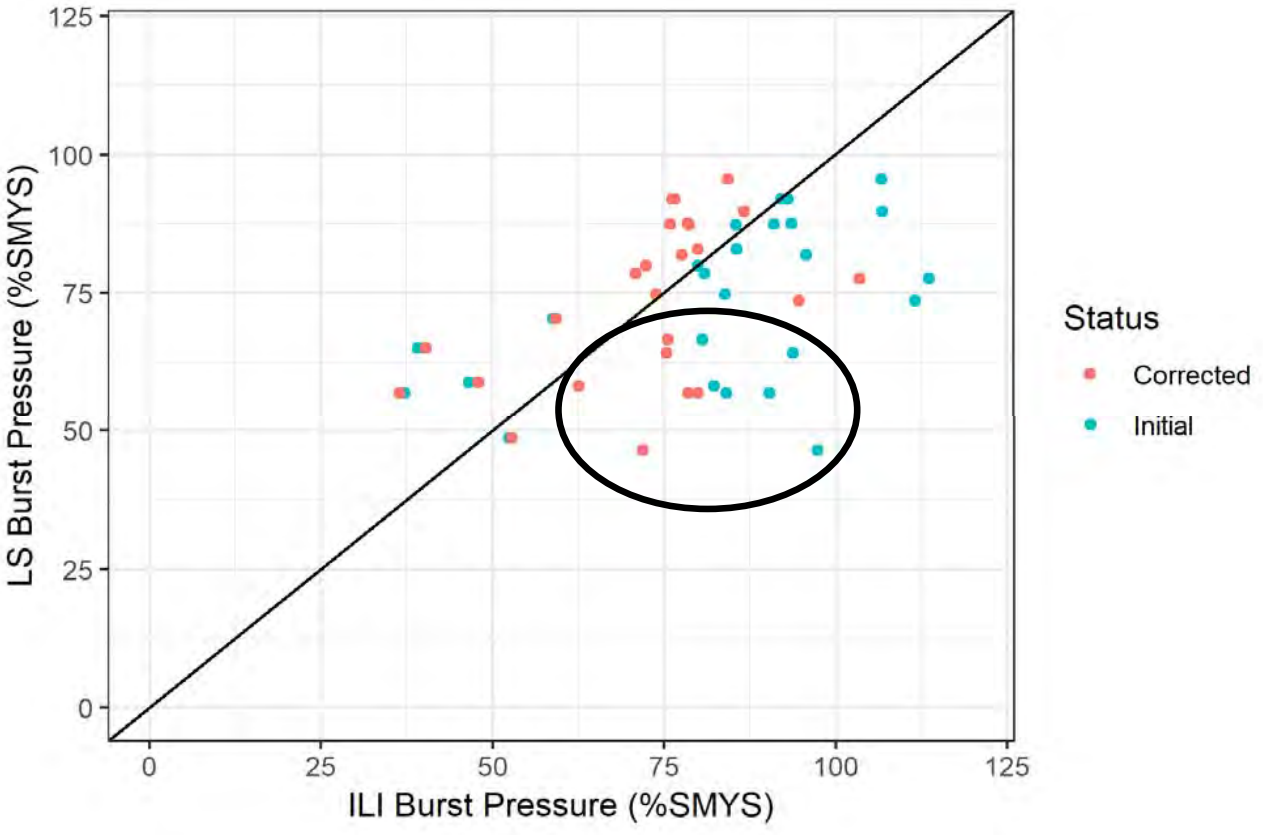
Sizing Correction





Status
Corrected
Initial

Sizing Correction Effect



Summary

- **Value to Industry**
  - A secure database of more than 100 high resolution laser scans of external corrosion was developed, which can be used by operators and vendors to drive ILI tool technology improvements.
  - Attributes to quantify corrosion morphology were developed, which can be used to compare different corrosion geometries.
  - Sizing correction models were developed for improved confidence in estimated burst pressure capacity of severe corrosion clusters.

- **Challenges**
  - Location and detection errors in ILI features reduced the number of validated one-to-one matched severe corrosion clusters
  - Longer duration between an ILI run and field measurements meant direct comparison between the measurements may not be accurate due to corrosion growth

Recommendations for Future Work

- Develop optimization algorithms for aligning ILI and LS clusters considering location and detection errors in the ILI data.
- Leverage multiple ILI measurements associated with high-resolution LS data to develop corrosion growth models.
- Develop approaches to improve the accuracy of ILI sizing using multiple ILI measurements that are unlikely to be affected by corrosion growth.
- Compare the predicted burst pressures from ASME B31G models to the burst pressure predictions obtained from other models.

Pipeline Research Council International

Guidelines for Integrity Assessment of Difficult to Inspect Pipelines

2020 Research Exchange
The Westin, San Diego
March 4, 2020

PRCI Project NDE 3-3

PR-430-173869

LEADING PIPELINE RESEARCH

- **Principal Researcher**

  Mr. Ben Mittelstadt
  Dynamic Risk Assessment Systems, Inc.
  ben_mittelstadt@dynamicrisk.net

- **Project Team Lead**

  Mr. Richard McNealy
  Chevron Energy Technology Company
  RMcNealy@chevron.com

- **Program Manager**

  Mrs. Zoe Shall
  Pipeline Research Council International
  zshall@prci.org

Introduction – Is the Highest Resolution Always the Best Choice?

- **Regulatory codes and standards that govern integrity assessment of hazardous materials pipelines specify multiple options for integrity assessment, namely; hydrostatic testing, ILI, DA, or "other methods".**
  - Any pipeline can be constructed or modified to allow passage of ILI – generally providing the highest resolution – but is that always the best choice?
  - Available "other methods" vary from low-resolution screening assessments to full coverage non-destructive examination.
  - If not ILI or hydrostatic testing, other methods must provide an "*equivalent understanding*"

Project Overview

- **Primary Objectives**
  - To develop a guideline to evaluate integrity assessment solutions for difficult-to-inspect (DTI) pipelines with concise documentation that can be relied upon (referenced) to justify technology with/to PHMSA and/or similar entities
  - The guideline must provide a mechanism to evaluate methods for DTI pipelines with emphasis on establishing “equivalent understanding”

- **Value Proposition**
  - For one pipeline operator project team member, potential savings from use alternative technologies for integrity management was estimated at $650M over a ten year time horizon benefiting from scheduled deferral of piggability conversion.

Related Prior Research

- **This project builds upon and relies on a broad swath of current and previous PRCI projects. These include:**
  - NDE-1-4 (Guidelines for Validation of MAOP under IVP)
  - NDE-2-5 (Literature Review of DTI Inspection Technologies)
  - NDE-3-1 (Large Standoff Magnetometry Techniques)
  - NDE-3-2 (Evaluating Select Areas with High Resolution NDE)
  - NDE-1-3 (Integrated ILI Cleaning Tool)
  - IM-1-4 (Condition Assessment Using EMIT Technology)

- **Prior projects researched/tested/presented *methods* but a *structured process* for application was a gap. Development of a process for application was recommended by NDE-3-2.**

Technology Summary

	Low-resolution or Screening Methods	High-resolution Inspection Methods
Inside the Pipe	• Multi-sensor ball • Integrated Cleaning/Inspection Pig (ICIP) • Remote Field Eddy Current (RFEC) • Hydrostatic Testing	• High-resolution ILI technologies such as MFL, UT, EMAT, Eddy Current, Caliper/Geometry, Inertial Mapping
Above the Pipe	• Large Standoff Magnetometry • Acoustic Leak Detection • Electrical surveys such as those used for ECDA	• Dynamic Pulsed Eddy Current • Remote Field Eddy Current • Saturated Low Field Eddy Current
On the Pipe	• In-situ Yield Strength Determination • Guided Wave UT • ECDA, ICDA, SCCDA • Limited NDE combined with statistical-based methods – random or stratified sampling	• Pit Gauge • Laser or White light Profilometry • Field Metallography • Full coverage High Resolution NDE

"Other Technology" – Regulatory Requirements

- **§192.921(a) & §195.452(c)(i)**
  - *… An [operator] must assess the integrity of the line pipe in each covered segment by applying one or more of the following methods…*
    - ILI, Pressure Test, DA, "other technology"
      - *As of July 1, 2020 GWUT is expressly allowed by 192 and "ILI" is no longer limited to technologies listed in ASME B31.8S-2004 section 6.2*
- **§192.921(a)(4) & §195.452(c)(i)(D)**
  - *Other technology that an operator demonstrates can provide an **equivalent understanding** of the condition of the line pipe.*
- ***CSA Z662-19 Annex N.1.12.3***
  - *When an inspection is performed using indirect methods (e.g., in-line inspection or close-interval surveys) operating companies shall consider whether supplemental inspections using more direct methods are needed.*

History of Notifications (PHMSA)

Technology	Internal	Gas Transmission	Hazardous Liquids	Total
GWUT/Long Range UT	No	118	71	189
SCCDA	No	34	-	34
Direct Examination	No	8	5	13
ECDA	No	-	9	9
DA (not specified)	No	-	8	8
Not Specified / Other	No	4	-	4
Visual	No	1	3	4
Unknown	No	-	4	4
EMAT (External)	No	-	2	2
EMAT (Internal)	Yes	5	-	5
RFEC	Yes	4	-	4
TFI (seam inspection)	Yes	2	-	2
Laser Deformation Sensor	Yes	1	-	1
Visual (Video)	Yes	-	1	1
Grand Total		177	103	280

Evaluation of History

- **Part 192 References ASME B31.8S-2004, Section 6.2**
  - Defines ILI as MFL, liquid coupled UT, and Geometry tools only.
  - The reference notes that *"Other proven integrity assessment methods may exist for use in managing the integrity of pipelines"*
    - *Note: Effective July 1, 2020: Part 192 will no longer incorporate B31.8S-2004 Section 6.2 and instead incorporates API 1163 and NACE SP0102*

- **Part 195 References API 1163, 2nd Edition (2013) *In-Line Inspections Systems Qualification***
  - *"This standard applies to both existing and developing technologies"*

Observations

1. PHMSA, ASME, and API prescribe ILI capable of detecting corrosion and deformation but do not define or prescribe any particular type of technology nor any expectations for performance.
2. Non conventional technologies can meet the requirements set forth for ILI (and they have). API 1163 is applicable to emerging technologies.
3. If technology deployed in-line, inspects or screens full length, has a performance spec that can be verified or validated using API 1163 then it is ILI.
4. So if API 1163 provides guidance for ILI, the primary gap is for externally deployed assessment methods – but the principles of this standard still apply.

Essential Elements for Any Integrity Assessment

1. Specify the target threat(s) intended for integrity assessment (e.g. ASME B31.8S, API 1160);
2. Include specific description of the qualification process (i.e. demonstrate that the technology is capable to assess for the threat)
3. Specify the target defect or condition to be identified (e.g. B31G, API 579)
4. Include a written performance specification for the system capabilities to identify and classify features
5. Include specific validation of the performance versus the performance specification

Equivalent Understanding – 2 Approaches

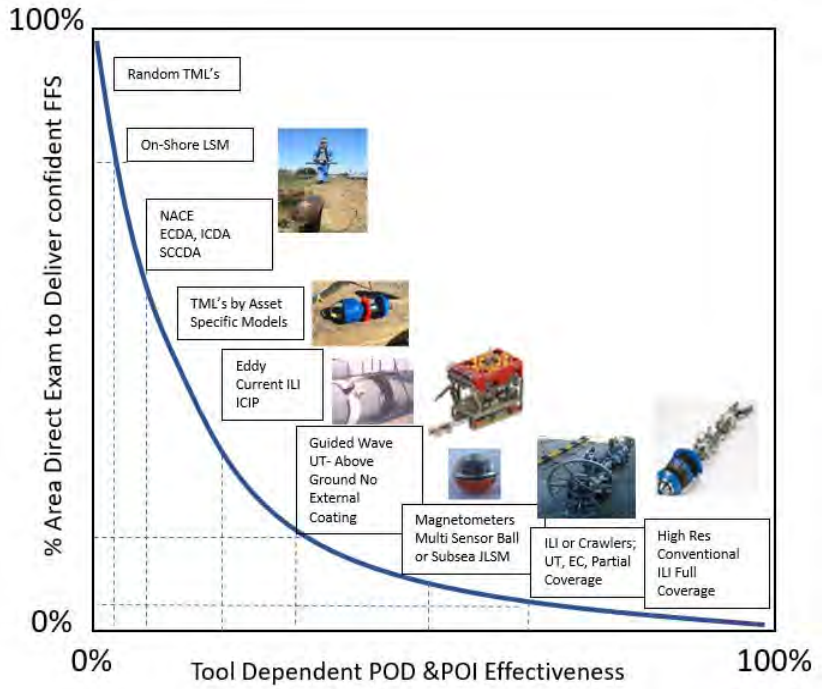
- **Limit States Equivalence**
  - Use to establish equivalent understanding for technologies that can detect and measure defects in the wall of line pipe
    - *Comparison to empirical failure models for limit states for leak and rupture*
    - *Example – Hydrostatic testing was historically used to validate FFS models (B31G, Rstreng) & emerging ILI processes*
- **Risk-based Equivalence**
  - Similar in potential use as with structured Direct Assessment (DA) processes
    - *Evaluates susceptibility factors and requires direct examination to confirm effective threat management*
    - *Requires demonstrated understanding of characterization of factors and direct examination for confirmation*
  - Use for inspection technologies that categorize factors that cannot be understood by applying equivalents to limit states, but can demonstrate understanding of threat likelihood (and subsequently, risk)
    - *e.g. environmental factors, coating condition, stress intensification factors*

Integrity Assessment Process

- **Guideline Document Presents Integrity Assessment Process in General Terms**
  - Planning
    - *Data integration, feasibility, technology selection, qualification, development of a performance specification*
  - Inspection
    - *Data collection*
  - Validation
    - *How many measurements are required for evaluation vs. performance specification. Were there false positives? False negatives?*
  - Review
    - *Evaluate effectiveness. Were goals achieved?*

Technology Effectiveness vs. Validation Effort

- **Spectrum**
  - Random NDE or low resolution screening
    - *High # of measurements up to full inspection of the pipeline*
  - High Resolution ILI
    - *Potentially no validation measurements (e.g. API 1163 Level 1 Validation based on established performance)*



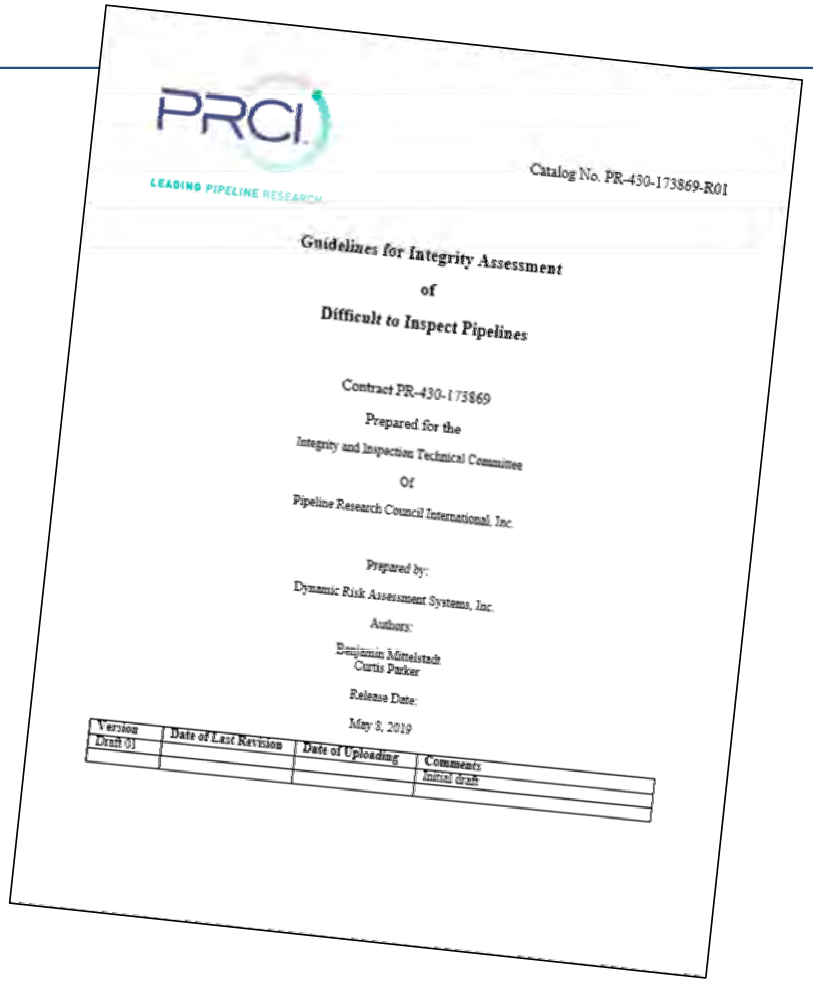
Any integrity assessment technology (even long-established methods such as ILI) follows this structured process. The difference lies in the sample of direct examination sites required to establish limit state equivalence or risk-based equivalence.

Practical Application of the Principles

- **Scenario – Integrity Assessment of Unpiggable Above Ground Gas Pipeline**
  - Target Threat – Corrosion metal loss: internal/external
- **Options – High resolution ILI (MFL), Low resolution screening ILI (ICIP), GWUT**
- **Tool: Guided Wave Ultrasonic Testing (GWUT) with High Resolution NDE**
  - Qualification – Screening technique typically categorizes metal loss as mild (<25%), medium (<50%), or severe (>50%). Consideration given to UT attenuation by coating, girth welds: vendor specifications typically indicate inspection lengths of ~100' or across up to 6 girth welds.
  - Validation Strategy – Demonstrate "equivalence" (i.e. FFS) through UT wall measurement at every GWUT indication above the detection sensitivity threshold
  - Effectiveness Review – (Were goals achieved?) Evaluation straight-forward given production rate (feet/day) of NDE crew vs. cost of line modification and ILI

Acknowledgements

- Pipeline Research Council International
- Chevron
- Contributing team members



PRCI

LEADING PIPELINE RESEARCH

Catalog No. PR-430-173869-R01

Guidelines for Integrity Assessment

of

Difficult to Inspect Pipelines

Contract PR-430-173869

Prepared for the

Integrity and Inspection Technical Committee

Of

Pipeline Research Council International, Inc.

Prepared by:

Dynamic Risk Assessment Systems, Inc.

Authors:

Benjamin Mittelstadt
Curtis Parker

Release Date:

May 8, 2019

Version	Date of Last Revision	Date of Uploading	Comments
Draft 01			Initial draft

BACK TO AGENDA

PRCI 2020 Research Exchange

In-line Inspection Crack Tool Reliability and Performance Evaluation

PRCI Project NDE 4-7

Presenter: Smitha Koduru, C-FER Technologies

Project Team Leaders:
Steven Bott, Enbridge
Mohammad Al-Amin, TC Energy

LEADING PIPELINE RESEARCH

Introduction

NDE-4E Suite of Projects:

- **Motivation**
  - Establish comprehensive reliability assessment of crack ILI
  - Improve program effectiveness by knowing the strengths and weaknesses of measurement technologies

- **Objectives**
  - To collect, validate and store existing industry data on the measurement, characterization, assessment and repair of crack and crack-like features measured by ILI and field excavation techniques
  - To evaluate the performance, capability of different ILI technologies in detecting, identifying and sizing cracks and crack-like features

Project Objectives

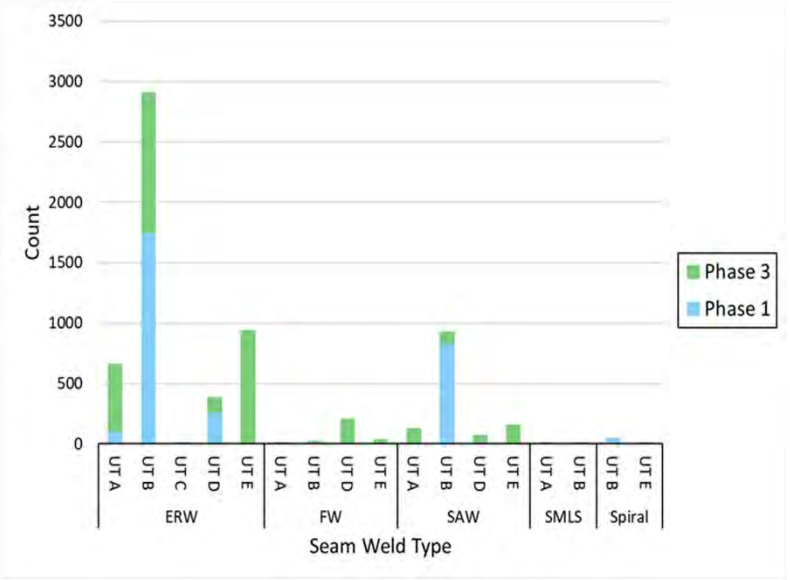
- **Characterize performance of crack ILI tools as function of pipe attributes**
  - Wall thickness
  - Pipe size
  - Seam weld type
- **Investigate reduction of sizing uncertainty through multiple ILI runs**
- **Investigate use of crack profile data to evaluate tool performance and burst pressure calculation**

Database and Tool Performance Summary

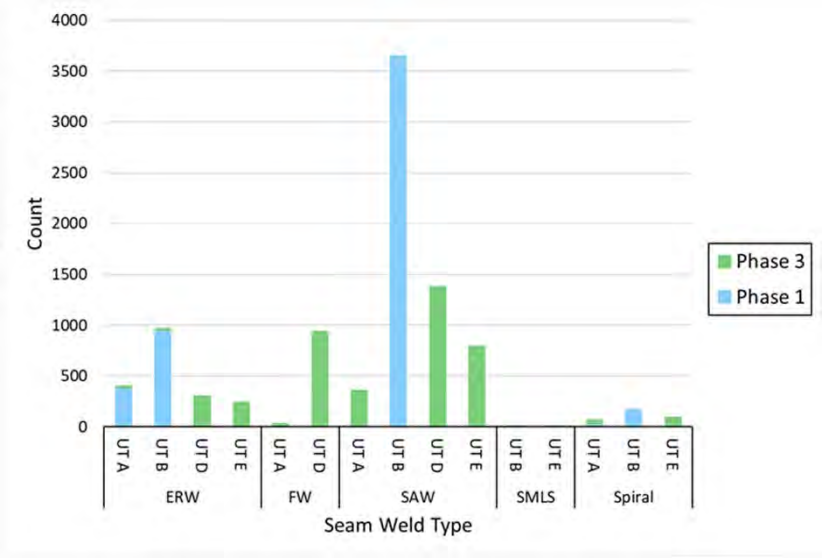
- **Continued operator collaboration**
  - Data collected from eight operators
  - **database growth -** 26% increase in the data size and four **new tool types**
- **Overall, most tool types meet the performance specifications for Rate of Detection**
  - UT B has contained significant Phase 1 Data and did not meet specifications for cracks at the weld overall
- **Overall, all tool types meet the performance specifications for sizing accuracy in all cases with few exceptions**
- **Overall, all tool types meet the specification for identification**
- **Tool performance in relation to available pipe attributes did not show specific trends**

Database Highlights

- Representative of multiple weld types and tool types
- Each record is a crack feature that is either ILI-detected, NDE-detected or by both



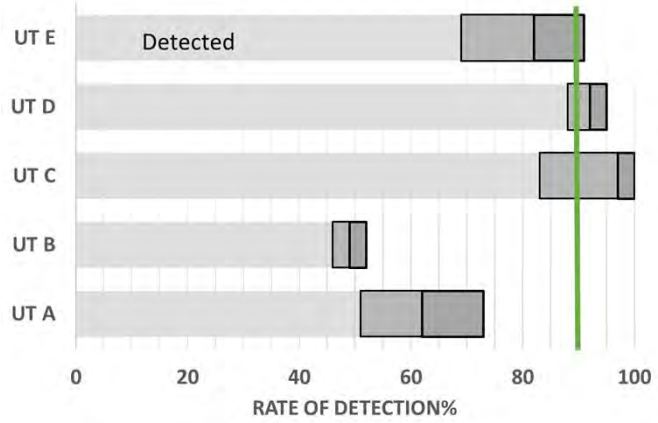
Single Crack Features



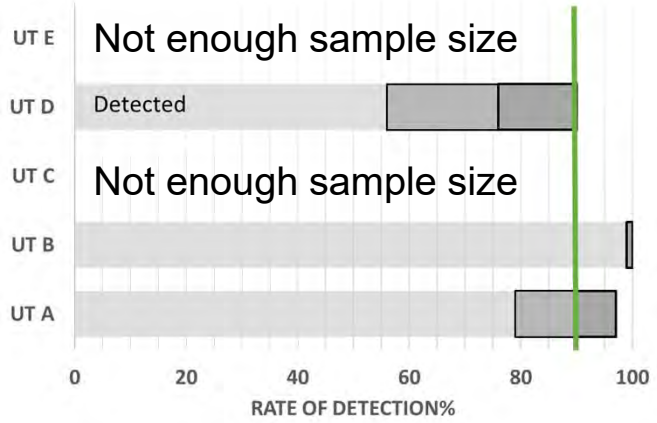
Stress Corrosion Cracking (SCC)

Tool Performance Highlights

- **Performance evaluated in terms of detection, identification, false positives, and sizing**
- **Detection**
  - Performance evaluated separately for crack and SCC features
  - Estimated ROD of certain tools compromised due to Phase 1 data set, low sample size, and data skew towards a single poor performance tool run



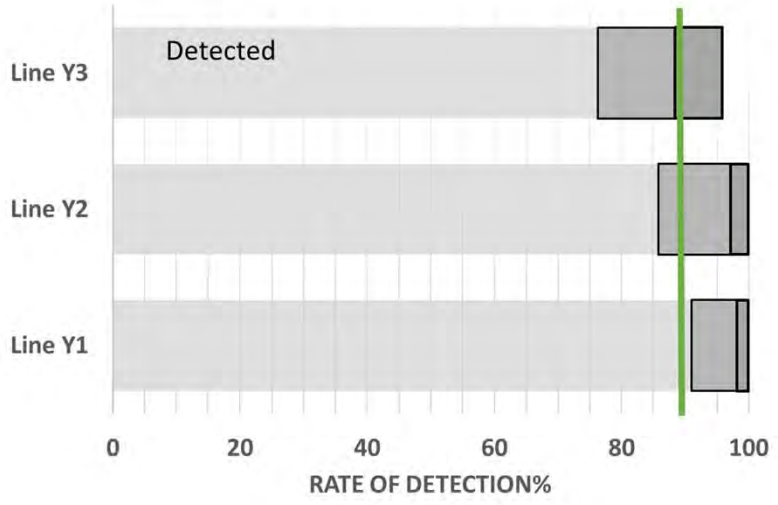
NPS 14-24 for Crack



NPS 26-42 for SCC

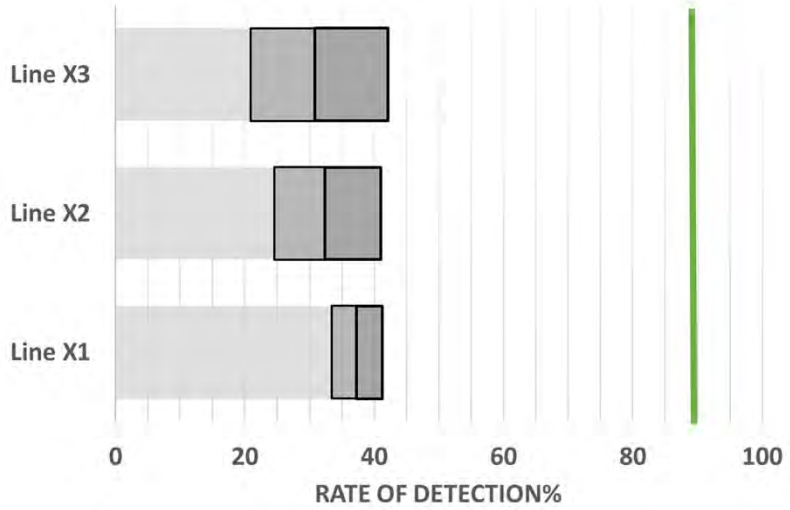
Tool Performance Highlights

- Differences in performance of same tool for different runs on different lines
- Data shown for features above vendor specified tool detection threshold



Single Crack Features

Phase 1 data

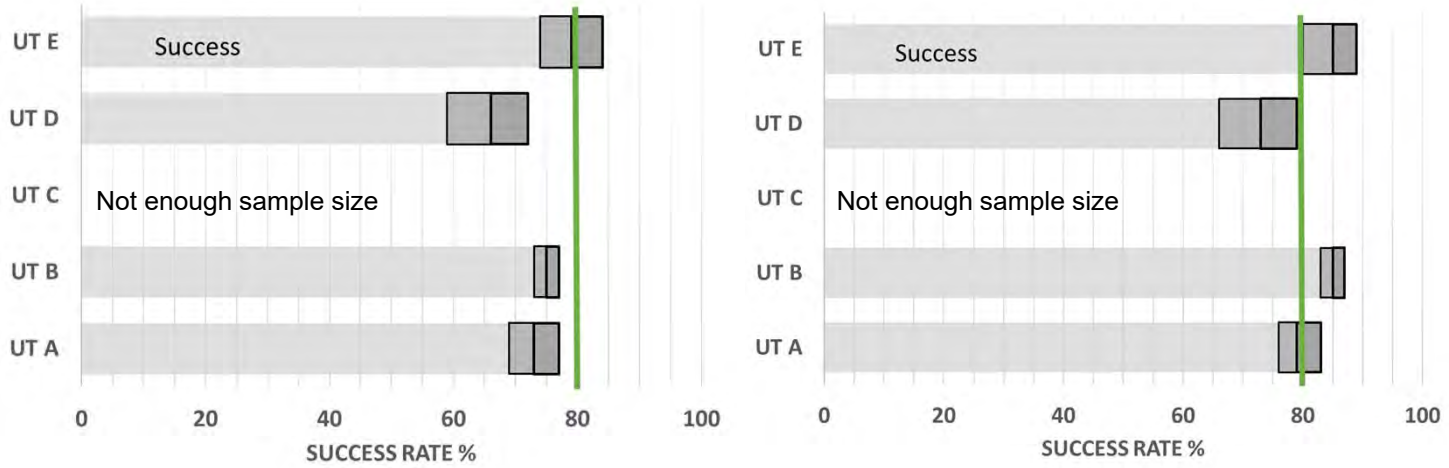


Single Crack Features

Tool Performance Highlights

- **Sizing Accuracy**
  - NDE sizing is assumed to have no error
  - Inclusion of NDE sizing error improves overall success rate
    - *Approximately 0.5mm standard deviation for NDE sizing error assumed*

Near-Weld Depth Sizing for Crack



Without Including NDE Sizing Error **Including NDE Sizing Error**

Multiple Measurements Summary

Project Outcomes:

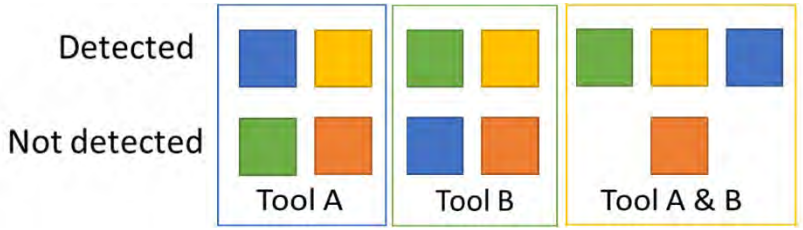
- Leveraged all available data from multiple ILI runs on the same pipeline to improve confidence in detected feature size
- Accounted for improved accuracy in ILI feature sizing compared to older ILI technologies
- Improved estimate of the undetected feature size distribution

Future Potential:

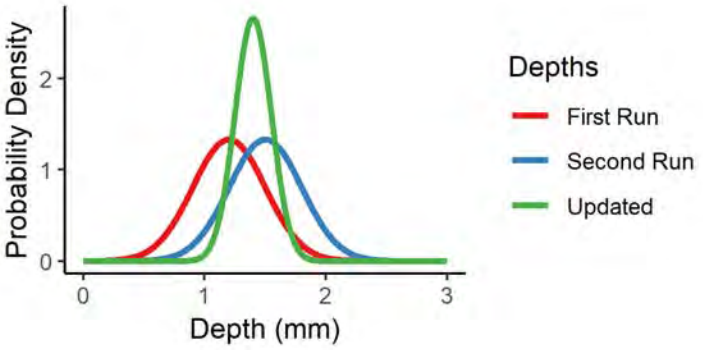
- Multiple ILI runs from multiple vendors to assess the impact of multiple runs on feature detection

Multiple Measurements Highlights

- **Multiple measurements of same set of features through**
  - Multiple ILI runs & multiple field NDE measurements
- **Detection**



- **Sizing**



Features Detected by Tool A only

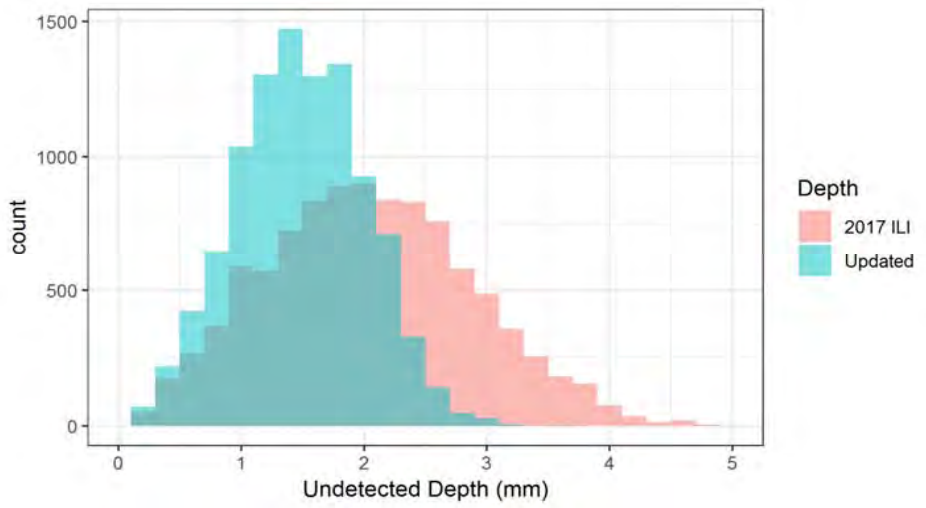
Features Detected by Tool B only

Features Detected by Tool A and B

Features Not detected by both tools

Multiple Measurement Analysis

- **Undetected feature depths estimated based on**
  - Detected feature depth distribution
  - Rate of detection of ILI tool
- **Improved confidence in detected feature depths used to update the estimated depth distribution of undetected features**



Profile Factors Summary

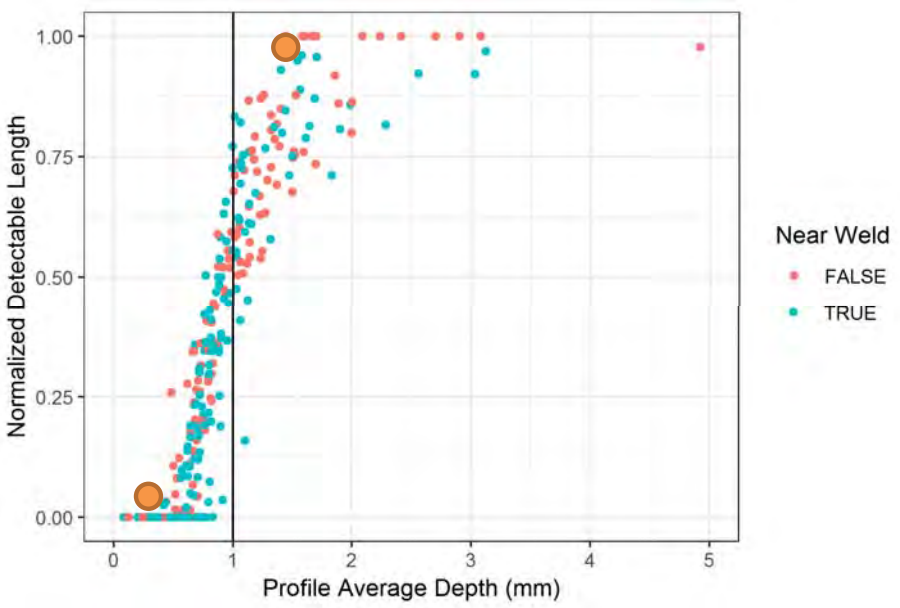
Project Outcomes:

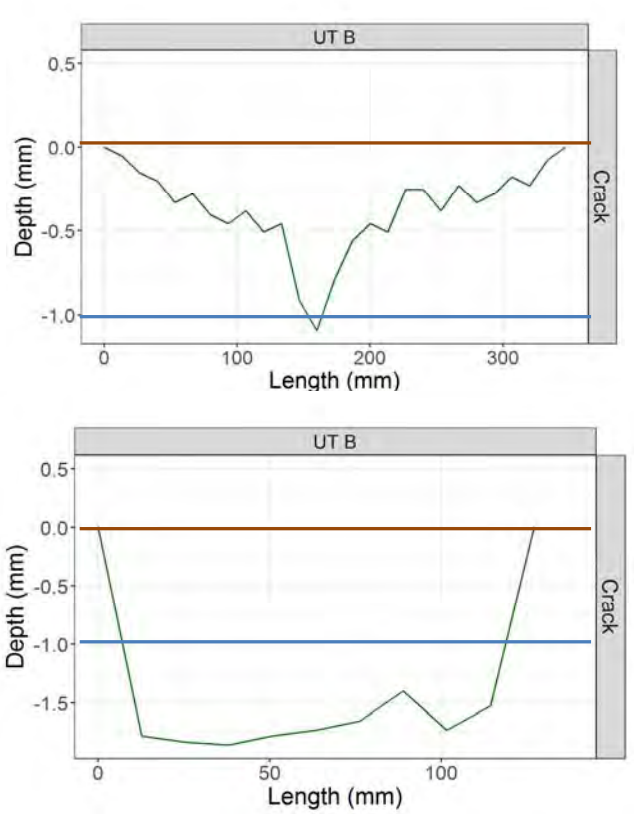
- Simplified factors developed to assess crack shape and leverage the information for integrity management
- Ability to distinguish between long-shallow and deep-short cracks based on quantitative metrics

Future Potential:

- Profile measurements for undetected cracks to understand the technology gaps in crack detection

Crack Profile Factors Highlights





Profile factors can be used distinguish crack shapes numerically

Project Highlights

Outcomes:

- Large data set of high quality due to rigorous data processing and validation
- Tool performance assessment in relation to pipe attributes
- Methodology to leverage all available data from multiple ILI runs
- Simplified factors to assess crack shape and leverage the information for integrity management

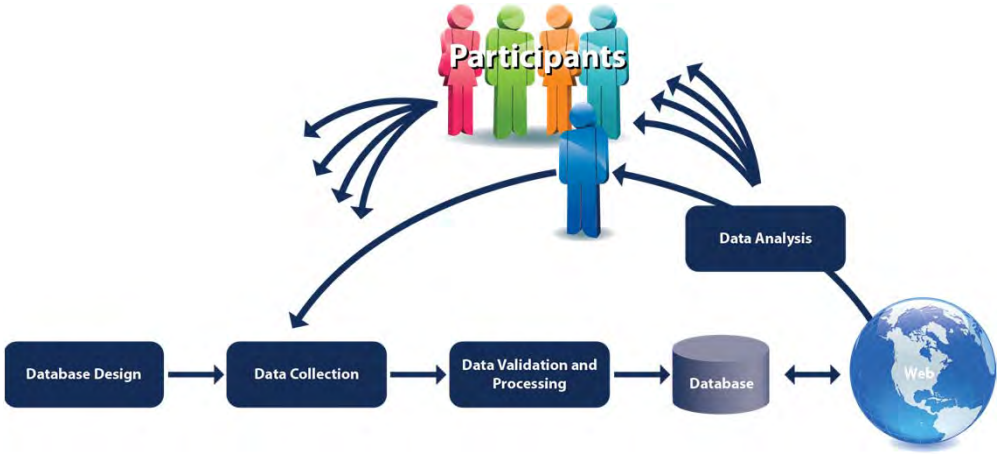
Challenges:

- Large section of data specifications were un-filled due to unavailable pipe tally data from operators
- Confidentiality issues to identify the ILI tool versions in published reports
- NDE detection and sizing performance unknown

Looking Forward

Database Development:

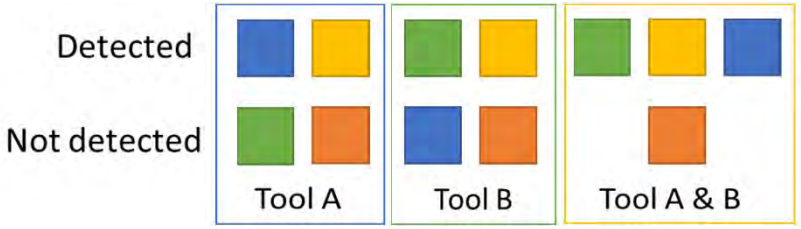
- Automate the process of data upload, cleaning and quality control and provide better control of data transfer and validation by operators
- Provide interactive dashboard for data visualization and ability to filter data to attributes of interest



Looking Forward

Methodology Development:

- Crack detection assessment based on multiple ILI runs by different vendors
- Quantify impact NDE detection performance on the ILI tool performance assessment
- Influence of crack profile shape on detection



PRCI Strategic Research Priority – Crack Management

- **Extension of industry-wide database**
  - Circumferential cracks
  - Spatial correlation between external corrosion and SCC
  - Factors guiding susceptibility to SCC
- **Methodology for data use from multiple inspections**
  - Data fusion from low-resolution and high-resolution measurements
  - Improved confidence in feature detection and sizing
  - Crack growth estimation
- **Crack profiles**
  - Effect of crack profile on estimated burst pressure capacity
  - Efficient use of resources for crack management to target cracks critical to pipeline integrity

BACK TO AGENDA

PRCI 2020 Research Exchange

Representing MFL Performance under Casings to Improve ILI Based Decision Making

Dongliang Lu, Ryan Sager, Jennifer Klementis,
Shahani Kariyawasam, Terry Huang, Irfan Ali, Scott Currier,

PRCI 2020 Research Exchange Meeting
San Diego, California
March 3-4, 2018

LEADING PIPELINE RESEARCH

TC Energy

ROSEN
empowered by technology

Project Objectives

- **By working with ILI vendors, TC Energy would like to better understand MFL performance within casings to ensure**
  - Probability of detection (POD) is adequate;
  - Sizing uncertainties are appropriately accounted for;
  - Effective ILI-based corrosion management of cased pipes can be achieved.

- **Specifically, through this project the following questions will be answered:**
  - What is the detection and sizing performance of MFL tools for corrosion anomalies within casings?
  - How does the performance differ for various casing configurations and conditions (e.g. OD, wall thickness, casing eccentricity, shorting conditions)?
  - Does presence spacers affect the MFL performance for features under them?
  - What are other factors that could affect the MFL performance?

Project Tasks

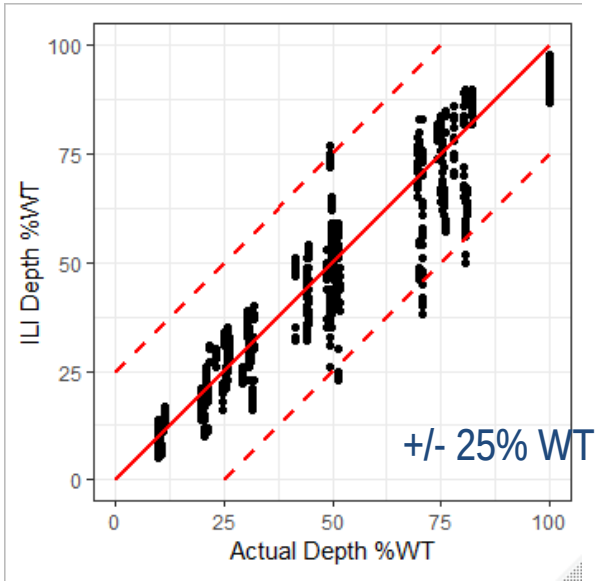
- **Phase I (Completed)**
  - Perform full-scale pull tests on known corrosion features for various casing configurations using the ROSEN MFL-A system
  - Develop preliminary probabilistic characterizations of the MFL system performance for various casing scenarios
- **Phase II (Ongoing)**
  - Additional pull tests on other OD and wall thickness combinations of casings and pipes
  - Additional pull tests with varying tool speeds
  - Pull tests on single point touching scenarios
  - More comprehensive data analytics for better characterization of MFL performance within casings
- **This presentation summarizes Phase I results**

Highlights of Phase I Results

- **Full scale testing was completed successfully by ROSEN at its Lingen Facility in Germany.**
- **Testing data show that ILI performance under casings in detection and sizing is comparable to uncased pipe in vast majority of cases.**
  - Excellent rate of detection demonstrated in Phase I test – similar to performance on uncased pipes
  - Overall good sizing performance in concentric scenarios, and eccentric scenarios when local annulus is greater than 1.5 in.
- **Feature sizing in certain small areas will have to be adjusted for bias**
  - ILI reported depth is biased when local annulus distance is small
  - The ILI bias can be quantified and accounted for by operators in the ILI-based corrosion management program
- **Identification of eccentricity and its clock position is possible, which may be used to further estimate local annulus distance (to be confirmed in Phase II).**

Importance of Accurate Characterization of MFL Perf.

- Generally very good performance under casings
- Relatively poor performance when the air gap between casing and carrier pipe is very small (typically only a small percentage of pipe surface area is affected)
- Implications to integrity management:



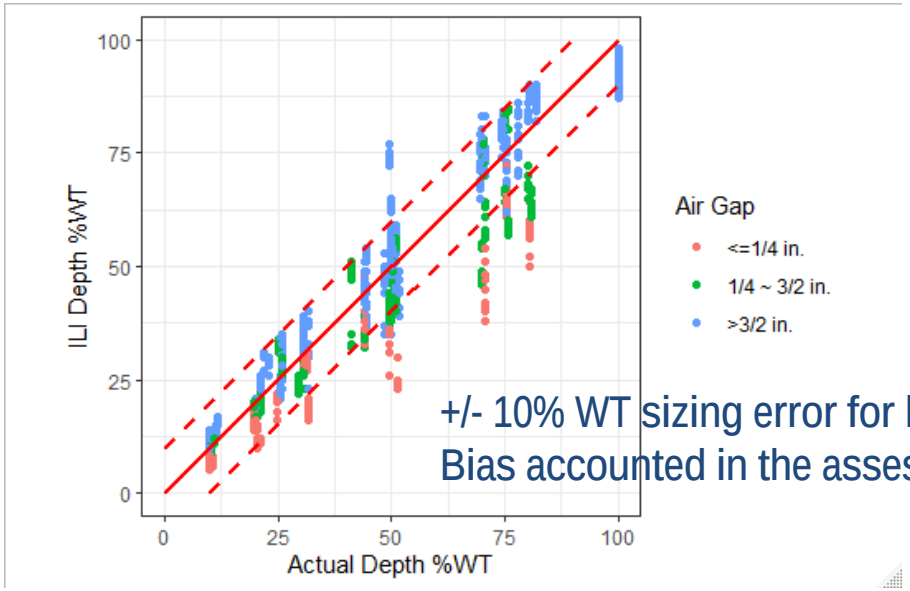
+/- 25% WT sizing error

Applied to heavily corroded pipeline with a large number of corrosion features:

490 repairs

Importance of Accurate Characterization of MFL Perf.

- Generally very good performance under casings
- Relatively poor performance when the gap between casing and carrier pipe is very small (typically only a small percentage of pipe surface area is affected)
- Implications to integrity management:



Applied to a heavily corroded pipeline with a large number of corrosion features:

19 repairs

+/- 10% WT sizing error for large air gap cases
Bias accounted in the assessment for small air gap cases

Background

- **Problems:**
  - Older pipeline systems have cased crossings - some shorted
  - Shorted casings can have higher growth rates
  - Failures under shorted & non-shorted casings and on pipe
- **Regulators concerns:**
  - If heightened integrity is required- clear all shorted casings - high cost
  - Can ILI effectively identify and size anomalies?
  - Can ILI be used to effectively manage corrosion growth in shorted casings?



External Corrosion within Casings – Industry Studies

- **US survey results on 51,500 casings [2]**
  - 17% shorted (metallically or electrolytically)
  - 4% corroded - 2% shorted, 2% non-shorted
- **Low incidence of corrosion at cased crossings – but higher consequence[5]**
- **Gibson – 50+ years of good service with shorted & isolated casings [3]**
- **Perry - appears to be very little evidence of issues with casings [4]**
- **OPS concurs based on survey of 1043 casings – "it appears that corrosion of the carrier pipe inside a casing is not dependent on the casing being shorted"[1]**

TCE Experience

- **In System XX**
  - 3 failures – 2 leaks and 1 rupture
  - 5 failures – 3 shorted(leaks), 2 non-shorted (1 leak and 1 rupture)

Cased?	EC Incidents			
	# of Leaks	# of Ruptures	Total # of Incidents	Incident Rate (/km/yr)
No	2	1	3	1.05E-05
Yes	3+1	1	5	1.81E-03

To prevent failures both shorted & non-shorted casings need to be managed – as well as uncased

Phase I Testing Plan

- **Phase I full-scale testing focused on investigating the performance of High Resolution ILI within shorted and non-shorted casings**
- **Tool used : ROSEN RoCorr High Resolution MFL-A**
- **Pipe sizes tested:**
  - Carrier pipe: 30” (762 mm) OD x 0.5” (12.7 mm) wall thickness
  - Casing: 34” (864 mm) OD x 0.374” (9.5 mm) wall thickness
- **Machined anomalies on carrier pipes:**
  - Joint #1: Pitting, Pinholes and Pitting in General
  - Joint #2: Axial Slotting/Grooving, Circum. Slotting/Grooving, Pitting, Pinholes and General

Phase I Testing Scenarios

Majority of scenarios on pipelines

Scenario #	Description	Eccentricity and Shorting Conditions
Baseline	Baseline test without casing	NA
1	Eccentric casing – metallic short – carrier pipe sitting on bottom of casing – no spacers	Eccentric casing / Metallic short
2	Eccentric casing – no short – casing adjusted to have 0.5” annulus at 6 o’clock – no spacers	Eccentric casing / No short
3	Eccentric casing – no short – casing adjusted to have 1” annulus at 6 o’clock – no spacers	Eccentric casing / No short
4	Concentric casing – spacers installed on Joint 1 at specific locations over top of corrosion features – not shorted	Concentric casing / No short
5	Concentric casing with water – same setup as scenario 4 – casing partial fill with water	Concentric casing / Electrolytic short

Casing Configurations

Concentric Casing



Eccentric Casing



Concentric and Hydrolytically Shorted



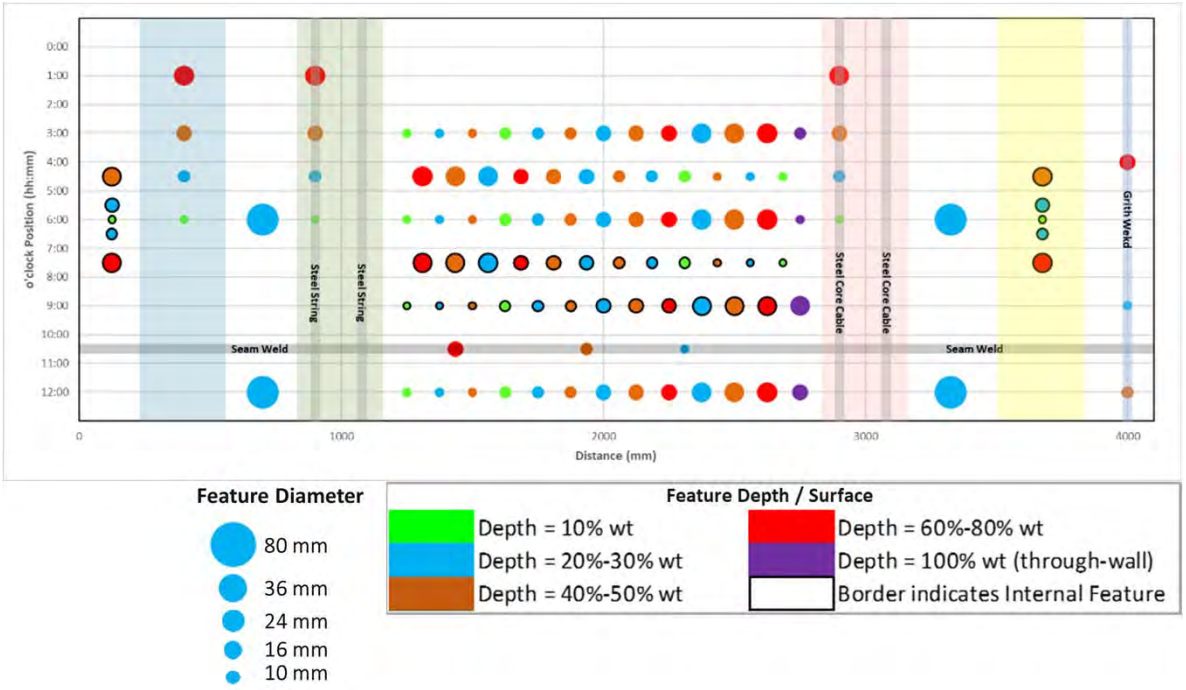
Type of Spacers in Concentric Scenarios

- **Casing centralized using 3 common types of spacers**
  - "Advanced" spacer for new construction (AP)
  - Rubber spacer shoes with steel cables – circa 1950 (TDW)
  - Wood spacer slats with metal banding (Wood)



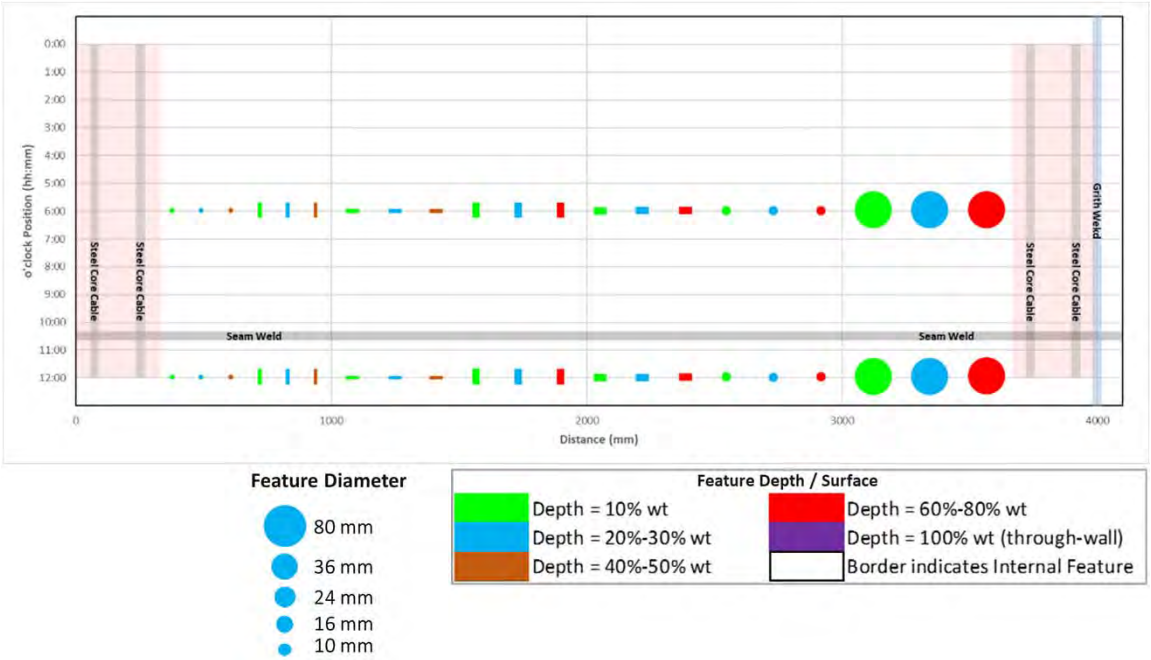
Joint #1 Anomalies

- **Feature set for Joint #1**
  - 108 individual features
  - Depths range from 10% wt to 100% wt (through-wall)
  - Metal loss ϕ ranges from 10 mm to 80 mm
  - Internal and external features
  - Features located along girth weld & long seam weld, as well as under spacers



Joint #2 Anomalies

- **Feature set for Joint #2**
  - 42 individual features
  - Features used to cover POF definitions for pinhole, axial slotting/grooving, circumferential/grooving, pitting, and general corrosion anomaly definitions
  - Depths range from 10% wt to 70% wt
  - All external features



Machined Anomalies







Rate of Detection

- **for features with a tool spec:**
  - 100% detection, including features at 10% WT, in Weld/HAZ, under spacers (general corrosion, pitting, axial grooving, Circumf. Grooving and slotting)
- **for features with no tool spec*:**
  - 100% detection for pinhole and axial slotting deeper than 20% WT, including features in Weld/HAZ and under spacers
  - Lower rate of detection for 10% WT pinhole and axial slotting features, when the local annulus distance between the casing and pipe is small

*axial slotting and pinhole



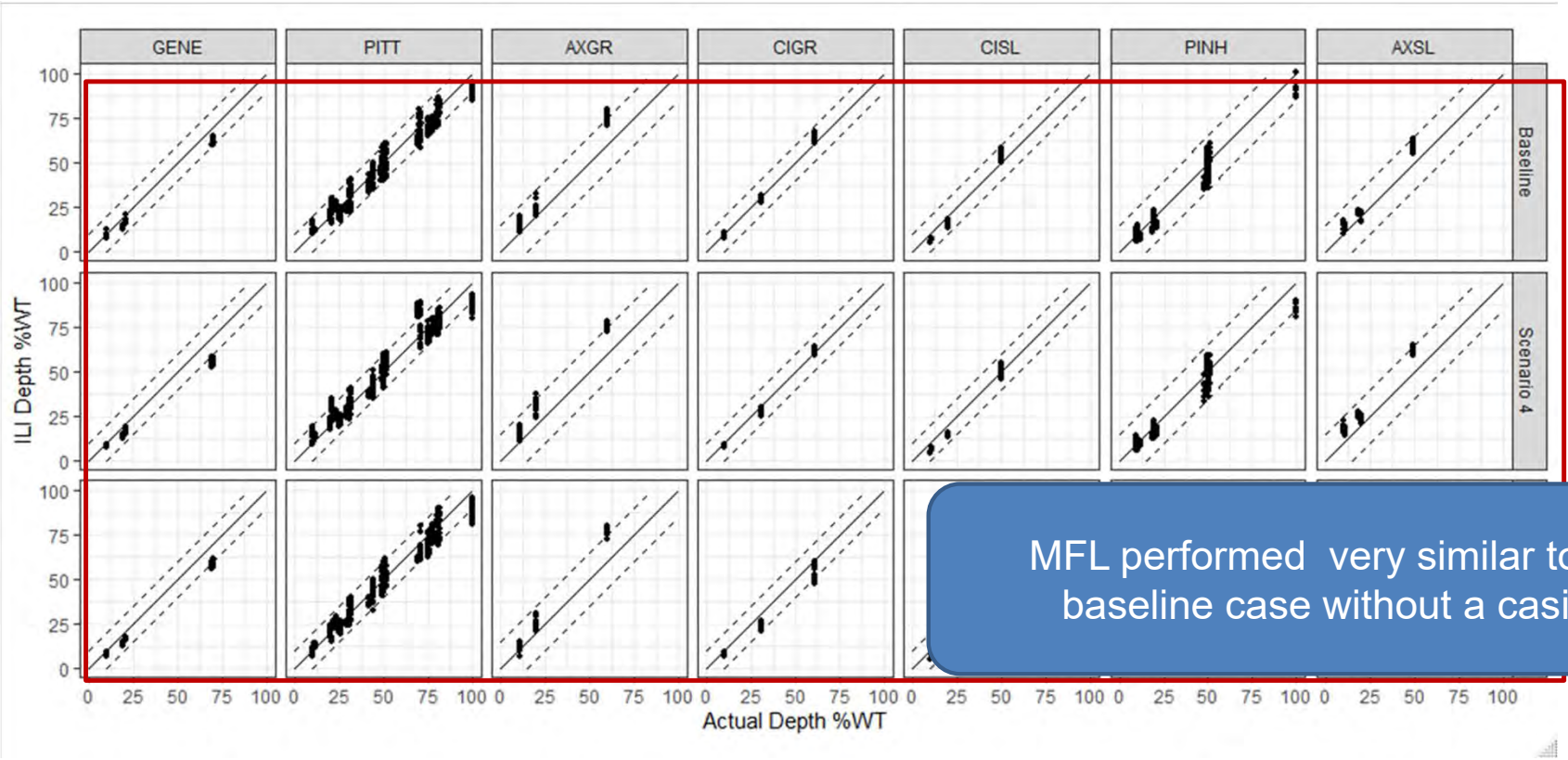
Annulus Distance	PINH *		AXSL *	
	Feature Count (detected/total)	Percent Detected	Feature Count (detected/total)	Percent Detected
0 ~ 1/4 in.	48/70	69%	3/10	30%
1/4 in ~ 3/2 in.	193/200	97%	19/20	95%
> 3/2 in.*	298/300	99%	70/70	100%

Sizing – Concentric Scenarios

Scenario #	Description	Eccentricity and Shorting Conditions
4	Concentric casing – spacers installed on Joint 1 at specific locations over top of corrosion features – not shorted	Concentric casing / No short
5	Concentric casing with water – same setup as scenario 4 – casing partial fill with water	Concentric casing / Electrolytic short

- **Features in pipe body, Weld/HAZ, under wooden spacer and TDW spacer**
  - Performance in the concentric cases (no short and electrolytic short) very similar to the Baseline scenario (water had little effect)
  - Sizing tolerance met or very close to the tool specification (±10% WT or ±15% WT depending on feature location)
- **Features under AP Spacer**
  - ILI reported depths have a negative bias (reported depth less than actual depth)
  - After bias is corrected, ILI reported depths met the tool specification (i.e., small random spread in ILI reported depth)

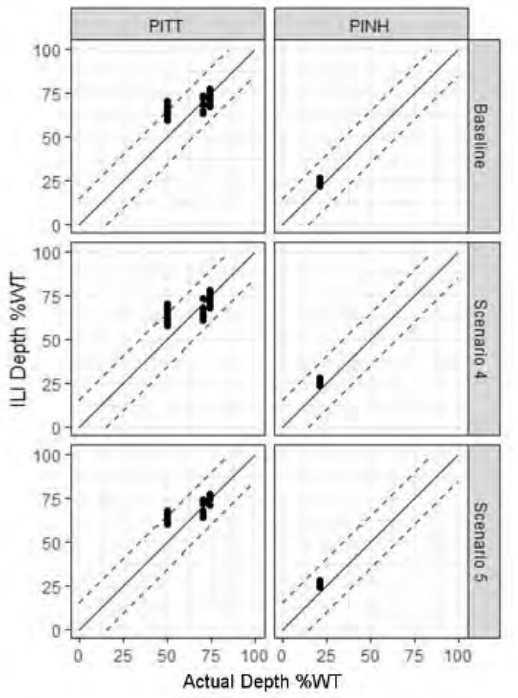
Concentric Scenarios – Pipe Body



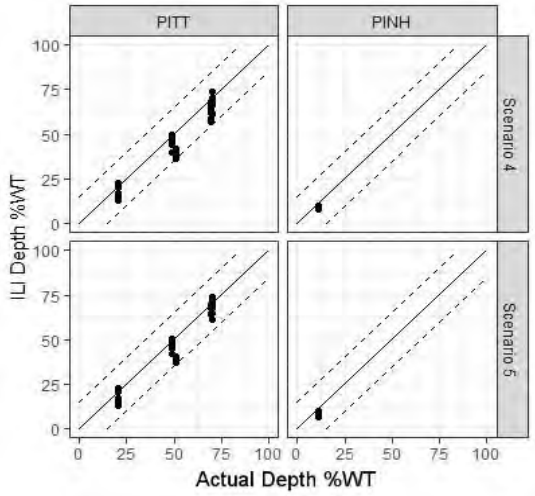
MFL performed very similar to the baseline case without a casing

Concentric Scenarios – Weld and Wood/TDW Spacers

Weld/HAZ



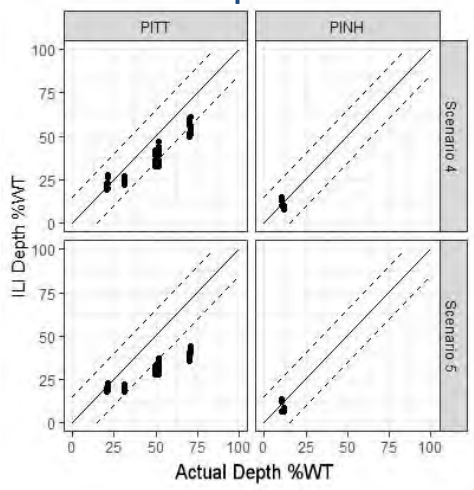
Wooden/TDW Spacer



Sizing Accuracies all met +/- 15% WT at 80% of certainty.

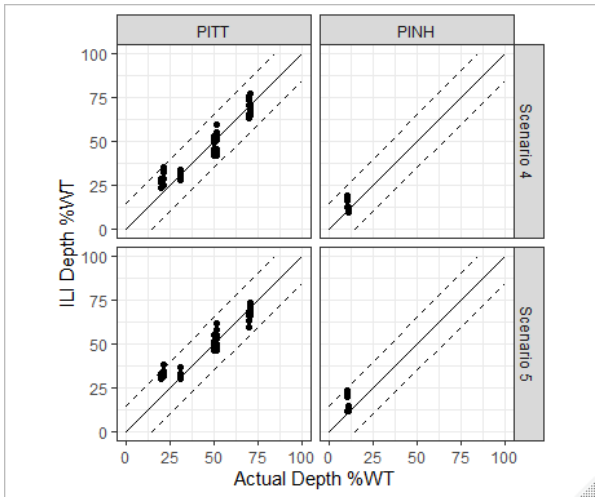
Concentric Scenarios – AP Spacers

ILI Reported



Bias can be corrected in program. Scatter can be reduced only by improving ILI technology or analysis.

After bias is corrected



Quantification of ILI bias

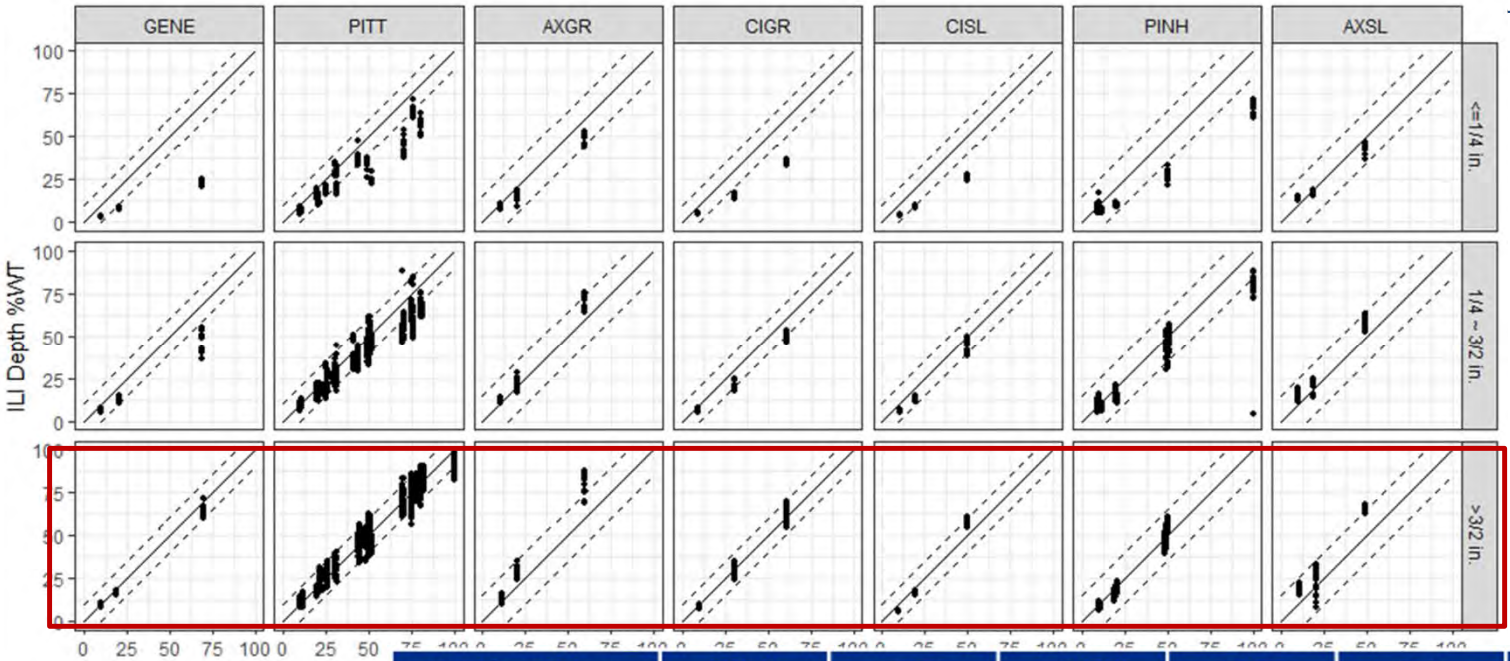
- **Pitting – Scenario 4 (not shorted)**
  - 21% lower than the actual depth
- **Pitting – Scenario 5 (electrolytically shorted)**
  - 40% lower than the actual depth

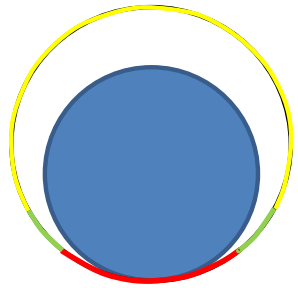
With Sizing Bias Correction Sizing Accuracies all met +/- 15% WT at 80% of certainty.

Sizing – Concentric Scenarios

- Performance similar to Baseline scenario when local annulus distance is greater than 1.5 in.
- ILI reported depths have negative bias, but small random spread (variability).
- After bias is accounted for, ILI reported depth met tool specification

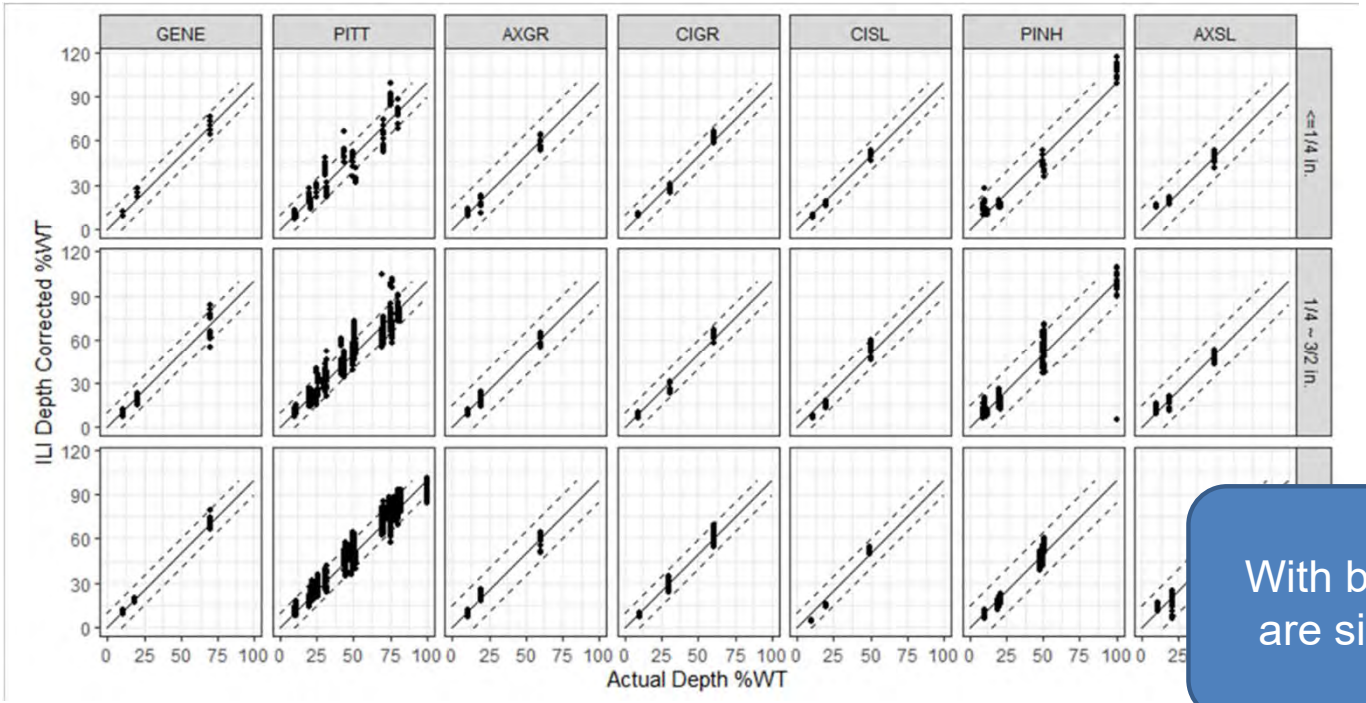
Eccentric Casing – ILI Reported Size





Annulus Distance	GENE	PITT	AXGR	CIGR	CISL	PINH*	AXSL*
0 ~ 1/4 in.	-67%	-27%	-18%	-44%	-48%	-38%	-11%
1/4 in ~ 3/2 in.	-35%	-16%	17%	-21%	-17%	-20%	20%
> 3/2 in.	-9%	-3%	36%	0.3%	12%	0.4%	32%

Eccentric Casing – ILI Reported Size (Bias Corrected)

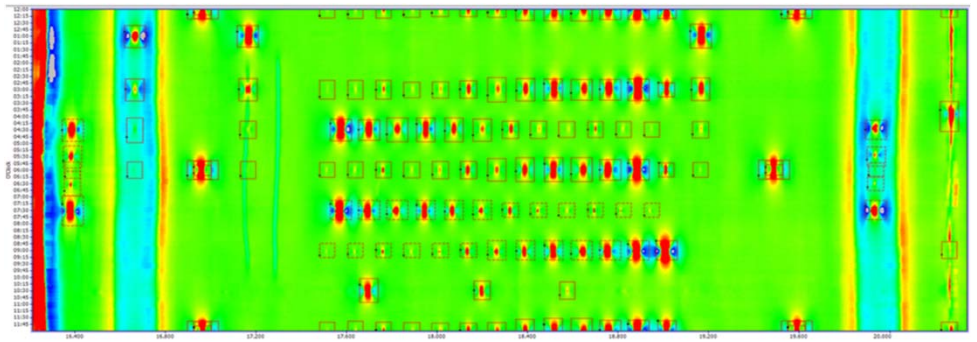


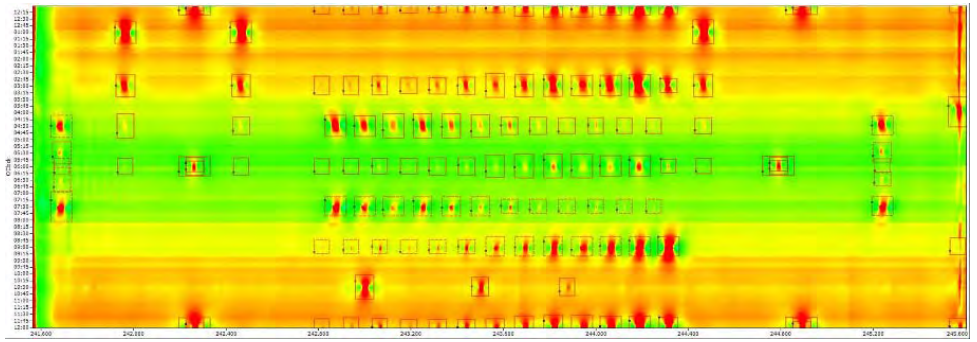
With bias corrected sizing accuracies are similar to that for uncased pipes

Eccentricity Identification

- Magnetization level variation in circumferential direction allows identification of eccentricity and its clock position

- Additional work is planned to investigate methods to better estimate local annulus gap from ILI readings.





Summary of Phase I Results

- **ILI performance under casings in detection and sizing is comparable to uncased pipe in vast majority of cases.**
  - Excellent rate of detection demonstrated in Phase I test – similar to performance on uncased pipes
  - Overall good sizing performance in concentric scenarios, and eccentric scenarios when local annulus is greater than 1.5 in.

- **Feature sizing in certain small areas will have to be adjusted for bias**
  - ILI reported depth is biased when local annulus distance is small
  - The ILI bias can be quantified and accounted for by operators in the ILI-based corrosion management program

- **Identification of eccentricity and its clock position is possible, which may be used to further estimate local annulus distance (to be confirmed in Phase II).**

Questions?



BACK TO AGENDA

PRCI 2020 Research Exchange

Guidelines to Calculate Erosional Velocity for Liquid Hydrocarbon Transmission Pipelines

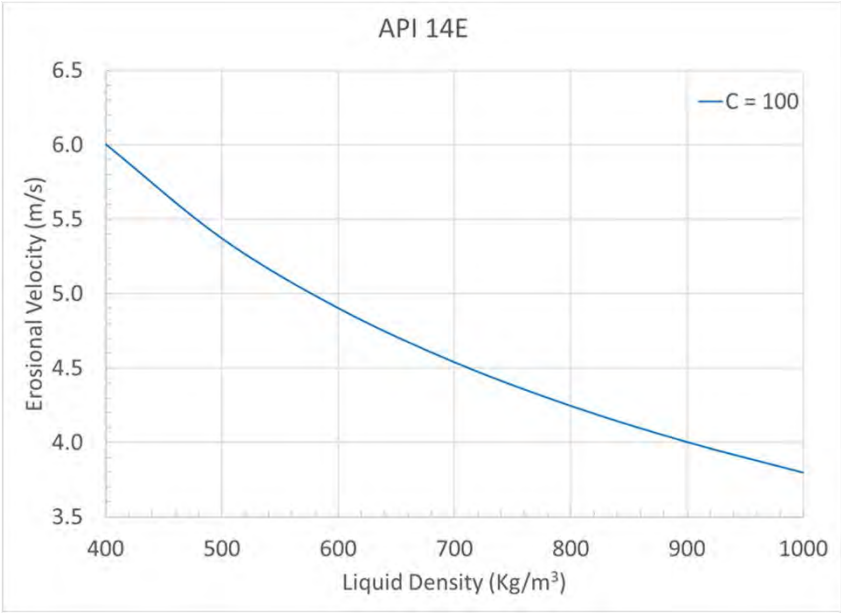
PRCI Contract - PR-186-184509

Jose Vera, Richard Eckert, Francois Ayello (DNV GL)

LEADING PIPELINE RESEARCH

Introduction

- Currently, no industry-recognized guidance document or standard for determining erosional velocity limits for liquid petroleum pipelines.
- The general form of the API RP 14E equation, used by some operators, does not properly address the effects of key parameters affecting erosion in liquid pipelines and could give erroneous results in some cases.



Objective

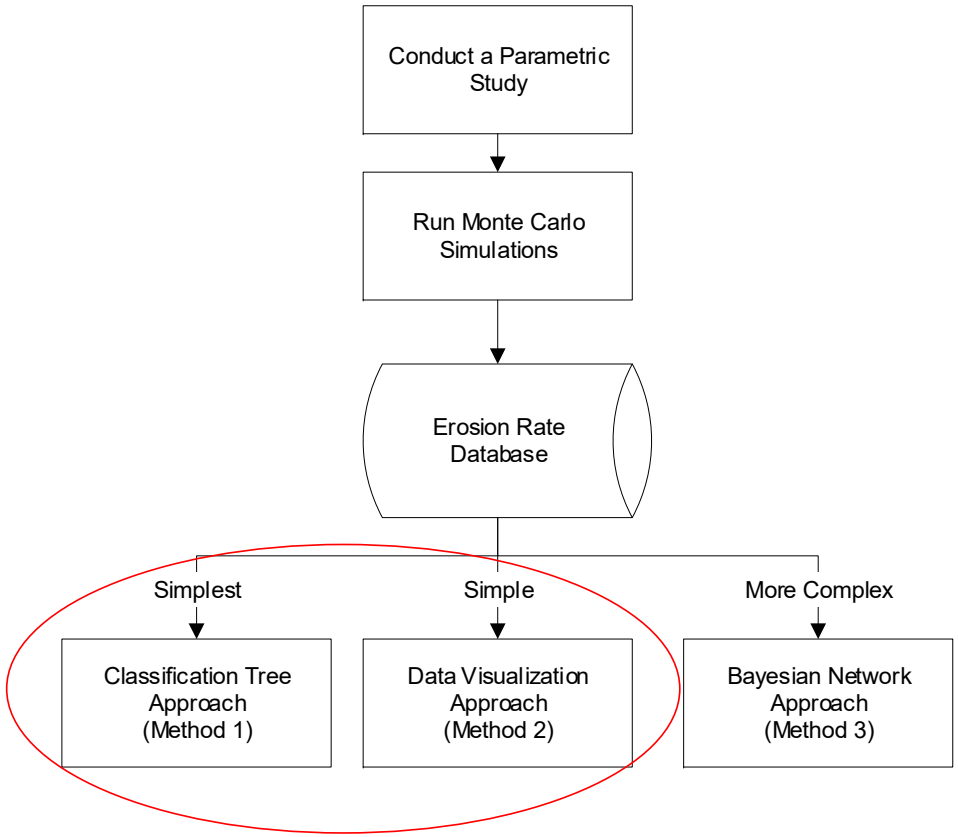
- Develop a guidance document for determining erosional velocity limits at conditions typically found in pipelines transporting crude oil and liquid hydrocarbons, based on a multi-analytical risk-based approach that integrates industry knowledge and erosion prediction models.

General Approach

The general approach to determine erosional velocity included the following tasks:

1. Conducting an industry experience and literature review to select the erosion prediction models and the range of parameters to be evaluated.
2. Implementing a multi-analytical probabilistic approach to integrate results from two models selected to predict erosional velocities under specific conditions of liquid hydrocarbon transmission pipelines.
3. Developing a guideline for determining maximum allowable velocities to control erosion in liquid petroleum pipelines.
4. Transferring the technology to PRCI members.

Multi-Analytical Probabilistic Approach



1. Conduct a parametric study of DNV GL RP O501 and U. Tulsa SPPS v5.3 models
2. Run Monte Carlo simulations with both models
3. Create a simple classification tree based on the results of all simulations
4. Combine results of all simulations using a visual interface
5. Implement a Bayesian probabilistic model combining all results

Multi-Analytical Probabilistic Approach Monte Carlo Simulation

Range of Parameters Evaluated

Parameter	Unit	range	
		DNV GL RP-O501	SPPS 5.3
Oil rate	m/s	[1-3] [3-5] [5-7] [7-9] [9-11] [11-13] [13-15]	[1-3] [3-5] [5-7] [7-9] [9-11] [11-13] [13-15]
Pipe diameter	inch	[3-5] [5-7] [7-9] [9-13] [13-17] [17-21] [21-36]	[3-5] [5-7] [7-9] [9-13] [13-17] [17-21] [21-36]
Particle diameter	µm	[50-250] [250-500] [500-1000]	[50-250] [250-500] [500-1000]
Radius of curvature	-	1 1.5 5 20	1 1.5 5 20
Particle hardness	Vickers	N/A	[65-500] [500-2000]
Oil viscosity	cp	[0.4-4] [4-40] [40-400]	[0.4-4] [4-40] [40-400]
Oil density	kg/m^3	[400-600] [600-800] [800-1000]	[400-600] [600-800] [800-1000]
Particle density	kg/m^3	[2000-3000] [3000-5400]	[2000-3000] [3000-5400]
Steel hardness	Vickers	114 131 200	114 131 200

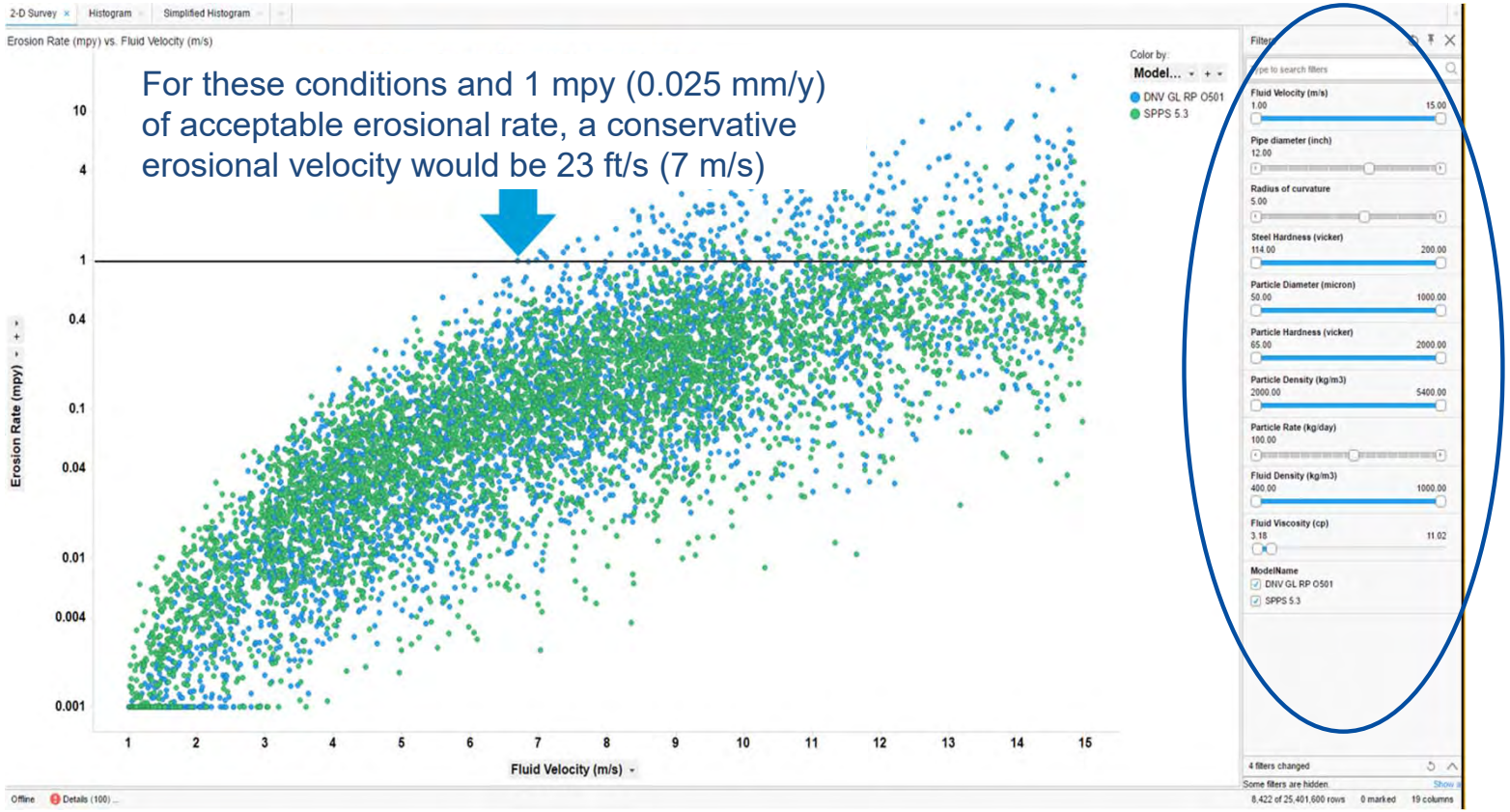
~47 million simulations:

- 31,752,000 for SPPS 5.3
- 15,876,000 for DNV GL RP-O501

Parameters Assumed Constant

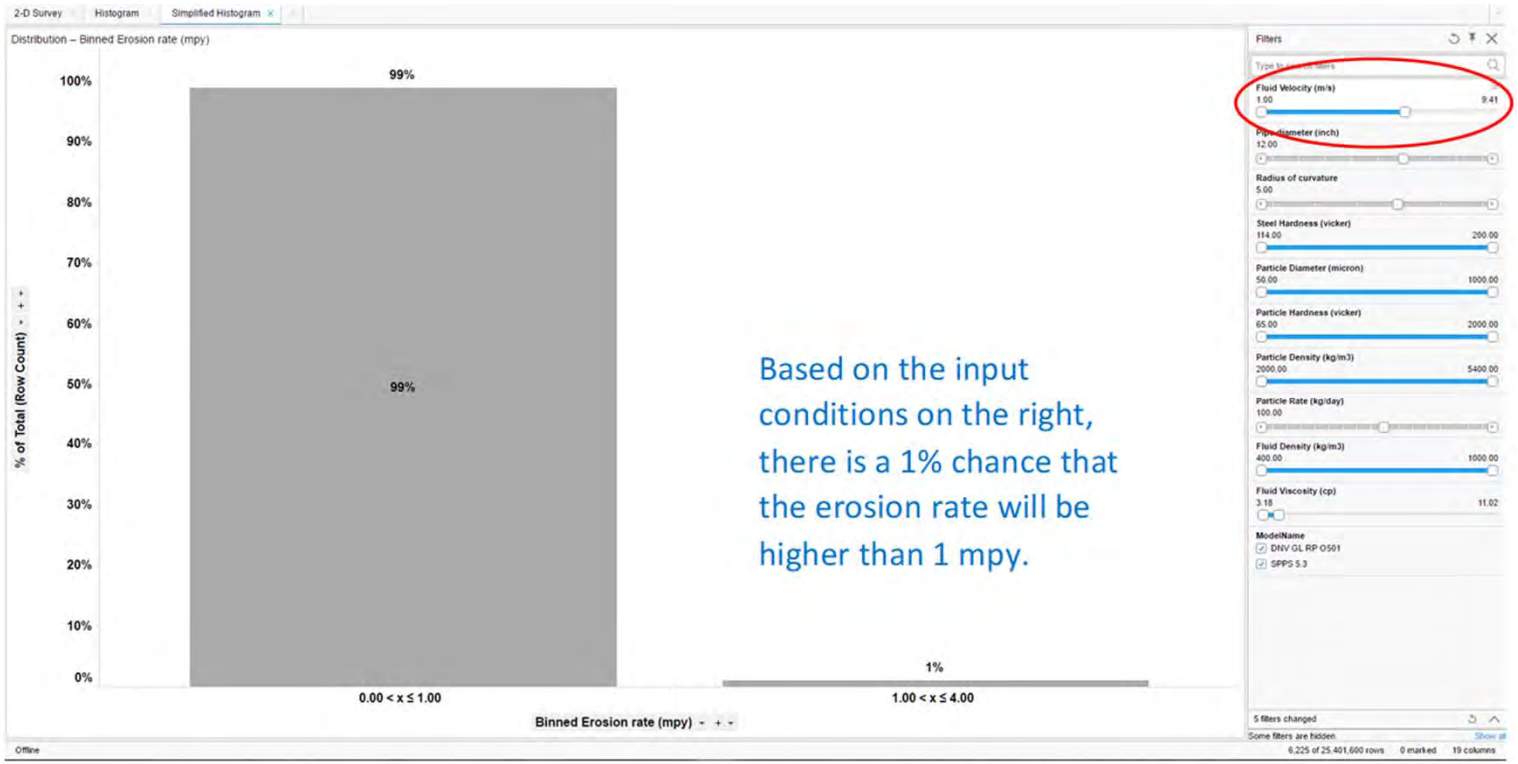
Parameter	Unit	Value
Steel type	-	Carbon Steel
Steel Density	kg/m^3	7850
Pipe Roughness	-	0.001
Particle Sharpness (SPPS)	-	0.5
Geometry Factor GF (DNV GL)		2
Flow Regime	-	Single Phase

Multi-Analytical Probabilistic Approach
Third Party Visualization Tool



Pipeline conditions may be adjusted as needed

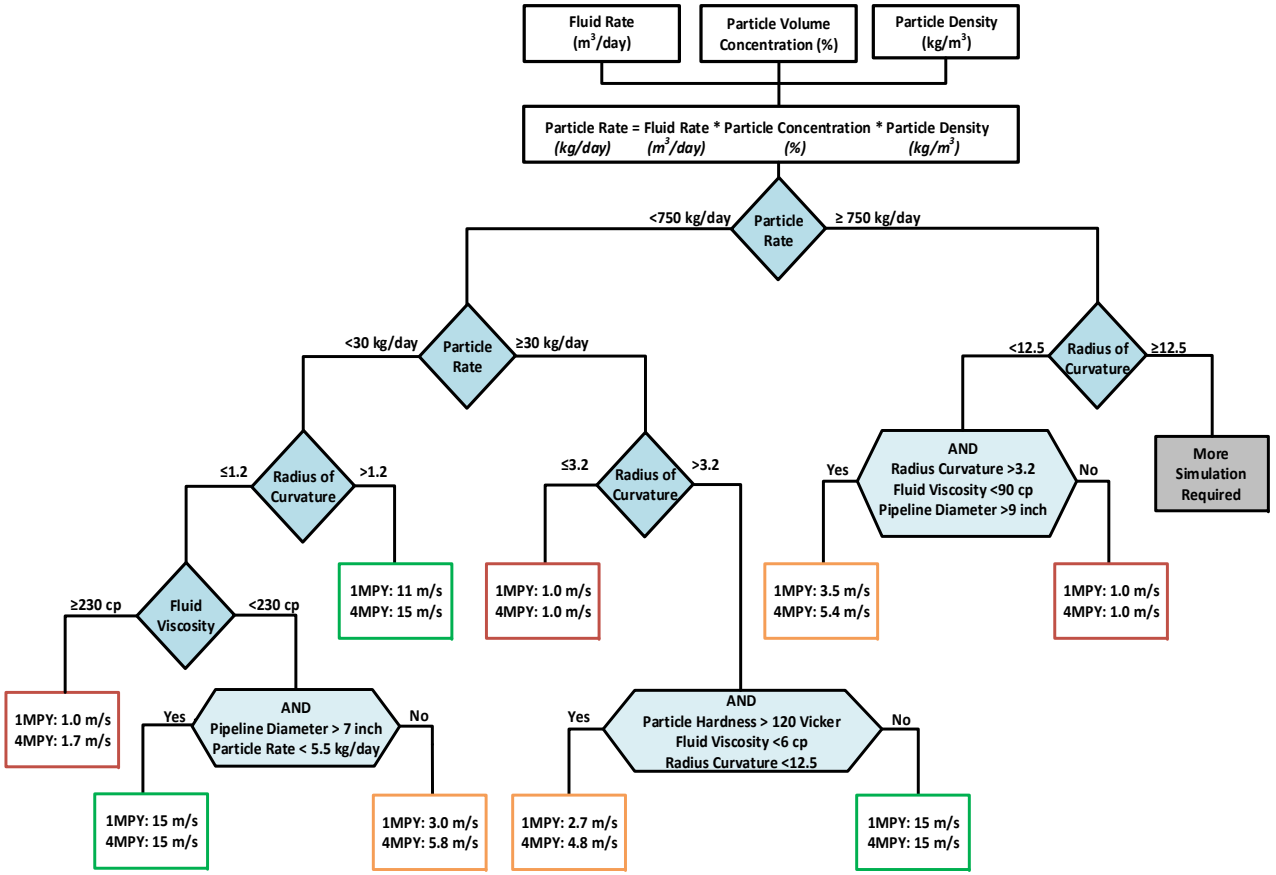
Multi-Analytical Probabilistic Approach
Third Party Visualization Tool – Histogram



Adjust flow velocity until probability is acceptable

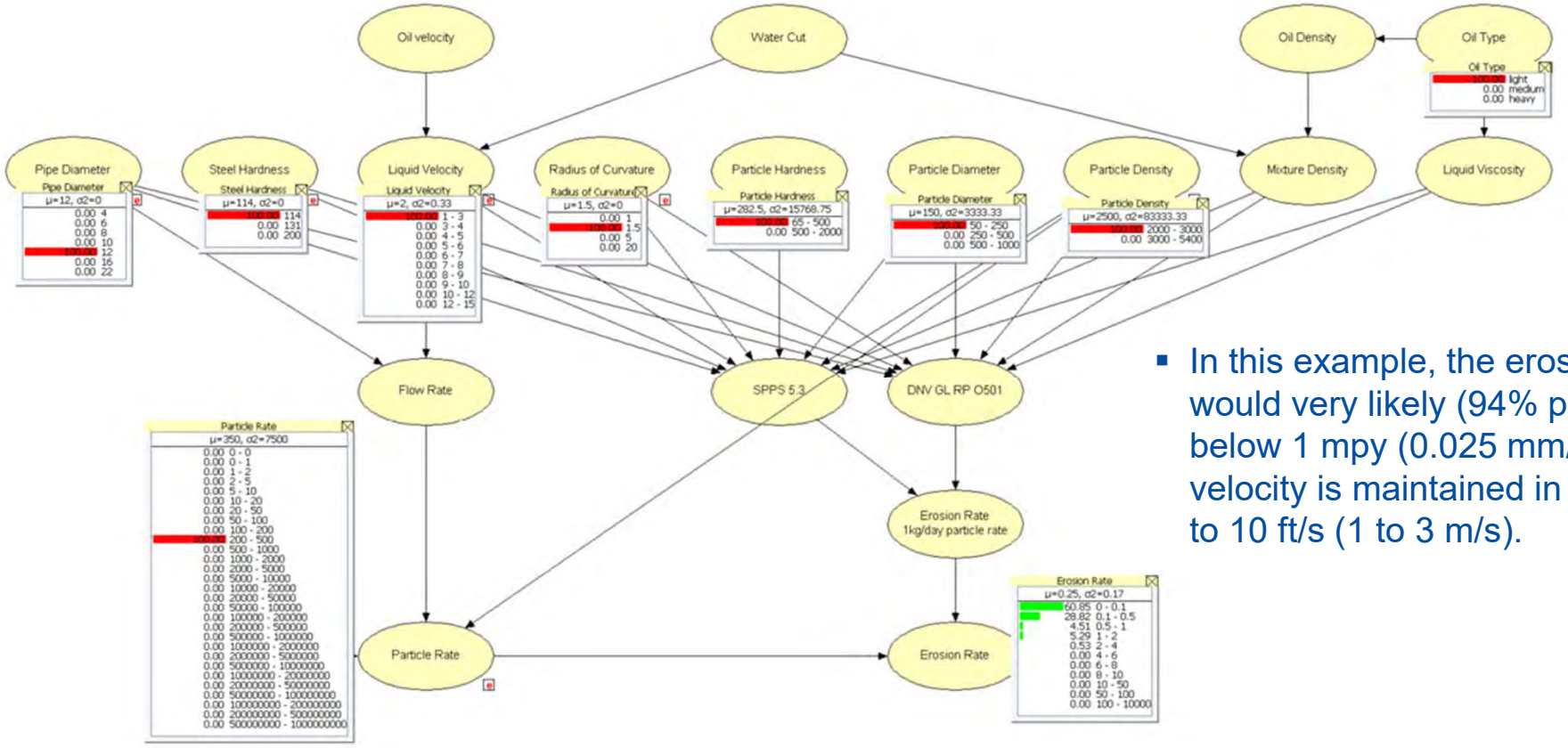
- E.g., 31 ft/s (9.4 m/s)

Multi-Analytical Probabilistic Approach Classification Tree



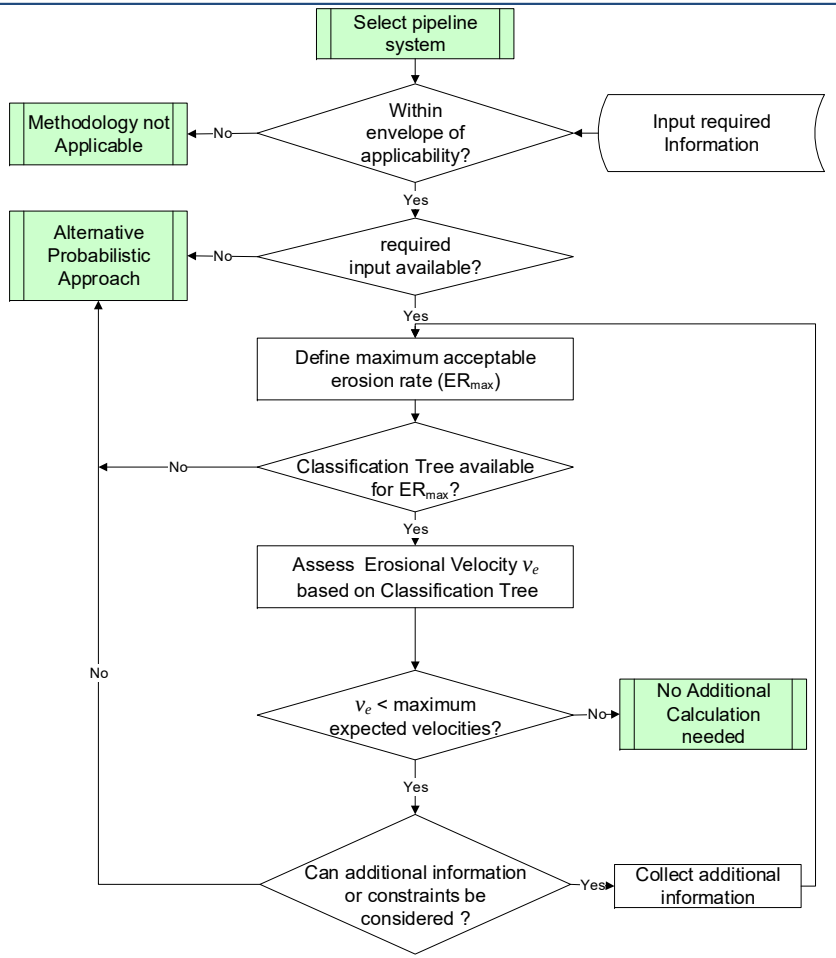
- Tolerable erosion rates of 1 and 4 mpy (0.025 and 0.1 mm/y)
- Erosional velocities calculated with 99% confidence

Multi-Analytical Probabilistic Approach Bayesian Network



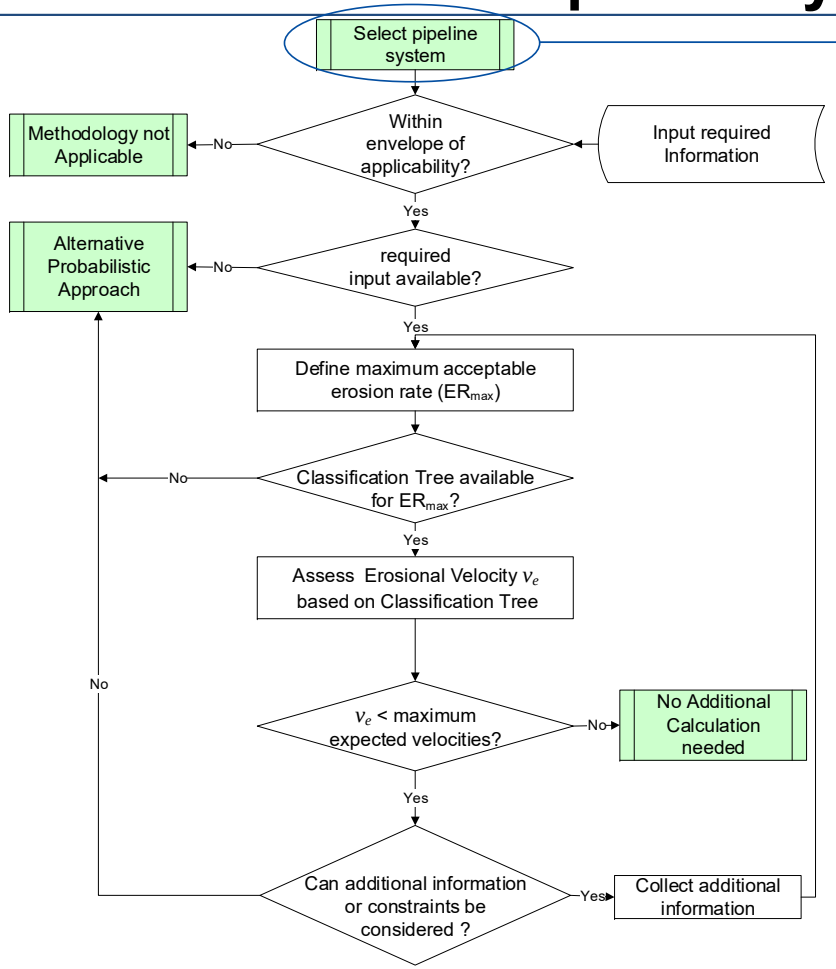
- In this example, the erosion rate would very likely (94% probability) be below 1 mpy (0.025 mm/y) if the fluid velocity is maintained in the range 3.3 to 10 ft/s (1 to 3 m/s).

Erosional Velocity Guideline



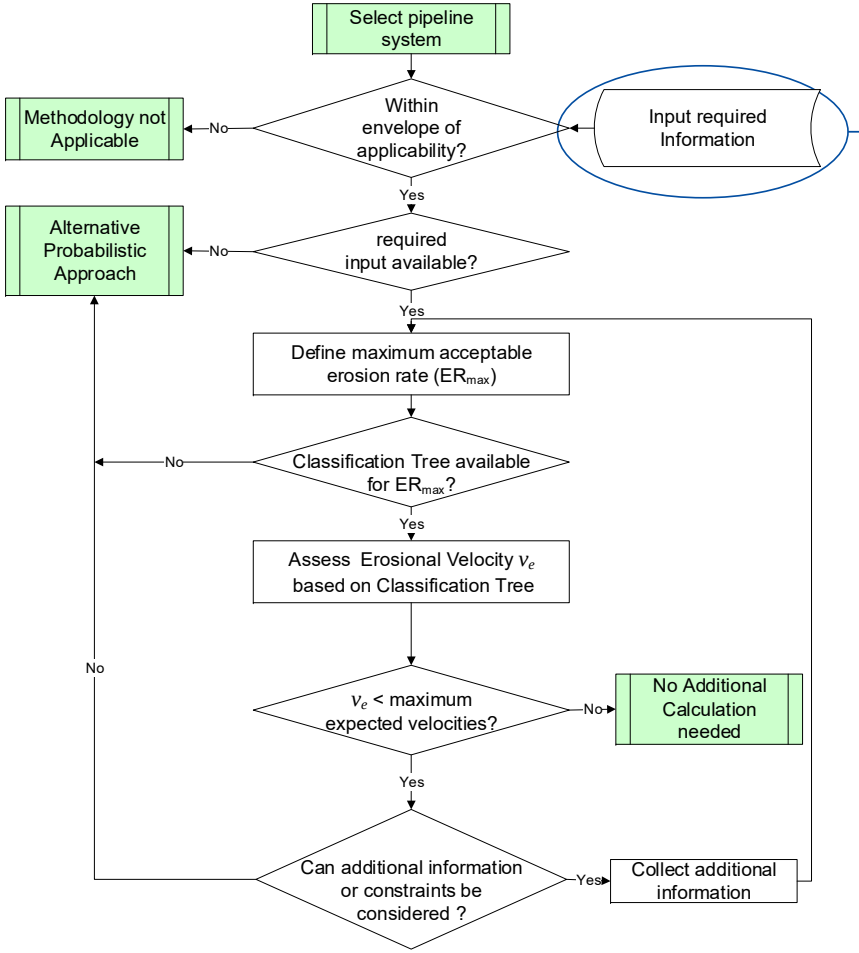
- Guideline included in the final report as a self-contained appendix.

Erosional Velocity Guideline
Select Pipeline System



- Define the boundaries of the pipeline system to be evaluated.
- The more uniform the system is, the more accurate the predictions.

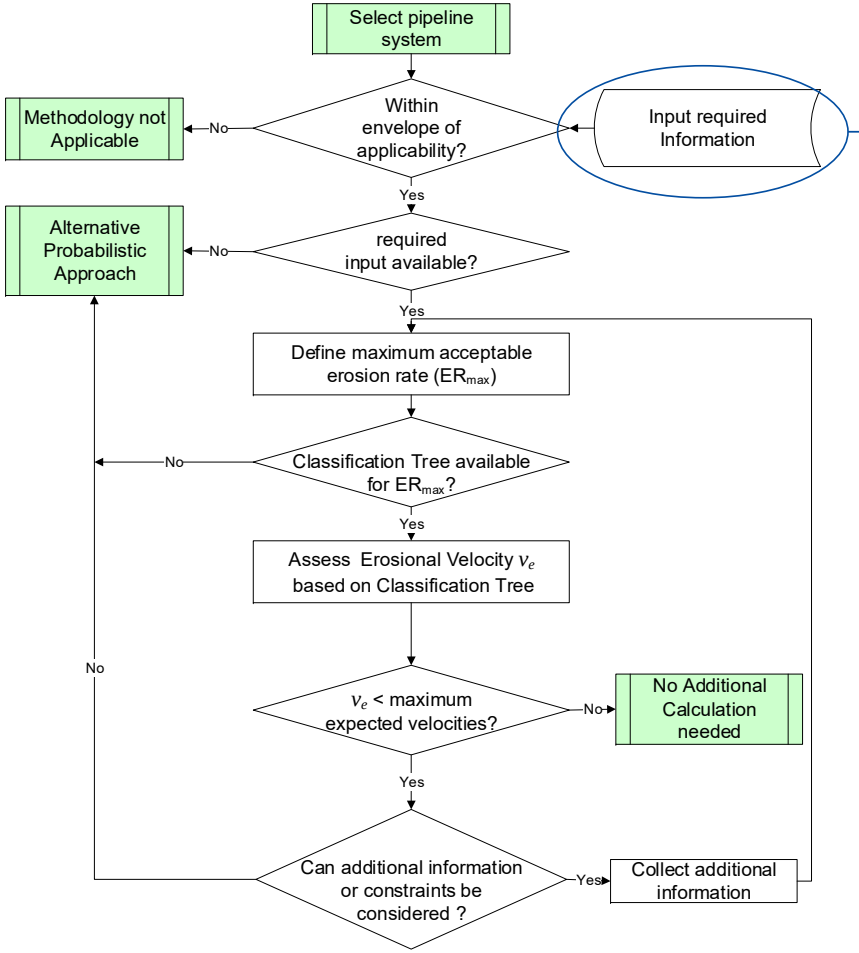
Erosional Velocity Guideline
Input Required Information



Parameter	Level of Importance
Pipe Geometry, Configuration and Materials	
Internal Diameter	1
Radius of curvature	1
Steel Hardness	2

- Carbon steel API grades B, X40, X70
  - SPPS: 117, 132, 200 Hv
- Internal Diameter
  - Nominal Diameter and wall thickness
- Highly sensitive to radius of curvature
  - Assume the shortest radius in the system

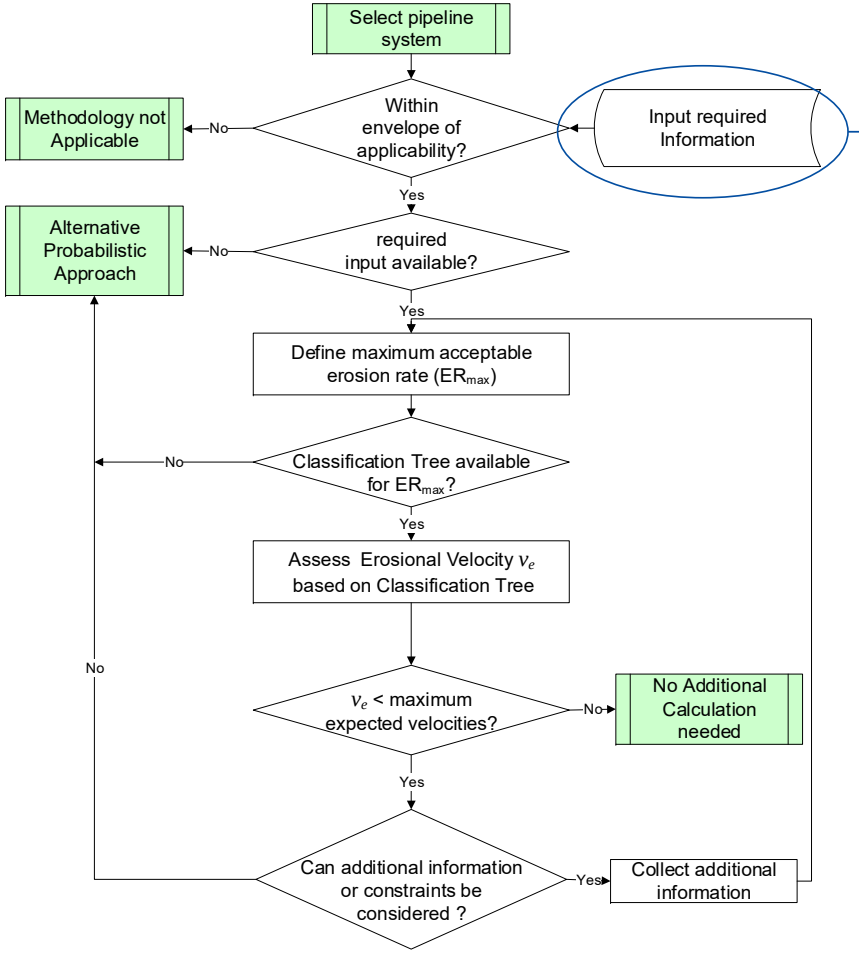
Erosional Velocity Guideline
Input Required Information (cont.)



Parameter	Level of Importance
Solid Concentration and Properties	
Particle Content (concentration or rate)	1
Particle Diameter	1
Particle Density	2
Particle Hardness	2

- Particle size and composition
- Concentration - most important parameter
  - Not typically reported
  - Measured: e.g., ASTM D4007, ASTM D473
  - Only particles with hardness > 160 Hv
    - *Typically, Sand and iron oxides*
    - *Exclude organic solids, clay, silt or other particles having less than 3 in the Mohs scale*
  - Nominally solid free: 1 ppmv

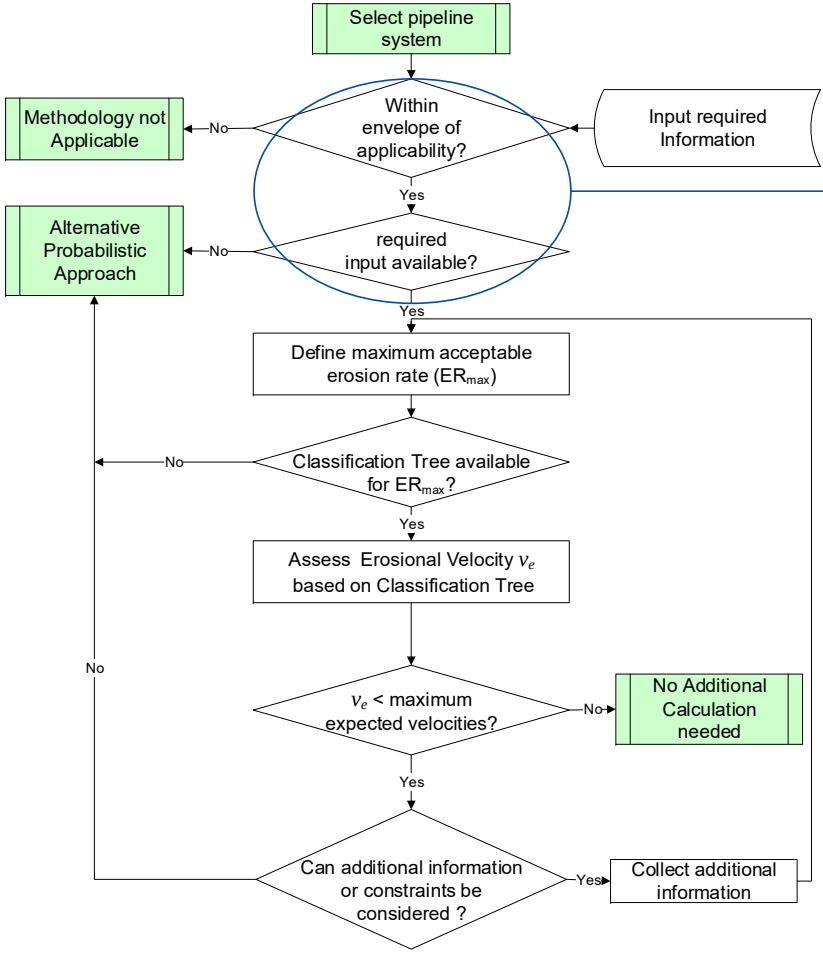
Erosional Velocity Guideline
Input Required Information (cont.)



Parameter	Level of Importance
Operational Data	
Flow Rate	1
Oil Density	2
Oil Viscosity	2
BS&W	2

- Range of expected volumetric flow rates
  - Required to calculate particulate rates and flow velocities.
- Oil density and viscosity and water content
  - Affects erosion rates, but in less degree compared to other parameters evaluated.
  - Range of values can be used as starting point.

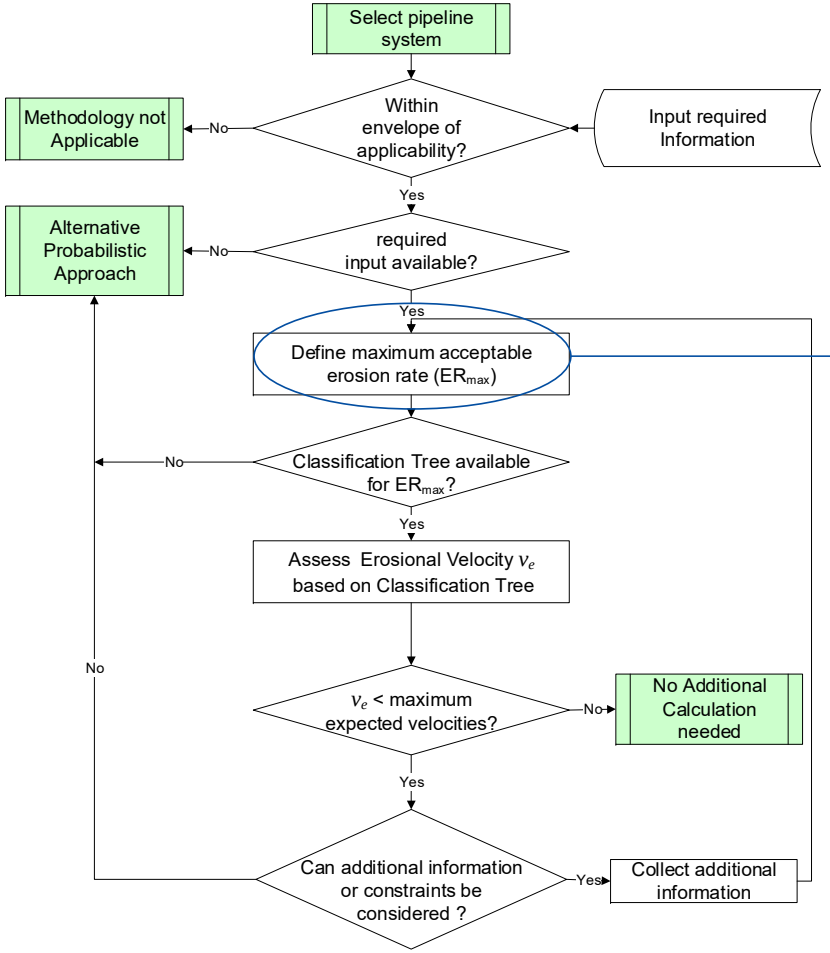
Erosional Velocity Guideline Envelope of Applicability



Parameter	Unit	Minimum	Maximum
Pipe diameter	inch	4	48*
Radius of curvature		1	20
Steel type	-	CS	CS
Steel Hardness	Vickers	113	200
Particle Diameter	micron	50	1000
Particle Hardness	Vickers	65	2000
Particle Density	kg/m^3	2000	5400
Oil Density	kg/m^3	400	1000
Particle Concentration	Vol%	0.001	0.25
Oil Viscosity (kinematic)	cp	0.4	400
Oil Rate	m/s	1	15
BS&W	Vol%	0.1	3
Flow Regime	-	Single Phase (liquid)	
* Assume, conservatively, 36 inches for pipe diameters between 36 and 48 inches			

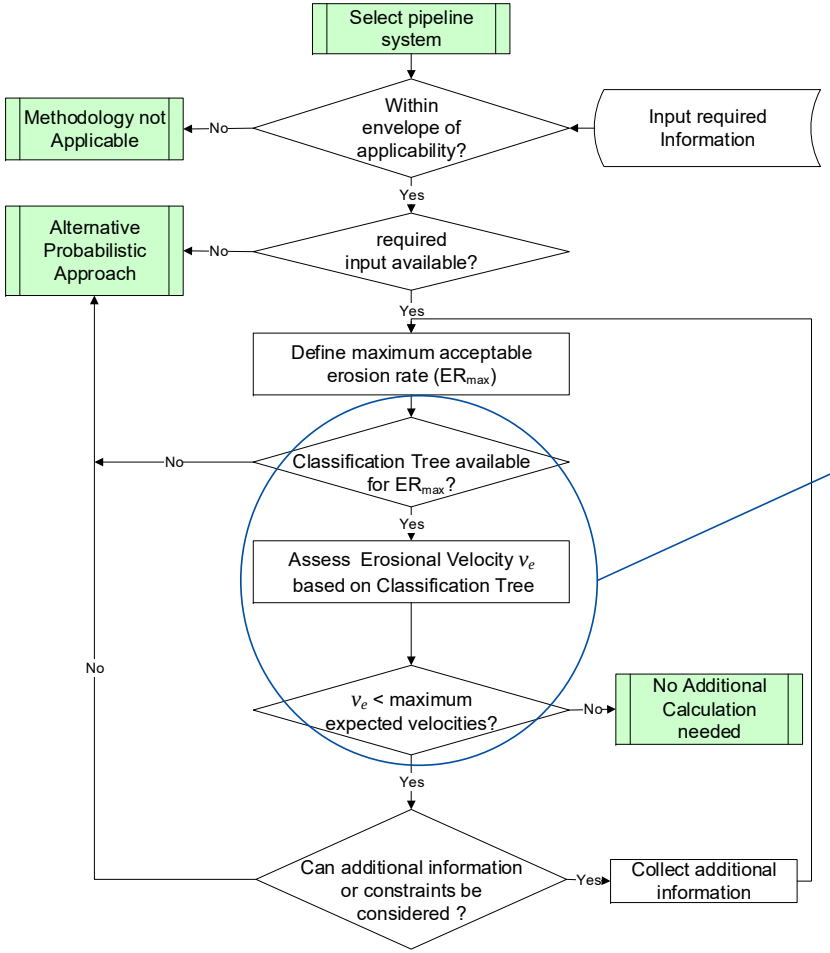
- If conditions are outside of this envelope
  - SME should have the competence to decide if additional information can be obtained to justify the use of this methodology.
  - Otherwise, the envelope of applicability could be extended or a deterministic model used.

Erosional Velocity Guideline
Maximum acceptable erosion rate (ER_{max})



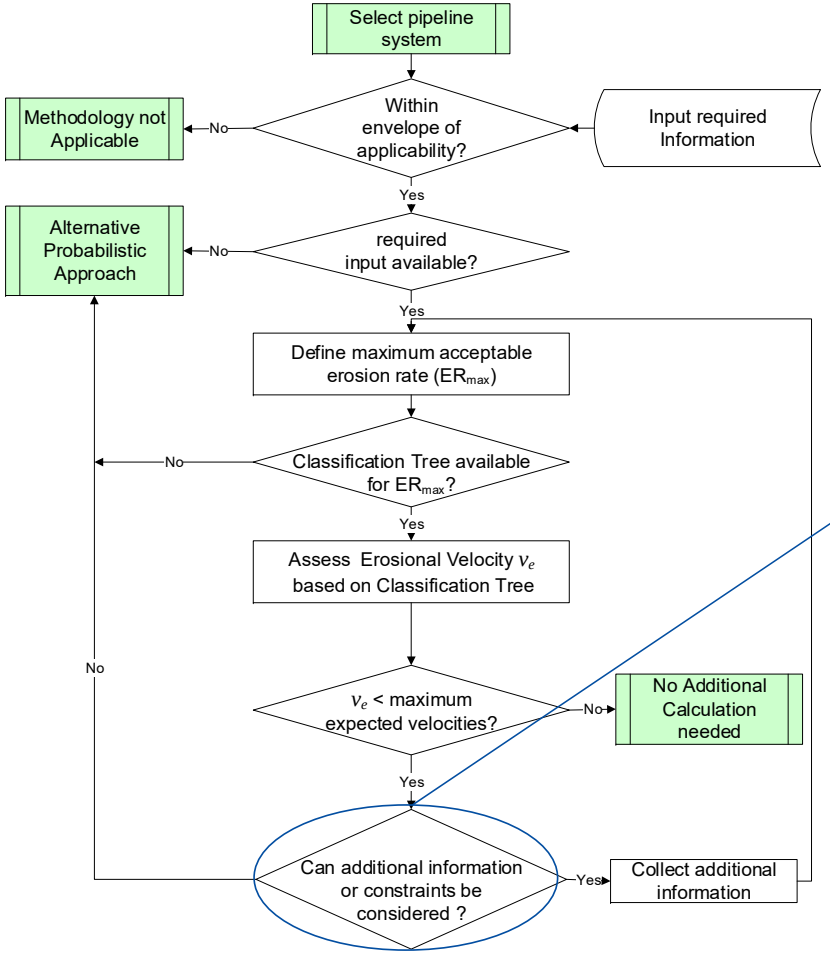
- ER_{max} must be specified.
- Minimum 1 mpy (0.025 mm/y).
- The following options have been used to define an acceptable erosional allowance consumption at the end of the service life:
  - A fixed value (e.g., 20 mils or 0.5 mm), with reference to accuracy of traditional UT equipment.
  - 25% of the original design wall thickness, based on US pipeline regulations defining an “immediate” integrity concern, with a 50% additional safety factor.
  - According to pipe class specification, considering also the level of corrosive service.
  - Difference between nominal and minimum wall thickness requirement, according to specified system pressure rating

Erosional Velocity Guideline Calculation based on the Classification Tree



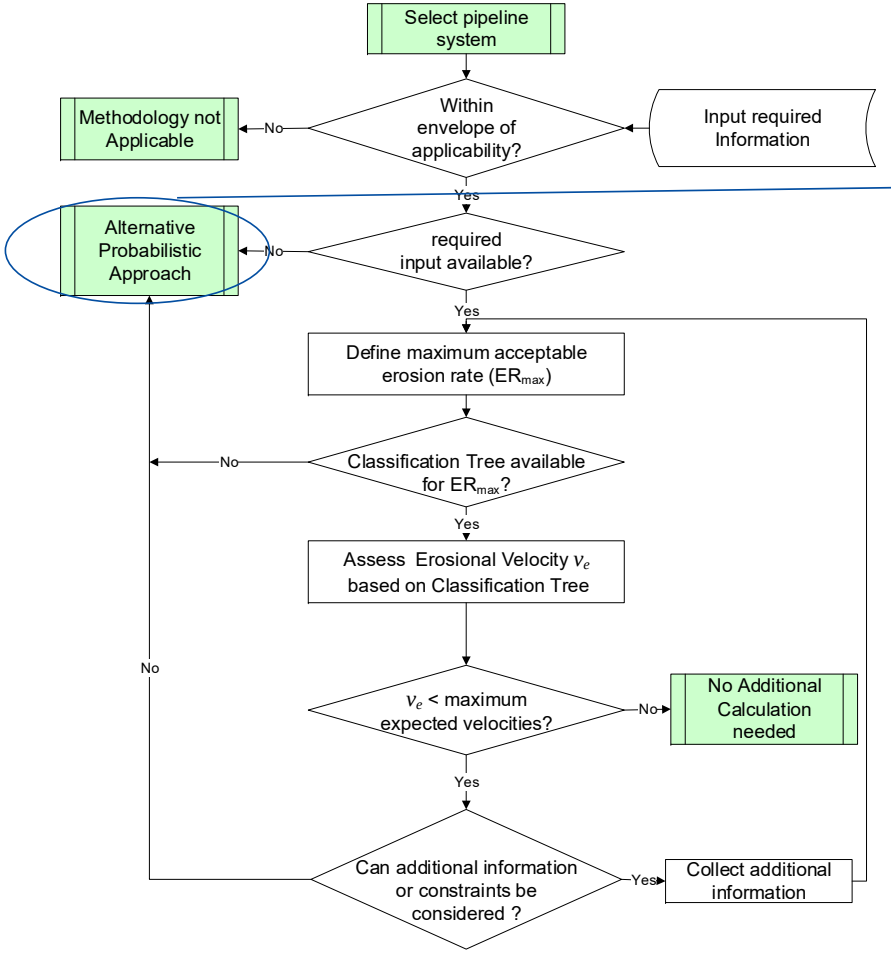
- Classification trees have been developed for selected ER_{max} values (1 and 4 mpy).
  - If a classification tree is not available for the ER_{max} defined and cannot be developed, then an alternative probabilistic approach should be used.
  - Otherwise, a conservative assessment of the erosional velocity V_e is obtained using the classification tree approach.
- If V_e is lower than the maximum expected velocities in the pipeline systems, then additional assessments or calculations are required.

Erosional Velocity Guideline
Additional Information or Constrains



- The classification tree approach requires limited information but tend to give conservative V_e values due to the high uncertainty derived from a wide range of parameters. Examples:
  - Particle concentration could be determined with more precision and/or measures could be implemented to control it.
  - Acceptable ER_{max} could be adjusted based on actual or expected pipeline conditions
- If additional information can be obtained, then V_e may be reassessed using the classification tree. Otherwise, an alternative probabilistic approach should be used

Erosional Velocity Guideline
Alternative Probabilistic Approach



- The Data Visualization approach may be used if the classification tree approach
  - Cannot be used (because too much data is missing)
  - The operator needs to increase the erosional velocity to values higher than indicated by the classification tree approach (which is highly conservative).

Conclusions

- Analysis of the erosional database indicated that it was not possible to determine a single critical velocity limit that could be applicable to all liquid pipeline conditions.
  - Data from solids characterization was found to be a critical parameter affecting erosional velocity that typically is not available or has a large degree of uncertainty, according to operators
  - The equation in API 14E can grossly underestimate or overestimate the erosional velocity, depending on the particle loading.
- A guidance document was developed to determine erosional velocities for liquid hydrocarbon transmission pipeline systems, based on the following general approach:
  - Use a classification tree approach as first approximation to determine erosional velocities, if available for the pipeline conditions and selected maximum acceptable erosion rate.
  - Conduct an alternative probabilistic approach to determine erosional velocity using the Monte Carlo simulation database and an appropriate visualization tool, in cases where the classification tree approach cannot be used, there is too much data uncertainty or the erosional velocity limit (which is highly conservative) is lower than the current or expected liquid velocity in the pipeline.

Value to Operators

- The guidance document developed in this PRCI project will allow pipeline operators to reduce capital costs when designing new pipelines or provide engineering justification for increasing the throughput of existing facilities (e.g., DRA), while maintaining pipeline integrity relative to the threat of erosion.

BACK TO AGENDA

PRCI 2020 Research Exchange

Pipeline Research Council International

Research Exchange REX2020

- **Overpressure Protection From Wildfire and Expanded Fire Study at Compressor Stations and Tank Terminals**

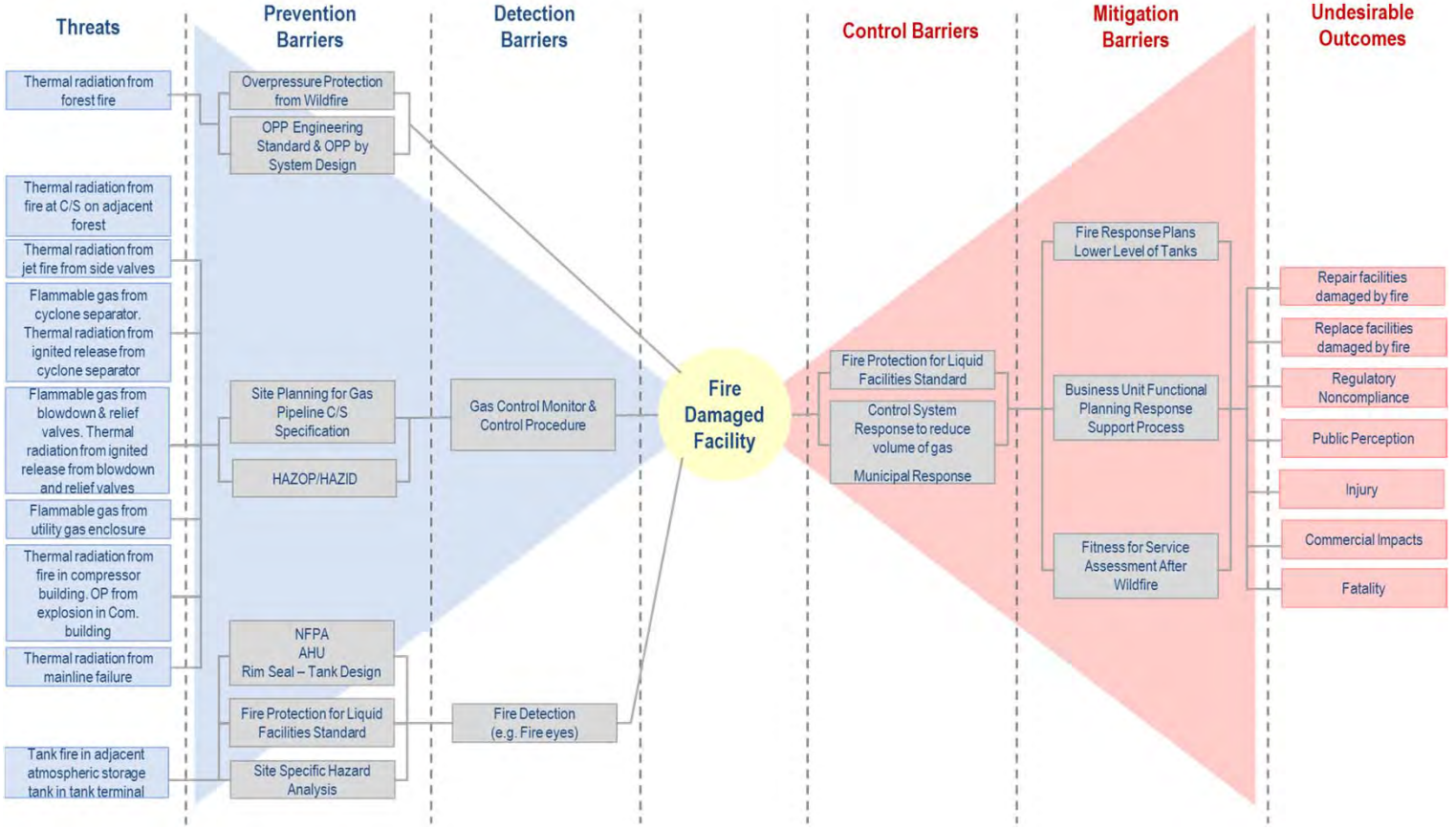
Perry Krebes P.Eng. TC Energy

LEADING PIPELINE RESEARCH

Introduction

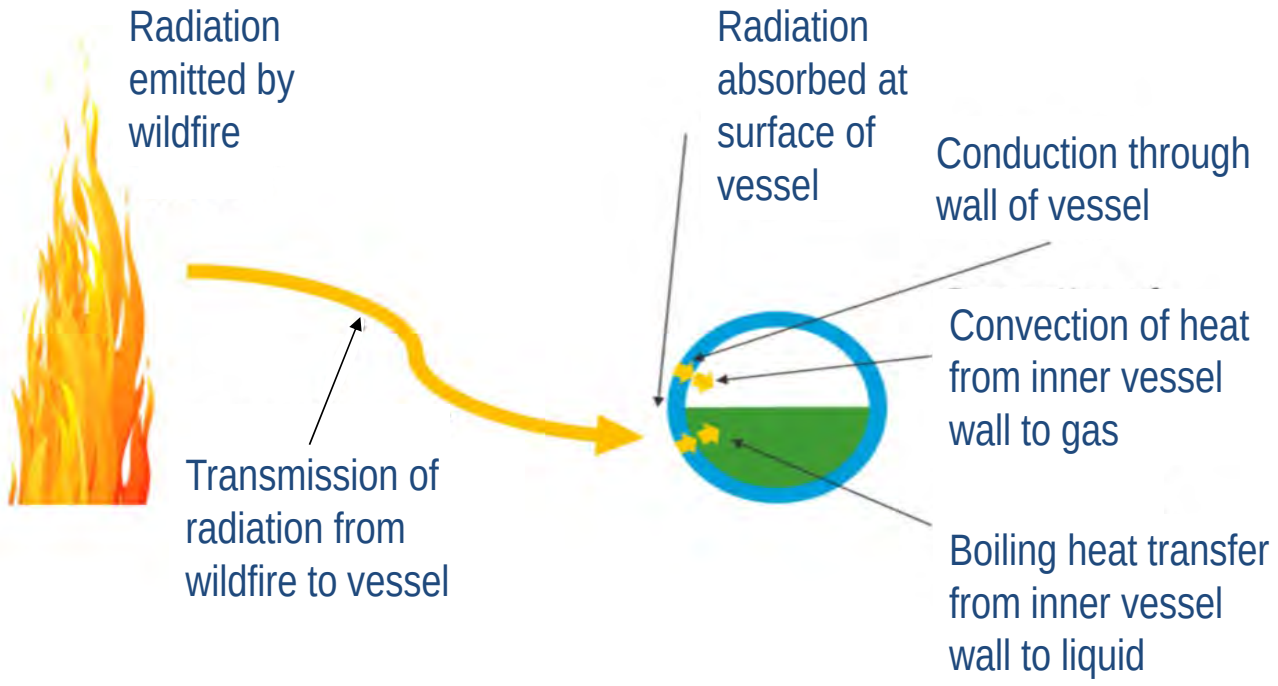
- **Fill in knowledge gap with respect to fire events on pressure vessels and atmospheric storage tanks at pipeline system facilities**
  - Goals:
    - Build on 65 years of owning operating safety with legacy best practices
    - Protect personnel
    - Avoid facility damage due to fire events
    - Demonstrate due diligence in support of regulatory requirements
    - Avoid Commercial impact due to fire events
  - Objectives:
    - *Quantify exposure levels due to specific fire events (e.g., radiative heat flux, piloted ignition)*
    - *Quantify piloted ignition distances (i.e., distances at which a fire might ignite other objects)*
    - *Improved efficiency of design and operation*
    - *Streamline Fitness for Service evaluation following fire events*

Fire Event Bow Tie Diagram – Scope of Work Progression



- Initially began looking at threat of overpressurization of meter station separator vessels due to wild fire exposure
- Expanded to cover broad range of fire threats on personal, facilities and environment through design and operation life cycle

Methodology Approach and Theory



Hazard → Heat Flux → Facility Response

Methodology

Threat	Scenario
Wildfire	• M/S scrubber vessel – Pressure Response • C/S pressure vessels – Does based on measure of steel heat up • C/S buildings – Piloted ignition
Compressor station facility fire	• C/S buildings – Piloted ignition • Surrounding forest – Piloted ignition
Jet fire from compressor side valve	• Thermal radiation – Does based on measure of steel heat up
Ignition of flammable gas release from cyclone separator	• Surrounding forest – Piloted ignition • Personnel – 1% lethality • Flammability limits
Ignition of flammable gas release from blowdown and relief valve	• Surrounding forest – Piloted ignition • Personnel – 1% lethality • Flammability limits

Methodology

Threat	Scenario
Ignition of flammable gas from utility gas enclosure	• Ignition due to facility buildings – flammability limits • Personnel – 1% lethality • Flammability limits
Fire in compressor building	• Facility buildings – Piloted ignition • Surrounding forest – Piloted ignition • Facility buildings – Dose based on measure of steel heat up • Pressure vessels – Dose based on measure of steel heat up
Mainline failure	• Facility buildings – Piloted ignition • Surrounding forest – Piloted ignition • Facility buildings – Dose based on measure of steel heat up • Pressure vessels – Dose based on measure of steel heat up
Atmospheric storage tank fire at tank terminal	• Impact of tank fire on adjacent tank – Dose based on measure of steel heat up • Impact of tank fire on adjacent tank – Ignition potential of flammable mixtures

Compressor Station Facility Fire

Building Offset from Compressor Building

30 m spacing adequate for:
- Dose based measure for steel heat up

Distance to achieve 400 C for 10 mm steel parameter:
- Control building
- Mechanical building
- Other compressor building

30 m is adequate for puncture diameter <~20 mm for pressure range

Fence Line Offset from Compressor Building

Effect on people 1% lethality distance reaches zero ~15 m from compressor building puncture diameter
- <15 – 20 mm diameter
- Pressure 8000 kPa



Suction Scrubber from Compressor Building

25 m spacing adequate for:
- Dose based measure for steel heat up
- For pressure range studied

Event

Puncture diameter:
- <~20 mm

NPS 36, 42, 48
Pressure Range 6000, 8000, 10932 kPa

Compressor Station Facility Fire

50 mm puncture 5625 kPa

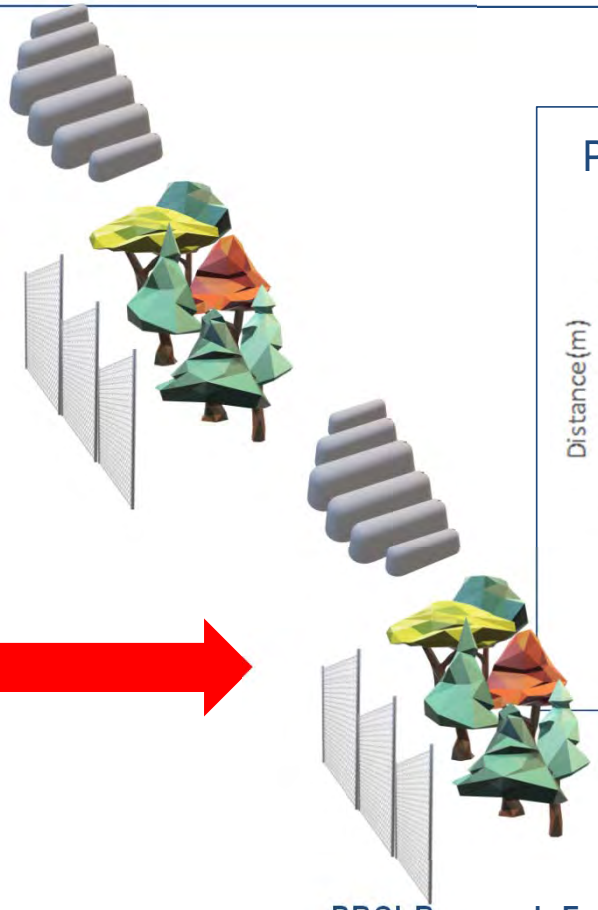
Piloted Ignition

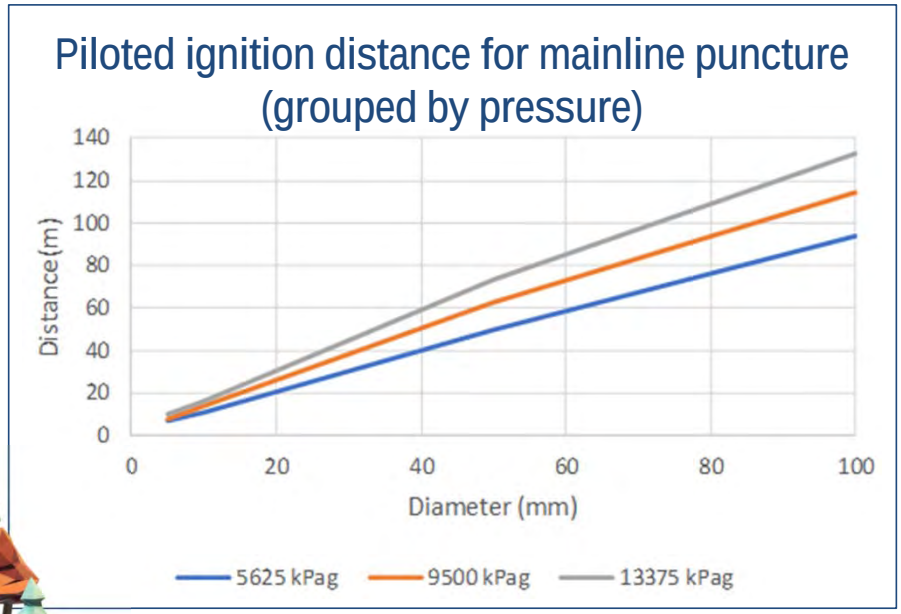
50 m

50 mm puncture 13375 kPa

Piloted Ignition

70 m





REX2020 PRCI RESEARCH EXCHANGE

Compressor Station Facility Fire



10 mm 400˚C
Steel Response

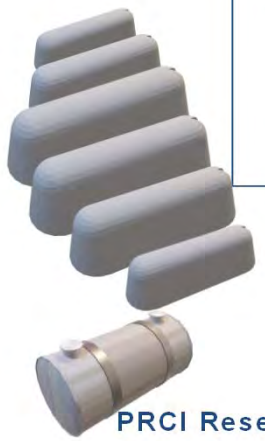
30 m



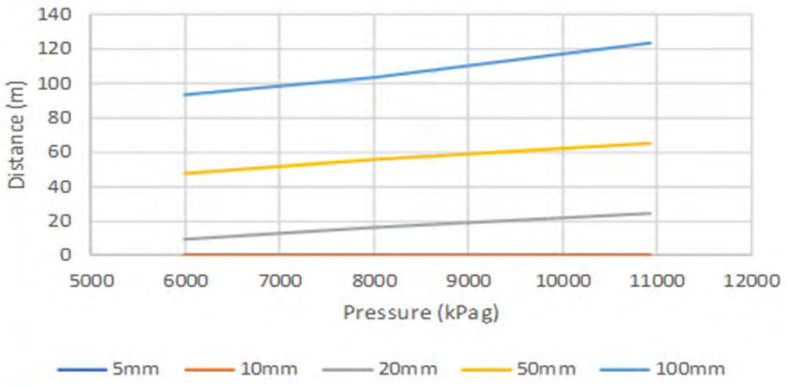


10 mm 400˚C
Steel Response

60 m



Steel response (10 mm, 400˚C) distance for compressor building puncture (grouped by diameter)



Compressor Station Facility Fire

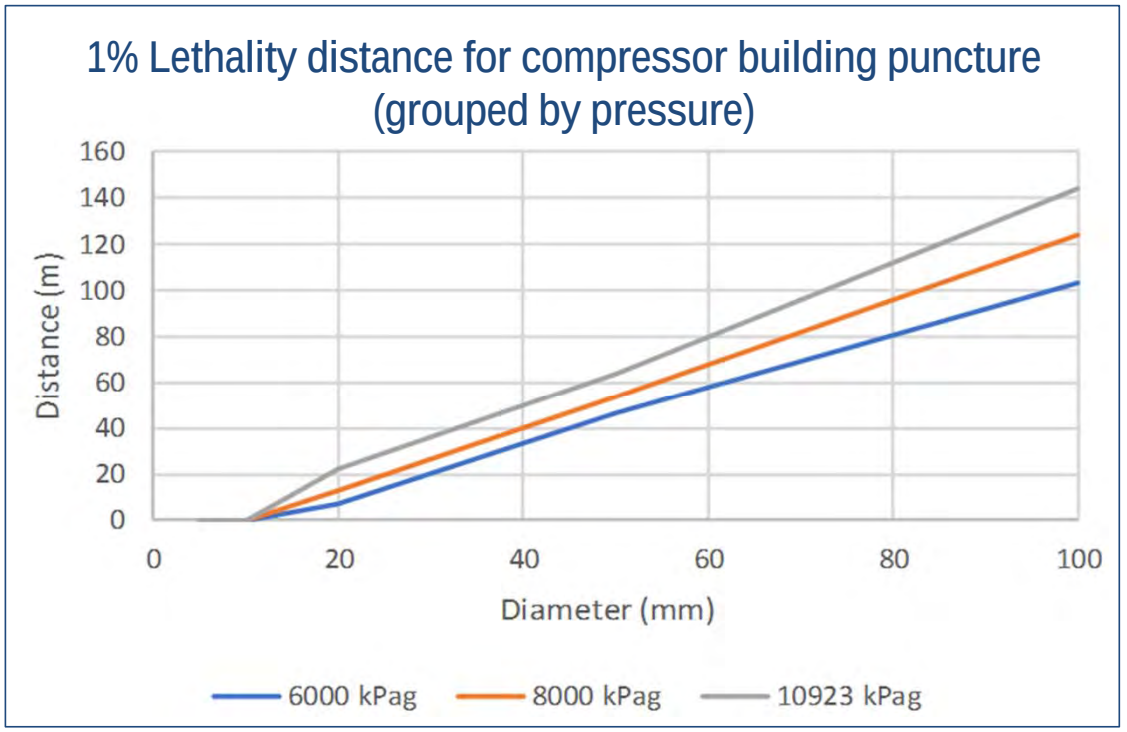


~15 – 20 mm puncture 11000kPa

1% Lethality

15 m

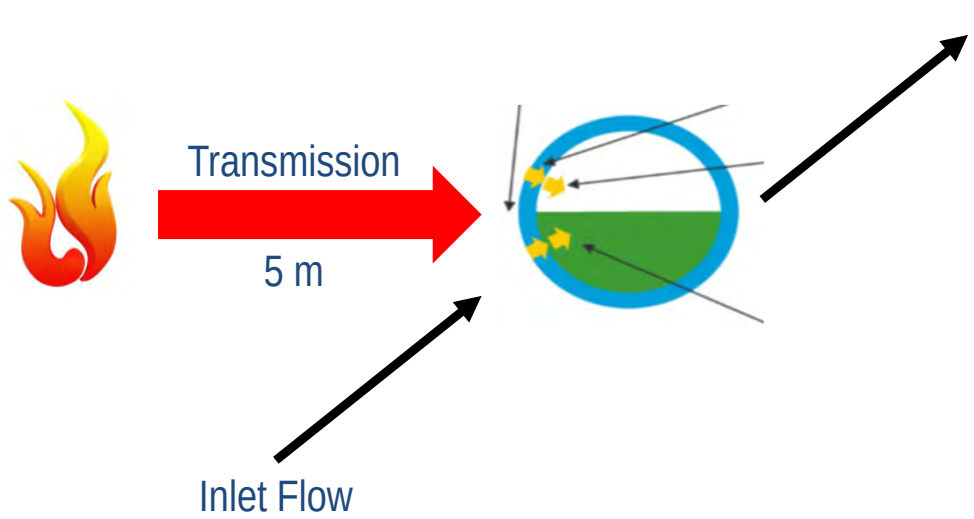




Results – What does it mean to TC Energy & Industry

Design:

- Meter station separator vessel will not overpressurize when exposed to extreme wildfire provided 5 m separation from the fire front and the station is not isolated from the pipeline system



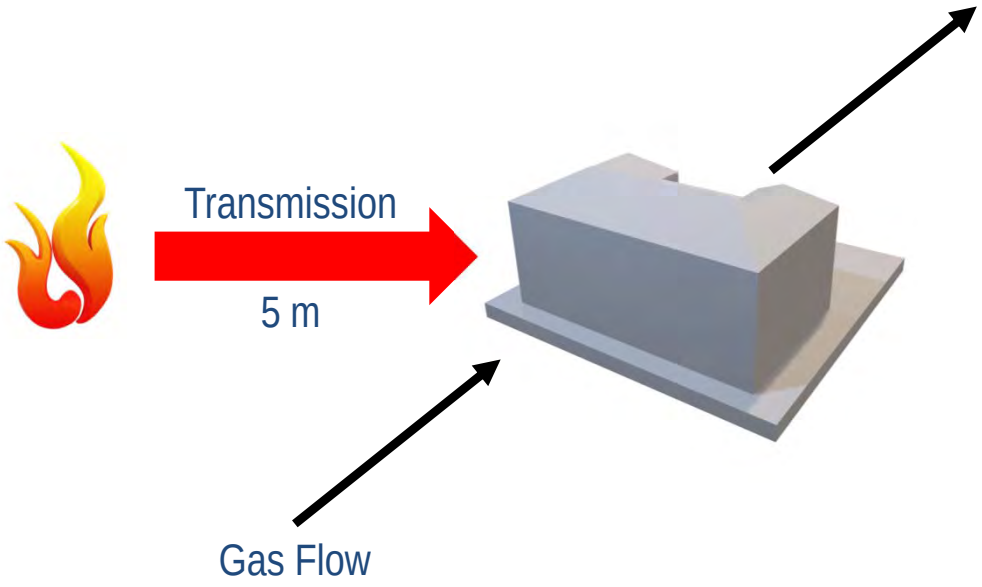
Incremental take away capacity function of:

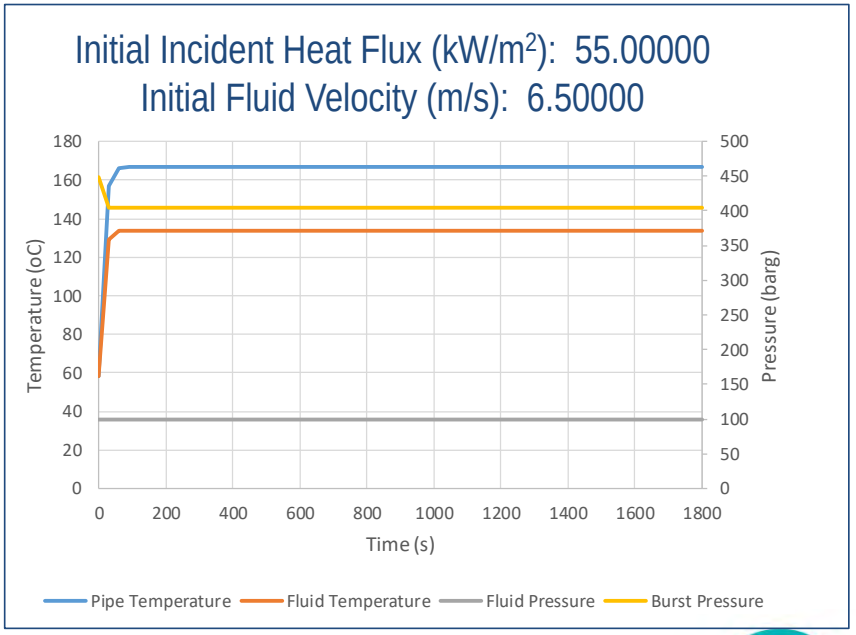
- Vessel Volume
- Heat Flux
- Liquid Mass Fraction & Molecular Weight
- Operating Pressure

Results – What does it mean to TC Energy & Industry

Design:

- Compressor station air cooled heat exchanger will not overpressurize provided 5 m separation from the fire front and sufficient flow exists or the station is depressurized





Results – What does it mean to TC Energy & Industry

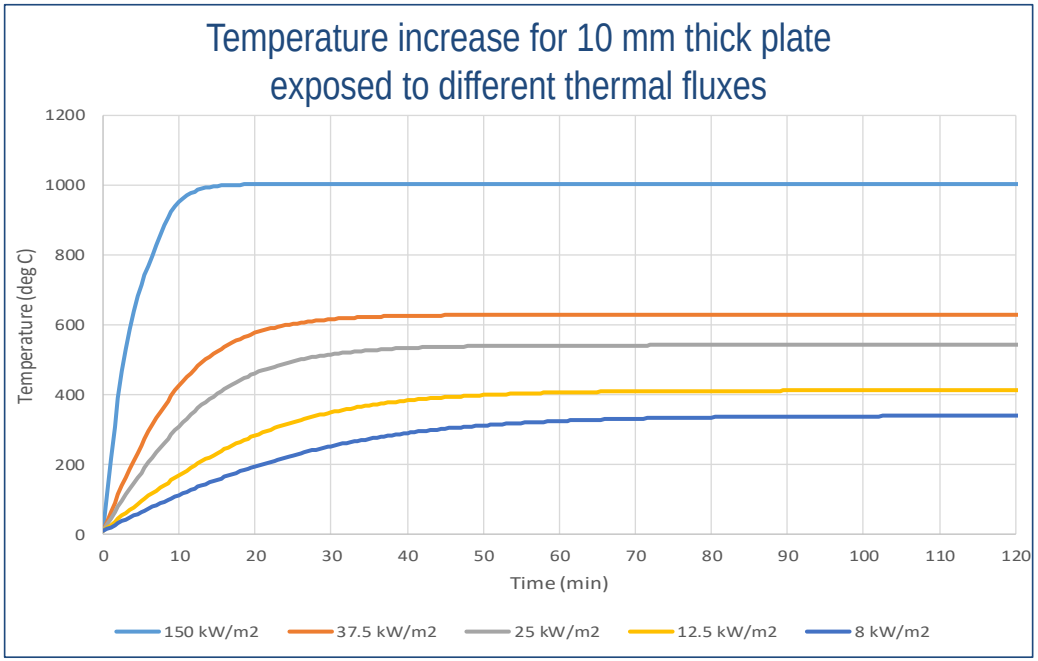
Design:

- Air cooled heat exchanger will not be heated to the point of causing an integrity concern when exposed to an ignited blowdown plume from PRV or station blowdown plume provided 35 m separation and blowdown time less than 5 minutes
- Setback distance requirements that prevent piloted ignition of adjacent forest for compressor station fire events were quantified
  - *Example: Ignited release from utility gas enclosure, blowdown valve, relief valve or cyclone separator*

Results – What does it mean to TC Energy & Industry

Emergency Response Planning, Post Fire Event Fitness for Service:

- Can determine exposed temperature based on distance, time, fire event to optimize evaluation of vessel fitness (consistent with API 579)



Implementation of Findings and Learnings

Stakeholder(s)	Implementation	Outcome	Status
Meter Station Designers	Include consideration of fire case in all Overpressure Risk Assessments	Supports current design standards	Implemented 2018

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Emergency Response	Assess appropriate protocols to respond to fire hazard based on type of asset	Provide platform for evaluation of response strategies	Incorporating into Business Unit Functional Plans
Post Fire Event Fitness for Service	Apply predictive model in support of Fit for Service Engineering Procedures	Fitness for Service Assessment (FFS) Post Fire Exposure	Implemented 2020 Canadian FFS After Wildfire Engineering Procedure

Thank You!



BACK TO AGENDA

Methane Emissions Solutions for the Gas Pipeline Industry

Brian Weeks
Business Development
R&D Operations

75-year+ History of Turning Raw Technology into Practical Energy Solutions

FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY ▶ CONVERSION ▶ DELIVERY ▶ UTILIZATION





RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

COMMERCIALIZATION

400+ EMPLOYEES



World-class piloting facilities headquartered in Chicago area

R&D Collaboratives Improve Characterization and Quantification of Methane Emissions

CALIFORNIA ENERGY COMMISSION

California Environmental Protection Agency AIR RESOURCES BOARD

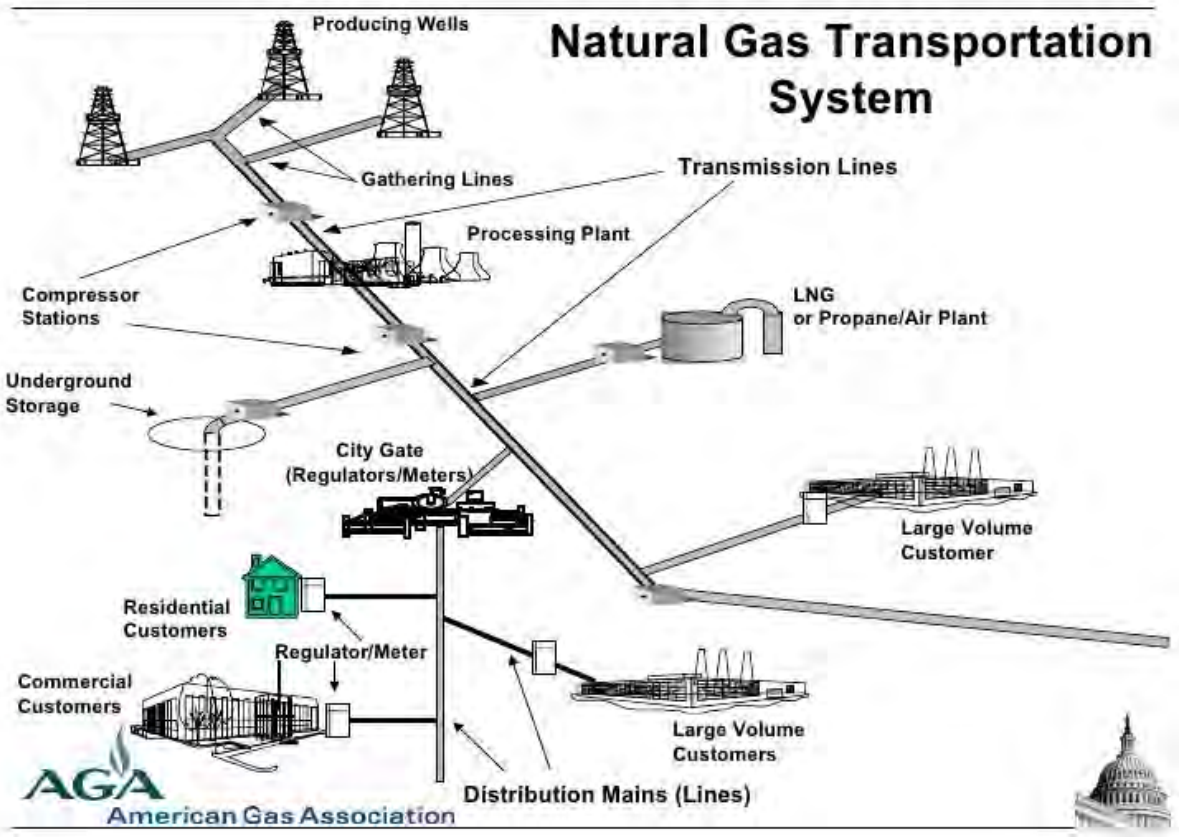
AGA American Gas Association

OTD Operations Technology Development

QH_4 COLLABORATORY TO ADVANCE METHANE SCIENCE

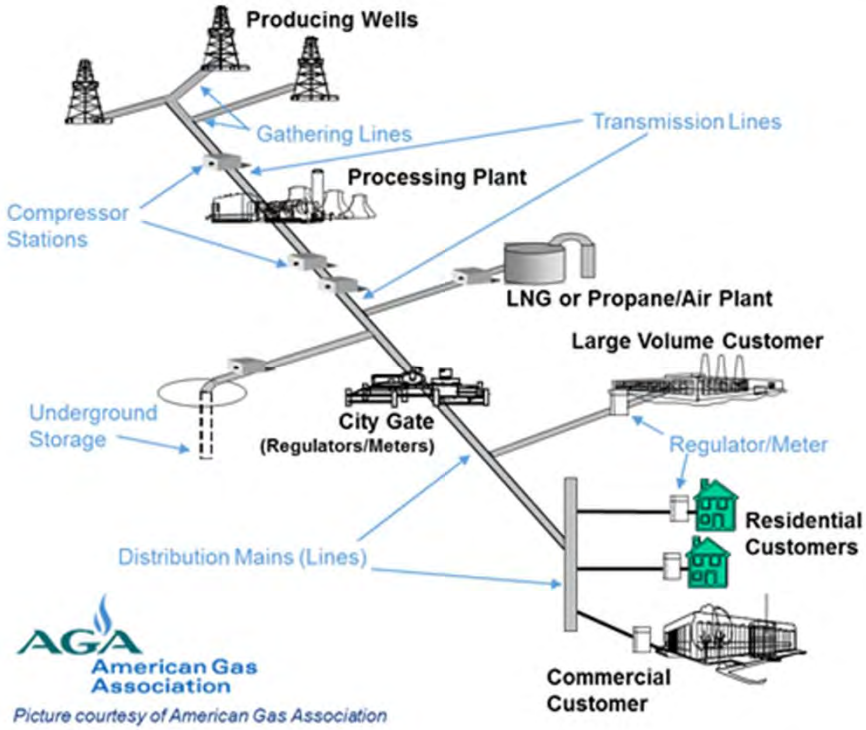
ENERGY.GOV

Canadian Energy Partnership for Environmental Innovation
A Strategic Innovation Collaboration



gti

Developing Technology Solutions for Methane Emission Sources Across the Value Chain



Production
- Pneumatic Controllers
- Gathering/Boosting Stations
- Tanks
- Chemical Injection Pumps

65% of total leaks across ~ 500,000 well sites
Largest source: Pneumatics ~16% of total

Gathering and Processing
- Reciprocating Compressors
- Centrifugal Compressors
- Gas Engines
- Blowdowns/Venting

7% of total leaks across ~ 500 plants
Largest source: Gas engines ~3.5% of total

Transmission
- Reciprocating Compressors
- Station Fugitives
- Engines
- Pipelines

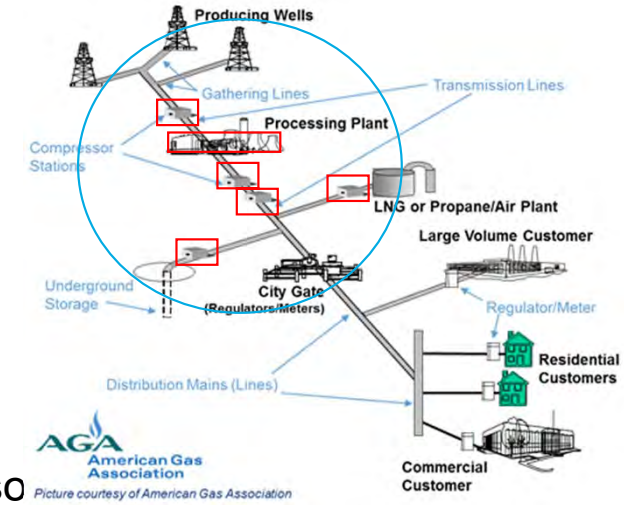
21% of total leaks across ~ 2,000 T&S sites
Largest source: Compressors ~11% of total

Distribution
- Mishaps (Dig-ins)
- Residential
- Mains - Unprotected Steel
- Services - Unprotected Steel

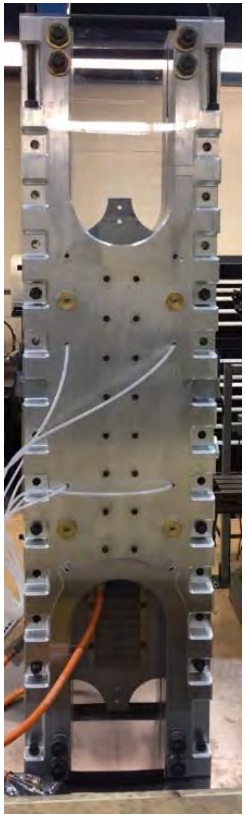
7% of total leaks across millions of use users
Largest source: Meters ~2% of total

Emission Recovery Market

- Methane emissions are concentrated at locations where gas is produced, compressed, stored, and processed
- Total midstream potential locations: 4,000 to 5,000 recovery compressors, saving:
  - 68 BCF natural gas
  - 32 MM tonnes CO_2e
  - Dollars CH_4 $200-$250 million in recoverable gas value
- Additional recovery opportunities:
    - Capture other site sources via a methane capture ‘utility’
    - Exploration and production locations
- User interest:
  - Discussions with multiple stakeholders and end users
  - Select utilities testing a low pressure leak recovery compresso
  - GTI offers unique variable speed, sealed, high pressure compressor solution



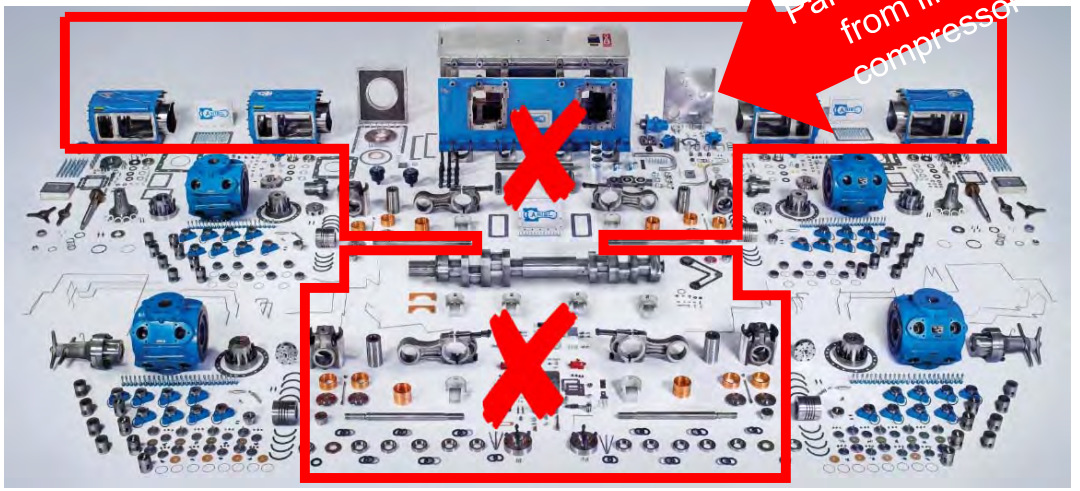
GTI Linear Motor Compressor Solution



30 kW prototype

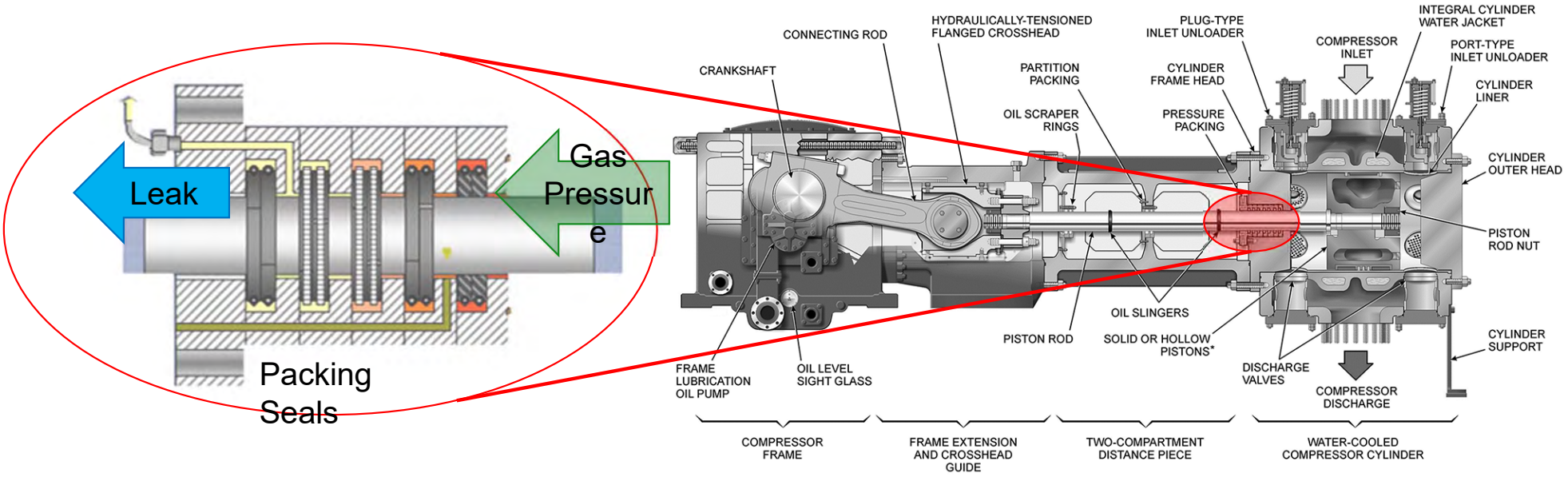
- Low pressure suction
- High pressure discharge to any pressure gas pipe
- Massive design simplification
- Fully variable speed/flow
- Near-zero maintenance
- Hermetically sealed





Compressor Packing Leak Recovery

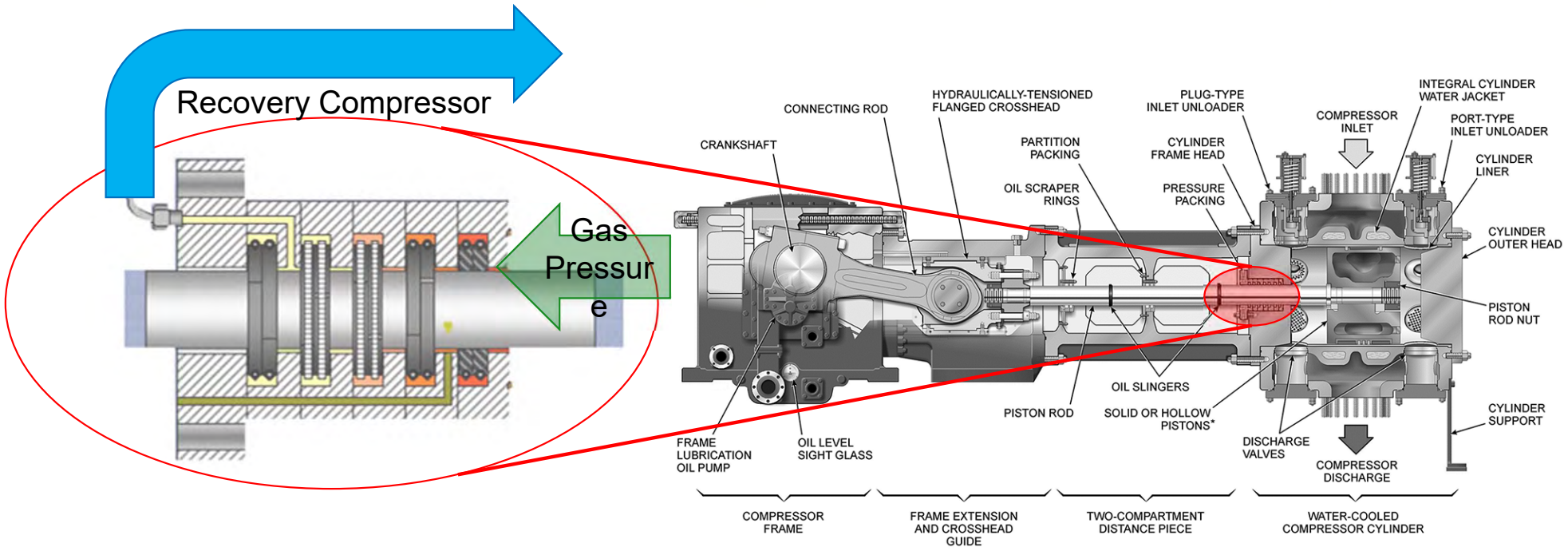
- Packing seals are used to seal compressor gas within the compression cylinder, but always leak



http://gasturbinespower.asmedigitalcollection.asme.org/data/journals/jetpez/929456/gtp_136_04_041601_f002.png

Compressor Packing Leak Recovery

- Capture leakage using small recovery compressor and discharge it downstream

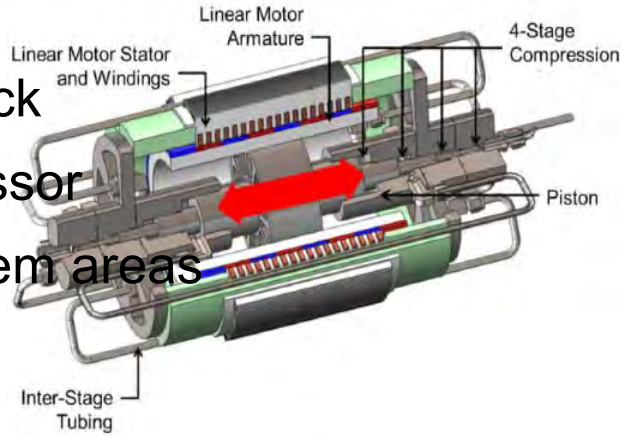


http://gasturbinespower.asmedigitalcollection.asme.org/data/journals/jetpez/929456/gtp_136_04_041601_f002.png

Differential Benefits of GTI's Linear Motor Compressor

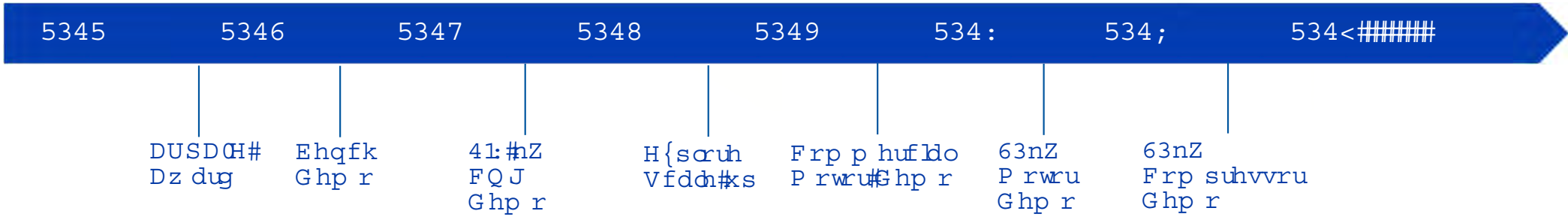
- GTI's compressor offers efficient methane capture
- Linear motor compressor pumps gas directly into pipe or storage
- Zero impact on site reliability
- Simplified design enables near–zero maintenance
- Cost effective:
  - Low unit cost and gas monetization drive fast payback
  - Avoid premature seal replacements in main compressor
  - Linear motor compressor run time can identify problem areas to focus remediation efforts





Free Piston Linear Motor Compressor

Linear compression development timeline

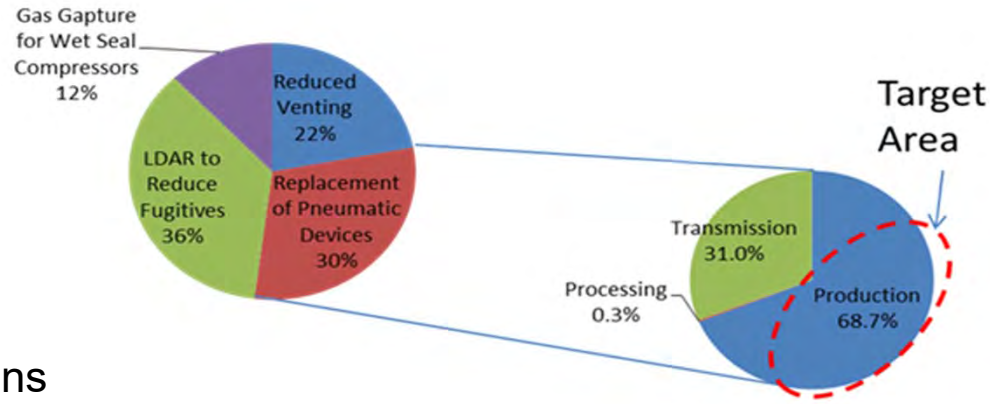


- Key programs / projects
- Over $5MM invested to-date
- Key milestones
  - Demonstrated technology feasibility under ARPA-E funding
  - Demonstrated potential for cost effective scaled-up designs under US DOE funding
- Patent filings and know-how protect mechanical design and control approaches

Methane Mitigation ThermoElectric Generator (MMTEG)

Problem Statement – Reduce Natural Gas Emissions

- Natural gas is working fluid for pneumatic actuators at wellheads
- Results to 518-826 Gg of methane emissions annually just in the United States[1]
  - $110-175M in lost revenue
  - 14500-23100 Gg of equivalent CO2 emissions
- Natural gas production is expected to increase by 40% within the next 10 years further increasing the problem



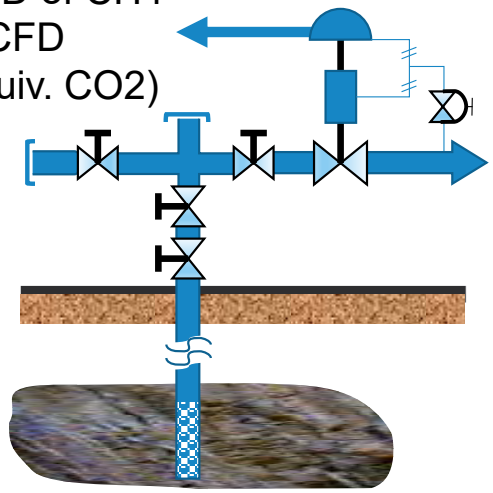
Distribution of Emission Reduction Potential (ICF, 2014)

[1]Allen, D. T. *et al.* Methane emissions from process equipment at natural gas production sites in the United States: Pneumatic controllers. *Environ. Sci. Technol.* **49,** 633–640 (2015).

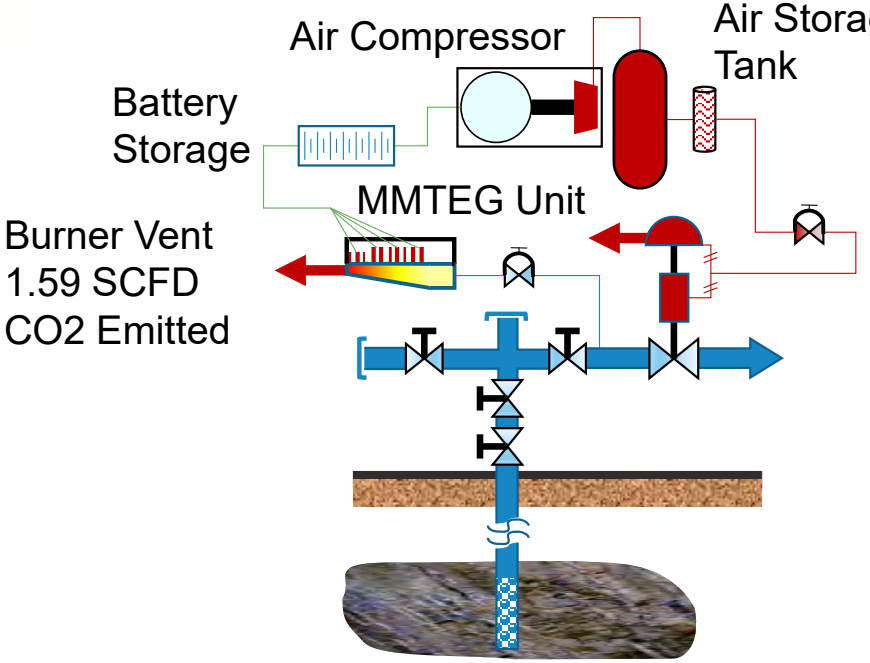
Simple Retrofit to Existing Wellhead Arrangement

Current

Actuator Vent
252 SCFD of CH4
(7056 SCFD
GHG Equiv. CO2)



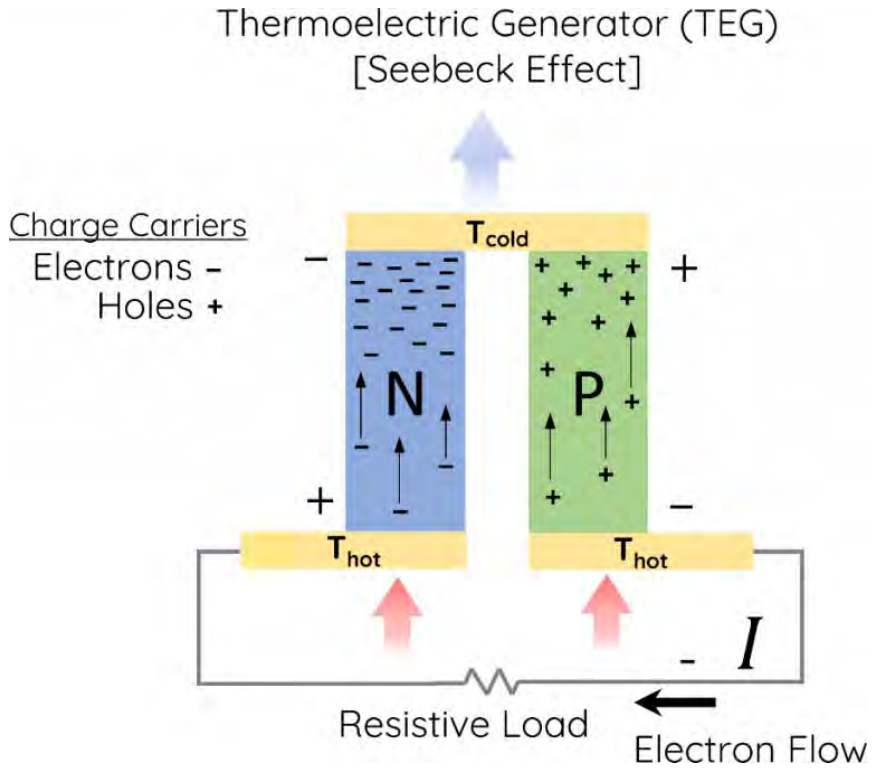
Future



Reduces emissions by 1000X & Increases Revenue

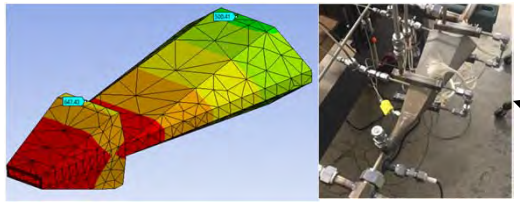
Thermoelectric Generator (TEG)

1. Converts heat directly to electrical energy
2. Solid-state devices with no moving parts to break or wear out makes them very reliable – Voyager 1 spacecraft in operation for >41 years and travelled 13 billion miles
3. Scalable to operate in milliwatts or kilowatts
4. Quiet
5. Compact and lightweight makes them easy to handle
6. Can be scaled up to provide remote power for additional applications such as CP



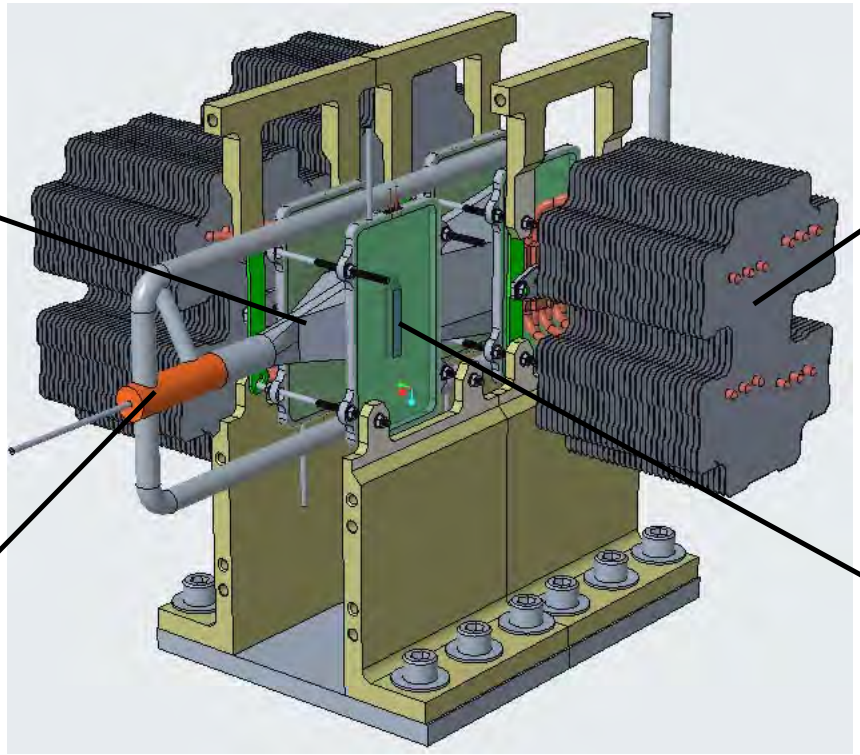
Integrated MMTEG System Utilizes Heat to Create Electricity

Engineered and proven heat exchanger



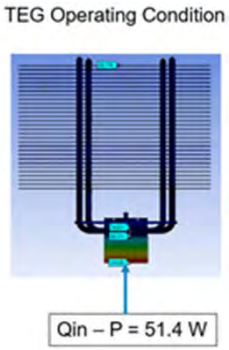
Swirl induced low NOx burner



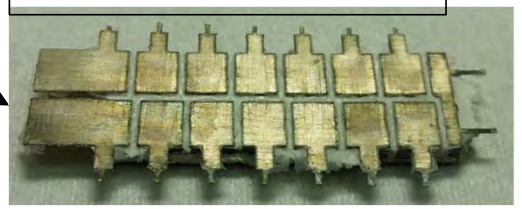


Passive off-the-shelf heat sinks





Hermetically sealed TEGs



Performance/Economic Targets

	Technology	System Complexity	Reliability/ Maintainability	GHG % Reduced	Recoverable Revenue %	Capital Cost	TRL	Applicability
	Pneumatic Actuator. Methane Working Fluid		Failure & Wear of Intermittent devices	0%	0%	N/A	9	Current
	Replace working fluid with Instrument Air (IA) via MMTEG system	Uses existing controls	Air Compressor	99.2%	82.7% (15 month Payoff)	Target <$1.5K	5	Proposed **BEST** Lowest Capital Cost and Highest Recoverable Revenue for mature technology
Other Candidate Technologies Evaluated								
A	Replace working fluid with IA via Advanced TEG system	Uses existing controls	Air Compressor	99.8%	83.5% 14 month payback	Target <$1.5K	3	**Not Applicable** – Does not meet TRL requirement and advanced TEG development cost is greater than available Doe Funding
B	Replace Working Fluid with IA via PV Panel	Added controls are solid state	Intermittency, site security issue-theft	100%	13.3%	$3K	9	**Abandoned** by operator due to high incidence of theft

KEY - Exceeds Requirement - Effort Required to Meet Requirement - Cannot Meet Requirement

MMTEG Most Attractive Option

gti

LCRI Conceptual Overview

...to 2050

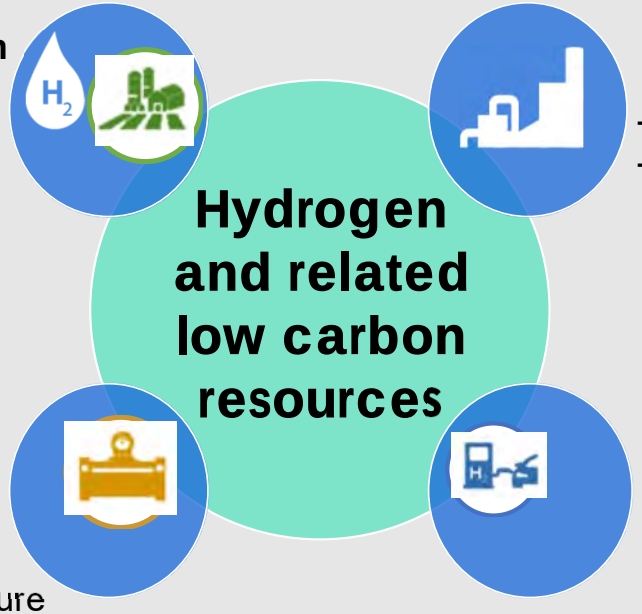
The **Low-Carbon Resources Initiative** will be a five-year, focused R&D commitment to reveal the pathway to advance low-carbon technologies for large-scale deployment approaching **2030.** Led by and funded through **EPRI and GTI**, the vision is to enable a risk-informed understanding of options and technologies for deep, economy-wide decarbonization, and advance these through applied engineering and technology acceleration.

WHY H_2 and related, low-carbon resources

Enabling infrastructure for future low-carbon fuel options

Hard-to-electrify sectors such bulk transportation, large industries, and heating networks in cold climates

Large-scale clean power utilizing combustion turbines



Low-carbon Resource Production
- Hydrogen
- Biofuels

Low-carbon Power Gen.
- CCUS
- Hydrogen turbines

Transport, Delivery & Storage
- Existing Infrastructure
- New

End Use
- Industrial
- Transport-ation
- Buildings

VALUE CO_2

Individual commitment to environmental, social, and governance (ESG) efforts

Increase optionality of low-carbon solutions

Leverage investments across relevant sectors

Identify approaches to mitigate stranded assets


Questions?
bweeks@gti.energy
281.235.7993

BACK TO AGENDA

PRCI 2020 Research Exchange

A Digital Alternative to In-Line Inspection

- Christopher De Leon and Michael Smith (ROSEN Group)

LEADING PIPELINE RESEARCH

Objective

Objective

- **Create a "*digital alternative to ILI*" – a predictive analytics solution for monitoring the condition of uninspected pipelines**

Tasks

Objective

- Create a "*digital alternative to ILI*" – a predictive analytics solution for monitoring the condition of uninspected pipelines

Tasks

1. **Data Engineering**
   - Develop Extract Transform Load (ETL) processes to collect and structure data
2. **Descriptive Analytics**
   - Conduct Exploratory Data Analysis (EDA) to understand trends
3. **Predictive Analytics**
   - Develop models using machine learning and Bayesian inference techniques

Results (*for one prototype model*)

Objective

- Create a "*digital alternative to ILI*" – a predictive analytics solution for monitoring the condition of uninspected pipelines

Tasks

1. Data Engineering
   - Develop Extract Transform Load (ETL) processes to collect and structure data
2. Descriptive Analytics
   - Conduct Exploratory Data Analysis (EDA) to understand trends
3. Predictive Analytics
   - Develop models using machine learning and Bayesian inference techniques

Results

- **ILI data and pipeline metadata collected for ~5,000 pipelines**
- **Bayesian Network used to predict internal corrosion growth rate in an uninspected pipeline, using ILI data from "similar" inspected pipelines**
- **Significant reduction in unnecessary digs compared to traditional modeling**

Tasks

Task 1: Data Engineering

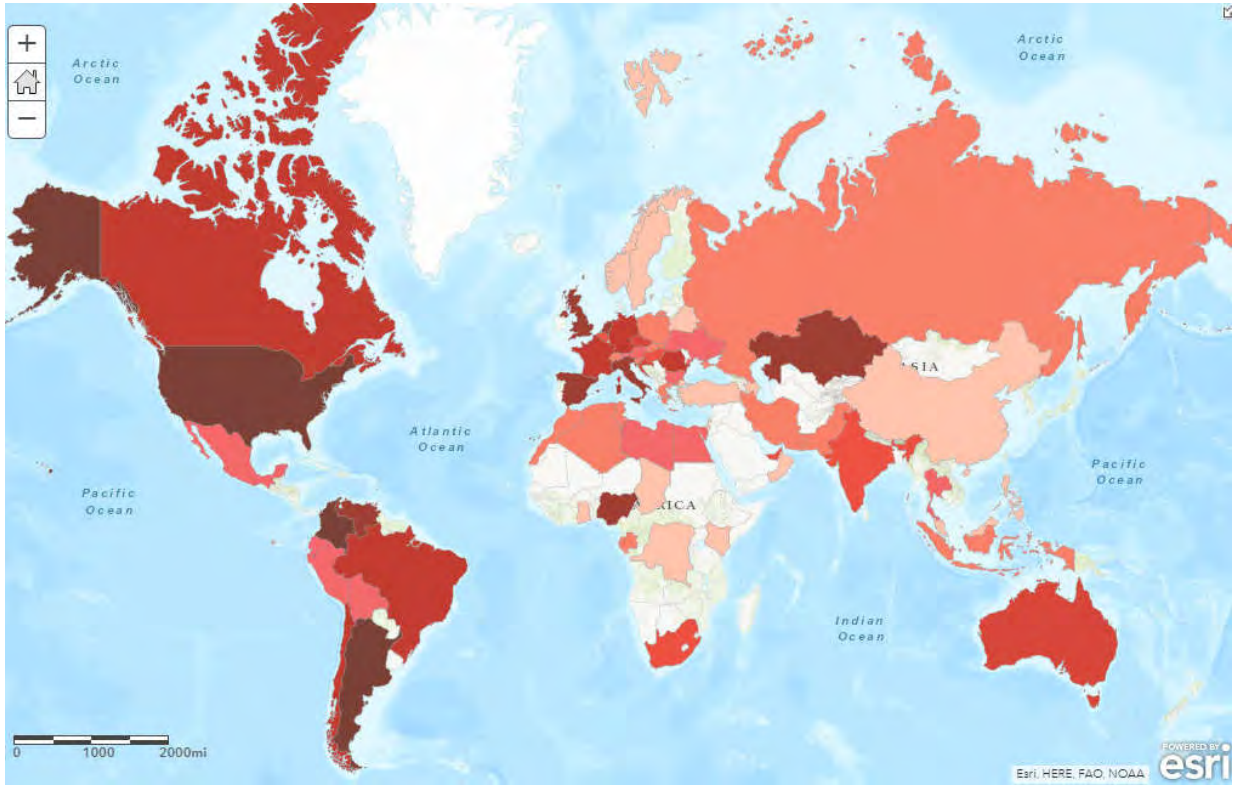
Task 1: Data Engineering



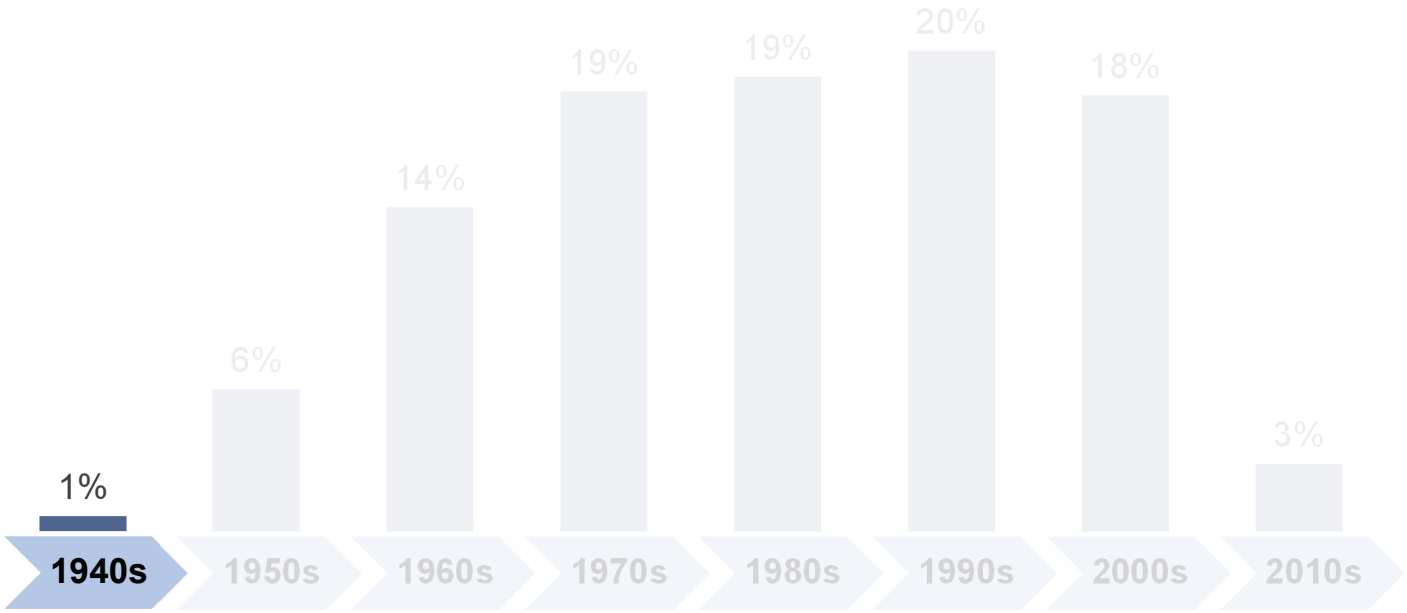
Tasks

Task 2: Descriptive Analytics

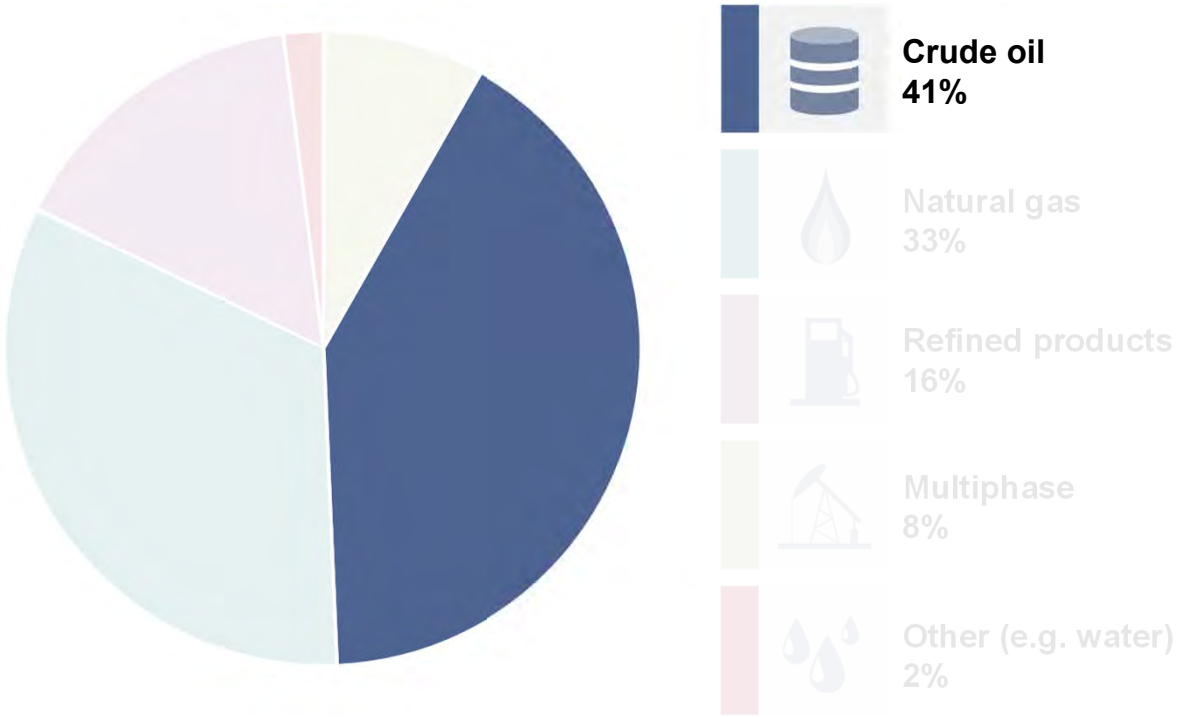
Task 2: Descriptive Analytics – *Locations*



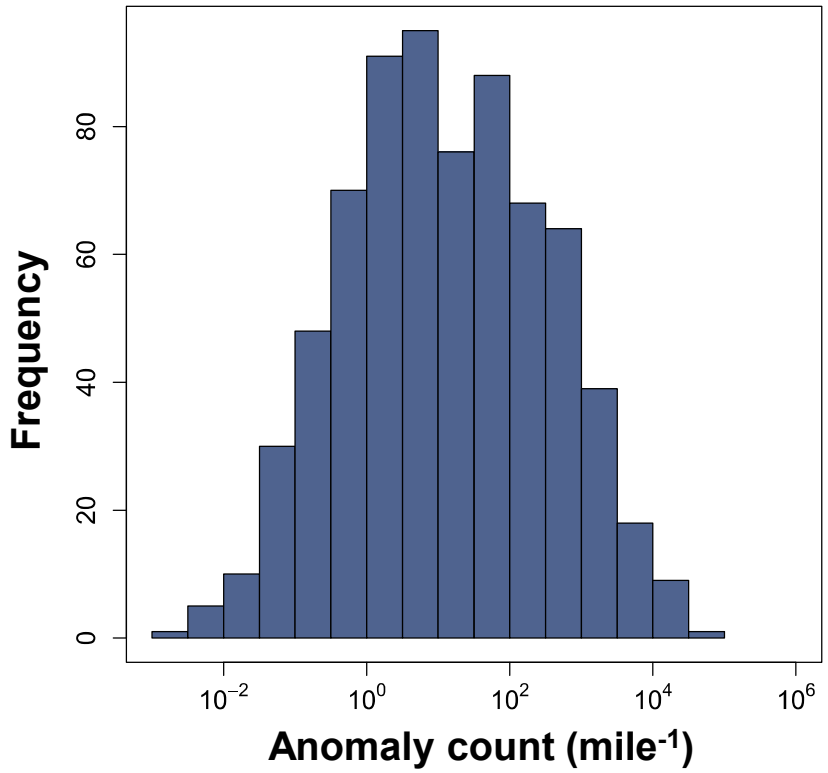
Task 2: Descriptive Analytics – *Construction Dates*



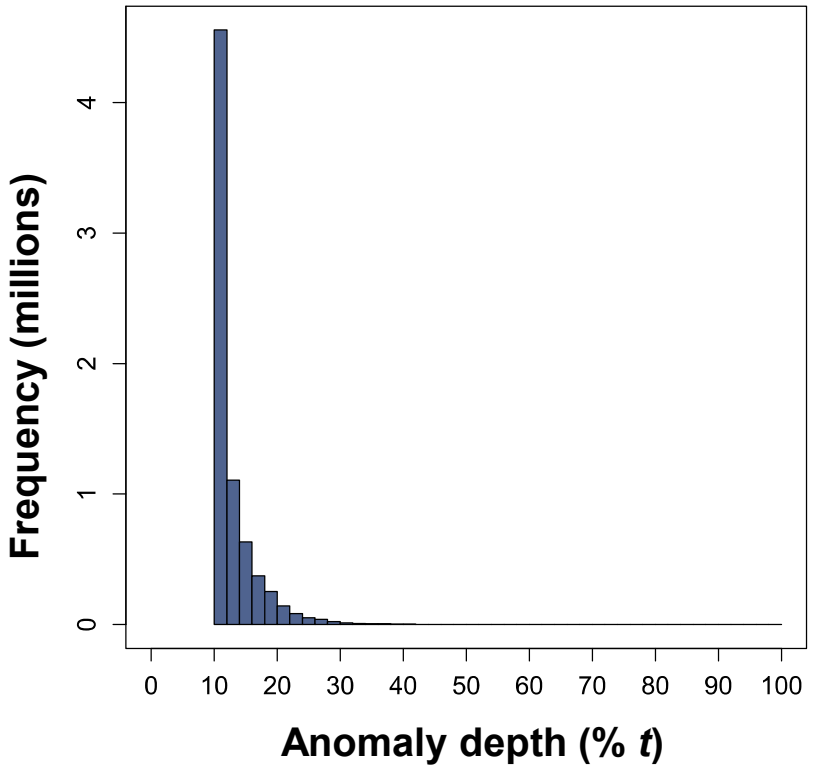
Task 2: Descriptive Analytics – *Products*



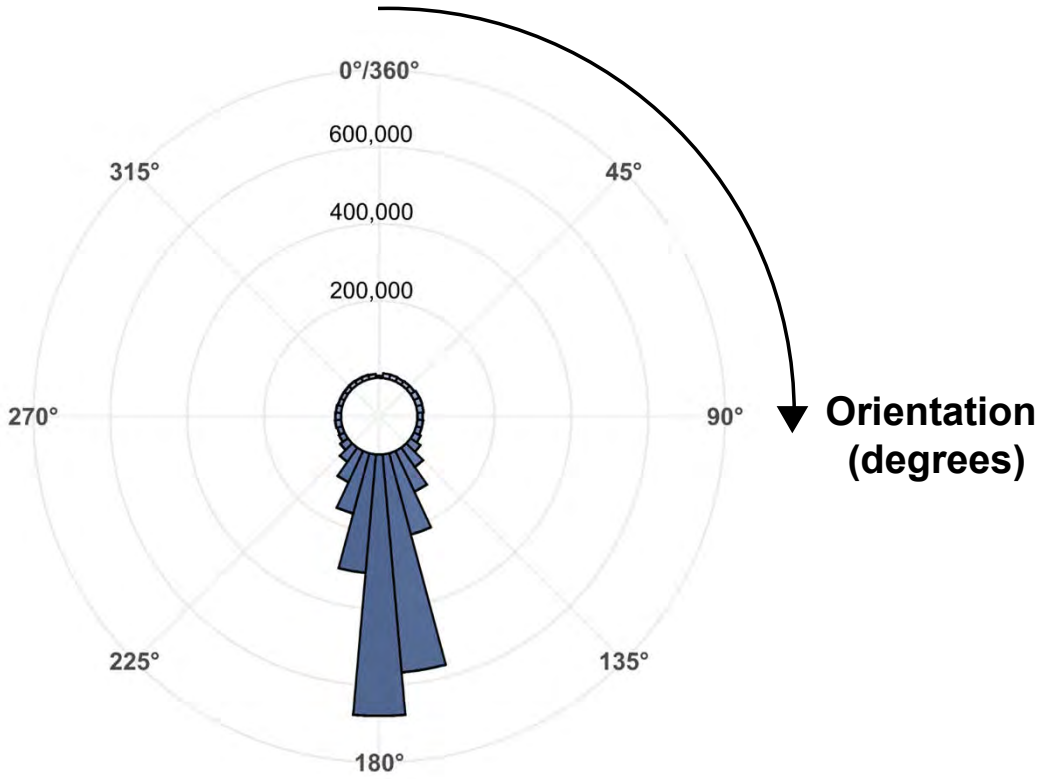
Task 2: Descriptive Analytics – *Internal Corrosion*



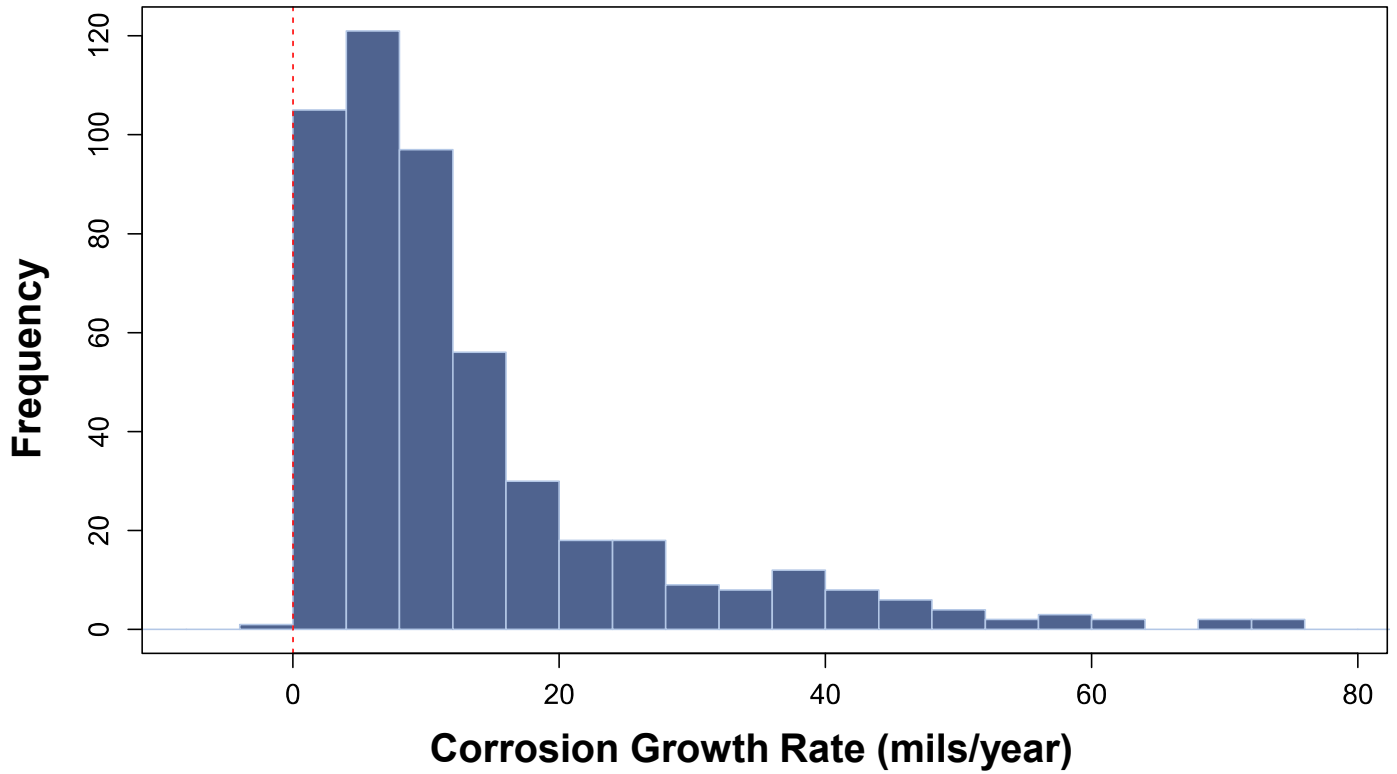
Task 2: Descriptive Analytics – *Internal Corrosion*



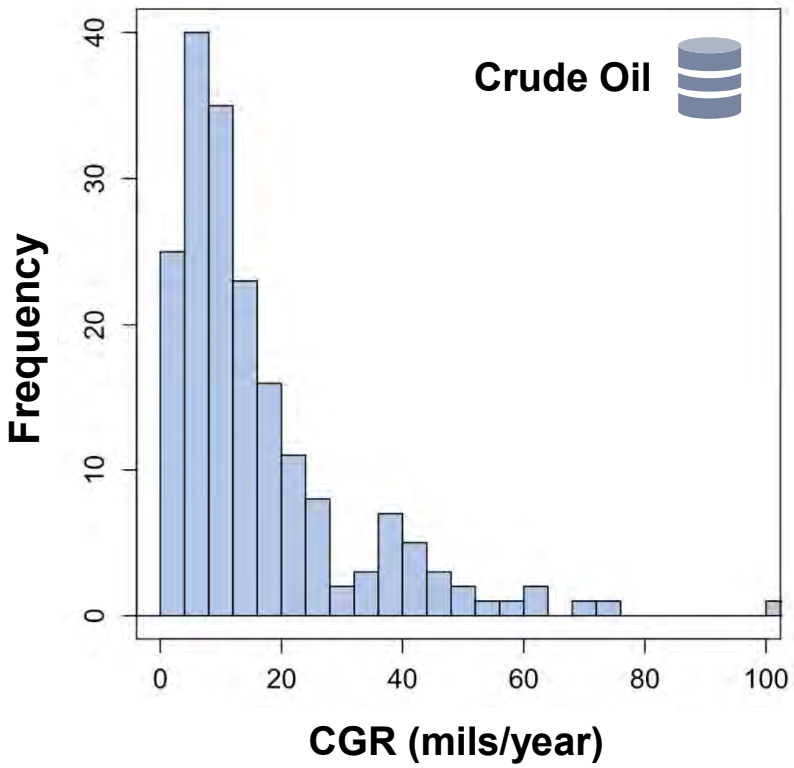
Task 2: Descriptive Analytics – *Internal Corrosion*

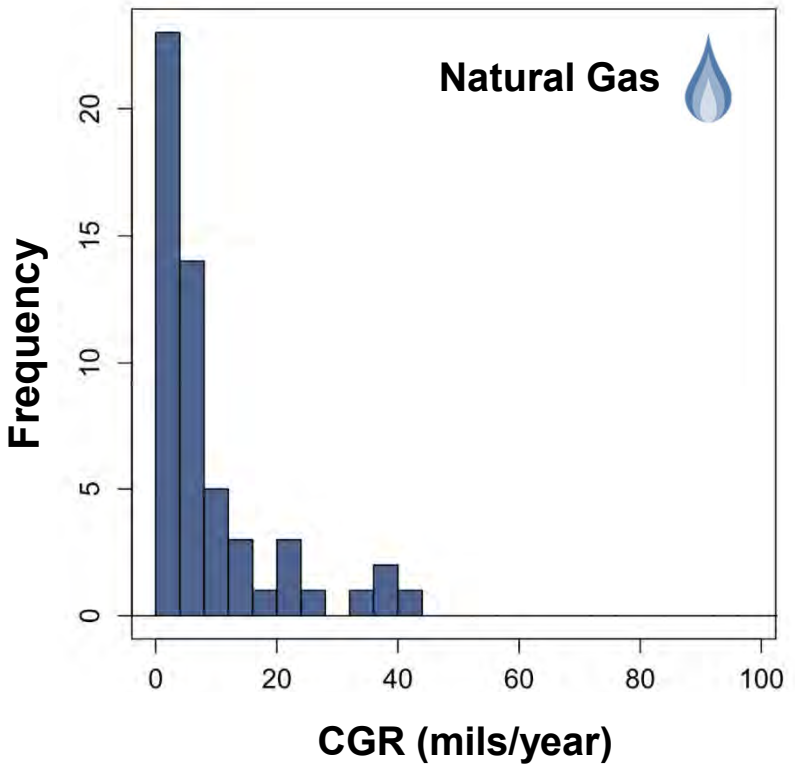


Task 2: Descriptive Analytics – *Internal Corrosion*



Task 2: Descriptive Analytics – *Internal Corrosion*

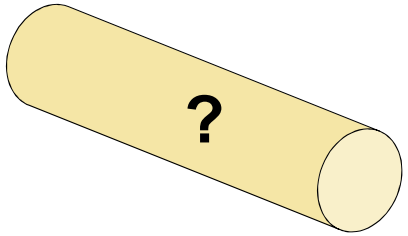




Tasks

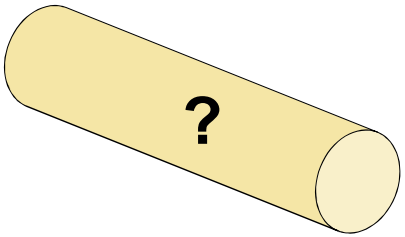
Task 3: Predictive Analytics

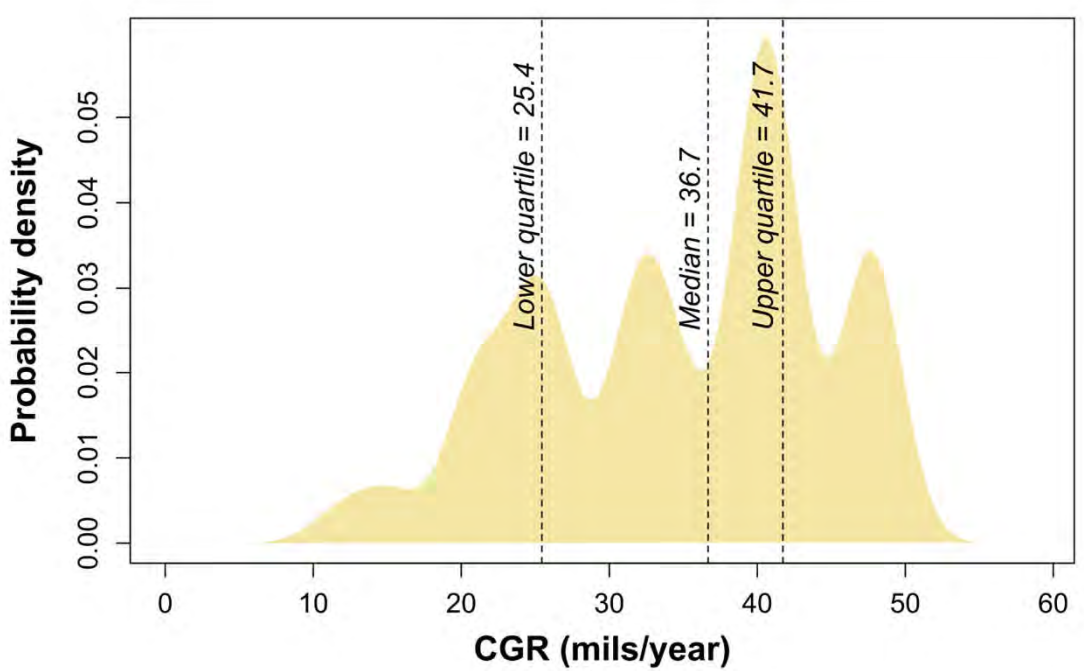
Task 3: Predictive Analytics



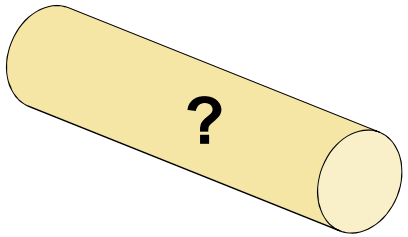
Product	Crude oil
Inlet temperature	120°F
Inlet pressure	640 psi
Velocity	1.4 m s^{-1}
CO_2 content	1.0 mol%
Basic sediment and water	< 5%

Task 3: Predictive Analytics

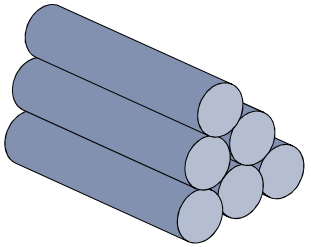




Task 3: Predictive Analytics

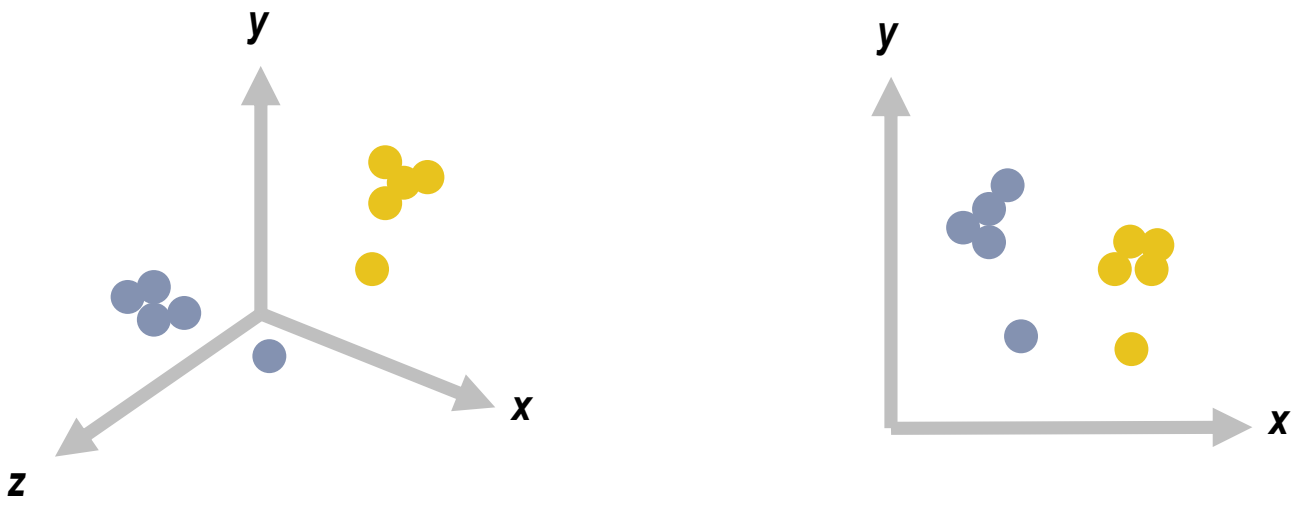






Similar inspected pipelines

Task 3: Predictive Analytics – *Dimensionality Reduction*

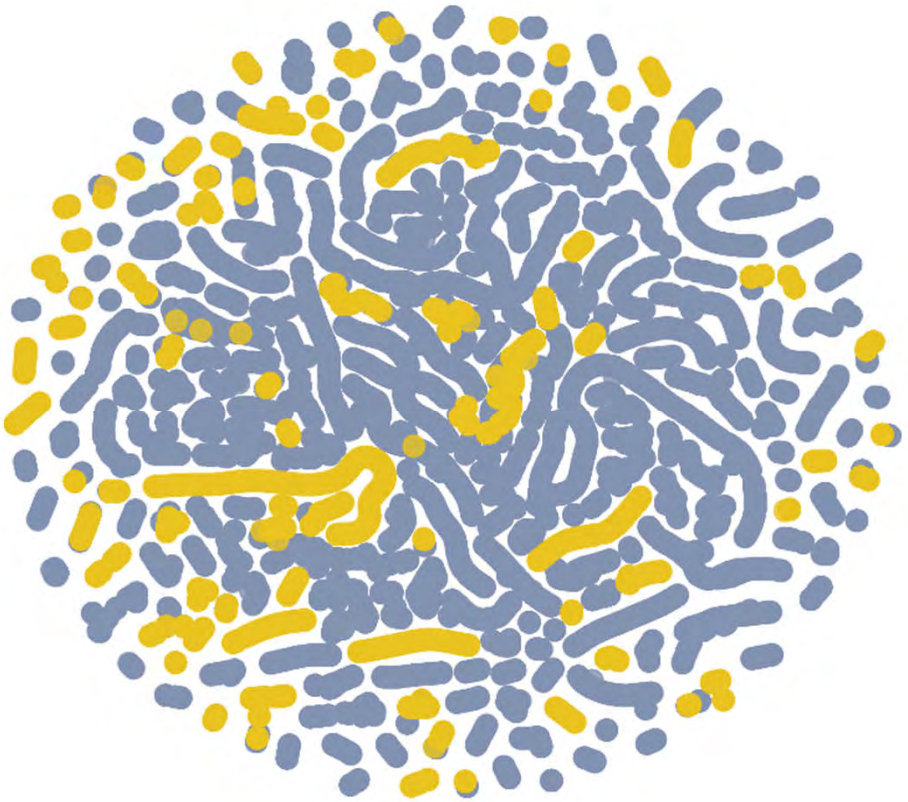


High dimensional data → **Low dimensional data**

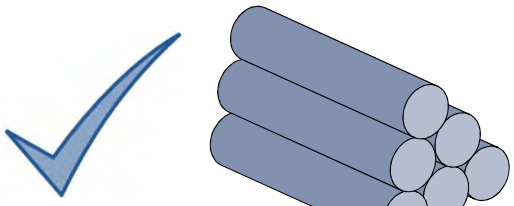
Task 3: Predictive Analytics – *t-SNE*

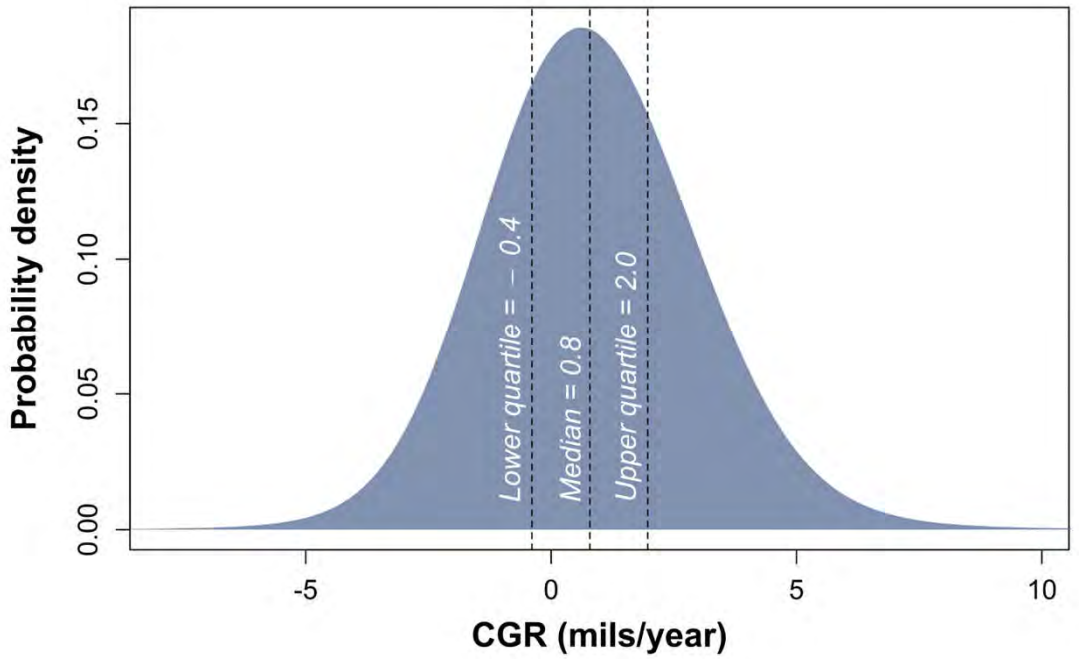
Inspected pipelines

Uninspected pipeline

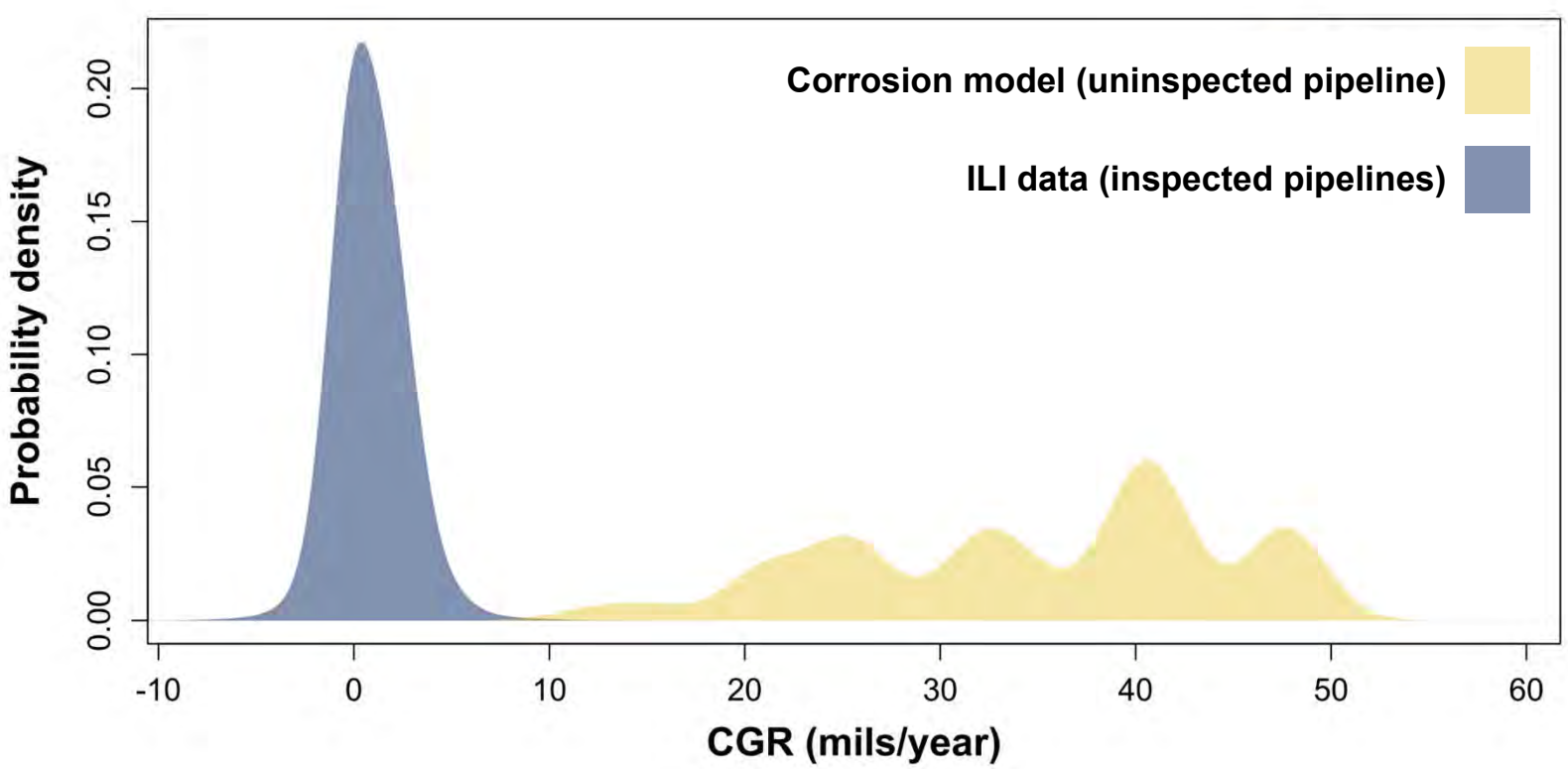


Task 3: Predictive Analytics



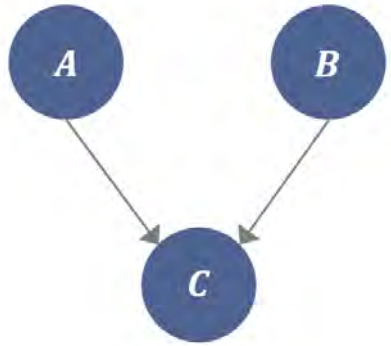


Task 3: Predictive Analytics



Task 3: Predictive Analytics – *Bayesian Networks*

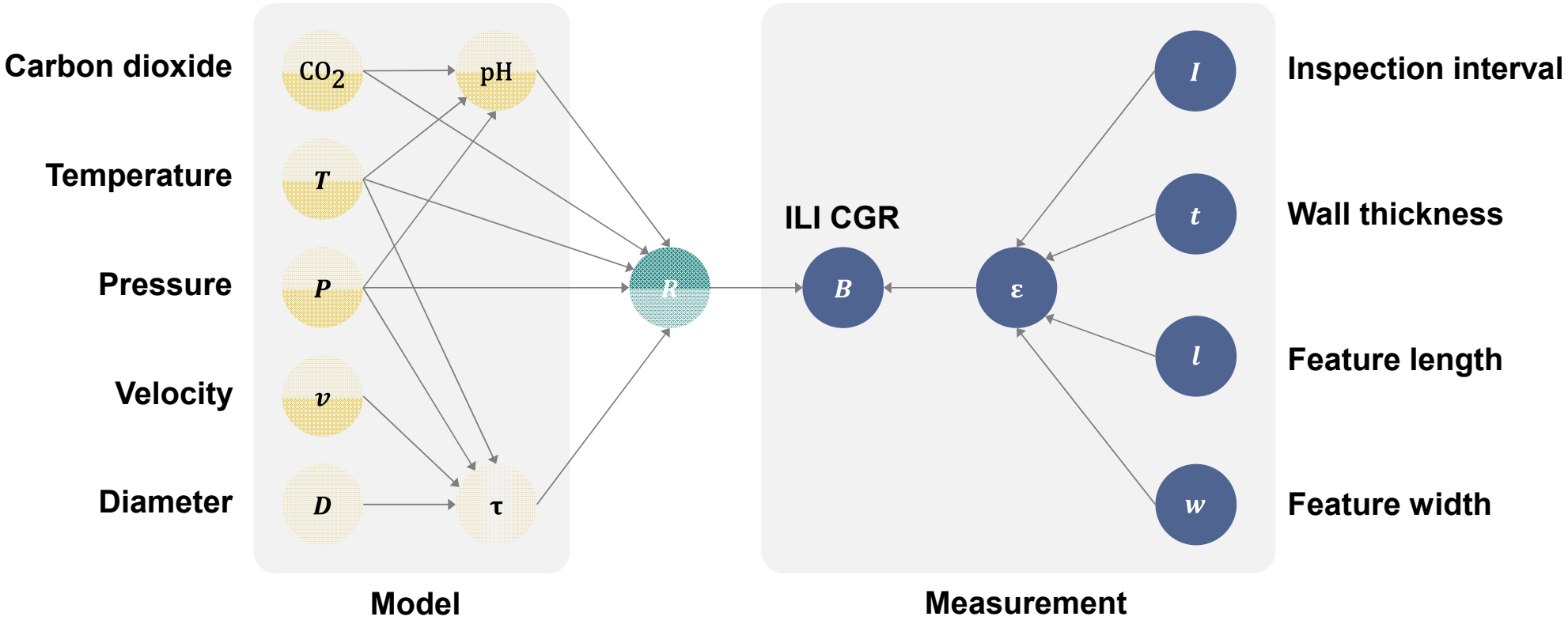
State of *A*	Probability
True	0.60
False	0.40



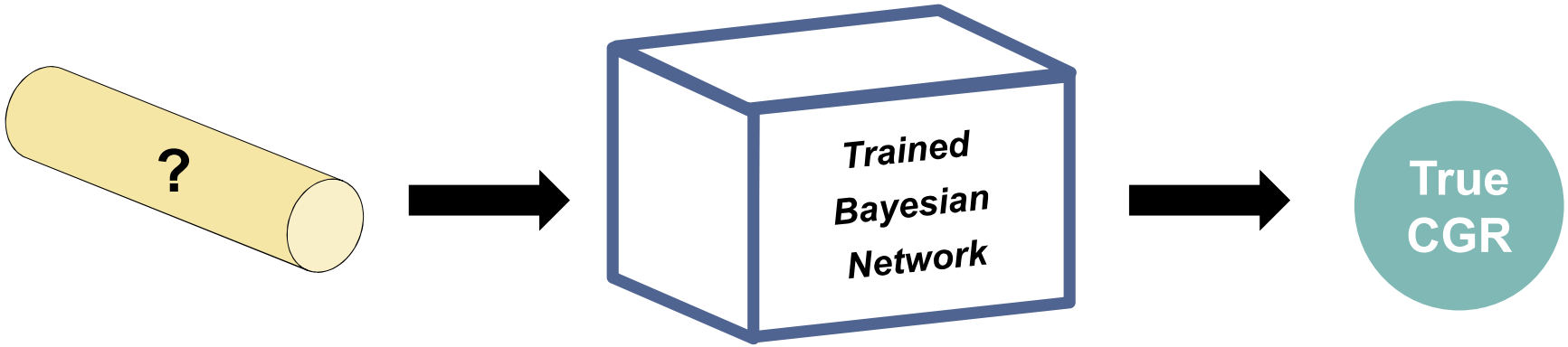
State of *B*	Probability
True	0.90
False	0.10

Conditional Probability Table (CPT)				
State of *C*	*A* = True *B* = True	*A* = False *B* = True	*A* = True *B* = False	*A* = False *B* = False
True	0.99	0.55	0.80	0.15
False	0.01	0.45	0.20	0.85

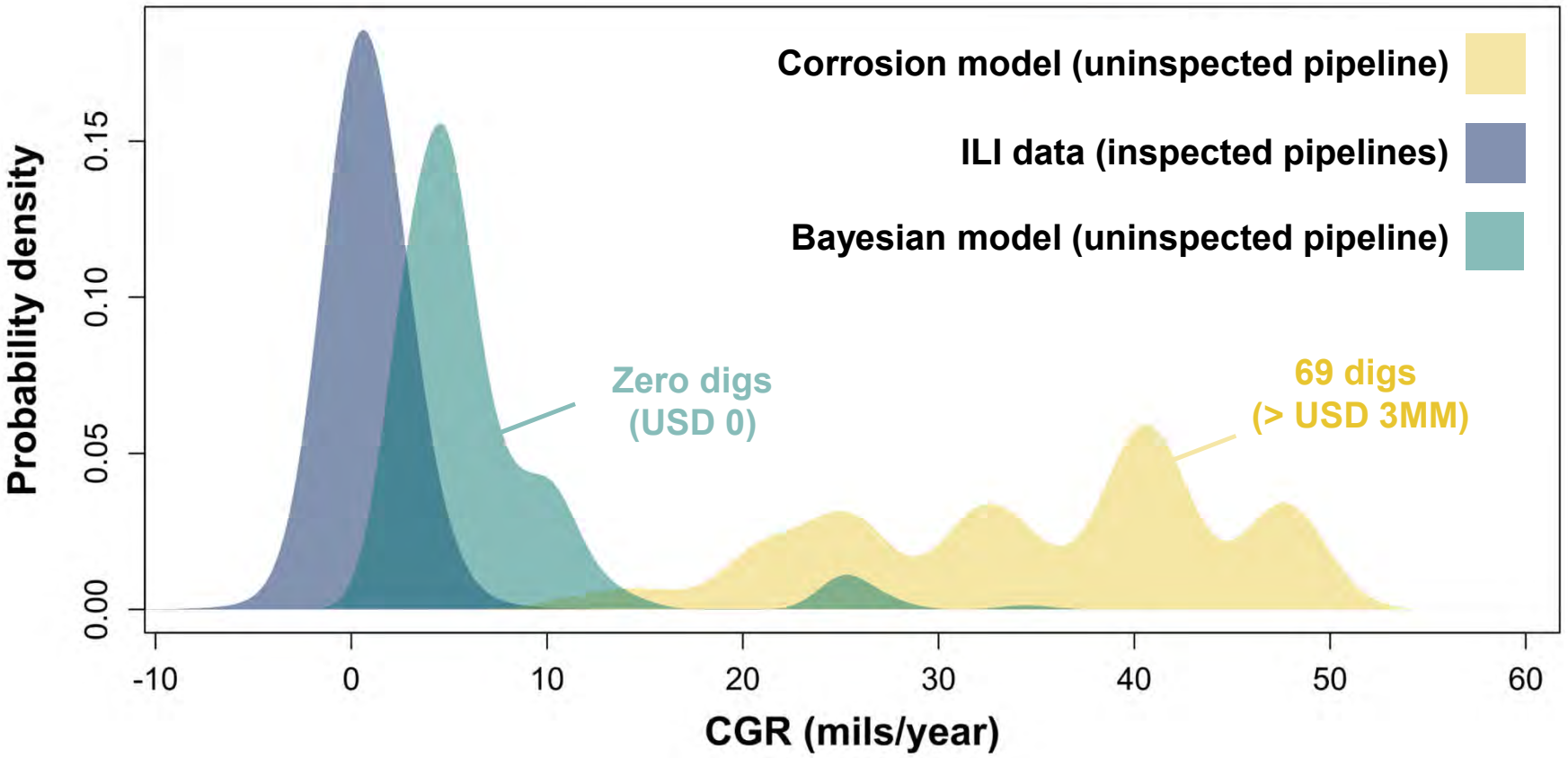
Task 3: Predictive Analytics – *Bayesian Networks*



Task 3: Predictive Analytics – *Bayesian Networks*



Task 3: Predictive Analytics – *Bayesian Networks*



Practical Application

Objective

- **Create a *"digital alternative to ILI"* – a predictive analytics solution for monitoring the condition of uninspected pipelines**

Potential applications?

1. Network prioritization
2. Input to direct assessment (dig prioritization)
3. Decision support for pipeline modifications (piggability)
4. Predictive maintenance between inspections
5. ILI Validation (API 1163 Level 1)

BACK TO AGENDA

PRCI 2020 Research Exchange

Using Machine Learning to Enhance Pipeline Reliability Assessment

Daryl Bandstra
Consulting Engineer, P.Eng

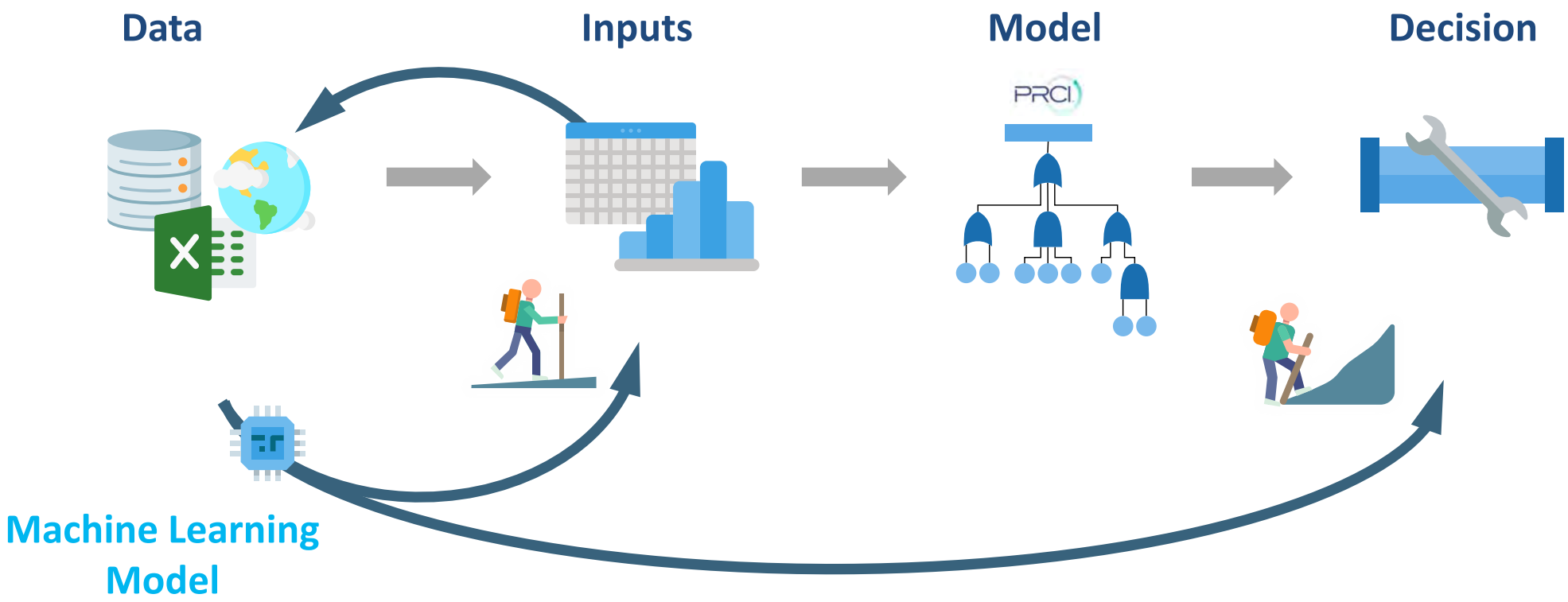
Mari Shironishi
Risk Assessment Manager

Integral ENGINEERING

SoCalGas
A Sempra Energy utility®

PRCI™
LEADING PIPELINE RESEARCH

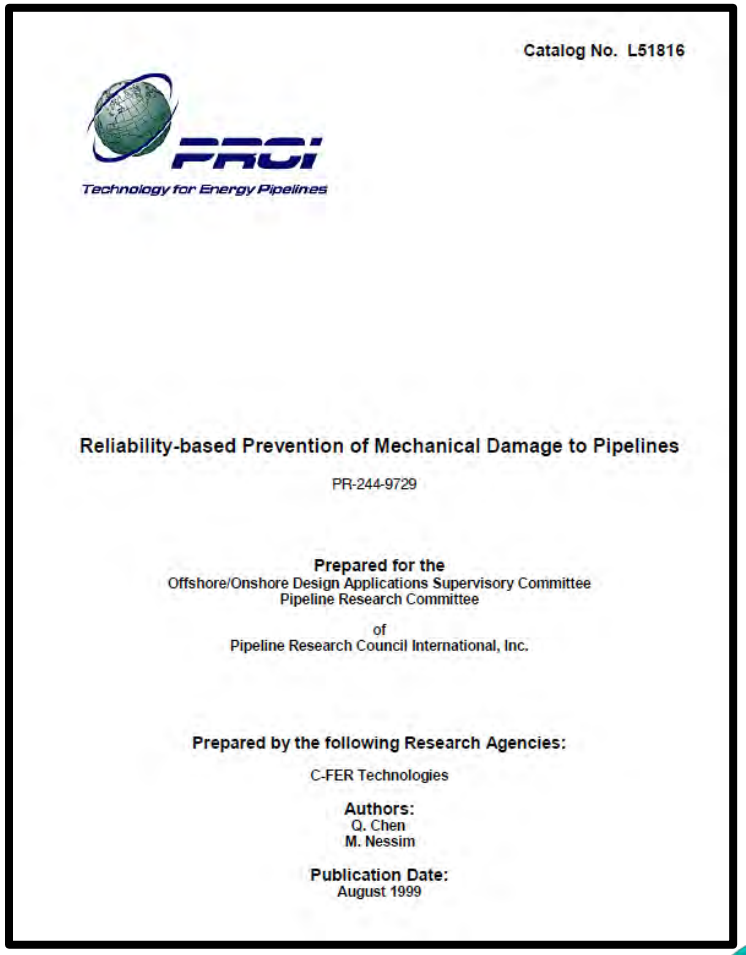
Project Objective



Project Objective

- **Excavation damage is one of the leading causes of failure for gas transmission pipelines, making up 14% of all events from 2010 to 2018 (PHMSA 2019)**

- **Work sponsored by PRCI[1] has resulted in a reliability-based approach that utilizes:**
  - A fault tree model for the frequency of mechanical interference by excavation equipment
  - A structural reliability model for the probability of failure given impact from excavation equipment



Catalog No. L51816

PRCI
Technology for Energy Pipelines

Reliability-based Prevention of Mechanical Damage to Pipelines

PR-244-9729

Prepared for the
Offshore/Onshore Design Applications Supervisory Committee
Pipeline Research Committee
of
Pipeline Research Council International, Inc.

Prepared by the following Research Agencies:
C-FER Technologies

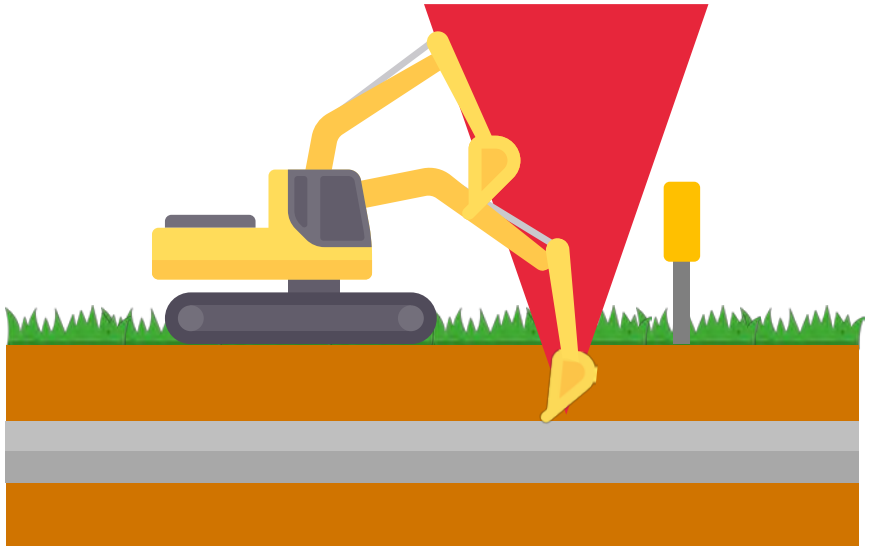
Authors:
Q. Chen
M. Nessim

Publication Date:
August 1999

1. Chen, Q. and Nessim, M. 1999. "Reliability-based Prevention of Mechanical Damage to Pipelines". Submitted to Pipeline Research Council International. Catalog PR-244-9729.

Project Objective

$$P_{Failure} = P_{Excavation}$$



Project Objective

$$P_{Failure} = P_{Excavation} \cdot P_{Prevention\ and\ Protection\ fails} \cdot P_{Failure\ Given\ Hit}$$

Operator Data

Land Use	Notifications	km·year	Notifications per km·year
Commercial / Industrial	30	118	0.26
High density residential (class 3)	46	359	0.13
Low density residential	29	166	0.18
Agricultural	403	10546	0.038
Remote	97	3282	0.030

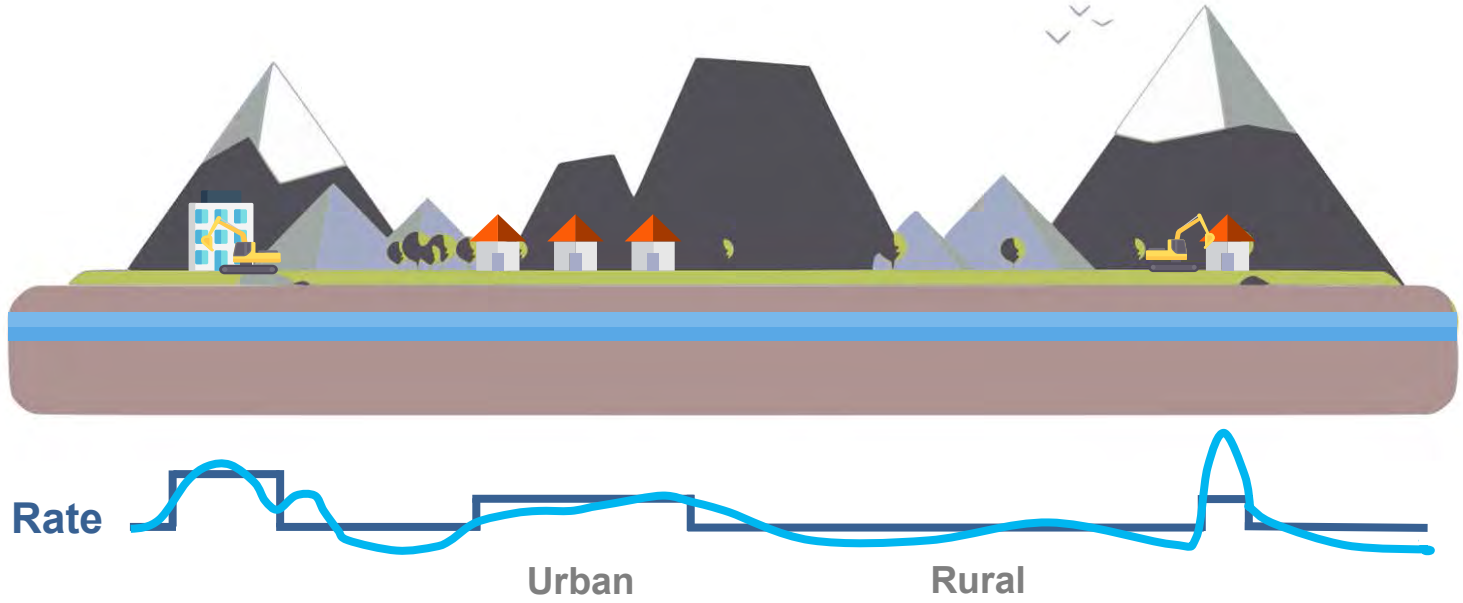
Table 4.1 Excavation notification as a function of adjacent land use (North America).

Fault Tree Model

Structural Reliability Model

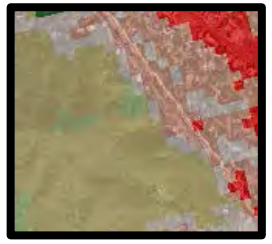
Project Objective: Enhance Model Inputs

- **Conventional Approach**
  - Classify regions
  - Calculate average historical rate
  - Look for discrepancies
  - Repeat process, adding regions
- **Machine Learning Approach**
  - No regions required
  - Location-specific prediction
  - Standardized evaluation metrics
  - Easily updated in future

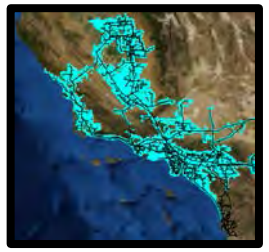


Project Methodology

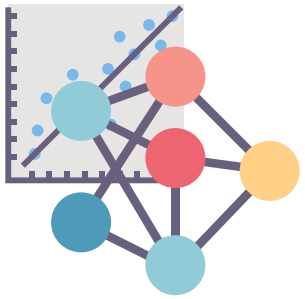
Data Sources (e.g. land use)



One-call notifications



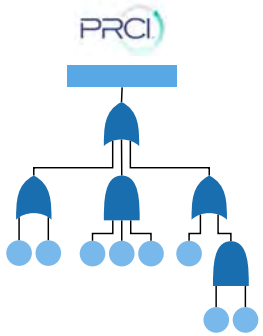
Machine Learning Regression Model



One-Call Notification Rate Prediction

Data Analytics

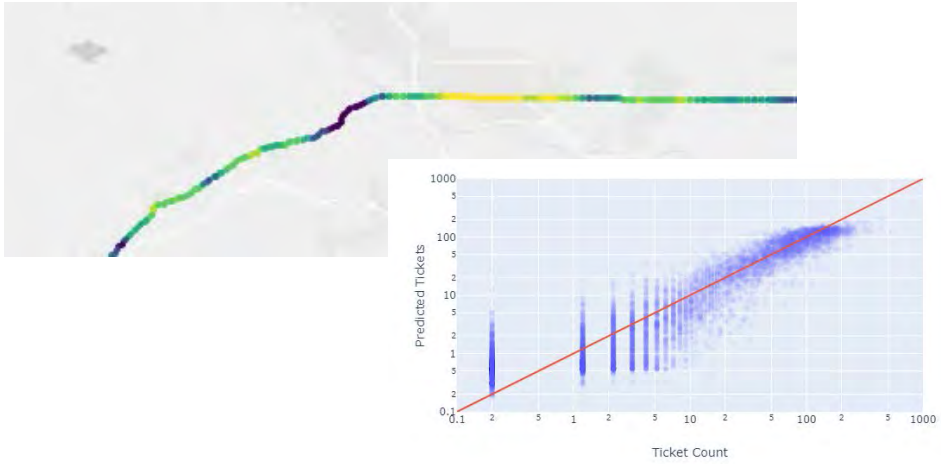
Engineering Model



Project Results

- **One-call data and public data sources were used with a machine learning regression model**
- **The model makes location-specific predictions of the rate of excavation notifications along a gas transmission pipeline network**

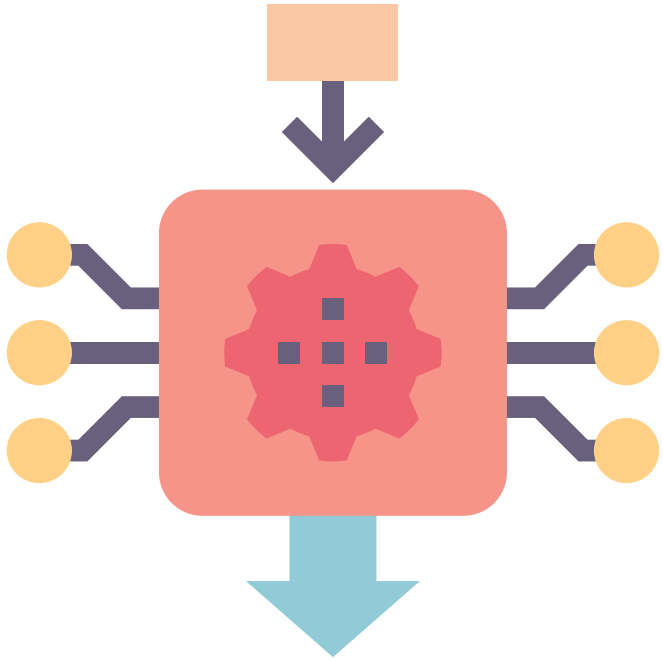




- **This project demonstrates**
  - A case study in how machine learning models can be used to enhance existing risk assessment approaches
  - How public data sources can be utilized to improve risk estimates
  - How an increase in accuracy comes with a cost of decreased interpretability, for many machine learning models

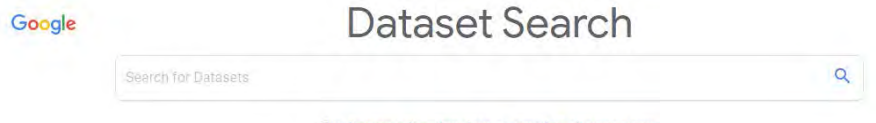
What is Machine Learning?

- **Machine learning is a term that encompasses a set of related algorithms**
- **These algorithms automatically fit to patterns in the input data in order to make a prediction**
- **Some of these technologies have made remarkable progress in recent years**
  - Self Driving Cars
  - Voice Assistants



Why now?

- Increased availability of data
- Increased computational power
- Increased access to algorithms
- Increased support from industry



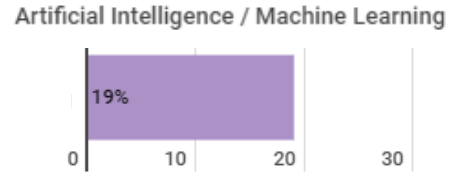


scikit learn

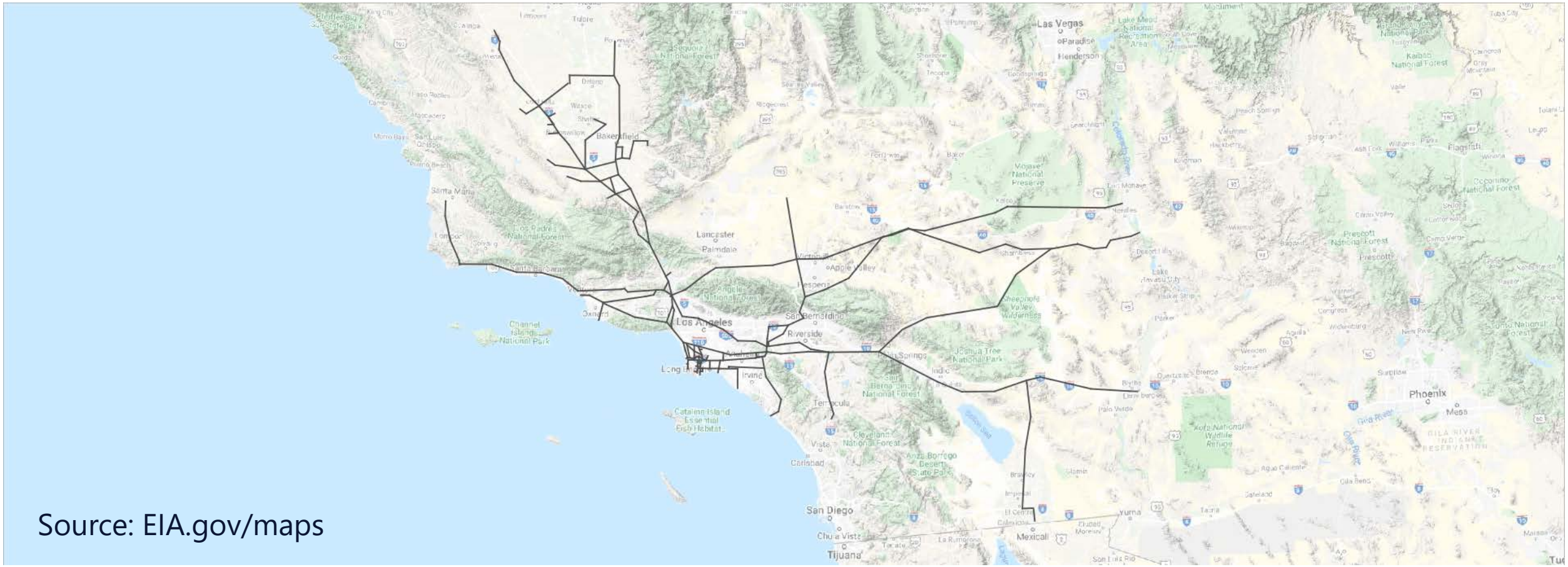
TensorFlow

Technologies in current use:
Oil & gas

Harvey Nash / KPMG CIO Survey 2019



REX2020
PRCI RESEARCH EXCHANGE

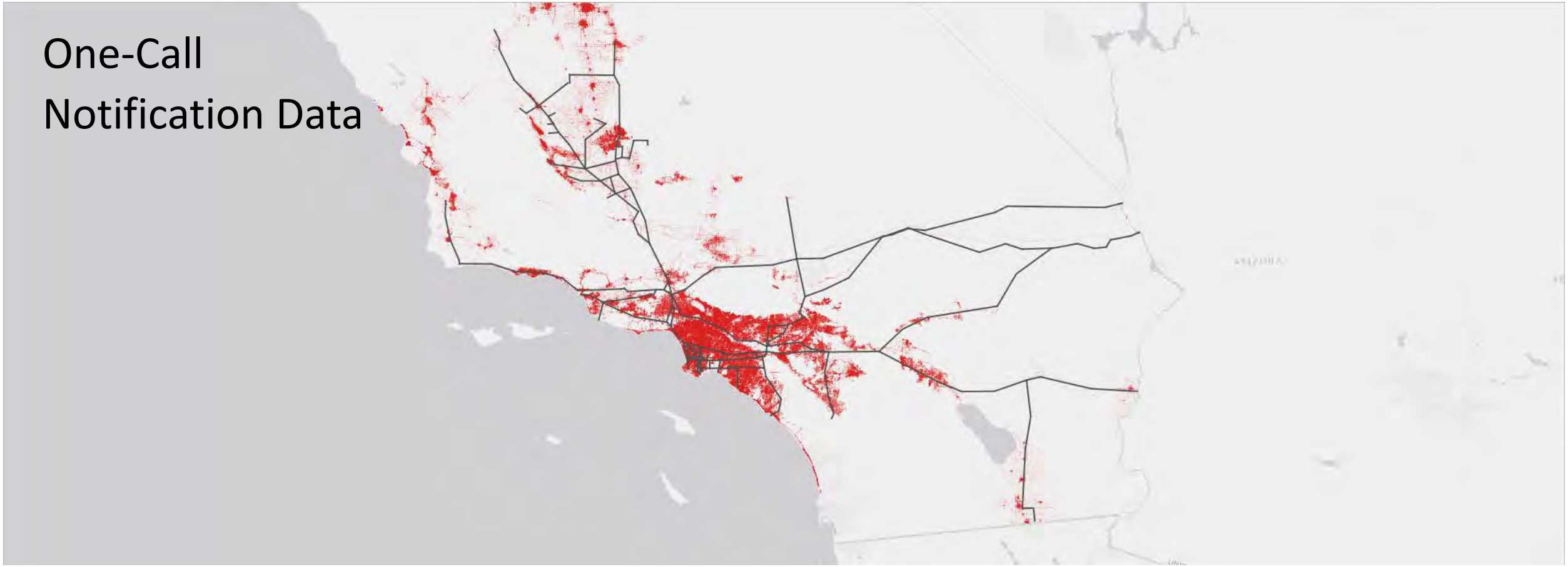


Source: EIA.gov/maps



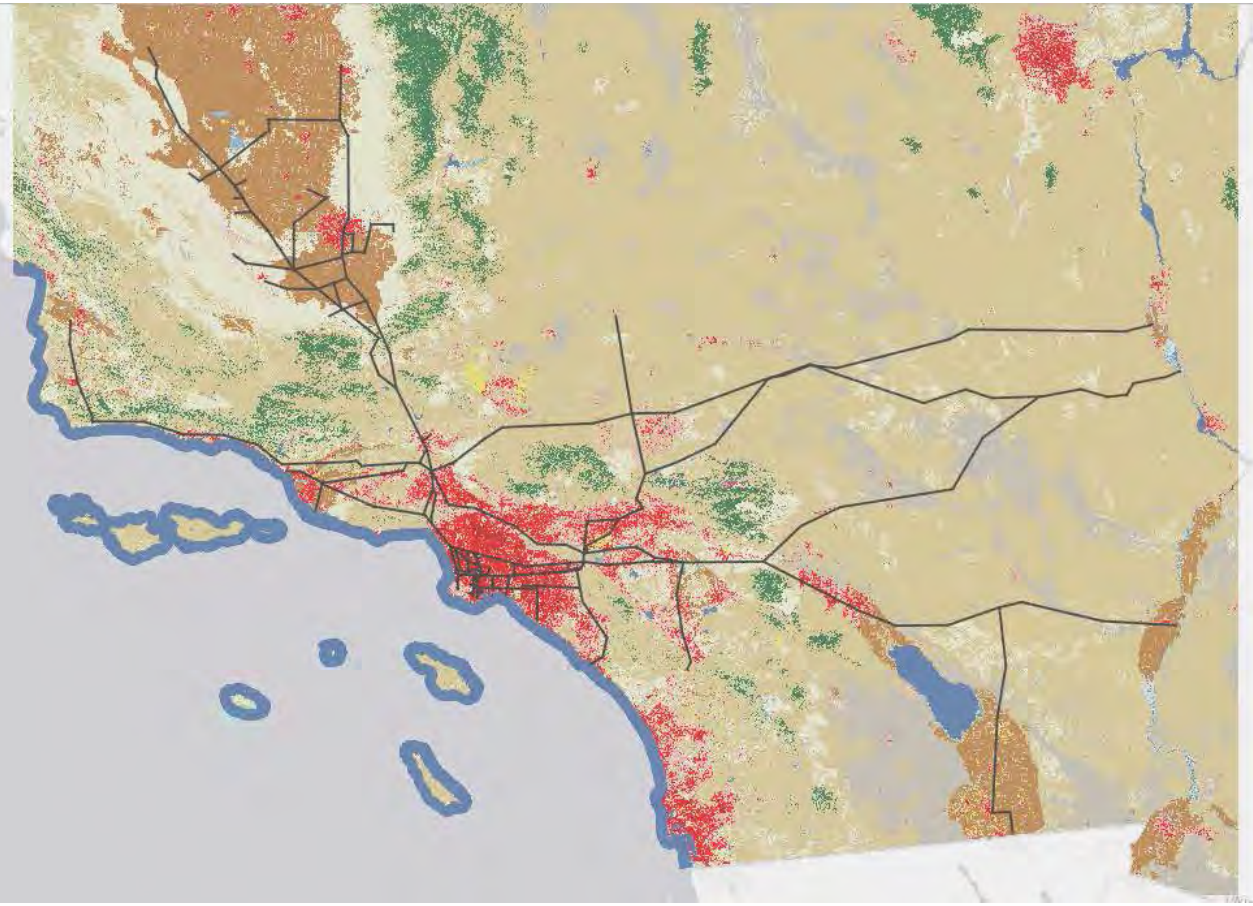
Source: EIA.gov/maps

One-Call Notification Data



Land Use

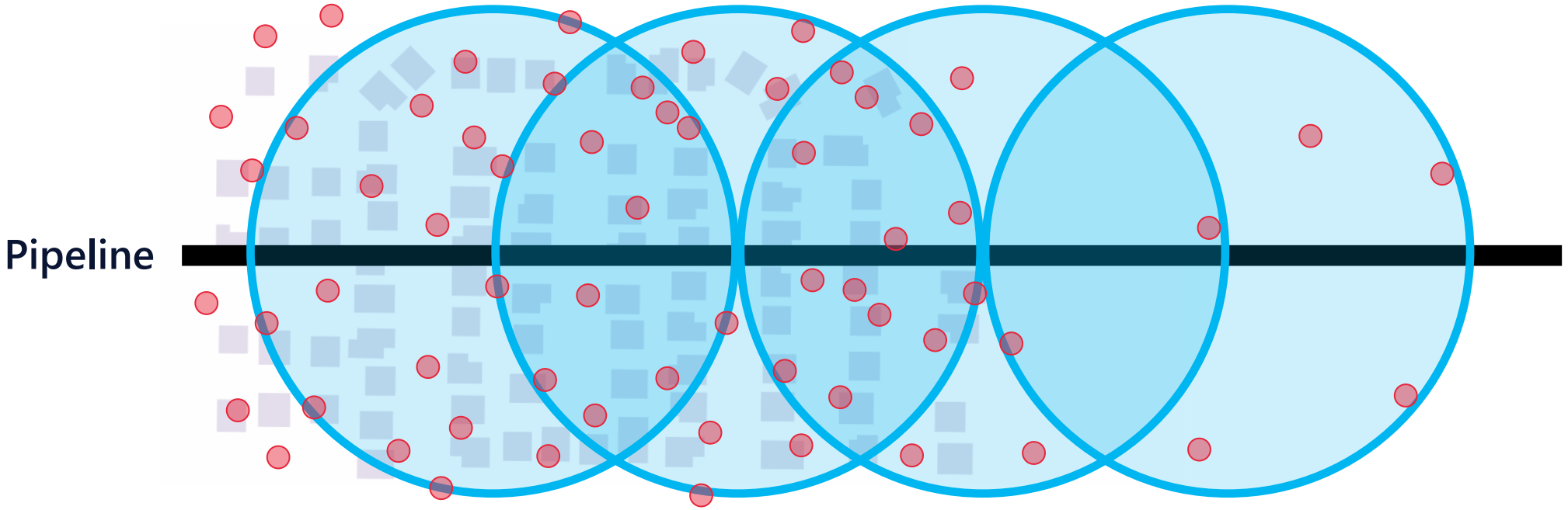
NLCD 2016



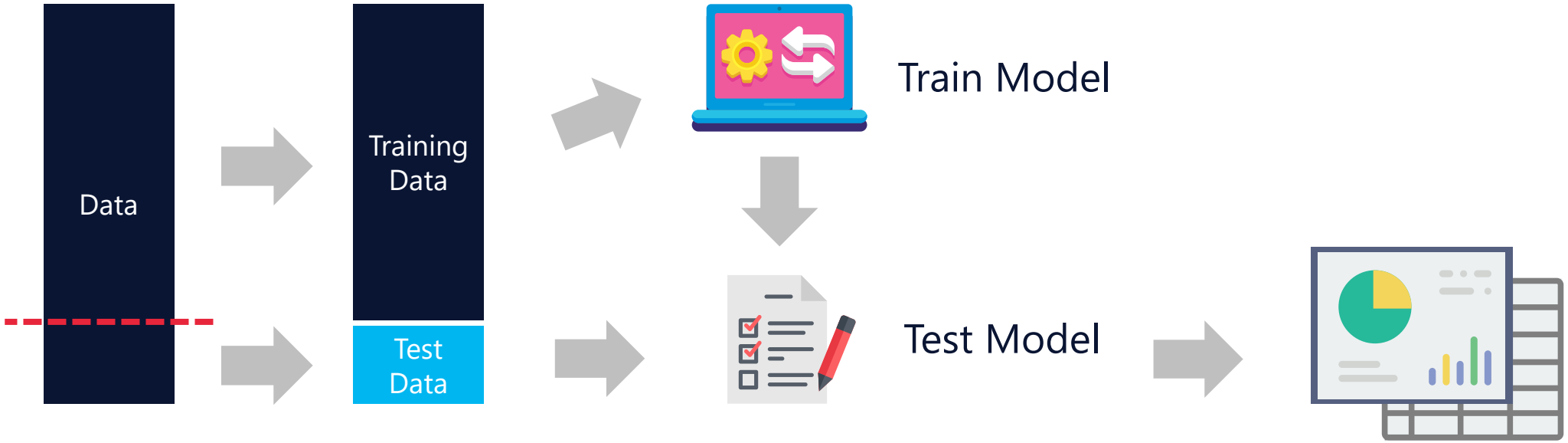
Data released May 10, 2019

Project Methodology

Land Use → One Call Notifications



Machine Learning Workflow



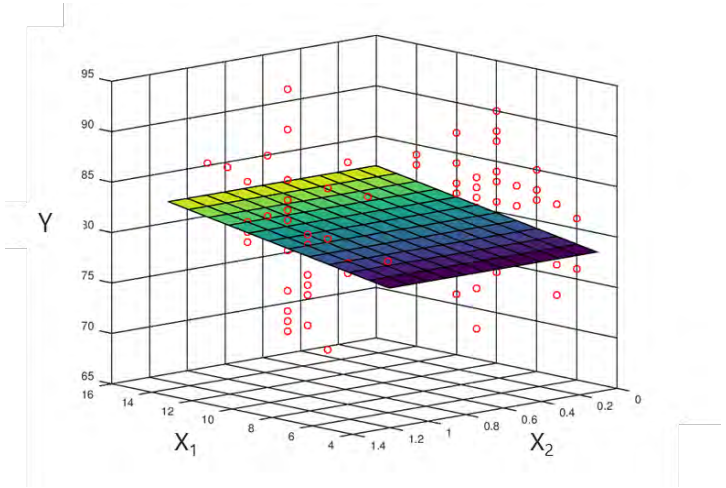
Collect Data

Train Model

Results

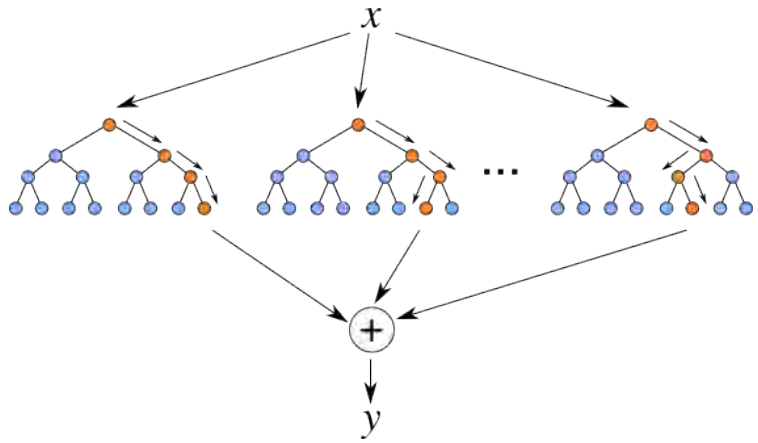
Model Types

Multiple Linear Regression



- Simple and interpretable
- Can extrapolate beyond training data
- Assumes an independent and linear relationship between features and target variable

Tree-based Ensemble Model

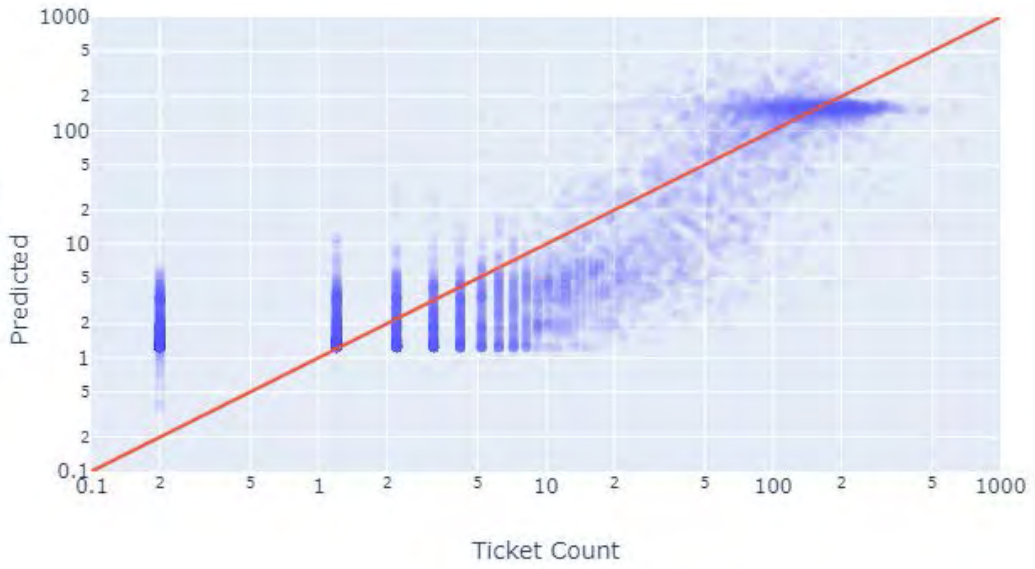


- Tree-based ensemble methods are widely used
- Able to capture higher order interactions
- Invariant to input scaling and co-linearity
- Can combine continuous and categorical data

Land Use Data Only

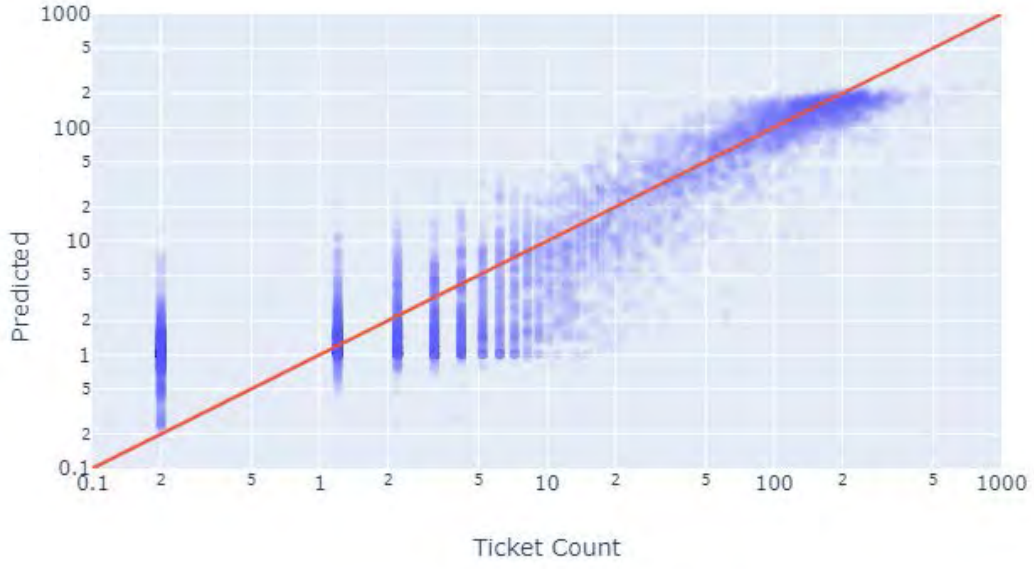
Multiple Linear Regression

R^2 (Test Data)	**0.71**
Average Error Ratio (Test Data)	**2.59**

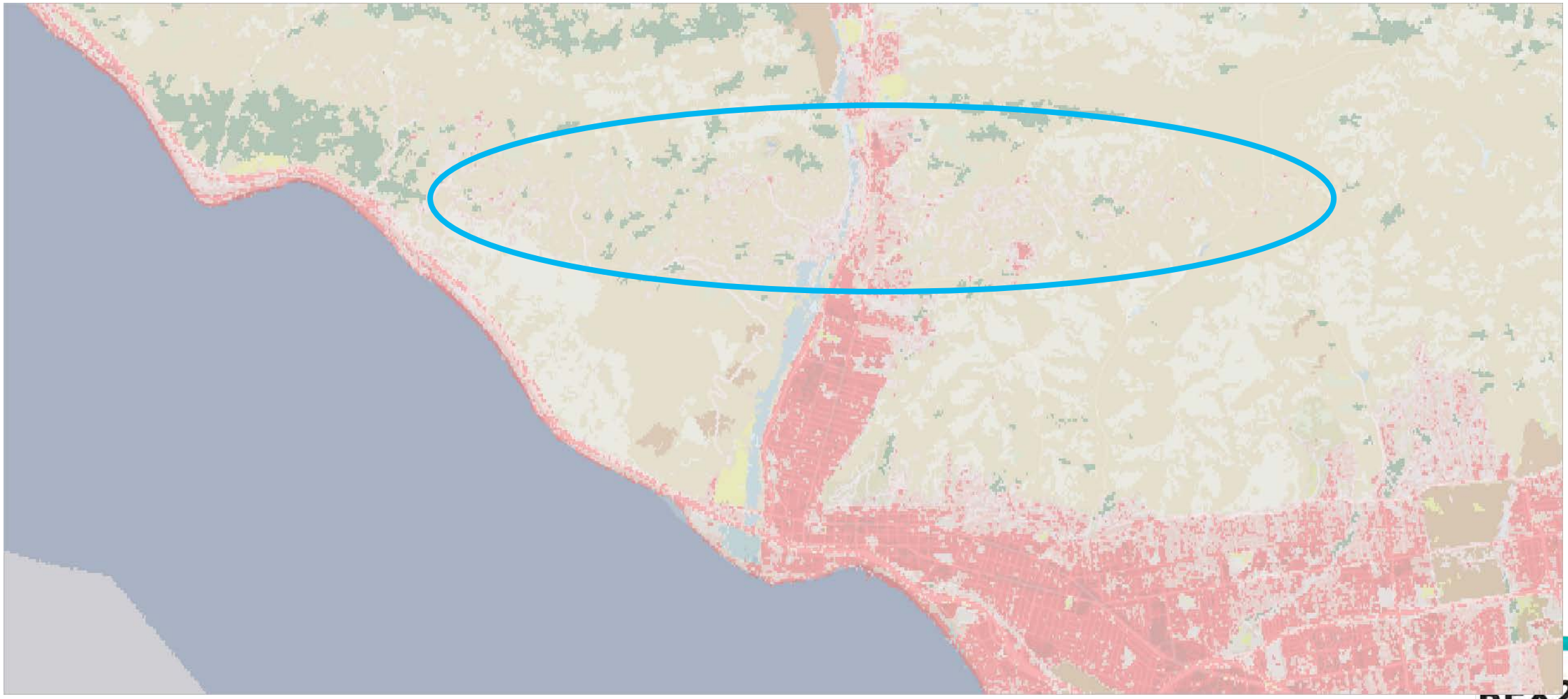


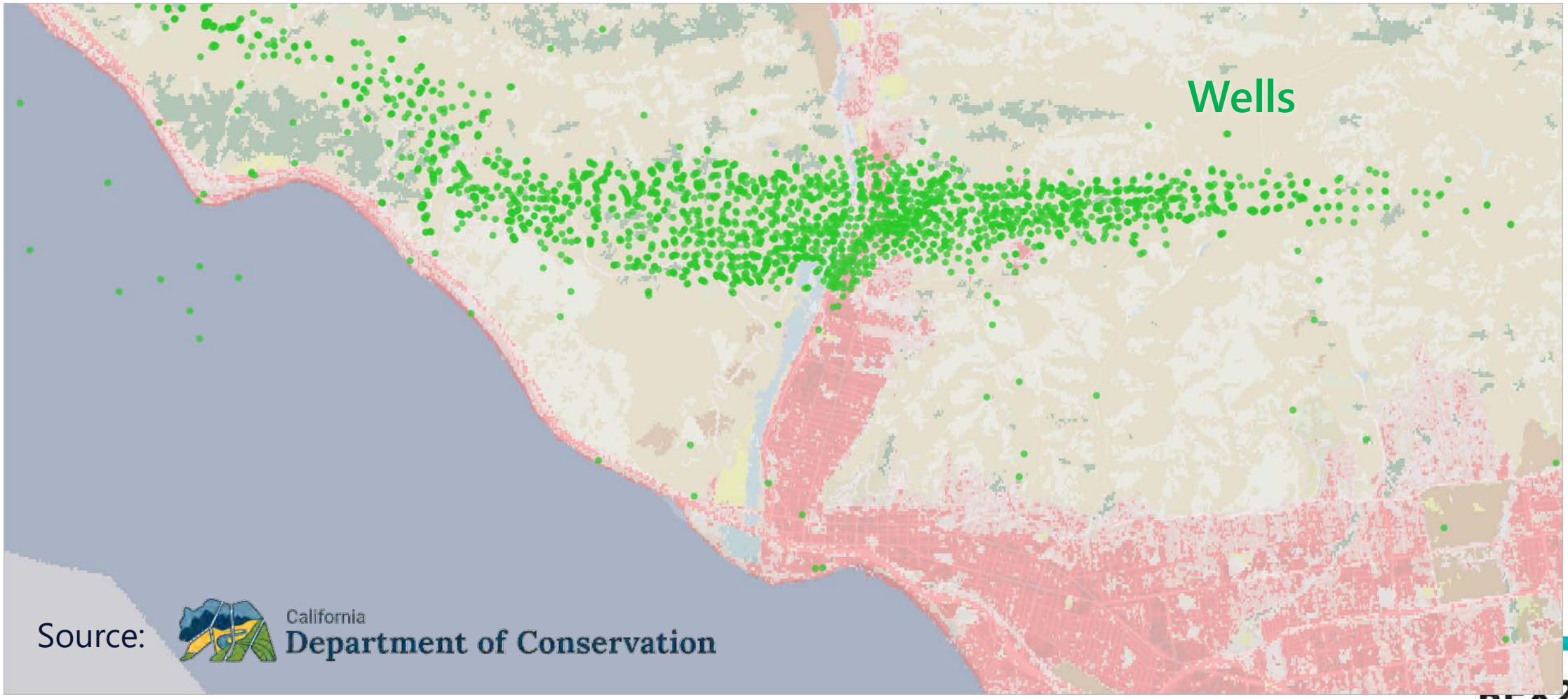
Tree-based Ensemble Model

R^2 (Test Data)	**0.78**
Average Error Ratio (Test Data)	**2.23**



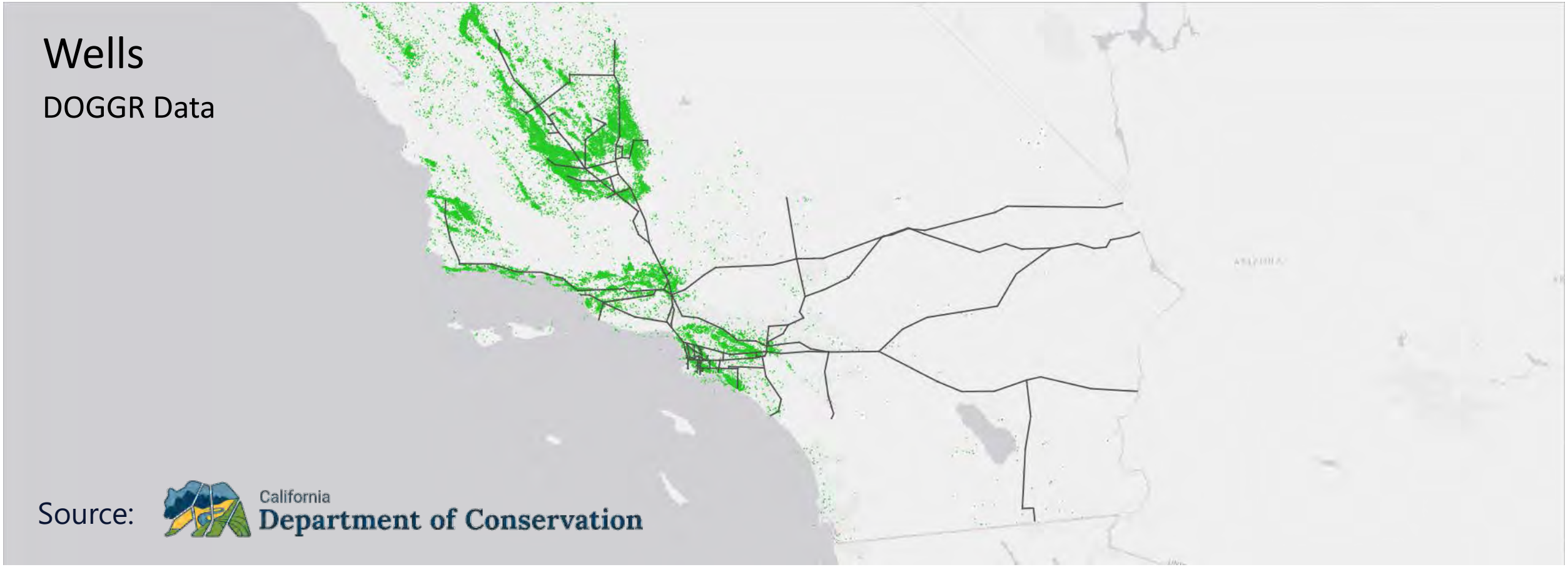
Area with more one-call notifications than predicted




Wells
Source:
California
Department of Conservation

Wells

DOGGR Data

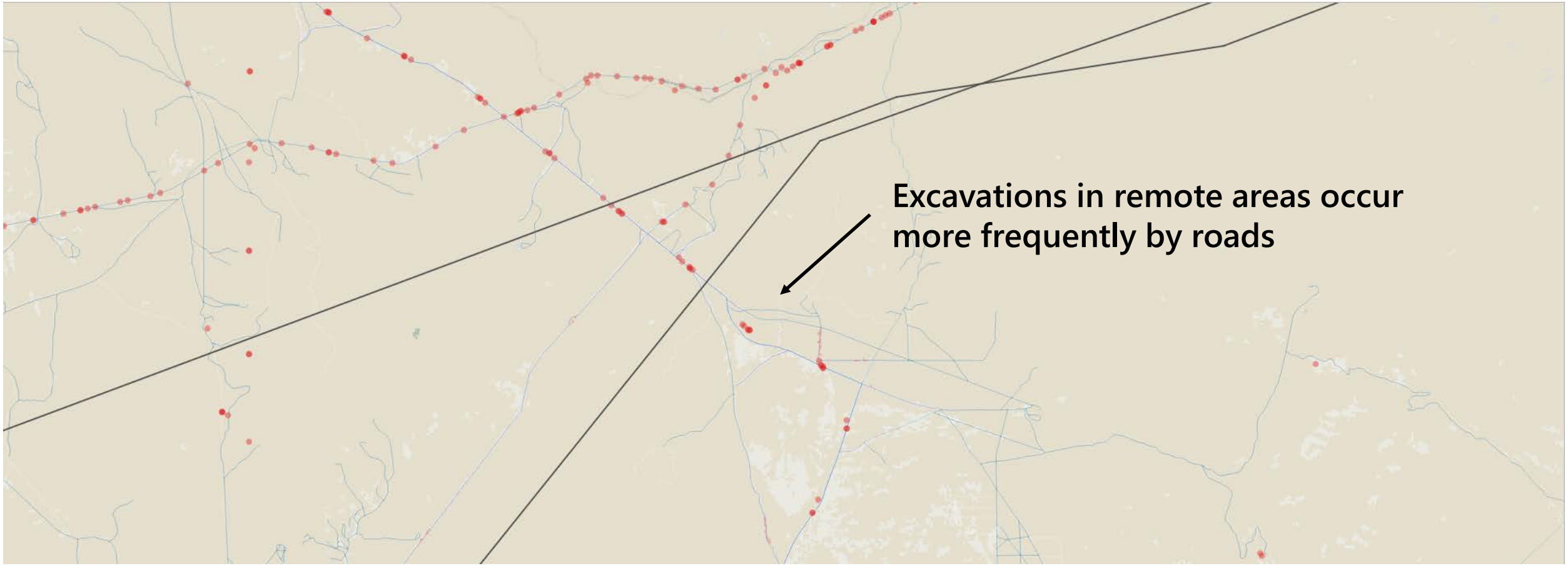


Source: California Department of Conservation

Parks

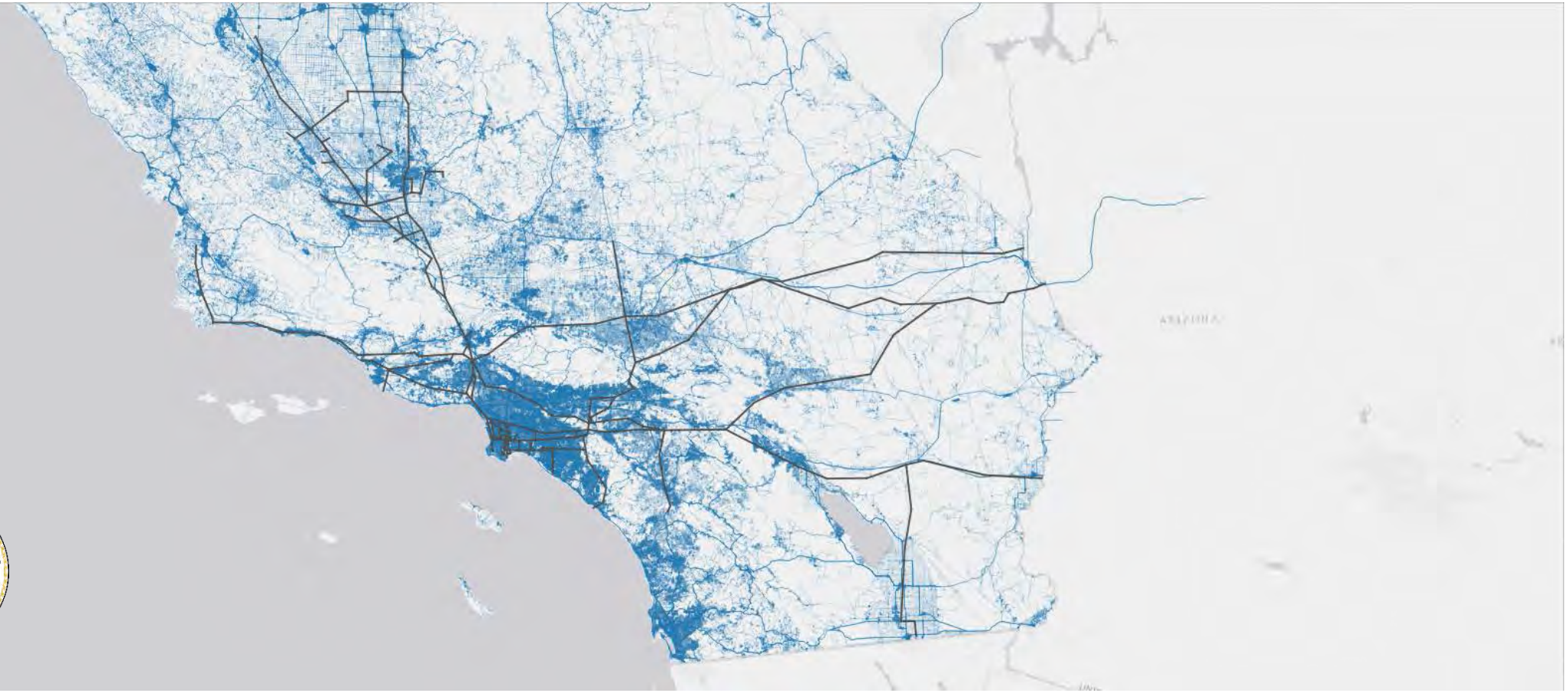


Source: California Department of Parks and Recreation


Excavations in remote areas occur more frequently by roads

Roads

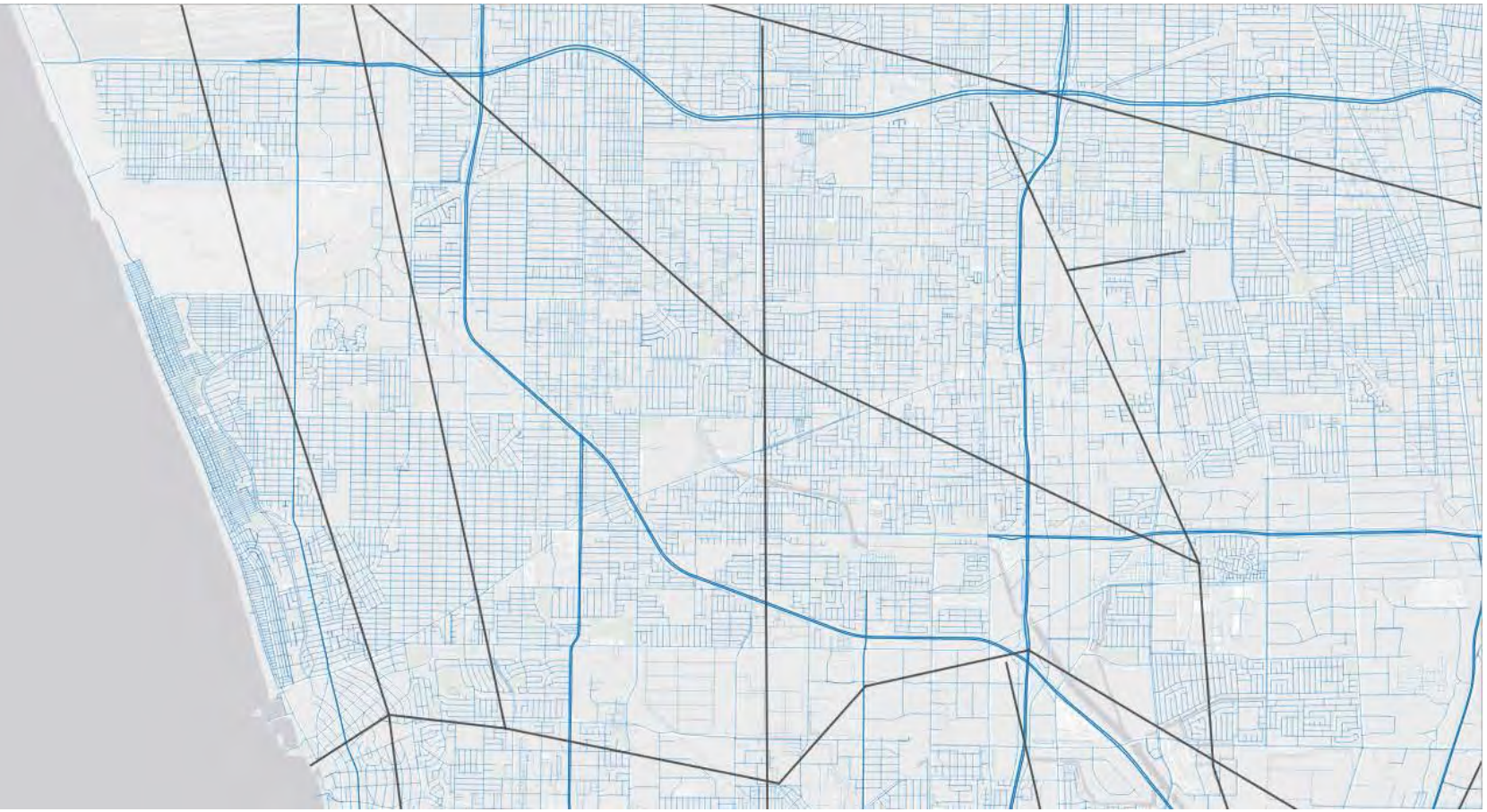
Tiger Data



Source:

Roads

Tiger Data



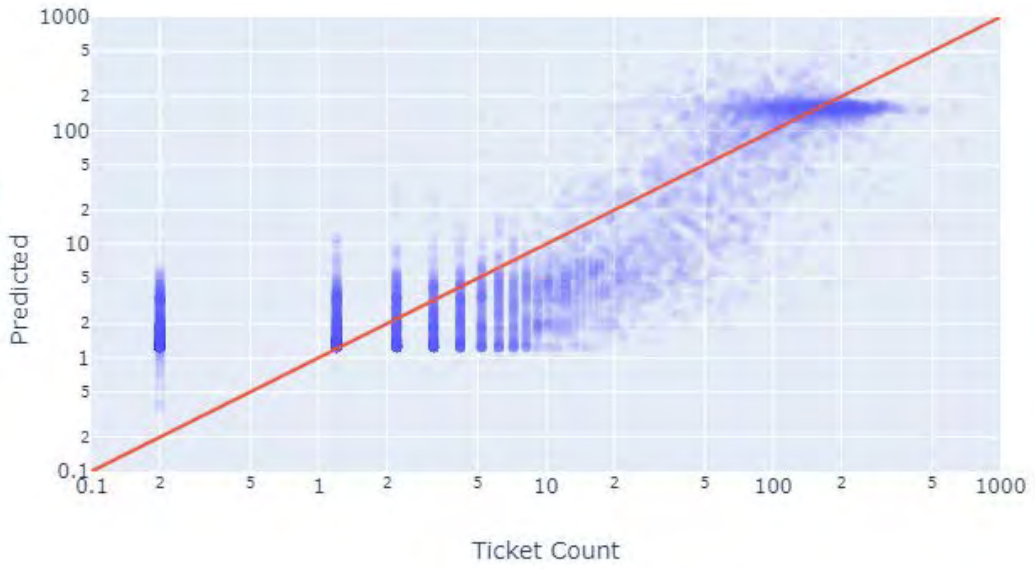
Source:

Initial Model Results

Land Use Data Only

Multiple Linear Regression

R^2 (Test Data)	**0.71**
Average Error Ratio (Test Data)	**2.59**



Tree-based Ensemble Model

R^2 (Test Data)	**0.78**
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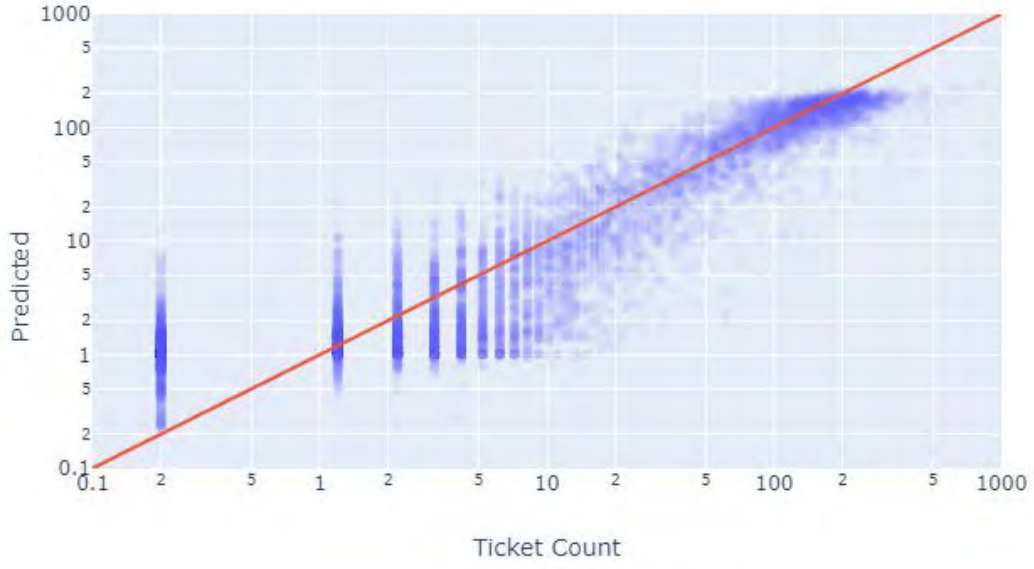
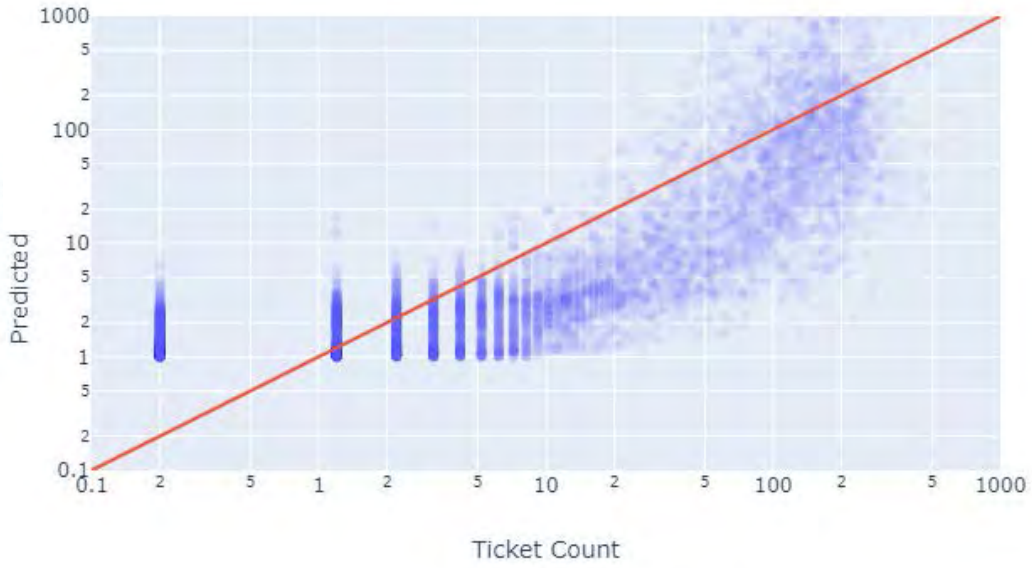


Updated Model Results

Land Use Data + Wells + Parks + Roads

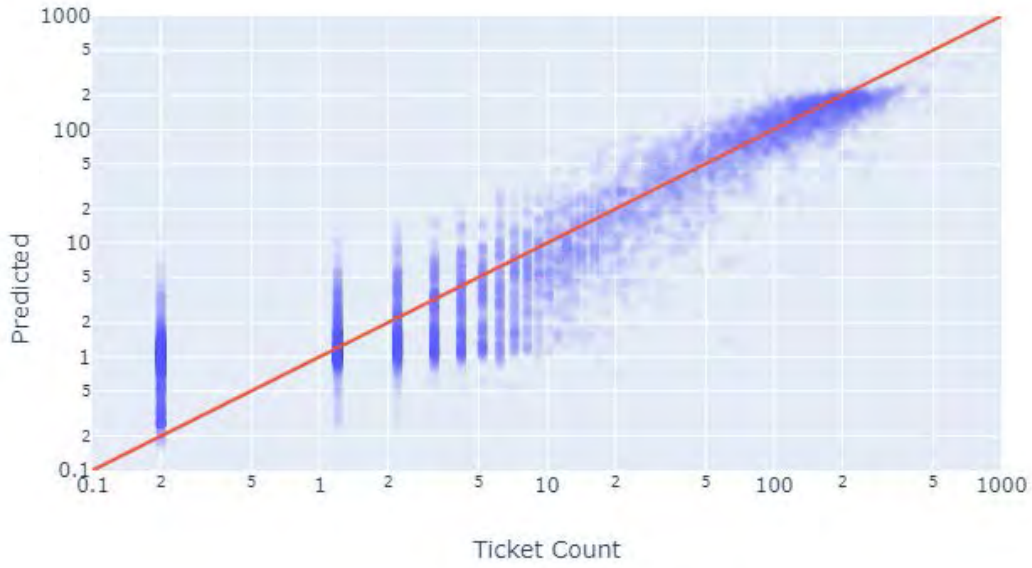
Multiple Linear Regression

R^2 (Test Data)	**0.60**
Average Error Ratio (Test Data)	**3.28**



Tree-based Ensemble Model

R^2 (Test Data)	**0.82**
Average Error Ratio (Test Data)	**2.04**



Lessons Learned

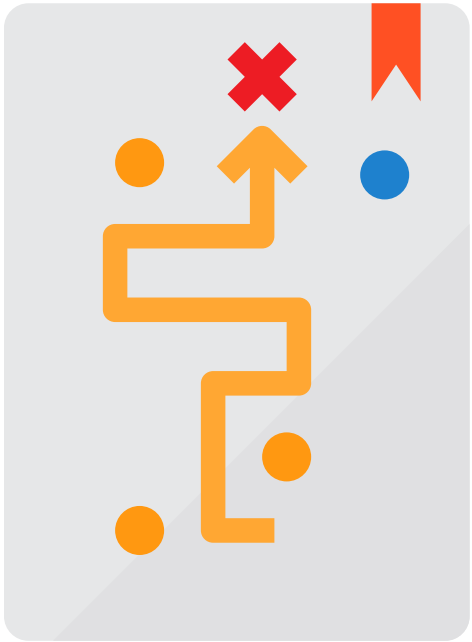
- Machine learning models can automate data processing, improve data quality and reduce cost.
- Some models, such as tree-based ensemble methods readily handle common issues like co-linearity, non-linearity and feature interactions, which are problematic for more conventional models such as linear regression



5 Steps for A.I. Adoption

From the *AI Transformation Playbook,* Andrew Ng

1. Execute pilot projects to gain momentum
2. Build an in-house AI team
3. Provide broad AI training
4. Develop an AI strategy
5. Develop internal and external communications



Ng, A. (2020). *AI Transformation Playbook: How to lead your company into the AI era*. January 2020, from https://landing.ai/ai-transformation-playbook/

Contact Information

Daryl Bandstra

dbandstra@integraleng.ca

780-700-8483



BACK TO AGENDA

PRCI 2020 Research Exchange

Natural Gas Transmission Prognostics with Machine Learning

Using Novel Signatures from Deployed Transmission Infrastructure & Sensors

Kayte Denslow, Naveen Karri, William Rosenthal, Francesca Grogan, Juan Brandi-Lozano, Arun Veeramany, Angela Dalton, Casie Davidson

Pacific Northwest National Laboratory

Richland, WA

PNNL-SA-151714

LEADING PIPELINE RESEARCH

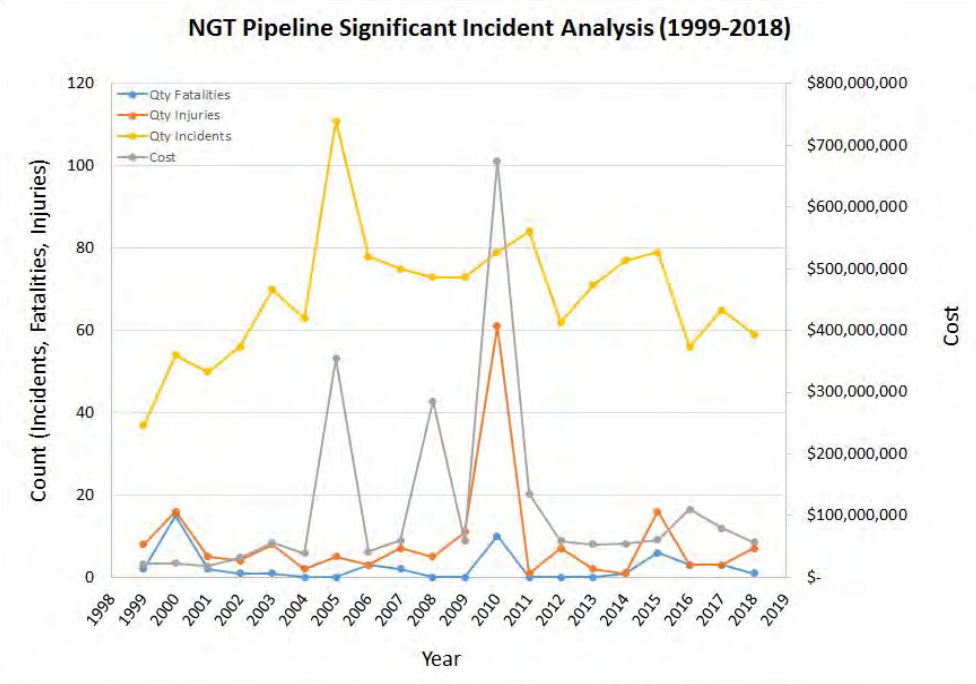
Introduction

Problem:

- Despite advances in inspection technologies, significant incidents continue to occur that undermine the safety and reliability of natural gas transmission pipelines
- Insights from past NGT lifecycle data and novel signatures from in-line inspection data can improve the prediction (and enable better avoidance) of incidents

Objective:

- Quantify current condition of pipeline networks by developing a Health Index from sensor measurements and historical operating data
- Forecast (predict) component and system condition and remaining useful life (RUL)/reliability expected over defined time horizons

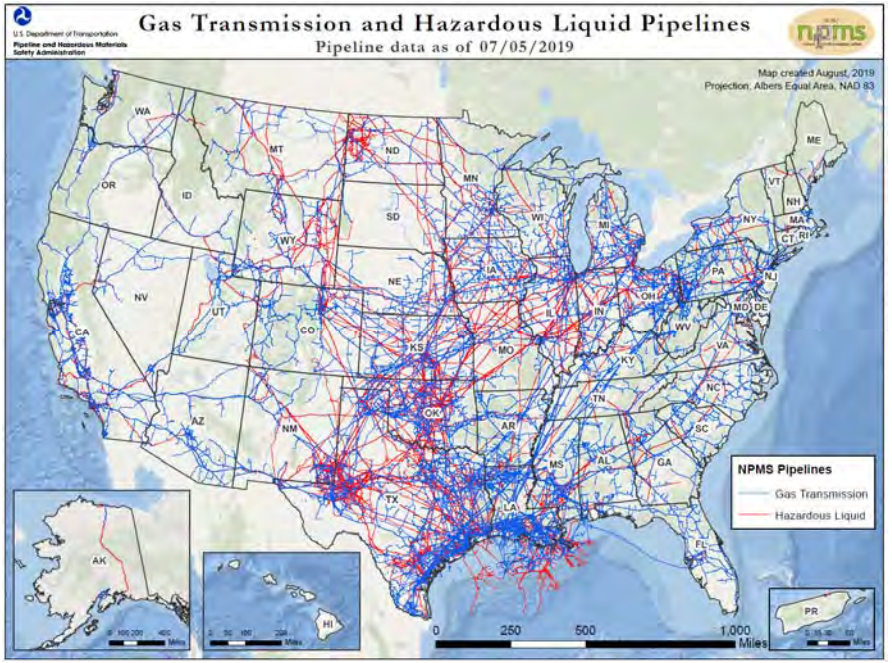


Data source: PHMSA (https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends)

Improve decision-making to increase critical infrastructure safety & reliability through reduction of risks of pipeline incidents/failures that compromise safety and result in property damage and supply interruptions

Motivation

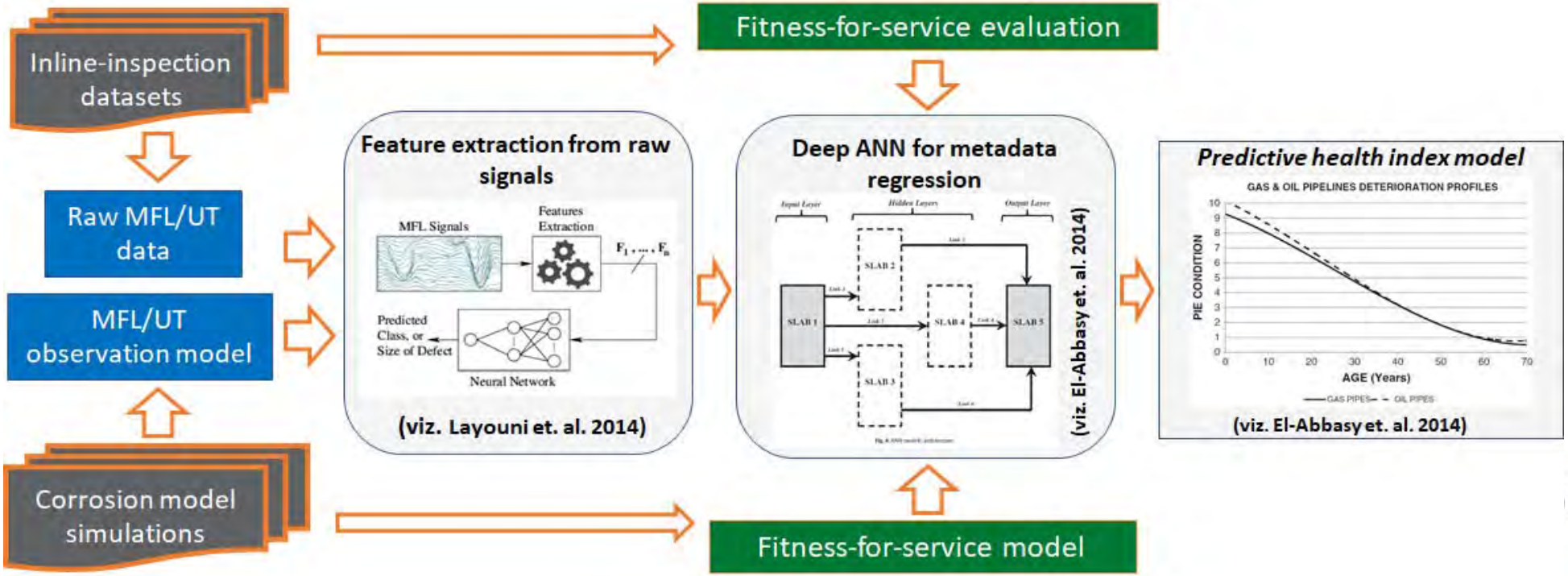
- Natural gas transmission pipelines represent critical infrastructure in U.S. energy sector
- Play vital role of facilitating transport of natural gas
- NGT reliability will continue to increase in importance as:
  - natural gas industry/operators strive to meet growing demand for natural gas, and
  - federal stakeholders and regulators strive to ensure its safe, uninterrupted supply
- Office of Fossil Energy interested in sustaining reliability of critical infrastructure (and safety)
  - goal shared by operators, researchers, regulator



Nationwide map of domestic natural gas transmission and hazardous liquid pipelines (Source: https://www.npms.phmsa.dot.gov/Documents/NPMS_Pipelines_Map.pdf).

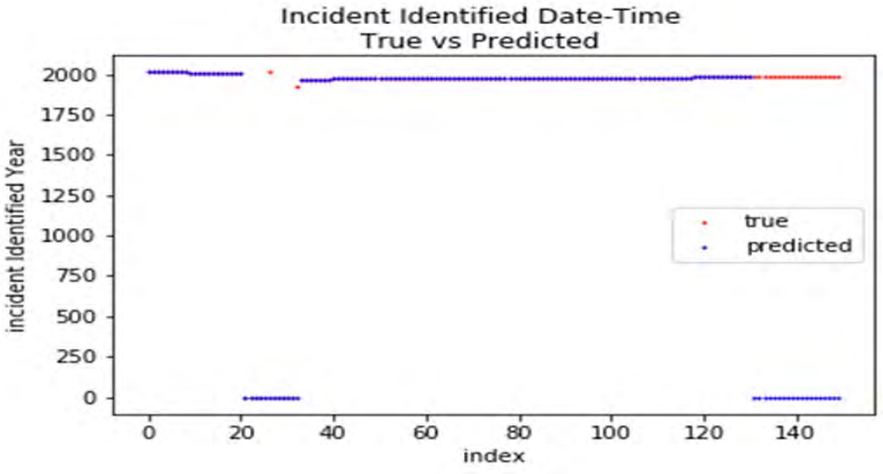
Progress to date

- Framework for health index & RUL prediction: Hybrid Physics-based/Data-driven (HBDD) model
- Defined HBDD data needs, started with feeding PHMSA incident data to the HBDD model
- Identified potential data sources and reaching out seeking partners who share the same goal



Preliminary Machine Learning Results

Feature Variables		Target Variable	
Column Name	# Possible States	Column Name	# Possible States
IYEAR	49	INCIDENT_IDENTIFIED_DATETIME	43
ON_OFF_SHORE	3		
ITEM_INVOLVED	3		
PIPE_TYPE	6		
PIPE_DIAMETER	83		
PIPE_MANUFACTURER	61		
PIPE_MANUFACTURE_YEAR	56		



- Use PHMSA Data to show DNN applications.
- Scripts were created to clean and give more consistent structure to data.
- Only PHMSA data with failure due to corrosion is used. About 1500 samples.
- Data was split into an 80/10/10 split.
- Predicting incident identification year.
- Model achieved a rough ~86% accuracy i.e., model correctly predicted the incident year 86% of the time.

Statistical Analysis of Predictive Capability of Pipeline Factors Using ANalysis Of Variance (ANOVA)

Key Outcomes for Pipeline Failure Prediction

- Quantified predictive power of factors that correlate with age of pipeline failure.
- Individually compared predictive power of both *categorical* and *continuous* factors.

Comparative analysis of predictive power of available failure data (PHMSA)

- Pipeline parameters generally significant alone; comparison of F ratios determines relative predictive power.

Caveats of ANOVA for failure analysis

- Data may not provide balanced sample counts, a best practice.
- Sensitive to continuous variable binning; but also enables model comparison.

Parameter	# Bins	# Samples		F	α
Continuous					
Duration of cathodic protection	5	$82 - 97$ (range of counts)		**78.64**	1.0000
Pipe diameter	5	$55 - 138$ (range of counts)		**4.5263**	0.9986
Discrete					
Defect location	2	Internal: 115 External: 319		**124.88**	1.0000
Pipe coating type	4	Coated: 286 None: 80	Wrapped: 42 Tarred: 26	**33.87**	1.0000

Variance explained by parameter:

$$MS_R = \frac{SS_R}{\text{dof}(SS_R)}$$

Degree of explained variance:

$$F = \frac{MS_R}{MS_E}$$

Variance not explained by parameter:

$$MS_E = \frac{SS_E}{\text{dof}(SS_E)}$$

Statistical Analysis of Predictive Capability of Pipeline Factors Using ANalysis Of Variance (ANOVA)

Initial results: ANOVA significance tests

Parameter	# Bins	# Samples	F	α
Continuous				
Pipe diameter	5	$232 - 582$ (range of counts)	**25.32**	1.0000
Maximum operating pressure	5	$425 - 589$ (range of counts)	**53.31**	0.9998
Pipe wall thickness	5	$454 - 559$ (range of counts)	**76.41**	1.0000
Seasonality	2	10/1-3/31: 1377 4/1-9/30: 1113	**0.0004**	0.0161
Discrete				
Cathodic protection	2	Yes: 1782 No: 483	**12.40**	0.9996
Pipe coating	2	Coated: 1523 Uncoated: 960	**131.3**	1.0000
Commodity released	2	Crude: 2070 Pressurized gas: 800	**33.87**	1.0000
Defect location	2	Internal: 1777 External: 713	**54.30**	1.0000

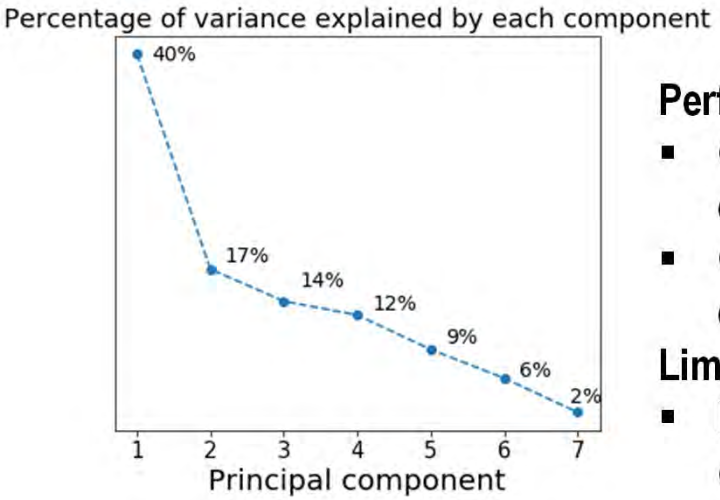
Application to Hazardous Liquid Transmission

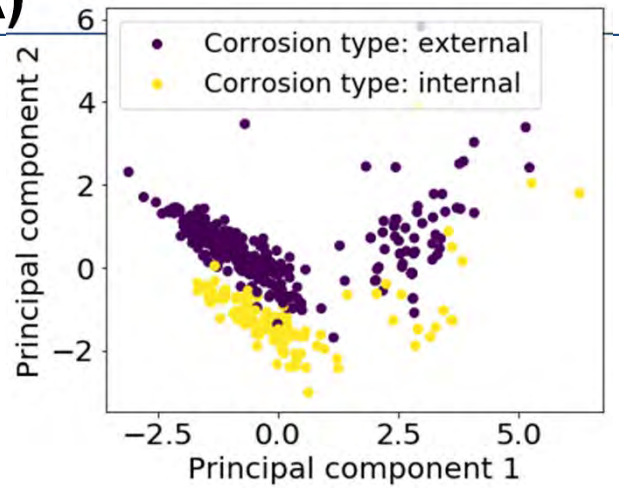
- Relative *F*-scores suggest a ranking of significance in predicting failure.
- For continuous parameters, *F-score* can be sensitive to binning
- Attempt made to balance category size when binning continuous variables
- As a control, considered seasonality of incidents. Not a significant predictor of time to corrosion failures.

Feature Extraction and Dimension Reduction Using Principal Component Analysis (PCA)

Applicability to End Objective

- With large data sets, dimension reduction techniques are necessary for sensible analyses.
- Having a set of features that are *relevant* and *non-redundant* → less computational expense





Performed PCA on PHMSA data set

- Output is a set of principal components, ordered by greatest amount of explained variance (left fig.)
- Can project the data set onto first two components to visualize clustering behavior (top fig.)

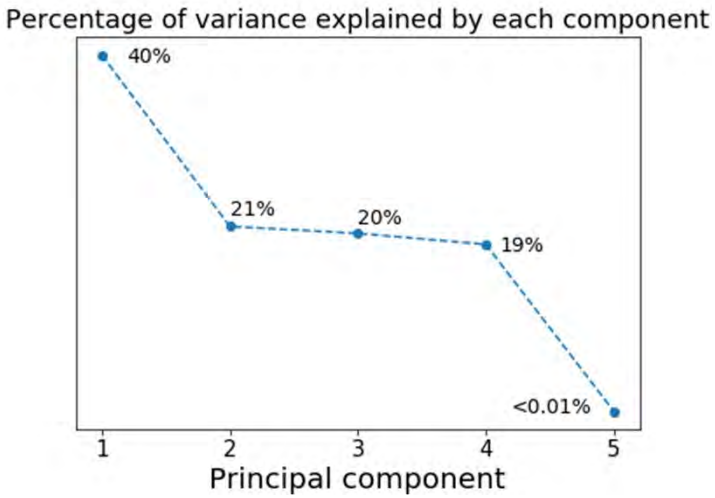
Limitation of Example

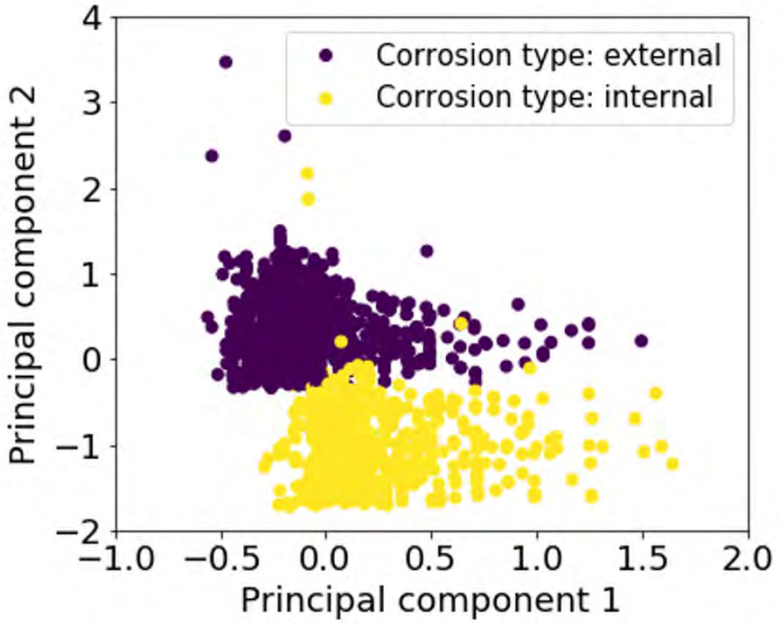
- Example data set contained a small amount of features and samples; dimension reduction was not really needed here, but will be needed in the future

Feature Extraction and Dimension Reduction Using Principal Component Analysis (PCA)

Initial results using hazardous liquid transmission data

- Feature extraction and machine learning techniques can be performed on both gas and oil data
- Curation recently begun for oil data, ongoing
- Significantly more samples (~2500)





Ultimate Project Objective

- Vision: Pipeline operators use a Pipeline Health Diagnostic (“PHD”) software tool as part of their SCADA that provides them:
  - pipeline health status (situational awareness)
  - predictions of when pipeline repair/replacement should occur (predictive maintenance)
- Ultimate Objective: Develop commercial-grade “PHD” software tool that provides pipeline health index and guidance on remaining service life per pipeline
  - based on calculations performed using pipeline in-line inspection data, operating conditions data, and a pipeline prognostic model
  - would be an optional tool provided to operators that provides predictions intended for “information only” to help operators



	Health Index	Estimated Remaining Service Life	Last Updated
Pipeline A	9	20 yrs	2022
Pipeline B	7	10 yrs	2023
Pipeline C	3	2 yrs	2025

Implementation Plan

- **Work with DOE and the O&G industry to establish the analytical capability behind the "PHD" software**
  - Develop analytical framework – will rely on:
    - *data analytics capability and NDE program at PNNL*
    - *previously-developed prognostic models at PNNL, and fitness-for-service models from API/ASME*
  - Perform machine learning on past pipeline data (the training data set) – will rely on:
    - *data analytics capability and NDE program at PNNL*
    - *past in-line inspection and operating condition data for access to a large data set owned by PHMSA/O&G industry*
- **Test a "research-grade" version of prototype PHD software for at least one pipeline/test case**
  - Will rely on smaller, *newly generated* pipeline data set (inspection, operating data) from at least one interested O&G pipeline operator

cont.

- Expand testing of the prototype PHD software to other pipelines/test cases
- Complete PHD version 1.0
- **Technology Transfer/Commercialization**
  - Work with a tech-transfer partner to produce commercial-grade PHD software for installation on a per-pipeline/operator basis
  - Offer PHD v1.0 for adoption by pipeline operators (industry “pull”)
  - Support sustainability and evolution of the PHD software
  - Metric for success: downward trend in PHMSA reportable incidents in all categories over time (e.g., 25% over a 5-yr. period)
    - *Count, Fatalities, Injuries, Cost*

To make it a reality

- For the HBDD model behind the PHD software to make reliable predictions that are useful to you, it needs to learn on a large set of aggregated data – ***preferably*** real world data
  - Want the PHD software tool to be ***operator data-driven*** to make it the most realistic and useful tool for operators

Proposed Path:

- Grab a copy of the 1-page summary that specifies the data types needed for HBDD training data set
  - Mainly focused on ex-service pipe data
- Contact us if you want to participate / provide data and leverage the DOE project to advance pipeline prognostics
- Data handling:
  - Material Transfer Agreement
  - Aggregate/anonymize data if necessary
  - Secure data storage

Research for this project is being supported by DOE – Office of Fossil Energy

- Interest: advancing prognostic tool through application of ML to rich set of pipeline data
  - PHD software would be made available to operators to empower predictive maintenance
  - Common goal: Overall increase in pipeline reliability (safety, uninterrupted supply)

Thank you!

BACK TO AGENDA

PRCI 2020 Research Exchange

Standardization of Weld Testing Methods – Single Edge Notched Test (SENT) Fracture Toughness Measurements API-2-1

PR-214-114509

March 2020

S. Tiku, N. Pussegoda, M. Ghovanlou, W.R. Tyson, Aaron Dinovitzer

LEADING PIPELINE RESEARCH

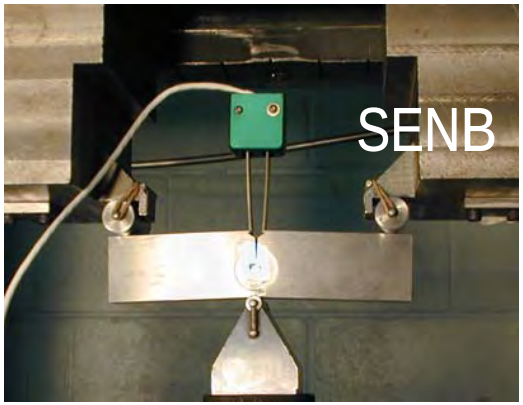
Overview

- Background
- Objective
- Activities
- Results
- Concluding Remarks

Background – SENT

- Widespread interest in fracture toughness testing of pipeline girth welds in tension
- Standard deep notched bend (SENB) specimen geometry is considered conservative. Not representative of actual pipeline loading conditions seen by girth weld flaws
- (SENT) geometry is more representative than SENB provides reduced constraint resulting in higher measured toughness thus reducing conservatism
- SENT test method used for pipeline ductile tearing resistance for tensile strain capacity prediction and strain-based design





Objective

- **Recommended Practice – Testing Standards**
  - CMAT – Single specimen procedure JR curve
  - ExxonMobil – Single specimen procedure – CTOD R curve
- **Develop a new and unified recommended practice for fracture toughness testing using single-specimen SENT samples**
  - CMAT and ExxonMobil test procedures
  - Provide sufficient guidance on all aspects of test method (e.g., side grooving, notch preparation, instrumentation, acceptability requirements and data processing)
- **Facilitate standardization of an improved SENT test method**

Scope

- Phase 1 – Conduct a workshop and develop draft test protocol for SET specimens
- Phase 2 - Round robin (RR) testing to confirm application and consistency of results for SENT Standardization for single specimen resistance curve
- Phase 3 – Additional tests @ BMT to address comments and Finalize test protocol

Phase 1 – Draft Test Protocol

- **Workshop conducted at BMT to discuss and finalize draft test protocol for round robin test program**
- **Participants:**
  - BMT
  - CMAT
  - ExxonMobil
  - CSM
  - TWI
  - NIST
  - DNV
  - SINTEF
  - Evaraz
  - Exova
  - Ludwig Associates

Standardization of Weld testing Methods-
SE(T) Fracture Toughness Measurements

Contract PR-214-114509

June 12, 2012

Phase 2 – Round Robin Test Program – (Participation)

- United States Naval Academy
- Ghent University
- TWI
- Applus
- EWI
- University of São Paulo
- SGS
- CSM
- Exova Houston
- CanmetMATERIALS (CMAT) Hamilton
- CanmetMATERIALS (CMAT) Calgary
- Engineering Mechanics Corporation of Columbus
- Defence Research Development Canada-Atlantic Research Centre
- ExxonMobil Upstream Research Company (URC)
- DNV GL Deepwater Technology Centre Singapore

Phase 2 – Round Robin - Pipe and Girth Weld

- **Materials**
  - NPS 36 x 15.7 mm (nominal wall) Grade 483 MPa (meeting Grade 550 – YS 600 MPa and UTS 686 MPa from pipe MTR)
  - Narrow Groove GMAW
  - Weld position – 1G (hot, fill and cap) and 5G (root)

- **CTOD (SENB)Testing @ 21°C**
  - Weld behavior ductile (δm); min. and max. value – 0.365 and 0.378 mm
  - HAZ behavior ductile (δm); min. and max. value – 0.630 and 0.645 mm

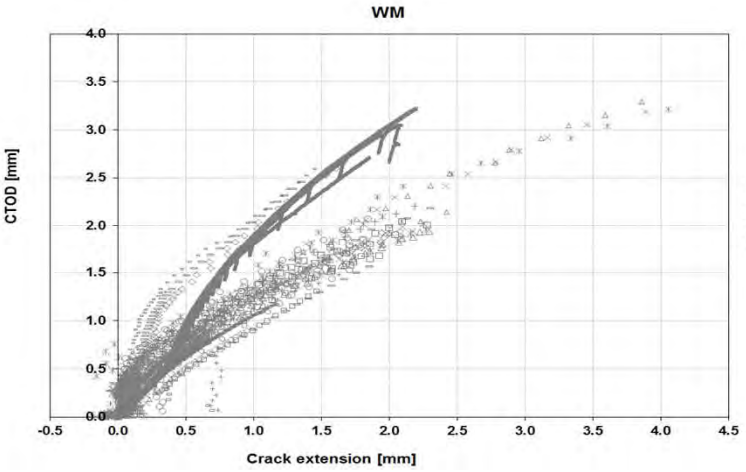
- **SENT testing at 21°C**

Phase 2 – Round Robin Program

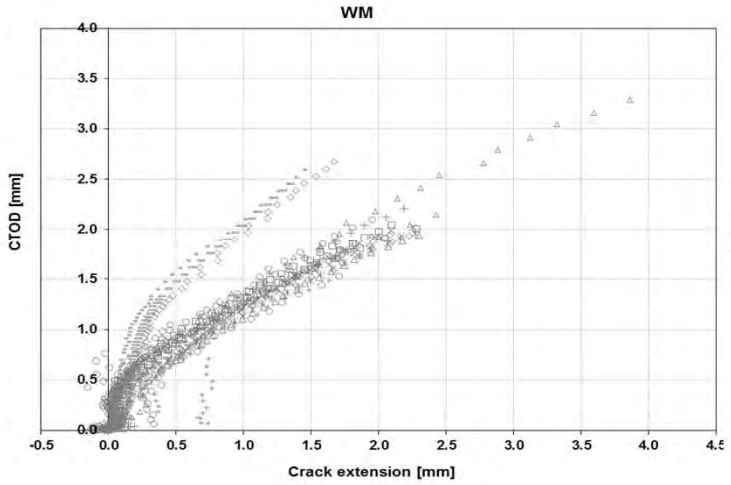
- **Test protocol was sent to all participants**
  - Double clip gauge was mandatory
  - Direct measurement of CTOD and CTOD-R curve mandatory
  - J-R curve optional
  - No fatigue pre-cracking
  - Crack sizing by unloading compliance or PD method
  - Validity requirements to be performed and reported
- **Specimens were machined and EDM notches placed by BMT**
- **Participants were to machine the side grooves**
- **Participants were asked to provide the resistance curves as well as the raw data used for resistance curves**
- **BMT separately analyzed all the raw data and developed resistance curves**

Results: CTOD-R Curve – WM

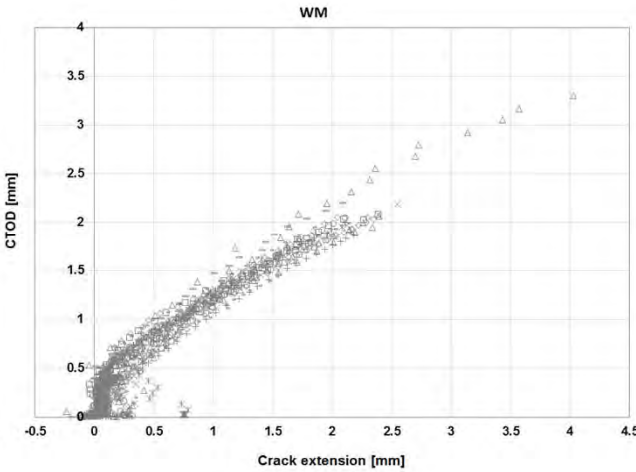
All data-RR



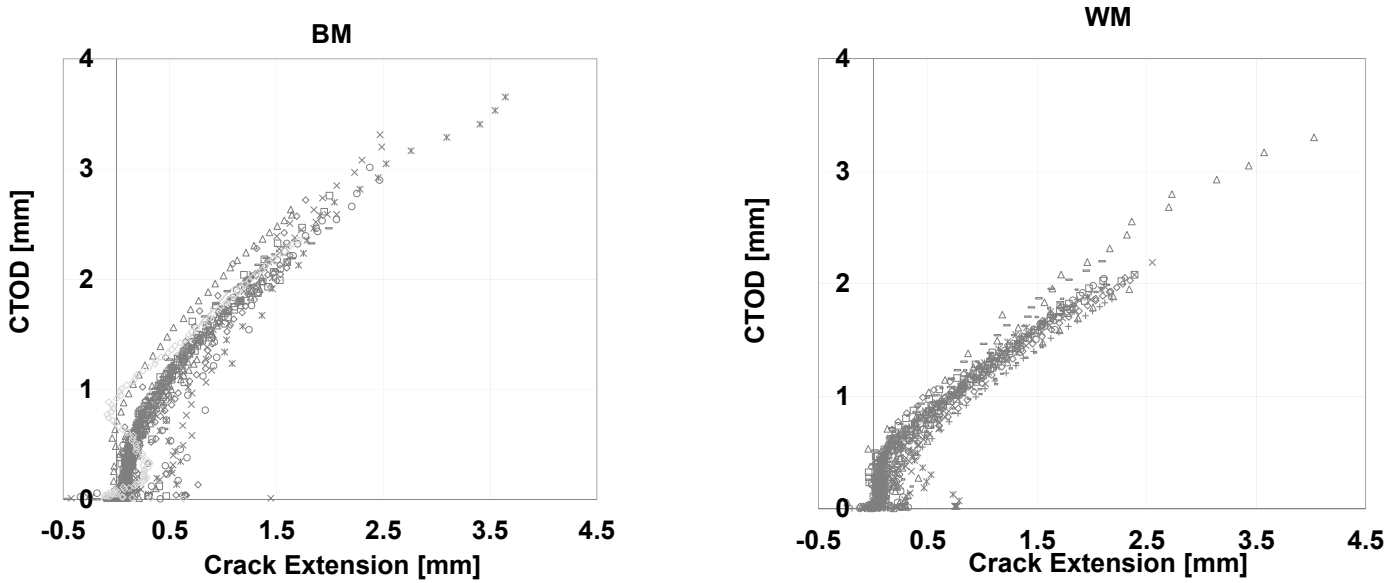
Valid data-RR



BMT Analysis RR-valid data

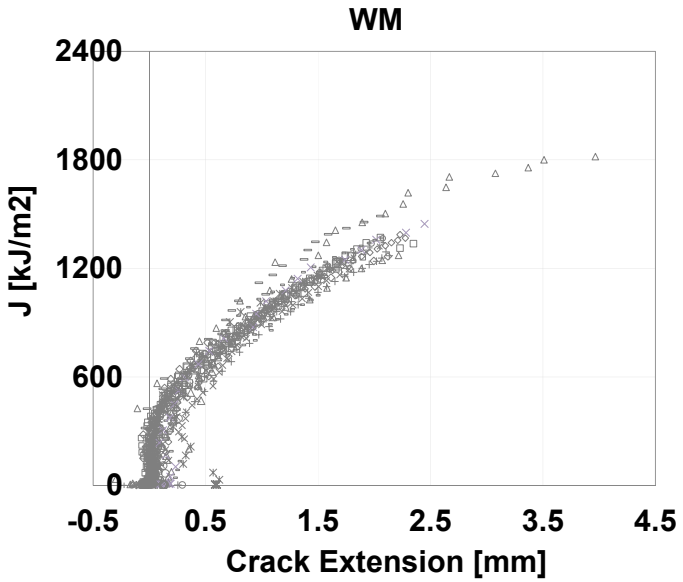


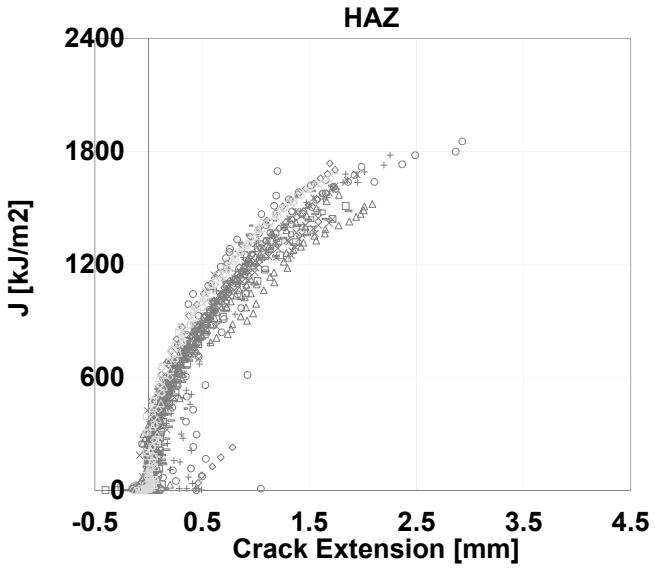
Phase 2 – Round Robin Results



CTOD-R data that met validity requirements

Phase 2 – Round Robin Results





J-R curve, unloading compliance data that met the validity requirements

Phase 2 – Round Robin Results - Validity Requirements

- 10.2/10.3 – Crack Straightness
- 10.4 – Initial crack size estimation (with +/- 0.5 mm of the measured)
- 10.5 – Final crack size estimation (within 15% of the measured extension)
- In addition, there is requirement of minimum 8 data points for a_{oq} estimation

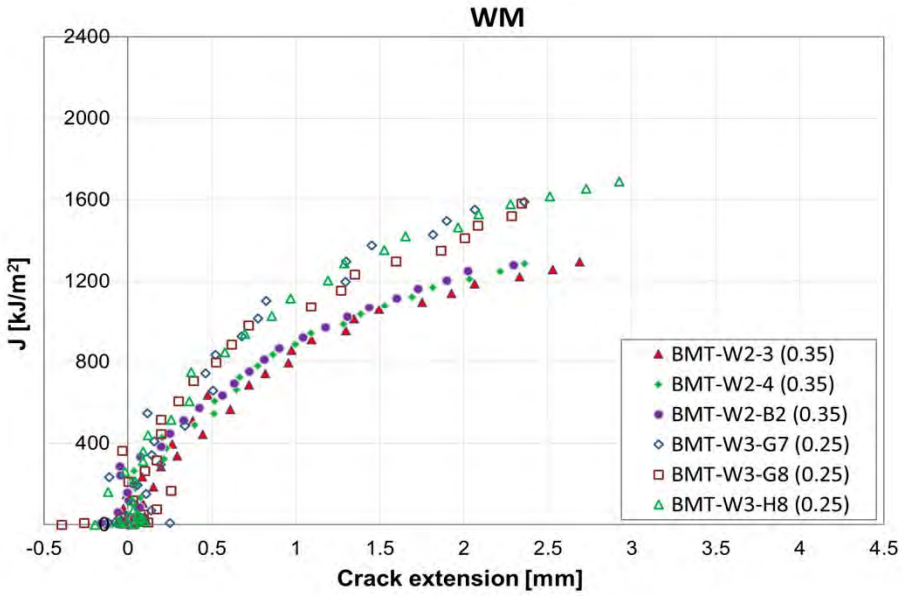
~ 37% of the RR data did not meet the validity requirements, most coming from 10.5 requirement

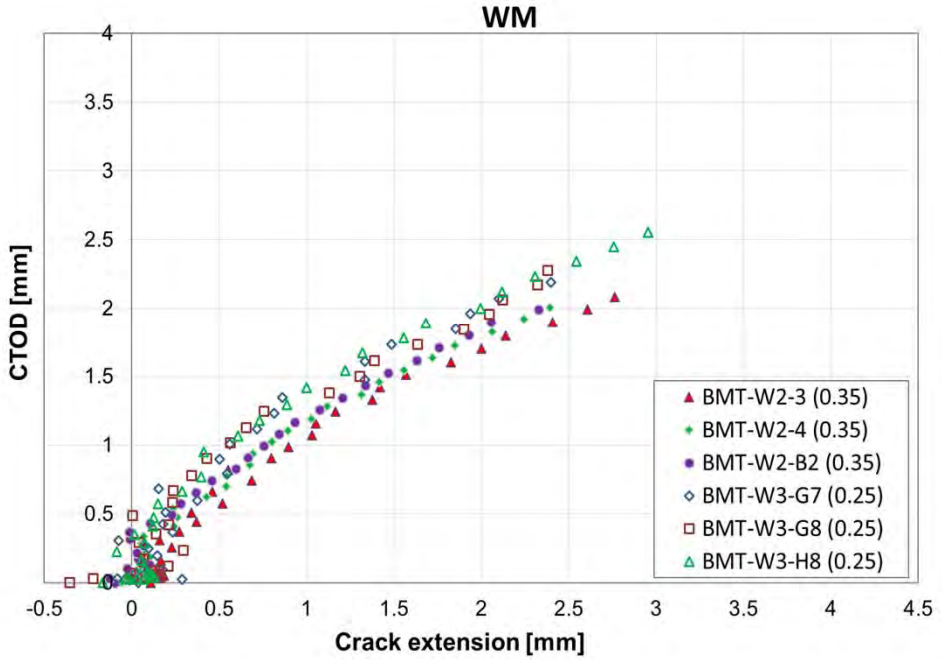
Phase 3 – Finalization of Test Protocol

- **Review RR participant recommendations**
- **Additional analysis**
- **Additional testing based on discussions during ASTM workshop**
  - Testing over the entire range of notch depth as recommended in the test protocol
  - Testing with fatigue pre-cracks – option in the test protocol

Phase 3 – Notch Size Effect (a_o/w = 0.25 vs 0.35)

Shallow notch - lower constraint – higher resistance curve

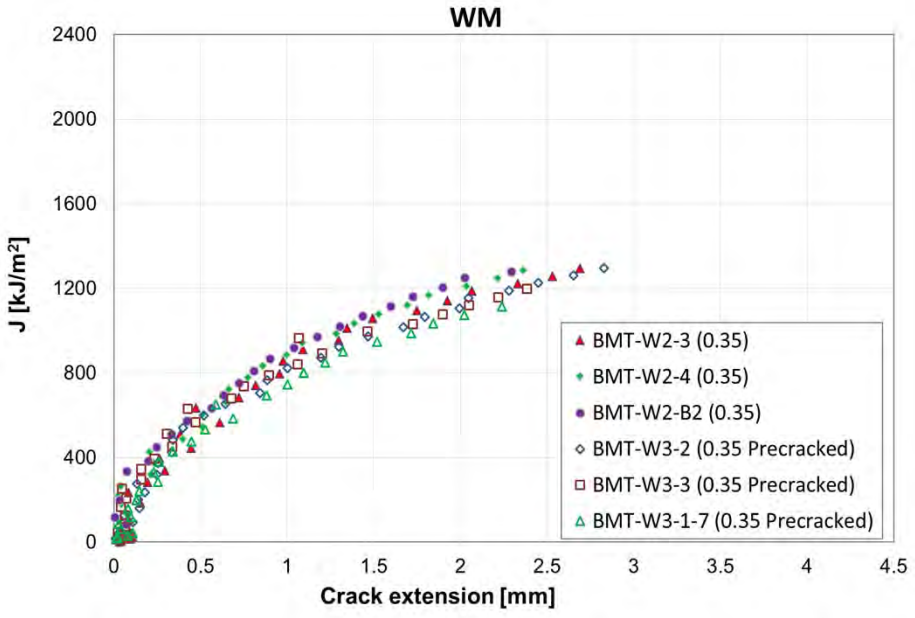


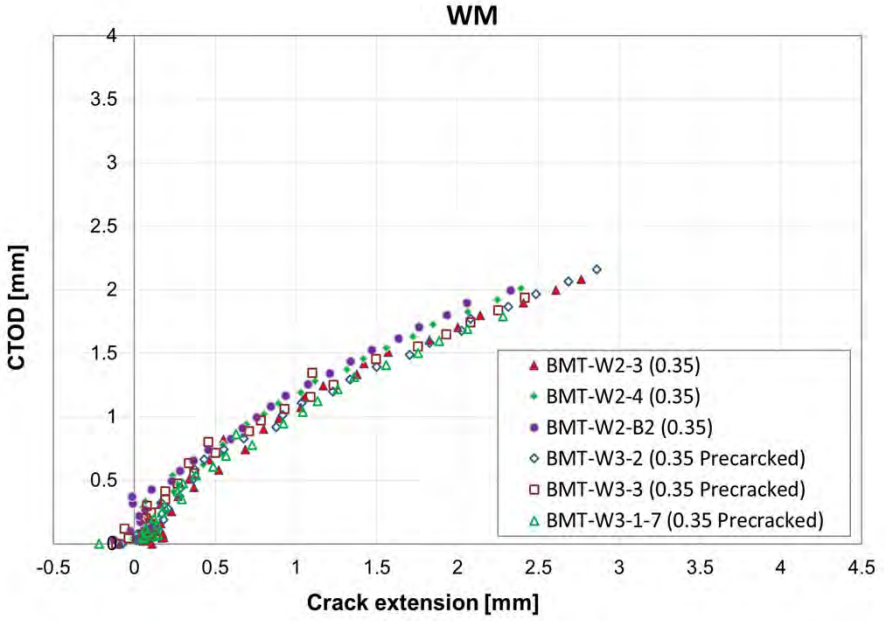


Phase 3 – Effect of Notch Type- EDM vs Fatigue Pre-crack

No effect of pre-crack type if behavior is ductile

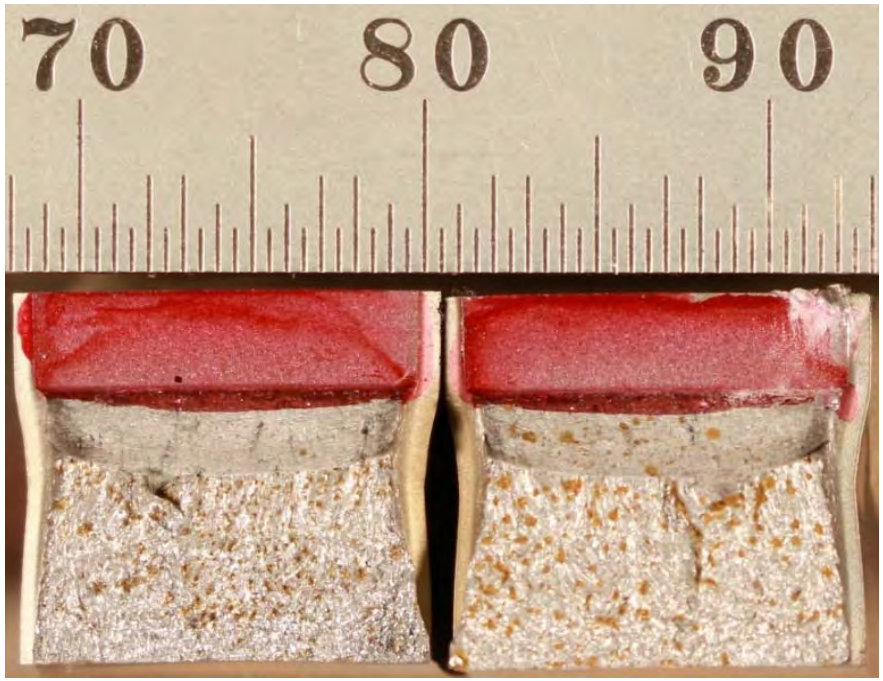
EDM notch radius was 0.1 mm

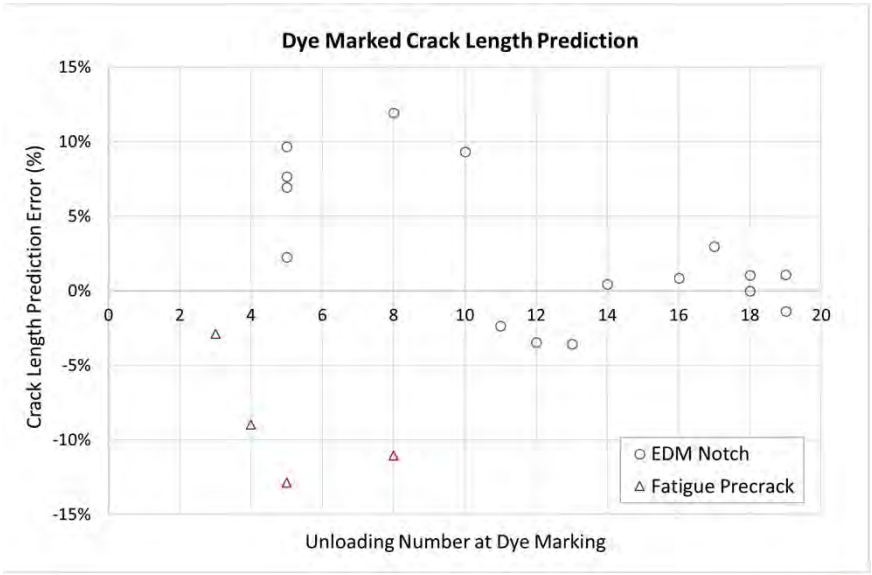




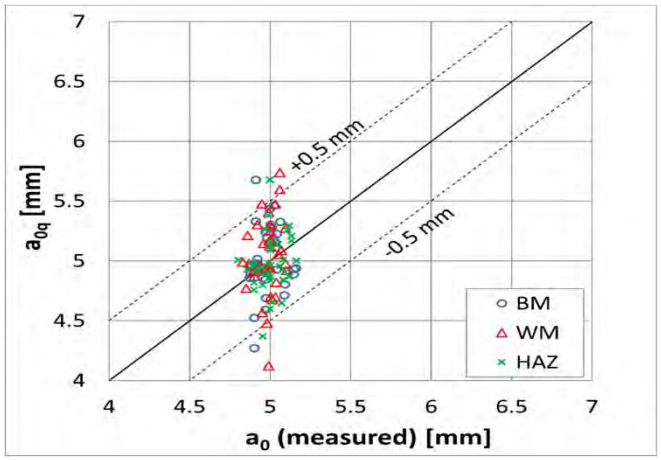
Phase 3 – Crack Growth Prediction during Initial Unloads

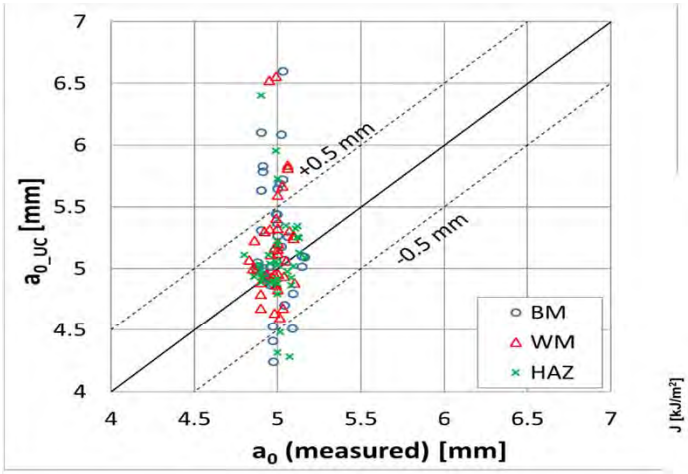
Dye-marking during initial unloads to mark crack front to compare predictions with actual crack extension Fatigue crack and EDM notch



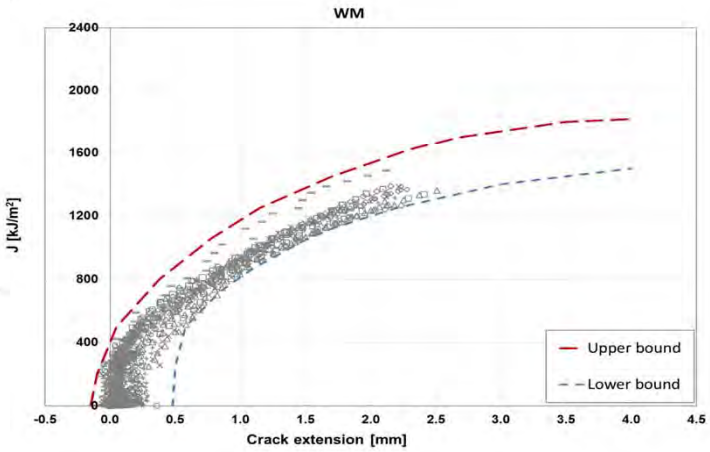


Phase 3 – Initial Crack Size Estimation





Using $a_o$uc instead of a_{oq}

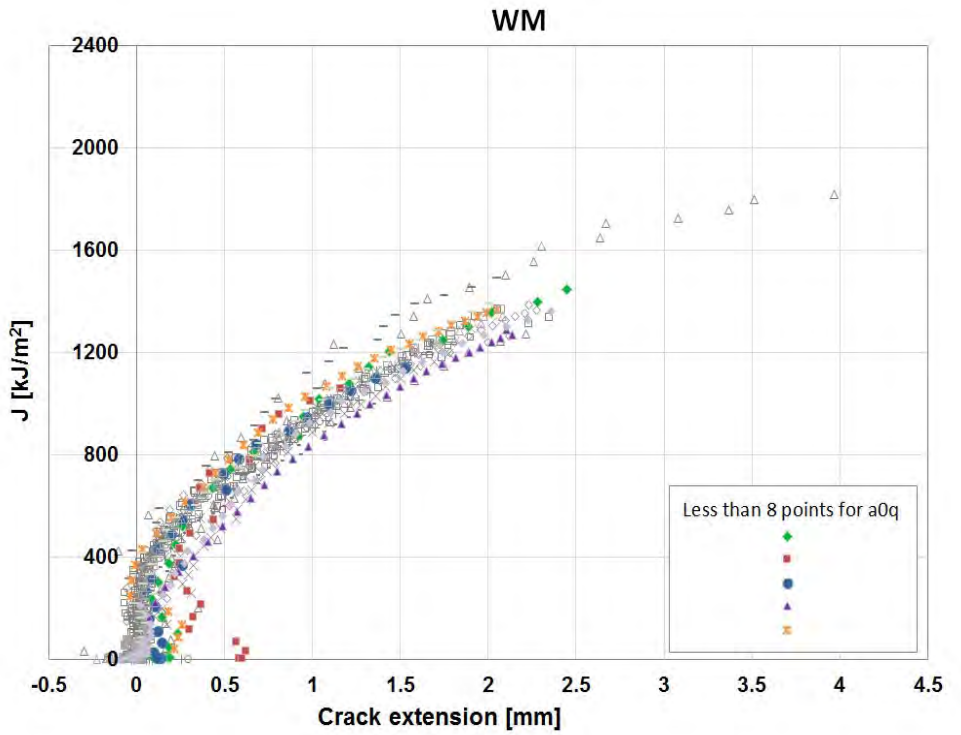


Evaluate_RR Comments –
$a_o$uc provides better estimates as compared to a_{oq} correction

Resulted in increase in scatter band

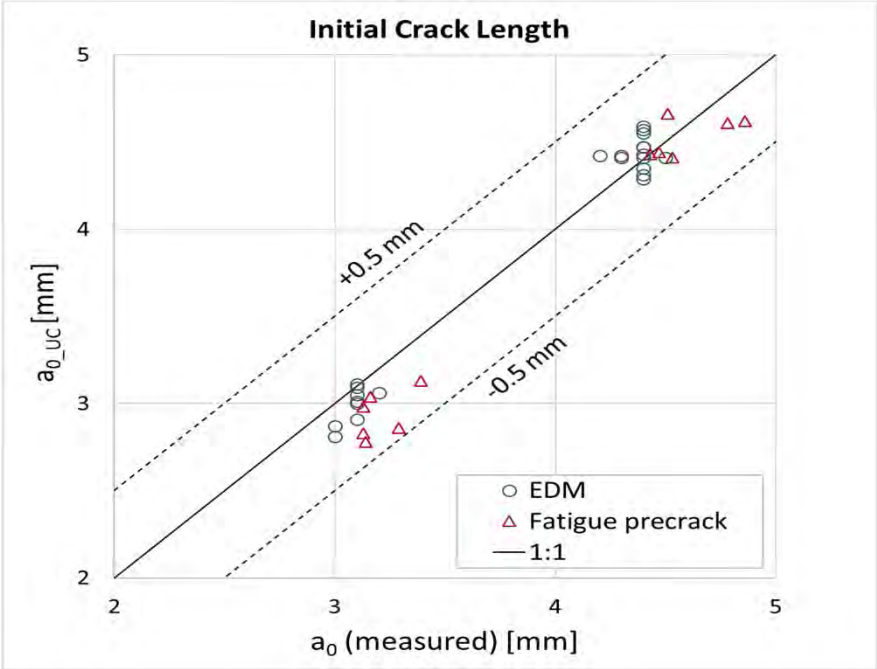
Phase 3 – Initial Corrected Crack Size - a_{oq} Requirements

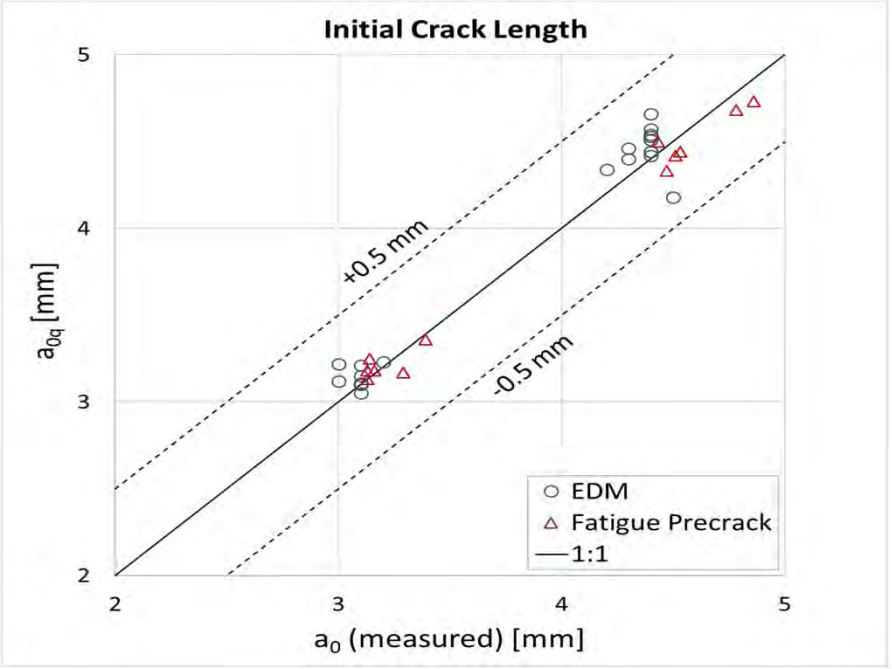
- **Relaxing minimum data points requirement led to**
  - ~ 46% invalid data
  - **Increase in scatter band**



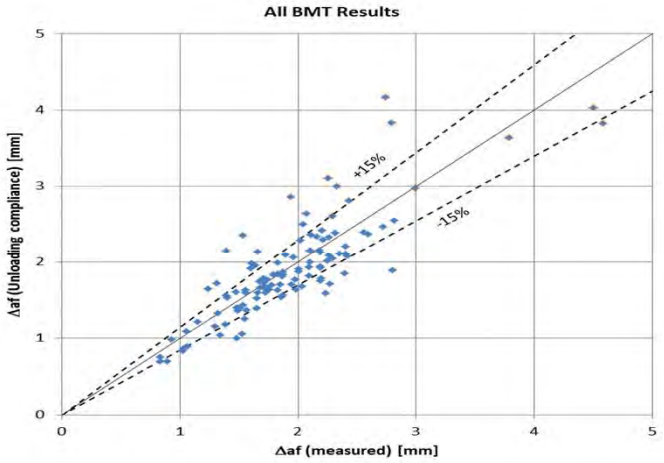
Phase 3 – Crack Growth Prediction

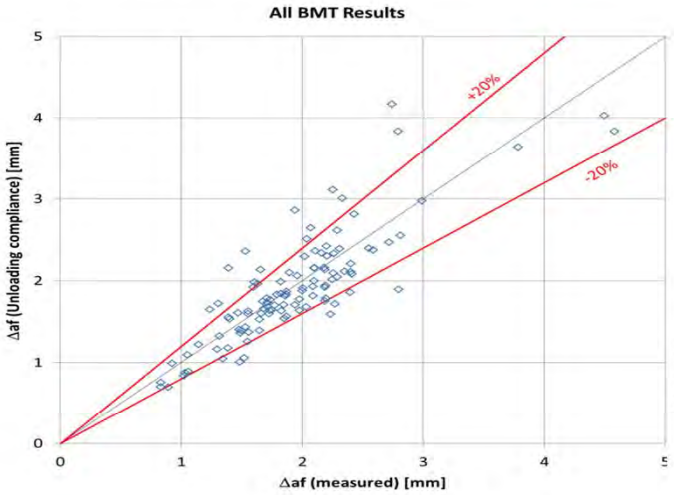
a_{oq} provides better crack size predictions

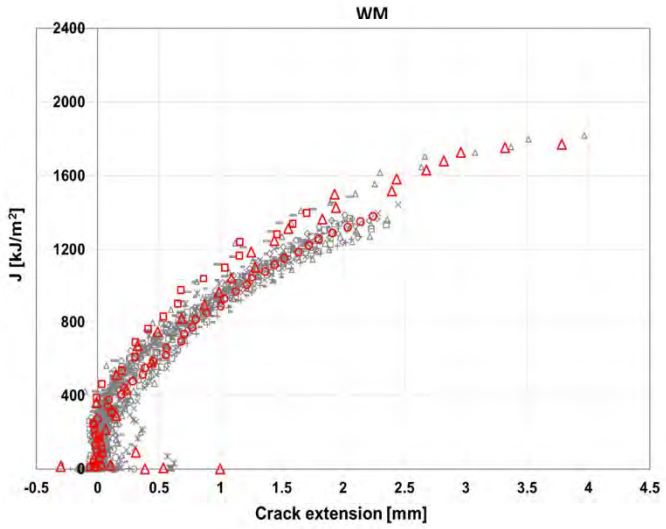




Phase 3 – Final Crack Size Estimation







Relaxing requirement from 15% to 20%
Did not affect R curve

<u>Resulted in a drop in invalid data from 37% to 25%</u>

Concluding Remarks

- Results from the round robin test program developed to assess the suitability of the draft test protocol are encouraging
- Test protocol was revised based on feedback from RR participants and subsequent testing and analysis work carried out at BMT
- Single test protocol provides consistent results for tests that meet the validity criteria
- All RR participants were provided individual reports showing comparison of their data with respect to others (anonymous) and asked to comment if there were issues with their data
- It was beneficial to ask for raw data from RR participants

Concluding Remarks

- **Final test protocol was delivered as part of the API-2-1 final report**

Test Protocol:

Measurement of Crack-Tip Opening Displacement (CTOD) and J-Fracture Resistance Curves

Using Single-Edge Notched Tension (SENT) Specimens

April 2019

- **Test protocol submitted to API and is currently on ballot as SENT TR**

Acknowledgement

- **Project team appreciates support and collaboration from**
  - PRCI
  - Workshop & Round Robin Participants
  - ASTM Committee E08.07.08 Task Group on Fracture Toughness of Welds/CTOD
  - Wentao Cheng, Justin Crapps, Dave Horsley, Marie Quintana, Robert Lazor

BACK TO AGENDA

PRCI 2020 Research Exchange

Vintage Girth Weld Management: A Pragmatic Application of PRCI and UKOPA Research

Practical Application of PRCI Projects: SIA-1-7, MATH-5-2, API-3-1 and SIA-1-4

Authors: Kalen Jensen (ATCO Pipelines), Dr. Andrew Cosham (Nineth Planet Engineering), Tim Rudd (Valero Logistics), Kristy McDermot (National Grid)

Presenter: Kalen Jensen, ATCO Pipelines

LEADING PIPELINE RESEARCH

INTRODUCTION

- This project aims to apply previously completed PRCI projects (SIA-1-7, MATH-5-2, API-3-1 and SIA-1-4) to the results of work completed by the U.K. On Shore Pipeline Association (UKOPA) investigating the mechanical properties of vintage girth welds and their impact on pipeline integrity.

- Work completed by UKOPA was intended to address the perceived integrity threat of vintage girth welds as a result of historic differences in weld strength overmatching, workmanship acceptance criteria and general QA/QC practices.
  - A suite of NDT and DT was completed on several pipeline girth welds (pre-1972) cut-out from existing assets in both Canada and the UK to examine:
    - *Defect Type and Frequency*
      - Comparison to modern acceptance criteria
    - *Tensile Properties, specifically tensile strain capacity*
    - *Toughness properties (Charpy V-notch only)*

- **The goal of this project was to assess the FFS of the identified vintage girth weld defects against assumed service conditions and the mechanical properties determined by the UKOPA/PRCI work**

OVERVIEW OF WORK

- **This work validates assumptions related to vintage girth weld management programs and demonstrates the applicability of existing FFS Assessment tools**
- **Welds examined under UKOPA project* were assessed for their ongoing fitness for service utilizing readily available PRCI research.**
  - measured mechanical properties, measured defect characteristics and assumed loading scenarios were utilized
- **Remaining life was evaluated and conclusions/recommendations given**
- **Work completed by UKOPA* to characterize mechanical properties, type of welding defects and remaining life are validated against previously completed PRCI projects to confirm conclusions are consistent across industry.**

* Analysis of the Properties of Vintage Girth Welds (PPIM 2020), Timothy Rudd, et. al

OUTCOME & KEY RESULTS

1. **Vintage girth welds are typically over-matched from a tensile strength perspective, display adequate toughness (i.e. are not brittle at operating temp.) and contain conventional welding defects**

2. **Pragmatic assumptions regarding mechanical properties can be made which are conservative without being unreasonable**
   a) Girth welds do not need to be treated like long seam welds!

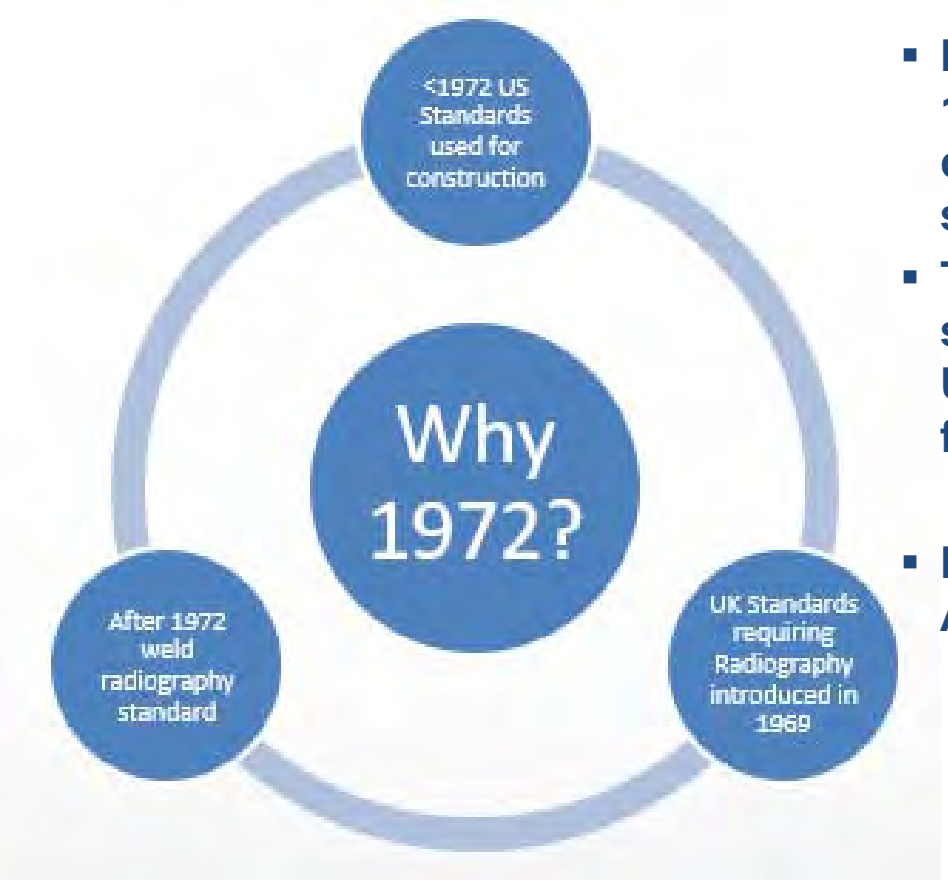
3. **The FFS of a given girth weld can be readily determined utilizing tools produced by PRCI (API-3-1) and documented with the rigor required for an FFS Assessment/ECA**

4. **The remaining life of defects can be conservatively determined utilizing S-N curves available within industry**

METHODOLOGY - OVERVIEW

- **Girth welds from 38 operating pipelines (installed between 1949 – 1972) from both the UK (29) and Canada (9) were investigated via NDT to assess the presence of weld flaws and appearance.**
  - Compared to modern and historic codes of construction for acceptability
  - Cross-section of D/t ratios and grade included
- **26 of these welds contained weld defects, and were subsequently subjected to DT**
  - Tensile, Wet-Chemical Analysis, Charpy, Hardness
- **The FFS of these welds was assessed utilizing:**
  - Nominal/specified D/T, YS, UTS
  - Conservative misalignment and Charpy values
  - Assumed conservative loading (both Hoop and Long'n stress)
  - Remaining life compared to defect free welds of similar vintage

WHY 1972?



- Pipeline girth welds constructed in the UK before 1972 were constructed using American construction companies, following American standards.
- The primary international welding workmanship standard, API 1104 was implemented in 1953. This US standard effectively set the quality of pipeline field girth welds internationally.

- Expanded from UK Operators only to include ATCO:
  - Similar construction methodology
  - Welded to API 1104 by US contractors

METHODOLOGY – PIPELINE SPECIFICATIONS

Outside Diameter: 168 – 610 mm (NPS 6 – 24)

Wall Thickness: 4.8 – 12.5 mm (0.188 – 0.5”)

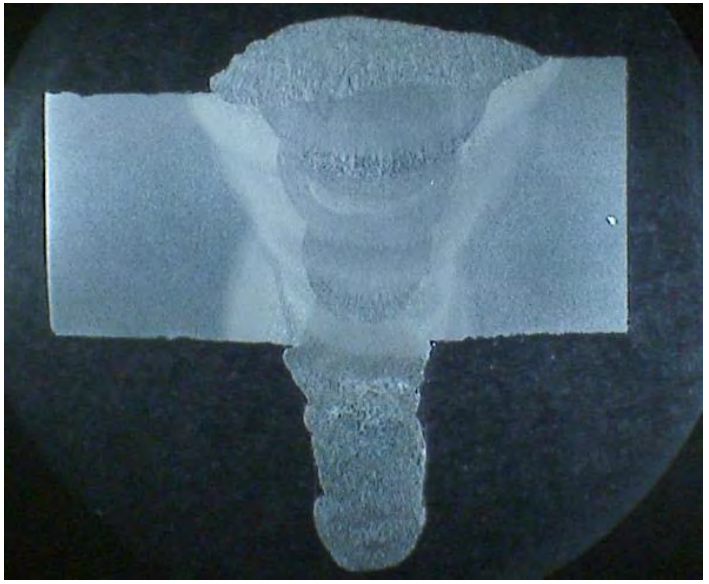
API 5L Grades: 240 – 359 MPa (B - X52)

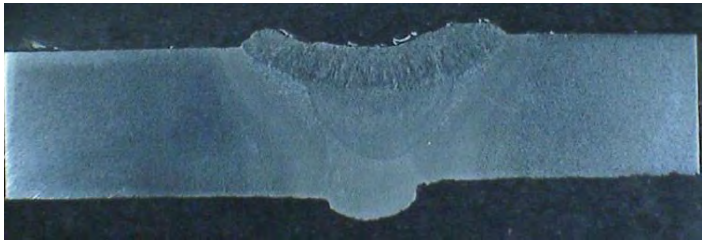
Vintage: 1948 – 1971

Welding Process Utilized: SMAW (cellulosic rods assumed based on results of visual examination)

METHODOLOGY – NDT (VT & RT)

Type of Defect	Number of Occurrences
Crack	1 (3%)
IP/LF	7 (18%)
Slag	4 (11%)
Por.	6 (16%)
Burnthrough	2 (5%)
Undercut	10 (26%)
Concavity	4 (11%)
Hi/Lo	Very common
Defect Free	4 (11%)









Majority of welds contain “Defects” but almost all are minor/non-injurious

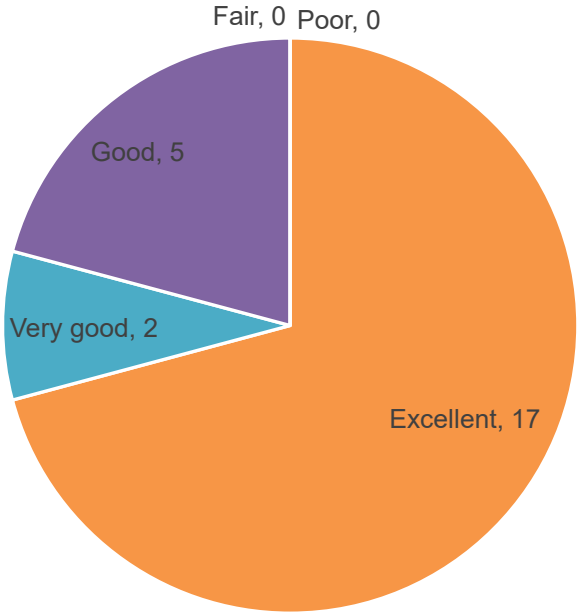
METHODOLOGY – MECHANICAL/PIPE PROPERTIES

Weld Property	Compared to	Why it matters
Chemistry	Established CE Ranges	Weldability
Tensile Strength	Weld overmatch	Tensile strain capacity
Hardness (HV)	Limitations in modern codes of construction	Propensity for cracking
Charpy V-Notch	Pipe body	Ductile behavior

MECHANICAL PROPERTIES – CHEMISTRY/WELDABILITY

$$CE_{\mathrm{IIW}} = C + \frac{Mn + Si}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

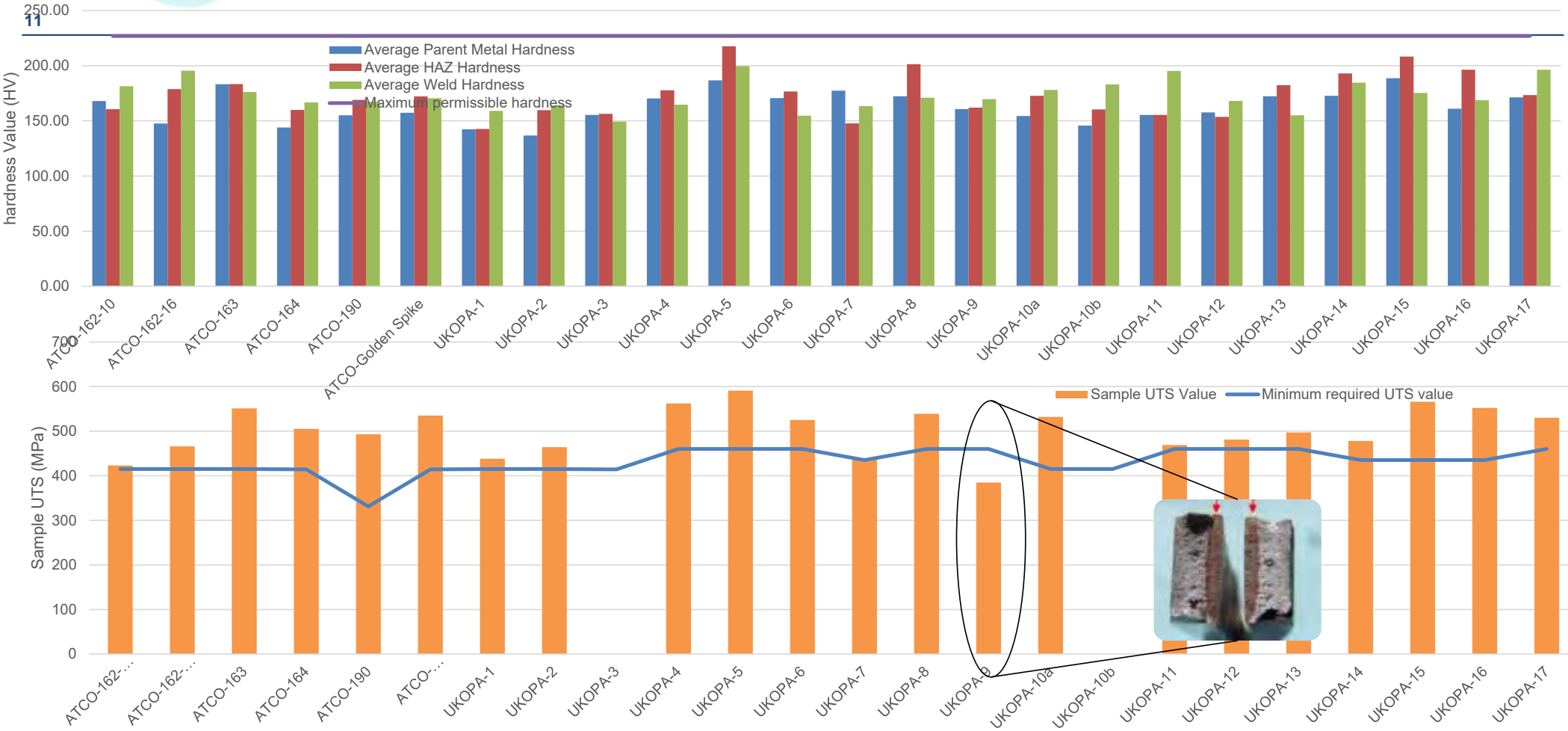
Carbon equivalent (CE)	Weldability
Up to 0.35	Excellent
0.36–0.40	Very good
0.41–0.45	Good
0.46–0.50	Fair
Over 0.50	Poor



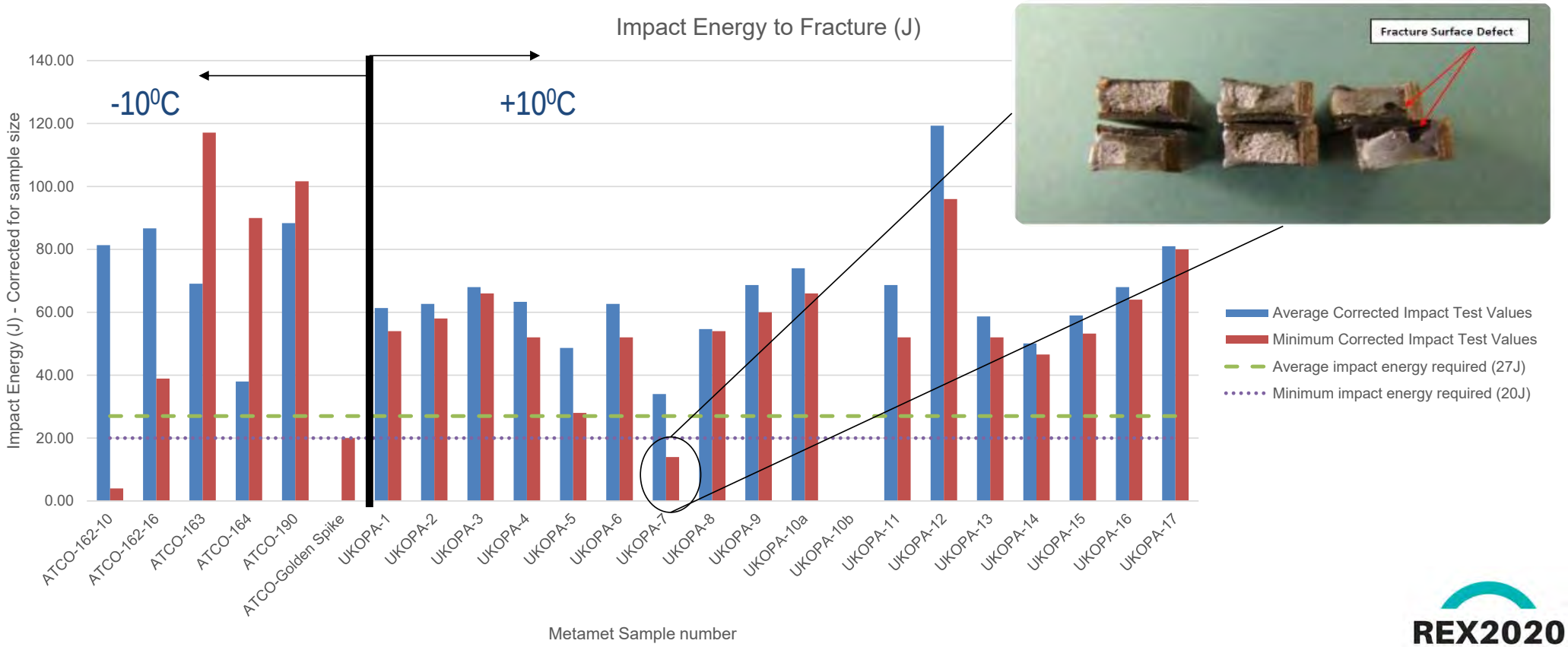
Composition of all materials consistent with expected grades.

- Slightly high Sulphur levels in 6 samples
- Low Molybdenum levels in 5 samples
- Microstructure was typically bainitic in weld metal to pearlite in base metal (no martensite observed)

MECHANICAL PROPERTIES – UTS/HARDNESS



MECHANICAL PROPERTIES – CHARPY V-NOTCH



METHODOLOGY – LOADING

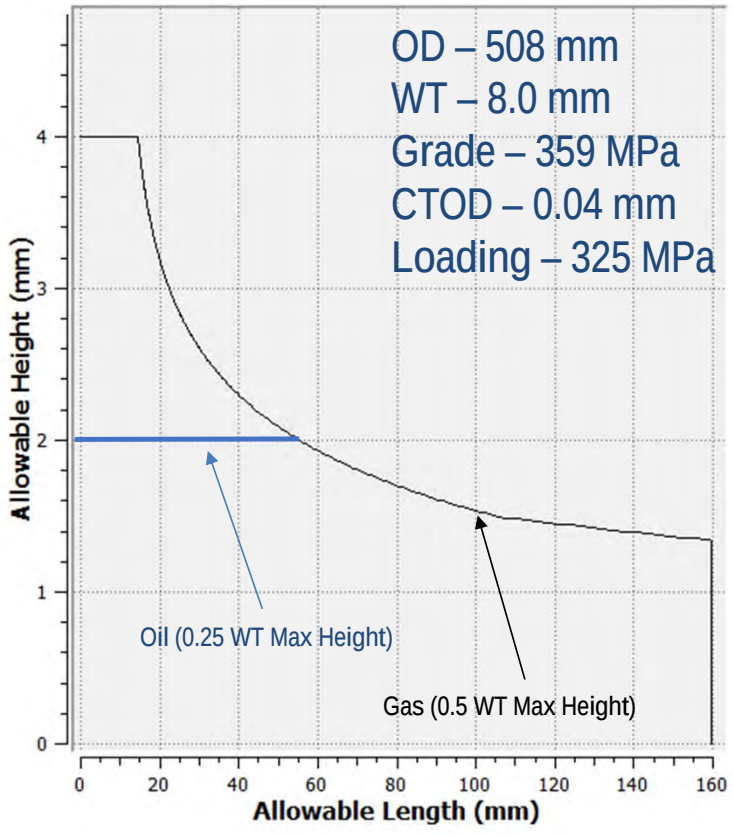
Assumptions:

1. **All Loading is within Elastic Regime (< SMYS)**
2. **Loading can be resolved into a uniaxial tensile stress**
3. **Primary stress is Axial/Longitudinal in nature**
   3. Internal pressure will not be the driving force behind a failure
   4. All axial loads considered are not "self-limiting"

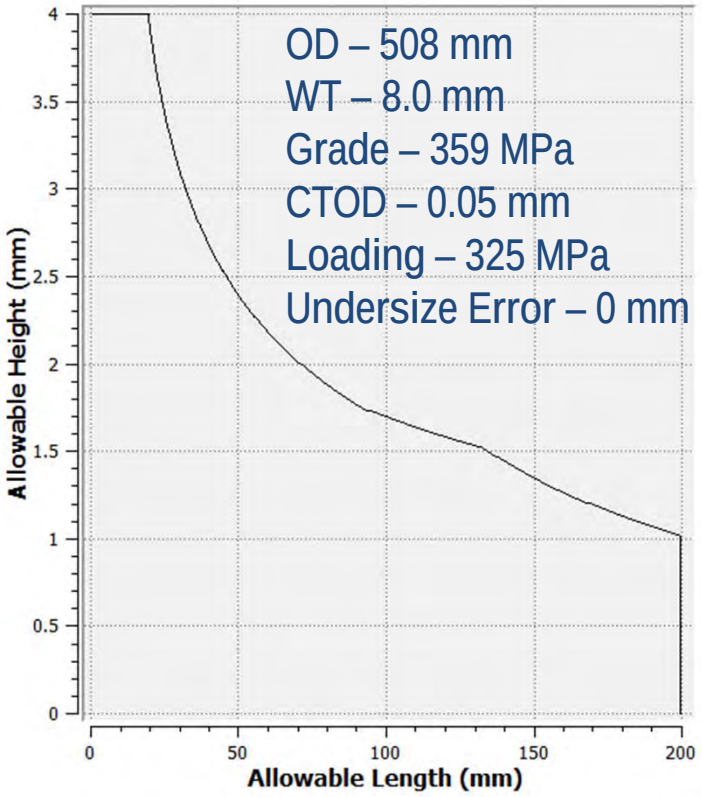
Assess at fixed loading values (80%, 90% SMYS)

RESULTS: Static Loading FFS Examples (MATH-5-2)

CSA Z662–15, Annex K



API 1104 – Annex A



RESULTS: Static Loading FFS

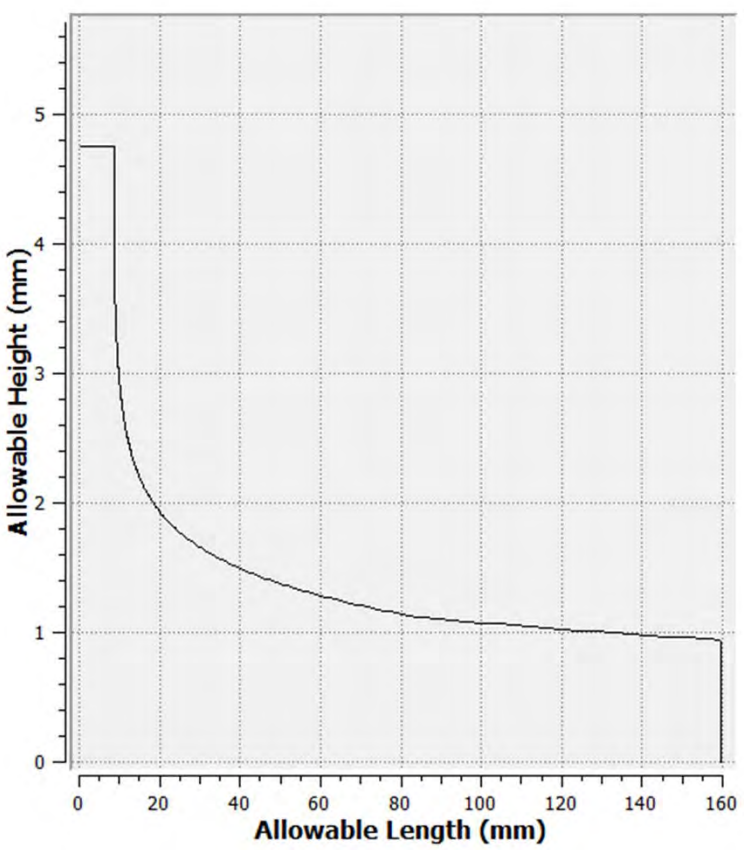
Elastic stress states only

OD (mm)	WT (mm)	D/t	Grade (MPa)	Length x Depth* (mm)	Axial Stress, %SMYS	API 1104 App. A	CSA Z662 Annex K**	T.S.C.***
168	7.1	23.7	240	25.4 x 2.5	90%	Pass	Pass	Pass
				50.8 x 2.5	80%	Pass	Pass	Pass
219	8.2	26.7	240	25.4 x 2.5	90%	Pass	Pass	Pass
				50.8 x 2.5	80%	Pass	Pass	Pass
273	9.25	29.5	240	25.4 x 2.5	90%	Pass	Pass	Pass
				50.8 x 2.5	80%	Pass	Pass	Pass
323	9.5	34.0	290	25.4 x 2.5	90%	Pass	Pass	Pass
				50.8 x 2.5	80%	Pass	Pass	Pass
406	9.5	42.7	290	25.4 x 2.5	90%	Pass	Pass	Pass
				50.8 x 2.5	80%	Pass	Pass	Pass
508	9.5	53.5	359	25.4 x 3.0	90%	Pass	Pass	Pass
				50.8 x 3.0	80%	Pass	Pass	Pass
610	12.5	48.8	359	25.4 x 3.0	90%	Pass	Pass	Pass
				50.8 x 3.0	80%	Pass	Pass	Pass

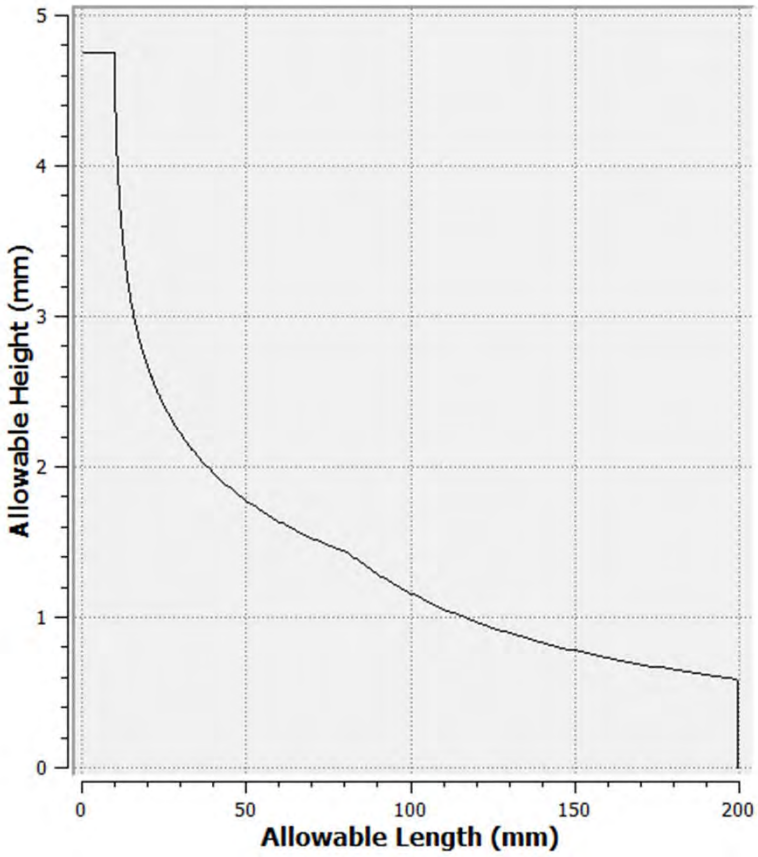
* All defects assessed as surface breaking planar
** Results for Gas Pipeline
*** Pass taken as > 0.2% strain

RESULTS: Static Loading at 100% SMYS

CSA Z662–15, Annex K



API 1104 – Annex A



OD – 508 mm
WT – 9.5 mm
Grade – 359 MPa
CTOD – 0.04 mm
Loading – 359 MPa

ego, CA

REX2020
PRCI RESEARCH EXCHANGE

RESULTS: Static Loading (beyond SMYS)

Flaw Size, mm (2c x a)	TSC (%)			
	80% mismatch	85% mismatch	95% mismatch	0% mismatch
25 x 2.5	0.26	0.31	0.42	0.47
40 x 3.5	0.22	0.25	0.32	0.35
50 x 4.5	0.20	0.22	0.27	0.29
60 x 6.0	0.18	0.20	0.23	0.24

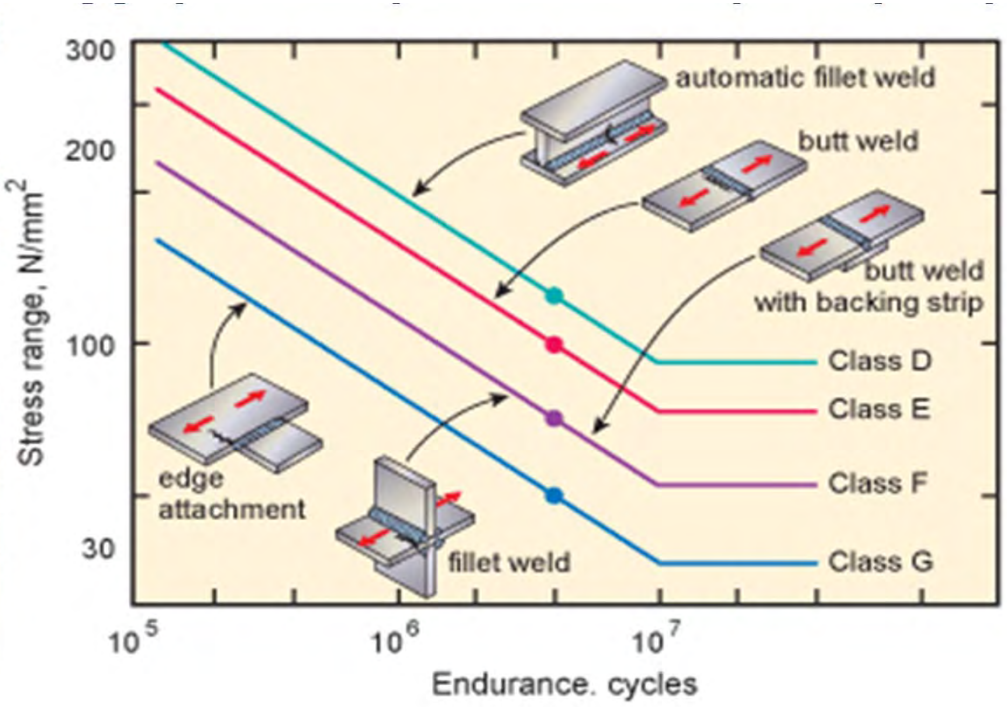
Assessment Assumptions:
OD – 508 mm
WT – 9.5 mm
Grade – 359 MPa
Hoop Stress Level – 80% SMYS
Charpy – 20 J
Misalignment – 1.6 mm

RESULTS: Dynamic Loading FFS

- Two suite[illegible] r UKOPA work:

1. Vint
2. Vint







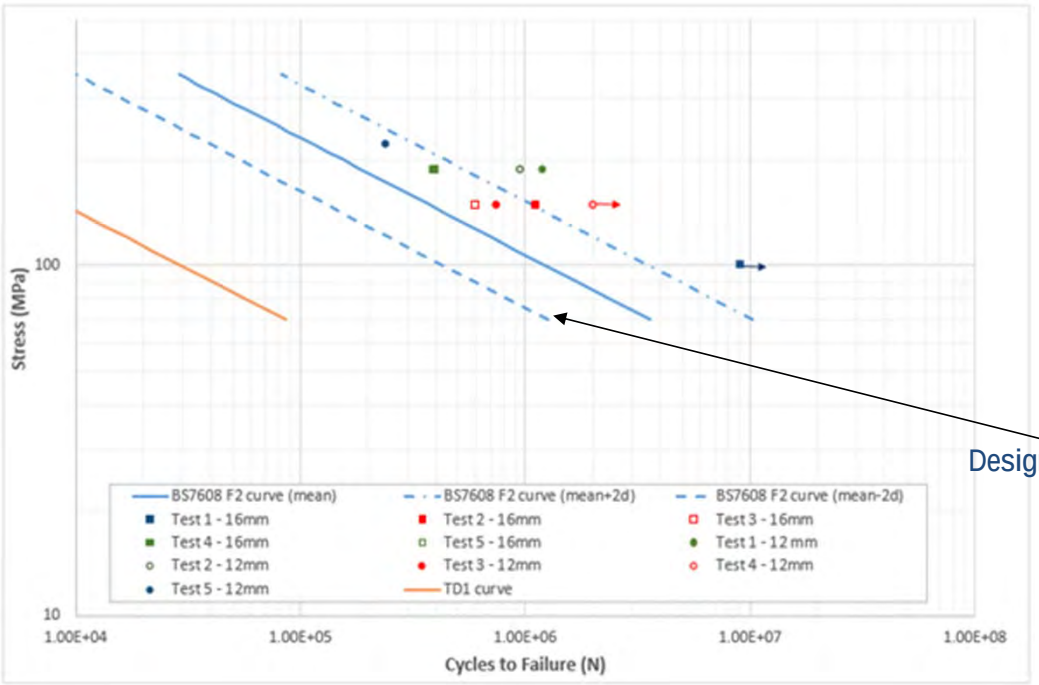
- Results from both suites of testing were plotted on BS-7608 "F2" and "E" S-N curves to evaluate remaining fatigue life

* Testing completed by Univeristy of Strathclyde
** Testing completed by Swansea Univiersity

REX2020
PRCI RESEARCH EXCHANGE

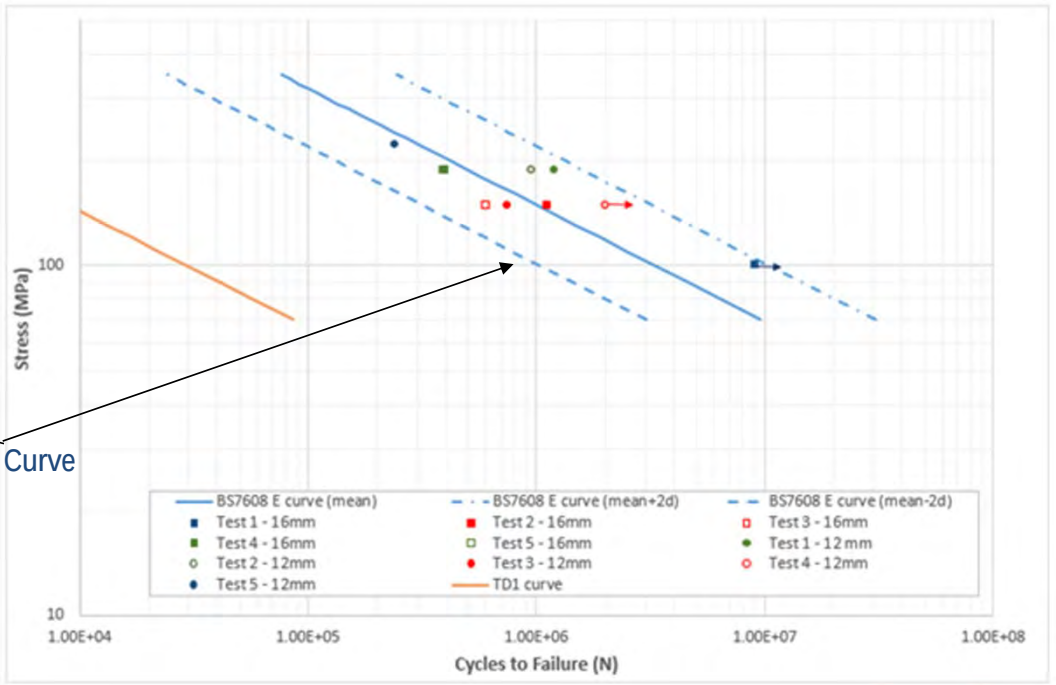
RESULTS: Dynamic Loading (Welds with NO Defects)*

BS-7608 'F2' S-N Curve



Design Curve

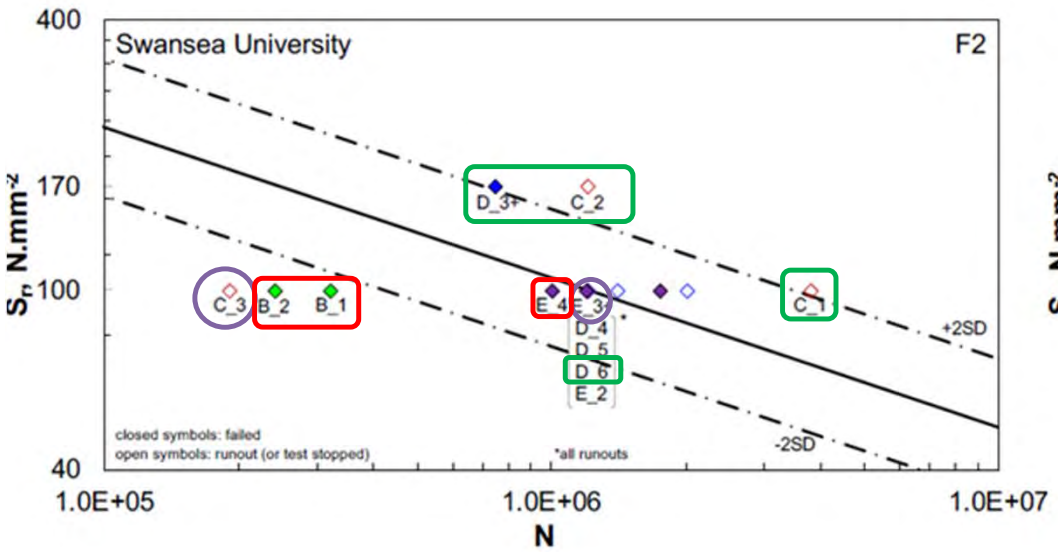
BS-7608 'E' S-N Curve



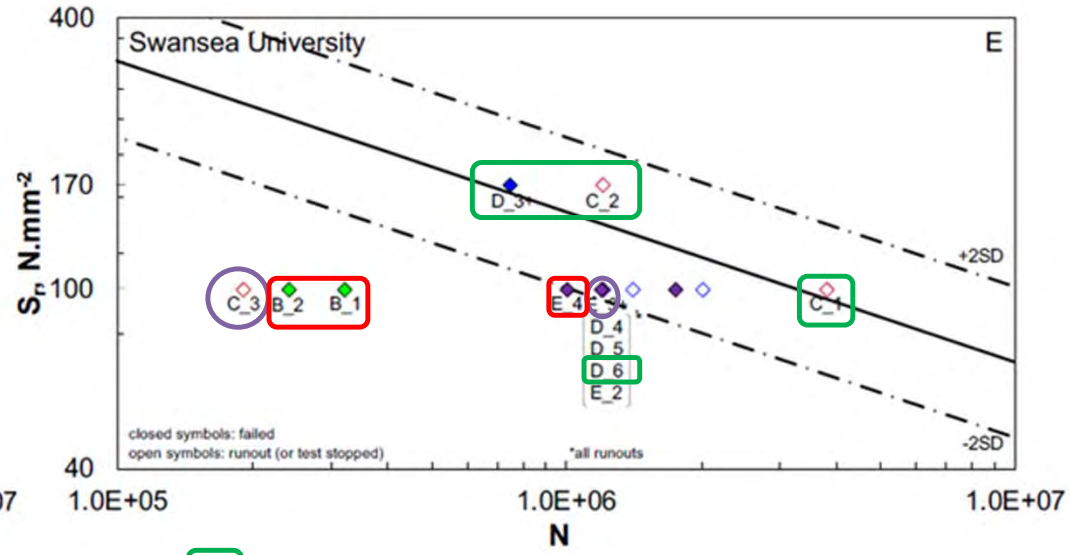
* Testing completed by Univeristy of Strathclyde

RESULTS: Dynamic Loading (Welds WITH defects)*

BS-7608 'F2' S-N Curve



BS-7608 'E' S-N Curve



Fractured (had longitudinal cracks, IP, mis-alignment and undermatch in specimen)

Contain: IP, IUC, Excess cap/root, Por, LoF

Test stopped due to rig issues

* Testing completed by Swansea University

COMPARISSON TO PRCI RESEARCH
(SIA-1-7, MATH-5-2, API-3-1 and SIA-1-4)

- **Frequency, type and nature of weld metal defects consistent between UKOPA completed work and PRCI project SIA-1-4**
- **Assumption of weld metal overmatch (tensile strength), ductile behavior and a reasonable microstructure (i.e. little or no martensite) is consistent between UKOPA completed work PRCI project SIA-1-4 and SIA-1-7**
- **Vintage Girth Weld tensile strain capacity exceeds the elastic range for reasonably sized defects under most conditions and can be determined using MATH-5-2**
- **Remaining life of vintage welds with/without conventionally non-injurious defects present can be determined utilizing S-N curves. Curve 'E' from BS 7608 can be utilized**

CONCLUSIONS

1. **Direct Assessment of vintage girth welds should be completed when coupled with other planned work (integrity or capital)**
   - Unique Integrity program not generally required
2. **Employ multiple inspection techniques when possible**
   - RT to identify, UT to characterize
   - Identified defects can be readily assessed and their Fitness For Service determined
3. **Reasonable assumptions can be made regarding mechanical properties**
   - Static and Dynamic Loading results can be determined utilizing conventional, established, industry accepted approaches
     - Conservative assumptions can be made to assess remaining life of Gas and Liquids Pipelines
       - » *assumptions need to be verified (particularly for liquids lines)*

BACK TO AGENDA

PRCI 2020 Research Exchange

Hydrogen Cracking Susceptibility

MAT-1-1 and MAT-1-3

Aaron Dinovitzer
Jeff Moulton, Christian Mihailescu, Darren Begg, Nick Pussegoda

BMT

LEADING PIPELINE RESEARCH

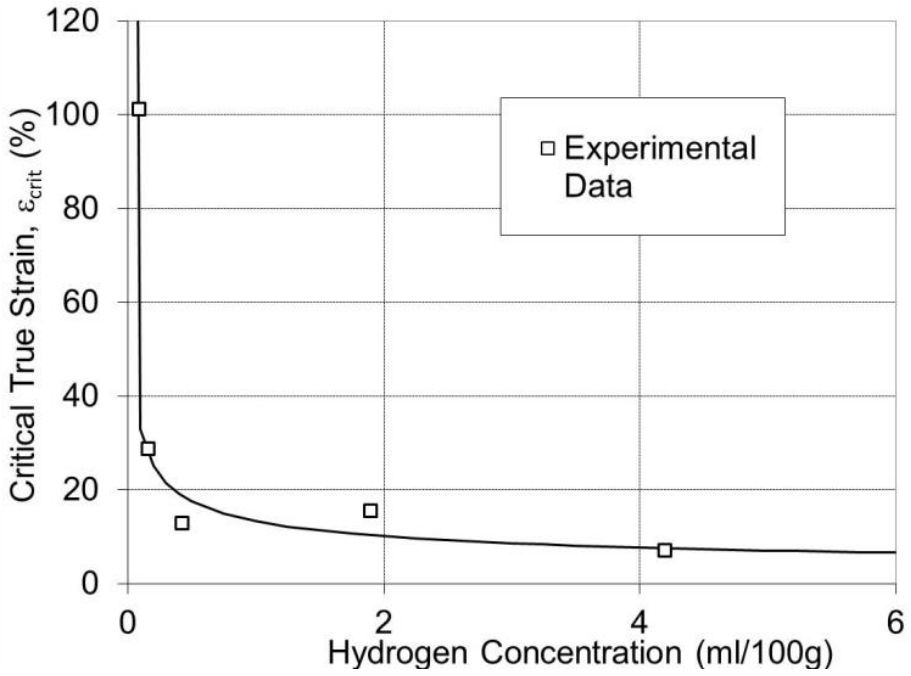
Presentation Outline

- **Project Overview**
- **Material Selection**
- **Material Characterization**
  - Background Properties
  - Hydrogen Cracking Susceptibility Testing
- **Hydrogen Embrittlement Curve Development**
- **Concluding Remarks**

Project Overview

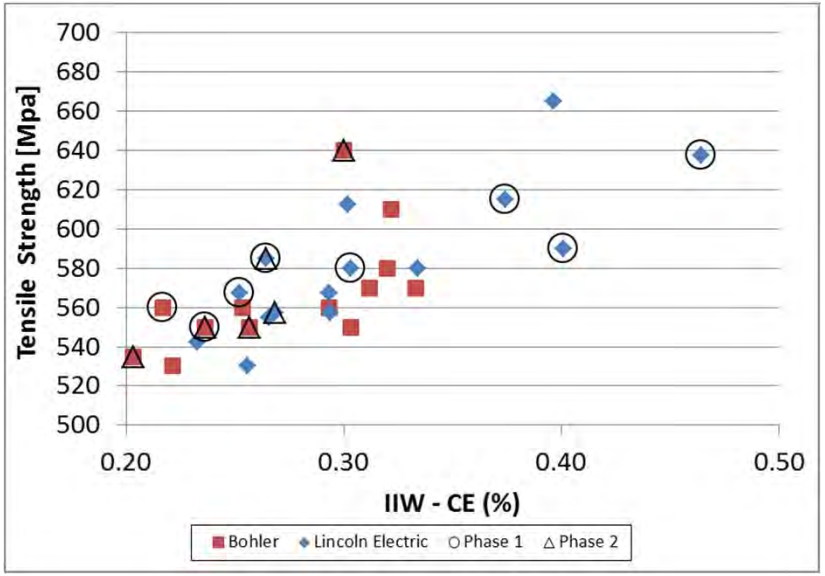
- **Motivation**
  - We know hydrogen cracking necessary conditions
  - We can not differentiate or select materials to minimize susceptibility

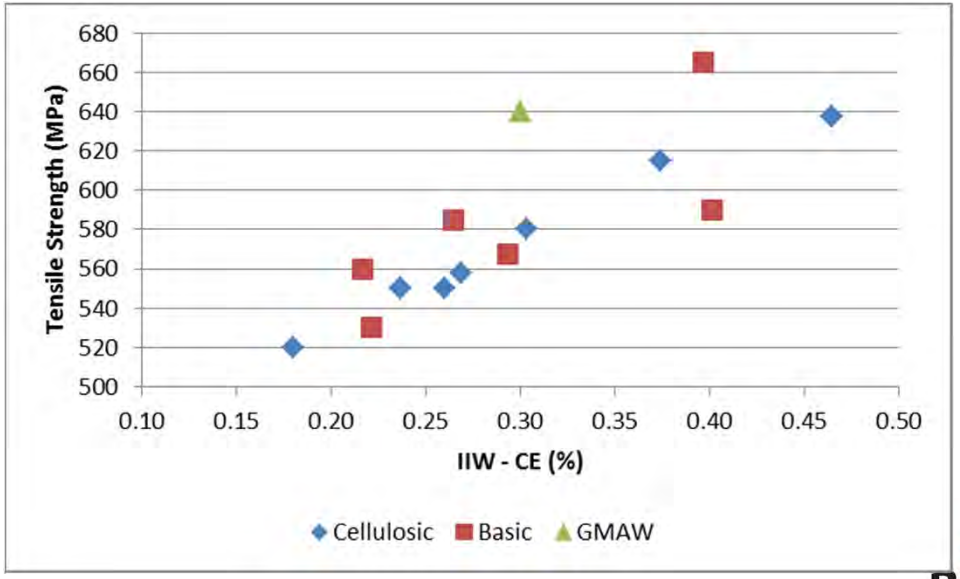
- **Objective**
  - Complete experimental trials to understand factors promoting hydrogen cracking in weld metals
    - Develop hydrogen embrittlement curves for a range of dissimilar weld metals
    - Use weld metal material properties to predict the hydrogen embrittlement curve
    - Document and standardize previously developed slow bend test procedure



Material Selection

- **Considered 15 Bohler and Lincoln SMAW electrodes, 1 GMAW wire**
  - Looking for a group of electrodes with contrasting:
    - Vendor
    - Classification
    - Chemistry
    - Strength
    - Toughness





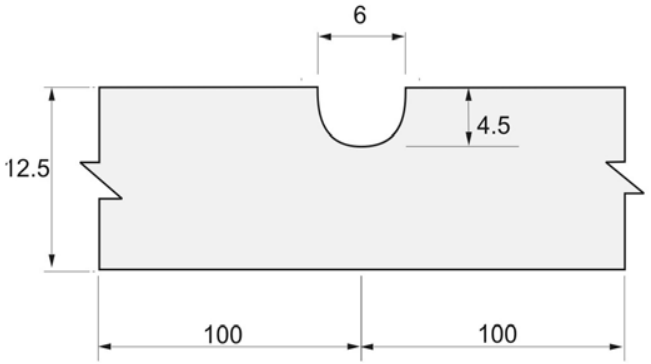
Material Selection

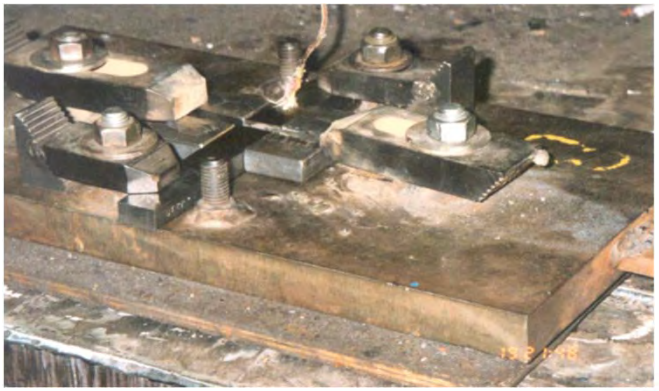
- **Based upon strength, toughness, chemistry, manufacturer, type**

	Manufacturer	Electrode Name	Type	AWS Classifcation
Phase 1	Lincoln Electric	Pipeliner 8P+	Cellulosic	E8010-P1
	Lincoln Electric	Shield-Arc 70+	Cellulosic	E8010-G
	Lincoln Electric	Shield-Arc HYP+	Cellulosic	E7010-P1
	Bohler	Fox CEL 75*	Cellulosic	E7010-P1
	Lincoln Electric	Excalibur 8018-C1 MR	Basic	E8018-C1 H4R
	Lincoln Electric	Pipeliner LH-D80	Basic	E8045-P2 H4R
	Lincoln Electric	Excalibur 7018-1 MR	Basic	E7018-1 H4R
	Bohler	Fox BVD RP	Basic	E8045-P2
Phase 2	Lincoln Electric	Shield-Arc 70+	Cellulosic	E8010-G
	Lincoln Electric	Pipeliner 6P+	Cellulosic	E6010
	Bohler	Fox CEL 70-P	Cellulosic	E7010-P1
	Bohler	Fox Cel+	Cellulosic	E6010
	Lincoln Electric	Pipeliner LH-D80	Basic	E8045-P2 H4R
	Lincoln Electric	Pipeliner 18P	Basic	E8018-G H4
	Bohler	Fox EV Pipe	Basic	E7016
	Bohler	SG 3-P	GMAW	ER70S-G

Material Characterization

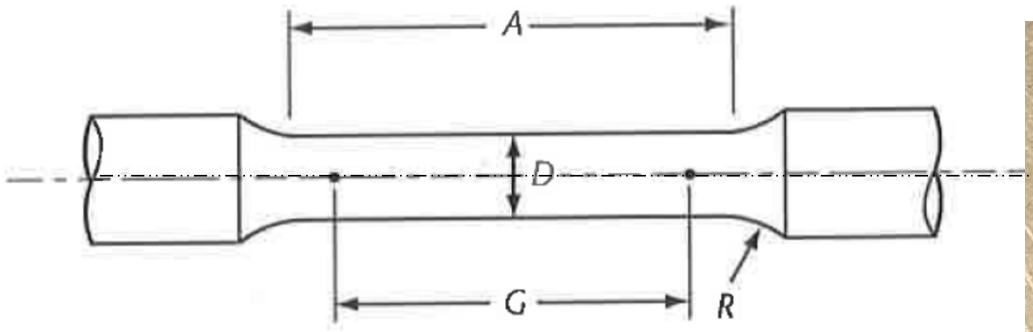
- **Documented weld specimen preparation and testing procedure and apparatus**
  - Specimen dimensions including grooving
  - Fixture for welding
  - Welding parameters (electrode specific) to achieve filled groove based upon vendor recommended practice
  - Base material tensile testing
  - All weld metal tensile testing

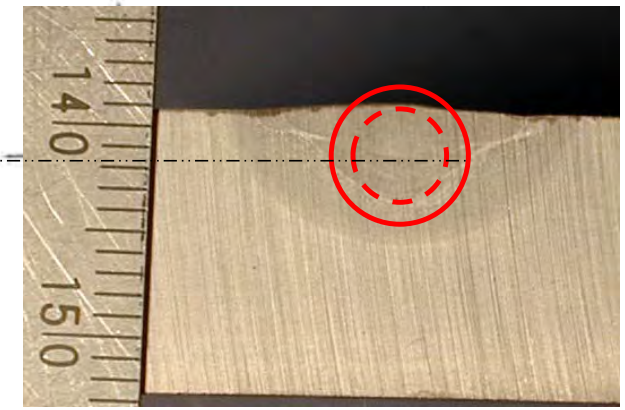




Material Characterization

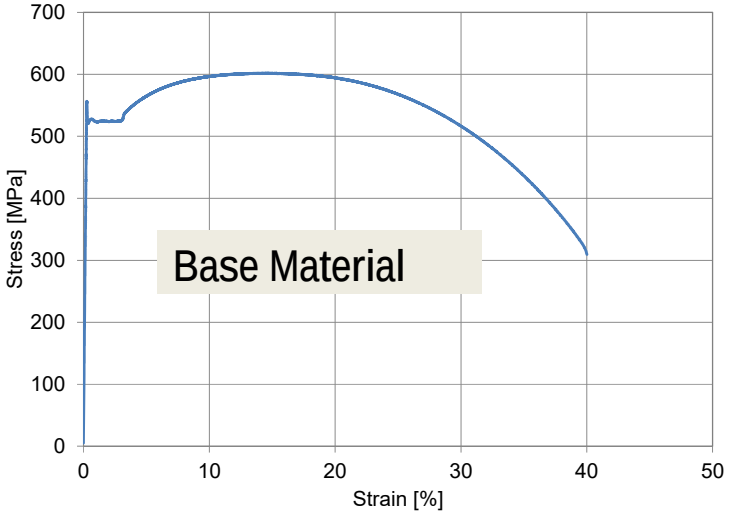
- **All weld metal test specimens prepared**
  - Testing completed
  - Machined 4mm diameter test specimens
- **Data to calibrate FE Model to infer bend test strain**
  - Data to support material characterization

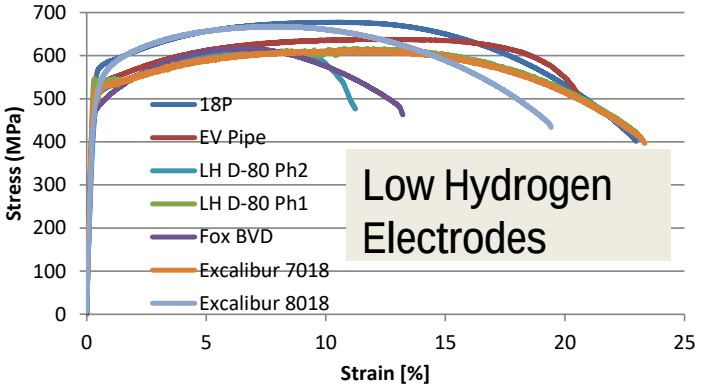


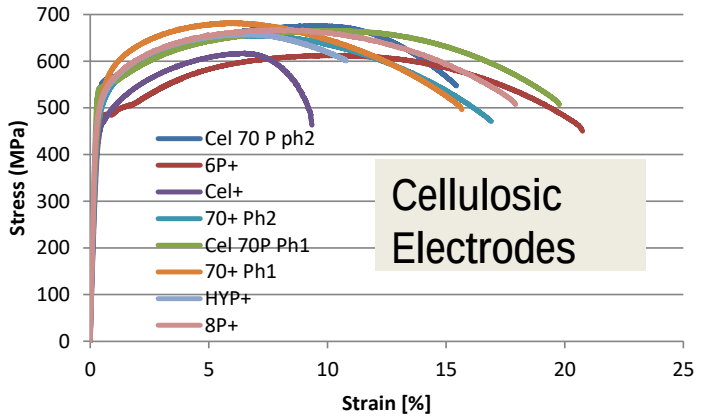


Material Characterization

- **Base metal and weld metal stress strain curves captured**
  - Aged 3h at 150°C

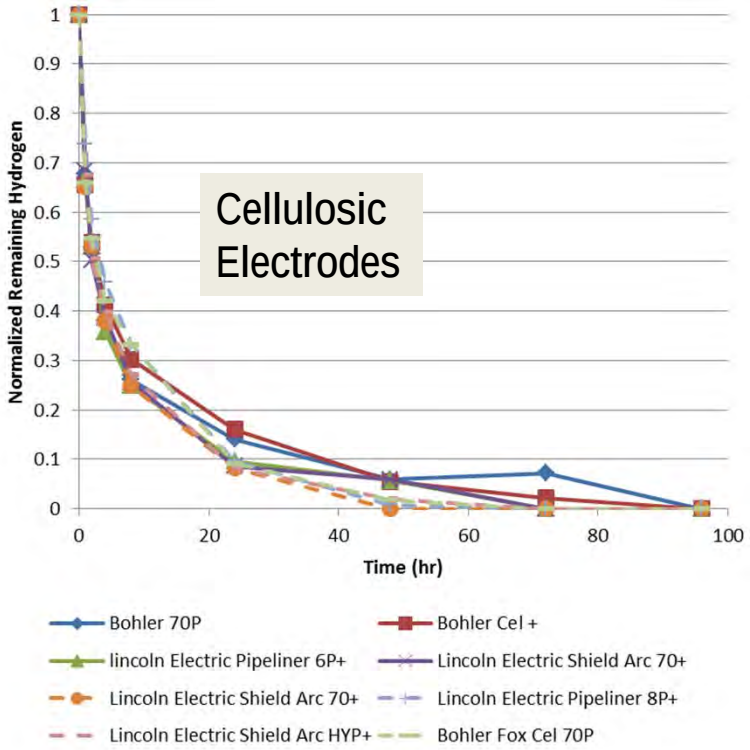


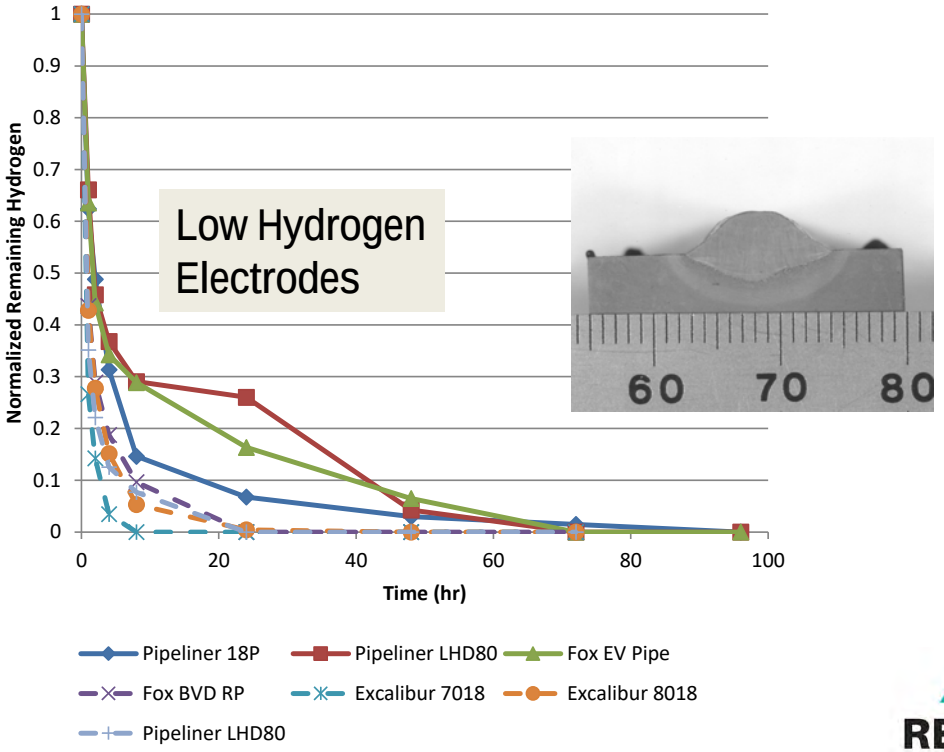




Material Characterization

- **Hydrogen effusion testing completed for all electrodes**





3/29/2020

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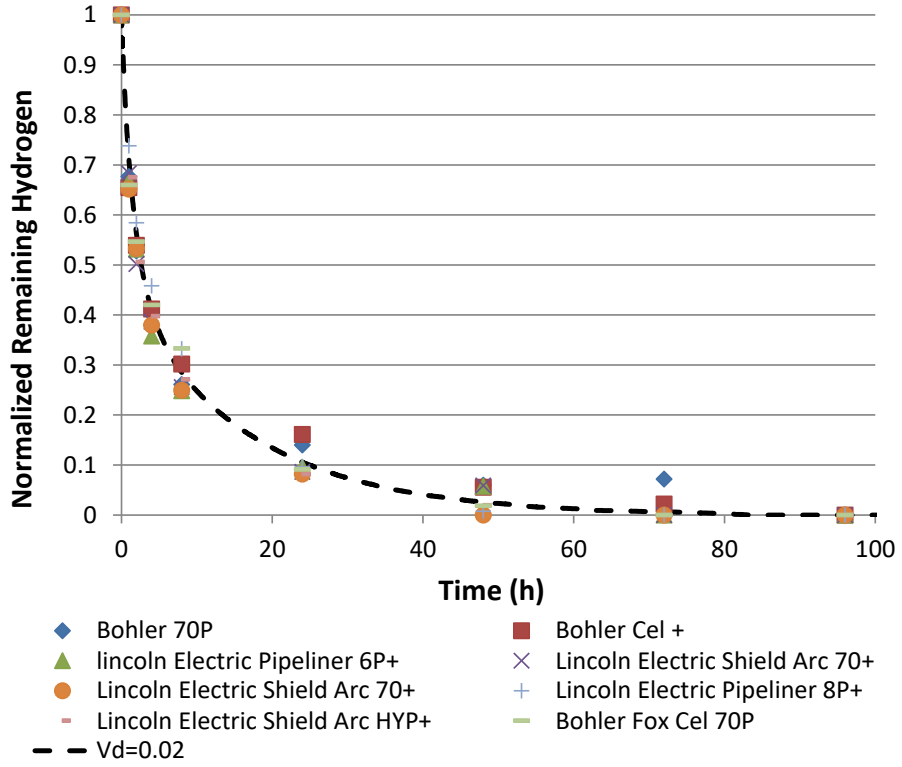
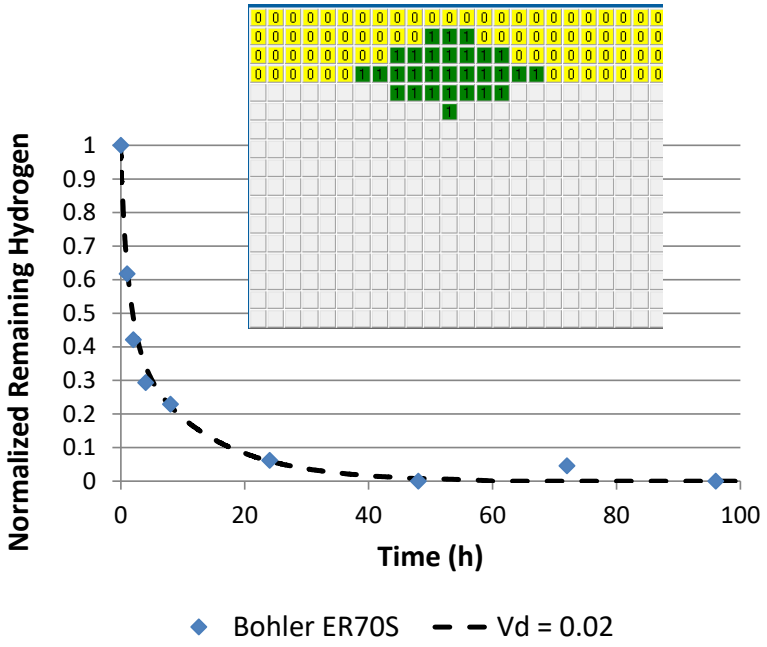
Material Characterization

- **Simulate Hydrogen Effusion – Observe similar behaviour for class**

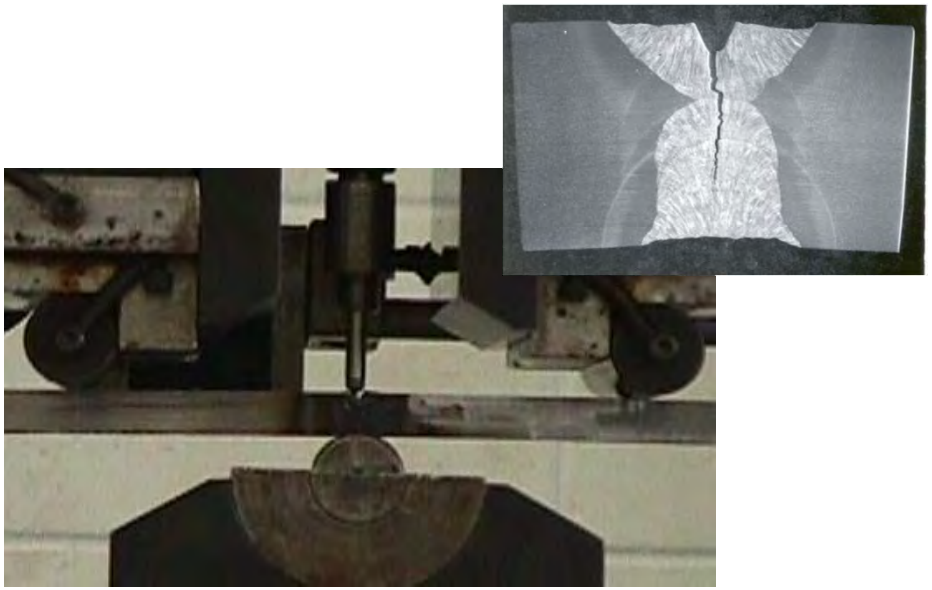




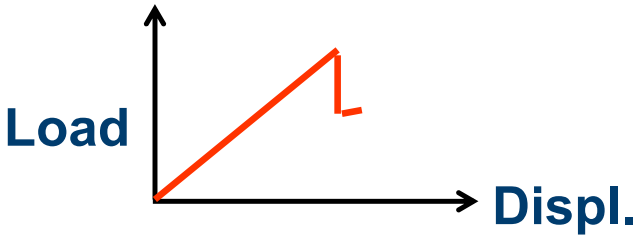
Material Characterization

- **Hydrogen Cracking Susceptibility Testing**
  - Test includes notched 3 point bend specimens with known applied load



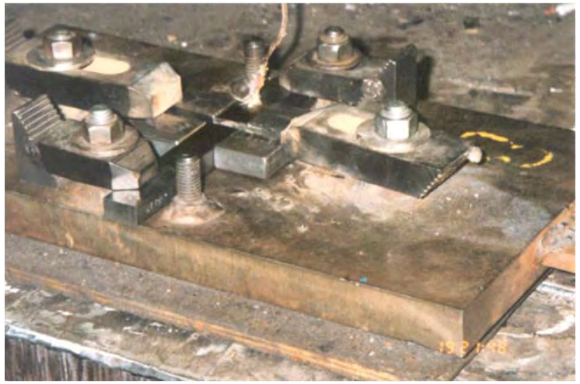


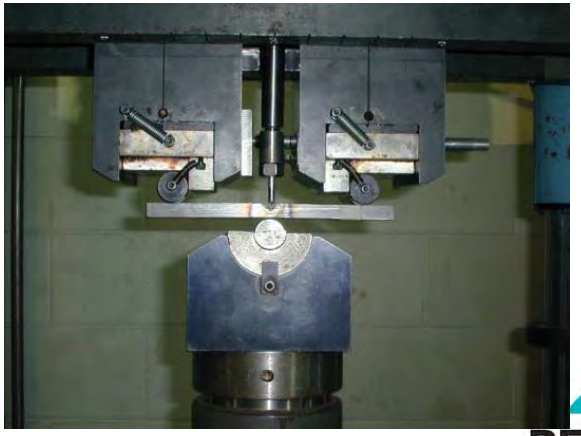
  - Notched Specimen Slow Bend



Material Characterization

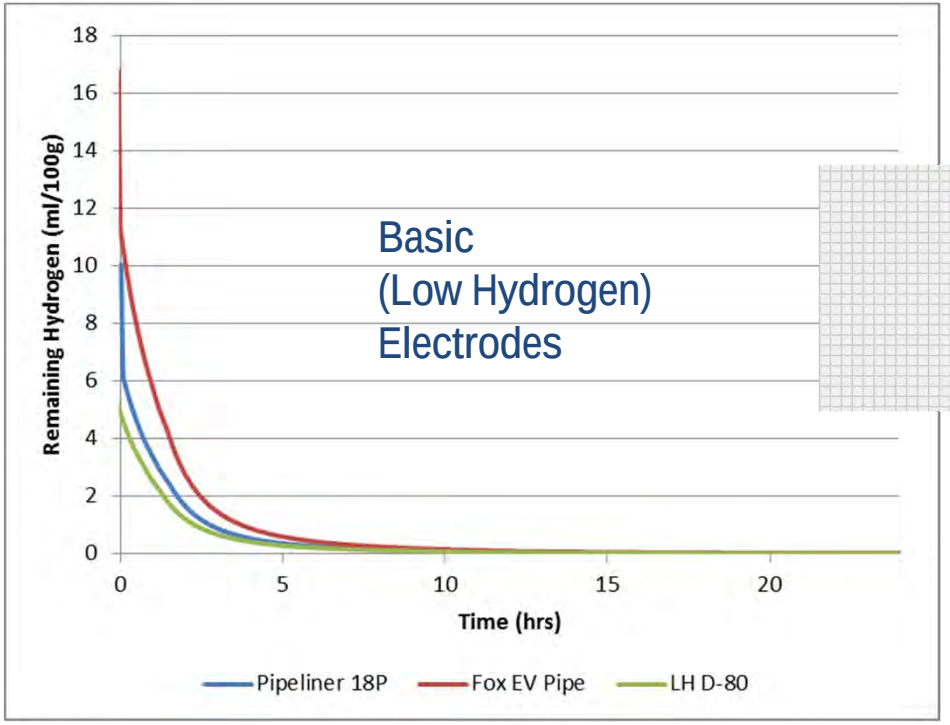
- **Slow Bend or Hydrogen Cracking Susceptibility Specimen Preparation**
  - Specimens cool after welding
  - Stored on dry ice (trap hydrogen)
  - Notches placed in WM
  - Age specimens to develop a range of hydrogen concentrations
  - Apply 3 point loading until load drop is measured (1.33mm/s cross-head displ.)
  - Hydrogen concentration at critical load is inferred from diffusion model



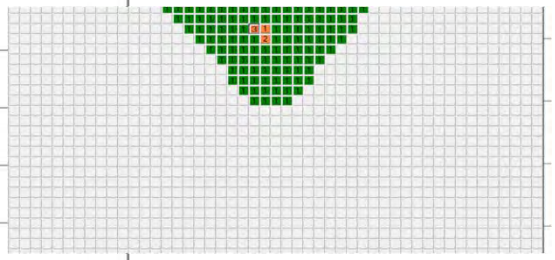


Material Characterization

- **Specimen Aging - Develop a range of hydrogen concentrations**

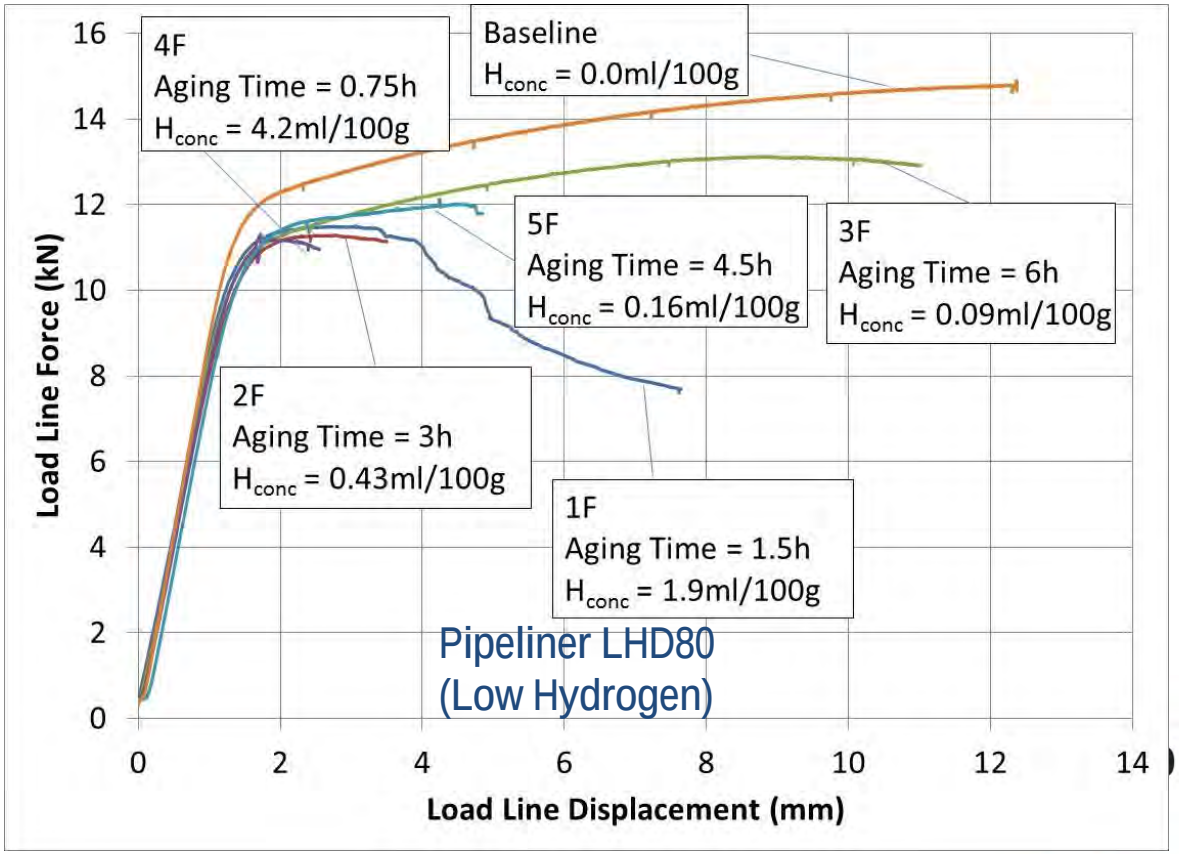


Basic
(Low Hydrogen)
Electrodes



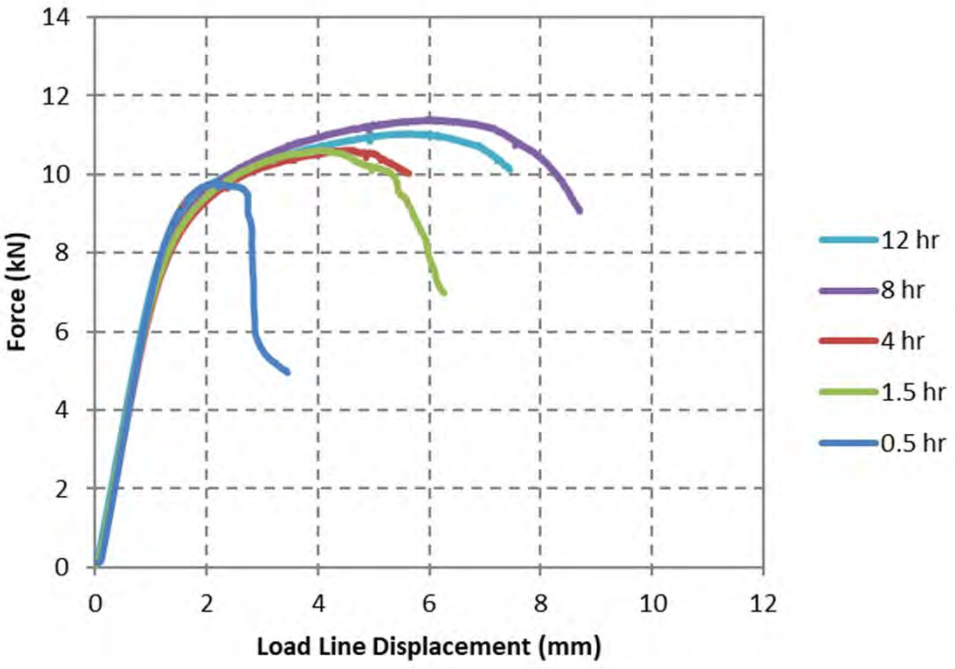
Material Characterization

- **Slow Bend Hydrogen Cracking Susceptibility**
  - Testing completed for all electrodes
  - Define critical deflection curves

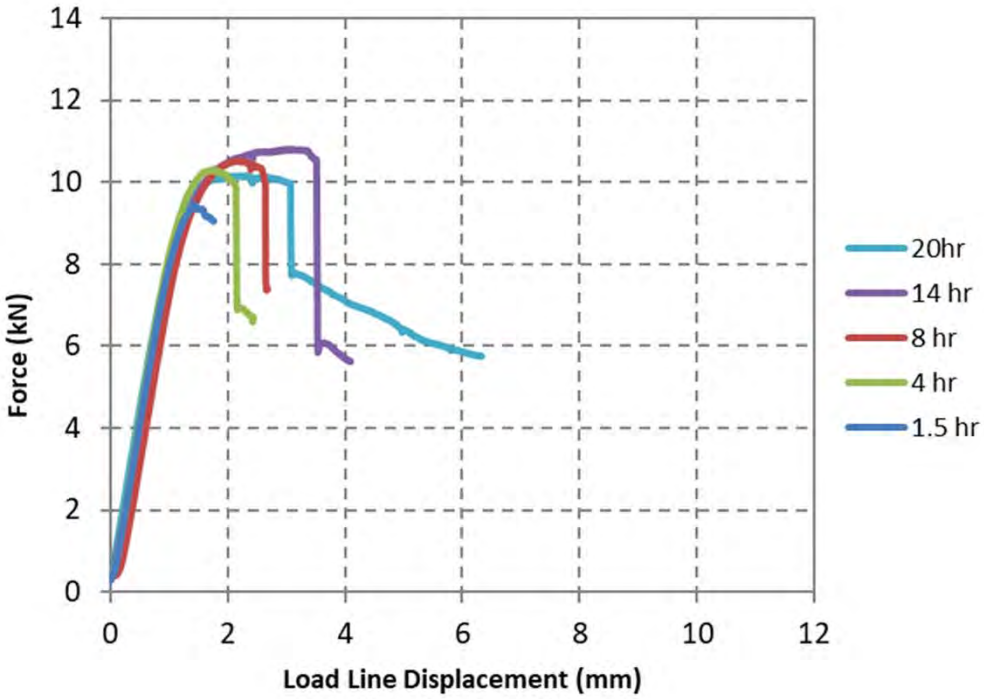


Material Characterization

- **Lincoln Pipeliner 6P+**
  . . . Possible manifestation of HELP or AIDE hydrogen cracking mechanism

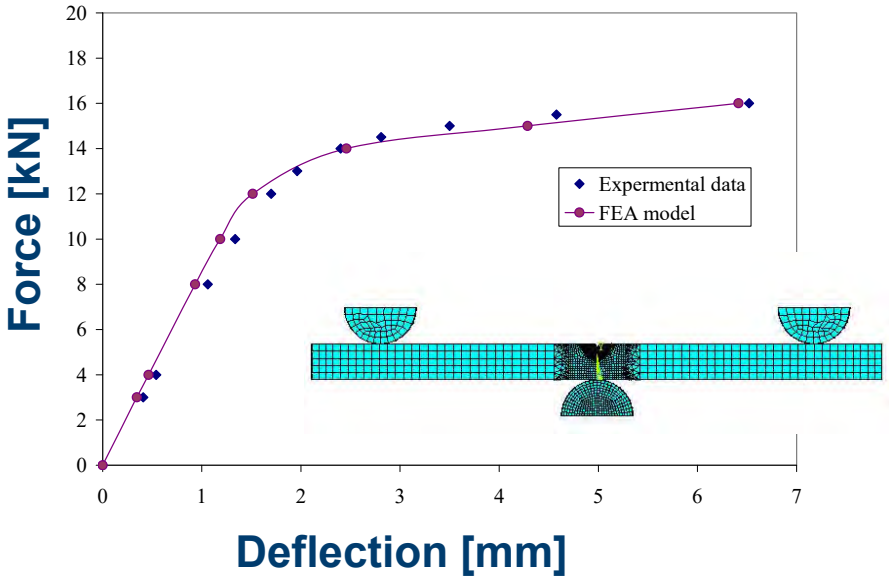


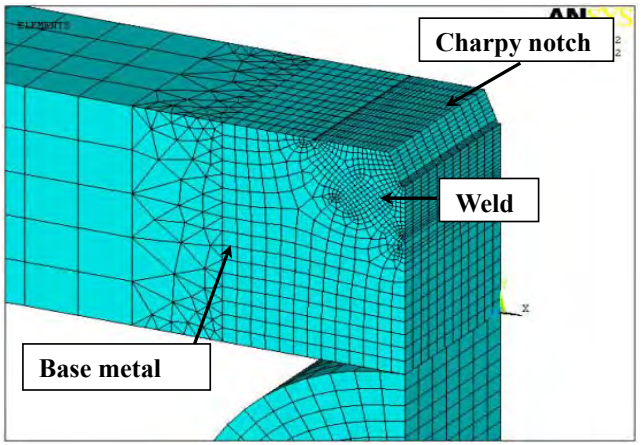
- **Lincoln Shield-Arc® HYP+**
  . . . Possible manifestation of HEDE hydrogen cracking mechanism



Material Characterization

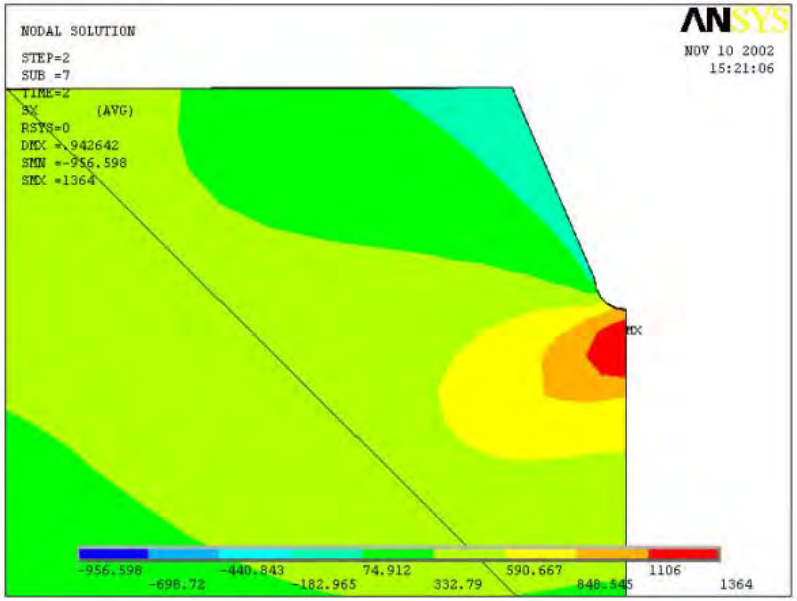
- **Specimen deflections are converted to applied stress or strain knowing the specimen and loading geometry**
  - Nonlinear ANSYS FEM with 20 node brick elements
  - Consider specimen geometry, materials and support contact

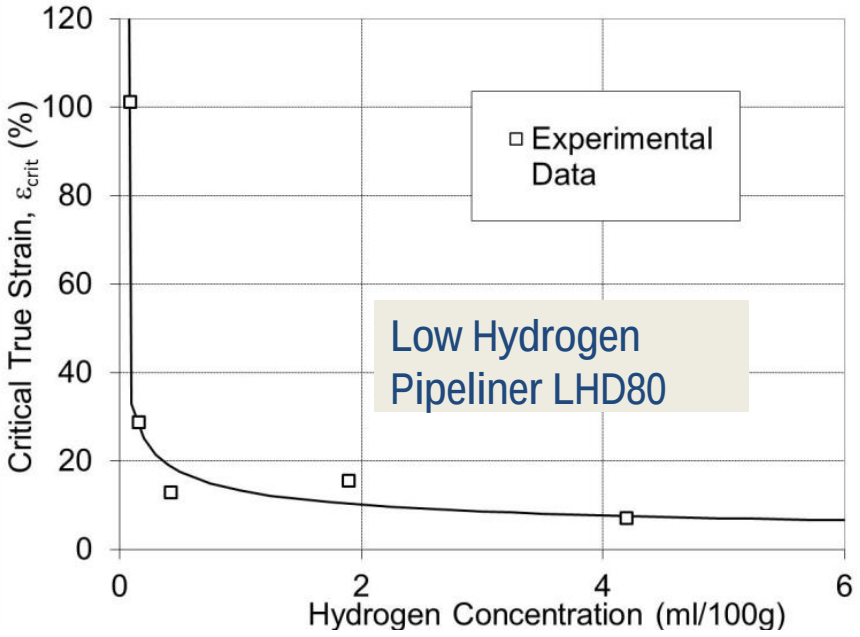




Material Characterization

- **Strains perpendicular to notch plane are used to characterize the cracking state**
  - Reported from 0.18mm sub surface (Previously 0.23mm)





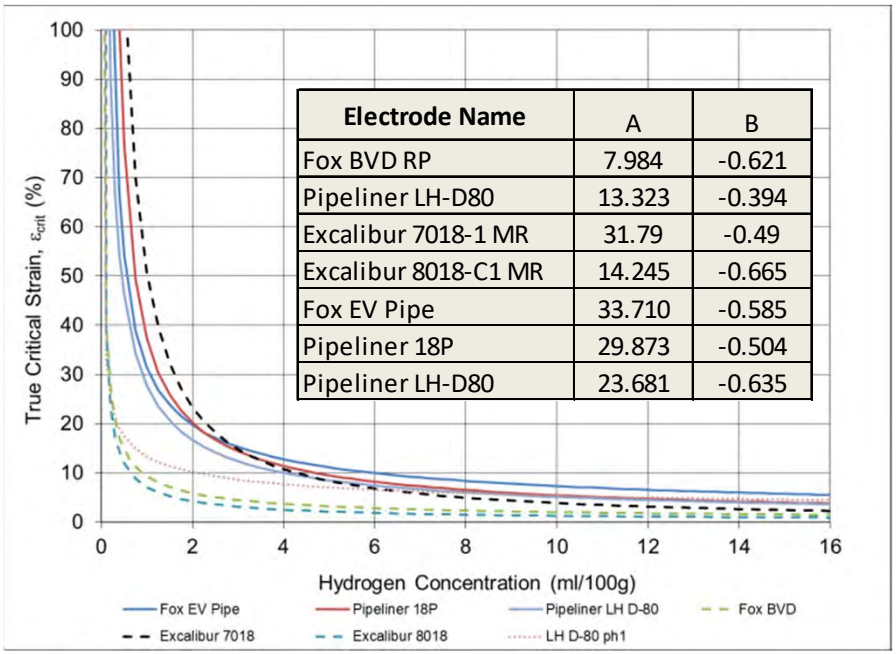
Hydrogen Embrittlement Curve Development

- **Goal: Identify critical strain (ε_{crit}) for different materials as a function of hydrogen concentration (H_{conc})**

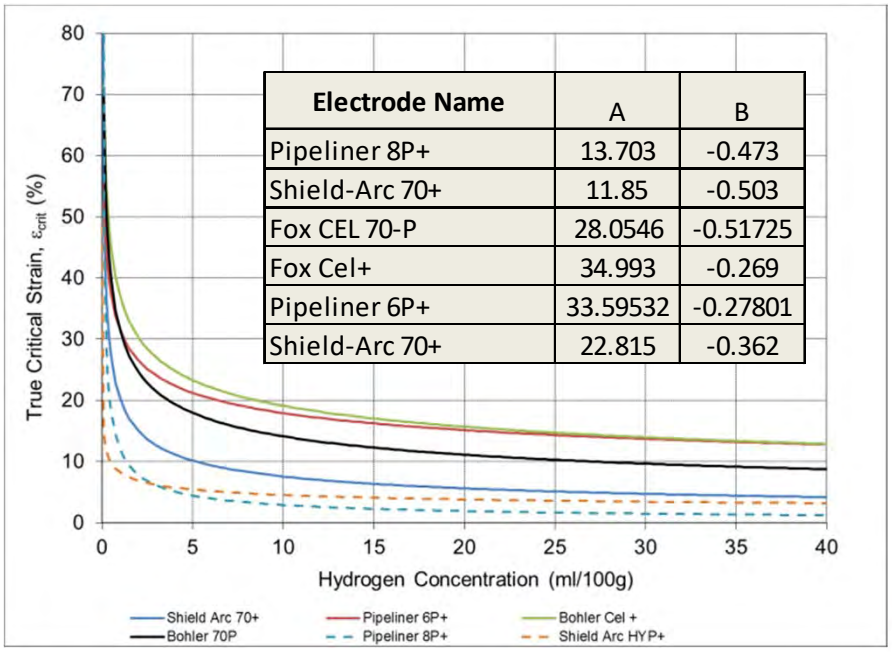
$\varepsilon_{crit} = A\,(H_{conc})B$

Embrittlement Index
B = f (?)

Ductility Index
A = f(?)



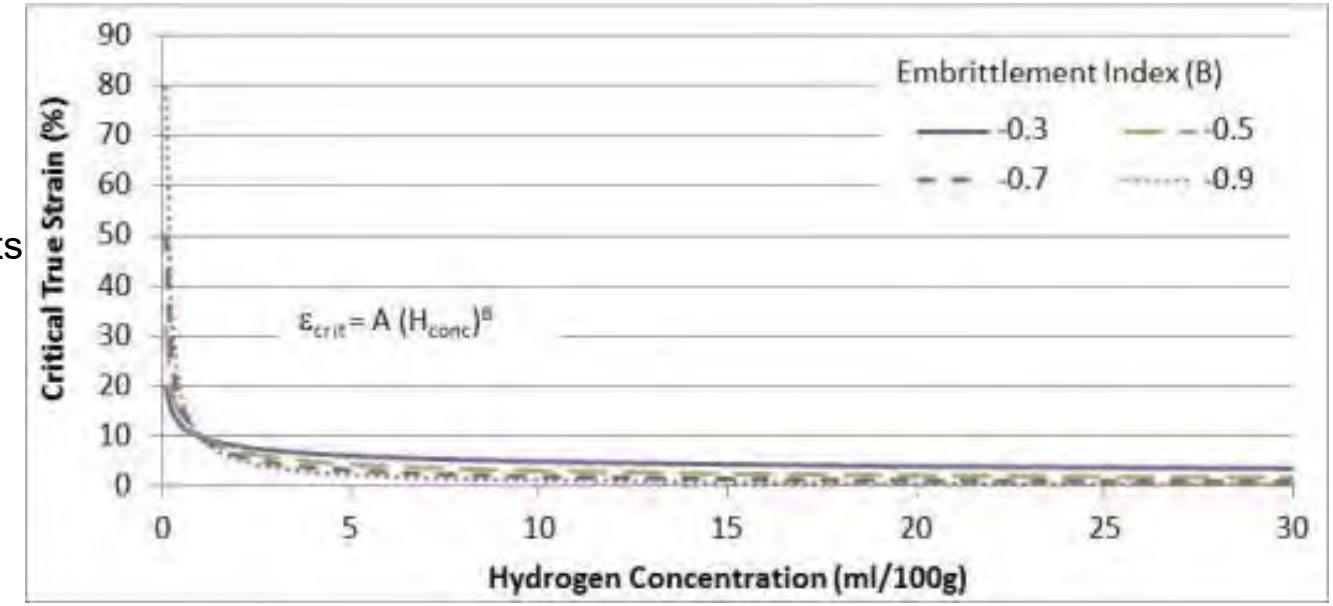
Electrode Name	A	B
Fox BVD RP	7.984	-0.621
Pipeliner LH-D80	13.323	-0.394
Excalibur 7018-1 MR	31.79	-0.49
Excalibur 8018-C1 MR	14.245	-0.665
Fox EV Pipe	33.710	-0.585
Pipeliner 18P	29.873	-0.504
Pipeliner LH-D80	23.681	-0.635



Electrode Name	A	B
Pipeliner 8P+	13.703	-0.473
Shield-Arc 70+	11.85	-0.503
Fox CEL 70-P	28.0546	-0.51725
Fox Cel+	34.993	-0.269
Pipeliner 6P+	33.59532	-0.27801
Shield-Arc 70+	22.815	-0.362

Hydrogen Embrittlement Curve Development

- **Ductility Index "A"**
  - Represents cracking strain at 1ml/100g hydrogen concentration
- **Embrittlement Index "B"**
  - Above hydrogen concentration of 1ml/100g
    - More positive B represents lower susceptibility to hydrogen cracking



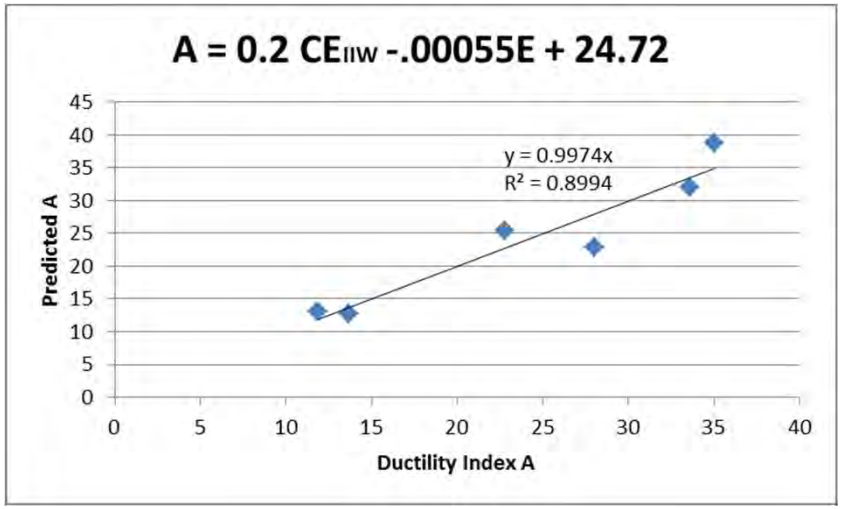
Hydrogen Embrittlement Curve Development

- **Examined experimentally obtained A, B parameters with range of material parameters and experimental data:**
  - Chemistry (C, Mn, Si, Ni, Mo, Cr)
  - CE (IIW, Yurioka, AWS, Pcm, CEw, Graville, CEN)
  - YS, UTS, % Elong., E, Resilience, Toughness, HV10
  - Microstructure AF (%), inclusion size distributions & AF (%)
  - Estimated $t_{T800-500}$

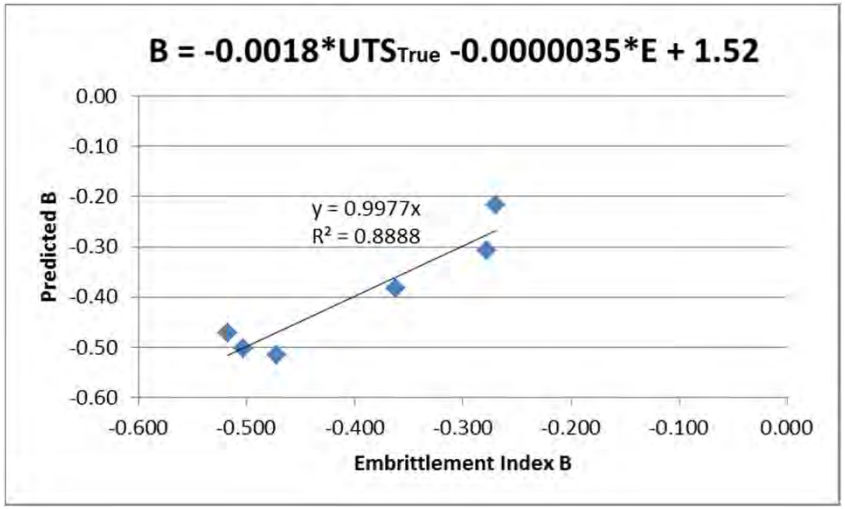
- **Results identified different behaviors for cellulosic and basic electrodes**

Hydrogen Susceptibility: Cellulosic Electrodes

- **Ductility Index 'A' Strong Correlation**
  - CEIIW (negative), E (positive)
- **Good Correlation**
  - Reported %el. (positive)
  - UTS, AF%, Mn% (negative)

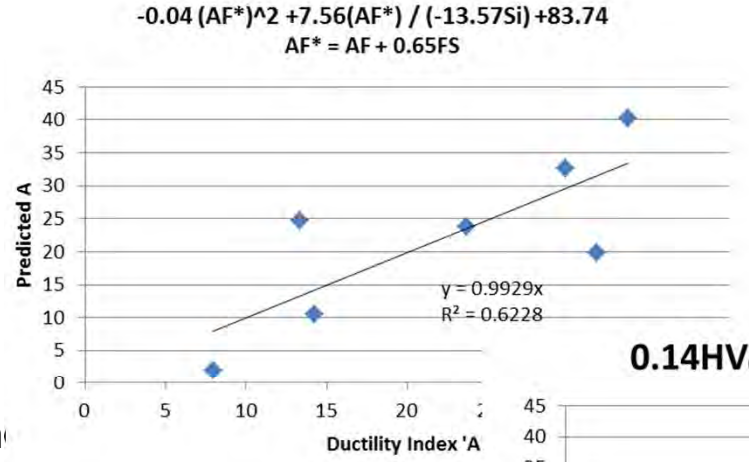


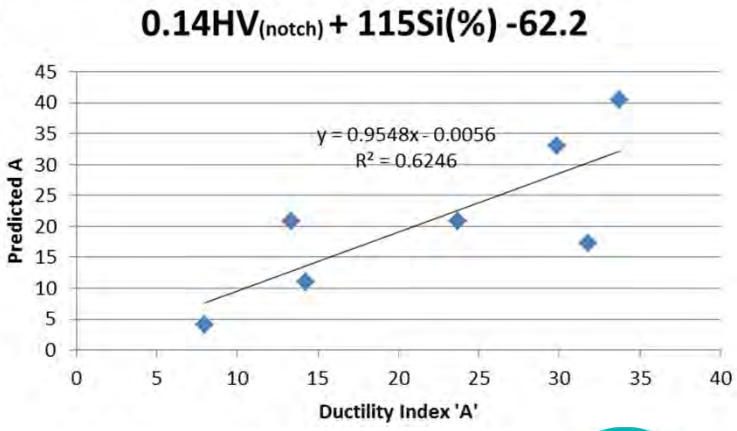
- **Embrittlement Index 'B' Strong Correlation**
  - True UTS, E (negative)
- **Good Correlation**
  - Elongation (positive)
  - YS, E, UTS, Resilience modulus (negative)



Basic Electrodes – Ductility Index ‘A’

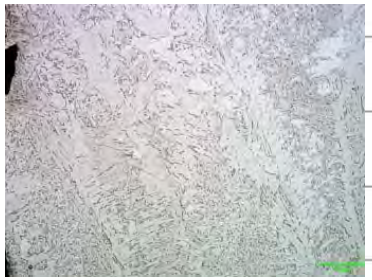
- **Positive Correlations**
  - Notch Hardness, Microstructure Constituents, Si% (positive)
  - Two relationships developed
    - Acicular ferrite (AF) + weighted fraction of FS, ferrite with secon phases (aligned & non aligned)
    - Hardness and Si weight percent
  - Potential to develop a hardness and metallurgical assessment for weld procedure development





Basic Electrodes – Embrittlement Index ‘B’

- **Correlates with Ferrite with Aligned Second Phase.**
  - Weight different microstructures based on theoretical susceptibility to embrittlement i.e. FS(NA) lower susceptibility than FS(A), while PF(I) & PF(G) are ductile structures
  - B = 1.2 x {FS(A) + 0.5*FS(NA) – 0.5*PF(I + G)} - 0.216

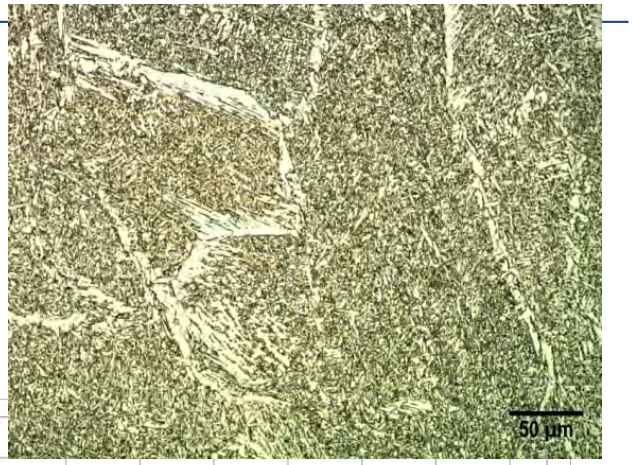


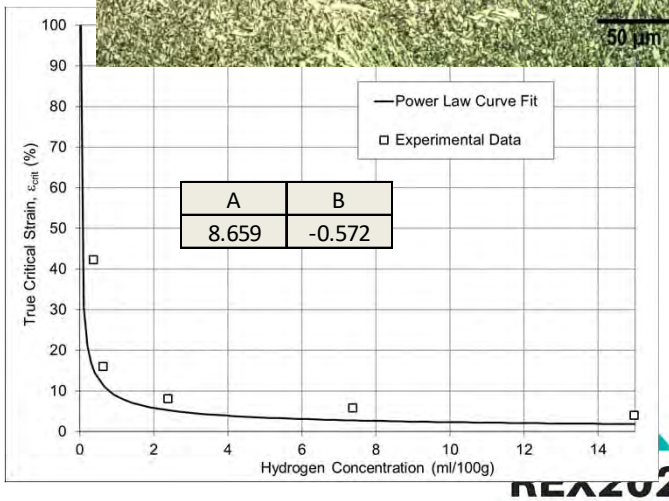
One outlier: Excalibur 7018 MR

- Widmanstatten structure from prior austenite GB
- Not observed with other materials tested

GMAW Electrode

- **Similar Microstructure to Basic Electrodes**
  - Low C, promotes ferrite along prior austenite GB
  - Concentrated heat source produces microstructure similar to a higher heat input SMAW Basic electrode weld
  - A slight increase in GMAW heat input would be expected to enhance development of ferrite structures
  - May produce lower residual stresses and hence in practice reduce susceptibility. Further investigation required to support hypothesis
  - Embrittlement Index predicted by microstructure relationship identified for basic electrodes





Concluding Remarks

- **General…**
  - 16 different consumables were tested, 13 unique
  - Microstructural trends observed for both cellulosic and basic electrodes and correlated to fracture morphology of slow bend samples

- **Cellulosic Electrodes**
  - Susceptibility curves as a function of weld metal hydrogen content were able to be predicted with the CE of the electrode and mechanical properties
  - Increasing strength, hardness, modulus and CE contribute to increasing hydrogen cracking susceptibility
  - Repeat electrode results suggest possibility of an embrittling threshold beyond which material becomes highly susceptible to all hydrogen contents

Concluding Remarks (cont'd)

- **Basic Electrodes**
  - Microstructure evolution showed correlation to the hydrogen susceptibility
  - Relationships between weld microstructure and hardness were found to correlate to hydrogen embrittlement susceptibility and may be beneficial for assessing weld procedure qualification testing
  - Welding procedure was found to influence the material properties and the susceptibility to hydrogen cracking
- **GMAW Wire**
  - Insufficient data points to draw strong conclusions, however, microstructural characteristics and mechanical tests show similar performance to low hydrogen SMAW electrodes, but at lower attainable heat inputs
- **Developed hydrogen cracking delay time estimates**
  - Define delay time for inspection to prevent hydrogen cracks from entering service for multipass basic and cellulosic girth welds

Recommended Future Investigation

- **Examine influence of welding procedure on microstructure formation and hydrogen susceptibility**
  - Reduced susceptibility was observed with increasing $t_{800\text{-}500}$ suggesting weld procedure may have appreciable influence
- **GMAW microstructure showed similarities to lower susceptible low hydrogen SMAW electrodes**
  - Further investigation of additional electrodes and weld procedure influence would confirm trends identified
- **Further investigation of hydrogen cracking / inspection delay time**

BACK TO AGENDA

PRCI 2020 Research Exchange

Welding Options and Specifications for Strain-Resistant Girth Welds

MATH-5-3B(PR-350-174507)

Yong-Yi Wang and Dan Jia (presenter)
Center for Reliable Energy Systems

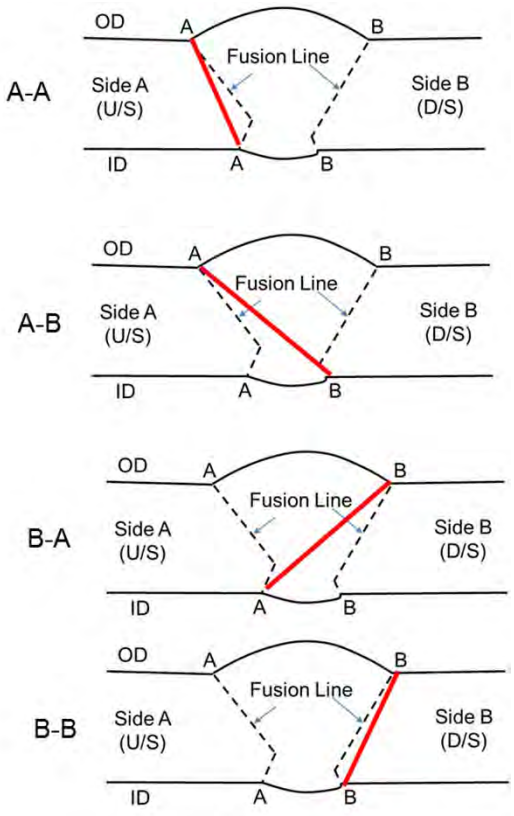
LEADING PIPELINE RESEARCH

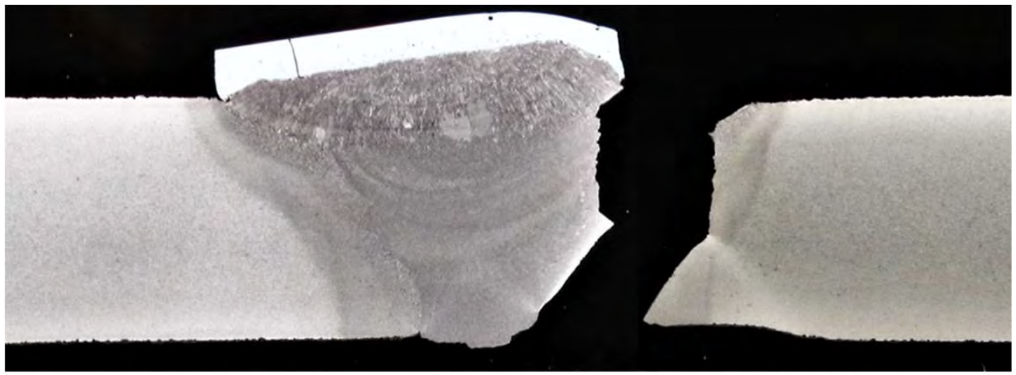
Problem Statement – Girth Weld Failures

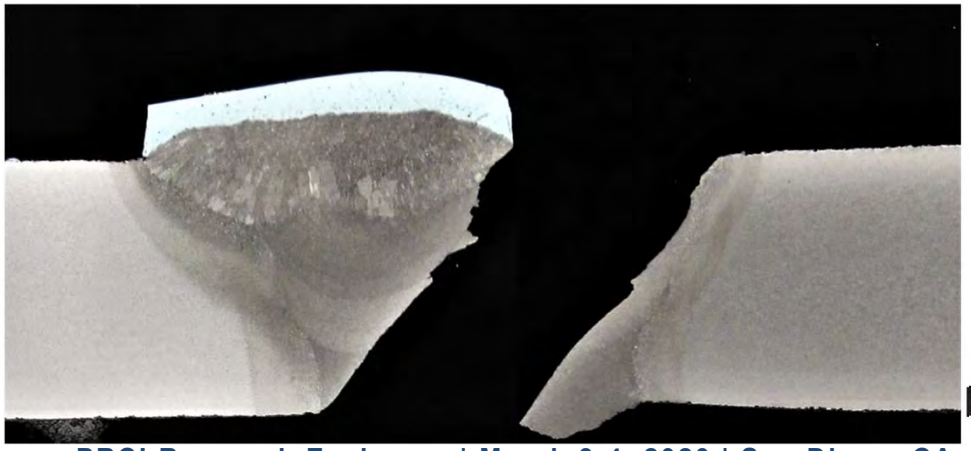
- **Girth weld failures**
  - Occurred in-service and during hydrostatic testing
  - About a dozen known in the US.
    - *Ten incidents with confirmed information, shown on in the table.*
  - More incidents are suspected to have occurred, but might not have been reported or known to the outside.
  - At least a dozen incidents have occurred in Asian countries. (all manual or semi-automatic welds)
- **Characteristics of failures in US**
  - X52 to X80, most X70
  - Welding - all manual
    - *SMAW: E6010 root, E8010 fill and cap passes*
    - *X70/X80: SMAW/E6010 root, FCAW fill and cap passes*

Incident No.	OD (inch)	Grade	Nature of Incident	Approximate Elapsed Time for Start of Service
1	20"	X70 PSL2	In-Service Rupture	1 Year
2	30"+	X80/X70	In-Service Rupture	6 years
3	12.75"	X52	In-Service Leak	14 years
4	30"	X70M	Hydrostatic Leak	N/A
5	30"	X70	Hydrostatic Leak	N/A
6	42"	X70 PSL2	In-Service Rupture	3 years
7	12.75"	X52/X65	In-Service Rupture	4-5 years
8	24"	X70	In-Service Rupture	3.5 years
9	36"	X70	Hydrostatic Leak	N/A
10	Information can't be released	X70	In-Service Rupture	Less than 1 year

Features of Failure Path

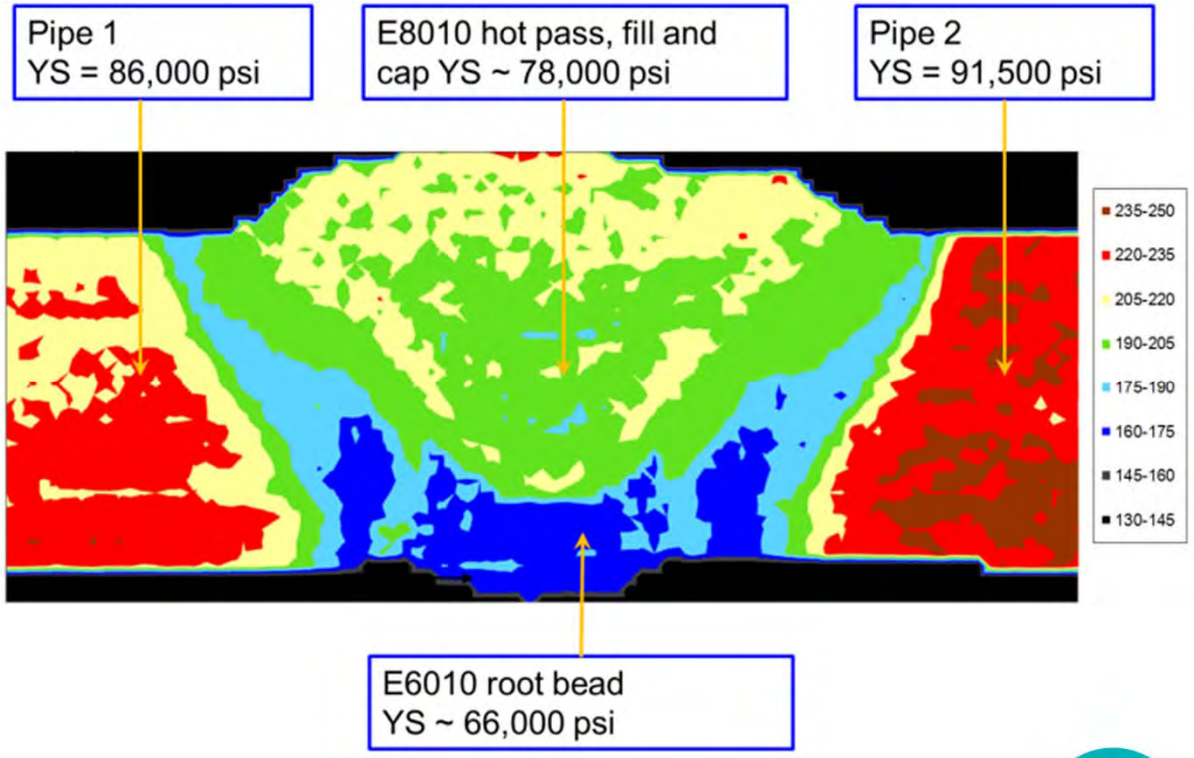






Hardness Strength Distribution

- **Representative hardness**
  - Pipe: 235 Hv
  - Root pass: 165 Hv (70% of pipe)
  - Fill pass: 205 Hv (87% of pipe)
  - HAZ: 185 Hv (79% of pipe)

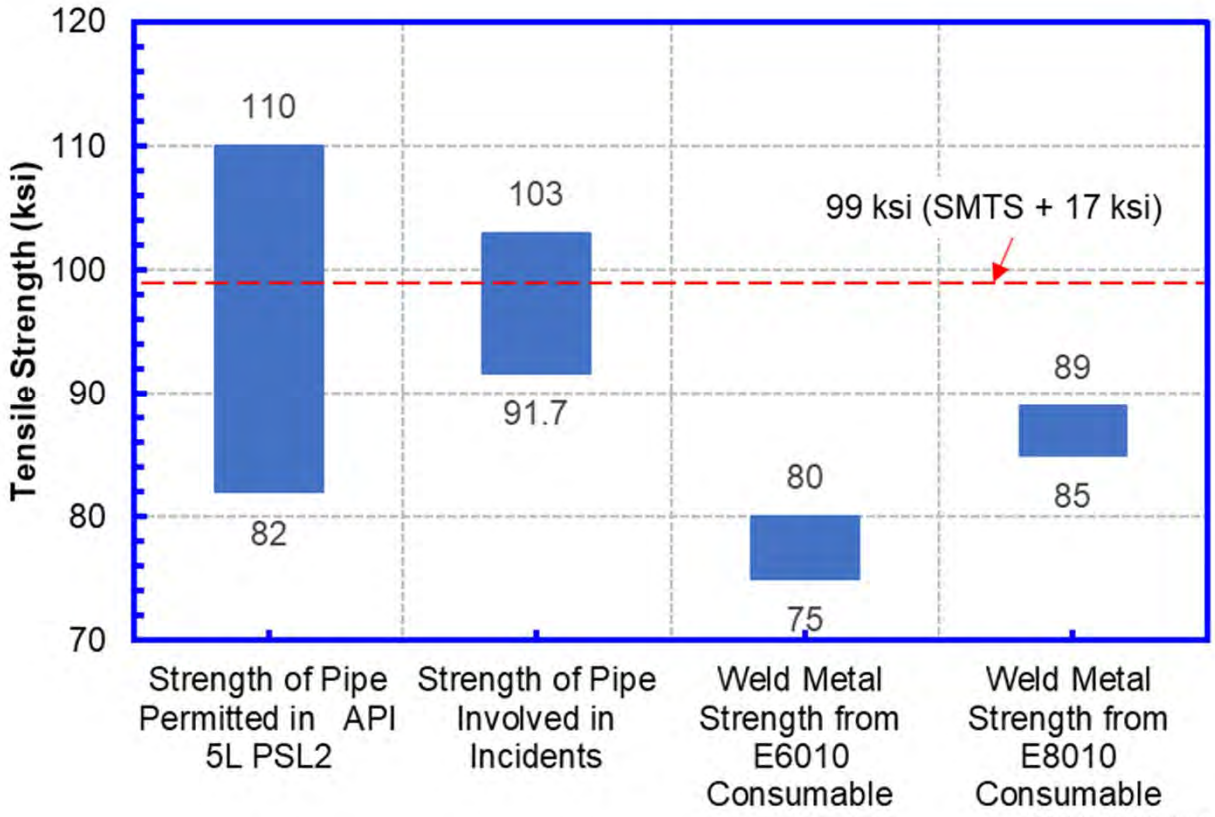


Contributing Factors to GW Failures

Contributors		Primary	Secondary	Not a Factor or Not Applicable	Not Sure
Tensile Strain Capacity	Weld Strength Undermatching	6	1	2	1
	HAZ Softening	7	1	1	1
	Weld Flaw	1	0	9	0
Strain Demand	External Load	3	4	1	2

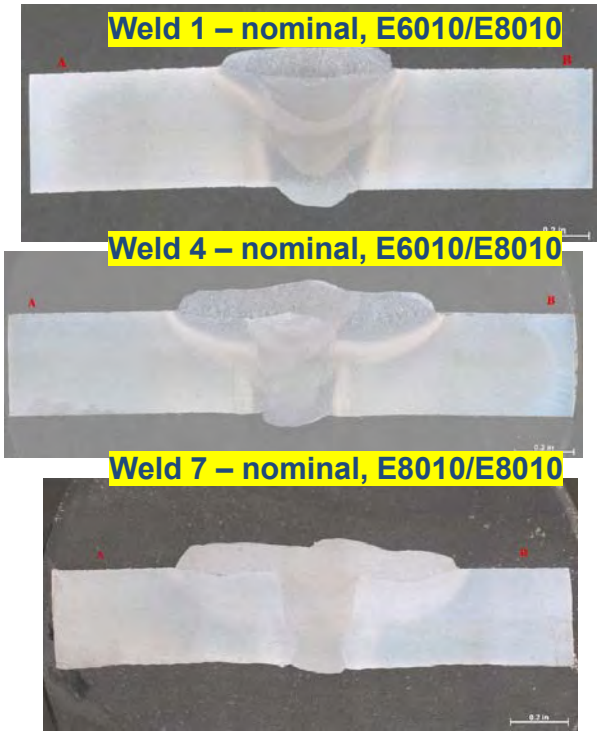
Weld Strength Undermatching in X70 Girth Welds

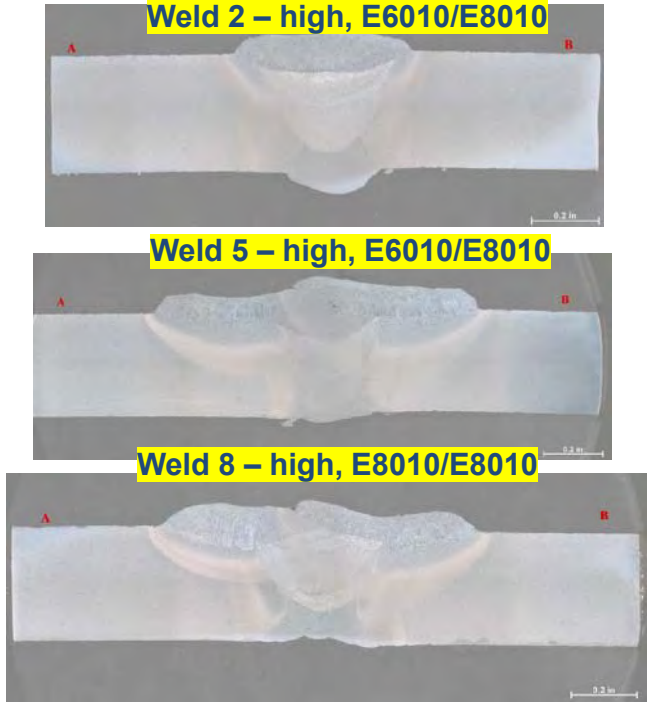
- Comparison of pipe vs. weld strength
- The weld strength from the E6010/E8010 consumables undermatches the strength of the X70 pipes.

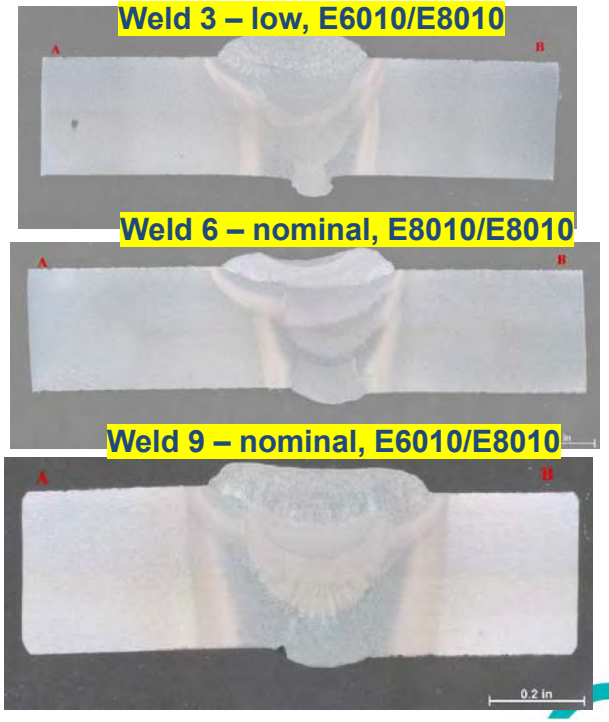


Alterative Welding Options – Weld Macros

- Nine girth welds made with different combinations of heat input and consumables

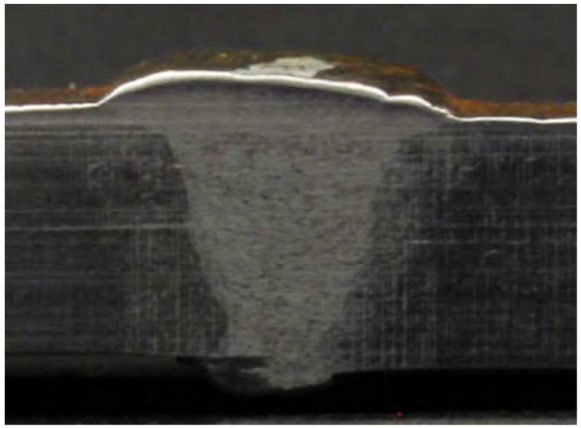




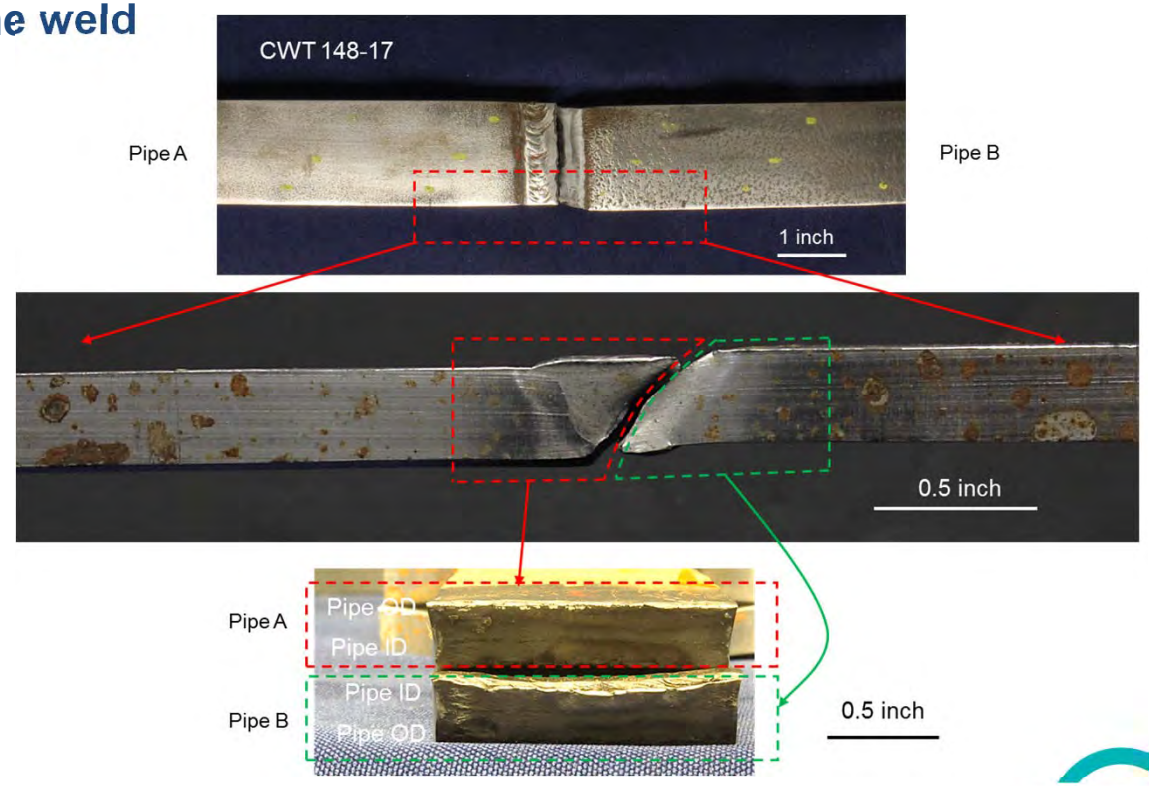


Failure Location and Cross-Section 1

- **Without reinforcement, fail in the weld**
  - Nominal heat input
  - E6010/E8010 consumables

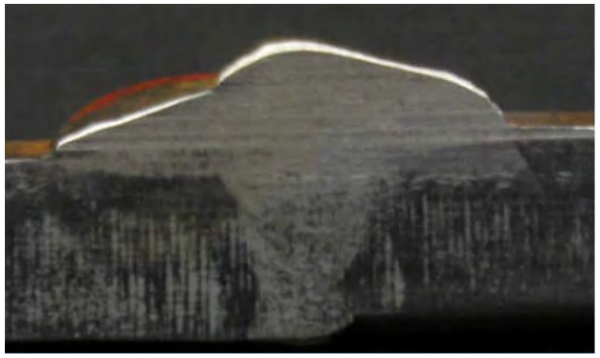


Cross-weld region before test

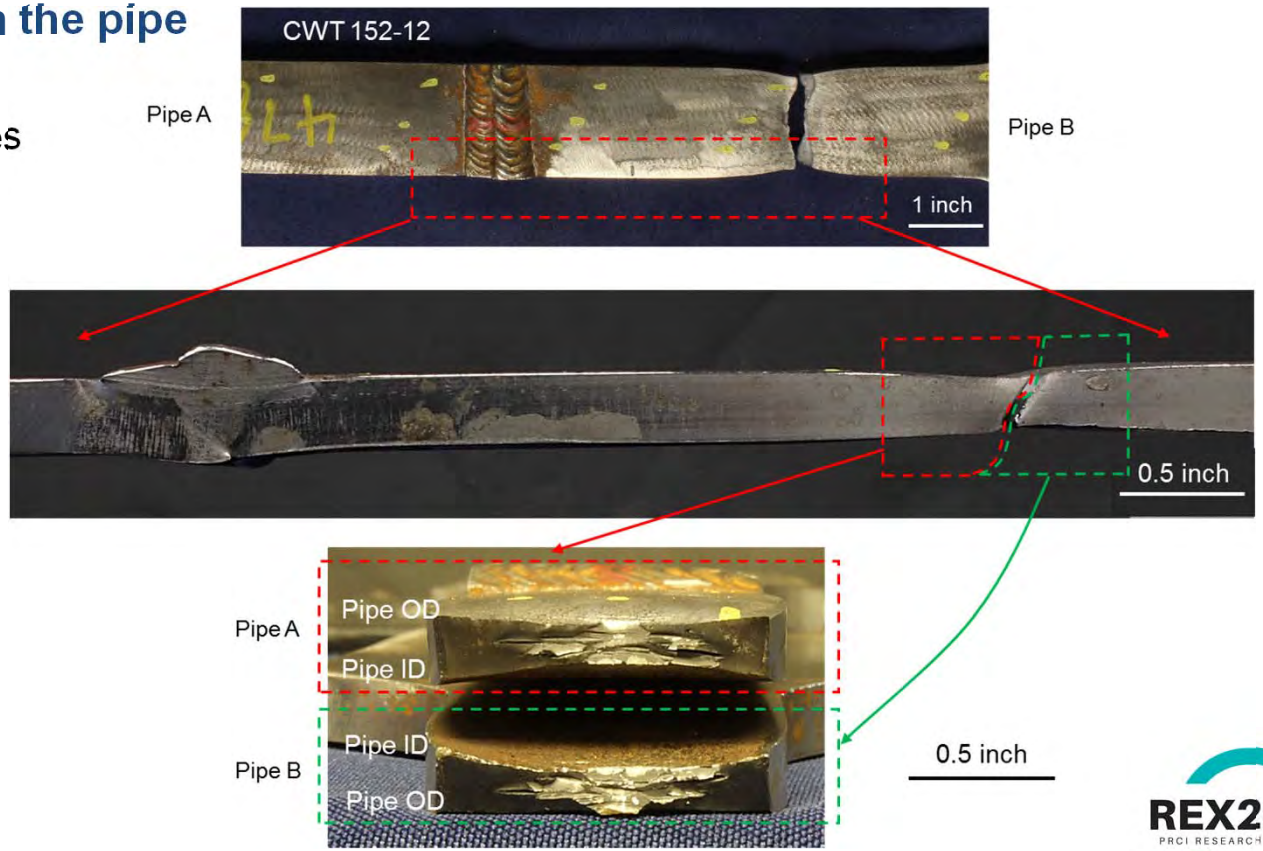


Failure Location and Cross-Section 2

- **With reinforcement, fail in the pipe**
  - High heat input
  - E6010/E8010 consumables



Cross-weld region before test

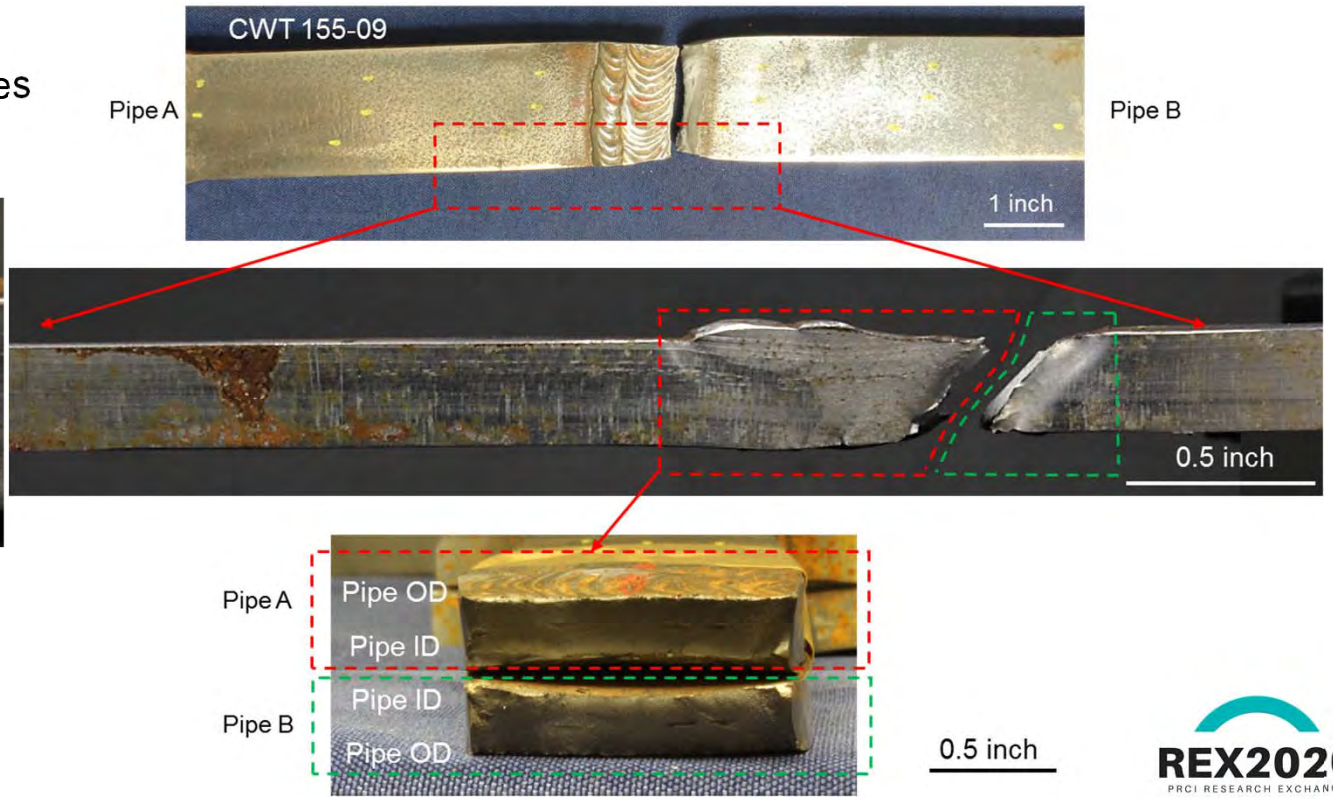


Failure Location and Cross-Section 3

- **With reinforcement, fail in the weld, cap not centered**
  - High heat input
  - E8010/E8010 consumables



Cross-weld region before test



Tensile Strain Capacity (TSC) Analysis

- **Welds analyzed**
  - Manual welds without extra weld cap, with and without flaws
  - Manual welds with extra cap, with and without flaws
- **Variables**
  - Wall thickness
  - Pipe strength (affecting weld strength mismatch)
  - Root strength (affecting root strength mismatch)
  - HAZ
    - *Level of softening*
    - *Width of softened zone*
  - Weld cap dimensions
  - High-low misalignment
  - Flaws

TSC Analysis – Without Extra Cap Reinforcement

- **Order of impact on TSC**
  - 1 – Weld strength mismatch
  - 2 – HAZ (level of softening and width)
  - 3 – Weld root strength
- **The parameters in lower order can play a more prominent role if the higher order parameters don't dominate**
- **Impact of pipe strength**
  - When pipe strength is in the upper bound, most TSC would not meet the requirement.
  - When pipe strength is in the lower bound, most TSC would meet the requirement
  - When pipe strength is in the middle, TSC is affected more prominently by parameters other than pipe strength (mismatch).

TSC Analysis – Extra Cap Reinforcement

- **Extra wide cap width usually makes positive contribution to TSC**
- **Extra wide cap with**
  - Regular cap height is effective if
    - *Welding strength undermatching is not excessive (<20%)*
    - *HAZ softening is not excessive (<15%)*
  - Extra cap height is needed if
    - *Welding strength undermatching is high (>20%)*
- **Extra cap may not be effective when**
  - HAZ is susceptible to high levels of HAZ softening, or
  - Cap is not centered

Recommendations – Girth Welding

- **Scope**
  - Selection of welding procedures, including consumables, and
  - Welding procedure qualification tests and requirements.
- **These recommendations are relevant to welds determined to need a target strain capacity of 0.75% under Class 1 pressure conditions.**
- **Assumptions**
  - The focus is on X70 pipes, although the same concepts can be applied to other grades.
  - The possible pipe properties are similar to those observed from pipes produced in the past 10-15 years.
  - Full range of tensile properties as demonstrated by the test data so far is possible.
  - Full range of chemical composition as demonstrated by the test data so far is possible.

Recommendations – Selection of Welding Processes

- **Selection parameters: (1) tensile strength and (2) chemical composition**

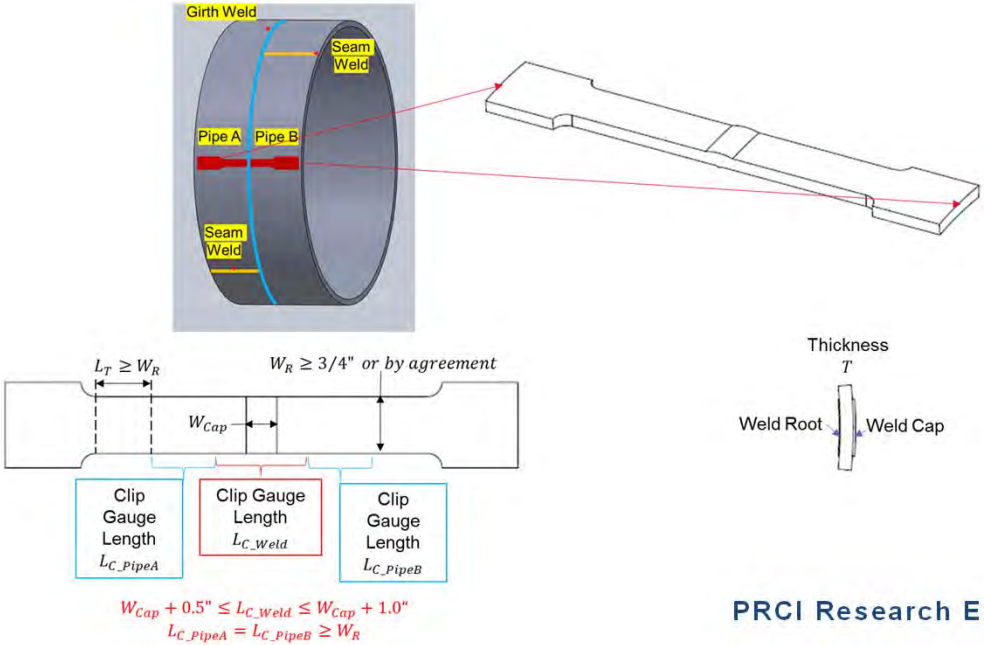
Pipe Conditions	Pipe UTS (ksi)	≤ 94	> 94			> 94		
	Pipe Carbon (%)	≥ 0.05	≥ 0.04			< 0.04		
	Pipe Pcm	≥ 0.16	≥ 0.14			< 0.14		
Welding options, when any of the three pipe conditions applies	Consumable of root pass	E6010	E6010	E8010	E8010	E6010	E8010	E8010
	Consumable of remaining passes	E8010	E8010	Low hydrogen 90+ ksi grade	90+ ksi grade FCAW	E8010	Low hydrogen 90+ ksi grade	90+ ksi grade FCAW
	Weld cap reinforcement	Regular	Wide width, See Figure 1	Regular	Regular	Wide width, See Figure 1	Wide width, See Figure 1	Wide width, See Figure 1
	Pass control	Regular	Regular	Regular	Pass sequence to minimize HAZ softening	Small diameter electrodes with more passes	Regular	Pass sequence to minimize HAZ softening

Recommendations – Welding Procedure Qualifications

- **Qualification criteria**
  - No failure in the weld region (weld metal, fusion boundary, and HAZ)
  - Permitting failure in the weld region, provided a target strain capacity is achieved
- **Selecting pipe for qualification tests**
  - Use UTS for the pipe strength selection
  - Choose carbon and Pcm towards the lower ends of possible distribution
  - When (a) and (b) cannot be met, select pipe with high-end strength and low-end hardenability

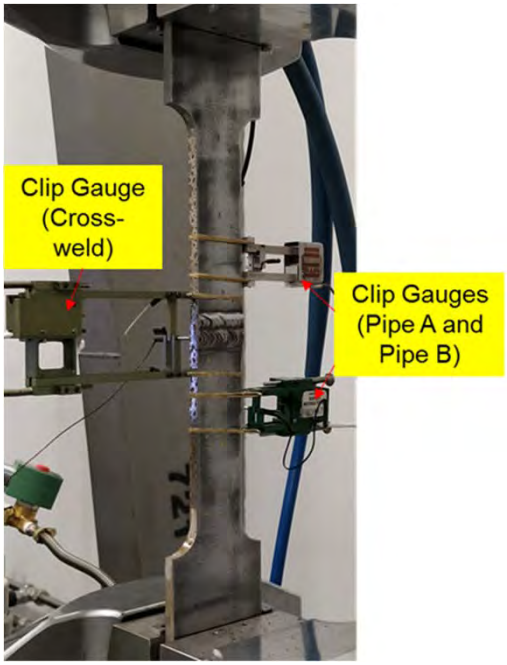
Recommended Practice for Cross-Weld Tensile Testing

- **Scope**
  - Evaluate the performance of girth welds by examining the relative strain accumulation between the weld region and the base pipe.
  - Provide the longitudinal stress-strain relation of the pipe base metal if the specimen does not fail at low strain in the weld area.



Multiple-Purpose Tool - Instrumented Cross Weld Tensile Testing

- **Evaluate the performance of girth welds (tensile strain capacity**
- **Understand likely failure location**
  - Reveal flaws in the welds if a specimen fails in the flawed plane of the weld
- **Provides the longitudinal stress-strain relation of the base metal if the specimen does not fail in the weld region**
- **Alternative to current welding procedure qualification tests**
- **HAZ softening**



Thank You

- QA

BACK TO AGENDA

Tracking and Traceability Marking Standard for Natural Gas Transmission Components

Shannon Katcher
PRCI 2020 Research Exchange
March 2020

75-year+ History of Turning Raw Technology into Practical Energy Solutions

IRU#D#EHWWHU#HFRQRP\#DQG#D#EHWWHU#HQYLURQPHQW

VXSSO\ ▶ FRQYHUVIRQ ▶ GHOLYHU\ ▶ XWLOL]DWIRQ





RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

COMMERCIALIZATION

360+ EMPLOYEES



Zruog0fodvv#slrwbj#dfldwhv#khdgtxduwhuhg#q#Fklfdjr#duhd

Operations Technology Development (OTD)

Stand-alone, not-for-profit, member-controlled company where gas utilities work together to develop technology solutions to common issues (est. 2003)



27 Members serving **50 million gas consumers** in the US and Canada

Research Foundation
Southern California Gas Company, A Sempra Energy utility
conEdison
PG&E Pacific Gas and Electric Company
ATMOS energy
SOUTHWEST GAS
Ameren FOCUSED ENERGY. For life.
PSNC ENERGY, A SCANA COMPANY
CenterPoint Energy
Entergy
PEOPLES GAS NATURAL GAS DELIVERY
INTERMOUNTAIN GAS COMPANY
NYSEG RG&E
National Fuel
Oklahoma Natural Gas, A Division of ONE Gas
AVISTA
MiSource
NW Natural We grew up here.
Nicor Gas
TECO PEOPLES GAS
ENBRIDGE
Washington Gas, A WGL Company
Dominion Energy
nationalgrid
Liberty Utilities
DUKE ENERGY
spire
Black Hills Energy

gti

Smart Utilities Program Area

- Key initiatives include:
  - GNSS Testing & Evaluation
  - Enhanced/Digital Data Collection
  - Tracking & Traceability (Steel Materials)
  - GIS Analysis & Mapping
  - Process-Based Business Analysis & Intelligence
  - Excavation Encroachment Notification System
  - Emerging Technologies



When there's No Global Standard….



What is GTI doing?

- Building the standard mark

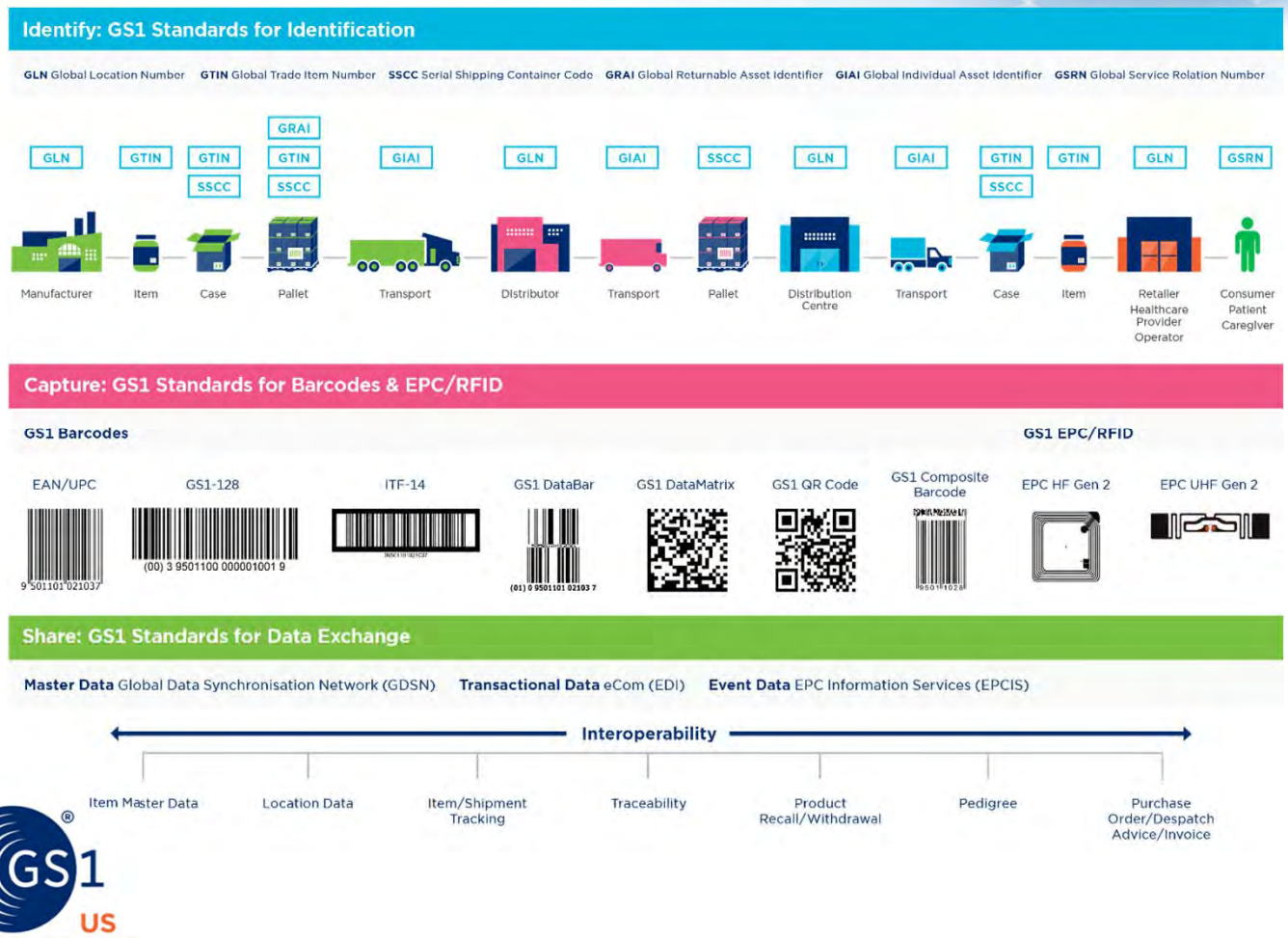
Attribute	GTIN	PSL	Pipe Type	Pipe End	Grade	Delivered Condition	OD	Wall	NPS	SPEC	Random Length	Protective Coating
Description	Global Trade Item Number	Product Specification Level	Process of Manufacturer Table 2	Type of Pipe End Table 2	Steel Grade	PHM?	Outside Diameter	Wall thickness	Nominal Pipe Size	Manufacturing Specification	API 5L Table 12	Coating Type
Sample Data	(01)081 000741 00360	2	HFW	Threaded	L290	As-rolled	3.0	.33”	3 “	API 5L 46t	20 ft	FBE

- Developing software
- Working with GS1 (standards organization)
  - Same organization that uses UPC codes
  - Examples of success include food industry and pharmaceutical industry



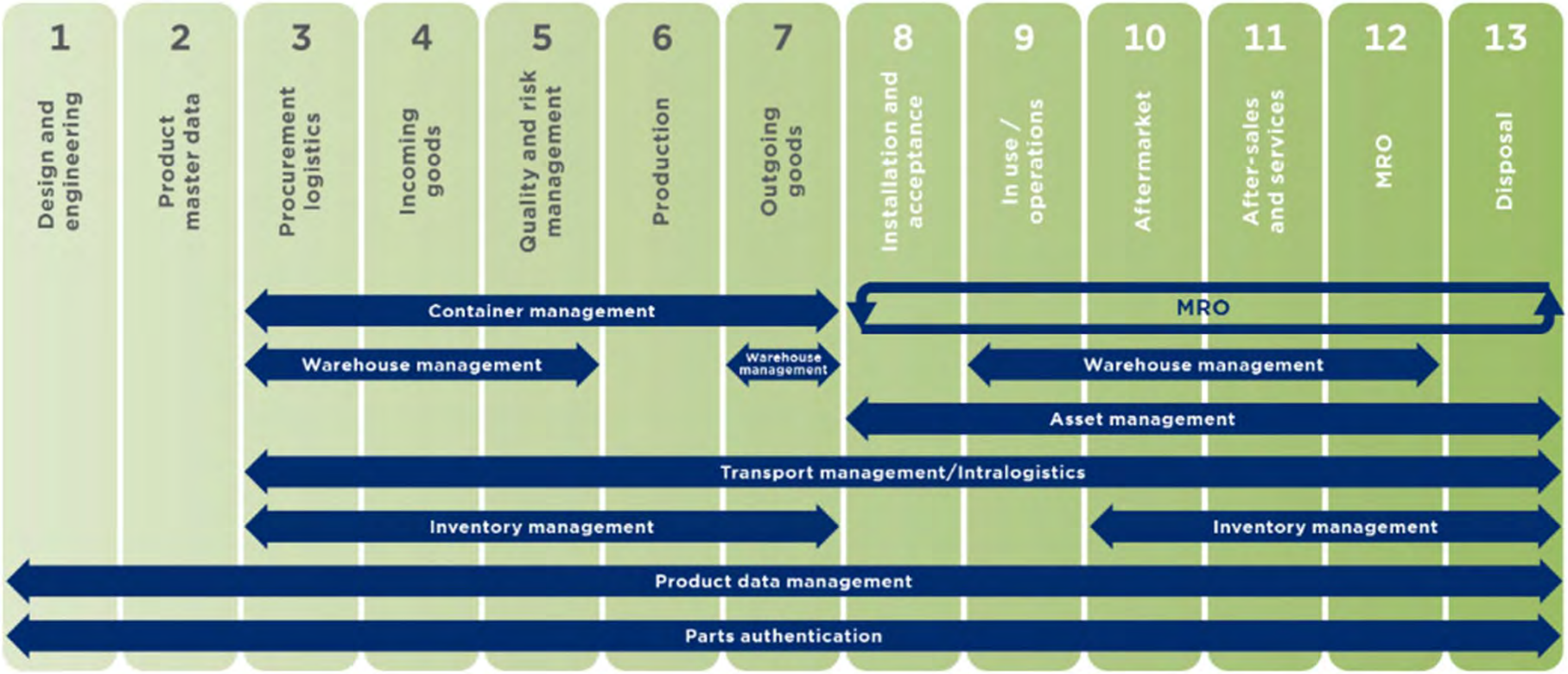
Why GS1?

- **International Standard** (we do not need to re-invent the wheel)
- **114 local member organizations**
- **2 million companies** use GS1 Standards
- **100 million products** carry GS1 barcodes
- **6 billion GS1 barcodes** are scanned every day

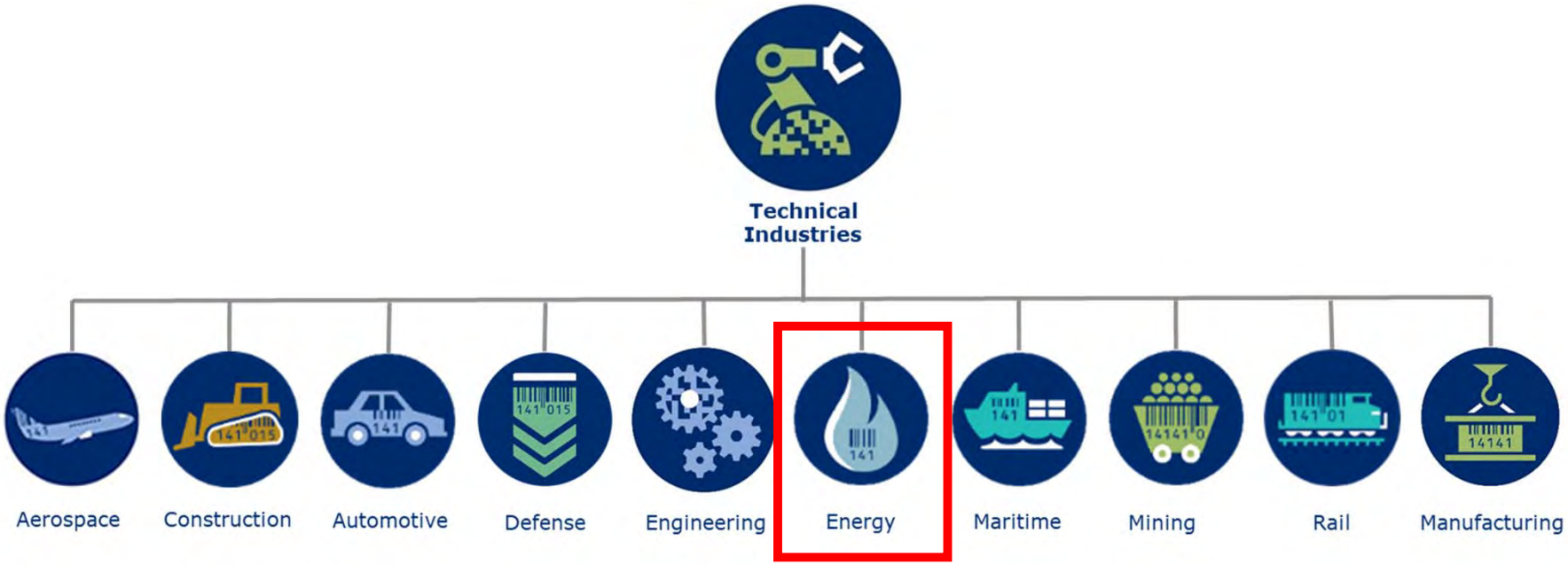


GS1 US

Tracking & Traceability throughout entire component lifetime



Technical Industries Served



Capabilities of New Mark

- Component Manufacturer
  - ID
  - lot code
  - *Heat number*
  - production date
  - material
  - Component type
  - Component size
- *Product Identification*
- *Install by date*
- *Product serialization (when needed)*
- *Manufacturing location*

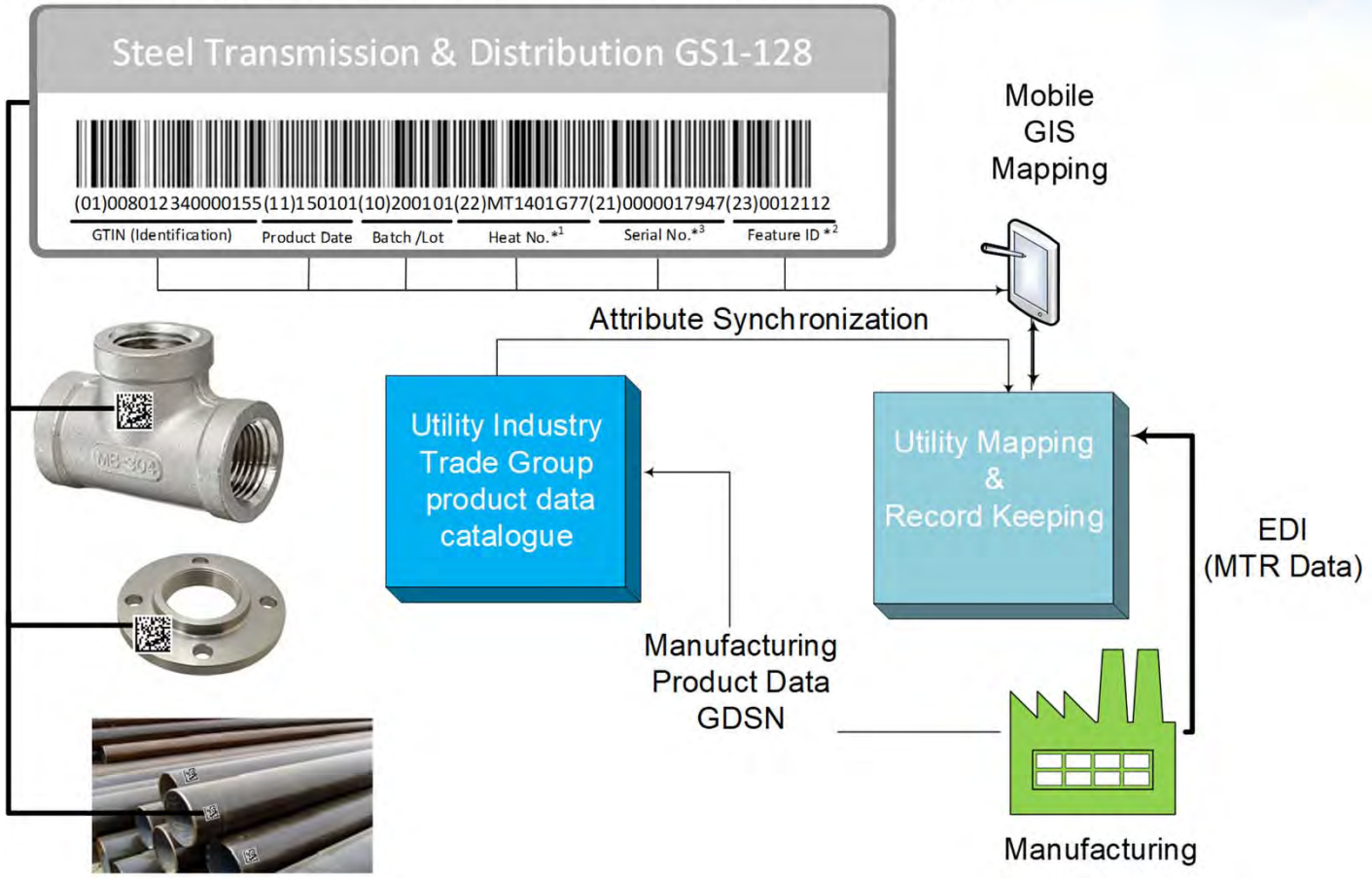
- *Components standardization across utility service (gas, electric, water, sanitary, part 195 pipeline services, telecom) – all network-delivered services*
- *Marking architecture standardized globally (components, subassemblies)*
- *Compatibility with existing standards (e.g. ASTM F2987)*
- *Improved warehousing, shipping, receipt acknowledgement and asset management*
- *Integrate electronic MTR (Material Test Reports) data*
- *Integrated master data (component manufacturers catalogue data)*

New Mark Capabilities **F2897 Capabilities**

Value From GS1 Standardization

- Predictable, **machine-readable** information
- **Automatic** component definition
- **Protection from counterfeit** construction products
- **Reduced risk:** knowing where a component is if recalled for repair, replacement, or counterfeit
- **Standardized** component classes and subclasses (pipe, valves, fittings, ...)
- Improved computer models (cartographic precision, network definition)
- **Electronic delivery** of inspection and test data (MTR Data), an instance of a component
- Support for open supply chain trading (manufacturer, distributor, supplier, contractor) ⇨ end user.
- **Flexibility** to meet changing business & regulatory requirements (modular marking construction)
- **Globally recognized** marking standards architecture
- Logistical support for packaging, shipping, receiving, warehouse and inventory management
- **Compatible** with existing standards e.g. (ASTM F2897)

Barcode shown below for illustration purposes
Data carrier is data matrix barcode shown on utility product



Data Flow via GDSN

Select one data pool as a SINGLE point of entry to the GDSN

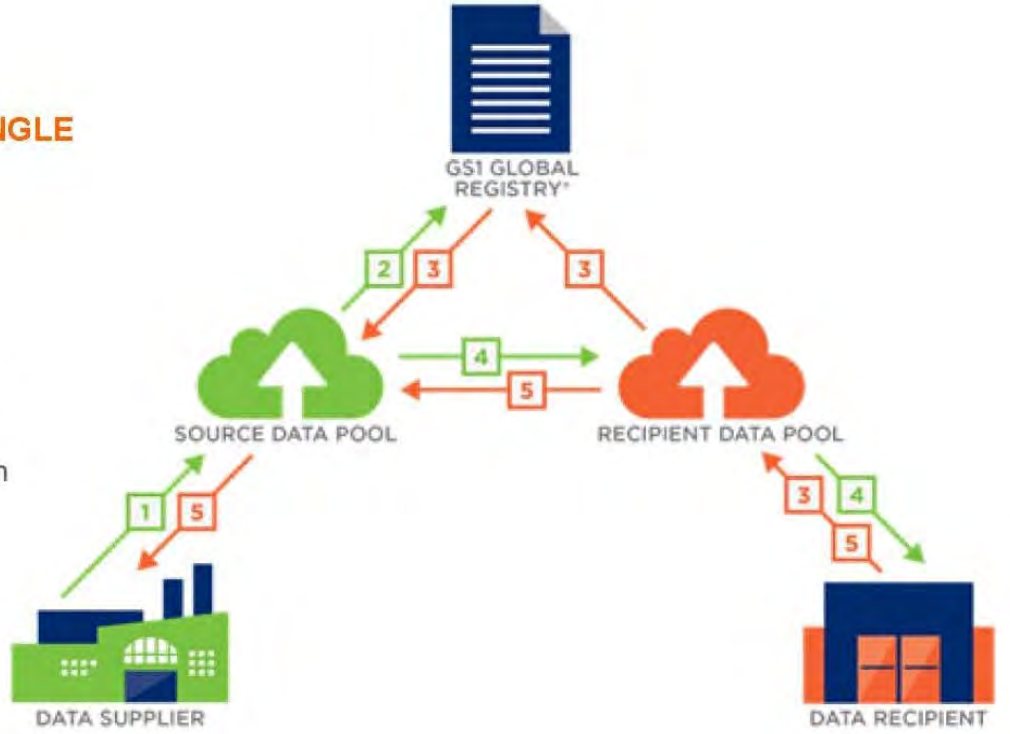
Step 1 : Load Data

Step 2 : Register Data

Step 3 : Subscription Request

Step 4 : Publish Data

Step 5 : Recipient Confirmation

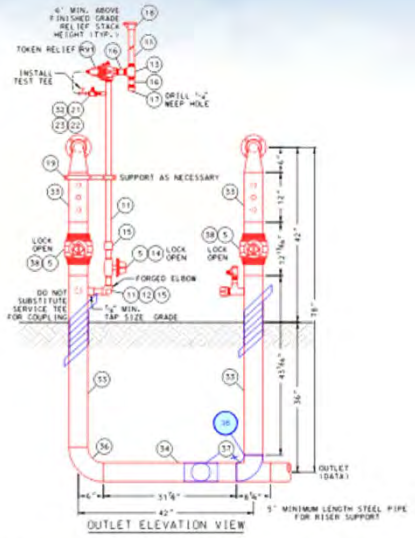


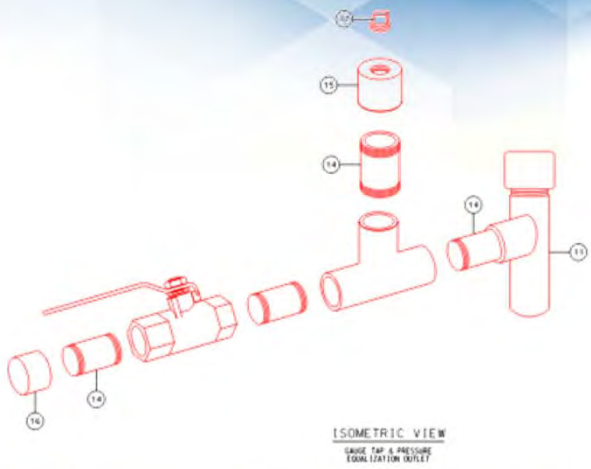
Participating Companies to Date

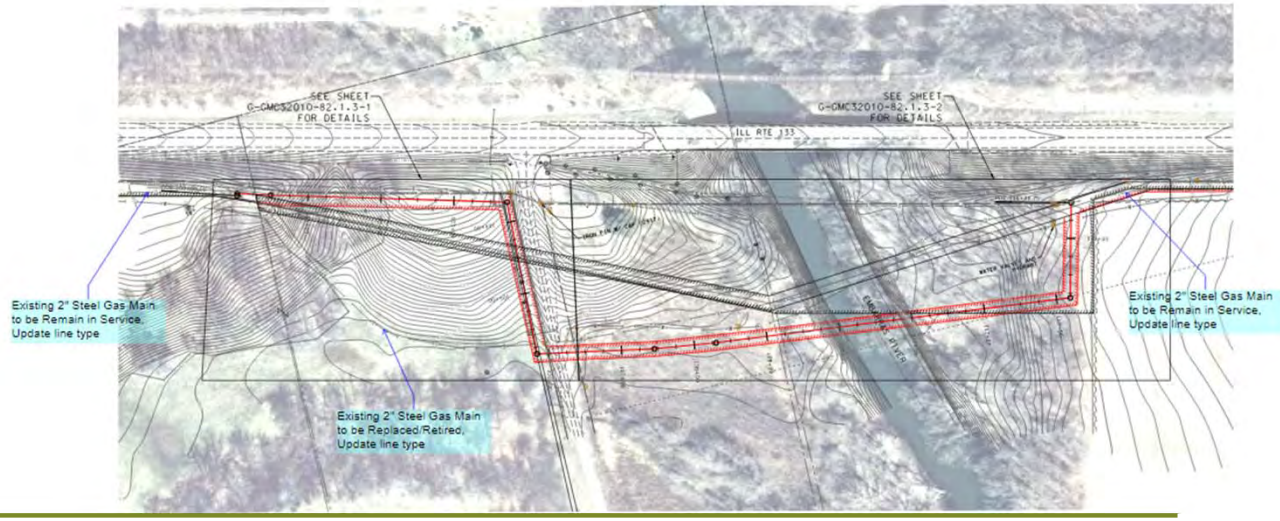
- Spire Energy (formerly Alagasco)
- National Grid
- Ameren
- NiSource
- APGA-RF
- NW Natural Gas
- Atmos
- Pacific Gas & Electric
- Duke Energy
- Piedmont Natural Gas
- Intermountain Natural Gas
- Dominion Energy / Questar
- Dominion Energy East Ohio
- LARDC
- SoCal Gas
- National Fuel
- Southwest Gas
- Consolidated Edison
- LocusView
- SoCal Gas / SDG&E
- Enbridge Inc.
- NIPSCO
- Tube Forgings of America, Inc.
- Balon Valve
- MRC Global
- American Steel Pipe
- GS1 Norway
- R.W. Lyall (Hubbell Inc)
- Steel Dynamics Inc.
- Mueller Company
- Liberty Pipe
- 1WorldSync
- Esri, Inc
- Wheatland Tube Company
- GS1 Global Brussels
- The Allied Group
- EPRI
- 3-GIS

Next Steps

- Pilot projects have begun:
  - Dominion Energy Ohio
  - Ameren
  - Wheatland Tube
  - Tube Forgings of America
  - DSI Dynamic Steel
  - Allied
  - MRC Global
  - GS1
  - 1WorldSync







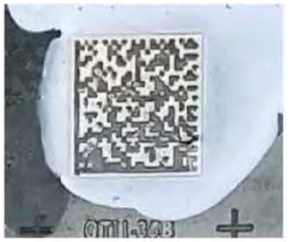
Laser Etch Project

Samples prior to corrosion test



Samples after corrosion Test





35B Prior to corrosion test

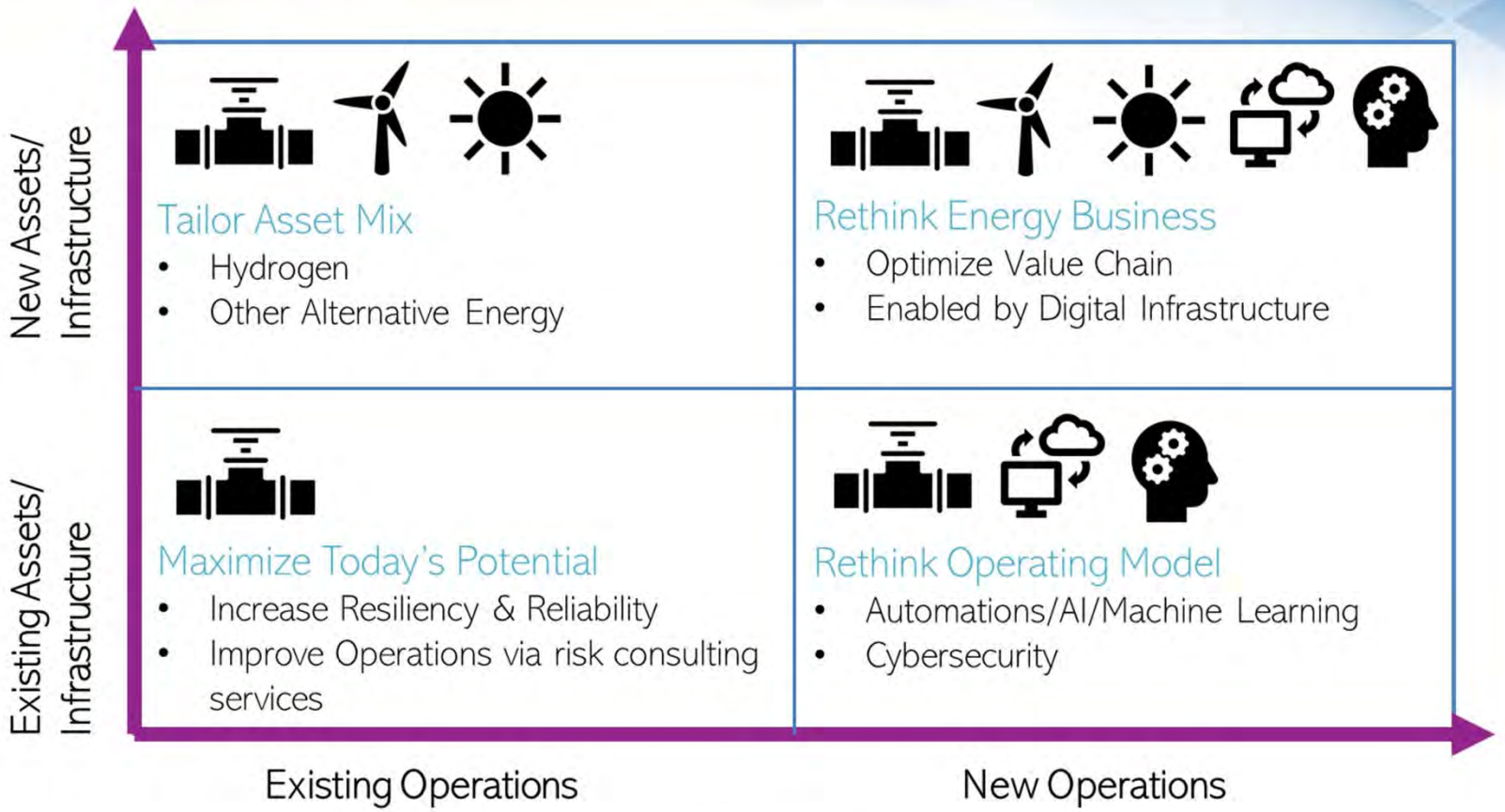


35B After corrosion test

1. *Corrosion resistance significantly increased*
2. *Metallurgy appears unaffected under laser etch plate*
3. *Metallurgy evaluation under way laser etch of forgings*
4. *Two application methods of anti corrosion agents complete*
5. *Test formulations of anti-corrosion materials continues*



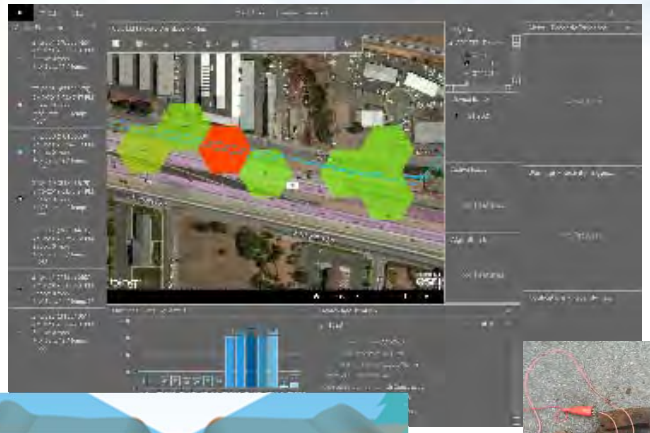
Untreated control barcodes Unreadable on all test samples < 1 hr. (high humidity exposure only).

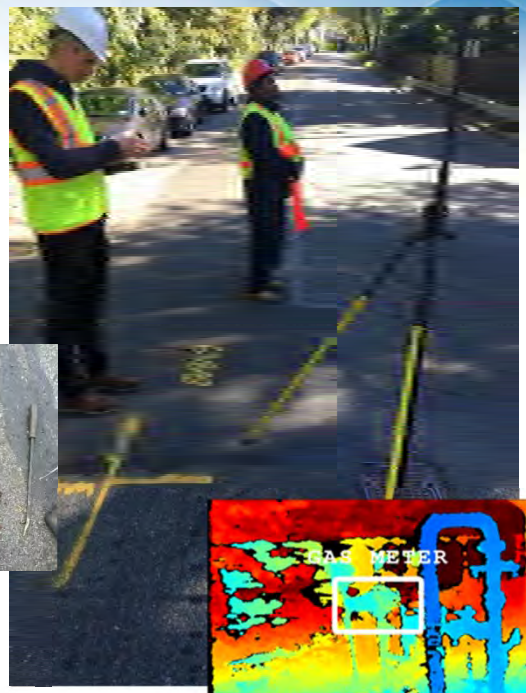


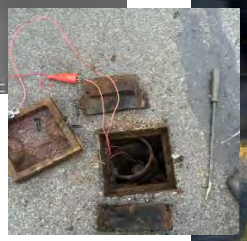
GTI image reimagined from:
https://www.energytoday.net/conventional-energy/the-energy-company-of-the-future-an-existential-crisis-for-oil-and-gas-companies/

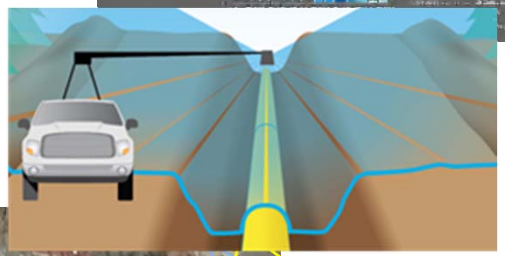
Thank you!

Shannon Katcher
R&D Manager
skatcher@gti.energy

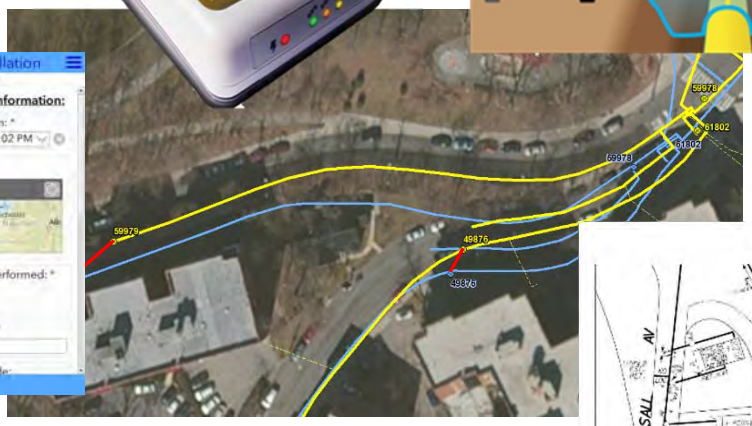


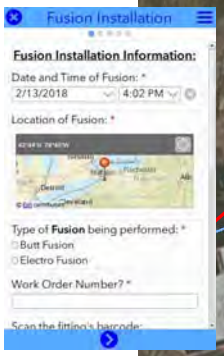


















BACK TO AGENDA

PRCI 2020 Research Exchange

Project: PRCI MAT-4-5

Fracture Initiation Transition Temperature Behavior of New Line-Pipe Steels

Mo Uddin, Fabian Orth, Sushma Pothana and Gery Wilkowski

Engineering Mechanics Corporation of Columbus (Emc^2)

3518 Riverside Drive - Suite 202, Columbus, OH 43221-1735

Phone: (614) 459-3200; Fax: (614) 459-6800

March 4, 2020

LEADING PIPELINE RESEARCH

Introduction

- **The past correlations for brittle fracture initiation (and propagation) from vintage steels using Charpy data is not working for new steels – transition is warmer than expected!**
  - Typically if Charpy has 100% SA, the surface crack has ductile initiation for vintage steels.
  - One new steel had 100% SA and 400J of Charpy impact energy at -46C, but cleavage fracture occurs in quasi-static test (compact tension) at +8C
    - *C(T) should have been fully ductile at much lower than +8C!!!*
  - Are API 5L PSL-2 pipe Charpy requirements giving you what you expected?

- **In 1901 Georges Charpy said, "The observed toughness differences …. between dynamic tests and static tests ....is not always in the same direction". Same problem again!**
  - See translated 1901 paper on Emc^2 webpage - http://www.emc-sq.com/the-story-behind-charpy-testing/

Objectives

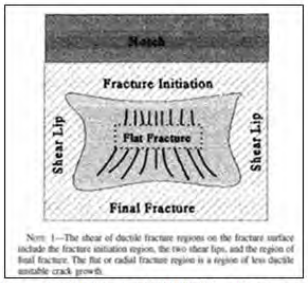
- **Fracture Initiation transition temperatures of surface or through-wall cracks in vintage pipes have large temperature margin from Charpy test**
  - Predictable methodology if CVP<200J; 27J of Charpy energy for PSL-2 pipe results in ductile initiation
  - Charpy specimens fracture differently in new steels than vintage steels!
  - Appearance, and energy or SA% vs temperature curves different shapes in vintage vs new steels - later
- **Question - Will surface and through-wall-cracked pipes have ductile initiation in new steels below Charpy transition temperature? (Is 27J of Charpy energy sufficient to ensure ductile initiation?)**
- **The objective of this effort was to evaluate transition temperature behavior of new line-pipe steels using Charpy and other complex fracture tests and compare with vintage line-pipe steels**

Summary of Outcome

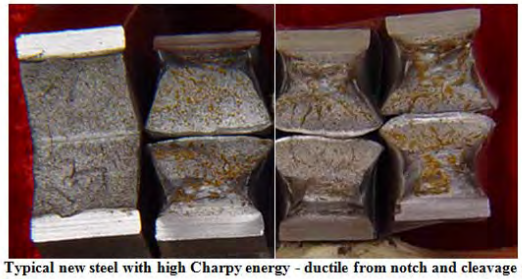
- **Transition temperature (TT) of surface-cracked (SC) and through-wall-cracked (TWC) pipe for new steels does not have as much margin as vintage steels at Charpy transition temperature – can't use prior methodology**
  - **SC transition temperature is lower than Charpy (thickness<0.875") for 2 of 3 pipes; warmer by 13C on 3rd steel**
    - SC TT should be <u>much</u> lower than Charpy TT (based on vintage steel trends)
  - **TWC transition temperature is warmer than Charpy (thickness<0.875") for all 3 pipes examined**
    - Should be <u>slightly</u> lower (vintage steels)
    - Worst case was TT at -5C in a TMCP pipe

Background

- **Vintage line-pipe steels had lower Charpy upper-shelf energy values and the transition temperature was relatively easy to define**
  - Vintage line-pipe steels had many large inclusions that gave lower upper-shelf energy, and the large inclusions easily triggered cleavage fracture
- **New line-pipe steels generally have low Sulphur content with fewer and smaller inclusions that result in;**
  - Very high Charpy upper-shelf values (300J to 500J), and
  - Fracture appearance of new steels is different in Charpy testing
    - *Hypothesis: the blunt Charpy notch may not give high enough triaxial stresses near the notch to trigger cleavage initiation in the smaller inclusions of new steels*



Typical older material from ASTM E23 – cleavage in center of ligament



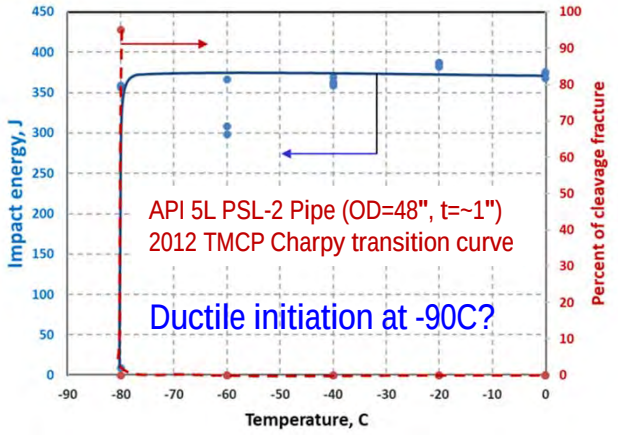
Typical new steel with high Charpy energy - ductile from notch and cleavage at back

Background

- **It is common now to have Charpy energy values that are 350J at -90C, and then the energy suddenly drops to 5-10J (100% SA to ~2%SA)**
  - vintage steels had a gradual Charpy energy/SA% transition temperature curves

- **Methodology developed in past for vintage steels showed transition temperature shifts when going from a Charpy specimen to through-wall cracked or surface-cracked pipe**
  - Surface cracked pipe have lowest transition temperature, and shallower surface cracks have lower transition temperature than deeper cracks – similar to SENT tests
  - Compact-tension (CT) specimen transition similar to through-wall-cracked pipe
  - But CT and SENT testing are too expensive for alternative tests in production

- **Examining if ASTM E208 DWT-NDT test procedure could be used, or if a temperature shift to Charpy V-notch testing might be possible for ensuring ductile initiation.**
  - One alternative not explored to date is fatigue pre-cracked Charpy impact test – might be worth looking at in future

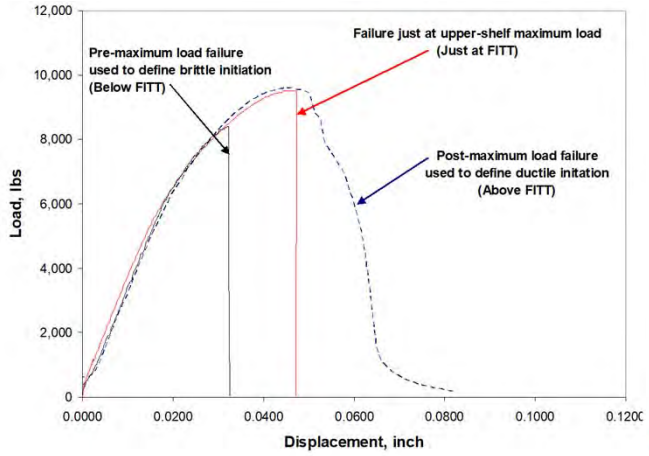


Background

- ***Master Curves of Fracture Transition Temperatures*** **method developed during PRCI 2006 project**
  - **Predicts lowest temperature for ductile initiation of TWC'ed or SC'ed pipe from Charpy (or CT specimen or SENT) specimens for any pipe thickness**
  - **Based on correlations from tests on vintage line-pipe steels**
  - **Validated by many full-scale tests – lower upper-shelf energy steels**
    - Straight pipes, elbow, valve weld neck, X100 girth weld, 6" thick nuclear pressure vessel
    - Methodology for ferritic pipe in nuclear plants (Appendix C of Section XI of ASME B&PV Code)
  - **Concern for steels having more than 200J CVP (most new steels)**
    - API 5L DWTT does not work well for dynamic transition temperature if CVP>215J (from API Database effort project at Emc^2) – sometimes called "abnormal or inverse fracture behavior"
    - Charpy specimen is affected even more by "abnormal/inverse fracture behavior" than DWTT specimen
      – Blunter notch, small ligament

Transition Temperature Definitions

- **Charpy (or DWTT) transition temperature is defined here as the temperature where 85% shear area occurs using an average fit of the test data**
- **DWT-NDT or Nil-Ductility Temperature is the warmest temperature where a break occurs – crack extends to edge of the specimen**
  - Defines lower-shelf of transition curve (we want the lowest temperature for being on the upper-shelf!)
- **For CT, SENT, through-wall-cracked or surface-cracked pipes, the fracture initiation transition temperature (FITT) is the lowest temperature where the failure load/pressure reaches the same value as if at a warmer temperature**

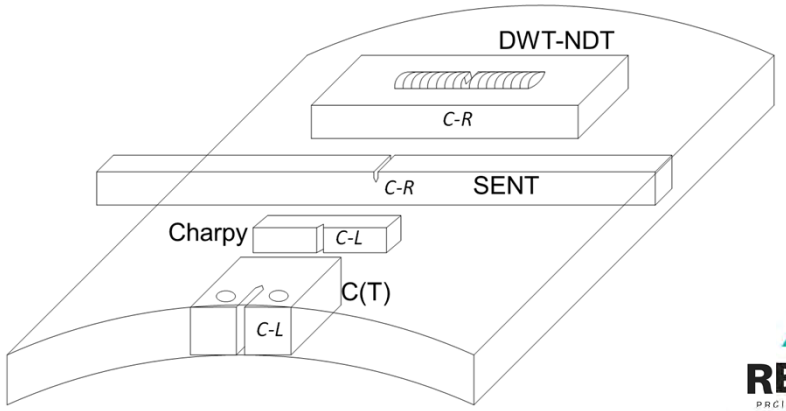


Test Matrix

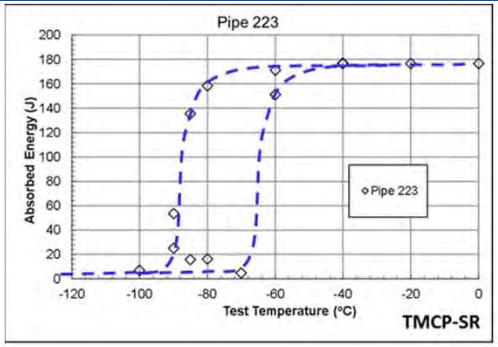
Pipe ID	Vintage	Grade	Diameter, inch	Wall Thickness, inch
Pipe 223	Modern (TMCP-SR)	X65	20	0.818
Pipe 303	Modern (TMCP)	X70	42	0.875
Pipe 312	Modern (Q & T)	X65	20	0.825
*SR-Stress Relieved				

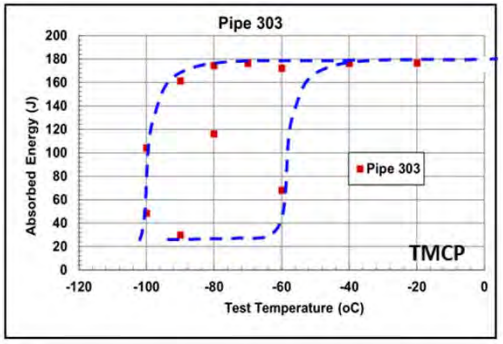
Notes: all materials from PRCI members

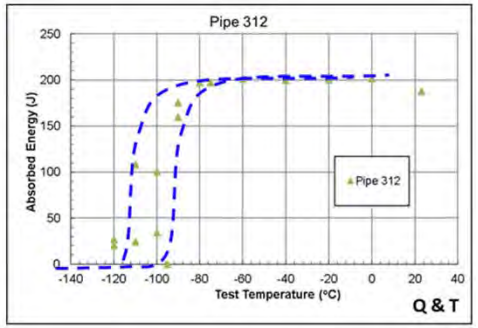
Specimen Type	Pipe 223	Pipe 303	Pipe 312
NDT	10	10	10
Charpy	12	12	12
CT	8	8	8
SENT (a/W= 0.5 and a/W=0.3)	16	16	16

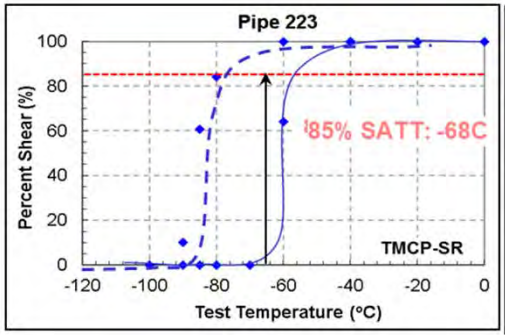


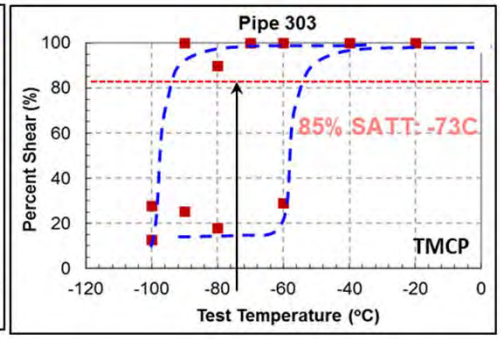
Charpy Test Results

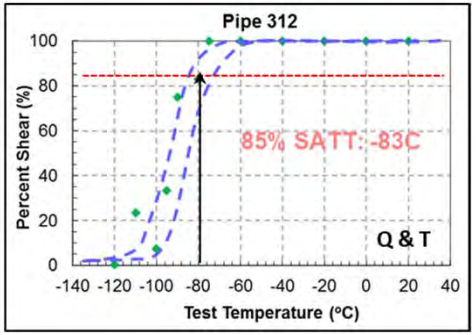










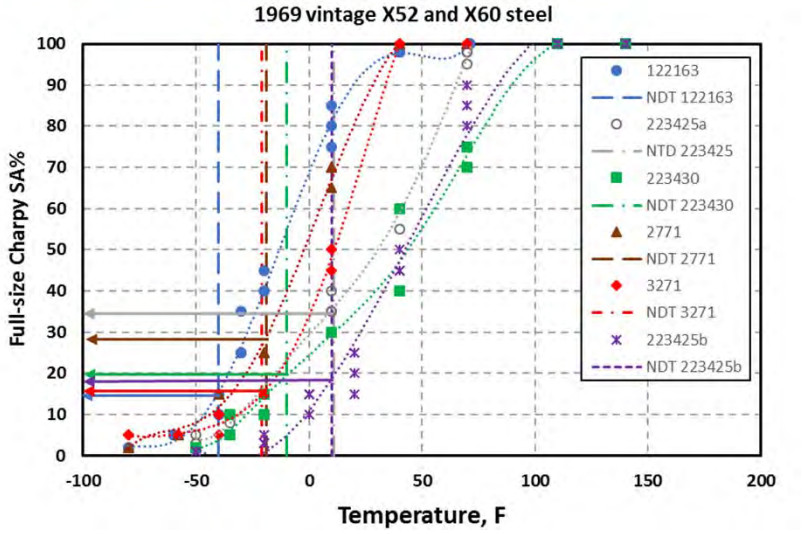


- *CVP was 180J to 200J for all 3 steels– very similar*
- *Not as high as many new materials we examined!*
- *Used average 85% SA transition temperature – some scatter*

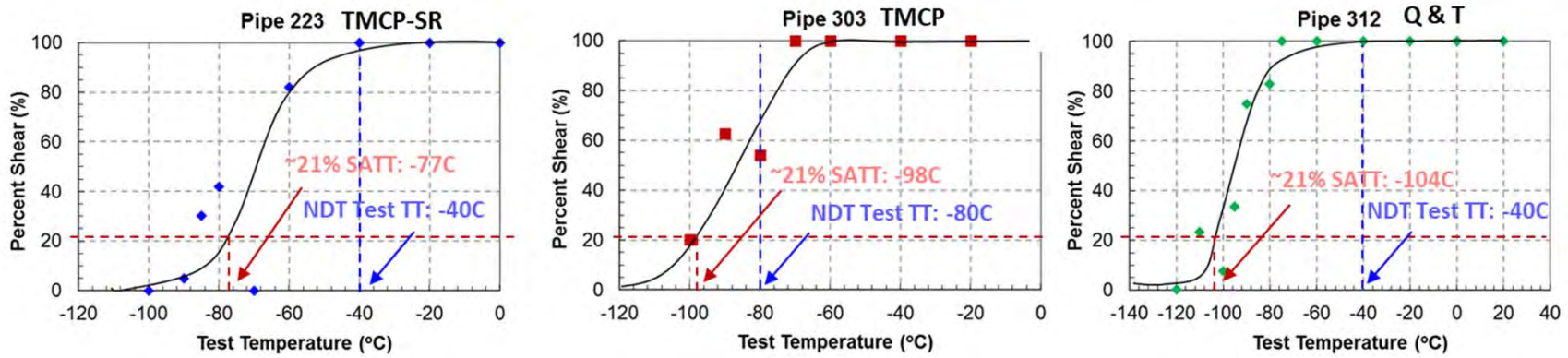
NDT and Charpy Data Trend – Vintage versus New Materials

- The NDT and Charpy test data from vintage X52 and X60 steels were analyzed to investigate the correlation between NDT and Charpy transition temperature from 1969 ASTM Symposium Report by AISI
- The Charpy SA% was determined for each heat at the NDT temperature
- Average NDT occurred at 21.5% SA in Charpy tests for vintage steels

Heat No.	SA% at NDT
122163	14
3271	15
223425b	18
223425a	20
2271	28
223425	34
Avg	**21.5**
Std dev	7.9
COV	37%



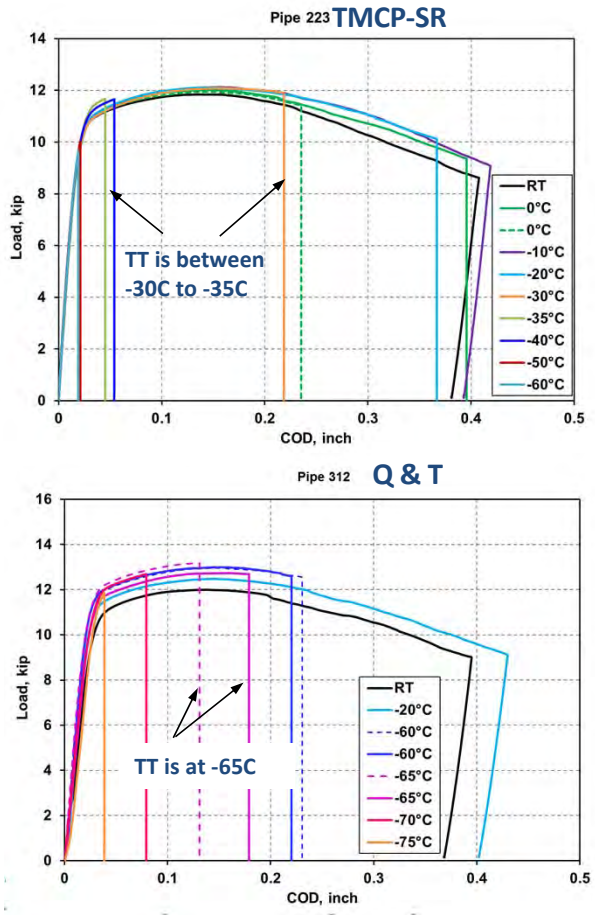
NDT and Charpy Data Trend – Vintage versus New Materials
(contd..)



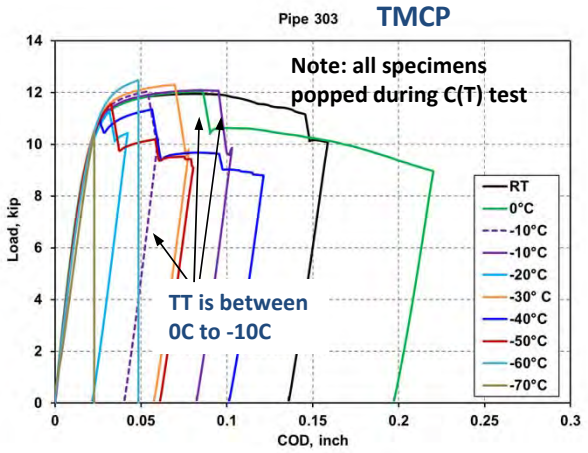
- **For the 3 new steels, the actual NDT was much warmer by 18C to 64C than using the trend of Charpy SA% to NDT for vintage steels**

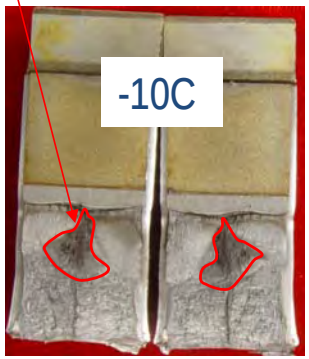
- **Interesting observation is that NDT for Pipe 223 and Pipe 312 are at Charpy upper-shelf region**
  - Pipe 303 different in other tests too

C(T) Test Results



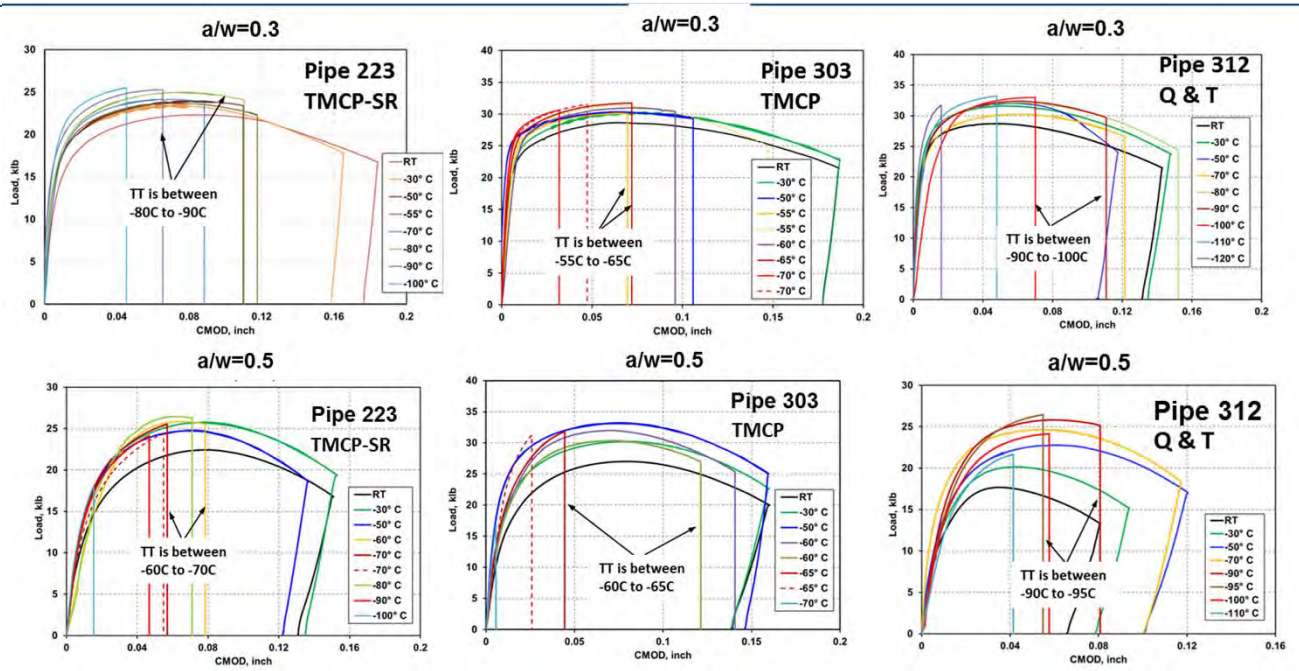
Pipe 303 CT specimens had unusual brittle fracture starting from mid-thickness plane that turned to C-L orientation indicating extended axial brittle fracture possible.





The transition temperature for C(T) specimens were warmer than Charpy transition temperature for all three newer linepipe materials

SENT Test Results



- The transition temperature for SENT specimens with two a/t values (0.3 and 0.5) were lower than (but still close to) Charpy transition temperature for Pipe 223 and Pipe 312
- But the transition temperature was warmer for Pipe 303 for both a/t values.

Transition Temperature from Various Tests

Test Type	Pipe 223 (TMCP-SR)	Pipe 303 (TMCP)	Pipe 312 (Q&T)
Charpy, 85% SATT	-68	-73	-83
NDT	-40	-80	-40
C(T)*	-32.5	-5*	-65
SENT** (a/w=0.3)	-85	-60	-95
SENT** (a/w=0.5)	-65	-62.5	-92.5

* C(T) specimen transition temperature similar to through-wall-cracked pipe
** SEN(T) specimen transition temperature similar to surface-cracked pipe with same (a/t, a/w)

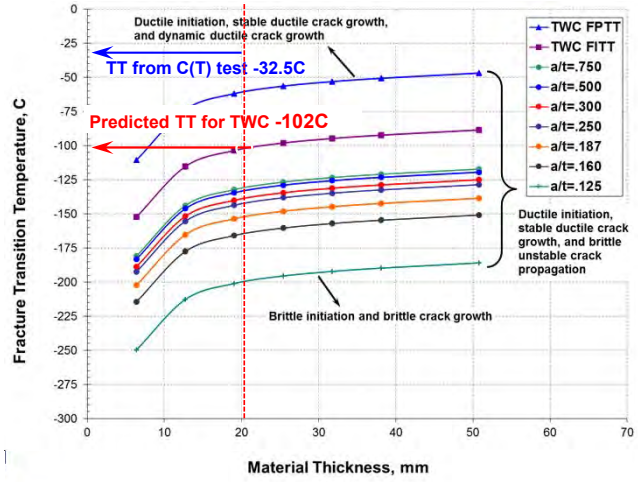
- **Pipe 303 CT specimens had unusual brittle fracture starting from mid-thickness plane that turned to C-L orientation indicating extended axial brittle fracture possible. (Not evaluated since that would involve additional out-of-scope brittle-weld DWTT testing.)**
- **Splitting not from center-line inclusions; probably from crystallographic texturing**
  - Might occur in strap-tensile tests, but did not do any strap tensile tests in this effort

Master Curve Transition Temperature Prediction Using Charpy 85% SATT

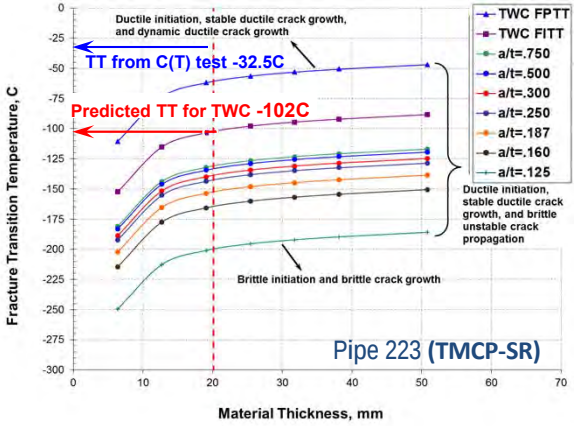
- *Master Curve for Fracture Transition Temperatures* was constructed based on Charpy 85% SATT for vintage steels (PRCI 2007 project) – for steels with CVP<200J
- Use Charpy 85% SATT for each new pipe materials to shift all the curves vertically
- Vertical dotted line corresponds to specimen thickness for which TT will be predicted (e.g., TWC is same as C(T) specimen, and SC is same as SENT)
- Predicted TT corresponds to intersection point of "thickness" vertical line and corresponding curve for which TT will be predicted (e.g., TWC curve for C(T) specimen, or a/t=0.3 surface cracks curve for SENT specimen with a/w=0.3)

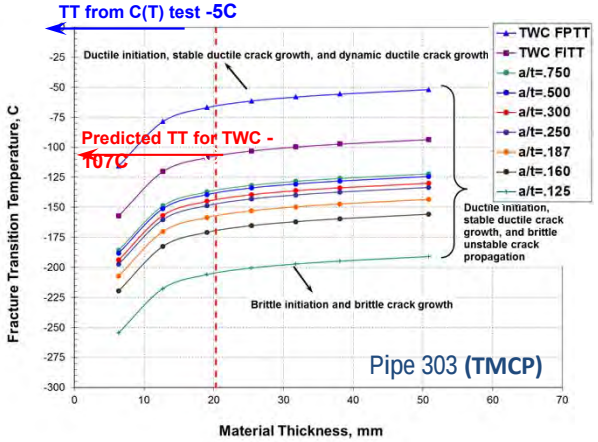
Example case - Prediction of C(T) TT using Charpy 85% SATT for Pipe 223

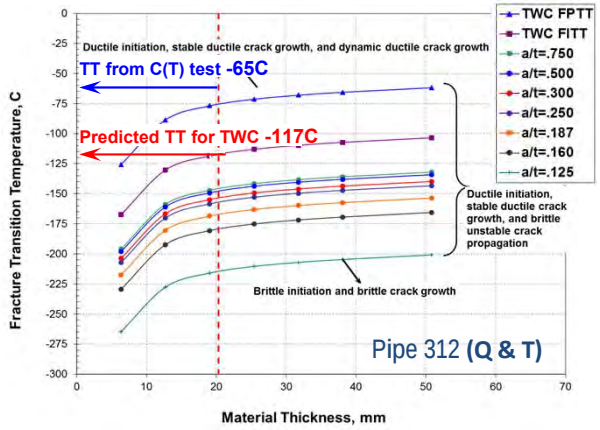
- *Charpy 85% SATT was -68C*
- *Draw "Thickness" line at 20.1 mm (CT specimen thickness)*
- *Intersection between "thickness" line and "TWC/CT" curve corresponds to predicted TT of -102C (red arrow)*
- *However, TT from C(T) test was -32.5C (blue arrow)*



Charpy and C(T) Transition Temperature Correlation – Vintage vs. New Materials

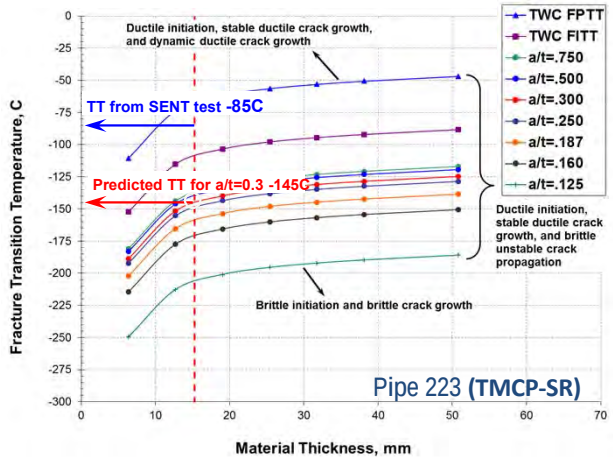


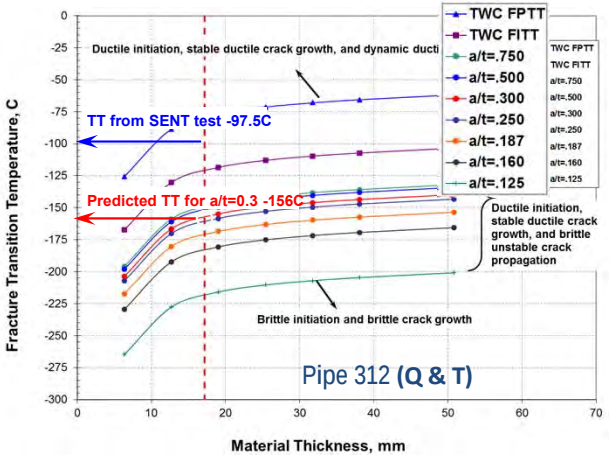


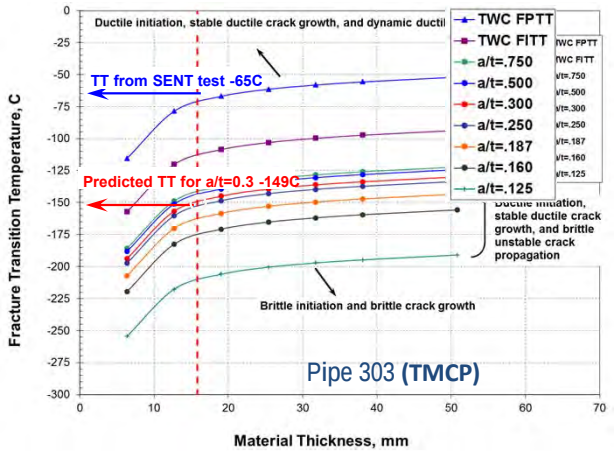


Actual C(T) transition temperatures [equal to TWC FITT in pipe] was 52C to 102C warmer than trend for vintage steel when using Charpy correlation

Charpy and SENT (a/t=0.3) Transition Temperature Correlation – Vintage vs. New Materials



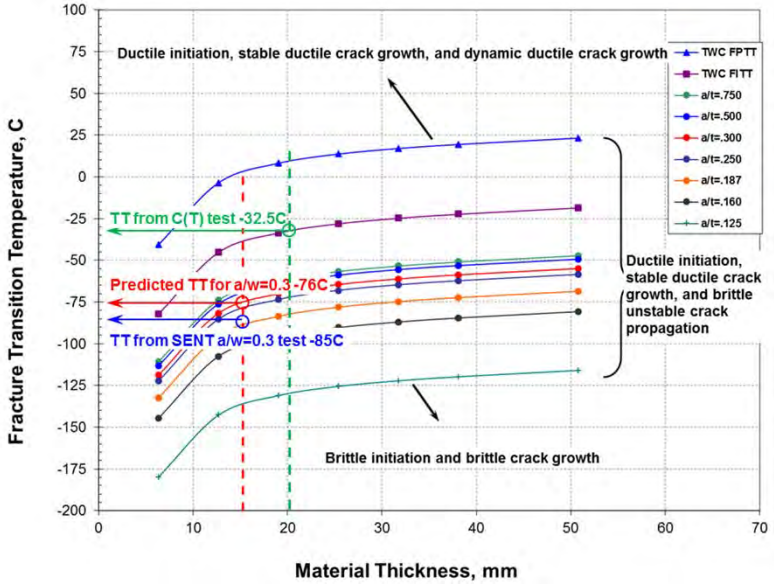




- **Actual SENT (a/w=0.3) transition temperatures [equal to SC (a/t=0.3) FITT in pipe] was 59C to 84C warmer than trend for vintage steel when using Charpy correlation.**
- **Similar trend for SENT with a/w=0.5**

C(T) and SENT Transition Temperature Correlation – Vintage vs. New Materials

- **The correlation between C(T) and SENT remain similar for vintage and newer materials, except for Pipe 303. The inconsistency (between vintage and newer materials) is probably coming from Charpy test data**
  - Curves for Pipe 223 shown below; made the CT TT to agree with TWC curve, then can see differences for SENT actual and SC pipe (supposed to be the same – reasonably close)



Summary

- **The correlations between Charpy and other more sophisticated specimen types [C(T) and SEN(T)] are very different for vintage and newer linepipe steels**
- **C(T) tests show that Charpy TT provide non-conservative estimation for through-wall cracks for all materials with thickness ~0.875″**
  - Significant difference for TMCP Pipe 303 due to mid-thickness cleavage plane
- **SENT tests show that Charpy transition temperature (TT) provide conservative estimation for surface cracks for two materials with thickness ~0.825″; but warmer by 13C on the 3rd steel**
  - New line-pipe steels do not have as much margin on ductile fracture initiation relative to Charpy data as vintage line-pipe materials
- **DWT-NDT values did not provide any consistent correlation with Charpy 85% shear area TT**
  - Charpy SA% value at NDT temperature trend for vintage steels not same with newer steels – for vintage steels Charpy SA% was about 21% at NDT temperature, but for new steels the NDT was near or in the Charpy upper-shelf region

Benefit to Operators

- **Knowing that the margin between Charpy transition temperature and true fracture initiation transition temperature could be different for vintage and new line-pipe materials, operators may assess the new line-pipe materials with caution**
  - **For surface-cracked pipe, for 2 of the 3 pipe materials there was a conservative margin of about 10C between pipe transition temperature and the Charpy transition temperature**
    - For 3rd pipe material the SC'ed pipe transition was ~13C warmer
    - Operator may want to specify a Charpy test temperature below the minimum service temperature (assuming these project results to date apply to all materials)
    - Fracture surface of Charpy specimen should also be examined to identify abnormal fracture appearance – indicator that there may be a problem in using Charpy test results
  - **For leak-before-break evaluation, brittle initiation for through-wall-cracked pipe can occur at a warmer temperature than Charpy transition temperature by 18-68C**
    - Charpy test temperature should be adjusted from minimum service temperature to account for temperature shift between Charpy and C(T) transition temperature

Thoughts on Future Work

- **Pipe 303 behaved differently because of large centerline cleavage split – maybe see that behavior in strap tensile tests to identify a possible abnormal fracture behavior in TMCP steels – include few round-bar test as well**
- **Test more materials with following variation**
  - Different TMCP processes – US (coil to pipe), Japanese plate, European plate materials
  - Grade X60-X70 materials, possibly one X80 material
  - Thicker pipes steels can give greater shifts than the ~0.875” pipes tested
- **Update Master Curve Methodology to include modern steel pipes with higher CVP (>200J) – need more data for statistical confidence**
  - Transition temperature shift differs for different new steels
  - Can we use strap tensile test results for screening unusual TMCP steels?
- **DWTT tests on Pipe 303 to see brittle propagation transition temperature?**
- **May want full-scale validation test in future if significant change in philosophy**

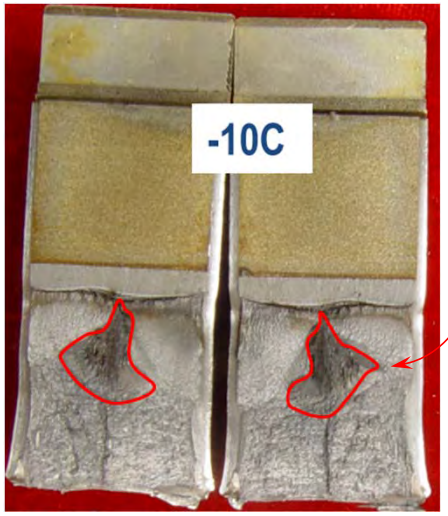
Thanks – Any Questions!

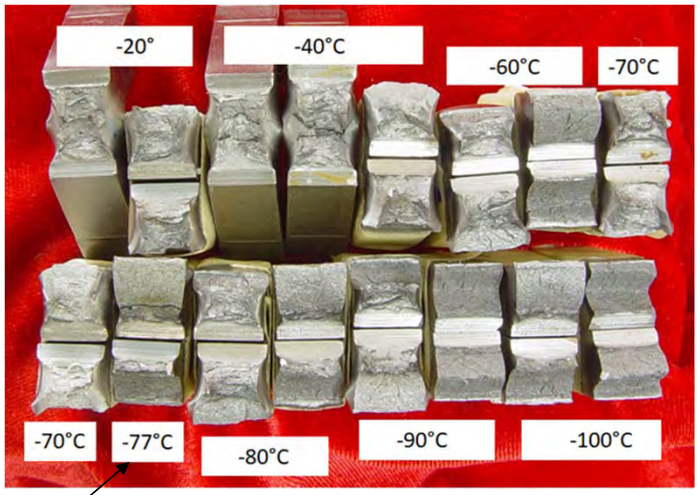
Summary

- **One pipe TMCP pipe material shows non-conservative Charpy TT for both surface and through-wall-cracked pipes –**
  - Larger scatter in Charpy tests – sudden transition from 100% shear area to ~20% shear area
  - All C(T) specimens had brittle pops during the tests (up to 0C) as evident in load-displacement curve and fracture surfaces
  - Splitting not from center-line inclusions; probably from crystallographic texturing, might occur in strap-tensile tests, but did not do any tensile tests in this effort

Pipe 303 Showing Unusual Behavior

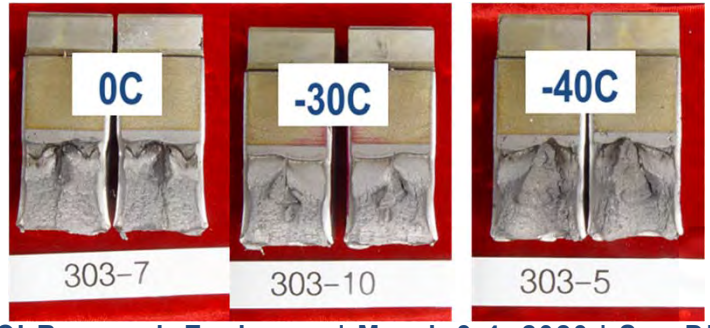
- Charpy specimens low fracture toughness exhibited unusual fracture behavior
- All C(T) specimen experience a **brittle pop-in** initiating at the center of the specimen parallel to plate surface, that twisted





Charpy Specimens

DA did not trigger



C(T) Specimens

BACK TO AGENDA

REX2020
PRCI RESEARCH EXCHANGE

Pipeline Research Council International, Inc.

Assessment of Pressure Isolation Tools for Onshore Pipelines via Full-scale Testing and Finite Element Modeling

2020 PRCI Research Exchange

Presented by Dr. Chris Alexander, PE | ADV Integrity, Inc.

Wednesday, March 4, 2020 | 2:00 to 2:30 PM PST

PRCI PLUG-1-01 Research Program

PRCI™

LEADING PIPELINE RESEARCH

Today's Presentation

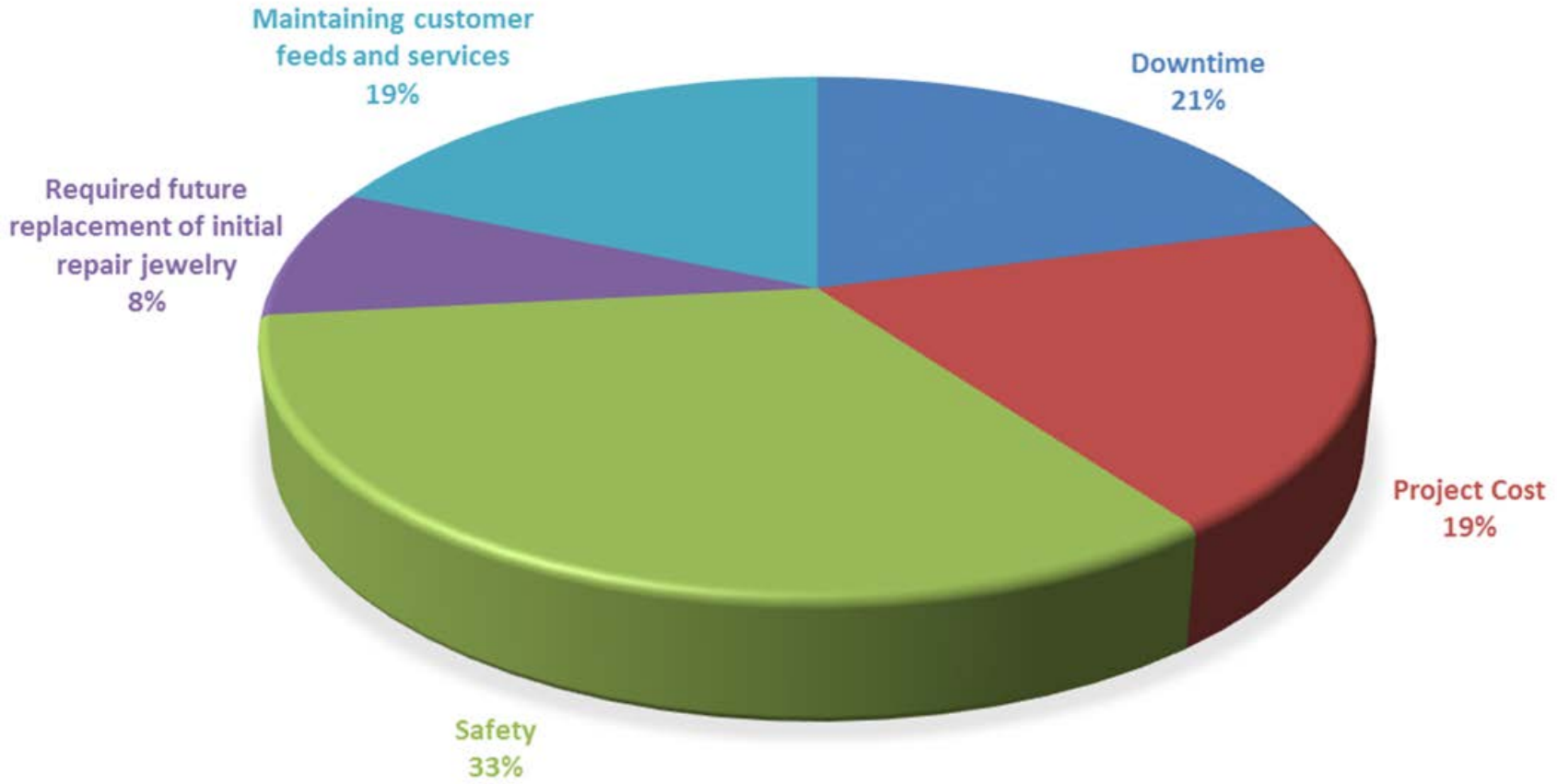
- Overview of project phases
- Industry survey results
- Participating technologies (three companies)
- Finite element modeling results
- Photos and results from testing
- Development of parametric tool
- Post-test inspection of inside pipe surfaces
- Considerations for future work

PLUG-1-01 Phases of Work

- Phase 1 – Industry survey
- Phase 2 – Numerical and test program review
- Phase 3 – Numerical modeling
- Phase 4 – Full-Scale Testing
- Phase 5 – FEA model calibration
- Phase 6 – Development of parametric based tool
- Phase 7 – Post-test inspection
- Phase 8 – Final reporting

Industry Survey Results

When repairing your pipeline, or replacing a valve, rate the following items in order of importance.

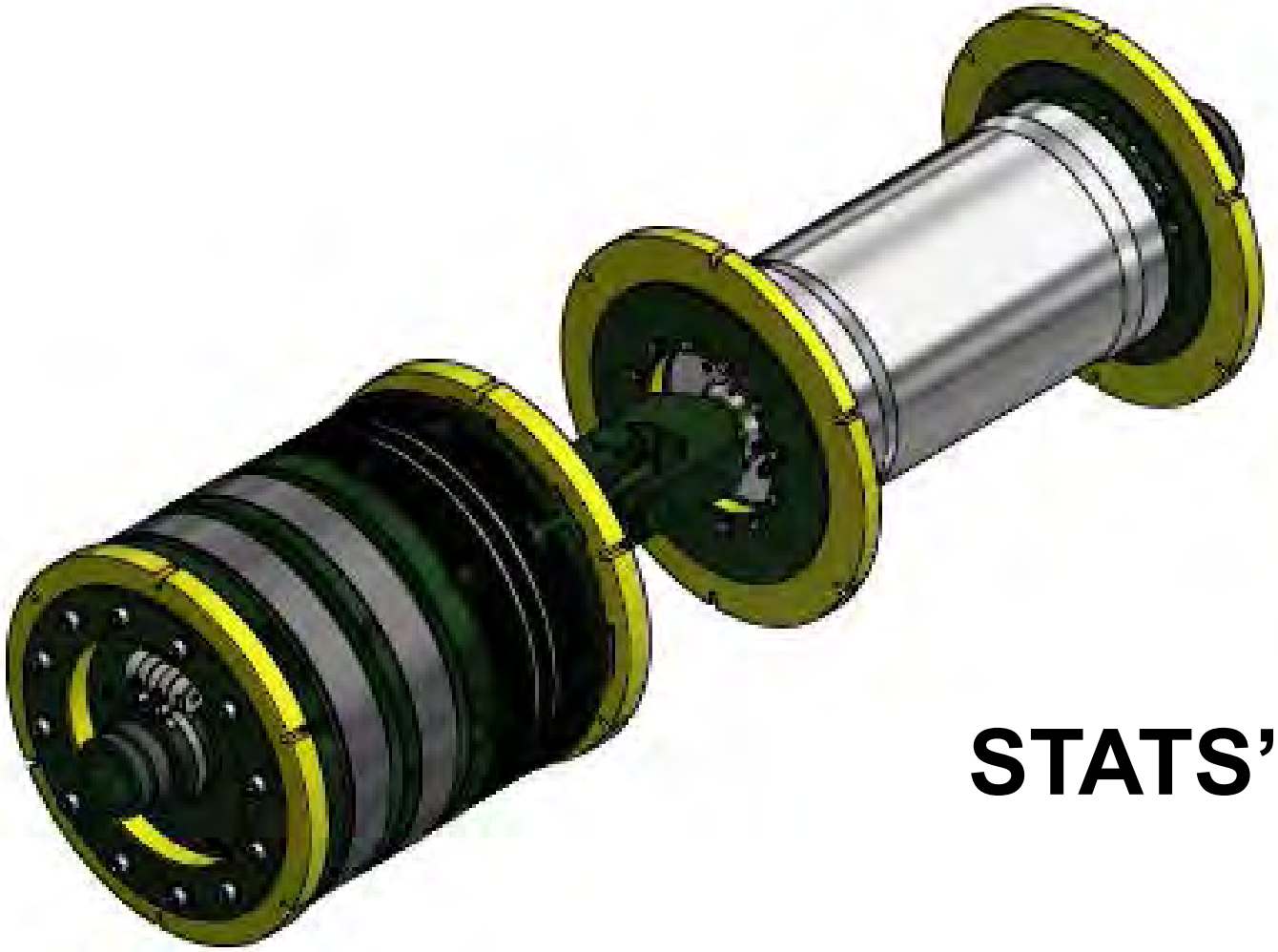


Participating Company (1/3)



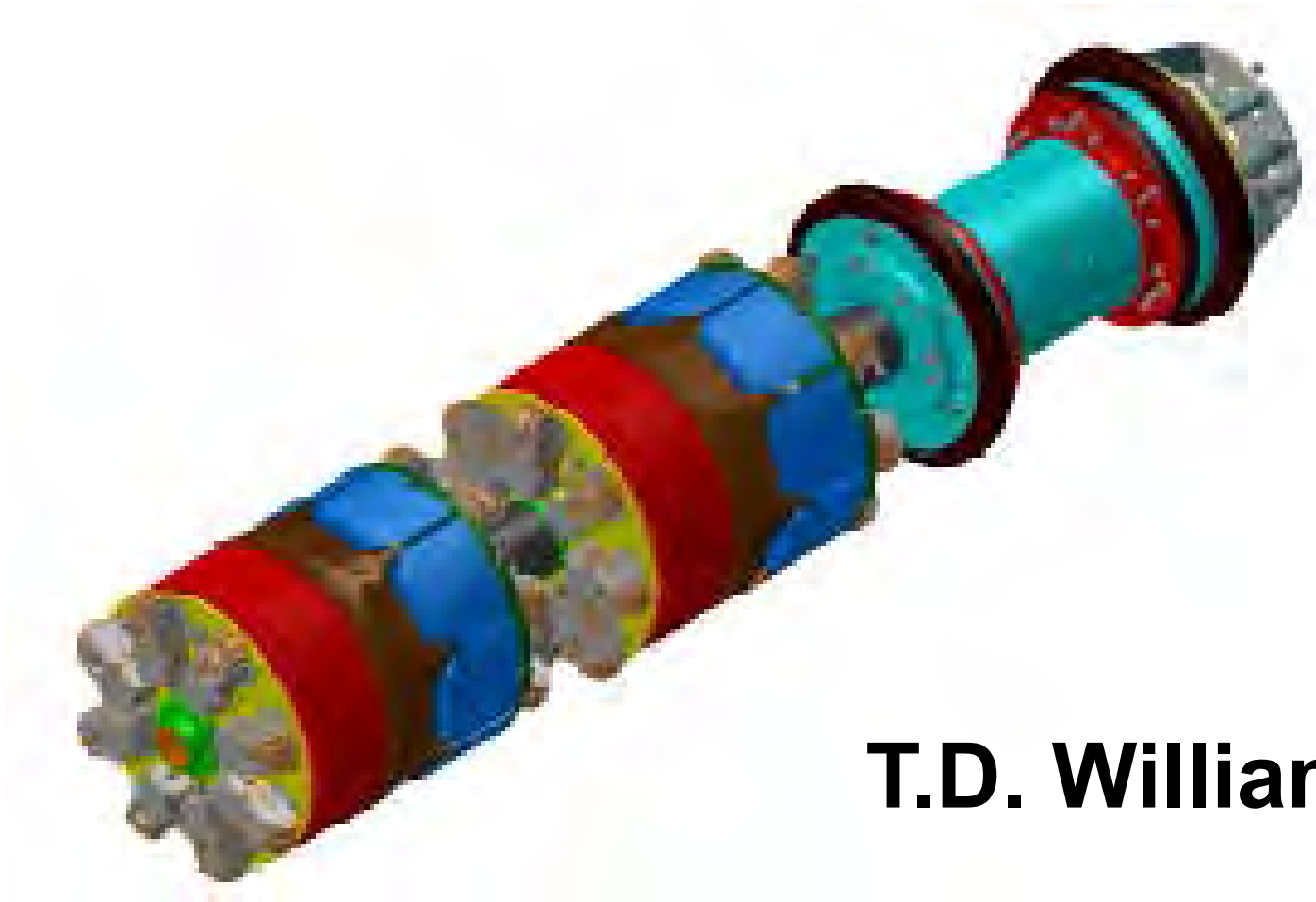
PPIG IsoPlug

Participating Company (2/3)



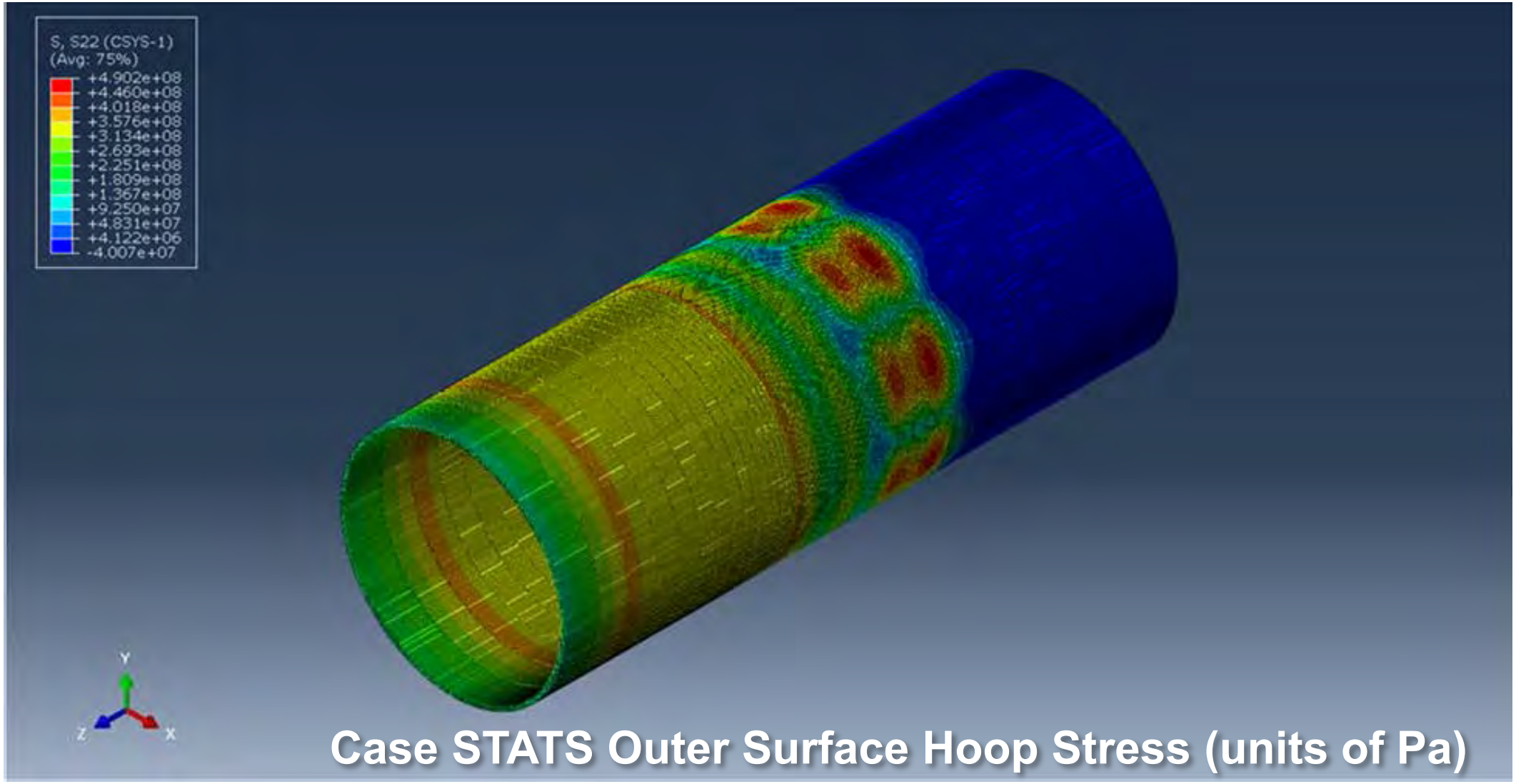
STATS' Tecno Plug

Participating Company (3/3)

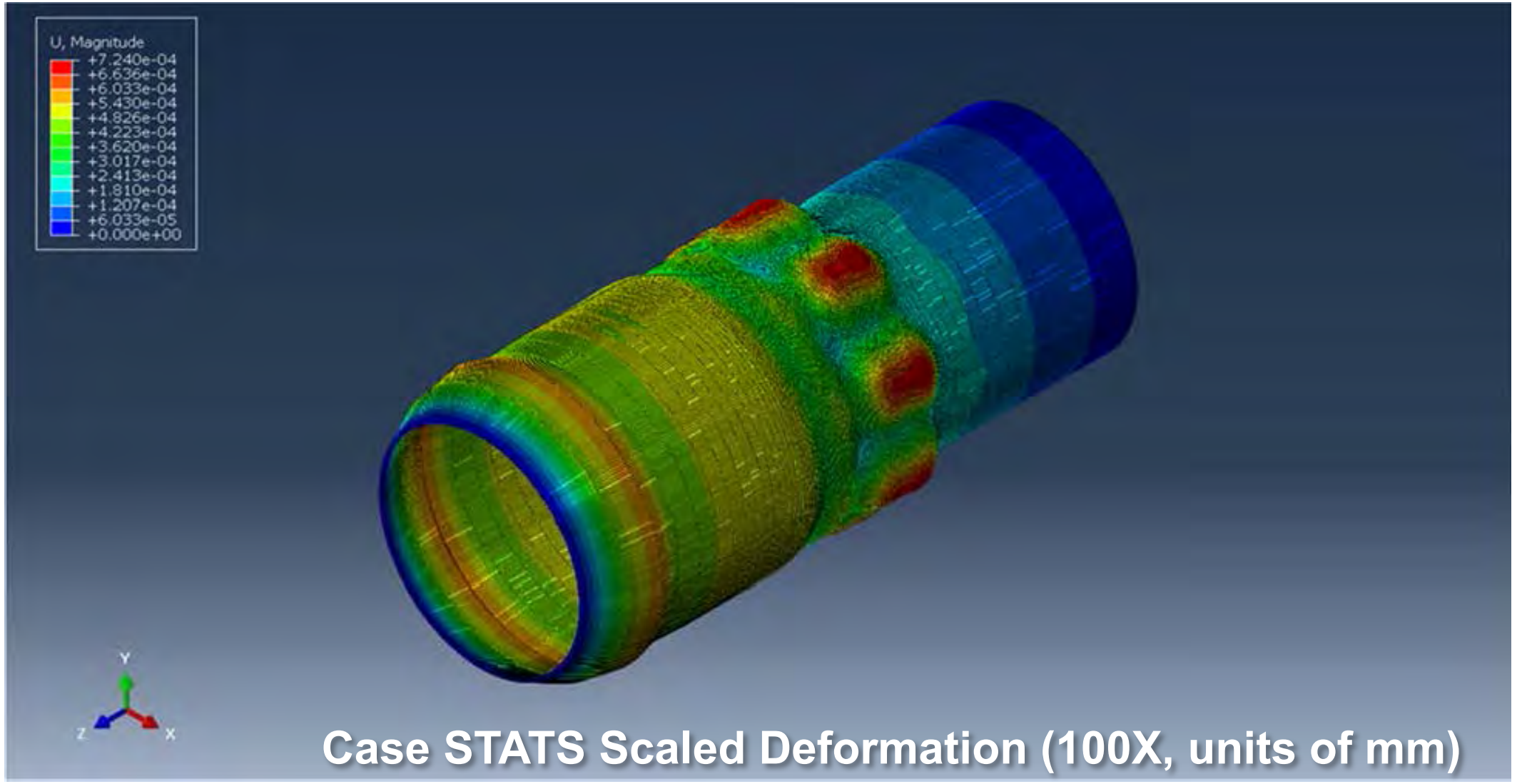


T.D. Williamson’s Smart Plug

Finite Element Model Results (1/2)



Finite Element Model Results (2/2)



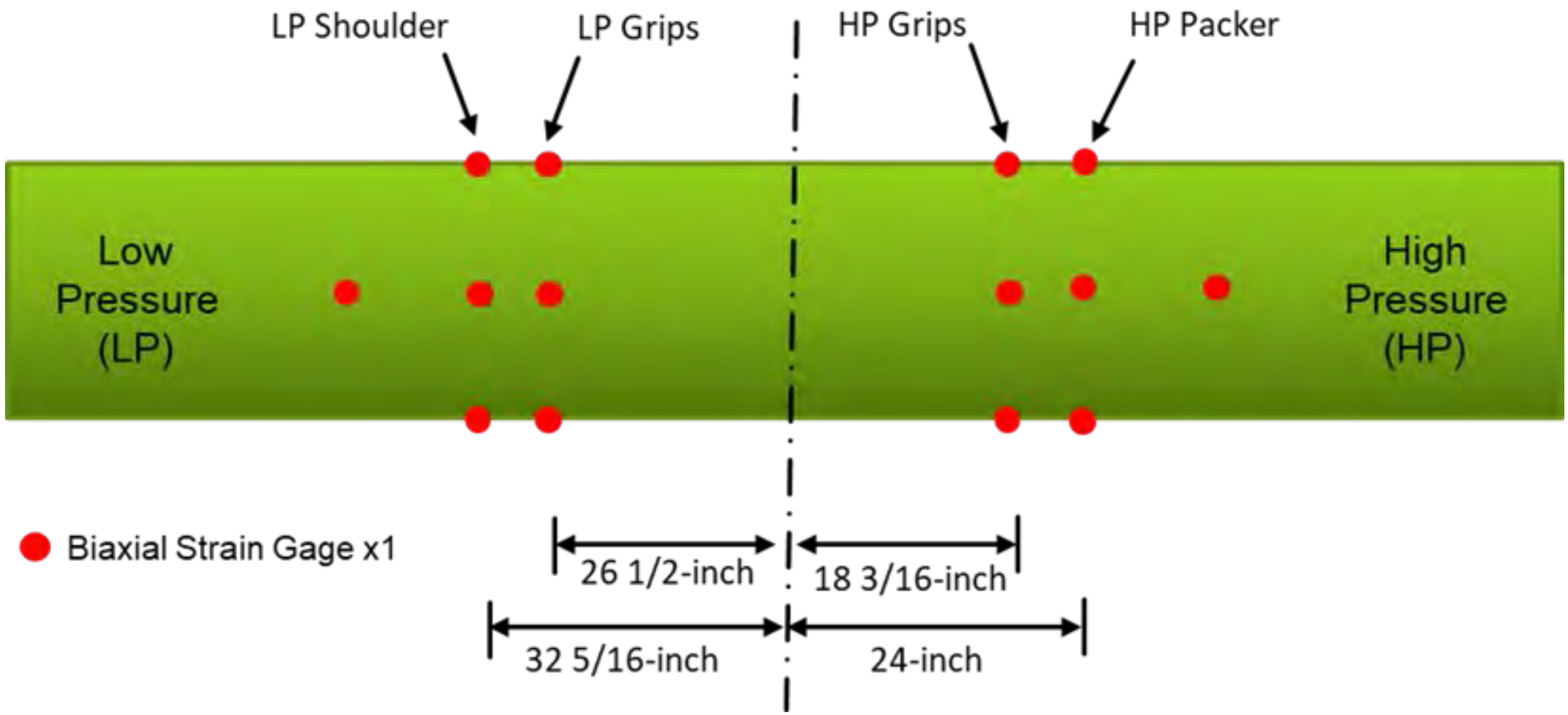
Final FEA Results (prior to calibration)

Cases	Contact Area (in^2) [mm^2]	Contact Pressure (psi) [MPa]	von Mises Stress (psi) [MPa]	Hoop Stress (psi) [MPa]	Plastic Strain
PPIG	638.6 [$4.12x10^5$]	2,362 [16.289]	73,838 [502.2]	82,019 [565.5]	0.48%
PPIG (Ovality)	638.6 [$4.12x10^5$]	2,362 [16.289]	73,172 [504.5]	83,455 [575.4]	0.54%
STATS	367.4 [$2.37x10^5$]	2,317 [15.980]	64,716 [446.5]	71,097 [490.2]	0.03%
STATS (Ovality)	367.4 [$2.37x10^5$]	2,317 [15.980]	67,443 [465.0]	74,868 [516.2]	0.08%
TDW	590.6 [$3.81x10^5$]	2,337 [16.114]	70,140 [483.6]	77,494 [534.3]	0.21%
TDW (Ovality)	590.6 [$3.81x10^5$]	2,337 [16.114]	71,185 [490.8]	80,148 [552.6]	0.29%

Photos from Testing

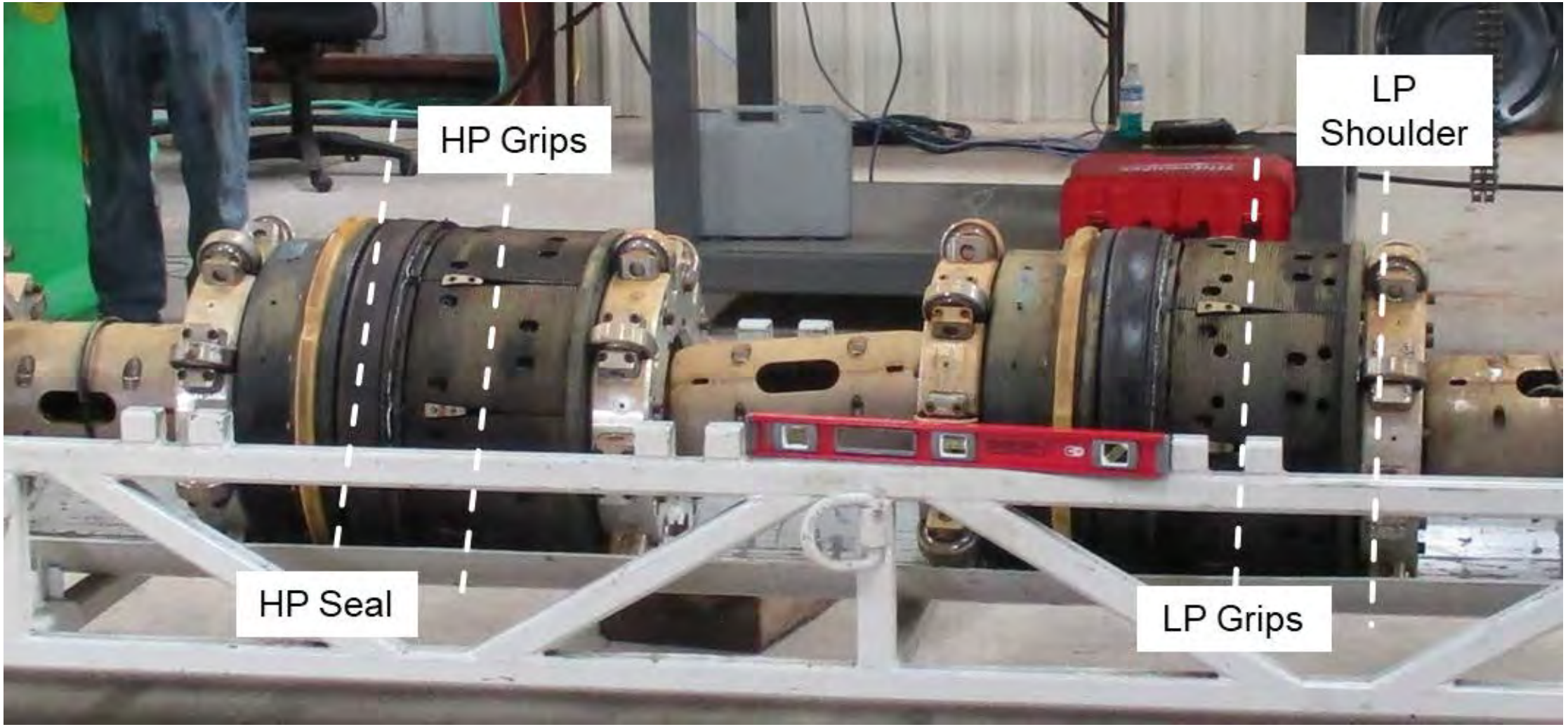


Location of Strain Gages

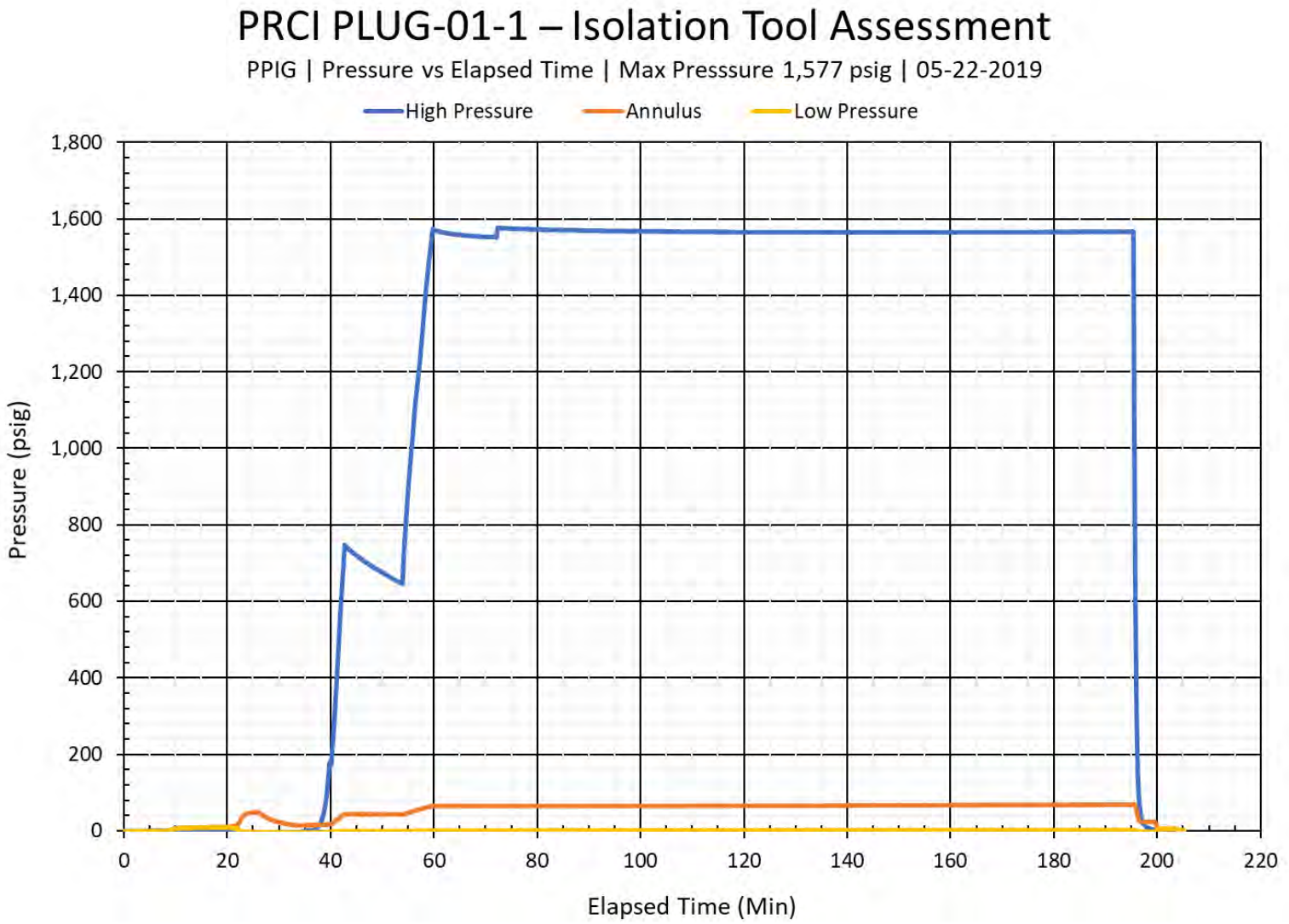


LEADING PIPELINE RESEARCH

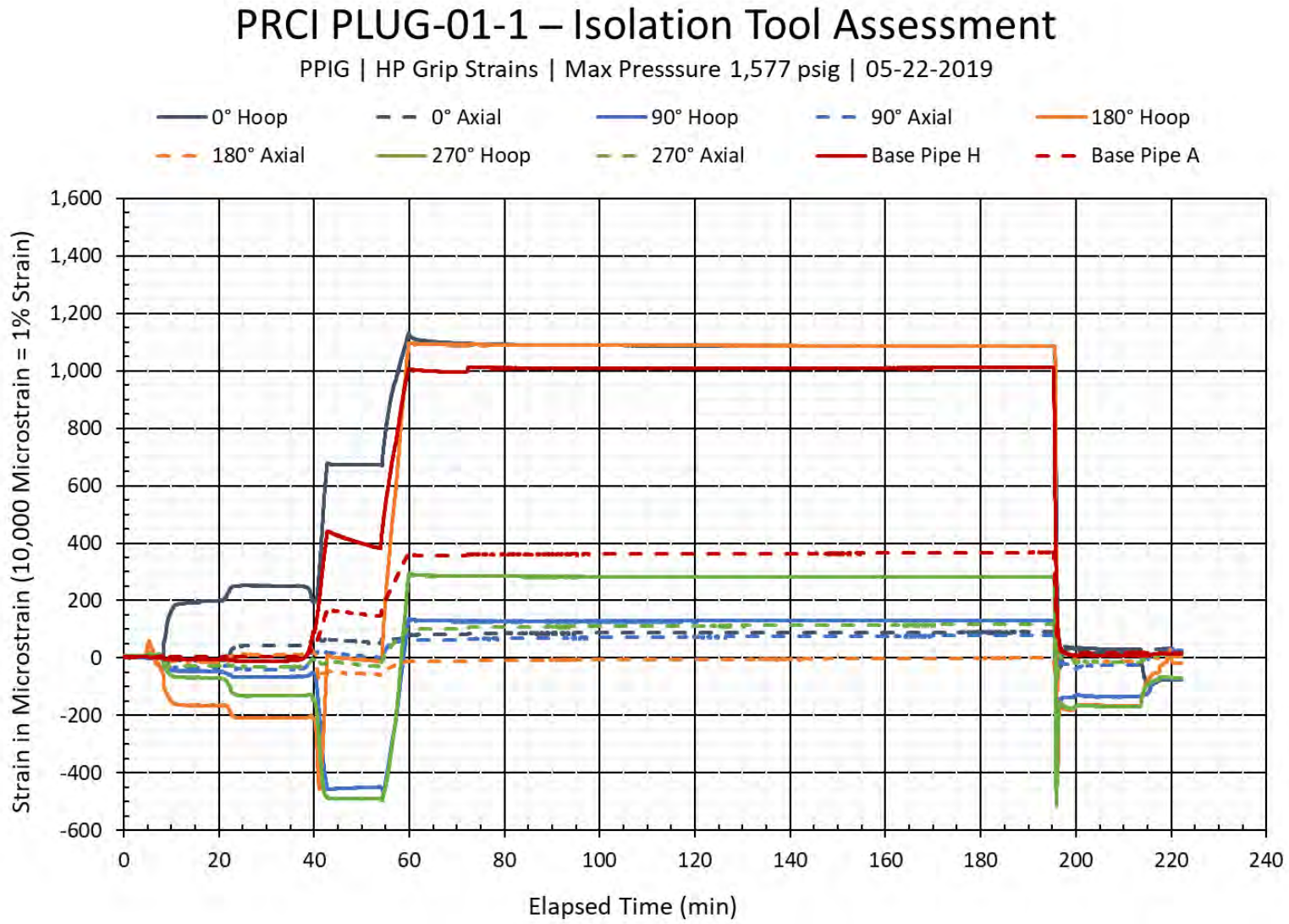
Photo from Testing (PPIG Tool)



Pressure Sequence

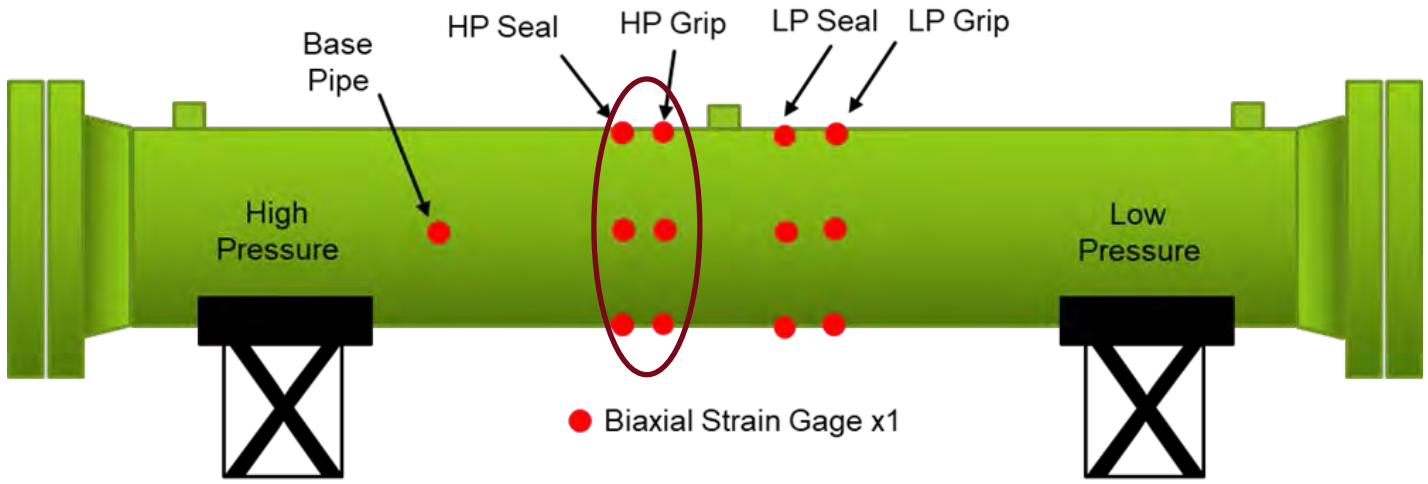


Hoop and Axial Strain Measurements



Observations from Testing

- For all three tools, largest strains were measured at high pressure seals & grips
- Sections of pipe were removed to capture the high pressure grip engagement area



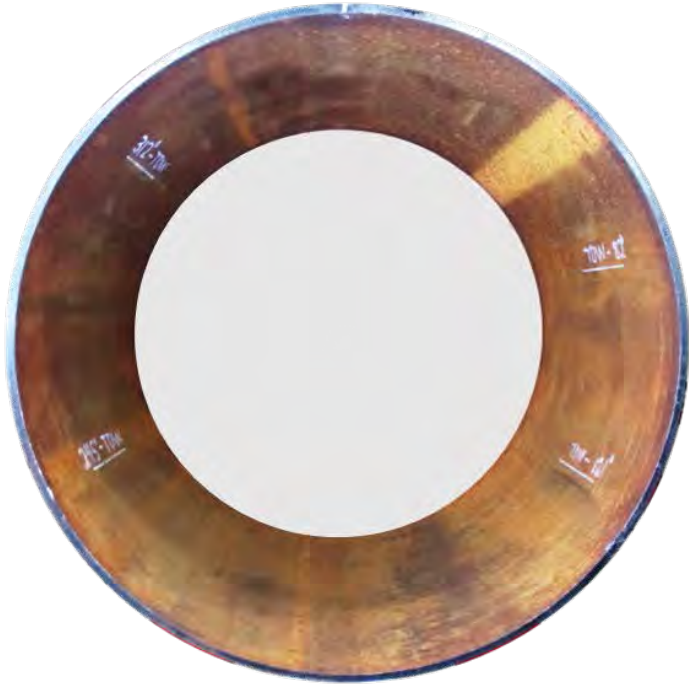
Overview of Post-Test Inspection

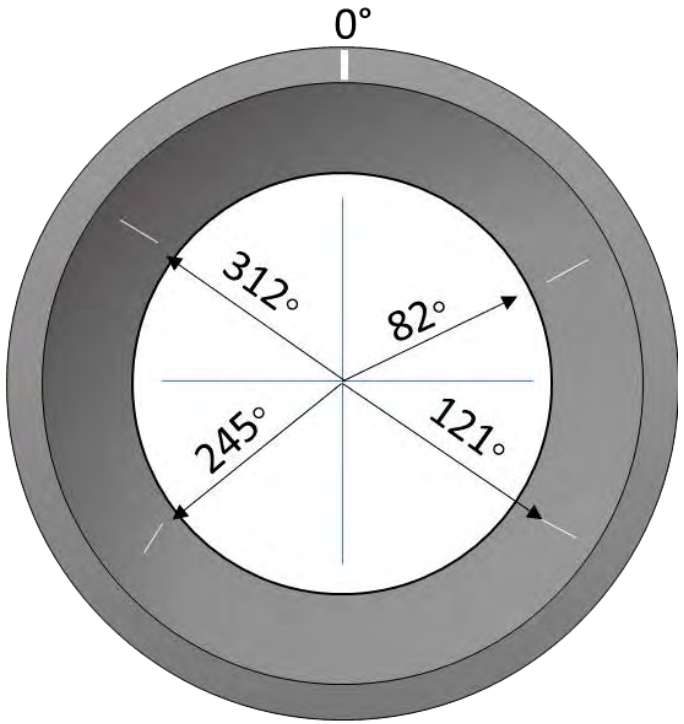
- Pipe rings removed from each pipe sample
- The rings were examined for penetrations as a result of grip engagement
- The deepest features in each quadrant were marked for sectioning and examination



LEADING PIPELINE RESEARCH

Post-test Inspection: TDW (1/2)

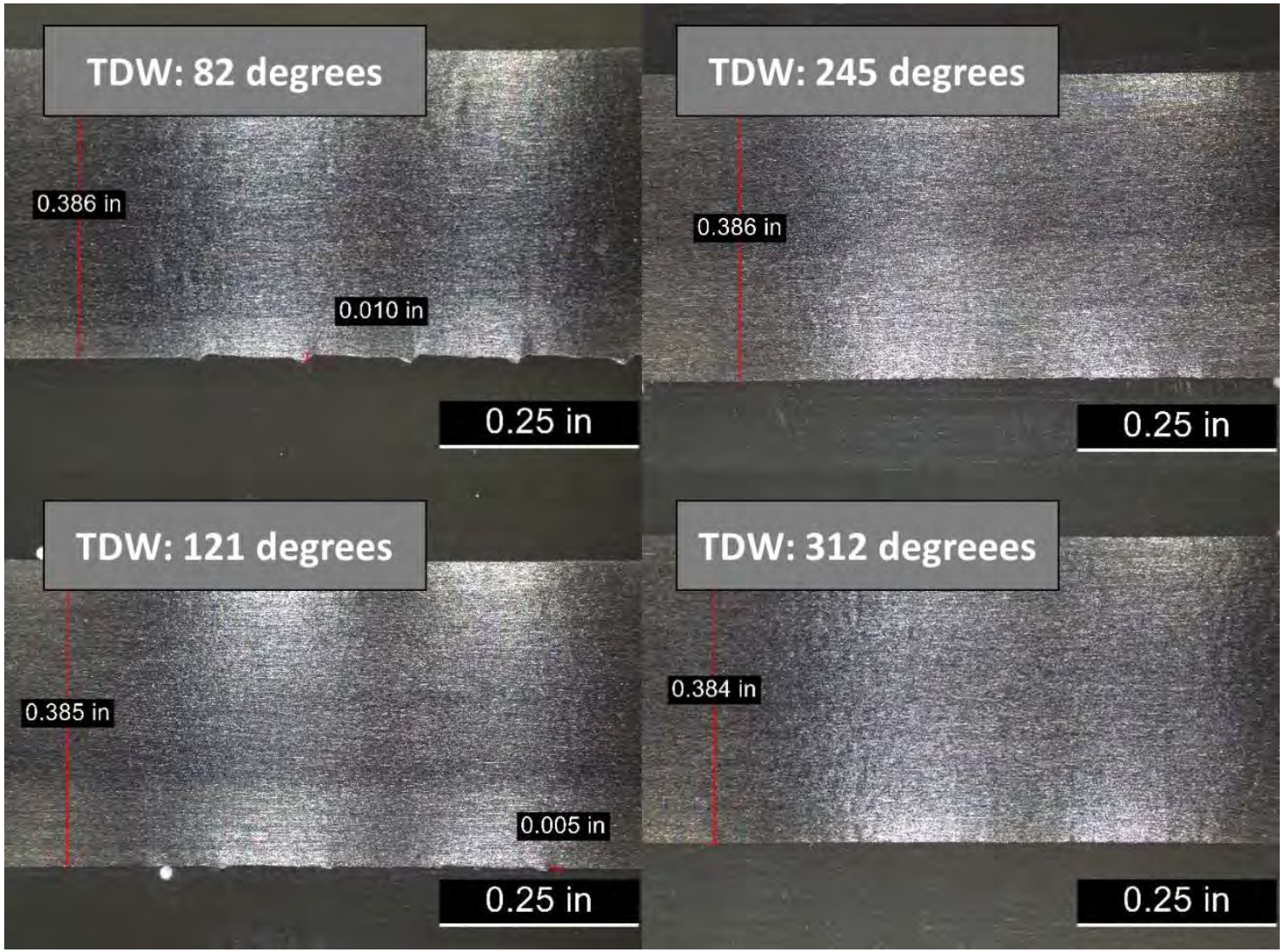








Post-test Inspection (2/2)





Development of Parametric Tool

- EXCEL-based tool
- Pipeline isolation tool manufacturers (3 options)
- Nominal pipe sizes: 10, 24, and 36 inches
- Pipe wall thicknesses: 0.165, 0.250, 0.375, and 0.500 inches
- Material grades: X42 and X65
- Operating pressures: 36% and 72% SMYS

ADVINTEGRITY

PIPELINE ISOLATION PARAMETRIC TOOL



Input		
		Units
Tool	PPIG	
OD	24	in
WT	0.375	in
Material	X65	
% SMYS	36	

Solve

Output		
	Grip	Seal
VM Stress (psi)	18,130	23,438
Hoop Stress (psi)	18,594	26,875
Axial Stress (psi)	5,903	13,407
Hoop Strain (με)	611	781

Observations and Conclusions

- Pipeline isolation tools successfully isolate a pipe section with both high-pressure and low-pressure sides.
- Isolation tools cause hoop and axial stresses to the pipe due to the grip engagement and seal activation.
- The highest hoop stresses occur at the seal activation location; axial loads are mainly constrained by the grips.
- The pipe does not undergo plastic deformation due to the isolation tool operations.
- The penetrations in the inner pipe walls due to the grip engagement are minimal and do not cause any loss of integrity.

Considerations for Future Work

- **Selection of a single tool vendor (PPIG, STATS, or TDW)**
- **Fabrication of a test spool assembly using a 24-inch diameter pipe with a "pronounced" seam weld including at least one of the following:**
  - Single shielded metal arc weld (SMAW)
  - Double-submerged arc weld (DWAW)
  - Electric flash weld (EFW)
- **Grade X42 pipe material**
- **Conduct pressure testing up to at least 90% SMYS to simulate hydrotesting**

BACK TO AGENDA

PRCI 2020 Research Exchange

PR-186-124510-Z02 Guidelines for the Determination of Pipeline Lifting and Lowering Stresses

- Yong-Yi Wang and Banglin Liu
- Center for Reliable Energy Systems

- William A. Bruce
- DNV GL USA, Inc.

LEADING PIPELINE RESEARCH

Background and Objective

- **Background**
  - High stresses can occur during lifting and lowering-in
    - *Impact on pipe integrity during construction and in-service*
    - *Impact on code compliance, e.g., if alternative flaw acceptance criteria are selected*
  - Few industry guidelines exist for stress management during lifting and lowering-in
  - Stress management during lifting and lowering-in is necessary to complete ECA
    - *Code requires a lifting and lowering-in plan that maintains a specified stress level*
    - *Stress level is used to develop alternative flaw acceptance criteria*
- **Objective**
  - Develop actionable guidelines for managing stresses during lifting and lowering-in

Work Scope

- Part 1: Review of Current Practice and Key Parameters Affecting Stresses
- Part 2: Analysis of Continuous Lifting and Lowering-in of Straight Pipe Strings
- Part 3: Analysis of Strings with Cold Bends
- Part 4: Analysis of Pipe Strings with Concrete Coating or River Weights
- Part 5: Development of Guideline Document
- Part 6: Development of Application Tool and Instruction Manual

Project Outcomes

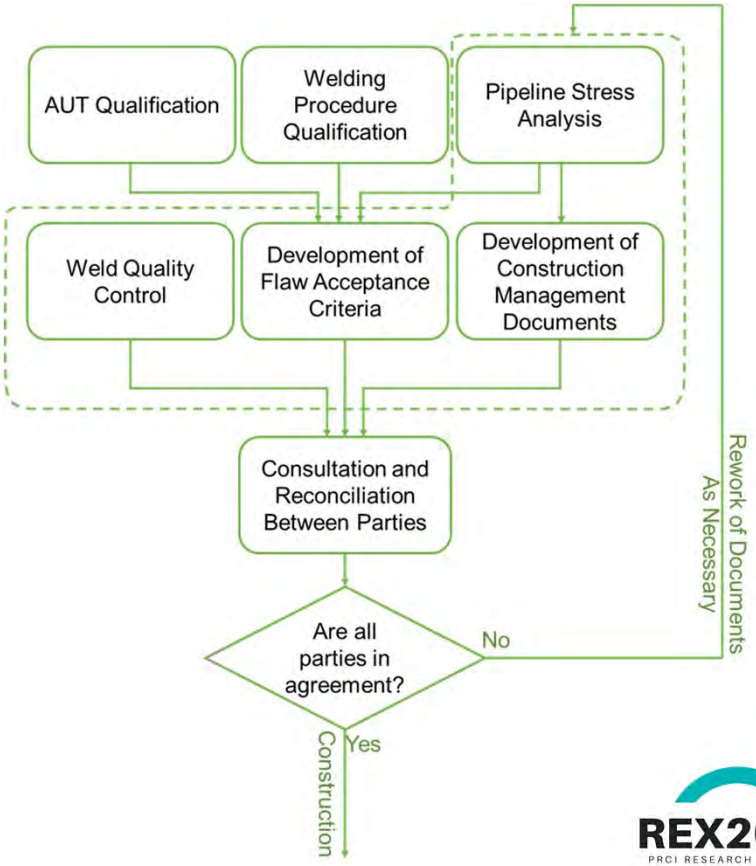
- **Guideline Document**
  - Straightforward instructions for stress analysis under different construction scenarios
    - *Pipe strings without river weights or concrete coatings*
    - *Pipe strings with river weights*
    - *Pipe strings with continuous concrete coatings*
  - Appendices to provide context of the stress analysis and assist in information collection
    - *Workflow for stress management and ECA*
    - *Key elements for performing ECA*
    - *Sample questionnaire for construction crew*
- **Application tool**
  - Software tool that automates stress analysis of continuous lifting and lowering-in
    - *Performing case-specific stress analysis based on user inputs*
    - *Conducting trade-off analysis to determine permissible range of construction parameters*
    - *Preparing lifting and lowering-in construction plan*

Example Application Scenario

- **Example application: developing a continuous lifting and lowering-in plan**
- **Workflow**
  - Step 1: identify relevant parties and build initial consensus
  - Step 2: collect information
    - *Construction practices*
    - *Field constraints*
  - Step 3: perform initial stress analysis using the application tool
  - Step 4: prepare draft construction parameters
  - Step 5: review and reconcile construction parameters
    - *Repeat Steps 3 and 4 as needed*
    - *Perform trade-off studies using the application tool as needed*
  - Step 6: finalize construction plan

Step 1 – Identify Relevant Parties and Build Initial Consensus

- **Consensus on**
  - Key elements and tasks to be considered in meeting the stress management target
  - Overall workflow
  - Parties responsible for each task
  - Expectations on the outcome of each task



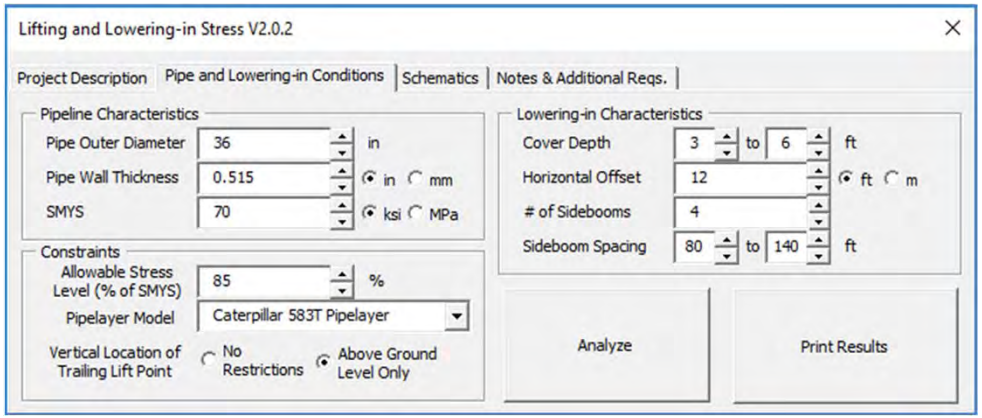
Step 2 – Collect Information

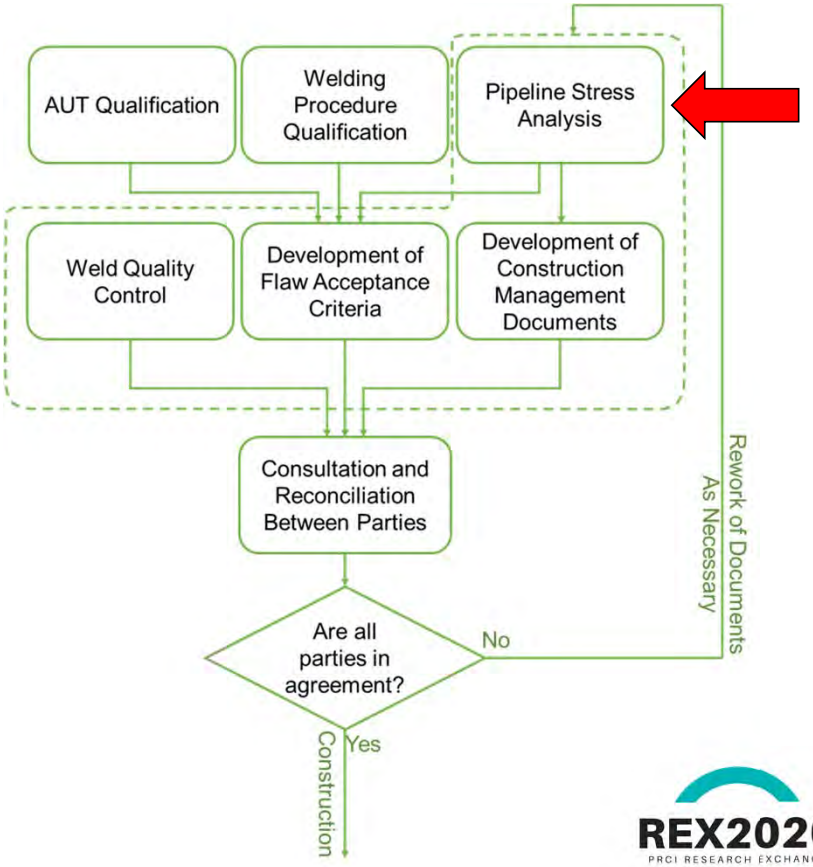
- **Collect information from construction crew**
  - Typical practices
  - Field constraints
  - Construction parameters relevant to stress analysis
- **Emphasis on the requested information being**
  - Unambiguous
  - Easy to collect

Parameter	Explanation	Value(s)
Outer Diameter	Nominal outside diameter	
Wall Thickness	Nominal pipe wall thickness(es)	
Pipe Grade	Grade of the pipe	
Nominal Skid Height	Nominal height of skids supporting pipe	
…	…	…

Step 3 – Perform Initial Stress Analysis Using the Application Tool

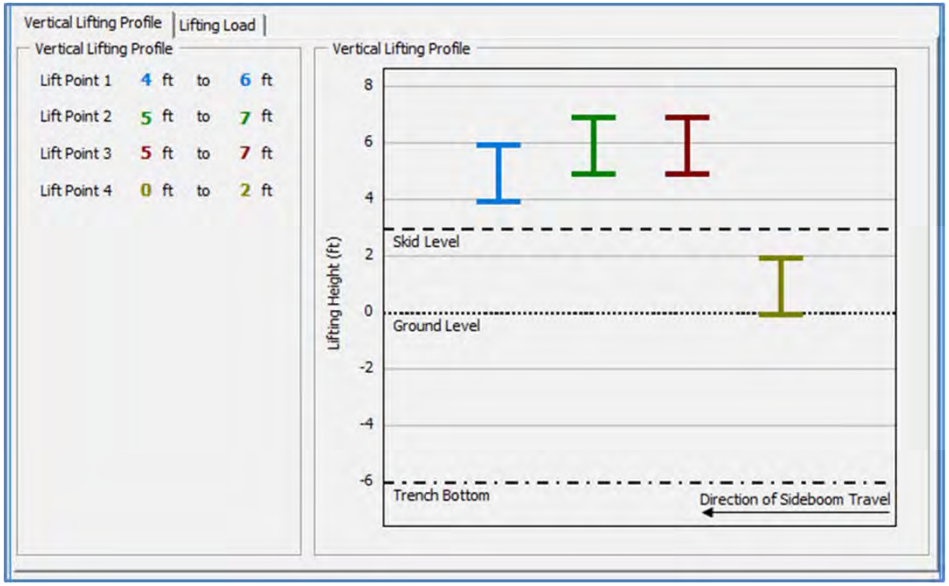
- **Inputs to the stress analysis application tool**
  - Pipeline characteristics
  - Lowering-in characteristics
  - Constraints

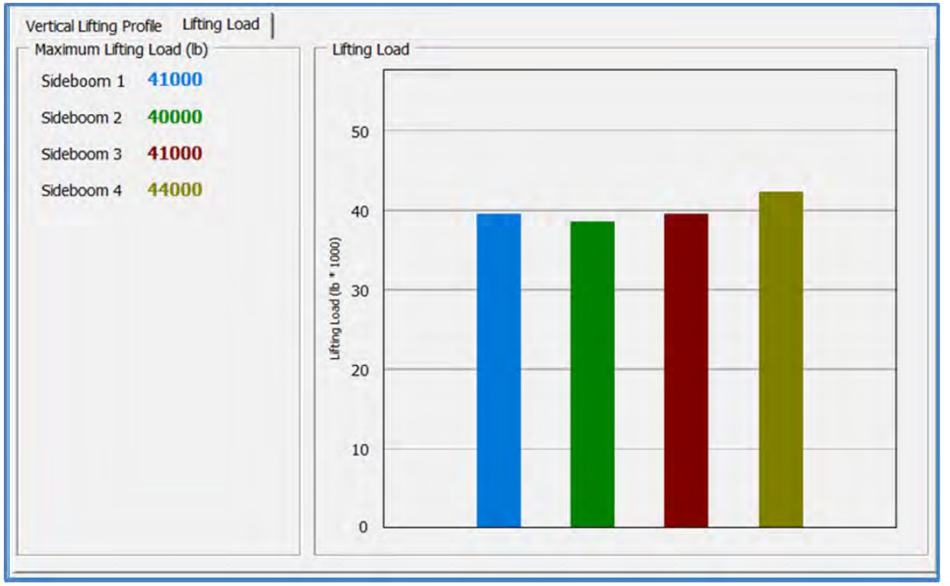




Outputs of the Application Tool

- Vertical Lifting Profile
- Maximum Lifting Load





Step 4 – Prepare Draft Construction Parameters

Project ID	CNST-2-2 Project A	Prepared By	CD
Job Number	1	Date Prepared	5/31/2017

Notes

Spread 1 - 80% Stress Limit

Inputs:

Pipe Data	
Pipe Outer Diameter	36 in
Pipe Wall Thickness	0.515 in
SMYS	70 ksi

Lowering-in Characteristics	
Cover Depth	4 ft
Horizontal Offset	12 ft
# of Sidebooms	4
Sideboom Spacing	105 ft

Lowering-in Constraints	
Acceptable % SMYS	81%
Sideboom Maximum Load Capacity	66000 lb

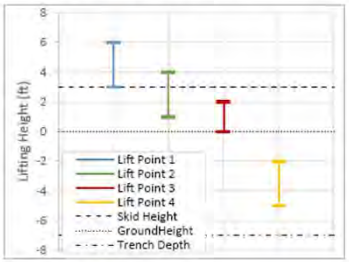
Outputs:

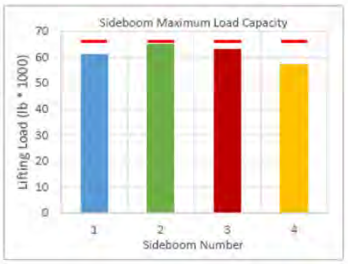
Vertical Lifting Profile			
Lift Point 1	3 ft	to	6 ft
Lift Point 2	1 ft	to	4 ft
Lift Point 3	0 ft	to	2 ft
Lift Point 4	-5 ft	to	-2 ft

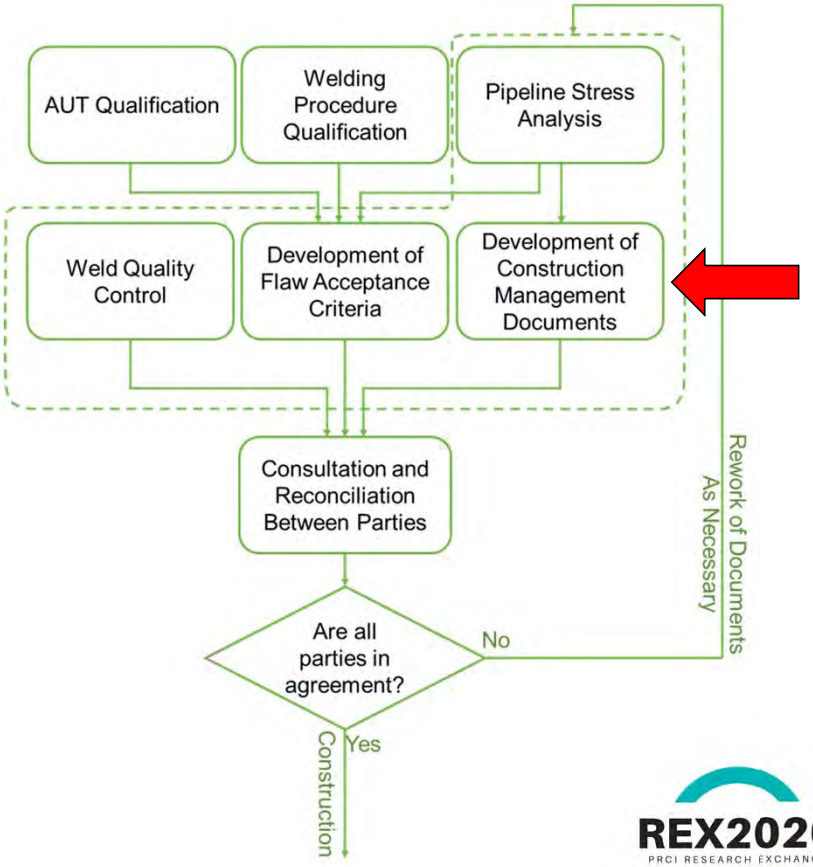
Additional Requirements

All Lift Points must be between the line of skids and the center of the trench. Lift Point 1 must be within 3 feet of the line of skids. From Lift Point 1 to Lift Point 4, the Lift Points must move progressively toward the trench.

Maximum Lifting Load (lb)	
Sideboom 1	61,000
Sideboom 2	65,000
Sideboom 3	63,000
Sideboom 4	57,000

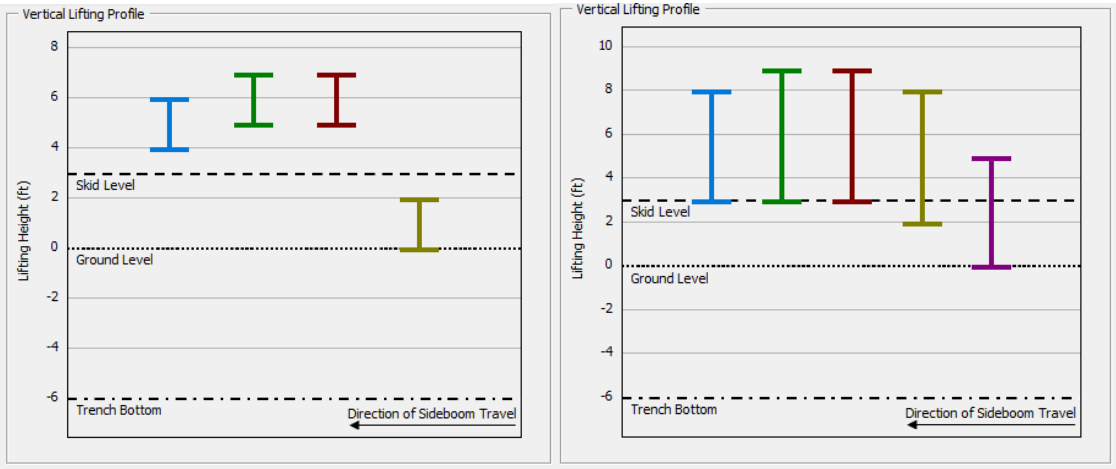


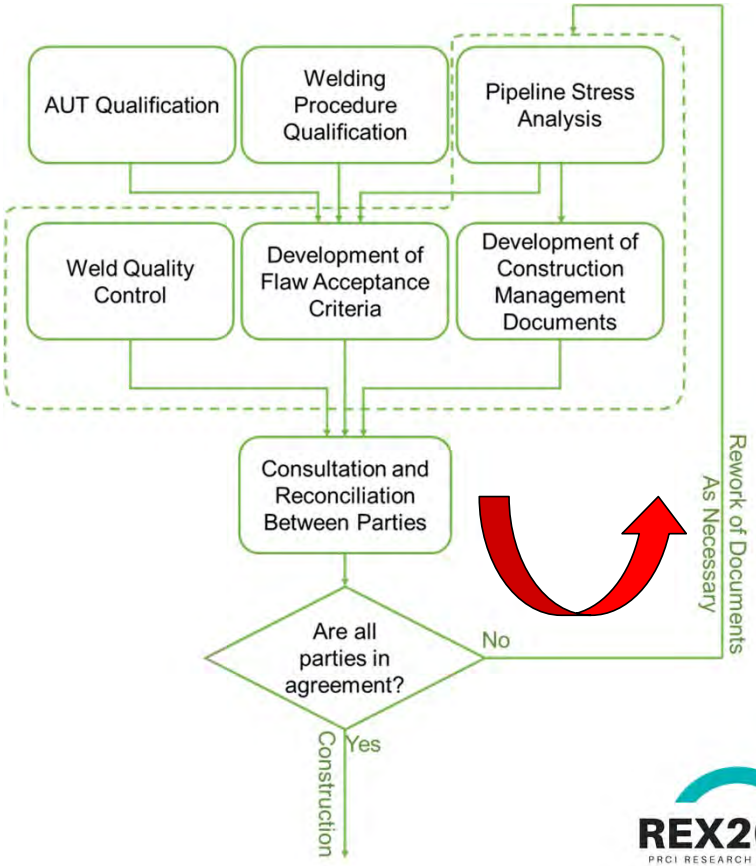




Step 5 – Review and Reconcile Construction Parameters

- **Determine tradeoffs of individual construction parameters, e.g.**
  - Adding a sideboom
  - Changing the spacing between sideboom
  - Changing the pipelayer model





Step 7: Finalize Construction Plan

CNST-2-2 Project B
v2.0
Continuous Lifting and Lowering-in Plan

Scope of Plan

Pipe OD: 36", Wall Thickness: 0.515"
Pipe SMYS: 70 ksi
Allowable Stress Level: 90% SMYS
Reference Number of Sidebooms: 4

Limitations

The profiles and the additional requirements on Sheets 2 and 3 are applicable under the following conditions:
1. The cover depth is between 3 ft and 6 ft.
2. The maximum horizontal offset is no greater than 12 ft.

DATE	BY	DESCRIPTION
09/24/19	CD	CNST-2-2 Project B

Lifting and Lowering-in Application Tool v2.0.3
Developed for PRCI for CNST-2-2: Management of Pipeline Lifting and Lowering-In Stresses
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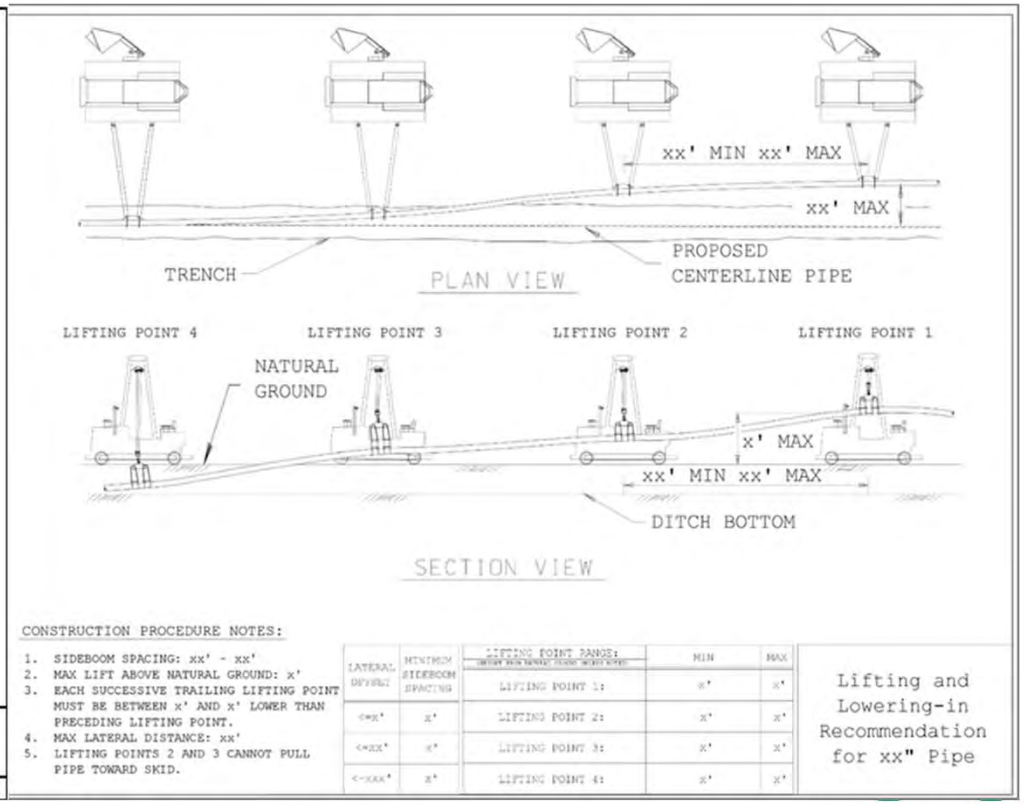
Pipe Specifications:
Pipe OD: 36", Wall Thickness: 0.515"
Stress Spread 1 - 90% Stress Limit

CNST-2-2 Project B v2.0

NOT TO SCALE | Sheet 1 of 3



CONSTRUCTION PROCEDURE NOTES:

1. SIDEBOOM SPACING: xx' - xx'
2. MAX LIFT ABOVE NATURAL GROUND: x'
3. EACH SUCCESSIVE TRAILING LIFTING POINT MUST BE BETWEEN x' AND x' LOWER THAN PRECEDING LIFTING POINT.
4. MAX LATERAL DISTANCE: xx'
5. LIFTING POINTS 2 AND 3 CANNOT PULL PIPE TOWARD SKID.

LATERAL OFFSET	MINIMUM SIDEBOOM SPACING	LIFTING POINT RANGE:	MIN	MAX
<=x'	x'	LIFTING POINT 1:	x'	x'
<=xx'	x'	LIFTING POINT 2:	x'	x'
<=xxx'	x'	LIFTING POINT 3:	x'	x'
<=xxx'	x'	LIFTING POINT 4:	x'	x'

Lifting and Lowering-in Recommendation for xx" Pipe

Thank You

- Questions?

BACK TO AGENDA

PRCI 2020 Research Exchange

Risk Consistent Safety Class System and Hoop Stress Factors for Pipeline Design

Maher A Nessim & Riski H Adianto, C-FER Technologies

Joint Industry Project sponsored by:
ATCO / CSA / Enbridge / Husky / TC Energy / Trans Mountain

LEADING PIPELINE RESEARCH

Introduction

- **Problem**
  - The current pressure design approach in CSA Z662 is based on
    - *Class location – function of the number of adjacent dwelling units*
    - *Permissible hoop stress factors – function of the class location*
  - This approach has significant limitations
    - *No consideration of environmental release consequences (liquids)*
    - *Inconsistent consideration of safety consequences for different products (HVP vs Gas)*
    - *Variable safety levels for different pipelines carrying the same product (size-dependent)*

- **Proposed solution**
  - Develop a new design approach that achieve known, acceptable and consistent levels of public safety and environmental protection
  - Support possible adoption of the new approach in CSA Z662

Approach

- **Technical methodology**
  - Build on risk-based methodologies already in Z662 (Annexes C & O)
    - *Developed over 20 years of industry-guided research (PRCI – JIPs)*

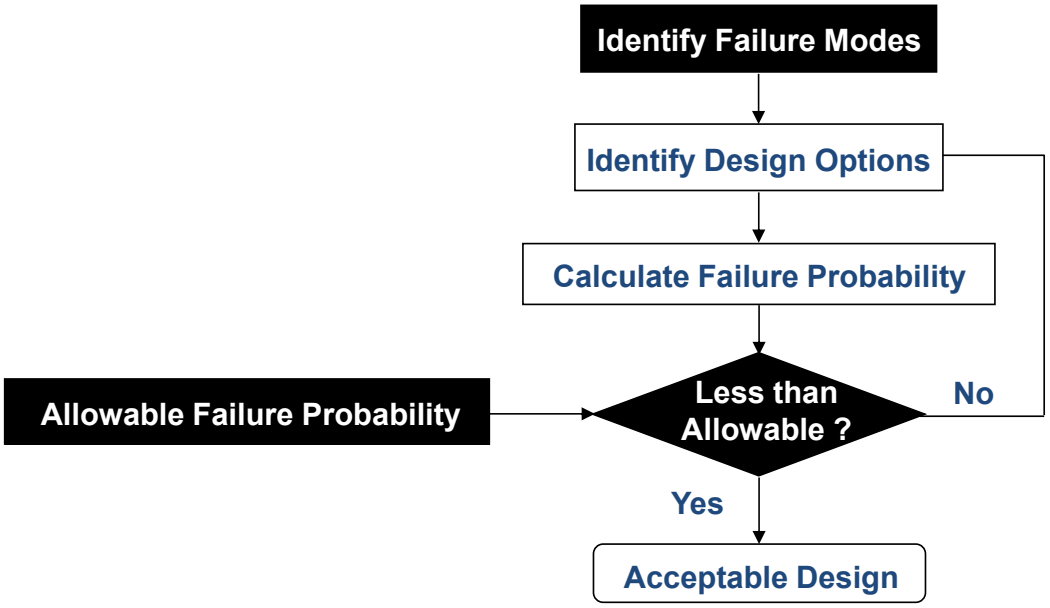
- **Development approach**
  - Demonstration phase for midstream natural gas and LVP pipelines (complete)
  - Full development for all pipelines and products within Z662 scope (ongoing)

- **Major technical tasks**
  - Develop a consequence-based safety class system
  - Develop hoop stress design factors for each safety class
  - Validate the approach through comparative design studies

Outcomes

- **Final product**
  - New wall thickness design approach
  - Draft revision of CSA Z662 to incorporate the approach
- **Key features**
  - Simple deterministic approach based on a hoop stress factor
  - Addresses internal pressure and accidental equipment impact loads
  - Achieves consistent risk levels by considering the true failure consequences
- **Practical impact**
  - Optimized use of resources to achieve known safety levels
  - More conservative designs for small diameter pipelines in high consequence areas – less conservative designs otherwise

Risk-based Design



- **Established precedent**
  - Other industries – 1970's (exclusive use)
    - *Civil structures / nuclear containment / Aircraft*
  - Submarine pipelines - 1990's (normative)
    - *DNV-OS-F101 / API RP 1111*
  - Onshore pipelines – 2000's (off ramp)
    - *ISO 13623 / IGEM TD 1 / AS 2885.1 / CSA Z662*

Simplify into hoop stress based design check

Slide 5

MN1 Maher Nessim, 8/7/2019

Key Components of the New Approach

- **Safety class – function of release consequences**
  - Service fluid, release size, site attributes
- **Hoop stress factor – a function of safety class and pipeline attributes**
  - Diameter, pressure, grade, toughness and mechanical protection

Safety Class System – Approach

Risk = Failure Probability x Failure Consequences

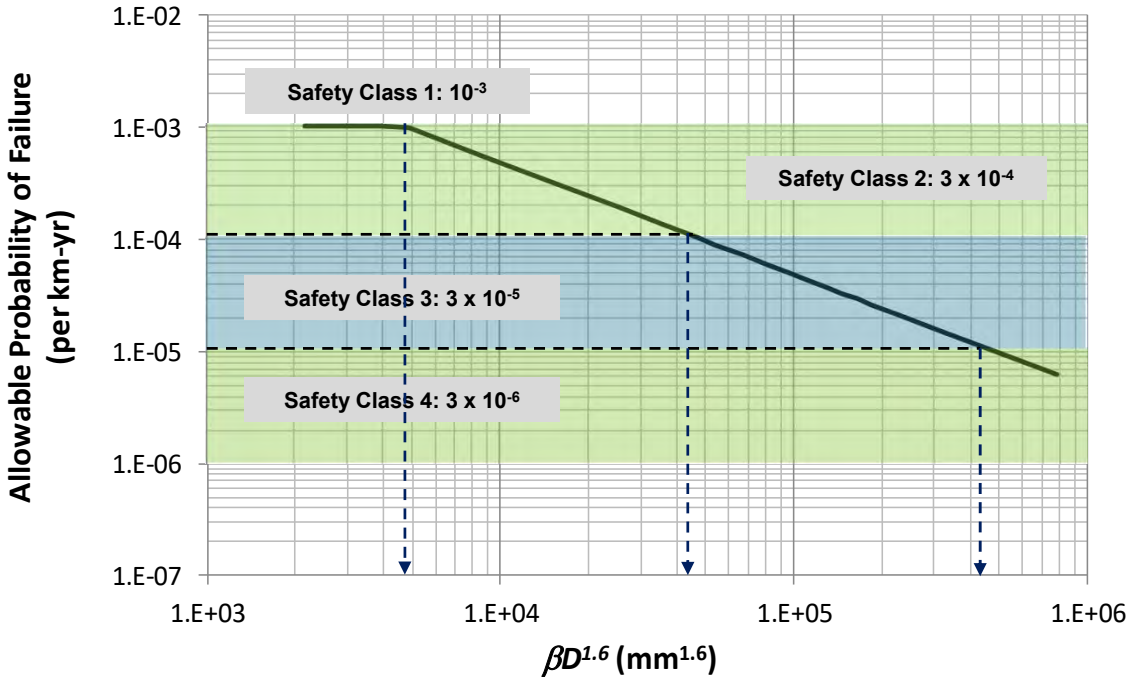
$$\text{Allowable Failure Probability} = \frac{\text{Acceptable Risk Level}}{\text{Failure Consequences}}$$

- **Acceptable risk level**
  - **Total risk implied by current Standard for new pipelines built with modern materials and technology, and operated to current best practices**

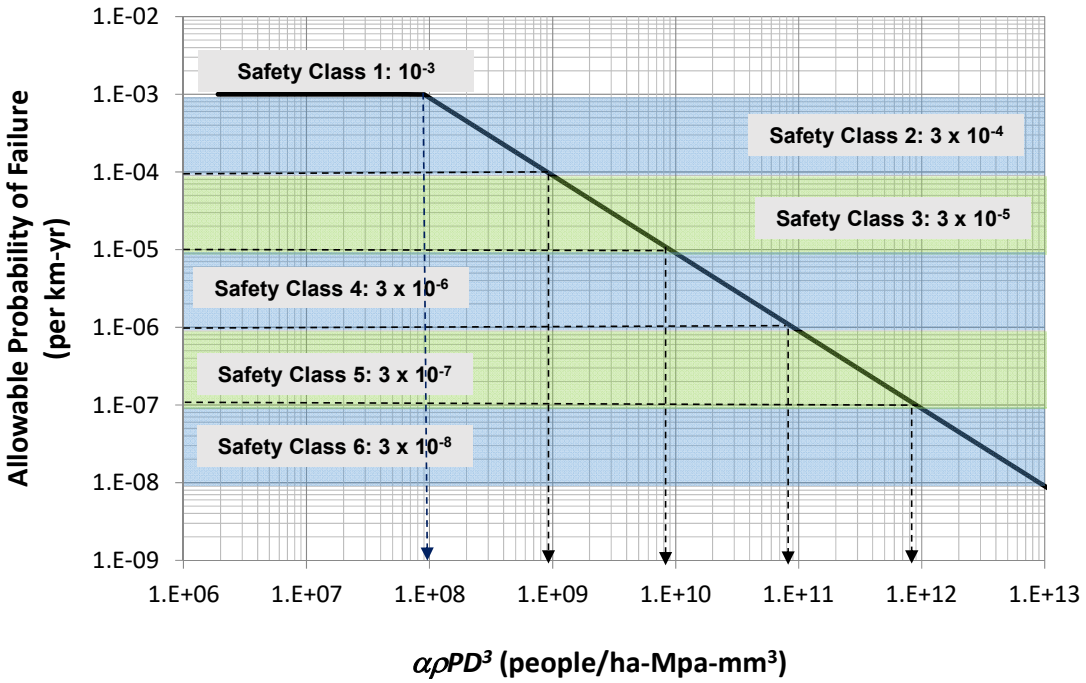
- **Failure consequences (LVP hydrocarbon liquids)**
  - Proportional to $\beta\ D^{1.6}$

Environmental Factor **Diameter**

Safety Classes – LVP Liquid Pipelines



Safety Classes – Natural Gas Pipelines



Safety Class – Format

Safety Class	Category	Gas (Safety Impact Based)	Low Flammability LVP Liquid (Environmental Impact Based)	Allowable Failure Probability (per km-yr)
1	Very low	$\alpha \rho PD^3 \leq 9.0 \times 10^7$	$\beta D^{1.6} \leq 4.8 \times 10^3$	10^{-3}
2	Low	$9.0 \times 10^7 < \alpha \rho PD^3 \leq 9.0 \times 10^8$	$4.8 \times 10^3 < \beta D^{1.6} \leq 4.8 \times 10^4$	3×10^{-4}
3	Medium	$9.0 \times 10^8 < \alpha \rho PD^3 \leq 9.0 \times 10^9$	$4.8 \times 10^4 < \beta D^{1.6} \leq 4.8 \times 10^5$	3×10^{-5}
4	High	$9.0 \times 10^9 < \alpha \rho PD^3 \leq 9.0 \times 10^{10}$	$\beta D^{1.6} > 4.8 \times 10^5$	3×10^{-6}
5	Very High	$9.0 \times 10^{10} < \alpha \rho PD^3 \leq 9.0 \times 10^{11}$	N/A	3×10^{-7}
6	Extreme	$\alpha \rho PD^3 > 9.0 \times 10^{11}$	N/A	3×10^{-8}

Simple function of failure consequence drivers

- α = product factor
- β = environmental factor (= 4.5 for DGA , = 1.5 for non-DGA)
- ρ = population density (people/ha)
- D = diameter (mm)
- P = design pressure (MPa)

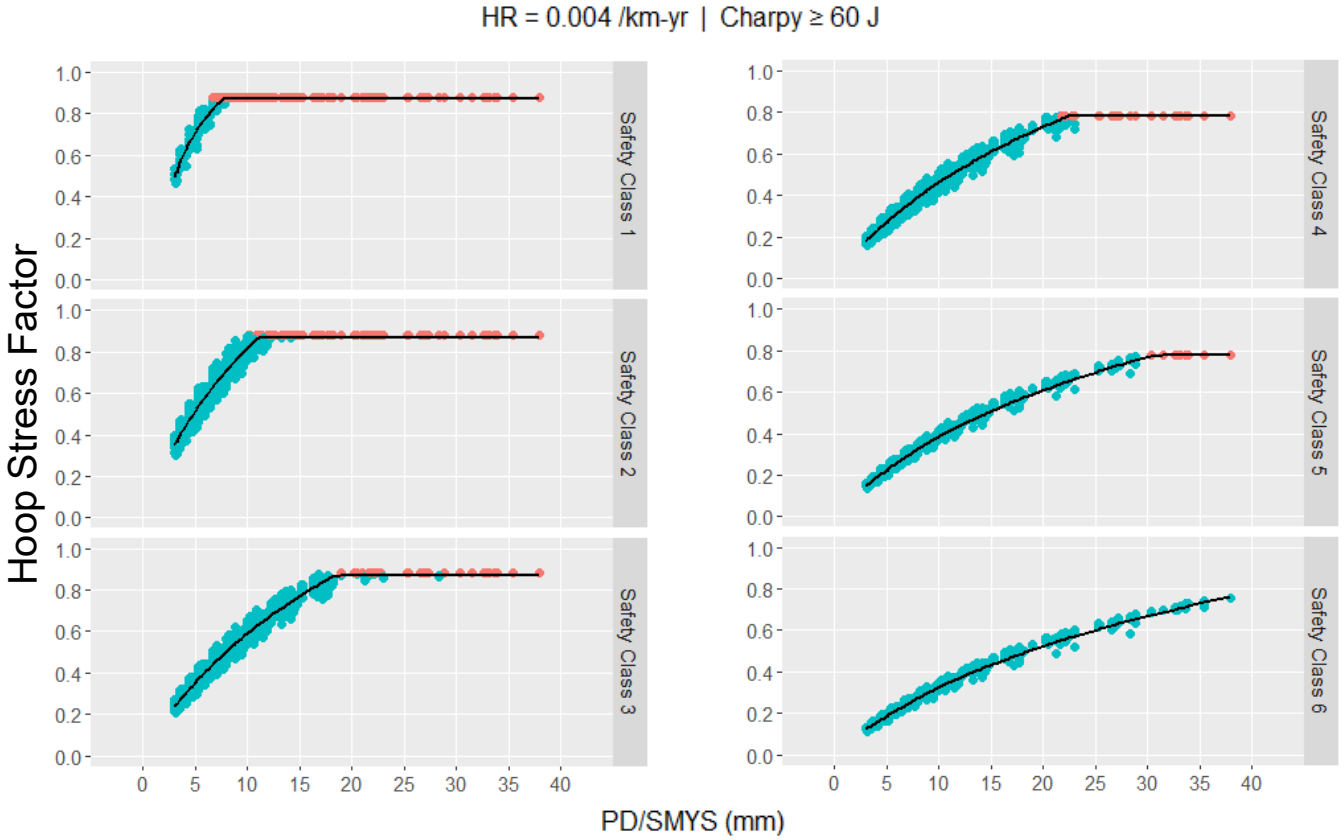
Safety Class System – Summary

- **Replaces class location system**
- **Considers true consequence drivers**
  - LVP liquid hydrocarbons – diameter (spill volume) and environmental sensitivity
  - Natural gas – product, diameter / pressure (release rate) and population density
- **Supports consistent safety levels**
  - All pipelines with equivalent consequence severity grouped in one safety class
  - Reliability target commensurate with consequence severity for each safety class

Hoop Stress Factor – Approach

- **Define wide range of pipeline cases**
  - NPS 6 to 52
  - Pressure 3.5 to 17.5 MPa
  - Grades 241 to 690
  - Safety classes 1 to 6
- **Calculate wall thickness required to meet reliability target**
  - Burst under internal pressure
  - Burst of gouged dent caused by equipment impact
- **Calculate hoop stress factor that gives same WT**
- **Synthesize results into a table (equation) format**

Hoop Stress Factor – Sample Results



Hoop Stress Factor – Format

$$HSF = F \cdot H \cdot C$$

F = Basic factor (Standard third party damage prevention, Charpy ≥ 60 J)

F	PD / SMYS (mm)						
Safety Class	3	6	10	15	20	30	40
1	0.49	0.78	0.87	0.87	0.87	0.87	0.87
2	0.35	0.59	0.82	0.87	0.87	0.87	0.87
3	0.24	0.41	0.59	0.77	0.87	0.87	0.87
4	0.18	0.31	0.46	0.61	0.73	0.78	0.78
5	0.15	0.26	0.38	0.51	0.61	0.77	0.78
6	0.13	0.22	0.33	0.43	0.52	0.67	0.78

Damage prevention adjustment factor

$$H = 1 - h \cdot \left(\log \frac{hit\ rate\ (km - yr)}{0.004} \right)$$

Toughness adjustment factor

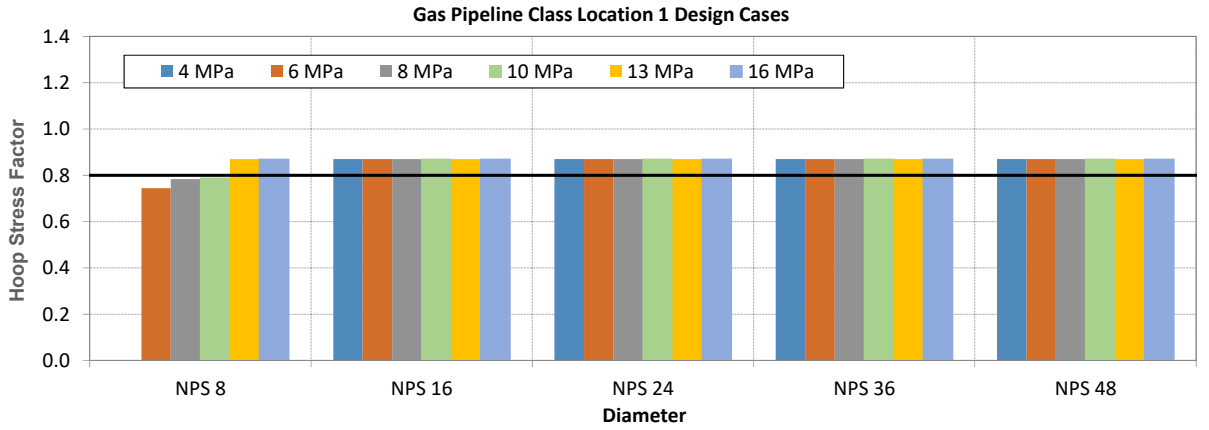
$$C = 1 + c \cdot (\min(charpy\ (J), 60)\ - 60)$$

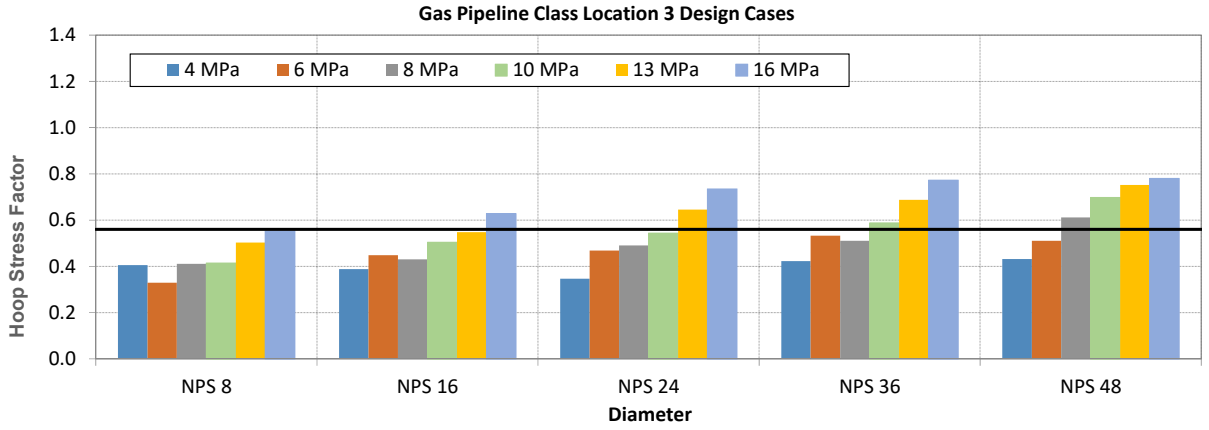
Safety Class	h	c
1	0.83	4.5e-3
2	0.65	5.3e-3
3	0.40	6.4e-3
4	0.31	6.9e-3
5	0.27	7.0e-3
6	0.24	7.3e-3

Hoop Stress Factor – Summary

- **Replaces class location factor**
- **Calibrated by safety class to maintain consistent risk**
- **Based on actual failure mechanisms under key applied loads**
  - Burst under internal pressure and failure due to equipment impact
- **Function of PD/SMYS (proxy for WT)**
  - Thicker pipe is less likely to fail at the same hoop stress
- **Gives credit for improved mechanical damage protection**
- **Compensates for low (or unknown) toughness**

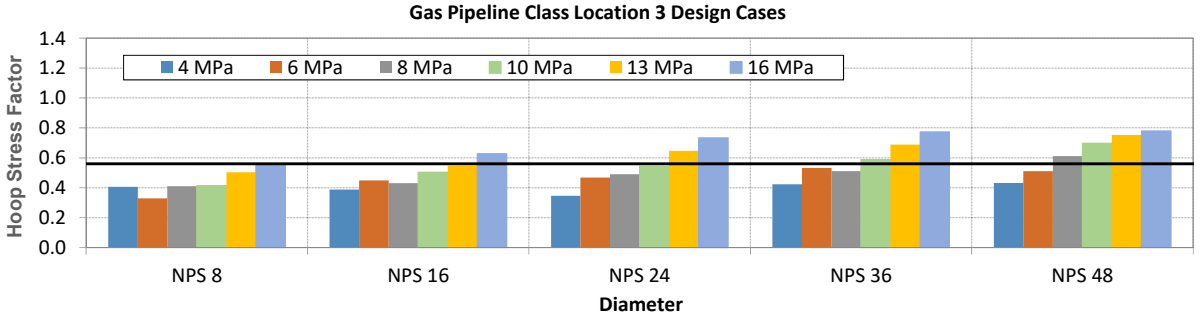
Wall Thickness Impact – Gas



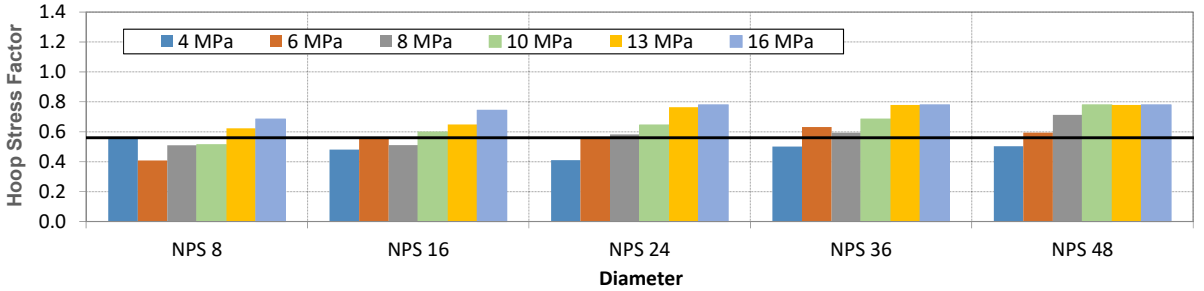


Equipment Impact Mitigation – Gas Class 3

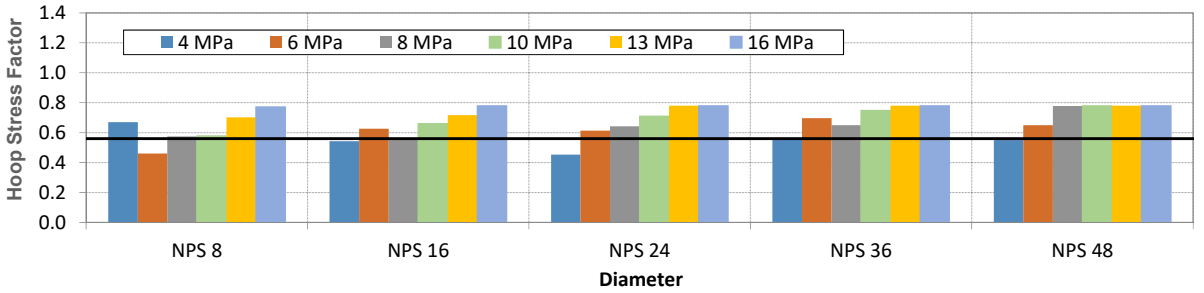
Base Case



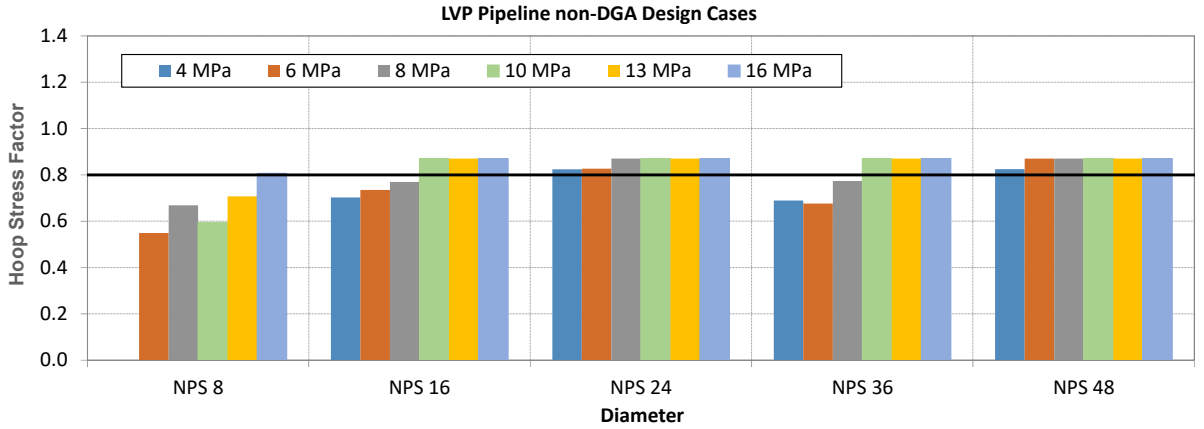
Double Depth of Cover

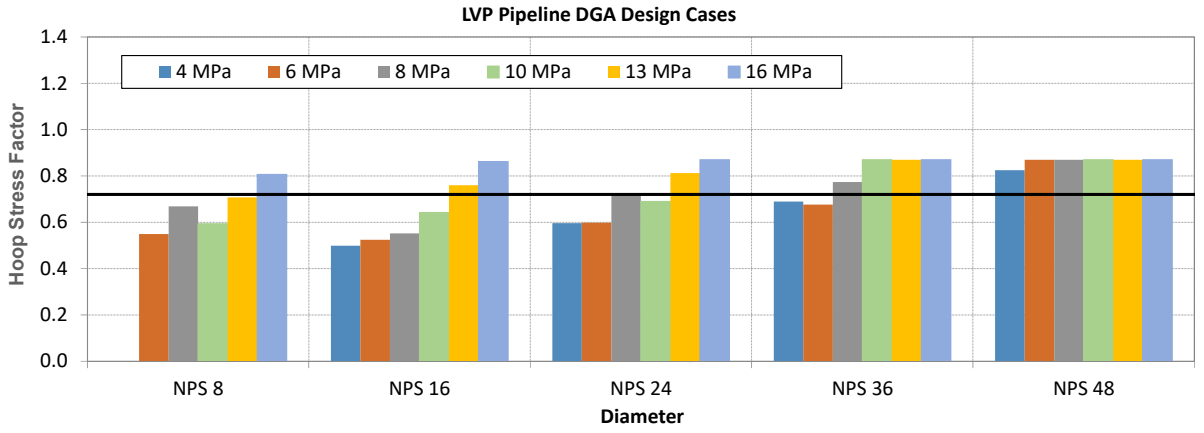


Mechanical Protection



Wall Thickness Impact – LVP





Summary

- **New design approach targeted for inclusion in CSA Z662**
- **Uses the familiar hoop stress factor approach**
  - Factors calibrated to achieve consistent safety levels
- **Based on a new defensible safety class system**
  - Accounts for true consequences of failure
  - Addresses inconsistencies in current approach
- **Optimizes use of resources to achieve consistent safety**
  - Cost savings for large diameter and low consequence pipelines
  - Re-invested in small diameter, high consequence pipelines

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Hydrostatic Test Limit Check

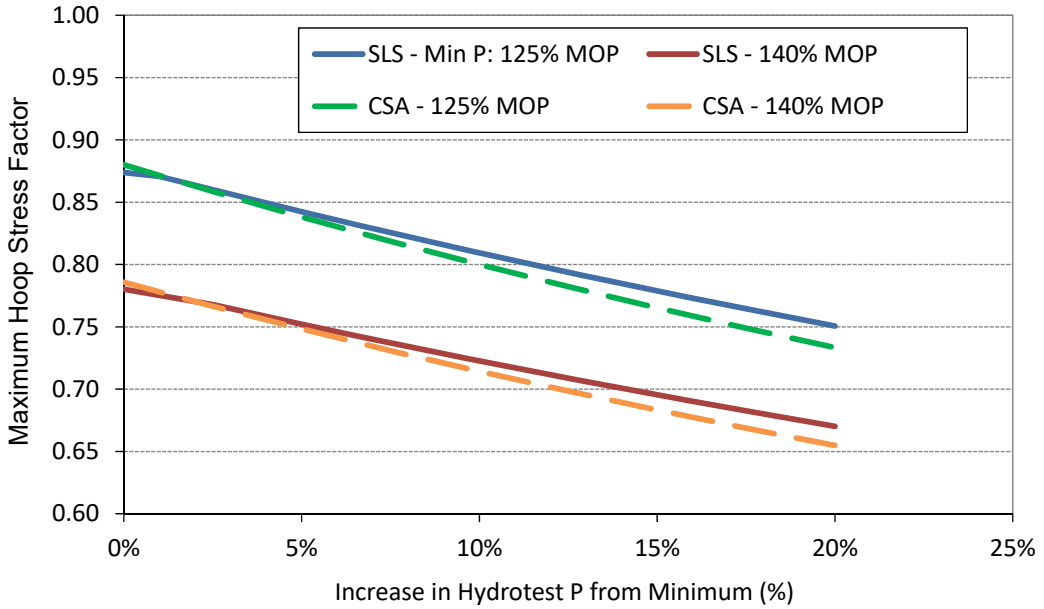
Ensure that pipe can be tested to specified pressures (Table 8.1)

1.25 MOP

$$HSF_{max} = \frac{1.09}{(1 + 0.85 \cdot \Delta P) \cdot 1.25}$$

1.40 MOP

$$HSF_{max} = \frac{1.09}{(1 + 0.85 \cdot \Delta P) \cdot 1.4}$$



$\Delta P = maximum\ hydrostatic\ head\ \ diferential\ (fraction\ of\ minimum)$

BACK TO AGENDA

PRCI 2020 Research Exchange

PR-350-144501 (SIA-1-4)
PR-350-154501 (SIA-1-7)
Tensile Strain Capacity of Vintage Pipelines

- Bo Wang, Dan Jia, Banglin Liu, and Yong-Yi Wang
- Center for Reliable Energy Systems

LEADING PIPELINE RESEARCH

Background

- **Vintage pipelines**
  - Built with hot-rolled and normalized steels with carbon content ≥ 0.2%
  - Large portion of transmission pipelines (>75% mileage pre-1970)
  - Not all girth welds inspected by non-destructive testing (NDT) methods
- **Failures occurred when**
  - Additional stress imposed > historical norm
- **Integrity management**
  - Site-specific assessment
  - Screening or developing integrity management plan

Incentives

- **Assessing maintenance priorities and avoiding unnecessary remediation work**
- **Making better-informed mitigation/repair decisions in a loading event**
- **Unique challenges associated with vintage pipelines**
  - Lack of record/limited data for performing fitness-for-service (FFS) assessment on vintage pipelines
    - *Girth weld mechanical properties*
    - *Flaw Characteristics*
    - *Applied stress/strain*
  - Lack of tensile strain capacity (TSC) model for vintage girth welds
    - *Strain demands in the range of 0.2% - 1.0% is of high practical relevance to integrity management*
    - *Existing FFS procedures, e.g., API 1104 Annex A, can be overly restrictive for strain demands exceeding 0.2%*
    - *There lacks a TSC model that considers the salient features of vintage girth welds*

Objective and Work Scope

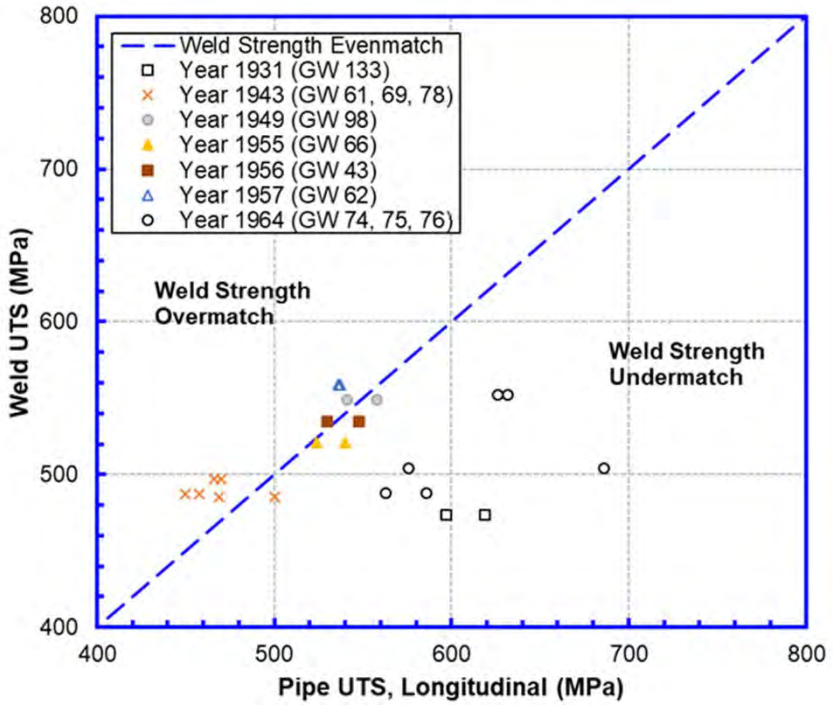
- **Objective**
  - Develop an estimation tool that permits accurate TSC assessment of vintage girth welds
- **Two parallel PRCI work scopes**
  - SIA-1-4, “Mechanical Properties of Vintage Girth Welds and Their Implications on Performance”
    - *Generation of material property inputs required for accurate FFS assessments of vintage girth welds*
    - *[check next slide]*
    - *Identification of characteristics of weld flaws reported by NDT*
    - *Evaluation of NDT techniques*
  - SIA-1-7, “Evaluation of Girth Weld Flaws in Vintage Pipelines”
    - *Development and validation of TSC model for vintage girth welds*
    - *Implementation of the TSC model as an application tool*
- **Interaction of the work scopes**
  - The outcome of SIA-1-4 provided
    - *Initial inputs and defined realistic focus areas for the TSC model development in SIA-1-7*
    - *Default values for key parameters in applying the TSC model, when line-specific information is unavailable*

Principal Outputs

- **SIA-1-4**
  - Material, geometry, and flaw characteristics of vintage pipelines
    - *19 girth welds tested*
      - Grade B – X52
      - 1929 - 1964
    - *Pipe mechanical properties*
    - *Girth weld mechanical properties*
    - *Girth weld profiles and flaw characteristics*
    - *Apparent CTOD toughness*
  - General understanding of the TSC performance of vintage girth welds
  - Key factors affecting TSC
  - Comparison of NDE technologies
    - *Flaw sizing from NDE vs. destructive tests*
- **SIA-1-7**
  - TSC model and estimation tool for vintage girth welds
  - Experimental validation of the TSC tool

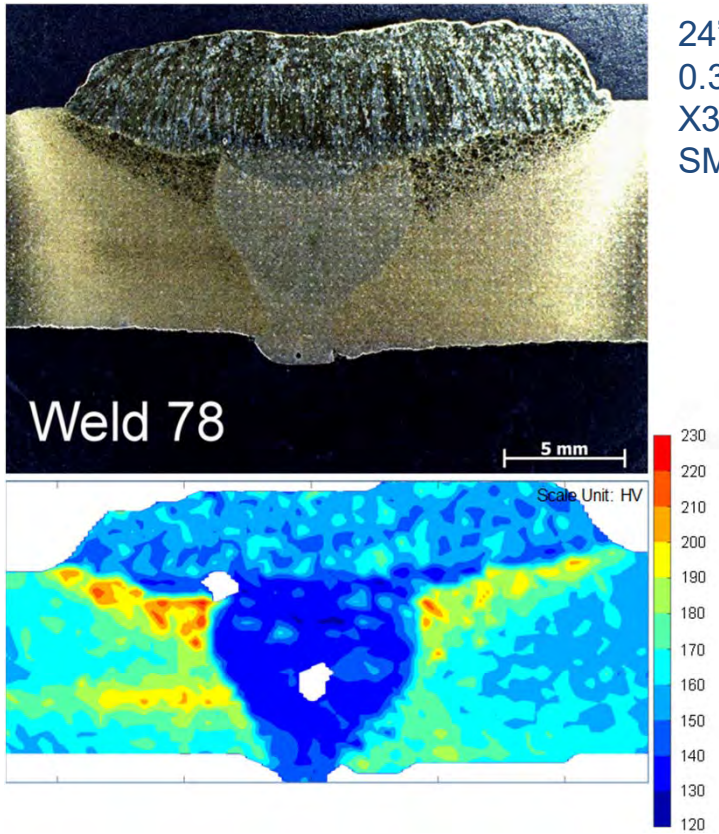
Key Findings from SIA-1-4

- **Pipe material**
  - Some pipes show significant strength anisotropy
  - Pipes on either end of a girth weld can have large strength difference
  - Yield strength can be higher than the specified minima
    - *X37 – X42: YS is slightly higher than SMYS in both hoop and longitudinal directions*
    - *X52: YS can be significantly higher than SMYS in hoop direction*
- **Girth weld material and flaw**
  - UTS of the weld generally undermatches that of the pipe
  - Ductile behavior is generally expected under normal service conditions
  - No obvious HAZ softening



Key Findings from SIA-1-4 – Continued

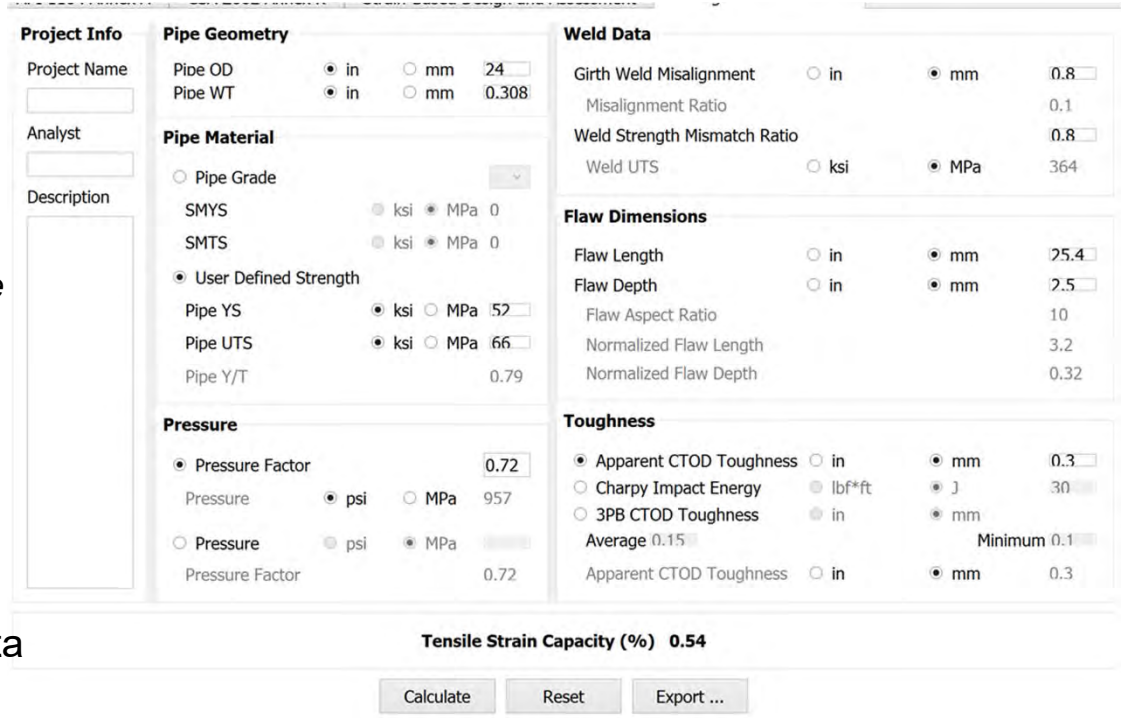
- **Girth weld flaws**
  - Some welds have long volumetric flaws
  - Flaw sizes vary
    - *Height is mostly of one bead height*
    - *Length is mostly below 2 – 4 inches*
- **Girth weld TSC performance**
  - Vintage SMAW welds generally performed well, despite having flaws
  - Features benefiting TSC performance
    - ***Weld cap reinforcement***
    - ***No HAZ softening***
  - Features detrimental to TSC performance
    - ***Weld strength undermatching***



24” OD
0.375” WT
X37 Seamless
SMAW, 1943

Development of TSC Estimation Tool

- **Case-specific TSC analysis**
  - Follows Level 4a procedures of the PRCI-CRES tensile strain models
  - Analysis scope based on outcome of SIA-1-4
    - *Key factors affecting TSC performance of vintage girth welds*
    - *Characteristics range and values for each analyzed factor*
- **Software tool development**
  - Implements the outcome of the TSC analysis
  - Default values provided based on data collected in SIA-1-4
  - User-friendly interface and help manual



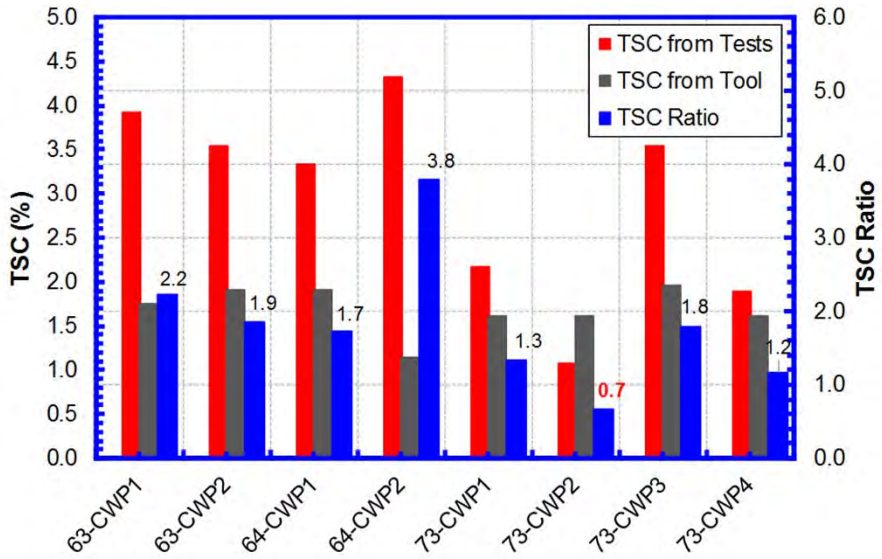
Validation of the TSC Estimation Tool

- **Eight (8) curved-wide plate (CWP) tests**
  - Simulated planar flaws were machined
    - *From the pipe ID*
    - *Targeting the HAZ*
    - *Nominal flaw size were 2.5 or 5 mm in depth and varied from 20 to 60 mm in length.*
  - Flaw dimensions were “designed” by CRES to produce results for meaningful comparison with the tool output.
  - Test protocols were developed at CRES
  - Tests were done at CFER
  - All eight samples were tested at room temperature
- **Accompanying small scale material characterization tests**
  - Provide input information for the TSC estimation tool



Validation of the TSC Estimation Tool – Continued

- **Comparison between TSC tool prediction and test results**
  - The tool is accurate and provides conservative TSC prediction in most cases
    - *The tool underpredicted the TSC of seven (7) specimens*
    - *The tool overpredicted the TSC of one specimen (73-CWP2)*
  - Specimen 73-CWP2 was examined post-test
    - *Pre-existing flaws missed by NDE were identified*



Example Application of the TSC Estimation Tool

- **Application scenario: conducting case-specific assessment after a confirmed loading event**
  - Determination of strain demands on the affected girth welds
    - *Collected through IMU and/or strain gauges, or*
    - *Estimated from pipe-soil interaction modeling*
  - Determination of strain capacity of the affected girth welds - using the software tool
    - *Feature dimensions*
      - ILI crack tools or in-ditch tools
    - *Girth weld geometry and material characteristics*
      - Weld-specific values based on available documents
      - Default values from the tool (based on data collected in SIA-1-4)
  - Comparison between strain demand and strain capacity provides important input for integrity decisions

Example Application of the TSC Estimation Tool

- **Application scenario: performing screening of girth welds on the basis of strain capacity**
  - Determination of a nominal strain demand level
  - Determination of strain capacity of the girth welds of interest
    - *Feature dimensions*
    - *Girth weld geometry and material characteristics*
  - Ranking of the girth welds by maintenance/mitigation priority
    - *By comparison between the nominal strain demand level and the strain capacity*
    - *By relative strain capacities among the girth welds*

Value to Integrity Management of Vintage Pipelines

- Determine maintenance priorities
- Avoid unnecessary remediation work
- Make decisions for repair and mitigation work after a loading event, such as ground movement

Thank You

- Questions?

BACK TO AGENDA

PRCI 2020 Research Exchange

Optimization of steel alloy design for critical welded pipeline structure

Dr. Maina Portella Garcia
Prof. Frank Barbaro

University of Wollongong - Australia

LEADING PIPELINE RESEARCH

Introduction

- A single failure of an operating high pressure oil or gas pipeline can be catastrophic

- The recent pipe girth weld failures which have occurred in North America has highlighted the consequences of such events and the perennial necessity for sound weld integrity of our critical pipeline energy infrastructures.





Failures in USA and China

[Huo Chunyong, TEC 2019 in Xi'an]

Failures

Main of external cause

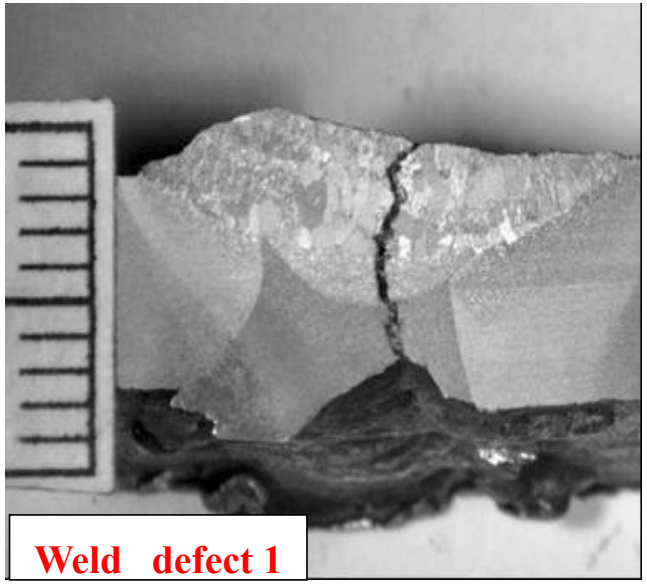


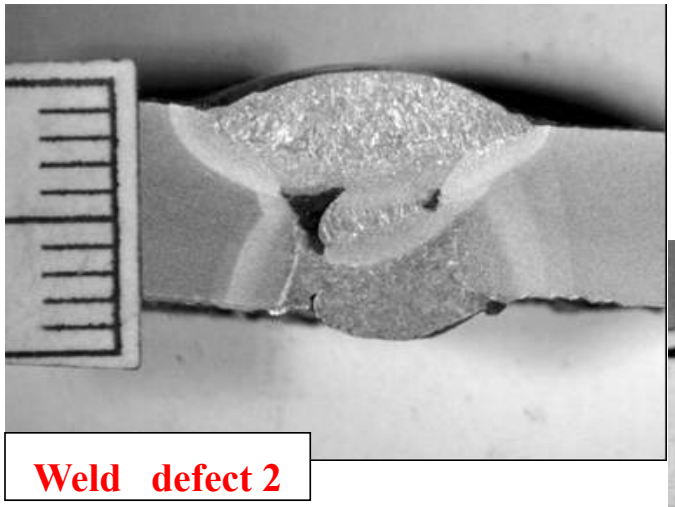


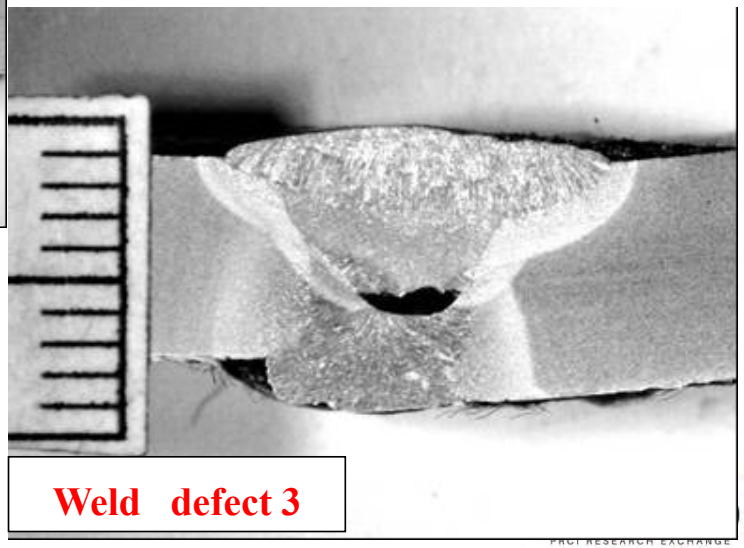
Ref: F.Yang ICPLP April 2015

Failures

Internal causes: Defects

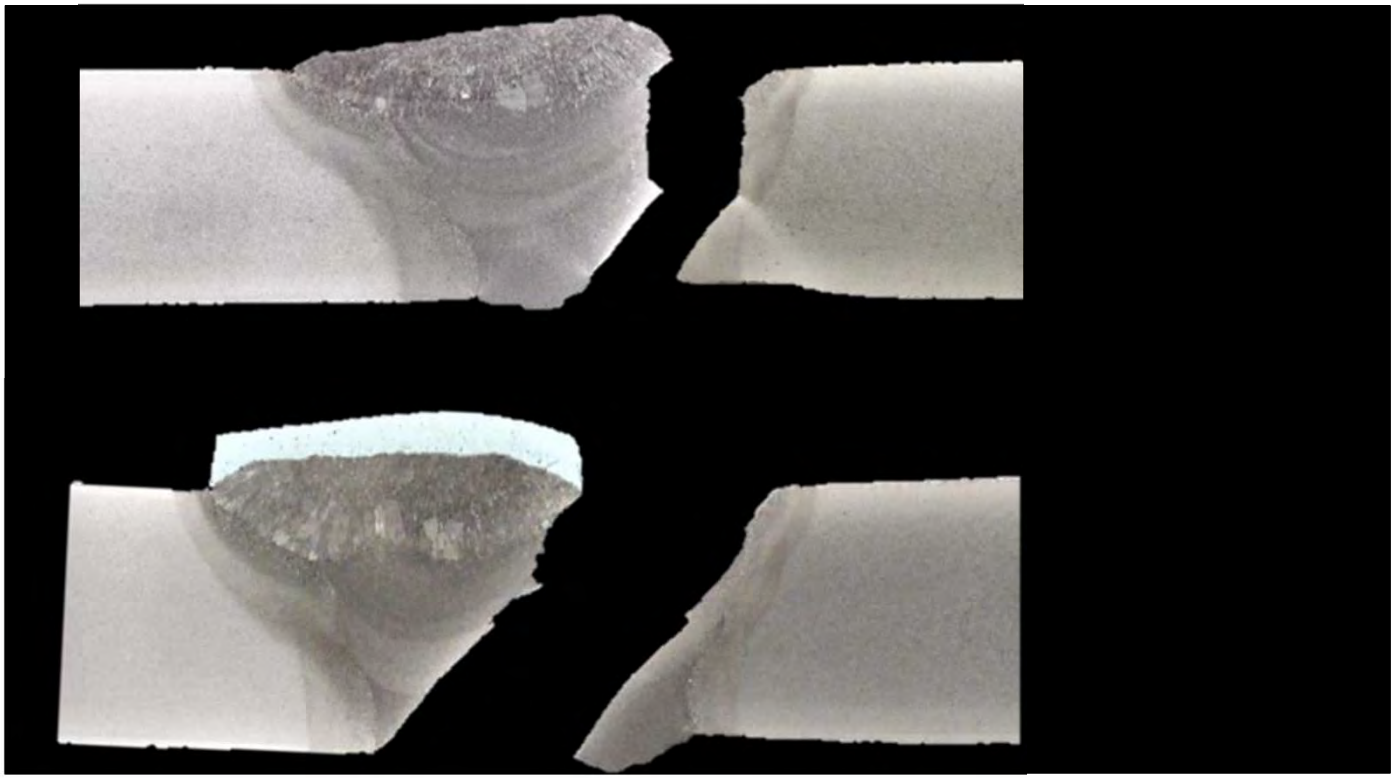






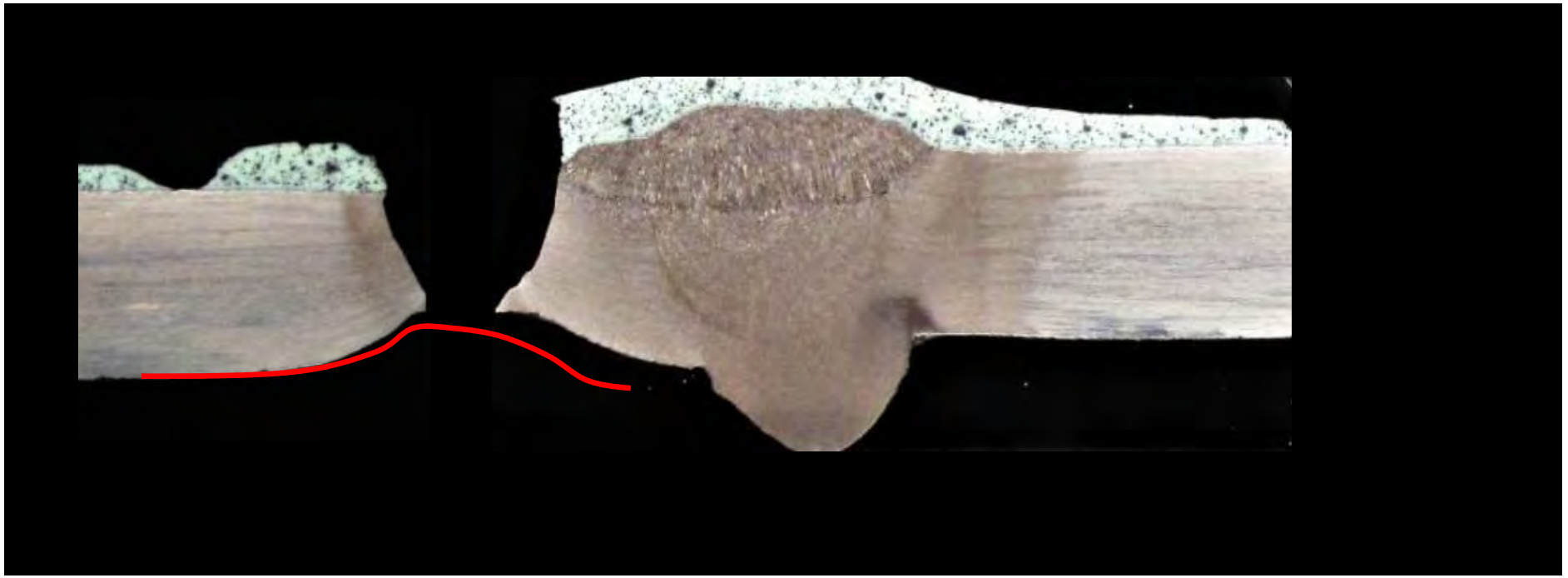
Ref: F.Yang ICPLP April 2015

Failures



Ref: Wang, Y.-Y., "*Girth Welding in the Age of Evolving Steel Manufacturing Processes and under Realistic Field Conditions,*" presentation at API 1104 and API 5L meetings, January 22, 2019

Failures



Ref: Wang, Y.-Y., "*Girth Welding in the Age of Evolving Steel Manufacturing Processes and under Realistic Field Conditions,*" presentation at API 1104 and API 5L meetings, January 22, 2019

Failures

China failures: girth weld with defects (weld quality)

type	Main reason	Suggestion	technology
Pipe	external interference & corrosion	periodical test	inner inspection and common NDT
Girth weld	Weld defect and external loading	Improve weld quality and monitor geologic hazard	Excavation in High Consequence Areas
Fitting	Poor quality in factory	enhance factory supervisor	NDT for in service fittings; well Heat Treatment for new fitting

Ref: F.Yang ICPLP April 2015

USA failures:

Failures

China failures: girth weld with defects (weld quality)

type	Main reason	Suggestion	technology
Pipe	external interference & corrosion	periodical test	inner inspection and common NDT
Girth weld	Weld defect and external loading	Improve weld quality and monitor geologic hazard	Excavation in High Consequence Areas
Fitting	Poor quality in factory	enhance factory supervisor	NDT for in service fittings; well Heat Treatment for new fitting

Ref: F.Yang ICPLP April 2015

USA failures:

- **Why these failures are occurring in recent years?**
- **What are the mechanisms for the recent failures?**

Modern Microalloyed steels - Facts

Modern Microalloyed steels - Facts

- **High strength steels have provided Significant cost benefits to the oil & gas industry,**
  - Reduction in pipe wall thickness reduces steel tonnage (12%/ grade increment),
  - Reduction in deposited girth weld metal (~25%)
- **The main issues in welding high strength linepipe are:**
  - Resistance to Hydrogen assisted cold cracking (HACC), and
  - Sufficient weld metal strength matching to the pipe – in presence of the max. allowable weld imperfection,
- **Modern high strength steels have virtually eliminated (designed out) the possibility of HACC as a result of the reduction in Carbon & Pcm (which avoids the formation of undesirable microstructures susceptible to HACC).**
- **This reduction in Pcm has been well managed by the effective use of microalloying additions which provide strengthening both through grain refinement as part of steel processing (controlled rolling & accelerated cooling) and also precipitation strengthening.**

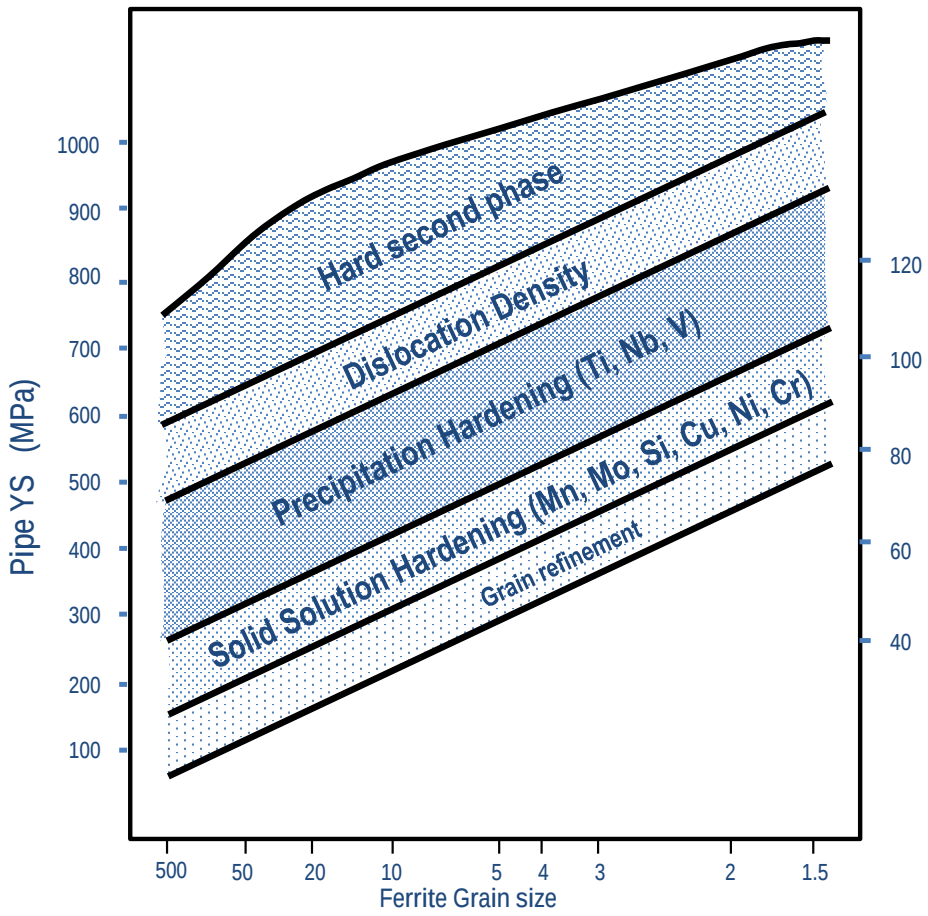
Modern Microalloyed steels - Facts

- **These technological advances have provided the steelmaker two methods to achieve steel strength, ie**
  - Steel Chemical composition — alloy design, and
  - Steel processing — thermo mechanical processing,

Competitive Economic pressure has forced the steel maker to review cost structures and unfortunately the overuse of thermos mechanical procesing, in some cases, resulted in the production of steels with minimal alloying and excessive use of controlled rolling and accelerated cooling

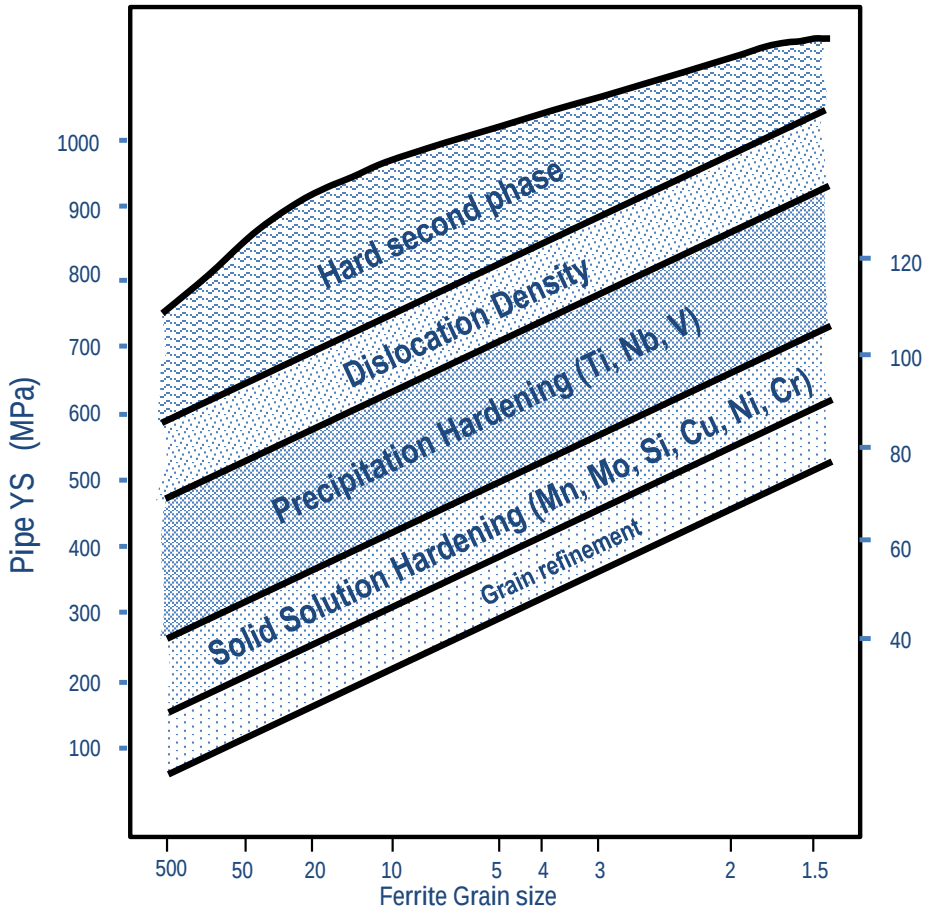
Excessive use of CR and ACC are fundamentally deformation induced strengthening processes, which when subjected to downstream thermal processes, such as welding, can eliminate a large proportion of essential strength, ie induced softening.

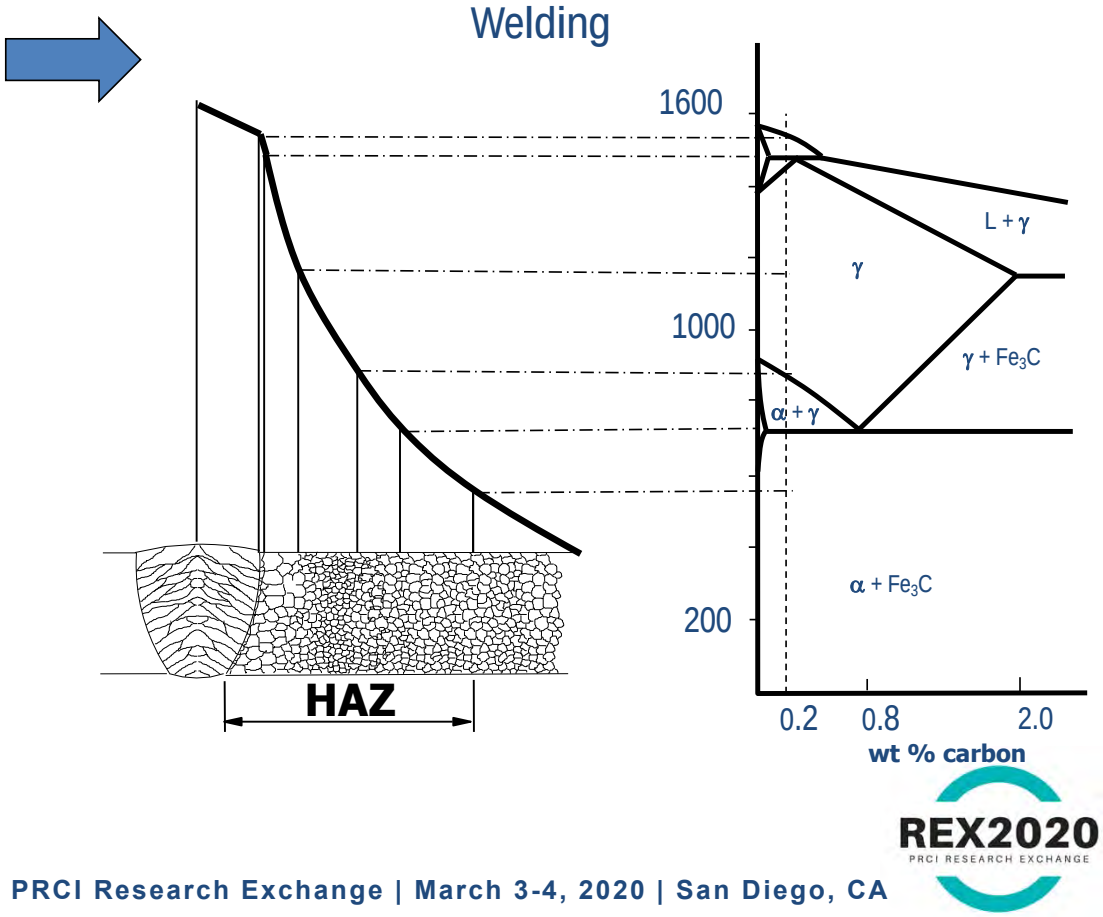
Strengthening mechanisms of pipe and the effect of welding



Welding

Strengthening mechanisms of pipe and the effect of welding





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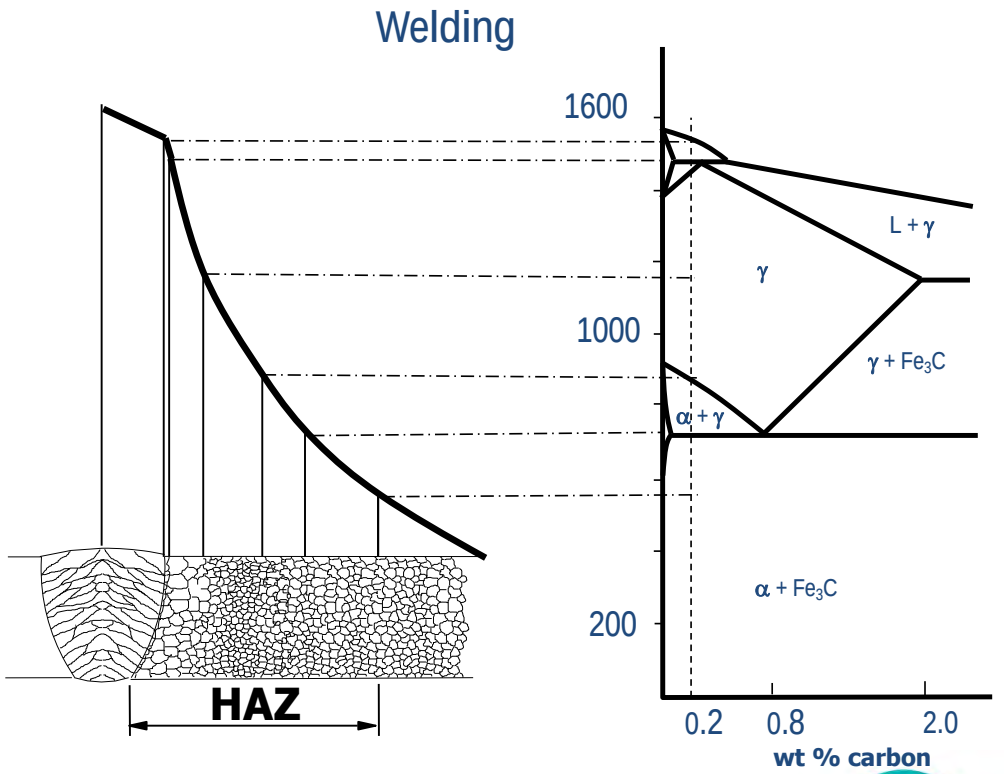

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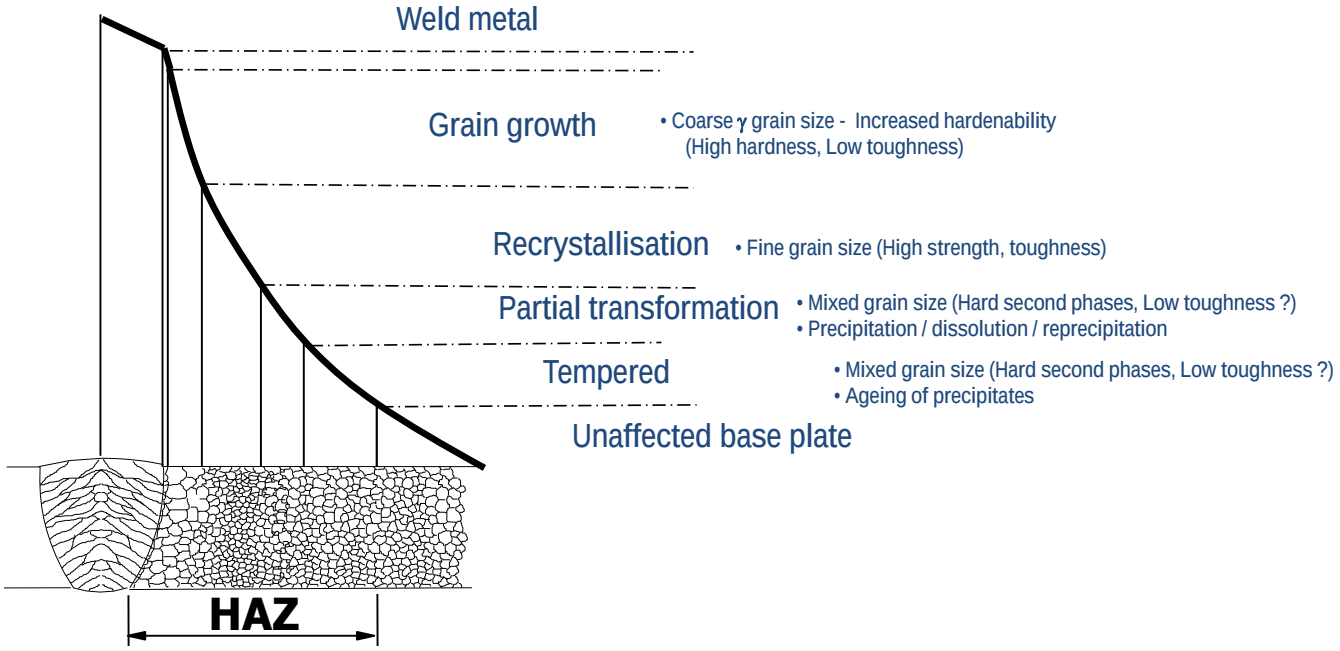
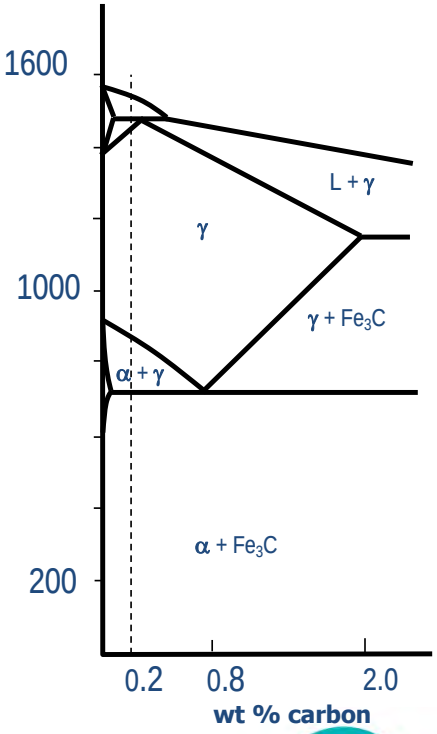
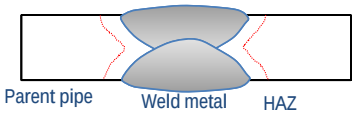


Welding

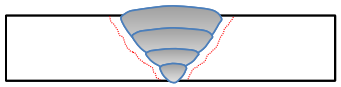


Causal Tree approach

Seam weld



Girth weld



Weld Joint Strength Matching

- Parent Pipe Strength
  - Pipe Composition
  - TMCP
- Weld Metal Strength
  - Consumable comp
  - Parent pipe dilution
  - Welding conditions
- Heat Affected Zone
  - Welding conditions
  - Pipe composition
  - Pipe wall thickness

Contributors of Failures

Weld Strength Matching is defined by the difference in:

Pipe Strength
&
Weld metal strength

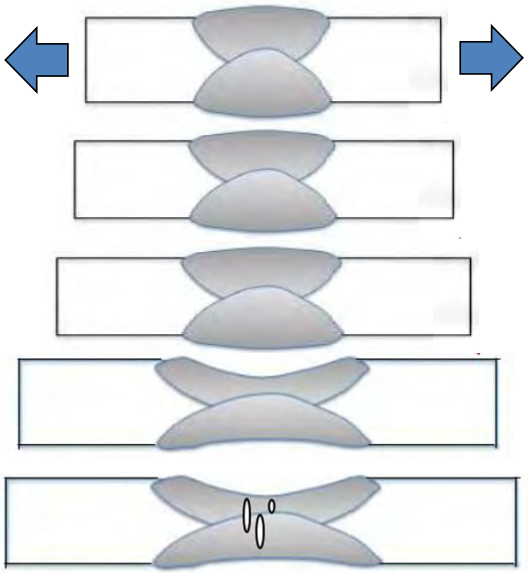
HAZ Softening is defined by the difference in:

Pipe Strength
&
HAZ strength

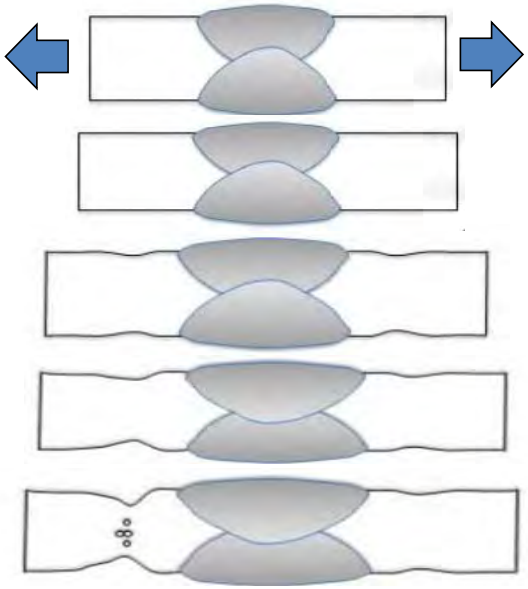
Introduction

- The potential mechanisms of failures include **weld strength** undermatching &/or **HAZ** softening.

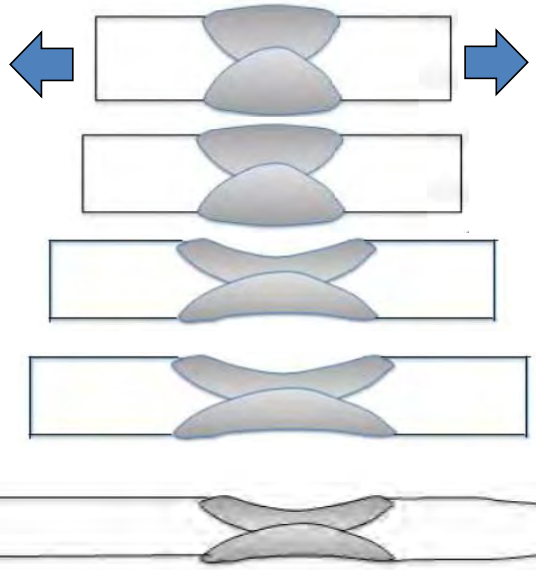
Weld Strength Undermatching



HAZ softening



Ideal situation



Introduction

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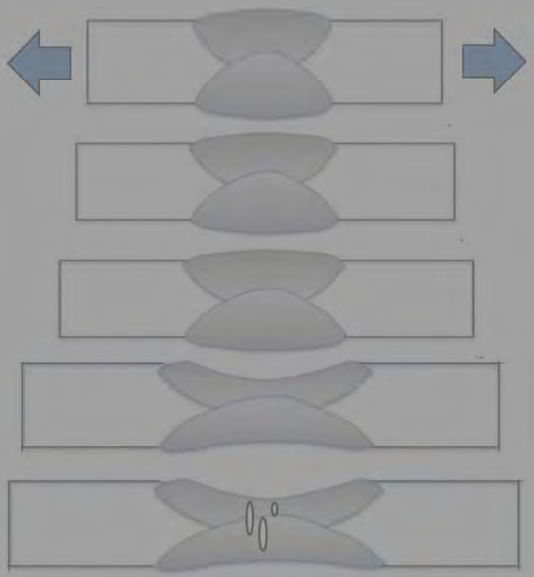
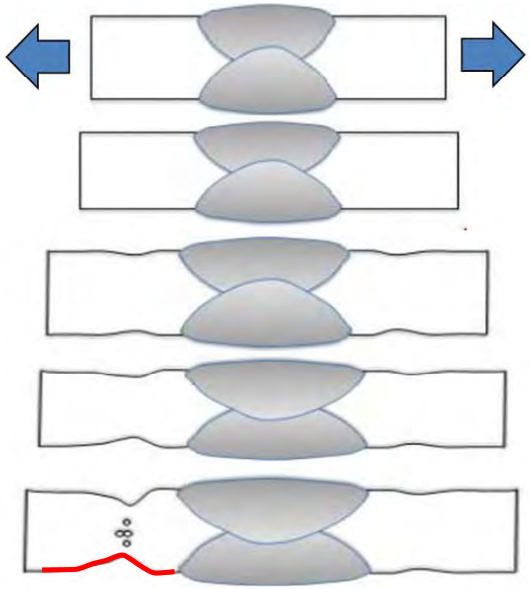
Weld Strength Undermatching



HAZ softening



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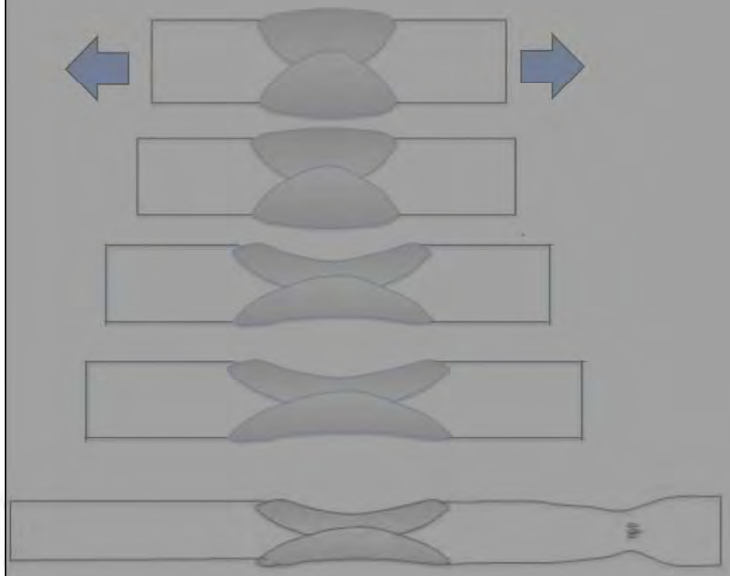

Introduction

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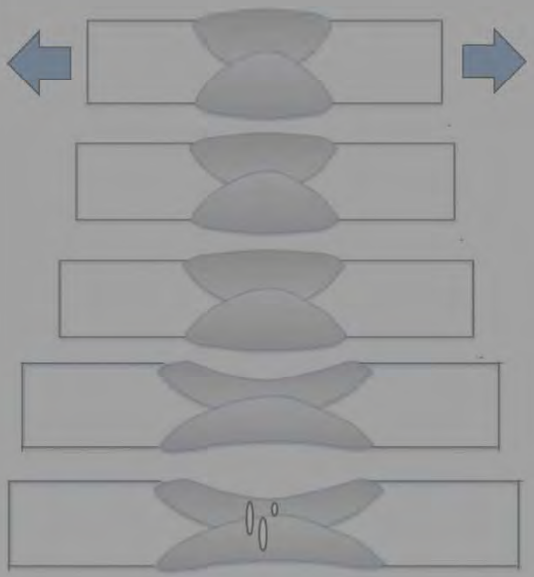
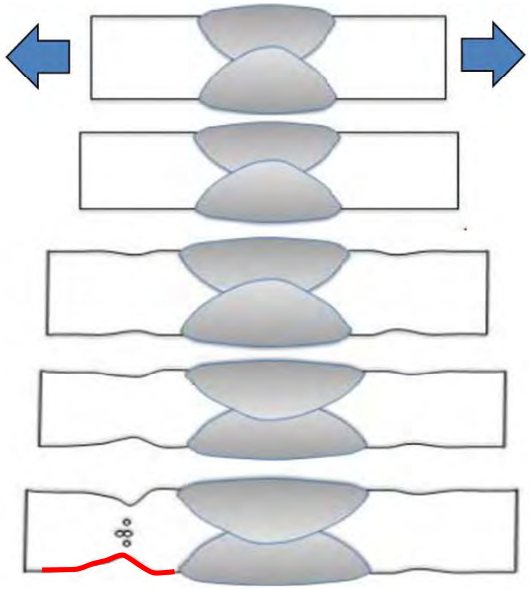
Weld Strength Undermatching



HAZ softening



Ideal situation





Ref: Wang, Y.-Y., 2019

Welding - Facts

- **Weld Strength matching is a critical component of weld quality,**
- **As the thickness & width of a weld are generally large in relation to plate thickness, Weld strength is far more important than HAZ Softening,**
- **HAZ Softening inevitably occurs, to some extent, following welding, but is typically narrow, relative to the plate thickness. Its influence is therefore complicated by strain hardening and triaxial strength,**
- **Influence of HAZ Softening is determined by:**
  - Welding conditions,
  - Depth & Width of softened zone,
- **All these parameters are exacerbated as wall thickness is decreased, (5mm is extremely thin for High pressure pipelines)**

Introduction

- Weld (HAZ) zone softening: what is it and why does it happen?
  - A region in the HAZ that experienced a decrease in strength (hardness).
  - It does happen due to the thermal process (welding).

But is softening a problem?

- Define when softening is a problem
- Pcm was developed to define the maximum HAZ hardness in order to limit the detrimental effects of Hydrogen cracking, there now exists a need to define a formula which predicts the minimum hardness based on steel alloy design following the welding thermal process.

University of Wollongong – HAZ Softening Project

Objective: Our research aim to predict the thermal effects of welding on HAZ softening.

- Our target is to develop a new formula to help the industry in the optimization of alloy design.
- The difference between the parent pipe strength (HV) and HAZ strength (HV) will define the limit of safety.

Experimental approach – Current range of steels

- Pipeline steels over a wide range of chemical composition was selected (wt.%)

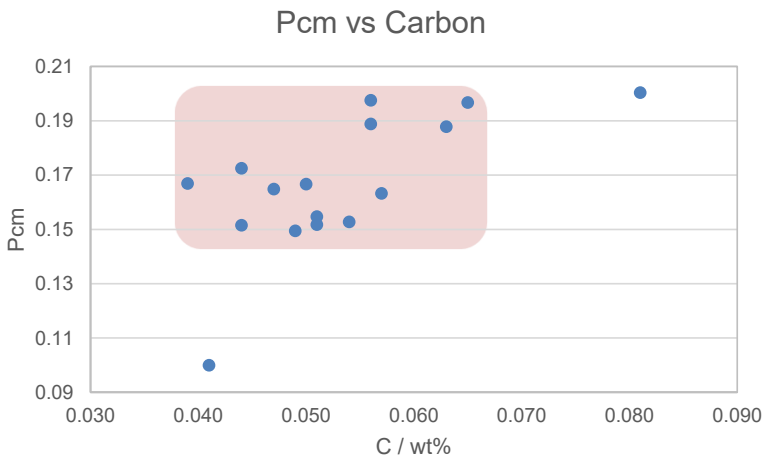
Pipe	C	Si	Mn	Nb	V	Mo	Cr	Cu	Ni	Ti	N	Pcm
X80 - 055	0.047	0.22	1.67	0.055	0.007	0.11	0.21	0.11	0.18	0.016	0.0037	0.16
X80 - 067	0.063	0.22	1.70	0.067	0.005	0.24	0.24	0.01	0.21	0.0092	0.0047	0.19
X80 - 071	0.050	0.20	1.62	0.071	0.006	0.17	0.24	0.01	0.26	0.013	0.0054	0.17
X80 - 079	0.044	0.18	1.69	0.079	0.005	0.21	0.23	0.18	0.18	0.014	0.0035	0.17
X80 - 085	0.056	0.20	1.82	0.085	0.038	0.17	0.32	0.06	0.06	0.012	-	0.19
X70	0.044	0.207	1.53	0.045	0.027	0.14	0.03	0.14	0.18	0.0064	0.0064	0.15
HTP X80	0.057	0.163	1.53	0.093	0.006	0.001	0.22	0.21	0.13	0.0093	0.0075	0.16
X65	0.041	0.135	0.37	0.077	0.003	0.006	0.42	0.26	0.13	0.0113	0.0074	0.10
S2W	0.065	0.301	1.76	0.023	0.006	0.21	0.01	0.29	0.21	0.0101	0.0058	0.20
T1W	0.039	0.251	1.82	0.055	0.006	0.20	0.02	0.18	0.28	0.0118	0.0063	0.17
S2E	0.081	0.175	1.74	0.029	0.037	0.15	0.02	0.18	0.16	0.0151	0.0038	0.20
R4	0.056	0.222	1.87	0.049	0.008	0.24	0.08	0.26	0.39	0.0147	0.0062	0.20
steel 1*	0.054	0.113	1.90	0.000	0.000	0.0	0.0	0.00	0.00	0.011	-	0.15
steel 2*	0.049	0.119	1.93	0.010	0.000	0.0	0.0	0.00	0.00	0.011	-	0.15
steel 3*	0.051	0.114	1.94	0.043	0.000	0.0	0.0	0.00	0.00	0.011	-	0.15
steel 4*	0.051	0.096	2.01	0.101	0.000	0.0	0.0	0.00	0.00	0.013	-	0.15

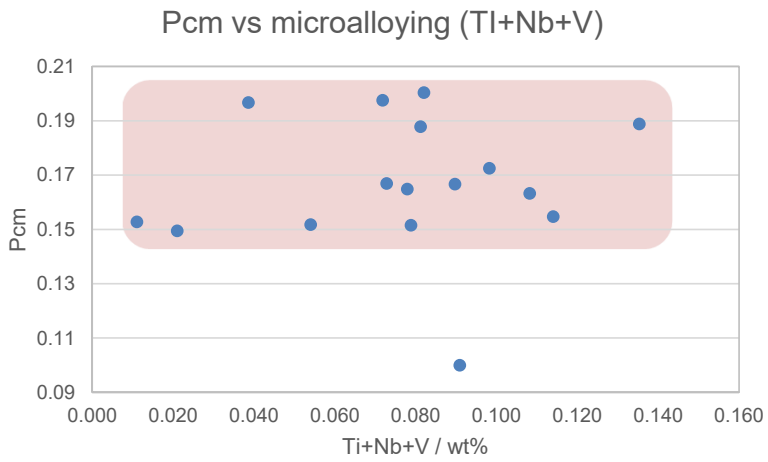
* Laboratory melts

$$\text{Pcm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

Experimental approach – Current range of steels

- Pipeline steels over a wide range of chemical composition was selected





- 16 steels

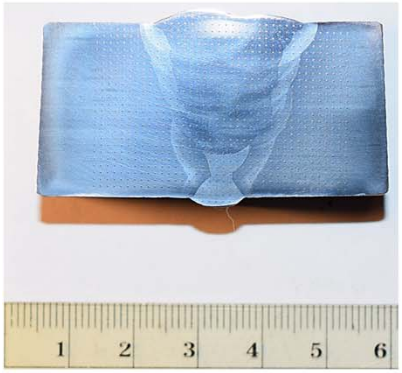
Range:

Pcm	= 0.10 - 0.20
C	= 0.039 - 0.08 wt%
Ti+Nb+V	= 0.011 - 0.135 wt%

EXAMPLES of Experimental Techniques

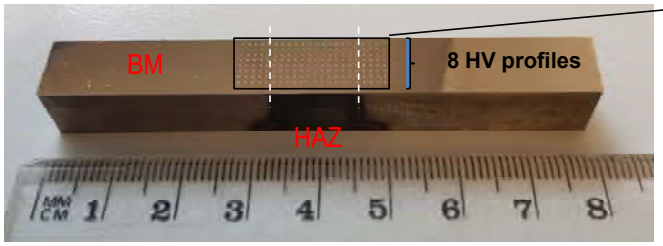
- Pipeline steels over a wide range of chemical composition was selected

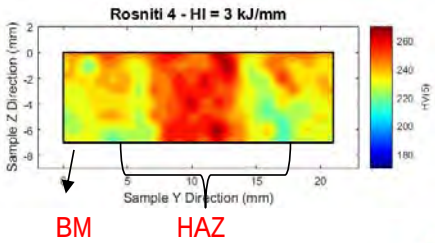
- Hardness mapping
  1. Real weld (girth weld)





  2. Heat-affected zone simulated samples (Gleeble)
     -1350°C for 5s
     -HI = 2.5, 3, 4 and 5 kJ/mm

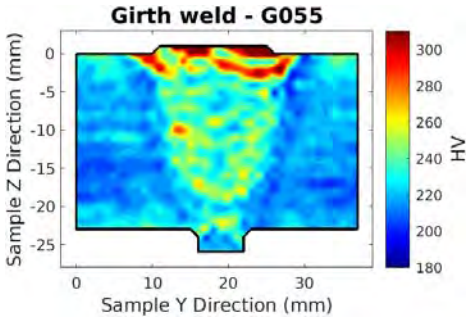


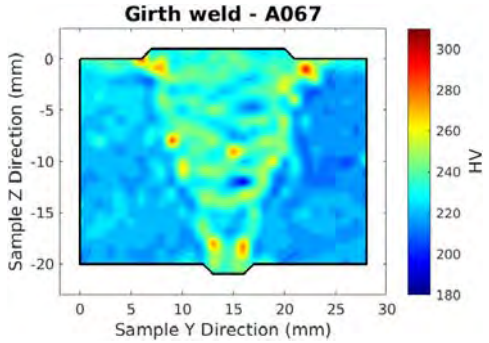


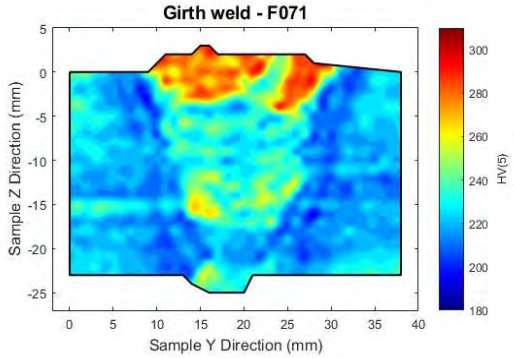
EXAMPLES - Results

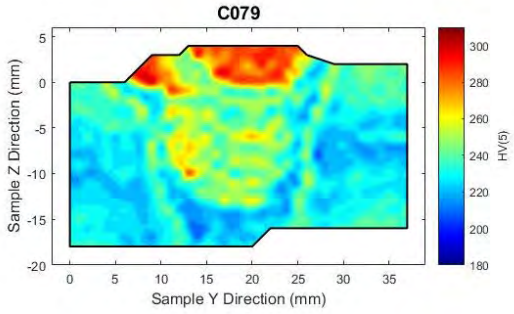
Hardness mapping

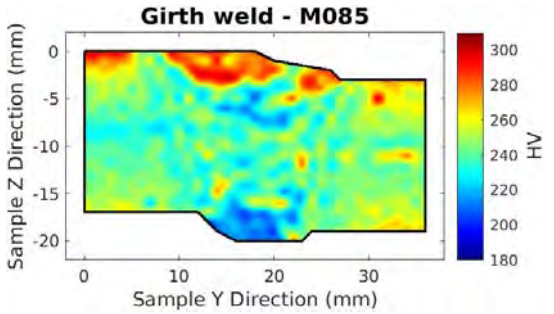
1. Real weld (girth weld)











EXAMPLES - Results

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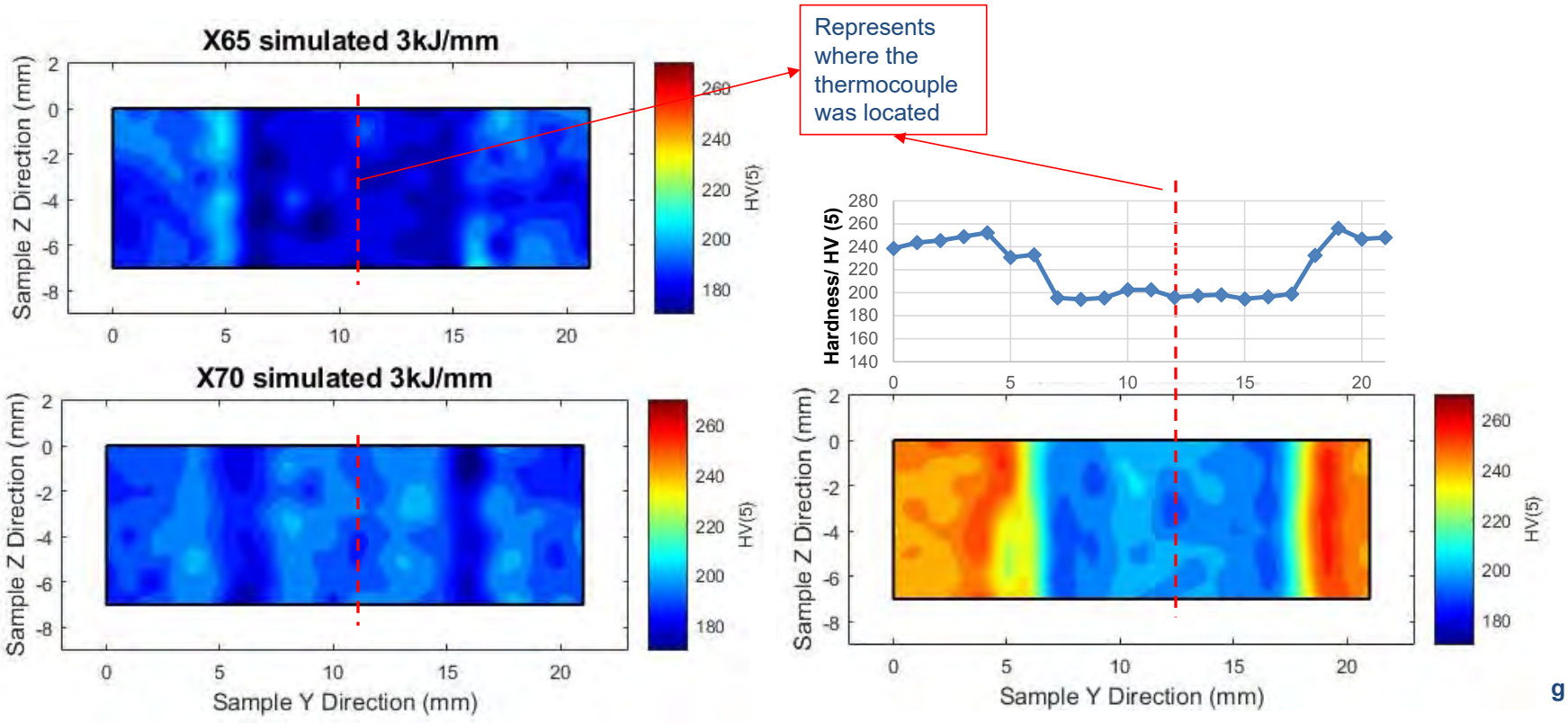

EXAMPLES - Results

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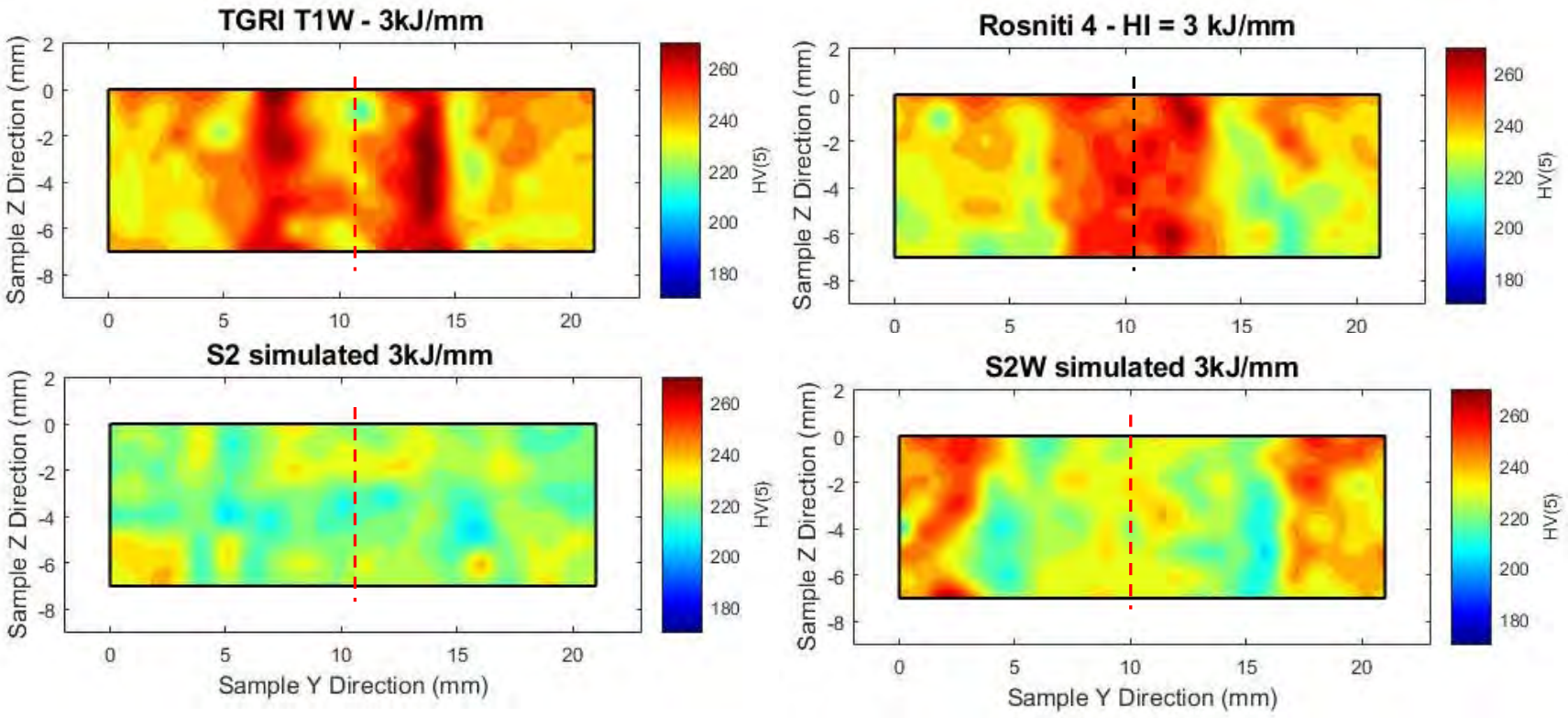

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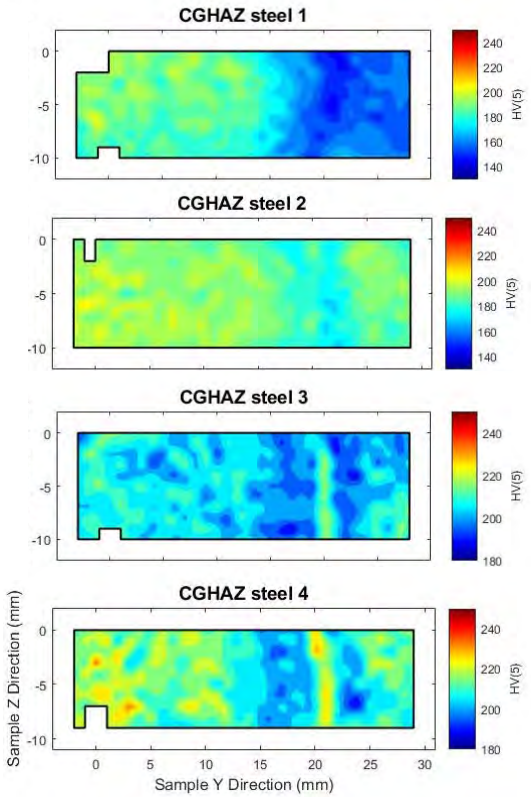
EXAMPLE - Results

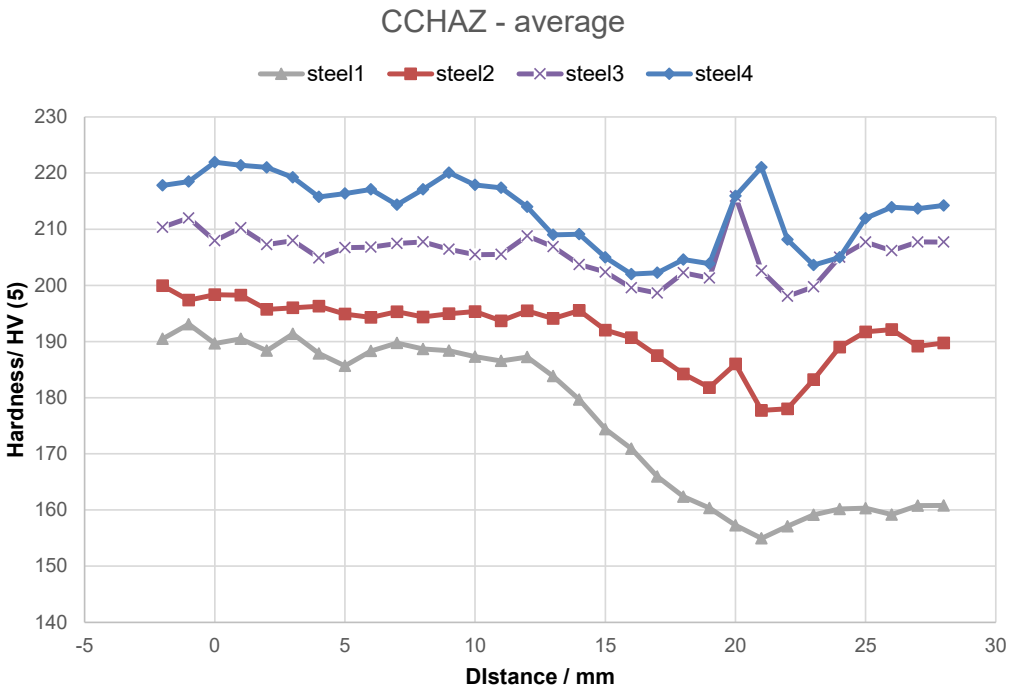
Nil Nb

0.01 Nb

0.04 Nb

0.10 Nb





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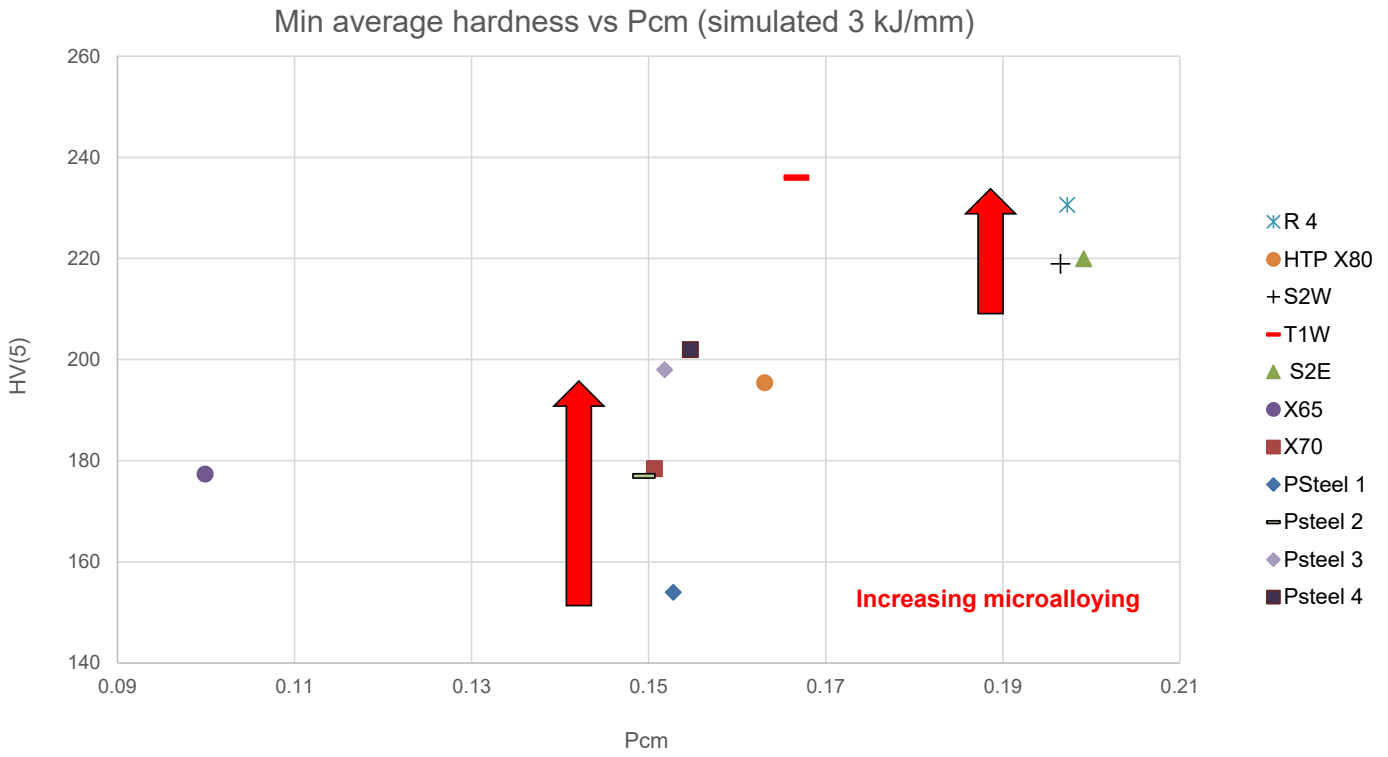
Results – Thus far

Simulated CGHAZ



Results – Thus far

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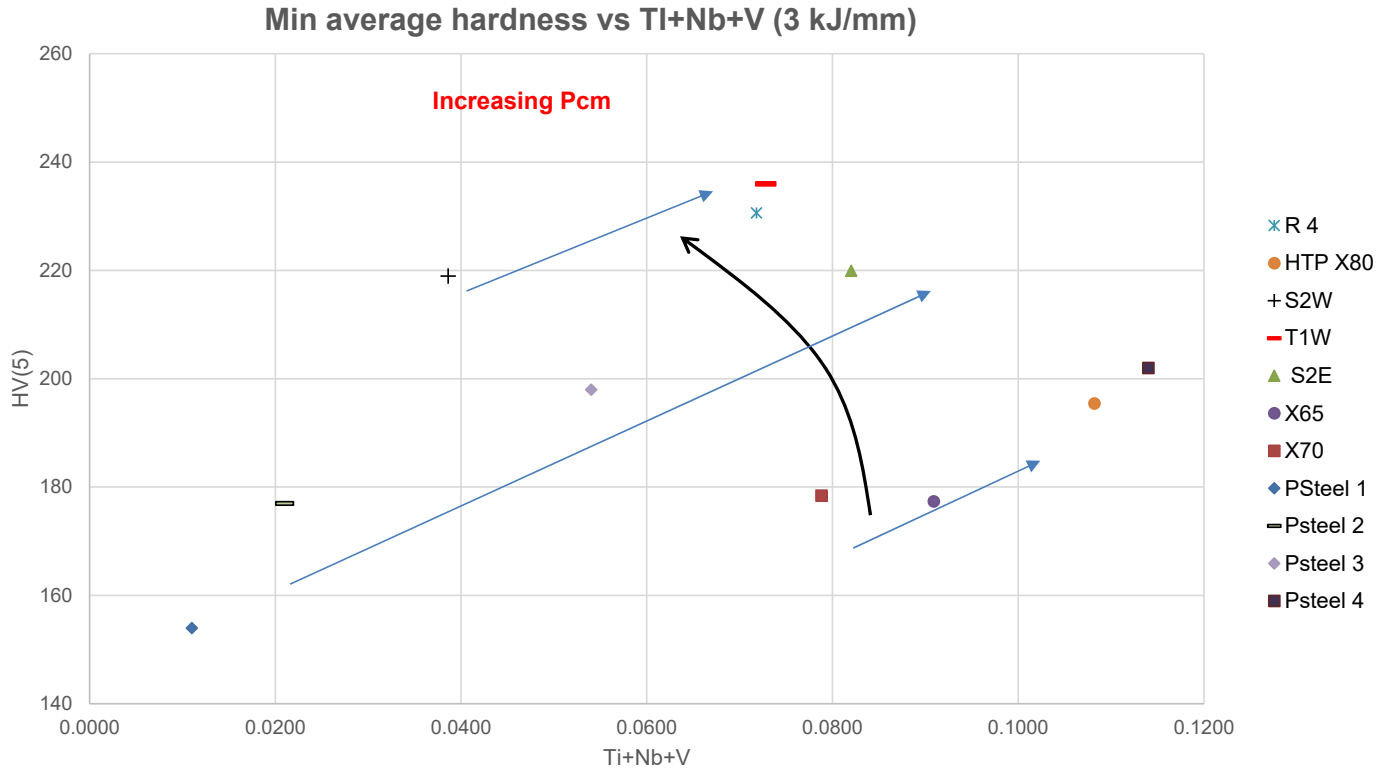


Highlights / Conclusions – Thus far

1. Microalloying addition (Nb+Ti+V) guaranteed a better minimum hardness in the HAZ

2. For a constant Pcm, the minimum HAZ hardness increased with microalloying content

Recommendation:

It is critical that steels of a certain strength level contains sufficient alloying that provide strength in the HAZ

Next steps

1. Cross weld tensile tests to evaluate softening effect
2. Regression Analysis of results
3. Modelling of critical input parameters on weld strain capacity
4. Softening Formula

Next steps

1. Cross weld tensile tests to evaluate softening effect
2. Regression Analysis of results
3. Modelling of critical input parameters on weld strain capacity
4. Softening Formula

Operators and owners knowing when and why weld HAZ softening in high strength microalloyed steels happen will have the knowledge to:

1. Identify the pipe they are working with and its tendency to have soften HAZ according to their carbon equivalent, microalloying content and heat input (HI) applied
2. Choose the best HI depending on the chemical composition of the pipe they are working with.
3. The use of these softening criteria will reduce the cost and incidents and ultimately increase the reliability of pipeline modifications and repairs

Thank you

BACK TO AGENDA

PRCI 2020 Research Exchange

Mechanical Damage Management

The work of PRCI & Others to Develop API RP 1183*

**US DOT PHMSA, CEPA, INGAA, API, Operating Companies*

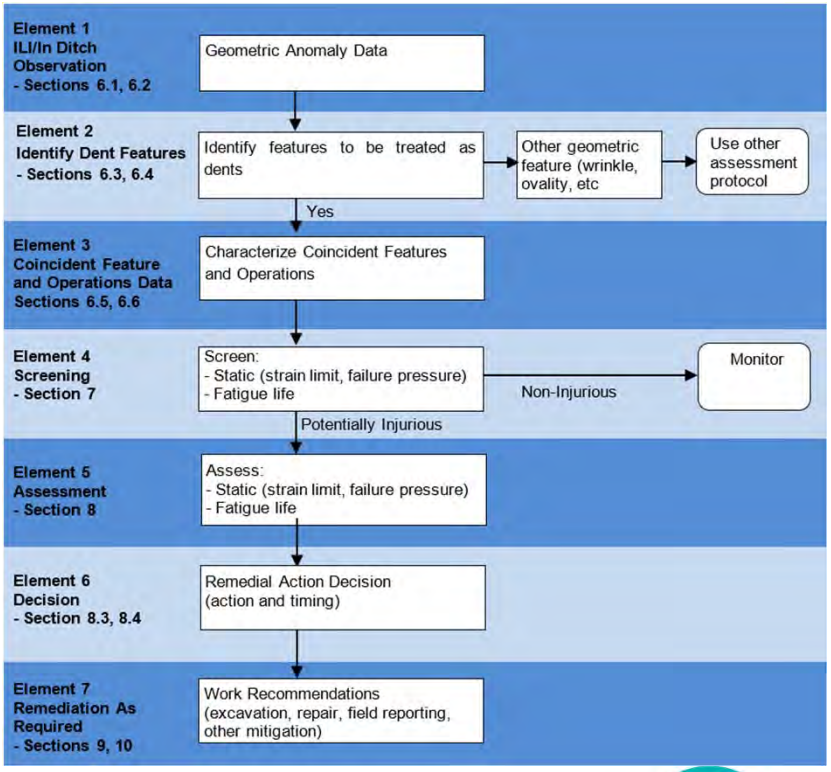
Aaron Dinovitzer
Sanjay Tiku, Vlad Semiga, Arnav Rana

BMT

LEADING PIPELINE RESEARCH

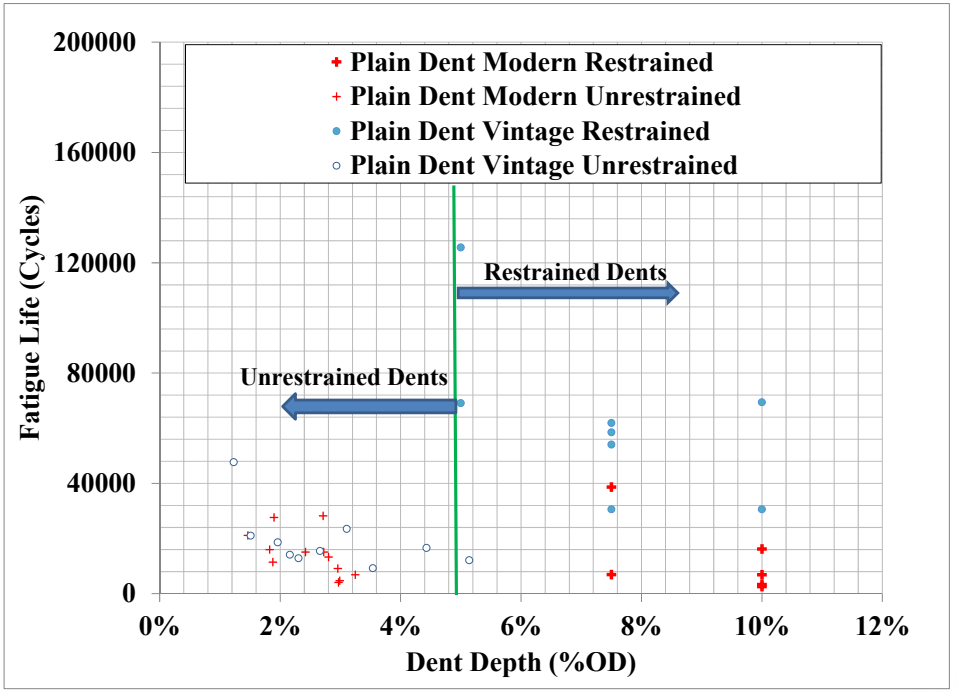
Presentation Outline

- **Background and Motivation**
- **Introduction to API RP 1183 (Capturing research)**
  - Scope of the recommended practice
  - Feature characterization
  - Identification of Dents
  - Coincident / Interacting Feature and Operation Data
  - Screening Tools
  - Assessment
  - Decision Support
  - Remediation
- **Ongoing Work /Next Steps**
  . . . What still remains to be learned



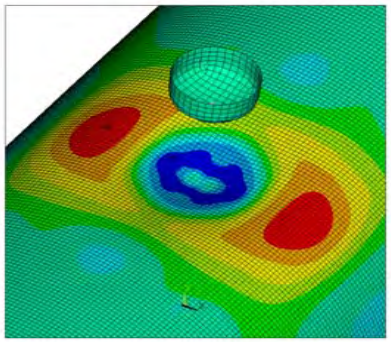
Background and Motivation

- **More than ten years ago, we noted that while depth is interesting, it does not adequately define a dent**
  - Dent shape is important
  - Some remediation of dents coincident with welds and corrosion unnecessary
  - Effect of operational loading not well considered
  - Initial focus should be on dent fatigue
  - Need both assessment and screening tools for dents with coincident features



Background and Motivation

- **Understanding of Dent Fatigue Developed Considering**
  - Physical trials
    - Full scale dent fatigue testing
    - Field observations and metallurgical investigations
  - Development of tools to assess life
    - Validate based upon physical trial data
    - Consider a range of behaviors
  - Gradual development supported by
    - PRCI
    - US DOT PHMSA
    - Individual operating companies
    - INGAA
    - CEPA
    - API



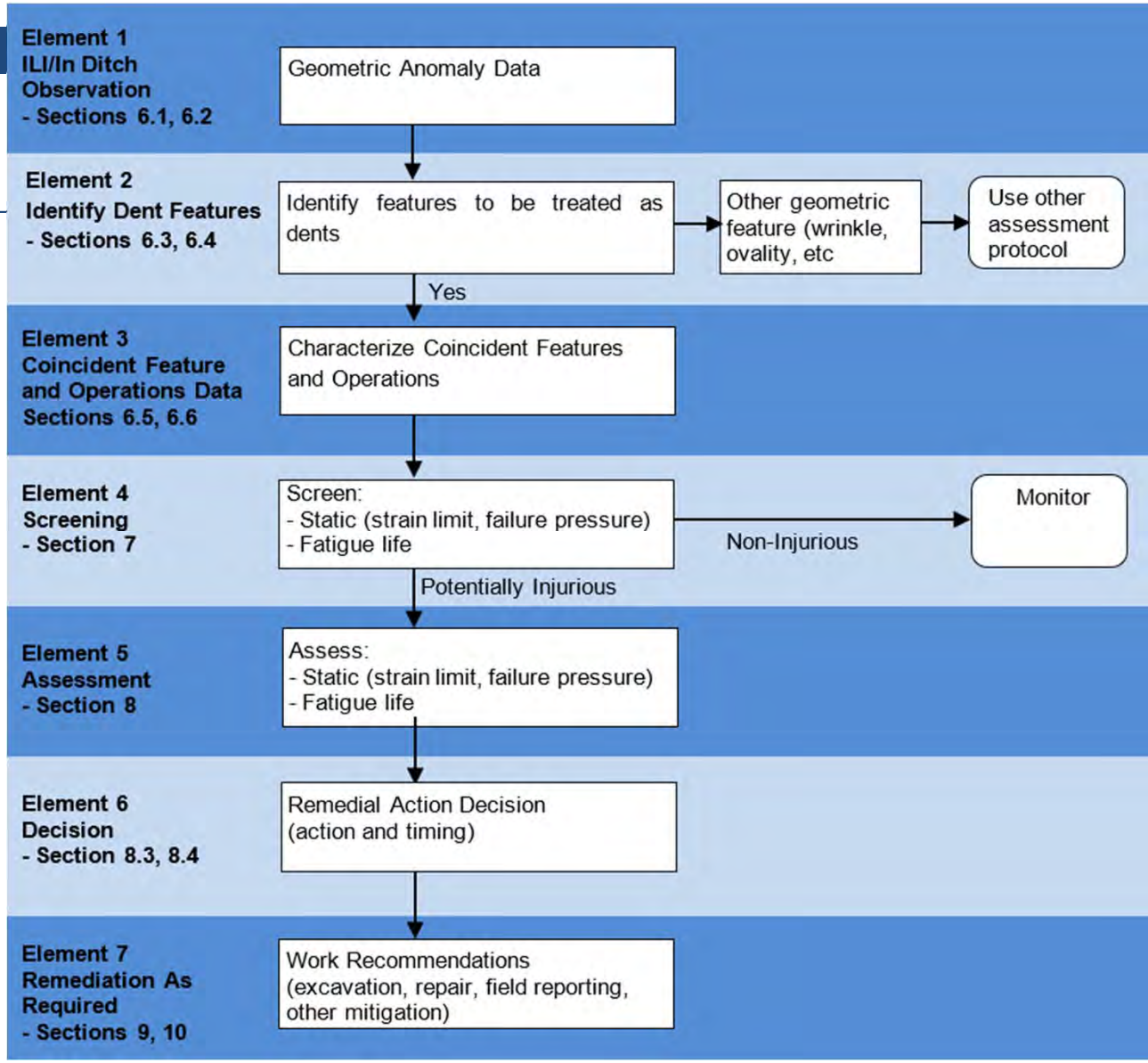


Background and Motivation

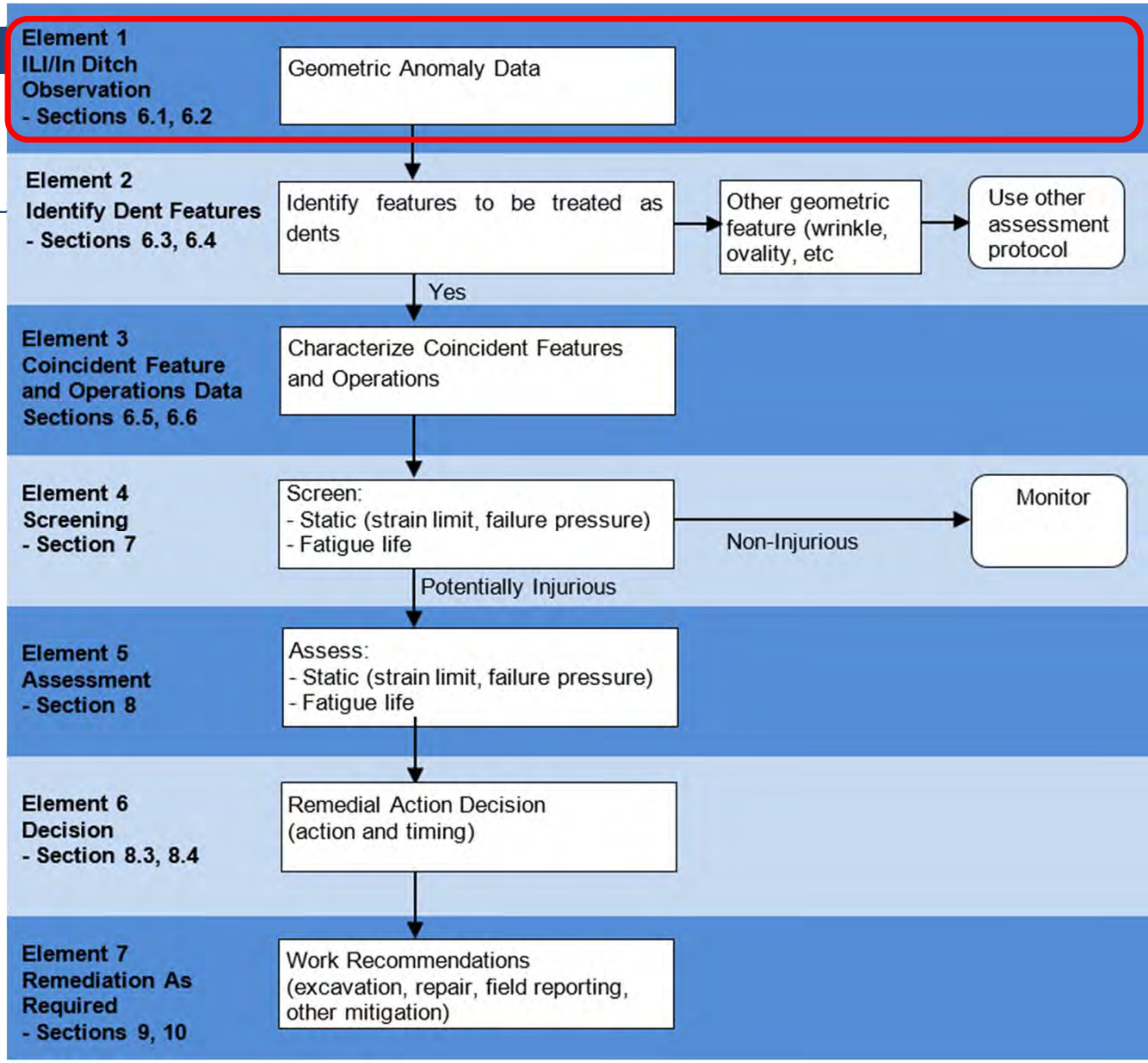
- **What we know about dents is being used in several efforts**
  - Development of PRCI MD-4-13 . . . Alternate Criteria for Time Response to Specific Mechanical Damage Defects.
    - Will provide guidance, tools and background for dent assessment and management and will identify gaps in the assessment of dents features
  - Development of API RP 1183 . . . Dent Assessment and Management
    - *Will provide guidance and tools with the goal of being adopted by DOT in regulations by reference.*
      - DOT has a mandate from NTSB to develop new rules for dent assessment and is participating in this development effort
  - Related PRCI MD-1-13, MD-3 and NDE-4-18 inspection projects
  - EPRG work related to mechanical damage limit pressure

Scope of API RP 1183

- **Assessment and Management of Pipeline Dents**
  - Considers dents through life
    - Identification & Assessment
      - Potential indentation cracking
      - Fatigue damage
      - Failure pressure
    - Decision making & Remediation
  - Does not consider
    - Design to preclude dents
    - In-service dent avoidance
    - Other feature types . . . wrinkle
    - Onshore vs offshore pipelines
  - Not all dents are injurious

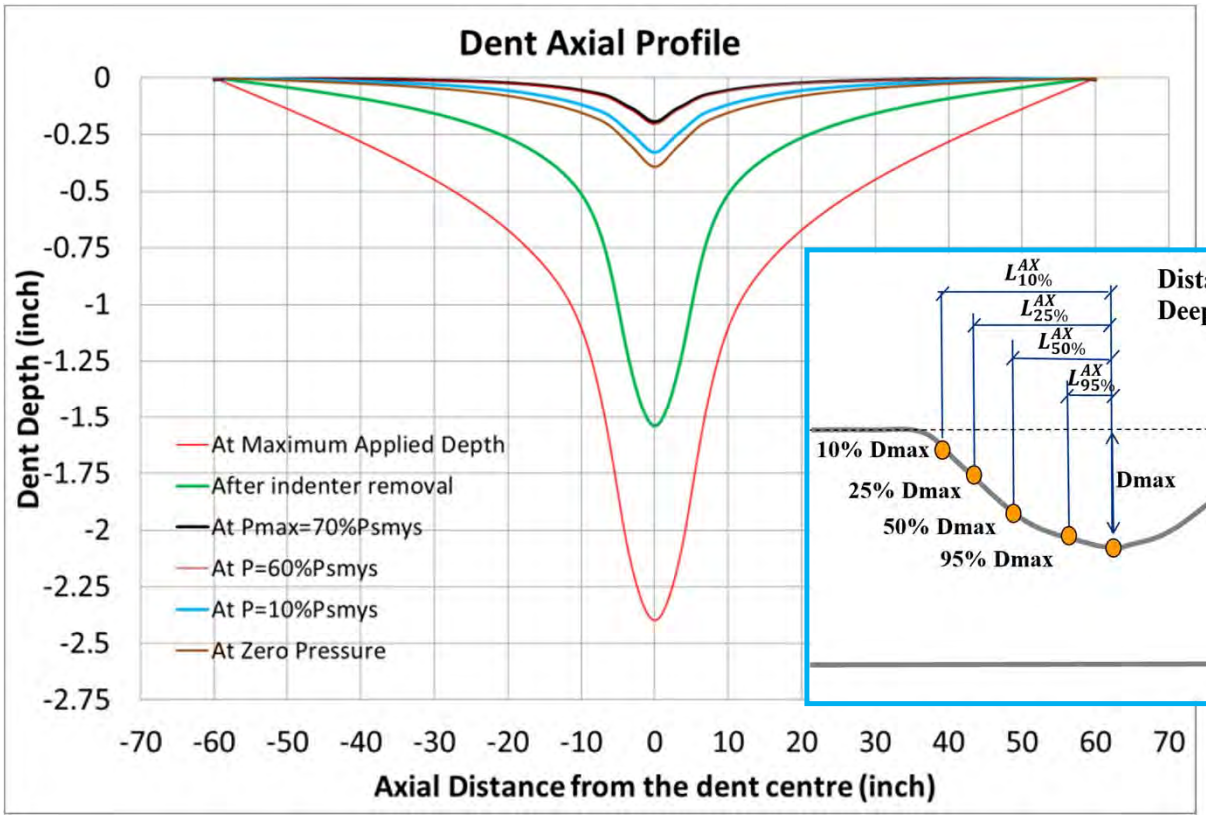


Dent Shape Characterization



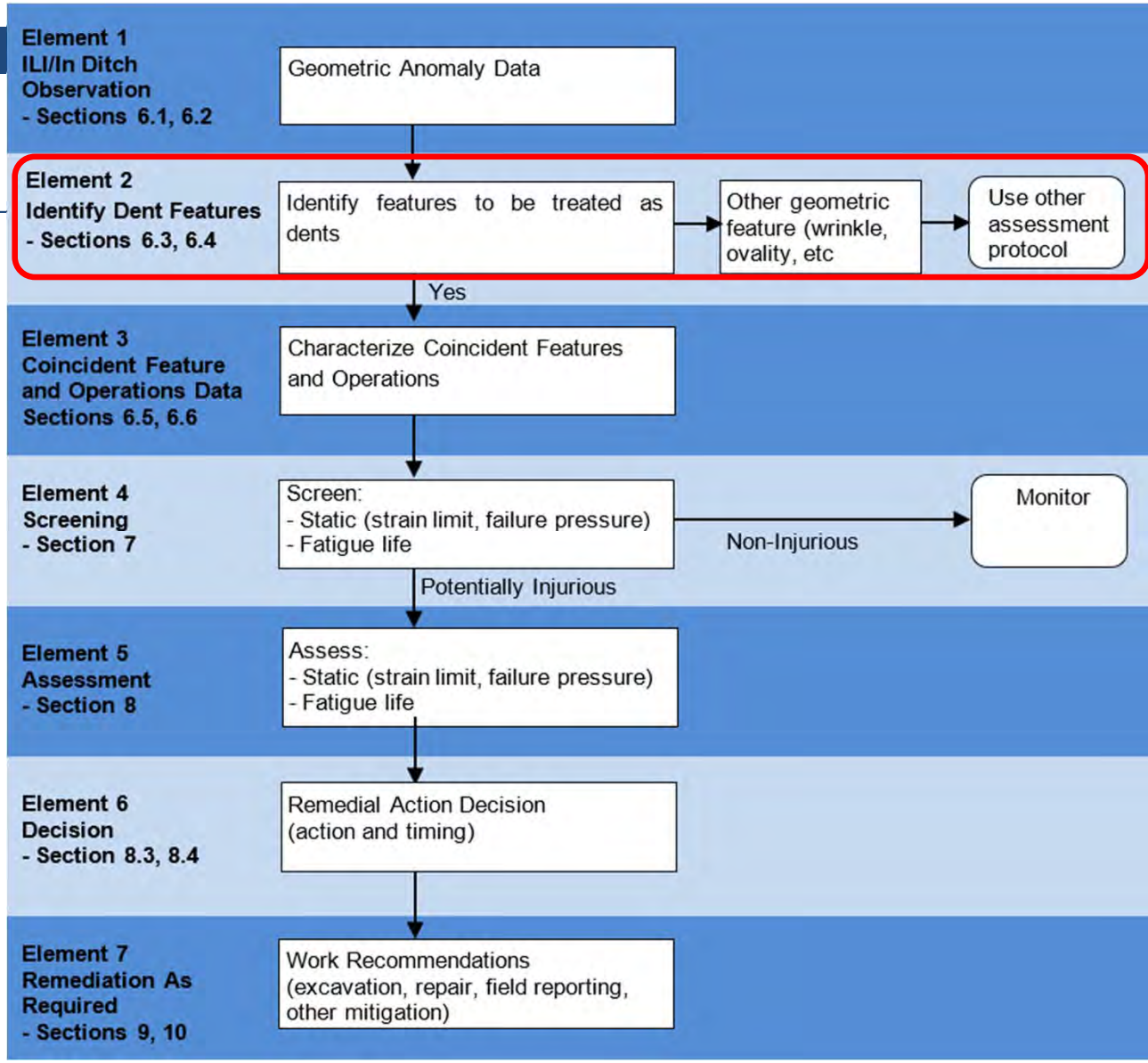
Dent Shape Characterization

- **Dent shape changes through life**
  - Formation
  - Rebound
    - Removal of indenter
  - Pressure induced
    - Permanent Rebound
    - Repetitive Rerounding
- **Shape changes in both axial and transverse directions**
  - Measured with ILI or in the ditch



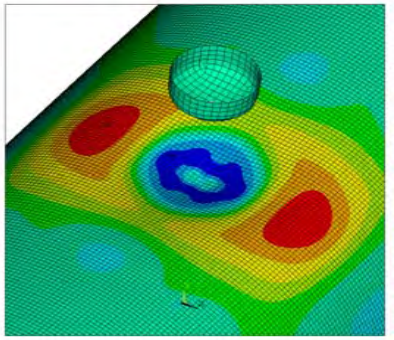
Identify Dent Features

- **Guidance on what may be considered a dent**
  - Based primarily on ILI data
  - Identify dents and their restraint condition
    - Restrained and unrestrained
- **Other feature types must apply assessment tools outside API RP 1183**



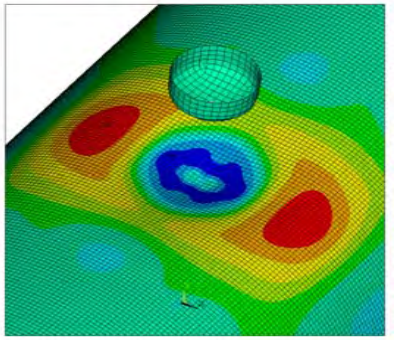
Identify Dent Features

- **Features that may be treated by API RP 1183 as dents consider**
  - Minimum feature depth
  - Feature sharpness
  - Is associated with out of roundness
  - Feature depth is greater than pipe ovality
  - Association with local magnetic signature indicating pipe wall plasticity
  - Geometric feature has multiple peaks



Identify Dent Features

- **Dent response will be different if the indenter remains in contact**
  - While dependent on dent shape, for simple single peak dents, the stress response to pressure fluctuation in
    - Restrained dents are maximum near the centre of the dent
    - Unrestrained dents are maximum at the periphery of the dent
  - While an unrestrained dent is likely to have a shorter fatigue life than a restrained dent, the response of the two features must be treated as different

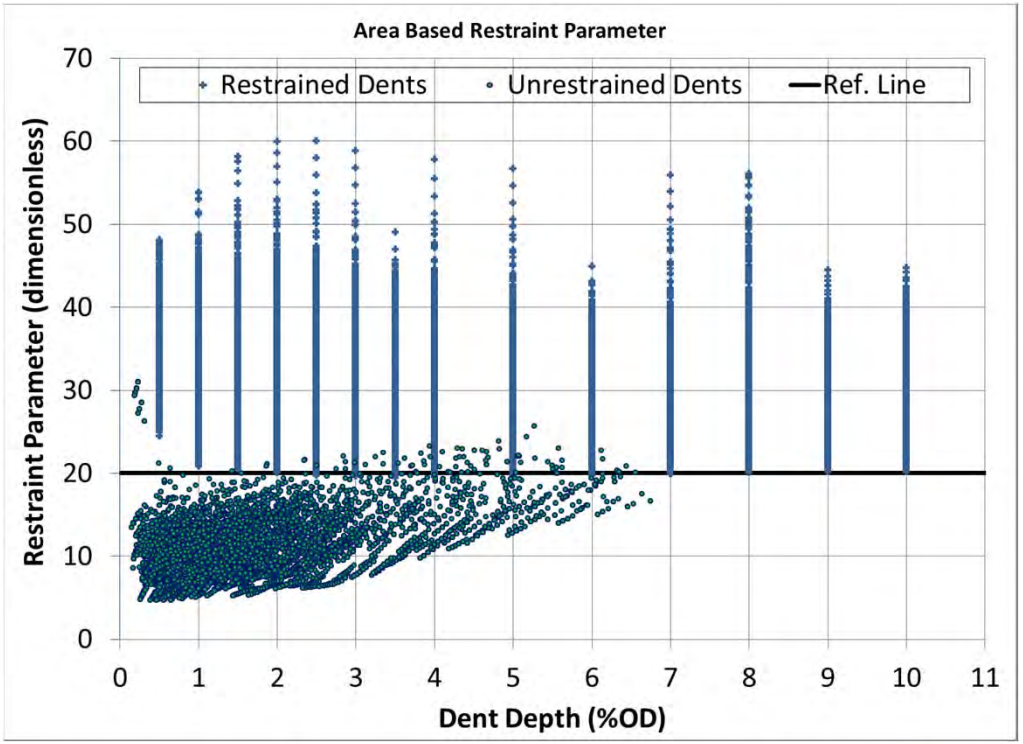


- **Restraint condition can be defined based on clock position**
  - Top side dents are unrestrained (above 4 to 8 O'clock)
  - Bottom side dents are restrained (below 4 to 8 O'clock)

Identify Dent Features

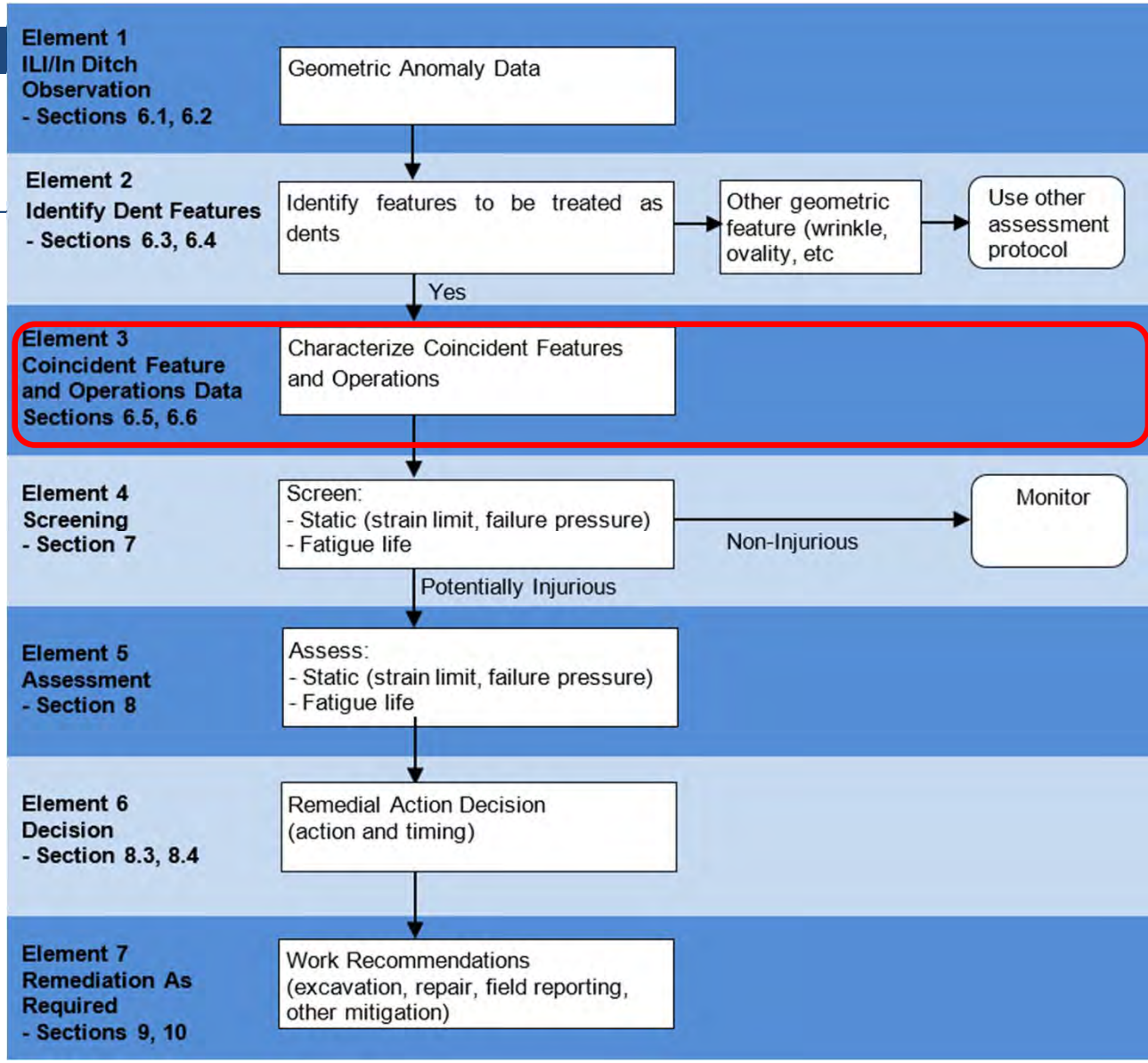
- **Restraint conditions can be defined based on dent shape**
  - Developed for d/t (24 - 128) & OD (4.5” - 42”)
  - Shallow and deep dents

$$RP = \max\left\{\begin{array}{l} \dfrac{18\left|A^{AX}_{15\%} - A^{TR}_{15\%}\right|^{1/2}}{L^{TR}_{70\%}}, \\ 8\left(\dfrac{L^{AX}_{15\%}}{L^{AX}_{30\%}}\right)^{1/4}\left(\dfrac{L^{AX}_{30\%} - L^{AX}_{50\%}}{L^{TR}_{80\%}}\right)^{1/2} \end{array}\right\}$$



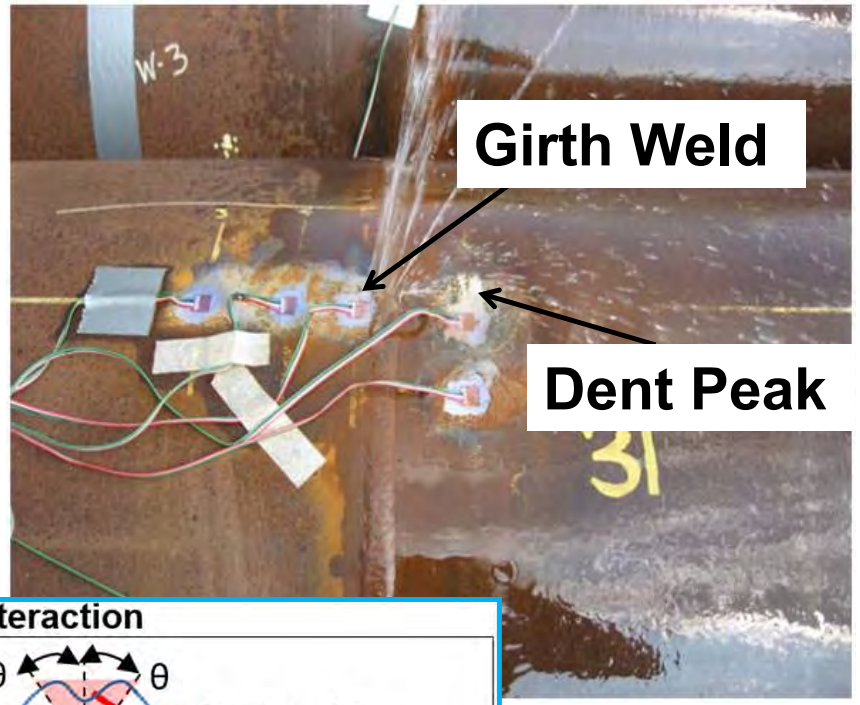
Characterize Coincident Features and Operations

- **Coincidence does not necessarily affect dent**
  - Section defines interaction and effects of interaction
    - Welds
    - Corrosion
    - Gouge
    - Crack
    - Dents
- **Consider operational (pressure) characterization**



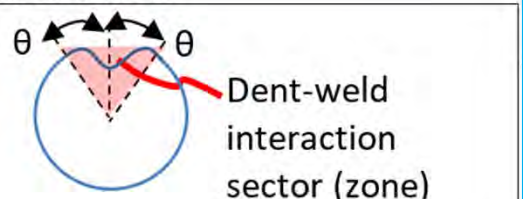
Coincident / Interacting Features

- **Welds coincident with dents are features that can be managed**
  - Welds located at dent maximum stress range location in full scale testing
    - Demonstrated fatigue life reduction is limited to a factor of 6.5 (assume 10 in assessment)
  - Numerical simulation demonstrated when does a weld reduce the fatigue life
  - Available for long seam and girth welds



Parameters for Dent Longitudinal Seam Weld Interaction

Restraint Condition	Long Seam Weld Interaction Sector Half Angle (θ) From the Dent Deepest Point	
	Degrees	Clock Positions
Restrained Dents	40	1.333
Unrestrained Dents	30	1

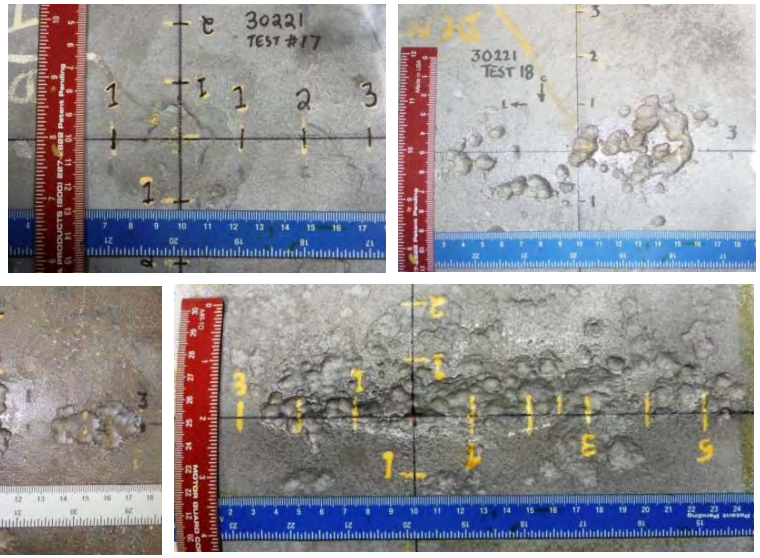


Coincident / Interacting Features

- **Corrosion coincident with dents are features that can be managed**
  - Corrosion located at dent maximum stress range location in full scale testing
    - Demonstrated fatigue life reduction dependent on restraint, corrosion surface and wall loss
  - Life reduction related to
    - Wall thinning (RF_{WT})
    - Surface roughening (RF_{sf})

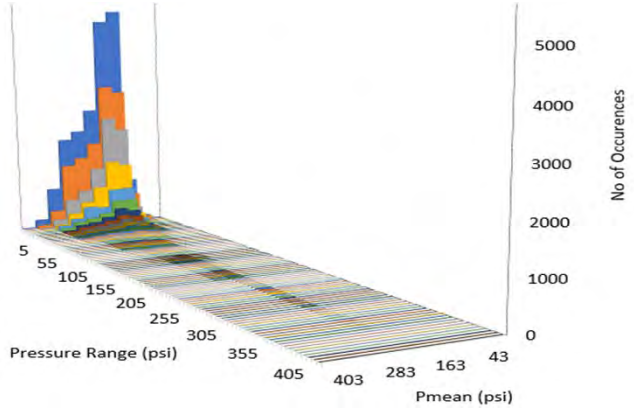
$$RF_{LTA} = RF_{WT} RF_{sf} = \left(K_{sf}\, t_{nom}/t_{LTA}\right)^3$$

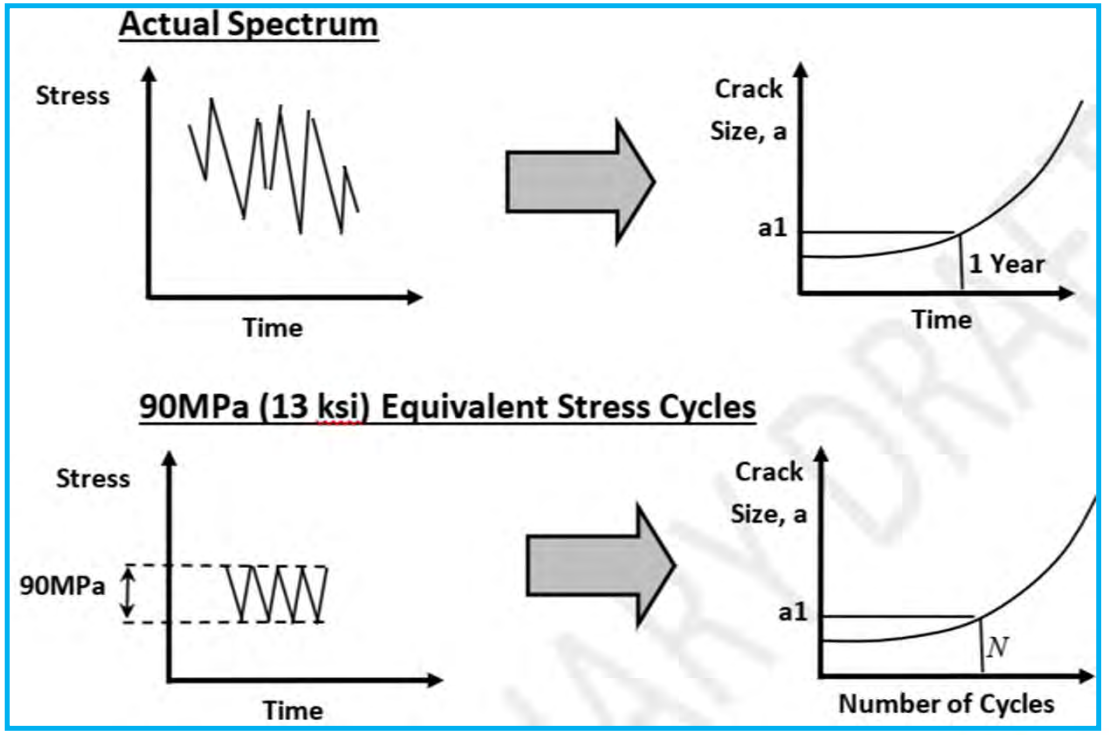
  - For OD corrosion up to 30% of pipe wall
    - Restrained dent . . . . . RF_{LTA} is 0 – 1.4X
    - Unrestrained dent . . . RF_{LTA} is 0 – 4X



Operational Characterization

- **Operational Pressure Characterization**
  - Max pressure
  - Max historic pressure
  - Pressure at ILI observation
  - Cyclic pressure characterization
    - Spectrum Severity Indicator (SSI)
    - Pressure mean and range characterization for assessment

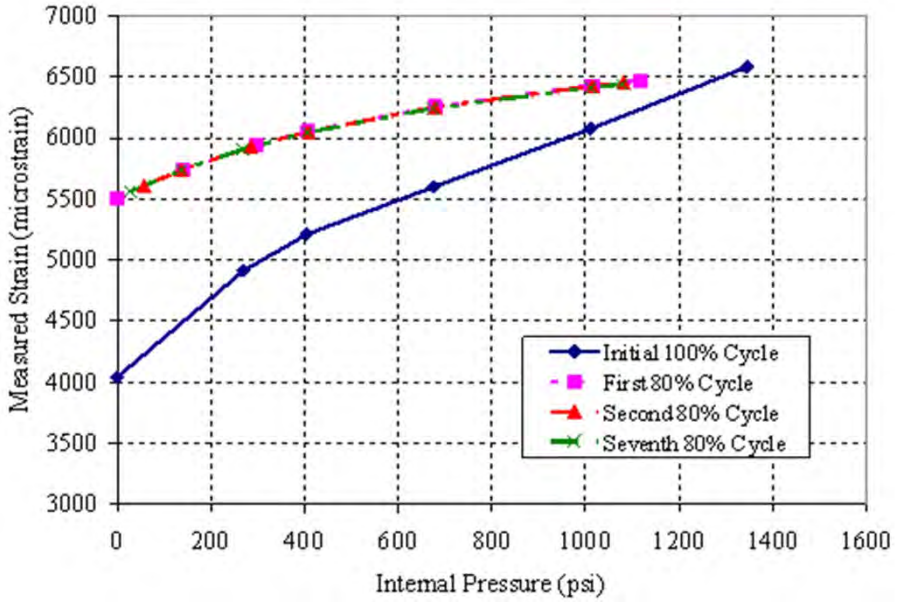




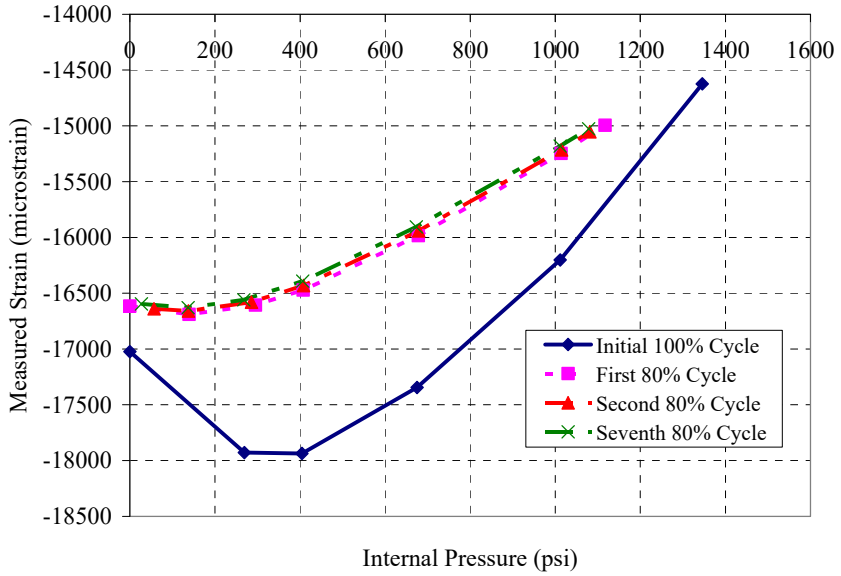
Operational Characterization

- **Nonlinear response between pressure & pipe strain requires pressure mean & range**

Axial Strains (6” from dent) versus Internal Pressure

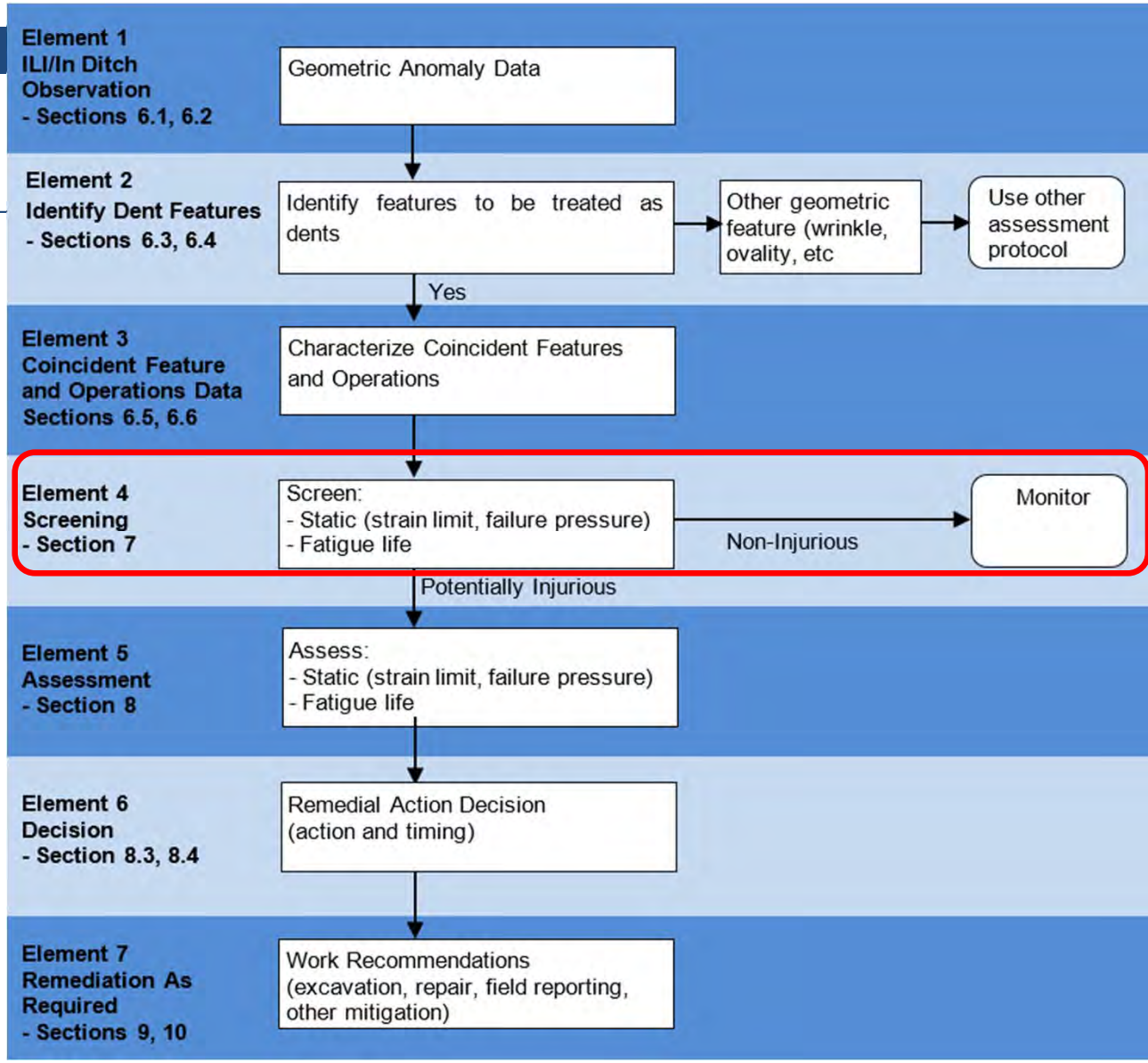


Axial Strains (4” from dent) versus Internal Pressure



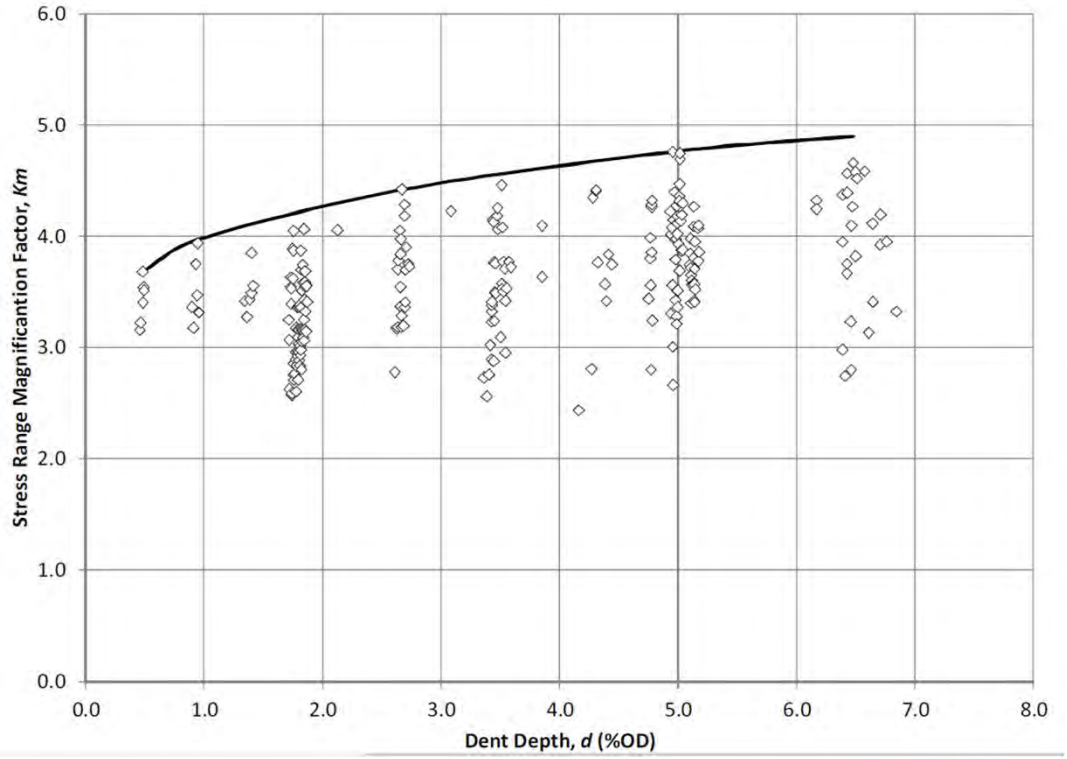
Dent Screening

- **Rapid conservative techniques to identify if a feature is benign**
  - Qualitative risk screening example
  - Dent Formation Strain
    - ASME B31.8 Appendix R 2018
    - Ductile Failure Damage Indicator (DFDI)
    - *ASME Section VIII, Division 2 - Strain Limit Damage (SLD)*
  - Failure Pressure
    - Plain dents
  - Fatigue Life - consider some/all of
    - Dent depth
    - Pipe D/t
    - Operational severity
    - Restraint condition



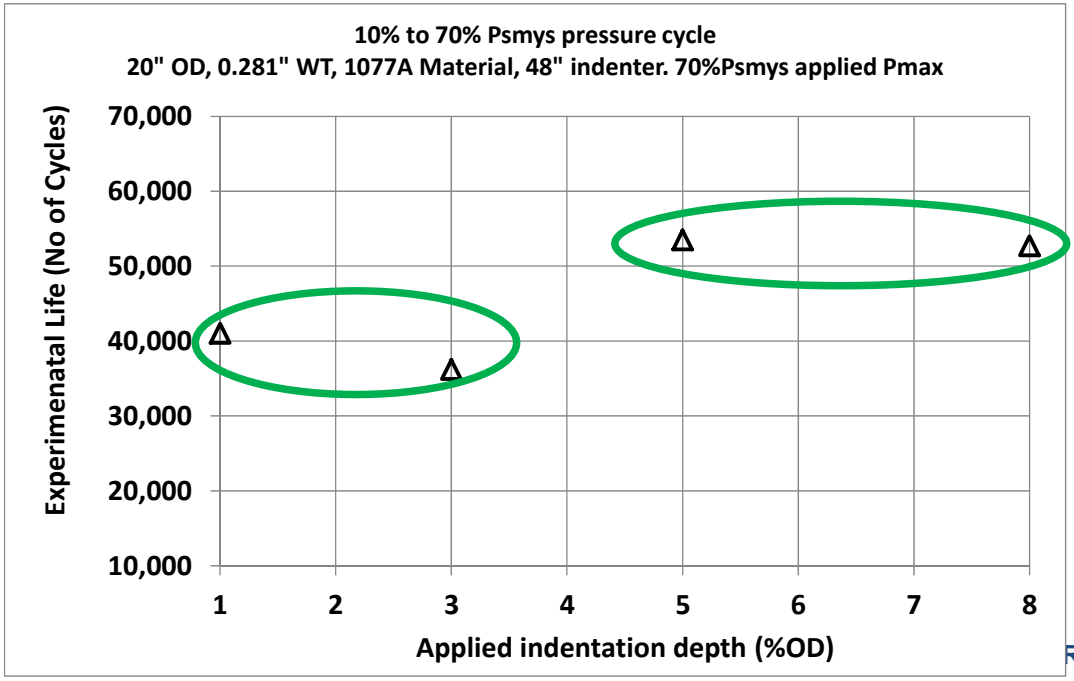
Dent Fatigue Life Screening Tools

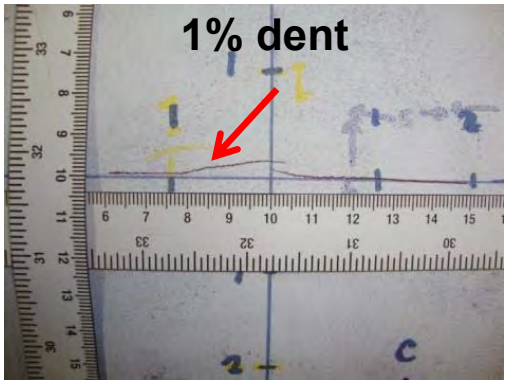
- **Operational Severity Screening (INGAA)**
- **Shallow Dent Fatigue Life Screening (CEPA)**
  - Consider just shape & restraint
  - Consider shape, operational severity and restraint condition
- **Shallow restrained dents are shown to behave differently than deep restrained dents**
  - Dents are defined as shallow under the following conditions:
    - Dent depth < 4% of pipe OD [for OD ≤ 12.75 in (324 mm)]
    - Dent depth < 2.5% of pipe OD [for OD > 12.75 in (324 mm)]

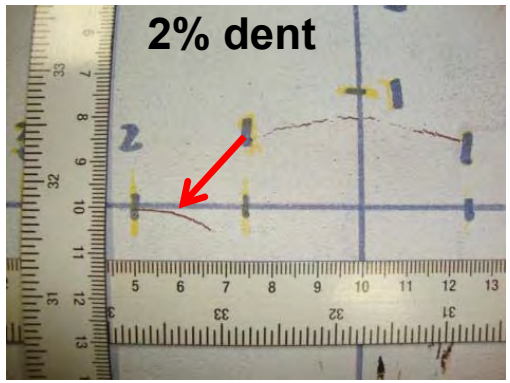


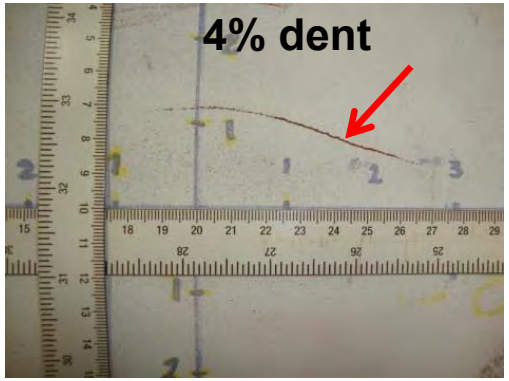
Dent Fatigue Life Screening Tools

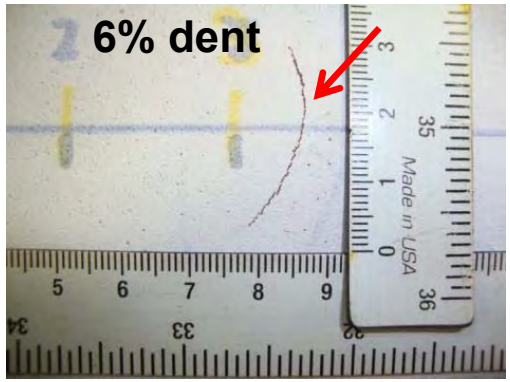
- **Shallow restrained dents behave differently than deep restrained dents**
  - Different crack orientation and shorter lives





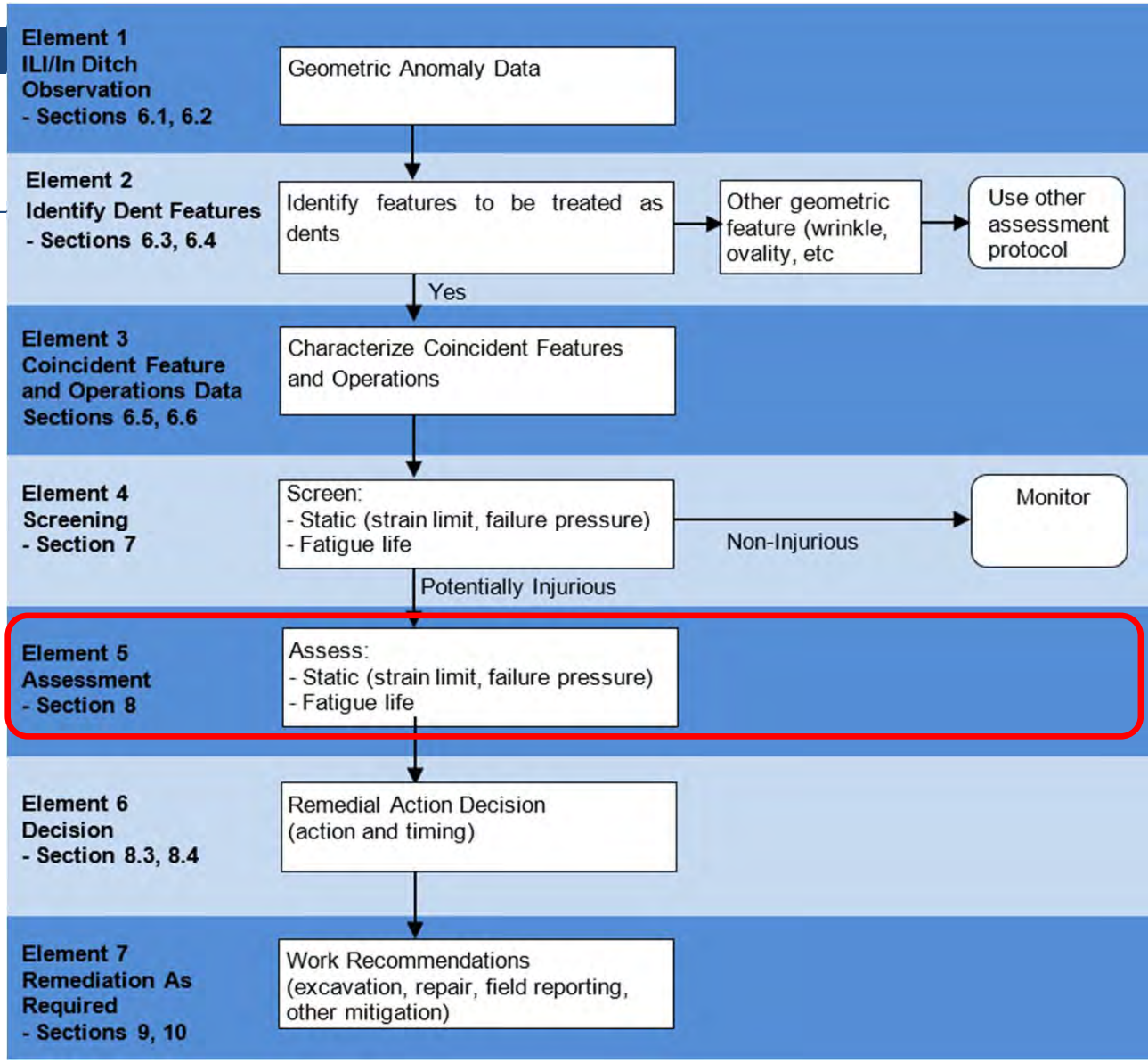






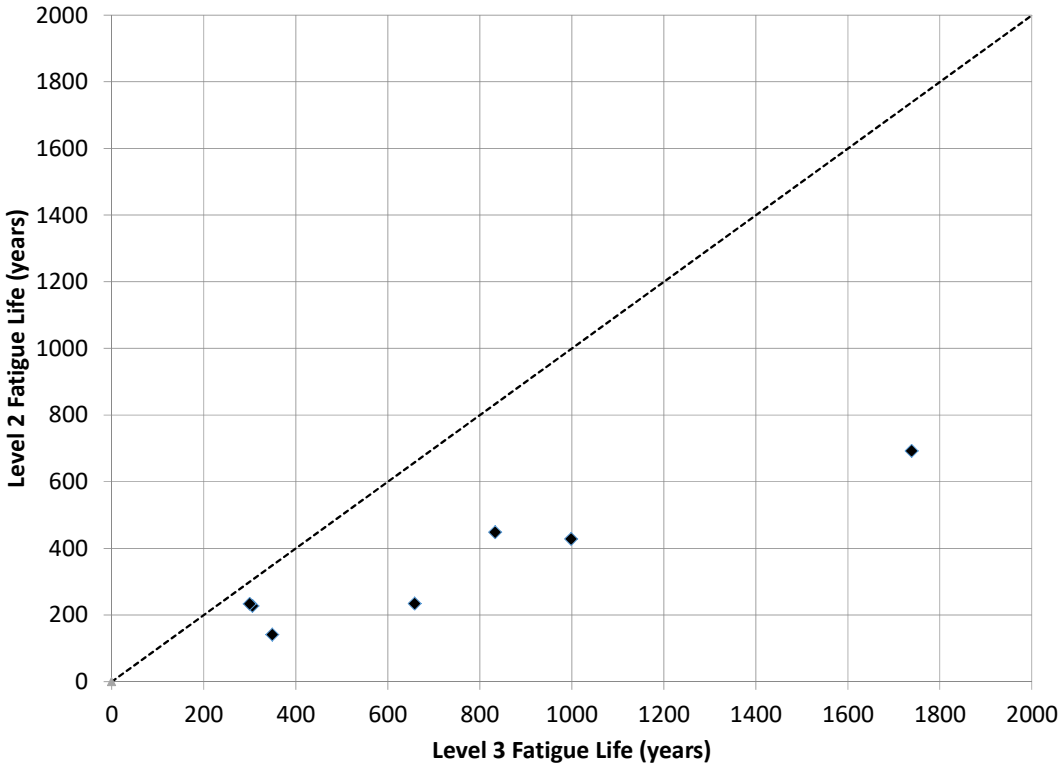
Dent Assessment

- **Assessment to identify if a feature requires remediation**
  - Dent Formation Strain
    - ASME B31.8 Appendix R 2018
    - Ductile Failure Damage Indicator (DFDI)
    - ASME Section VIII, Division 2 - Strain Limit Damage (SLD)
  - Failure Pressure
    - Failure assessment diagram
    - API 579 dent gouge
  - Fatigue Life
    - PRCI MD-4-9 Level 2
    - Level 3 detailed FEA



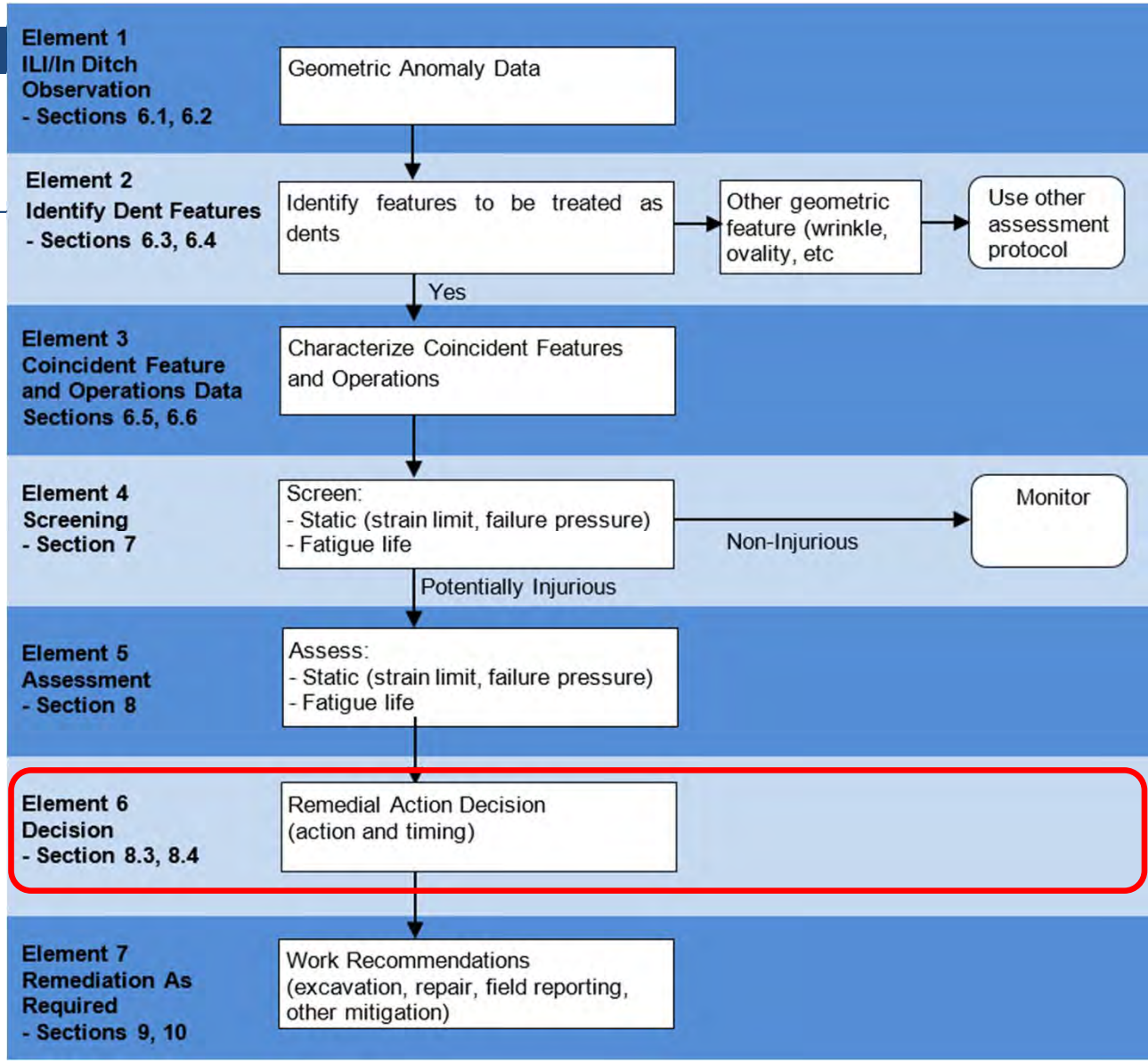
Dent Assessment

- **Dent Formation Strain**
  - Potential for a crack to form during indentation . . . Considered based on strain criteria
  - The potential presence of a crack may be considered a failure limit state
- **Dents surviving formation, fail at a max. pressure event or due to fatigue**
  - Failure pressure is evaluated using a failure assessment diagram approach
  - Single peak dent fatigue life may be evaluated using empirical equations (MD-4-9 Level 2)
    - Fatigue lives modified for interacting feature
  - Multi peak dents must consider detailed FEA (MD-4-9 Level 3)



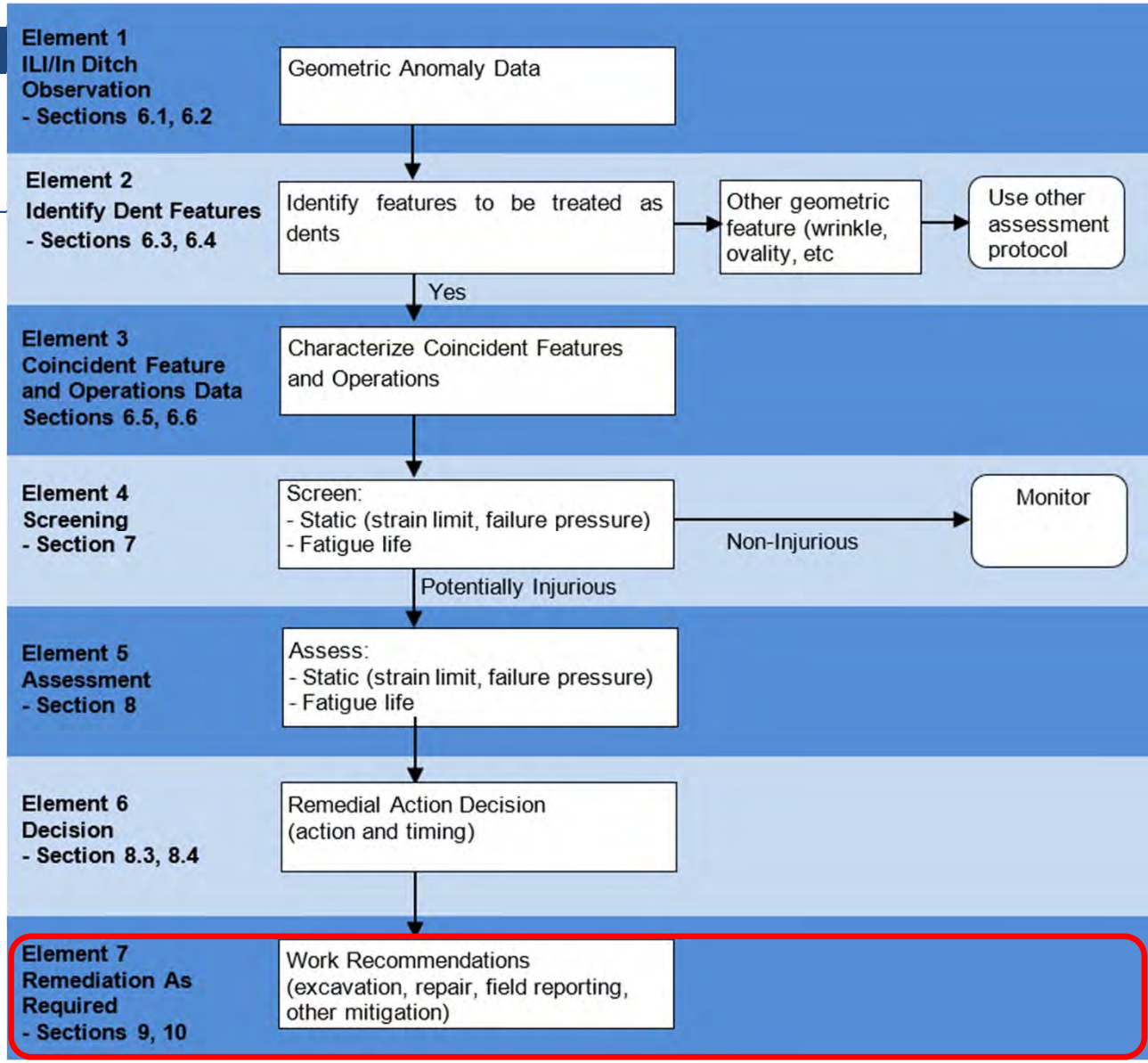
Decision Guidance

- **Provide factor of safety (FOS) guidance**
  - Factor of safety used in assessment not screening
  - Identify what to consider in defining factor of safety
    - Conservatism of approach
    - Certainty of data
    - Consequence of failure
    - Operator experience
  - Provide traditional ranges of factors of safety applied
- **Probabilistic Treatment**
  - Note the utility of considering uncertainty in assessment



Remediation

- **Guidance provided for field activities**
  - Excavation
  - Inspection and dent measurement
  - Documentation of field data
  - Cut out & removal guidance
- **Mitigative and Repair Actions**
  - Operational pressure
  - Mitigate coincident features
  - Repair guidance
    - Replacement
    - Sleeving



Remediation

- **Mitigative and Repair Actions**
  - Pressure reduction to manage peak strain or support field activities
  - Re-evaluation of operational pressure history may reveal lower operating spectrum severity
  - Management of pressure cycles can extend fatigue life of feature
    - Reducing the number of shutdowns
    - Using friction reducing additives
    - Minimizing pump starts and stops
    - Holding backpressure
    - Modifying product batching and delivery and receipt schedules
    - Controlling gradual, pump starts and stops or valve actuation
  - Guidance on coincident feature mitigation
    - Corrosion
    - Crack
    - Weld
    - Gouge
  - Repair method applicability
    - Replace as cylinder
    - Full encirclement sleeves (Type A & B)
    - Compression sleeves
    - Hot tapping
    - Grinding
    - Composite sleeves
    - Mechanical bolt-on clamps

Ongoing Work . . . Next Steps

- **Ongoing Research . . . PRCI Mechanical Damage Strategic Research Program**
  - Work co-funded with US DOT PHMSA
    - NDE-4-18 ILI performance trials for mechanical damage with coincident features
      - Detection, Identification, Sizing of Dents and Coincident Features
        - » Dens with corrosion, cracks, welds gouges
    - MD-5-2 Improve Dent/Cracking Assessment Methods
      - Dent formation strain evaluation
      - Dent conservatism of assessment techniques
      - Geometry measurement performance
    - MD-5-1 Systematize 20 Years of Mechanical Damage Research
      - History and content of dent research
  - PRCI considering in SRP
    - ILI, dig and metallurgical data collection and evaluation
    - Trials (pull and flow loop) with other pipe sizes

BACK TO AGENDA

PRCI 2020 Research Exchange

Example of Use of PRCI Research in Mechanical Damage as Data for University Research and Improve of Company Standards

MD 4-2- Full Scale Demonstration of the Interaction of Dents with Localized Effects

- **Husain Al-Muslim, PhD**
- **Saudi Aramco**

LEADING PIPELINE RESEARCH

Outline

- Background
- Probabilistic design analysis
- Development of assessment criteria
- Conclusions

Non-Business Use

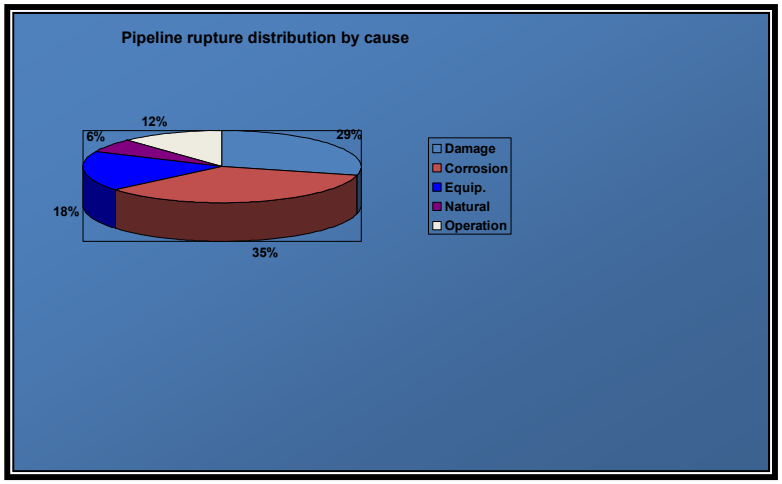
Mechanical Damage and Integrity

- **The most cause of failure**
  - Construction
  - Third party
  - Pipe movement
  - External pressure





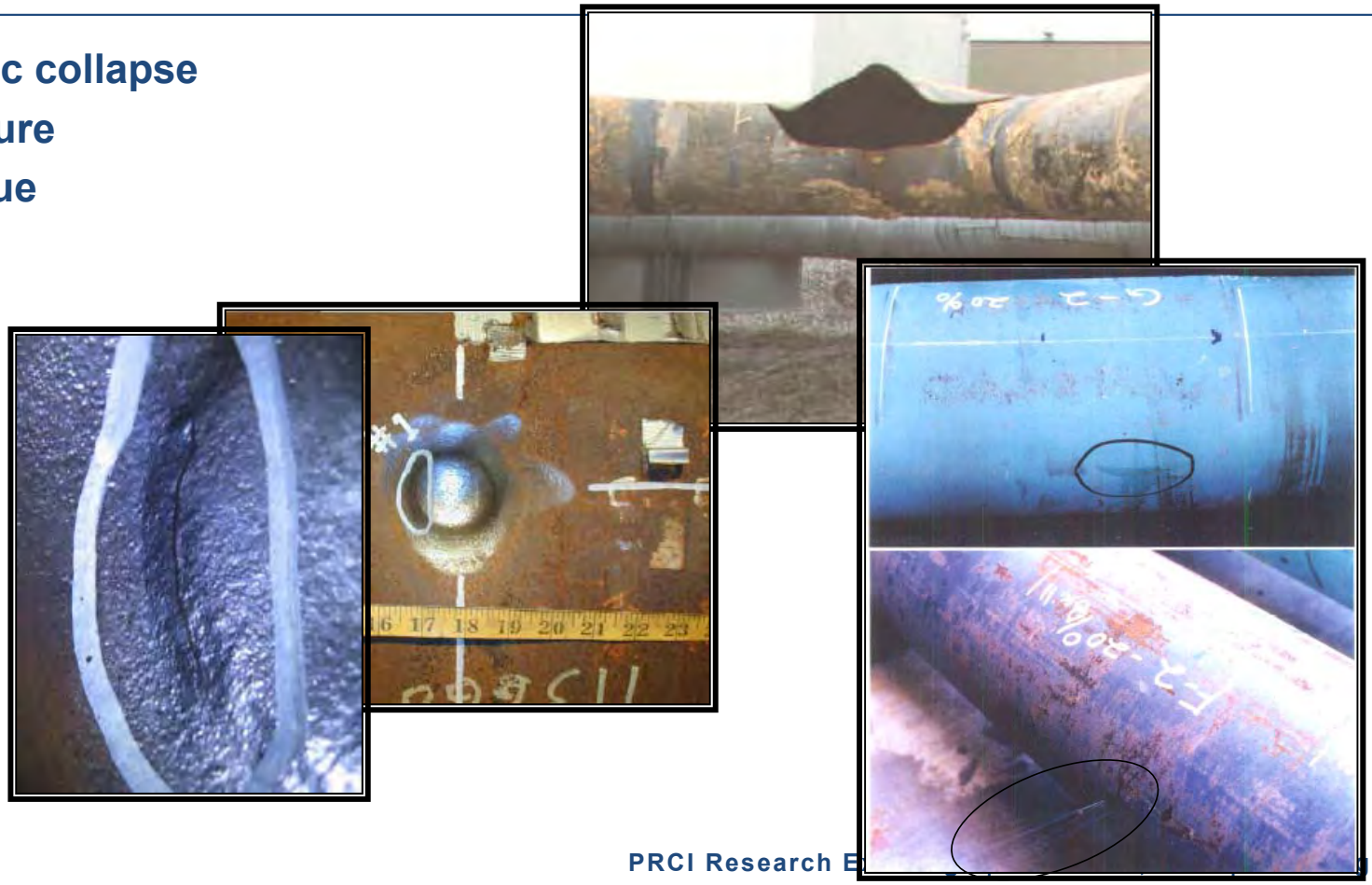




Non-Business Use

Modes of failure

- Plastic collapse
- Fracture
- Fatigue



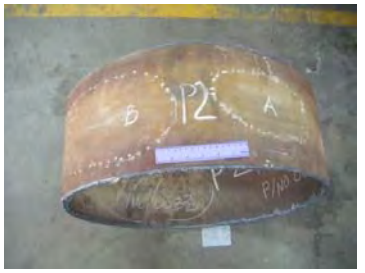
Non-Business Use

Illustrations of combined damages





Plain dents



2 dents





Dent with gouge

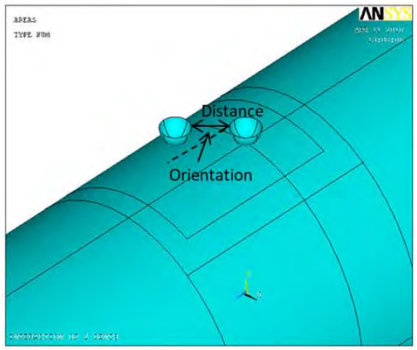


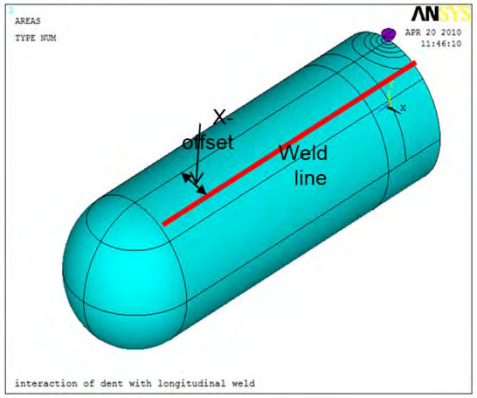
Dent with weld

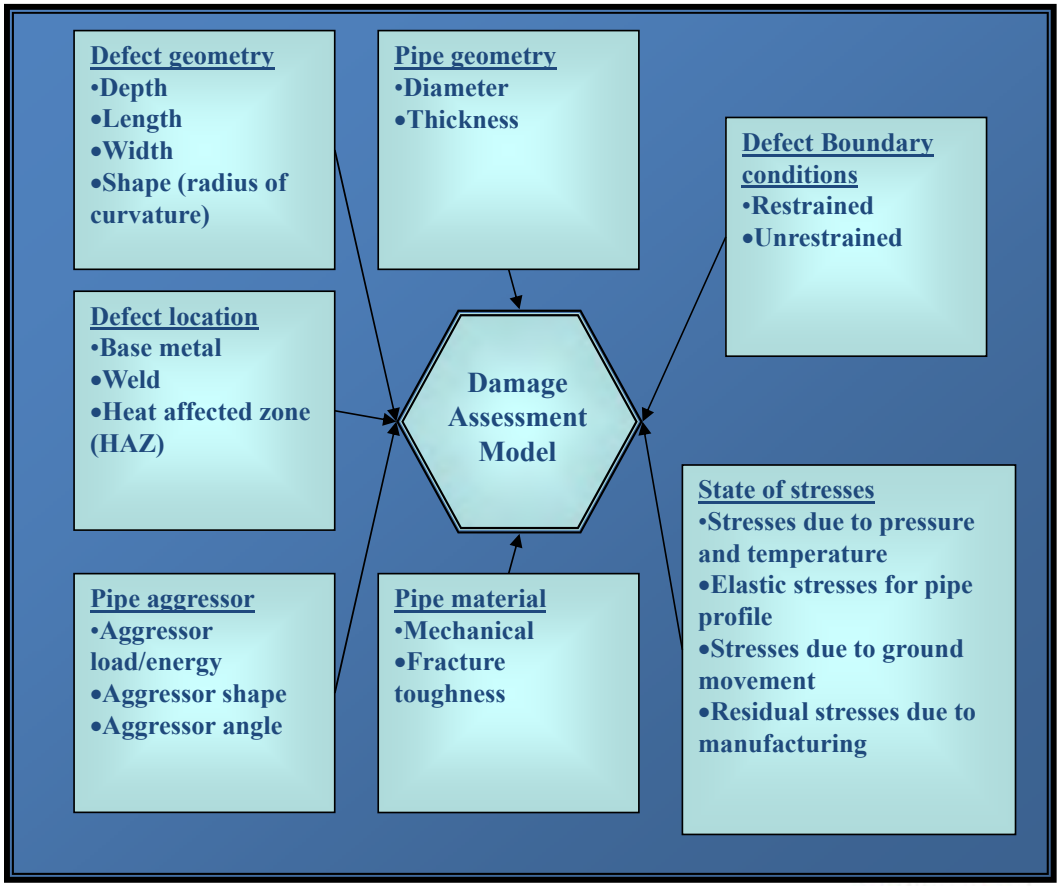
Non-Business Use

Research objective

- **Develop assessment model of combined mechanical damage**
  - 2 dents
  - Dent with metal loss
  - Dent with weld







Non-Business Use

Use of PRCI projects in Model development and validation

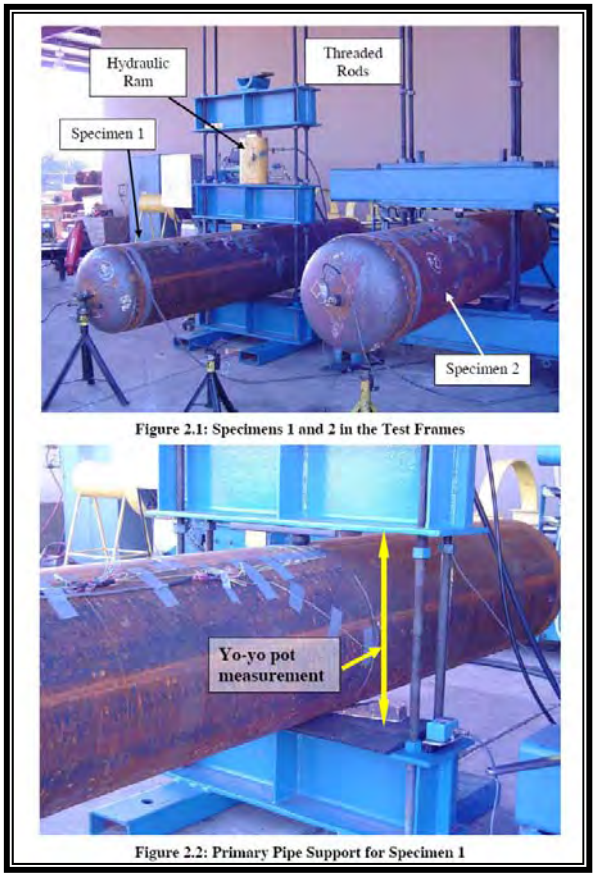


Figure 2.1: Specimens 1 and 2 in the Test Frames

Figure 2.2: Primary Pipe Support for Specimen 1

- Validation: PRCI MD-4-2 Full Scale Tests
- Creation of 12 different combination of plain dents
- Full instrumentation to record load, displacement and strains
- Constrained and unconstrained boundary conditions
- Initial pressure loading and cyclic pressure loading

Reference: Semiga, V., *Full Scale Demonstration of the Interaction of Dents with Localized Effects*, task 4 interim report to Pipeline Research Council International, Project MD 4-2, BMT Fleet Technology, Ltd., November 2007.

Non-Business Use

Use of PRCI projects in Model development and validation

1. Carroll, L. B., 2007, Full Scale Demonstration of the Interaction of Dents with Localized –Task 3 Material characterization, updated report to Pipeline Research Council International, Project MD-4B Task 3, BMT Fleet Technology Limited.
2. Carroll, L. B., Tiku, S., and A. Dinovitzer, 2006, Full Scale Demonstration of the Interaction of Dents with Localized Effects- State of the Knowledge Review, quarterly progress report to Pipeline Research Council International, Project MD 4-2B Task 1, BMT Fleet Technology Limited.
3. Semiga, V., December 2007, Inventory of Types of Mechanical Damage Experienced by Gas and Oil Pipelines, final draft report to Pipeline Research Council International, Project MD 2-1, Report No. PR-218—63511, BMT Fleet Technology, Ltd.
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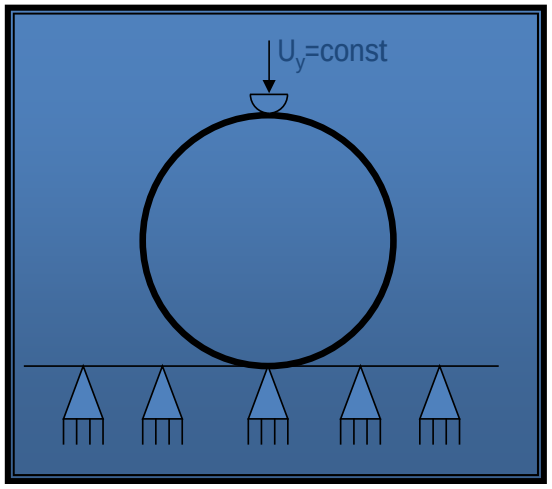
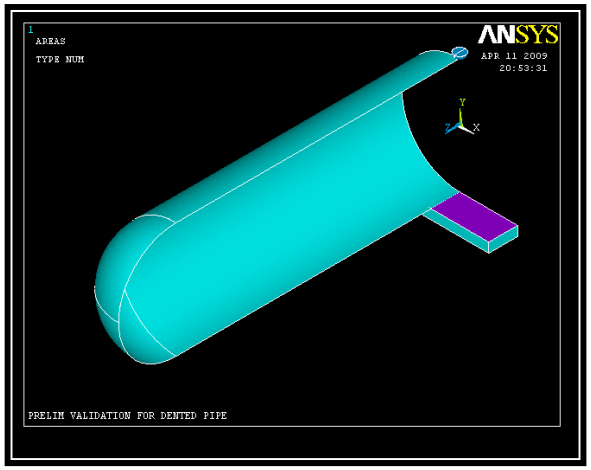
8. MD-4-4. Improved Model for Predicting the Time/Cycle Dependent Behavior of Dent + Gouge Model. Project funded by Pipeline Research Council International.
9. MD-4-6. Full-Scale Experimental Validation of Mechanical Damage Assessment Models-Extension of MD-4-1. Project funded by Pipeline Research Council International.
10. MD-4-7. Full-Scale Experimental Validation of Mechanical Damage Assessment Models-Options MD-1. Project funded by Pipeline Research Council International.
11. MD-1. Development of a Dual Field Magnetic Flux Leakage Inspection Technology to Detect Mechanical Damage. Project funded by Pipeline Research Council International.
12. MD-1-1. Dual Field Magnetic Flux Leakage Inspection Technology to Detect Mechanical Damage. Project funded by Pipeline Research Council International.
13. MD-1-2. Performance Characterization of Current In-Line Inspection Technologies for Mechanical Damage Detection. Project funded by Pipeline Research Council International.
14. MD-1-3. Understanding Magnetic Flux Leakage Signals “from Mechanical Damage in Pipelines. Project funded by Pipeline Research Council International.
15. MD-1-4. Field Testing and Verification of Existing Tool Capabilities for Mechanical Damage Detection and Characterization. Project funded by Pipeline Research Council International.
16. MD-1-5. Enhanced Mechanical Damage Database by Improving Mechanical Damage Assessment in the Ditch. Project funded by Pipeline Research Council International.
17. MD-1-6. Ultrasonic Measurements of Strains in Pipelines. Project funded by Pipeline Research Council International.
18. MD-5A. Inspection Procedures for Dent+Gouge Damage. Project funded by Pipeline Research Council International.
19. MD-5B. Easy Repair Procedures for Dent+Gouge Damage. Project funded by Pipeline Research Council International.

Non-Business Use

Model development and validation

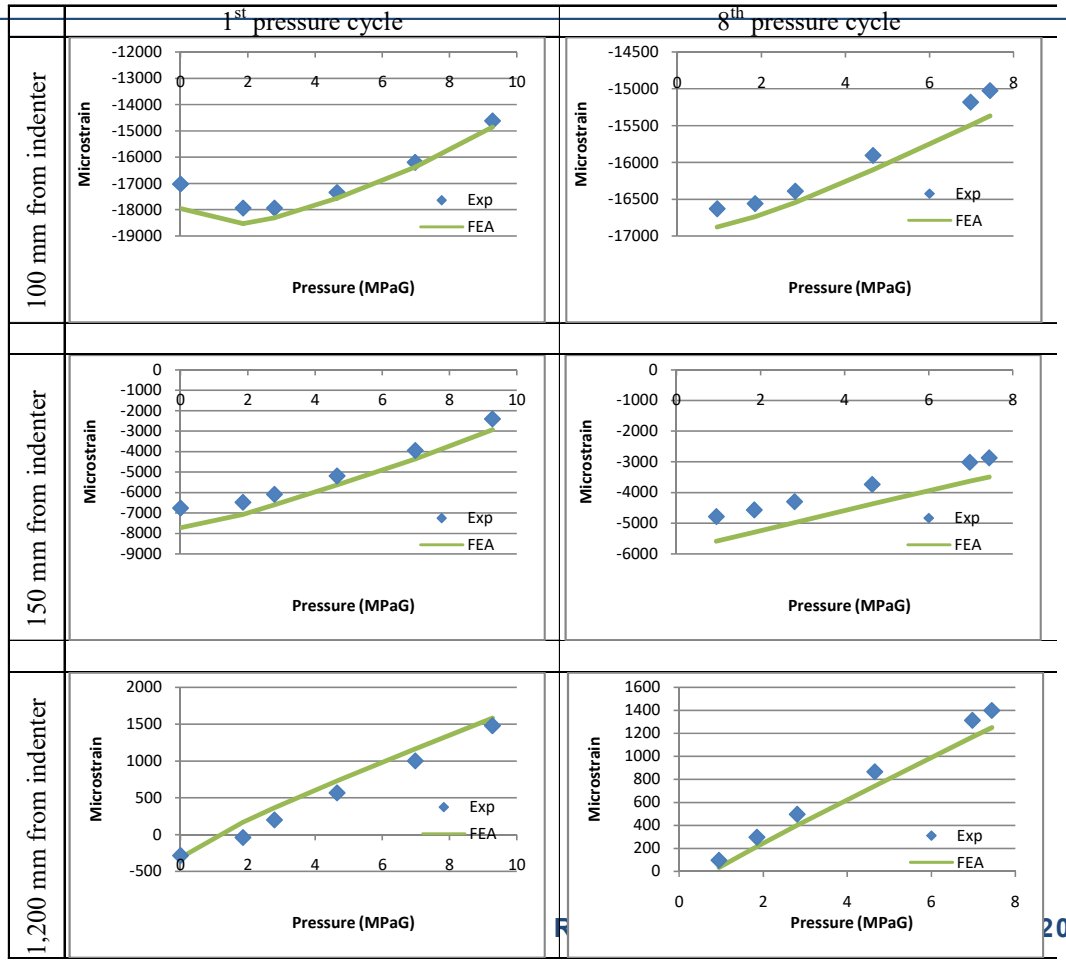
- Quarter-symmetry model
- Shell elements with uniform thickness
- Indentation at load steps from 0 to 46 mm
- Pressure loads (hydortest pressure followed by 7 pressure cycles)
- Non-linear elastic-plastic problem
  - Geometry (large displacement)
  - Material (elastic fully plastic)
  - Boundary conditions (indenter+support contact elements)





Non-Business Use

Base model development and validation



Probabilistic Design Analysis-Overview

- Probabilistic Design Analysis is an integrated Module in ANSYS
- Base (deterministic) FEA model is developed
- The input parameters and their statistical distributions are defined
- The number of analysis loops is defined, and the type of generation usually by Monte Carlo Simulation
- The analysis is run and the random output parameters are stored after each loop
- Statistical analysis is conducted on the output variables

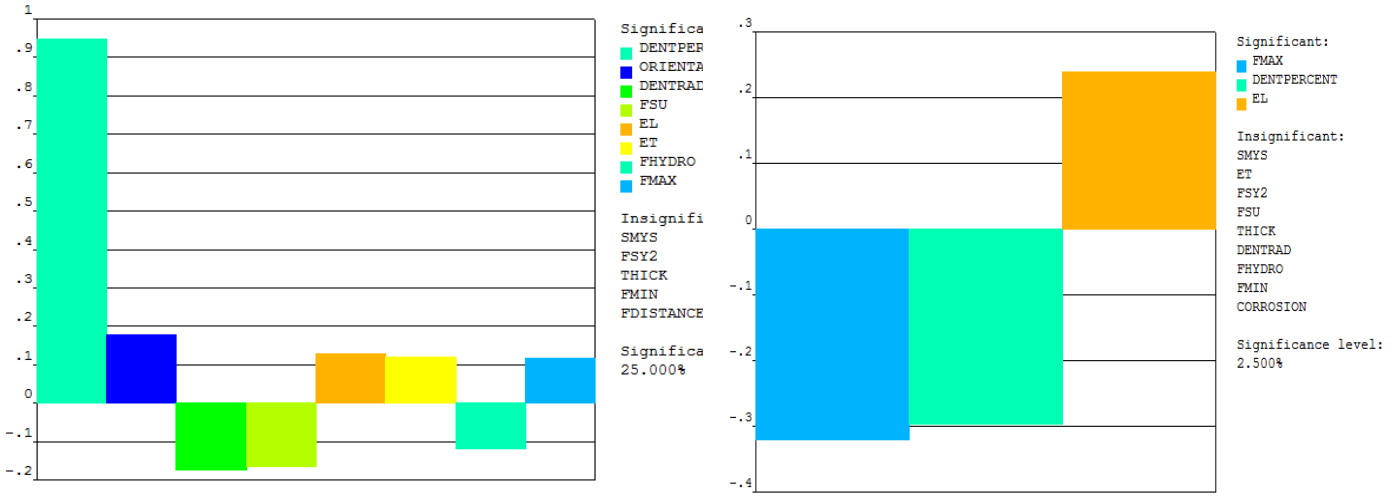
Non-Business Use

Probabilistic Design Analysis-Results

- Statistical distribution of output parameters
- Correlation between output/input variables
- Sensitivity of strain and stress fields to the various input parameters

Non-Business Use

Results-Sensitivity plots of fatigue life

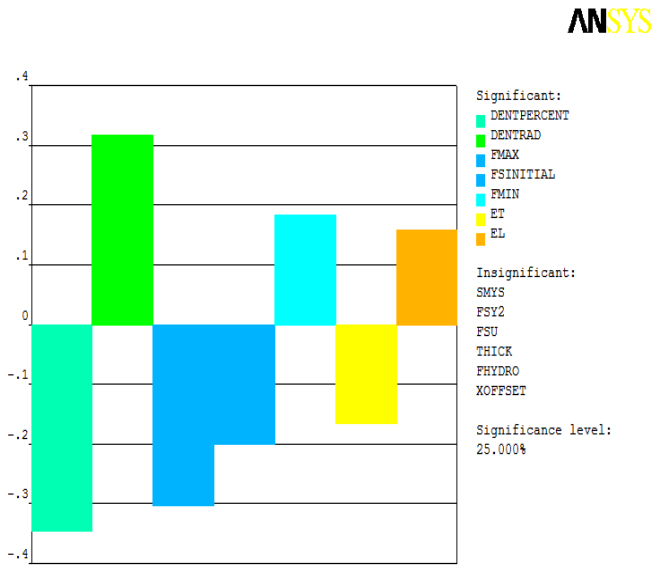


2 dents

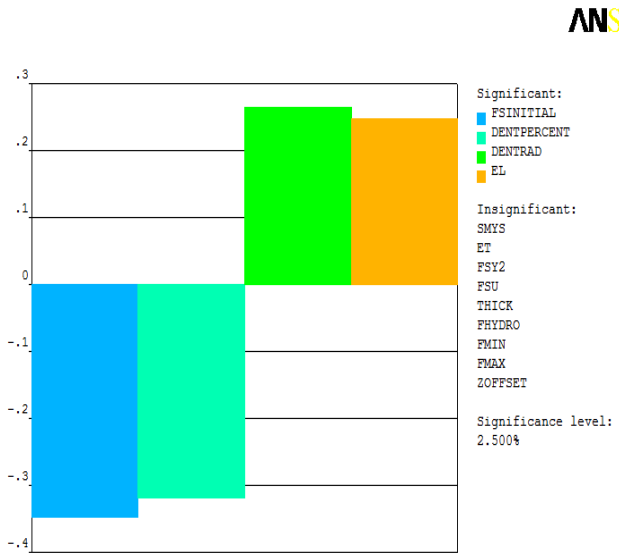
dent with metal loss

Non-Business Use

Results-Sensitivity plots of fatigue life



dent with longitudinal weld



dent with girth weld

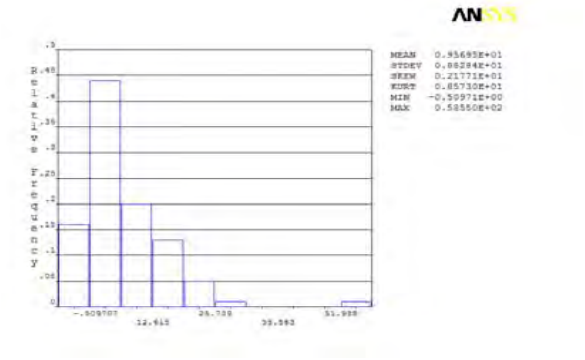
Non-Business Use

Results-Sensitivity plots of fatigue life

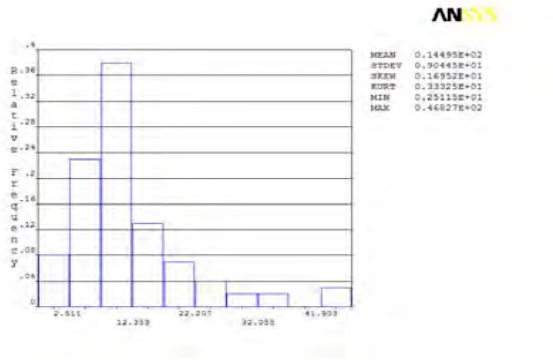
- **2 dents:**
  - Fatigue life increase with angle
  - Not sensitive to distance
- **Dent with metal loss:**
  - Fatigue life decreases with increase pressure and dent depth
  - Metal loss does not change sensitivity
- **Dent with weld residual stresses:**
  - Fatigue life decrease with increase of residual stress
  - Not sensitive to offset
- **Distance between 2 dents and weld offset were defined within a range known to have interaction effects**

Non-Business Use

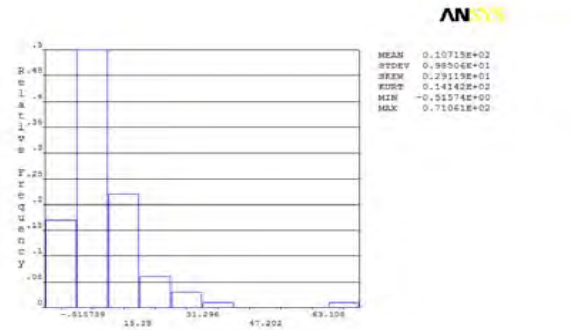
Results-Statistical distribution of fatigue life



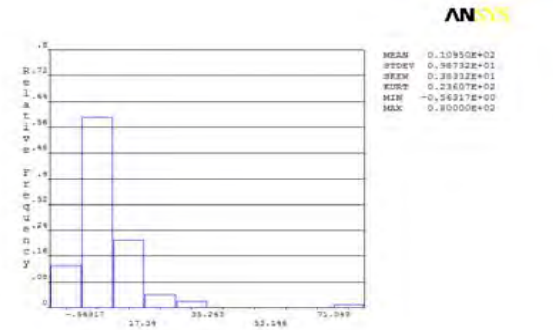
2 dents



dent with metal loss



dent with longitudinal weld



dent with girth weld

Non-Business Use

Comparison of probability of failures

Life	Single dent	2 dents	Dent with metal loss	Dent with long weld	Dent with girth weld
1,000	6.8	50.4	14.3	41.8	35.4
5,000	10.2	57.8	24.3	49.6	50.8
10,000	12.2	59.4	27.6	53.3	53.1
50,000	17.9	65.9	37.7	63.3	64.2
100,000	18.5	69.9	43.2	66.6	66.8
500,000	21.2	71.8	51.8	70.1	72.4
1,000,000	22.8	72.6	59.6	70.7	73.8

Non-Business Use

Comparison of probability of failures

- Interaction of dent with metal loss has the least impact of combined damage (2 times plain dent)
- Interaction of 2 dents has the most impact of combined damage (3 to 8 times of plain dent)
- Interaction of dent with welds also great impact (3 to 7 of plain dents)

Non-Business Use

Development of assessment criteria

- Probabilistic: determine failure frequency based on statistical distribution of output variables
- Deterministic: develop regression formulas relating output to input parameters

Non-Business Use

Probability of failure-risk assessment

- Risk = failure frequency x consequences
- Failure frequency = probability of failure x hit rate
- 9.6% of the cases have strain exceeding 20% (failure limit)
- Failure frequency (this work)= 0.096X3.14e-4=3.01e-5
- Failure frequency (historical data)=8.28e-5

Pipeline #	No. of dents	Length (km)	Years of service	Exposure (km.yr)	Hit rate (dents/km.yr)
1	8	30	4.8	144	5.56E-02
2	1	35	86.0	3,010	3.32E-04
3	2	17	12.0	204	9.80E-03
4	6	36	58.3	2,099	2.86E-03
5	13	55	44.6	2,453	5.30E-03
6	22	31	197.7	6,130	3.59E-03
7	56	46	104.0	4,784	1.17E-02
8	1	35	34.7	1,213	8.24E-04
9	25	38	34.7	1,317	1.90E-02
Sub Total-dented	134			21,354	6.28E-03
Total population	134			427,079	3.14E-04

Non-Business Use

Impact on Integrity Management

- Risk increase proportionally to the probability of failure
- Interaction of 2 dents and interaction of dent with welds must have priority in assessment and maintenance
- Dent with metal loss should be evaluated based on the dent dimensions and the pressure load

Non-Business Use

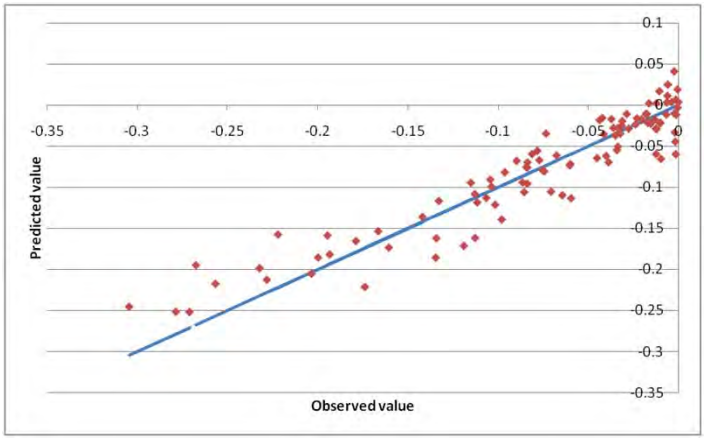
Regression formulas plain dent

$$Output\ variable = a_0 + b_1\frac{D}{t} + b_2\frac{d}{D} + b_3\frac{l}{D} + b_4\frac{w}{D} + b_5\frac{ldw}{D^2t} + b_6\frac{\sigma_{flow}}{E_{avg}} + b_7\frac{E_t}{E_l} + b_8\frac{P_{max} - P_{min}}{P_{SMYS}} + c_1\left(\frac{D}{t}\right)^2 + c_2\left(\frac{d}{D}\right)^2 + c_3\left(\frac{l}{D}\right)^2 + c_4\left(\frac{w}{D}\right)^2 + c_5\left(\frac{ldw}{D^2t}\right)^2 + c_6\left(\frac{\sigma_{flow}}{E_{avg}}\right)^2 + c_7\left(\frac{E_t}{E_l}\right)^2 + c_8\left(\frac{P_{max} - P_{min}}{P_{SMYS}}\right)^2$$

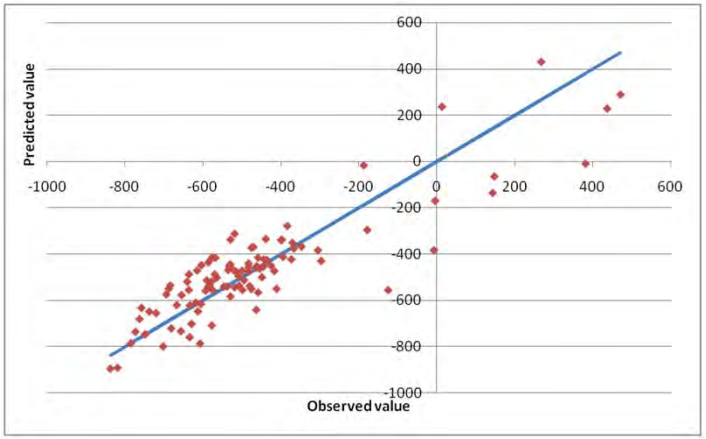
Non-Business Use

Probabilistic Design Analysis-regression

Axial strain-dent peak



Axial stress-dent peak



Non-Business Use

Regression example problems

Case no. Specimen 1

Input parameters (by user)

Pipe geometry		Damge inspection data			Pipe material properties				Operating pressure (in terms of pressure hoop stress ratio to SMYS)	
D (in)	t (in)	d (in)	l (in)	w (in)	σy (psi)	σu (psi)	Et (psi)	El (psi)	Fmax	Fmin
24	0.312	1.8	4.3	3	66300	87724	2.19E+07	2.70E+07	0.8	0.1

Calculation and output results

Dimension-less parameters	Name	D/t	d/D	l/D	w/D	ldw/D2t	sflow/Eavg	Et/El	Fmax-Fmin	D/t^2	d/D^2	l/D^2	w/D^2	ldw/D2t^2	sflow/Eavg^2	Et/El^2	Fmax-Fmin^2
	Value	76.92307692	0.075	0.179166667	0.125	0.129206731	3.15E-03	8.11E-01	0.7	5917.159763	0.005625	0.0321007	0.015625	0.0166944	9.921E-06	0.6579012	0.49
Regression coefficents	a0	b1	b2	b3	b4	b5	b6	b7	b8	c1	c2	c3	c4	c5	c6	c7	c8
N_log	-8.16E+01	1.26E-01	-8.57E+01	2.17E+01	-5.63E+02	-3.94E+01	3.53E+04	6.62E+01	1.70E+02	5.10E-04	1.96E+03	-4.22E+01	2.66E+03	-6.24E+01	-5.49E+06	-3.27E+01	-2.12E+02

	Predicted value	Experimental value	
ln (N)	7.5425242	Sepcimen 1	Specimen 2
N	1,887	6,948	38,685

	Regression	Exp 1	Exp 2
Specimen 1	1,887	6,948	38,685
Specimen 3	12,088	6,886	16,234

Non-Business Use

Regression formulas-combined damage

2 dents

$$\begin{aligned}\textit{Output variable} &= a_0 + b_1\frac{D}{t} + b_2\frac{d}{D} + b_3\frac{l}{D} + b_4\frac{w}{D} + b_5\frac{ldw}{D^2t} + b_6\frac{\sigma_{flow}}{E_{avg}} + b_7\frac{E_t}{E_l} \\ &+ +b_8\frac{d_{e-e}}{\sqrt{0.5\times Dt}} + b_9\emptyset + b_{10}\frac{P_{max}-P_{min}}{P_{SMYS}} + c_1\left(\frac{D}{t}\right)^2 + c_2\left(\frac{d}{D}\right)^2 + c_3\left(\frac{l}{D}\right)^2 \\ &+ c_4\left(\frac{w}{D}\right)^2 + c_5\left(\frac{ldw}{D^2t}\right)^2 + c_6\left(\frac{\sigma_{flow}}{E_{avg}}\right)^2 + c_7\left(\frac{E_t}{E_l}\right)^2 + c_8\frac{d_{e-e}}{\sqrt{0.5\times Dt}}^2 + c_9\emptyset^2 \\ &+ c_{10}\left(\frac{P_{max}-P_{min}}{P_{SMYS}}\right)^2\end{aligned}$$

dent with metal loss

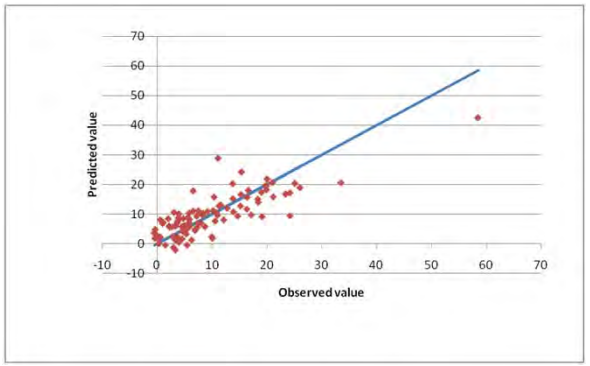
$$\begin{aligned}\textit{Output variable} &= a_0 + b_1\frac{D}{t} + b_2\frac{d}{D} + b_3\frac{l}{D} + b_4\frac{w}{D} + b_5\frac{ldw}{D^2t} + b_6\frac{\sigma_{flow}}{E_{avg}} + b_7\frac{E_t}{E_l} + b_8\frac{d_m}{t_m} \\ &+ b_9\frac{P_{max}-P_{min}}{P_{SMYS}} + c_1\left(\frac{D}{t}\right)^2 + c_2\left(\frac{d}{D}\right)^2 + c_3\left(\frac{l}{D}\right)^2 + c_4\left(\frac{w}{D}\right)^2 + c_5\left(\frac{ldw}{D^2t}\right)^2 \\ &+ c_6\left(\frac{\sigma_{flow}}{E_{avg}}\right)^2 + c_7\left(\frac{E_t}{E_l}\right)^2 + c_8\left(\frac{d_m}{t_m}\right)^2 + c_9\left(\frac{P_{max}-P_{min}}{P_{SMYS}}\right)^2\end{aligned}$$

dent with weld

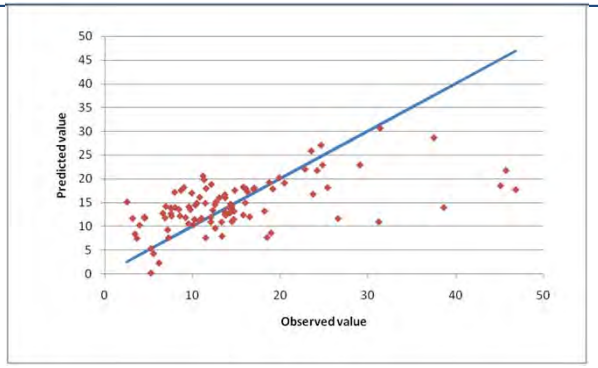
$$\begin{aligned}\textit{Output variable} &= a_0 + b_1\frac{D}{t} + b_2\frac{d}{D} + b_3\frac{l}{D} + b_4\frac{w}{D} + b_5\frac{ldw}{D^2t} + b_6\frac{\sigma_{flow}}{E_{avg}} + b_7\frac{E_t}{E_l} + b_8\frac{\sigma_{residual}}{\sigma_y} \\ &+ b_9\frac{offset}{D} + b_{10}\frac{P_{max}-P_{min}}{P_{SMYS}} + c_1\left(\frac{D}{t}\right)^2 + c_2\left(\frac{d}{D}\right)^2 + c_3\left(\frac{l}{D}\right)^2 + c_4\left(\frac{w}{D}\right)^2 \\ &+ c_5\left(\frac{ldw}{D^2t}\right)^2 + c_6\left(\frac{\sigma_{flow}}{E_{avg}}\right)^2 + c_7\left(\frac{E_t}{E_l}\right)^2 + c_8\left(\frac{\sigma_{residual}}{\sigma_y}\right)^2 + c_9\left(\frac{offset}{D}\right)^2 \\ &+ c_{10}\left(\frac{P_{max}-P_{min}}{P_{SMYS}}\right)^2\end{aligned}$$

Non-Business Use

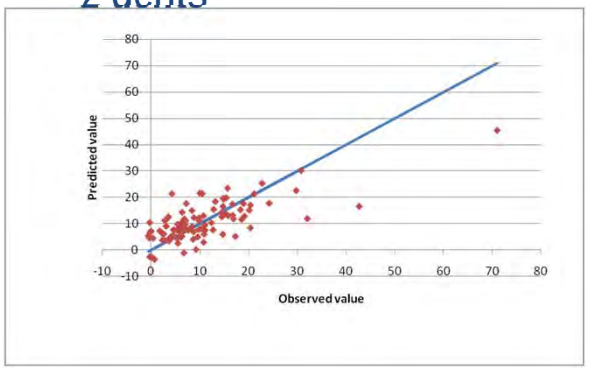
Results-Regression fit



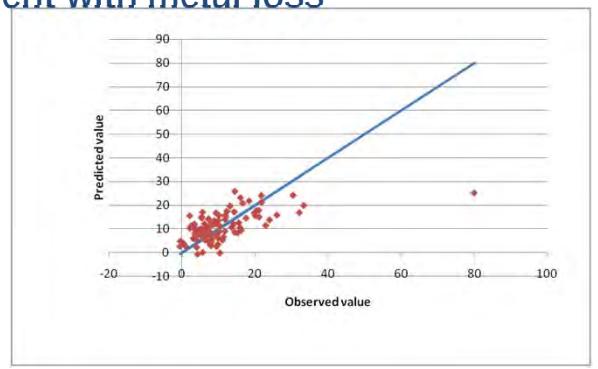
2 dents



dent with metal loss



dent with longitudinal weld



dent with girth weld

Non-Business Use

Results-Regression fit-example problems

Case	Pressure	Limited by	Recommendation
Plain dent	1080 psig	Code (72% SMYS)	No action
2 dents	1080 psig	Code (72% SMYS)	No action
Dent with metal loss	909 psig	Fatigue	Repair
Dent with longitudinal weld	455 psig	Fatigue	Repair
Dent with girth weld	483 sig	Fatigue	Repair

Non-Business Use

Value to other operators

- outcome of the study is practical qualitative and quantitative assessment criteria that can be applied by the pipeline operators to design against mechanical damage, assess severity of mechanical damage, rank and prioritize maintenance activities.
- The results were published in ASME Journal of Pressure Vessel Technology and IPC proceedings
- The results can be used into strain based assessment or coupled with fracture mechanics to assess cracks.
- The criteria developed have two features, input data are easily gathered by In-Line-Inspection tools and the assessment mathematical formulation can be automated.

Non-Business Use

Summary

- The PRCI research opens window for additional research for members collaborating with local universities.
- This avoids re-building expensive full-scale tests and utilize the available data as revalidation for numerical models.
- The specific tailored research will make it easier for the members to incorporate in their own standards and specifications.

Non-Business Use

Acknowledgment

Acknowledgement to Saudi Aramco for being member of PRCI and support to this research work

I would like to extend my sincere appreciation to Dr. AbulFazal M. Arif for his continuance guidance and support and availing his time for me whenever needed.

My thanks also to Dr. Bekir Yilbas, Dr. Anwar Sheikh, Dr. Abdel Salam Elieche, and Dr. Muhammad Kalimur Rahman for helpful discussions, comments and reviews.

Non-Business Use

QUESTIONS?

Non-Business Use

THANKS

Non-Business Use

BACK TO AGENDA

Pipeline Research Council International, Inc.

MD-1Q, PRC-328-133702

Full-scale Fatigue Testing of Crack-in-Dent and Framework Development for Life Prediction

Ming Gao, Uday Arumugam, Ravi Krishnamurthy
Blade Energy Partners,
Houston, Texas

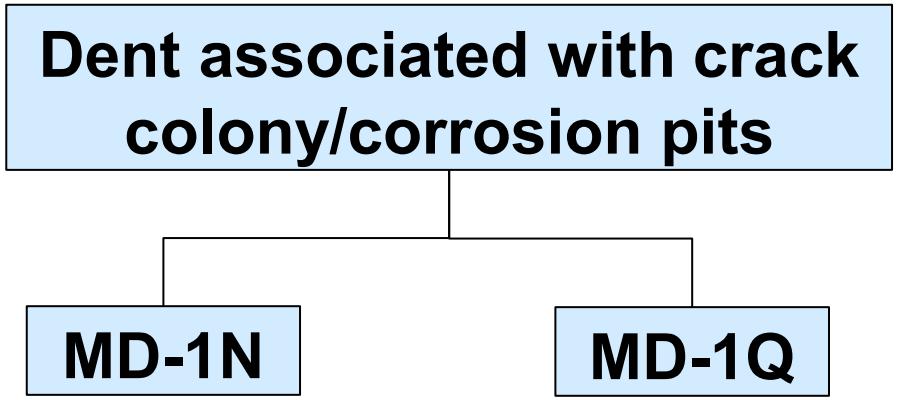
PRCI™
LEADING PIPELINE RESEARCH

BLADE ENERGY PARTNERS

Overview

- **Background**
- **Summary of previous MD-1N (phase-1) research finding**
- **MD-1Q**
  - Full-scale fatigue testing - setup & preparation
  - Test results
  - Crack growth rate & Stress intensity factor
- **Framework for life prediction**
- **Further research**

Two-phase Research

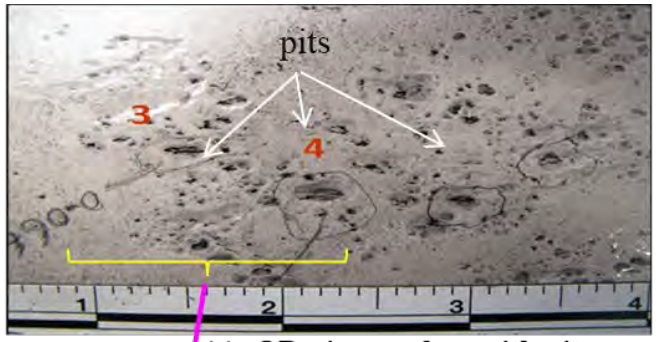


- MD-1N: Study of the Mechanism for Cracking in Dents in a Liquid Pipeline – Metallurgical Investigation
- MD-1Q: Full-Scale Fatigue Testing of Crack-in-Dent and Framework Development for Life Prediction

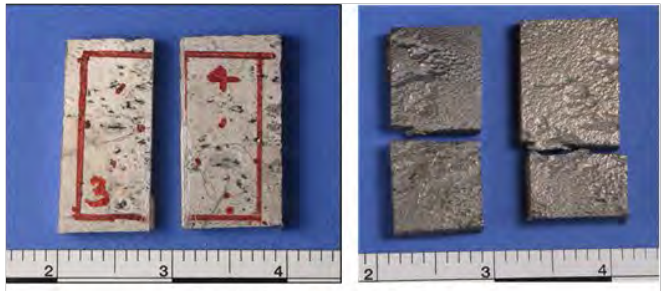
Phase 1: MD-1N Research "Study of the Mechanism for Cracking in Dents in a Liquid Pipeline"

- A total 6 pipe specimens removed from a 26 mile abandoned pipe section were used for lab investigation
- Well defined fatigue striations in 4 of 6 dent with crack samples. Other 2 samples showed evidence of fatigue striations but with heavily corroded crack wall.
- No evidence of SCC mechanism found

Example: Fatigue striations observed in a dent containing cracks/corrosion

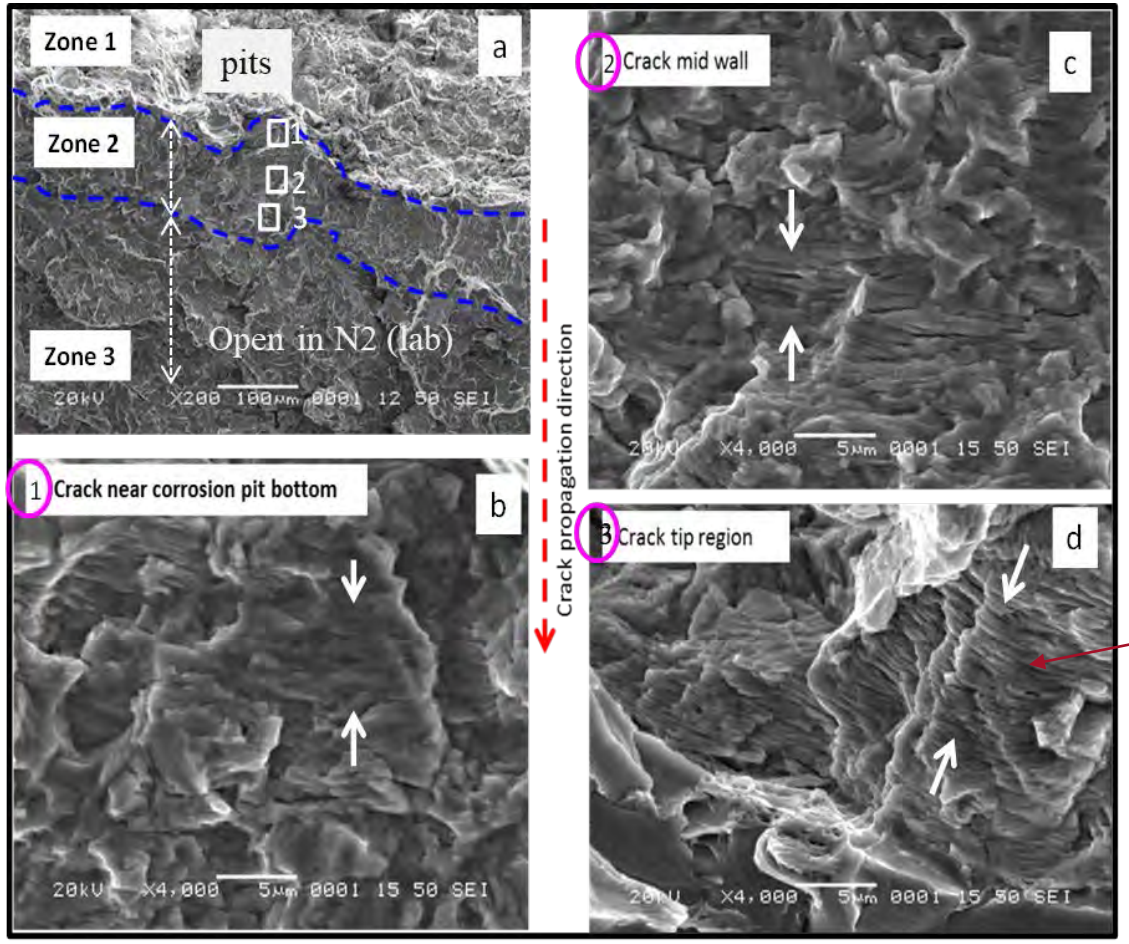


(a). OD pipe surface with pits



Crack Coupon 3 and 4

(b). Before Cleaning (c). After Cleaning



Well defined fatigue striations observed, confirming the growth mechanism by fatigue

Phase 1: MD-1N Research Finding

- Corrosion pits are the initiation sites for cracks in dent
- Growth of cracks in dent is driven by corrosion fatigue
- No evidence of SCC mechanism

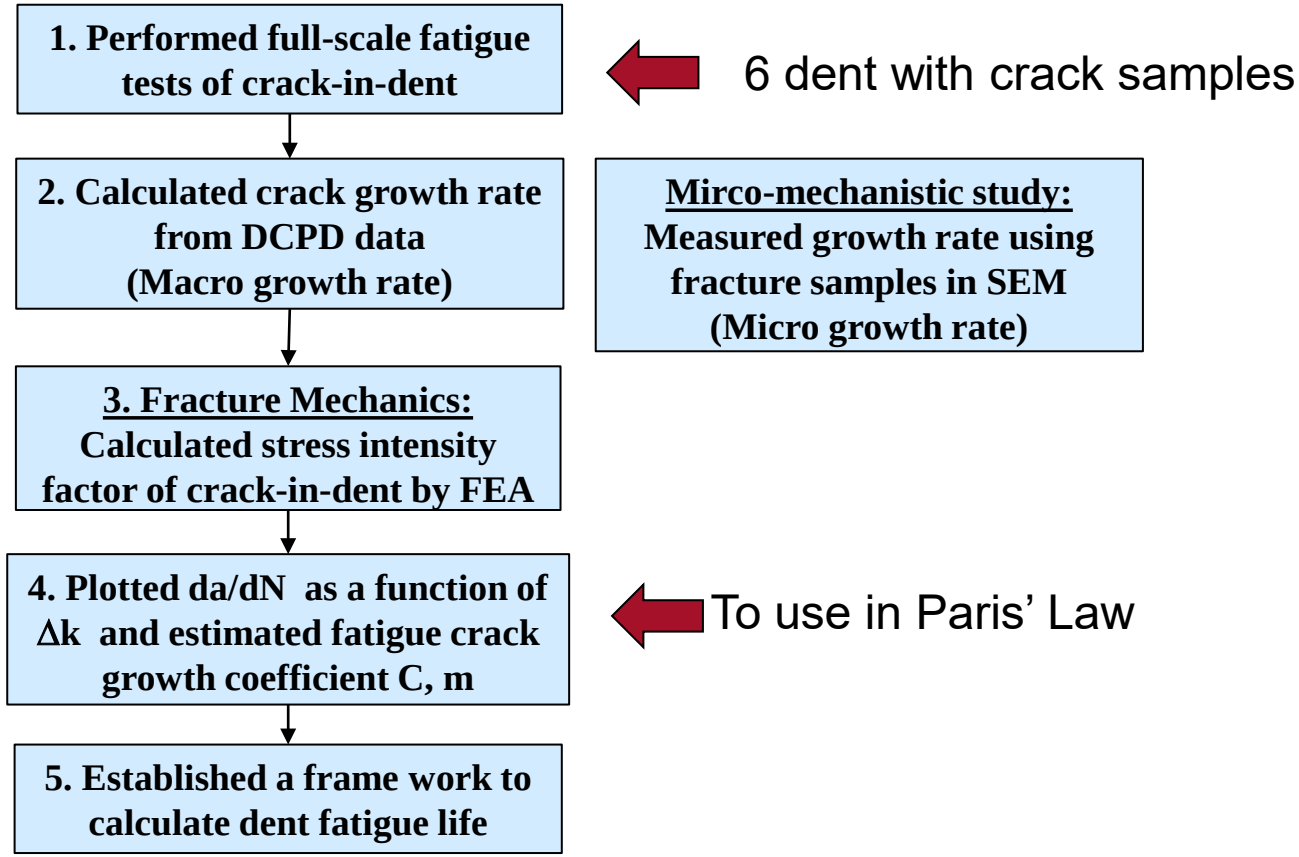
Questions arising from the MD-1N Study:

- What is the fatigue crack growth rate in dent?
- How does the environment impact crack growth rate in dent?
- How to estimate the remaining life of dent with corrosion fatigue crack?
- What would be the mode of failure, leak or rupture?

Phase 2: MD-1Q "Full-Scale Fatigue Testing of Crack-in-Dent and Framework Development for Life Prediction

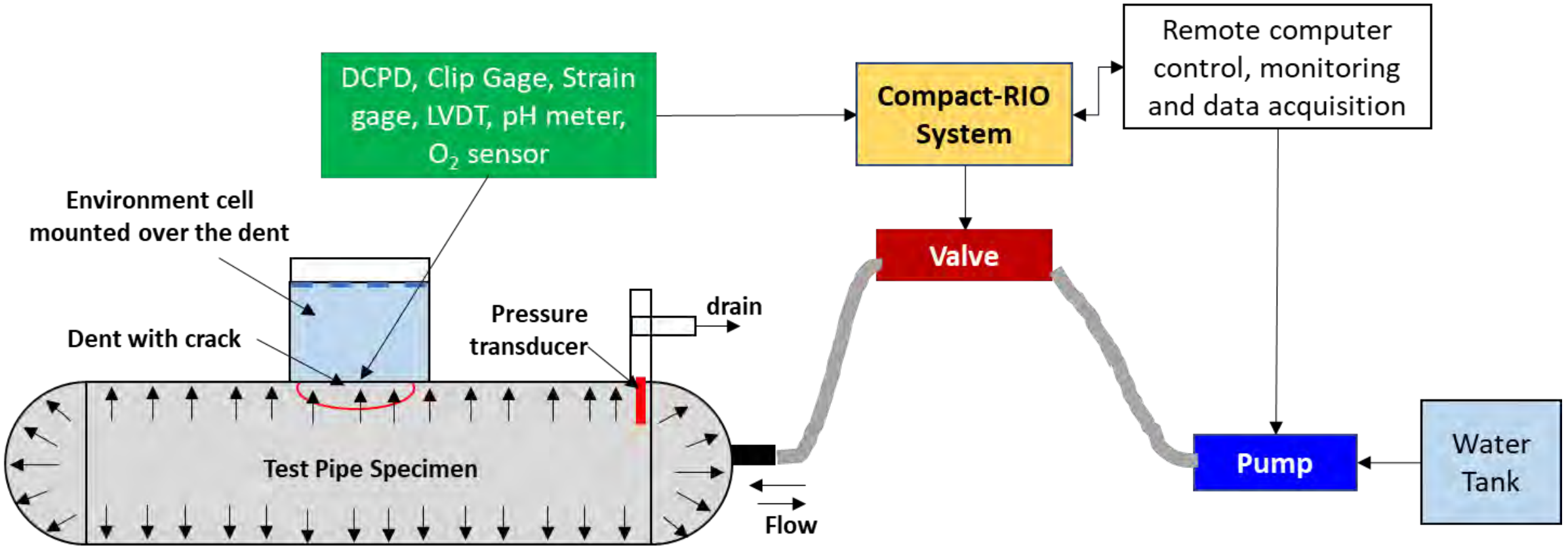
Objective

- Develop a framework for remaining life prediction for dents coincident with corrosion fatigue cracks

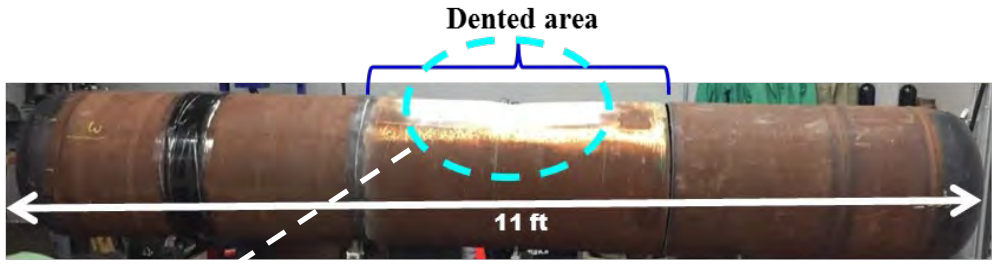


A total of 6 pipe samples containing dent associated with corrosion fatigue cracks were investigated

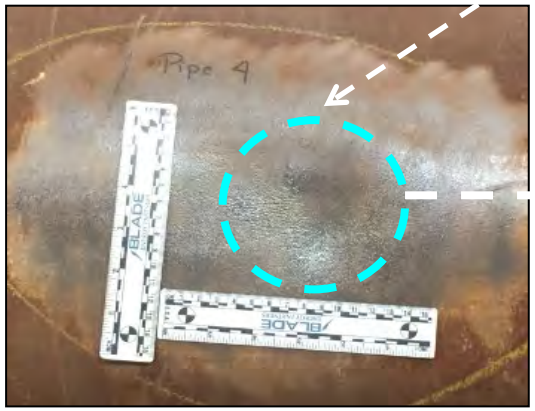
Full-Scale Fatigue Test System - Schematic



MPI and Phased Array UT



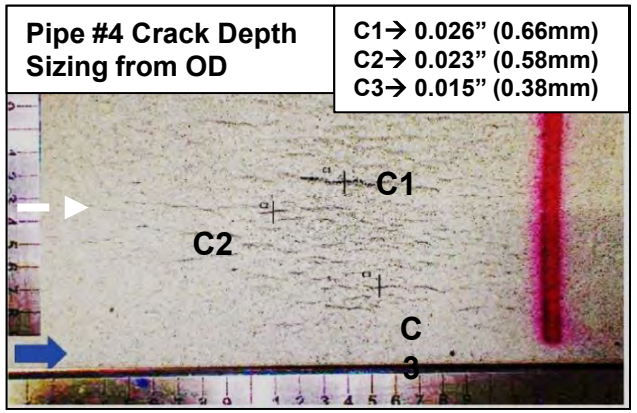
Full-scale pipe prepared for fatigue test



Dent region



Dent with corrosion/cracks



Dent with three tiny cracks (C1, C2, C3)

Test Pipe Sample #	Feature Type	NDE Reported Max. crack depth*, %nwt
Pipe #2	Dent with crack	34.0%
Pipe #3	Dent with crack	53.6%
Pipe #4	Dent with possible crack	10.4%
Pipe #7	Dent with crack	24.9%
Pipe#6	Dent with cracks	9.1%
Pipe#5	Dent with possible crack	5.2%

* NDE reported crack depth includes corrosion pit depth + crack depth

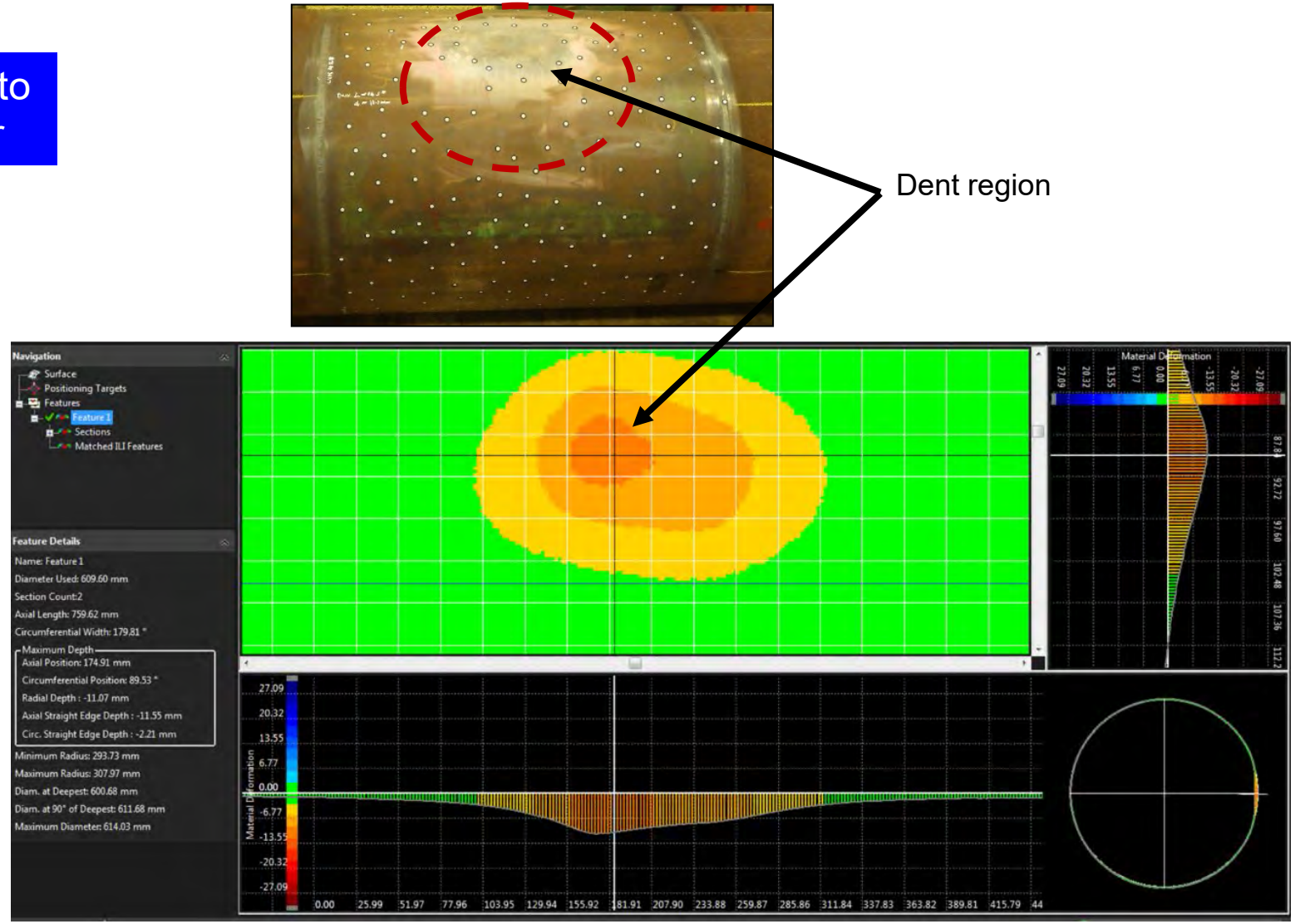
Performed MPI and Phased Array UT (PAUT) to size the cracks in all six dent samples

Laser scan to capture dent 3D geometry

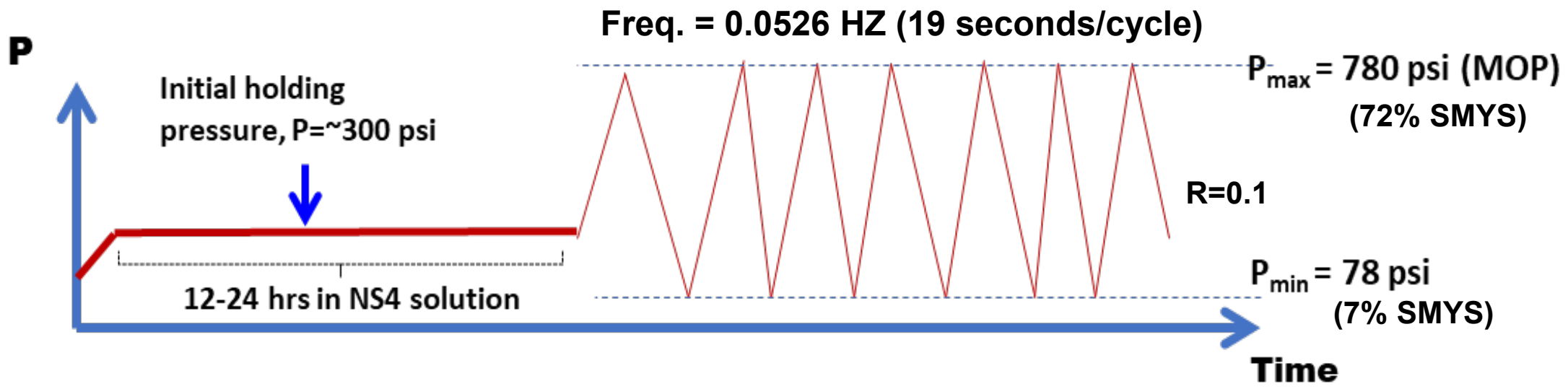
3D dent geometry data was used in FEA to calculate crack-tip stress intensity factor

Test Pipe Sample #	Feature Type	Dent Depth, %OD
Pipe #2	Dent with crack	1.5%
Pipe #3	Dent with crack	0.9%
Pipe #4	Dent with possible crack	1.6%
Pipe #7	Dent with crack	3.5%
Pipe#6	Dent with cracks	1.1%
Pipe#5	Dent with possible crack	0.9%

Note: The dent depth is defined as the maximum distance between the undeformed and deformed pipe surfaces in the radial direction at zero pressure



Loading Spectrum – Applied MOP Pressure Cycle

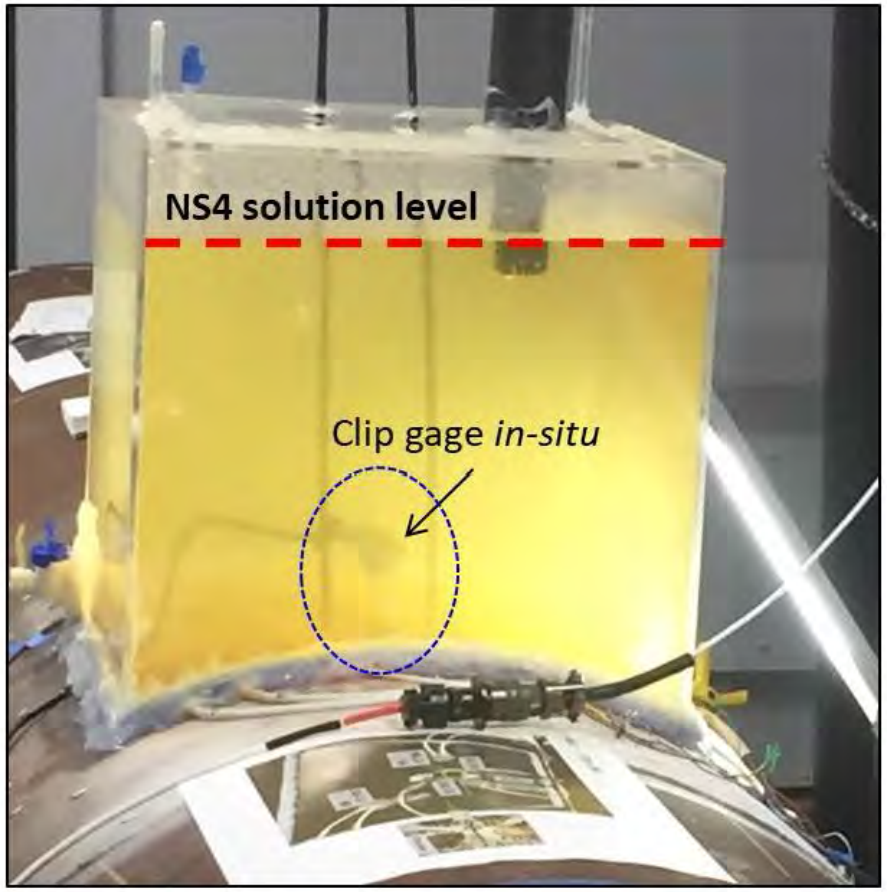


Loading spectrum was developed based on actual operating pressure data. Liquid (Water) was used in the fatigue test.

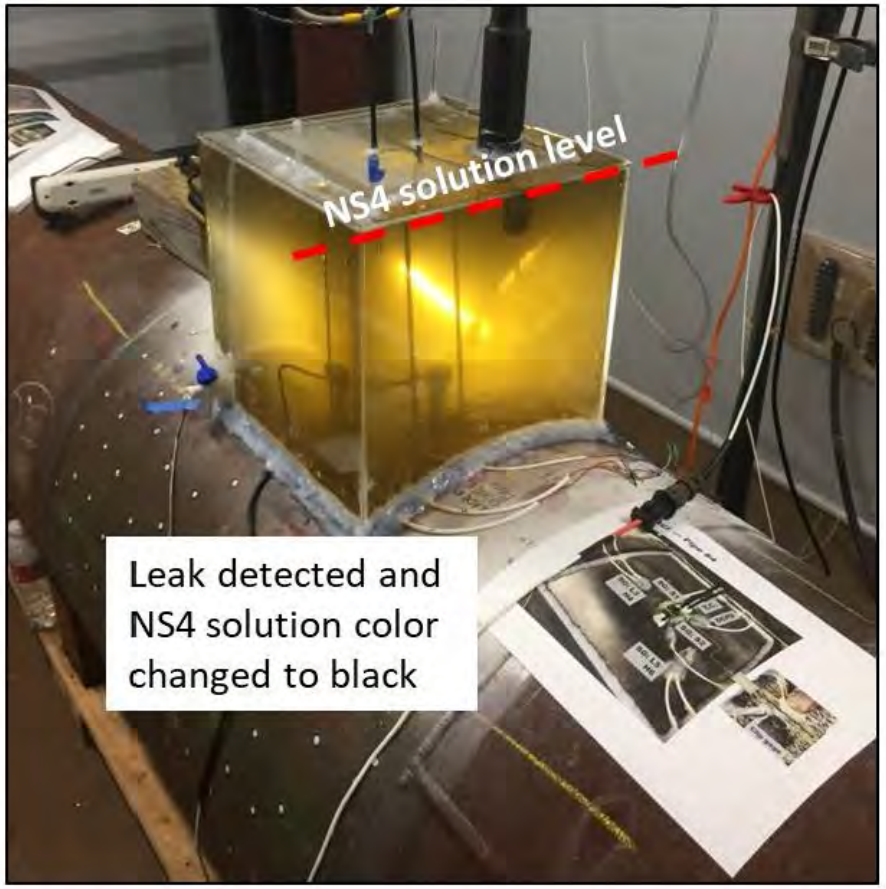
Leak Detection Technique in NS4 environment

Leak monitoring methods

1. **Remotely mounted HR video camera**
2. **DCPD software alert**
3. **Water color & the level of the cell**



(a) **Before Leak:** The color and level of NS4 solution remain clear, indication of no leak



(b) **After Leak:** The NS4 solution level changed and its color changed to black, indicating the leak occurred, which is consistent with DCPD/Clip gage/strain gage detection

Full-Scale Test Results

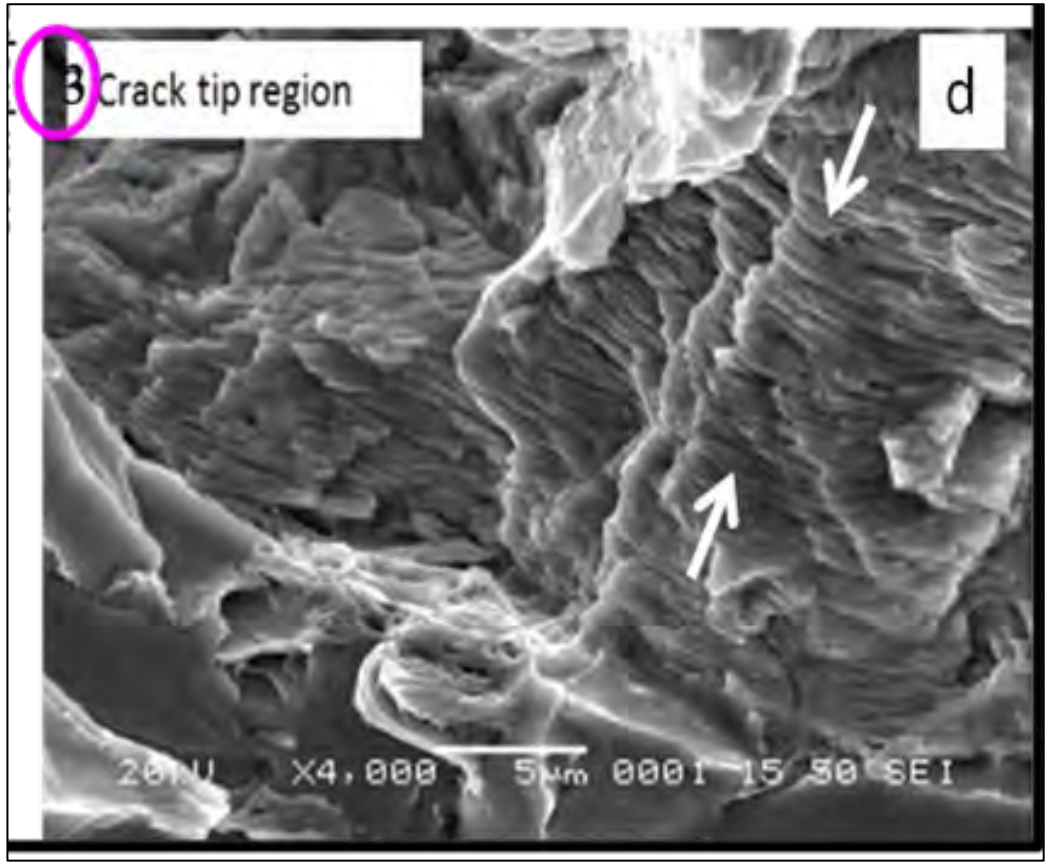
Test #	Pipe Specimen #	Feature Type	Dent Depth, %OD	NDE Reported Max. crack depth[4], %WT	Test Environment	Number of cycles to leak (cycles)	Remaining Life (years)
1	Pipe #2	Dent with crack	1.5%	34.0%	Air	2,882	32.1
2	Pipe #3	Dent with crack	0.9%	53.6%	NS4	2,779	30.9
3	Pipe #4	Dent with possible crack	1.6%	10.4%	NS4	2,294	25.5
4	Pipe #7	Dent with crack	3.5%	24.9%	NS4	2,272	25.3
5	Pipe#6	Dent with cracks	1.1%	9.1%	NS4	3,482	38.7
6	Pipe#5	Dent with possible crack	0.9%	5.2%	NS4	21,263	>100

- Dents with cracks leaked between 2200 - 3200 cycles
- Dent with no crack (plain dent with no pre-existing crack) leaked at 21,000 cycles
- Tests demonstrated minimum of 25 years remaining life based on operational pressure data
- Failure mode – First leaked-before-rupture

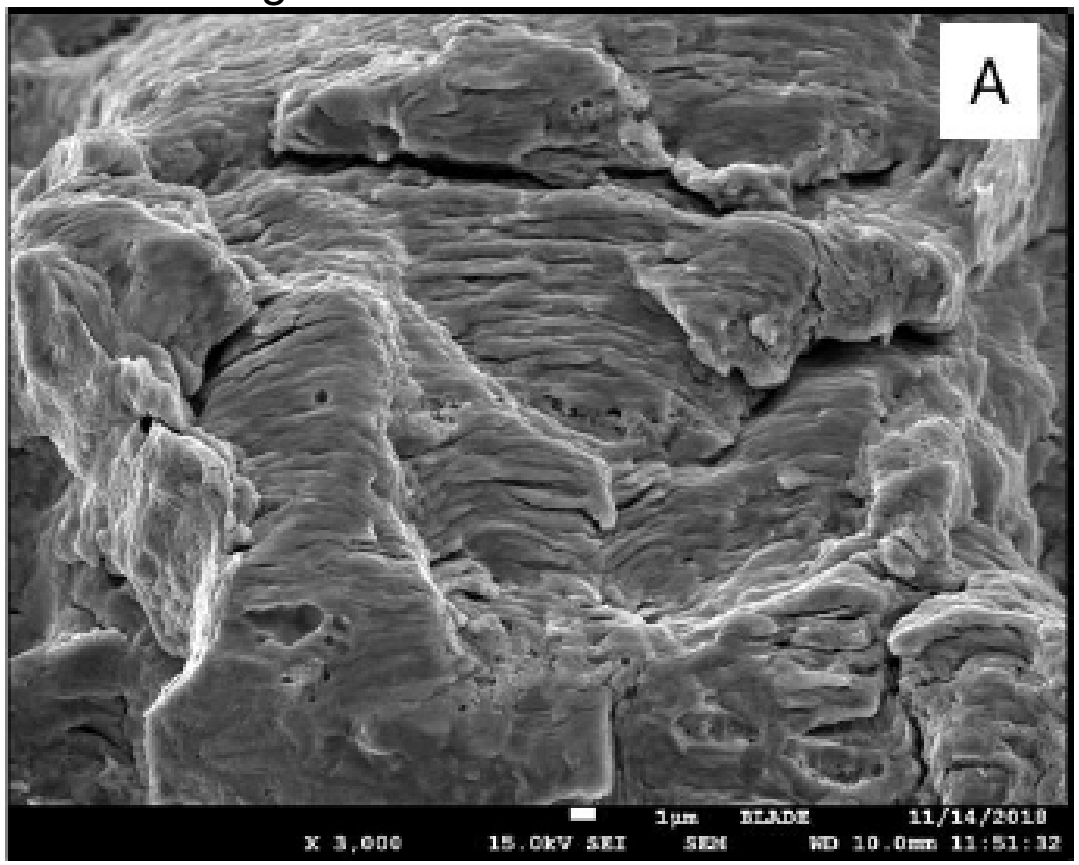
LEADING PIPELINE RESEARCH

Verified Field Observation of Fatigue Striation (Field sample vs Lab sample)

Field excavated dent with crack sample – Fatigue striations



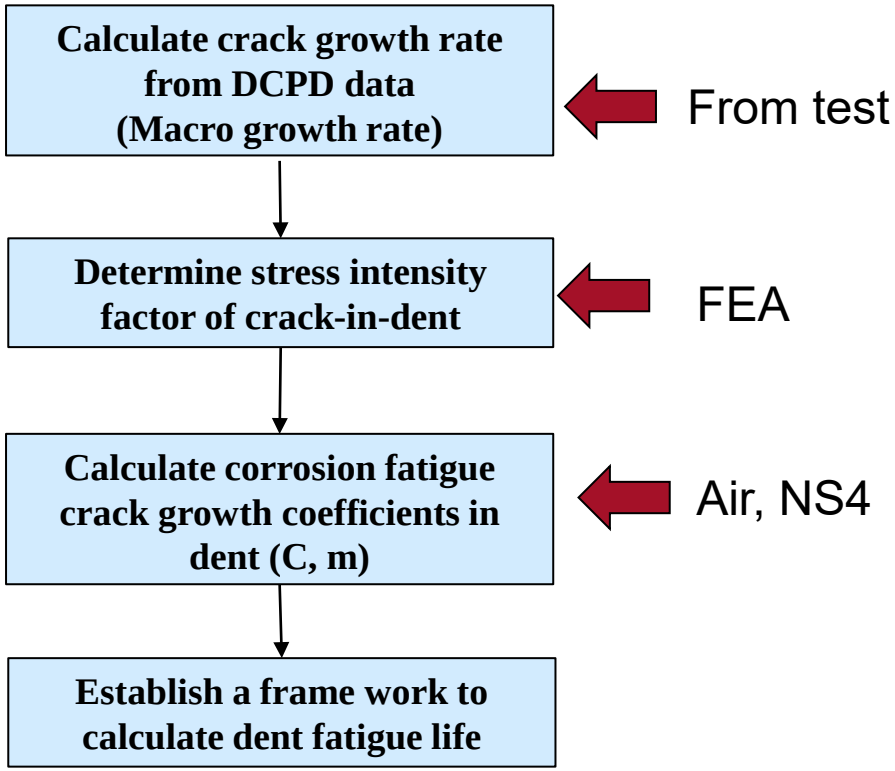
Laboratory full-scale fatigue testing – Fatigue striations



Observed identical fatigue striations between field and lab samples

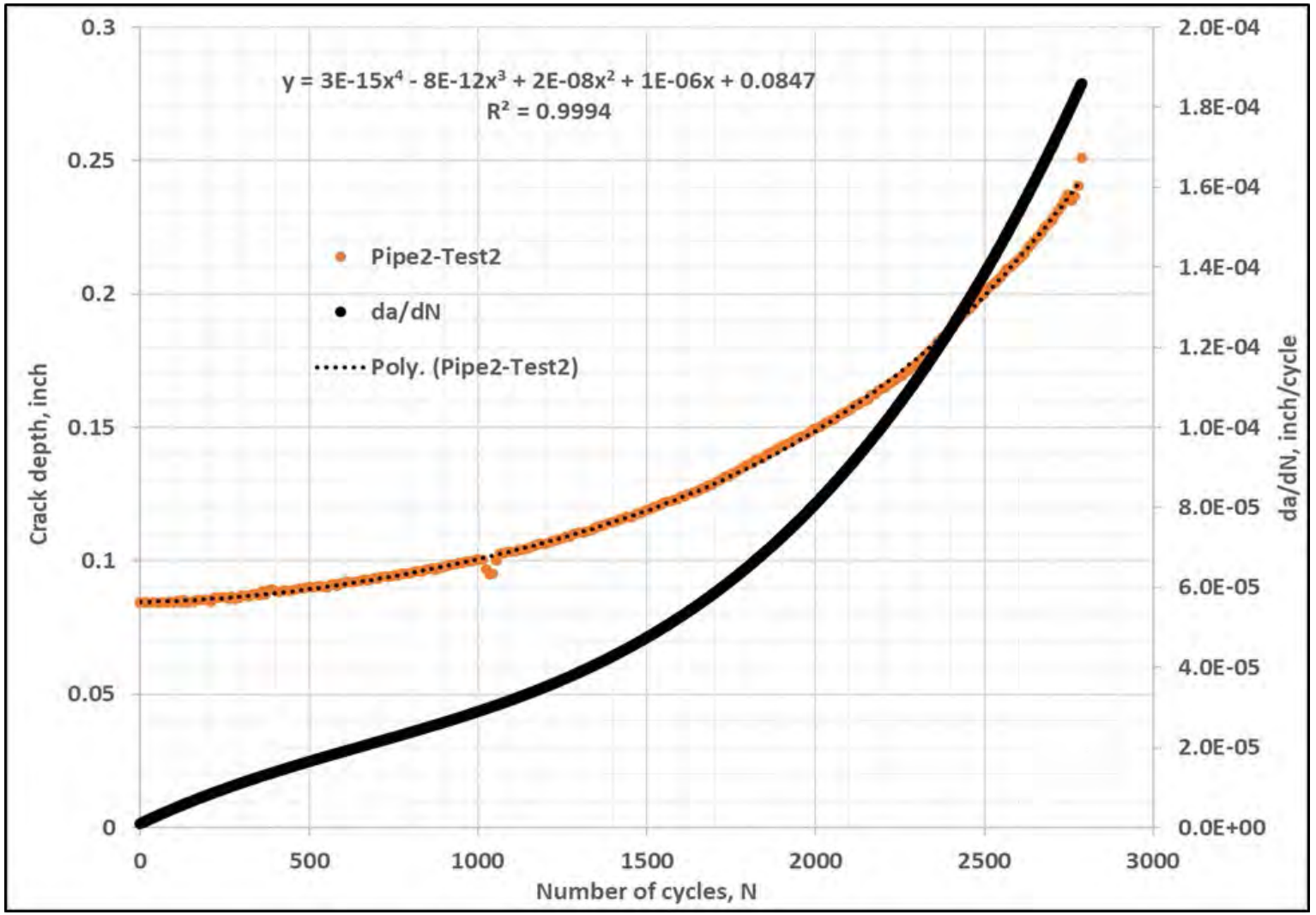
Fatigue Crack Growth Analysis and Elastic-Plastic Fracture Mechanics

1. Calculated fatigue crack growth rate (da/dN) using DCPD data - Macro growth rate
2. Performed FEA of dent with crack and determined Stress Intensity Factor ($\Delta K_{I\text{-}dwc}$) under cyclic pressure load
3. Plotted $\Delta K_{I\text{-}dwc}$ vs da/dN, and estimated corrosion fatigue crack growth coefficients, ***C and m*** in air and NS4

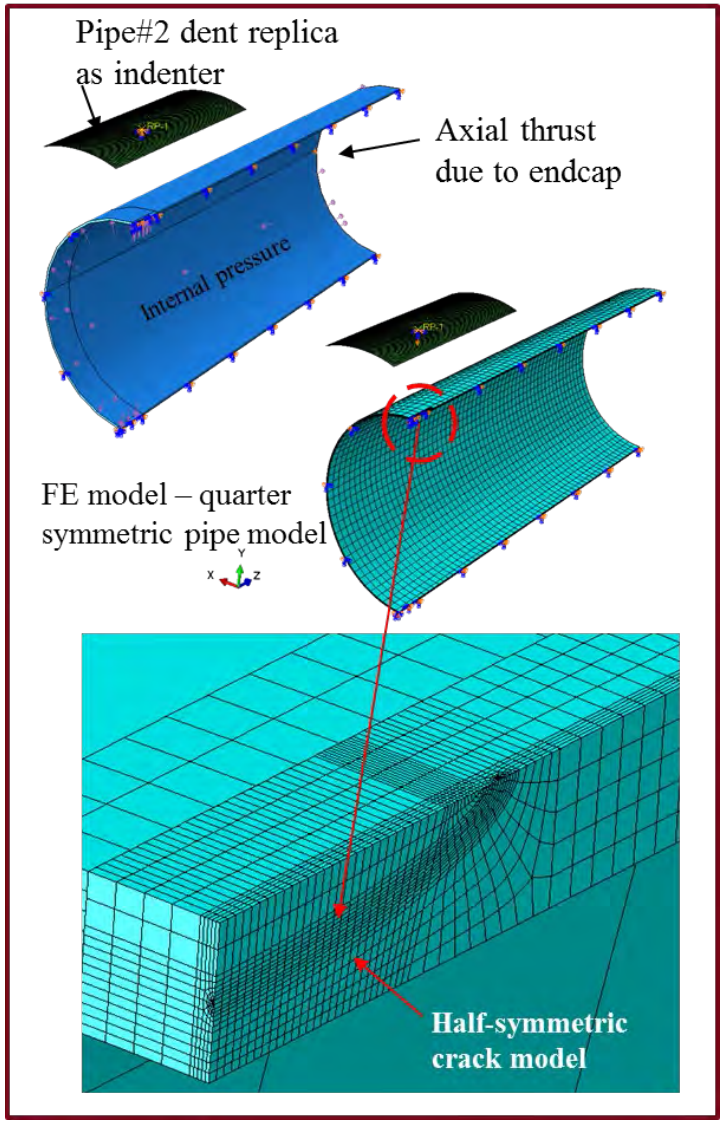


Fatigue Crack Growth Analysis

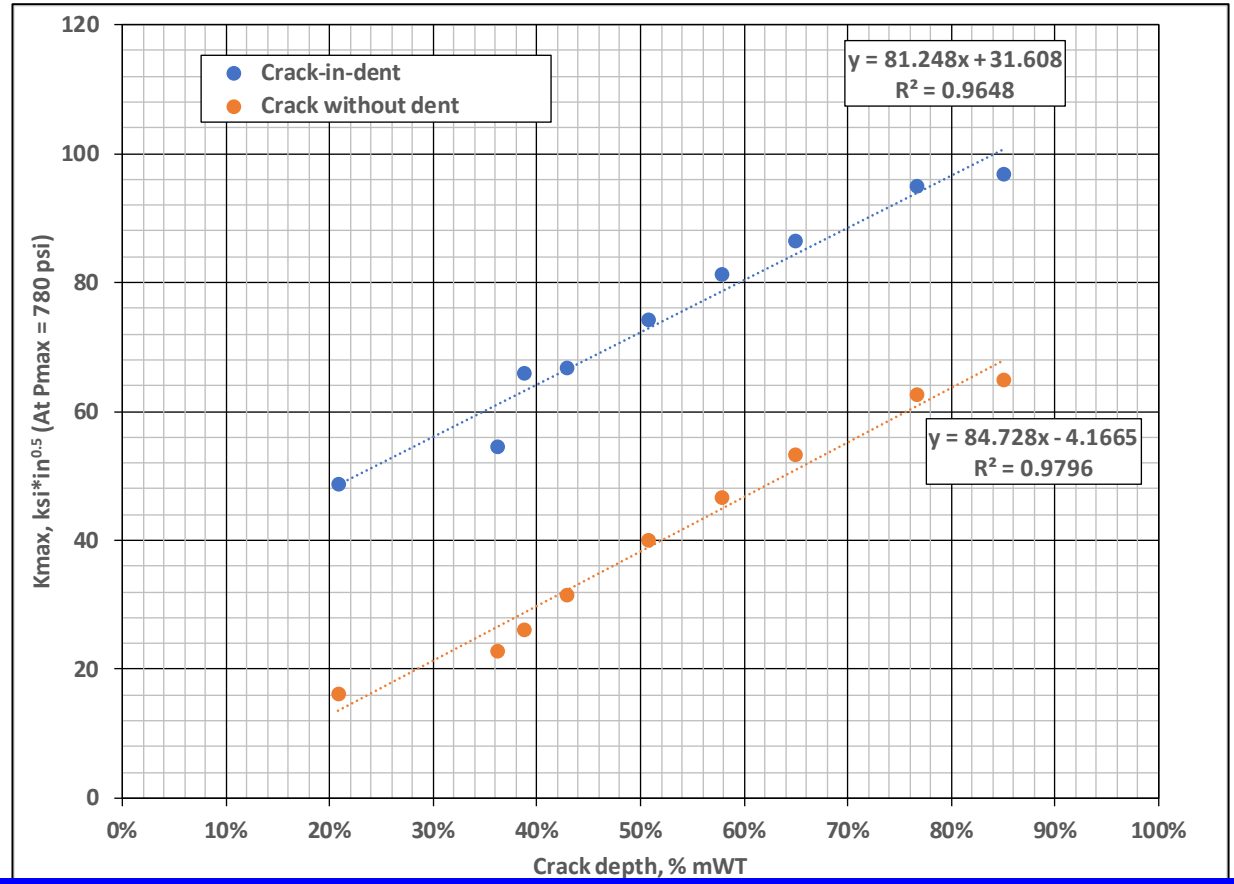
Fatigue crack growth rate was calculated using DCPD data obtained from full scale fatigue test



Elastic-Plastic Fracture Mechanics – Dent With Crack K-solution and ΔK



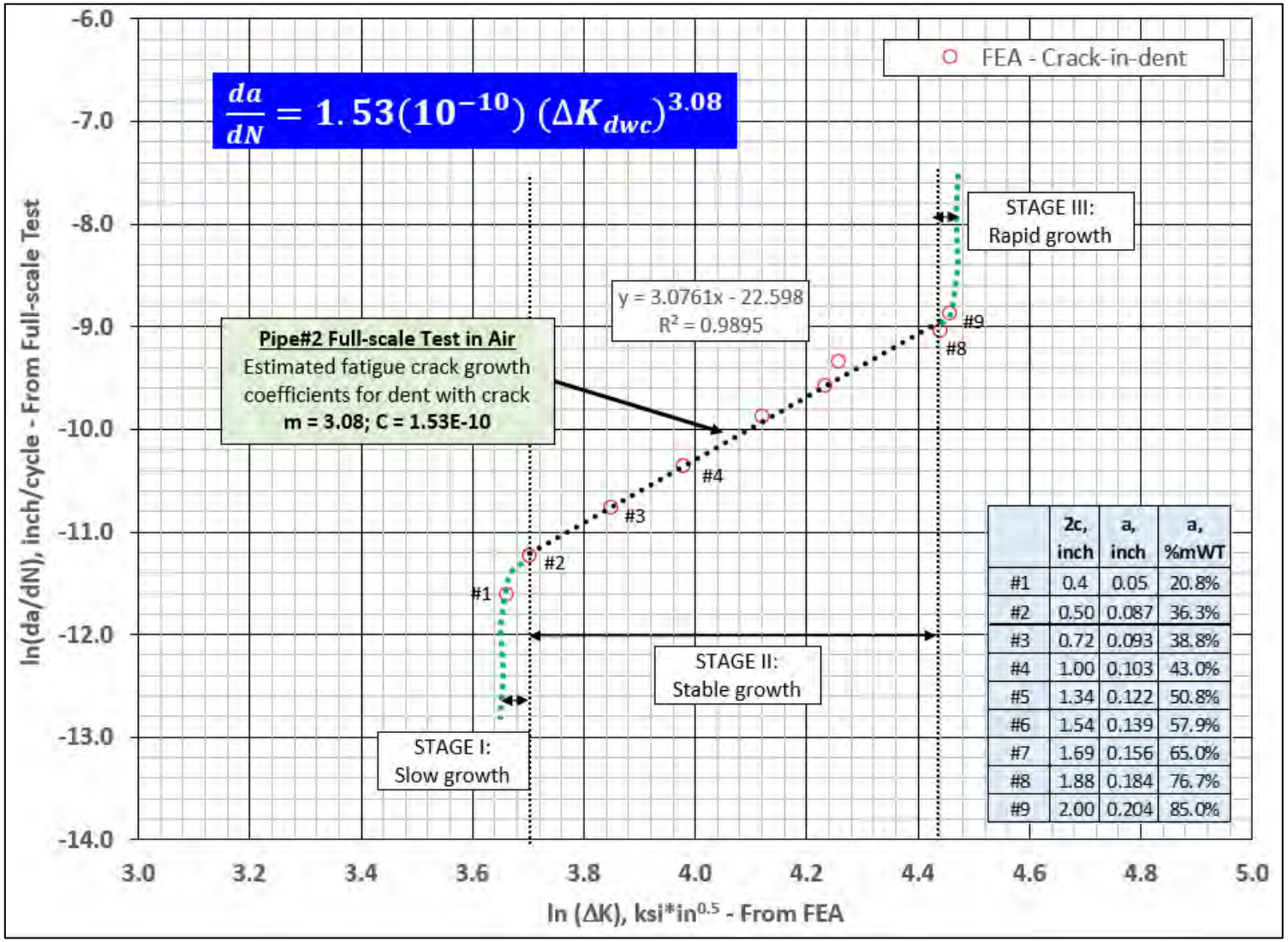
Stress Intensity Factor at Pmax – Crack-in-dent and No dent (1.5%OD Dent with external surface crack, 9 different crack sizes, i.e., 20% to 85% deep)



The stress intensity factor ratio of crack-in-dent and without dent ranges from 1.5 to 3.0 depending on the initial crack depths

LEADING PIPELINE RESEARCH

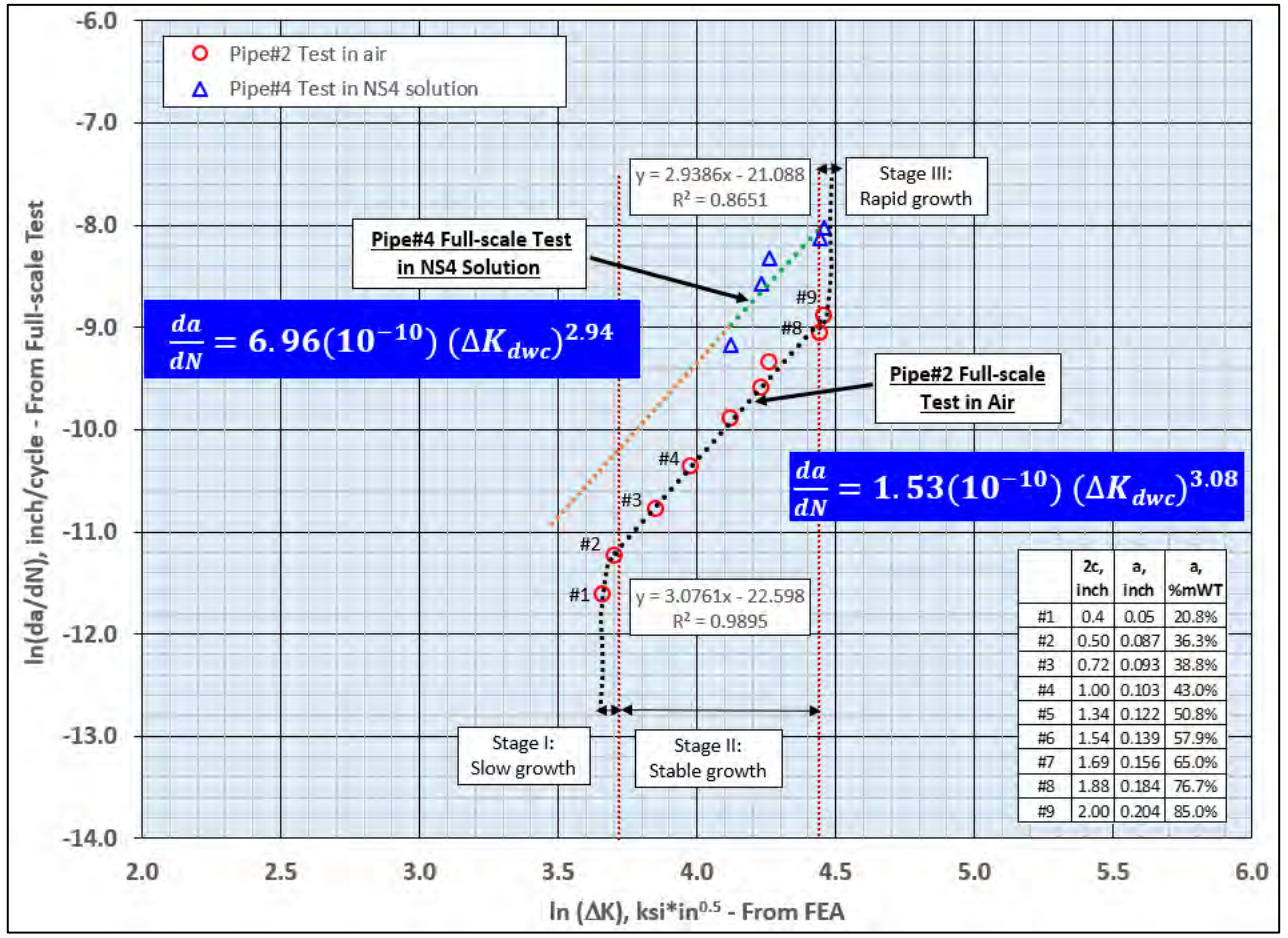
1.5% OD Dent with crack in Air – Pipe #2 Test ln(ΔK) vs. ln(da/dN) plot



	2c, inch	a, inch	a, %mWT
#1	0.4	0.05	20.8%
#2	0.50	0.087	36.3%
#3	0.72	0.093	38.8%
#4	1.00	0.103	43.0%
#5	1.34	0.122	50.8%
#6	1.54	0.139	57.9%
#7	1.69	0.156	65.0%
#8	1.88	0.184	76.7%
#9	2.00	0.204	85.0%

Estimated corrosion fatigue crack growth coefficients for pipe#2 dent in air : m=3.08, C=1.53E-10

Dent with crack - ΔK vs da/dN plot (Different environments but same dent depth)



	2c, inch	a, inch	a, %mWT
#1	0.4	0.05	20.8%
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#5	1.34	0.122	50.8%
#6	1.54	0.139	57.9%
#7	1.69	0.156	65.0%
#8	1.88	0.184	76.7%
#9	2.00	0.204	85.0%

P_{max} = 780 psi
P_{min} = 78 psi
ΔP = 702 psi
R = 0.1

Dent depth:

Pipe#2 = 1.5%OD (in air)
Pipe#4 = 1.6%OD (in NS4)

Paris' Law: $\frac{da}{dN} = C(\Delta K)^m$

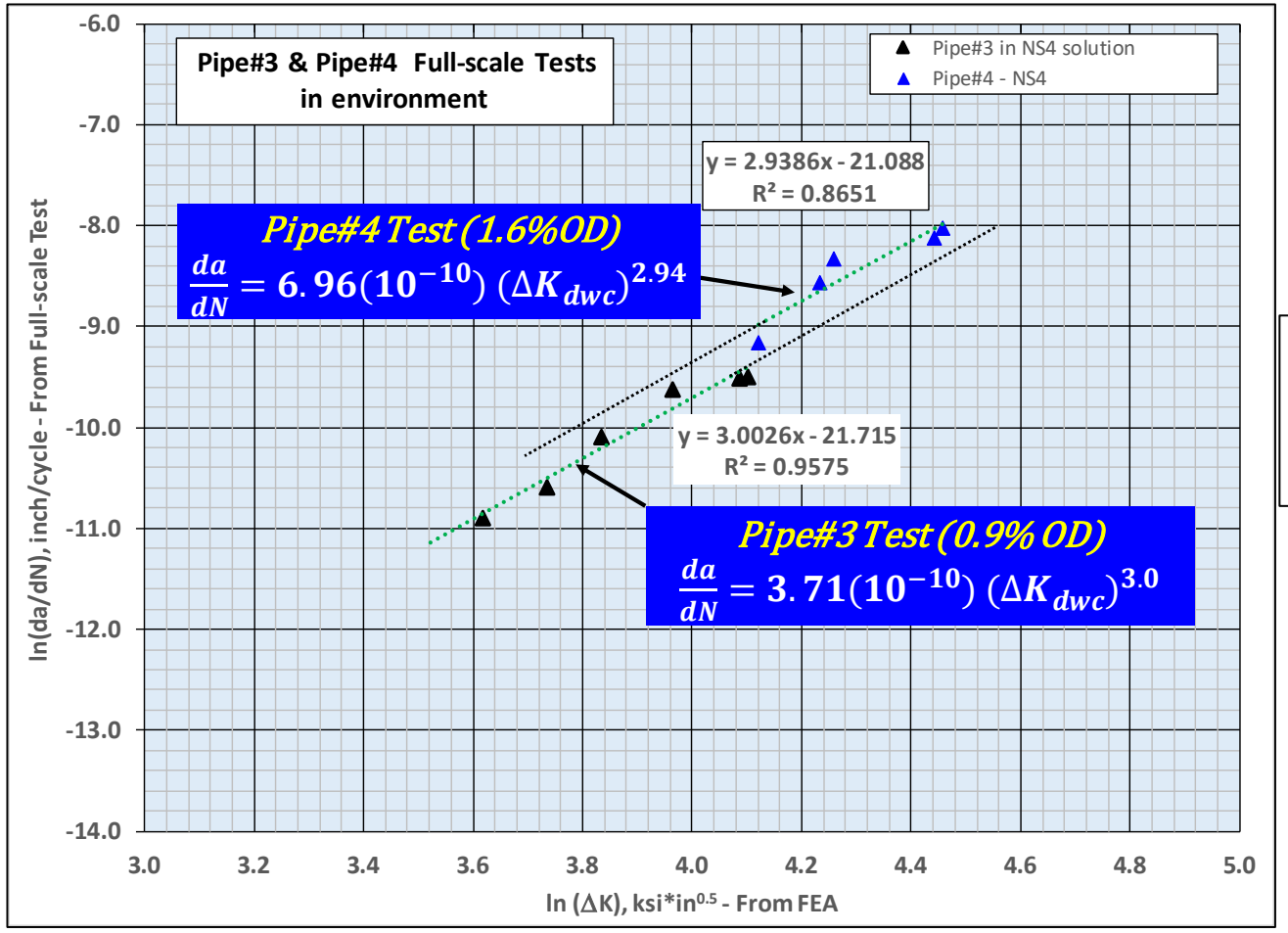
(or)

$\log (da/dN) = m \log \Delta K + \log C$

For a given dent depth, crack in dent can grow 4.5 times faster in NS4 than in air, i.e., as expected the growth coefficient "C" depends on the environment

LEADING PIPELINE RESEARCH

Dent with crack - ΔK vs da/dN plot (Same environment but different dent depth)



P_{max} = 780 psi
P_{min} = 78 psi
ΔP = 702 psi
R = 0.1

Dent depth:

Pipe#3 = 0.9%OD (in NS4)
Pipe#4 = 1.6%OD (in NS4)

Universal Equation – API 579/BS7910

The preliminary finding shows that for given environment, crack in deeper dent will grow faster than in shallow dent. It shows that the crack growth coefficient "C" depends on dent depth

Framework for Life Prediction

- Establish dent geometry, crack dimensions
- Quantify equivalent cycles for a given stress range
- Quantify the Stress Intensity factor range experienced by the pipeline
- Calculate cycles to failure using Corrosion Fatigue crack growth behavior (defined by experiments already conducted)
- Quantify remaining cycles before dent with crack at risk (appropriate safety factors)

Summary

- Performed 6 full-scale fatigue tests of pipe containing shallow dents < 2%OD with cracks in Air and NS4 environments
  - Leak occurred in crack-in-dent between **2200 – 3200** cycles
  - Failure mode: **Leaked first and then ruptured**
  - Demonstrated **minimum of 25 years remaining life**
- Calculated the fatigue crack growth rate in dent (using tests data) as function of stress intensity factor for crack-in-dent using FEA
- Established corrosion fatigue crack growth coefficients, **C and m** for dent with crack in air and NS4 environments, to use in Paris' Equation to calculate remaining life of dent with crack
- Developed a framework for remaining life prediction of dent associated with fatigue cracks
- Identified further research needs

Future Research needs

- Establish stress intensity factor (K-solution) for different crack sizes in various dent depths for different D/t ratio. This will allow estimation of stress intensity factor for cracks coincident with dents without the requirement of FEA

- Additional full scale testing to establish effect of dent depth, grade, D/t and verify the viability of existing corrosion fatigue crack growth rate guidelines in API579 and BS7910

Questions/comments?

Contact:

Uday Arumugam – uarumugam@blade-energy.com

Ming Gao – mgao@blade-energy.com

Ravi Krishnamurthy - ravimk@blade-energy.com

BACK TO AGENDA

PRCI 2020 Research Exchange

Improved ERW Fatigue Life Estimation



SIA-1-2 and IM-3-2

Aaron Dinovitzer
Sanjay Tiku, Morvarid Ghovanlou, Christian Mihailescu

BMT

LEADING PIPELINE RESEARCH

Presentation Outline

- **Background - Motivation & Research**
- **PRCI Development Program**
  - Material Testing
  - Full-Scale Testing
- **Implications**
- **General Observations and Nest Steps**

Background - Motivation

- **Pipeline Integrity Management**
  - 49 CFR 192 and 195 other standards (e.g. ASME B31) and good engineering practice require that operators manage the integrity of their pipeline system including:
    - Baseline assessment - line segment relative risk for failure
    - Asset integrity management - considering inspection and assessment
    - Remedial action planning – including repair and maintenance priorities and actions
  - The objective of integrity management is to consider:
    - Features identified by NDE, ILI or pressure testing → R&M decisions
      - Does feature threat increase with time/operation? . . .Will feature grow?
      - Does the feature need remediation? . . . . If yes . . .when?
      - When should next inspection be scheduled? . . . Monitor effect of operations and/or environment on progression towards failure.
  - Engineering analysis tools are used to answer these questions

Background - Motivation

- **Observations**
  - Fatigue life estimates vary depending on tools applied
  - Fatigue life estimates have been overly conservative

- **PRCI Research Project Objective**
  - Experimentation & analysis to demonstrate enhance fatigue life prediction accuracy and consistency
  - Focus on axial crack like features with specific attention to ERW weld seams



Background - Research

- **PRCI Research Program**
  - Phase I project
    - *Consider the source of differences between the fatigue life estimates produced by fatigue life assessment tools*
  - Phase II project (SIA-1-2)
    - *Determined the reasons for the variances and excessive conservatism*
    - *Developed solutions that can be used now by operators to improve their FFS determinations*
  - Phase III project (IM-3-2)
    - *Additional ERW linepipe material testing*
    - *Full scale testing to document enhancement of life estimation procedures*

Development Program - Material

- **Objective of this work was to:**
  - Through experimental and numerical analysis improve accuracy and consistency of fatigue life predictions (control conservatism)
    - Previous work demonstrated improved driving force estimation
      - API 579 axial flaw formulation
      - Eliminates over estimation of bulging correction factor for long or deep flaws
  - Current work improves material resistance data
    - Material testing defines linepipe fatigue crack growth rates
    - Full scale testing demonstrates life prediction improvement



Development Program - Material

- **Material Resistance – Fatigue Testing**
  - Development of Fatigue Crack Growth Data
    - Collected a range of material grades, vintages and manufacturing

      – Complete multiple compact tension fatigue tests for each base material and weld zone pipe sample

      – ASTM E647-11 – Compact Tension (CT) Specimen
        » No intentional defects in the material

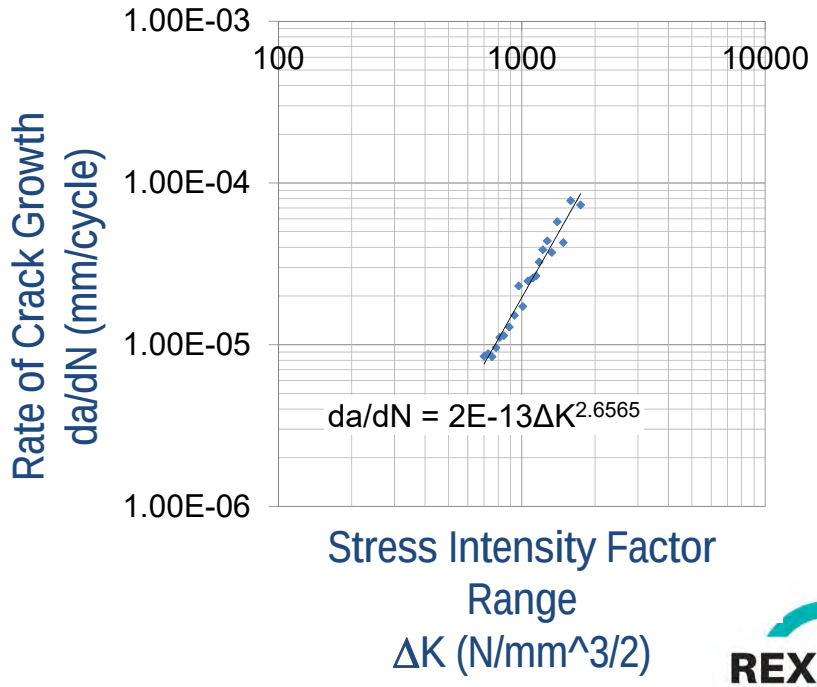




Development Program - Material

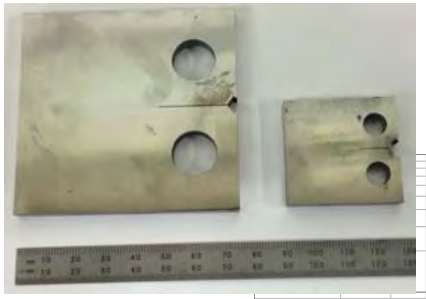
- **Material Resistance - Fatigue Testing**
  - Preliminary Data Reduction

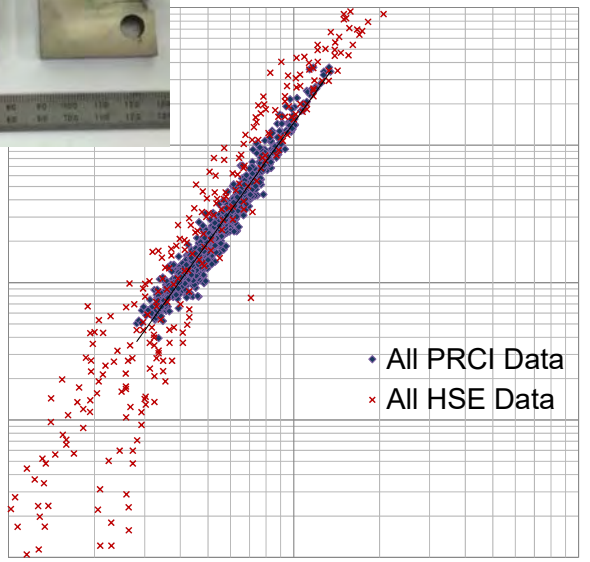
Power Law Constants	C	m
Test Result	$2.0x10^{-13}$	2.65
BS7910	$5.21x10^{-13}$	3.0



Development Program - Material

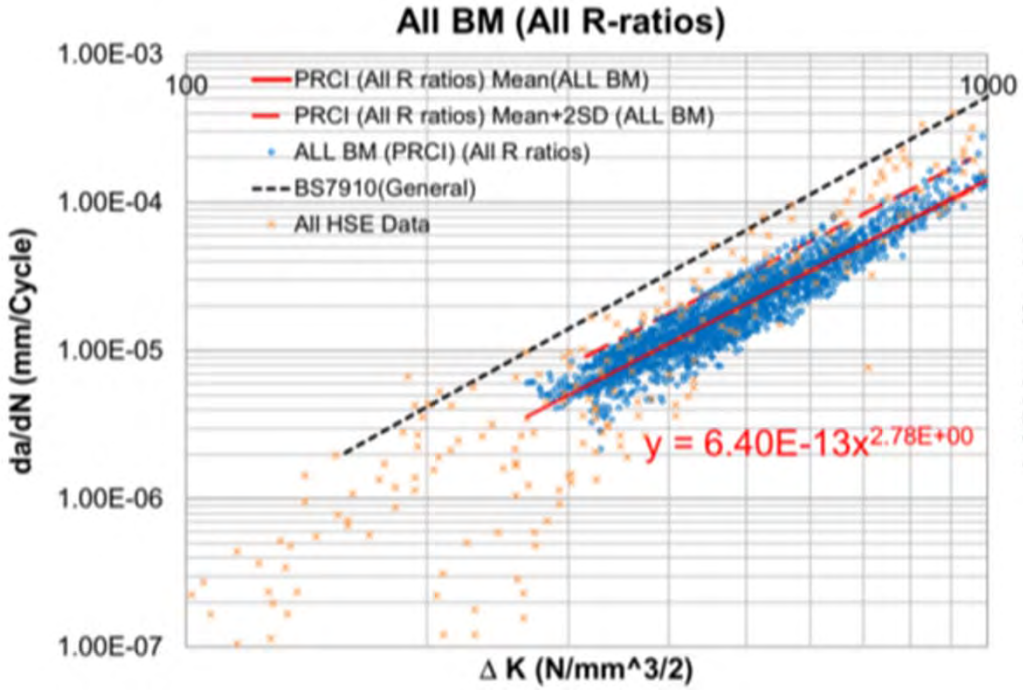
- **Enhancement of Fatigue Crack Growth Rate Parameters**
  - 45 materials tested
    - 185 fatigue tests
    - Approx. 17,000 crack growth rate measurements
  - Vintage 1936 to 2014
    - 50% of samples 1950 to 1970's
  - Diameter 10 in to 36 in (OD and WT checked)
  - Grade / Yield Strength
    - 42 ksi to 60 ksi
    - Flattened strap testing for undefined materials
  - Two specimen sizes used (30 / 60 mm)
  - Some specimens shown to include small weld inclusions

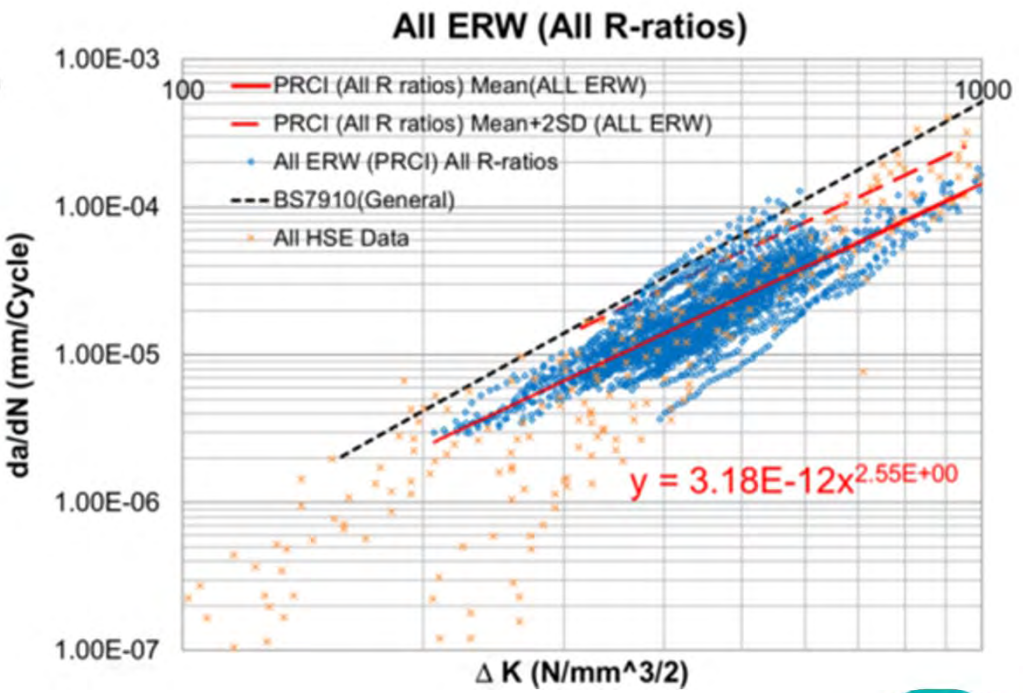




Development Program - Material

- BM & ERW growth rates lower than existing standards





Development Program – Full-Scale Testing

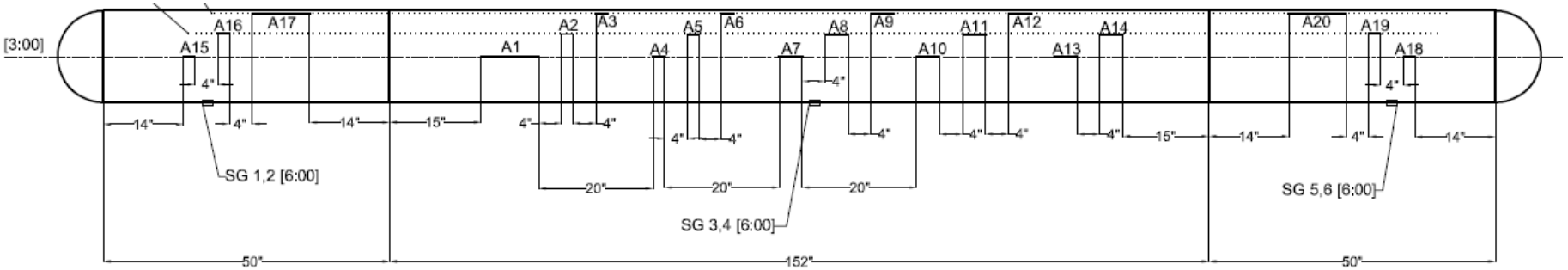
- **Two end capped pipes with crack like defects**
  - Machine combinations of shallow/deep and short/long defects
  - Cycle pressure to initiate fatigue cracks then monitor growth
  - Dye pen, NDE and instrumentation to monitor crack size
  - Fillet welded patch to be used to cover leaking flaws to finish test





Development Program – Full-Scale Testing

- **Testing Details**
  - 21 ft test specimen with 29 features (19 BM / 10 WCL)





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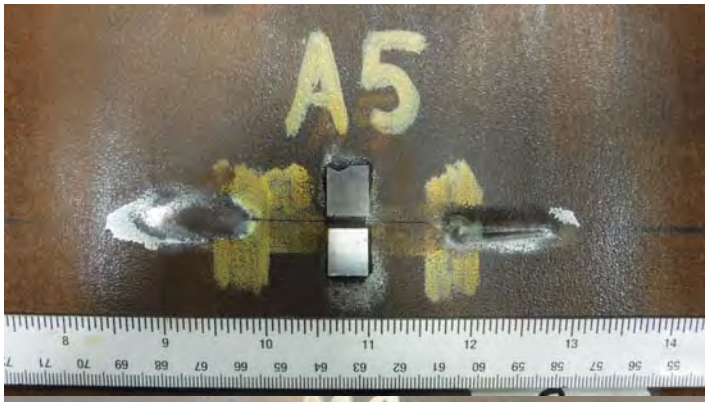
Development Program – Full-Scale Testing

- **Testing Details**
  - Each feature was cut to specified depth and length (0.15 mm / 0.006 in.)
  - Range of depths
    - 20% to 70% WT
  - Range of lengths
    - 50 to 250 mm (2 to 10 in)



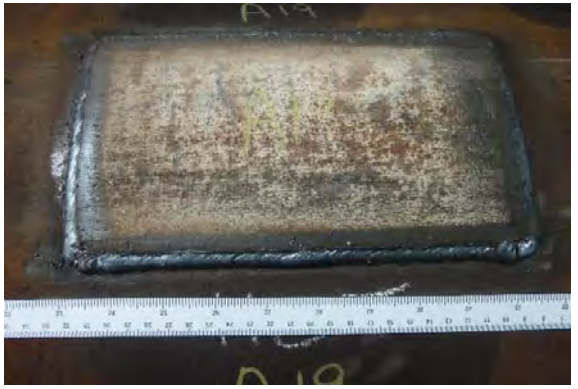




Development Program – Full-Scale Testing

- **Testing Process**
  - Set up test specimen
    - Add end caps
    - Machine notches
    - Calibrate crack measurement
  - Fatigue Crack Growth
    - Apply cyclic pressure
    - Intermittent compliance measurement
    - Stop test when crack leaks
  - Repair test specimen
    - Cut out cracked pipe area
    - Patch test specimen
    - Continue fatigue testing
  - Evaluate Test Results
    - Consider actual crack size
    - Define initiation life
    - Compare results to prediction



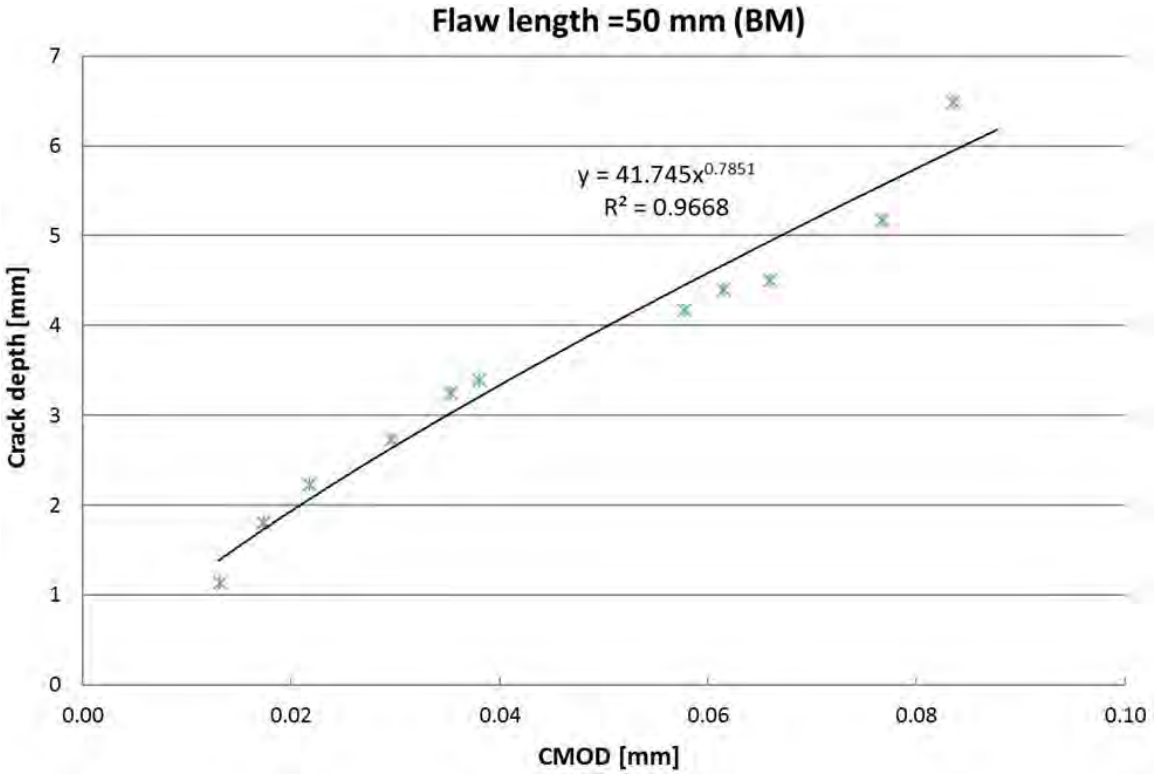




Development Program – Full-Scale Testing

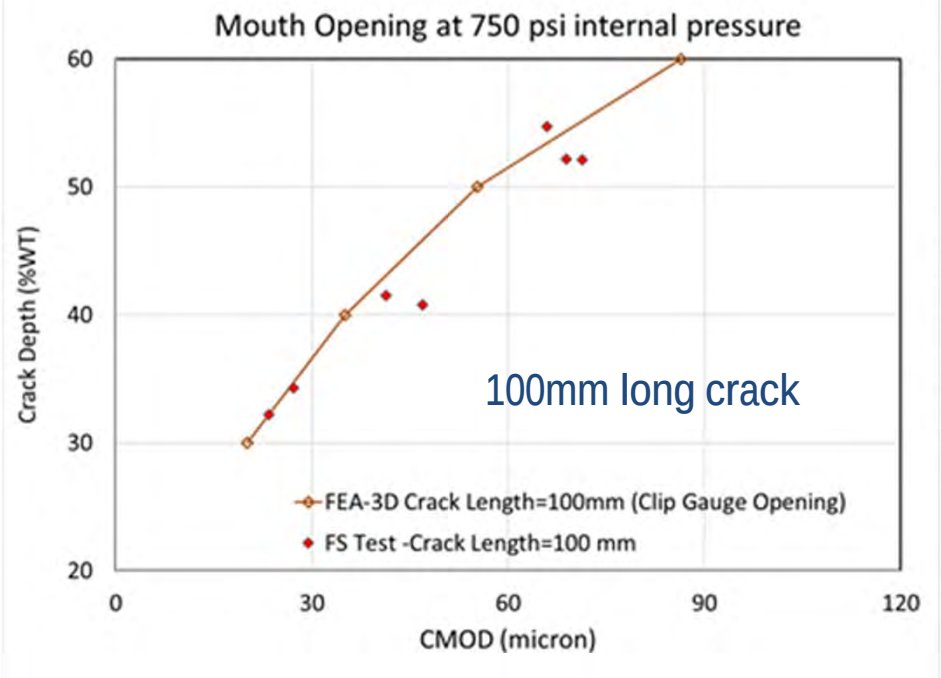
- **Testing Details**
  - Monitor crack size (calibration)
  - Completed for a range of lengths



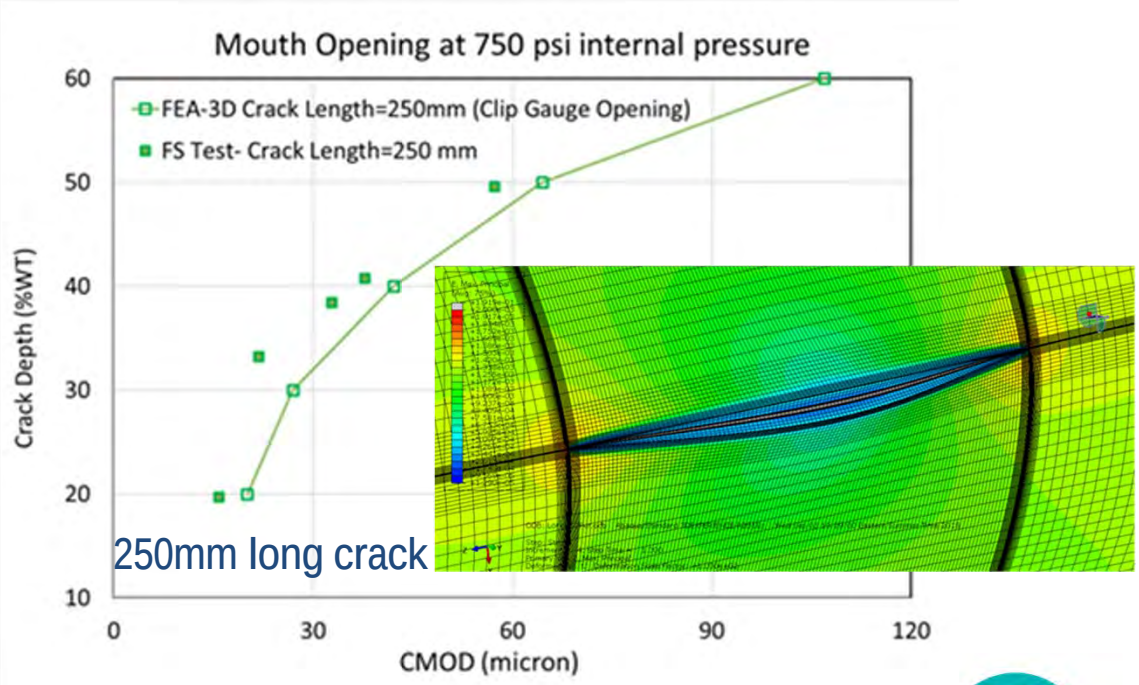


Development Program - Full Scale Comparison with FEA

CMOD-FEA vs Full Scale Test Measurements

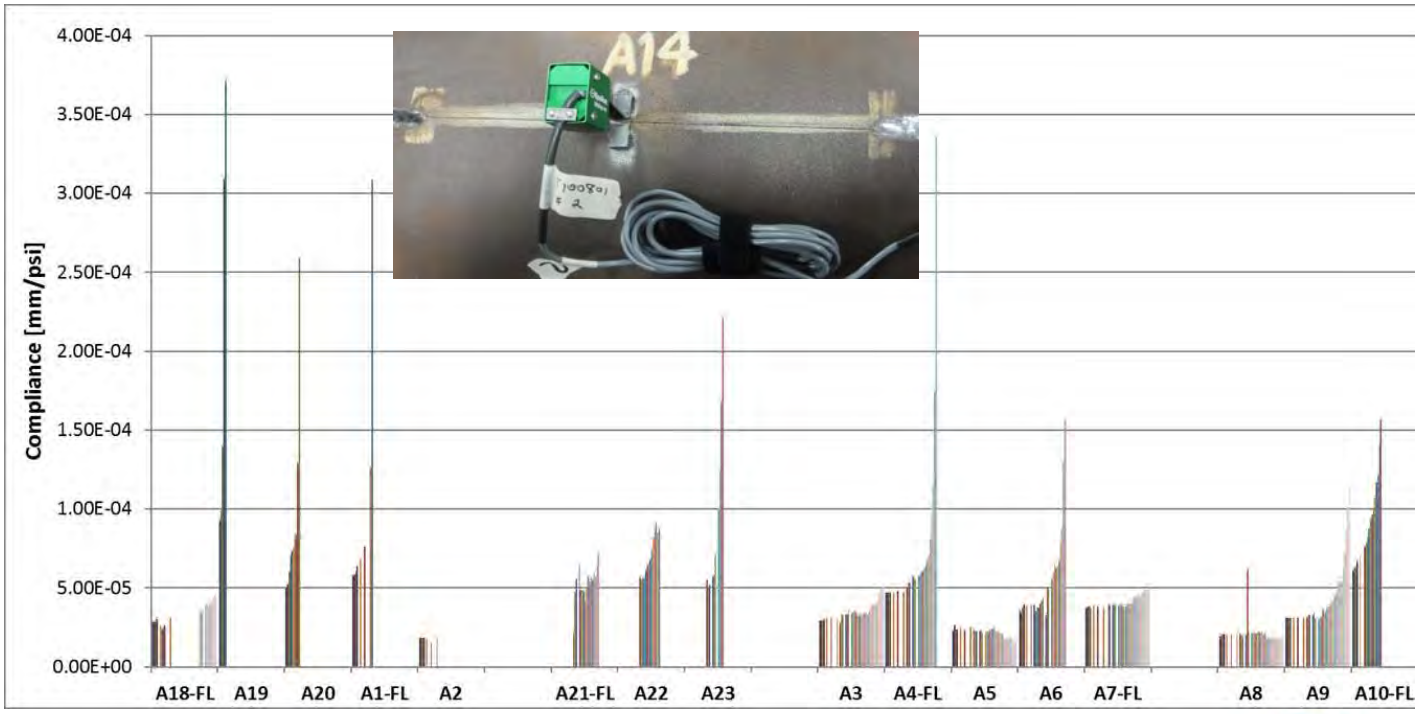


FEA Analysis to Validate CMOD vs Crack Depth



Development Program – Full-Scale Testing

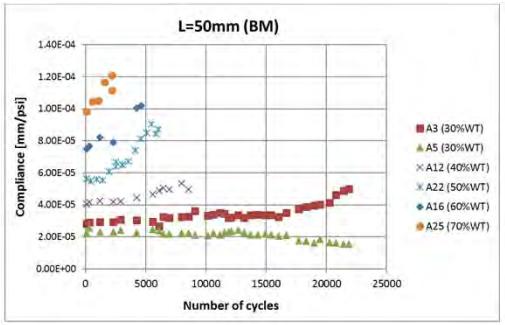
- **Testing Details**
  - Monitoring of crack size
  - Pause cyclic testing at intermediate points and measure compliance (size)

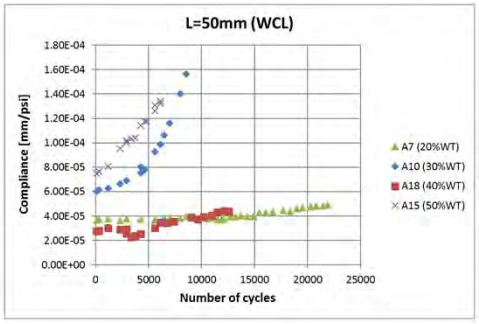


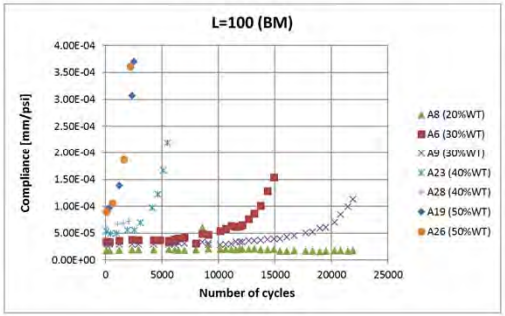
Development Program – Full-Scale Testing

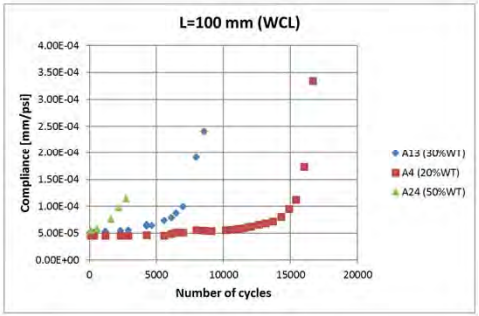
- **Testing Details**
  - Monitoring of crack size
  - Compliance (size) increases with cycles
  - Flat zone represents initiation
    - Initiation at 0.1 mm growth in crack depth

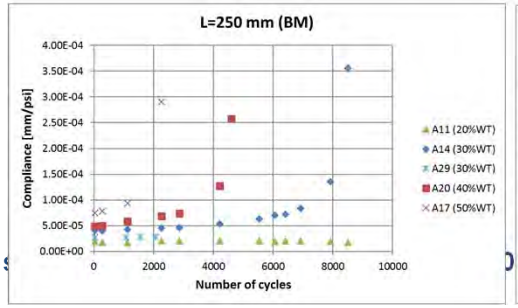


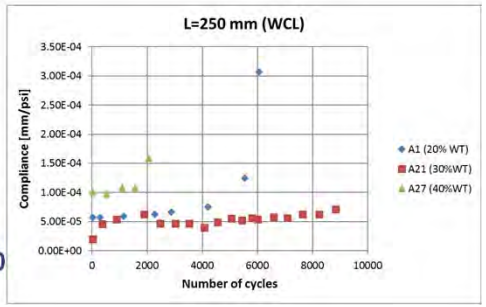






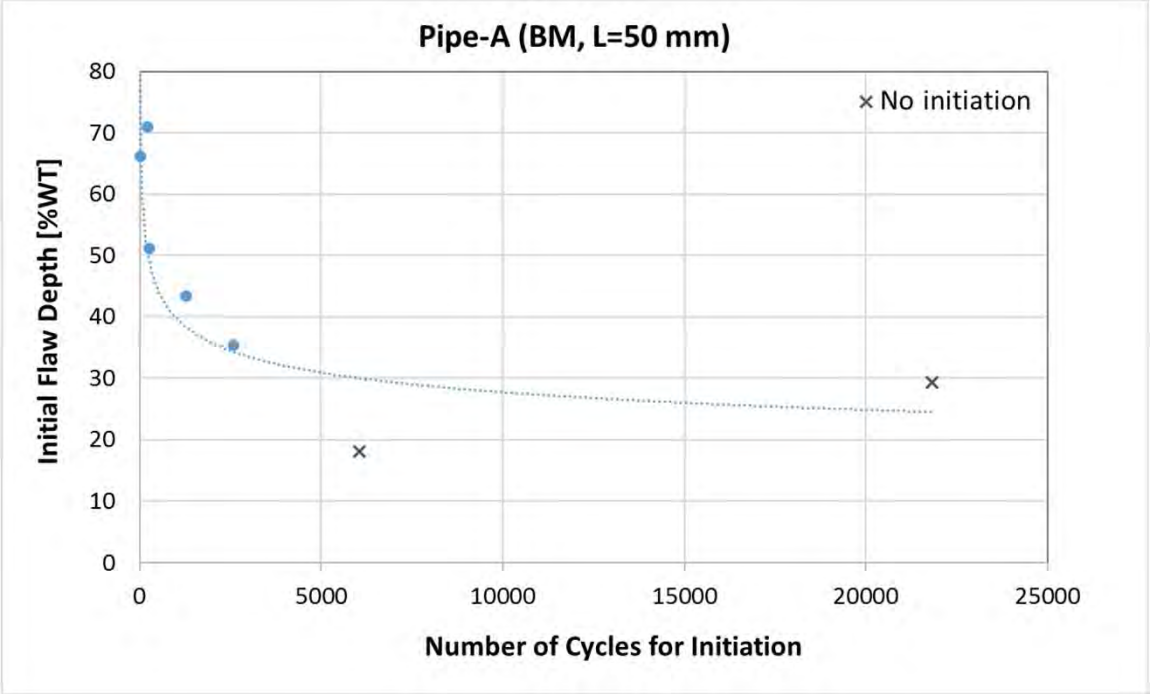






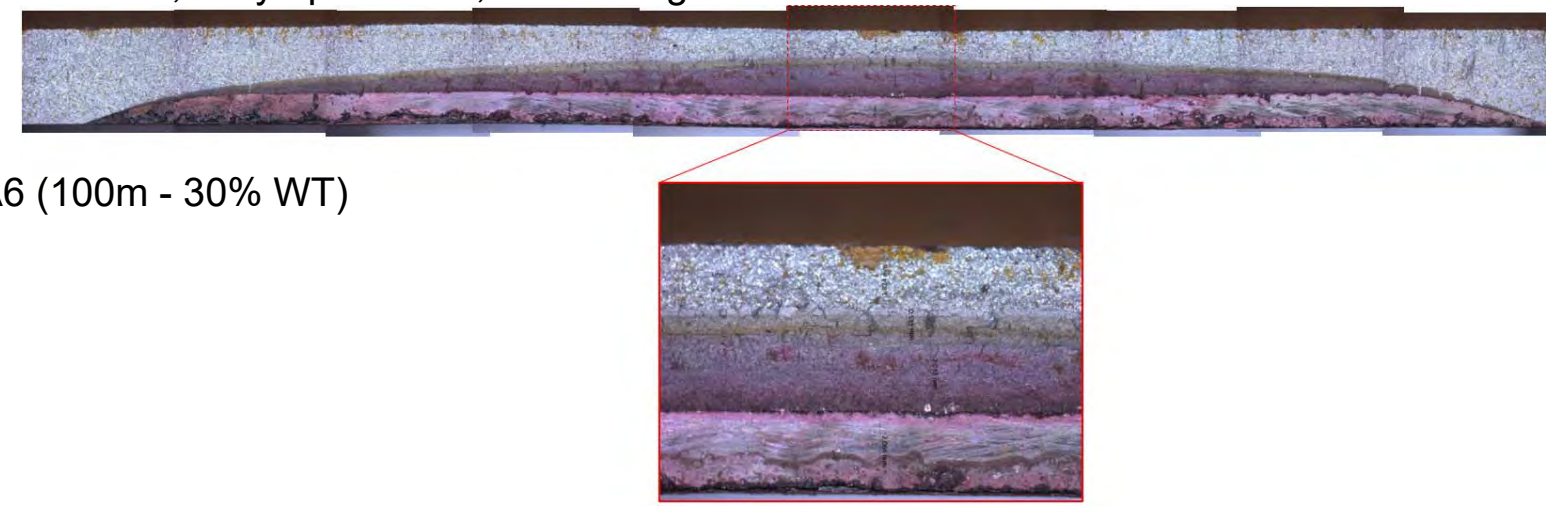
Full Scale Testing – Additional Observations

- **Initiation Life . . . . Some thoughts**
  - The number of cycles to grow from starter slit can be related to initiation life of lack of fusion defects
  - A 30% deep 50mm long blunt defect has an initiation life > 20,000 cycles
    - The crack growth life was <20,000 cycles
  - Developing further understanding of this data could provide better prediction fatigue life of blunt defects
  - Must be able to differentiate between crack and blunt planar flaws



Development Program – Full-Scale Testing

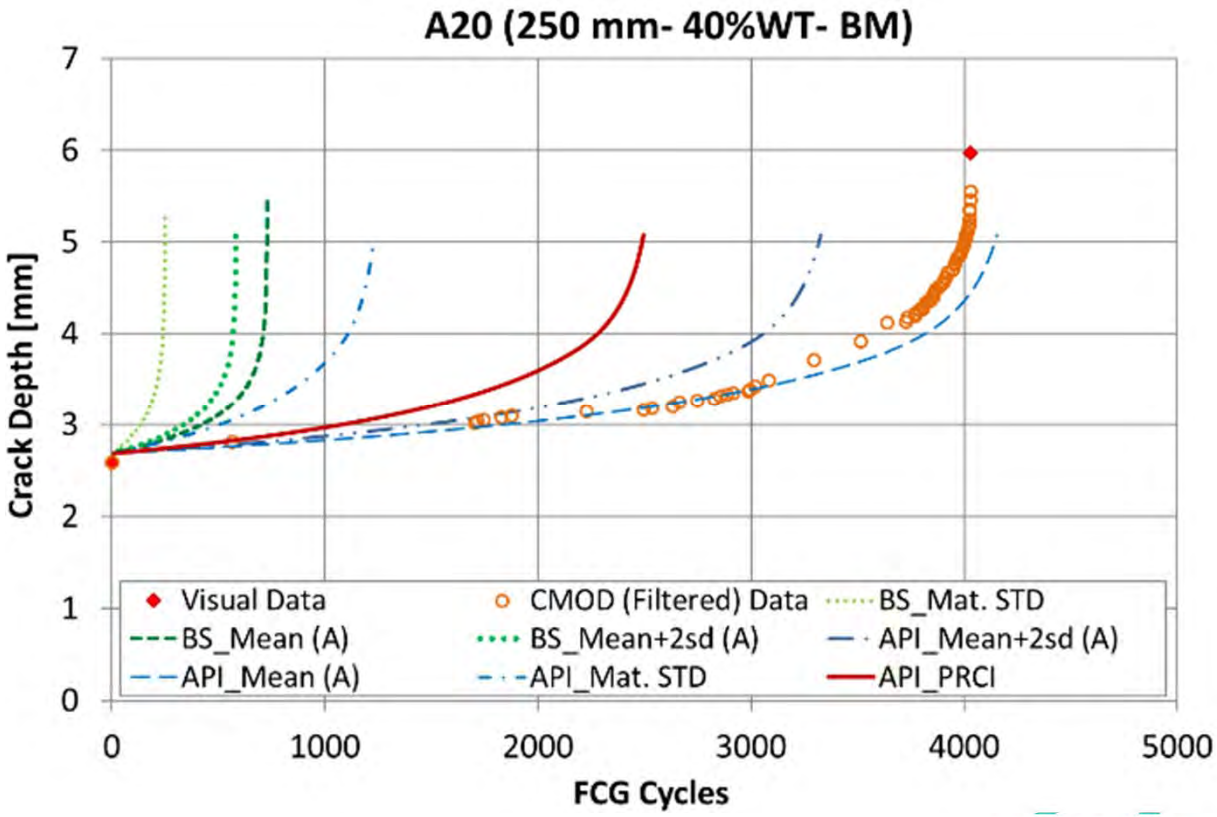
- **Testing Details**
  - Feature / Crack Size Confirmation
    - Initial cut, Dye penetrant, Final ligament failure



  - A6 (100m - 30% WT)

Development Program – Full-Scale Testing

- **Comparison with predictions**
  - Traditional and new (API 579) fracture mechanics crack growth formulations
  - Traditional, new and material specific fatigue crack growth rate material data
    - Symbols – FS data
    - Green – BS7910
    - Blue – API
    - Red – API formulations
      + PRCI database



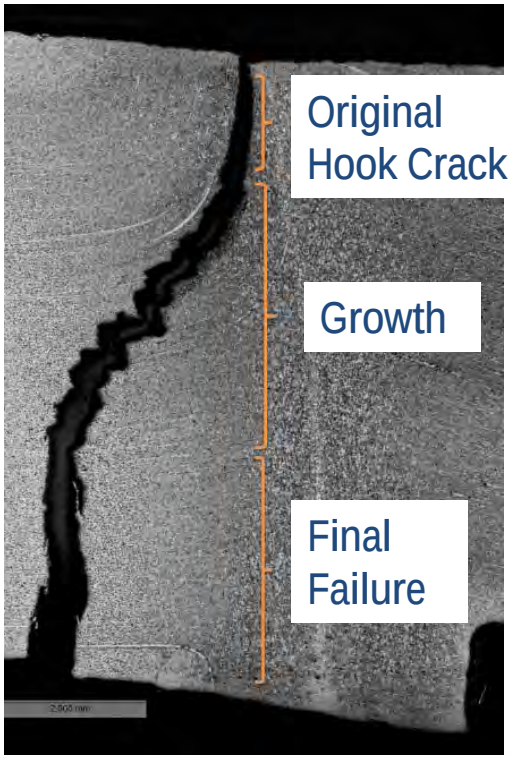
Implications

- **What does this mean in terms of fatigue life estimates**
  - For constant amp. loading life conservatism reduced 2 to 7 fold
  - For longer and deeper initial flaws differences will be higher

OD/t	Initial Flaw Length (mm)	Initial Flaw Depth (a/t)	BS7910 Curved Shell	API 579	API 579 PRCI C and m	
96	20	0.1	150,000	163,000	304,000	(2.0)
		0.6	10,000	12,100	24,200	(2.4)
	75	0.1	89,000	97,500	188,000	(2.1)
		0.6	600	1,500	3,100	(5.1)
26	20	0.1	150,000	207,000	391,000	(2.6)
		0.6	18,000	26,000	50,000	(2.8)
	75	0.1	72,000	107,500	209,000	(2.9)
		0.6	900	3,300	6,700	(7.4)

Implications

- **Measured fatigue crack growth rates are lower than recommended values in standards**
  - Base material are 3 times lower
  - ERW weld seam are 1.3 times lower
- **Hook cracks fatigue growth likely in base material**
- **Need to consider LOF growth**



General Observations & Next Steps

- **Axial flaw fatigue life prediction improved by**
  - Application of new crack growth rates
  - Application of API 579 newest formulation
- **Greatest improvement seen for long and deep flaws**
  - Improvement in incorporation of bulging effect at crack
- **Should consider fatigue growth rates in other welds**
  - DSAW
  - Girth welds

General Observations & Next Steps

- **Should consider fatigue growth rates in other welds**
  - DSAW
  - Girth welds
- **For ERW and EFW welds should consider**
  - Effect of reinforcement
  - Hook crack SIF
- **Need to improve detection and characterization of LOF and hook cracks**
- **Need to improve discrimination of cracks vs lack of fusion**

BACK TO AGENDA

PRCI 2020 Research Exchange

Innovation in reliability-based pipeline integrity methods; making the best information accessible in a reasonable time period.

Aidan Charlton CEng MIMechE, Senior Engineer, Penspen

Mike Brown CEng MIMechE, Principal Consultant, Penspen

LEADING PIPELINE RESEARCH

Objectives of research project

- Pipelines are expensive assets which are often expected to operate under less than ideal circumstances with impeccable safety.
- Pipelines are often required to operate beyond design life as EOR techniques improve, in many cases the expected future availability of pipelines for export can impact field economics.
- Quantifying the PoF will be increasingly more important in making decisions WRT safety. The most robust methods of calculating PoF are computationally expensive.
- This project aims to reduce the computational time of calculation of PoF to times comparable with deterministic methods.

Iterations	Time per defect
1.00E+4	1 Sec
1.00E+5	10Sec
1.00E+6	1.7 Min
1.00E+7	16.7 Min
1.00E+8	2.8 Hours
1.00E+9	1.2 Days
1.00E+10	1.7 Weeks
1.00E+11	16.5 Weeks
1.00E+12	3.2 Years

Brief review of tasks undertaken

- Practical prior research was identified in *PR-244-05302 Guidelines for Reliability Based Pipeline Integrity Methods.*
- A computer model was built in C++ & CUDA to allow GPU parallel processing.
- A Probability of Failure (PoF) surface was constructed for the example pipeline.
- A multi-variable, multi-degree polynomial was constructed and optimised to calculate the PoF as a function of feature length and feature depth.
- Sensitivity and bounding have been optimised.
- Testing has been undertaken at deterministic speeds.

Highlights

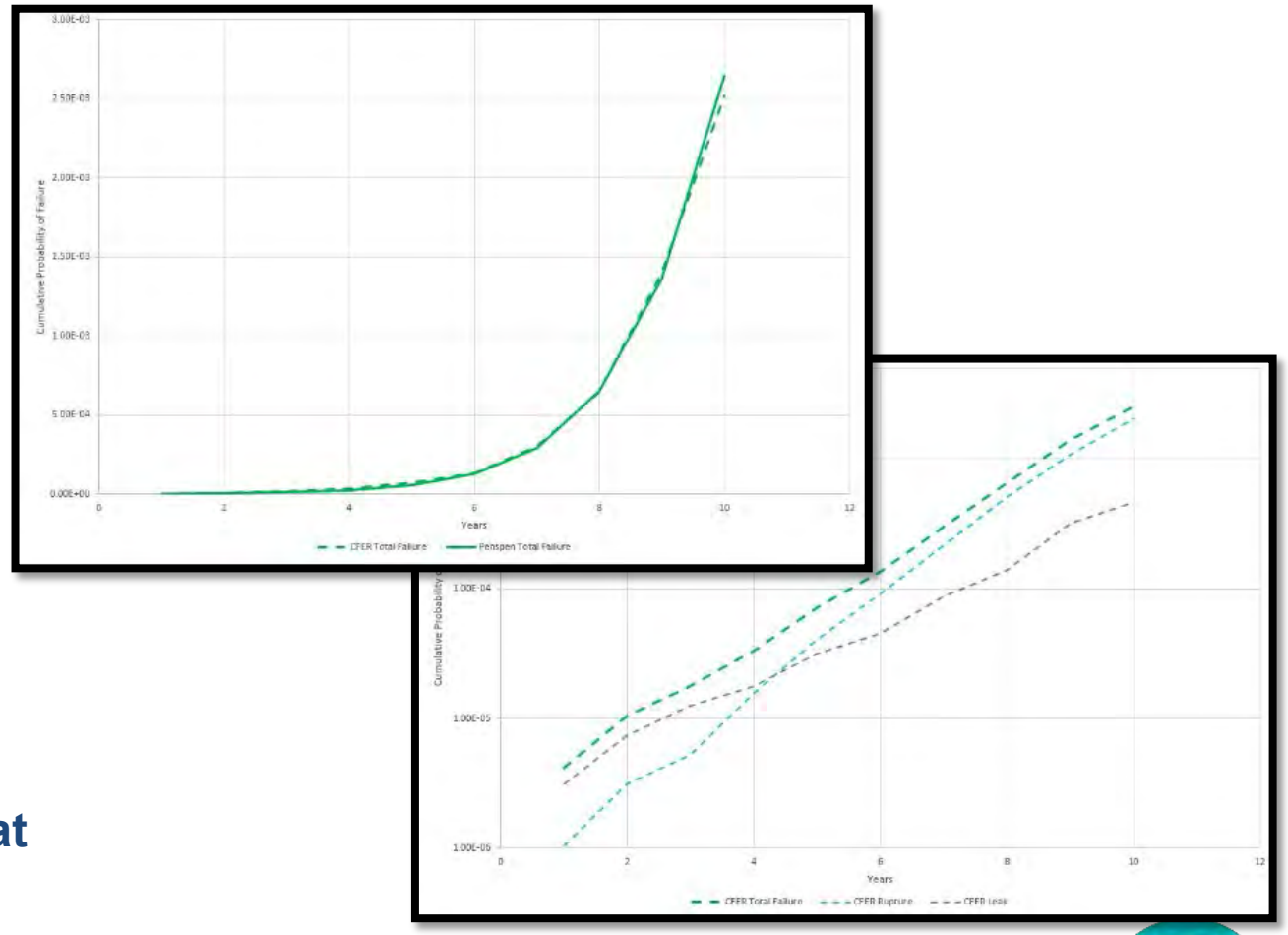
- Applying this method, model run-time is improved to deterministic speeds for any further defect analysis on the example pipeline.
- Accuracy is targeted in the region 10^{-3} to 10^{-6}, the results show very good correlation within these bounds.
- Calculation of PoF for use within analyses previously only accessible to deterministic analysis is now practical.
- Analysis that could benefit from this method include optimisation of operating parameters such as chemical injection which can help reduce cost to industry, or analysis of complex geometry.
- Removal of any requirement for Machine Learning (ML) has removed the ‘black box’ and allows a quantifiable and justifiable degree of uncertainty in the results to be produced.

Origin of research project

- This research project builds on PRCI project *PR-244-05302 Guidelines for Reliability Based Pipeline Integrity Methods.*

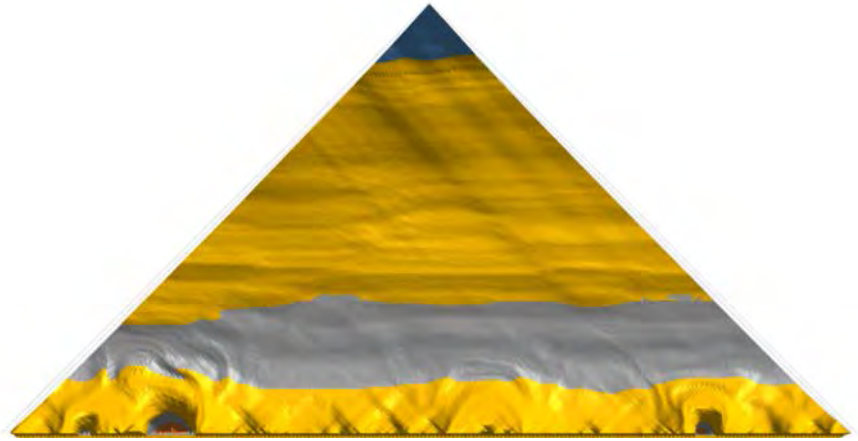
- The original methodology is well accepted, but cannot be made to run at speeds comparable to deterministic, for example to allow multiple ‘what if’ scenarios to assist optimisation of asset management.

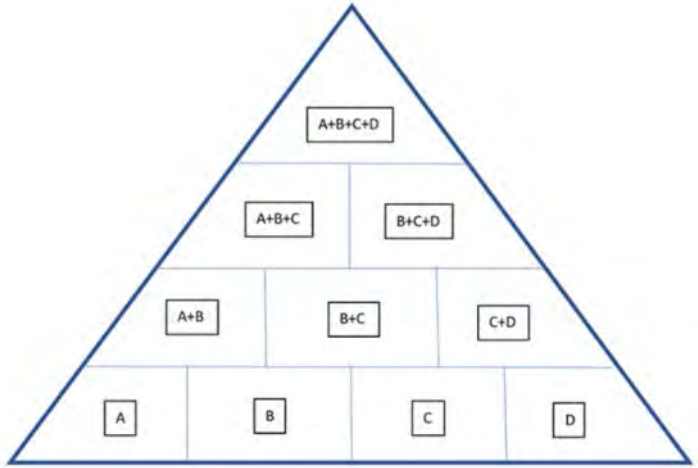
- The target of this research is to develop a methodology to allow calculation of PoF at deterministic speeds with reasonable level of convergence.

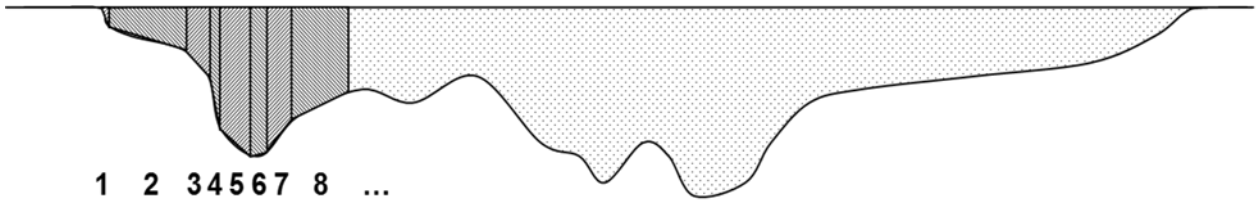


Foundation built on PTC2019 & RIO2019 research

- Consider the probability of failure for a corrosion feature with complex geometry.
- At 1.5 mm measurement resolution this forms a diagonal 8000x8000 matrix.
- n = 8000, Total = n(n+1)/2
- There are 32,004,000 combinations to be assessed (which will take considerable time using Monte Carlo, FORM or SORM simulations).

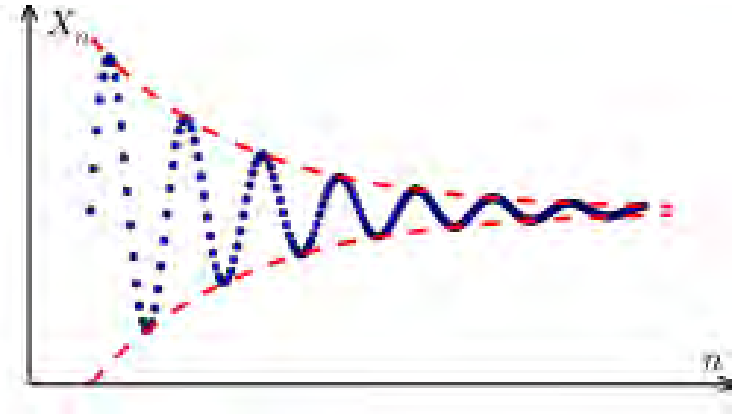


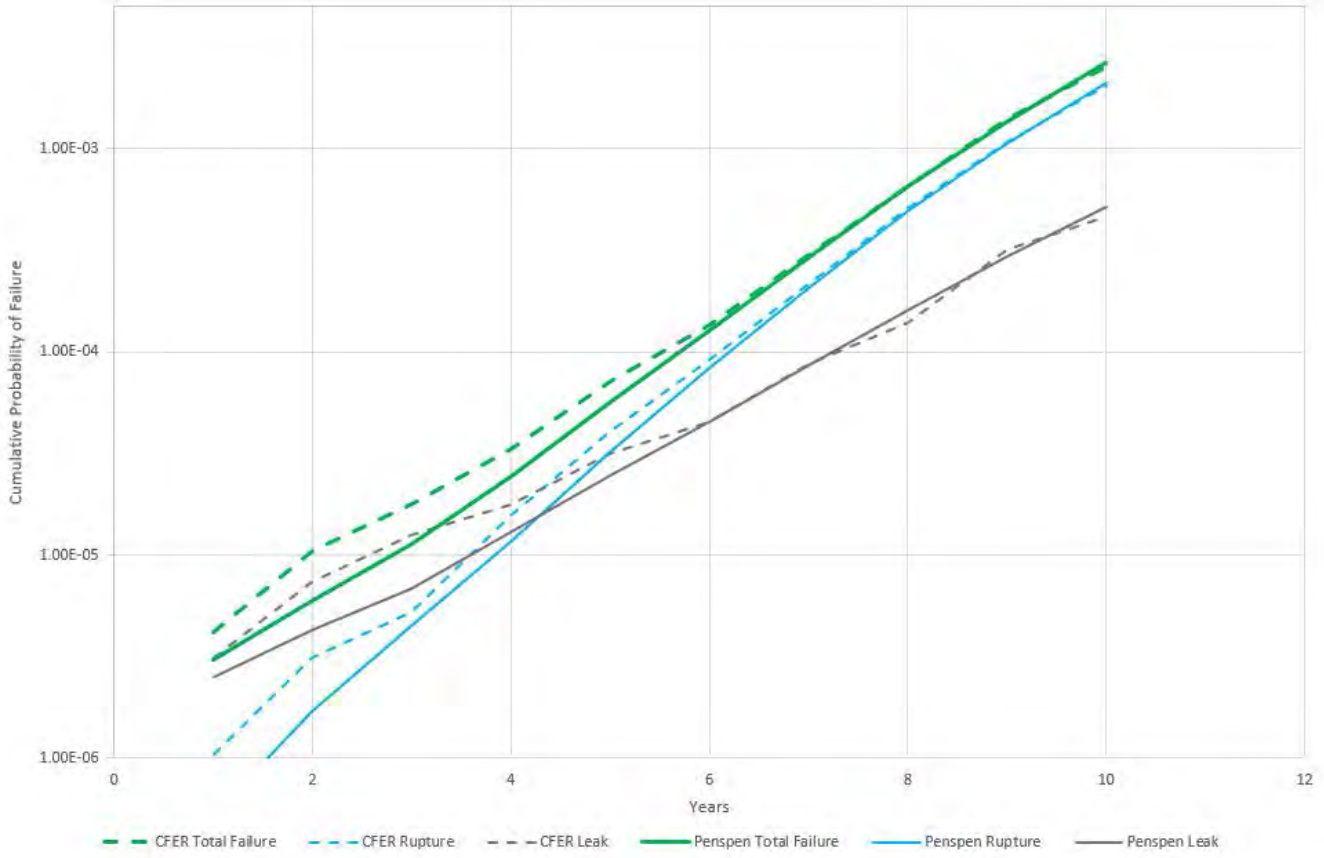




Developing a baseline of convergence

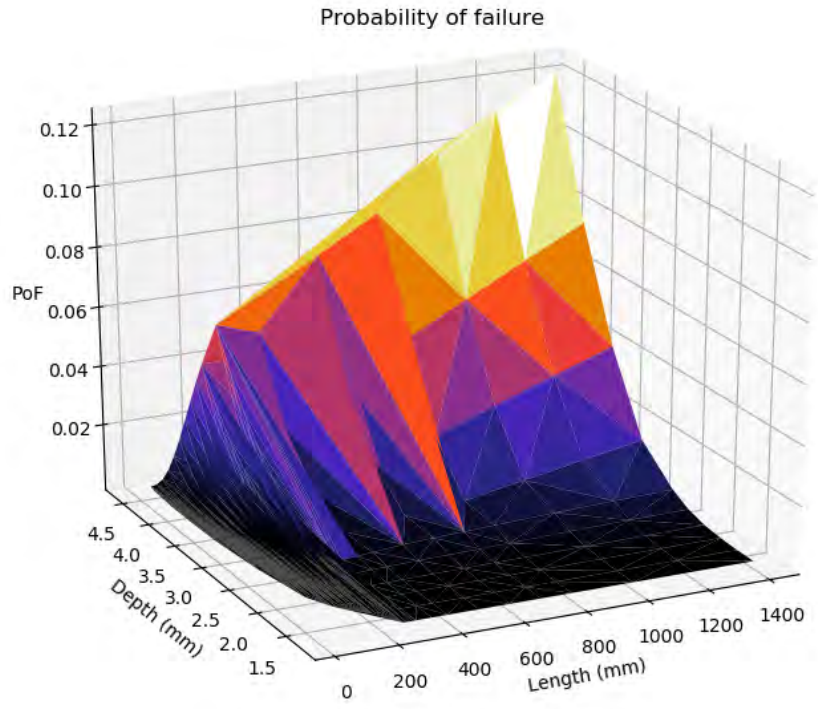
- Initial research work was developed in C++ with CUDA to allow massive parallel processing via GPU.
- GPU processing allows defects to be assessed to a point closer to convergence, or more features to be assessed in the same time period.





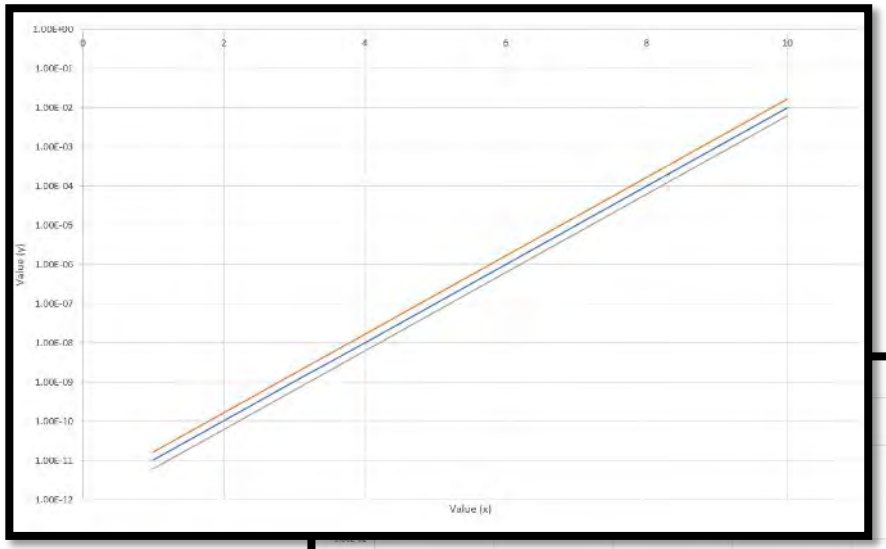
Developing a probability of failure surface

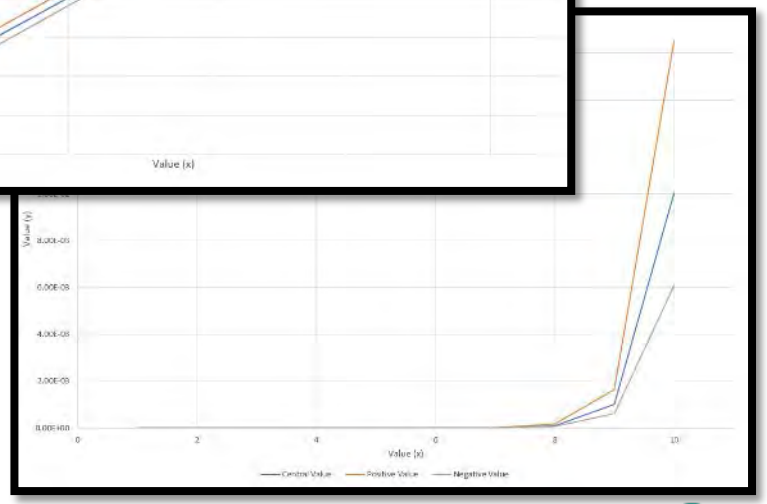
- Using GPU processing a probability of failure surface can be developed in a reasonable time frame.
- Once a speed improvement of approximately 10^3 orders of magnitude has been achieved, new applications are possible.
- Using a partial probabilistic assumption where many iterations will tend to the mean, it is possible to map the probability of failure from time basis to length & depth dimensions.
- The partial probabilistic assumption is valid provided many iterations are undertaken. The iteration requirement for stability is reduced due to the way the *PR-244-05302* equations are formulated.

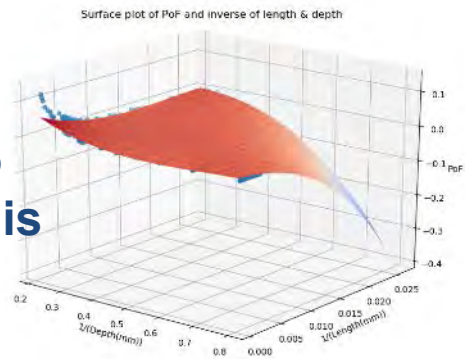


Determining optimum workspace

- The majority of the locations on the failure surface are near to zero. This can lead to predictive functions predicting negative PoF with very little margin for error.
- Curve fitting typically operates on an absolute error basis characterised by statistics such as Root Mean Square Error (RMSE).
- Locations with high PoF can have highly variable absolute value when converted from LN(PoF) to PoF using the natural exponential function.
- Use of the natural logarithm to convert values to LN(PoF)can be better provided appropriate care is taken.

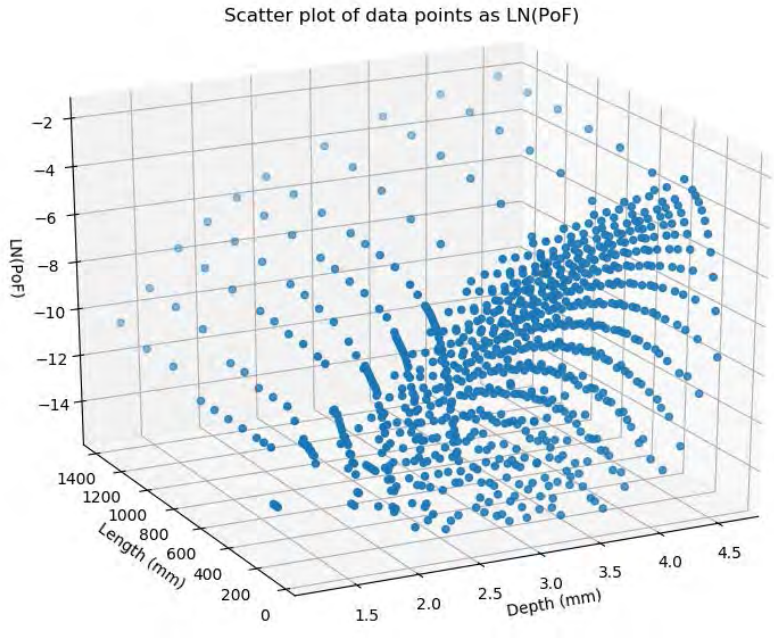




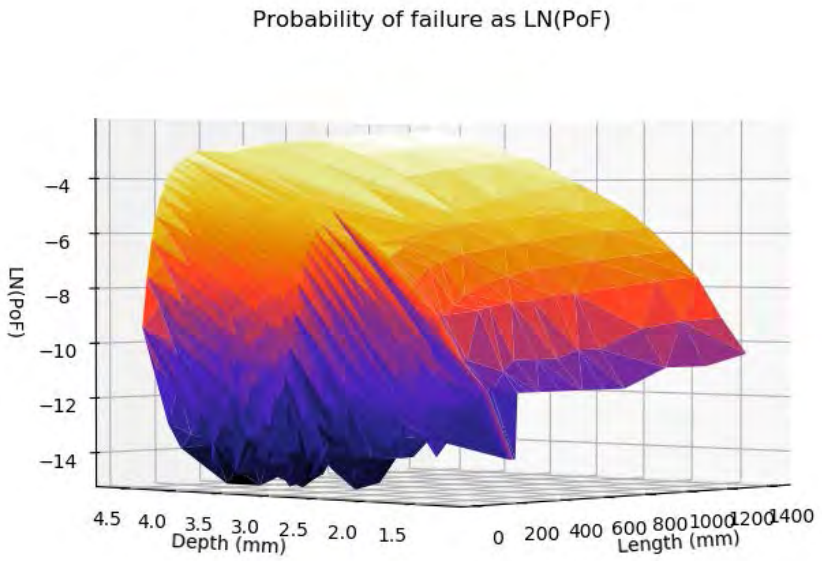


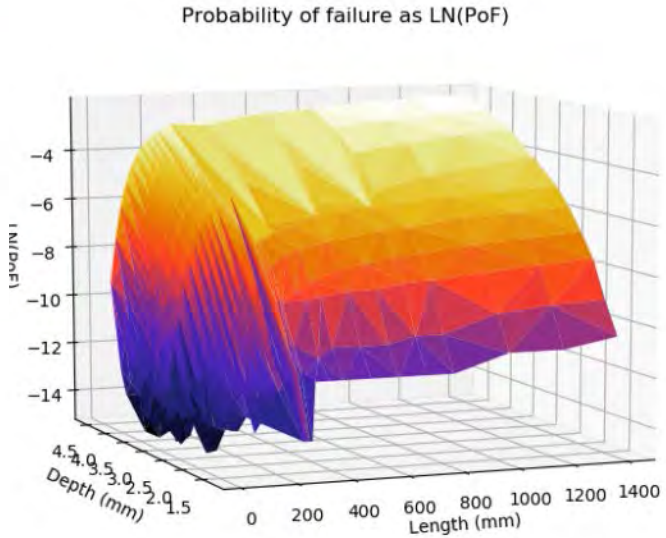
PoF surface in LN(PoF)

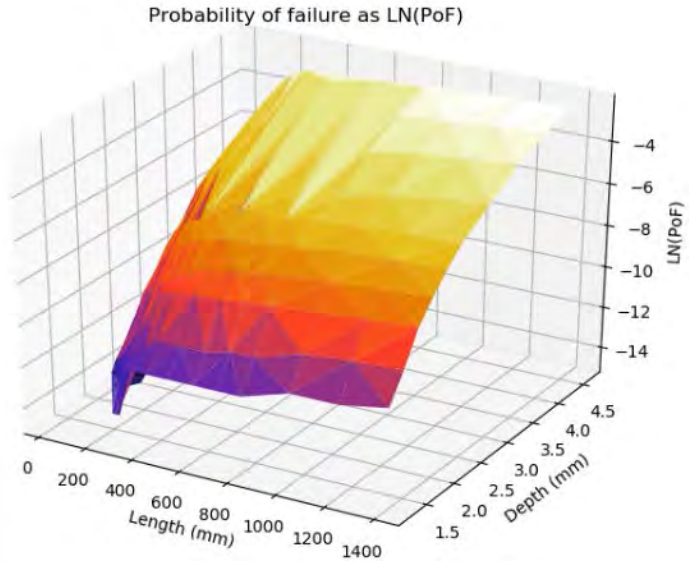
- In general using PoF as LN(PoF) returns more accurate results.
- The set of datapoints used for research is shown in LN(PoF).
- A simple surface can be directly mapped to the point cloud to assist visualisation.
- Regions below 10^{-7} (approximately LN(PoF) = -16) show some instability which indicates the possibility of insufficient convergence.



Raw LN(PoF) Surface for example given in *PR-244-05302*

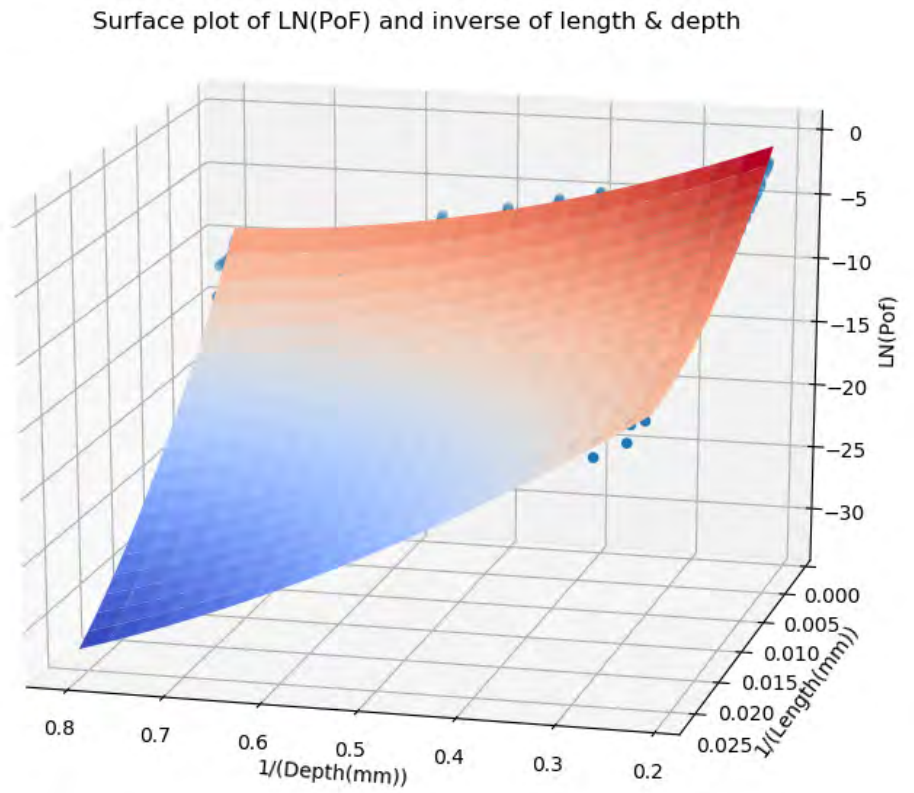






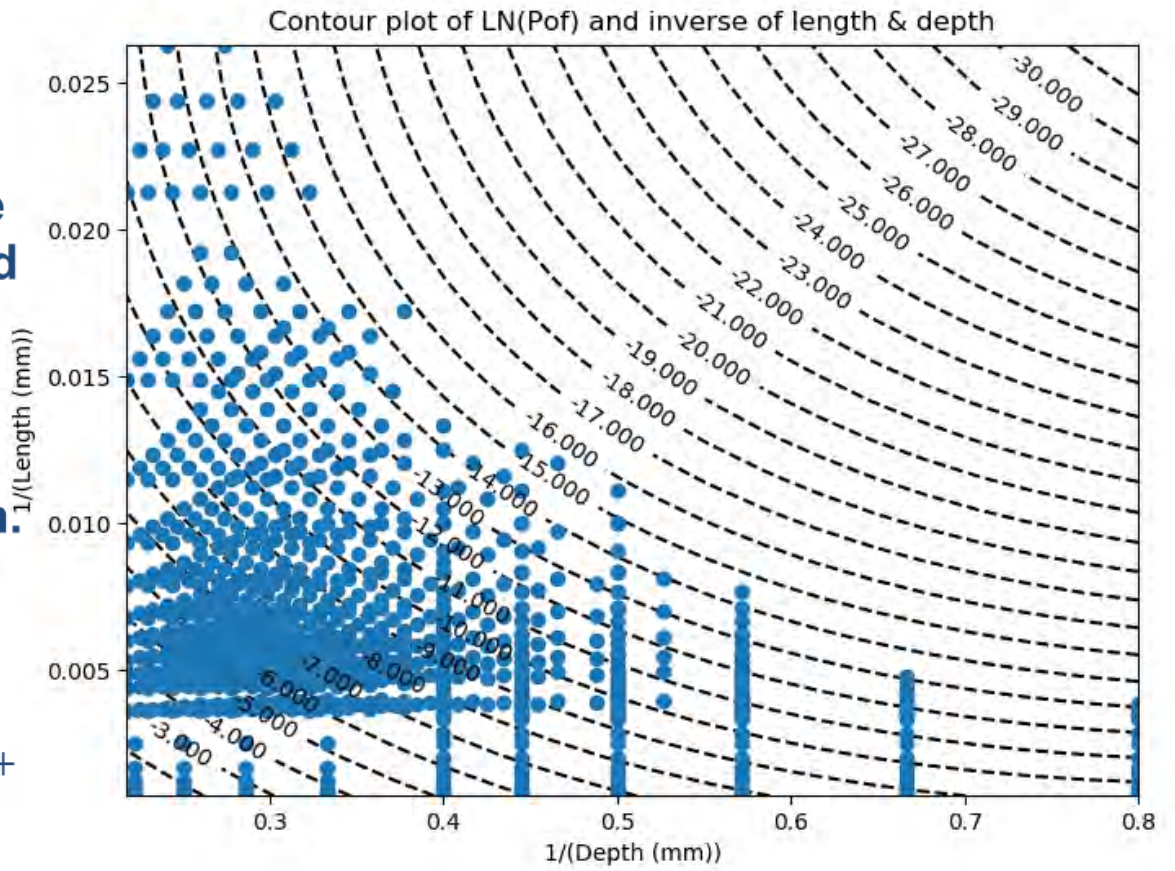
Reciprocal of length and depth

- The failure surface remains an exponential function even when plotted as LN(PoF).
- Prediction of PoF is further improved by working with the reciprocals of both length and depth.
- Variable confidence values in data point accuracy are used to target areas of interest such as the region 10^{-3} to 10^{-6} while retaining good accuracy in regions at higher likelihood of failure.
- Regions of low certainty such as those of 10^{-7} or lower are assigned a reduced confidence value.



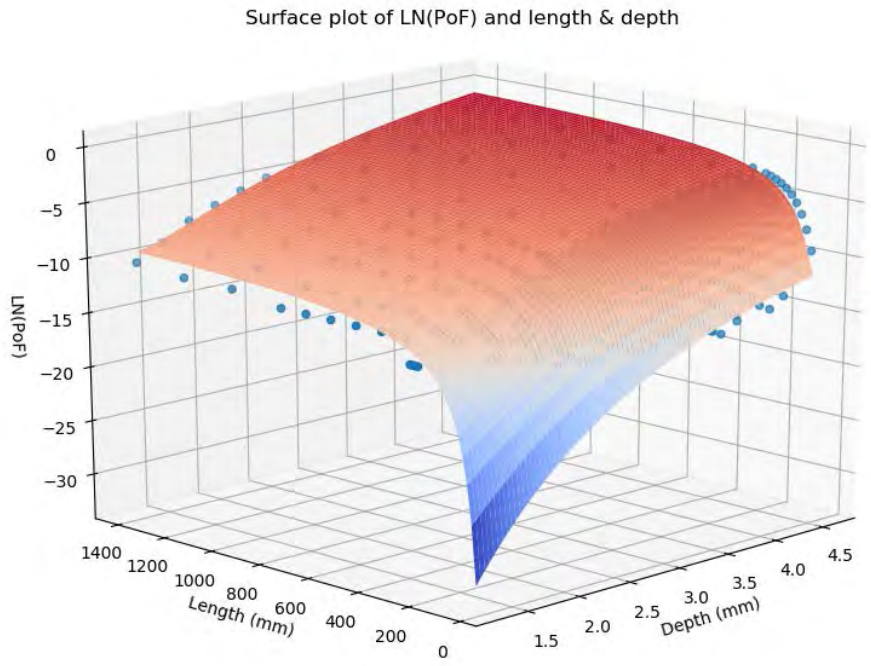
Typical contour plot result

- The contour plot to the right shows a typical result.
- The polynomial$_{22}$ equation is not suitable, there are a minimum of two curves in both length and depth axis.
- Polynomial$_{33}$ is an option while polynomial$_{44}$ provides a better fit, provided that care is taken.
- Equation used:
- $f(x,y) = a + b*x + c*y + d*x^2 + e*x*y + f*y^2 + g*x^3 + h*x^2*y + i*x*y^2 + j*y^3 + k*x^4 + l*x^3*y + m*x^2*y^2 + n*x*y^3 + o*y^4$



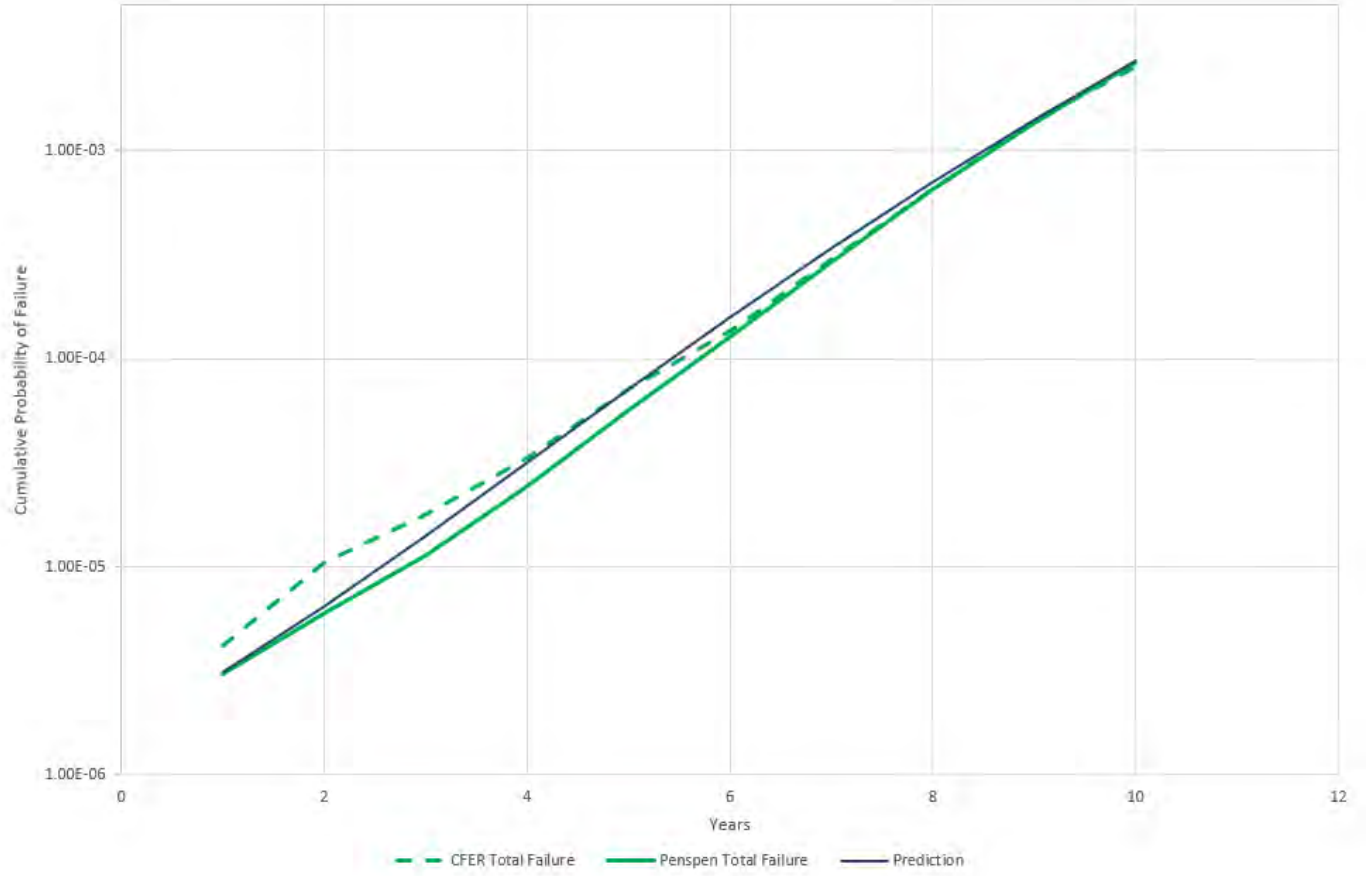
Output PoF surface in LN(PoF)

- The resulting surface of best fit is plotted in LN(PoF) against length and depth.
- Fit is reasonably good without extensive optimisation. Unweighted values of RMSE = 0.6 and R-squared = 0.96 are reasonably simple to achieve.
- It has been noted that polynomial$_{33}$ can appear to give improved RMSE and R-Squared, however this does not normally include a weighting for error in the region 10^{-6} to 10^{-3} or higher.
- The weighted RMSE and R-squared values show much improved fitting within the areas of interest using polynomial$_{44}$.



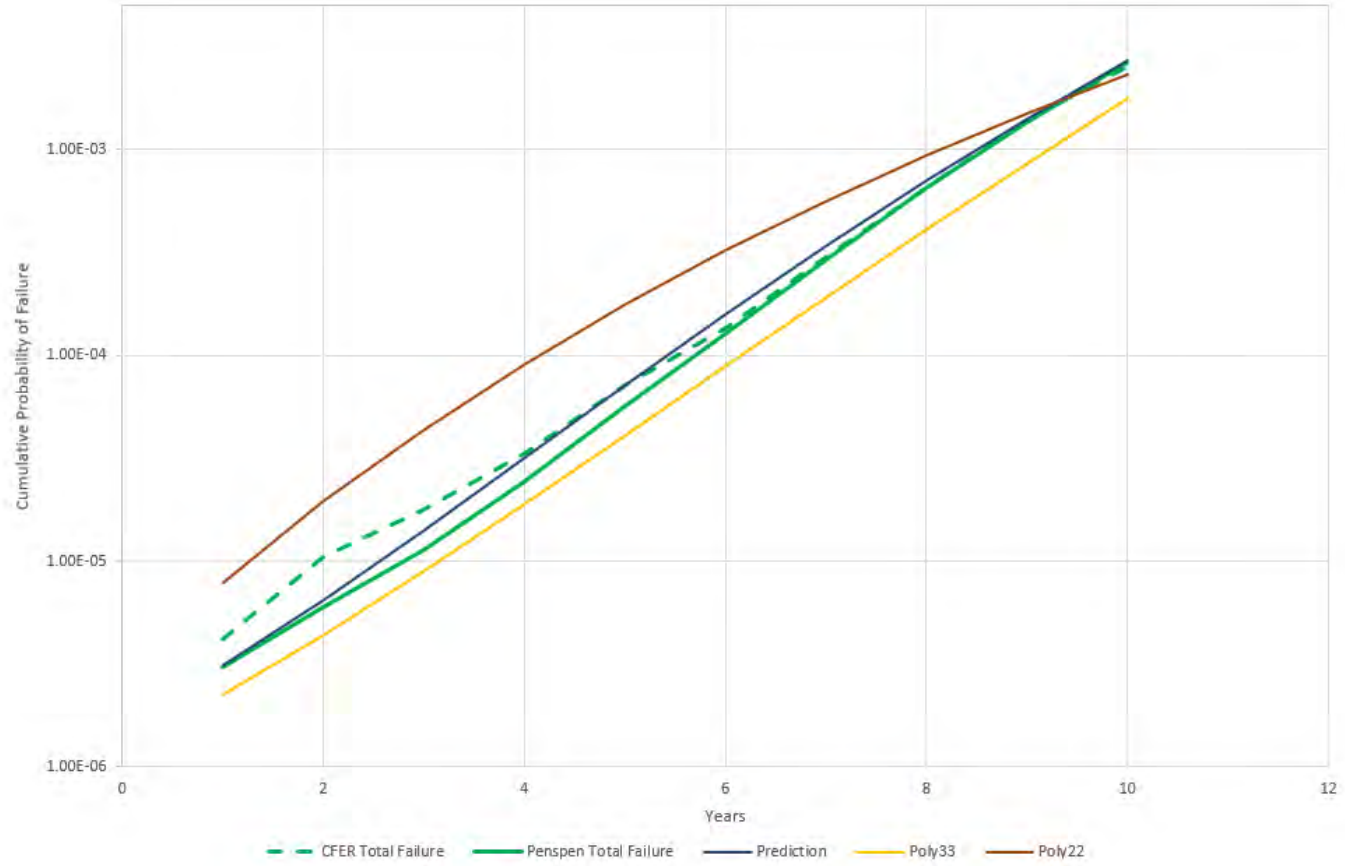
Comparison of prediction to example results

- The prediction of PoF is compared against the PoF values provided in *PR-244-05302*, and those previously calculated by Penspen.
- Results typically show good coherence in the region 10^{-3} to 10^{-6}
- The target of minimum absolute deviation in LN(PoF) at higher probabilities of failures has been achieved with adequate coherence at lower probabilities.



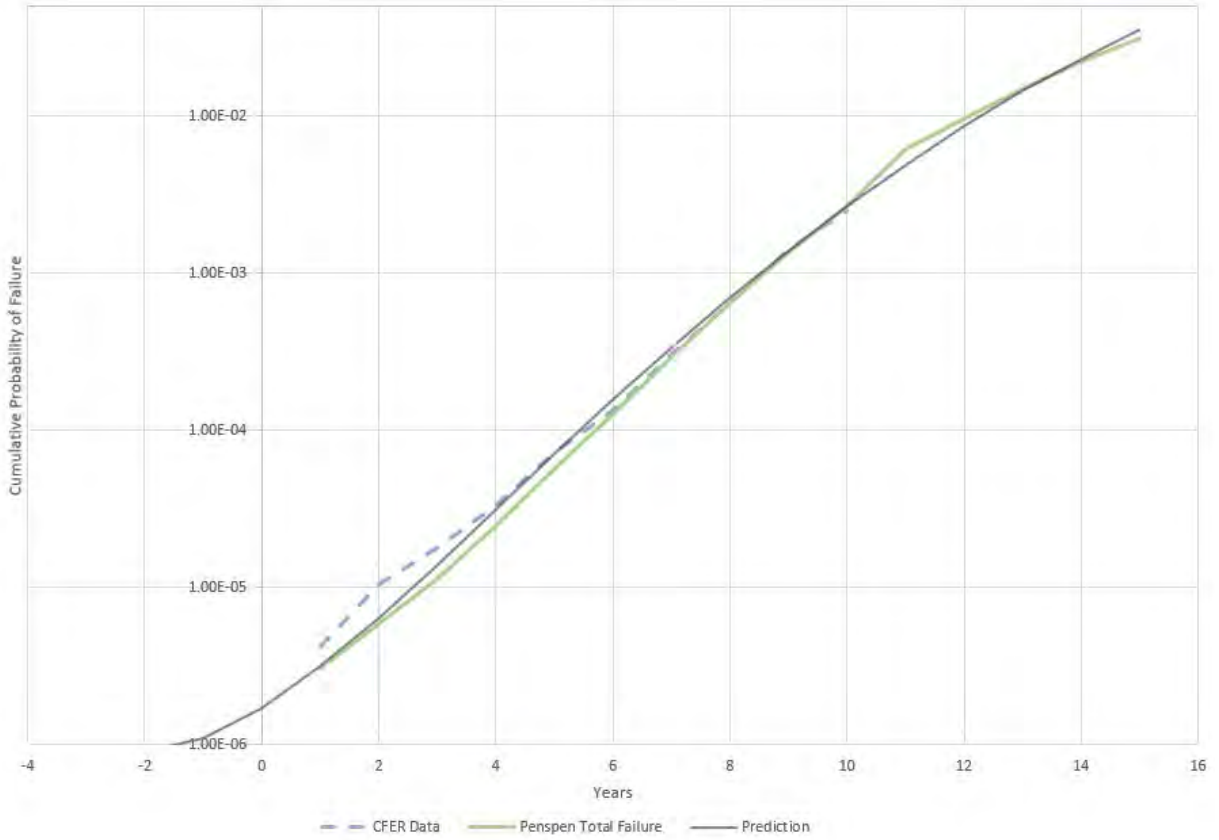
Comparison fitting methodologies

- The prediction is made using polynomial$_{44}$ where $i = 4$ and $j = 4$.
- Polynomial$_{33}$ is potentially adequate, but not so stable over a larger range of validated data points.
- Polynomial$_{22}$ is not adequate.



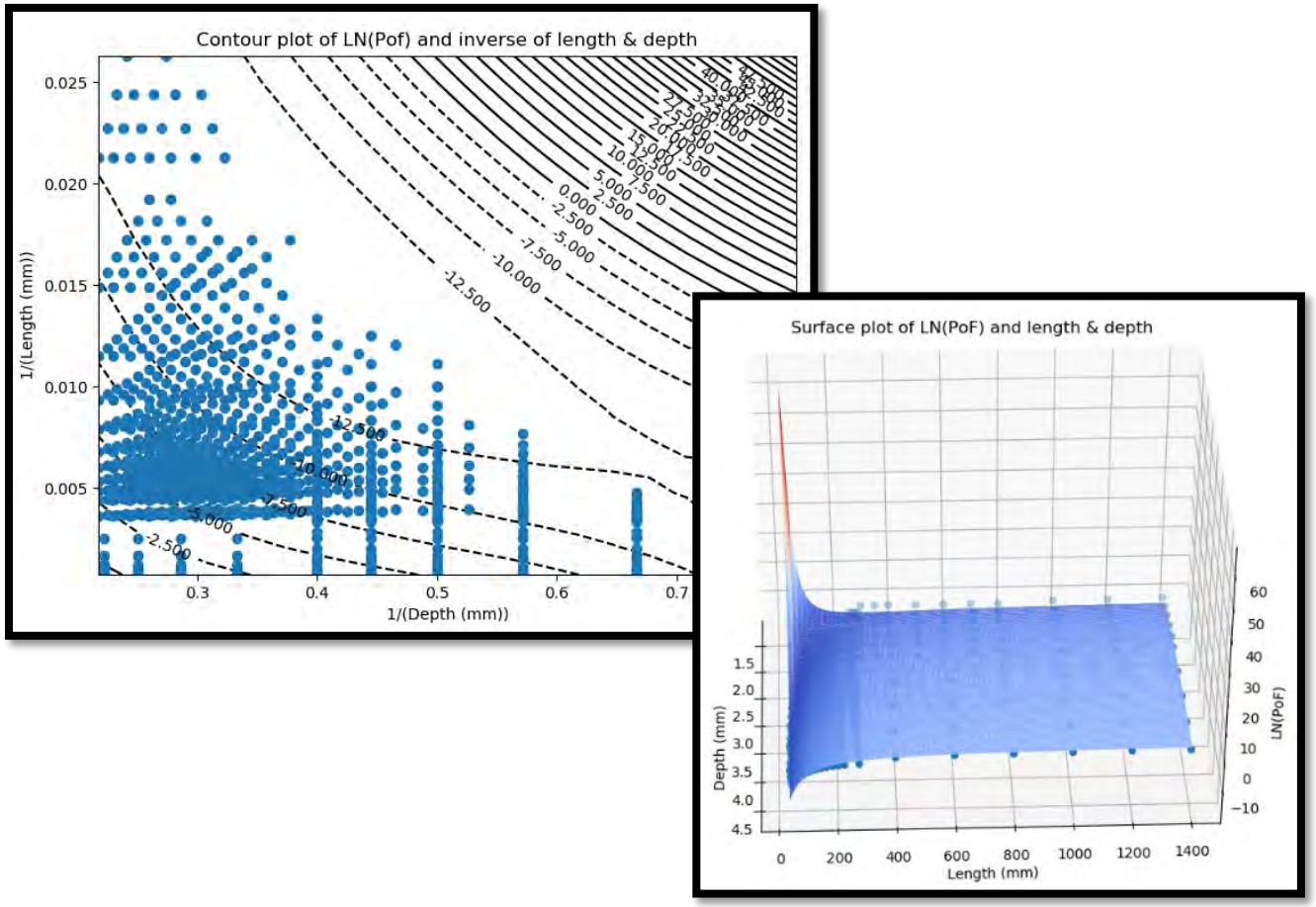
Validation

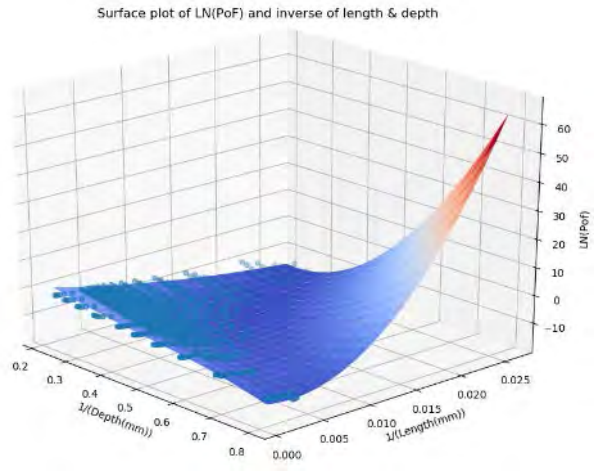
- Validation is performed on multiple representative datapoints.
- As an example the standard metal loss feature indicated in *PR-244-05302* is assessed by Monte Carlo for a further five years.
- The prediction holds with good accuracy for the additional years.



Caveats

- The polynomial$_{44}$ can be overfitted to the data, in particular care must be taken given the use of the reciprocal of length and depth.
- It is possible for the value near length = 0 and depth = 0 to be very high, or very low. A lower bound of applicability must be determined.

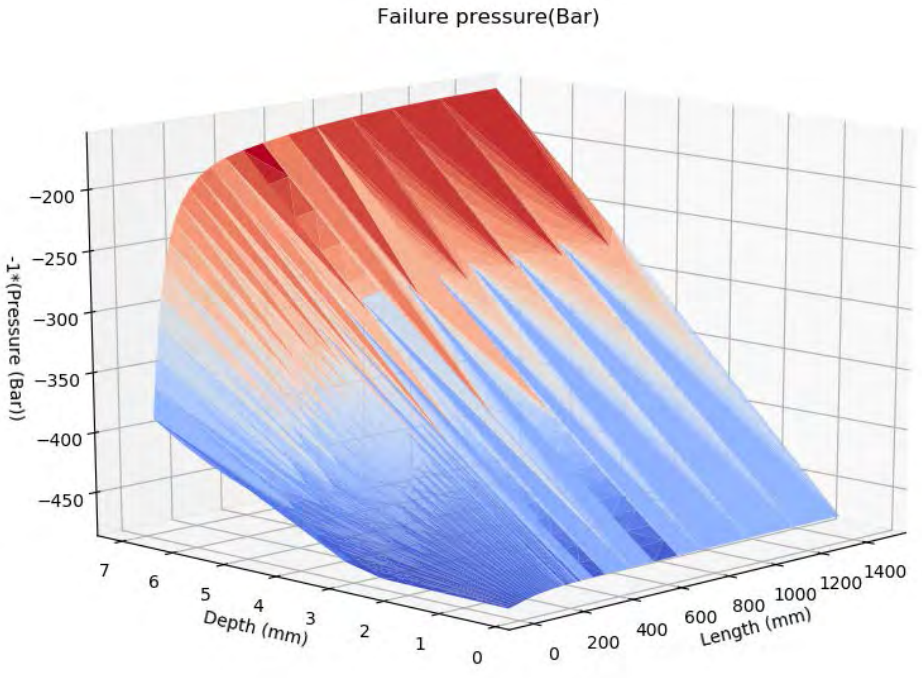




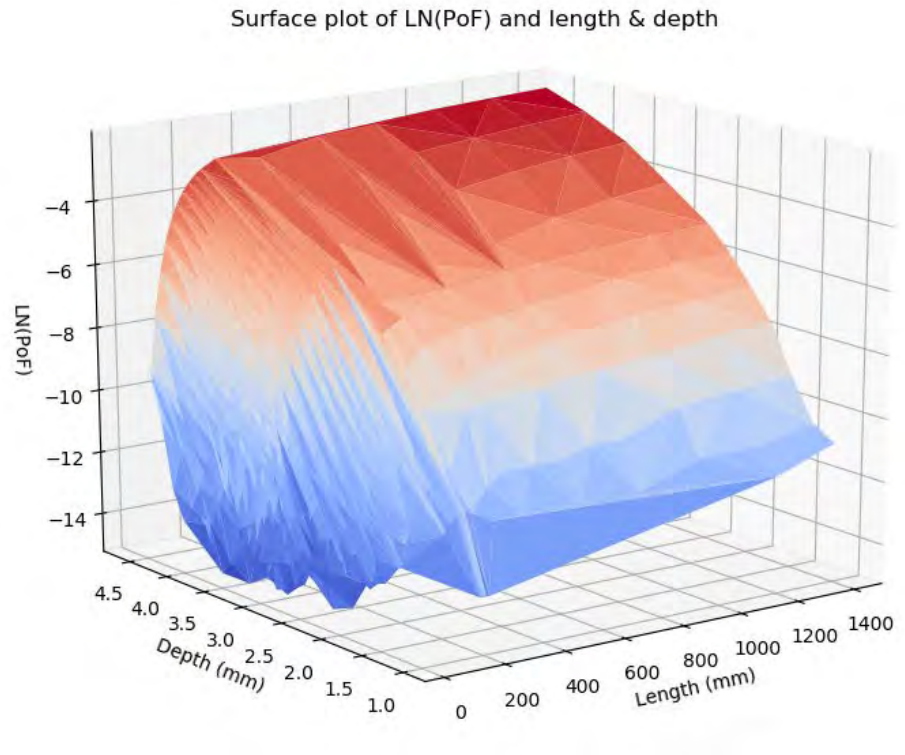
The future

- The fitting of polynomials to existing data allows very fast interpolation and use of the data to calculate PoF for and defect dimension within bounds.
- But it remains too slow, we still need to generate the dataset in the first place!
- The future will be about how we generate the data & how much data we actually need to describe the surfaces.
- The next few slides examine the lower limits of data requirements, and the reduction in time required that is really possible.

Comparison of failure pressure and LN(PoF)

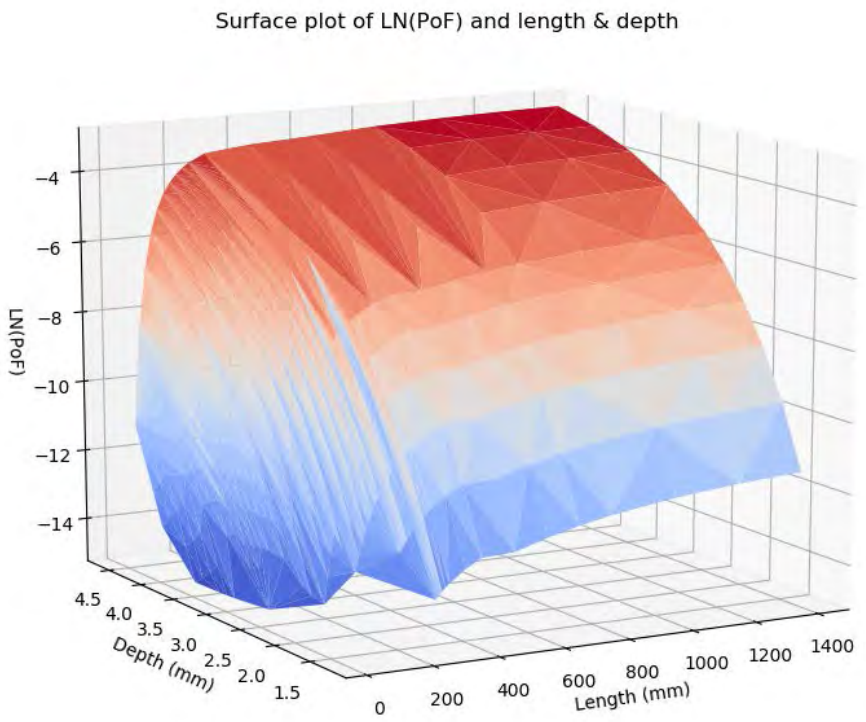


Direct Calculation (ASME Mod B31G)

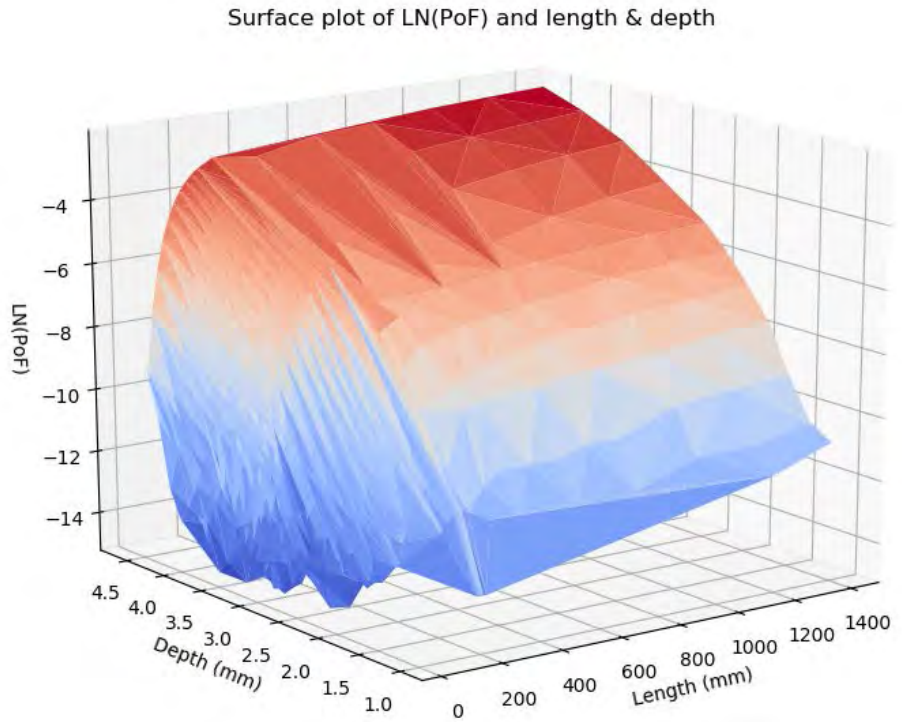


Monte Carlo

Comparison of LN(PoF) and LN(PoF)

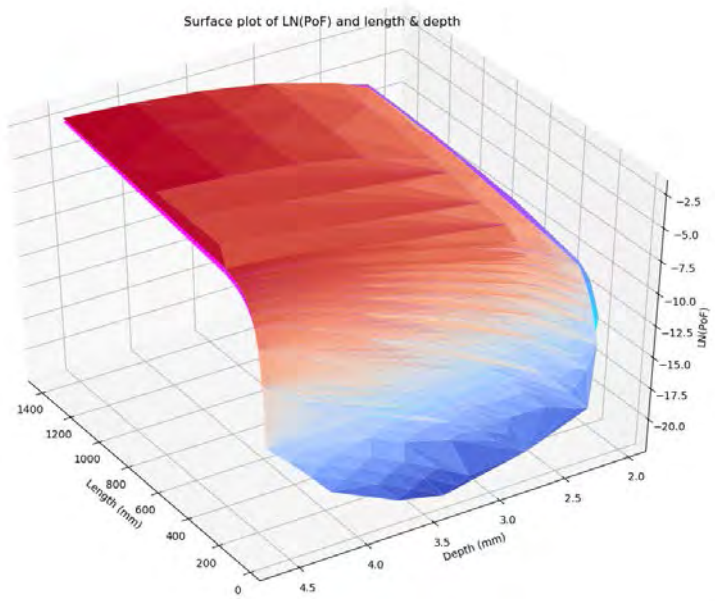


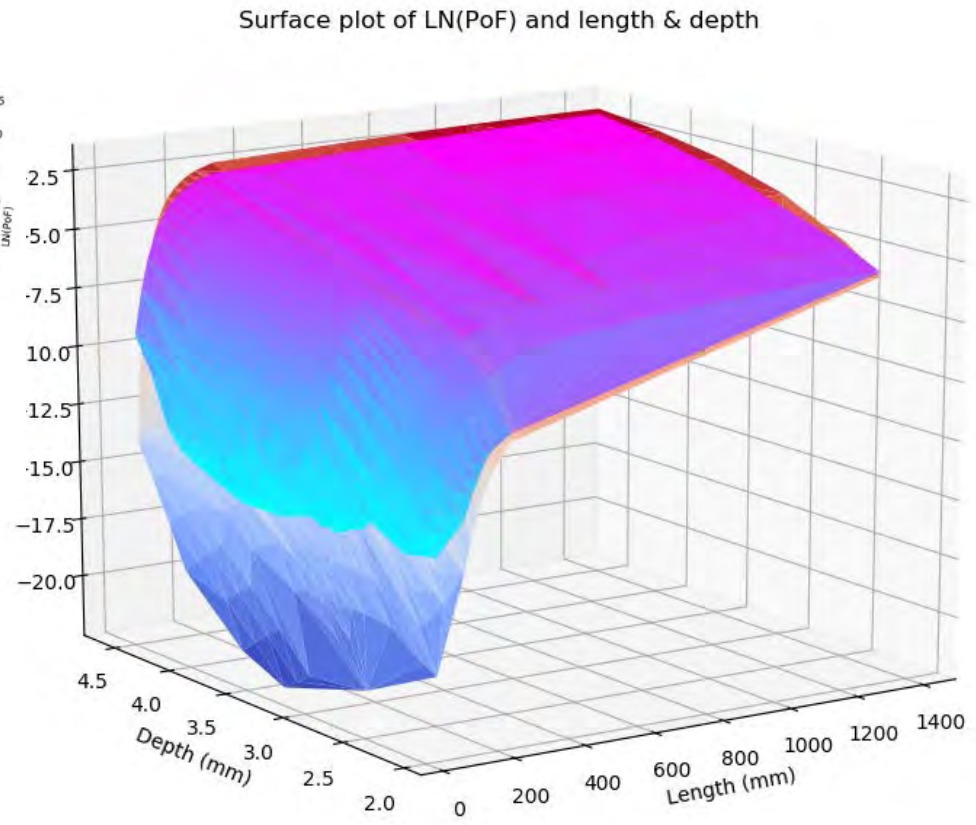
Direct Calculation (Penspen modified ASME Mod B31G)

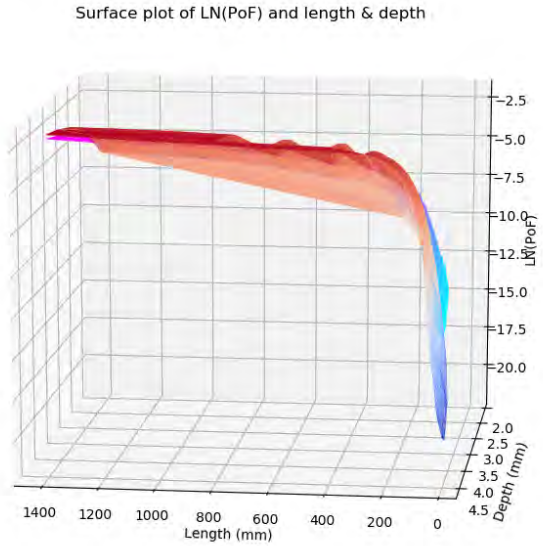


Monte Carlo

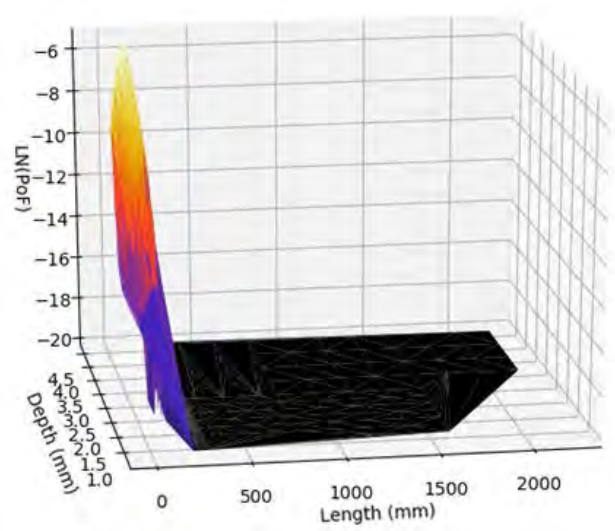
Comparison of MC LN(PoF) and calculated LN(PoF)



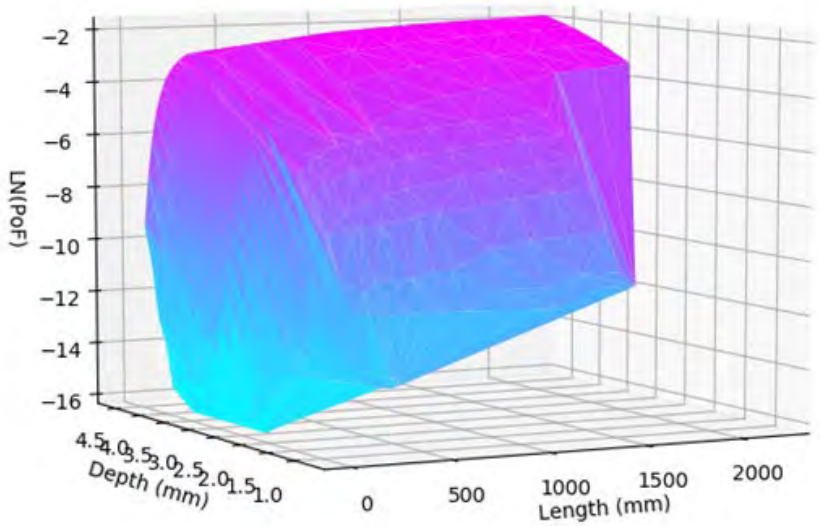




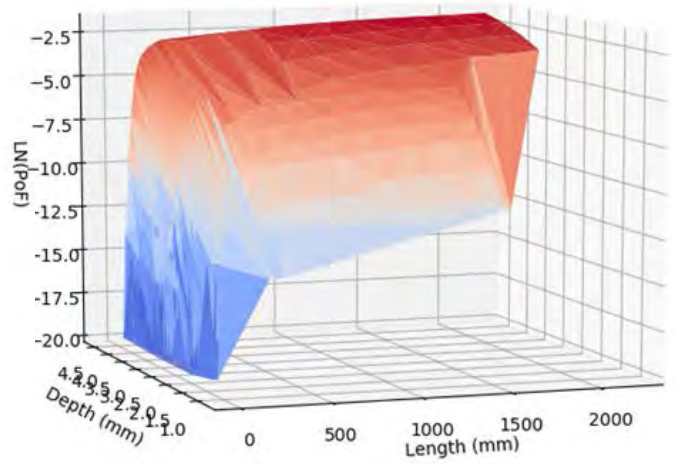
Components of the failure surfaces



Leak surface

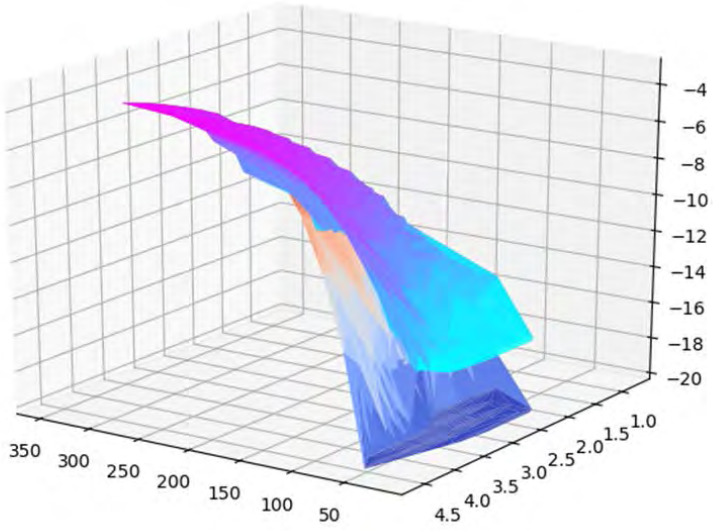


Combined surface

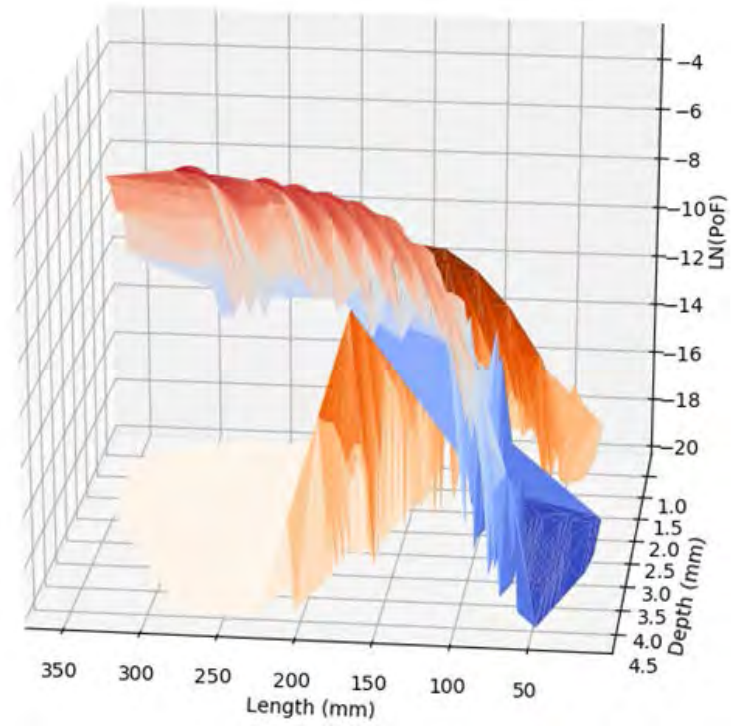


Rupture surface

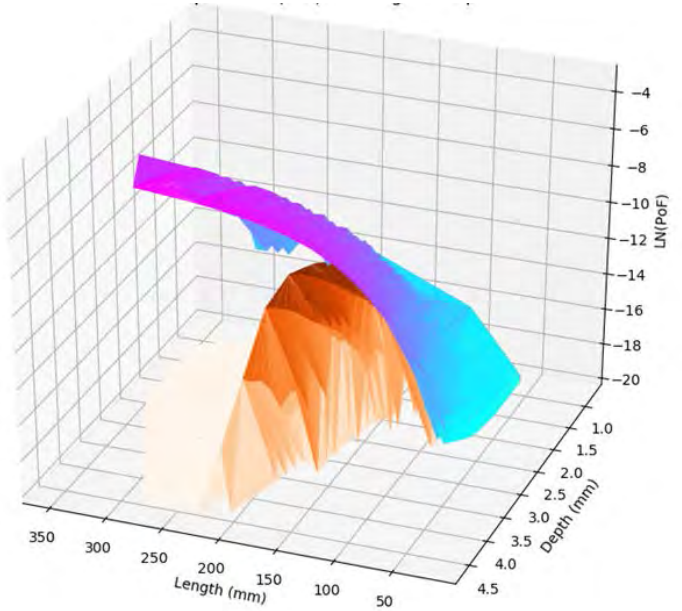
Components of the failure surfaces



Rupture & Total surfaces

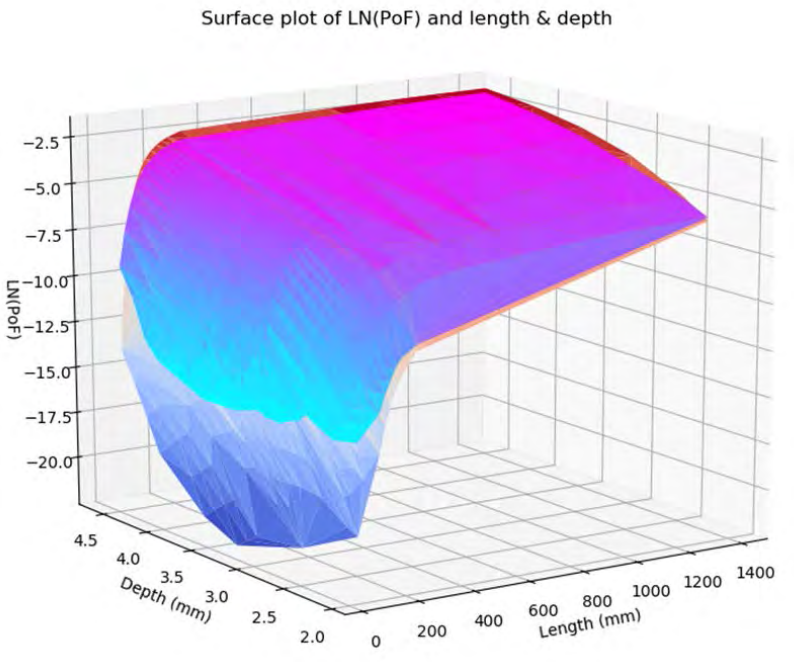


Leak & Rupture surfaces



Leak & Total surfaces

Summary



Summary:

- The surfaces are readily scalable from the results of direct calculation.
- Scaling factors can be derived from a very limited number of MC simulations.
- The PoF surfaces show good cohesion to simulation results.
- The method is fast. The whole surface can be described in a few hours.
- All additional calculations are then performed at deterministic speeds.
- Calculation of PoF at deterministic speeds allows new methodologies to be developed, and existing uses to be performed routinely with little cost of time or resource.

The future: Target form

Questions?

Aidan Charlton:
a.charlton@penspen.com

Mike Brown:
m.brown@penspen.com

BACK TO AGENDA

PRCI 2020 Research Exchange

PR-328-163605
SCC-6-3

Methodology for Assessing Seam Weld Anomalies Using In-Line Inspection Data

Sam Tandon, Ming Gao, Ravi Krishnamurthy

Blade Energy Partners
Houston, TX

LEADING PIPELINE RESEARCH

Project PRCI SCC-6-3: Background

- EMAT/USCD identify large number of seam weld linear anomalies
  - Discrimination to identify C-L features, hook cracks, notch type LOF, inclusions is limited
- Assessment of linear indications using crack assessment methods results in large number of features requiring excavations – many of them being unnecessary
- Full scale burst test showed that the existing crack assessment methods are overly conservative
- Hence, there is a need for better identification/ discrimination of seam weld anomalies, establishment of associated database, and process for management of seam weld anomalies

Project PRCI SCC-6-3: Objective

- Establishment of associated database for seam weld defects
- Help operators to address the issues related to the integrity of the seam weld defects
- Devise integrity management strategies that are **safe** and **cost effective** for seam weld defects
- Improvement of the assessment methods to make it reasonably conservative and appropriate for the feature types is required on the basis of a better discrimination both from the ILI and in-ditch NDE

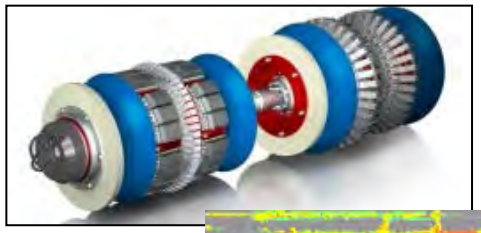
Project PRCI SCC-6-3: Approach

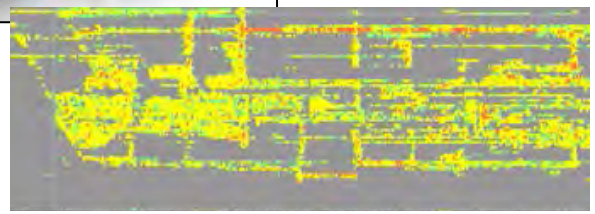
- Review and quantify capability of the current technologies to detect, discriminate, and characterization of weld defects
  - ILI
  - NDE
- Calculate conservatisms of models for assessment of different types of seam weld defects
- Define a process/methodology for better detection, discrimination, and assessment of seam weld defects

Available Data

Operator	Line	Gas/Liquid	OD (inch)	ILI Data	Weld	Year	Manufacturer	Assistance with MFL	Length of Inspection (miles)	Digs	NDE 1	NDE 2	Lab (Actual Size)	Burst Test
A	A/1	Gas	22	EMAT	**EFW**	1949	A.O.Smith	X	**120.0**	13	UT		Yes	Yes
A	B/1	Gas	30	EMAT	**ERW**	1956	A.O.Smith	X	**60.5**	7	UT	New UT	Yes	Yes
A	C/1	Gas	22	EMAT	**ERW**	1956	Youngstown	X		13	UT		Yes	Yes
B	D/1/2	Gas	12.75/ 16	EMAT	**ERW**			X	**NA**	4	UT		Yes	Yes
C	E/1	Liquid	12.75	Ultrasonic	**ERW**	1972	Ipsco	X	**113.0**	27	UT		None	No
D		Gas	18	Pull Test: EMAT, Circ MFL, Axial MFL	**SAW**			X	**NA**	NA	Radiographic		None	No
Total									**>293**	**64**				

Available Data

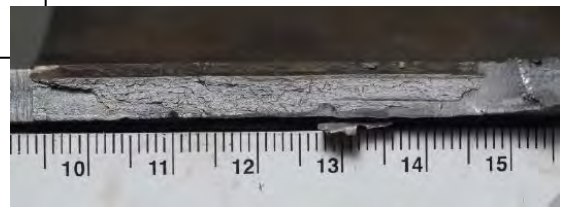




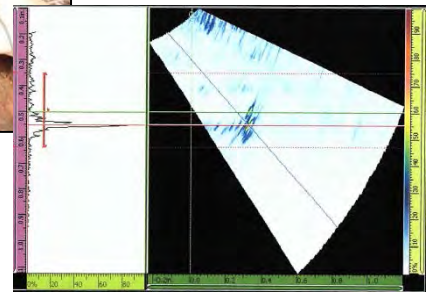
ILI



Destructive Examination



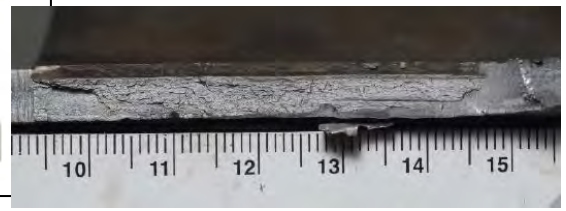




NDE Ultrasonics/ Other Technologies



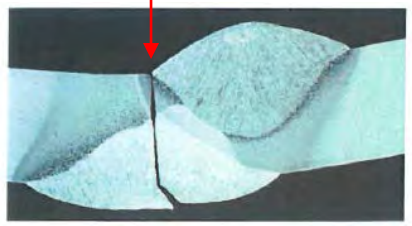
Destructive Examination



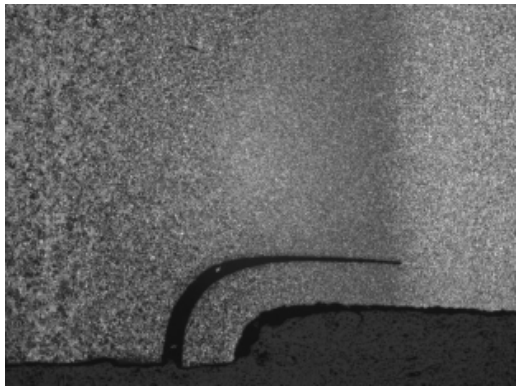
Type of Features at Seam Weld

- Toe Crack
- Lack of Fusion
  - ID, OD ,Midwall
- Hook Crack
  - ID, OD
- Lack of Penetration
- Seam Overtrim
- Seam Undertrim
- Seam Misalignment
- Hot Crack
- Undercut
- Porosity
- ----

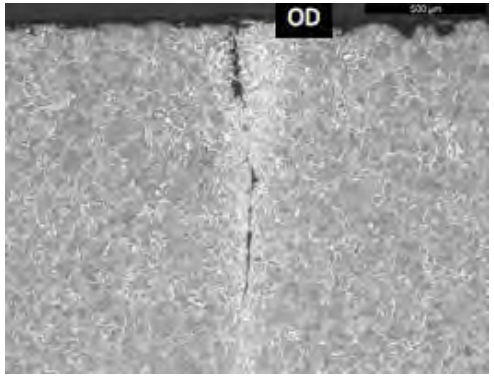
Toe Crack
(Contains Offset)



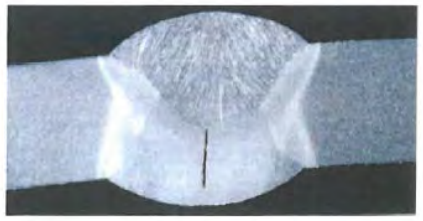
Hook Crack



Lack of Fusion with
Porosities

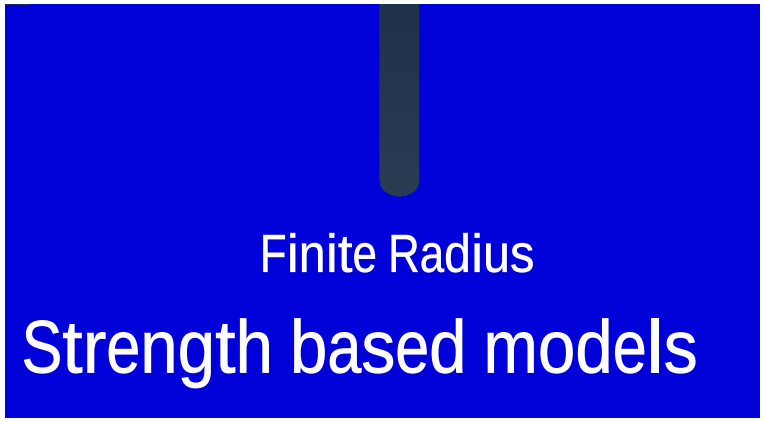


Weld Metal Crack
(Hot Crack)

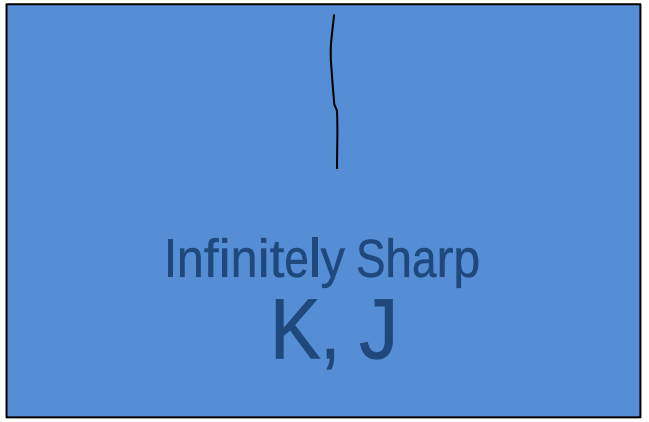


Crack vs. Notch Assessment Models

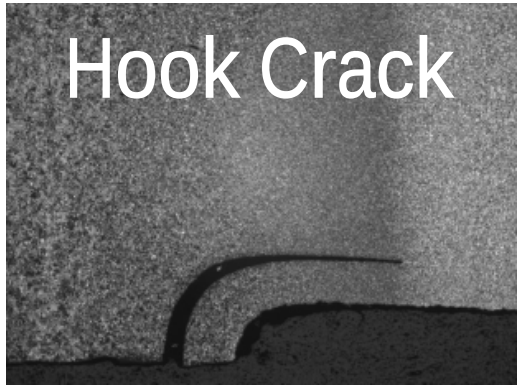
Notch



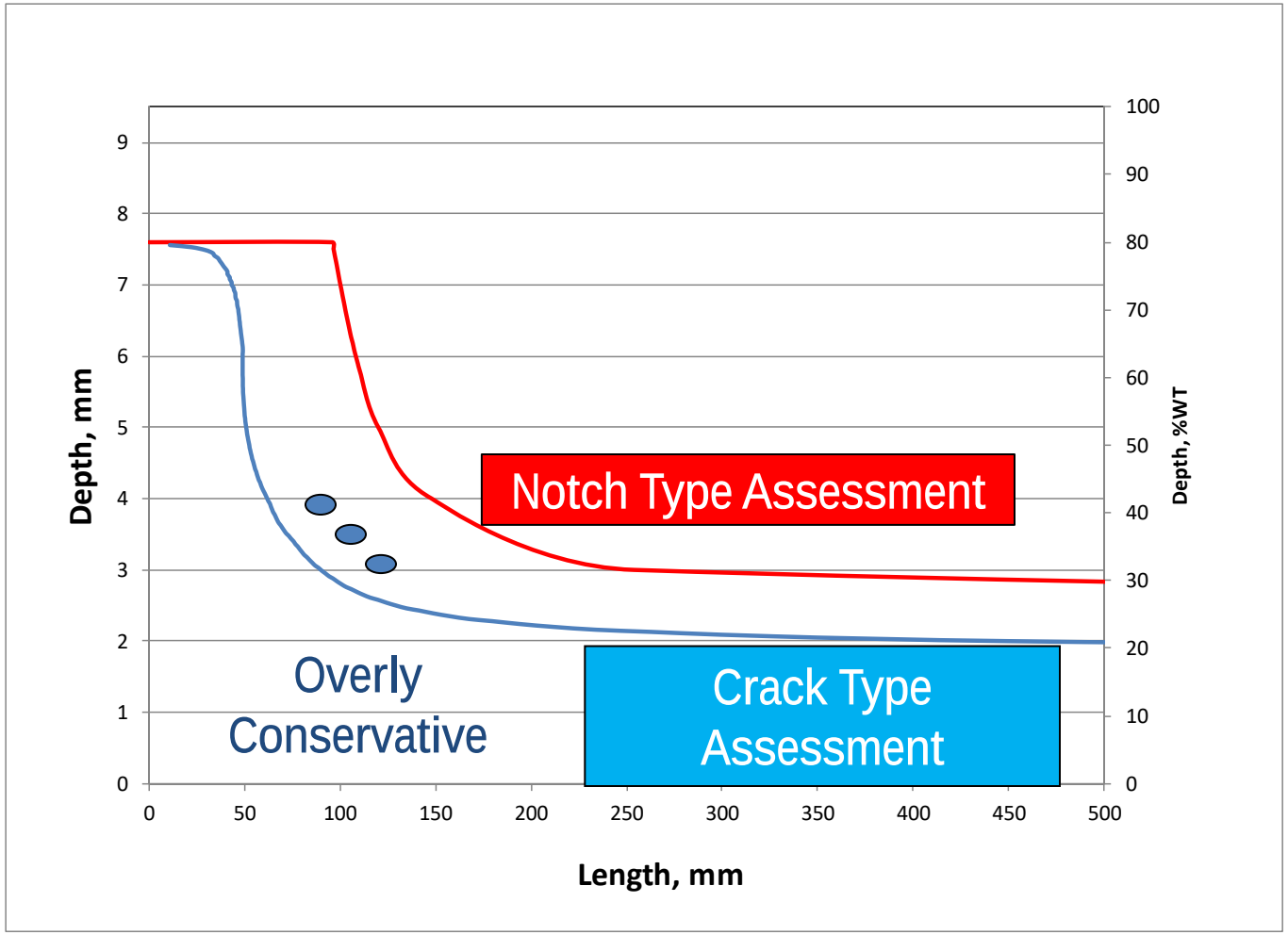
Crack



Fracture Mechanics



Crack vs. Notch Type Defects Assessment



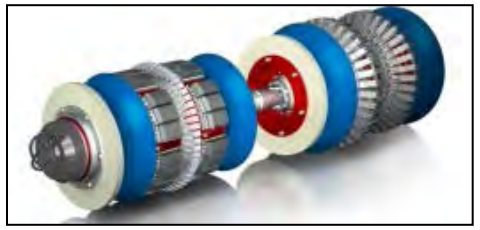
Performance Measures

- Measures
  - Probability of Detection (POD)
  - Probability of Identification (POI)
  - Probability of False Call (POFC)
  - Sizing Tolerance (e.g., ± %wt for depth)

- Indicators
  - Accuracy
  - Certainty or Certainty Interval
  - Confidence level

- Methods
  - Binomial
  - Clopper Pearson

Seam Weld Anomaly
ILI Performance Verification





Detection (ILI vs. Actual)

Line	# Observations	Success	Success Rate	Binomial probability @ 95% confidence level	Clopper Pearson Probability Interval @ 95% confidence level	
					Lower	Upper
2	13	13	100%	-	-	-
3	9	9	100%	-	-	-
4	4	4	100%	-	-	-
Total	26	26	100%	89.1%	89.1%	100.0%
1*	17	17	100%	83.80%	>83.8%	100%

- Detection Success Rate (Above tool detection threshold) 100%
- ILI lists Feature types as “Linear feature in Long Seam Weld Area/ Seam Weld Anomaly”
- Does **not** classify between various kinds on features

*ILI vs. NDE validation

Identification

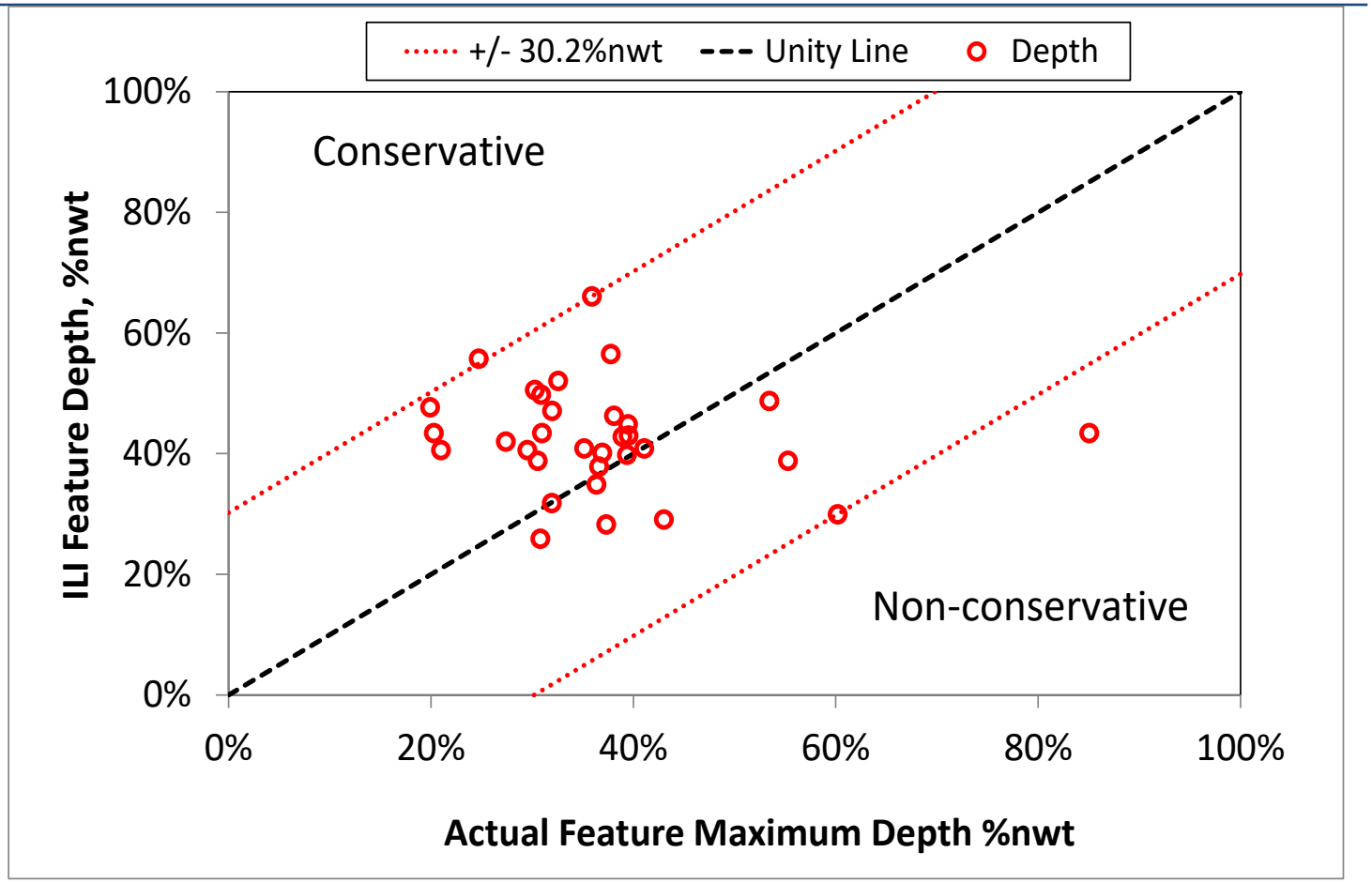
Linear vs. Non- Linear Feature Success Rate

Line	# Observations	Success	Success Rate	Binomial probability @ 95% confidence level	Clopper Pearson Probability Interval @ 95% confidence level	
					Lower	Upper
2	13	13	100%	-	-	-
3	9	9	100%	-	-	-
4	4	4	100%	-	-	-
Total	26	26	100%	89.1%	89.1%	100.0%

- ILI Lists Feature types as “Linear Feature in Long Seam Weld Area/Seam Weld Anomaly”
  - Does not identify the type of defect – Hook crack, Lack of Fusion, Misalignment, Mid Wall LOF
  - Does not distinguish whether feature is in OD or ID of the pipe ?

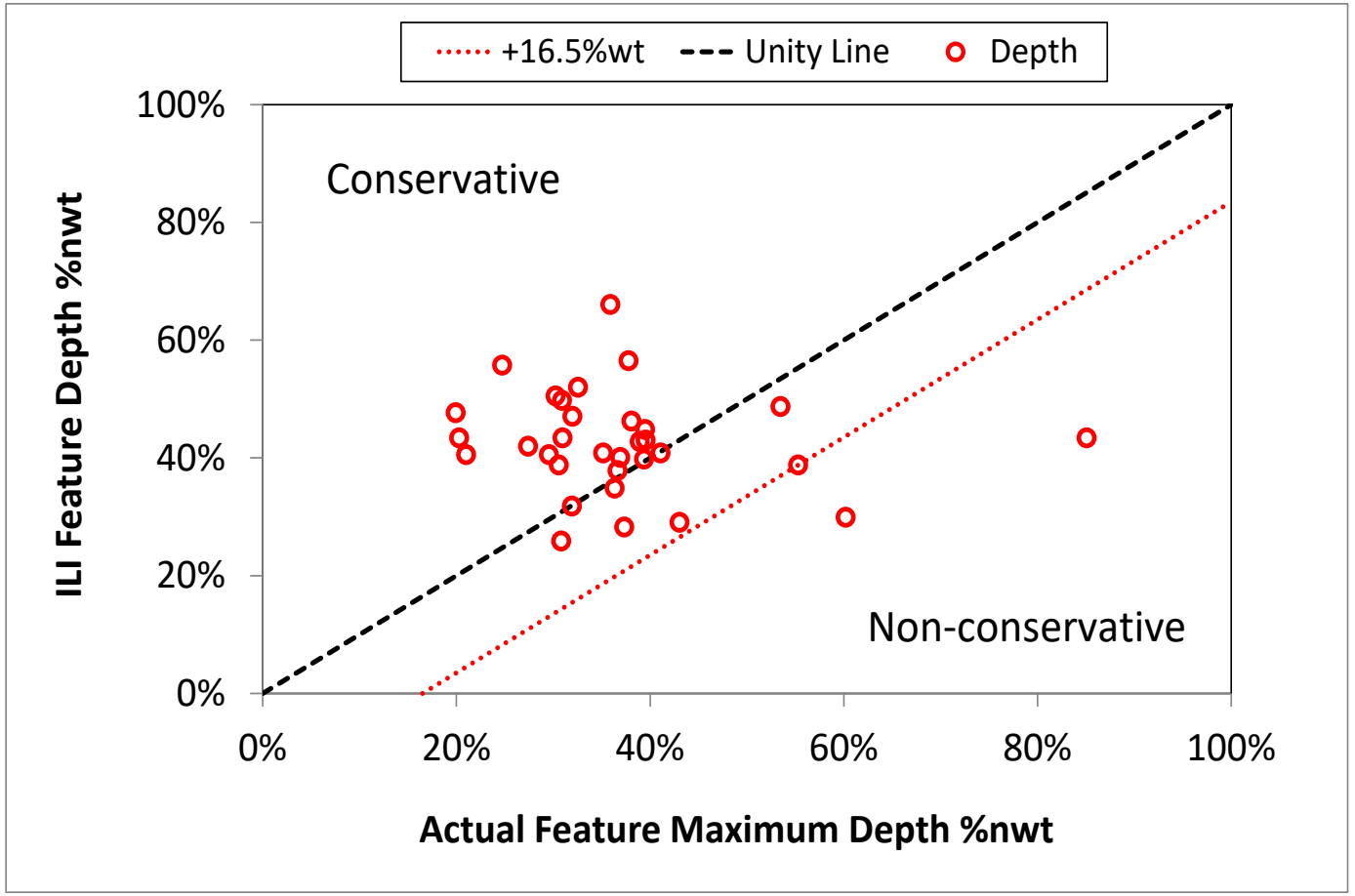
Depth Sizing (Tool Tolerance)

- **Depth sizing mostly conservative with some outliers**
- **With tolerance of ±30.2%nwt, Success rate is 93%**
  - Clopper Pearson
    - *Lower Certainty – 81% @ 95% confidence level*
    - *Higher Certainty – 98% @ 95% confidence level*



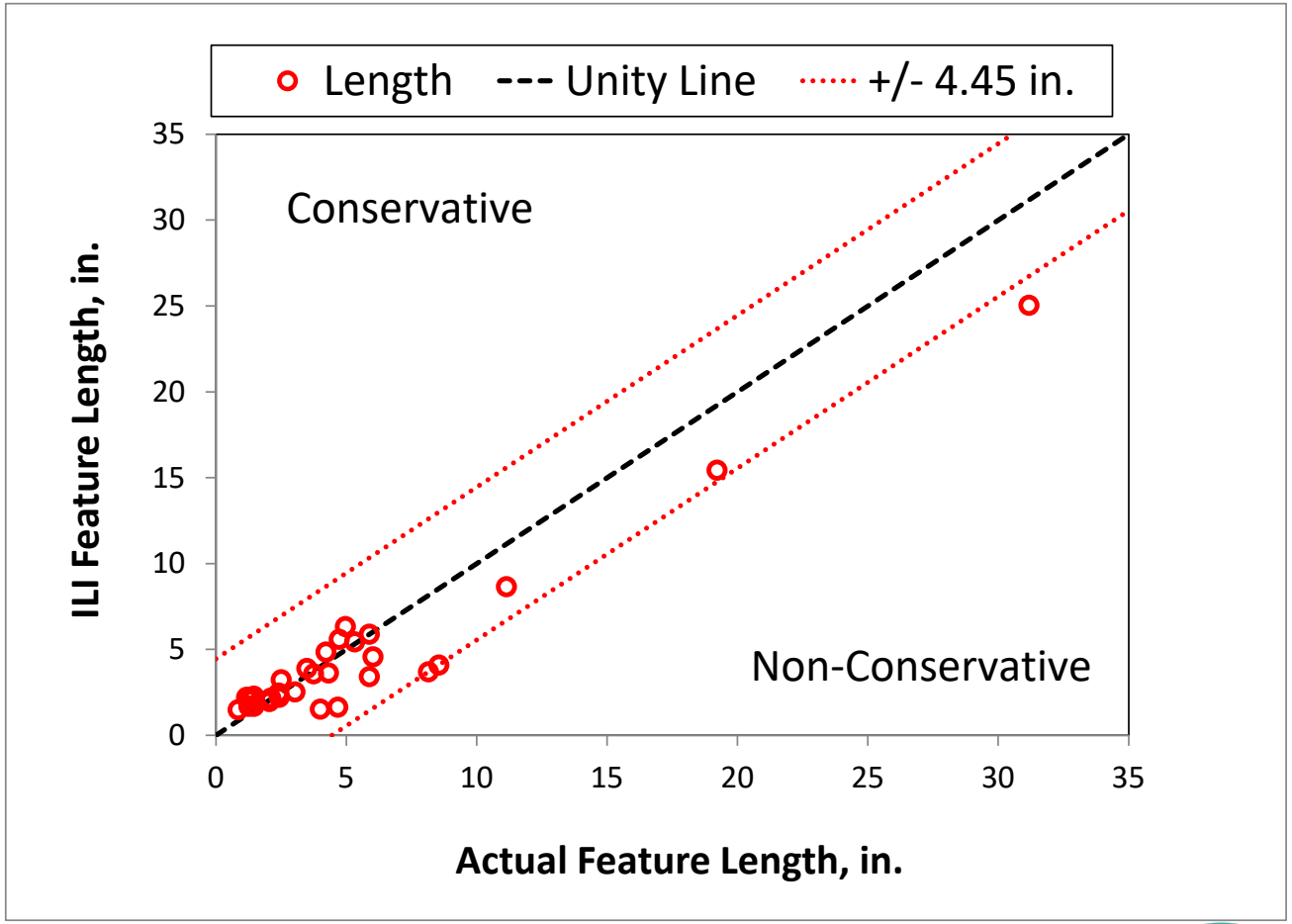
Depth Sizing (Integrity)

- **Depth sizing mostly conservative with some outliers**
- **With +16.5%nwt, Success rate is 93%**
  - Clopper Pearson
    - *Lower Certainty – 81% @ 95% confidence level*
    - *Higher Certainty – 98% @ 95% confidence level*



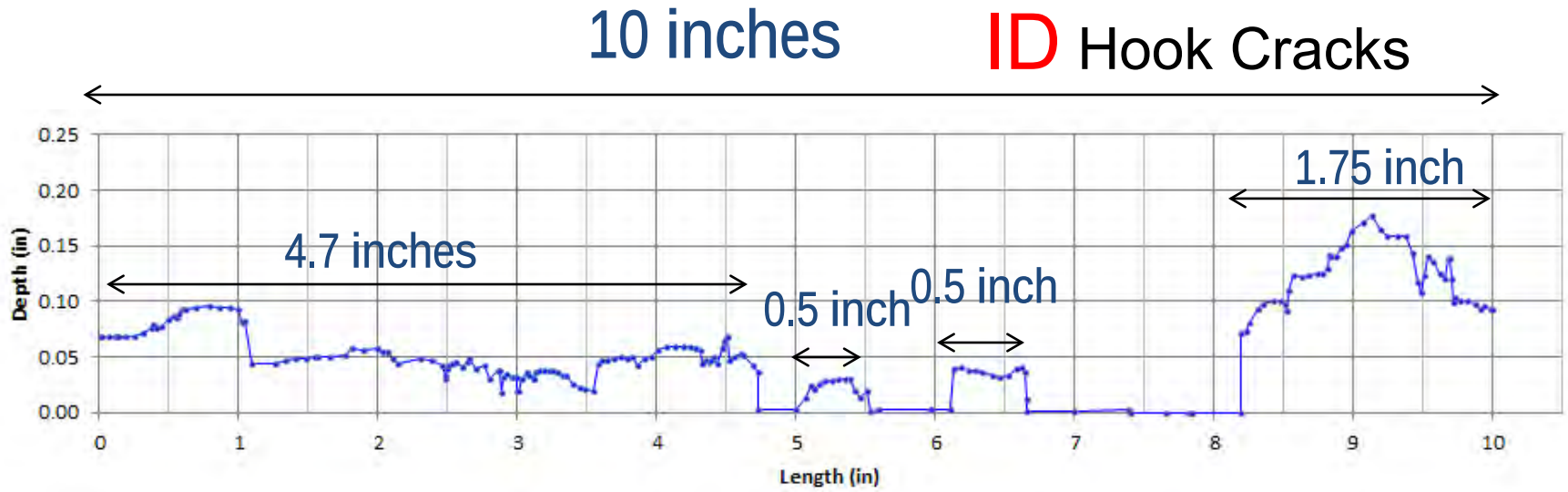
Length Sizing (Tool Tolerance)

- **Length prediction follows the unity line with some outliers**
- **However, tool length tolerance is ±4.45 in.**
  - Success Rate 96%
  - Clopper Pearson at a 95% confidence level
    - *Lower Probability 86%*
    - *Higher Probability 99%*



Intermittent Length

- **As Found Length - What is the objective**
  - Integrity?
  - Length comparison ?



Tool detects defects that are of depth is 2 mm or greater; Length needs to be Over 30 to 50 mm in length

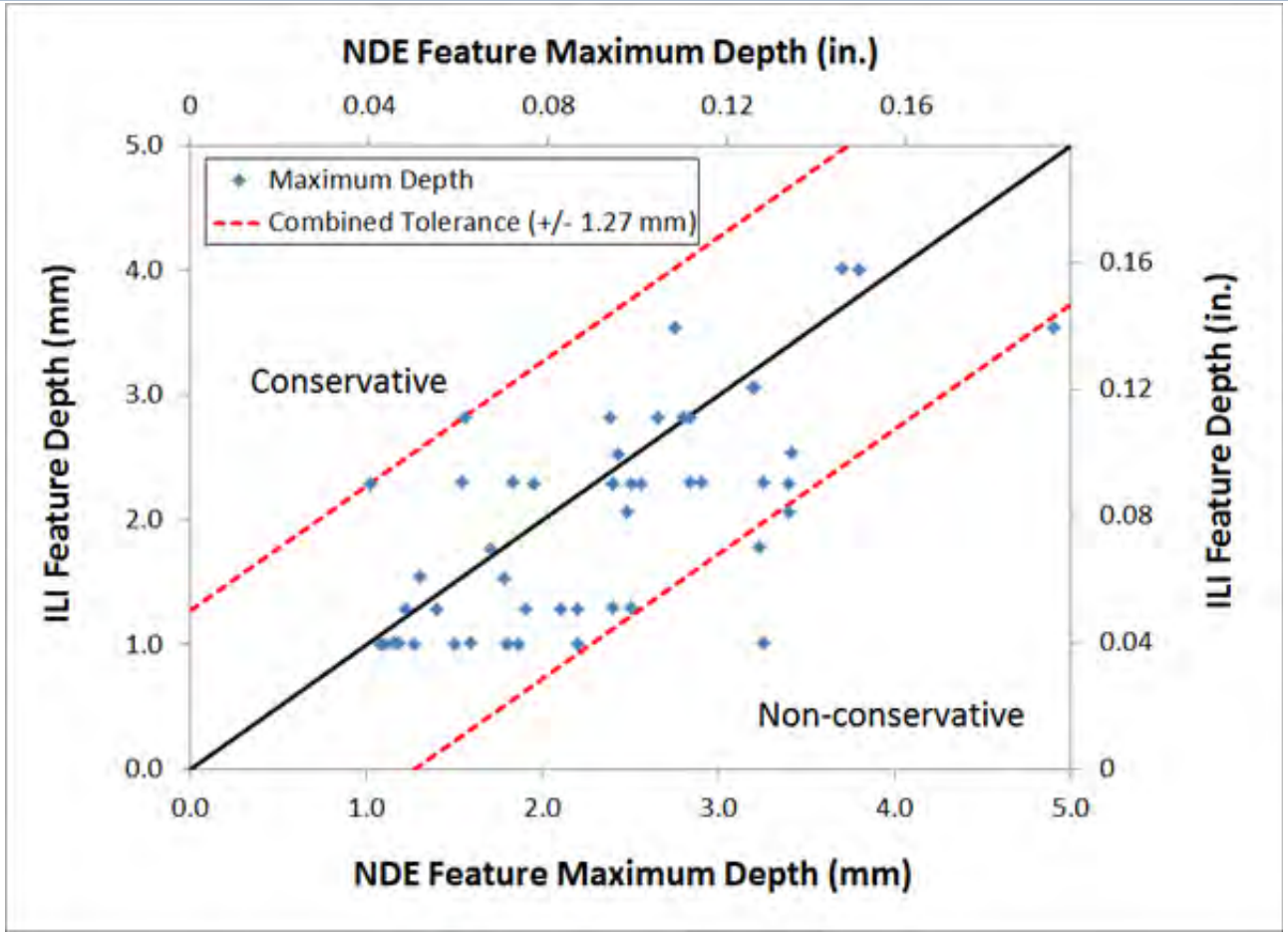
Ultrasonic ILI Performance

Detection and Identification

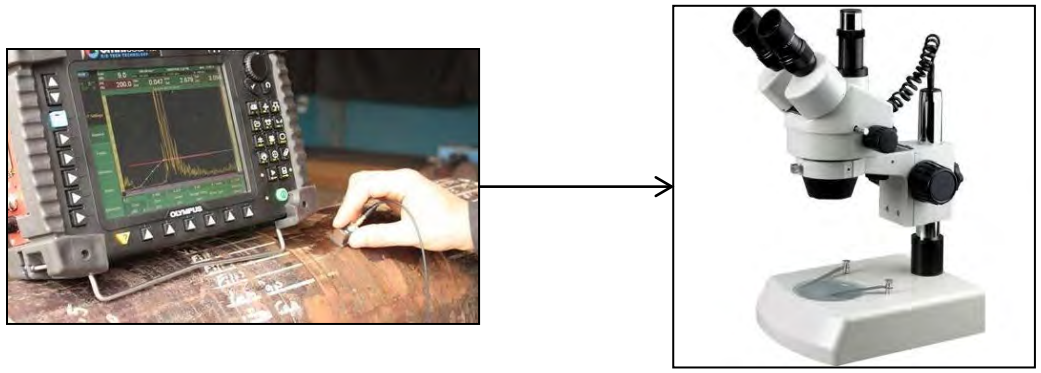
- **Pipeline: 12” inch Crude Oil, NWT: 4.8 mm**
  - *MFL Axial, and Ultrasonic Inspection (for Axial crack detection)*
- **26 Joints Excavated - 50 ILI features**
  - Finding 357 Lack of Fusion Features in the Field
    - *350 were External Lack of Fusion*
    - *None confirmed in the lab*
- **Success rate of detection = 100%**
  - Based on re-analysis
- **Success rate of Identification* 100%**
  - No false negatives

ILI vs. Excavation – Depth Sizing Tool Tolerance

- **For depth tolerance of ±1.27 mm (0.05 in.)**
  - 46 out of 50 is within tolerance
  - Success Rate: 92%
  - Binominal probability: 85% at a 95% confidence level
  - Clopper Pearson: 82-97% certainty at a 95% confidence level



Ultrasonics Phased Array NDE Performance Verification



Ultrasonics NDE Performance Overall - Identification

- **Misidentifies Hook Crack as**
  - LOF
  - Crack Like @ Midwall
  - Long Seam Anomaly
- **Misidentifies ID Hook Crack as Crack Like @ Midwall**
- **NDE Operator Dependent**

	Actual Found →					
NDE Feature Type↓	**Hook Crack**	**LOF**	**Offset**	**Weld Toe Crack**	**False Positive**	Total
Lack of Fusion	9	1	5		1	16
Hook Crack	9					9
Linear	1			5		6
Long Seam Anomaly	2	1			1	4
Crack Like @ Midwall	13					13
Total	34	2	5	5	2	48

Ultrasonics NDE Performance Overall - Identification

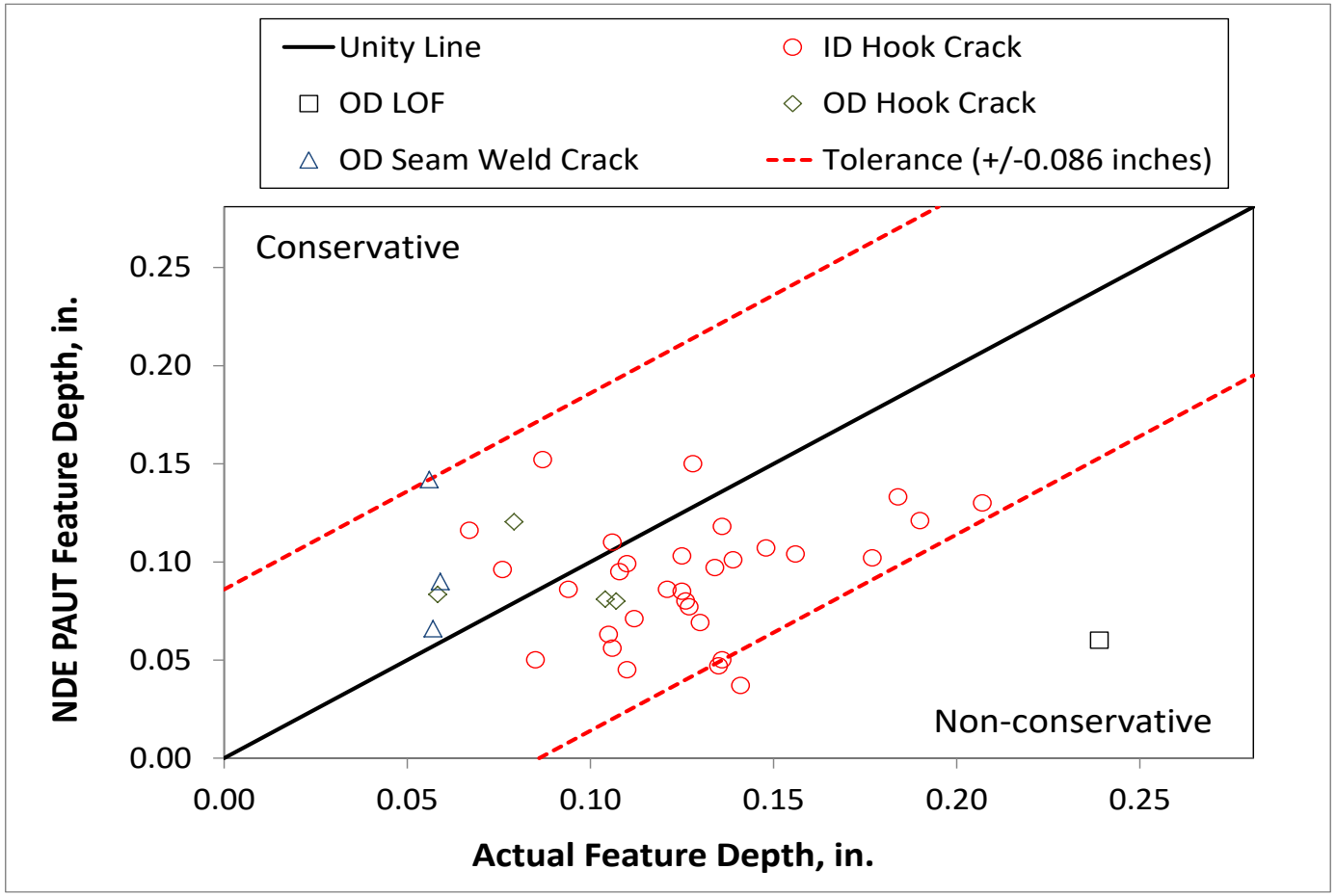
- **Identification success rate is low – 41% success rate**

Line	# Observations	Success	Success Rate	Binomial probability @ 95% confidence level	Clopper Pearson Probability Interval @ 95% confidence level	
					Lower	Upper
1	15	1	7%	18.1%	0.30%	27.90%
2	22	9	41%	27.0%	23.30%	60.50%
3	9	9	100%	-	-	-
Total	46	19	41%	31.0%	29.0%	54.5%

Definition includes all false negatives and false positives

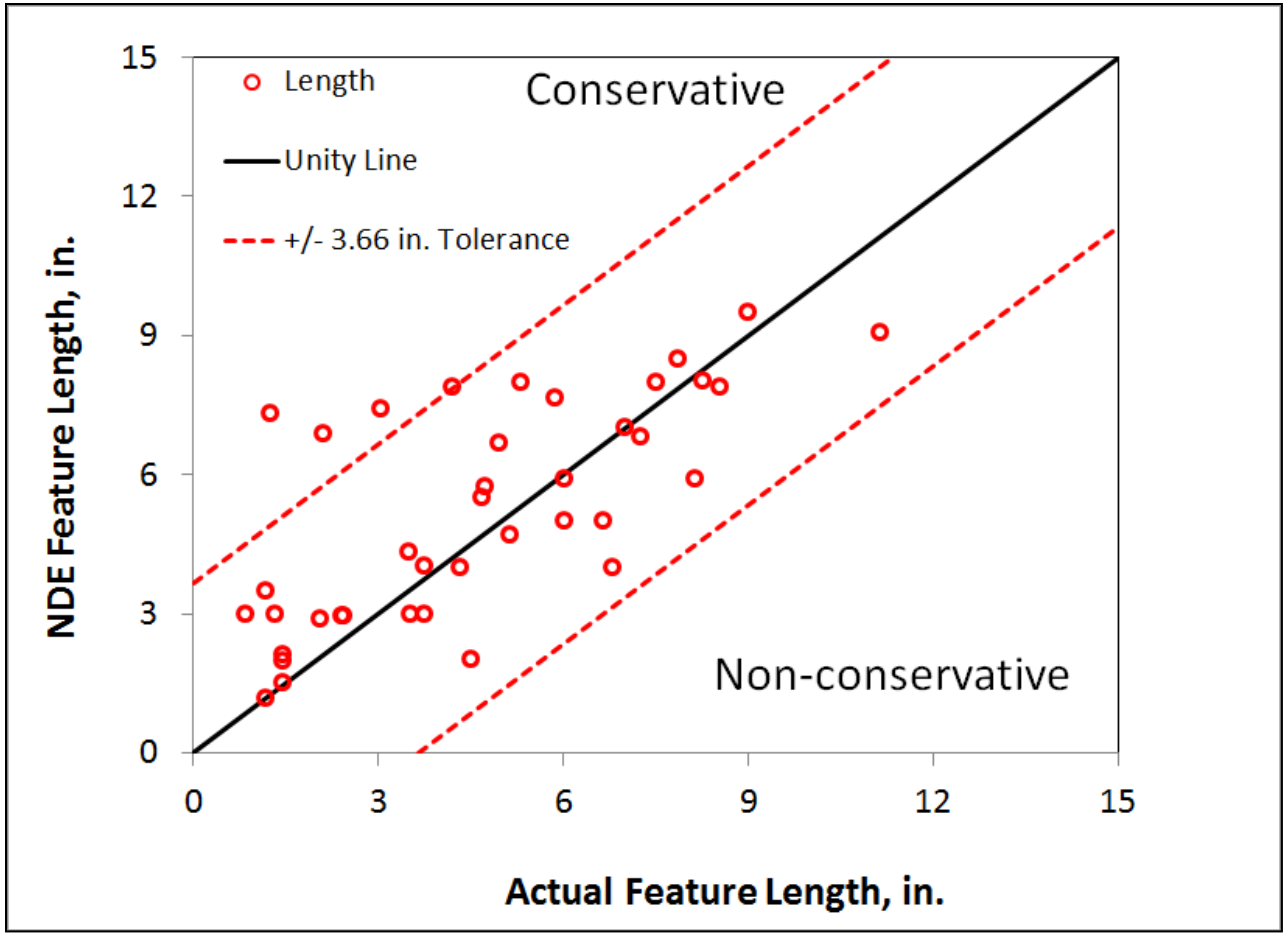
NDE Depth Error

- Depth Tolerance 2.18 mm (±0.086 in.)
  - **Success Rate 92%**
  - Clopper Pearson lower probability 81%
  - Performance acceptable



Length Performance

- Length tolerance ±3.66 in.
  - Success Rate 92%
  - Clopper Pearson Lower Probability 81%



Failure pressure models

Notch model

Comparison (OD Surface Notch)

Reference Stress

API-579 Limit Load

$$\sigma_{ref} = \frac{gP_b + \left[(gP_b)^2 + 9(M_s P_m (1-\alpha)^2)^2\right]^{0.5}}{3(1-\alpha)^2}$$

DNV Capacity Model

$$P_{Cap} = 1.05 \frac{2t.\sigma_u}{(D-t)} \frac{\{1-(d/t)\}}{\left\{1-\frac{(d/t)}{Q}\right\}}$$

End cap factor of 1.10

Failure Pressure Prediction (Burst Test)

- API-579, DNV Capacity utilized for predictions using specified minimum properties

#	Feature Type	OD	WT	Length	Depth	Testing Pressure	Testing Pressure	Failed	Actual Failure Pressure / Predicted 'Failure' Pressure	
		in	in	in	in	%SMYS	%SMUTS		API-579	DNV
1	OD J Type	22.00	0.244	5.1	0.104	140%	110%	Yes	1.37	1.23
2	Flash Missing/Midwall LOF	22.00	0.254	7.0	0.020	143%	113%	No	>1.03	NA
3	ID J Type	22.00	0.254	7.3	0.094	140%	110%	No	>1.37	>1.2
4	ID J Type	22.00	0.259	9.0	0.076	98%	78%	No	>0.89	>0.79
5	OD Seam Weld Toe Crack	22.00	0.304	31.2	0.083	145%	114%	No	>1.24	>1.19
6	OD Seam Weld Toe Crack	22.00	0.296	19.2	0.079	145%	114%	No	>1.25	>1.19
7	OD Seam Weld Toe Crack	22.00	0.302	11.1	0.055	126%	100%	No	>0.97	>0.9
8	ID Hook Crack	22.00	0.297	6.0	0.087	129%	102%	No	>1.11	>0.96
9	OD Seam Weld Toe Crack	22.00	0.301	8.5	0.059	135%	106%	No	>1.04	>0.96
10	OD Seam Weld Toe Crack	22.00	0.301	8.2	0.059	135%	106%	No	>1.04	>0.95
11	ID Hook Crack	16.00	0.248	7.8	0.050	159%	125%	Yes	1.31	1.17
12	ID Hook Crack	16.00	0.248	4.4	0.067	144%	113%	Yes	1.22	1.05
13	OD Hook Crack	12.75	0.237	8.3	0.058	122%	96%	Yes	0.98	0.92
14	OD Hook Crack	12.75	0.230	7.3	0.079	116%	91%	Yes	1.01	0.98

All Failures were Strength based failures

Process for better detection, discrimination and characterization of weld defects

- **ILI challenges: Discrimination**
  - Midwall, ID, OD
    - *Validation in-field*
  - Hook crack vs. LOF vs. Misalignment

- **NDE Challenges**
  - Discrimination
    - *Midwall / ID*
    - *Feature Type*
  - Depth Sizing - Higher tolerance can be utilized for integrity

- **Different assessment models for crack, notch, misalignment**
  - **One size fits all strategy does not work**

Process (Gas Pipeline)

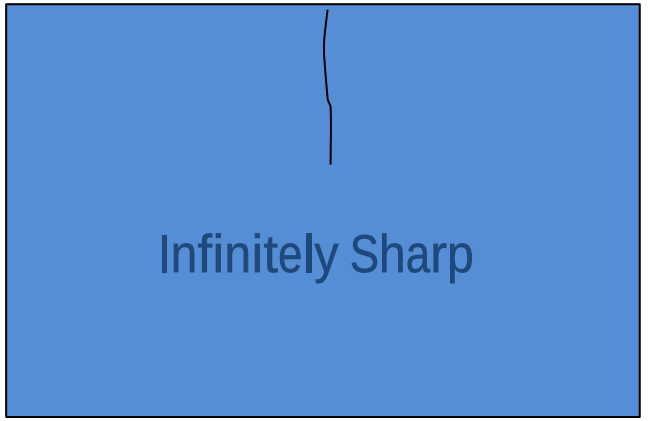
- Inspect
  - EMAT (Gas) with Circumferential MFL (multiple pipeline runs)
  - Limitations:
    - *Inability to discriminate/identify*
- Assess based on fracture mechanics approach
- Excavate
  - Classify the seam anomalies based on excavation (NDE also unable to discriminate)
    - ***Laboratory Sectioning or Historical Data on Type of Seam Defect***
- Assess :
  - Hook cracks - Limit Load Analyses (net section yield)
  - Lack of fusion – Limit Load or Fracture based models
  - Toe cracks – Limit Load Analyses or Fracture based models
  - Ensure no fatigue risk
- Establish future Assessment approach

Liquid Line: Fatigue Analysis

Notch



Crack



"S-N" Curve?

Paris Law

Process (Liquid Pipeline)

- Inspect
  - UT (shear wave) with Circumferential/Axial MFL
- Assess
  - Fracture Mechanics based models assuming crack like features
  - Fatigue analyses – Paris law
- Excavate
  - Classify the seam anomalies based on excavation (NDE also unable to discriminate)
    - ***Laboratory Sectioning or Historical Data on Type of Seam Defect***
- Assess :
  - Hook cracks - Limit Load Analyses (net section yield) & S-N
  - Lack of fusion – Limit Load or Fracture based models & S-N or Paris Law
  - Toe cracks – Limit Load Analyses or Fracture based models & S-N & Paris Law

Summary: ILI and NDE Performance

- Four operators, 5 line segments, 4 different ILI technologies, 64 digs, 293 miles inspection length, 3 NDE technologies, Lab verifications, 14 burst tests data

	ILI (Gas Line)	ILI (Liquid Line)	NDE - Phased Array Ultrasonic
Detection	√	√	√
Identification (Linear vs. Non–Linear)	√	√	
Identification (Actual feature type)	Challenges	-	Challenges
Depth Sizing	√	√	High (+) Tolerance
Length Sizing	High (+)Tolerance		√ (+) Tolerance

Summary – Assessment Methodology

- **Burst test**
  - Over fourteen burst test data verified the limit load equation of API 579 and DNV capacity equations

Questions

Sam Tandon: standon@blade-energy.com
Ming Gao: mgao@blade-energy.com
Ravi Krishnamurthy: ravimk@blade-energy.com

Burst Test – Sample Failed

#	Testing Pressure %SMYS	Testing Pressure %SMUTS	Sample Failed	Actual Failure Pressure/ Predicted 'Failure' Pressure API-579	Actual Failure Pressure/ Predicted 'Failure' Pressure DNV
1	140%	110%	Yes	1.37	1.23
11	159%	125%	Yes	1.31	1.17
12	144%	113%	Yes	1.22	1.05
13	122%	96%	Yes	0.98	0.92
14	116%	91%	Yes	1.01	0.98
			Average	1.18	1.07
			Stdev	0.18	0.13

API-579 Rectangular Profile
Measured Body material properties

	Actual/ Predicted FP	Actual/ Predicted FP/1.1
	0.90	0.82
	0.96	0.87
	1.11	1.01
	1.10	1.0
	1.05	0.96
	1.28	1.16
Average	1.06	0.97
Stdev	0.13	0.12

API-579 Rectangular Profile
Measured Fusion line properties

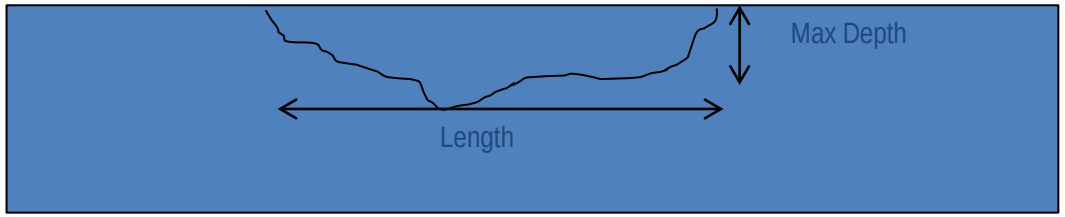
	Actual/ Predicted FP	Actual/ Predicted FP/1.1
	0.87	0.79
	0.88	0.80
	1.09	0.99
	1.10	1.00
	0.96	0.87
	1.14	1.04
Average	1.0	0.91
Stdev	0.11	0.10

Ultrasonic ILI Performance

Overview

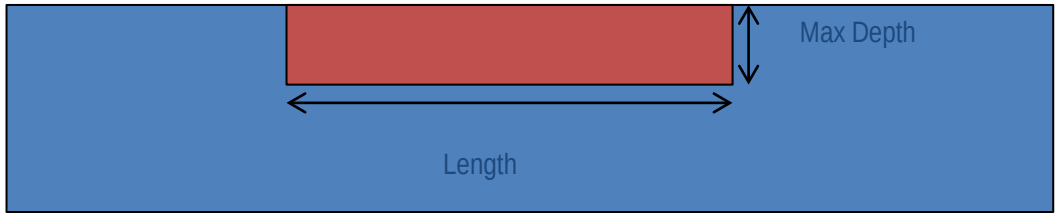
- Pipeline: 12” inch Crude Oil, NWT: 4.8 mm
- MFL Axial, and Ultrasonic Inspection (for Axial crack detection)
  - 475 Crack Like Anomalies
  - 184 manufacturing related signals
  - 36 deformation anomaly – dent locations have been reported of these 6 have been detected with metal loss
  - 12 manufacturing related signals
  - 8 extra metal
- **26 Joints Excavated - 50 ILI features**
  - Finding 357 Lack of Fusion Features in the Field
    - *350 were External Lack of Fusion*
    - *None confirmed in the lab*

Data Availability

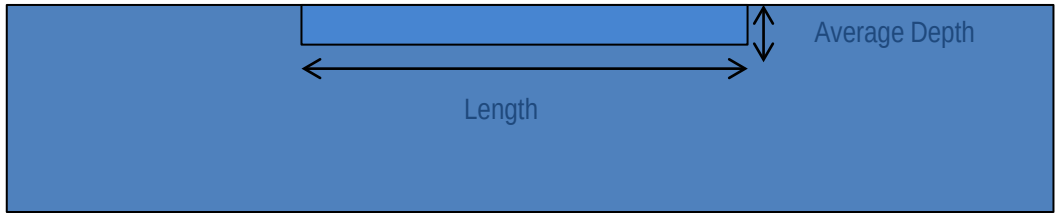


Reality — Not available

Crack/Notch Profile



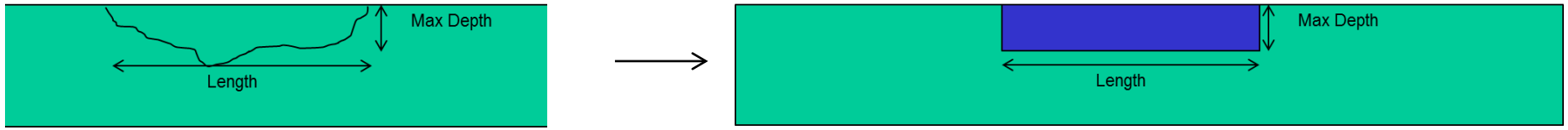
Very Conservative Assumption — MAX DEPTH

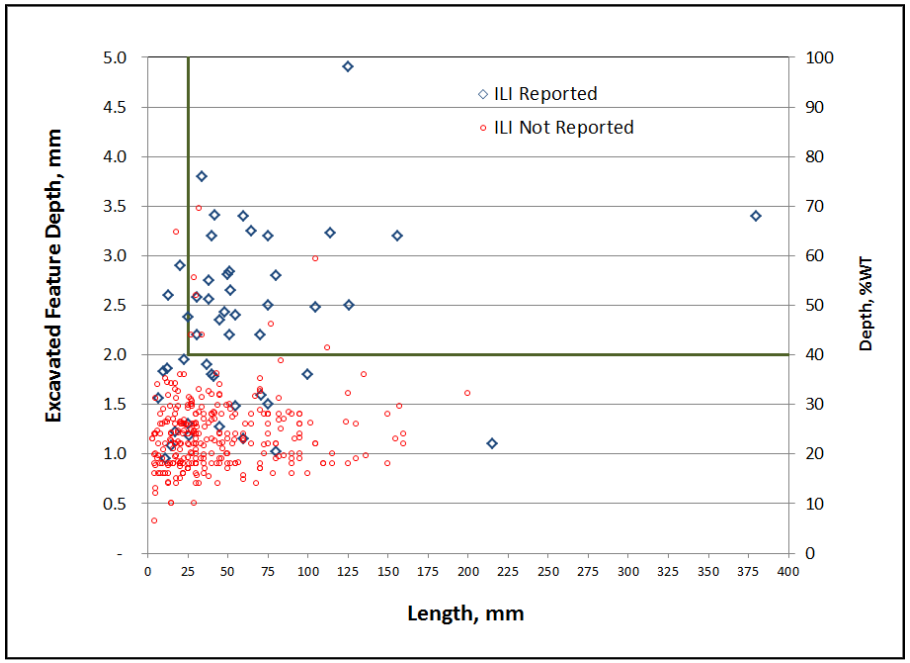


Assumption conservative or non-conservative? — AVERAGE DEPTH

Feature Max Depth vs. Length

- Assuming that feature is continuous for entire length of the crack having a maximum depth, excavated feature depth vs. length is plotted – no measurement error included





Most missed defects are below tool threshold

Revisiting not reported features

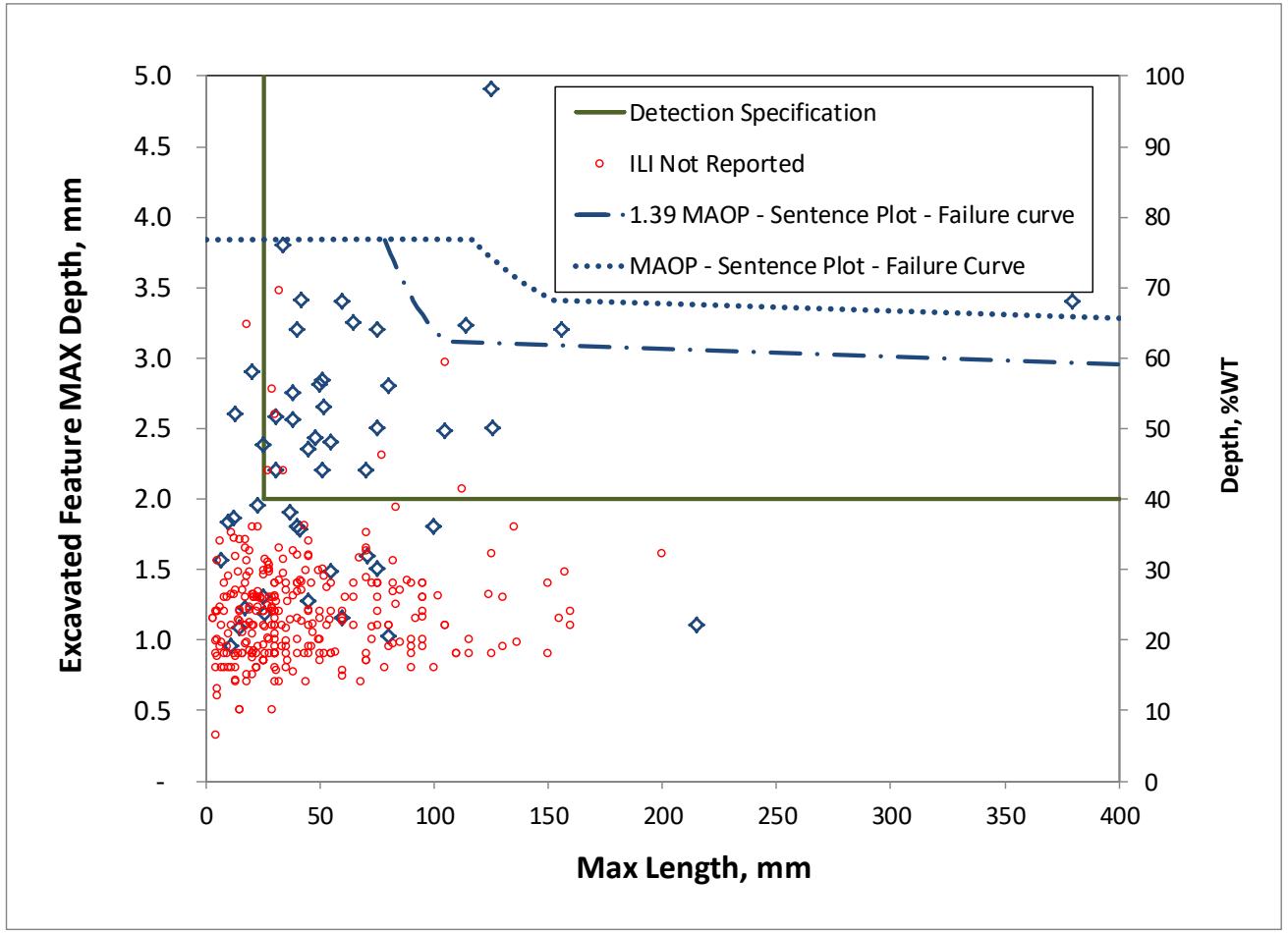
- Features in five joints with features with PAUT max depth > length above tool detection specifications were reviewed
- Signals were detected by the ILI for all features
  - LOF were not reported
    - *Due to proximity to the other feature or*
    - ***Below depth** reporting threshold*

RGW	ID	Anomaly	PAUT max depth reported	PAUT length reported (mm)	ILI Feature Depth (mm)	ILI Feature Length (mm)	Comments
100900	1	EXT LOF	3.0	105	1.2	41.8	Close proximity to the reported feature. Would have fallen under the cluster rule
100900	2	EXT LOF	3.5	32	0.7	39.8	
99670	1	EXT LOF	2.1	112	0	91.8	Below reporting criteria
99610	1	EXT LOF	2.2	34	0.4	51.9	
99610	2	EXT LOF	2.2	27	0.3	49.8	
86480	1	EXT LOF	2.8	29	0	29.9	
86480	2	EXT LOF	2.3	77	0.5	49.9	
73560	1	MW LAM	3.0	240	N/A	348.3	Reported Feature. ILI does not report lamination depth

Assuming it holds for other joints with not reported features POD (Signal) Success rate = 100%

Sentence Plot

- All the Not reported features are below the sentence plot (critical curve)

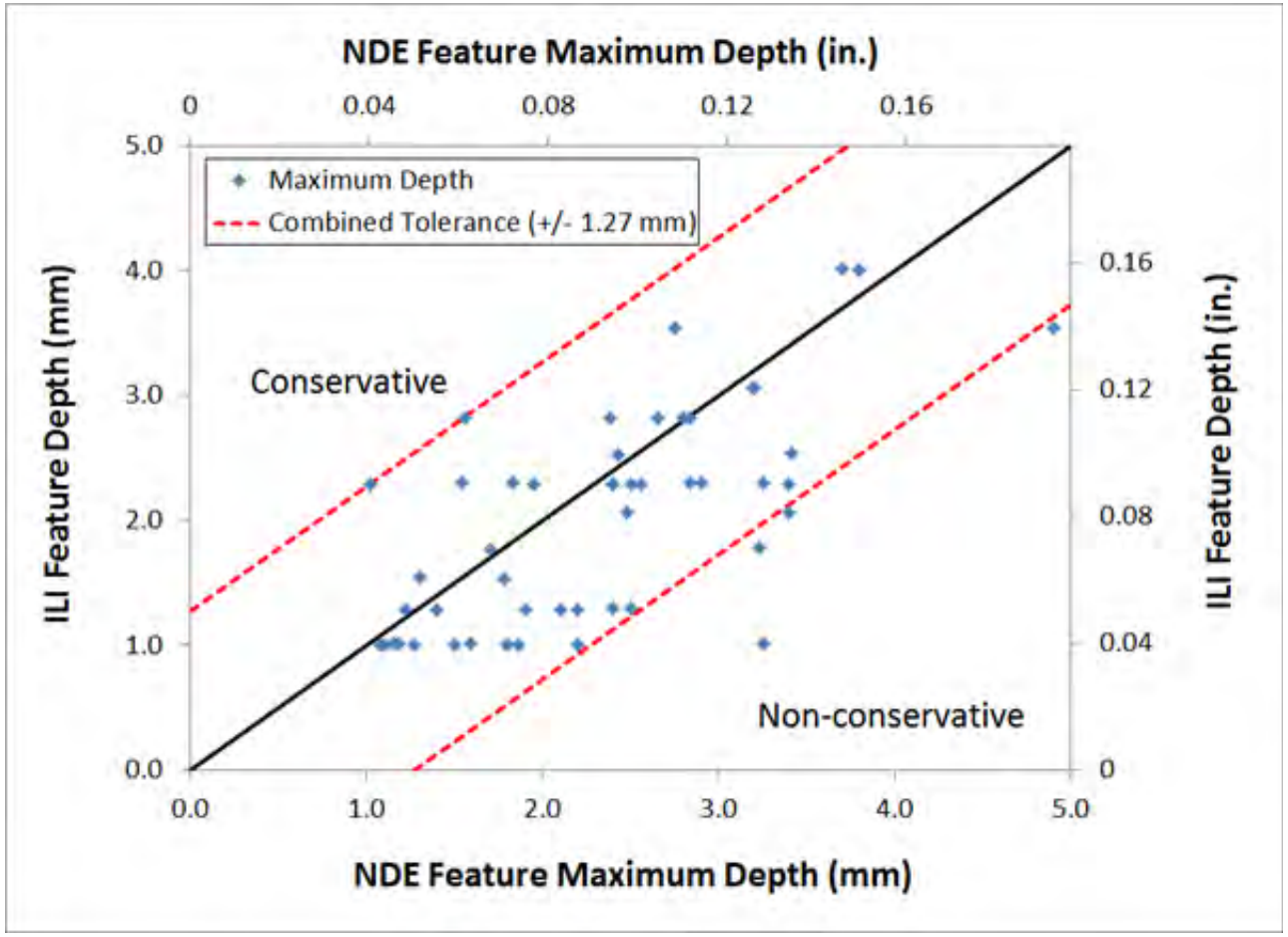


Identification Capability

- 50 Crack-Like Anomalies reported by ILI
  - 34 Lack of Fusion (True Positive)
  - 16 Pipe Seam Anomalies (False Positive)
  - No False Negatives
- Success rate of Identification* 100%

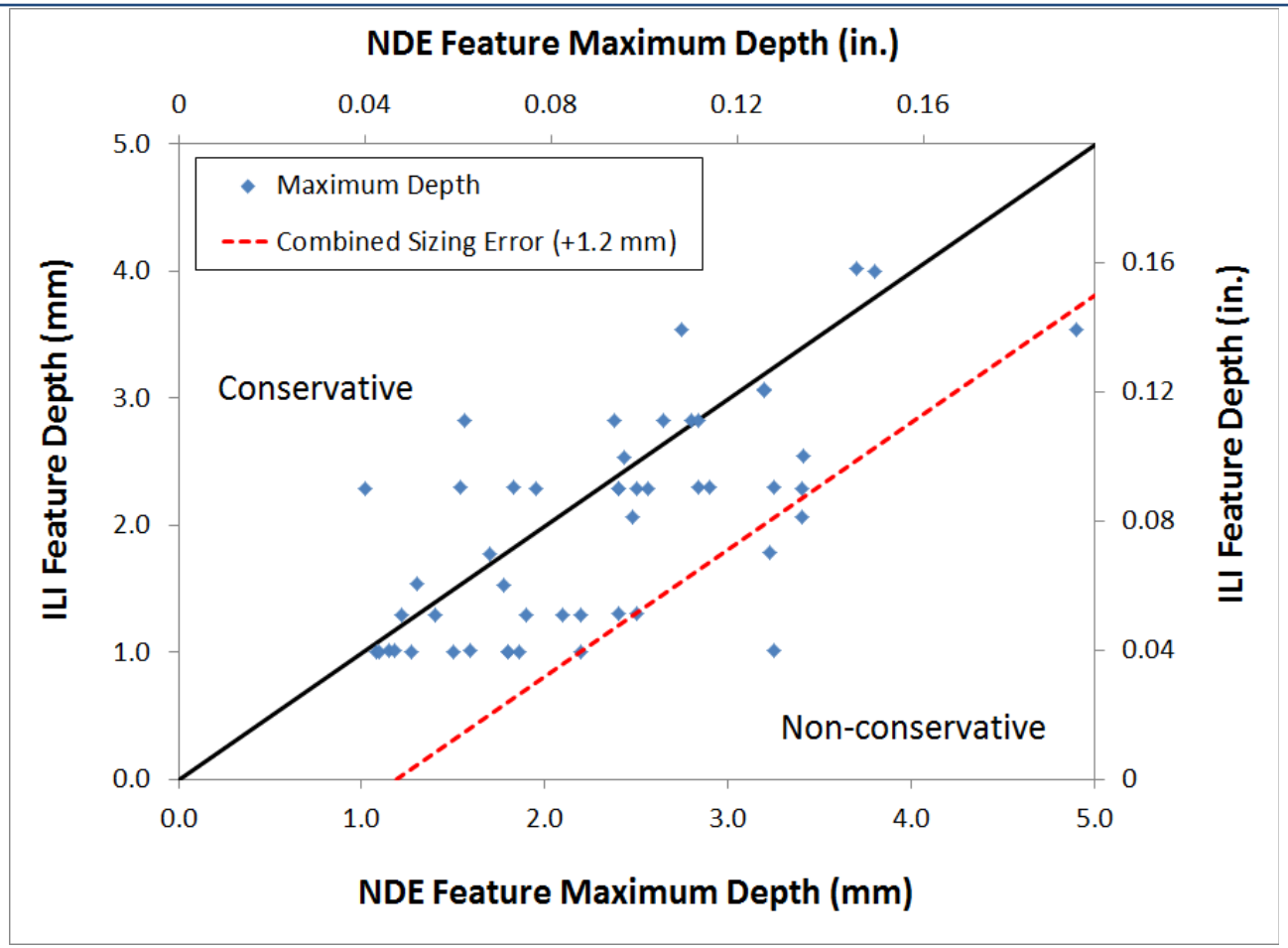
ILI vs. Excavation – Depth Sizing Tool Tolerance

- **For depth tolerance of ±1.27 mm (0.05 in.)**
  - 46 out of 50 is within tolerance
  - Success Rate: 92%
  - Binominal probability: 85% at a 95% confidence level
  - Clopper Pearson: 82-97% certainty at a 95% confidence level



ILI vs. Excavation – Depth Error for Integrity

- **ILI tolerance of +0.96 mm (+0.0377 in.)**
  - Combined tolerance of +1.2 mm (0.047 in.)
  - 46 out of 50 is within tolerance
  - Success Rate 92%
  - Clopper Pearson lower certainty 82% at a 95% confidence level



Pull Test

Pull Test

- **Pull test was performed on Pipe with OD of 450 mm, Weld Type: SAW, Year of Manufacture 1959**

- **ILI Tools utilized**
  - EMAT – crack features
  - Axial MFL – volumetric features
  - Circumferential MFL – volumetric features
  - Caliper – for out of roundness of pipe

- **Radiography was utilized to validate the findings from ILI tools**
- **Detection Success Rate is reported for Crack, LOF, LOP, and Aligned Inclusions**

Pull Test

Detection Success Rate (%)						
	ILI Tool	Cracks	Aligned inclusions	**Lack of Fusion**	**Lack of Penetration**	Lack of Thickness
All radiographic indications	EMAT	100%	50%	**83%**	**75%**	50%
	Circumferential MFL	100%	90%	**83%**	**100%**	50%
	Axial MFL	100%	60%	**100%**	**100%**	50%
Total		1	10	**6**	**4**	2

Results table provided. The background data was not analyzed

Pull Test: Interpretation

- Detectability by technologies strongly depends on the typology of longitudinal weld failure

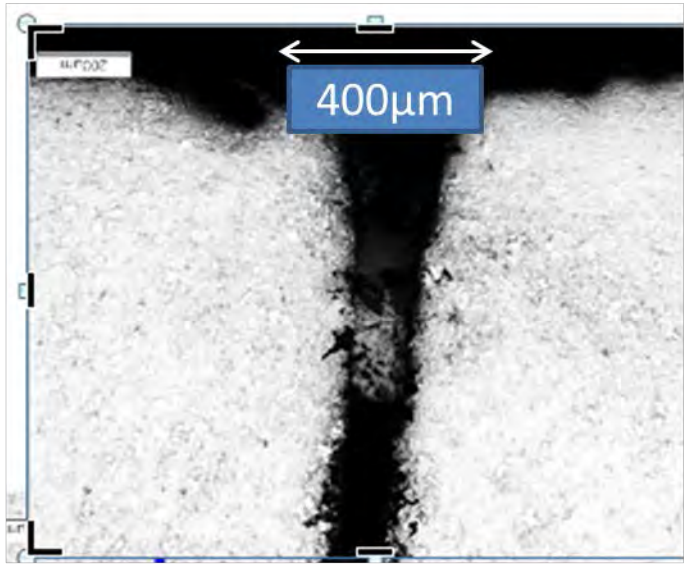
- MFL along with caliper can be used to detect flaws in SAW
- EMAT can be used depending on feature types on the line for Fitness for Purpose
  - Defect size characterization

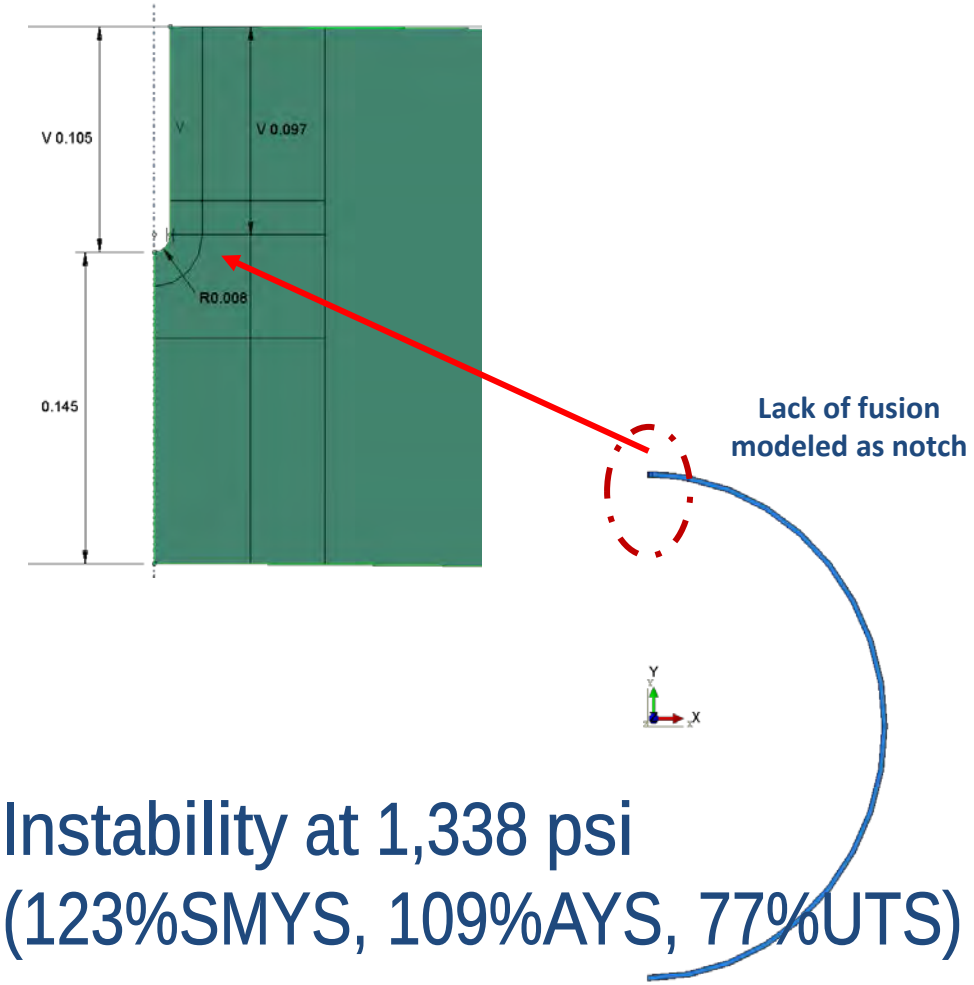
Failure pressure models

Notch model

Case 1 : FEA Modeling Lack of Fusion

OD = 24-inch, WT= 0.25, Grade = X52
Depth = 0.104 inch (2.64 mm) = 42%wt
Feature: Notch
Length: Infinite
Material Property: Actual Tensile Curve
Elastic Plastic
YS 58.6 ksi, UTS 83.4 ksi

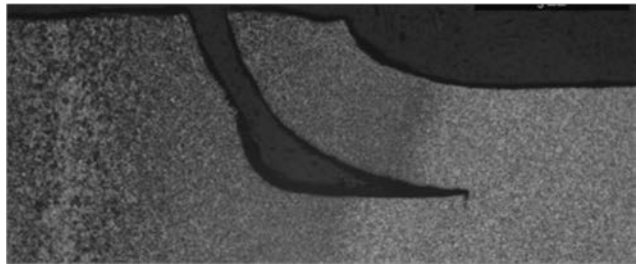




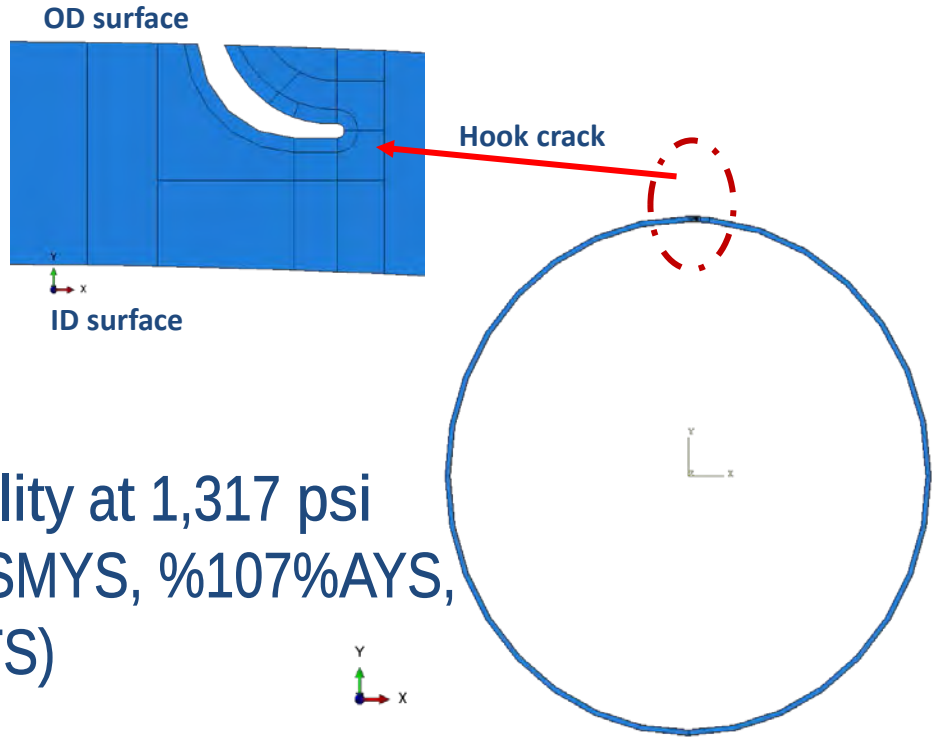
Instability at 1,338 psi
(123%SMYS, 109%AYS, 77%UTS)

Hoop stress is perpendicular to the crack front

Case 2 : Modeling Hook Crack



Hook crack depth = 42%wt
Notch length = Infinitely long

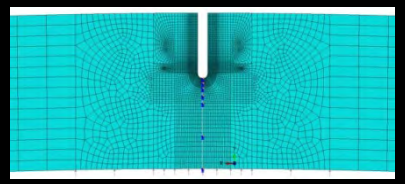
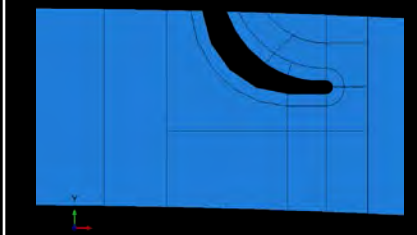


Instability at 1,317 psi (121%SMYS, %107%AYS, 76%UTS)

Hoop stress is not perpendicular to the crack front due to the crack shape

Comparison – LOF vs. Hook Crack

- API-579 Limit Load Method is conservative compared to the actual failure pressure predicted by FEA simulation

	API-579 Limit Load	Lack of Fusion	Hook Crack J - Type
			
Instability	1,091 psi	1,338 psi	1,317 psi

BACK TO AGENDA

PRCI 2020 Research Exchange

Ensuring the Permanency of Pipeline Composite Repair Systems

MATR-3-4

Colton Sheets, PE
Senior Associate
Stress Engineering Services, Inc.

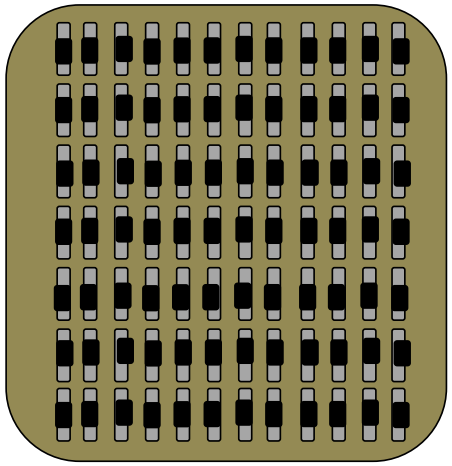
LEADING PIPELINE RESEARCH

Agenda

- Introduction
- Project Overview
- Results Summary
- Methodology
- Results Continued
- Supplemental NDE
- Implementation
- Summary
- Questions

Introduction

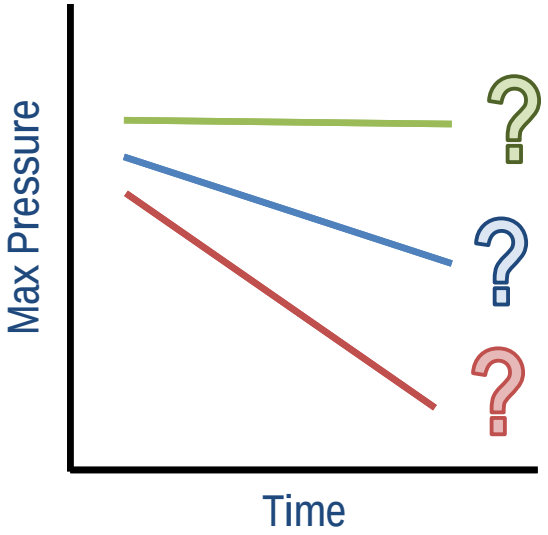
- ***Ensuring the Permanency of Pipeline Composite Repair Systems***
  - *Program examining the long-term performance of composite repair systems used for pipeline applications*



Periodic Bursts







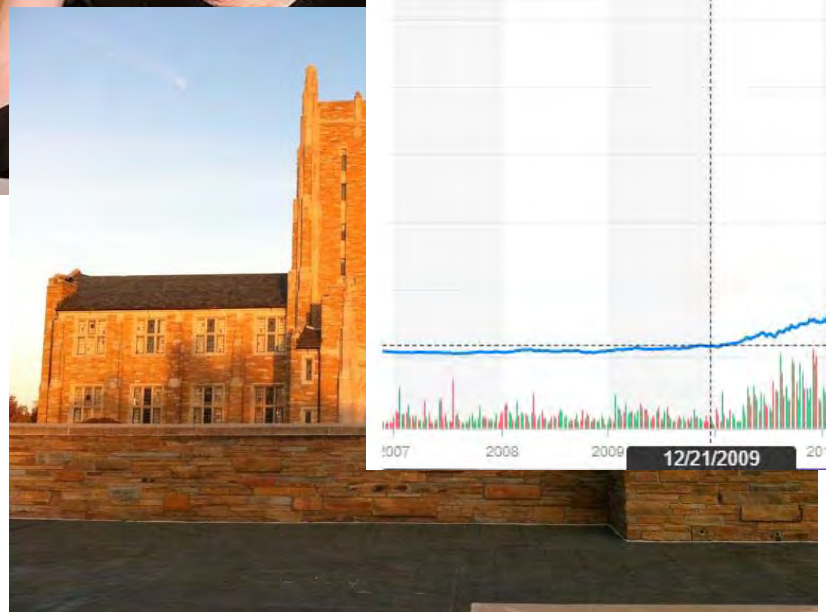
Project Overview



- **Over 180 pipe samples buried at Stress Engineering's test facility in Waller, TX for up to 10 years**
  - 2008 - 2019
- **Pipe samples 12.75-inch OD x 0.375-inch WT, Gr. X52**
  - 40%, 60%, and 75% machined wall loss regions
  - Reinforced using composite repairs from 12 manufacturers
- **Burst tests performed at designated intervals**
  - Year 0 – Baseline tests
  - Year 1
  - Year 2
  - Year 3
  - Year 5
  - Year 7.5
  - Year 10 – Final bursts

Project Overview – 10 years?

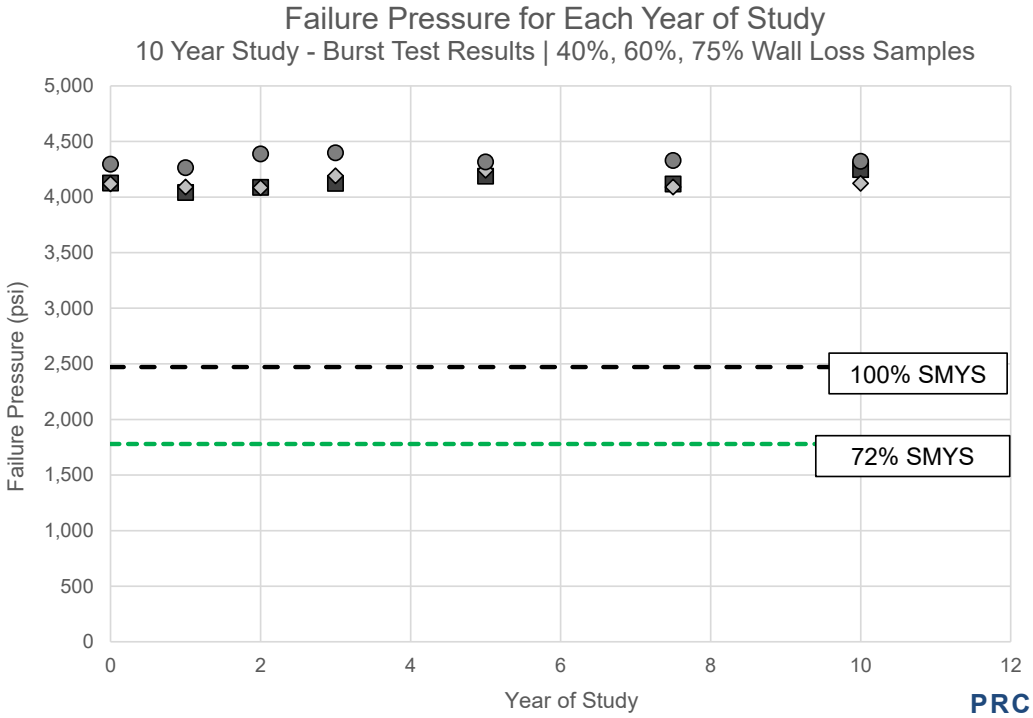






Results Summary

- **Typical results showed failure pressures in excess of 150% SMYS across all years of the study and for 40%, 60%, and 75% wall loss samples**
- **Failures located in base pipe and underneath composite**

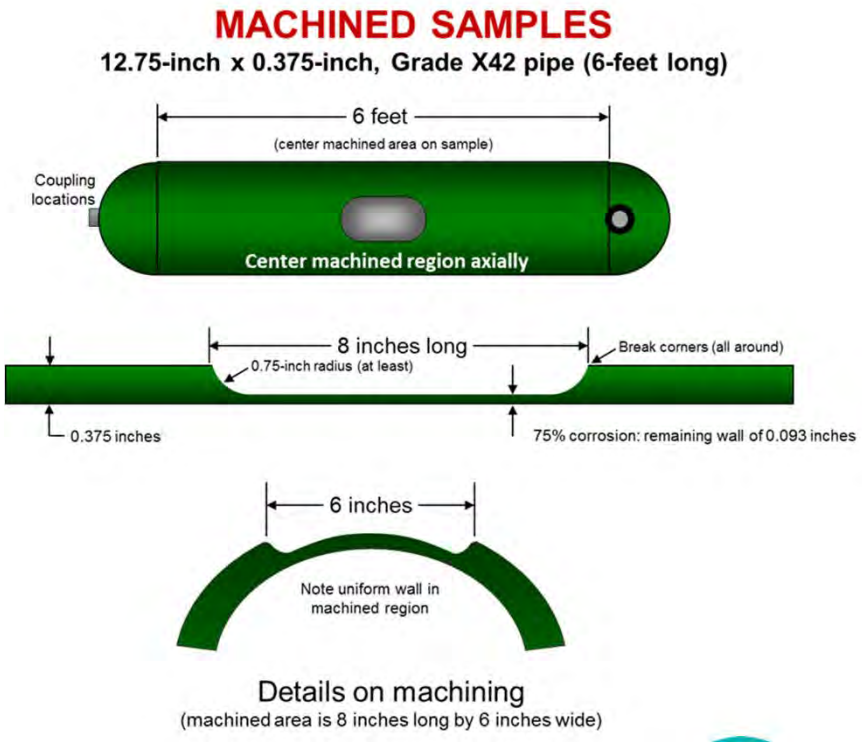




Methodology – Participation and Wall Loss Geometry

- **Back to the beginning……**
  - Over 180 samples fabricated with three machined wall loss depths (40%, 60%, 75% of pipe wall thickness)
    - *Three samples left unreinforced for baseline comparisons*
    - *Other samples reinforced using products from 12 manufacturers*

System Designation	Burst Test Year						
	0	1	2	3	5	7.5	10
A	Y	Y	Y	Y	Y	Y	Y
B	Y	Y	Y	Y	Y	Y	Y
C	Y	Y	Y	Y	X	X	X
D	Y	Y	Y	Y	X	X	X
E	Y	Y	Y	Y	Y	Y	Y
F	Y	Y	Y	Y	X	X	X
G	Y	Y	Y	Y	Y	Y	Y
H	Y	Y	Y	Y	X	X	X
I	Y	Y	Y	Y	X	X	X
J	Y	Y	Y	Y	X	X	X
K	Y	Y	Y	Y	X	X	X
L	Y	Y	Y	Y	X	X	X



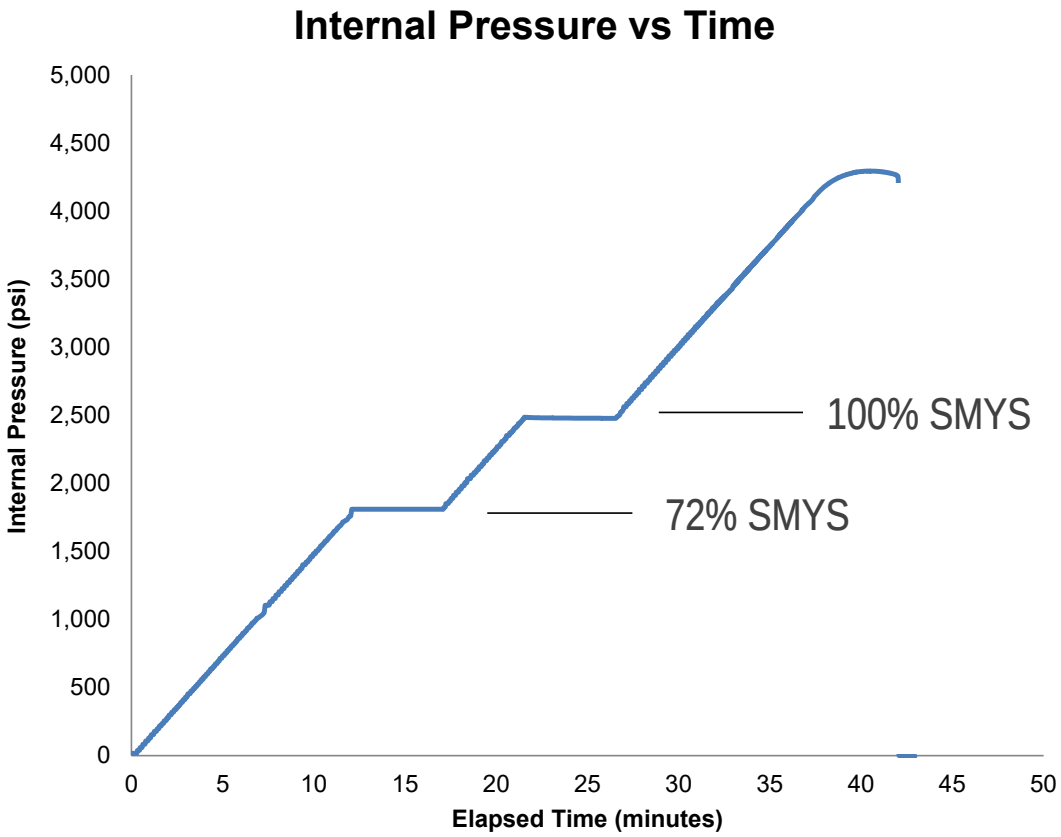
Methodology - Burial, Service Description, and Repair Design

- **While samples were buried:**
  - Three year samples maintained at constant 36% SMYS (890 psi)
  - Pressure cycling
    - *900 cycles / year @ 36 – 72% SMYS*
  - Spike testing
    - *Four spikes / year @ 0 – 1,780 psi*
- **Repair Design**

Material Type	Corrosion Depth (%)	Thickness (inches)
E-glass	40	0.56
	60	0.64
	75	0.72
Carbon Fiber	40	0.40
	60	0.54
	75	0.68
Other (Kevlar)	40	0.29
	60	0.59
	75	0.65



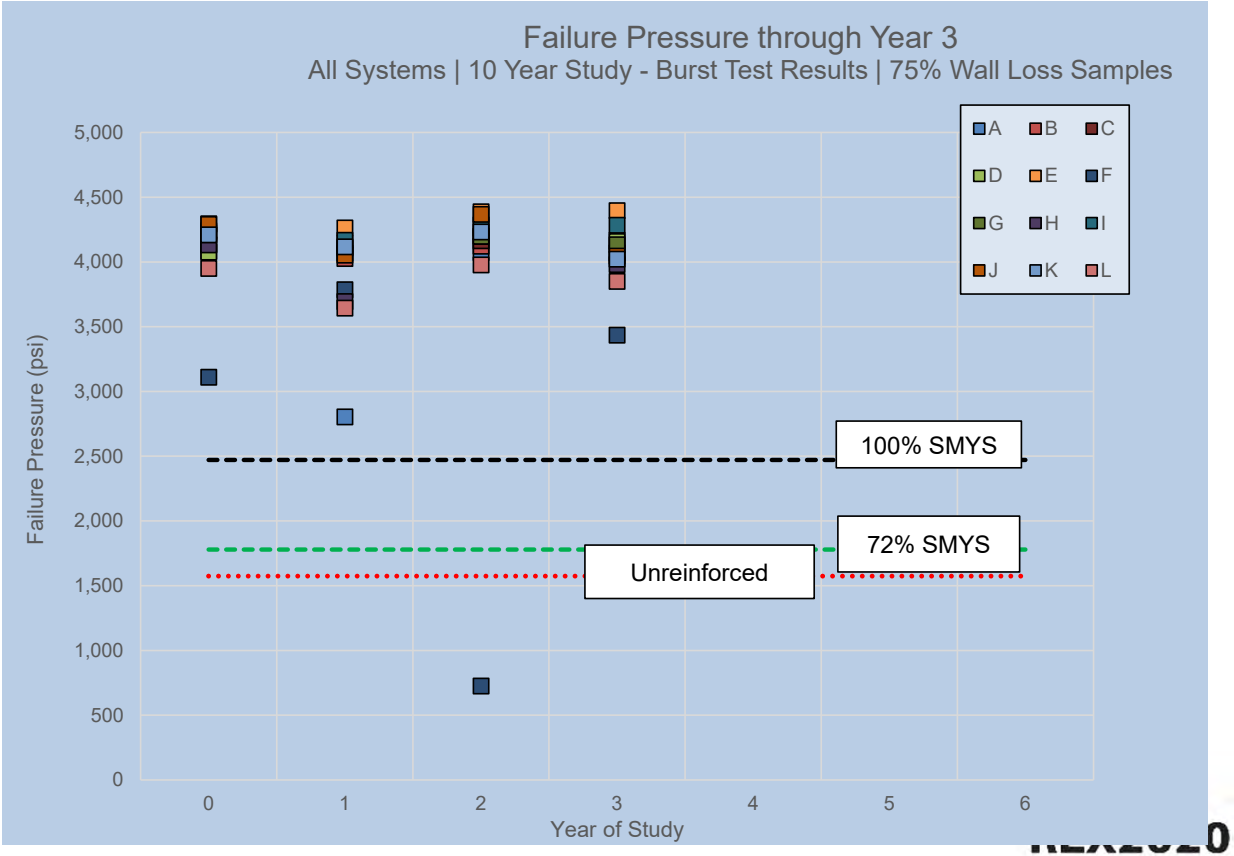
Methodology – Burst Testing





Results Continued – through Year 3

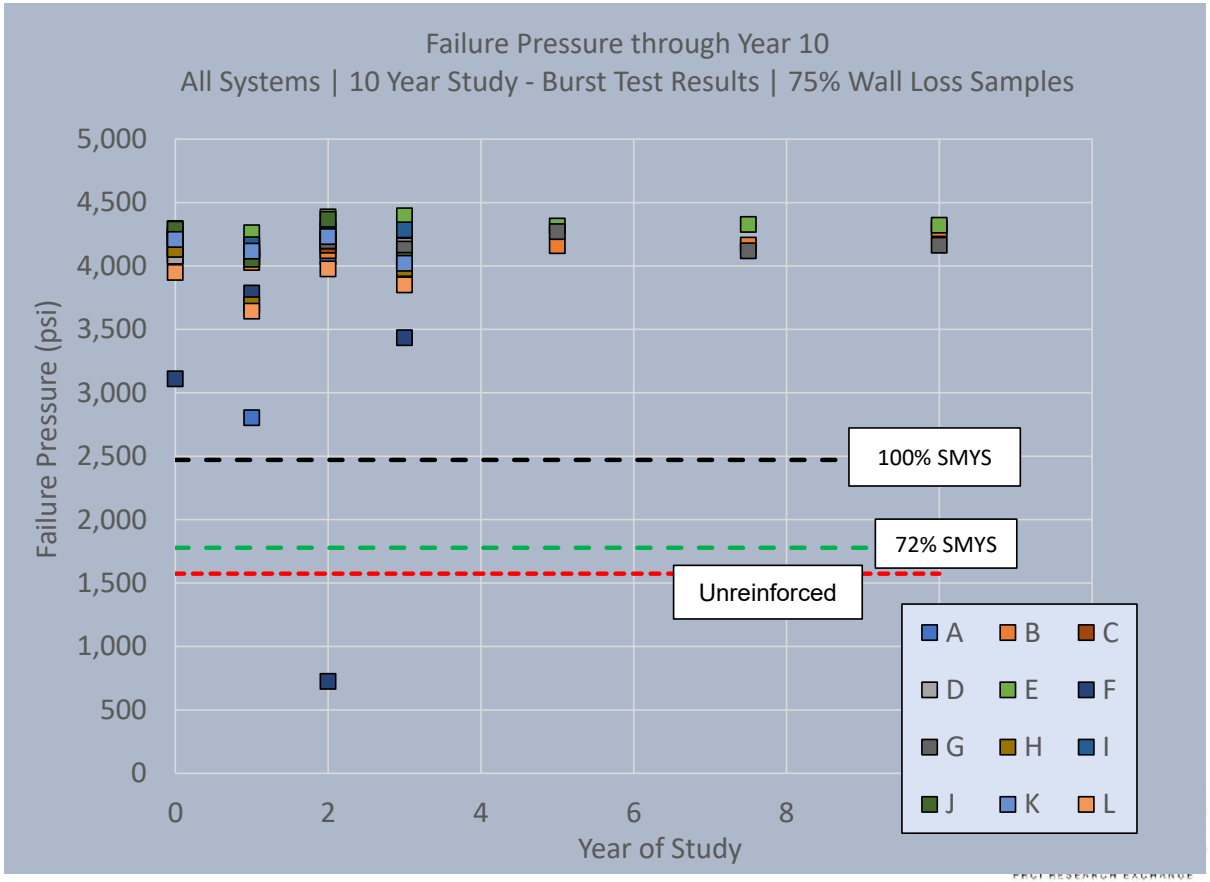
- **40% Results through Year 3**
  - Average failure pressure: 4,133 psi
  - Median failure pressure: 4,141 psi
  - Std. Deviation: 106 psi
  - Failures in repair: 12 / 48
  - Unreinforced failure: 3,386 psi (137% SMYS)
- **60% Results through Year 3**
  - Average failure pressure: 4,156 psi
  - Median failure pressure: 4,151 psi
  - Std. Deviation: 77 psi
  - Failures in repair: 8 / 48
  - Unreinforced failure: 2,521 psi (102% SMYS)
- **75% Results through Year 3**
  - Average failure pressure: 3,987 psi
  - Median failure pressure: 4,128 psi
  - Std. Deviation: 566 psi
  - Failures in repair: 14 / 48
  - Unreinforced failure: 1,574 psi (64% SMYS)



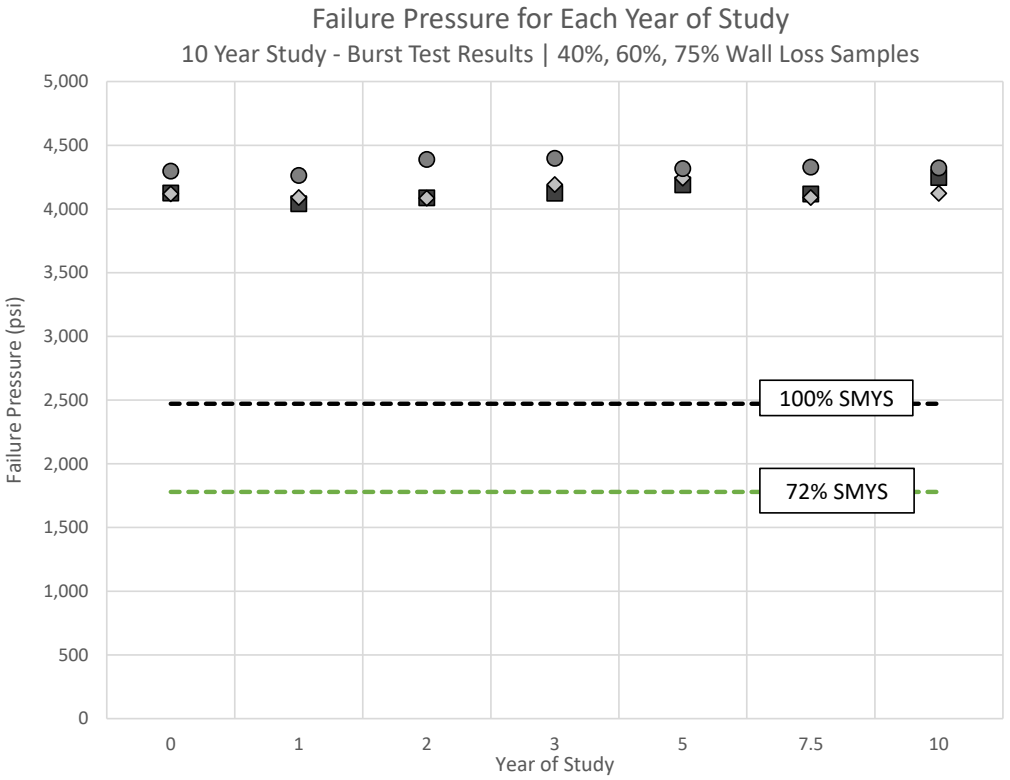
Results Continued – through Year 10

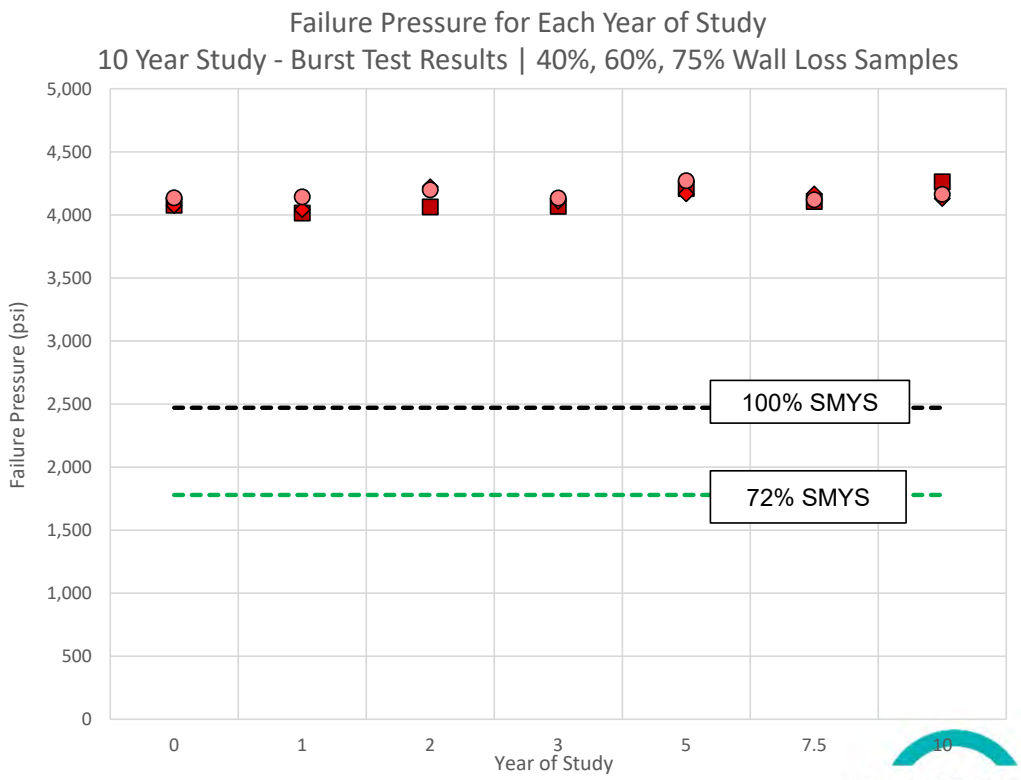
- **Results through Year 10**

- **40% Results through Years 5 - 10**
  - Average failure pressure: 4,153 psi
  - Median failure pressure: 4,195 psi
  - Std. Deviation: 125 psi
  - Failures in repair: 6 / 12
  - Unreinforced failure: 3,386 psi (137% SMYS)
- **60% Results through Year 5 - 10**
  - Average failure pressure: 4,089 psi
  - Median failure pressure: 4,130 psi
  - Std. Deviation: 154 psi
  - Failures in repair: 4 / 12
  - Unreinforced failure: 2,521 psi (102% SMYS)
- **75% Results through Year 5 - 10**
  - Average failure pressure: 4,216 psi
  - Median failure pressure: 4,219 psi
  - Std. Deviation: 100 psi
  - Failures in repair: 3 / 12
  - Unreinforced failure: 1,574 psi (64% SMYS)



Results Continued – through Year 10





Supplemental NDE

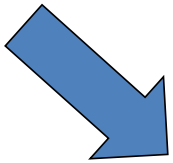
- **Opportunity for additional value**
  1. Samples removed “from service”
  2. Designated for destructive testing
- **Two manufacturers provided new ‘Control’ samples to serve as reference points**



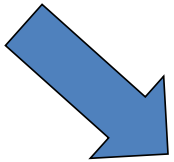


- **Does NDE predict performance?**

Field Inspection



Interpretation



IM Decision

Supplemental NDE

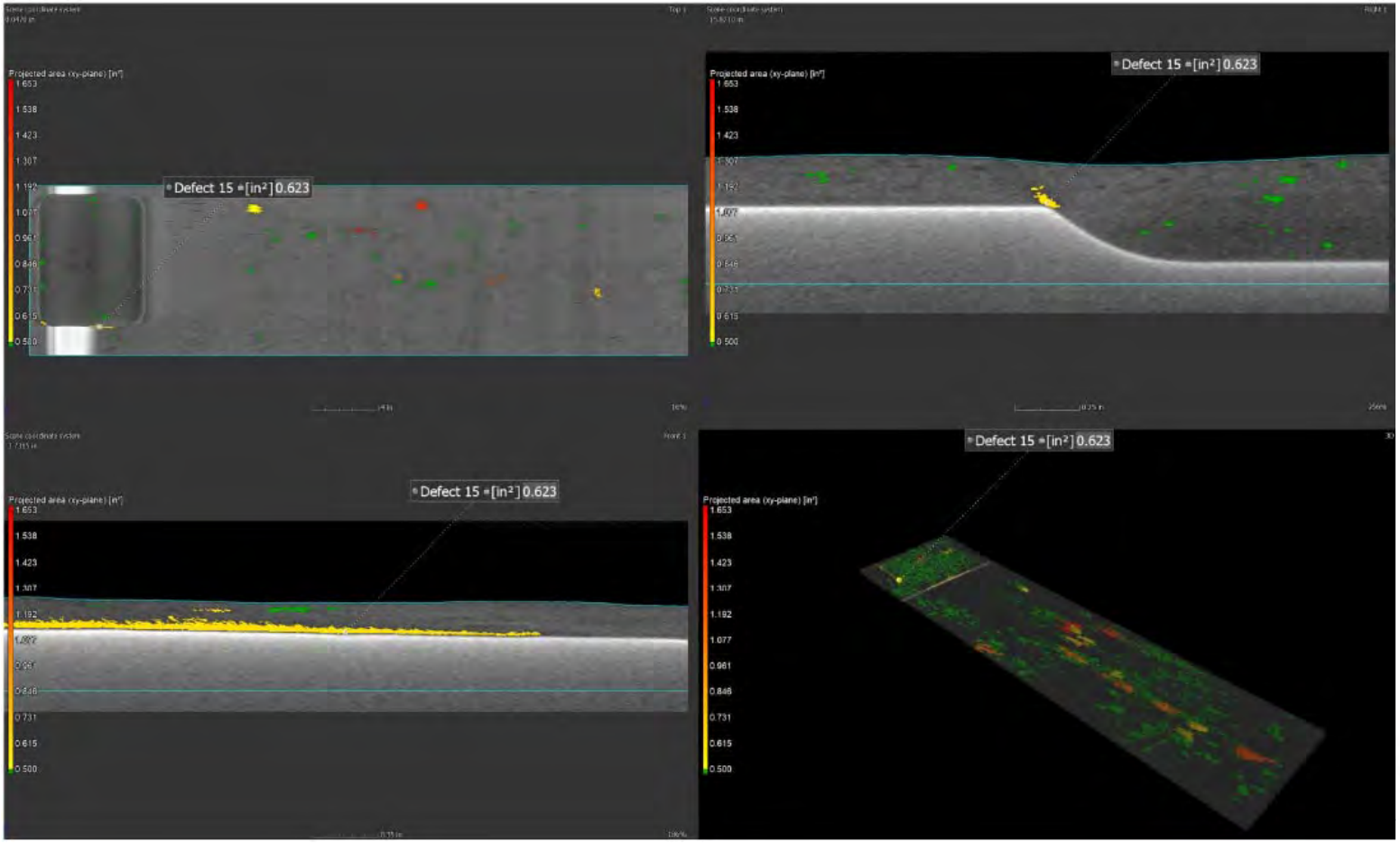
- **Inspections performed:**
  - BIS Salamis
    - *Olympus Bond Testing Probe*
  - Inspection Associates
    - *Computed Tomography (CT)*
  - Sonomatic
    - *Dynamic Response Spectroscopy (DRS)*

- **Results are still being processed but:**
  - At least two of three techniques identified defects / anomalies in the repair
    - *Third technique still processing data*
  - Inspections performed using both exposed samples and control samples



Supplemental NDE - CT

Control Sample



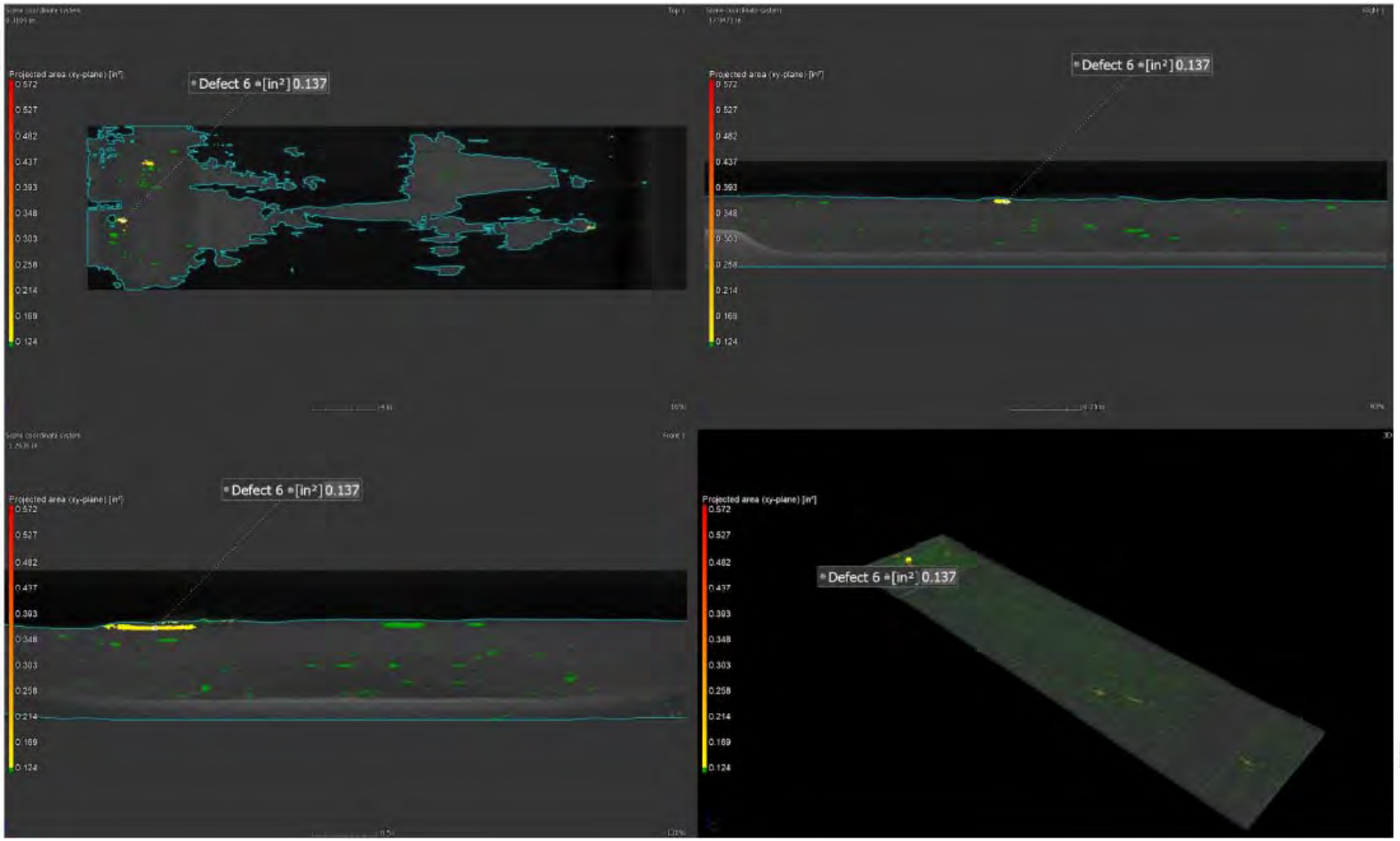
Supplemental NDE - CT

Control Sample



Supplemental NDE - CT

Exposed Sample



Implementation

- **Test Results:**
  - Burst test results show fairly consistent results, but some significant outliers
  - Variations appeared to be more manufacturer dependent – not time-dependent
- **What does this mean?**
  - Highlights importance of selecting manufacturer with demonstrated performance
    - *Review test data, participation in relevant test programs, material / test data representative of field conditions*
  - ASME PCC-2 Article 4.1 provides design methodology and testing that sets solid foundation
    - *Review requirements of PCC-2, what the standard does and doesn't cover, use engineering judgement!*

- **NDE of Composites:**
  - NDE results identified several anomalies / defects located within composite repairs – even control repairs
  - Despite these findings – acceptable performance was observed during 10-year burst tests
- **What does this mean?**
  - If inspection is a primary objective of industry, further work must be performed to quantify injurious anomalies

Summary

- **Summary**
  - Over 180 pipe samples with composite repairs buried and periodically burst over the course of 10 years
    - *12 composite repair manufacturers participated through 3-years*
    - *4 composite repair manufacturers participated through 10-years*
  - The vast majority of samples achieved failure pressures in excess of 100% SMYS and most had failure pressures exceeding 150% SMYS
    - *Demonstrated composite repairs can be suitable for long-term applications*
  - Variations in performance appear to be more manufacturer dependent than time dependent

- **Next Steps?**
  - Continue NDE effort with existing data and remaining samples
  - Provide high-level overview of NDE results to PRCI
  - Is composite inspection important to industry?
    - *If so, need to refine understanding of injurious defects*

Questions



Colton Sheets, PE
Stress Engineering Services, Inc.
colton.sheets@stress.com
281-955-2900

PRCI 2020 Research Exchange

Status of Efforts on Hydrotest Optimization of Older Liquid Pipelines

Independent efforts of interest to PRCI Members

- By Gery Wilkowski[(a)], Yunior Hioe, Fabian Orth, Bud Brust, J-K Hong, Suresh Kalyanam, Sushma Pothana, Cameron Orth, Dave Utz, Mike Fishman, and Russ Hattery
- Engineerig Mechanics Corporation of Columbus

  3528 Riverside Drive – Suite 202

  Columbus, OH 43221

  [(a)] Presenting author – gwilkowski@emc-sq.com

LEADING PIPELINE RESEARCH

Introduction

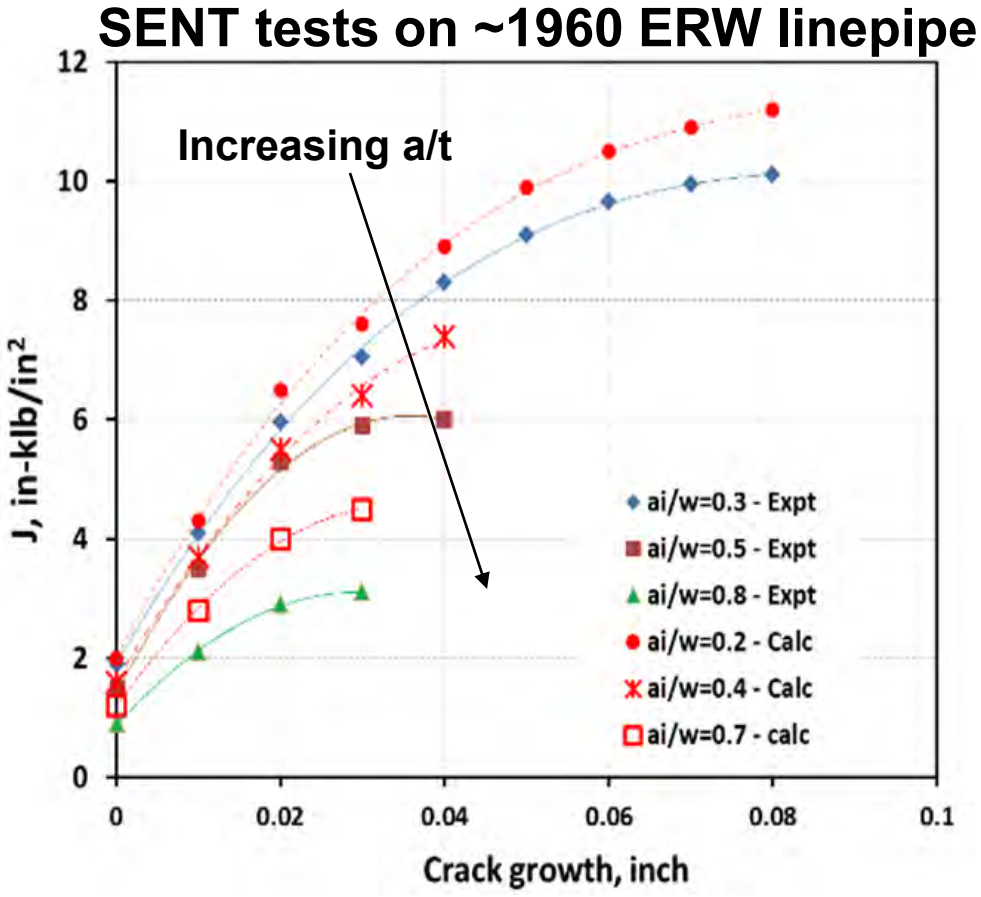
- Program objective is to develop data and analyses to determine how to optimize hydro-testing for liquid pipelines
- Scoping study expanded on research performed at Battelle in early 1990's
- Approach: The problem that is being solved is to determine how high of a hydrotest pressure gives the most benefit without reduction of integrity by growing cracks during ductile tearing
- Liquid lines may operate much lower operating pressures (perhaps 40% SMYS) compared to gas lines that have much higher hydrotest pressures (90-100% SMYS). There is a large margin between a hydrotest of 1.25 times 40% SMYS and 90-100% SMYS
- Initial concern - Don't want such a high pressure that there can be ductile crack growth in large numbers of remaining flaws after a hydro test, but want to maximize cyclic or SCC life

Approach

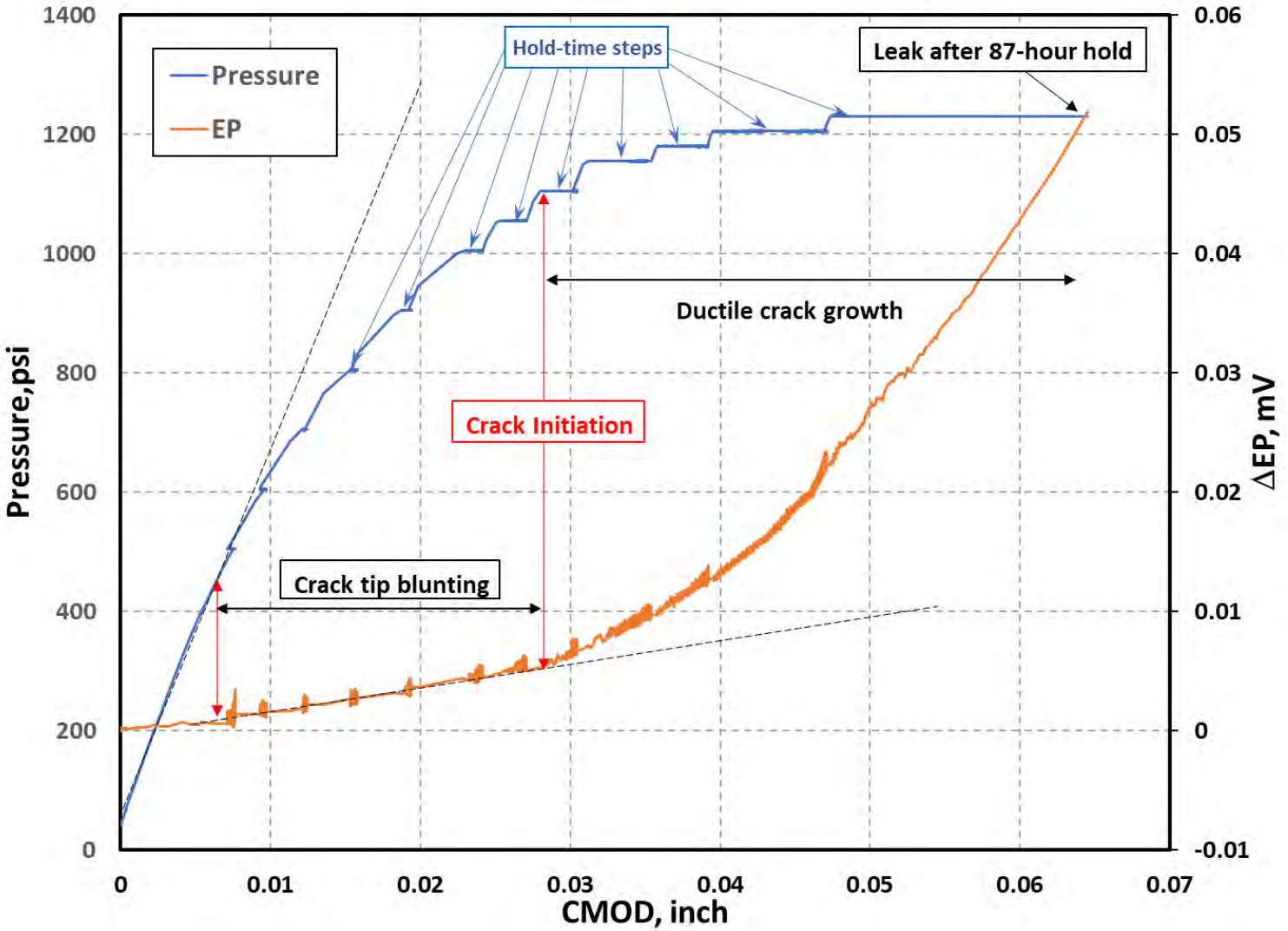
- **Efforts to date have focused on developing some key test data on vintage ERW pipe**
  - Experimental efforts involved;
    - *SENT specimen fracture tests with different initial flaw depths – **showed toughness decreases as a/t increases** (same result at Emc² for many materials and surface-cracked pipe)!*
    - *Pipe tests with step-hold pressure loading – monitored crack growth and how crack grow stabilized with hold times at different pressure levels*
    - *Pressure cycling of surface-cracked pipe after simulated hydrotests with monitoring of subsequent fatigue crack growth rate*
  - Supporting analysis efforts involved;
    - *Evaluation of constraint effects to see if that explained why fracture resistance decreases with increasing flaw a/t – ASME PVP international round-robin efforts*
    - *Time-dependent crack growth modelling determining limitations of past PRCI software (by Brust)*
    - *3D FE fracture analyses for guidance*

Some Key Results – (a) Toughness changes with flaw depth!!!

- **Toughness decreases with increasing a/t or a/w in surface-flawed pipe and SENT tests**
  - Virtually all flaw evaluation procedures assume toughness is a constant for all flaw sizes, i.e., in vintage Battelle analyses, CorLAS/DNV, Anderson FAD approach, etc.
    - *Old Maxey axial surface-crack bulging factor was really a combination of toughness change with flaw depth and a smaller actual bulging factor*
    - *Decrease in toughness with flaw depth is key aspect in why leak-before-break occurs with ductile tearing – a 70% deep surface crack might have 1/3 of CT specimen toughness*
    - *Occurs with all materials tested at Emc² (X46, X52, X70, X100, stainless steel, Inconel, ferritic axial seam welds,...)*
    - *Needed to understand toughness changes in flaw depth to predict effects of hold-time on crack growth behavior*

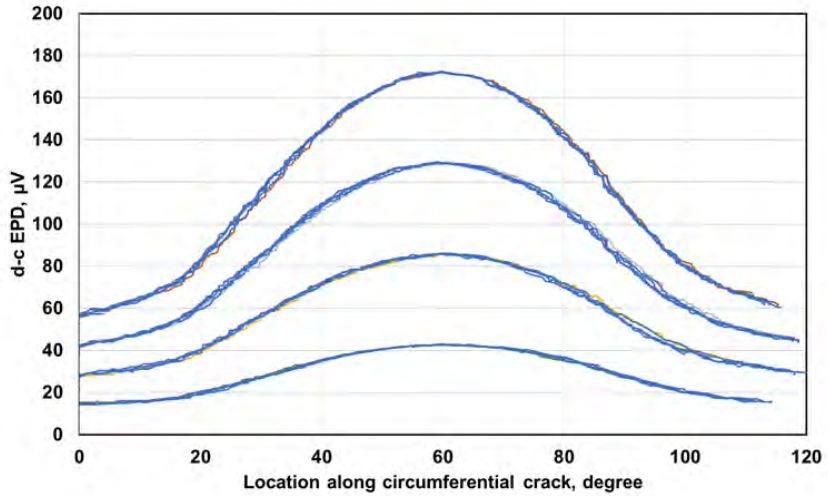


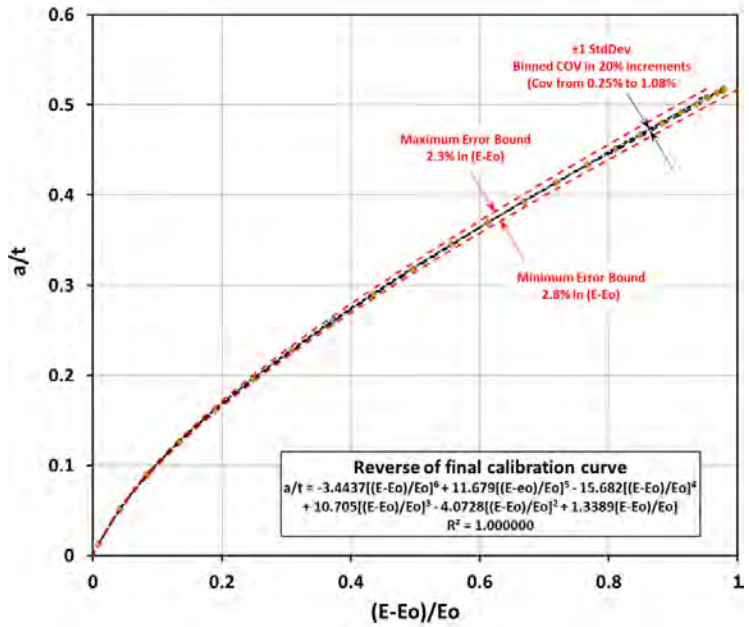
Some Key Results – Crack Growth Monitoring During Step-Hold Axial Surface-Cracked Pipe Tests



- **Axial surface-cracked pipe tests on ~1960 X46 pipe**
  - Up to 4 flaws in same vessel test – sometimes identical for reproducibility assessment
  - Example of leaking flaw that was one of 4 identical flaws in same pipe
  - Careful monitoring of crack growth by d-c electric potential method – much more accurate than any UT measurements
    - *16-inch diameter by 0.25" thick pipe may only have 0.015 to 0.030 inch of ductile crack growth from initiation to burst (varies with flaw size)*
    - *Held pressure until cracks stabilized*

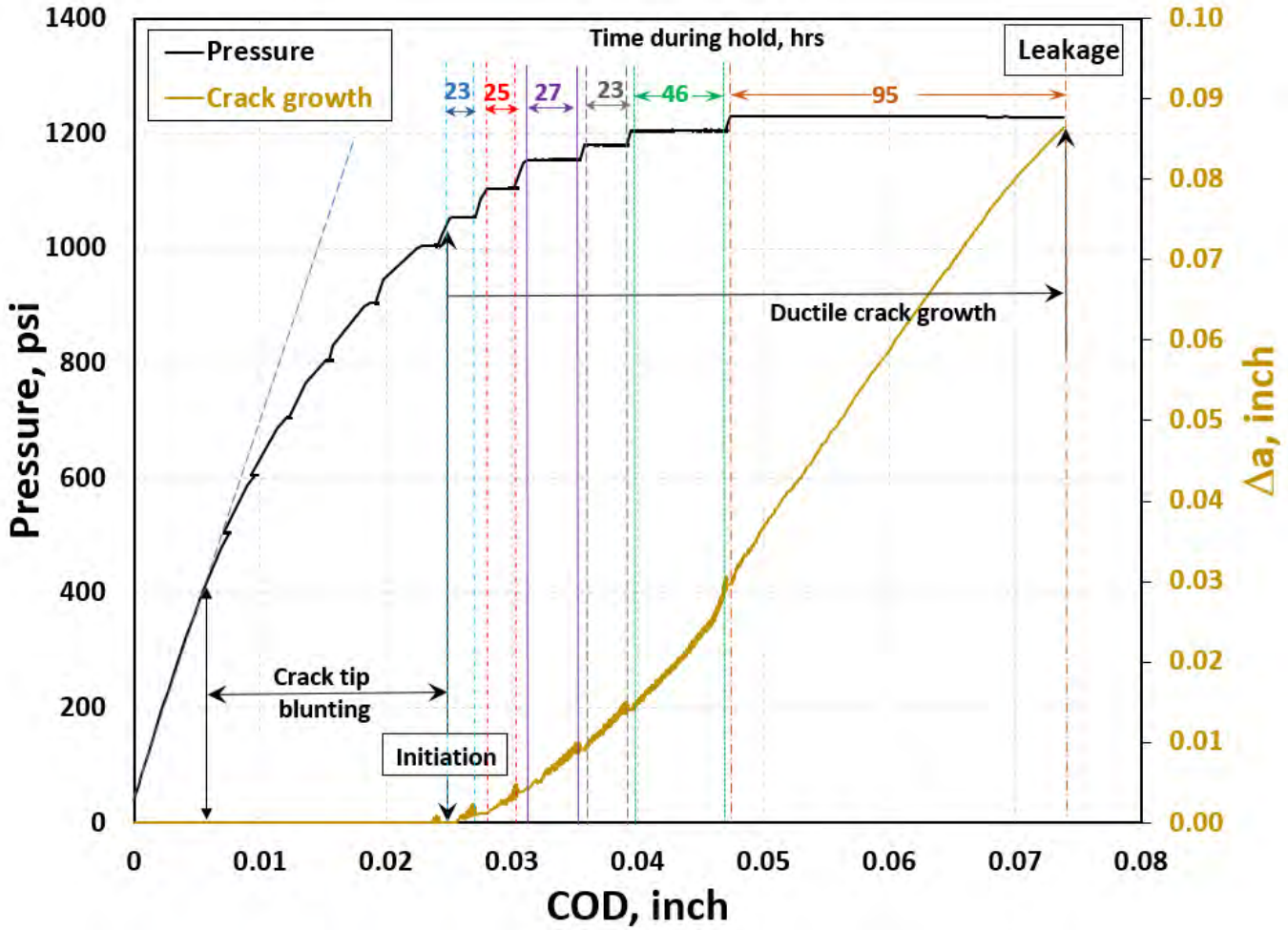
Converting d-c EP to Crack Growth is an Art – Doing It for Over 30 years





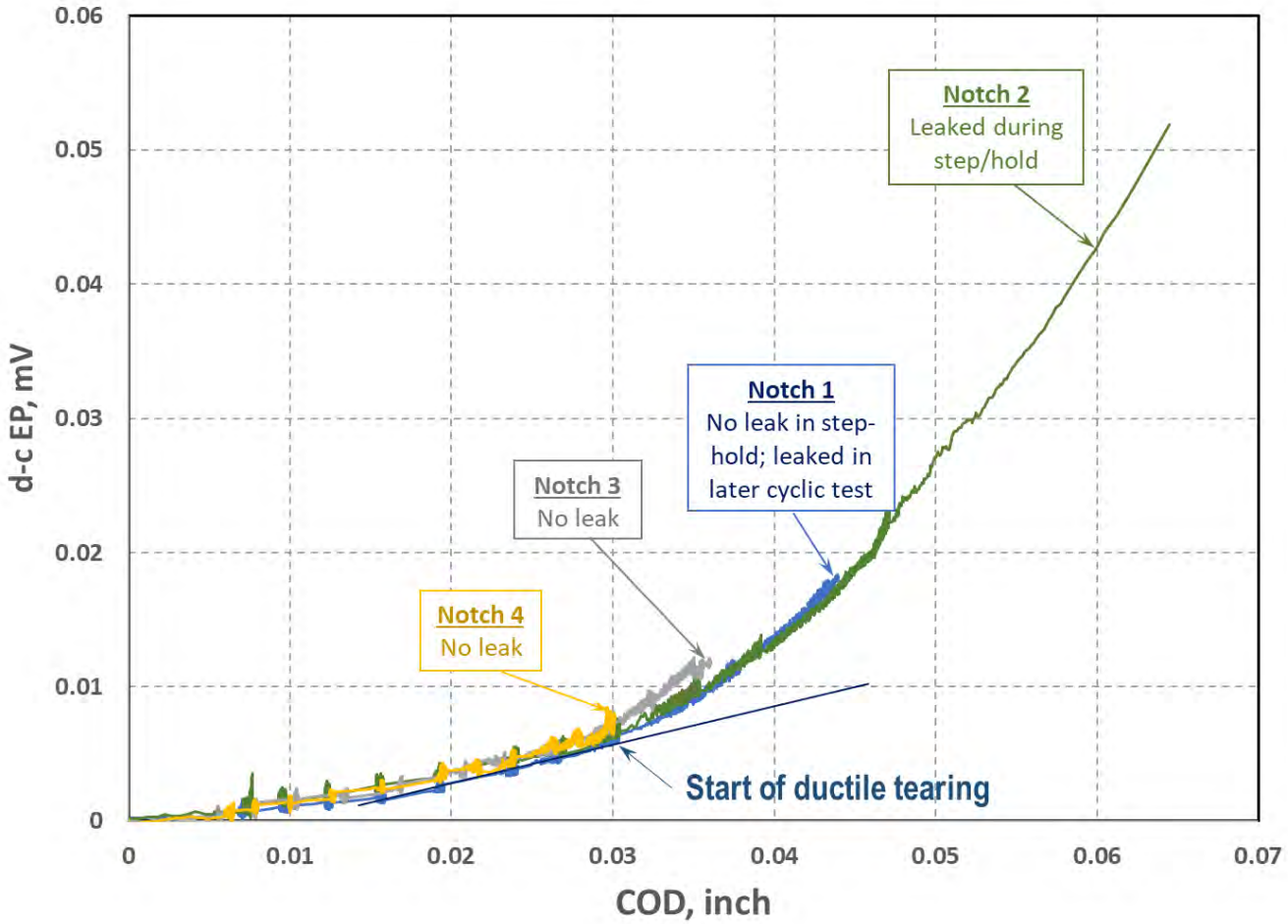
- Digital DAQ is much better than early analogue pioneering efforts
- Possible to scan along an entire surface crack and get the shape
  - *Example of 5 replicate scans across surface crack, at 4 different applied current values*
- Or put in stationary probe wires for crack growth at each probe wire location
  - *Error in measurement has COV of 0.25% to 1%*
  - *For our 16” diameter pipe with 0.25” thickness, the error in the crack depth monitoring is 0.00125” to 0.00031 inch (0.008mm to 0.00312mm) – probably 10 times better than by most advanced UT*
  - *Probe wires at 3 locations along each of 4 surface cracks*

Crack Growth Monitoring During Step-Hold Pipe Tests



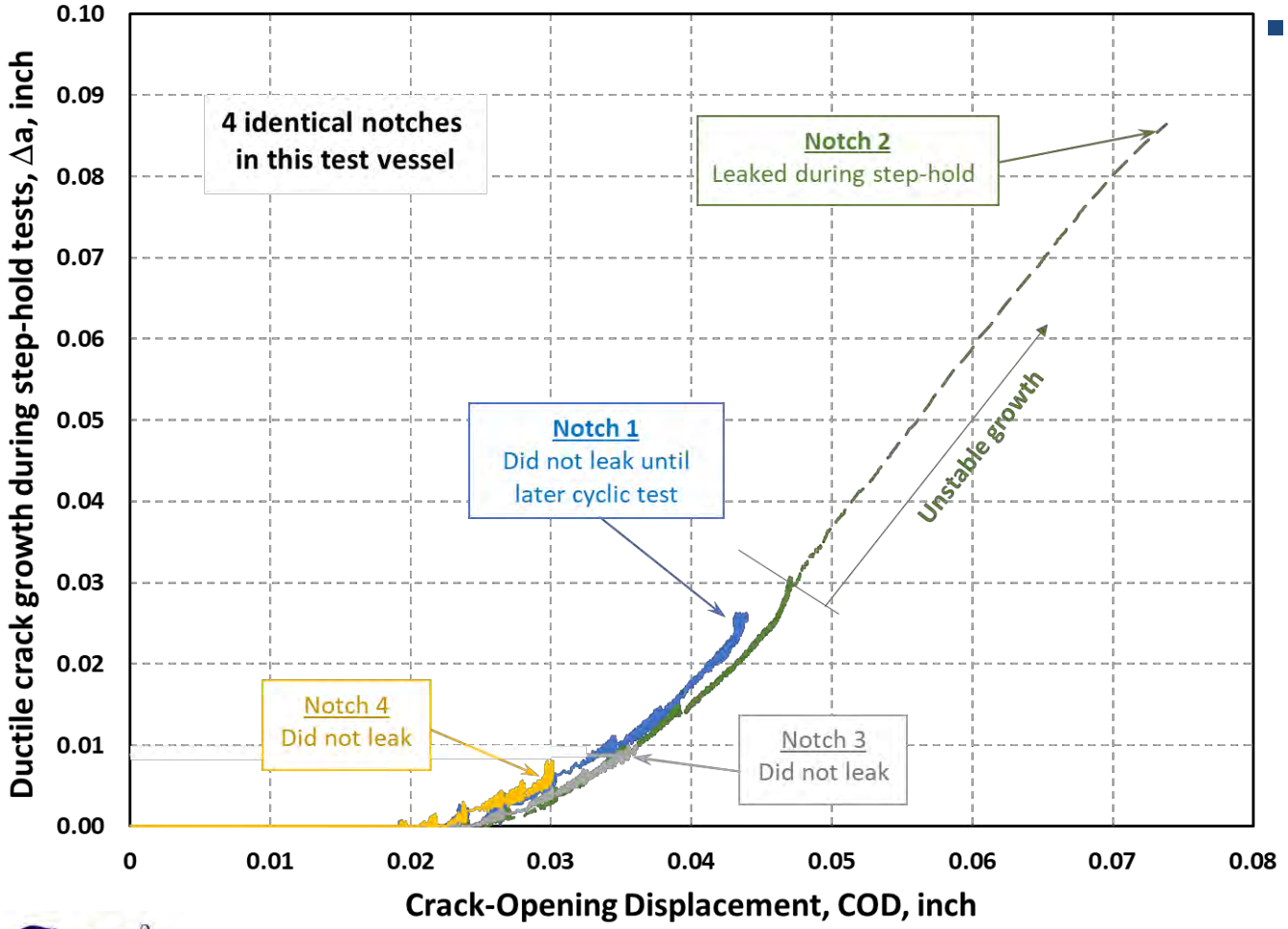
- **Axial surface-cracked pipe tests done on vintage X46 pipe**
  - 4 identical flaws in this pipe test, 3 others had smaller amounts of ductile tearing
  - Converted d-c EP to crack growth showed the following result for the flaw that grew to leakage
    - *3 d-c EP locations along the surface crack*
    - *This d-c EP data at location half way between the center and end of this flaw shown)*
    - *~250 hours during test with 130,000 readings*

Looking at Worst-Case Location for Each of the Four Cracks



- "Identical" initial surface cracks; a/t = 0.65
- Notch 2 leaked in Step-Hold test. Ductile tearing in other 3 flaws
- All flaws follow similar d-c EP blunting line, with start of ductile tearing very similar condition
- Ductile crack growth during Step-Hold tests showing similar crack growth trend for all 4 notches

Crack Growth Monitoring During Step-Hold Pipe Test

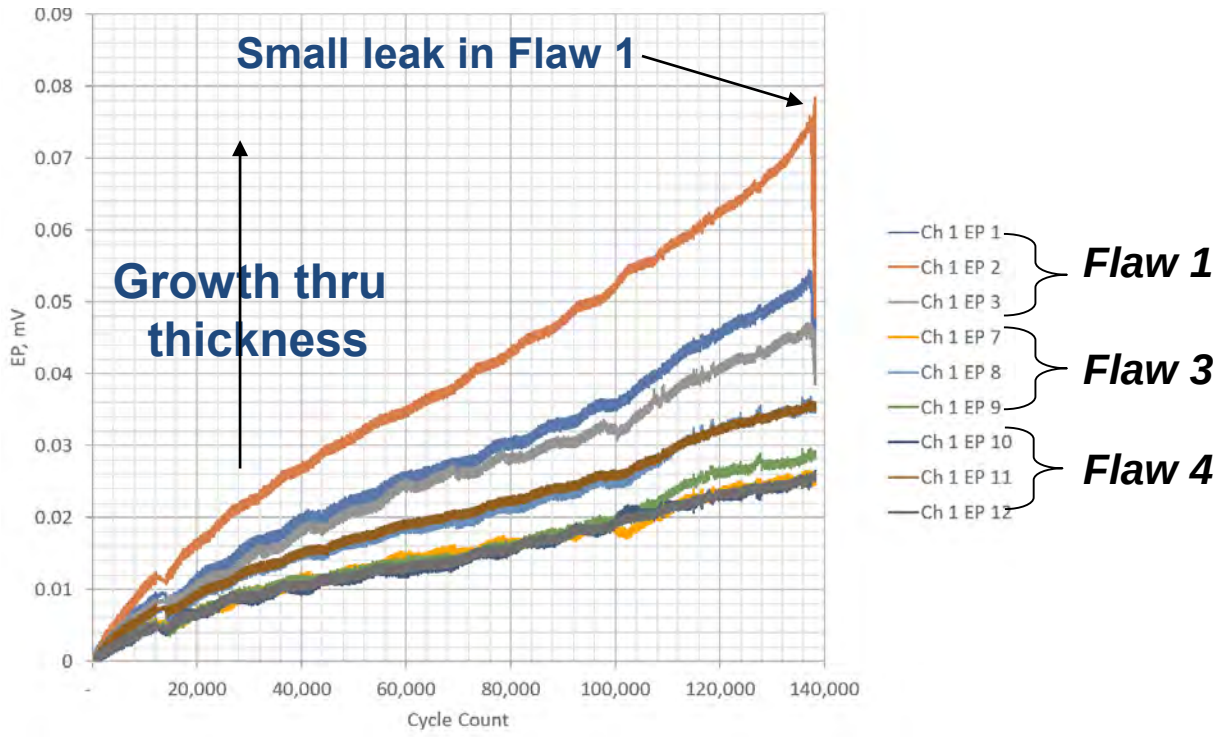


- **Converting the d-c EP to crack growth**
  - All axial surface crack had some ductile tearing during this step-hold pressure test
  - For Notch 2, can see that unstable growth started after 0.030” of stable tearing – quite close to detailed 3D FE predictions
  - Notch 1 – very close to the instability point of 0.030” of ductile tearing for this case
  - Notches 3 and 4 had considerably less tearing
    - *Resolution of crack growth extremely good*

Pressure Cyclic of Surviving Flaws

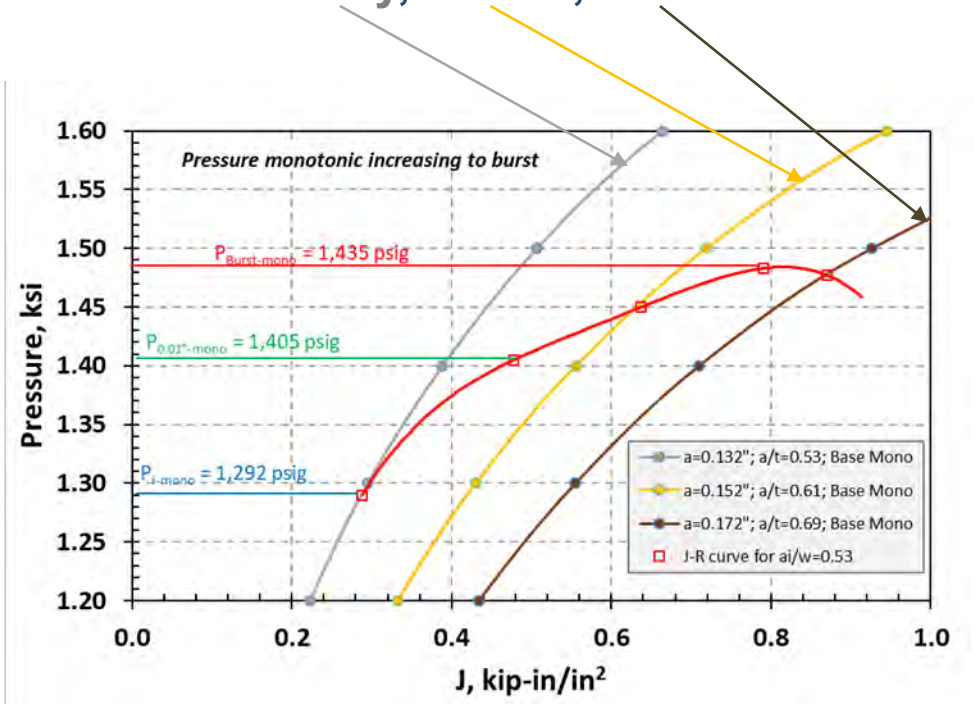
- **Each of 3 surviving flaws had different amounts of ductile tearing during step-hold axial-surface-cracked pipe tests**
  - Step/hold max pressure of 1,250 psig (77% SMYS)
  - Pressure cycled same vessel (repaired leaking crack with patch)
    - *d-c EP measurements at 3 locations along each crack*
    - *Initial 129,600 cycles of 35-350 psig typical condition (22% SMYS)– had small slow fatigue crack grow!*
    - *Increased cyclic pressure to higher level of typical service experience 54 to 540 psig (33% SMYS). One flaw leaked (small dripping) after additional 137,800 cycles*

2nd sequence of pressure cycling



Some Key Results – Analytical/Numerical Modelling

Example: $J_{applied}$ curves from 3D FE for axial surface cracks of different depth; Grey, Yellow, Brown curves



- **3D FE analyses also conducted for guidance to tests**
  - Easy to conduct large matrix of FE analyses to extract relationship that can be used in improved sustained-load (hydrotest crack growth) modelling
- **SENT J-R curve with initial a/w = 0.53 on left J_i determines very start of ductile tearing**
- **Interpolation gave burst pressure at a/t = ~0.65 gives ~0.028" of ductile crack growth – Pipe test gave 0.030"**
- **Initiation predicted at 89% of burst pressure; test was at 86%**

Key Results – Compared Fatigue Crack Growth after hydrotest – Typically high-cycle fatigue analysis versus test data

- **After the simulated hydrotest, there was plasticity from the various degrees of ductile tearing. How does this affect the fatigue crack growth relative to predictions using simplified/traditional fatigue analysis**
  - Hydrotest has some surviving flaws with various degrees of crack tip plasticity
  - ILI can eliminate large flaws, without inducing crack tip plasticity
  - Is the crack tip plasticity good or bad for fatigue life? Certainly ductile tearing reduces the crack ligament for fatigue crack growth which would be negative aspect.

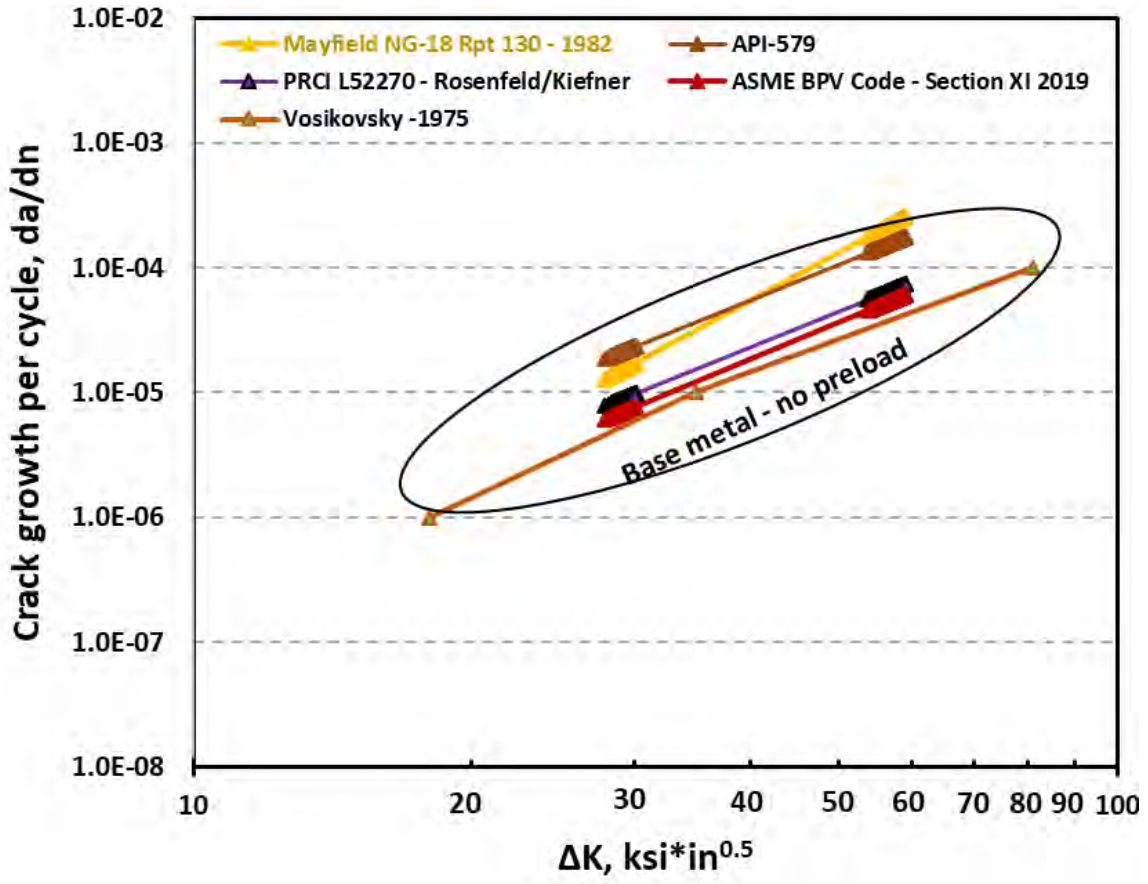
Key Results – Compared Fatigue Crack Growth after Hydrotest – Typically High-Cycle Fatigue Analysis Versus Test Data

- **Experimental data**
  - Determined experimental fatigue crack growth rates (da/dn) during surface-cracked pipe cyclic testing ***after*** the Step-Hold tests for 3 surviving notches with different amounts of ductile crack growth
  - Used 3D FE calculations of K (converted from J), but ignored overload from Step-Hold test – initial simple assumption.
  - Plotted experimental da/dn versus dK

- **Compared to Fatigue Crack Growth (FCG) curves of ferritic steels (air, R=0.1)**
  - Mayfield ERW pipe base metal – air fatigue X52 – 1982 (NG-18 report 130)
  - API 579 (2016 ferritic steel curve for below 100C and non-aggressive environment – Eq. 9F.95)
  - ASME B&PV Section XI 2019 ferritic air-fatigue with R-ratio adjustment to 0.1 of pipe tests
  - PRCI L52270 – Rosenfeld/Kiefner "Basics of Metal Fatigue in Natural Gas Pipeline Systems - Primer of Gas Operators (data from Figure 6)
  - Vosikovsky X65 air-fatigue curve - 1975

Key Results – Compared Fatigue Crack Growth after Hydrotest – Typically High-Cycle Fatigue Analysis Versus Test Data

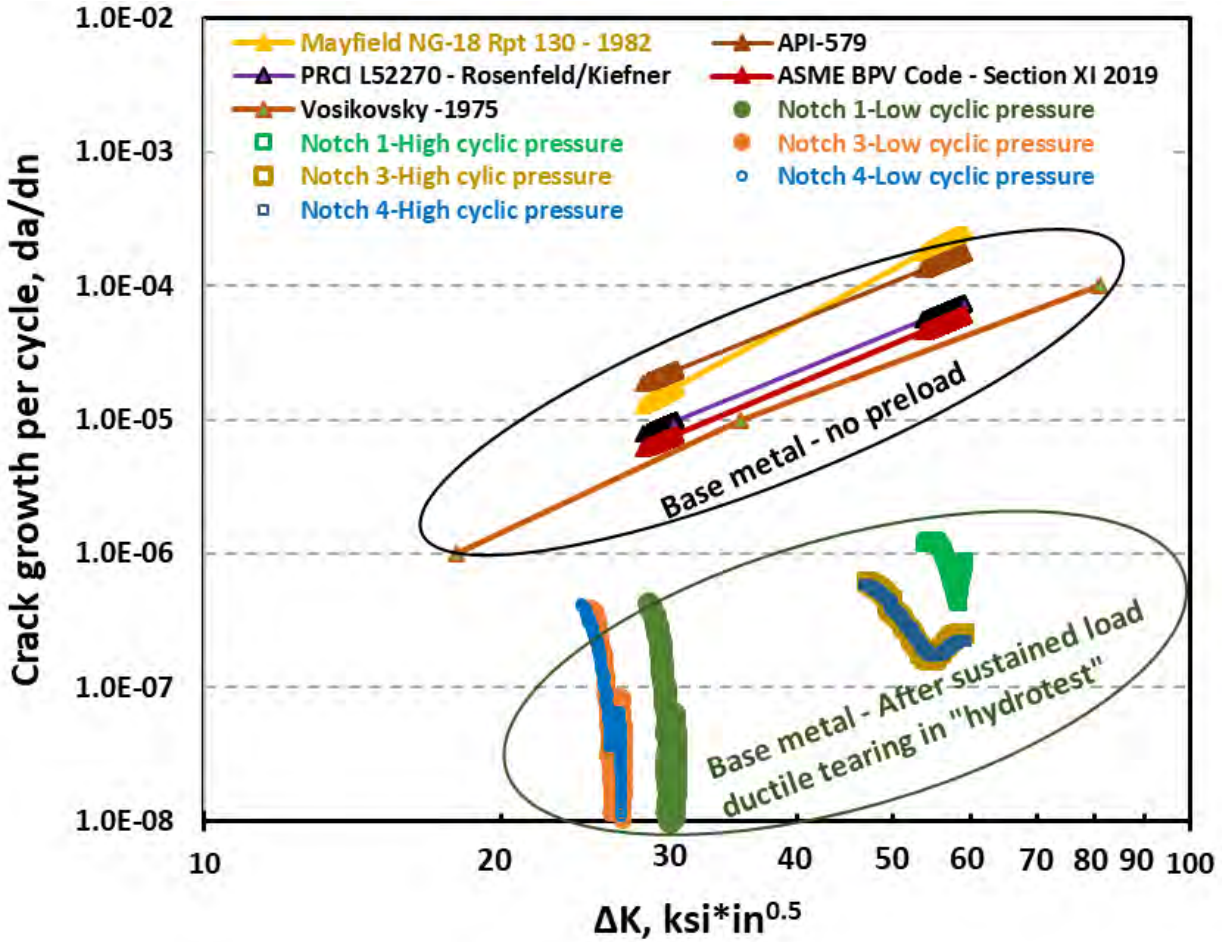
- **Published FCG curves reasonably similar – Mayfield and API-579 slightly higher than others**



Key Results – Compared Fatigue Crack Growth after Hydrotest – Typically High-Cycle Fatigue Analysis Versus Test Data

- Published FCG curves reasonably similar – Mayfield and API-579 slightly higher than others

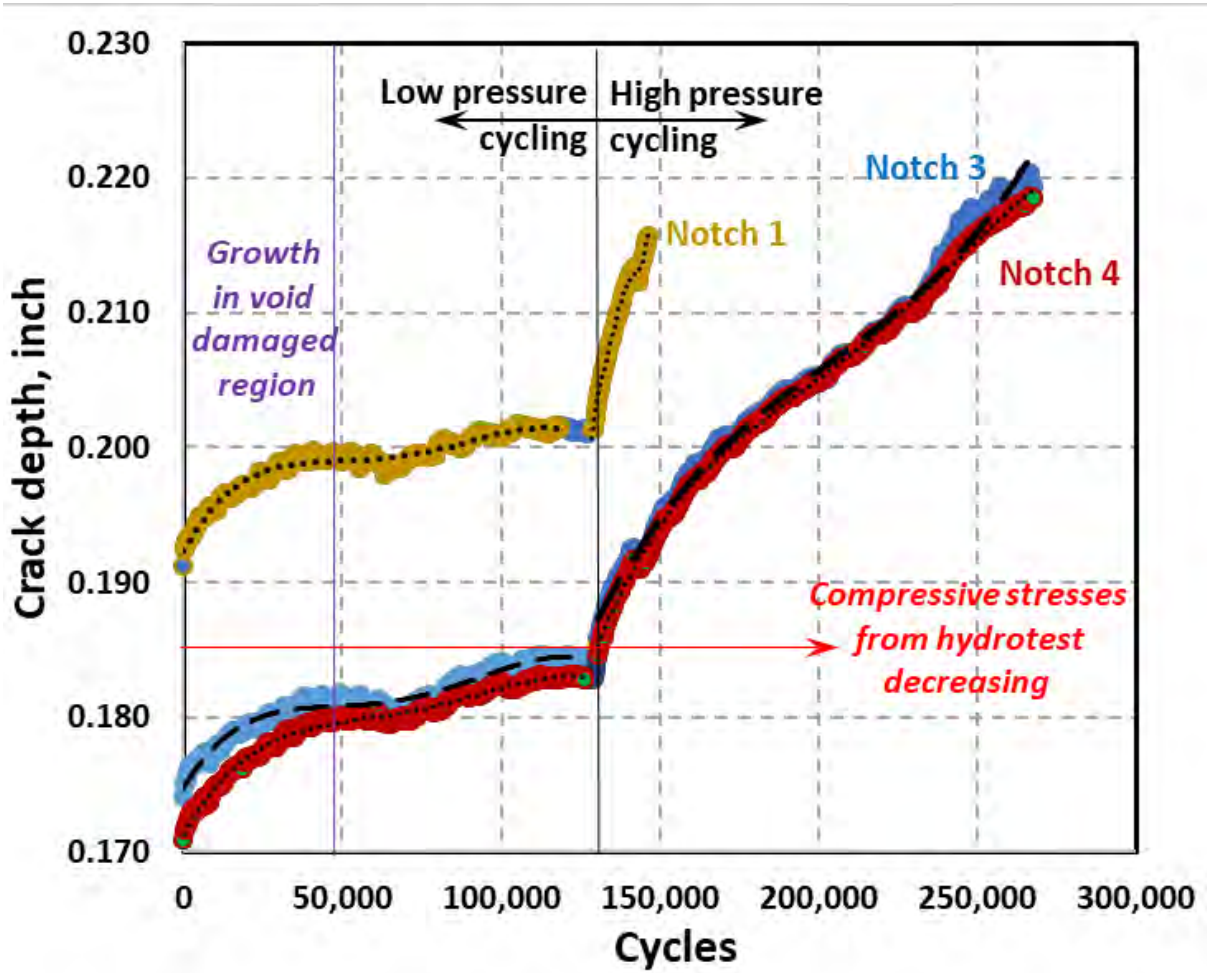
- **Experimental post-hydrotest crack growth rates of axial surface-cracks had much lower fatigue crack growth rates**
  - About 1.5 to 3 orders of magnitude slower FCR rates
  - Notches 3 and 4 (very similar) that had less ductile tearing in “hydrotest” had even slower crack growth rate than Notch 1
  - More predictable if plasticity/damage included
  - Shape of experimental curve unusual, but affected by several factors…..



Key Results – Fatigue Crack Growth after Hydrotest

- **Shape of experimental fatigue crack curve after ductile tearing and plasticity from hydrotest affected by;**
  1. Fatigue growth through higher damaged region of voids close to the crack tip – void decrease with distance from crack tip,
  2. After unloading after the Step-Hold test, magnitude of residual plastic strain decays with distance from the crack tip, and
  3. Then fatigue grows back to "virgin" material, although in these tests the ligaments went fully plastic in the "hydrotest"

(a/t limited to ~0.85 in the graph to the right)



Key Results

- Saw that toughness changes with surface-crack depth – needed this for hold-time analysis
- Hold-time analysis form past PRCI work was reasonable over very limited flaw sizes, but needs improvement to be more general
- Experimental Step-Hold tests with 4 “identical flaws” showed different amounts of ductile tearing – only one flaw leaked
- Subsequent pressure cycling of other flaws (leaking flaw repaired) showed that even with ductile tearing there is a reduction of fatigue crack growth rates, but more improvements with less ductile tearing
- Hence hydrotest offers benefits on cyclic life that ILI will not provide (for same flaw sizes)

Now What?

- **Work to date focused on developing data on base metal flaws for evaluation of analyses without significant scatter**
  - Further examination of lesser degrees of crack tip damage (various degrees of blunting) on subsequent fatigue crack growth rates needed to fine tune optimization of hydrotest
- **May look at hook cracks in ERW welds – can simulate hook cracks and test natural hook cracks in SENT tests**
  - Address why there is frequently no fatigue crack growth for hook-crack flaws removed from service
- **For SCC susceptible pipelines, can show if regrowth of SCC crack after a hydrotest is retarded – other than just blowing out bad flaws**
- **Possible coordination with PRCI and/or DOT for refining application tools and expanding materials looked at**

Benefits

- **Results are showing much longer fatigue life after a hydrotest than from traditional evaluations, but could be further optimized**
  - Crack growth rates 1.5 to 3 orders of magnitude slower
- **Could provide better guidance for flaw assessment/repair criteria**
- **Hydrotest if done right give beneficial effect for enhancing life after hydrotest, not just removing worst-case flaws**

BACK TO AGENDA

PRCI 2020 Research Exchange

Tripartite Project on Delayed Failure

Time-Delayed Failure in Line Pipe Steels, EPRG Report 191
by A Cosham & B N Leis (presenter), 20 October 2019

- **EPRG 137: Atkins (Cosham) / Battelle (Leis); Preliminary Analysis**
- **PRCI MD-4-8 ΦI: EWI / Leis Consultant Inc; Test Planning & Lab Tests**
- **EPRG 184: Engie CRIGEN; EPRG & APGA Full-Scale Tests (FST)**
- **PRCI MD-4-8 ΦII: EWI / Leis Consultant Inc; PRCI FST**
- **EPRG 191: 9th Planet Engr / Leis Consultant Inc; Analyze & Report**

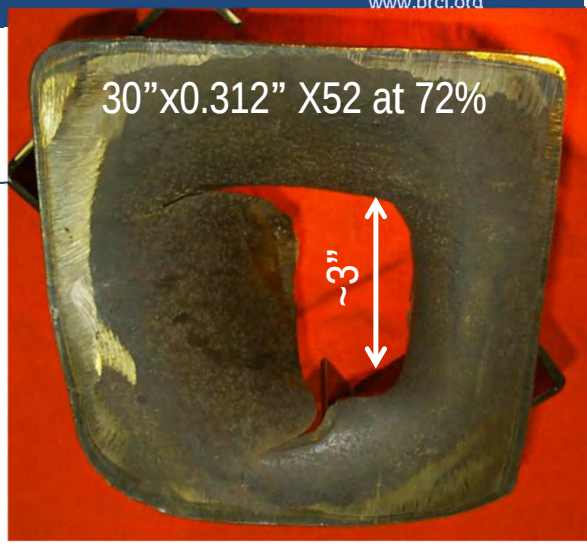
PRCI™

LEADING PIPELINE RESEARCH

Outline

- Issue / Motivation
- Risk Managed & Related Objectives
- Scope / Work Plan & Approach
- Some Technical Details –
  - the Steels & Key Properties
  - the Full-Scale Test Protocol
- Results & Practical Implications
- Takeaways – Codes/Standards Aspects
- Summary & Conclusions

Motivation: Examples & Traits



Oelwein, Iowa, USA, 12 November 1999

- 10” natural-gas line punctured but stable & doesn’t ignite
- ruptured 2½ hours later, while leak was being assessed
- one company man dead, another injured

Ghislenghien, Belgium, 30 July 2004

- 40” natural-gas line ruptured ~2¼ hours after the leak was reported
- damaged by a third-party about six weeks prior
- 1991 X70 construction involving a very tough steel
- after four days: 18 dead (rose to 24), with 74 hospitalized, 51 of whom were in specialized burn centers



Key Traits:

stable tearing crack advance driven in part by stress-activated creep

not unique to mechanical damage

Issue / Motivation



- Opposed jet fires / associated craters
- Fatalities/Injuries
- Local devastation
- Source of negative press & social media exposure

Risk to be Managed & Project Objectives

Issue & Motivation

- Failures occur at defects whose size suffices to initiate & grow due to stress-activated creep
- Opens to potential catastrophic failure (leak becoming a rupture) that could be delayed in time, examples: the mechanical damage events just noted, or Hydro pressure-reversals
- Poses a threat to operator personnel or first-responders called in to assist, which can be offset by a pressure reduction
- A delayed catastrophic failure involving tough modern line pipe brought into question the viability of criteria to manage such scenarios that were developed for much earlier steels
- Other delayed failures have likewise been catastrophic, another motivating consideration

Objectives

- Determine the viability of current pressure reduction criteria for the range of steels of interest to the transmission pipeline industry
- Develop alternative criteria as necessary

Scope / Work Plan & Approach

Work Plan / Scope

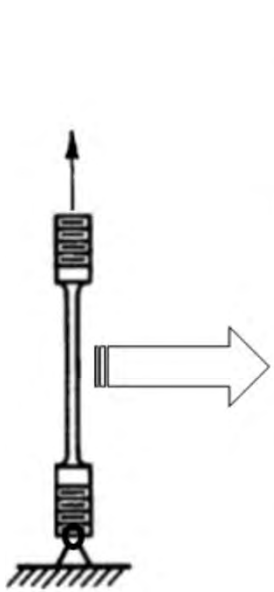
- Quantify the stress-activated creep response of tough higher-strength steels, then contrast that to data typical of the steels that underlie current criteria
- Develop steel properties to support NLFM analysis involving stress-activated creep
- Quantify the stress-activated creep cracking susceptibility as a function of pressure
- Develop validation full-scale tests on Grades of interest to the Tripartite entities

Approach

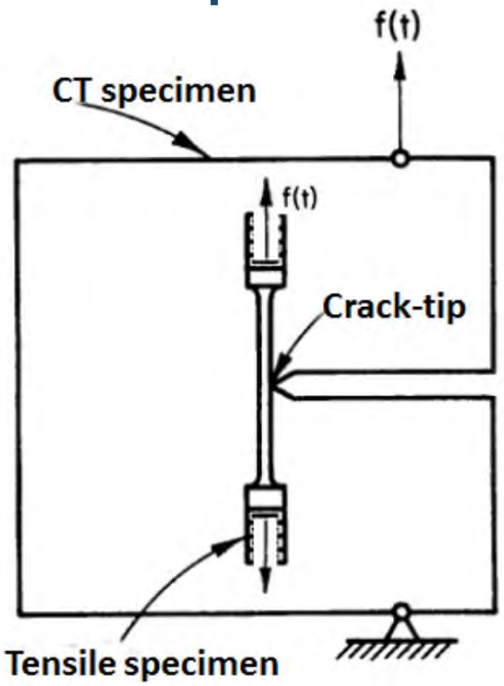
- Adapt NLFM analysis to quantify axial stress-activated creep cracking in line pipe
- Demonstrate utility and validate via model-scale predictions
- Extend to full-scale applications and complete the full-scale testing
- Assess existing criteria relative to the above and develop alternatives as needed

Work Plan & Approach in Schematic

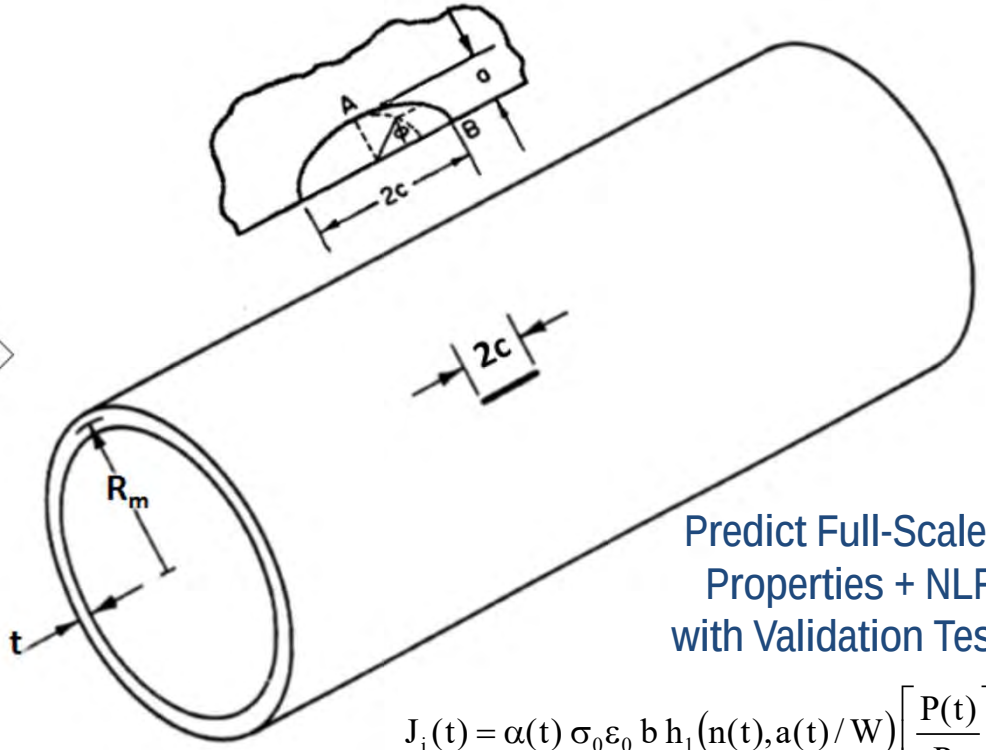
- **Work Plan / Scope**



Lab-Scale Properties



Predict Model-Scale via Properties + NLFM with Validation Testing



Predict Full-Scale via Properties + NLFM with Validation Testing

$$J_i(t) = \alpha(t)\,\sigma_0\varepsilon_0\,b\,h_1\left(n(t), a(t)/W\right)\left[\frac{P(t)}{P_0}\right]^{n(t)+1}$$

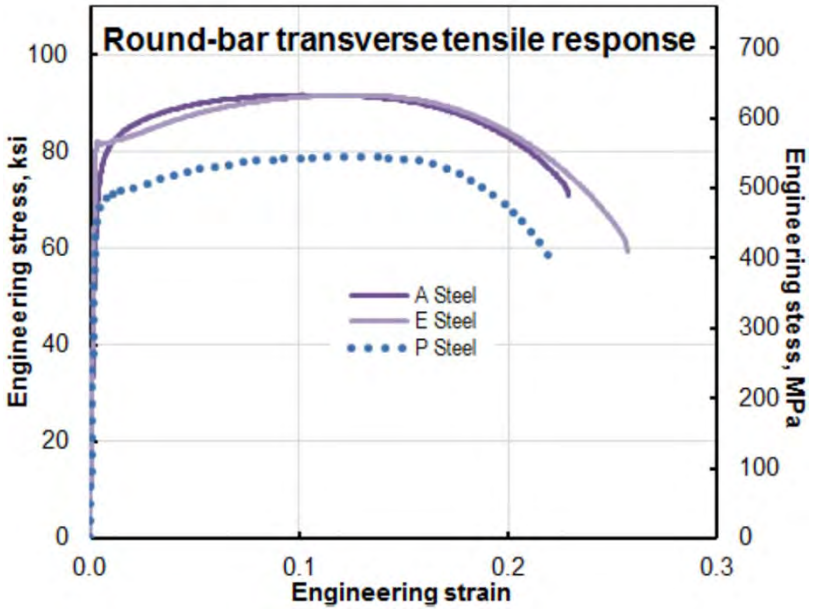
Technical Details – Tripartite Selected Steels

The Steels

- APGA: “A” Steel –
  - *457 mm (18”) X70 HFI ERW pipe with D/t=50*
  - *Uncoated as received*
  - *Australian production in 2011*
- EPRG: “E” Steel –
  - *1016 mm (40”) X70 DSAW pipe with D/t=75*
  - *FBE coated, removed as needed*
  - *European production circa 1991*
- PRCI: “P” Steel –
  - *24” (610 mm) X65 DSAW pipe with D/t=95*
  - *FBE coated: removed as needed*
  - *Unknown production details & date (FBE implies mid-1960s or later)*

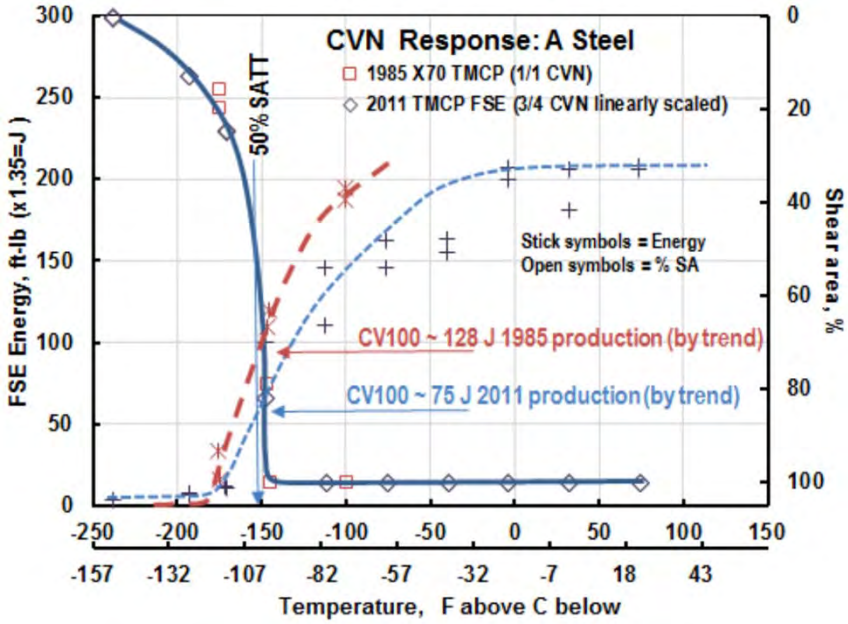
Technical Details – Properties

- **Usual Line-Pipe Mechanical & Fracture Properties**



All made grade across all required metrics

A & P showed roundhouse trend vs sharp yield for E – but nothing unusual



All steels very tough vs typical 1960s data

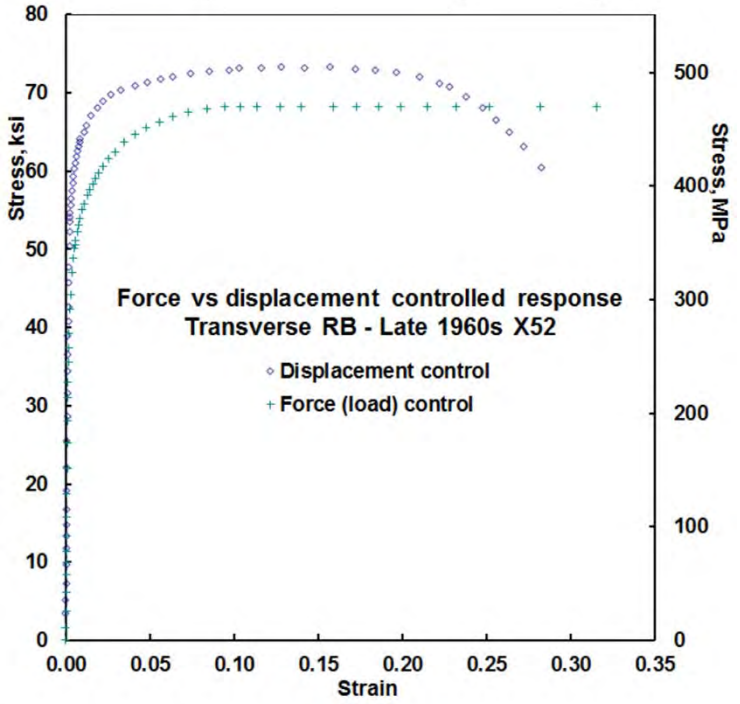
A steel shows a strong rising shelf

A & E otherwise similar – tougher than P

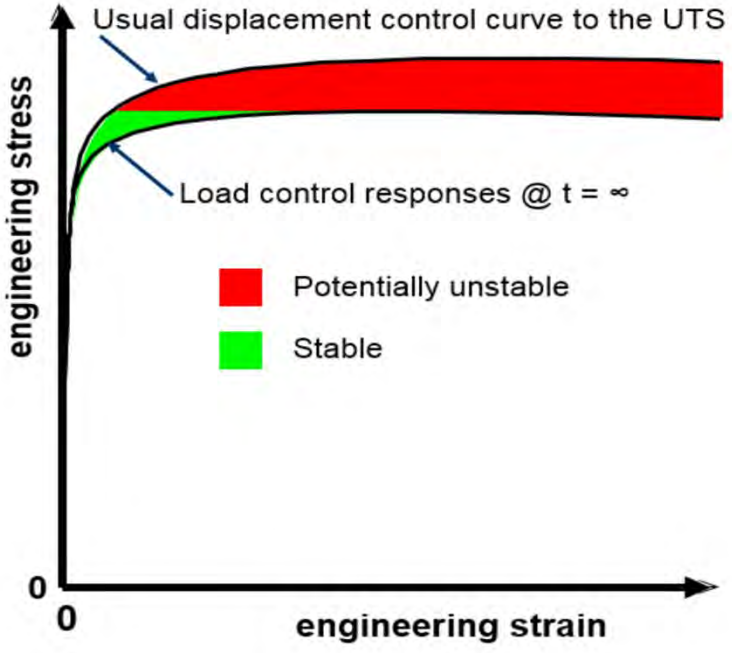
Technical Details – Key Properties

- **Pipeline-Like Mechanical Properties Experiments**

Load (Pressure) **vs** the usual **Displacement** (Strain) **Control**



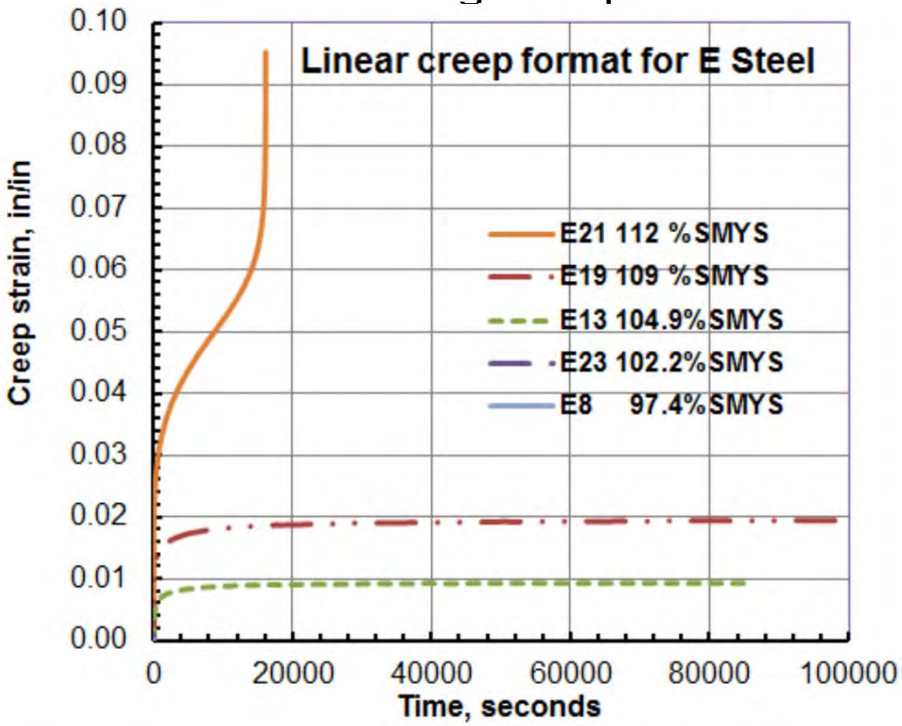
Load Control with Rapid Step Rate – develops Stress-Activated Creep (Schematic)



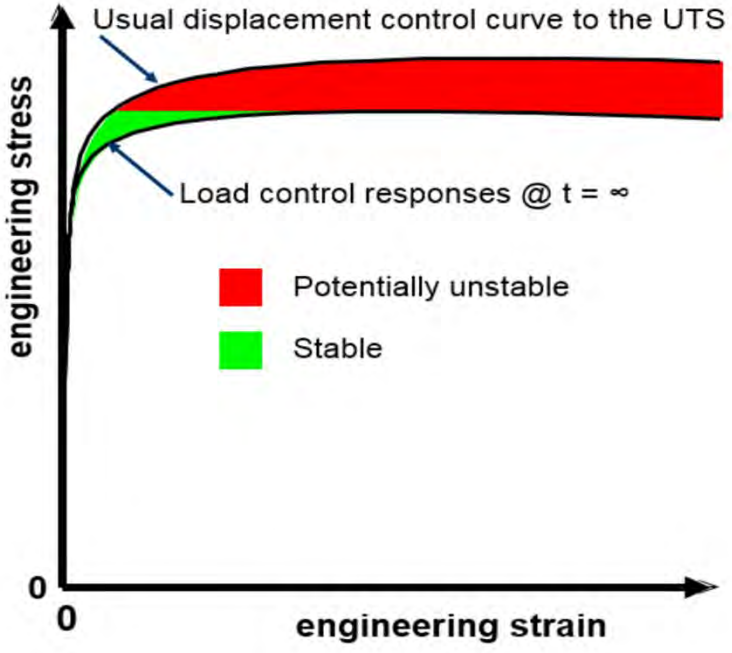
Technical Details – Key Properties

- **Results of the Step-Load-Controlled Mechanical Properties Experiment**

Step-load in load-control & measure the resulting Creep strain



Load Control with Rapid Step Rate – develops Stress-Activated Creep (Schematic)

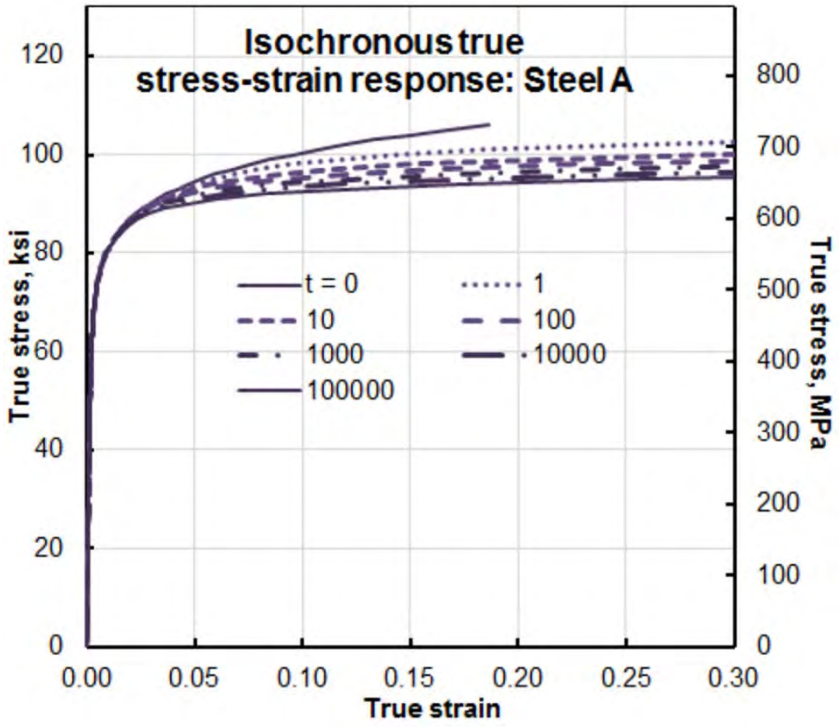


REX2020 PRCI RESEARCH EXCHANGE

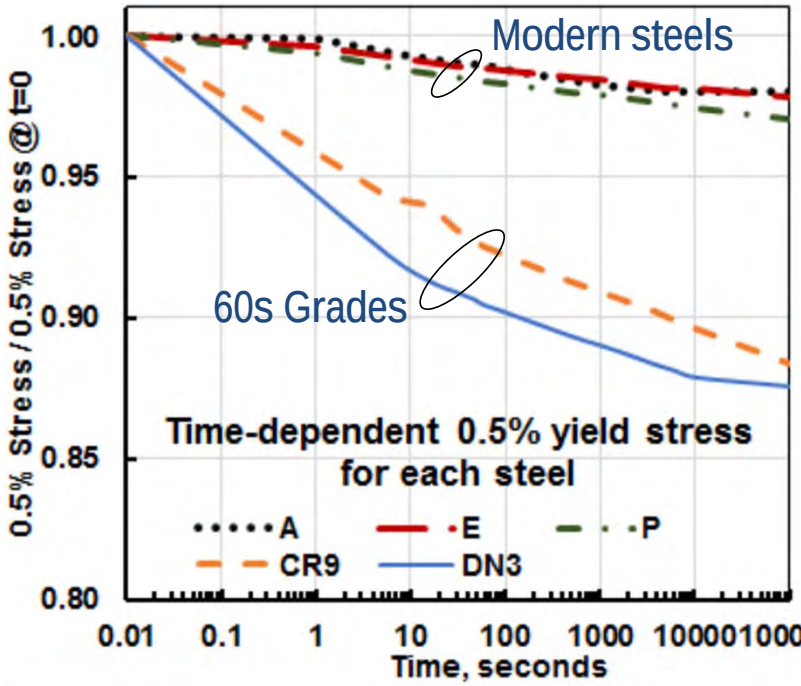
Technical Details – Key Properties

- **Time-Dependent Mechanical Properties – Isochronous Stress-Strain Curves**

Creep strain accumulation as a function of stress at constant times (isochrones)

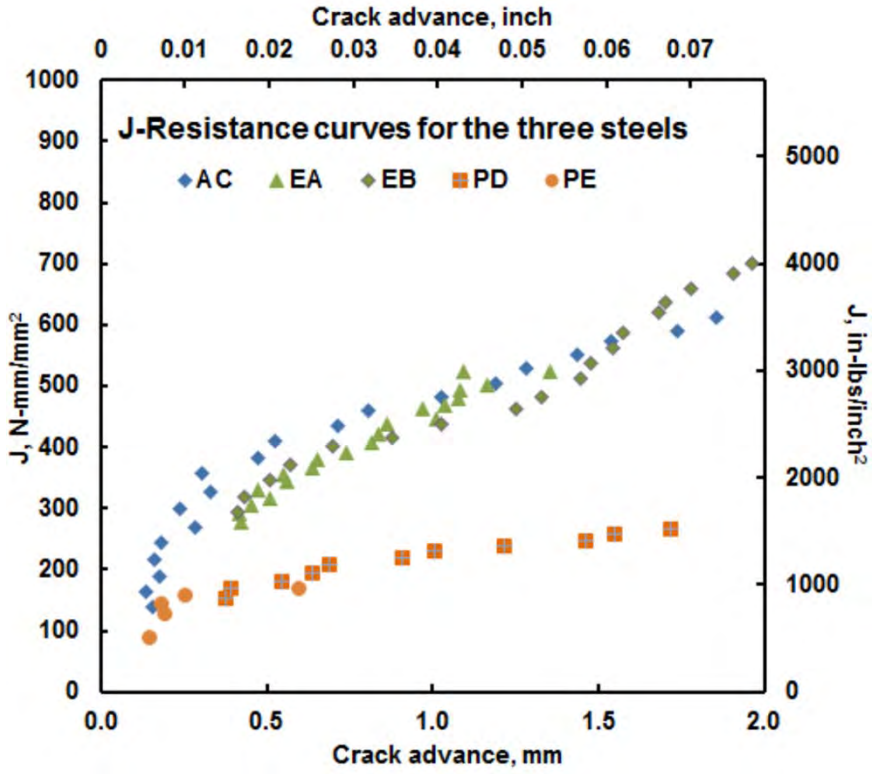


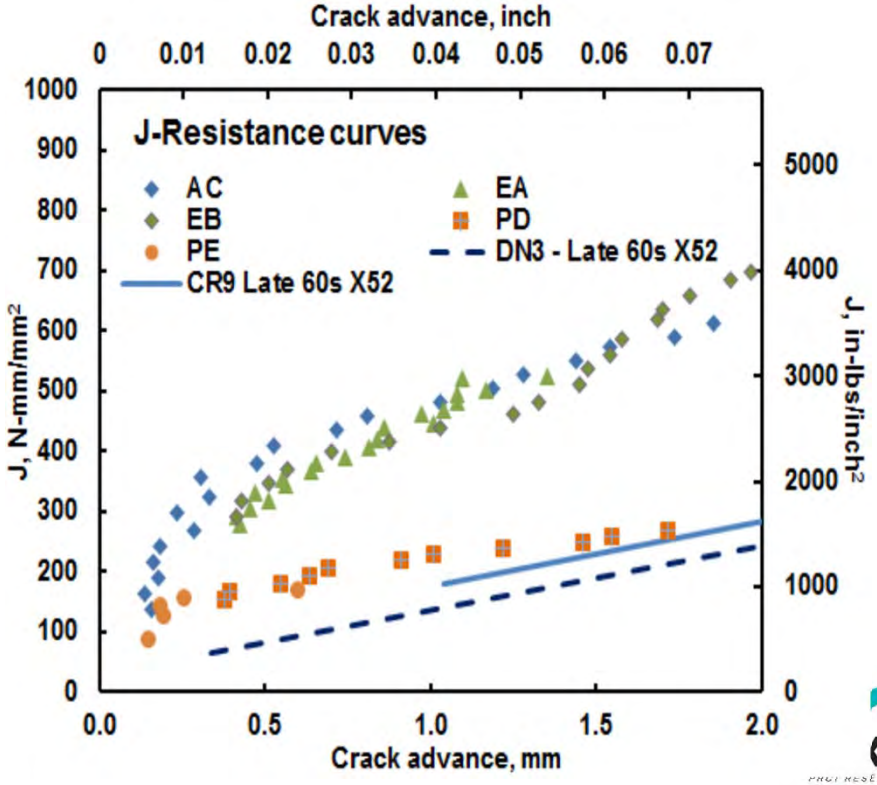
Modern steels (X65 & X70) contrasted to 1960s (X52) steels



Technical Details – Key Properties

- **Fracture Properties & Late 1960s Comparison**





Outcomes & Practical Implications

Modern vs Early Steels at the Lab-Scale

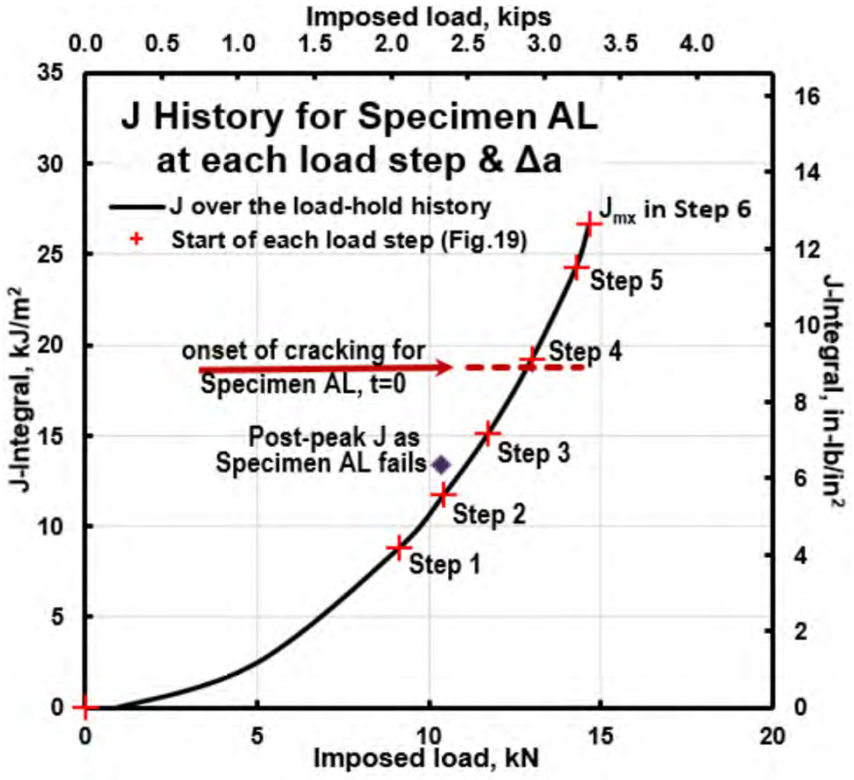
- Modern steels are tougher and so more resistant to stable tearing, which is the mechanism of crack advance for stress-activated creep
- Modern steels sustain relatively higher stress at a given strain and so will be more prone to stress-activated creep

Modern vs Early Steels for the Pipeline (the Full-Scale)

- Outcomes at the lab-scale reflect opposing drivers that cannot be simply interpreted without the NLFM analysis steps to the Model and Full-Scale scenarios

Technical Details – Model-Scale Validation

NLFM & Properties used to predict crack advance in step-loaded C(T) geometry
Outcomes compared to corresponding model-scale (C(T)) experiment



Outcomes demonstrate the predictive approach & validate its utility for the full-scale work

- Compliance prior to a load step used to quantify cracking increments per step, Δa
- Scale of Δa small prior to that prompting instability – just two steps of stable Δa
- Predicted Δa per step slightly less than observed
- Predicted initiation was consistent with that observed
- Eventual failure also predicted as it occurred
- Point to point scatter along the *J*-R curve was large & would easily rationalize any minor disparities

Technical Details – Full-Scale Validation

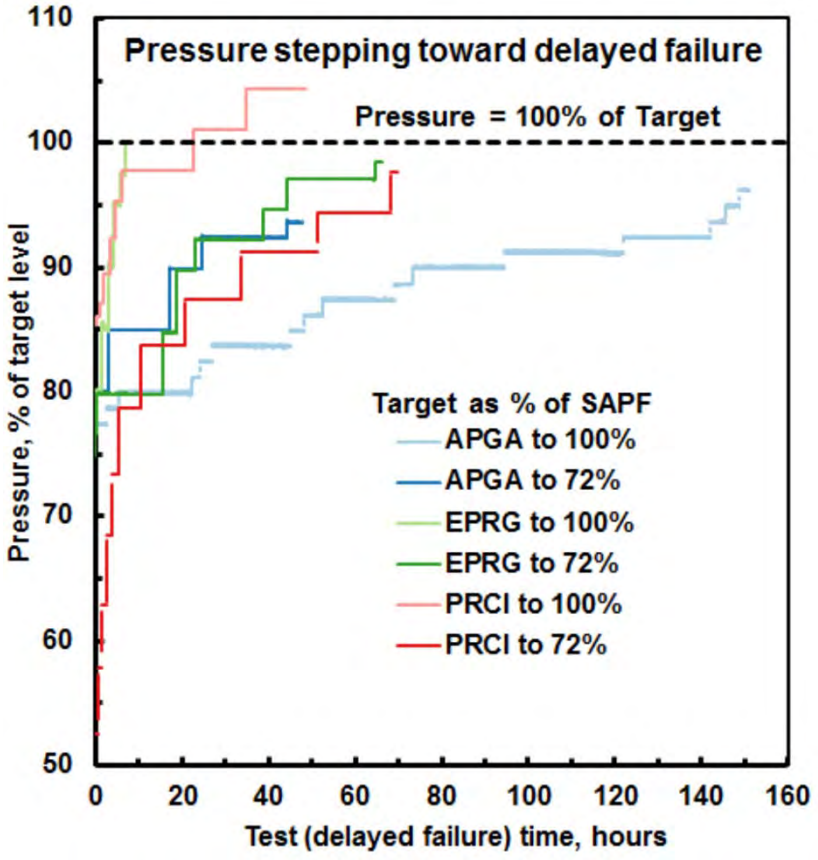
Six experiments under circumstances predicted to develop four types of failure in an experimental design based on model-predicted defect response

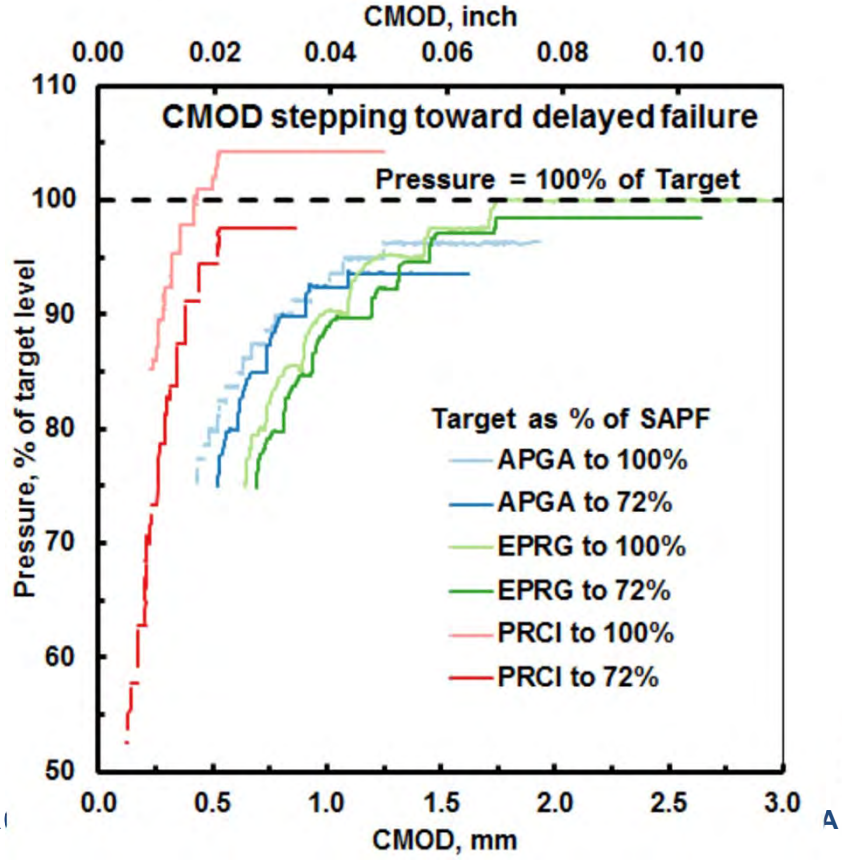
- **Defect sizes were predicted to develop four characteristic time-dependent responses at the target maximum test pressure**
  a. ***not initiate – "benign"***
  b. ***initiate, but exhibit little through-wall growth – "marginal growth"***
  c. ***initiate and exhibit significant through-wall growth, but not fail – "significant growth"***
  d. ***initiate, grow through-wall, and fail – "tend to instability"***
- **Property variability can confound discriminating cases b & c and possibly also other cases**

- **Three tests targeted 100% SMYS (hydro-like); Three tests targeted 72% SMYS (service-like)**
- **Six tests in total: Four defects each = 24 defect sizes to behave as predicted**
- **Results follow next for the cases predicted to tend to instability**

Technical Details – Full-Scale Validation

Six experiments under circumstances predicted to develop four types of response





Summary – Full-Scale Validation

Six experiments under circumstances predicted to develop four types of failure

- **Predicted outcomes were within the usual tensile properties scatter and so were well matched to the actual response –**

Test No.	SAPF, barg (%SMYS)	Comment
APGA 1	191.1 (100)	Defect A4 failed at 96.3% of target after 2.1 hrs
APGA 2	138.3 (72)	Defect A8 failed at 93.7% of target after 3.3 hrs
EPRG 1	138.6 (100)	Defect E4 failed at 99.9% of target after 1.0 hr
EPRG 2	100.9 (72)	Defect E15 failed at 98.5% of target after 1.7 hrs
PRCI 1	111.8 (100)	Defect P4 failed at 104.4% of target after 13.9 hrs
PRCI 2	66.0 (72)	Defect P5 failed at 97.7% of target after 1.3 hrs

- **Full-scale testing validated the predictive scheme and provide a database that with the model was the basis to establish pressure-reduction GUIDELINES**

Outcomes & Practical Implications

Modern vs Early Steels for the Pipeline (the Full-Scale)

- Outcomes at the lab-scale reflect opposing drivers which cannot be simply interpreted without the NLFM analysis steps to the Model and Full-Scale scenarios
- Model-scale and more critically full-scale testing validates the model predictions – which taken together become the basis to establish the viability of current pressure-reduction guidance to offset concern for stress-activated creep and manage delayed failures
- A small increase in load or pressure was sufficient to transition from slow stable growth to a time-delayed failure –

  Thus, the length of time that a defect has been stable is not a consideration in deciding whether or not to reduce the pressure – it must be reduced

Takeaways – Code/Standards Aspects

What does this mean for Pipelines?

- The six step-load-hold tests indicate that their delayed failures would be offset by a pressure reduction to 85% of that when the contact occurred
- Current code / operator criteria for pressure reduction (e.g., ASME B31.4 & B31.8, & National Grid's T/PM/P/11) recommend a drop to 80% - 85% of that when the contact occurred or the pressure at which the circumstances had remained stable
  - *A larger drop should be considered if the extent of the defect is large or the damage is severe - e.g., T/PM/P/11 & PR-218-06353 note dropping the pressure to a level corresponding to 30% SMYS*
- Code language should be updated to reflect the broader utility of the current criteria

Summary & Conclusions

Targeted Two Objectives

- Determine the viability of current pressure reduction criteria for the range of steels of interest to the transmission pipeline industry
- Develop alternative criteria as necessary
- These objectives were met successfully

Conclusions:

- Higher relative stress at a given creep strain was evident for the modern steels, which drives stress-activated creep – this was offset by their greater resistance to stable tearing, leading to a balance much like that developed for the earlier steels
- Current Code / Operator pressure reduction criteria are also viable for modern steels
- Code language should be updated to reflect its broader utility

BACK TO AGENDA

REX2020
PRCI RESEARCH EXCHANGE

Pipeline Research Council International, Inc.

Validating Computed Tomography Using Crack-like Features in Full-scale Test Samples

2020 PRCI Research Exchange

Presented by Dr. Chris Alexander, PE | ADV Integrity, Inc.

Wednesday, March 4, 2020 | 9:30 to 10:00 AM PST

(in association with the NDE-2-11 co-funded PHMSA study)

PRCI™
LEADING PIPELINE RESEARCH

Today's Presentation

- The need for "truth data"
- What is computed tomography (CT)?
- Technology Readiness Levels (TRL) case study
- Elements of the validation study
- Growing cracks via full-scale testing
- Comparison of actual and CT results
- Overall observations
- PHMSA / PRCI NDE-2-11 CT Study

The Need for "Truth Data"

- Aging pipelines have created the need for advanced engineering assessment methods.
- Inspection technologies are critical, primarily in-line inspection (ILI) and in-the-ditch technologies.
- To validate ILI technologies, it is essential to have advanced NDE inspection technologies to verify ILI measurement accuracy.
- Inspection of cracks and seam anomalies remains a significant challenge.
- Computed Tomography (CT) can deliver greater accuracy than conventional NDE methods.

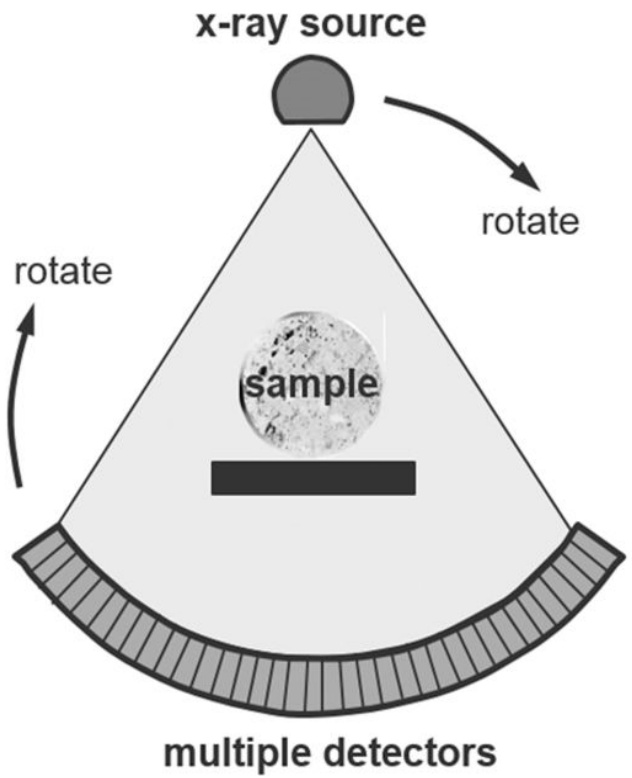
What is CT?

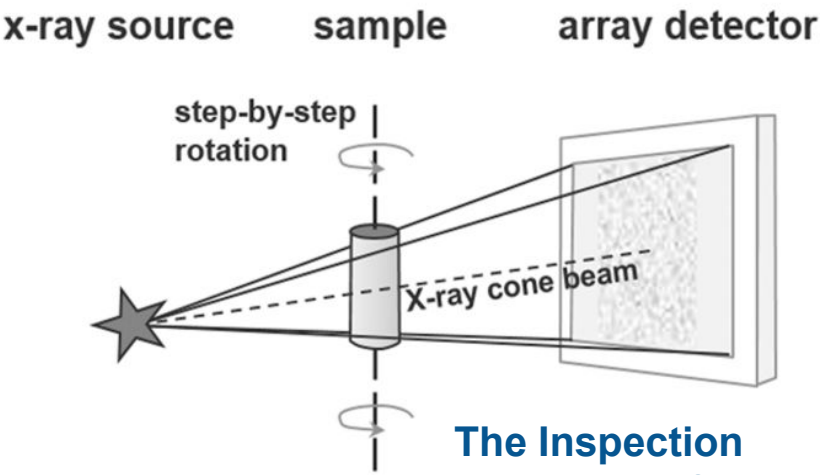
- CT scanning is an X-ray computer-aided tomographic process that uses irradiation to produce three-dimensional internal and external representations of a scanned object.
- Industrial CT scanning has been used in many areas of industry for internal inspection of components.
- Industrial uses for CT scanning have been flaw detection, failure analysis, metrology, assembly analysis, and reverse engineering applications.

Inspection Associates' Field Deployable CT Tool



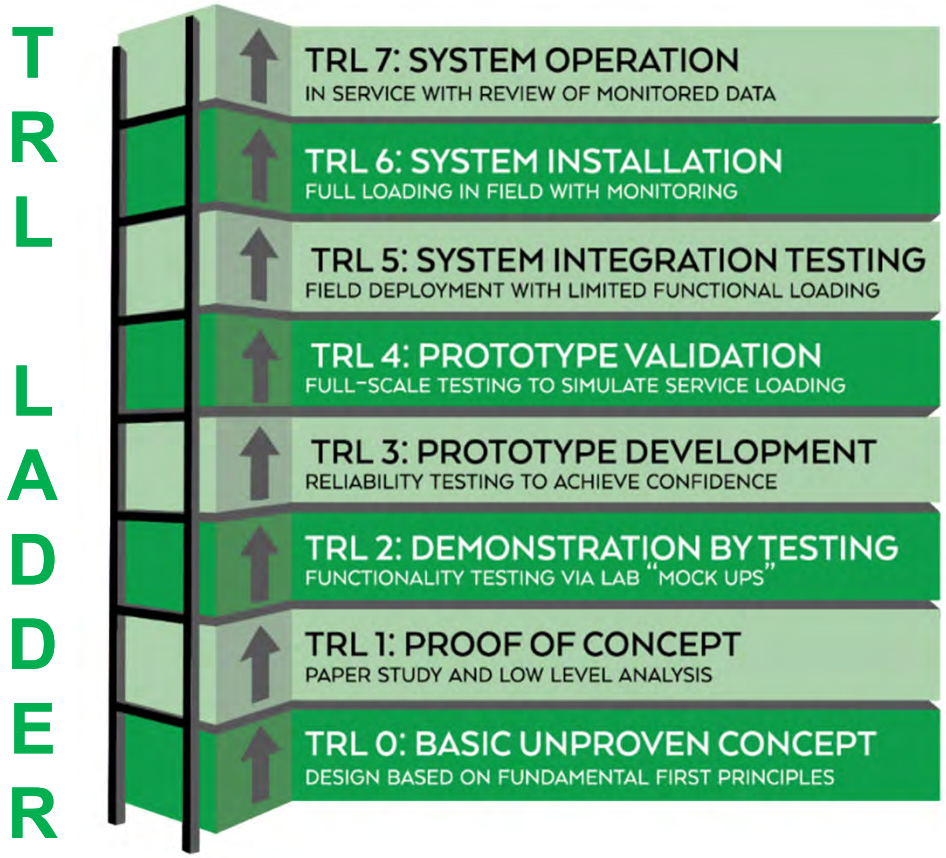
CT Process Overview (Schematic)





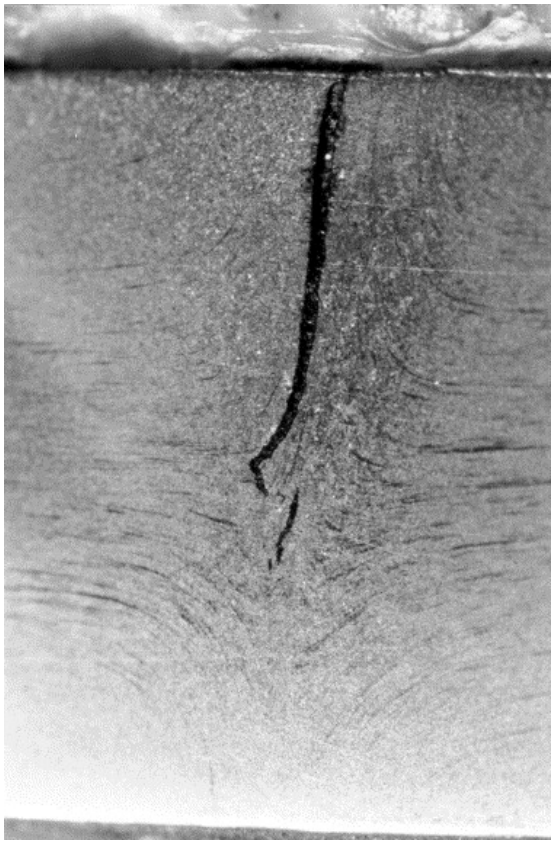
The Inspection Associates CT system rotates the source, not the sample.

TRL CT Case Study (1/4)

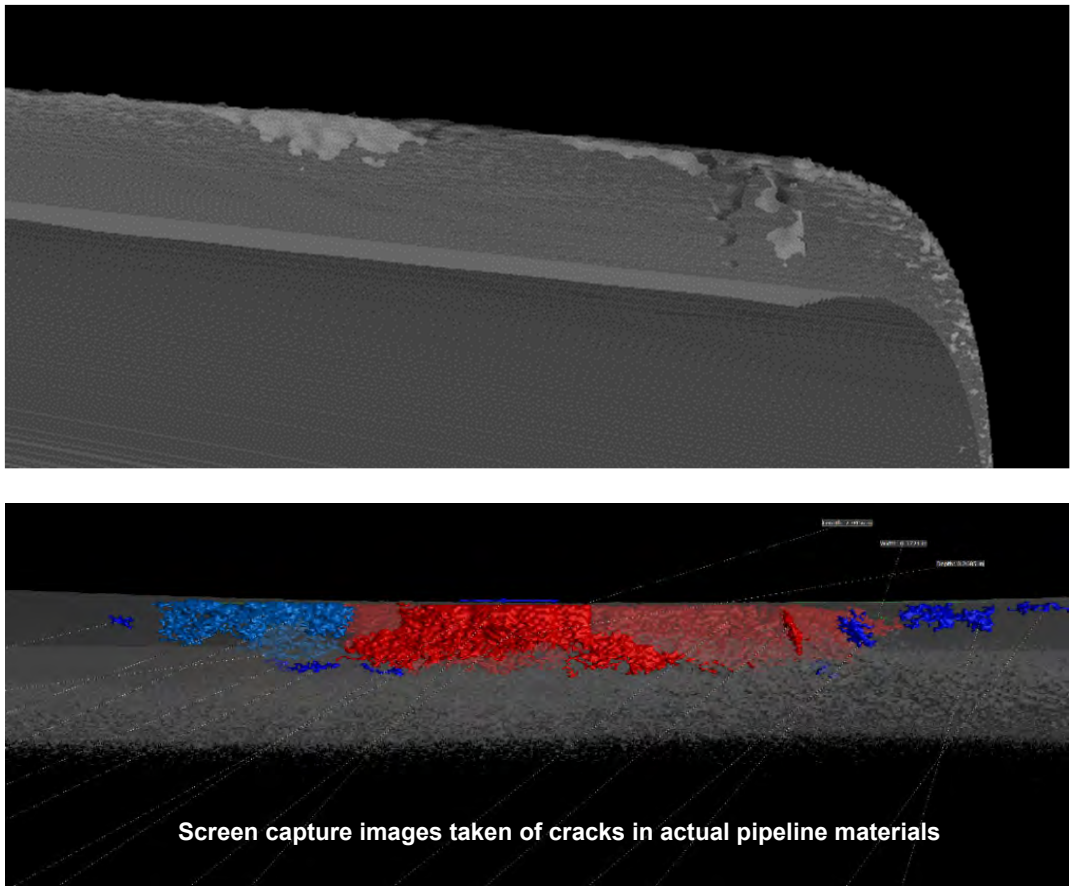


TRL CT Case Study (2/4)

- Crack-like features are difficult to inspect and “size”
- Cracks have contributed to pipeline failures
- With ILI technology advances, in-the-ditch inspection is critical
- Proposed solution: Computed Tomography



TRL CT Case Study (3/4)



Screen capture images taken of cracks in actual pipeline materials

TRL CT Case Study (4/4)

Technology Readiness Assessment (TRL: 3)

TRL Phase	Description	Satisfactory Demonstration	Notes / Commentary
0	Basic Unproven Concept	YES	
1	Proof of Concept	YES	Initial inspection work very promising
2	Demonstration by Testing	YES	Benchmark testing complete
3	Prototype Development	YES	Prototype built
4	Prototype Validation	NO	
5	System Integration Testing	NO	
6	System Installation	NO	
7	TRL 7: System Operation	NO	

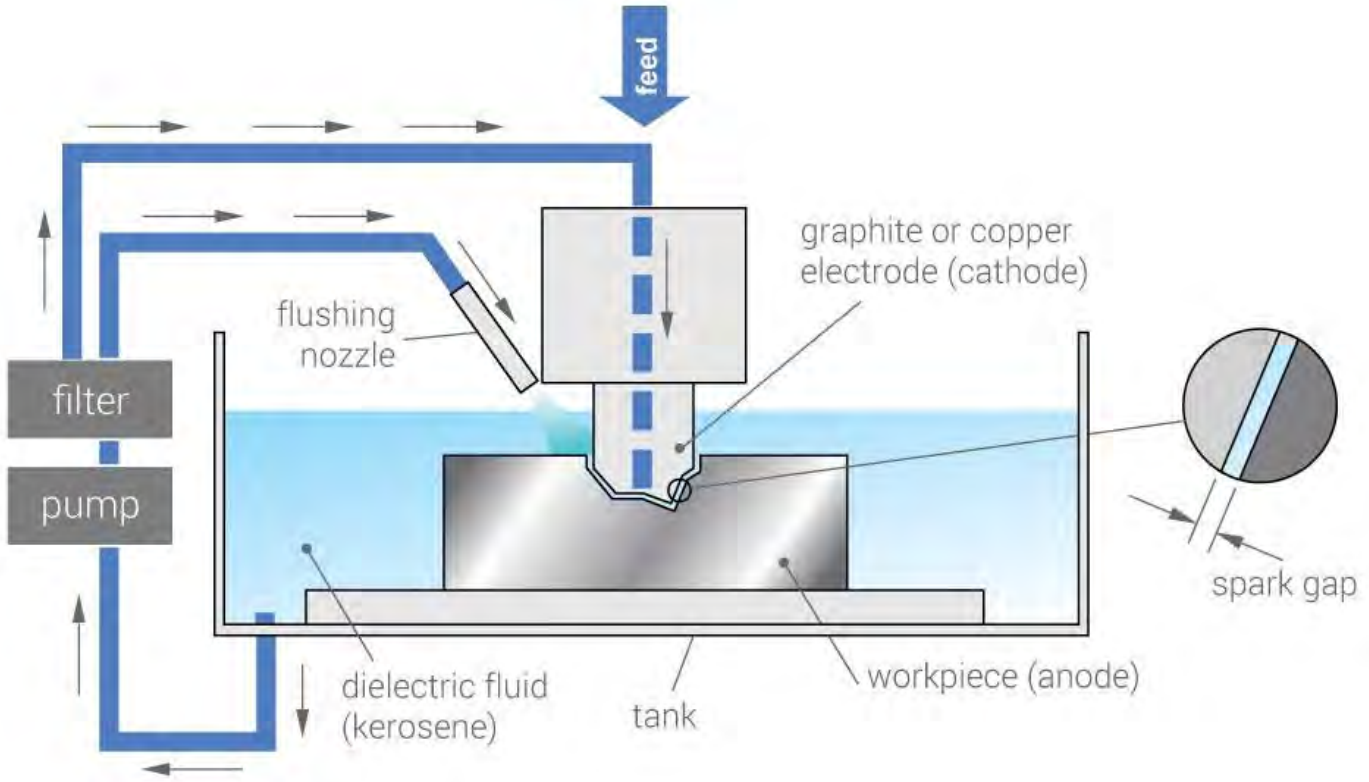
Recommended course of action:

1. Additional lab testing required to validate technology; sufficient sampling size required to achieve industry consensus and buy-in.
2. Look at operational efficiency prior to field deployment to minimize time required in the ditch.
3. Need to identify a pipeline operator who will support a field trial.

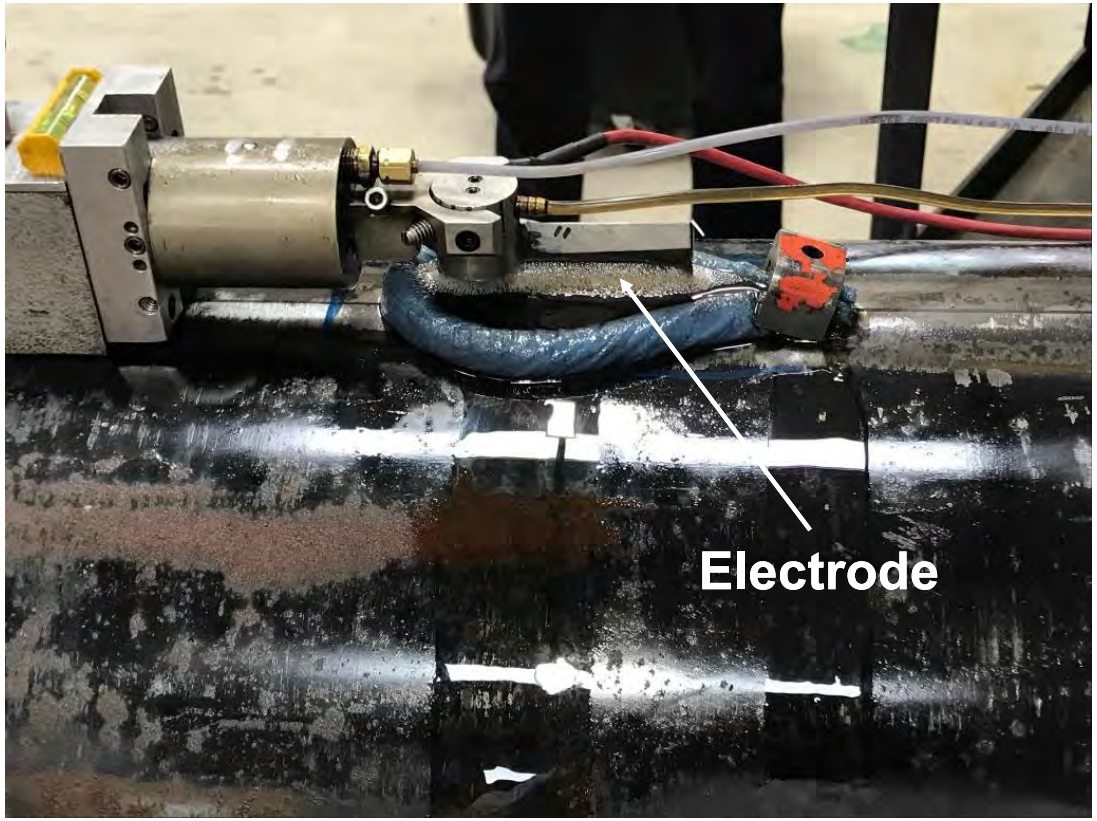
Validation Study

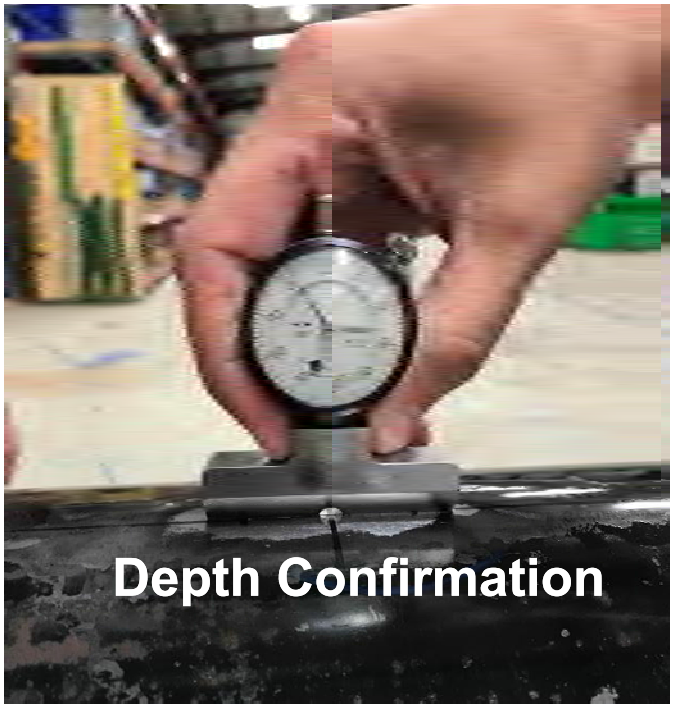
- Three pipe samples, 12.75-inch x 0.375-inch, Grade X42 HF-ERW pipe material
- Features created using EDM “starter” notches
- Cyclic pressure used to generate microcracks
- Features scanned first, and then broken up to determine final crack geometries

Electric Discharge Machining (EDM)

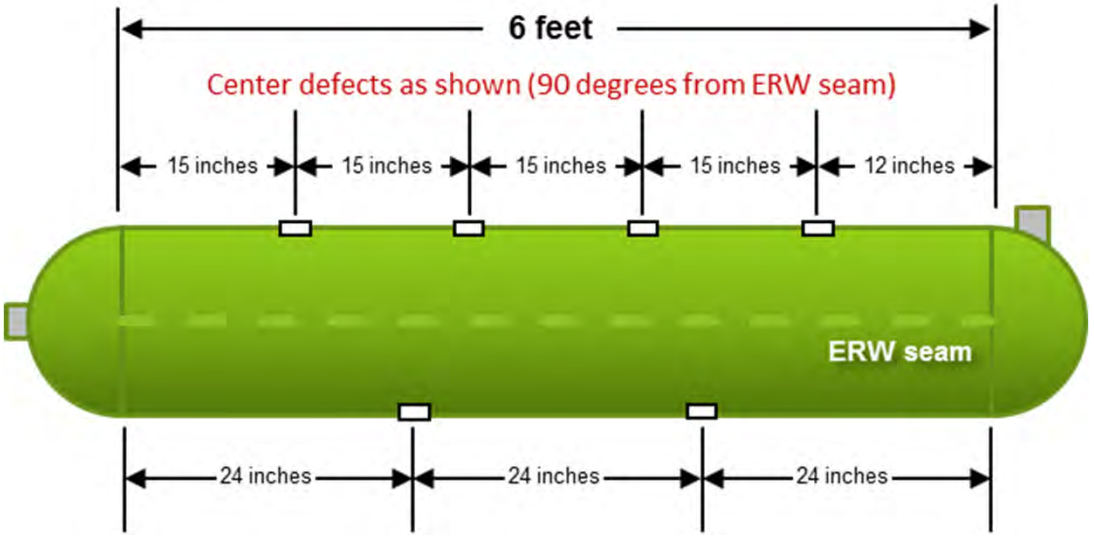


EDM Notch Generation





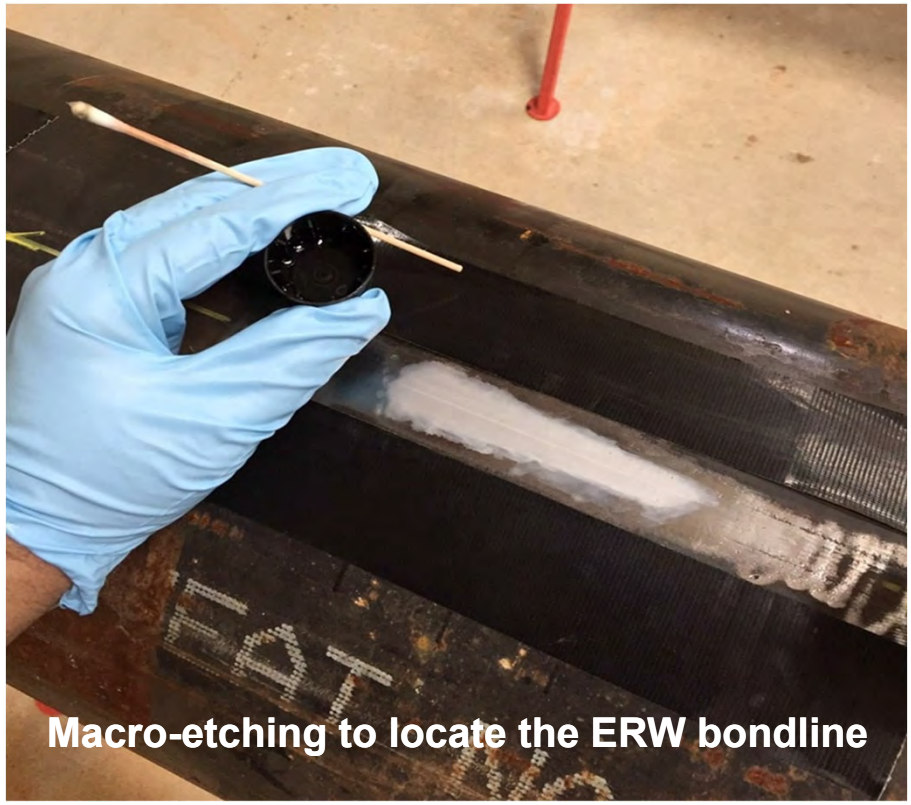
Sample Configuration (1/2)

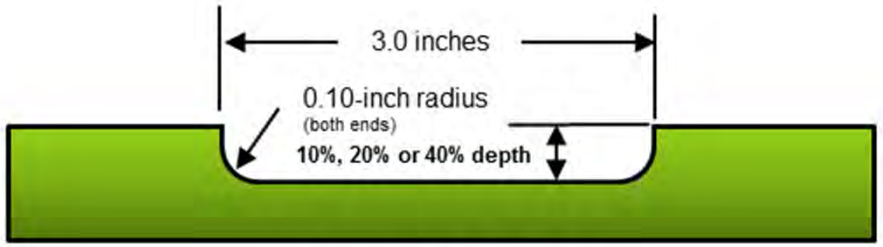


Notch	Depth %WT
A	5%
B	10%
C	15%
D	20%
E	25%
F	30%

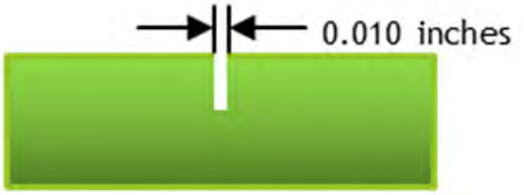
Sample Number	EDM Notch Length	EDM Notch Location	# of notches	EDM Depths %WT
100111-OD-1	3-inch	OD base pipe	6	5-30%
100111-OD-2	3-inch	OD ERW seam	4	5-20%
100111-ID-3	3-inch	ID ERW seam	4	5-20%

Sample Configuration (2/2)



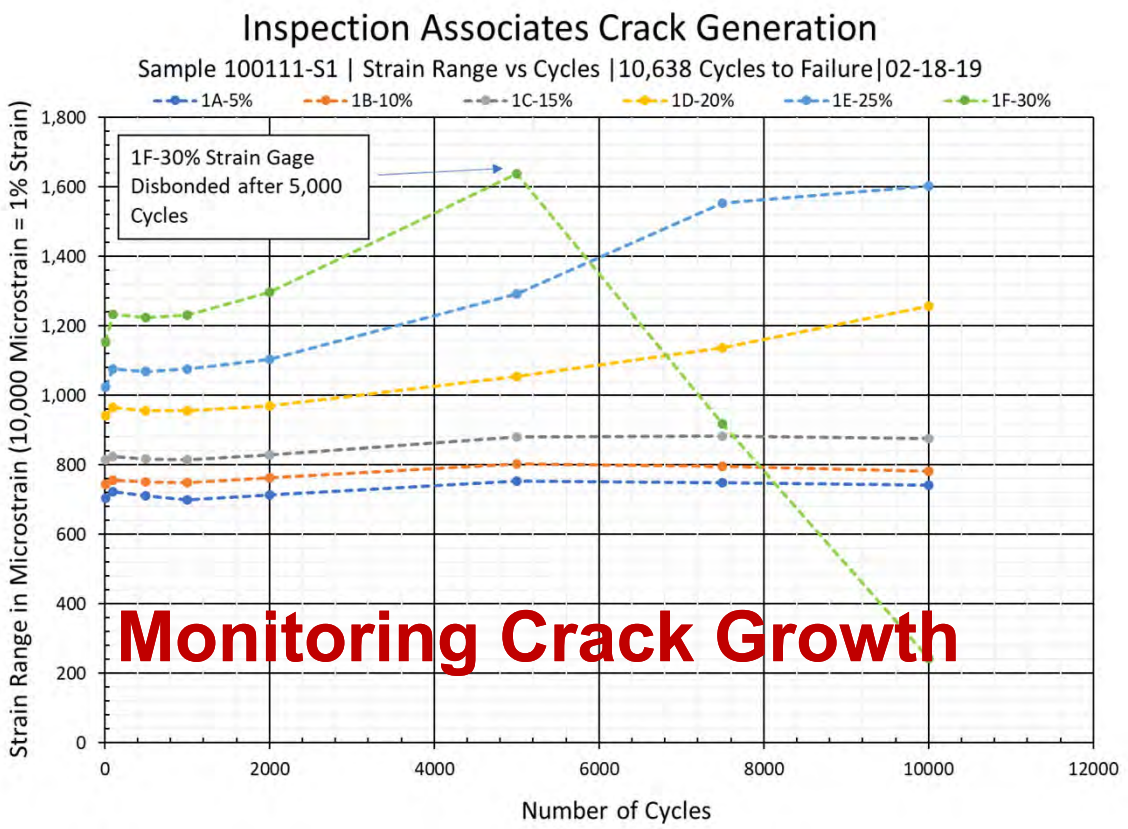


EDM Notch Details



Cross-sectional profile

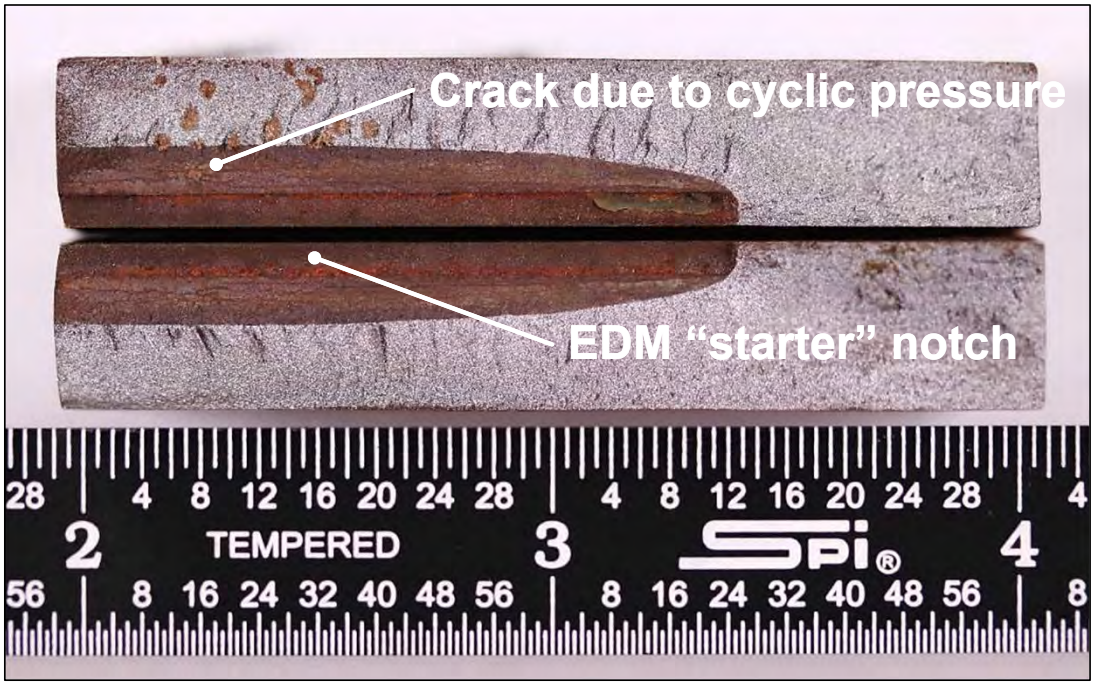
Test Set-up and Results



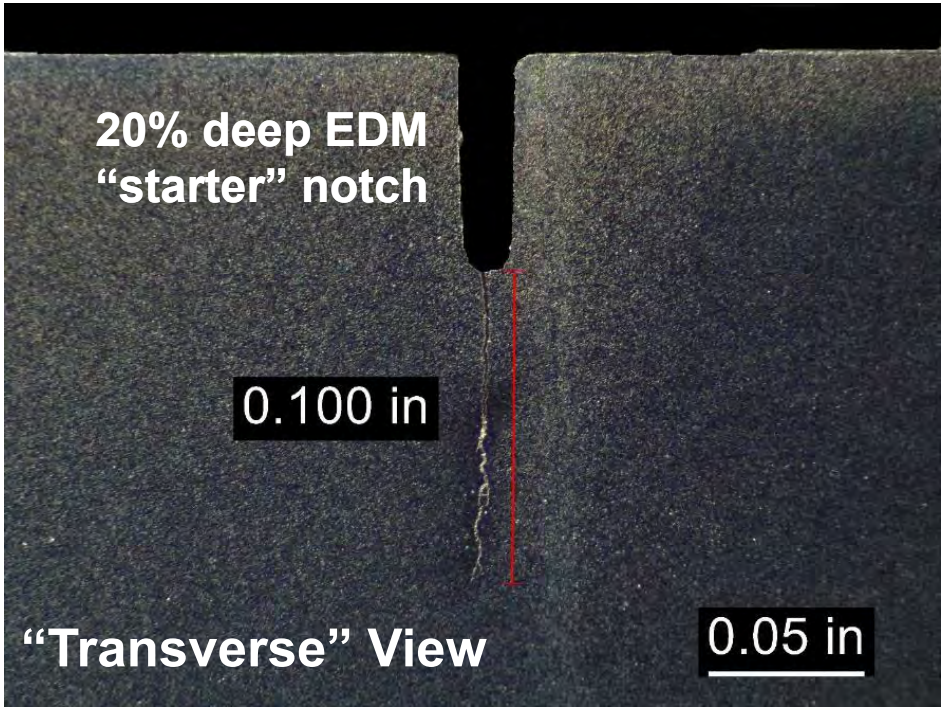




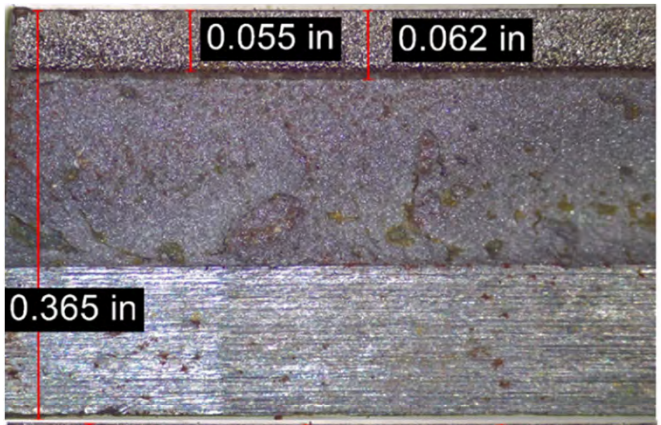
Example: Sample 2, Notch D

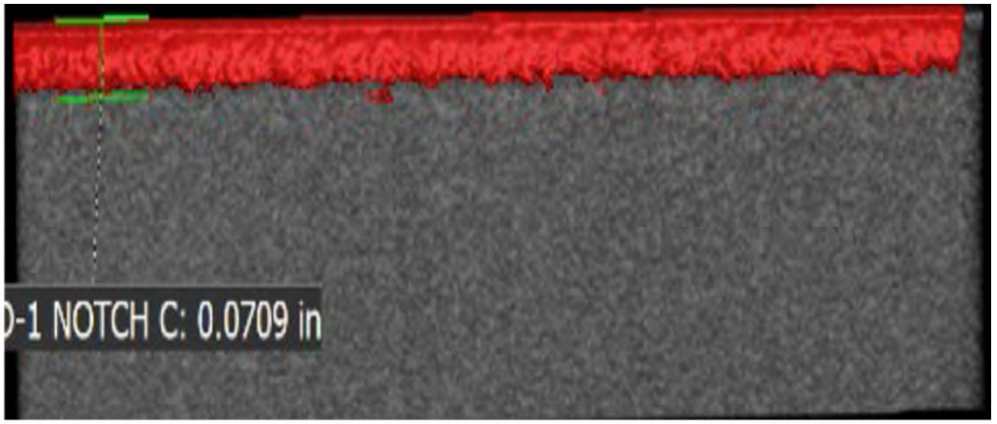


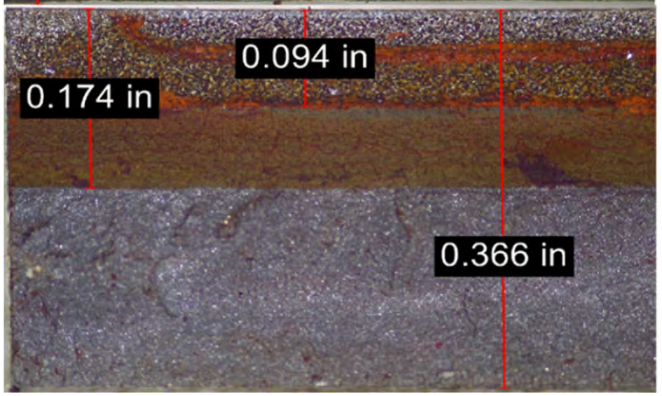
"Longitudinal" View

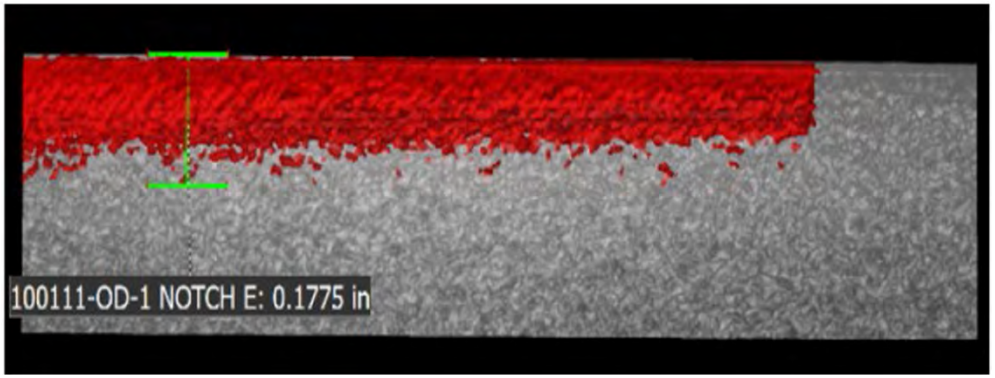


Validation Comparison Images



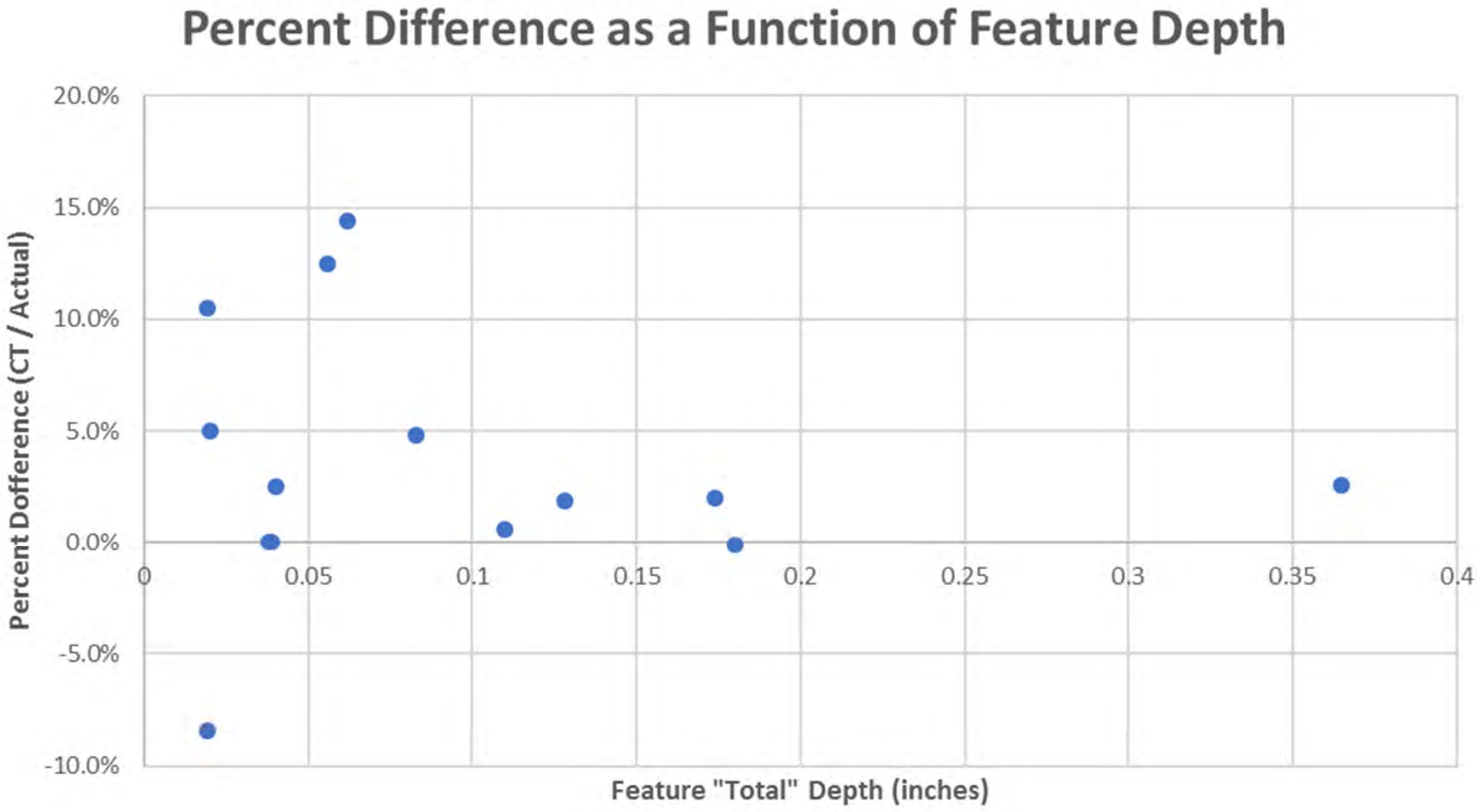




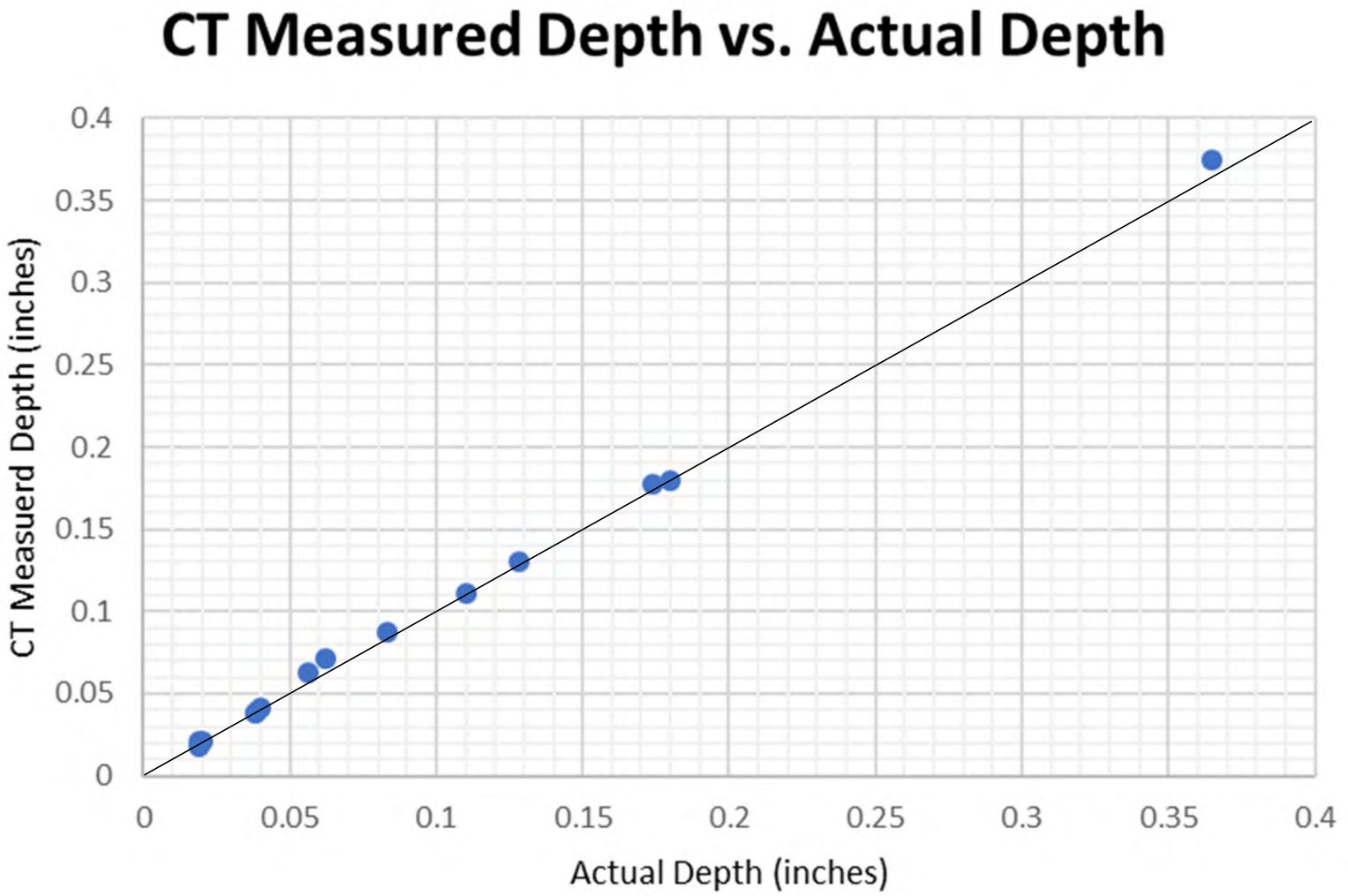


Summary of Test Results

Sample	Notch	WT (in)	EDM Depth (in)	Measured Total Depth (in)	CT Depth (in)	% Difference
100111-OD-1	A	0.364	0.019	0.019	0.0174	-8.4%
100111-OD-1	B	0.363	0.038	0.038	0.0380	0.0%
100111-OD-1	C	0.365	0.055	0.062	0.0709	14.4%
100111-OD-1	D	0.360	0.074	0.110	0.1107	0.6%
100111-OD-1	E	0.366	0.094	0.174	0.1775	2.0%
100111-OD-1	F	0.365	0.105	0.365	0.3745	2.6%
100111-OD-2	A	0.376	0.019	0.019	0.0210	10.5%
100111-OD-2	B	0.369	0.040	0.040	0.0410	2.5%
100111-OD-2	C	0.372	0.066	0.128	0.1304	1.9%
100111-OD-2	D	0.369	0.072	0.180	0.1798	-0.1%
100111-ID-3	A	0.382	0.020	0.020	0.0210	5.0%
100111-ID-3	B	0.378	0.039	0.039	0.0390	0.0%
100111-ID-3	C	0.380	0.056	0.056	0.0630	12.5%
100111-ID-3	D	0.382	0.075	0.083	0.0870	4.8%


Percent Difference as a Function of Feature Depth
Percent Dofference (CT / Actual)
20.0%
15.0%
10.0%
5.0%
0.0%
-5.0%
-10.0%
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Feature "Total" Depth (inches)

UNITY PLOT


CT Measured Depth vs. Actual Depth
CT Measuerd Depth (inches)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Actual Depth (inches)

Overall Observations

- This validation study involved three 12-inch NPS samples and a total of 14 EDM notch features.
- Longitudinal profiles were accurately reproduced by the CT scan; however, the transverse view did not always show the correct orientation of the crack.
- Crack measurements were shared with Inspection Associates to aid their efforts in determining the best way to present the data.
- Largest “errors” occur on the shallowest features.
- Depth, which is arguably the most important measurement, showed average and maximum errors of 3.5% and 14.4%, respectively.

PHMSA / PRCI NDE-2-11 CT Study

- Co-funded study evaluating CT technology
- Program involves the generation of synthetic features
- Inspection data set:
  - 40 synthetic features
  - 10 real-world features
- We are still looking for additional donated pipe material



PRCI NDE-2-11 Computed Tomography Study

Call for Pipes to support the PRCI-PHMSA research effort

Prepared by Chris Alexander | January 31, 2020

The NDE-2-11 study is being co-funded by PRCI and PHMSA. The aim of this study is to reduce uncertainty in pipeline assessment methods by generating a set of "truth data" based on fabricated synthetic crack-like features that can be used to validate both in-line and in-the-ditch inspection technologies. An important aim of this project is to develop and validate processes for fabricating synthetic features on a repeatable and reliable basis using full-cylinder pipe samples. These manufactured samples will be used to calibrate the CT technology system and verify sizing accuracy.

An essential element in this program is acquiring pipeline materials. Although it is possible to use modern pipe, it is preferable to use vintage pipe materials in this study, especially pipe having low frequency ERW seam welds. For this reason, PRCI and ADV Integrity, Inc. are requesting the donation of pipe materials with diameters 24 inches or less. If available, we are requesting the following information:

- Pipe diameter, wall thickness, and grade
- Year of construction and manufacturer
- Type of service / product

Pipe materials can be shipped to the following address:

ADV Integrity, Inc.
Attn: Chris Alexander
28246 FM 2920
Waller, Texas 77484

Prior to shipping, please notify Chris via e-mail at chris.alexander@advintegrity.com. Also, if you are shipping pipe that has asbestos coating, please remove prior to shipment.

Thank you for your help!

Chris Alexander
chris.alexander@advintegrity.com | (281) 450-6642 (cell)

Copy: Tim Burns (Shell), Richard Kania (TC Energy), Mark Piazza (Colonial), Zoe Shall (PRCI), John Lynk (PRCI), and Dave Katz (Consultant)

BACK TO AGENDA

PRCI 2020 Research Exchange

CORRELATION OF SINGLE-RUN ILI IMU BENDING STRAIN FEATURES TO GEOHAZARD LOCATIONS

Presenter

Bailey Theriault, PG

Senior Geologist and Associate

Golder Associates

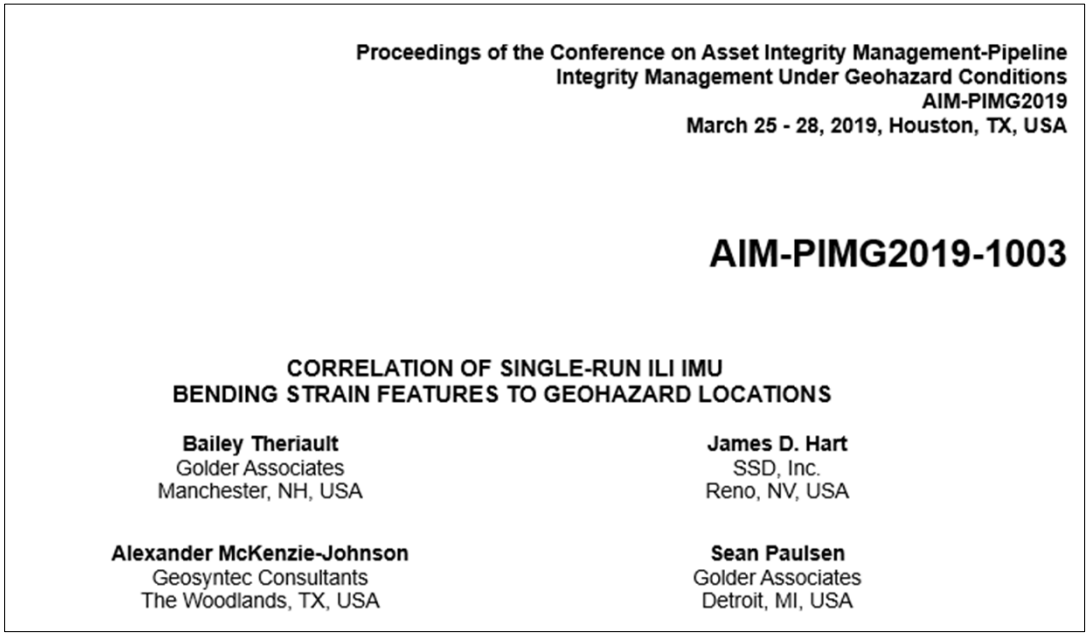
Co-authors

James D. Hart, Alexander McKenzie-Johnson, and Sean Paulsen

LEADING PIPELINE RESEARCH

Research Overview

- This research was conducted for and presented at the ASME Conference on Asset Integrity Management-Pipeline, Integrity Management Under Geohazard Conditions in March 2019



Proceedings of the Conference on Asset Integrity Management-Pipeline
Integrity Management Under Geohazard Conditions
AIM-PIMG2019
March 25 - 28, 2019, Houston, TX, USA

AIM-PIMG2019-1003

CORRELATION OF SINGLE-RUN ILI IMU BENDING STRAIN FEATURES TO GEOHAZARD LOCATIONS

Bailey Theriault
Golder Associates
Manchester, NH, USA

James D. Hart
SSD, Inc.
Reno, NV, USA

Alexander McKenzie-Johnson
Geosyntec Consultants
The Woodlands, TX, USA

Sean Paulsen
Golder Associates
Detroit, MI, USA

Statement of Problem

- In-line-inspection (ILI) inertial measurement unit (IMU) data can be used to identify sections of pipelines bent or deflected by an outside force (e.g., a geohazard).

- As multiple operators have experienced, the list of bending strain features provided by the ILI vendors often does not correlate to any apparent anomaly when excavated, nor any apparent geohazard.

- Absent context and supporting information, IMU bending strain data can appear to be essentially meaningless with little value added to real-World situations.

Project Objectives

- Evaluate how In-line-inspection (ILI) inertial measurement unit (IMU) data can be used to assess impacts to pipelines from geohazards.
  - Provide context and examples for how IMU bending strain data have been used to successfully identify real-World impacts to pipelines from geohazards.
  - Show how IMU bending strain data can be used to aid in the prioritization of response (e.g., mitigation, monitoring).
  - Show how IMU bending strain data can be used in to identify new geohazards.

Inertial Measurement Unit (IMU) Data

WHAT ARE THEY?

- IMU tool used during ILI runs.
- A measure of the curvature of the pipe or its “out-of-straightness.”
- Used to identify sections of pipeline bent or deflected.
- ILI vendors review IMU data and exclude intentional construction-related bends (e.g., cold bends, sag bends, etc.).
- Bends that extend across one or more girth welds are inferred to not have been deliberately constructed, and are reported as “bending strain features.”
- Bending strain features exceeding a specified threshold magnitude are inferred to have formed post-construction.

IMU Data

WHY ARE THEY USEFUL?

- IMU tool is regularly used to more accurately map pipeline centerlines; thus, the additional **cost of the bending strain report is low**!

- Typically assumed that bending strain features are imposed by an external force, post-construction.
  - Geohazards (e.g., landslide)
  - 3rd party impacts

IMU Data

WHAT'S THE PROBLEM?

- So much data!
- The majority of reported bending strain features do not correlate to any apparent anomaly nor to geohazards.
- Most appear likely construction-related, with only a small subset originating from external forces.
- How can data be sorted/filtered/reviewed such that value can be recognized?

Our Study

IMU DATA REVIEW

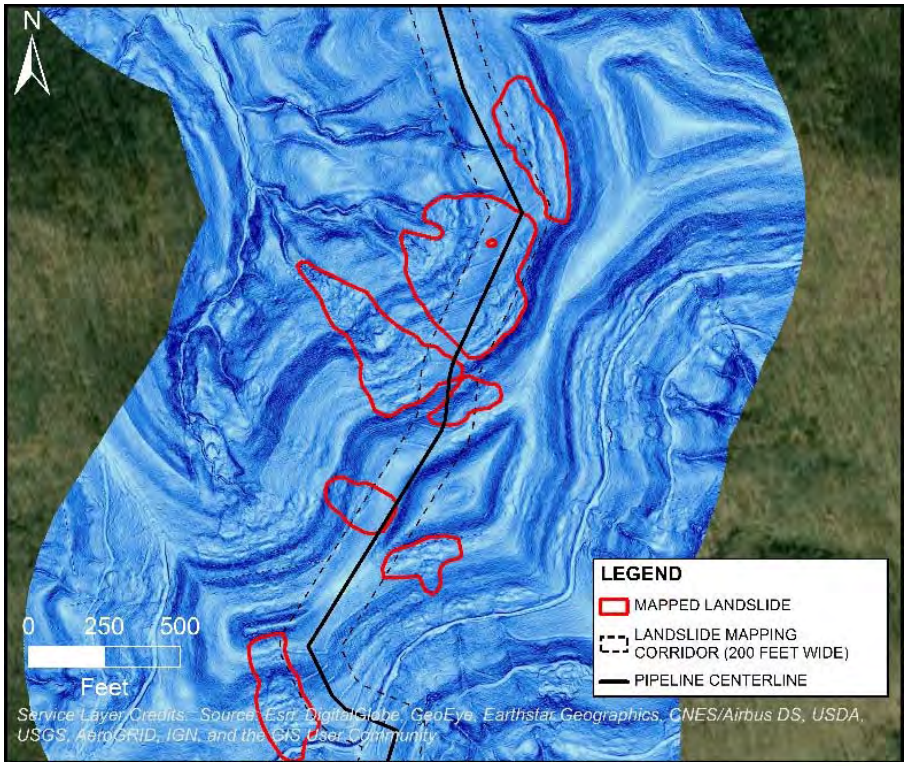
- Reviewed 4,618 bending strain features
  - Single-run results only, did not look at run-to-run.
  - Collected by three different IMU survey vendors.
  - Located along NG pipelines across the US.
  - Large percentage of pipelines were located in the eastern US, within areas with high densities of known landslides.
- Bending strain features were compared to:
  - Previously identified locations of known or possible landslides.
  - LiDAR data and aerial imagery.

Our Study

LANDSLIDE IDENTIFICATION MAPPING

- Landslides identified from high-resolution LiDAR data and/or aerial imagery, and then confirmed through field visits.

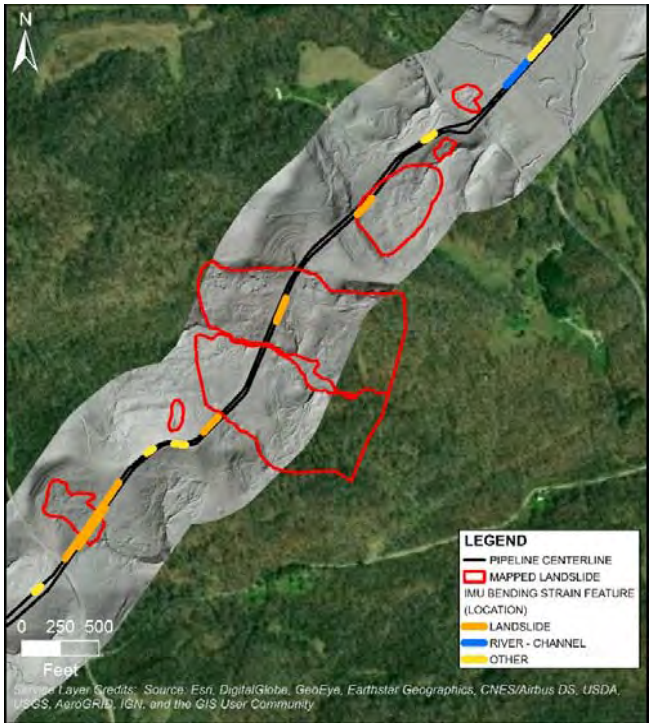
- Landslides within 100 feet of pipeline are delineated.



Our Study

IMU DATA REVIEW

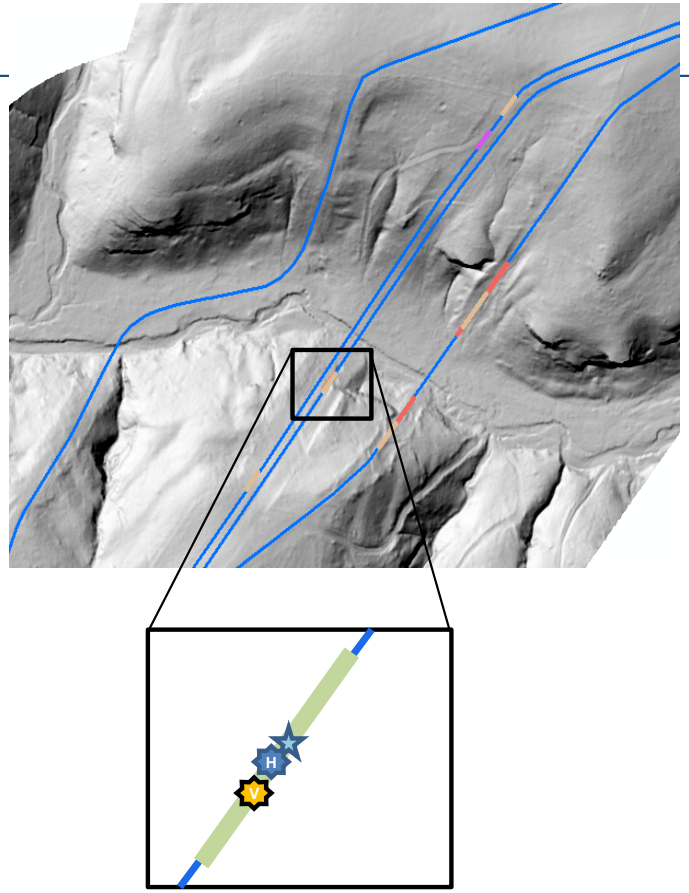
- Discrete segments along pipeline alignment with distinct start and end points.
- Bending strain features assigned a location type
  - Landslide (Orange)
  - River Channel (Blue)
  - Other (Yellow)



IMU Data

KEY PARAMETERS

1. Strain magnitude: The overall maximum calculated resultant bending strain for the bending strain feature.
2. Max Horizontal strain: The maximum calculated horizontal component of bending strain for the bending strain feature.
3. Max Vertical strain: The maximum calculated vertical component of bending strain for the bending strain feature.



IMU Data

- EXAMPLE TABULAR DATA

BAKER HUGHES a GE company

Client Name: XXXXX
Contract: 450564_30H
Launch/Receive: XXXXX
Diameter: 30 in
Length: 66 miles
Strain Report Date: 23-Nov-18
Reporting Threshold: 0.125 % Bending strain reporting threshold
0.020 % Strain change reporting threshold

Go back to Table of contents

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Bending Strain and Strain Change Assessment Report

Strain Reporting Threshold: Bending strain features and strain change features are greater or equal to the bending strain reporting threshold and length greater than 40ft (nominal pipe spool length)
The strain values summarized below represent axial bending strain only and do not include any additional axial strain due to other loading mechanisms

Notes:
Click on Strain feature no. in column A to view GW strains, list of bends, geometric anomalies & ILI features within strain event, loading type and stacked strain chart

Strain Feature or Strain Change ID	Abs Dist (ft)	Velocity (ft/s)	Strain Magnitude (%)	Peak Strain Distance (ft)	Strain Orientation	Horizontal Strain At Peak Strain (%)	Vertical Strain At Peak Strain (%)	Max Horizontal Strain (%)	Max Vertical Strain (%)	Strain Direction	Strain Change Magnitude (%)	Strain Change Orientation (hh:mm)	Strain Change Horizontal (%)	Strain Change Vertical (%)	U/S Weld
1	590.2	4.6	0.158	563.0	6:16	-0.023	-0.157	0.111	-0.157	Horizontal / Vertical					240
2	5881.5	5.8	0.161	5842.6	11:25	-0.048	0.154	-0.057	0.154	Vertical					1630
3	6299.4	5.4	0.145	6303.5	12:16	0.021	0.144	-0.076	0.144	Horizontal / Vertical					1770
4	10856.7	8.2	0.180	10844.2	5:46	0.020	-0.179	0.061	-0.179	Vertical					3030
5	33715.6	10.2	0.081	33689.0	11:54	-0.004	0.081	0.038	0.081	Horizontal / Vertical	0.054	12:09	0.033	0.054	9240
6	43941.1	10.5	0.143	43995.8	5:45	0.019	-0.142	0.104	-0.142	Horizontal / Vertical					11855
7	45951.5	11.7	0.153	45941.9	6:00	-0.001	-0.153	0.025	-0.153	Vertical					12420
8	61818.5	10.8	0.132	61807.7	6:34	-0.039	-0.126	0.046	-0.126	Vertical					16590

Our Study

SUMMARY OF IMU DATASET

- Most bending strain features have a strain magnitude of less than 0.2%
  - 3,572 out of the 4,618 analyzed features; ~77%
- Magnitudes of greater than 0.3% are very rare
  - 116 out of the 4,618 features; ~2.5%
- Magnitudes of greater than 0.4% are exceedingly rare
  - 17 out of 4,618; ~0.4%

Results

IMU DATA VS. GEOHAZARDS

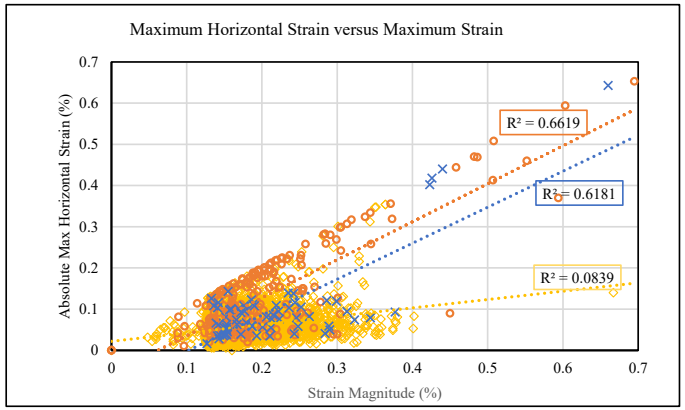
- Likely geohazards (i.e., landslides and river channels) amount to 298 features out of 4,618 (6%).
  - 229 associated with landslide locations
  - 69 associated with river channels

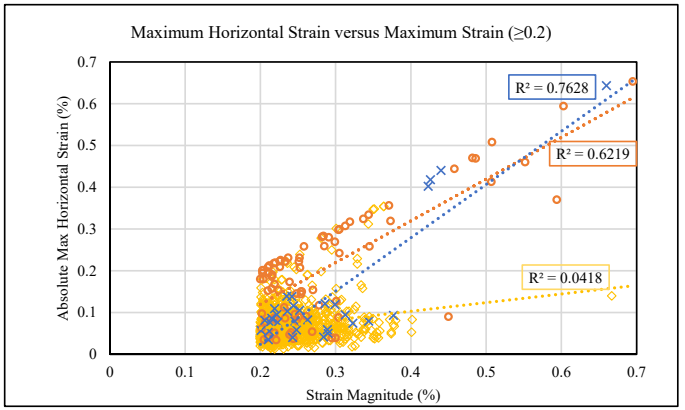
- Landslide Locations - ~64% of bending strain features had strain magnitude <0.2%

- River Channel Locations – 55% of bending strain features had strain magnitude <0.2%

Results – Scatter Plots and Linear Regression Lines

MAX HORIZONTAL STRAIN



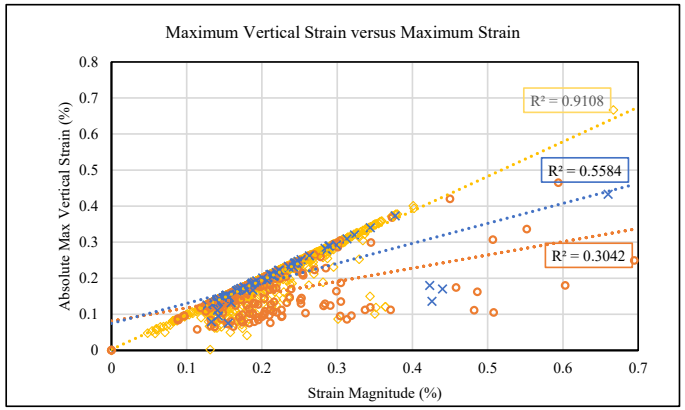


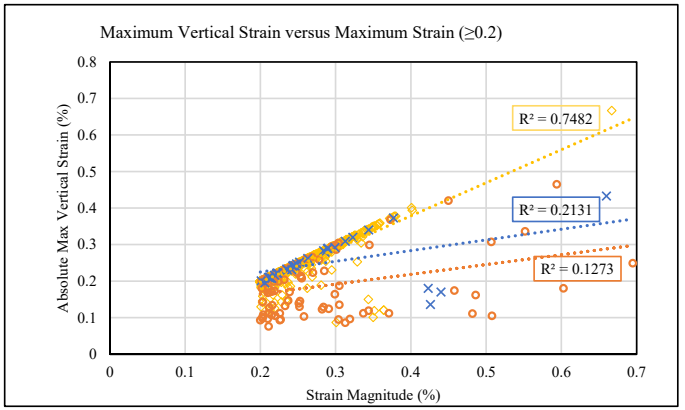
- **Landslides = orange / River channels = blue / Other = yellow**

- Higher regression coefficient (R^2) values indicate a given strain component is becoming dominant (e.g., the horizontal strain is nearly equal to the strain magnitude)
- Landslides and River Channels have higher R^2 Values than Other; thus, stronger relationship between horizontal strain and geohazards.

Results – Scatter Plots and Linear Regression Lines

MAX VERTICAL STRAIN



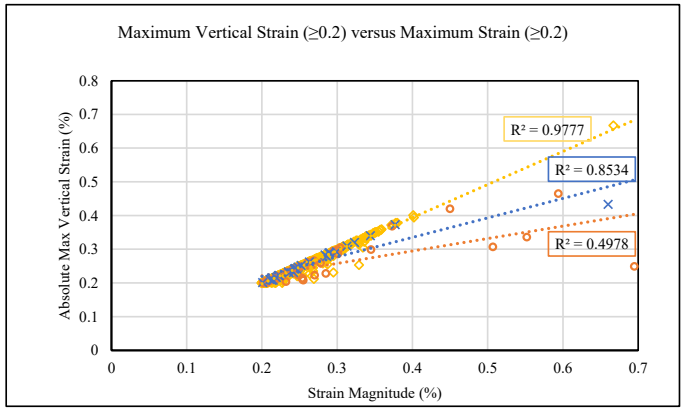


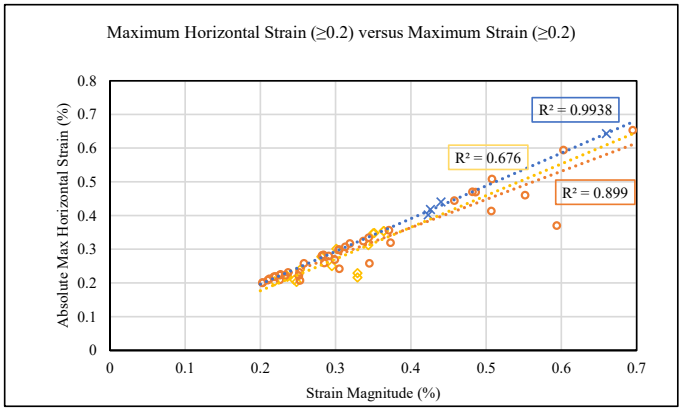
Landslides = orange / River channels = blue / Other = yellow

- Other have higher R^2 Values than Landslides and River Channels; thus, weaker relationship between vertical strain and geohazards.

Results – Scatter Plots and Linear Regression Lines

MAX VERTICAL/HORIZONTAL STRAIN, FILTERED



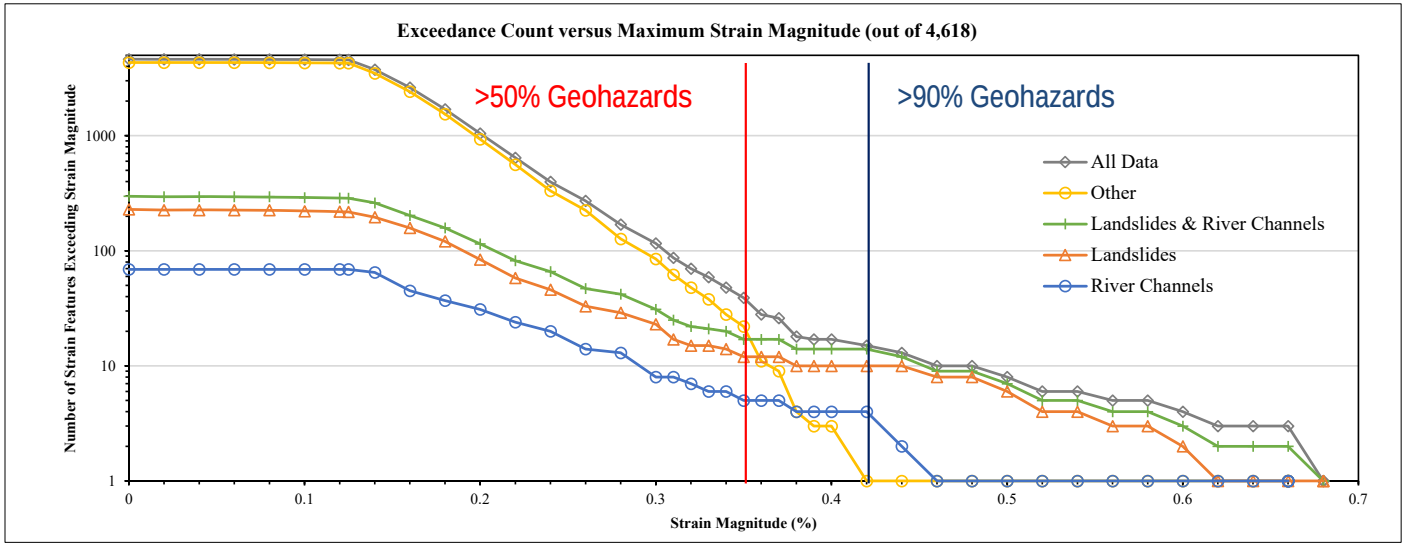


Landslides = orange / River channels = blue / Other = yellow

- Filtered data show similar overall relationships as unfiltered data.

Results – Exceedance Plots

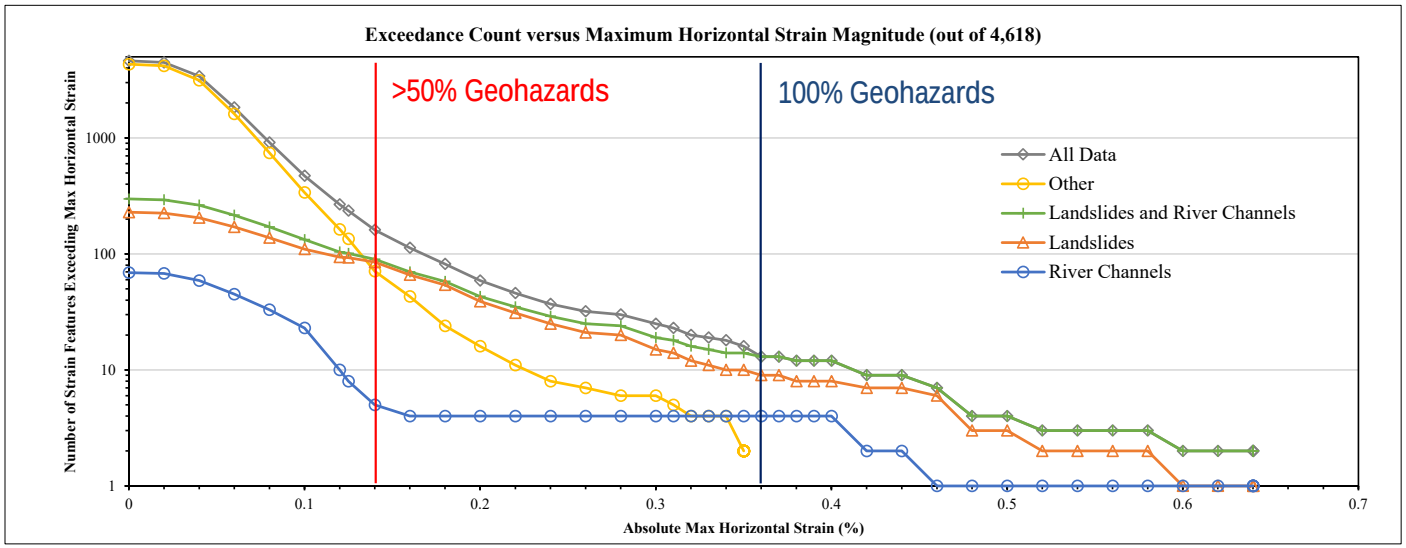
STRAIN MAGNITUDE



- Shows the number of features within a given location group that exceed increasing levels of strain.
- Intended to show what strain levels a given location group (if any) becomes most prominent.

Results – Exceedance Plots

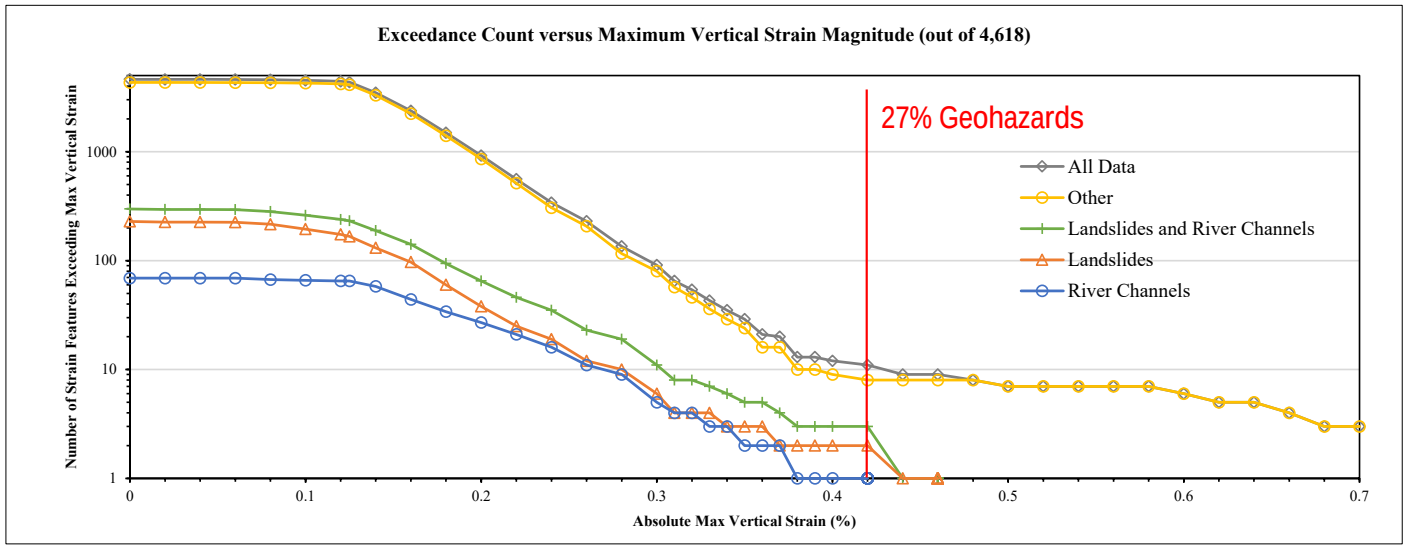
MAX HORIZONTAL STRAIN



- The relationship between horizontal strain and likely geohazards is stronger than overall strain magnitude.

Results – Exceedance Plots

MAX VERTICAL STRAIN



- The relationship between vertical strain and likely geohazards is relatively poor.

Results

HOW TO USE LOW MAGNITUDE DATA?

- What about all the low magnitude bending strain features (i.e., <0.2%) that also appear to be associated with geohazards?!
- A small percentage of a large dataset! How to utilize?
- If the bending strain features can be overlain with previously identified geohazards, the data can still be efficiently reviewed and screened to identify possible locations where the pipe may be impacted by geohazards.

Conclusions

- The correlation between geohazards and bending strain features rises with increases in strain magnitude.
- The relationship between horizontal strain and likely geohazards is stronger than overall strain magnitude.
  - High horizontal strain magnitude is predictive of likely geohazards.
- In contrast, the relationship between vertical strain and likely geohazards is relatively poor.
  - Vertical strain magnitude is not predictive of likely geohazard locations.

Conclusions

- Bending strain is a useful tool for evaluating whether a pipeline has been affected by a likely geohazard.
  - When the location of a likely geohazard is known, it allows for an evaluation of whether the geohazard has already induced bending on the pipeline and the relative severity of the bending.
  - Reported bending strain features in locations without known geohazards can prompt a geomorphic review of that area, to evaluate if there could be a previously unknown geohazard affecting the analyzed section of pipe.

THANK YOU!

Bailey Theriault
btheriault@golder.com





PRCI 2020 Research Exchange

Developing a Representative Soil Response Model

- **Ryan Phillips**
  ryan.phillips@c-core.ca

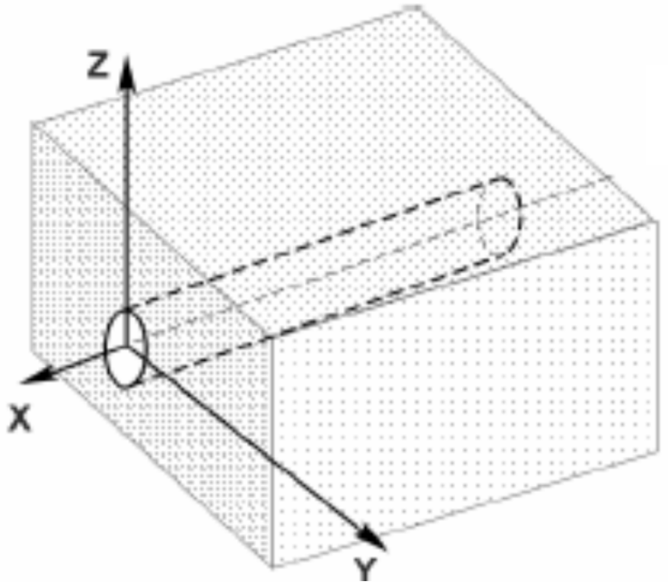
- **Acknowledgement**

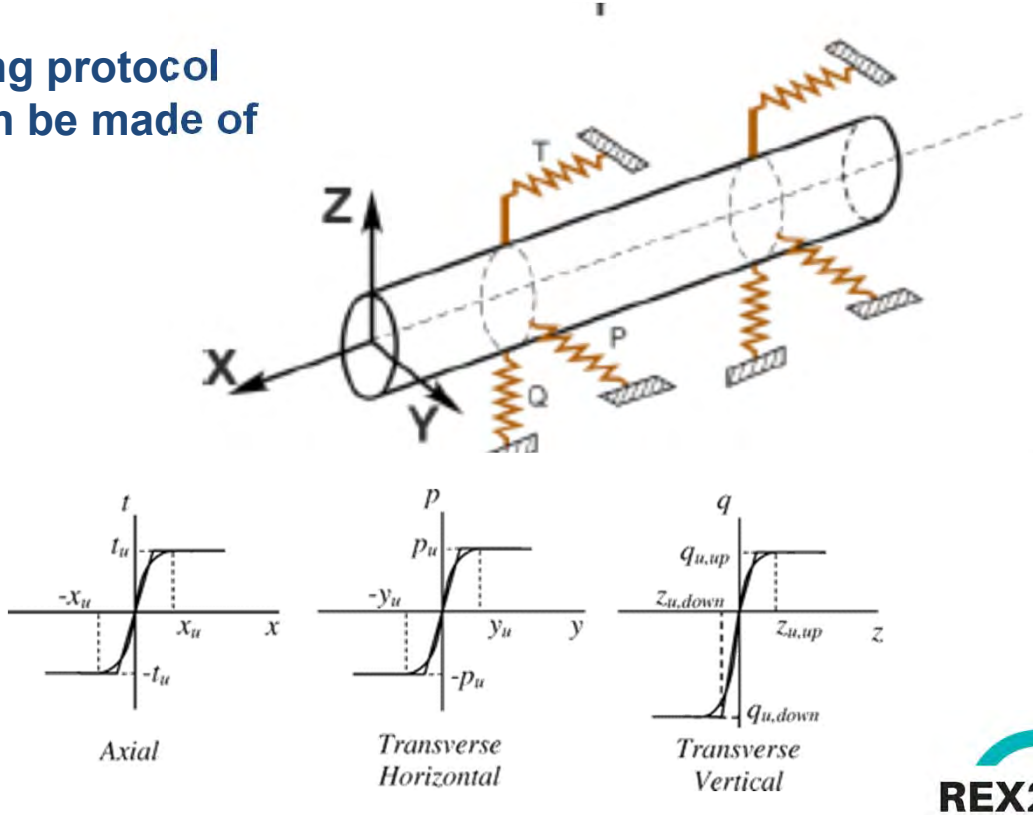
LEADING PIPELINE RESEARCH

Introduction

Objective:

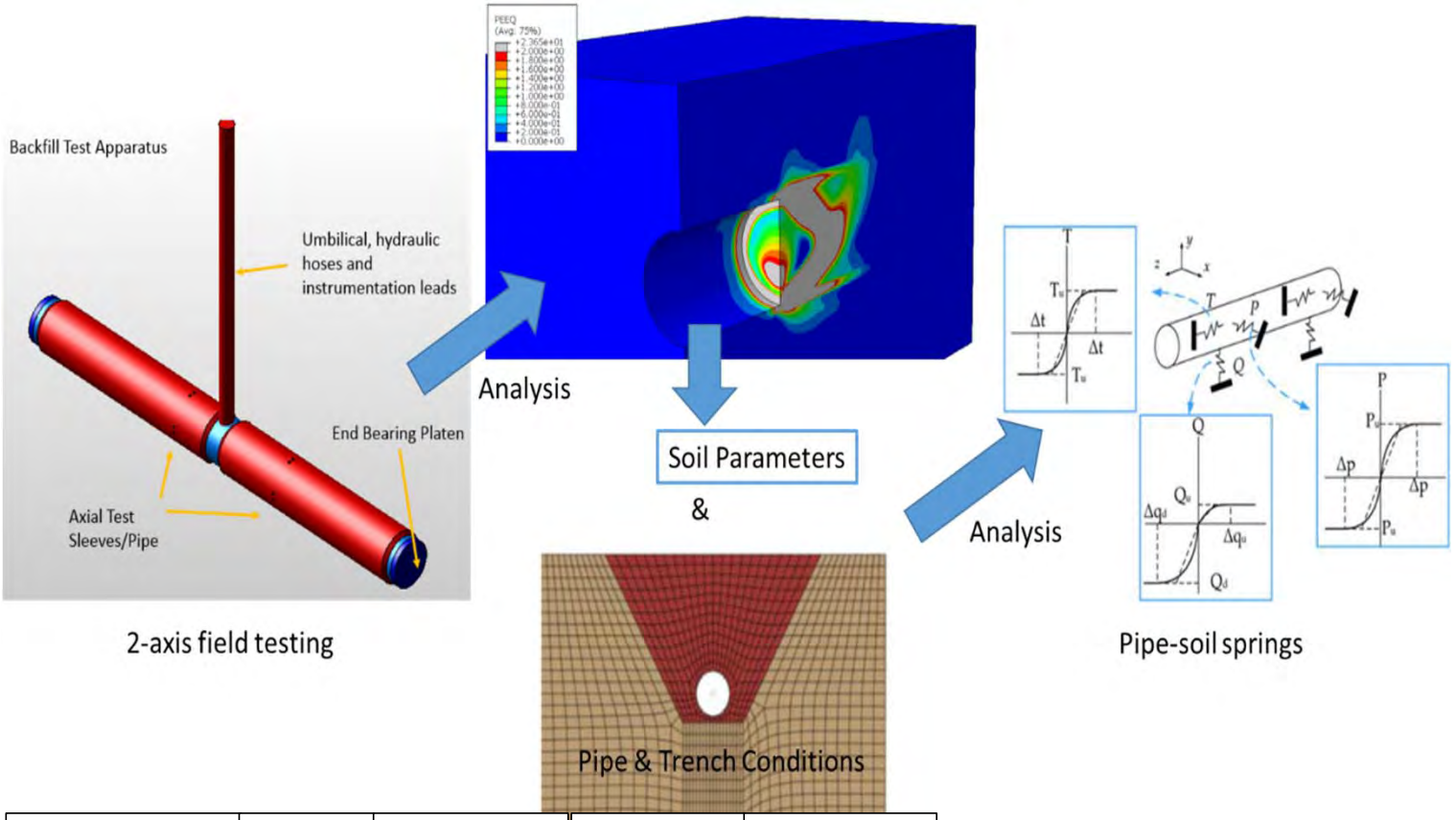
- to advance a new simple field testing protocol from which a direct assessment can be made of pipe-soil spring response





REX2020
PRCI RESEARCH EXCHANGE

Project Review



- Modelling
  - Lab & field testing
  - Numerical
- Prototype equipment:
  - Development & commissioning
- Numerical Analysis
- *.....Database*

Background





Soil Spring Assessment
N. Albertan pipeline

IPC2014-3319
McAffee, Phillips & Martens

REX2020
PRCI RESEARCH EXCHANGE

Background – TC Energy RoWs



Test in native soils

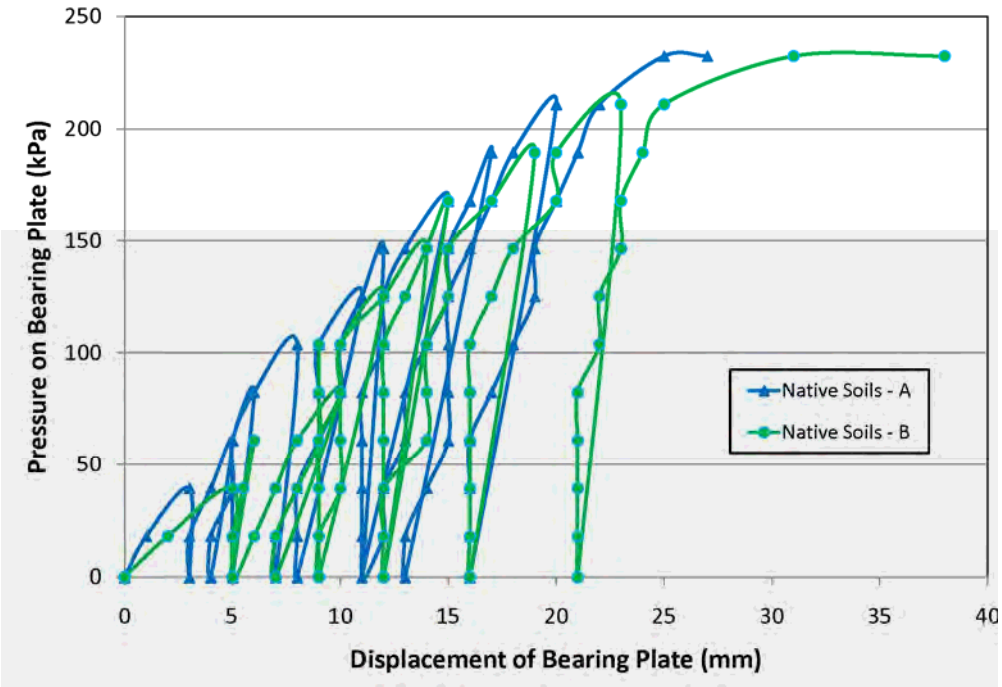




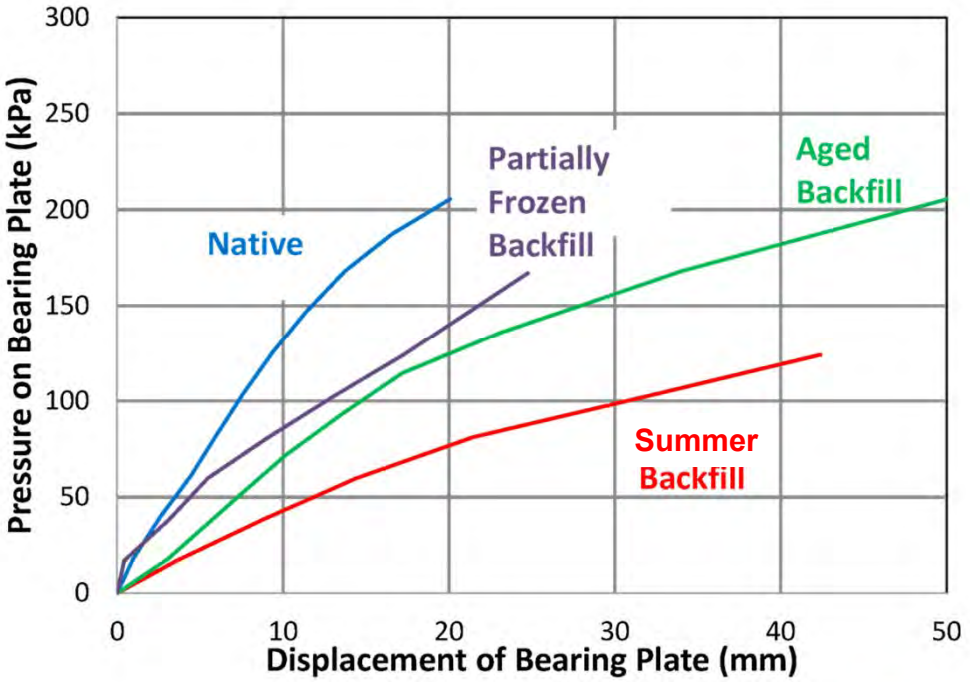
Test in backfill soils

Background - Typical Results

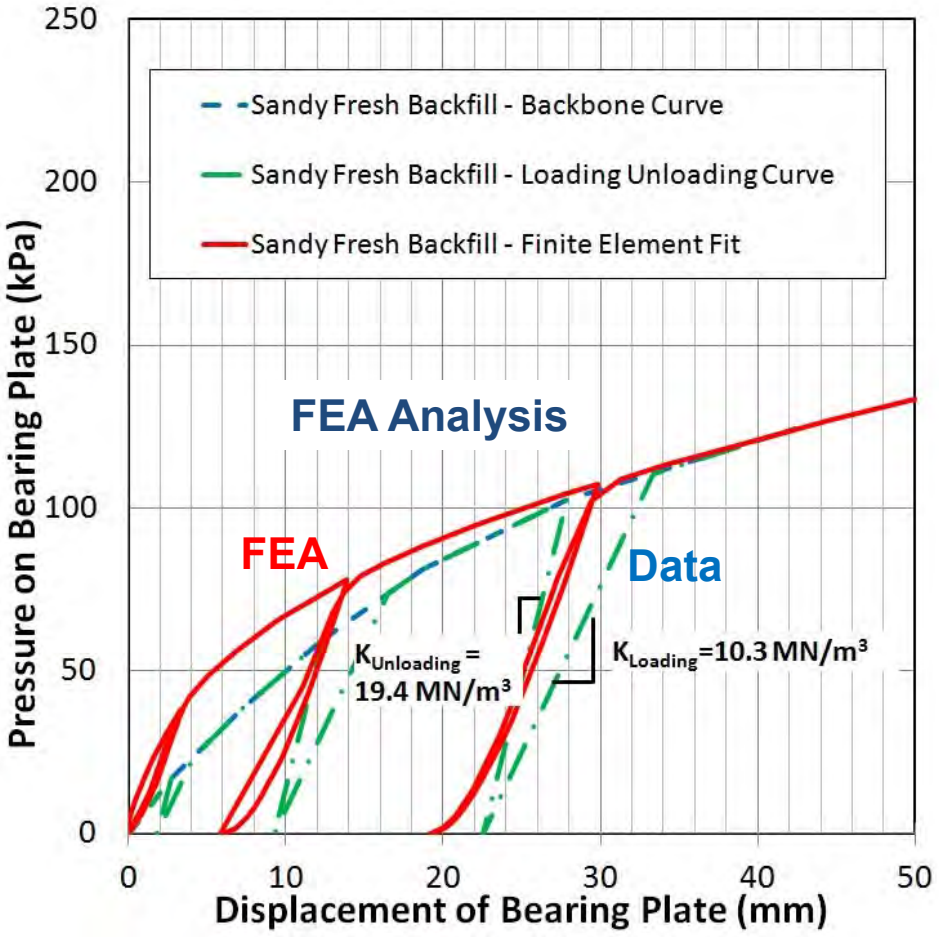
Bearing plate test response

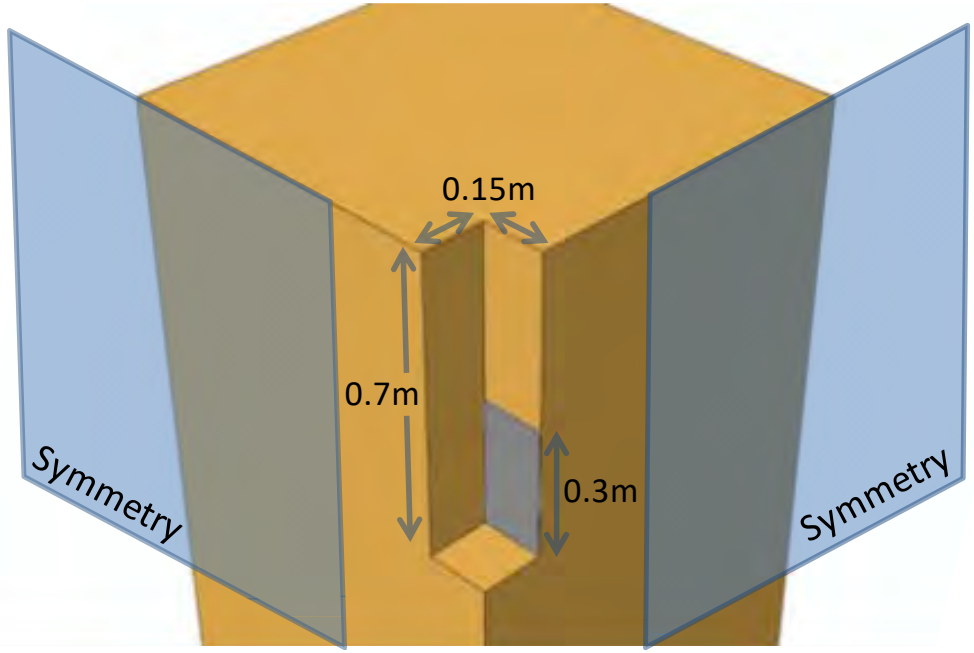


Average backbone curves



Background - Numerical Analysis – Step 1





FEA Geometry

Background - Numerical Analysis – Step 2

Step 1 – Soil Parameters

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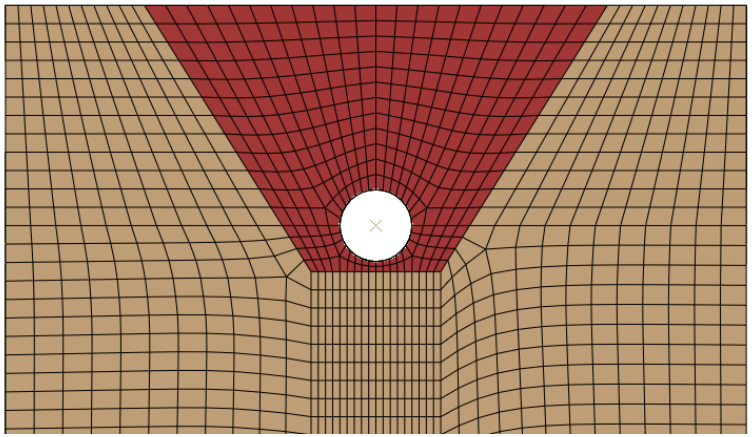
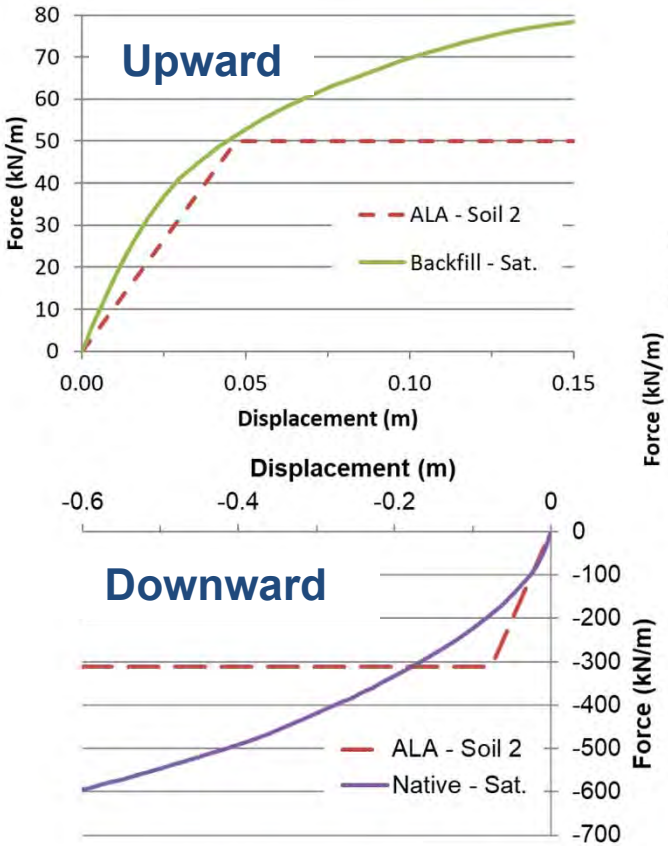
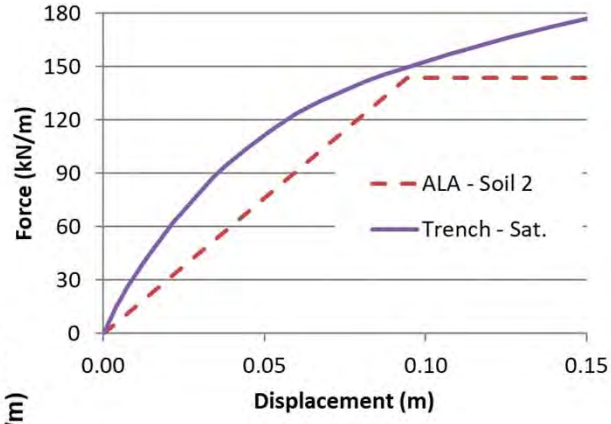
Pipe & Trench Geometry





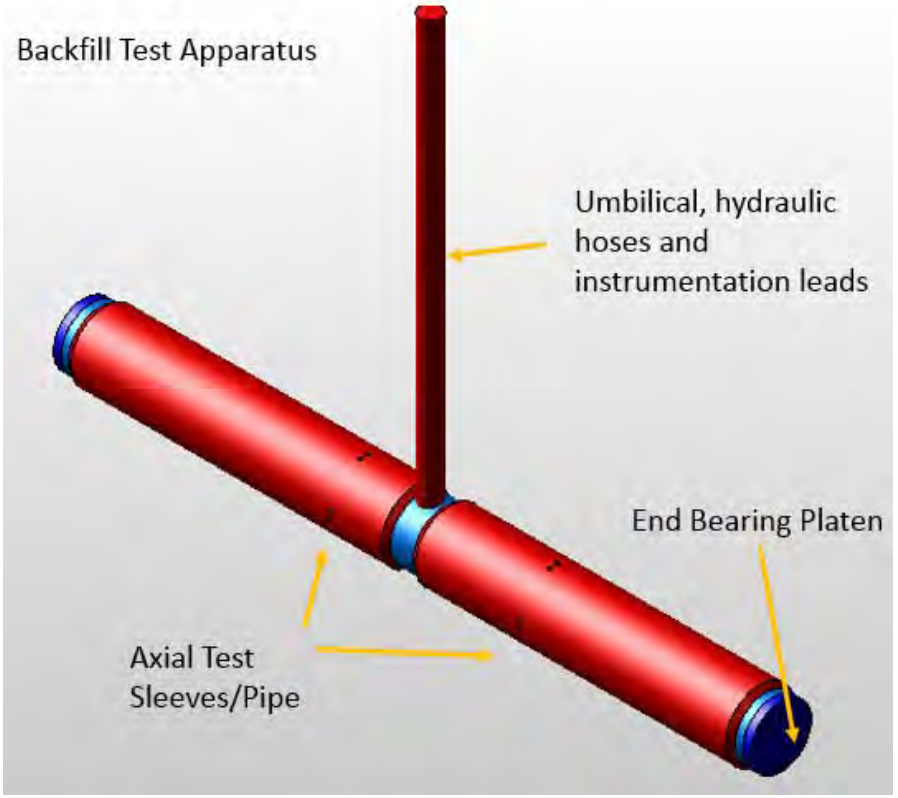
Soil Springs

Horizontal



TC Energy Project

Self-reacting 2-axis Concept

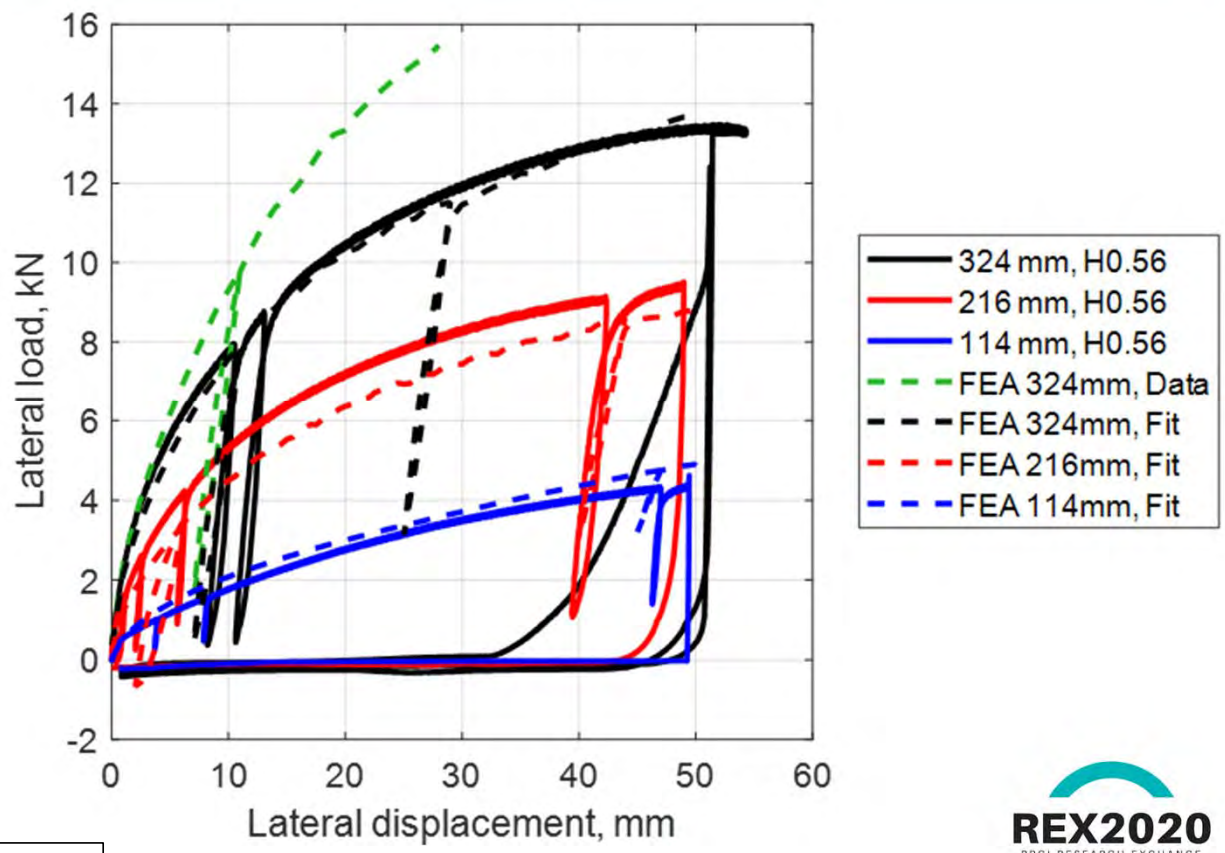


NL Field Testing



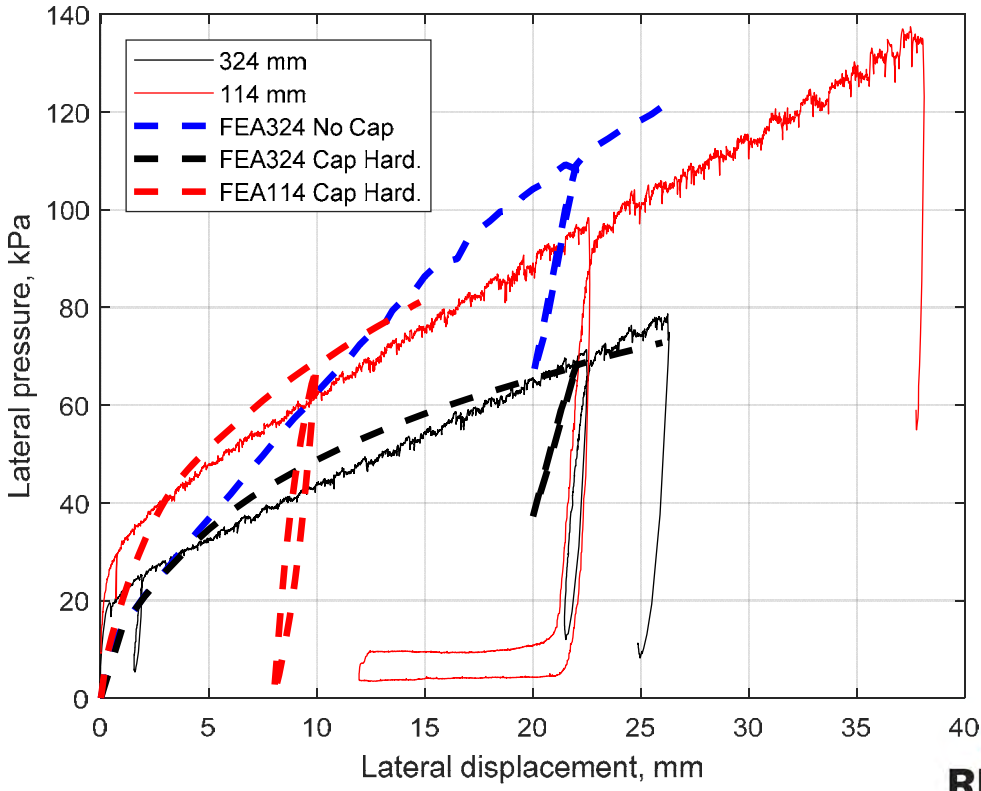
Modelling – Lab – Bearing Test





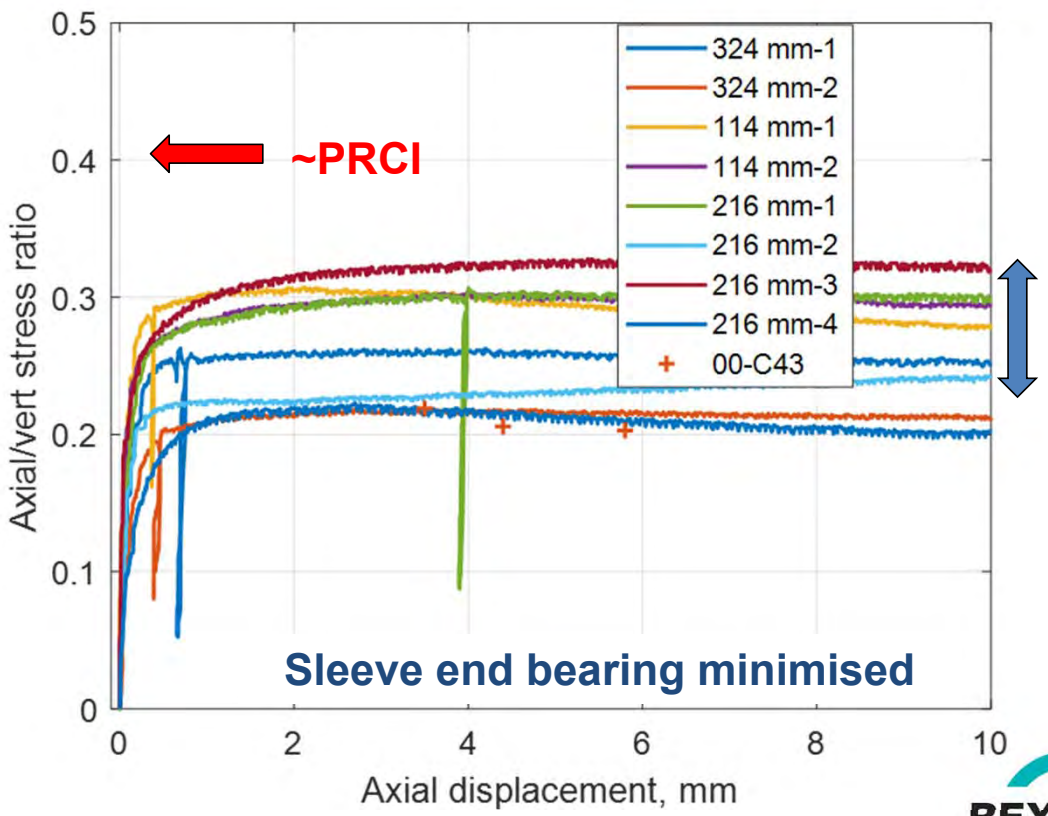
Modelling – Field – Bearing Test





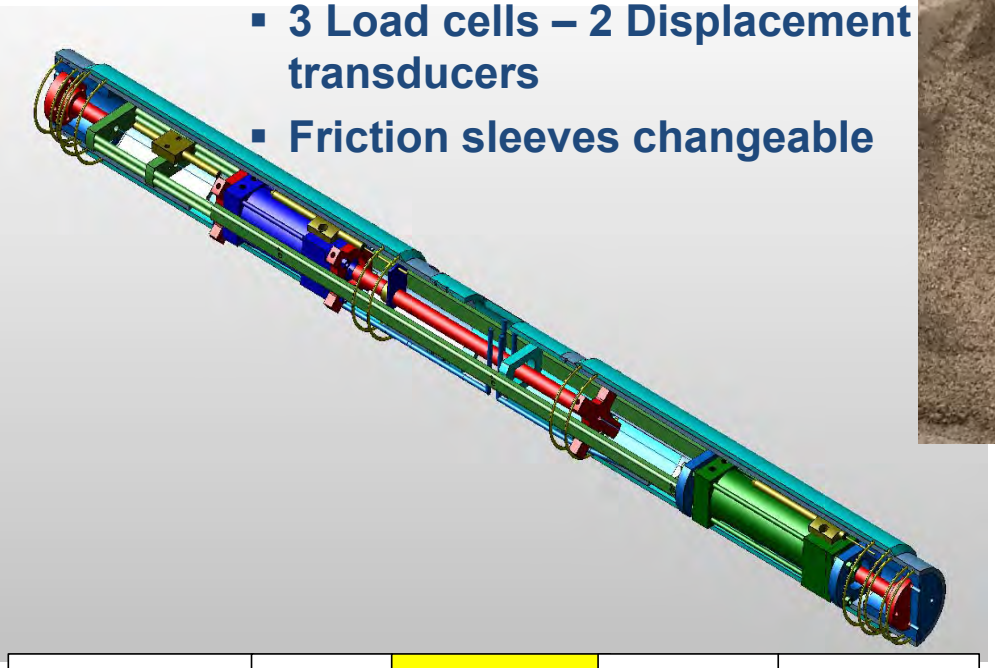
Modelling – Lab – Axial Test





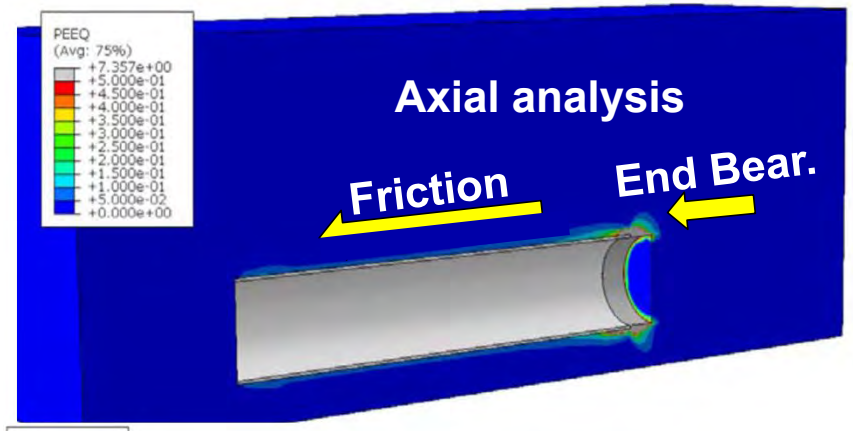
2-Axis Prototype

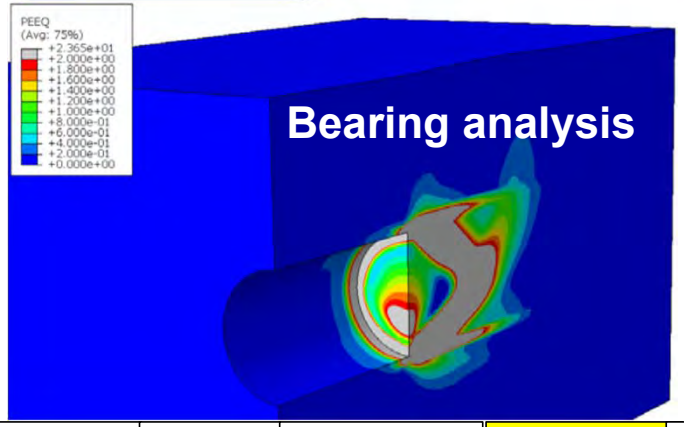
- 114 mm diameter x 1.4 m long
- 35 kg mass
- 2-axis : 2 hydraulic actuators
- 3 Load cells – 2 Displacement transducers
- Friction sleeves changeable

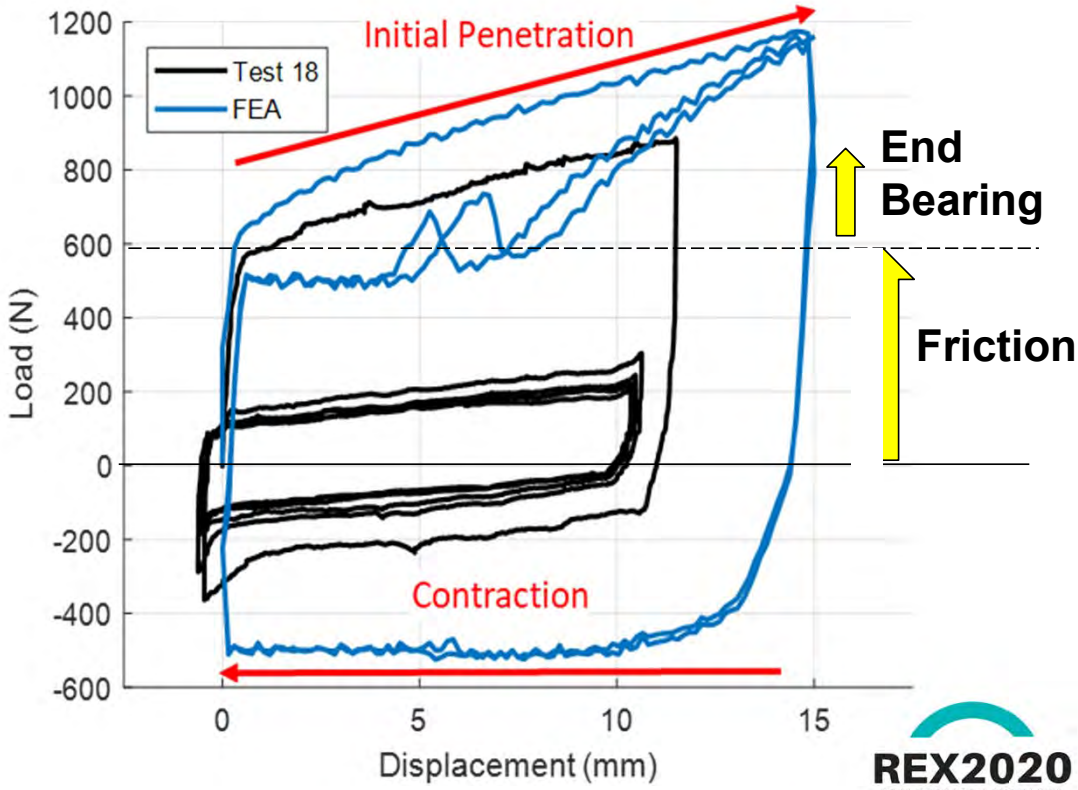




Numerical Analysis – Step 1







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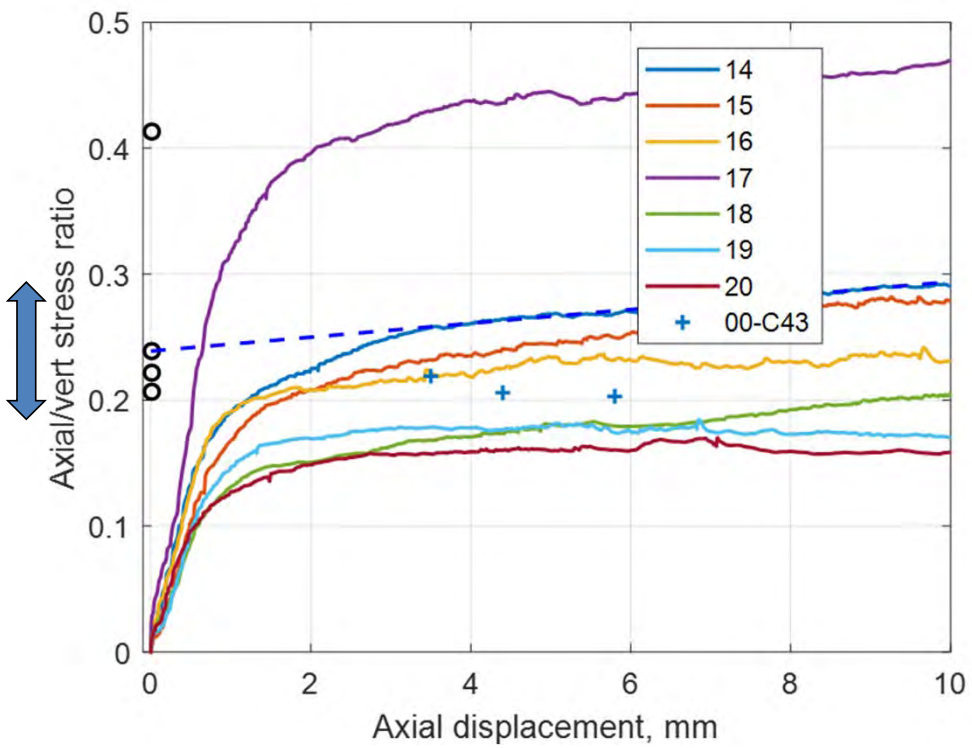
Commissioning – Lab - Axial Tests

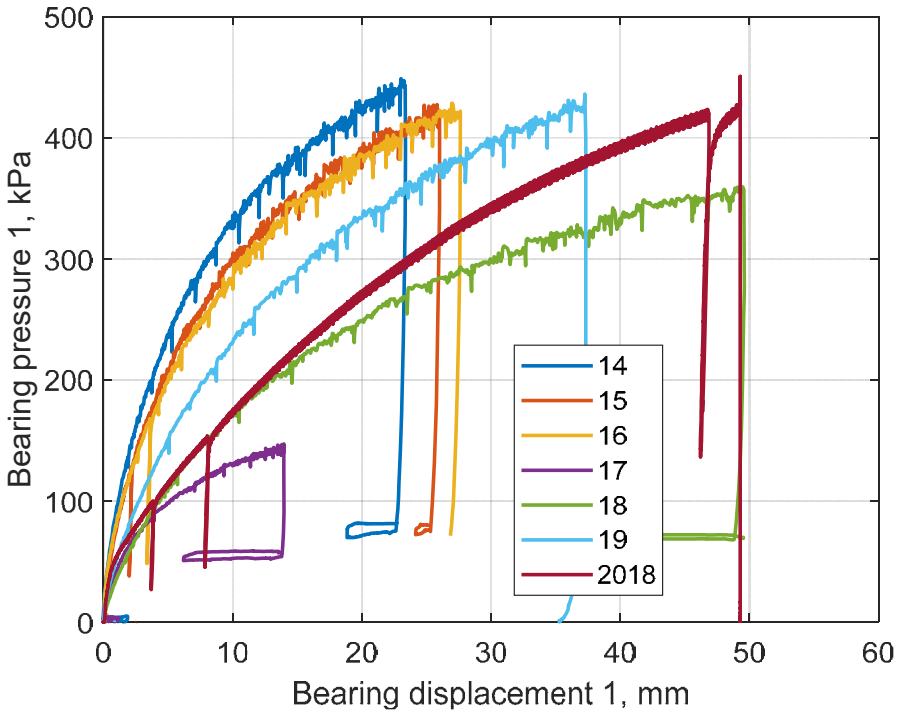
2-axis Tests

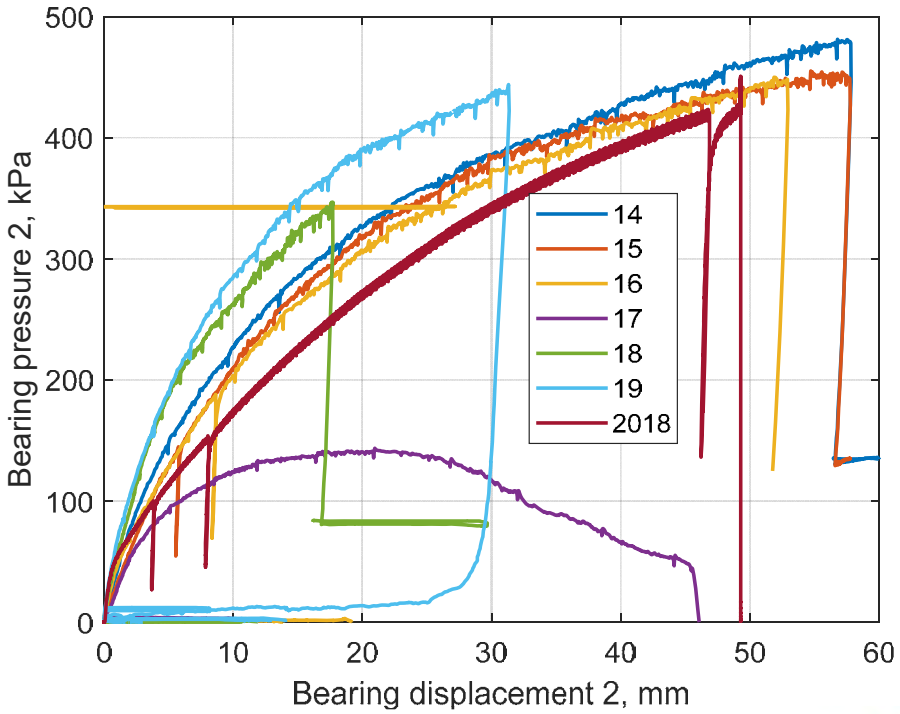


2002 JIP



Commissioning – Lab - Bearing Tests



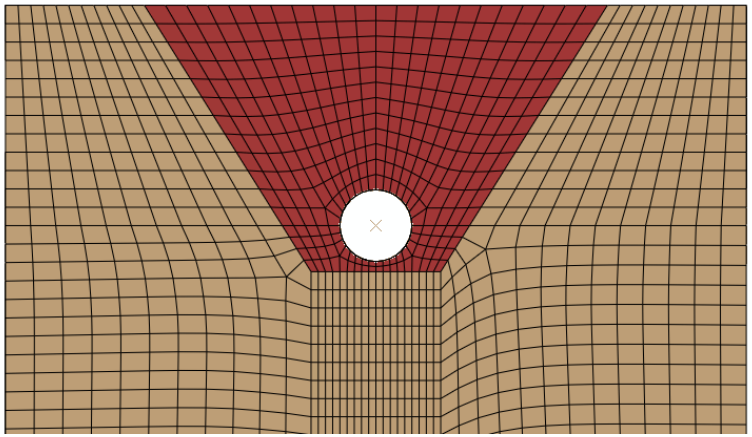


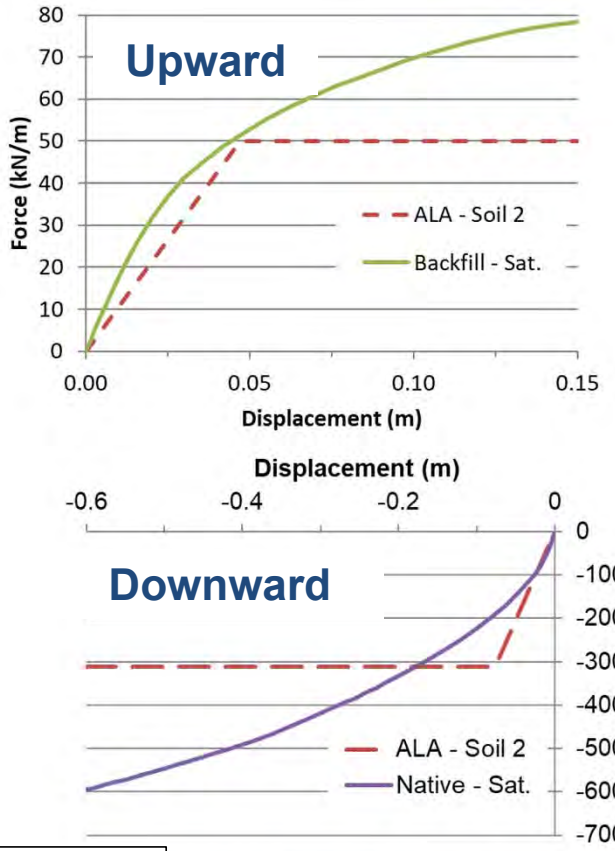
Numerical Analysis – Step 2

Step 1 – Soil Parameters

+

Pipe & Trench Geometry

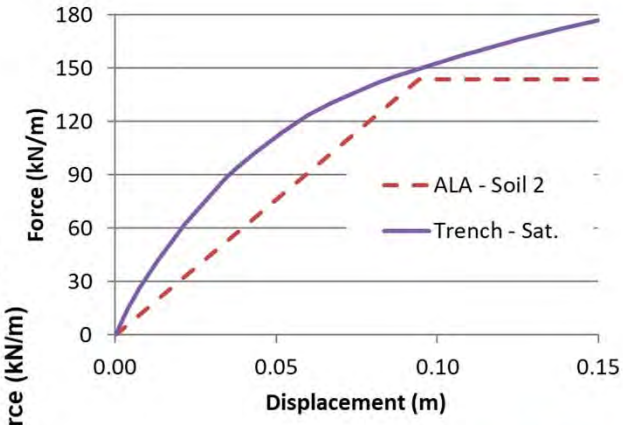




Soil Springs

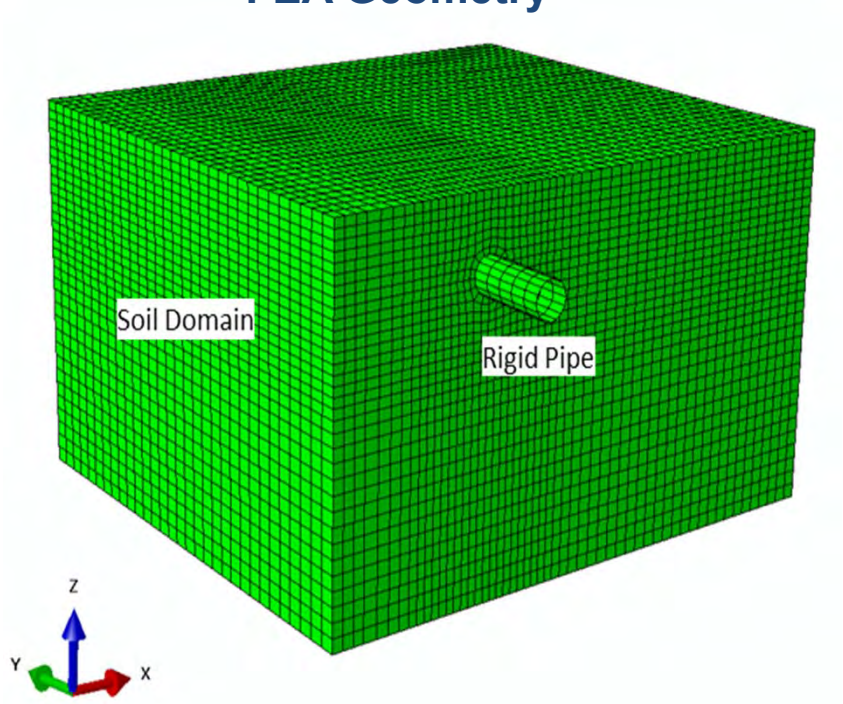
+ Axial

Horizontal

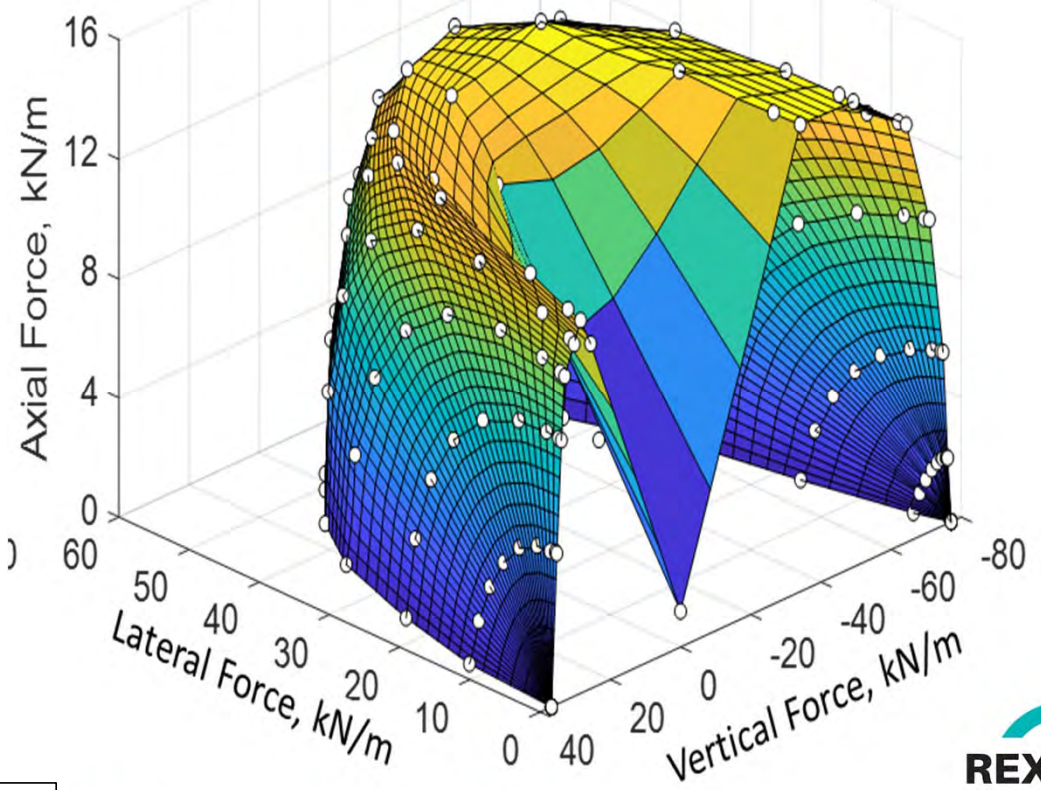


Interdependent soil springs

FEA Geometry



Soil Spring - 3D Yield Surface



- **Phillips & Barrett, IPC (2020)**

PRCI – DMC - Ballot idea 2985

Alignment: Improve models used in design of pipelines

Objective: Improved pipe-soil spring methodology based on actual field measurements.

Scope: Field testing along, or in vicinity of, 6 different pipeline RoWs.

- **Analysis of data**
- **Produce pipe soil springs, and**
- **Compare to those from existing guidelines**

- **Development of generic data database to identify new soil type - spring correlations.**

Conclusions

- New soil spring methodology developed
- 2-axis field test equipment prototype
- Design based on physical modelling under lab & field conditions, and
- Numerical modelling
- 2-step Numerical analysis of data to assess soil-springs
- Next step, field deployment

BACK TO AGENDA

PRCI 2020 Research Exchange

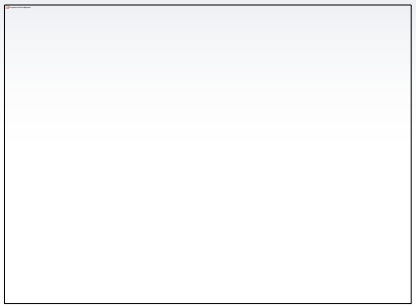
GHZ-2-03 PR-686-183908
InSAR Monitoring of Pipeline Geohazards in Vegetated and Very Large Non-Vegetated Areas

Final Results

Presenters: David Mackenzie and Kris Covey, 3vGeomatics

04 March, 2020

Prepared for the Surveillance, Operations and Monitoring Committee of PRCI



InSAR Monitoring of Pipeline Geohazards in Vegetated and Very Large Non-Vegetated Areas - Overview

Background:

- **InSAR:**
  - Satellite-based monitoring of ground displacement over large areas
  - Recent satellites and algorithms have improved InSAR's accuracy, speed, and price

Research Objectives:

- **Identify and characterize geohazards near pipelines using InSAR in two study areas with different vegetation conditions.**

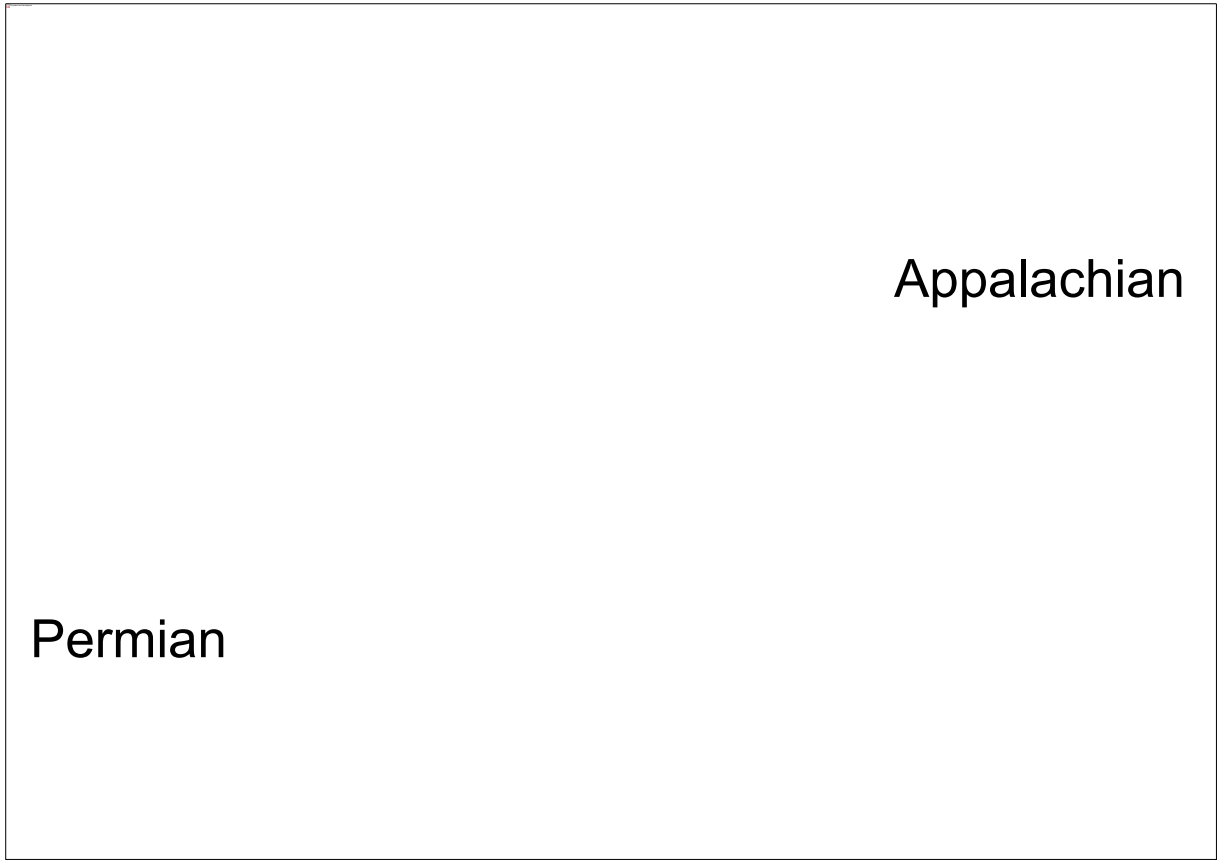
Principal investigator: Murray Down from 3vGeomatics

PRCI Project Team Leader: Patrick Fleck, from Marathon Pipe Line LLC

Value to Members

- Most useful to operators with assets covering large areas prone to geohazards where monitoring is hindered by land access, rough terrain, and lack of visible signs of displacement
- Recommendations will help operators design an effective InSAR program for identifying unknown geohazards and monitoring known geohazards

Two Study Areas



Permian Study Area

- Arid areas in Texas and New Mexico, USA
- Wavelength: 5.6 cm (short, C-band)
- Satellite: Sentinel
- Pixel spacing: 5 m x 20 m
- 80 images over 4 years
- Nov 2014 - Nov 2018

Appalachian Study Area

- **Vegetated hills in Kentucky, West Virginia, and Ohio, USA**
- **Wavelength: ~24 cm (long, L-band)**
- **625 km of member operator pipelines**
- **Satellite: ALOS-2**
  - 3 m pixel spacing
  - 19 images over 1 year
  - Sept 2018 - Sept 2019
- **Satellite: ALOS-1**
  - Pixel spacing: 10 m
  - 14 images over 4 years
  - June 2007 - Feb 2011

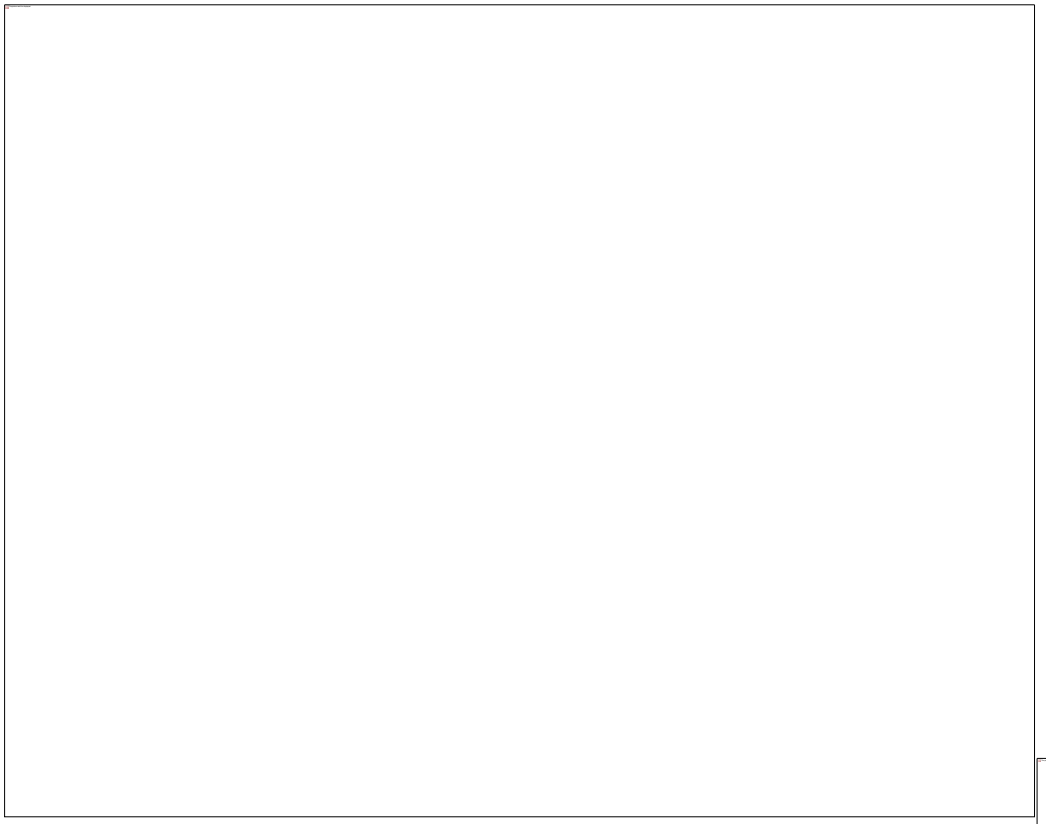
Work Performed

Advanced InSAR processing and product generation:

- **3 SAR footprints**
- **113 images**
- **44,000 square km covered**
- **26 million points with time series graphs**
- **Error analysis with SNR contours highlighting significant displacement areas**
  - Including 135 SNR contours within 500 m of member operator ROWs

Permian Sentinel Results

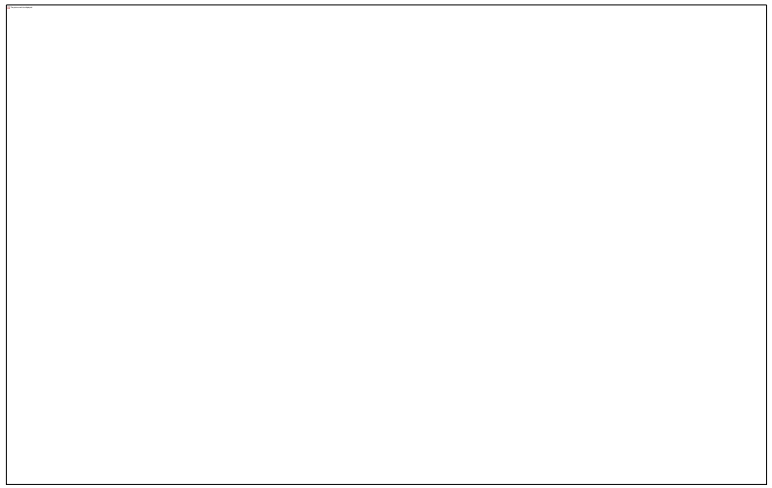
- Time series for 13,545,394 points
- Analysis covering 250 x 188 km



Permian Sentinel Results

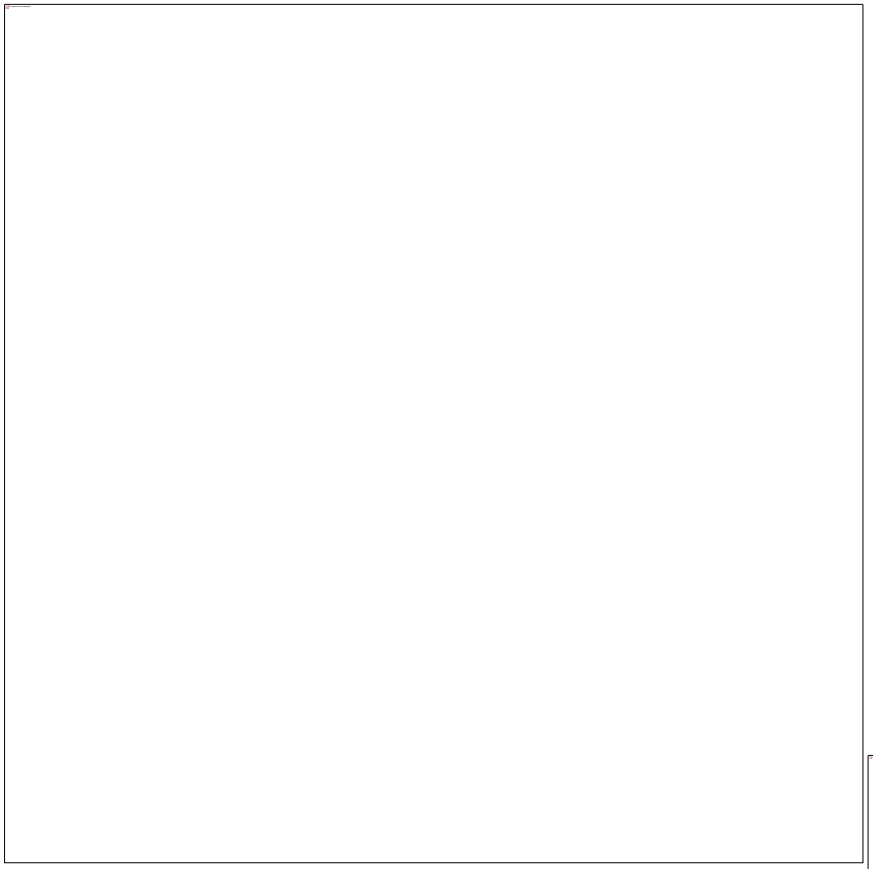
Delivery formats:

- ArcMap Databases with 3vG toolbar
- KMZ summary for high level overview in Google Earth



Appalachian ALOS-2 Results

- Time series for 12,591,882 points
- Analysis covering 50 x 68 km



Appalachian ALOS-2 Results

Primary format: database with 3vG ArcMap toolbar for analysis of all 12,591,882 points



Signal to Noise Ratio (SNR) Analysis

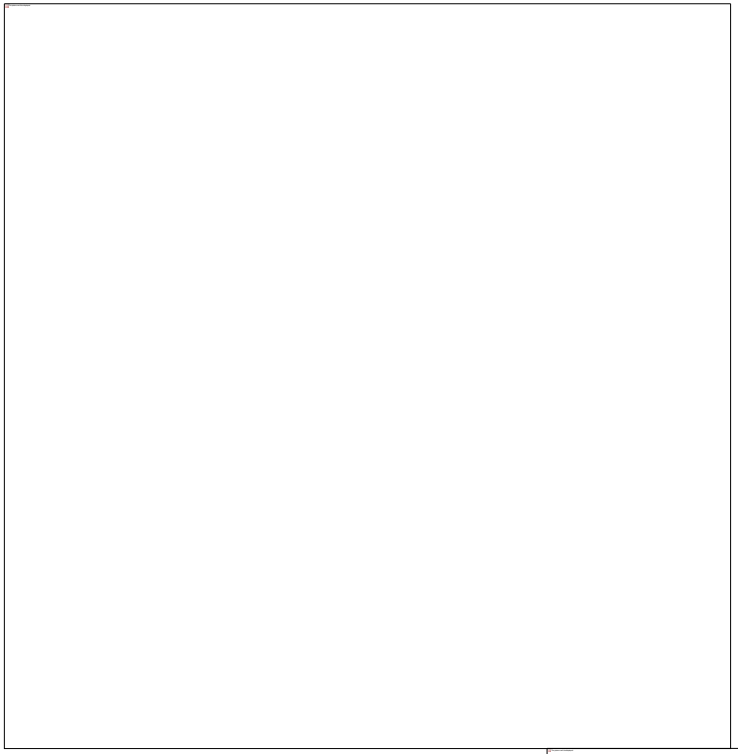
- **Highlights significant displacement areas**
- **Varies spatially for a set period of time**
- **Threshold contours at three levels:**
  - SNR 4.0 sigma: strong evidence for displacement,
    - *Low chance of anomaly being caused by noise alone*
  - SNR 3.0 sigma: reasonable evidence for displacement
  - SNR 2.0 sigma: weak evidence for displacement
    - *Should be treated with caution*

$$\text{SNR} = \left| \frac{\text{displacement signal}}{\text{measurement noise}} \right|$$

Signal to Noise Ratio (SNR) Analysis

- **SNR ≠ rate threshold**
- **Should be interpreted in conjunction with rate**
  - Noisy strong displacement and clear subtle displacement can produce the same SNR level
- **SNR analysis requires rate coverage**
- **Noisy areas have higher detection threshold**

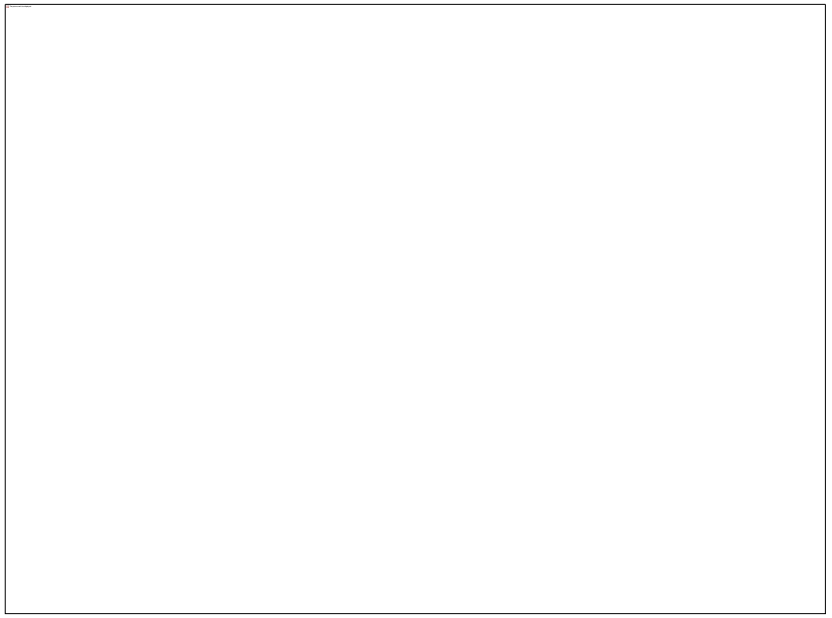
- **Within Appalachian study area:**
  - 95 areas of SNR 4.0
  - 252 areas of SNR 3.0
  - 905 areas of SNR 2.0
    - *135 areas of SNR 2.0 within 500 m of member operator ROWs*

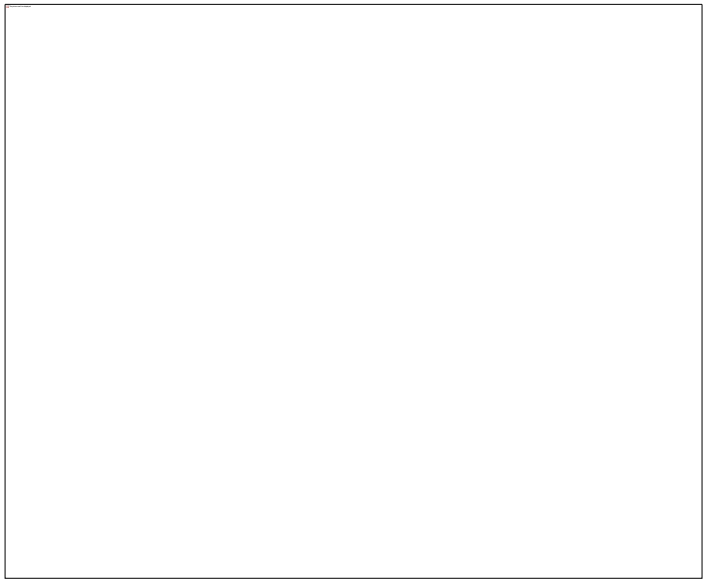


Appalachian ALOS-2 Results

Secondary format: KMZ product

- Lightweight version of results for non-technical users
- Only 15,000 time series points (clustered more densely within contours)
- Custom version focused on client-specific ROW buffer can be produced





Ground-Truth Verification

PRCI member operators verified InSAR with:

- In-Line-Inspection
- Surveying
- Lidar
- Visual signs of displacement

LOS Considerations For Ground-Truth Verification

InSAR underestimates the actual displacement magnitude, because it only captures the component that is along the LOS

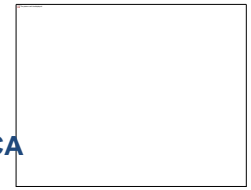




Block slide illustration from USGS

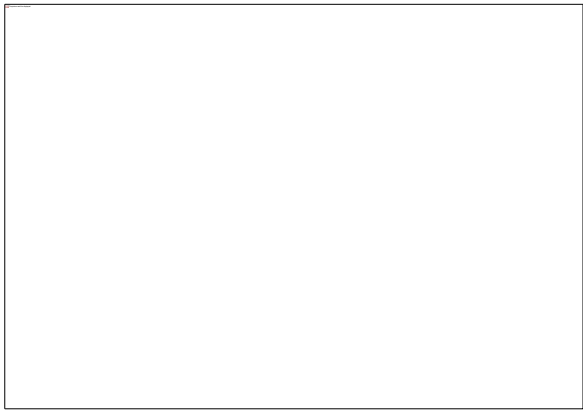


Translational slide illustration from USGS



LOS Considerations For Ground-Truth Verification

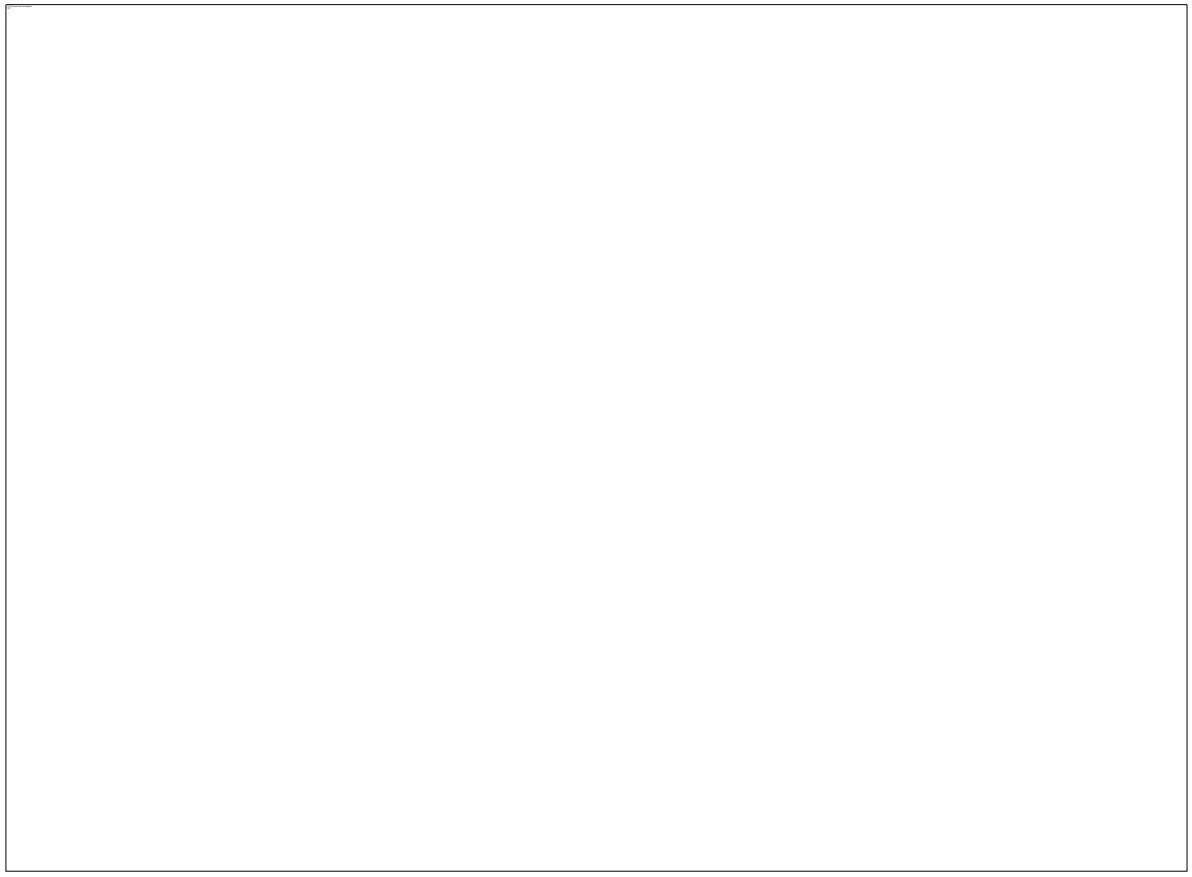




Rotational slide illustration from USGS

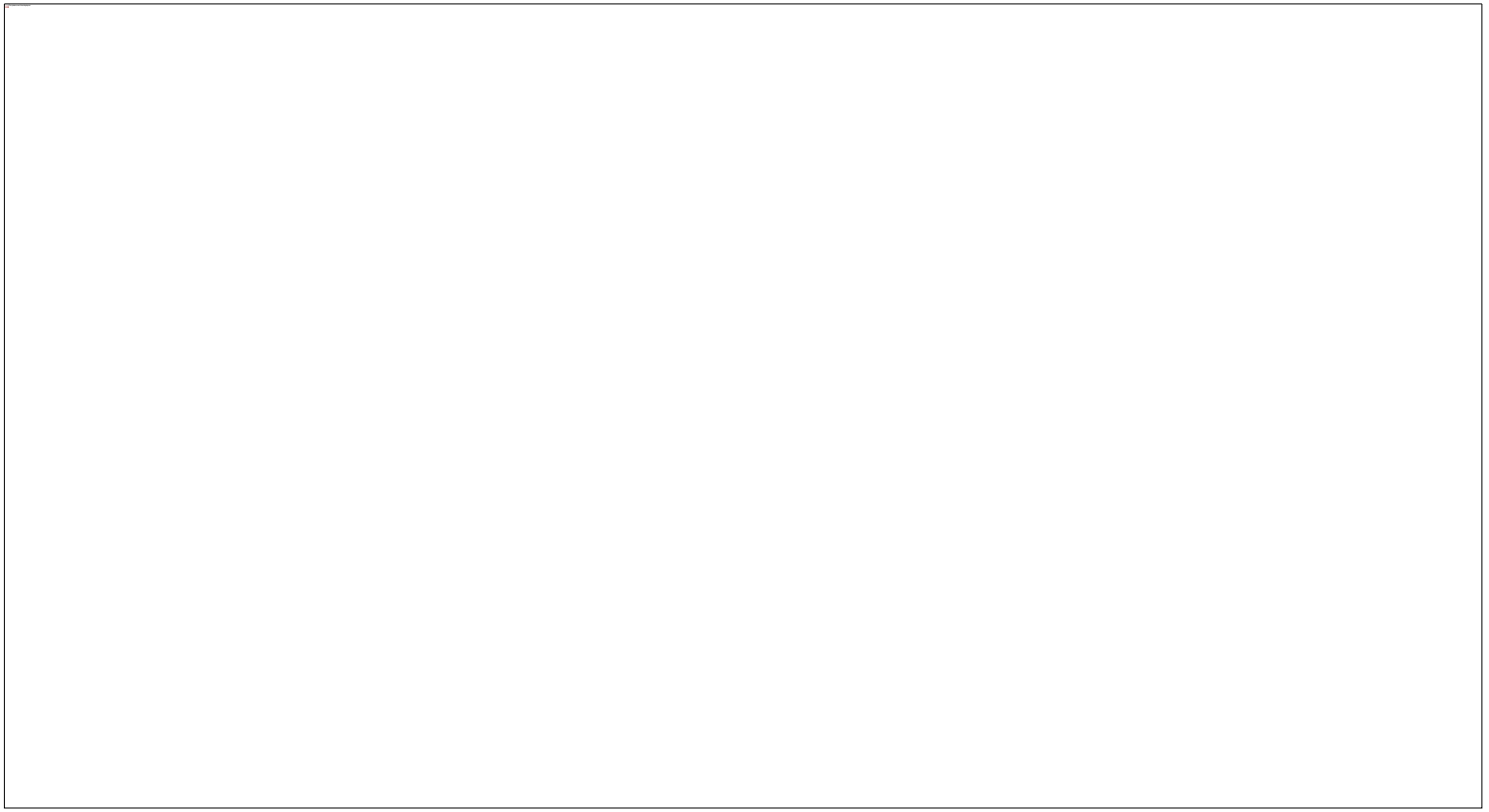
- Likely rotational slide measured from east-looking satellite LOS.
- Displacement towards the sensor is blue.
- Displacement away from the sensor is red.

Ground-Truth Verification: In-Line-Inspection



Displacement rate with SNR contours outlined in white. Member Operator's centerline is shown in black with confirmed ILI strain locations indicated by two stars.

Ground-Truth Verification: In-Line-Inspection



ArcMap product screenshot with graph of displacement from a selection of points near a strain location identified by ILI.

Ground-Truth Verification: ILI



Google Earth view of SNR contours (white), displacement points, centerlines (black), and ILI strain locations (yellow pins).



Aerial photograph of the same location from November 2019.

Ground-Truth Verification: Surveying

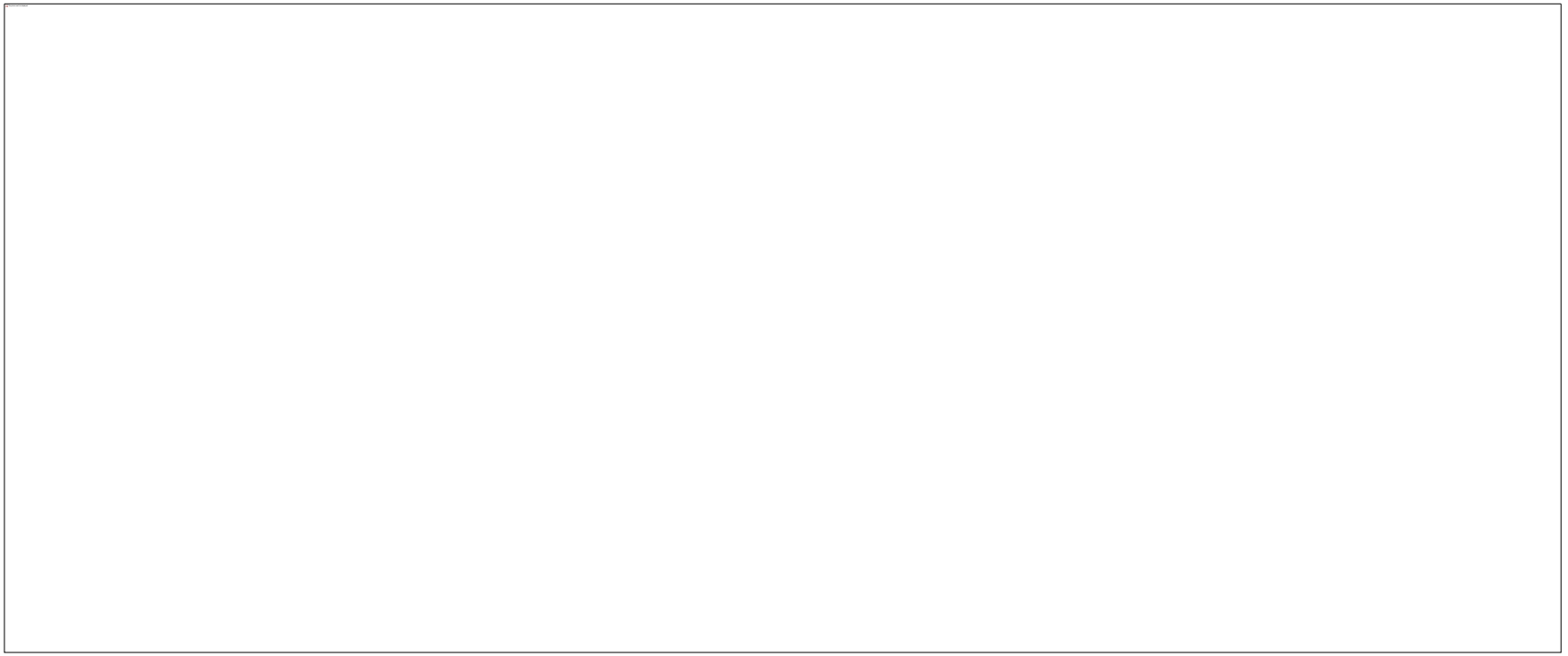


ArcMap screenshot with graph of displacement area (denser points in bottom left) which was also surveyed



Timeline of surveying (red) and InSAR (blue)

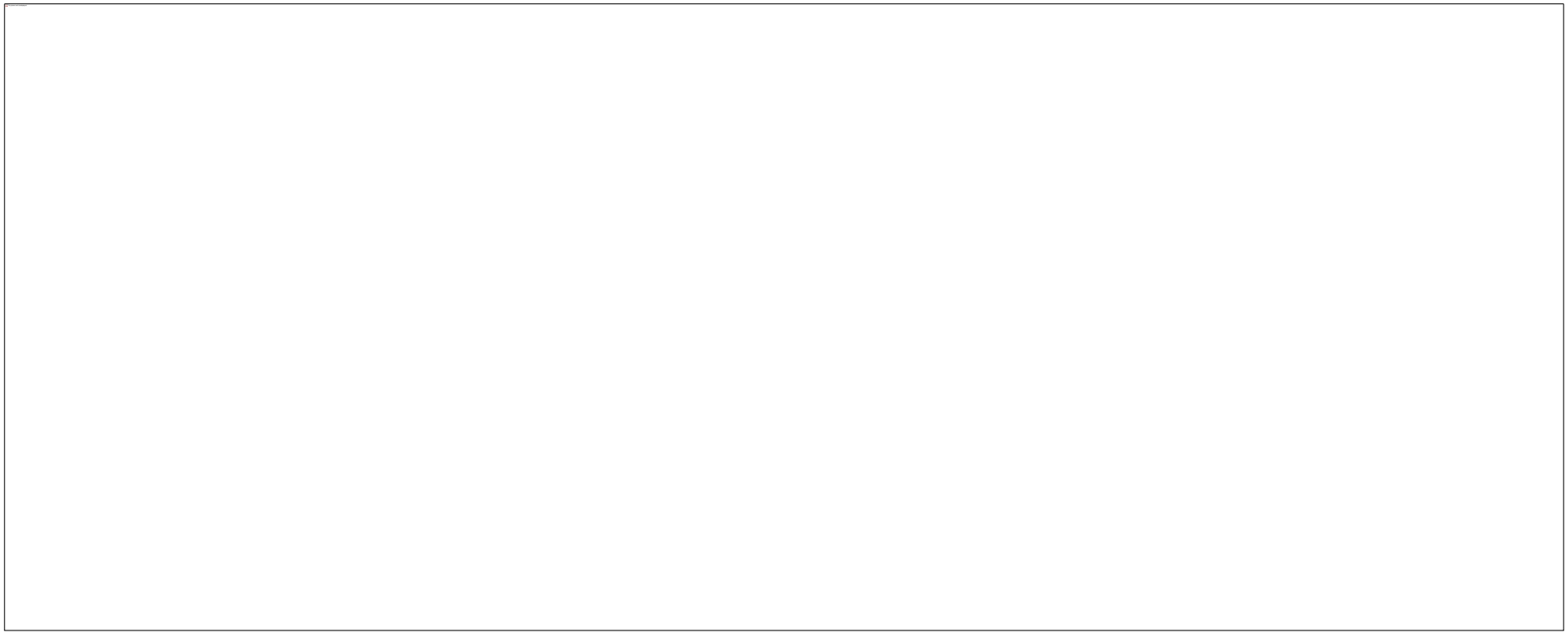
Ground-Truth Verification: Surveying



Selected InSAR points in cyan

Projection of displacement from survey point 03 (red line) compared to average InSAR displacement (blue line).

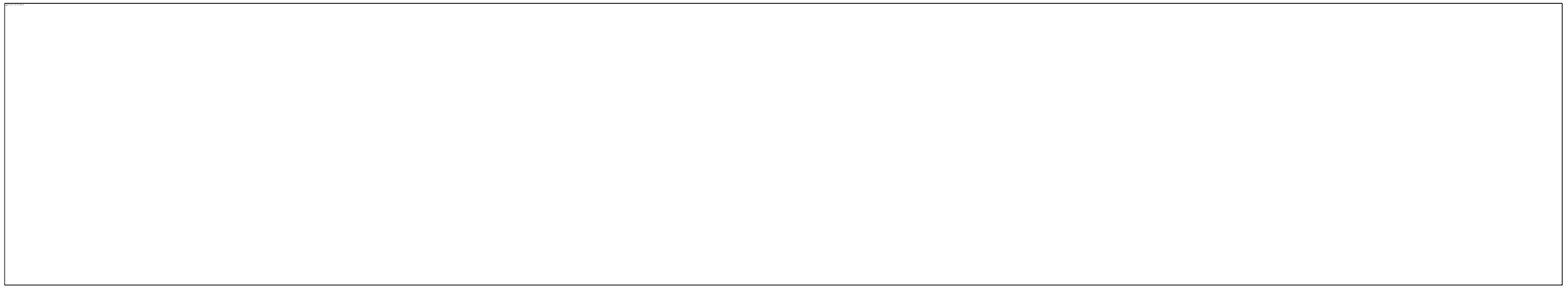
Ground-Truth Verification: Surveying



Selected InSAR points in cyan

Projection of displacement from survey point 06 (red line) compared to average InSAR displacement (blue line).

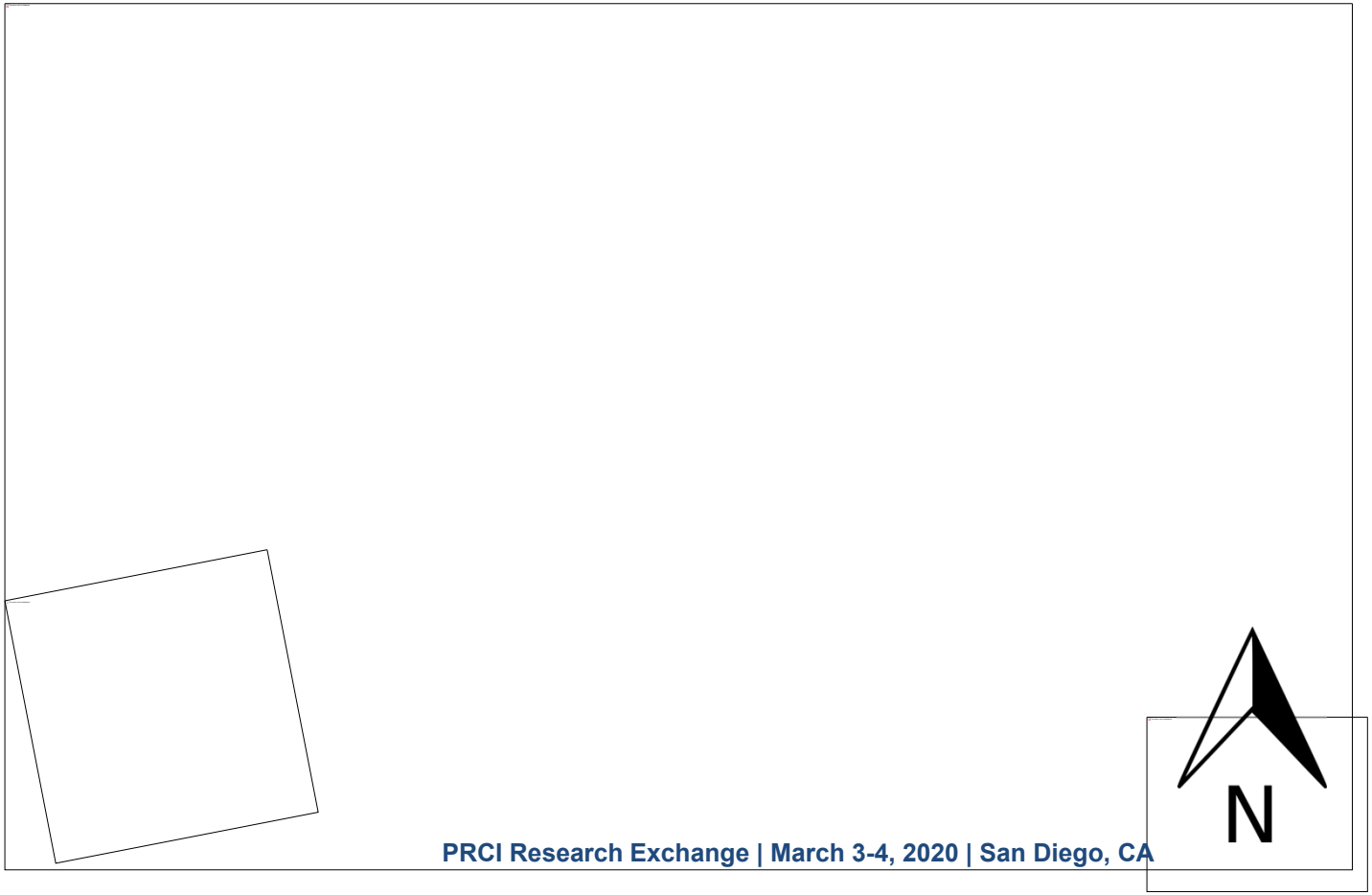
Ground-Truth Verification: Lidar



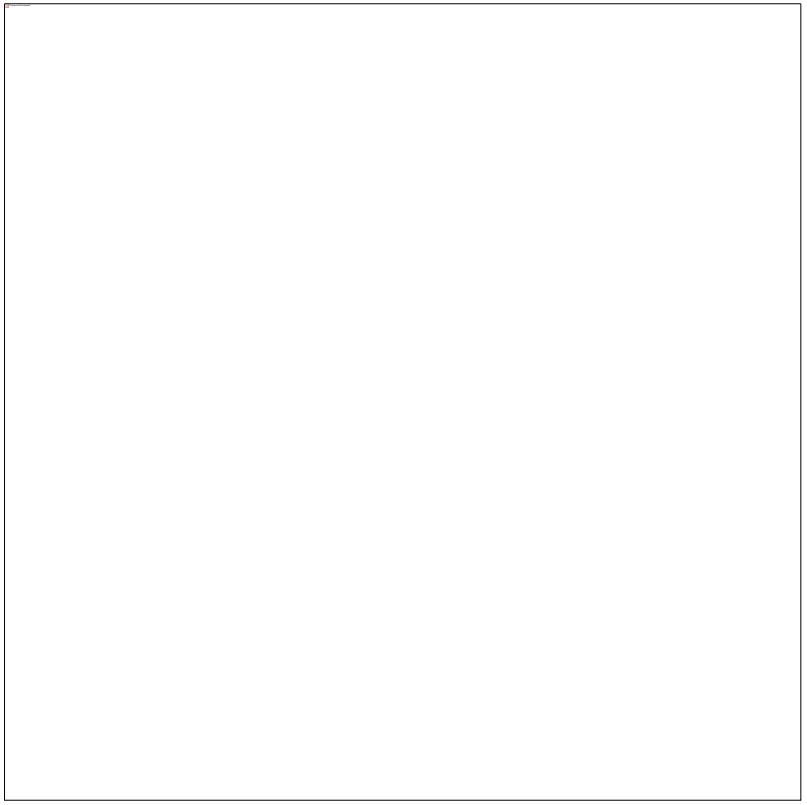
Only two lidar passes were acquired (red), yielding only one change detection period between March 2018 - March 2019.
The 19 InSAR image dates (blue) overlap the lidar change detection period by ~6 months.

Ground-Truth Verification: Lidar Example

- Direct overlap of lidar change detection area (black angled line fill) with SNR contours (white lines)
- Positive displacement area (towards sensor) moving westward



Ground-Truth Verification: False Positives



- PRCI member operator conducted detailed comparison to LiDAR, field recon and geomorphological evidence for 20 areas of SNR 2.0 or greater near their ROW
- Out of these 20 areas, only two were unlikely related to geohazard ground displacement
- One of these false positives (left image) is likely caused by strong changes in water content associated with wet, boggy ground

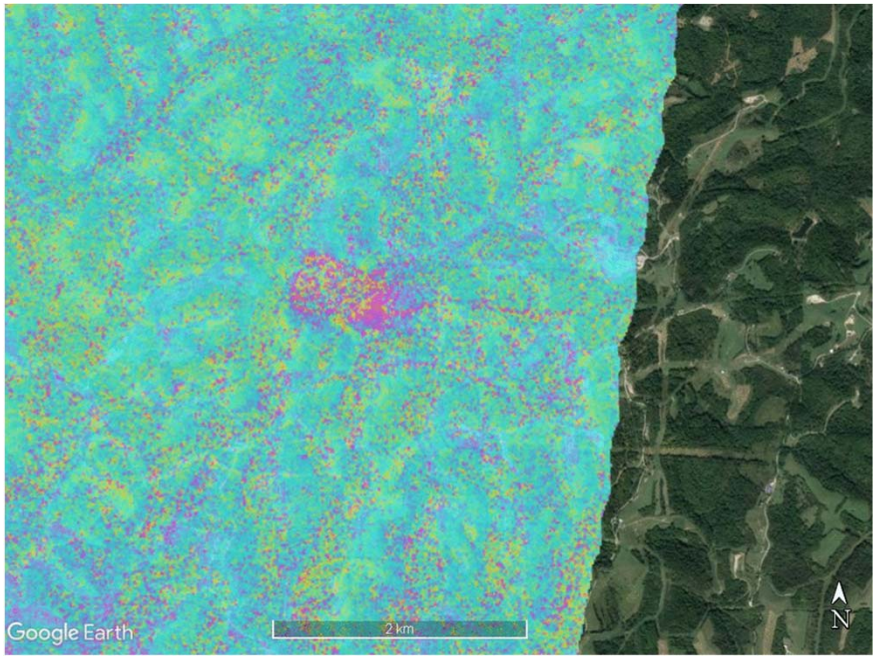
Ground-Truth Verification: False Negatives / Data Gaps



- **Field analysis identified several areas where displacement was identified by lidar, surveying, or visually, but not by InSAR**
- **Potential causes:**
  - Slow displacement below noise floor of L-band sensor
  - No data coverage due to:
    - *Layover or shadow*
    - *Surface disturbance such as digging or dumping*
  - Too small. Area threshold for ALOS-2 is around 25m x 25m
- **Most false negatives can be resolved by either:**
  - Second look-direction
  - Continuous multi-year image acquisitions

Long-Wall Mining

- InSAR detects subsidence from underground mining
- Migrating subsidence areas are tracked over time



20190813

20190924

20191022

Recommendations

	Wavelength Band	**Low Resolution** Suited to: Background/Reconnaissance	**High Resolution** Suited to: pipeline integrity monitoring
Arid Regions (e.g. Permian)	X- or C-Band (2-6cm)	Sentinel-1 (20m res.)	TerraSAR-X, COSMO-skymed (3m res.)
Vegetated Regions (e.g. Appalachians)	L-Band (~23 cm)	[NISAR, 2022+]	ALOS-2 (3m res.)

- **L-band InSAR (e.g. ALOS-2) for vegetated areas susceptible to landslides**
- **X-band or C-band to monitor pipelines for small (<100m) geohazards in arid regions**
- **Continued image acquisitions and analysis to provide multi year datasets for enhanced displacement detection threshold and improved capacity to differentiate signals**
- **Second look direction if available for dual-look analysis**
- **Sharing data acquisition costs between operators with assets nearby**

Value to Members/Knowledge Transfer

Target audience: Operators of pipelines covering large areas prone to geohazards

- **Operations managers**
- **Geohazard teams**
- **Planners of new pipeline routes**

Value:

- **InSAR, an emerging technology, has been demonstrated as an effective tool for monitoring ground displacement across wide areas**
- **InSAR has been validated against traditional monitoring tools and shown to be effective in identifying and monitoring threats to pipeline integrity**
- **Recommendations presented here will help operators design effective InSAR monitoring programs for pipeline networks in both vegetated and arid settings**

Phase 2

Continue ALOS-2 image acquisitions for 2nd year over Appalachia

- **Model longer-term trends to improve filtering and statistics**
- **More reliably identify subtle ground creep and seasonal cyclical displacement patterns (e.g. freeze/thaw, seasonally correlated precipitation events)**

Monthly reports starting spring 2020

- **Fast actionable measurements covering the latest 70-day period**

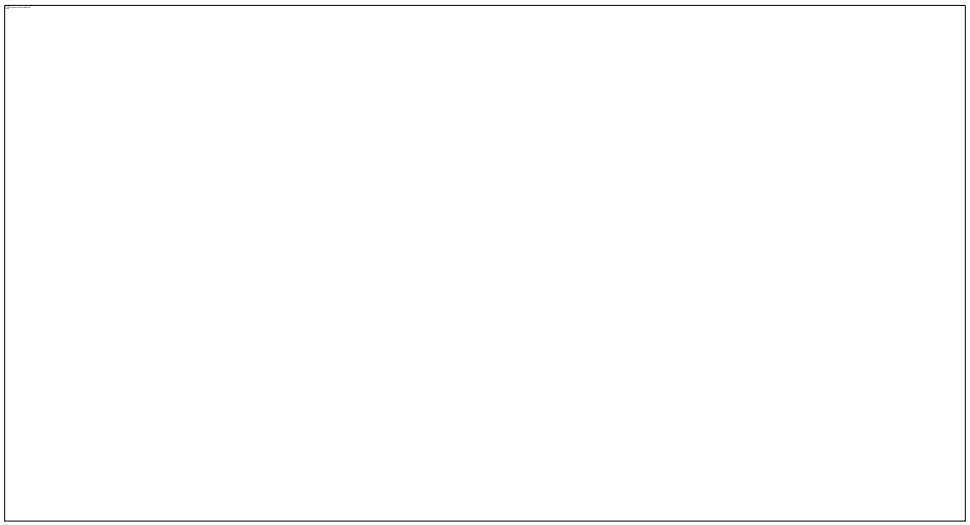
Evaluate SAR amplitude and coherence change detection techniques

- **Potential to identify new construction activity near ROW**

Motionary2

3vG's internally developed web-based platform for InSAR results

- Accessible: Through web browser anywhere with internet connection
- Simple: No FTP, no software, no licenses, minimal training
- Customizable: Change units, rate scale, import other data overlays
- Automated: Updated by 3vG after new measurements
- Scalable: From pilot projects to continent-wide pipeline networks



Conclusions

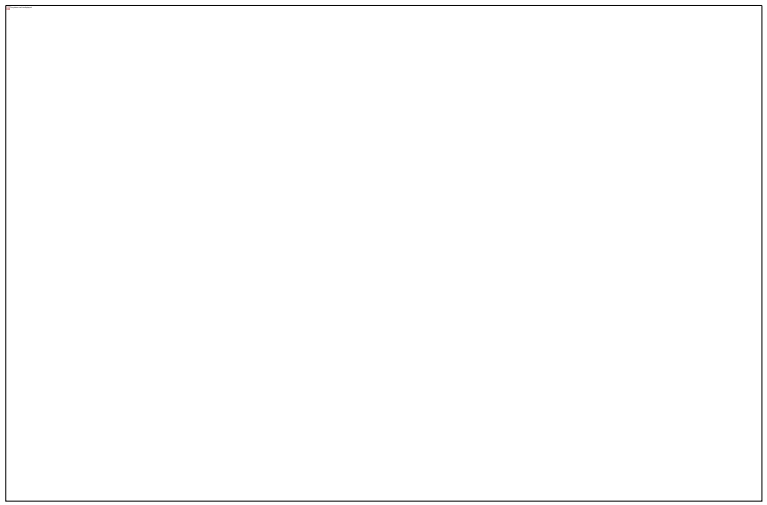
- **InSAR is an effective tool to:**
  - Identify unknown geohazards
  - Monitor known geohazards
  - Cover vast pipeline networks in both vegetated and non-vegetated terrain
  - Provide updates as frequently as every 14 days without any need for on-site instrumentation, human site visits, or aircraft
  - Identify locations for ground instrumentation, field verification and maintenance programs
  - Design and plan routing for new pipelines
  - Detect and track subsidence caused by longwall mining or fluid extraction

Appendix: Future Satellite Options



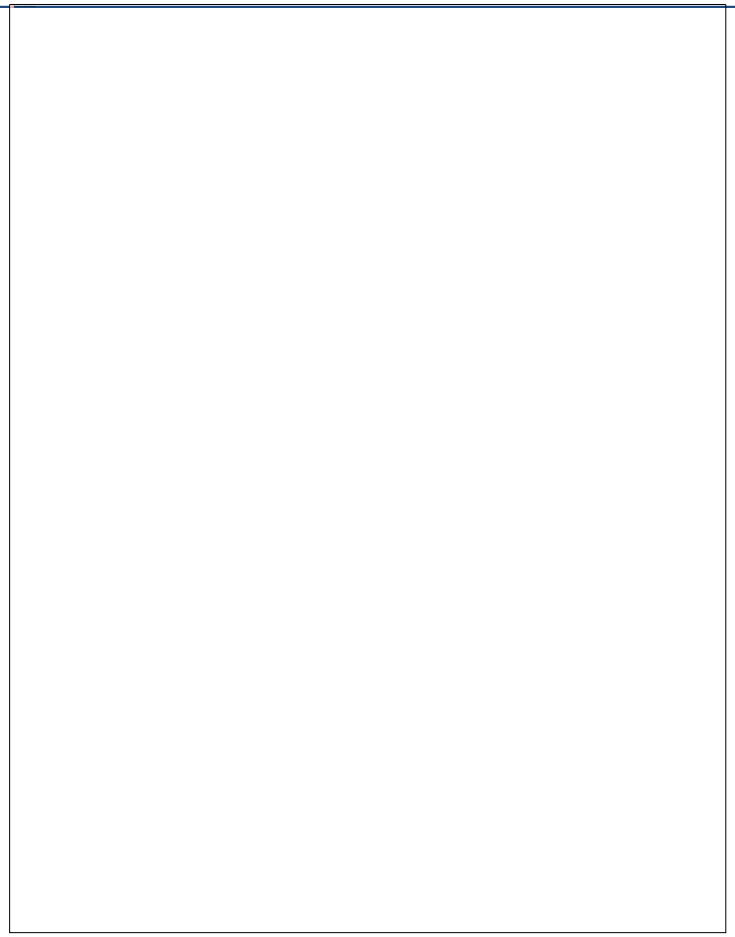
Appendix: Future Satellite Options - ALOS-4

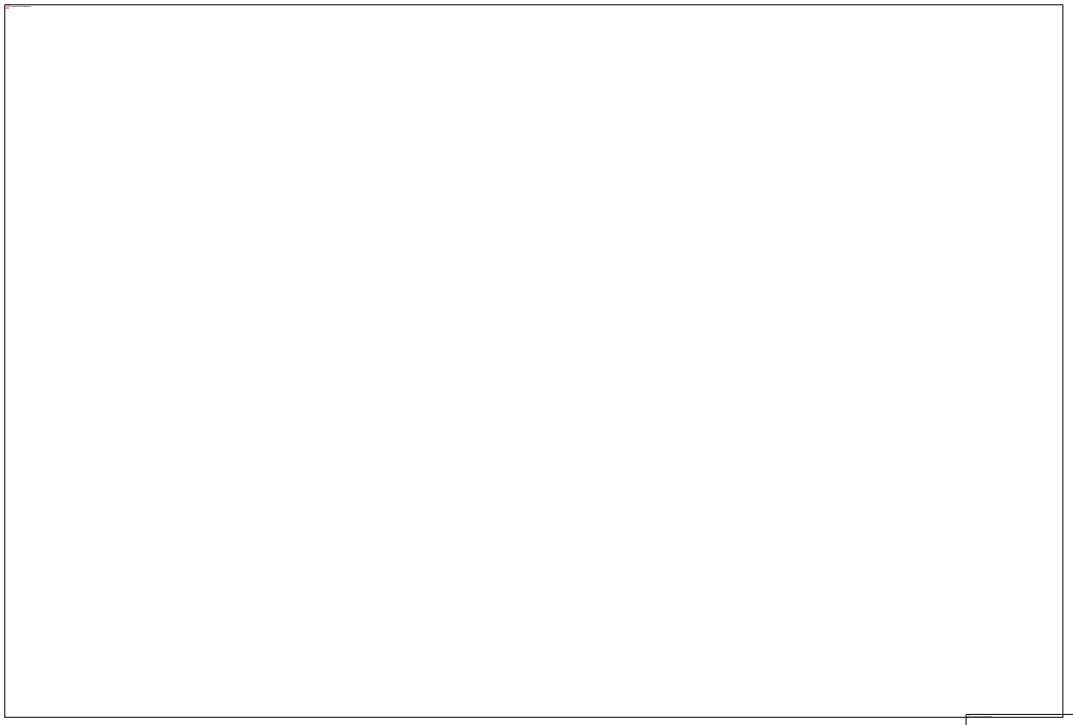
- Successor to ALOS-2
- Same wavelength (24 cm) and max resolution (3m) as ALOS-2
- 200 km swath width
- Compatible with ALOS-2 images for long-term analysis and redundancy
- Launch: ~2021
- Design life: 7 years





Appendix: Appalachian InSAR Coverage





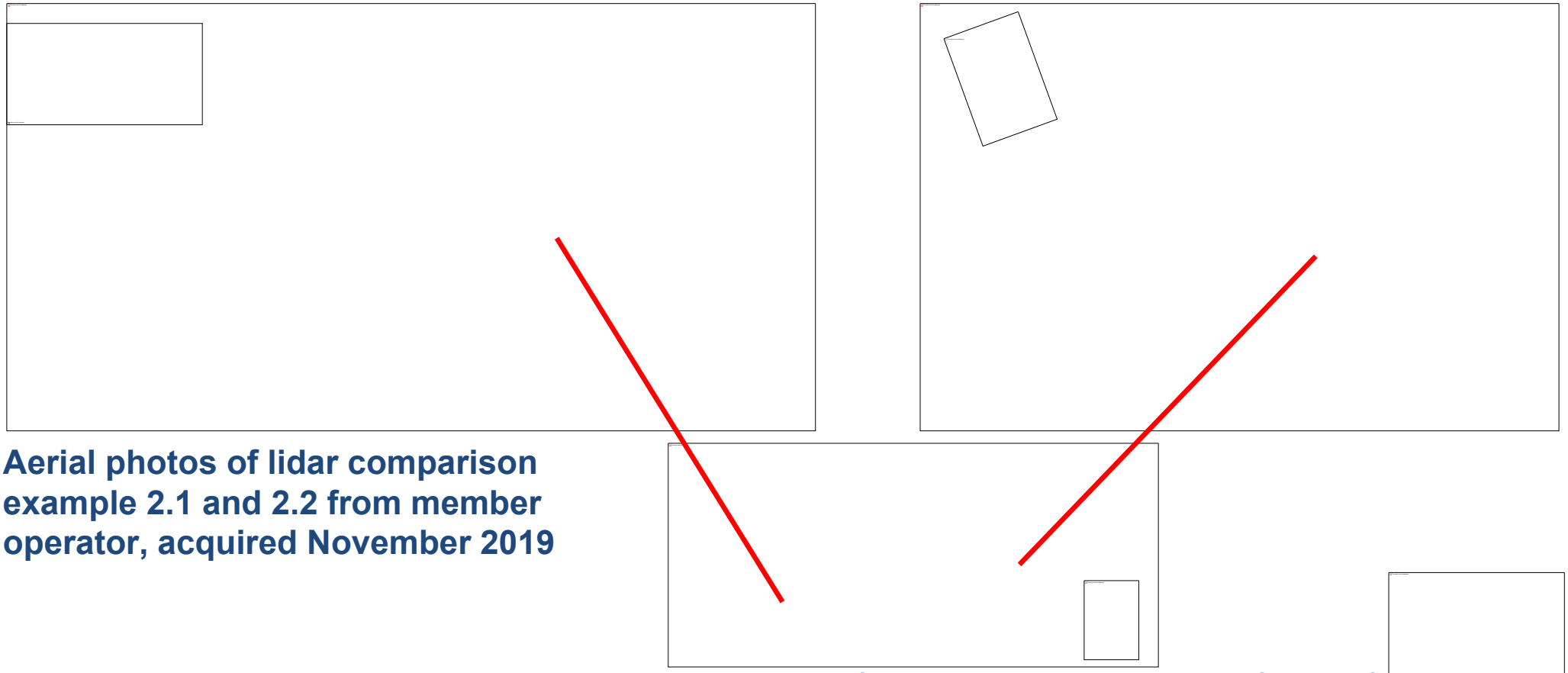
Ground-Truth Comparisons: Lidar Example 2

- No direct overlap of SNR contours (purple) with lidar change contours but very close (~10 m) to lidar at location 2.1
- Additional nearby displacement area (2.2) identified by InSAR and confirmed by inspection, but not identified by lidar



Ground-Truth Comparisons: Lidar Example 2

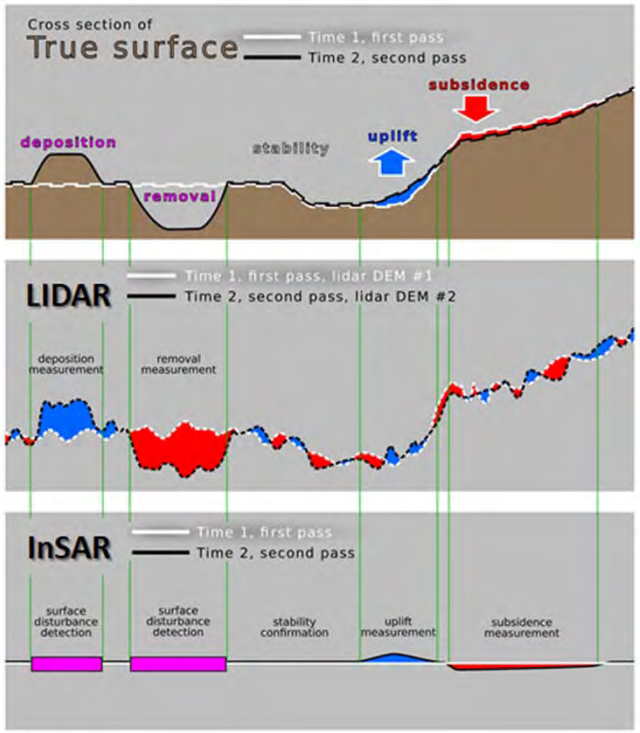
Ground-Truth Comparisons: Lidar Example 2



Aerial photos of lidar comparison example 2.1 and 2.2 from member operator, acquired November 2019

Appendix: LiDAR Vs InSAR

- LIDAR is ideal for creating periodic Digital Elevation Models (DEMs), and can be used for elevation change detection
- InSAR is ideal for change detection and monitoring displacement, but is not well suited for creating accurate DEMs
- InSAR can more cost effectively measure large areas more frequently without complexities/costs of aircraft



BACK TO AGENDA

PRCI 2020 Research Exchange

Life-Cycle Management of Geohazards for Pipelines

Yong-Yi Wang
Center for Reliable Energy Systems

LEADING PIPELINE RESEARCH

Overview

- **Why this topic?**
- **Life-cycle management**
  - Technical
    - *Management of hazards*
    - *Fitness-for-service assessment*
  - System-wide for our industry
- **Example of integrated approach**
  - Response after a ground movement event
- **Gaps and system-wide improvements**
- **Concluding remarks**

Why This Topic?

- **Management of geohazards is expensive.**
  - There are no quick and easy answers.
  - Each circumstance is different.
- **These problems can't be effectively solved by any one traditional technical discipline.**
  - Geotechnical engineer
  - Pipeline integrity engineer
  - Welding engineer
- **Evolving conditions not recognized by the industry**
  - Linepipe
  - Welding
- **Many problems go beyond technical solutions.**

Why This Topic?

- **Entire eco-system**
  - Industry-wide
    - *Codes and standards*
    - *Regulations*
  - Company wide
    - *Division of responsibilities among different departments*
    - *Profit centers*
  - Technical
    - *Geotechnical engineers*
    - *Pipeline integrity engineers*
- **Many problems can be solved more effectively if**
  - We don’t kick the cans down the road.
  - Spend a bit more upfront, rather than having to spend a lot later
  - Better link between service conditions and design requirements

Ultimate Objective – Safety and Integrity of Pipelines

- **Near- and longer-term goal**
  - Assess the health of the pipeline at the moment
  - Maintain integrity for the future
- **Fitness-for-service assessment**
  - Safe condition

$$\varepsilon_d \text{ (strain demand)} \leq \varepsilon_d^L \text{ (strain demand limit)}$$

$$\varepsilon_d^L = f \text{ (safety factor)} \times \varepsilon_c \text{ (strain capacity)}$$

- **Factors affecting assessment**
  - Strain demand
  - Strain capacity
  - Strain demand limit (safety factor)
  - Impact level
- **Consider hazards (strain demand) and pipeline conditions (strain capacity) simultaneously**

FFS Assessment

- **Strain demand**
  - IMU
  - Strain gauges
  - Fiber optic cables
  - Pipe-soil interaction modes
- **Strain capacity**
  - Tensile strain capacity (TSC)
  - Compressive strain capacity at maximum load (CSC_{ML})
  - Compressive strain capacity post maximum load (CSC_{PML})

FFS Assessment – Impact Level

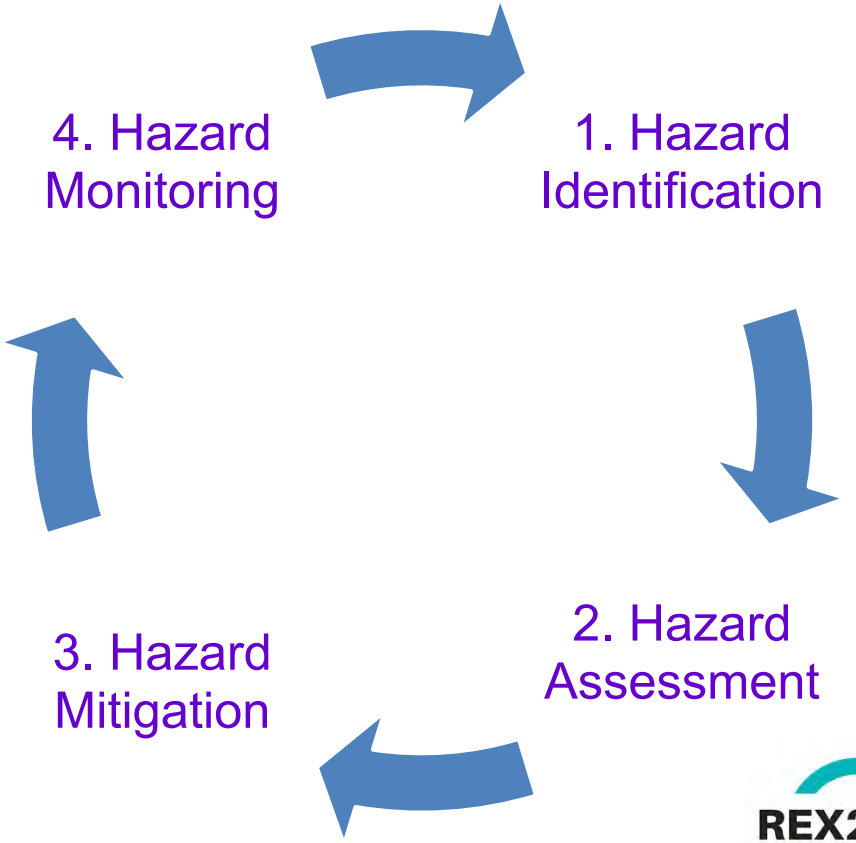
- **Impact level**
  - Level 1: low impact (e.g., little environmental or human safety concerns)
  - Level 2: nominal/medium impact – nominally conservative
  - Level 3: high impact (e.g., crossings, populated areas, environment impact)
- **Select level of conservatism appropriate for the impact level**

Nature of Hazards vs. Strain Demand

- **Strain demand on a pipeline depends on**
  - Nature of hazards
  - Interaction between hazards and pipe
- **Loading on pipelines by hazards**
  - *Load control*: the magnitude of the applied load is not affected by the displacement/deformation.
  - *Displacement control*: the magnitude of the applied displacement is affected by the load/stress applied.
- **Most forms of longitudinal loading in pipelines is a combination of load- and displacement-controlled.**

Management Process Focusing on Hazards (Don West)

- **For a particular segment of a pipeline, the starting point can be any point in the process.**
- **Hazard identification/characterization**
  - Phased approach
  - Facilitate hazards mitigation and monitoring
- **Hazard identification and monitoring may involve the same techniques/tools.**
- **"Doing nothing" is an option in hazard mitigation.**



Tools for New Construction

- **New construction – strain demand reduction**
  - Understand geohazards along the right of way (ROW)
  - Route around geohazards, such as horizontal direction drilling (HDD)
  - Stabilize of hazards
  - Use special trench design
  - Monitor strains
- **New construction – strain capacity enhancement**
  - Line pipe
    - *Increase wall thickness, use lower grade pipe*
    - *Specify the right pipe, e.g., high strain hardening, limiting the upper bound of pipe strength distribution, right chemistry to reduce the propensity of HAZ softening*
  - Girth welding
    - *Weld strength overmatching the pipe strength*
    - *Weld cap reinforcement*

Tools for In-Service Pipelines

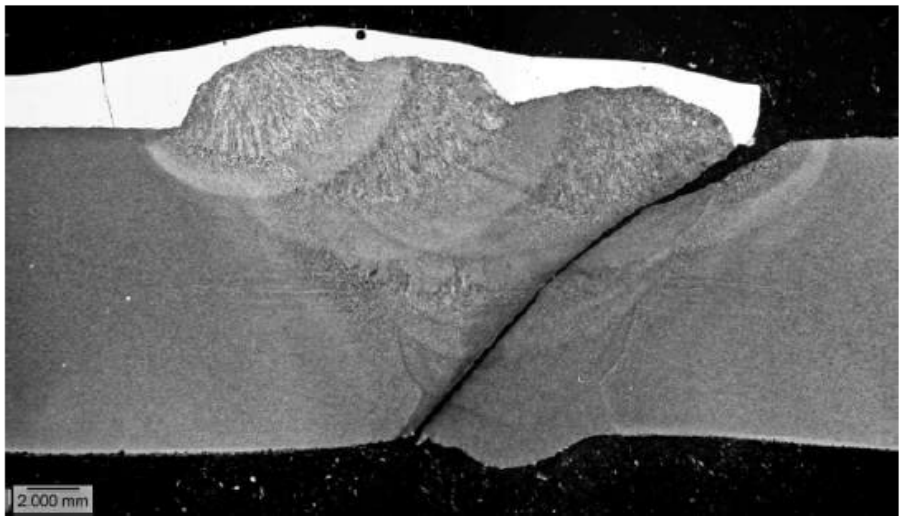
- Understand geohazards along the ROW
- Develop screening process, risk ranking, prioritization
- Determine best options between strain demand reduction and strain capacity enhancement
- Site mitigation and strain monitoring
- Enhancement of weak girth welds
- Establish future intervention threshold

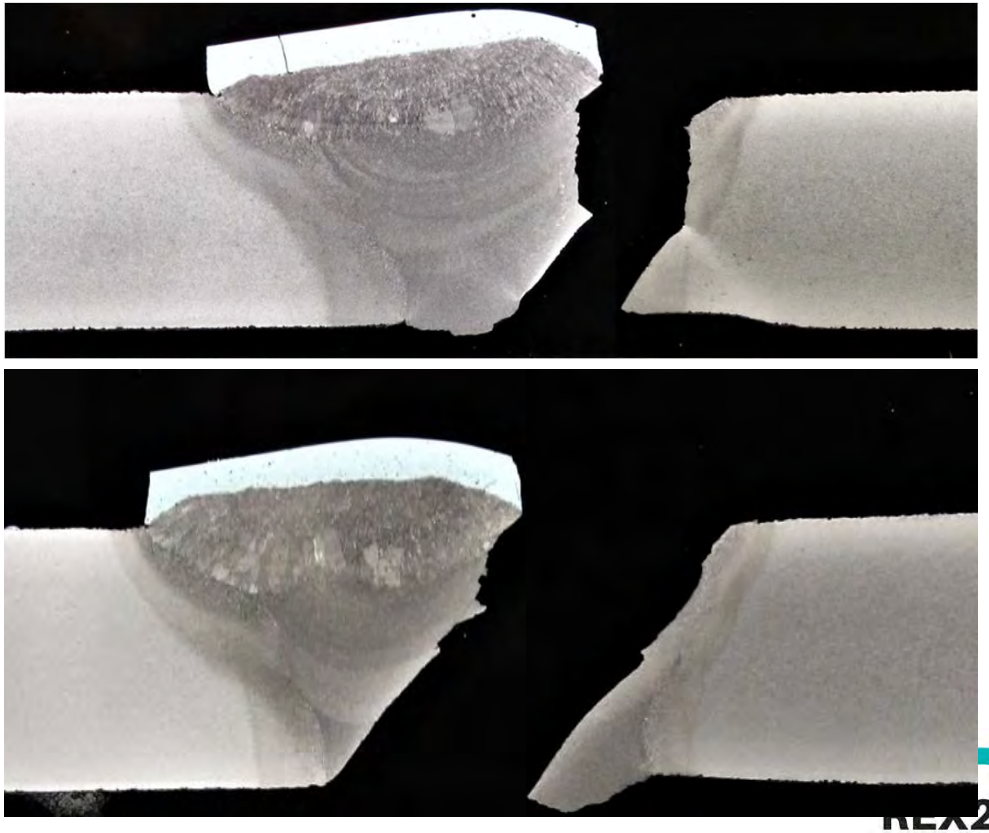
Gaps between Design and Field Conditions – Operation beyond Design

- **Our practice - conventional stress-based design**
  - Longitudinal stress is limited to 90% SMYS.
  - Combined equivalent stress is limited to 90% SMYS.
  - Implications: pipelines are “only required” to be able to tolerate strains up to 0.2%.
- **Field conditions/practice**
  - Internal pressure, thus hoop stress, is actively managed.
  - Longitudinal stress/strains in most cases are not actively managed.
    - *High strain locations exist more frequently than many expect.*



Failure of Girth Welds in Newly Constructed Pipelines





Requirements in Welding Qualification is not Sufficient

Factors Affecting Girth Weld Performance		Factors Addressed in API 1104
Pipe wall thickness		Mostly Yes
Pipe strain hardening capacity		No
Weld strength mismatch	YS mismatch	No
	UTS mismatch	No
HAZ strength (Softening)		No
Weld profile	Cap reinforcement	Mostly No
	Misalignment	No
	Bevel geometry	Yes
Weld flaw	Flaw type	Yes
	Flaw dimensions	Yes
Toughness		No
Applied stress/strain		No

- **API 1104 focuses on the prevention, detection, and repair of flaws exceeding certain limits**
- **Effective integrity approach**
  - No failure in nearly defect-free welds
  - Remove large flaws
- **Requirements on welds, e.g., flaw acceptance criteria, should be tied to performance requirements**
  - Loading conditions
    - *Station welds vs. tie-in welds in hilly areas*
  - Guard against overspecifying

Systematic Gaps

- **Perception about standards**
  - Standards committees
    - *Standards are minimum requirements.*
    - *Additional requirements can be added by companies.*
  - Purchasing and contract departments
    - *Standards are sufficient.*
    - *May challenge any additional requirements*
  - Contractors
    - *Standards are the base and "everything".*
    - *"If you ask more, you pay."*
- **Purchasing department gets API 5L pipes with the lowest cost.**
- **Welding engineers don't wish to get "punished" when they have to work with "bad" pipes.**
  - Welding engineers may not have influence on pipe procurement and contracts.
- **Construction crew wants to meet project deadlines.**
- **Operations: Some are proactive; many are reactive**

Available Resources

- **JIP on the management of geohazards**
- **PRCI guidelines**
- **PRCI/PHMSA and operators**
  - Strain capacity
  - Interacting threats
- **Failure of girth welds in newly constructed pipelines**
  - a paper tomorrow
  - Ongoing PRCI project
- **PHMSA Special Permit Conditions**
- **Recommended procedures**
  - Excavation and backfill
  - Enhancement of girth welds

Concluding Remarks

- **Integrated/holistic approach at all levels**
  - Industry wide
  - Company wide
  - Technical
- **Approach to geohazards management**
  - Pipelines need to tolerate some (a minimum) level of strains
  - Geohazards management for high level strain events
- **Much to learn**
- **A continuous improvement process must be adopted.**

Thank You!

- Q&A
- Further contact
  - ywang@cres-Americas.com
  - 614-376-0765

BACK TO AGENDA

Pipeline Research Council International, Inc.

PR-396-183905

Project GHZ-2-01: System for Monitoring Integrity, Geohazards, and Leaks at River Crossings

Presented By Nick Tzonev
Syscor Controls & Automation Inc
March 3-4, 2020

PRCI™
LEADING PIPELINE RESEARCH

SYSCOR
controls & automation inc

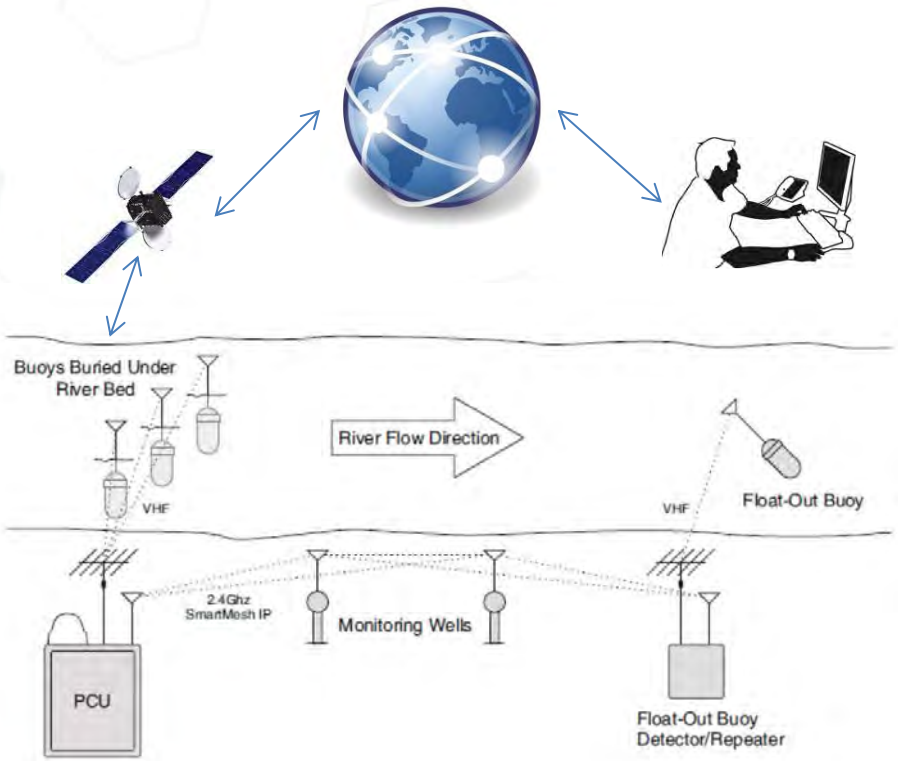
Application

Primary Objective: To develop a comprehensive IIoT system for monitoring underground pipeline facilities at river crossings, especially those without ready access to power and communications.

Secondary Objective: Maintain flexibility that permits deployment in other ROW settings.

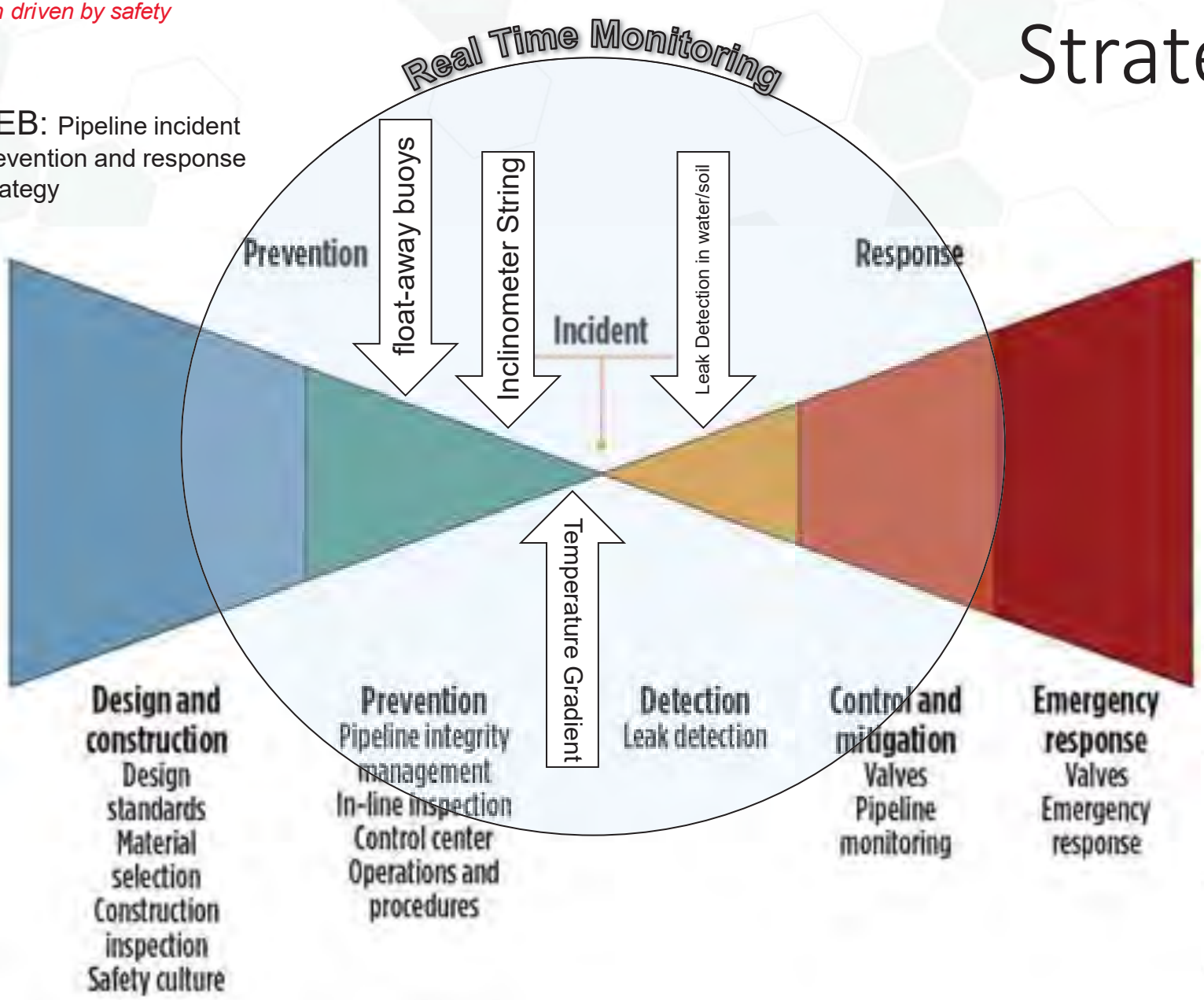
The system utilizes sensor fusion techniques to derive advanced threat awareness by monitoring:

- River bed scour using float-away VHF buoys.
- Escaping hydrocarbons using polymer absorption sensors.
- Vibration patterns using MEMS accelerometers.
- Earth movement using MEMS inclinometer strings.
- Pipeline temperature changes attributable to cooling of exposed pipe sections. (potential partnership with PureHM)



Strategy

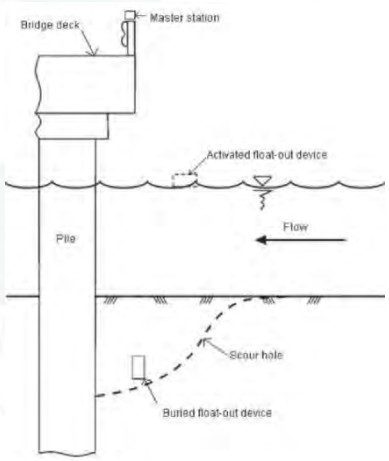
NEB: Pipeline incident prevention and response strategy



Float-outs

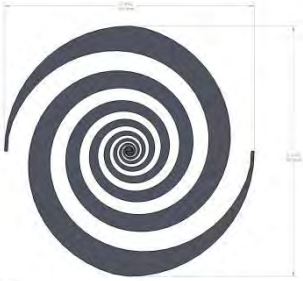
Pros:
- "Old school" proven technology for decades.
- Early detection of scour with sufficient time to react.
- Highly deterministic - minimal false alarms.
- Simple.
- Inexpensive.

Cons:
- Installation difficulties => cost.
- Existing solutions communicate when surfaced. Underwater communication requires new approach to antenna design and frequency selection.
- Traditionally not designed for pipelines.

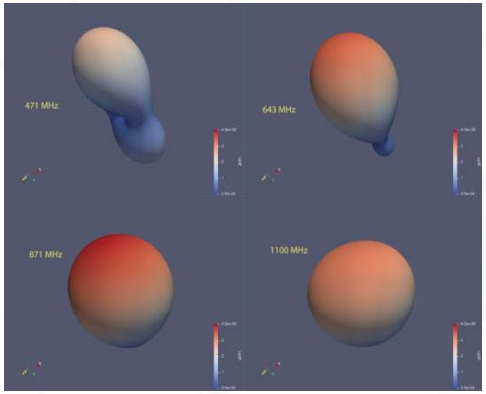


GHZ-02-01 Groundbreaking Approach:
- Novel broadband 27/160MHz communication antennas that work in air, underwater, and deep in the mud. Verified to ~50ft water depth and ~1km range.
- Periodic "I am alive" confirmation.
- Secondary 433MHz frequency upon activation/dislodging.
- Completely wireless listening stations that communicate to the central base station via 2.4GHz mesh protocol.

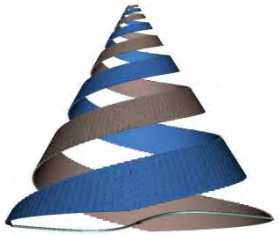




Work Completed:
- Antenna design – 3D and 2D.
- End to end communication.
- In-water concept testing.









Outstanding Work:
- Final mechanical design.
- Deployment strategy.
- Testing.

In-place Inclinometer Strings

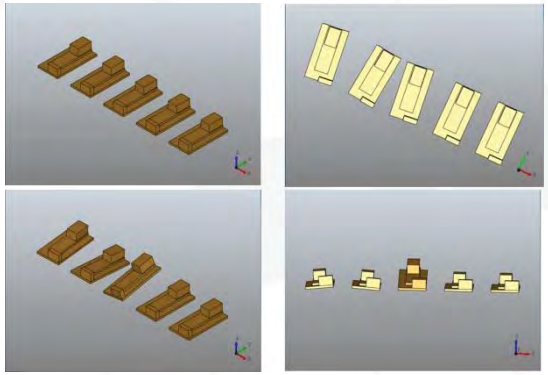
Pros:
- "Old school" proven technology for decades.
- Early detection of slope instability.
- Highly deterministic - minimal false alarms.

Cons (specific to pipeline monitoring):
- Existing solutions take periodic readings (1-2) per day and will miss slope collapse.
- Can be heavy - typically made of stainless steel.
- Commissioning can be challenging - stacking sequence and initialization.
- Consume too much power for real time operation.
- Need guides/rollers to preserve relative horizontal reference.

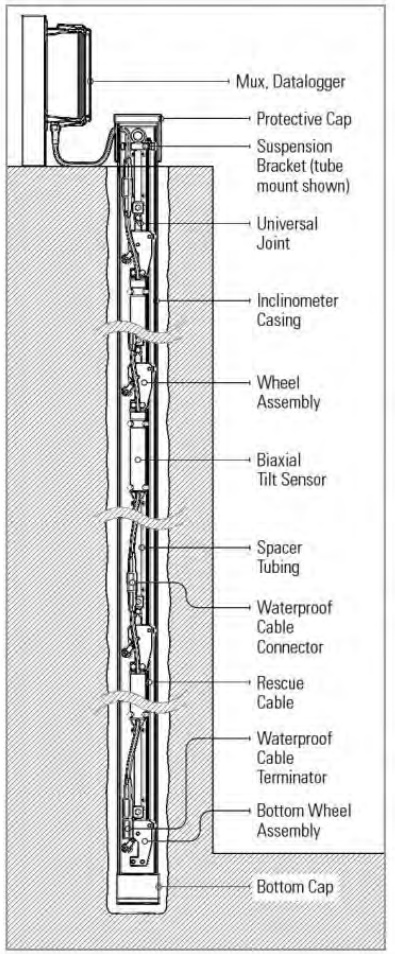
GHZ-02-01 Groundbreaking Approach:
- Dynamic inclinometers measure slope angle as well as acceleration triggered by slope movement.
- Light - Carbon fiber rods.
- Automatic stacking configuration.
- Automatic horizontal alignment through magnetometer. No need for directional guides.
- Ultra low power. 10-year primary battery operation.

Work Completed:
- Proof of concept completed.
- Configuration technique developed.
- Battery power sources completed.

Outstanding Work:
- End-to-end software integration.
- Final mechanical design.
- Sensor fusion.







Shown: Geokon 6150F digital addressable in-place inclinometer system

Proposed partnership: Temperature Gradient

Pros:
- Relatively easy deployment.
- Potential for reliable detection of Vortex-Induced Vibrations (VIV) in exposed pipelines.
- False alarm mitigation through utilization of upstream “normal” heat loss profiling.

Cons:
- Potential sensitivity “blackout periods” when water temperature and product temperature are comparable.
- May need significant pipeline exposure to generate reliable signal to noise ratio SNR for detection.

River Scour Monitoring System (RSS) Groundbreaking Approach:
- Direct measurement of VIV – induced heat transfer as an unmistakable sign of pipeline exposure to flowing water.

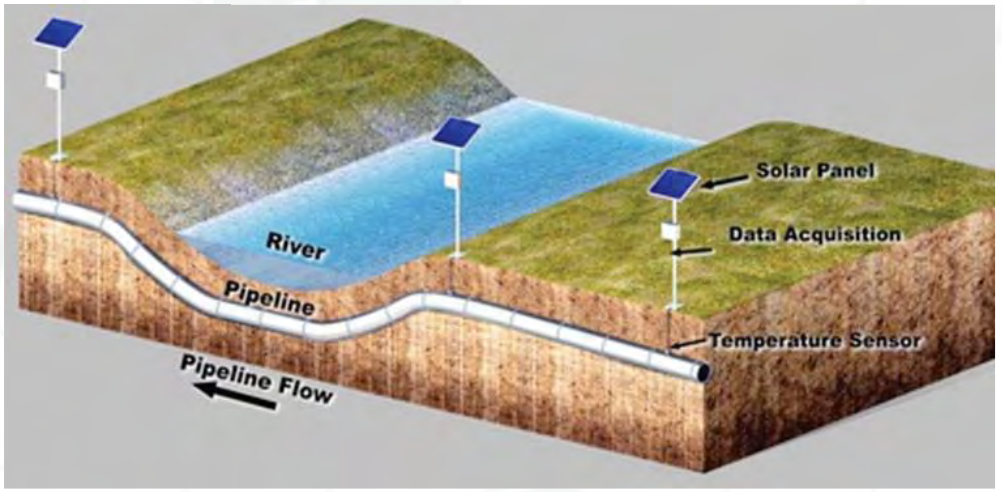
Work Completed:
- Proof of concept test system completed and deployed.
- Detection Software V1 completed.
- Encouraging results demonstrate feasibility.

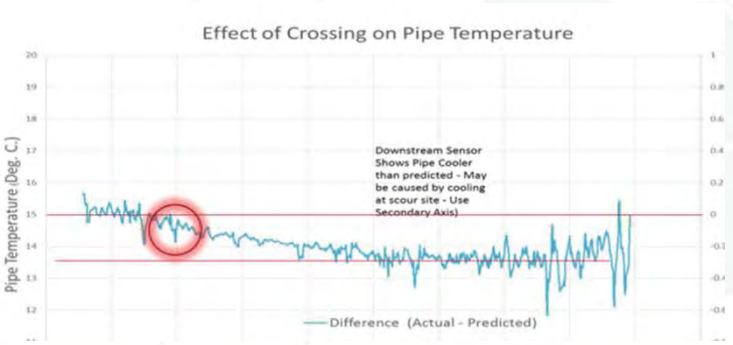
Outstanding Work:
- TBD
- TBD

PHMSA Contract Number: 693JK31810011

Arizona State University

pureHM a xylem brand







In-situ leak detection

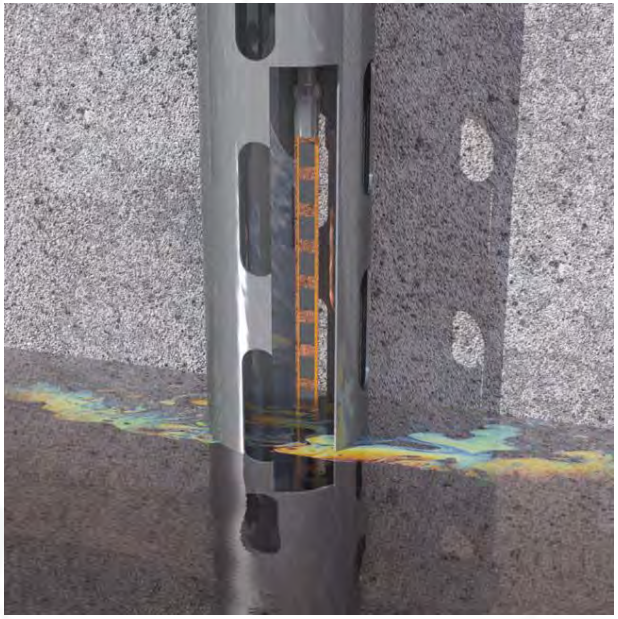
Pros:
- Relatively easy deployment.
- Utilizing Polymer Absorption sensing (PRCI developed technology). Unmistakable indication of hydrocarbons floating on water.
- No need for calibration.
- Fast reacting in water, ice, air.
- Ultralow power.
- Inexpensive.

Cons:
- Partially reversible. Sensitivity gains at the expense of reversibility.

GHZ-02-01 Groundbreaking Approach:
- Rapid deployment.
- No maintenance.
- Opportunities to develop next generation intelligent systems for monitoring hydrocarbon releases into water ways.

Work Completed:
- Multiple successful water/ice tests.
- Sensors electrode corrosion issues resolved through PTFE nanoparticle coating that acts as amplifier.
- Tape sensor developed to ensure there is always a sensor at the water/air interface.

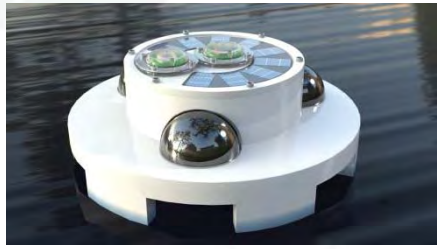
Outstanding Work:
- Final mechanical design.
- Testing new RF impedance approach to sensor reading. Partner Analog Devices.











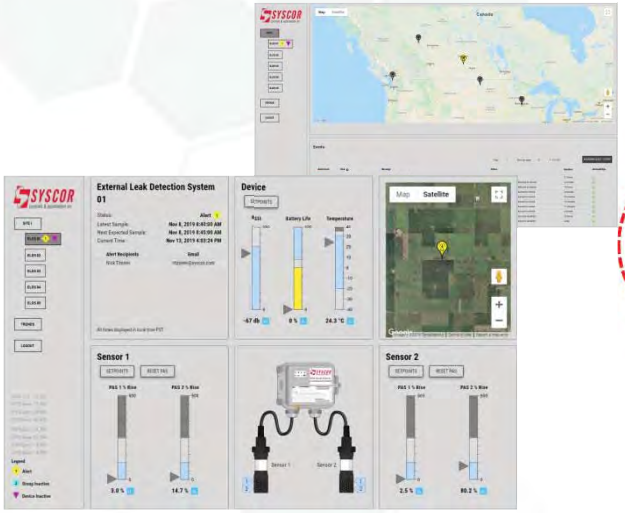
Rapid Deployment IIoT ROW leak detection

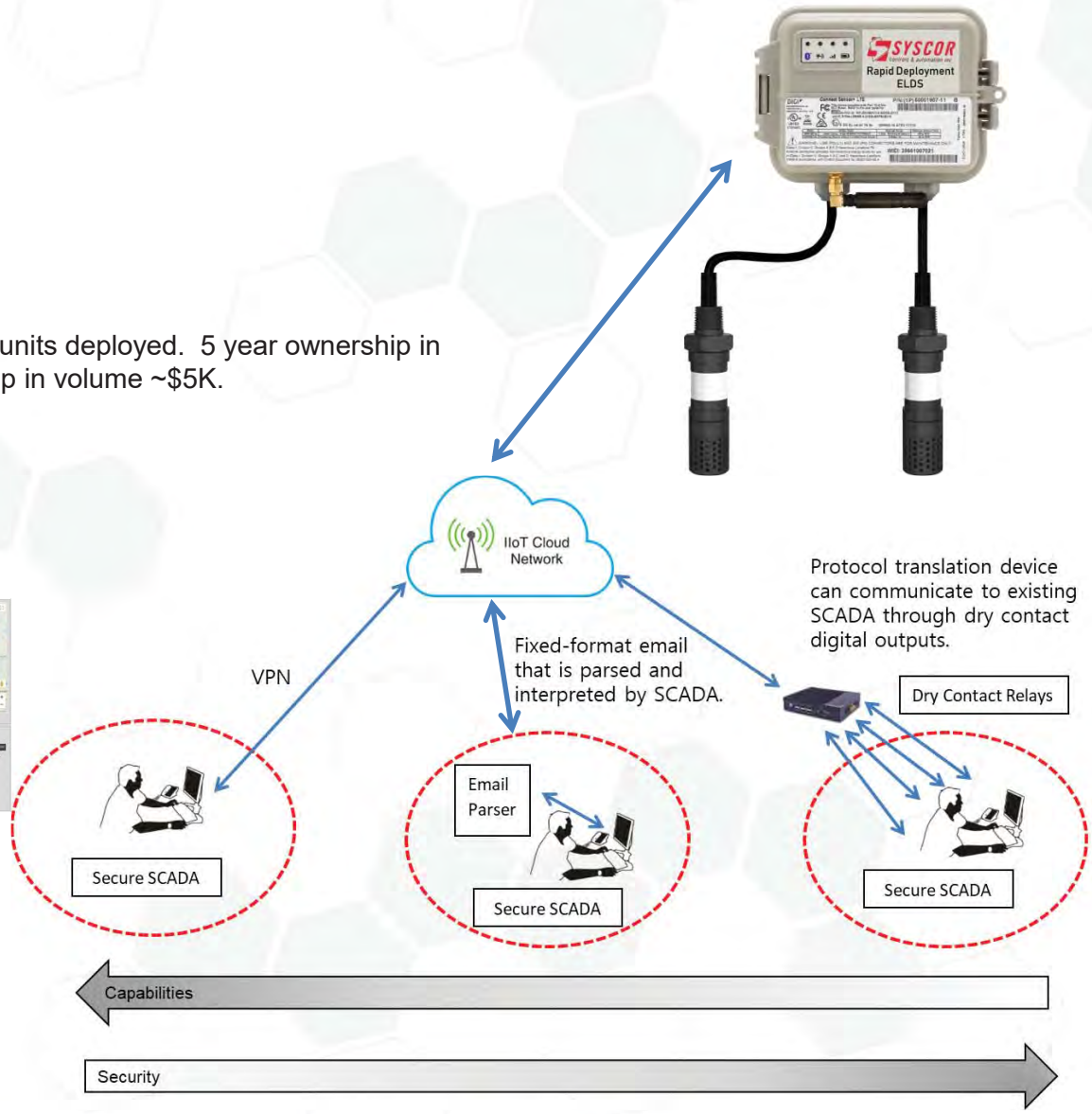
Pros:
- Rapid Deployment.
- Battery powered:1-10 years.
- Complete end-to-end solution.
- Globally scalable.
- Ultralow power.
- Inexpensive (~$2K per point).
- IT remotely managed as service.

Cons:
- Monthly fees: $50 - $200 depending on units deployed. 5 year ownership in small quantities ~$15K. 5 year ownership in volume ~$5K.

Work Completed:
- Ready for trials.

Outstanding Work:
- Commercialization.





Project Review

- ✓ Technology selected (Sept 2018)
- ✓ Alpha prototype HW (Apr 2019)
- ✓ Alpha integration (June 2019)
- ✓ Phase 1 report (Sept 2019)
- ✓ Pre-beta prototype (Mar 2020)
- ✓ Pre-beta integration(May 2020)
- ✓ Phase 2 report (June 2020)

Project Applications	Phase 1 (Sept 2018-Sept 2019)	Phase 2 (Sept 2019-June 2020)	Project Deliverables
Scour detection	Proof-of-Concept	Pre-beta proto-type	VHF river buoy
Hydrocarbon detection in water	Pre-existing and commercially available		HCD Sensor Probe
Vibration detection	Pre-existing and commercially available		HCD Sensor Probe
Inclination detection	Pre-existing, but new proof-of-concept required	Pre-beta proto-type	Inclinometer Strings
Power and communication	Pre-existing and commercially available		Syscor's WirelessHART Sensor Hub and Repeater

BACK TO AGENDA

PRCI 2020 Research Exchange

Significance of Ground Movement on Pipeline Integrity

SBD-1-3

Aaron Dinovitzer
Abdelfettah Fredj, Rick Gailing

BMT

LEADING PIPELINE RESEARCH

Presentation Outline

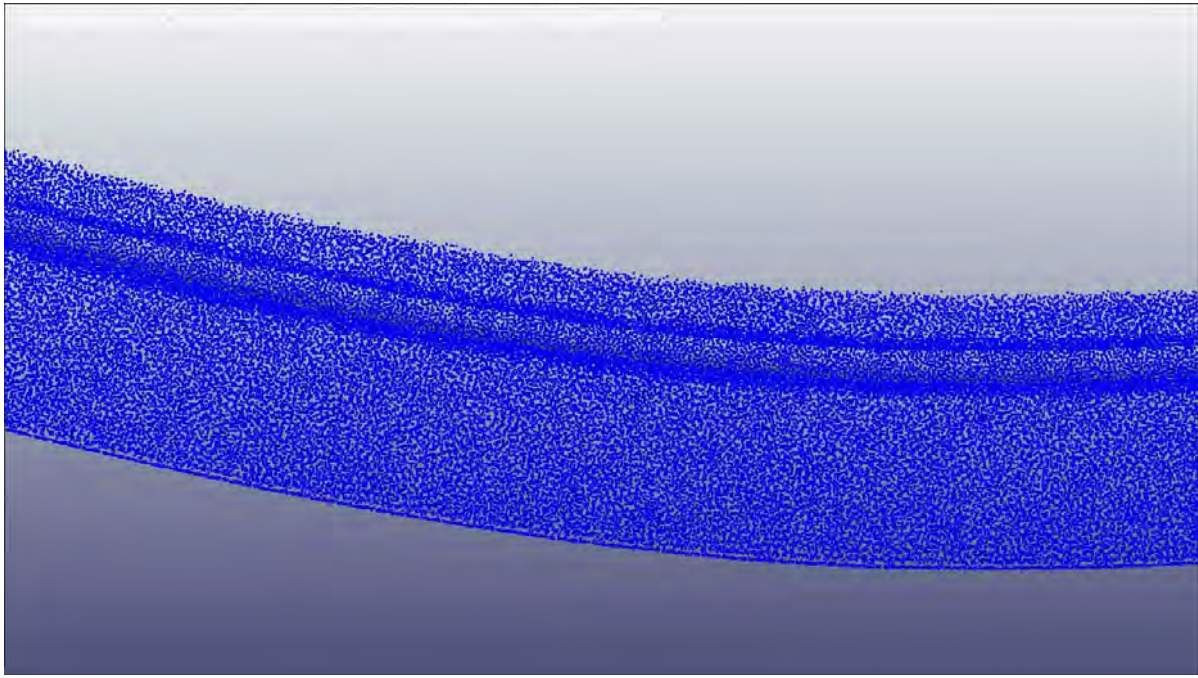
- Introduction
- Pipe Soil Interaction Model
  - Description and Validation
- Relate Surface Expression to Mechanism
- Slope Geohazard Simulation
- Slope Modelling Results
  - Format of Results
  - Slope Modelling Result Sensitivity
- Application of Results
- Parallel US DOT PHMSA Project
- Concluding Remarks

Introduction - Project Objectives

- **Develop a method or "tool" to support slope movement assessment based on ground surface observations and general line properties**
  - Relate surface expression of ground movement to pipe strain
- **The tool as initially posed to characterize the severity of the present site conditions over the pipeline as potentially damaging or not.**
  - Total strain is being delivered for strain based design & assessment
- **Utilizes BMT's pipe-soil interaction model that has been validated against both field and experimental results**
- **Project ran in parallel with BMT's DOT PHMSA project**
  - Considers movement transverse to the pipeline and subsidence

Pipe Soil Interaction Model

- **The BMT Pipe-Soil Interaction Model Developed in LS-DYNA**
  - Pipeline
    - Shell elements with 9 integration points through thickness
    - Non-linear material stress-strain curve
  - Soil Constitutive Model
    - Soil foam model considering volumetric strain effects
    - Yield surfaces

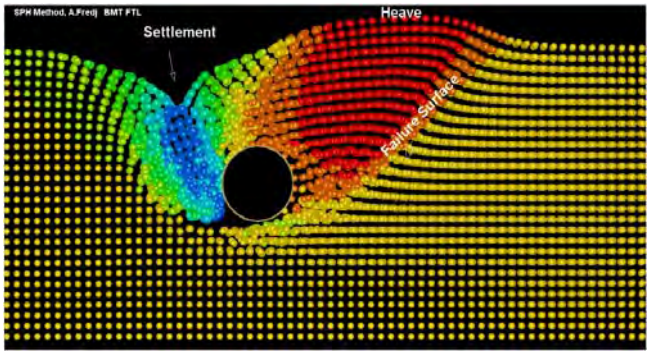


Pipe Soil Interaction Model - Validation

- Compare Soil Displacement Mechanism and Patterns

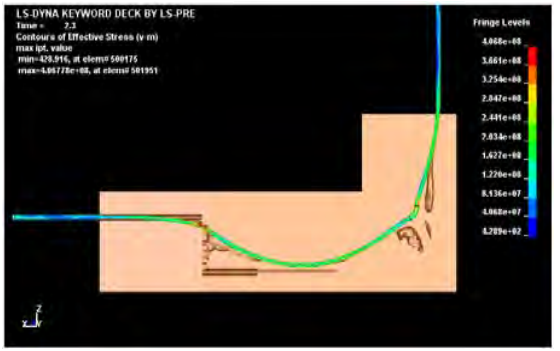
UBC Trial





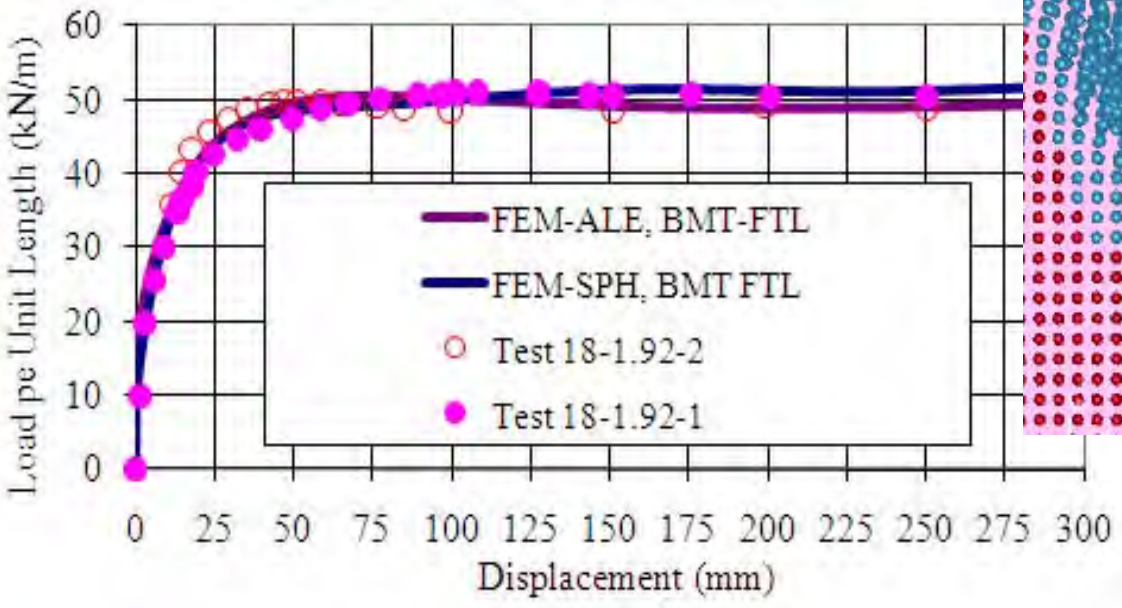
Cornell & Tokyo Gas Trial

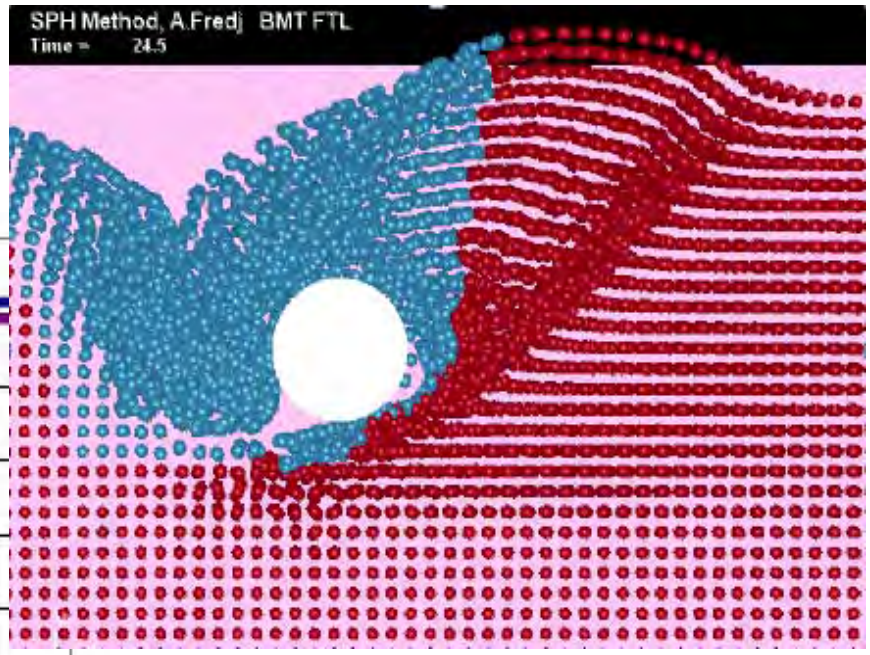




Pipe Soil Interaction Model - Validation

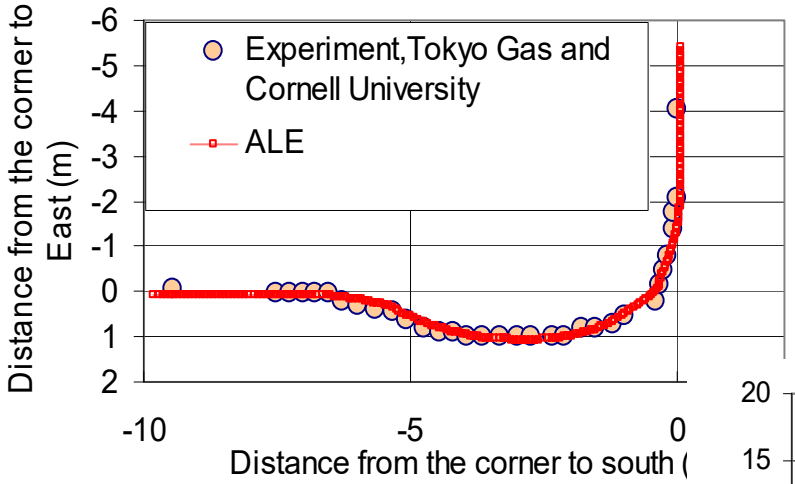
- Compare Load Displacement





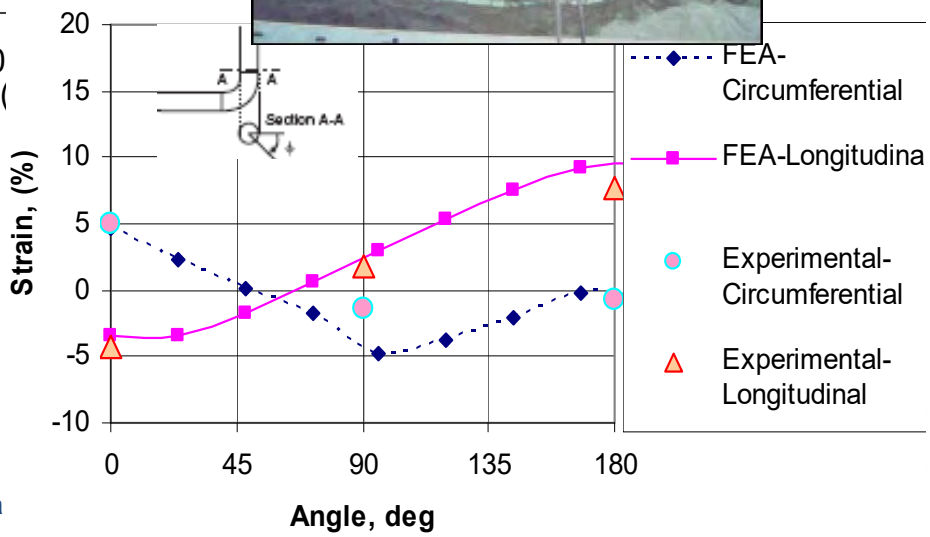
Pipe Soil Interaction Model - Validation

- **Compare Pipe Deformation**



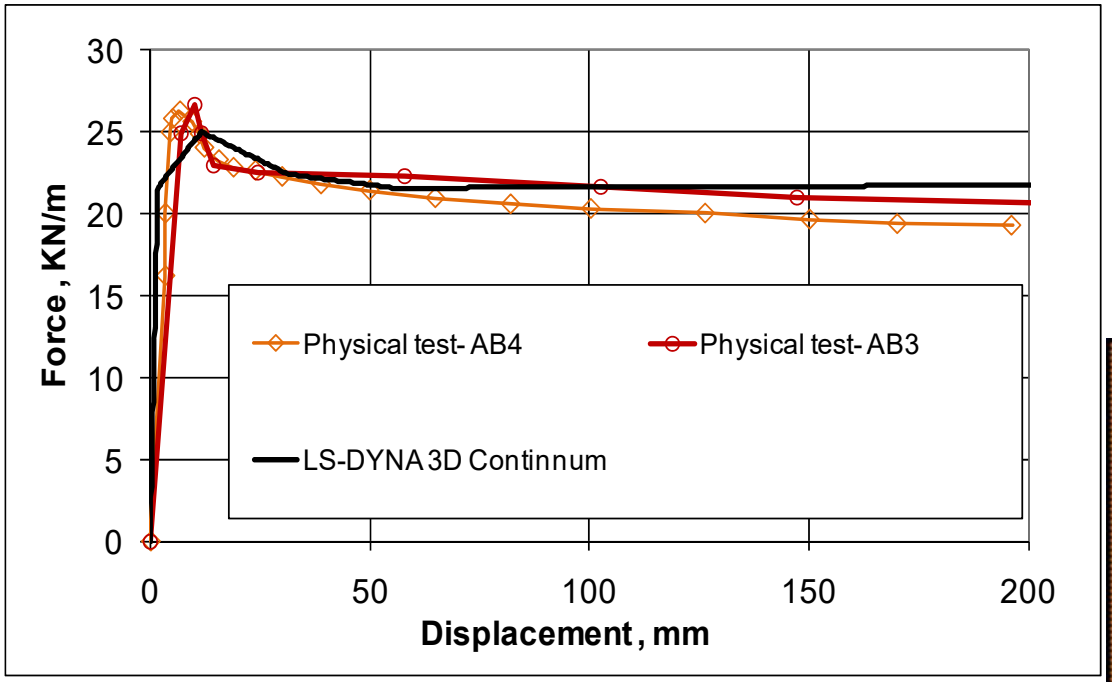


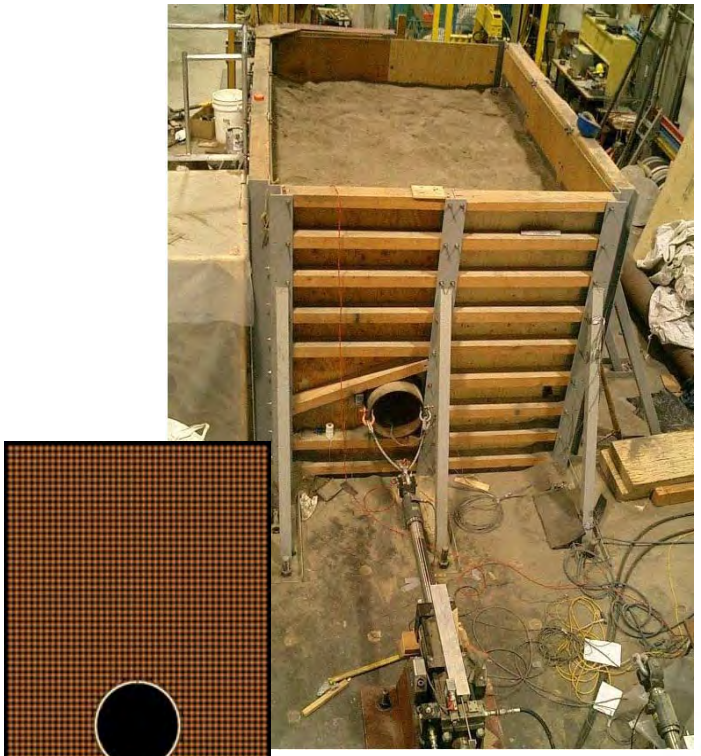
- **Compare Pipe Strains**



Pipe Soil Interaction Model - Validation

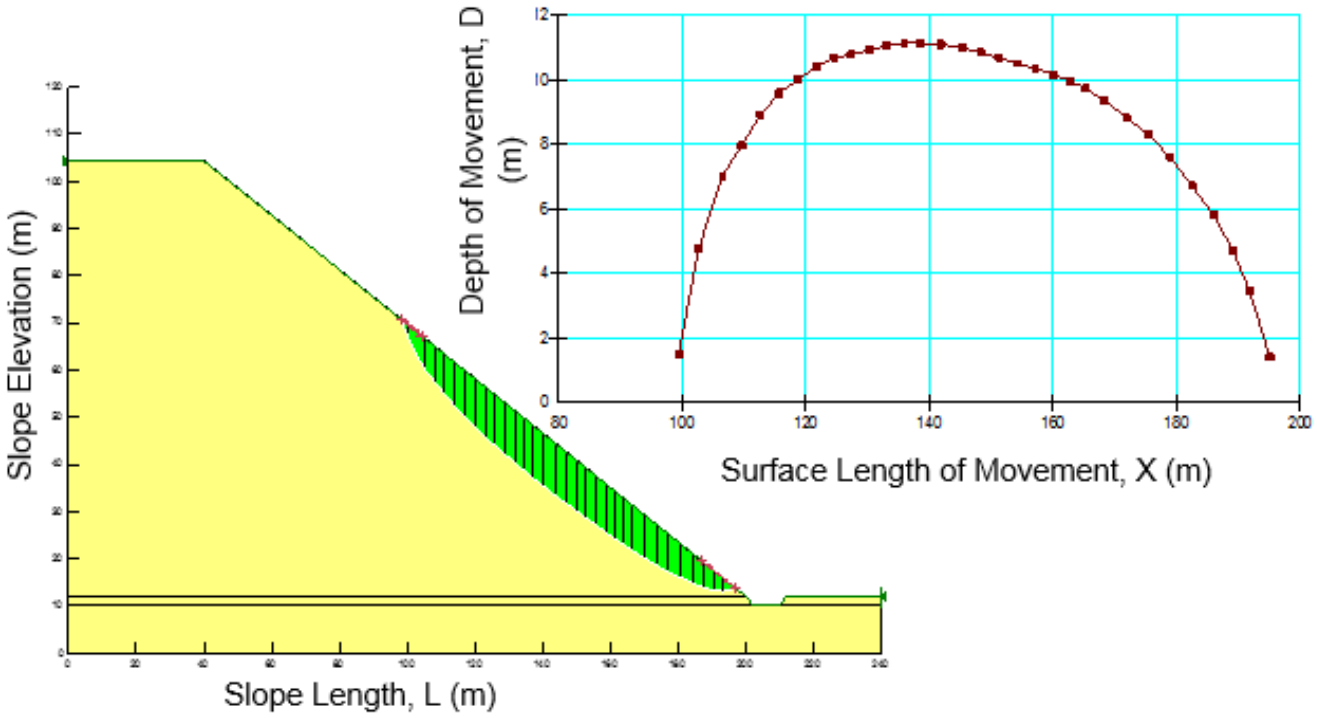
- **Compare Pipe Load and Displacement**
  - Consider soil and coating type





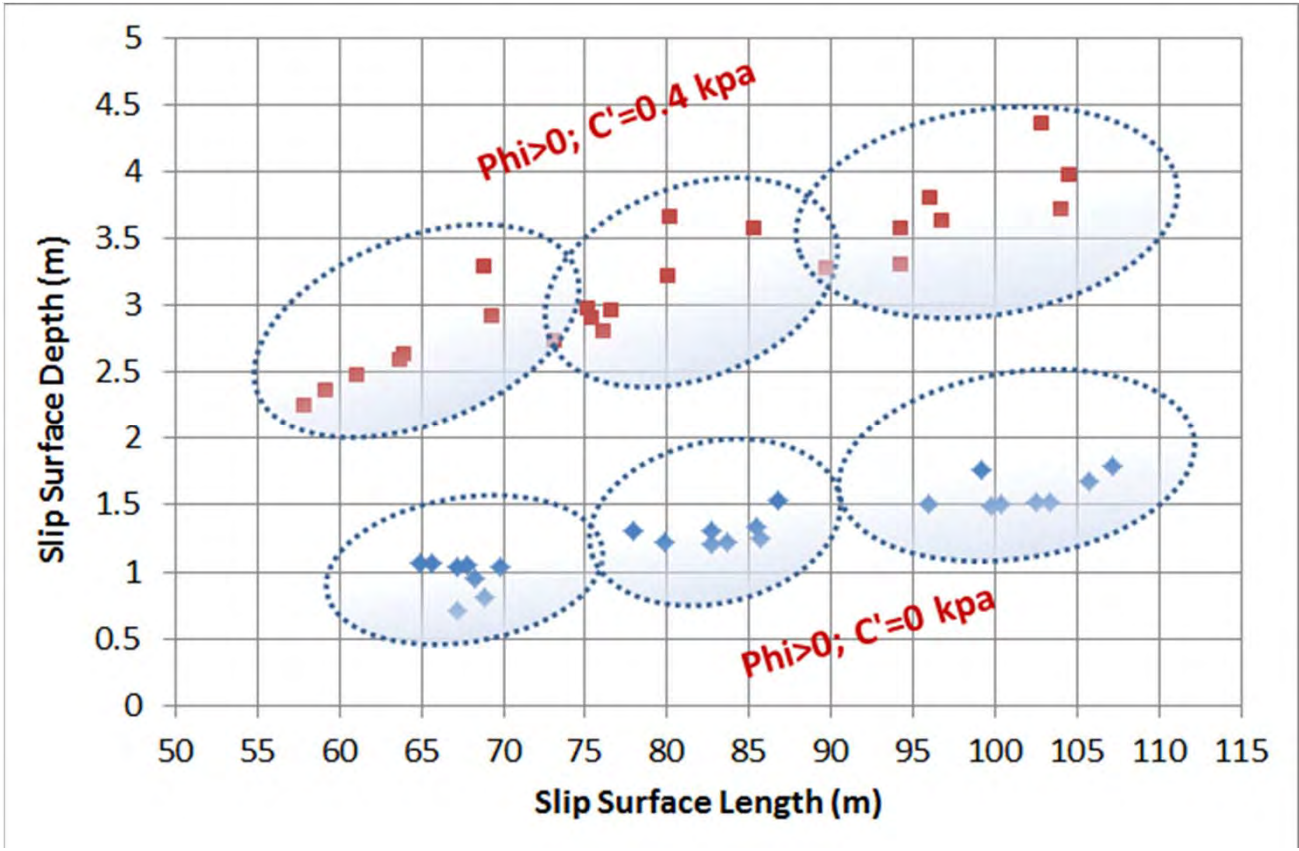
Relate Surface Expression to Expected Depth

- **Augment Field Geotechnical Observations**
  - Apply 2D slope model without pipe to evaluate relationship between slope an soil properties to expected slip plane
  - Assumes uniform soil



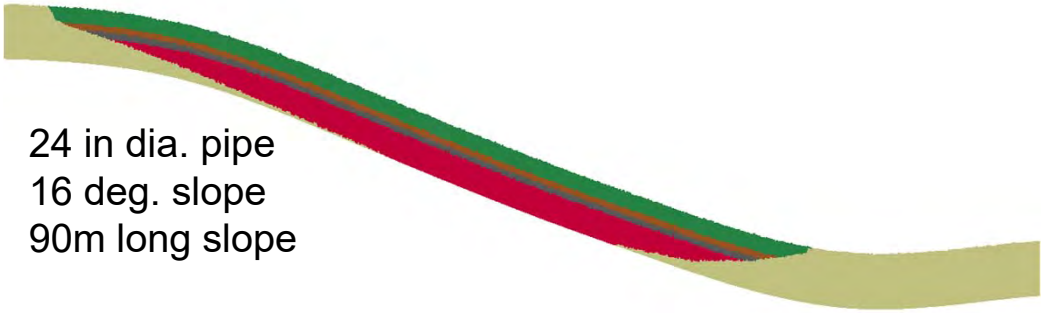
Relate Surface Expression to Expected Depth

- **If field geotechnical observations are uncertain provide indicator of possible mechanism**
  - Apply 2D slope model without pipe to evaluate relationship between slope an soil properties to expected slip plane
  - Assumes uniform soil

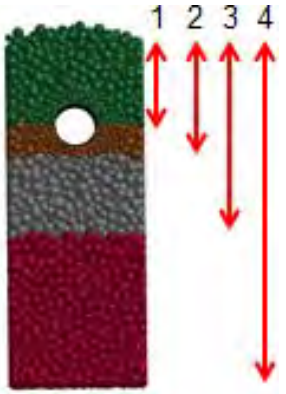


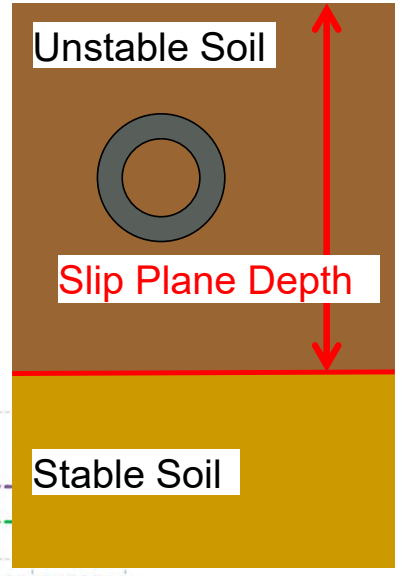
Slope Geohazard Simulation - Demonstration

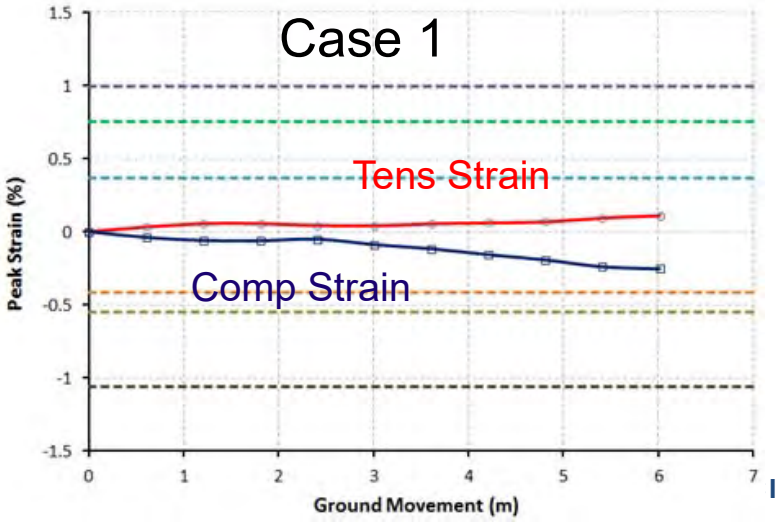
- **Results Illustrate Effect of Shear (Slip) Plane Depth**

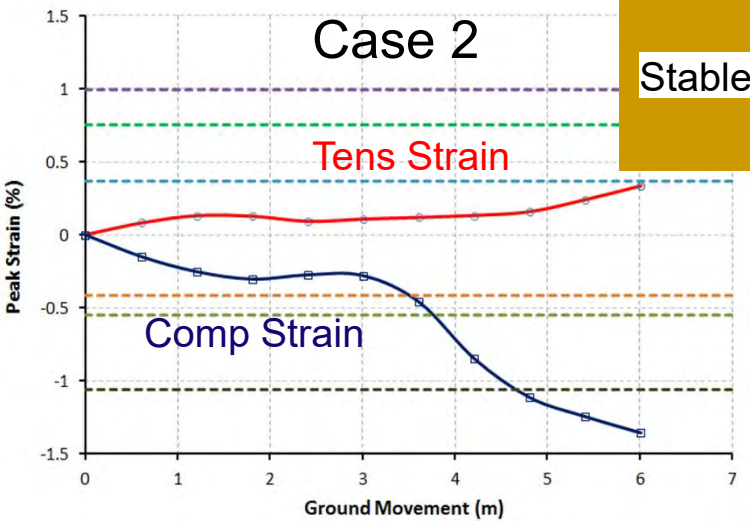


24 in dia. pipe
16 deg. slope
90m long slope









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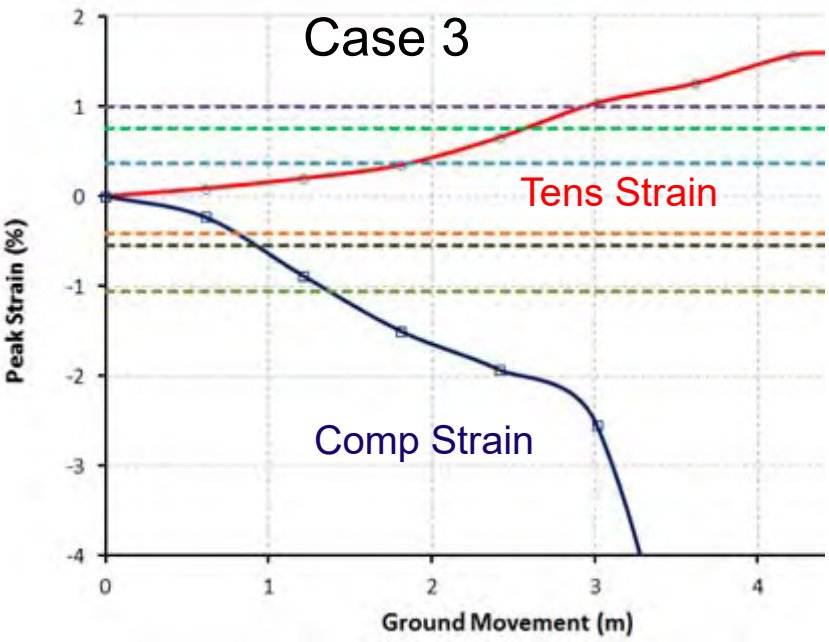
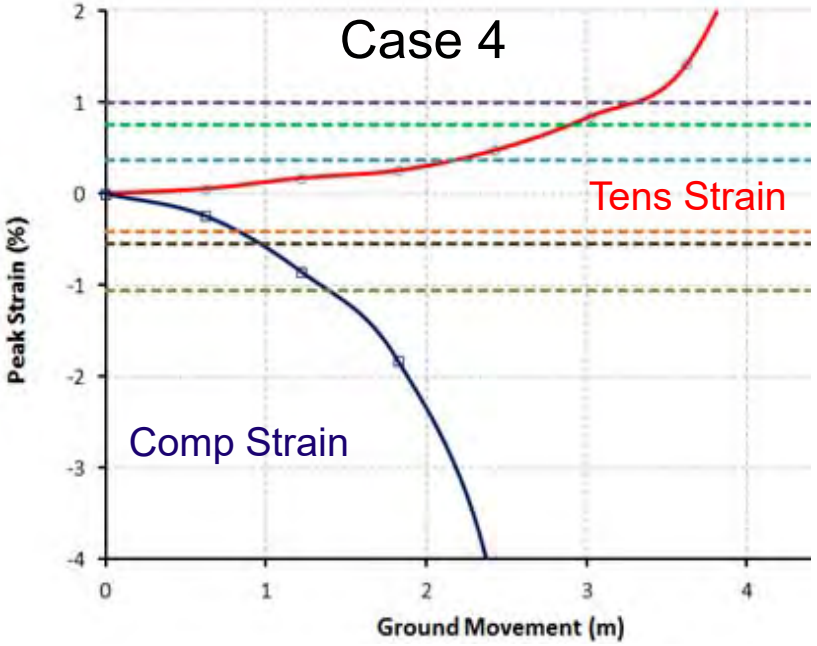
PRCI RESEARCH EXCHANGE

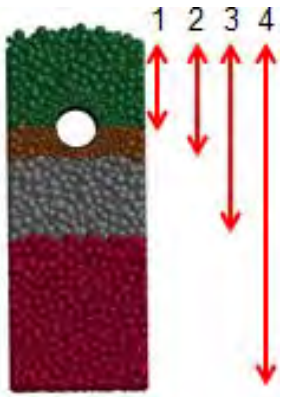
Slope Geohazard Simulation - Demonstration

- **Results Illustrate Effect of Shear (Slip) Plane Depth**



A pipe wrinkle formed at the toe for soil movement of 3.2 m

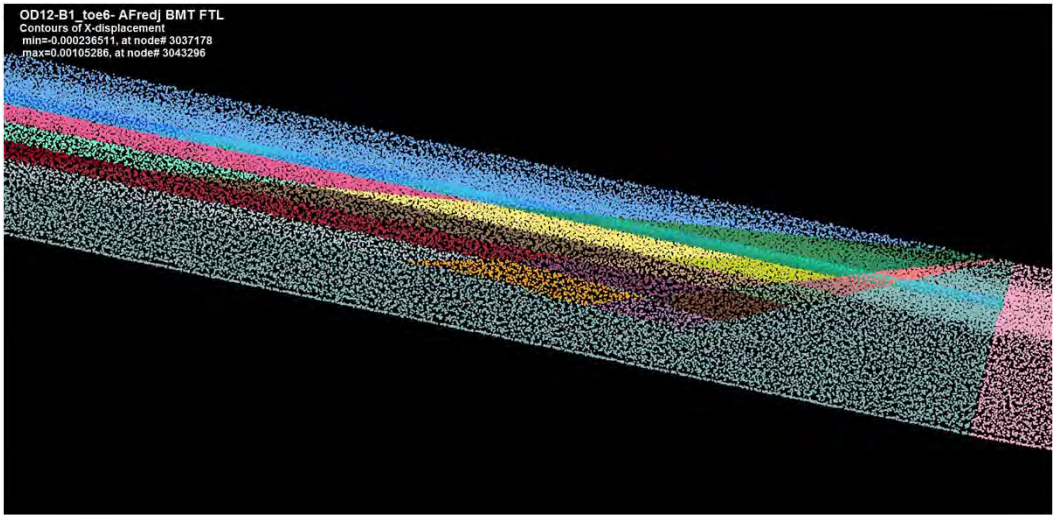


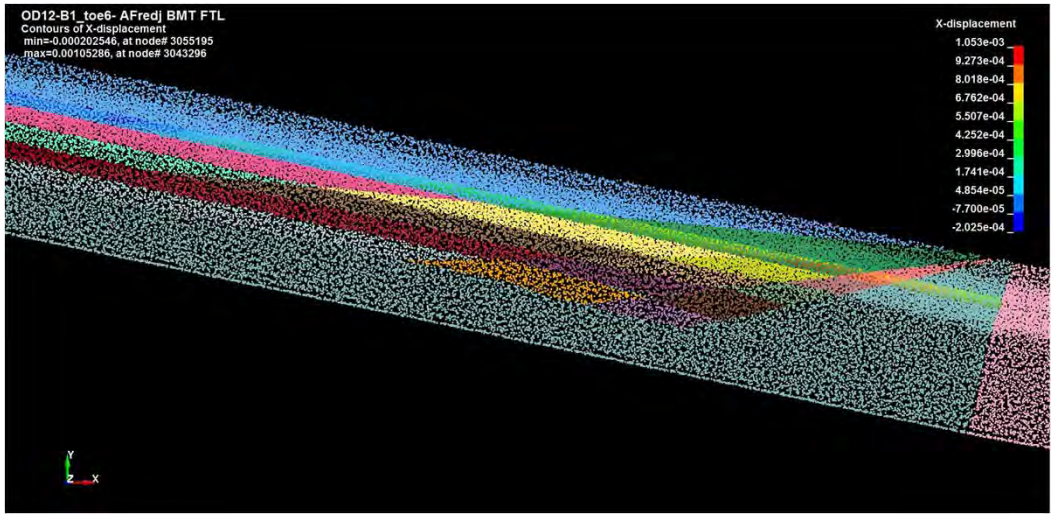


A pipe wrinkle formed at the toe for soil movement of 2.2 m

Slope Geohazard Simulation - Demonstration

- **Results Illustrate Effect of Slip Plane Toe Angle**
  - 12” dia 0.18” thick 100 m (328 ft) slip plane, 2 m (6 ft) below the pipeline
  - Higher slip toe angle
    . . . Rotational movement

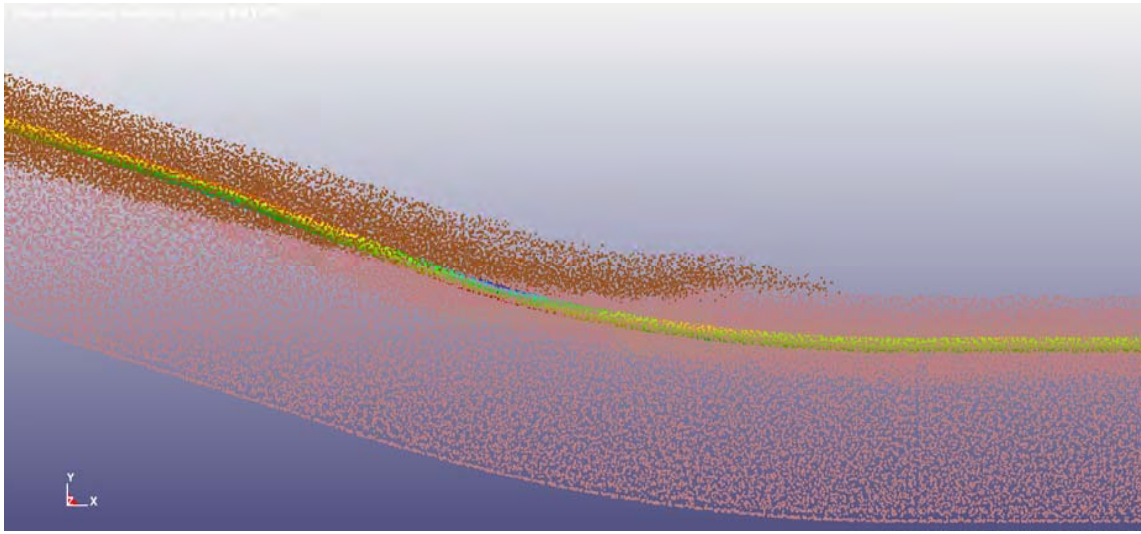




  - Lower slip toe angle
    . . . Translational movement

Slope Geohazard Simulation

- **Consider a Range of Slope Movement Scenarios**
  - Slope angle – 15 deg. to 50 deg. .. . .incl. shallow slopes (4 – 12 deg.)
  - Slope length – 60 m to 100 m (~196 ft to 328 ft)
  - Landslide length (or pipeline length passing through landslide) (3)
  - Angle between slip plane and pipeline at toe of slope (3)
  - Pipeline burial depth (or burial depth to pipeline diameter ratio) (1 to 3)
  - Soil types (2 types)
  - Pipe coating – coal tar enamel and FBE
  - Pipe diameter – 12 in and 24 in
  - Pipe wall thickness – (2) (D/t = 60 to 100)
  - Pipe grade – X52 (lower grade)
  - Operating pressure – 50% SMYS
  - Temperature differential – 300C to 450C

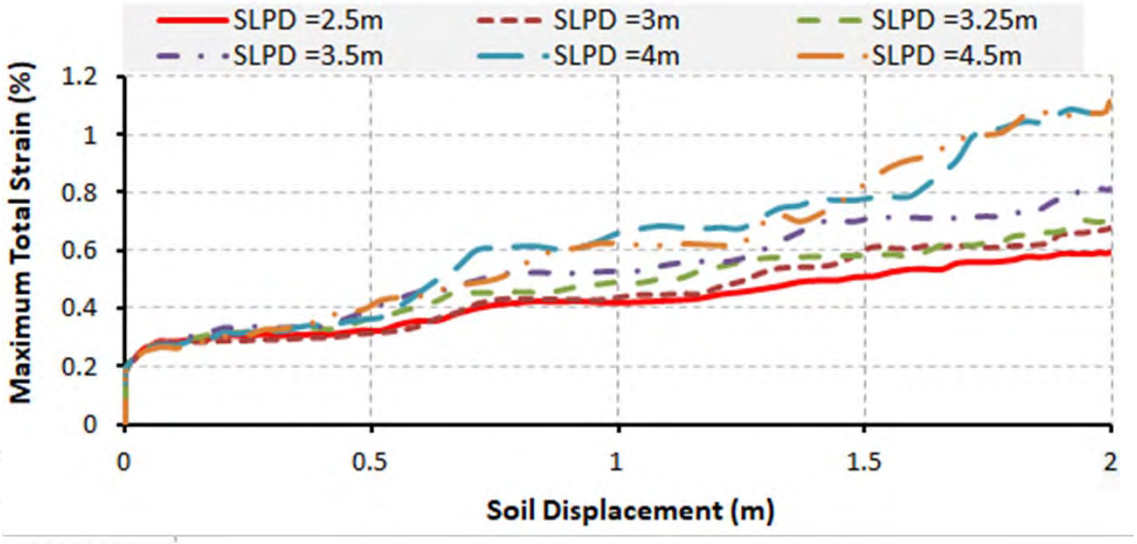


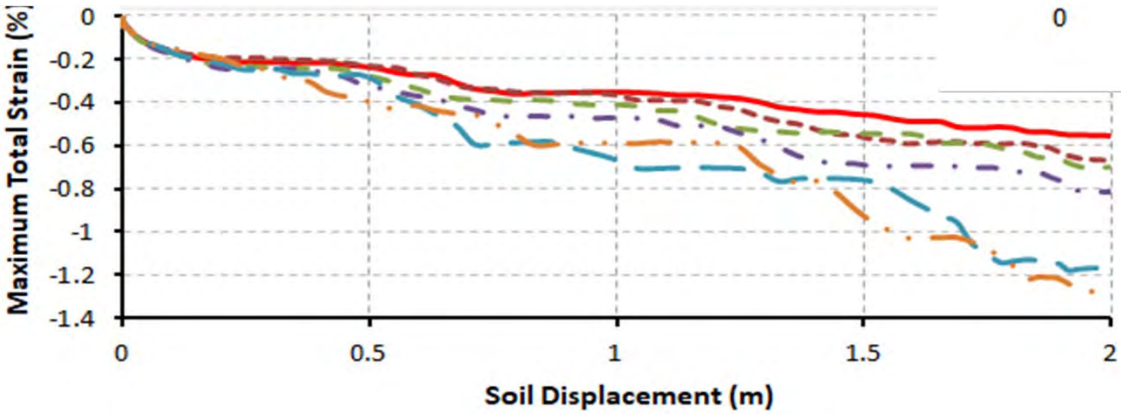
Slope Modelling Program

- **Present Results in 5 formats (all in report appendices)**
  - Graphs
    - Strain versus soil displacement (for each slip plane depth)
    - Strain versus slip plane depth (for each ground movement magnitude)
    - Slip plane depth versus soil displacement (for limit strains)
  - Tabular data
    - Assessment data, soil displacement, slip plane depth, strain
    - Displacements promoting 0.25%, 0.5% and 1% strain

Slope Modelling Program - Sample Results

- **Present results as total tensile and comp. strain for each scenario**
  - Results here for NPS 12 (D/t=71)
  - Presents average strain accumulation rate strain / m movement





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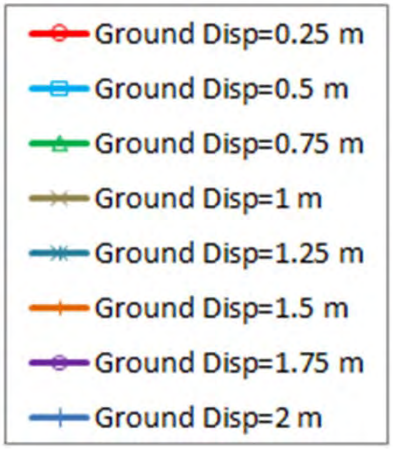
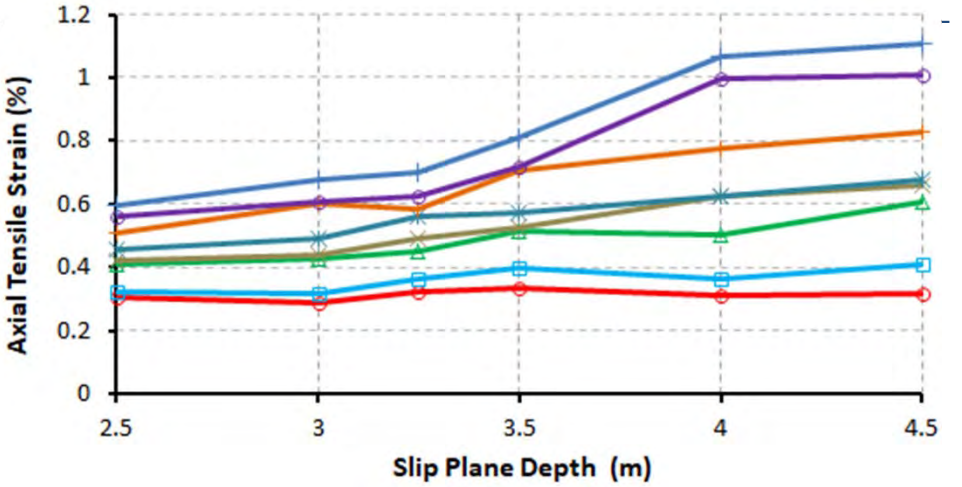
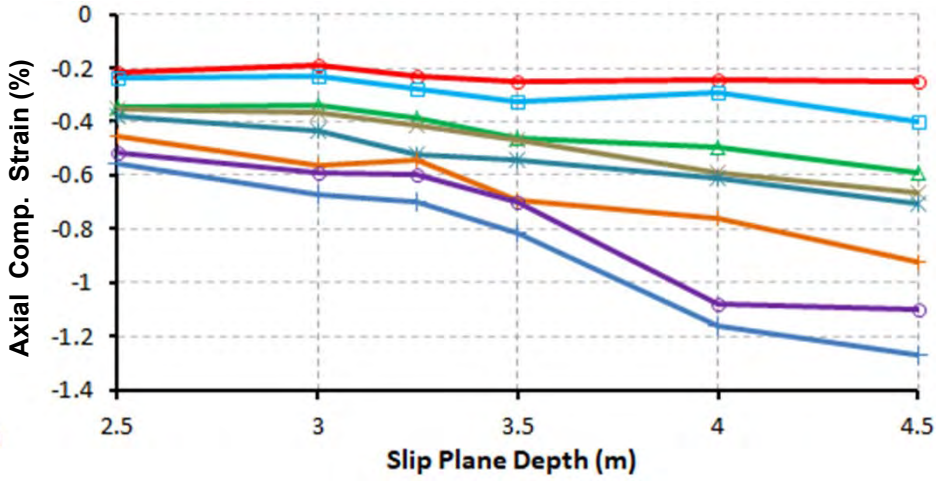
Slope Modelling Program - Sample Results

- **Present Results for Limit Ground Movement**
  - Results here for NPS 12 (D/t=71)
  - Can identify ground movement that initiates rapid strain accumulation
  - Can identify scenarios with little strain accumulation

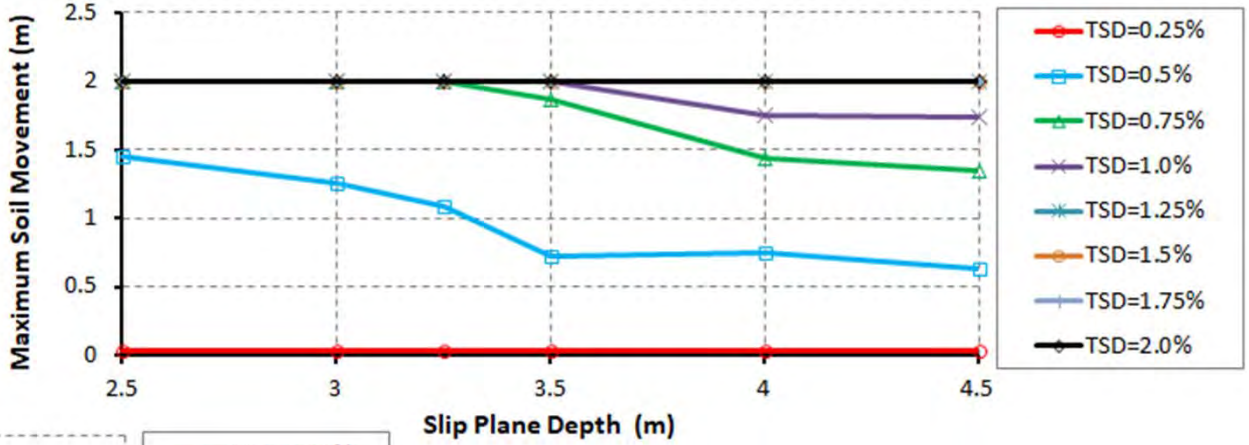


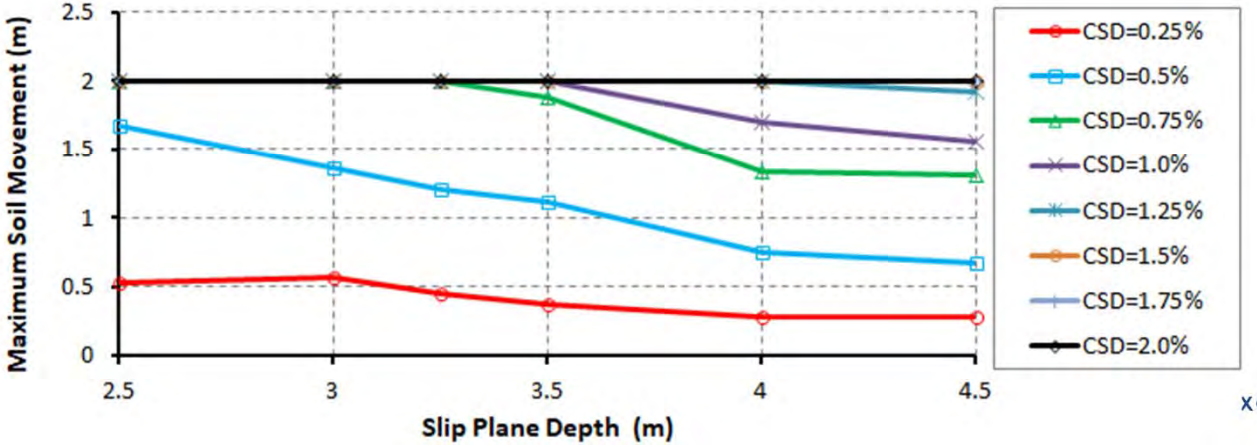




Slope Modelling Program - Sample Results

- **Present Results As Strain Demand Envelopes**
  - Results here for NPS 12 (D/t=71)
  - Can compare strain demand with resistance





Slope Modelling Results Sensitivity

- **By comparing all analysis results was able to define relative importance of problem parameters**

Higher Importance	Medium Importance	Lower Importance
- Magnitude of slope displacement - Slope displ. pattern (trans. vs rot.) - Slip plane depth - Slip plane toe angle, for deep slip planes	- Pipe diameter - Operating pressure - Temp. differential - Soil stiffness - Pipe-to-soil friction - Slip plane toe angle, for shallow slip planes	- Pipe wall thickness - Length of ground displacement - Material grade - Slope angle - Pipe depth of cover

Compiled Response Appendix

- **Describes analyses results for any application considering**
  - Pipe diameter, thickness, grade
  - Pressure temperature
  - Surface friction, depth of cover, slope angle
  - Slip length, depth, toe angle, depth below pipe
  - For each ground displacement
    - Define max tensile and compression strain
  - Displacements form 0.25m to 2m
- **Data provided in report tables and as a spreadsheet**
  - Support empirical model development for deterministic or probabilistic treatment

Application of Results

In the absence of detailed geotechnical report

1) Characterize soil type

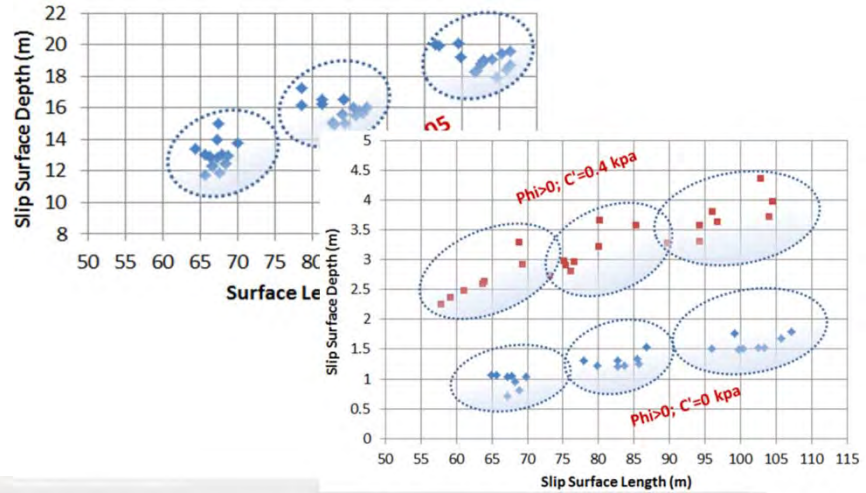
- high cohesion (clay)
- low cohesion (sand)

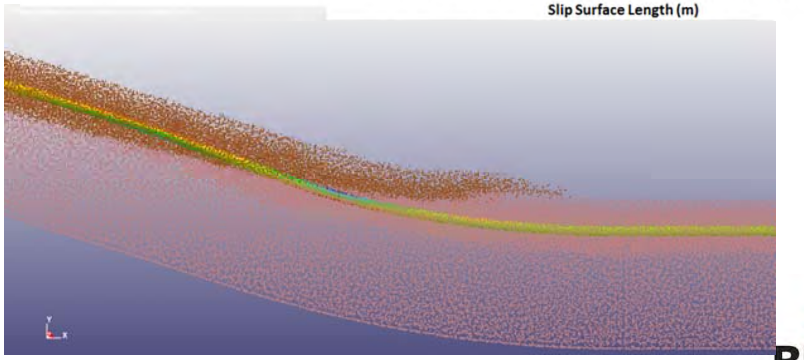
2) Define surface length of slope movement

3) Estimate depth of slope movement

4) Lookup strain demand

- Use tables of data with appropriate interpolation





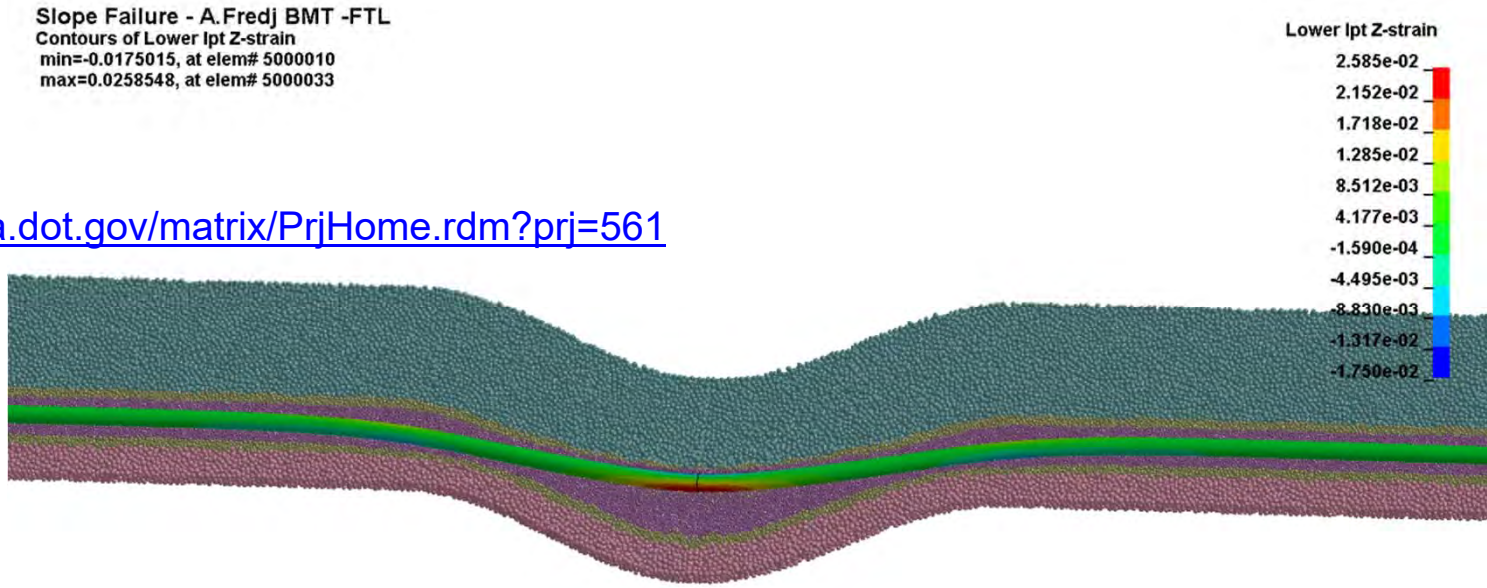
Application of Results – Conservative Interpolation

- **Since results are limited provide guidance on problem parameters to estimate conservative (higher) strains**

Parameter	Conservative Approximation
Pipe diameter	Smaller diameter
Wall thickness	Smaller wall thickness
Operating pressure	Lower operating pressure
Change in pipe wall temperature	Higher change in temperature
Material grade	Lower material grade
Soil friction magnitude	Higher friction
Depth of cover	Higher depth of cover
Slope angle	Higher slope angle
Slip surface length	Longer slip surface length
Slip surface depth	Higher slip surface depth
Slip surface toe angle	Higher slip surface angle

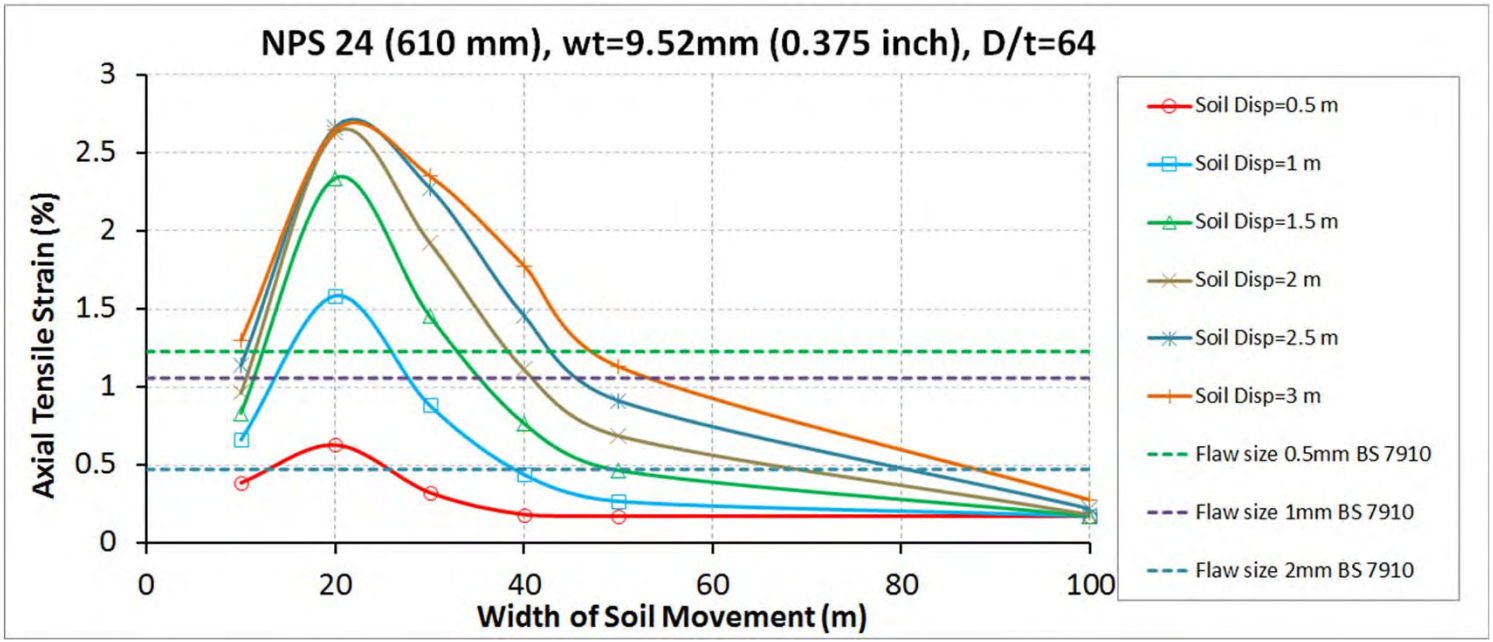
Parallel US DOT PHMSA Project

- **Parallel US DOT PHMSA Sponsored Project**
  - Considering soil movement across pipeline and subsidence
  - Considering sensitivity of pipe strain to geotech event parameters
    - *Pipe geometry and grade, soil, internal pressure, preload, width of ground movement*
  - Results in graphical and tabular form
  - Report available on US DOT PHMSA web site
  - https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=561



Parallel US DOT PHMSA Project

- **Considering soil movement across pipeline**
  - Sample result for a range of movement widths



Concluding Remarks

- **Project completion provides**
  - Description of geohazard assessment tool . . . Validated model
  - Understanding of relative importance of problem parameters
  - Methodology for conservatively estimating strain demand
  - Data to support screening or risk modelling

- **Similar modelling results can be used to explore**
  - Response to fault crossing or arbitrary angle movements
  - Complex or shallow surface loading effects on pipeline
  - Explore relationships between axial strains and flexural deformations to extend IMU ILI data

BACK TO AGENDA

PRCI 2020 Research Exchange

Guidance for Integrity Management of Buried Pipelines Subjected to Ground Movement

SBD-1-2 (PR-350-164501)

Yong-Yi Wang and Dunji Yu
Center for Reliable Energy Systems

Mike Cook, Project Lead
ExxonMobil

LEADING PIPELINE RESEARCH

Why Is this Subject Relevant?

- **The number of pipeline incidents at least partially attributed to geohazards is increasing in the US.**
  - Consistent with Steve Nanney's presentation at March 2019 ASME Conference on the management of geohazards
- **Geohazards have caused pipeline incidents in other parts of the world.**
- **Mitigating geohazards can be expensive.**

High-Level Premise of the Work

- **Every geohazard is different**
  - Not all geohazards lead to integrity concerns.
- **Post-event response differs, depending on**
  - Nature of the event
  - Location of the event
  - Level of impact on pipelines
  - Conditions of the pipelines
  - Short- and long-term ROW conditions
  - Access to site
  - Number of simultaneous events one has to deal with
  - Risk and consequences
  - Company philosophy
- **There has to be a rational evaluation process to make mitigation feasible.**
- **Appropriate response to each geohazard event varies depending on local conditions.**

Report Outline

- **Introduction**
  - Potential Geologic Hazards (Geohazards)
  - Possible Failure Modes of a Pipeline Due to Ground Movement
  - Longitudinal Stress and Strain Limits in Standards
  - Acceptance of FFS Assessment for In-Service Pipelines
- **Response after a Ground Movement Event – Flowchart**
  - Phase 1 – Immediate response
  - Phase 2 – Follow-on assessment and actions
  - Phase 3 – Long-term management
- **Appendices**
  - Appendix A – Pipeline and Site Records and Data
  - Appendix B – Guidance on Performing Strain-Based Assessment
  - Appendix C – Hazard Identification and Monitoring
  - Appendix D – Excavation Near Affected Pipelines
  - Appendix E – Examples of Continued Management
  - Appendix F – Examples of Responses to Ground Movement Events

Geohazards of Focus in the Response Plan

- Landslide
- Subsidence





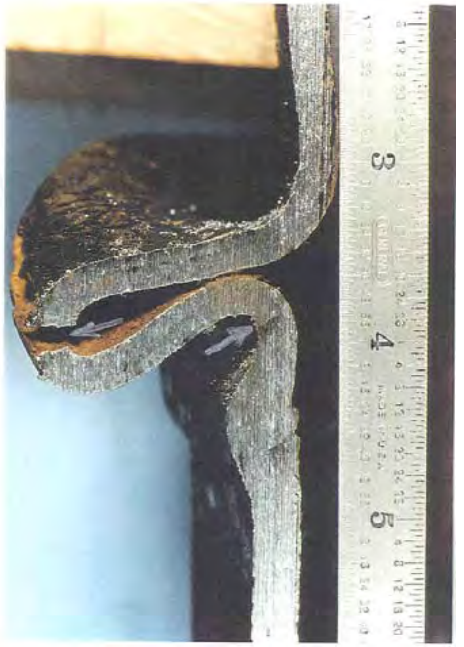
Potential Failure Modes - Immediate

- **Tensile leak/rupture**





- **Compressive buckling**
  - Buckles are usually not immediate integrity concerns.
  - In some cases, large buckles could cause leak.
    - *Circumferential crack due to overstraining in longitudinal direction*
    - *Seam weld integrity due to high hoop strain*



Potential Failure Modes – Delayed Failure of Wrinkles

- **Immediate considerations**
  - Regulatory requirements
  - Company requirements
  - Serviceability issue – pig passage?
- **Long-term considerations**
  - Is ground stable?
  - Would the buckle grow?
  - Fatigue failure of the buckle
  - Possible corrosion damage due to coating damage



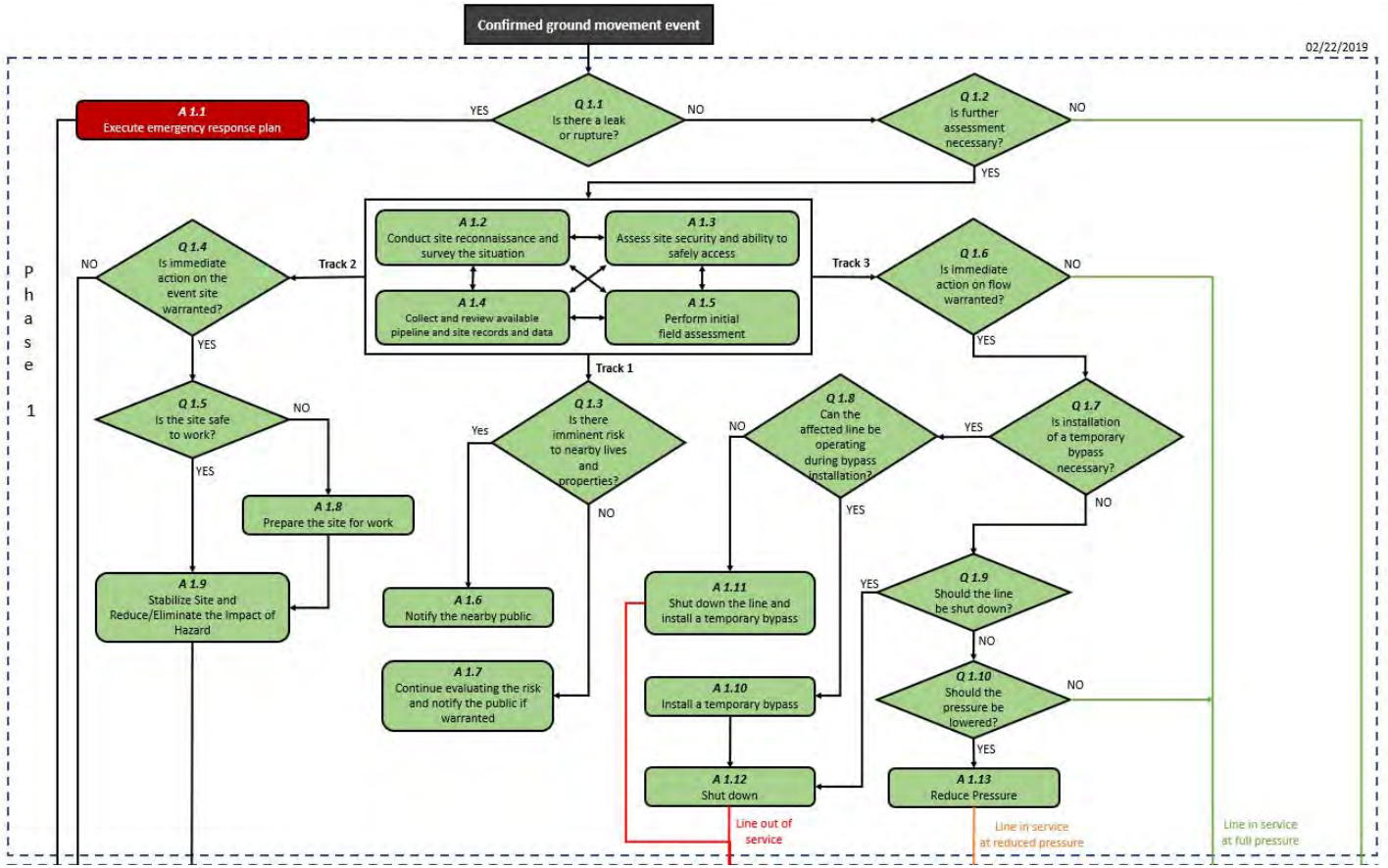
Response Plan after a Ground Movement Event

- **Scope**
  - Ground has moved; impact on the pipeline is unknown
  - Exclusions
    - *Impact on the pipeline is found to be minimal, e.g.,*
      - very small movement
      - pipe segments are confirmed being able to tolerate larger movements than that observed.
    - *Leak or rupture has occurred.*
- **Format of response plan**
  - Flowchart
    - *Questions → Answers → Actions*
  - Questions are explained in text.
    - *Most relevant questions are covered.*
  - Guidance is provided on answering the questions.
  - Actions are explained.

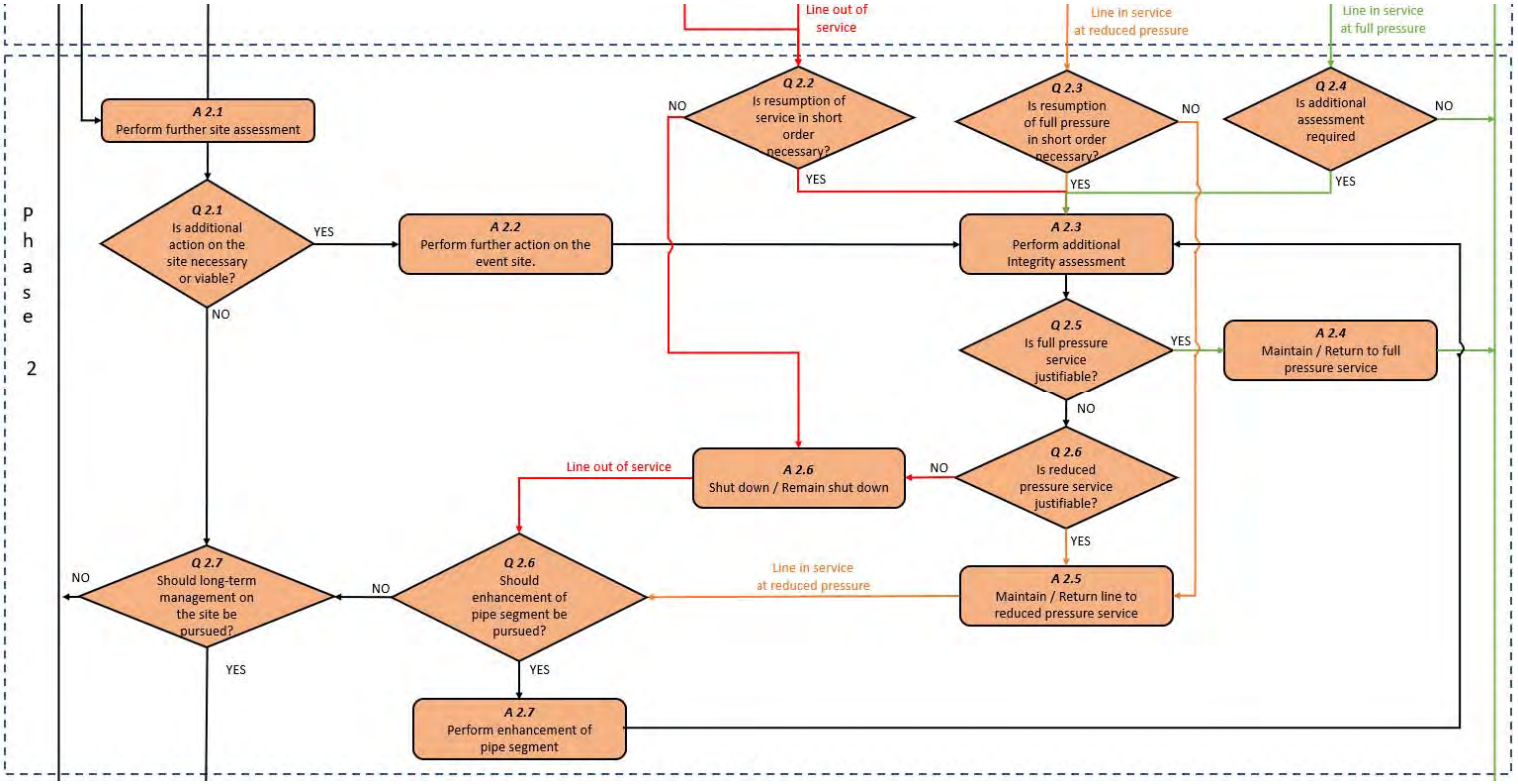
Three Phase Response Plan

- **Phase 1 – Immediate response**
  - Duration: a few days or weeks
  - Goal:
    - *Minimize the risk of pipeline failure*
    - *Reduce the potentially negative impact on properties and the environment*
- **Phase 2 – Follow-on assessment and actions**
  - Duration: weeks to months
  - Goal:
    - *Return the affected pipeline(s) to full service*
- **Phase 3 – Long-term management**
  - Manage long-term threats, if not completely addressed in prior phases
  - Goal: reduce and maintain risk to an acceptable level

Phase 1 – Immediate Response



Phase 2 – Follow-on Assessment and Actions



Phase 3 – Long-Term Management

- **Develop and execute long-term management plans**
  - Understand conditions that make Phase 3 necessary
  - Develop plans for long-term management
  - Execute long-term management
- **Options for long-term plans**
  - Reducing strain demand on the pipeline
  - Increasing strain capacity of the pipeline, and/or
  - Installing monitoring devices and establishing future intervention criteria.

Appendix A Pipeline and Site Records and Data

List of pipeline and site-specific records and data that can be useful for making decisions as a part of a response plan

- **Pipeline/Girth welding records**
  - Original construction:
    - *OD, WT, Grade, MTRs, MAOP/MOP, etc.*
    - *WPS, PQR, Inspection reports*
  - Modifications at location of incident
- **ILI records at location of incident**
  - IMU
  - Geometry tools (wrinkles/buckles, dents, etc.)
  - Crack tools
  - Girth weld anomaly
  - MFL (corrosion)
- **Site records**
  - Prior history of movement
  - Soil properties
  - Prior mitigation measures
- **Other records**

Appendix B Guidance on Performing Strain-Based Assessment

Terms and procedures for performing strain-based assessment

- **Assessment: comparison of strain demand and strain demand limit**
- **Strain demand limit = strain capacity × safety factor (less than 1.0)**
- **Determine tensile strain capacity (TSC)**
  - Default values
  - Using existing TSC models
- **Safety factor and strain demand limit in tension**
- **Safety factor and strain demand limit in compression**
- **Estimate strain demand**
  - Location of pipeline
  - Strain gage
  - IMU
  - Pipe/soil interaction

Appendix C Hazard Identification and Monitoring

Various monitoring techniques, applicability and limitations

- **Ground monitoring techniques**
  - Visual monitoring
    - *Rebar across scarps, titled trees, pipeline/landslide deflection, photography*
  - Subsurface monitoring
    - *Probe inclinometer, in-place inclinometer, ShapeAccelArray, extensometer conversion, time domain reflectometry, electronic maker system balls*
  - Land based surface monitoring
    - *Conventional and global positioning system surveys*
    - *Ground based LiDAR surveying*
  - Aerial/Satellite based surface monitoring
    - *Airborne LiDAR, InSAR*
- **Pipe monitoring techniques**
  - IMU
  - Strain gages
  - Other emerging tools

Appendix D Excavation Near Affected Pipelines

Provides additional considerations when excavating in areas of geohazards

- **Possible state of loading on pipeline**
  - Tension, compression, bending, or combination of tension/compression and bending
- **Orientation of movement relative to pipe segment**
  - Parallel, oblique, perpendicular
- **Considerations for excavation**
  - Safety to the crew and public
  - Environmental impact
  - Integrity of pipelines, including nearby pipelines
    - *Mechanical damage*
    - *Buckles*
    - *Further soil movement*

Appendix E Samples of Long-Term Management

Examples of long-term approaches to possible future ground movements

- **Example No.1**
  - Background
    - *Multiple girth weld failures occurred in a relatively old pipeline system.*
  - Actions:
    - *Vintage pipes/welds were replaced in areas with geohazards.*
    - *A multi-tier monitoring program was developed.*
- **Example No. 2**
  - Background
    - *A girth weld rupture occurred due to low strain capacity and nominal settlement load.*
  - Actions
    - *The strain capacity of various types of girth welds was evaluated.*
    - *A screening process was developed by comparing identified IMU bending strain features and strain capacity.*
    - *Type-B sleeves were installed on welds that did not pass the screening criteria.*

Appendix E Samples of Long-Term Management

Examples of long-term approaches to possible future ground movements

- **Example No. 3**
  - Background
    - *Lateral movement of a pipeline was observed due to a nearby excavation activity.*
  - Actions
    - *The line was shutdown and segment was exposed.*
    - *The welds were X-rayed and accepted/mitigated on the basis of FFS-derived acceptance criteria.*
    - *Site stabilization measures were implemented.*
- **Example No. 4**
  - Background
    - *A rupture occurred on a pipeline partly due to ground movement.*
  - Actions
    - *A temporary above-ground segment was installed with strain monitoring and action threshold.*
    - *A new segment was installed via HDD so the pipeline would be below the ground movement.*

Thank You!

- Q&A
- Further contact
  - ywang@cres-Americas.com
  - 614-376-0765