Comparison of Circumferential Flaw Growth of xLPR vs MRP-216 R1 FEA Natural Flaw Growth

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3rd International Seminar on Probabilistic Methodologies for Nuclear Applications
Rockville, MD
October 22-24, 2019

MRP-216R1 Context

- Addressed the potential need for accelerated refueling cycles or mid-cycle outages in response to crack indications in pressurizer nozzle Alloy 82/182 dissimilar metal butt welds at Wolf Creek (October 2006)
- By demonstrating leak detection as a means to preclude rupture, MRP-216 R1 successfully addressed the short-term safety concern of potential circumferential cracking of other nozzles not yet effectively examined or mitigated across other plants
- MRP-216 R1 utilized FEACrack, ANSYS, and PICEP to perform crack growth, stability, and leak rate simulations from initiation until critical size
- Advanced FEA (AFEA) to simulate “natural” flaw shape development allowed removal of unnecessary conservatism that surface flaws retain a semi-elliptical profile while growing

Previous xLPR Benchmarking with FEA

- xLPR was benchmarked to AFEA as part of the Framework acceptance testing (2016) (xLPR-STRR-FW-Acceptance V1)
- Several axial cracks from industry OE were modeled using both deterministic xLPR and AFEA
  - VC Summer Unit 1 (2000)
  - North Anna Unit 1 (2012)
- Crack shape as a function of time was compared between the two modeling approaches

Previous xLPR Benchmarking with FEA (cont'd)

VC Summer Case

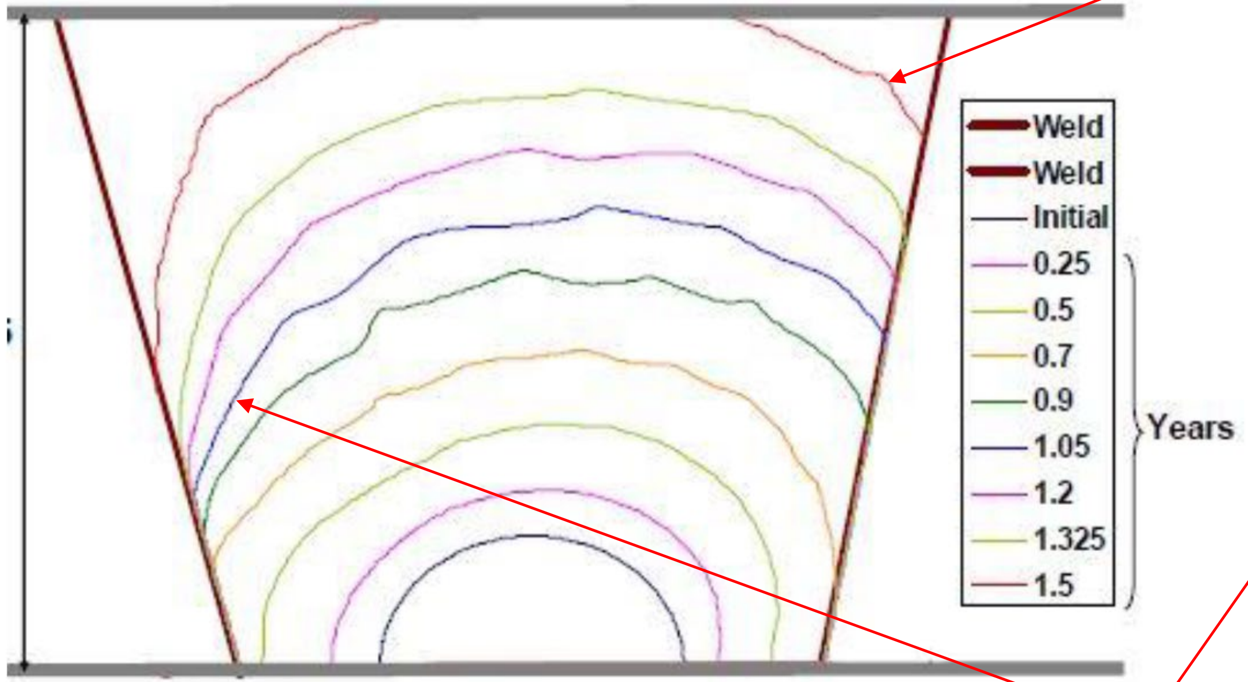
AFEA

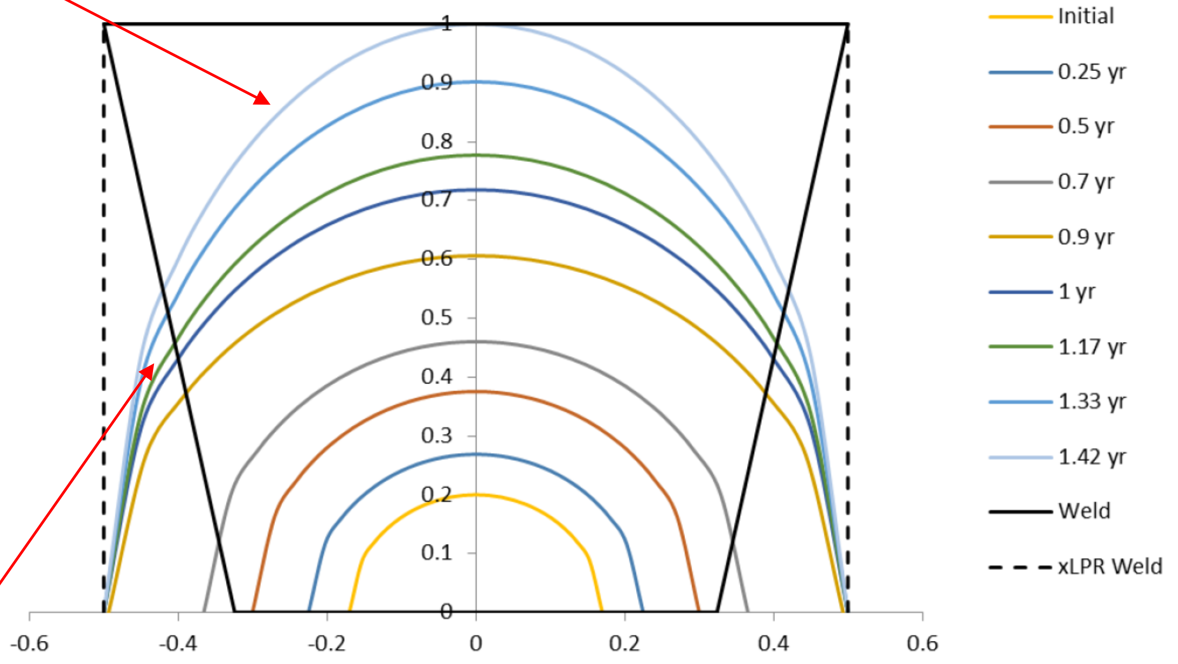
Figure 22 of xLPR-STRR-FW-V1

xLPR

Figure 26 of xLPR-STRR-FW-V1

TW @ approx. 1.5 years





Similar growth lines near edge of weld

MRP-216R1 vs xLPR Crack Shape/Growth

MRP-216R1

- FEA used to calculate crack shape development
- K-distribution is calculated at each point along the crack profile
- Growth at each point normal to the crack front determined by K at that location and MRP-115 crack growth equation
- Transition to TW occurs at 93% depth
- Shape of new TW crack taken as the final surface flaw profile but with areas where less than 10% of wall thickness remains converted to an open crack face

xLPR

- FORTRAN module used to implement MRP-115 crack growth equation
- K is calculated at ID surface tips and deepest point (or surface tips for TW flaw)
- Shape of part depth flaws are always semi-elliptical
- Flaws transition to TW at 95% depth
- Initial TW flaws are trapezoidal shape
- Correction factors are applied to non-ideal TW flaws based on FEA simulation; flaws tend towards ideal shape
- Nearly ideal flaws will “snap” into ideal flaws

MRP-216 Example Crack Shapes

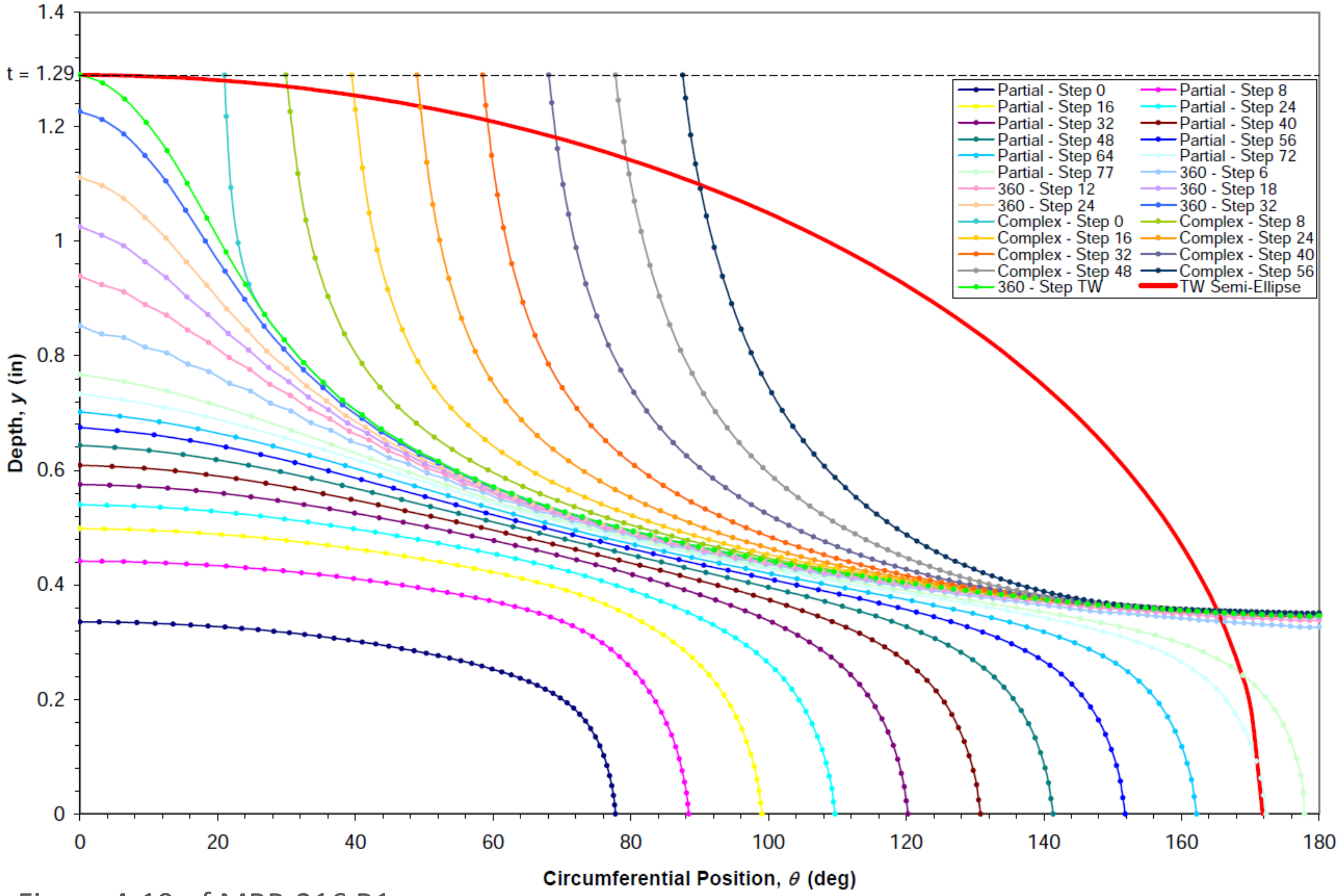


Figure 4-19 of MRP-216 R1

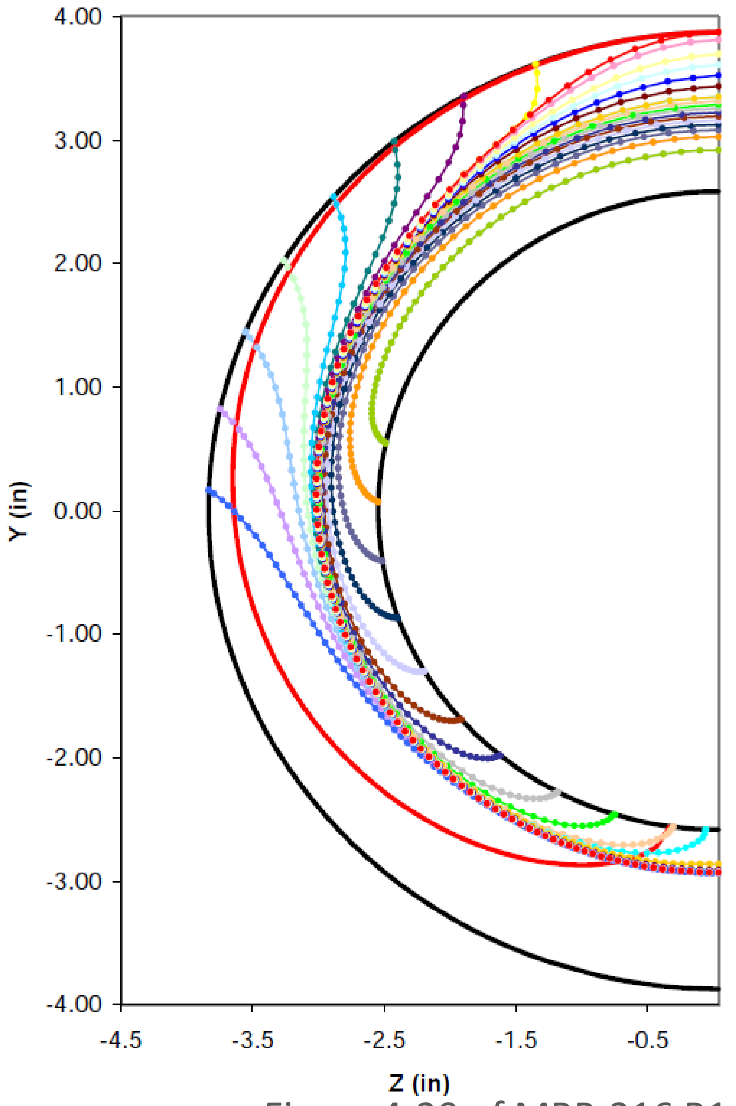
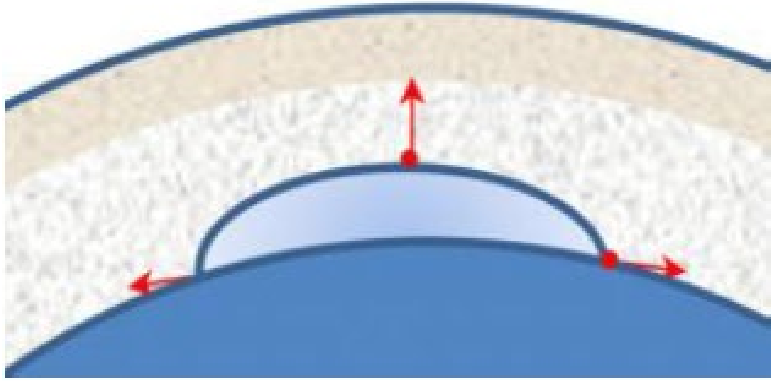
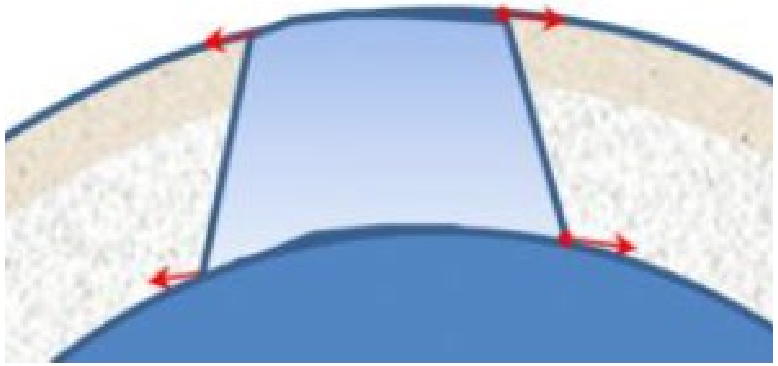


Figure 4-20 of MRP-216 R1

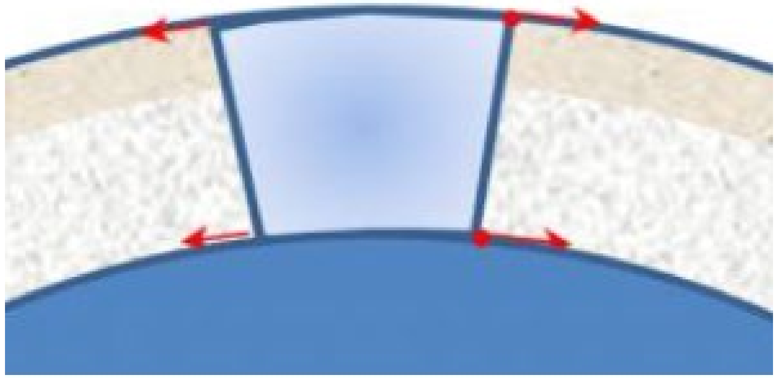
xLPR Example Crack Shapes



Semi-elliptical Surface



Transitioning (Trapezoid)



Idealized Through-wall

Taken from xLPR-SDD-Coalescence V3 Table 5

Types of Comparison

- **Two xLPR benchmark cases:**
  - **Case 1: matching initial surface flaw length and depth**
  - **Case 2: matching initial TW flaw ID and OD length**
- Crack profile at select time points
- Surface crack phase (Case 1 only)
  - Crack depth vs Time
  - ID normalized crack length vs Time
- Through-wall crack phase (Cases 1 and 2)
  - ID normalized crack length vs Time
  - OD normalized crack length vs Time
  - Crack opening displacement (COD) vs Time
  - Crack opening area (COA) vs Time
  - Leak rate vs Time

MRP-216R1 Case 17b (1 of 3)

- Chosen as example of growth from circumferential surface flaw to TW flaw useful for benchmarking comparison
- Pressurizer surge nozzle Alloy 82/182 butt weld
- OD of 15 inches
- Wall thickness of 1.58 inches
- Loading:
  - Pressure = 2,235 psi
  - Membrane Stress (including pressure end cap force) = 3.72 ksi
  - Bending Stress = 13.57 ksi
  - Weld residual stress (shown on next slide)

MRP-216R1 Case 17b (2 of 3)

Polynomial fit applied in MRP-216R1 Case 17b and xLPR benchmarks

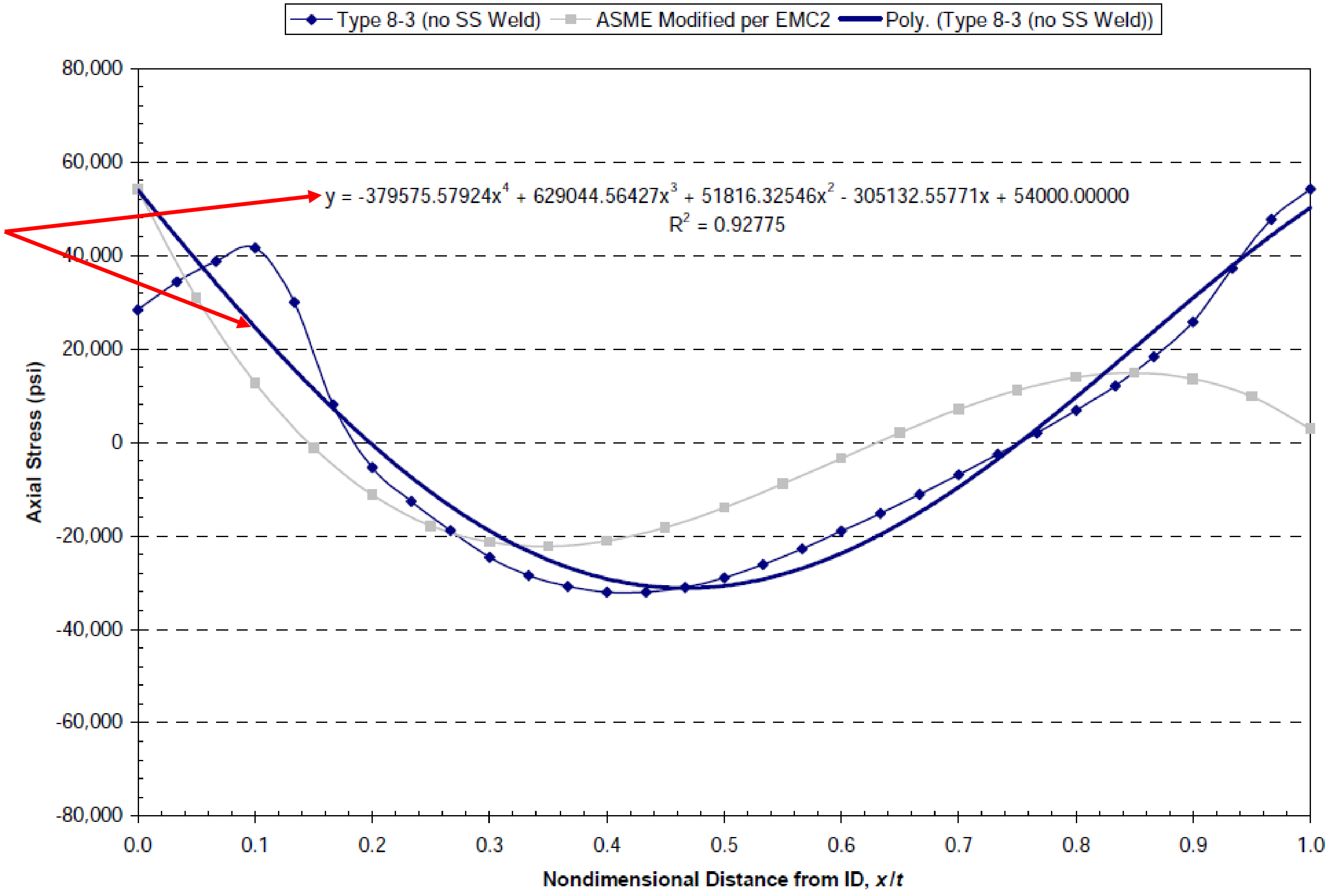
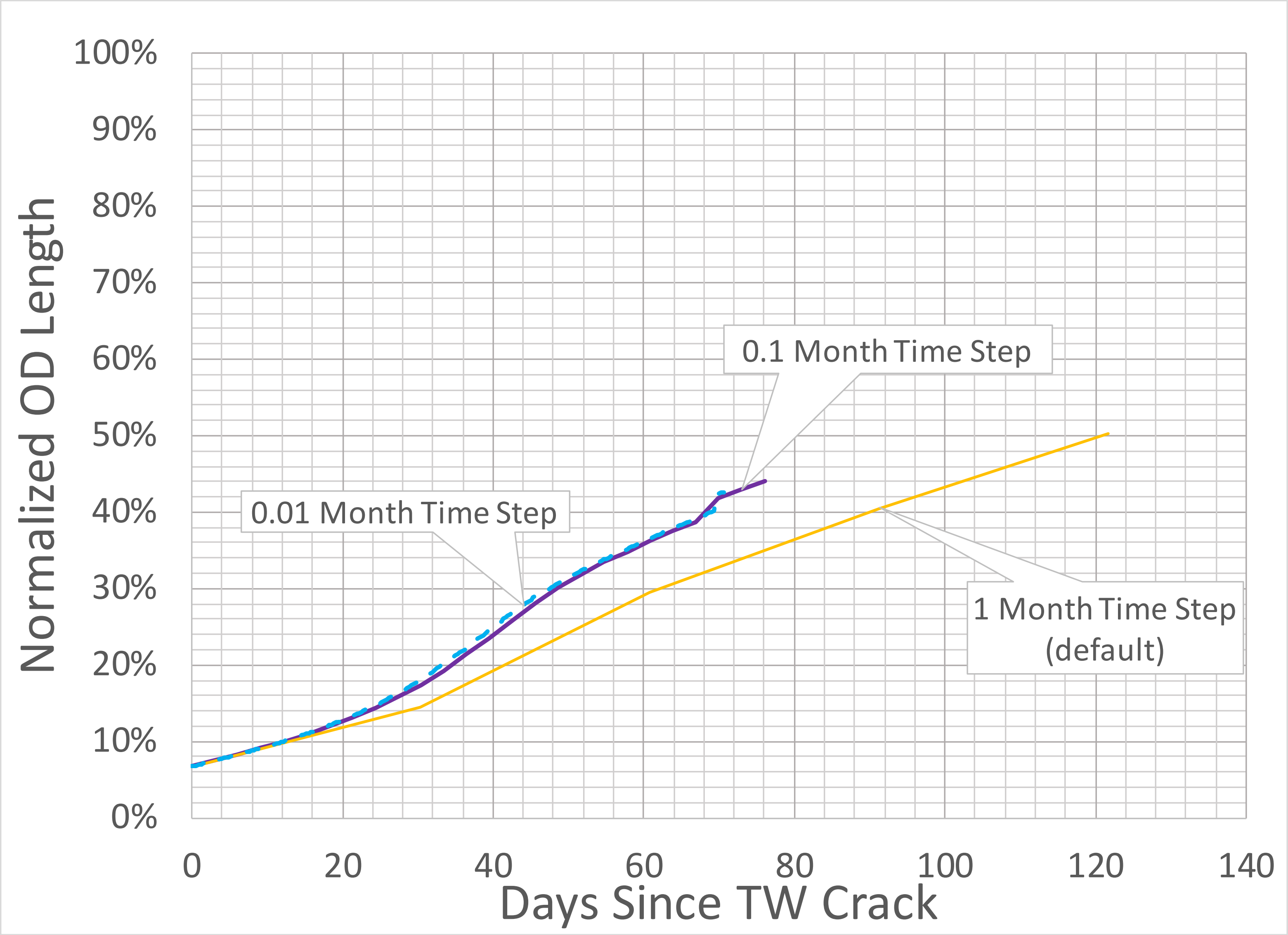


Figure 7-7 of MRP-216 R1

MRP-216R1 Case 17b (3 of 3)

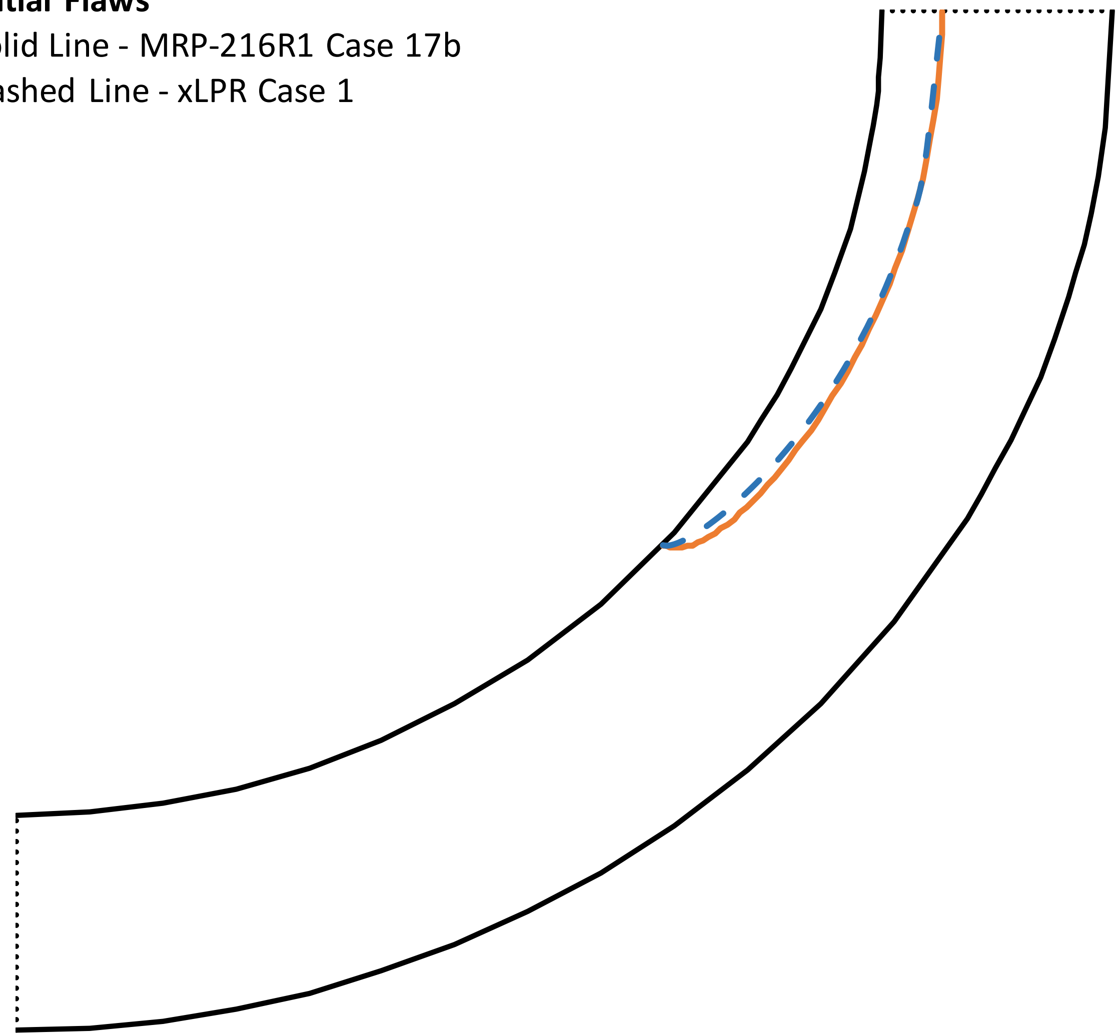
- Initial flaw:
  - Aspect ratio 2*c*/*a* = 21
  - Depth = 26% through-wall
  - Shape = “natural” based on previous AFEA simulation
- Crack growth per MRP-115 for Alloy 182 weld metal
  - $C_{75th,650°\text{F}} = 5.372 \cdot 10^{-7} \frac{\text{in}/\text{hr}}{(ksi{-}in^{0.5})^{1.6}}$ for CR
  - K exponent = 1.6

xLPR Time Step Selection

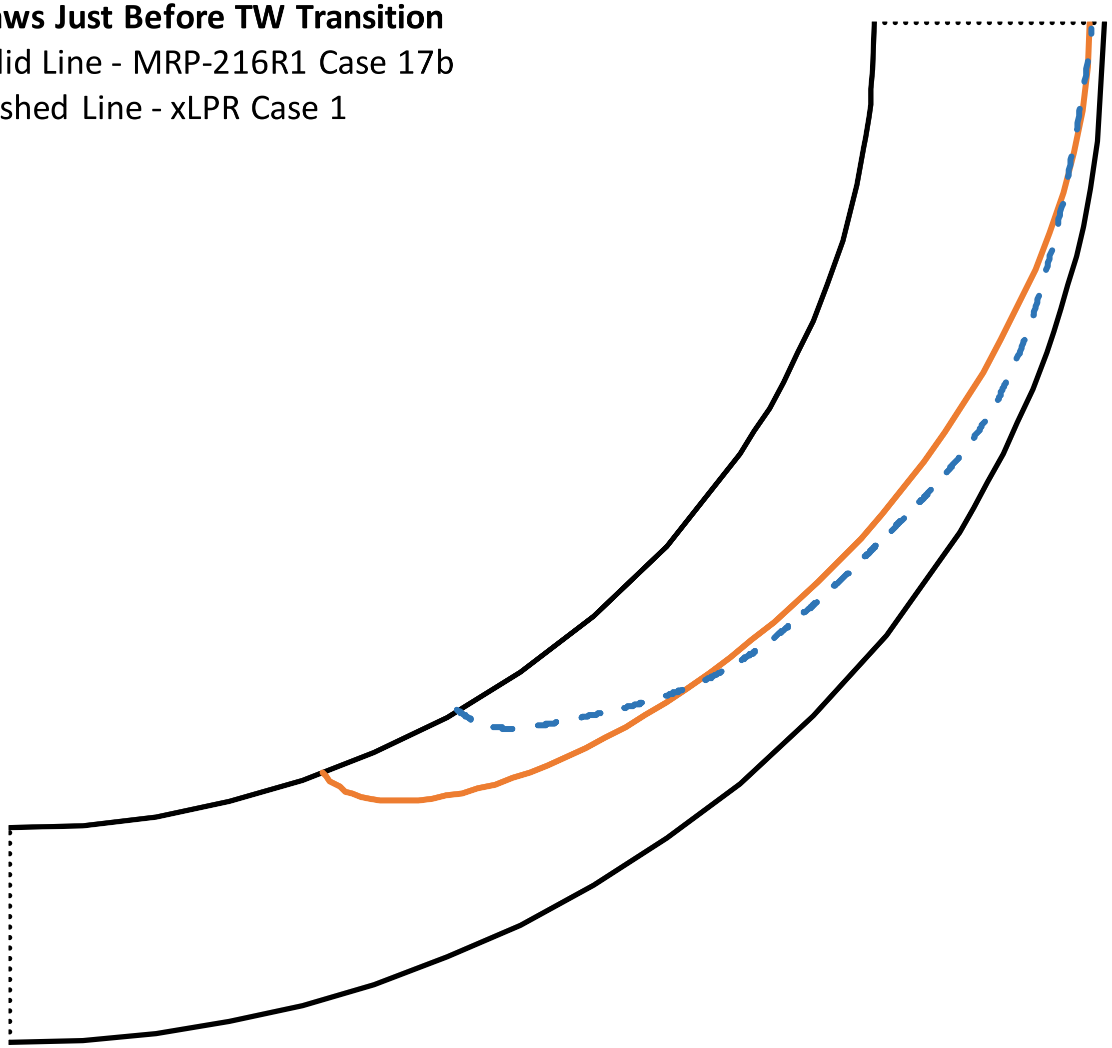


Crack Profile Comparison - xLPR Case 1 (1 of 2)

Initial Flaws
Solid Line - MRP-216R1 Case 17b
Dashed Line - xLPR Case 1



Flaws Just Before TW Transition
Solid Line - MRP-216R1 Case 17b
Dashed Line - xLPR Case 1

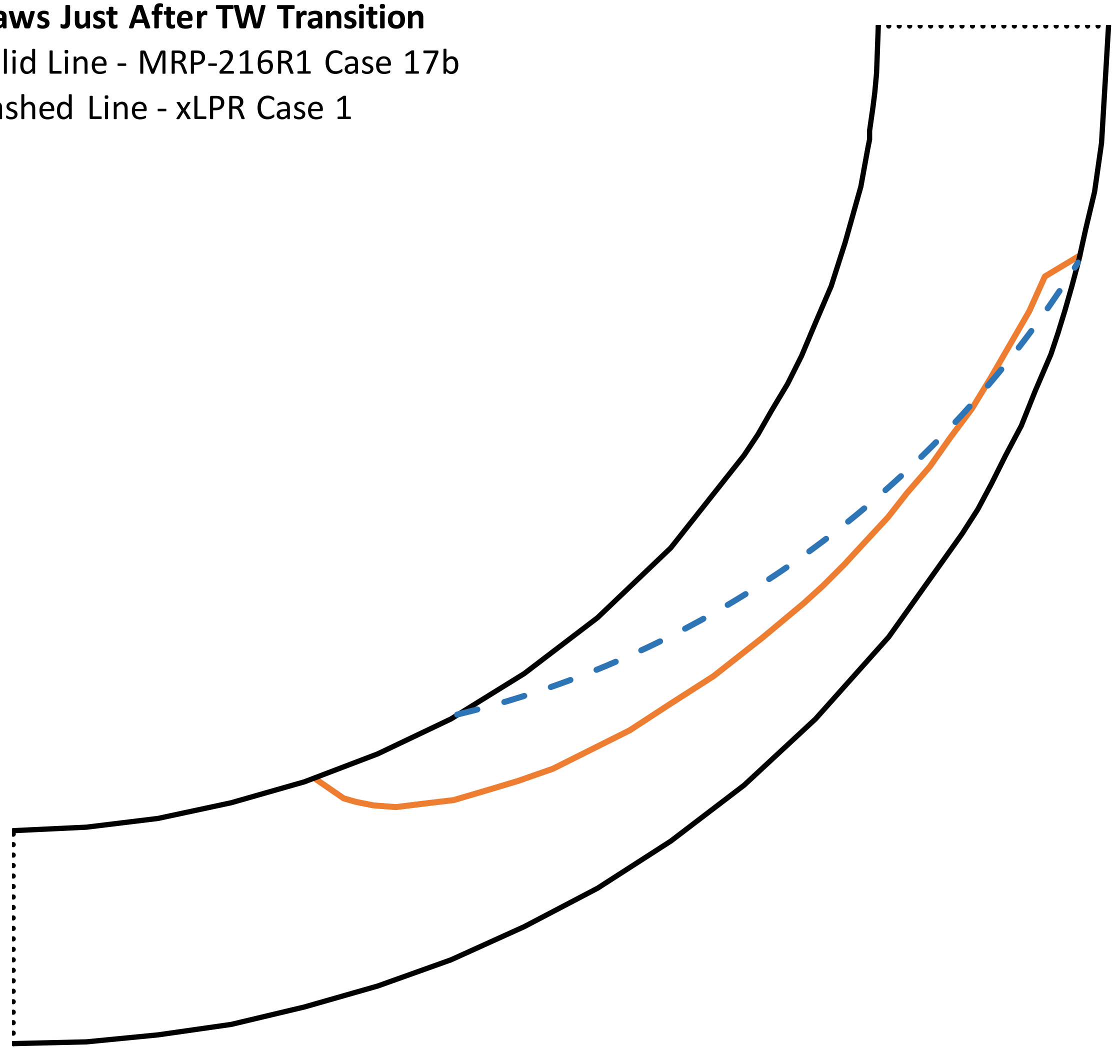


Crack Profile Comparison - xLPR Case 1 (2 of 2)

Flaws Just After TW Transition

Solid Line - MRP-216R1 Case 17b

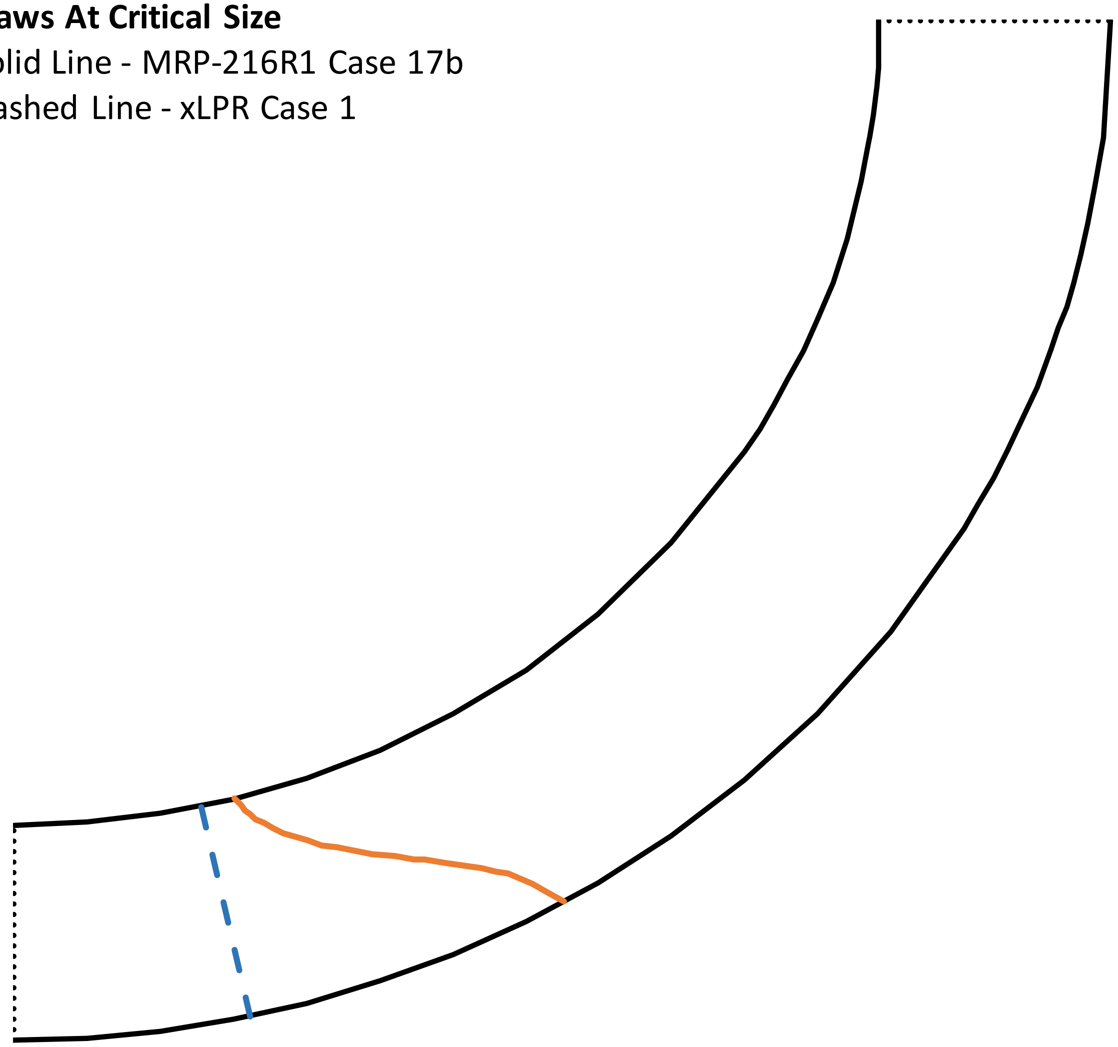
Dashed Line - xLPR Case 1



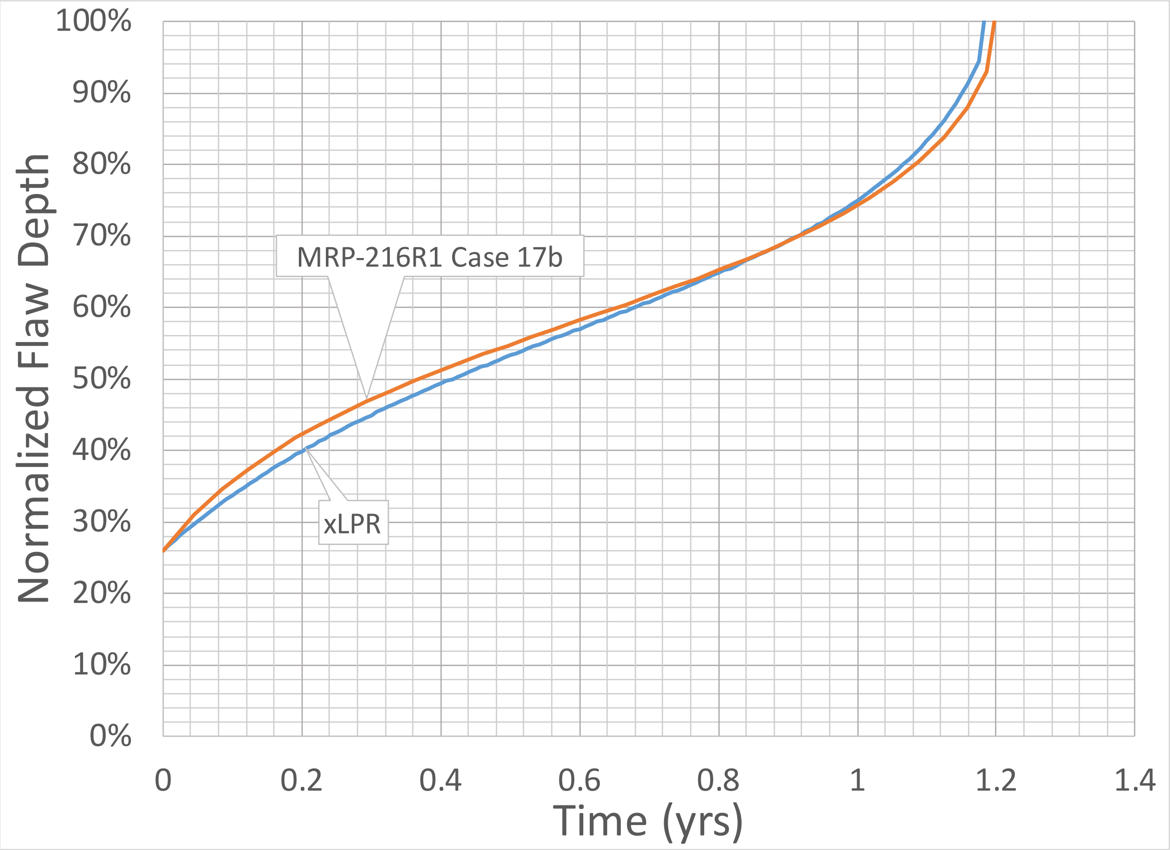
Flaws At Critical Size

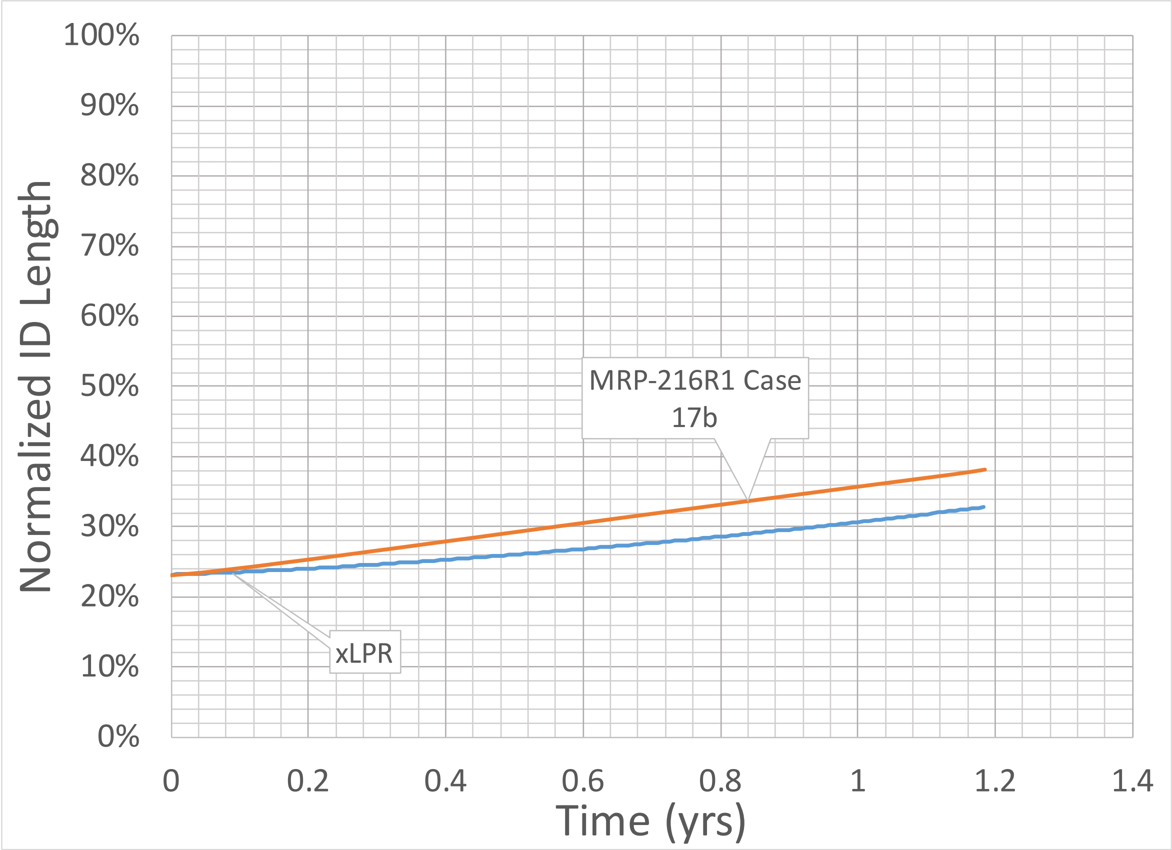
Solid Line - MRP-216R1 Case 17b

Dashed Line - xLPR Case 1

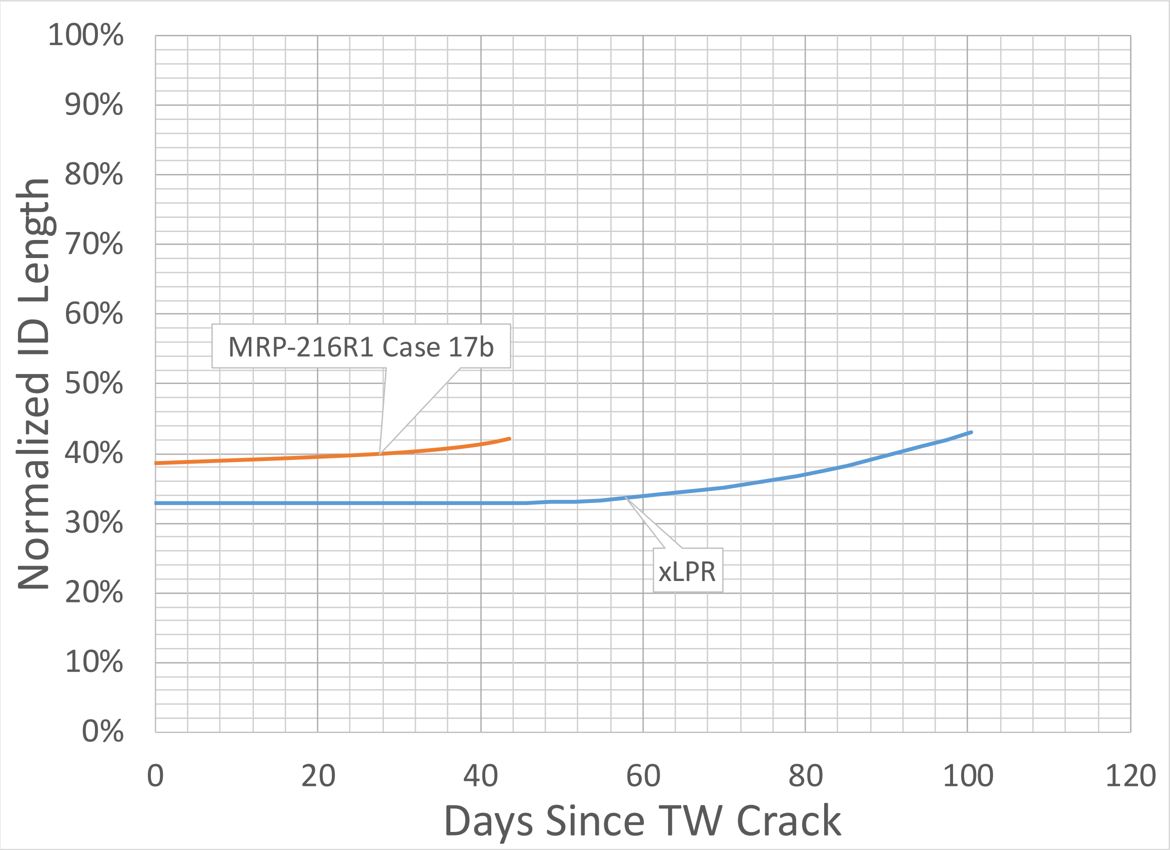


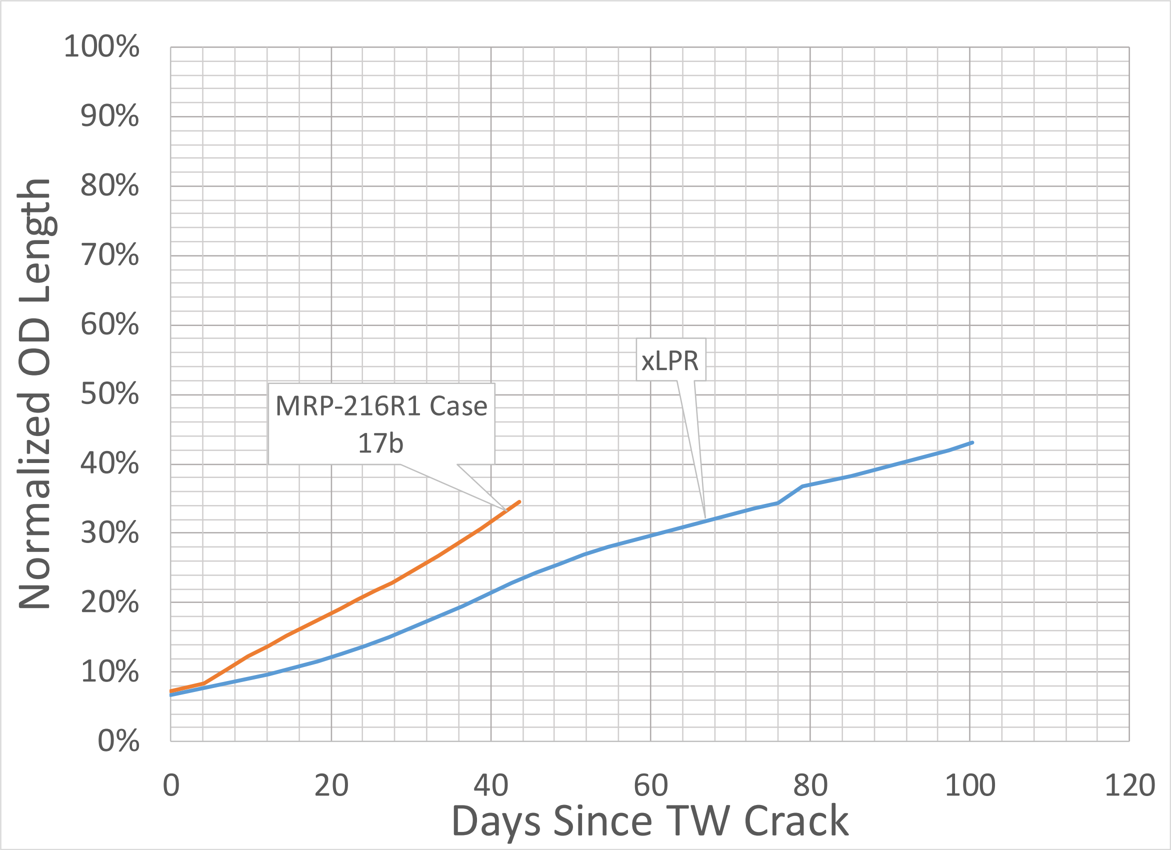
Surface Crack Comparison – Flaw Length and Depth (Case 1)



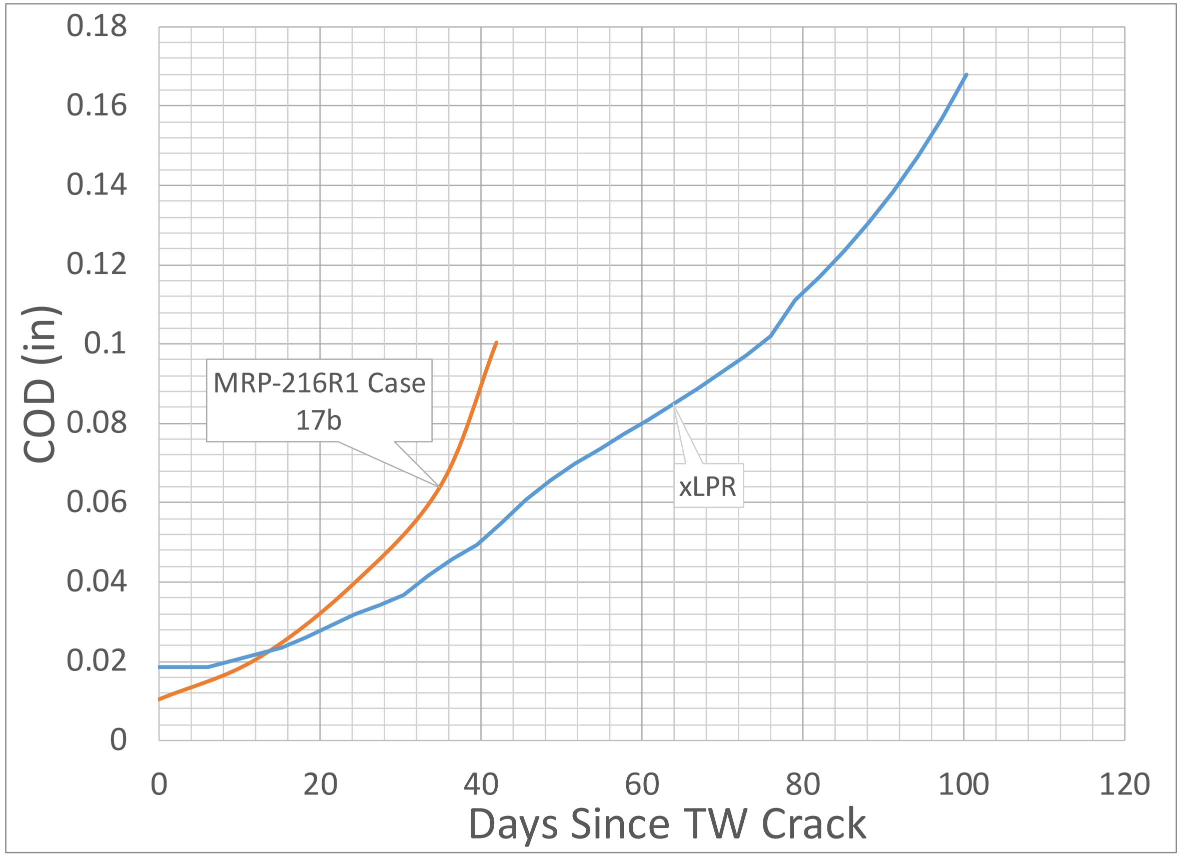


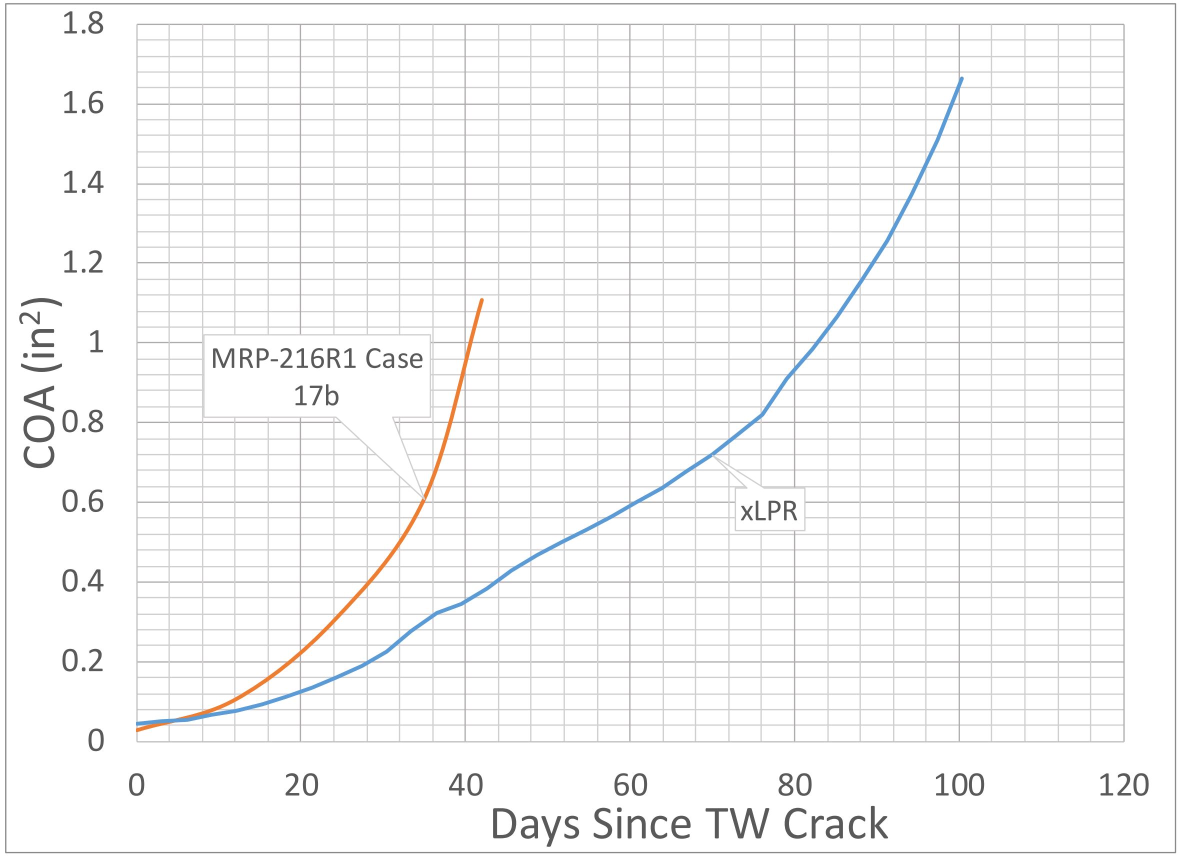
TW Crack Comparison – ID and OD Flaw Lengths (Case 1)



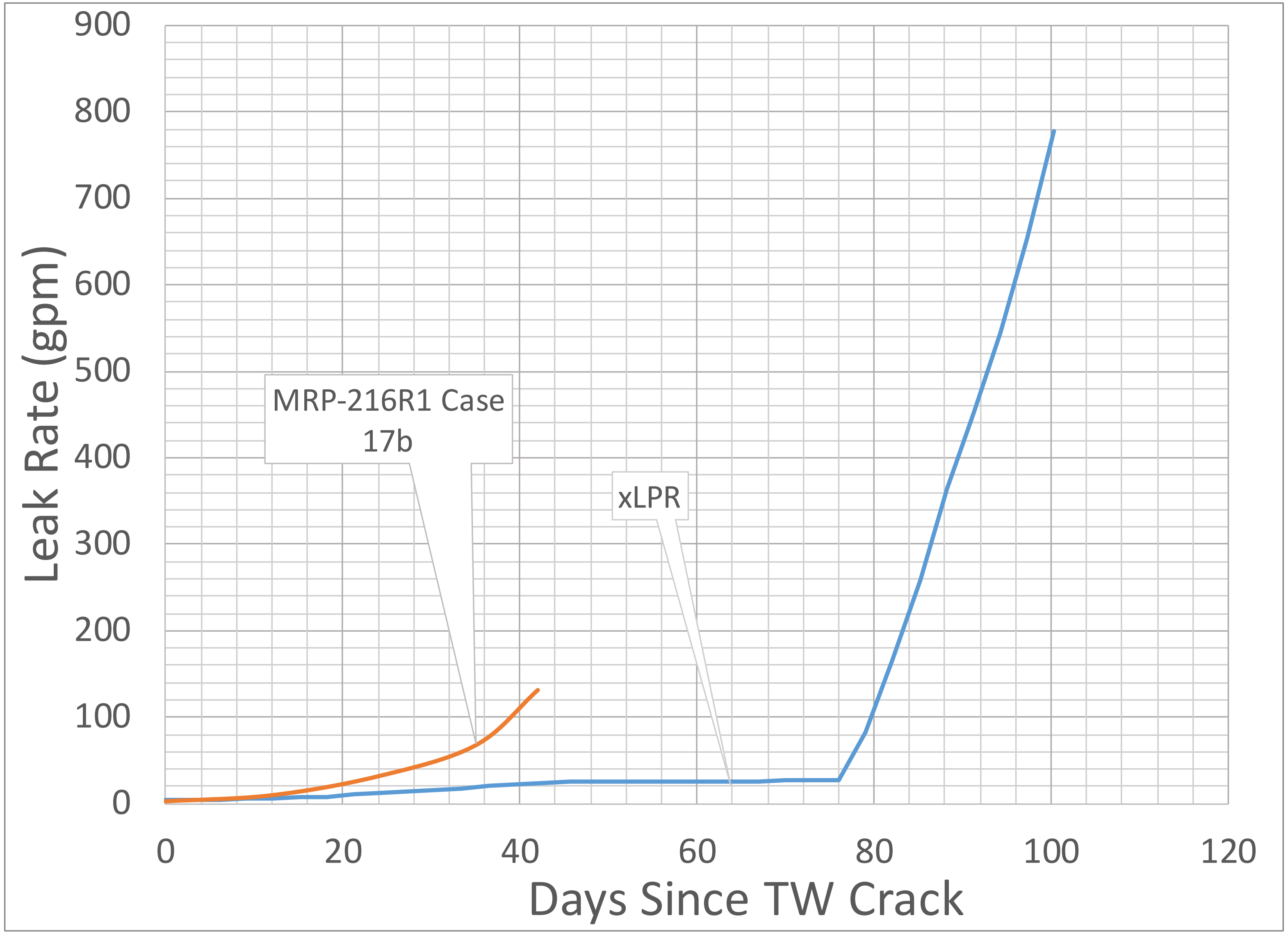


TW Crack Comparison – Crack COD and COA (at OD) (Case 1)

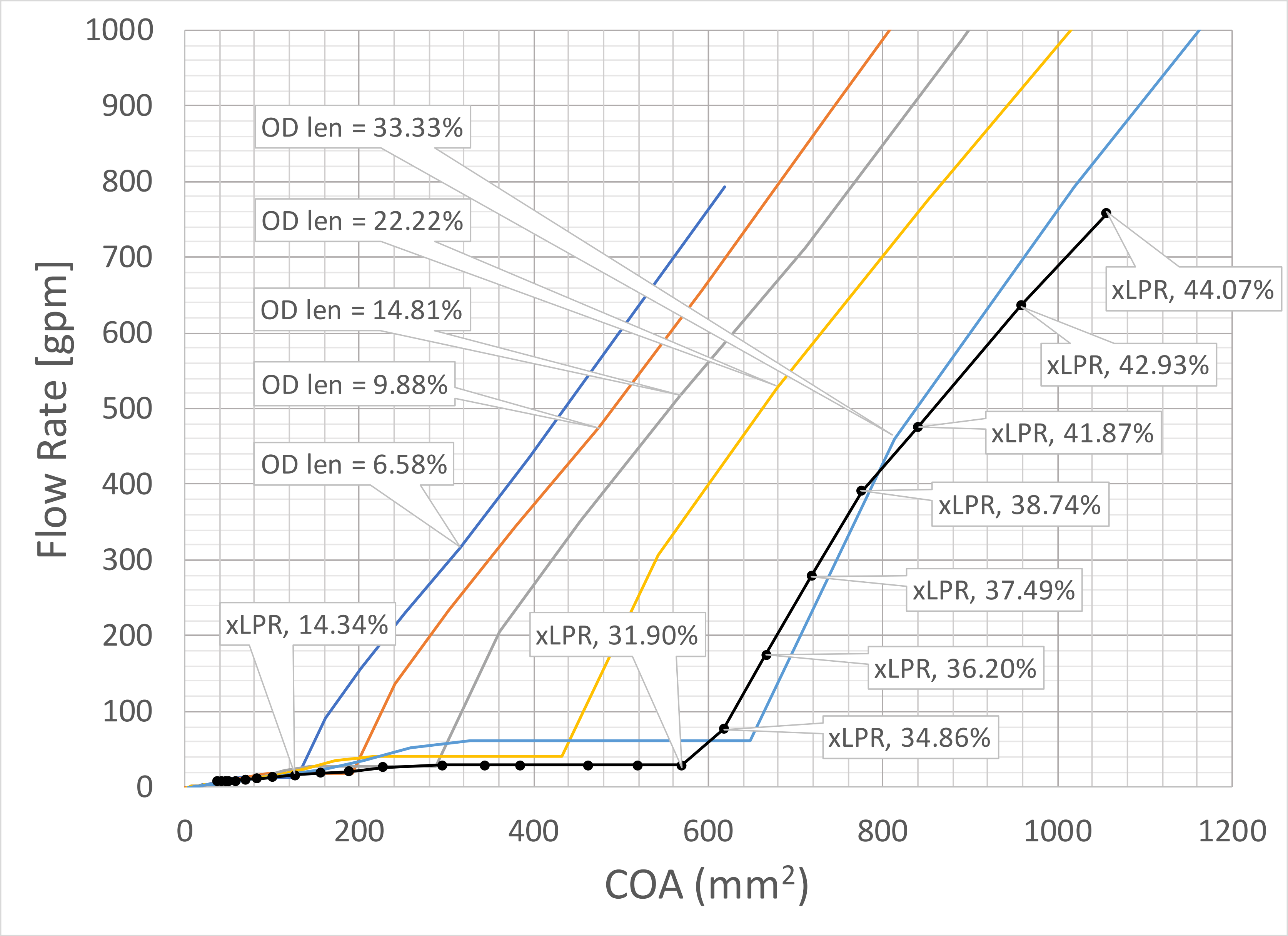




TW Crack Comparison – Leak Rate (Case 1)

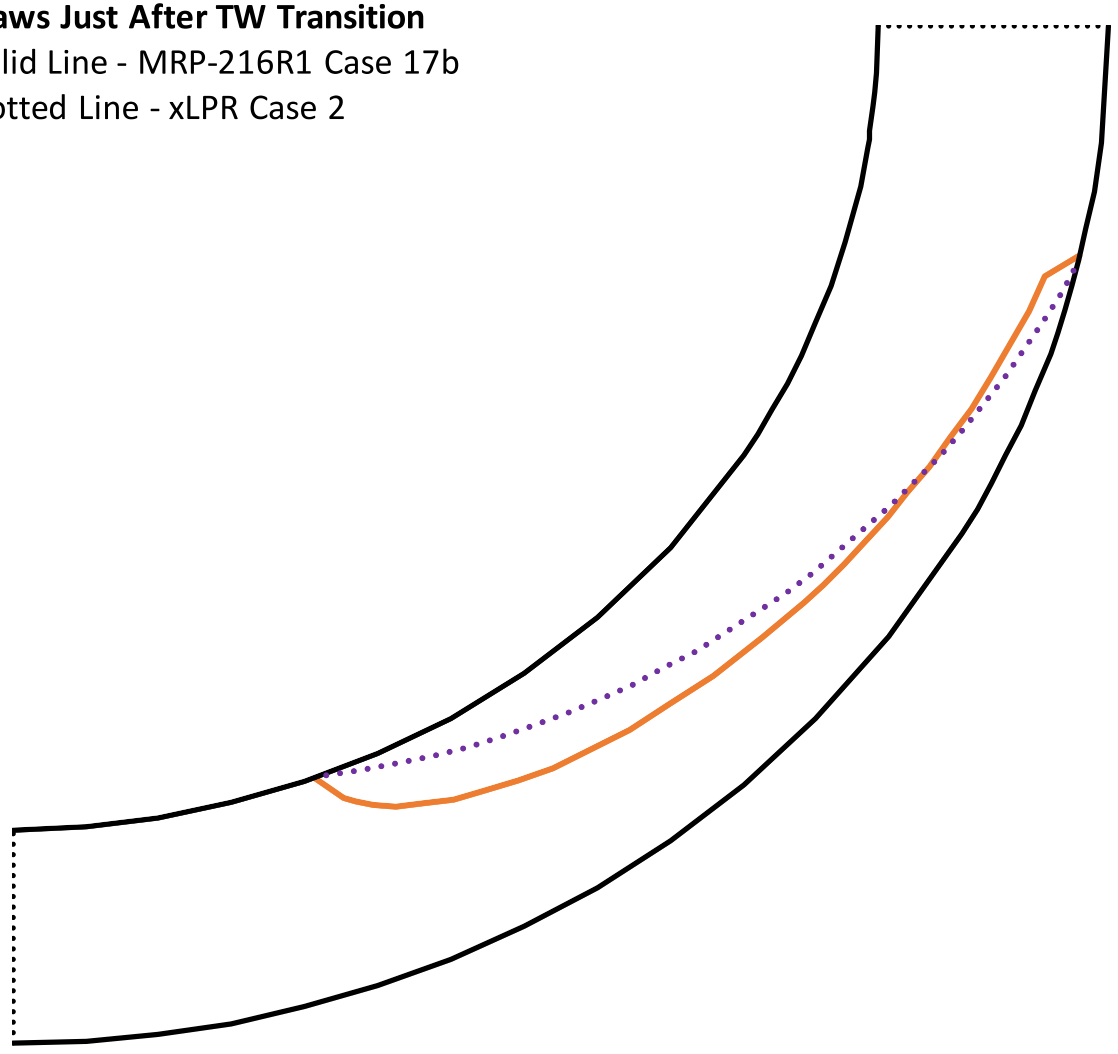


xLPR Leak Rate Modelling

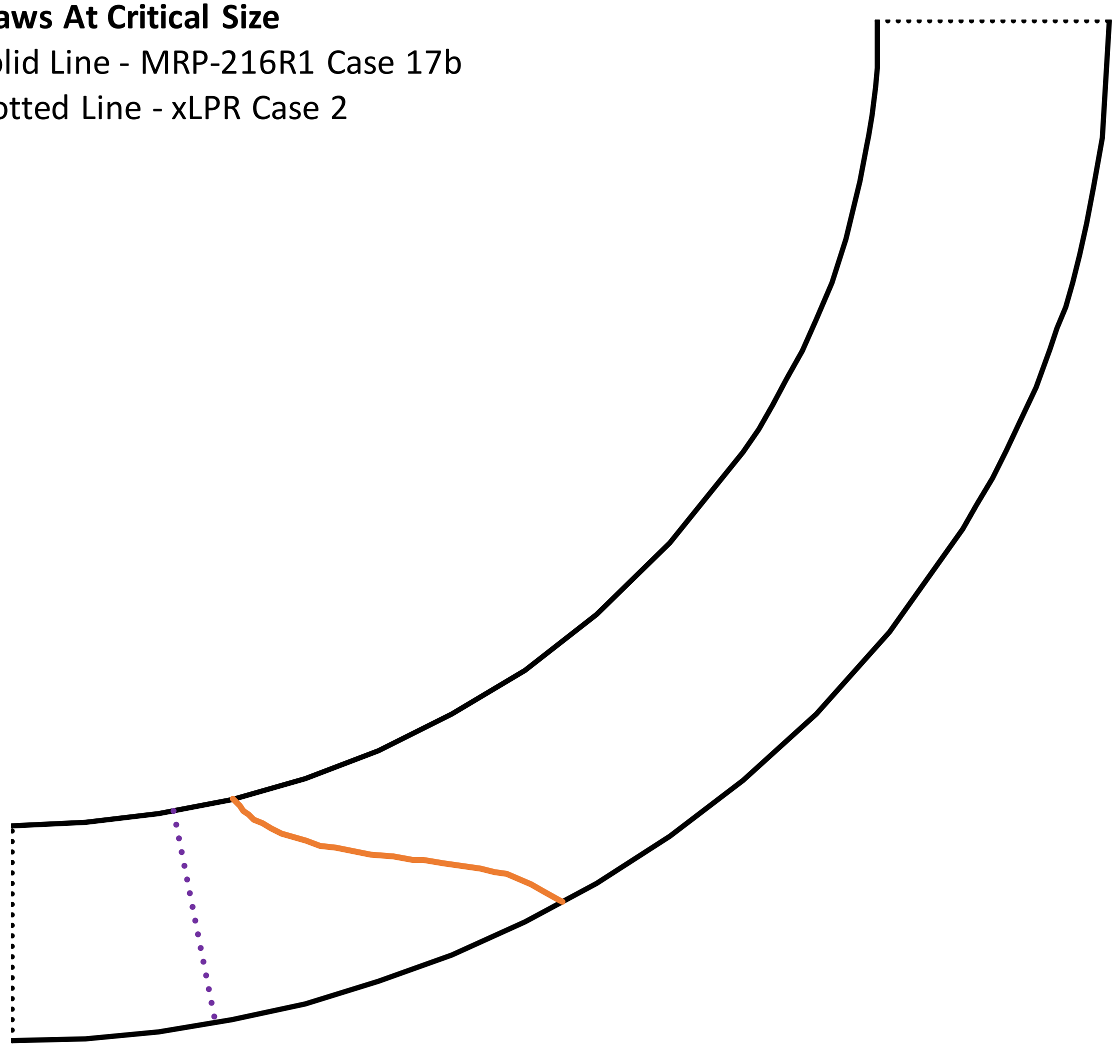


Crack Profile Comparison - xLPR Case 2

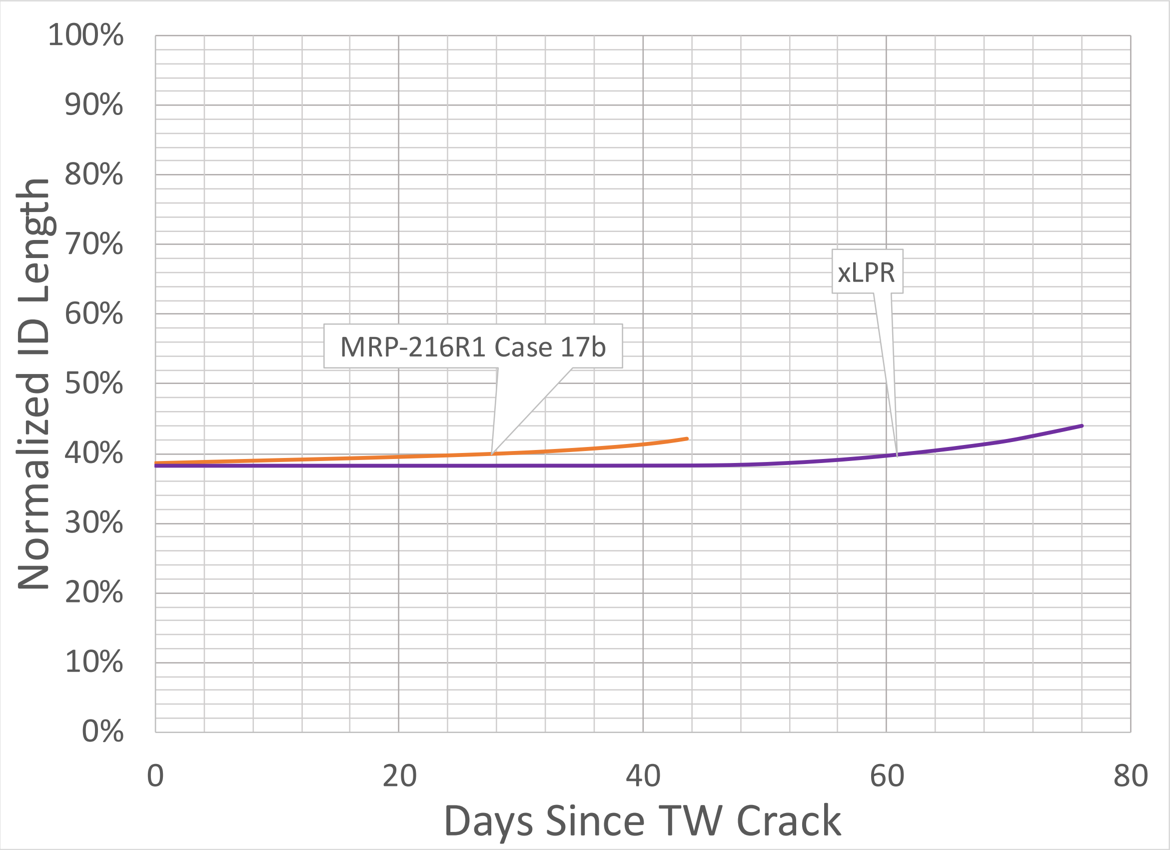
Flaws Just After TW Transition
Solid Line - MRP-216R1 Case 17b
Dotted Line - xLPR Case 2

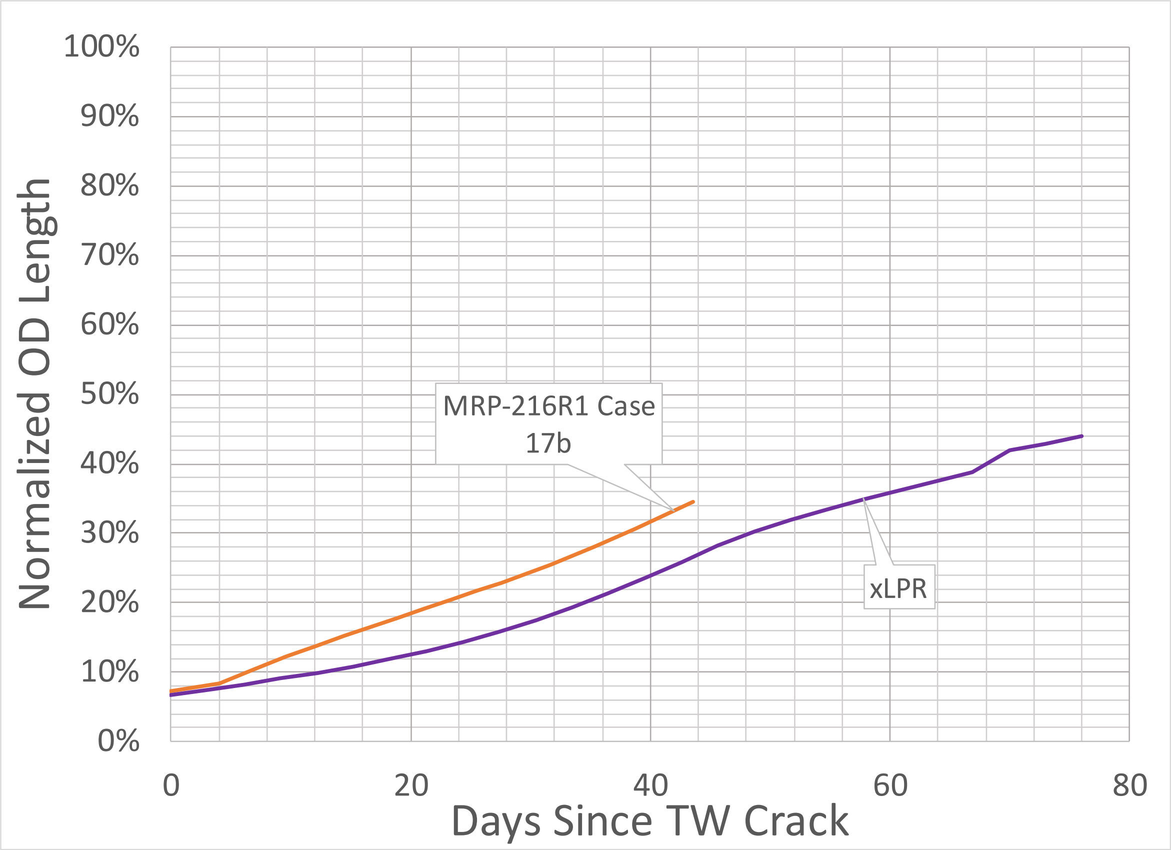


Flaws At Critical Size
Solid Line - MRP-216R1 Case 17b
Dotted Line - xLPR Case 2

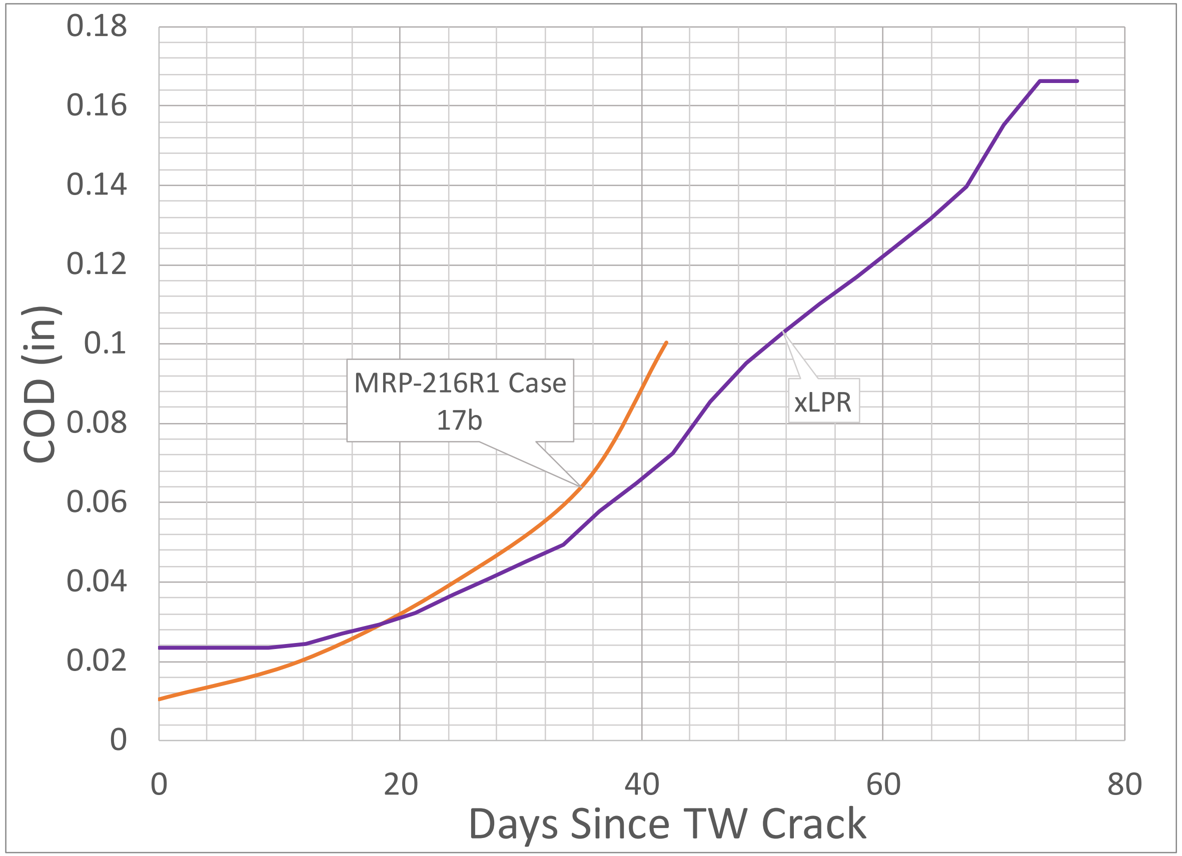


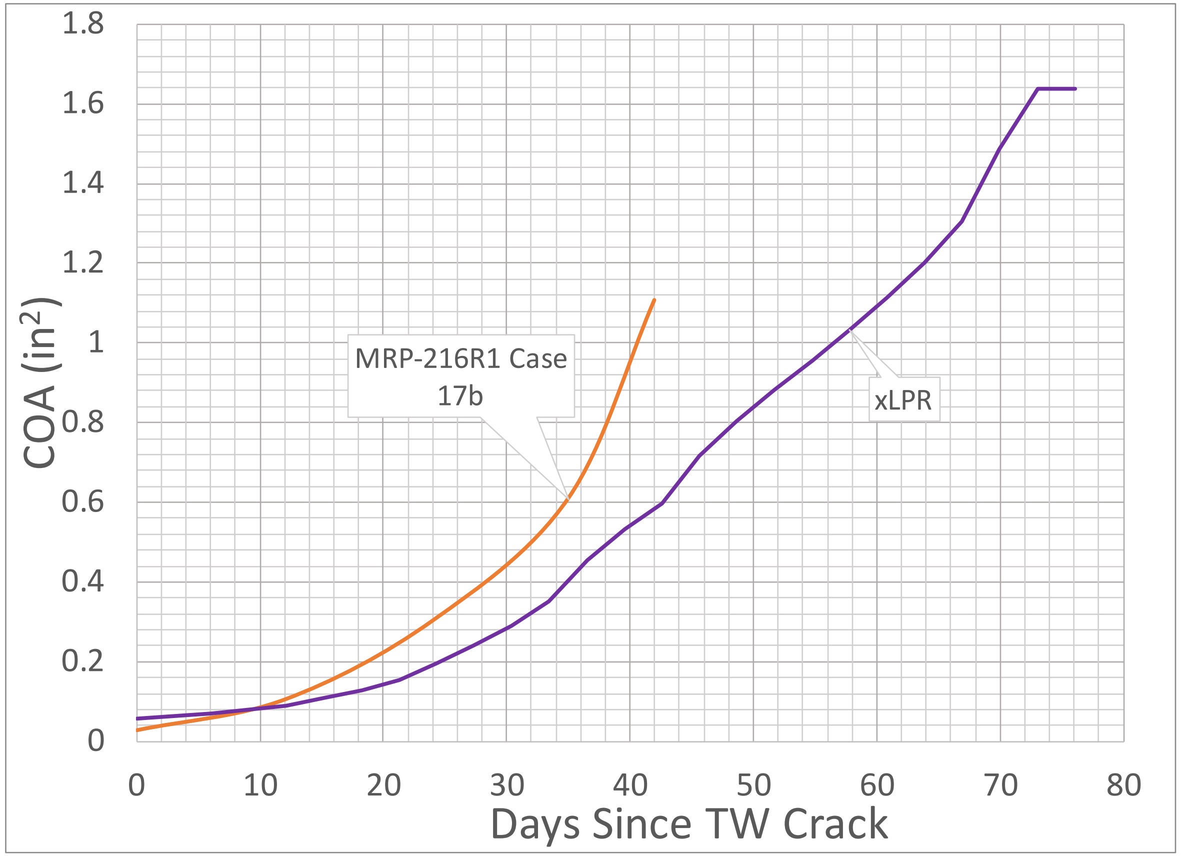
TW Crack Comparison – ID and OD Flaw Lengths (Case 2)



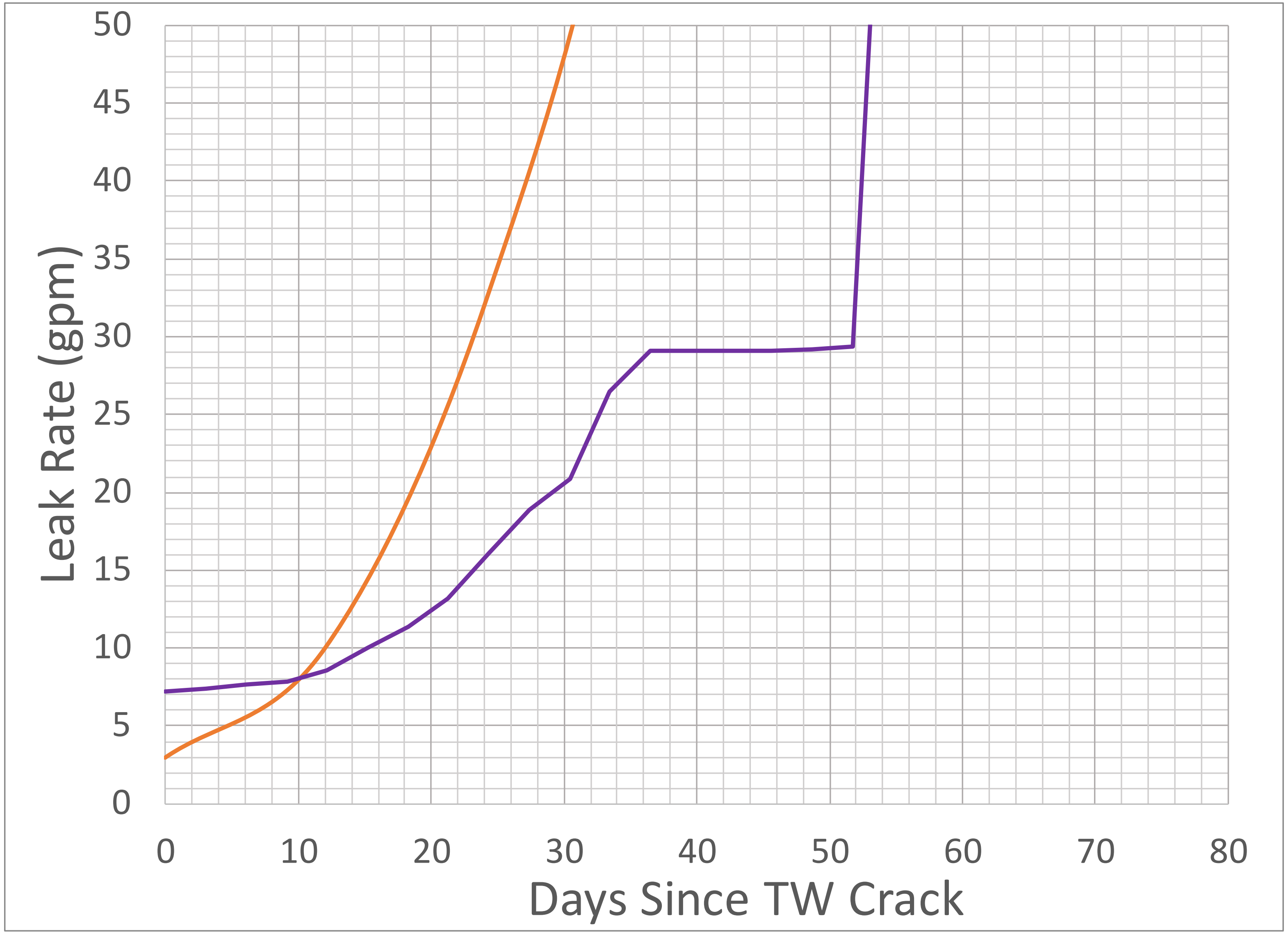


TW Crack Comparison – Crack COD and COA (at OD) (Case 2)





TW Crack Comparison – Leak Rate (Case 2)



Summary of Comparison

	MRP-216 (17b)	xLPR Case 1	xLPR Case 2
Time to TW (yrs)	1.20	1.18	-
Normalized ID Length @ TW	38.5%	32.8%	38.2%
Normalized OD Length @ TW	7.18%	6.71%	6.71%
Crack Cross-section @ TW	24.0%	18.2%	20.6%
Leak Rate @ TW (gpm)	2.55	4.98	7.19
Normalized ID Length @ Critical Size	42.2%	43.1%	44.1%
Normalized OD Length @ Critical Size	34.6%	43.1%	44.1%
Time to Critical Size (yrs)	1.56	1.46	-

Discussion of Example Cases

- Close agreement obtained for depth progression of surface flaw, even given difference in initial flaw profile
- Reasonable agreement in flaw length also obtained, especially when xLPR solution is temporally converged
  - Observed difference in length progression due to differences in ID crack length at TW penetration, crack "fullness," and K solution
  - K correction factor of xLPR for ID tips of trapezoidal flaw appears to overcompensate
- Leak rate "plateau" behavior of xLPR not observed in PICEP simulations

Conclusions

- Trapezoidal flaw approach of xLPR provides much more realistic crack growth and leak rate behavior than idealized TW flaws
- K solutions of xLPR appear to be accurate
- As expected, modest differences in flaw dimensions and profile do lead to some differences in subsequent crack development and leak rate

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