Overview

- Observed circumferential crack growth cases & modeling
- Spiral weld fatigue loading
- Spiral weld fatigue test result and growth model comparison
- Pump station proximity – pressure scaling
- Off-axis crack limit state (burst) model
- Surviving flaw theory review
- Applying surviving flaw theory to off-axis cracking

Industry Composite: A,B,C growth, D dormant

TABLE 1 OBSERVED GIRTH WELD FATIGUE GROWTH AND NO-GROWTH CASE DATA

Case & Grade	OD, in	WT, in	Defect Size, depth x length, in	TSC, %	API-579 Solution	Actual TCL, years	Predicted TCL, years
A, X52	34	0.281	0.219 x 7.25	0.18	9B.5.13	21	24
B, X52	34	0.281	0.211 x 34	0.11	9B.5.7	36	0
B_i			0.211 x 13.5	0.14	9B.5.13	36	12
B_{ii}			0.211 x 5	0.22	9B.5.13	36	34
C, X52	24	0.500	0.275 x 4.32	0.22	9B.5.13	70*	571
D, X52	34	0.357	0.17 x 2.13	0.44	9B.5.13	∞	6200

*Near through-wall, no leak.

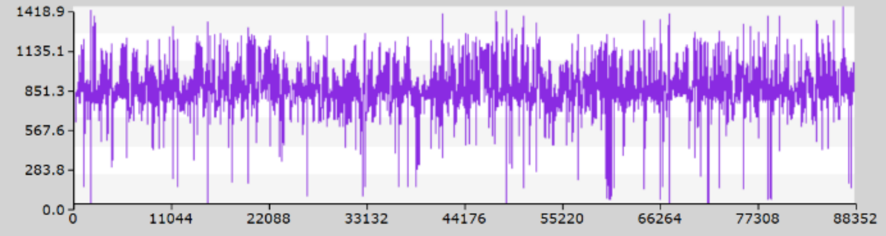
Case	Pump Sta. Distance miles	Pressure Scaling Factor	Bend Prox-imity	SSI_{13} Annual Cycles	Carbon %, CE	PTCL c/w 26 ksi tension, years	PTCL c/w hi heat residual., years
A	13.3	0.80	N/A	3500	0.27,0.58	17	23
B_{ii}	16.0	0.85	N/A	3500	0.30,0.60	23	32
C	0.9	1	N/A	2590	0.29,0.48	389	489
D	2.5	0.97	N/A	1340	N/A	3210	4780

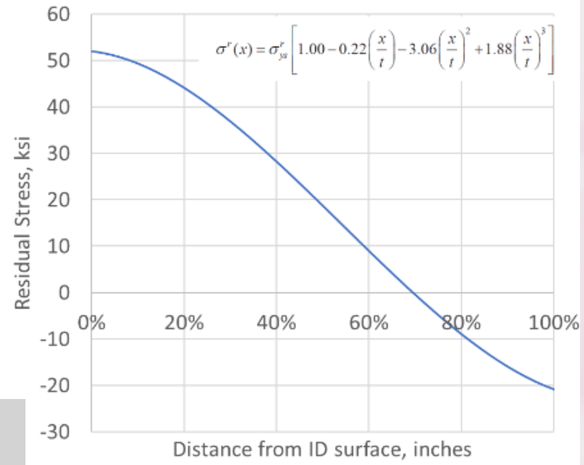
Case B was a very long crack, effective length much shorter

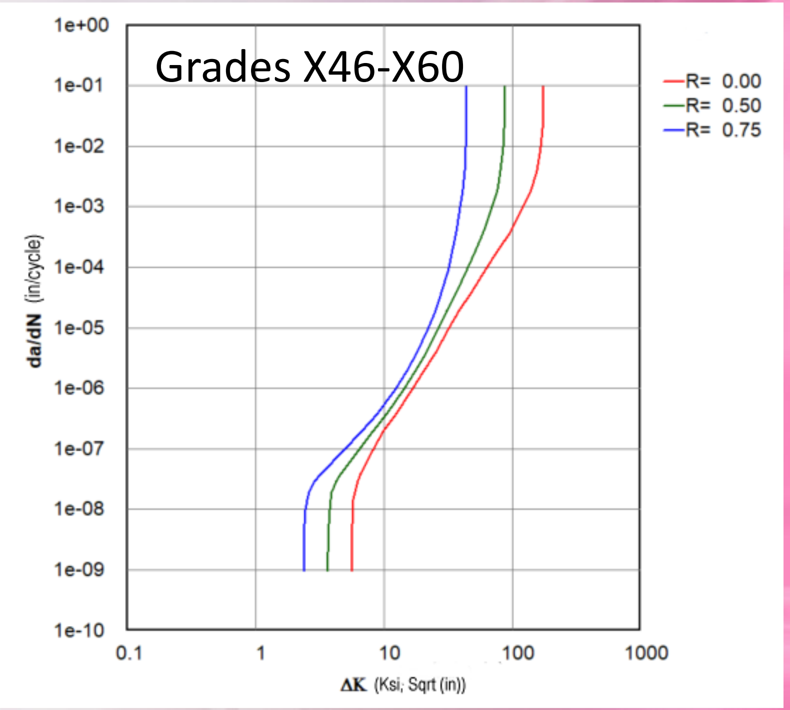
Case C was a bit of head scratcher at first. Slow growth is predicted, and striation zone matches expectation – Theory: crack grew into a weld imperfection and jumped to near through-wall.

Growth Modeling Performance

- AFGROW application
- Tabular da/dN, AFMAT database
- API-579 9B.5.13Stress intensity ***0.6**
- Steady stress compensation capable
- Sample 1-year pressure history:

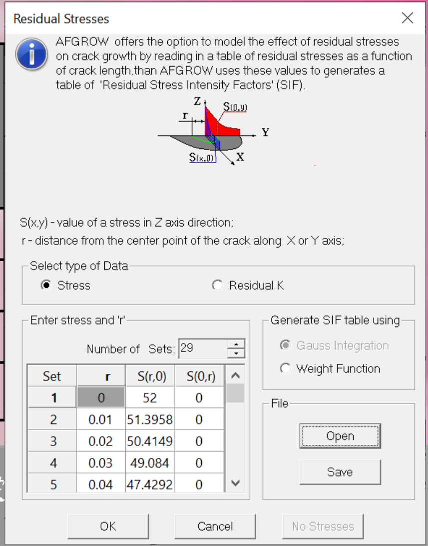






Growth model works for circumferential orientation, but what about spiral weld (helical) orientation?

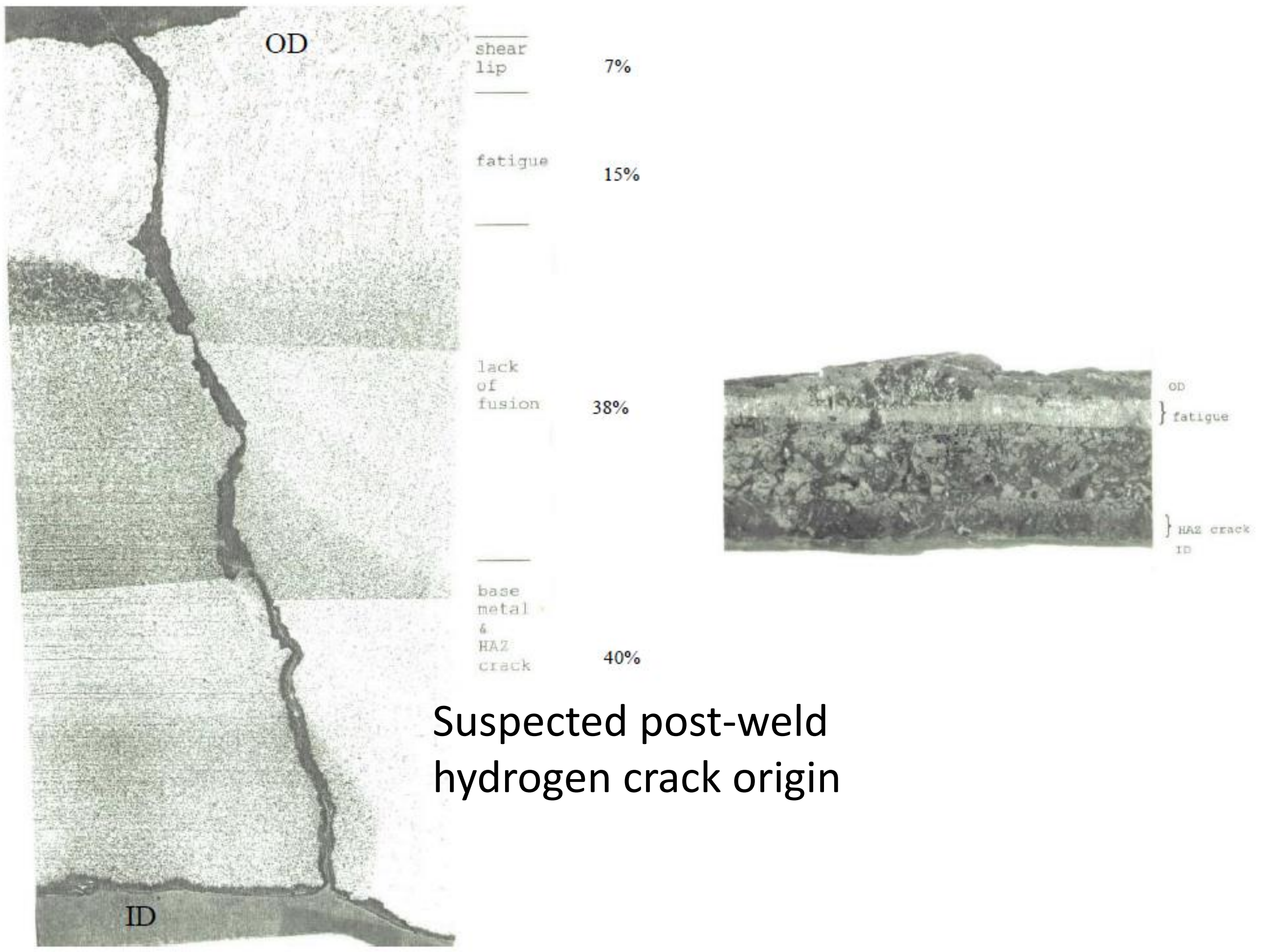
Case	Pump Sta. Distance miles	Pressure Scaling Factor	SSI_{13} Annual Cycles	Actual Life, years	Predicted Life, years	Life with 26 ksi tension, years	Life with hi heat residual., years
A	13.3	0.80	3500	21	24	17	23
B_{ii}	16.0	0.85	3500	36	34	23	32
C	0.9	1	2590	70	571	389	489
D	2.5	0.97	1340	∞	6200	3210	4780



Observed Circumferential Crack Growth, Case A

Grade	OD, in	WT, in	Defect Size, depth x length, in	Time to Leak, years
X52	34	0.281	0.219 x 7.25	21

- At girth weld
- 1967 construction, 1988 leak
- 13.3 miles from pump station
- Pressure scaling factor: 0.8
- $SSI_{13\ ksi}$: 3500 annual cycles
- % Carbon: 0.27
- Carbon Equivalent: 0.58%
- Not close to a bend
- Crack + LOF: 78%



Suspected post-weld hydrogen crack origin

API 579 Model Geometry and Dimensions

Geometry | Dimension | Load

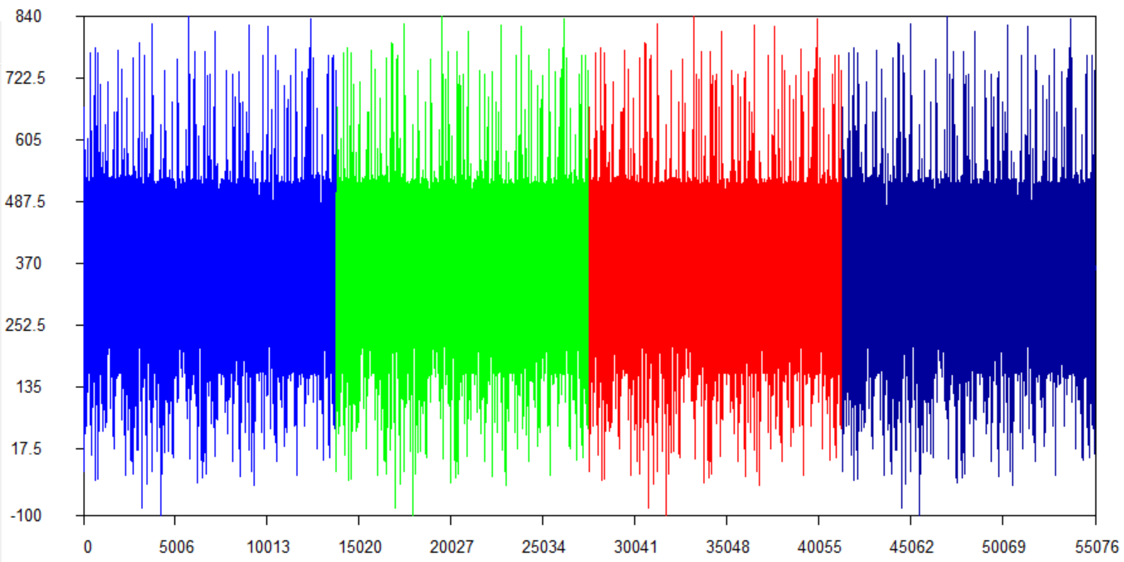
Select Solutions

- (•) Pressure

Stress Distribution: ( ) Weight Function ( ) Polynomial

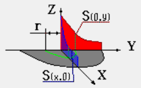
Select crack geometry by clicking on corresponding icon

Model	Description of the Configurations	Beta Solution
☐	Longitudinal Through Crack In Cylinder (9B.5.1)	Application De...
☐	Circumferential Through Crack In Cylinder (9B.5.3)	Application De...
☐	Infinite Longitudinal Surface Crack In Cylinder (Internal) (9B.5.4)	Application De...
☐	Infinite Longitudinal Surface Crack In Cylinder (External) (9B.5.4)	Application De...
☐	Circumferential Crack In Cylinder (Internal) (9B.5.7)	Application De...
☐	Circumferential Crack In Cylinder (External) (9B.5.7)	Application De...
☐	Longitudinal Surface Crack In Cylinder (Internal) (9B.5.10)	Application De...
☐	Longitudinal Surface Crack In Cylinder (External) (9B.5.10)	Application De...
☑	Circumferential Surface Crack In Cylinder (Internal) (9B.5.13)	Application De...
☐	Circumferential Surface Crack In Cylinder (External) (9B.5.13)	Application De...



Residual Stresses

AFGROW offers the option to model the effect of residual stresses on crack growth by reading in a table of residual stresses as a function of crack length,than AFGROW uses these values to generate a table of 'Residual Stress Intensity Factors' (SIF).



S(x,y) - value of a stress in Z axis direction;
r - distance from the center point of the crack along X or Y axis;

Select type of Data: (•) Stress ( ) Residual K

Enter stress and 'r' — Number of Sets: 29

Set	r	S(r,0)	S(0,r)
1	0	26	26
2	0.01	26	26
3	0.02	26	26
4	0.03	26	26
5	0.04	26	26

Generate SIF table using: ( ) Gauss Integration ( ) Weight Function

File: Open | Save

CASE A

API 579 Model Geometry and Dimensions

Geometry | Dimension | Load

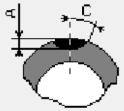
Model dimensions are initialized to default values at start-up or when a new model configuration is selected.

Enter specimen dimensions

Outer Diameter (Do): 34

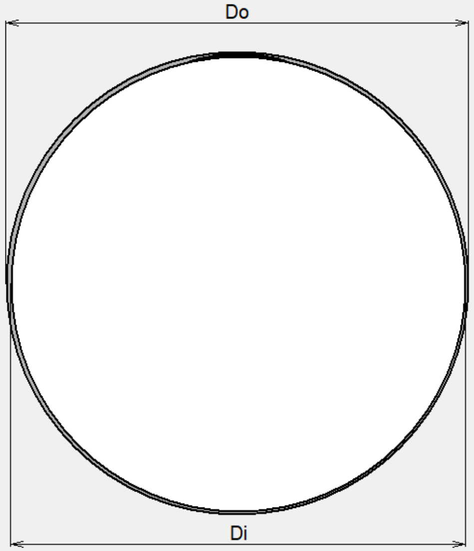
Inner Diameter (Di): 33.438

Enter crack dimensions



Crack Length -'C' Direction: 3.625

Crack Length-'A' Direction: 0.2192



OK | Cancel | Apply | Help

Spectrum

Spectrum Multiplication Factor [SMF] multiplies the stress or load levels found in spectrum files.This allows normalized spectra to be used. If actual stress levels are used in the spectrum files, SMF should be set to 1.

Residual Strength Requirement [Pxx] is the value of stress (or load for models using load input) which must be carried at all crack sizes. It is used to determine the critical crack size - if a non-zero value is entered.

Preload [PL] is used to account for pre-existing stresses. This value is added to the max and min spectrum stresses after they have been multiplied by SMF.

Enter

Spectrum Multiplication Factor(SMF): 0.00048

Residual Strength Requirement (Pxx) : 0

Preload (PL) : 0

Poisson governs:
0.3/0.5 = **0.6**
Scaling factor @ 13.3 miles: **0.8**
Psi to ksi: **0.001**
0.6*0.8*0.001=
0.00048

Case C – Slow Growth to Interacting Flaw(?)

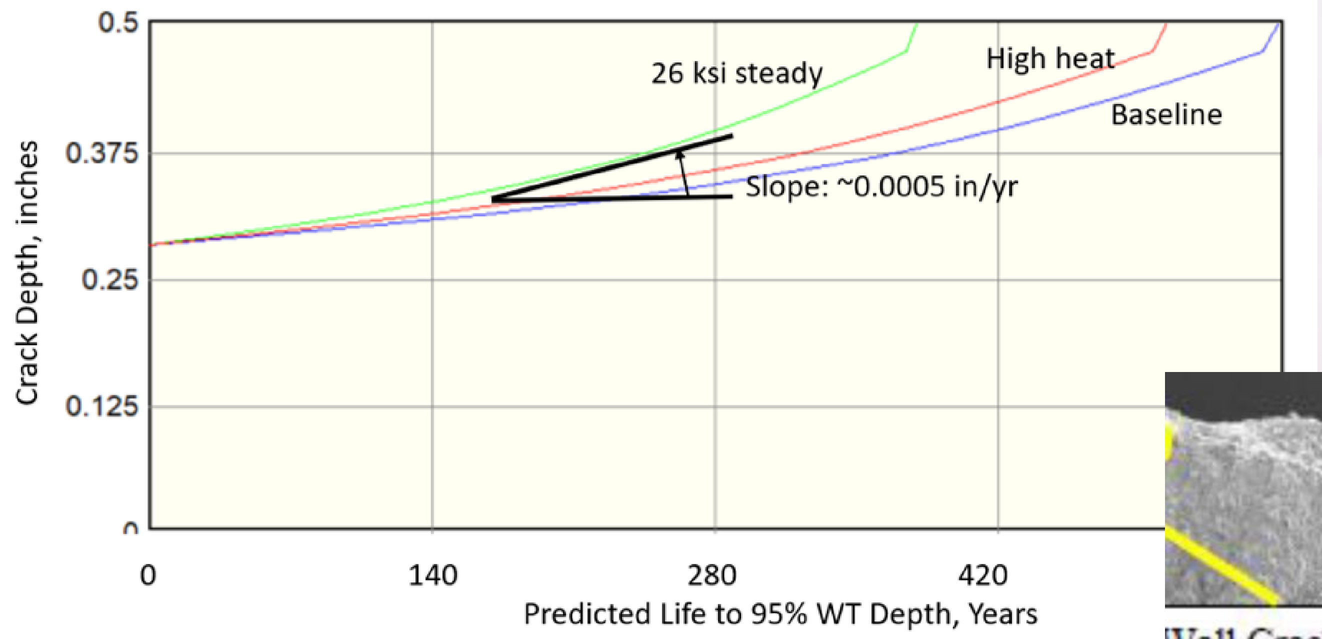
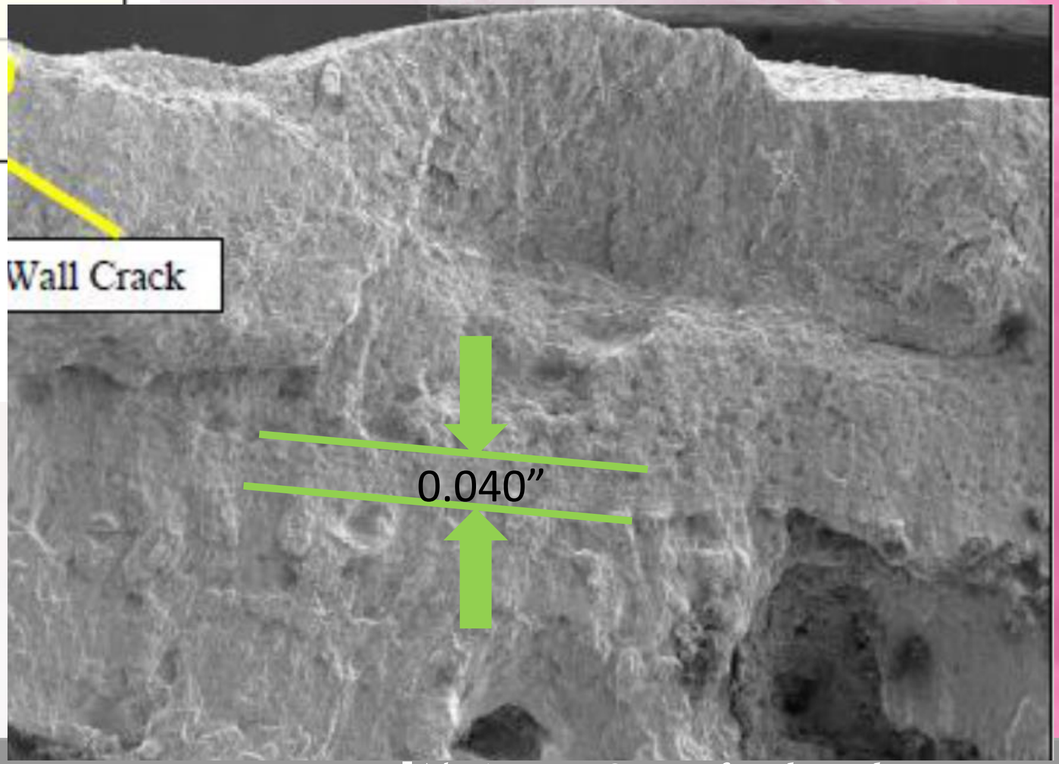


FIGURE 2 CASE C CRACK GROWTH RATE COMPARISONS

70 yr * 0.00051 in/yr = 0.0036", roughly matching the observed high cycle striation zone width of 0.040".



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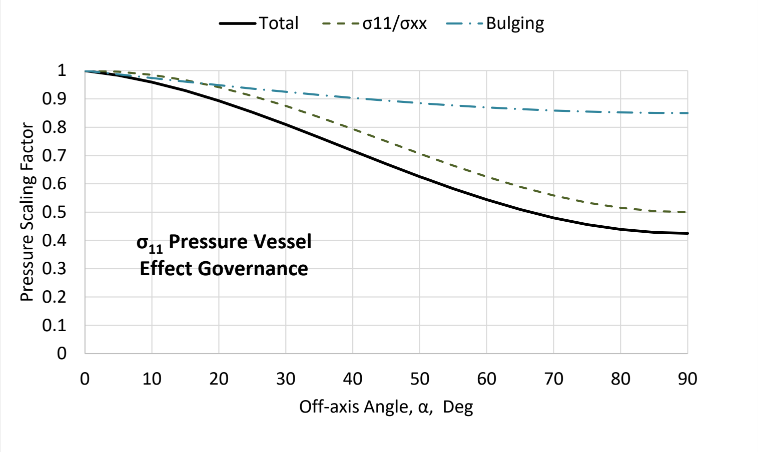
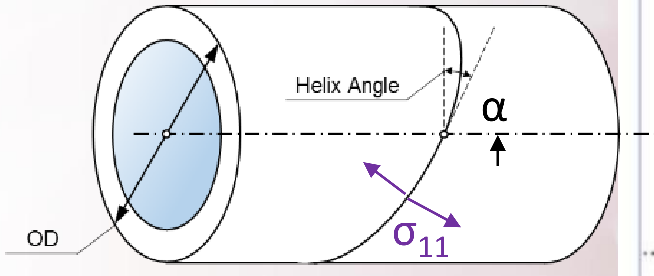
Spiral Weld Fatigue Loading

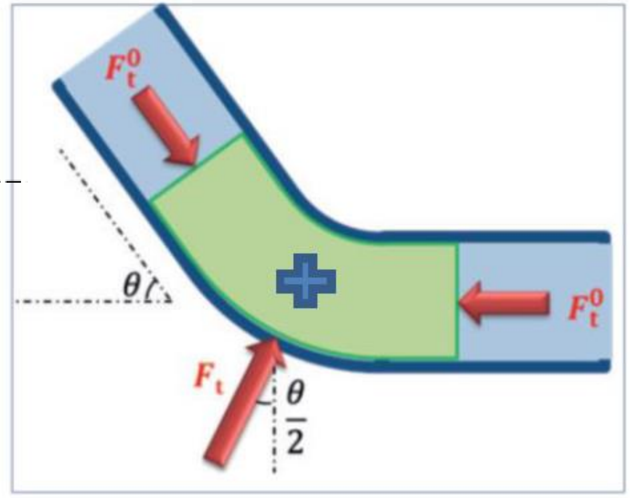
- Pressure effects only
- Thermal/seasonal not shown
- Mode 1 growth domination
- Shear stress effects neglected
- Bulging factor decay

TABLE 2 PREDOMINATE NORMAL STRESS CONTRIBUTION, INTERNAL PRESSURE, VARIABLE FLAW ORIENTATION & LOCATION

Orientation	Location	Predominate Normal Stress	Other Stresses
Longitudinal	Any	Hoop	Negligible
Circumferential	Above ground	0.5 Hoop	External forces
Circumferential	Buried, close to bend	0.5 Hoop	External forces
Circumferential	Buried, far from bend	0.3 Hoop	External forces
Spiral weld angle	Above ground	Resolved c/w 0.5 Hoop Long.	External forces
Spiral weld angle	Buried, close to bend	Resolved c/w 0.5 Hoop Long.	External forces
Spiral weld angle	Buried, far from bend	Resolved c/w 0.3 Hoop Long.	External forces







$$\sigma_{11} = \sigma_{xx} (\cos \alpha)^2 + \sigma_{yy}(\sin \alpha)^2 \qquad \text{Equation 2}$$

where:

σ_{11} = stress normal to off-axis plane at angle α
σ_{xx} = hoop stress
σ_{yy} = longitudinal stress
α = angle from pipe axis to off-axis plane

Spiral Weld Fatigue Test and Growth Model Result Comparison

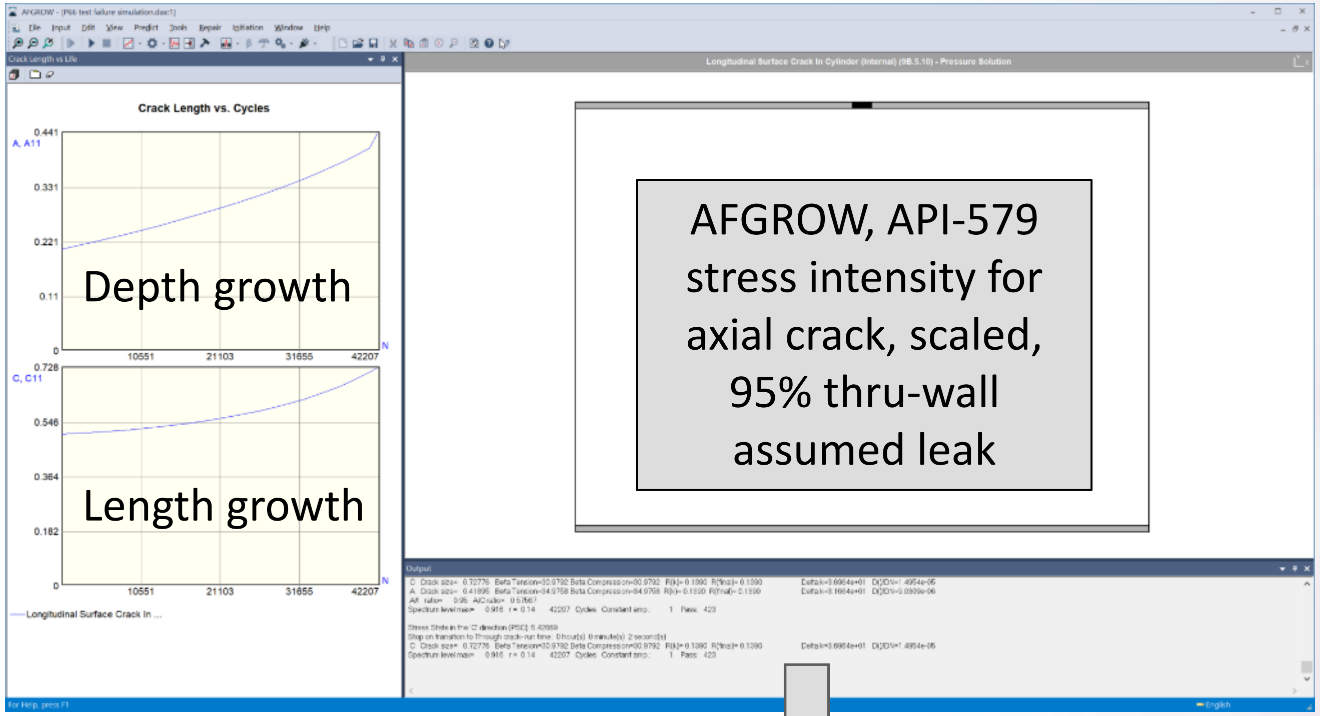


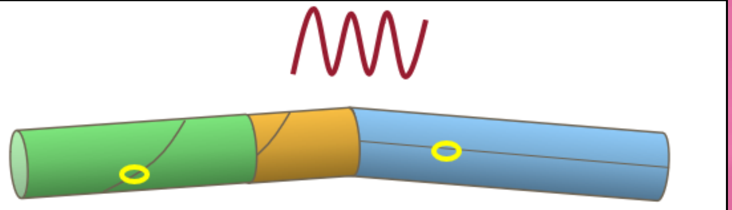
TABLE 3 SPIRAL WELD FATIGUE TEST LEAK SUMMARY

Parameter	Value	Comments
Grade, Dia.	X70, 30 in	
Wall Thickness	0.441 in	
Spiral weld angle, α	50.8°	DSAW
Cycles to leak	44,240	
Min Pressure	206 psi	10% SMYS
Max Pressure	1482 psi	72% SMYS
Stress Ratio	0.139	
Years @ 2500 SSI$_{13}$	658, 3294	Note 1
Years @ 5000 SSI$_{13}$	329, 1647	Note 1
Years @ 10000 SSI$_{13}$	165, 824	Note 1
Initial flaw length	~1 in	$=0.27\sqrt{Dt}$
Initial flaw depth	~45%	
Total Scaling Factor	0.618	Figure 11
AFGROW life, cycles	42,200	
@thru-wall length	1.45 in	(AFGROW)

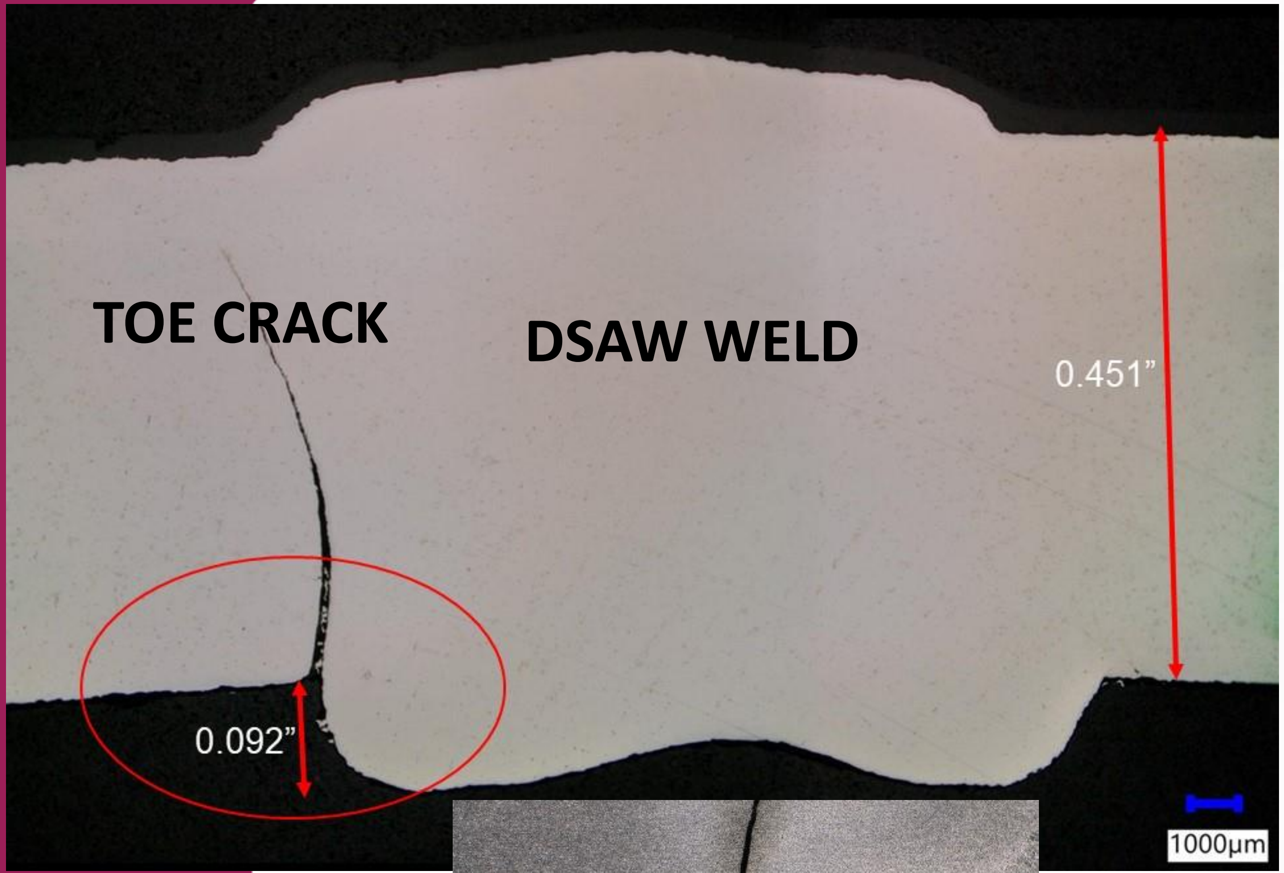
Note 1. SSI$_{13}$ per Equation 1. Equivalent years are: above ground, buried.

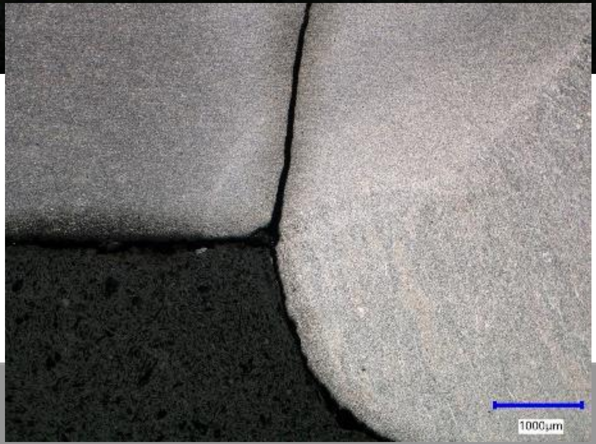
Output

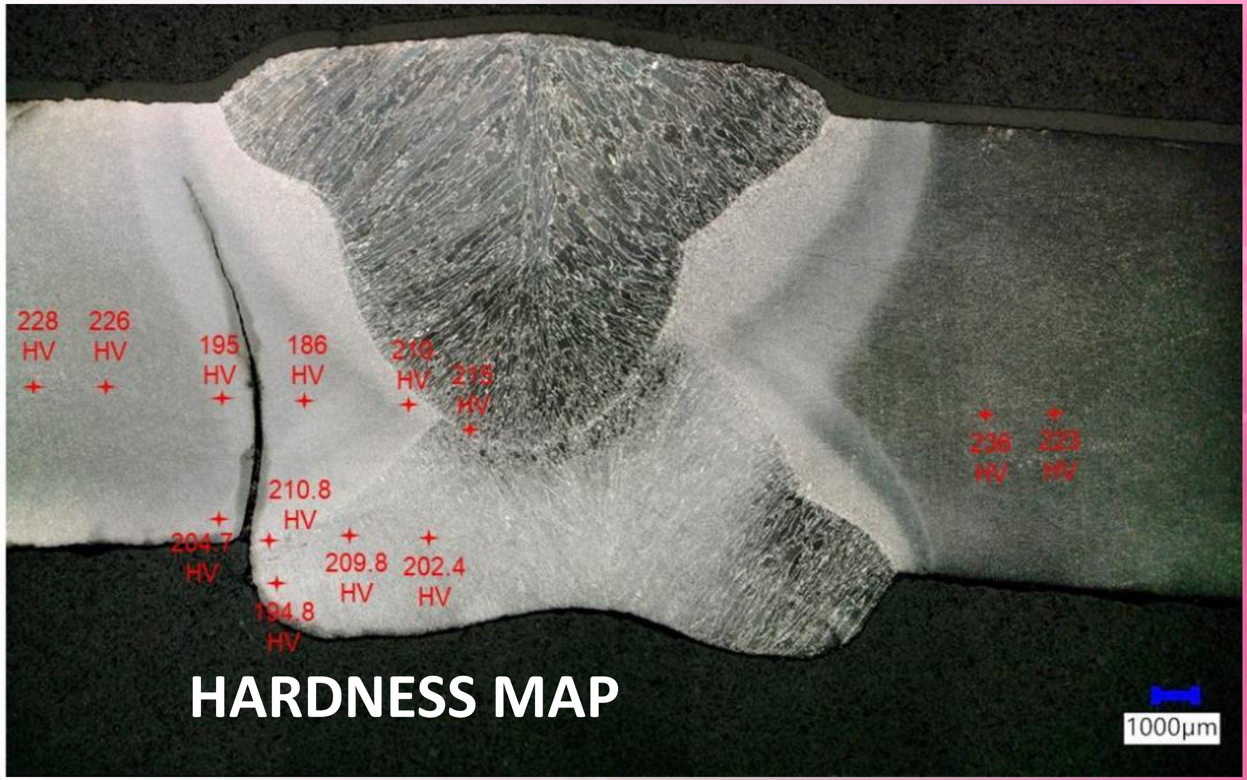
```
C  Crack size=  0.72776  Beta Tension=30.9792 Beta Compression=30.9792  R(k)= 0.1390  R(final)= 0.1390     Delta k=3.6964e+01  D()/DN=1.4954e-05
A  Crack size=  0.41895  Beta Tension=34.9758 Beta Compression=34.9758  R(k)= 0.1390  R(final)= 0.1390     Delta k=3.1664e+01  D()/DN=9.0309e-06
A/t  ratio=    0.95   A/C ratio=   0.57567
Spectrum level max=    0.916   r = 0.14     42207  Cycles   Constant amp.:     1   Pass:  423

Stress State in the 'C' direction (PSC): 5.42669
Stop on transition to Through crack- run time:  0 hour(s)  0 minute(s)  2 second(s)
C  Crack size=  0.72776  Beta Tension=30.9792 Beta Compression=30.9792  R(k)= 0.1390  R(final)= 0.1390     Delta k=3.6964e+01  D()/DN=1.4954e-05
Spectrum level max=    0.916   r = 0.14     42207  Cycles   Constant amp.:     1   Pass:  423
```



Spiral DSAW Fatigue Test Leak

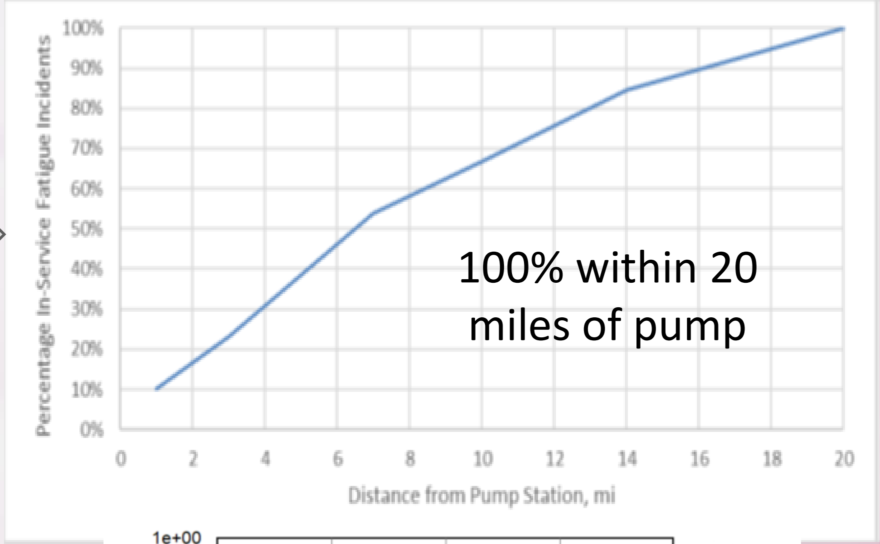


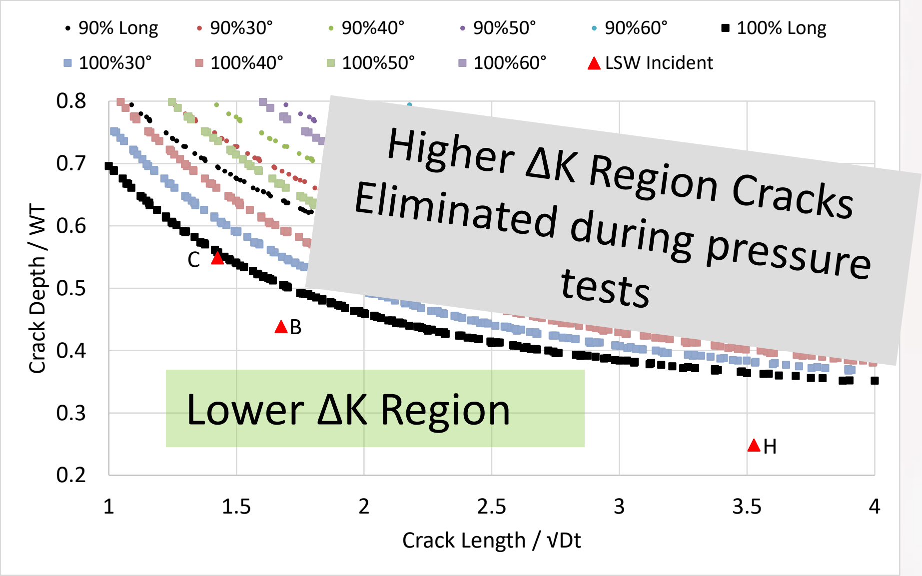


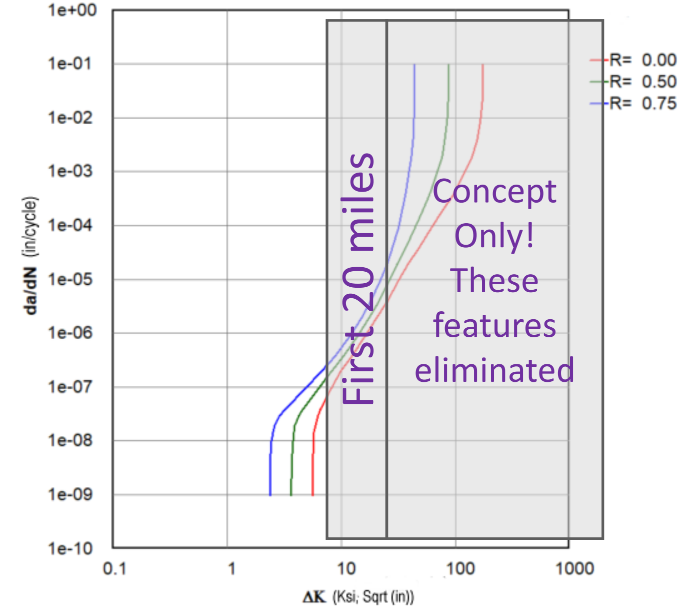


Pump Station Proximity Susceptibility Driver

- What be learned from axial crack?
- 39 confirmed fatigue events
- 57 fractures beyond 20-mile marker confirmed no fatigue
- Surviving flaw theory accounts for this







Off-Axis Limit State (Burst) Model

- General performance to unity
- Length cap needed
- Data is sparse
- KorLAS axial crack model
- Projected length
- Flow stress solution for grooves
- Toughness constraint correction: 1.5
- A limit state model is needed to quantify surviving flaw sizes.

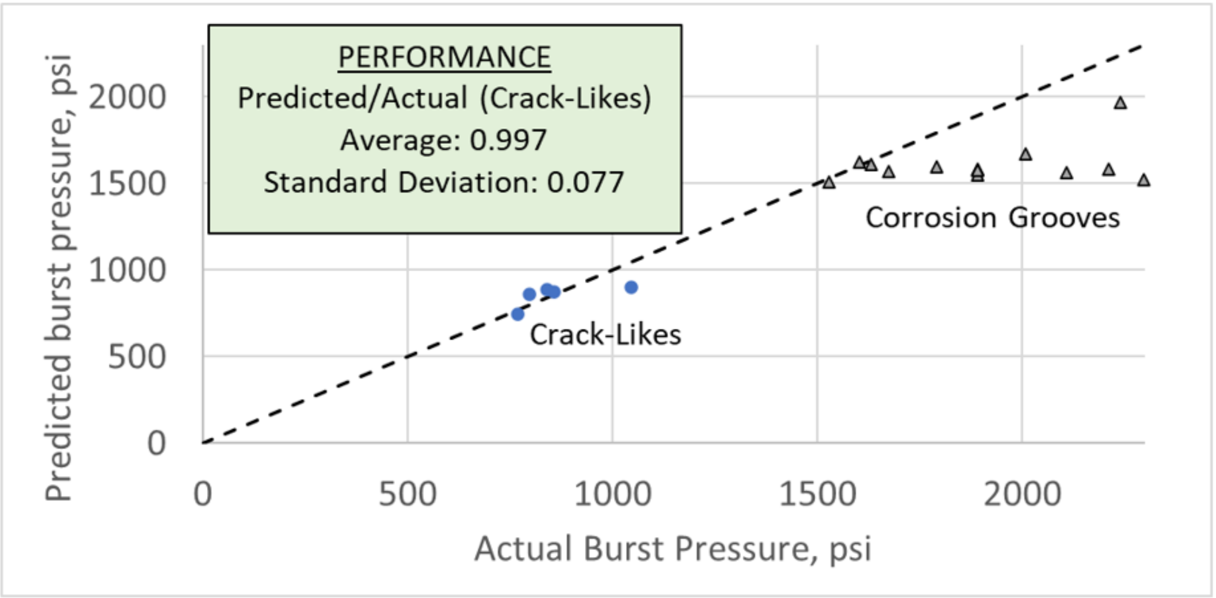


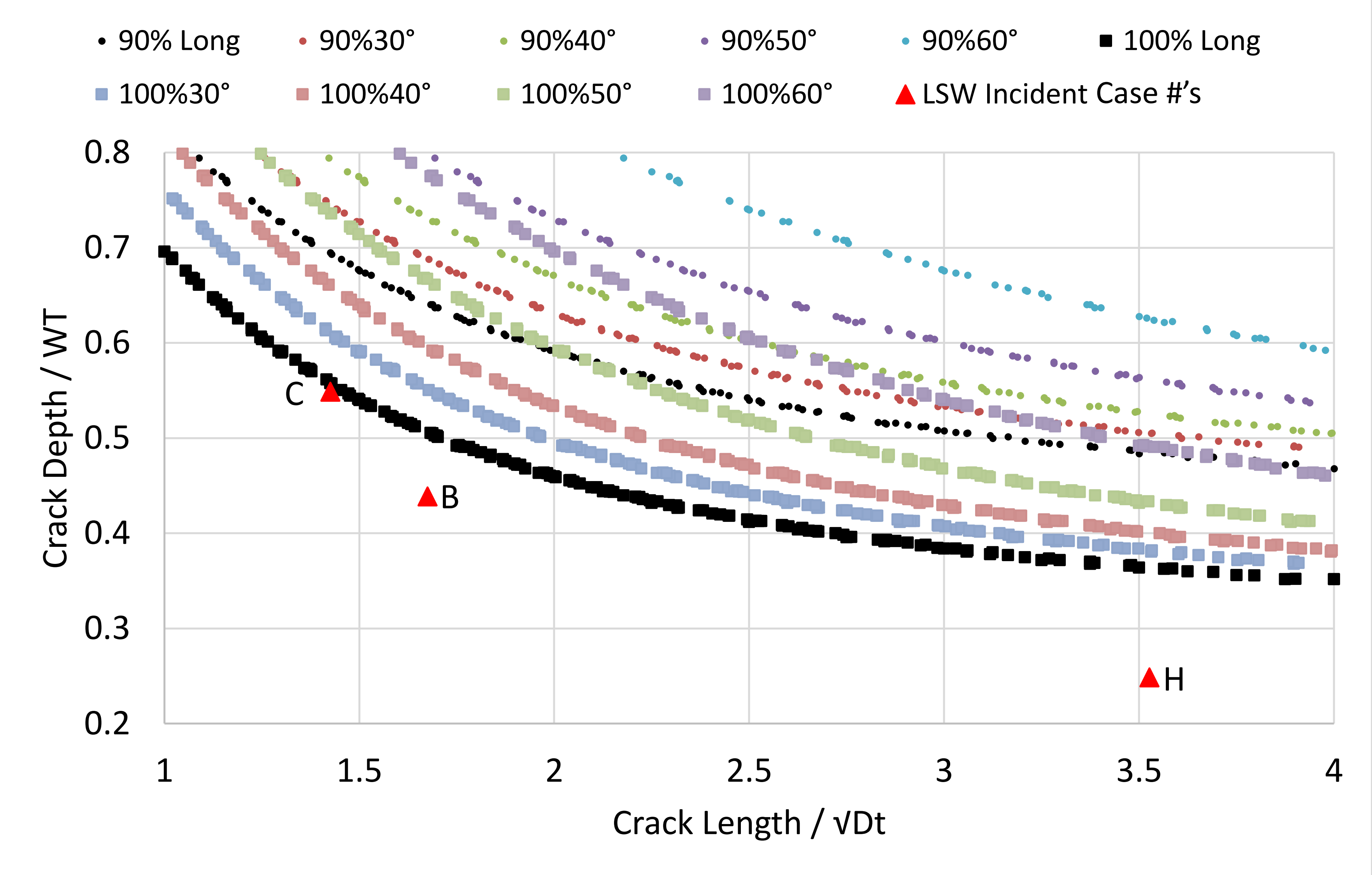
FIGURE 5 BURST MODEL PERFORMANCE TO UNITY

Longitudinal Seam Weld Crack Incident Validation Review

Incident & Grade	OD, in	WT, in	Defect Size, in	SSI_{13} Annual Cycles	Actual TTF, years	Level 2 TTF, years	Implied LRF
A, X52	30	0.254	0.136 x 8.0	898	4.5	3.2	<1.0
B, X70	24	0.328	0.144 x 4.7	2684	14	7.9	<1.0
C, X70	24	0.328	0.180 x 4.0	2300	9	2.2	<1.0
D, X52	34	0.280	0.112 x 5.0	2732	5	2.0	<1.0
E, X52	26	0.281	0.080 x 3.1	2200	50	49	<1.0
F, X52	26	0.281	0.090 x 5.0	2200	50	24	<1.0
G, X52	34	0.344	0.090 x 13	1253	50	76	1.5
H, X70	30	0.386	0.096 x 12	3506	10	24	2.4

$$SSI = N_{eq} = \frac{\sum_{i=1}^{n} \Delta p_i^n N_i}{\Delta p_{eq}^n}\left(\frac{1\ year}{\Delta t}\right)$$

Surviving Flaw Theory Review, Grade X70



Conclusions

- Circumferential crack growth AFGROW modeling insights:
  - ✓ Poisson effect appears to govern buried pipelines
  - ✓ Pressure scaling effect appropriate
  - ✓ Confidence in dormancy prediction
- Spiral weld fatigue test and AFGROW modeling insights:
  - ✓ AFGROW prediction matches test – exactly
  - ✓ Crack did not turn and reorient longitudinally as originally expected
  - ✓ Surviving flaws may be bounded – and are relatively small

Ongoing and Future Work

- More burst data needed to validate/refine limit state model
- More fatigue growth tests of spiral weld flaws needed
- Susceptibility methodology can be greatly expanded
- NSERC project at the University of Alberta supporting these goals
  - Extensive lab test program, coupon and full scale
  - Machine learning element
  - Net Carbon Zero 2050 – free hydrogen risk escalator consideration
  - Liquid flow stagnation pressure effects at bends
- PRCI project IM-3-05 kicking off to amplify utility of NSERC project
- NDE-4-24 (Circumferential Crack Risk Framework) results can be leveraged for quantitative risk assessment & geohazard linkage

Questions?

Thanks for attending, questions and comments are welcomed.

Lyndon.lamborn@enbridge.com