# Probabilistic Assessment of Chemical Mitigation of PWSCC

## Zinc Addition and Hydrogen Optimization

*Presented To:*

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# Background

*MRP-263 (EPRI 1019082, 2009) – Technical Bases for Chemical Mitigation*

- Hydrogen optimization reduces crack growth rates
  - Rate decreases with distance from electrochemical potential of Ni/NiO transition
  - Zinc addition reduces rate of new initiations
  - Concentration of zinc not important
- Hydrogen has no effect on initiation over the range of interest
  - Very low hydrogen concentrations can lower initiation rate
  - No effect once above the Ni/NiO transition
- Zinc appears to have a limited effect on crack growth rate
  - Data mixed
  - Possible mitigative effect at low K (lab data for Alloy 600 plus SG tube experience)
- Recommended probabilistic approach:
  - Capture benefit on initiation from zinc
  - Address other uncertainties

# Model Description

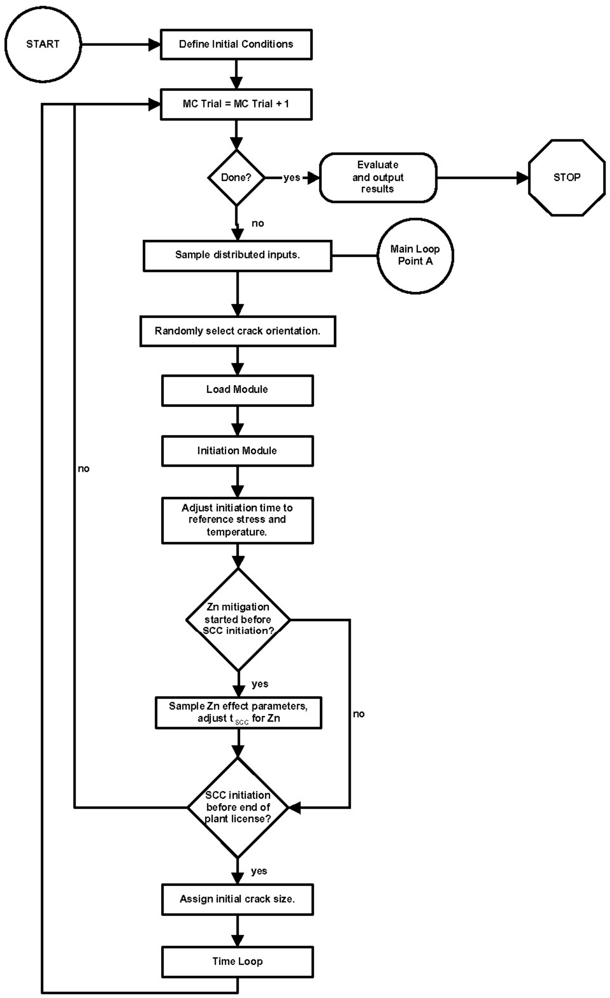
# Overall Model

- Partially based on xLPR work
- Monte Carlo simulation
- Distributed input parameters
- No separation of aleatory and epistemic uncertainty
- Reduced complexity of model output vs. xLPR (e.g., through-wall cracking, single initiation per weld, etc.)

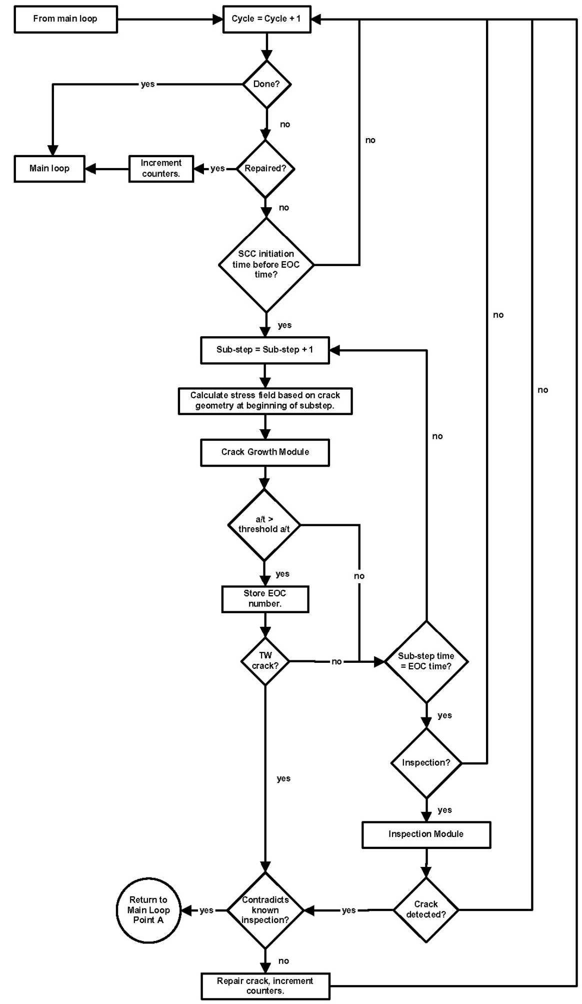
| Initiation | | | No Initiation |
|---|---|---|---|
| Repair | Through-wall | Not Through-wall | No Initiation |
| Repair | >75% Through-wall | <75% Through-wall | No Initiation |

Note: Not to scale. Typically, most Monte Carlo trials did not result in initiation.

# Model Flow Charts




Main Loop




Time Loop

# Main Model Components

- Initiation
- Propagation
- Load
- Detection

# Initiation Model

- Simplified approach relative to xLPR, based on empirical plant data and one flaw per weld
- Step 1: select a reference initiation time using a Weibull distribution

$$F\left(t_{ref}\right)=1-e^{-\left(\frac{t_{ref}}{\theta}\right)^{\beta}}$$

- Step 2: adjust reference initiation time for stress and temperature

$$t_f = t_{ref}\left(\frac{\sigma_{ref}}{\sigma}\right)^n e^{\left(\frac{Q}{R}\right)\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}$$

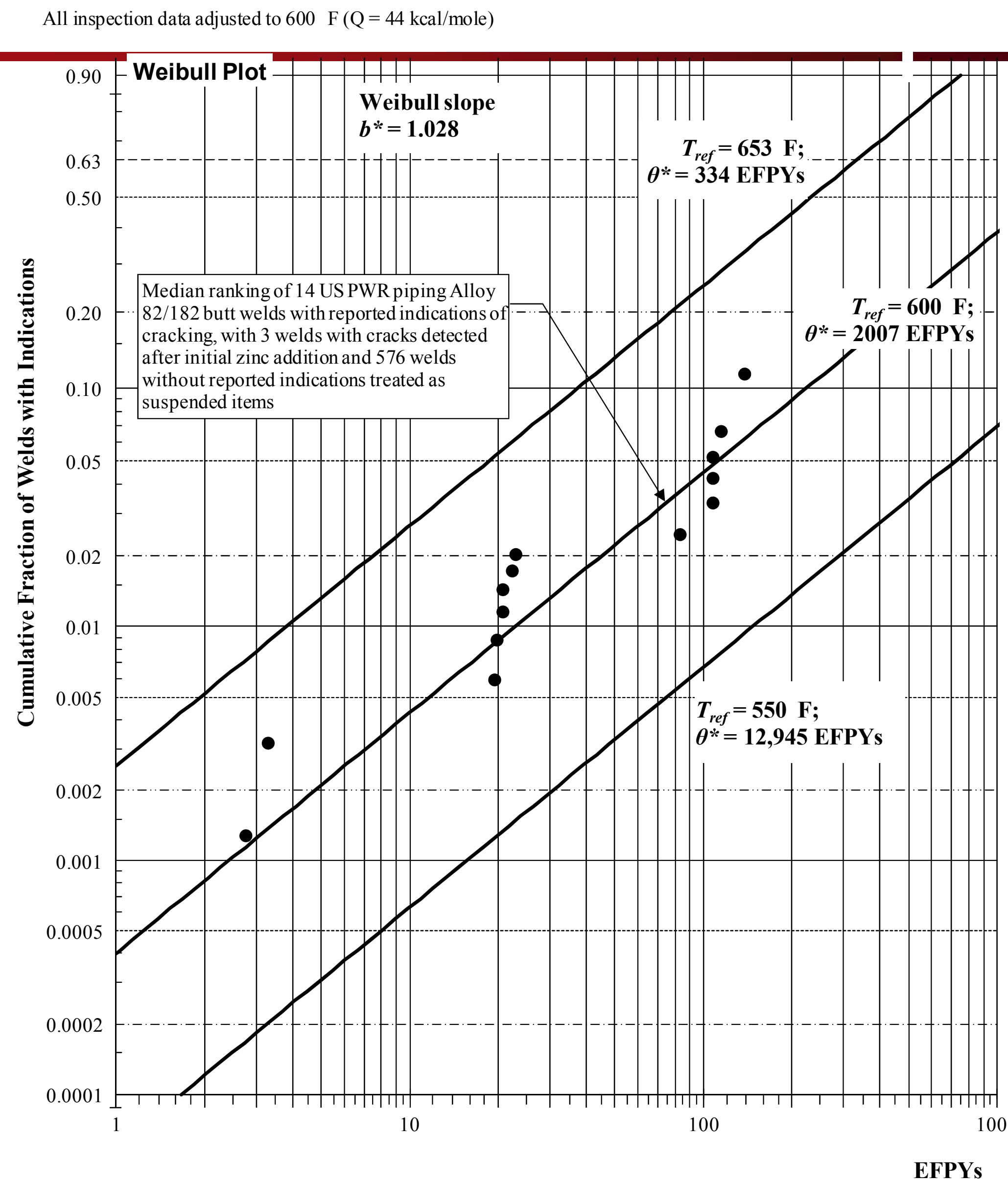
- Step 3: adjust reference time for chemical mitigation (zinc)

$$t' = t_{ZM} + FOI_{Zni}\left(t_f - t_{ZM}\right)$$

# Initiation Model

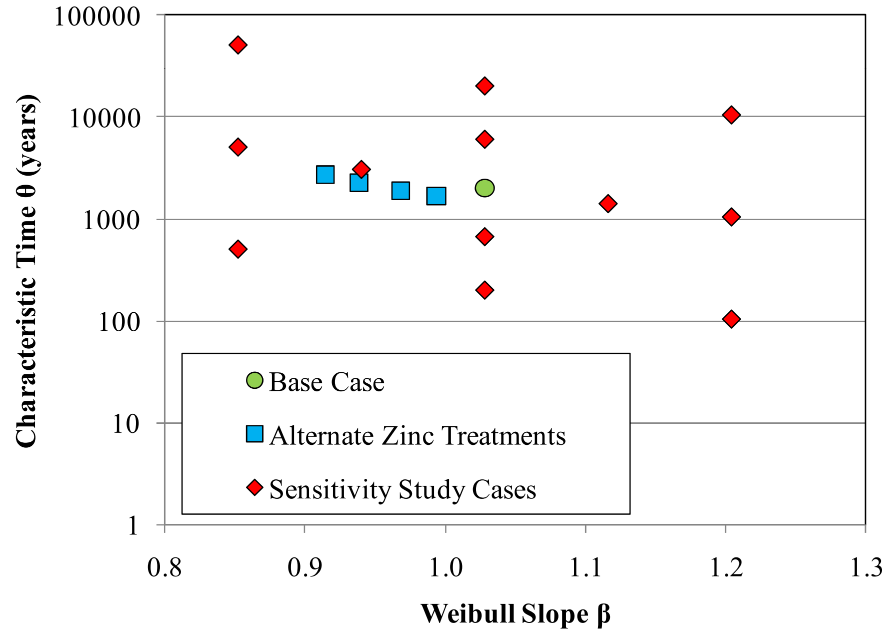
*Step 1: Weibull Distribution (Plant Data)*

- Based on plant data
  - US plants
  - Alloy 82/182 piping butt welds with PWSCC tabulated in detail (but not exhaustively)
  - Welds without indications treated as suspended samples

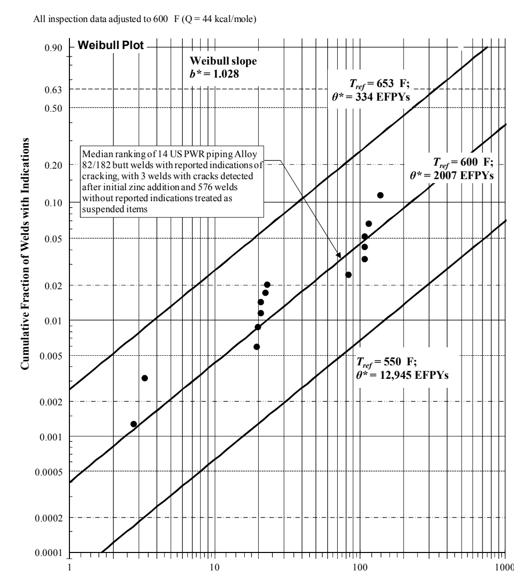


# Initiation Model

*Step 1: Weibull Distribution (Uncertainties)*




- Weibull Slope
  - Normal distribution
  - μ = 1.028, σ = 0.088
  - Based on plant data
- Characteristic Time
  - Normal distribution on the linearized Weibull intercept
  - Based on plant data




- Focus of a specific set of sensitivity studies
  - Weibull parameters
  - Treatment of data from plants already on zinc

# Initiation Model

*Step 2: Temperature and Stress Adjustment*

- Activation Energy
  - Normal distribution
  - $\mu$ = 184.23 kJ/mol, $\sigma$ = 12.82 kJ/mol
  - Based on laboratory data
  - Mean used in assessment of plant data to determine Weibull distribution
- Stress Exponent
  - Stress dependence of crack initiation not modeled (i.e., n = 0)
  - Little data on surface stresses for particular plant welds
  - Variation in initiation time due to stress captured by Weibull distribution
    - Assume surface stress distribution in 593 inspected welds is representative of total population
    - Fit to plant data incorporates aleatory and epistemic uncertainty
      - Surface stress = lack of knowledge (epistemic)
      - Stochastic initiation = inherent randomness (aleatory)

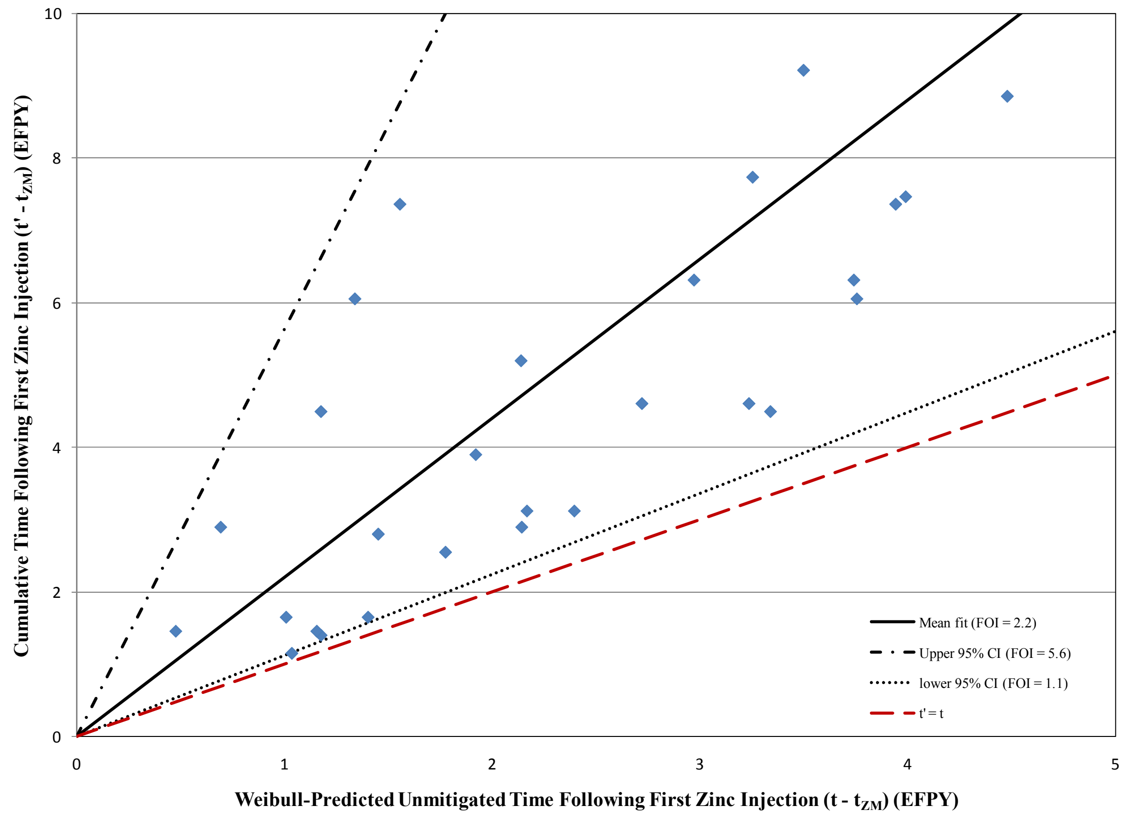
# Initiation Model

*Step 3: Adjustment for Zinc (1/2)*

- SG tube data used for quantification
- Supported by lab testing for Alloy 600
- Compare time to reach additional fraction failed to time predicted by pre-zinc Weibull trend

$$FOI_{Zni,j} = \frac{(t' - t_{ZM})_j}{(t - t_{ZM})_j}$$

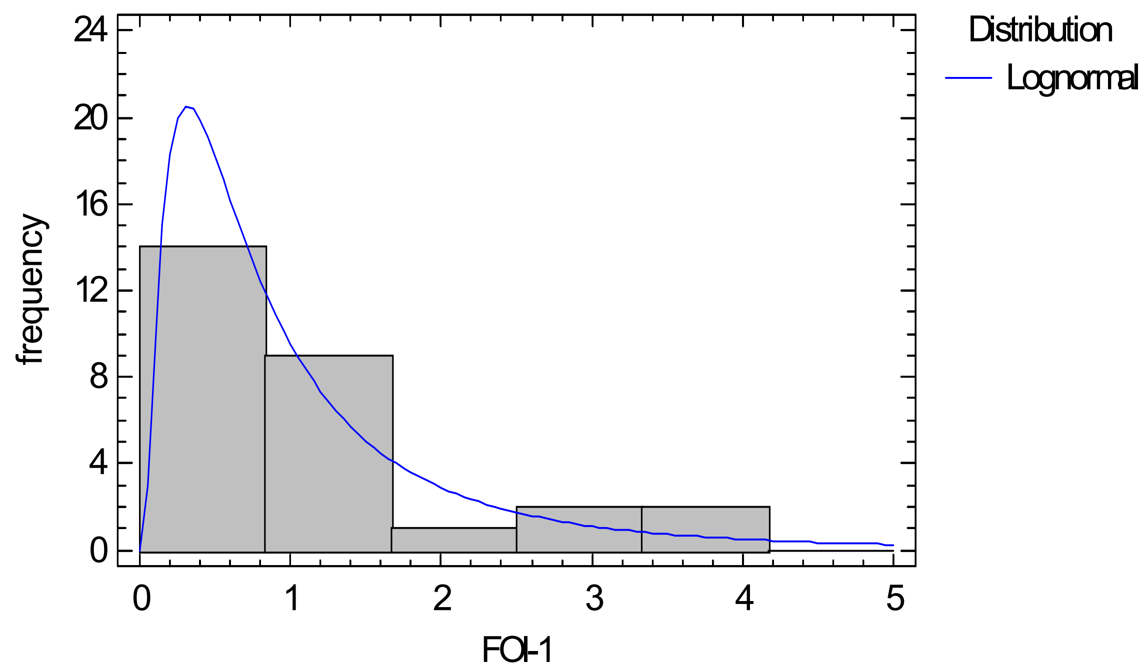
$$t' = t_{ZM} + FOI_{Zni}\left(t_f - t_{ZM}\right)$$



# Initiation Model

*Step 3: Adjustment for Zinc (2/2)*

- Normal in ln(FOI-1)
  - μ = -0.29, σ = 0.93 (mean FOI = 1.75)
  - Fit to plant data (SG tubes)
  - Lower truncation (FOI > 1) justified by corroborative lab data
    - All studies show some improvement



# Initiation Model

*Other Aspects*

- Orientation (circunferencial vs. axial) randomly selected
  - Match to plant data
- Initial flaw depth
  - Flaw depth is assumed to be finite upon initiation
  - Normal distribution in ln(fraction through wall)
  - $\mu = -3$, $\sigma = 0.35$ (mean fraction = 0.05)
  - Results in SIFs greater than the assumed cut-off for zinc mitigation of propagation
    - Effectively, no mitigation of crack growth rates by zinc addition
- Initial aspect ratio
  - Normal distribution in ln(AR)
  - Based on data from plant inspections
  - Independently evaluated for circ and axial flaws

# Propagation Model

*MRP-263 Model with Hydrogen Effect*

$$\dot{a} = e^{-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \frac{\alpha}{f_{Zn}} f_{weld} f_{ww} \left(K_I - K_{Ith}\right)^b \left[\frac{1}{P} + \frac{(P-1)}{P}\exp\left(-0.5\left(\frac{\Delta ECP_{Ni/NiO}}{c}\right)^2\right)\right]$$

$$\Delta ECP_{Ni/NiO} = 29.58\left(\frac{T}{298.15}\right)\log_{10}\left(\frac{[H_2]}{[H_2]_{Ni/NiO}}\right)$$

$$[H_2]_{Ni/NiO} = 10^{(0.0111T_c - 2.59)}$$



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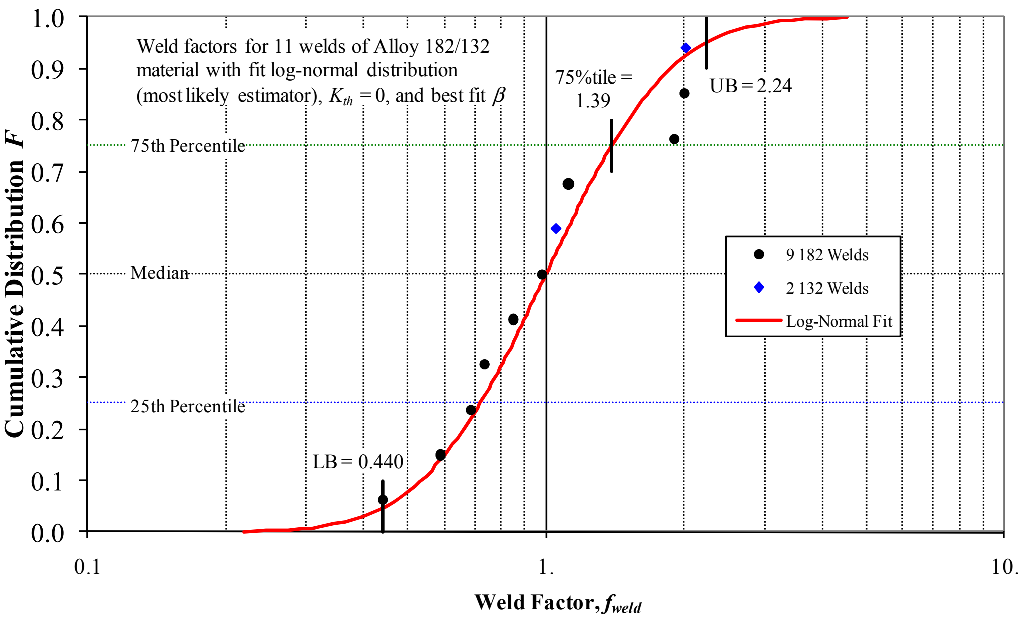
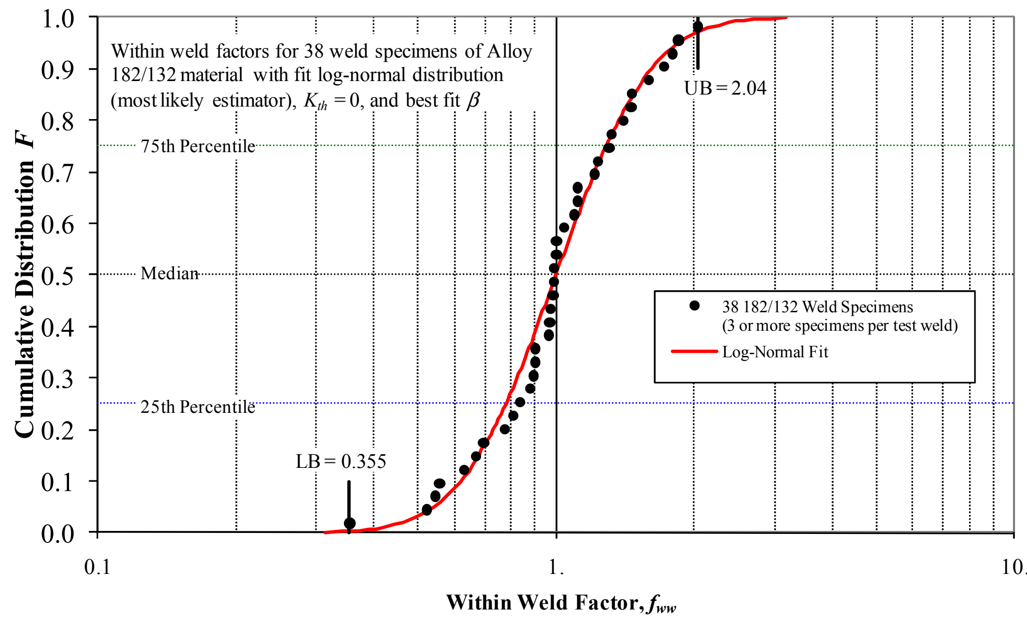
# Propagation Model

*Material Factors*

## Weld Factor, $f_{weld}$




## Within Weld Factor $f_{ww}$



# Propagation Model

*Zinc Effect*

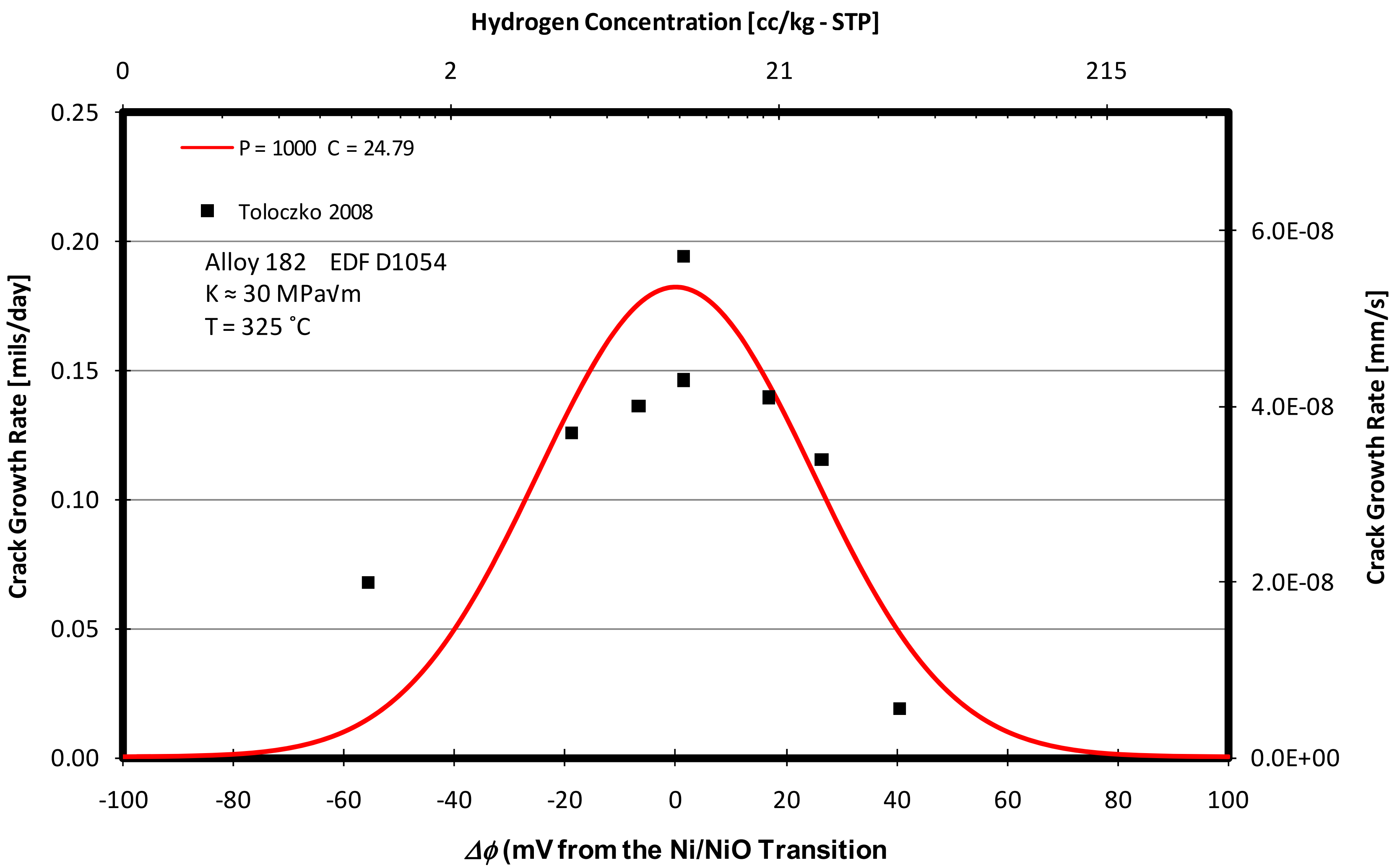
- Normal distribution in ln($f_{Zn}$-1)
  - $f_{Zn}$ > 1 corroborated by SG tube data
- Only applied for K<16.5 MPa√m
- Due to finite initial crack size, generally not applied during model run time

Data summary from MRP-263

| K (Mpa√m) | Zinc (ppb) | FOI |
|---|---|---|
| 27 | 57 | 1.25 |
| 27 | 22 | 0.64 |
| 22 | 108 | 1.08 |
| 16.5 | 50 | 5.67 |
| 16.5 | 50 | 2.83 |
| 16.5 | 50 | 1.00 |
| 16.5 | 50 | 1.00 |
| 27.5 | 50 | 0.62 |
| 27.5 | 150 | 1.72 |

# Propagation Model

*Hydrogen Effect – Example Test Data*



# Propagation Model

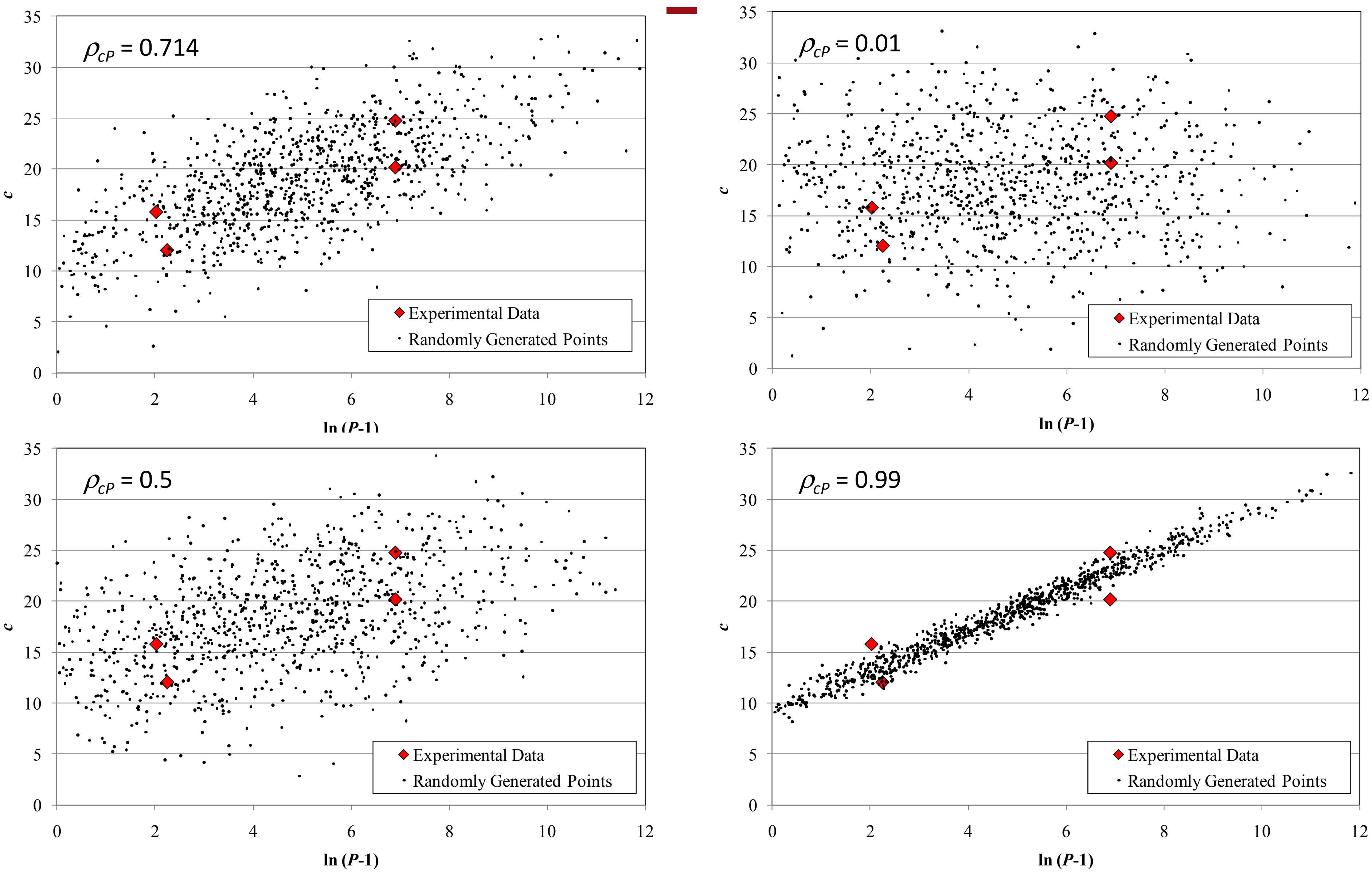
*Hydrogen Effect – Data Analysis*

- Four test sets for Alloy 182
  - Corroborated by additional Alloy 600 data
- Peak width parameter *c*
  - Normal distribution
  - $\mu = 18.5$, $\sigma = 5.5$
- Peak height parameter *P*
  - Normal distribution in ln(*P*-1)
  - $\mu = 4.52$, $\sigma = 2.75$ (mean *P* = 93)
  - *P* > 1 supported by data from other nickel alloys (600, 82, X750)
  - Form of equation used makes value of *P* unimportant if >~17

| Data Set | Peak Width, *c* (mV) | Peak Ratio, *P* |
|---|---|---|
| A | 20.2 | 1000 |
| B | 24.79 | 1000 |
| C | 12.06 | 10.5 |
| D | 15.81 | 8.6 |

# Propagation Model

*Hydrogen Effect – Correlation of Parameters Sensitivity Study*



# Propagation Model

*Other Aspects*

- Threshold $K_{Ith} = 0$
- Stress exponent b taken as a single value
  - 1.6 per MRP-115
- ΔECP taken as having no uncertainty
- During model run time, cracks grown in one month intervals

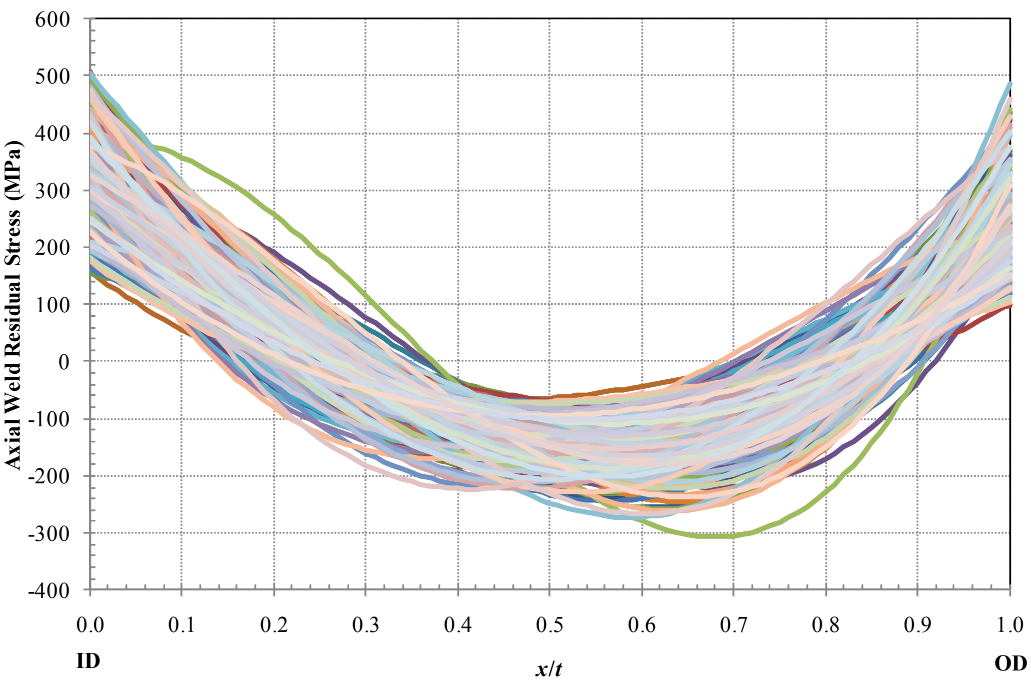
# Loads

*General Model Information*

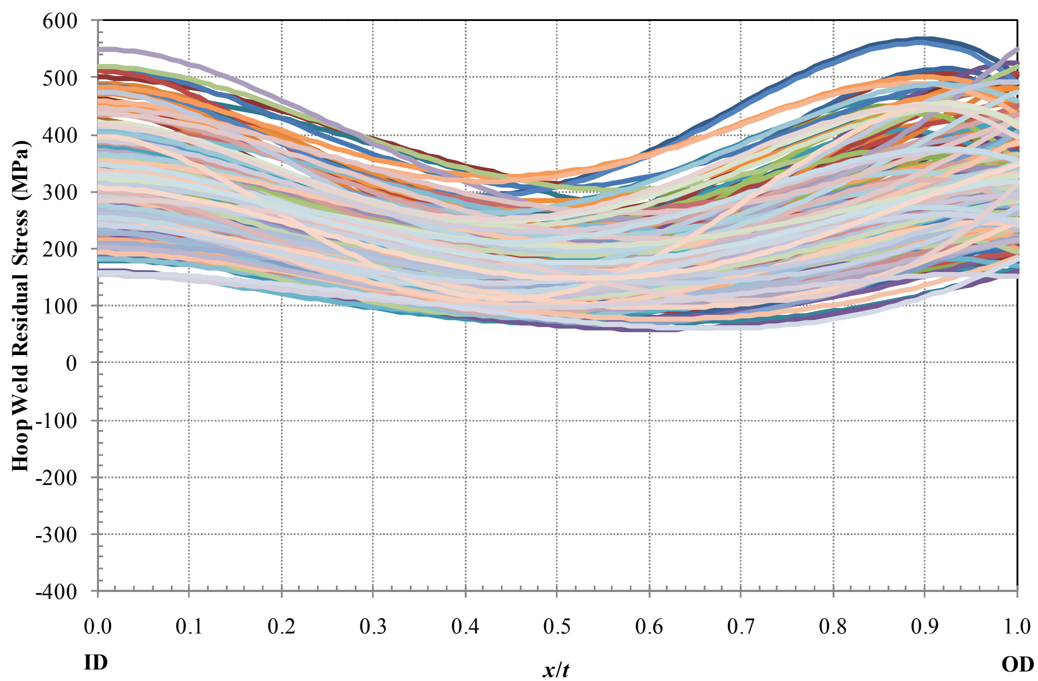
- Axial and hoop stresses considered
- Considers pressure, pipe thermal expansion, dead weight, and welding residual stresses
- Uses fourth order polynomial for residual stresses
- No seismic or thermal stratification loads (no surge nozzle cases)
- Axisymmetric welding residual stresses
- CEA K-solutions used
- Similar to xLPR models except that:
  - Axial flaws included
  - CEA K-solutions used instead of WRC/API K-solutions
  - Hoop stresses include welding residual stresses

# Loads
*Examples*

Axial Welding Residual Stress

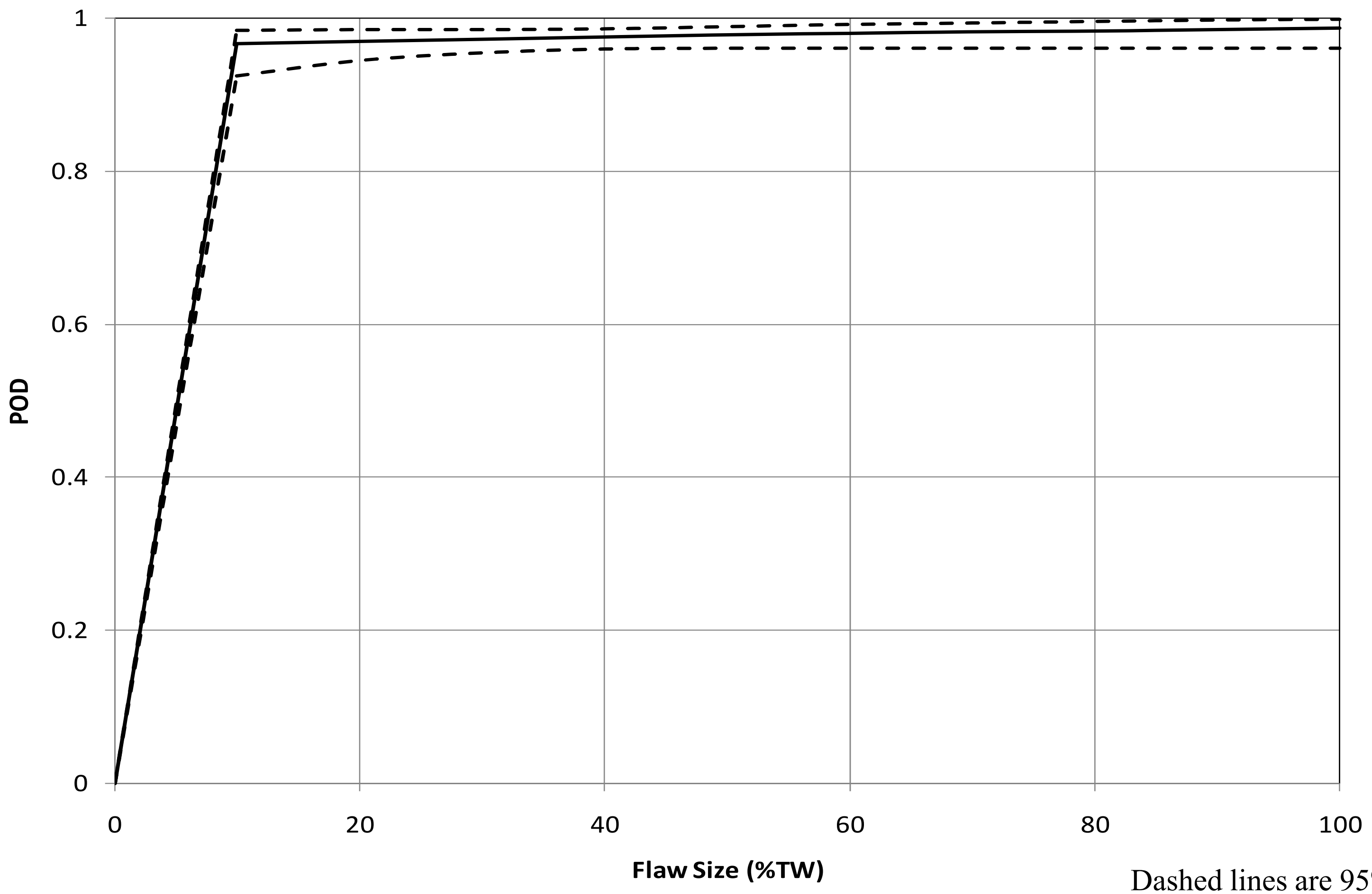



Hoop Welding Residual Stress



# Detection

- Used xLPR model, extrapolating to (0,0) from 10%

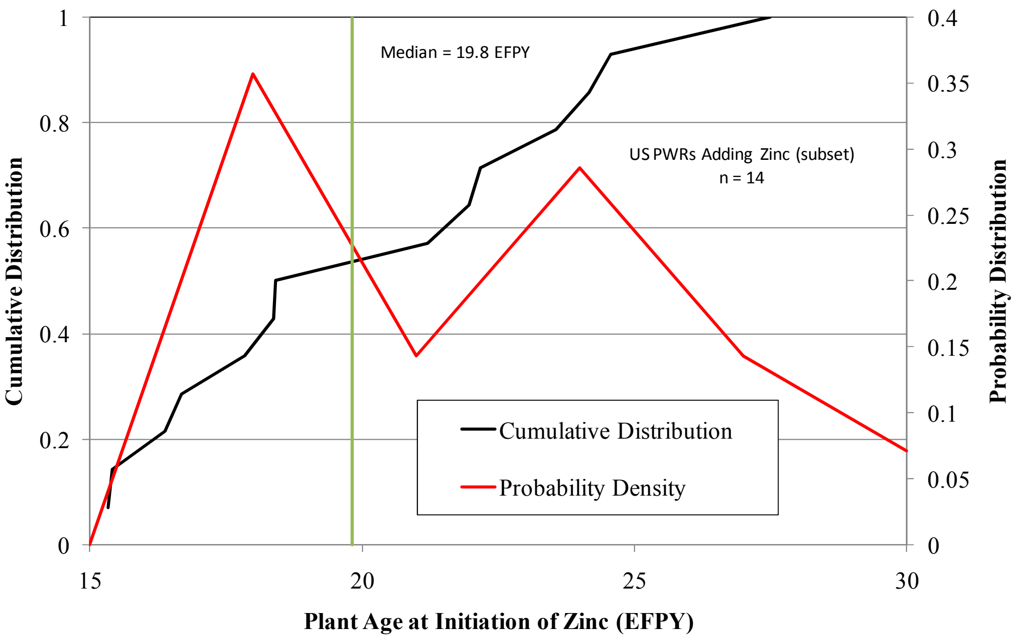


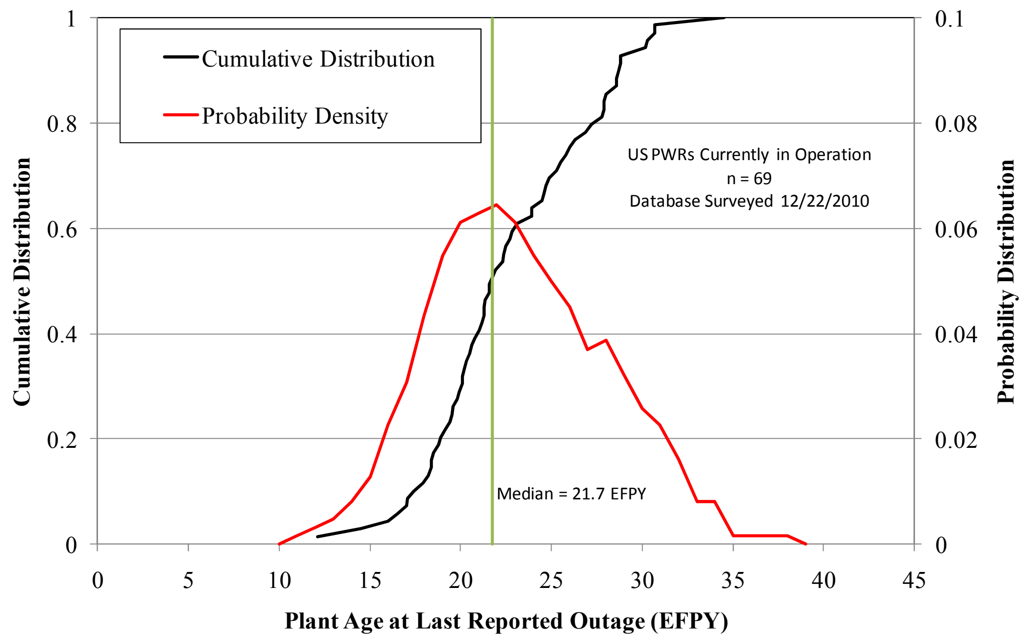

Dashed lines are 95% confidence bounds

# General Inputs

- Westinghouse RV Outlet Nozzle (RVON)
  - Others considered, but not presented here
- Typical geometry selected as fixed input
  - Thickness 2.75 in
  - Diameter 36 in
  - Width 1.75 in
- Aged component
- 315°C
- Un-optimized hydrogen = 37 cc/kg

# Aged Components

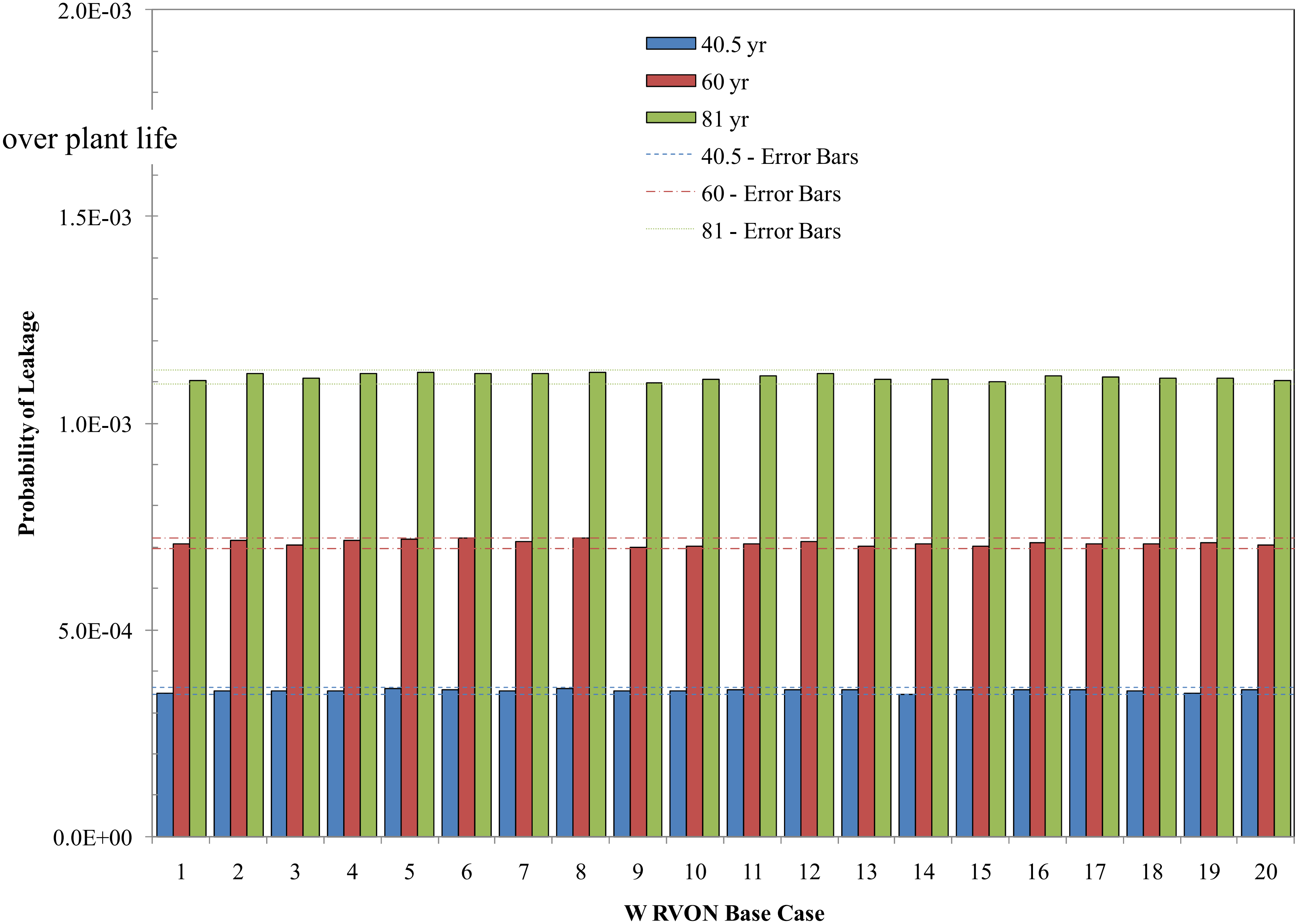


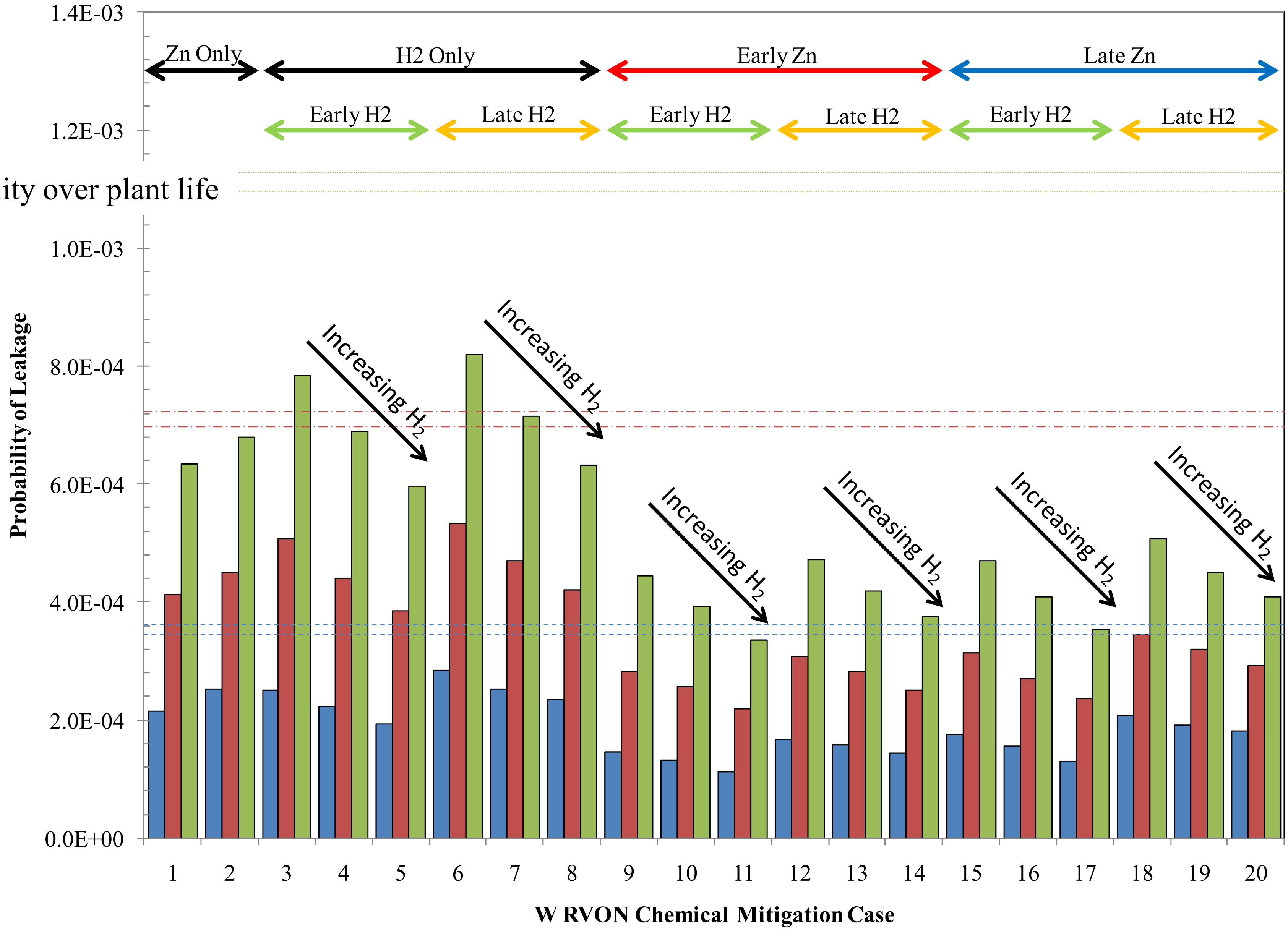
# Example Results

# Evaluation of Repeatability

Probability over plant life

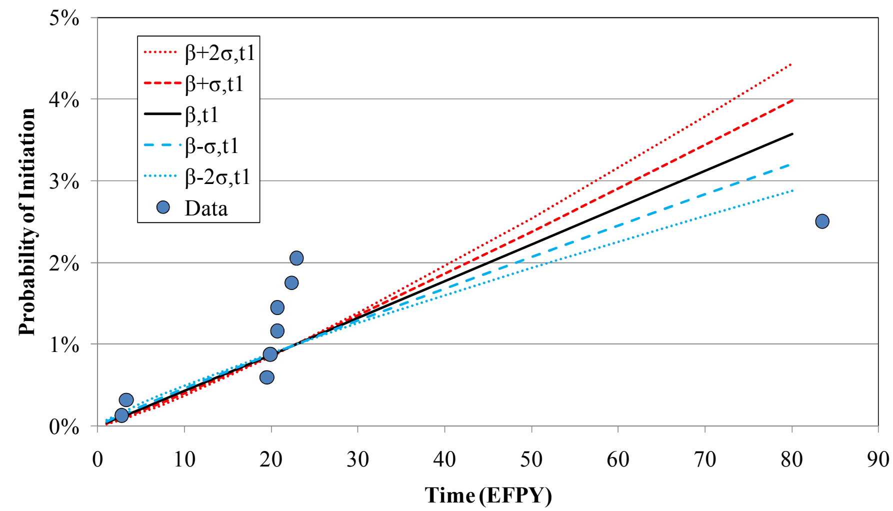


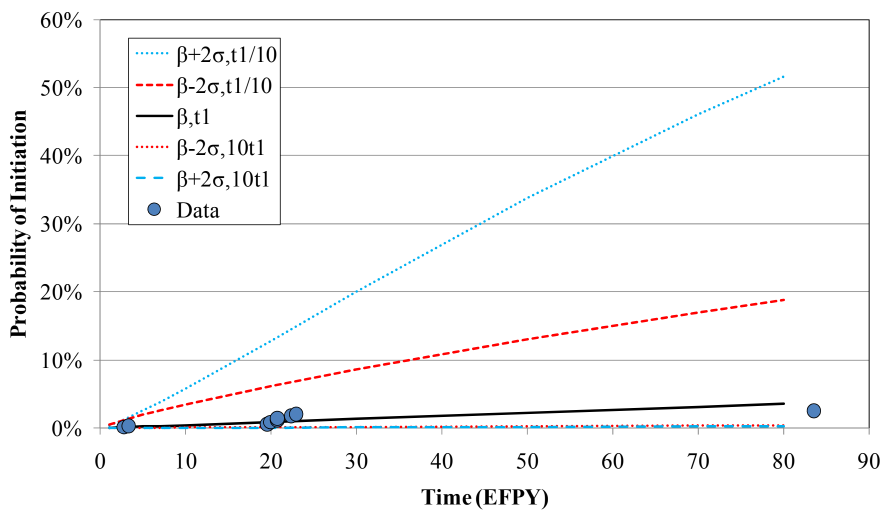
# Different Strategies Considered

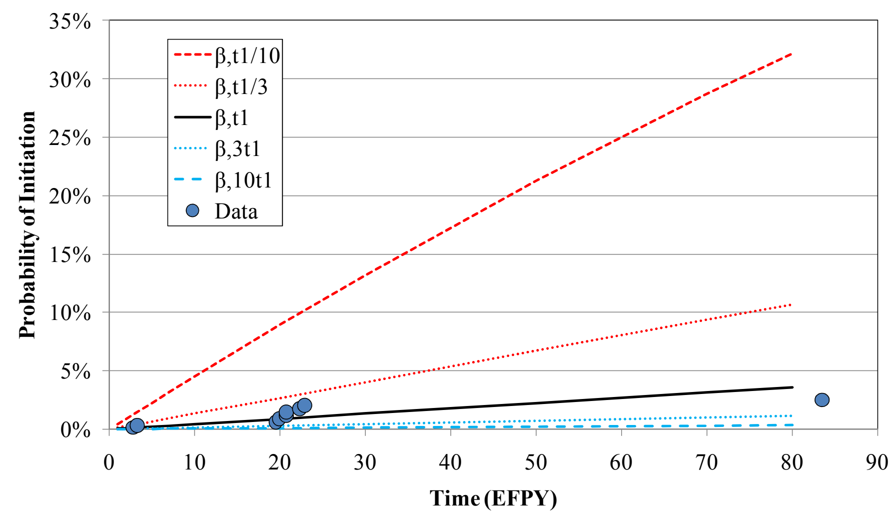


# Initiation Sensitivity Study – Inputs

| Case | $\beta$ | $t_I$ | $\theta$ |
|---|---|---|---|
| 1 (base) | 1.028 | 22.9 | 2007 |
| 2 | 0.940 | 22.9 | 3051 |
| 3 | 0.852 | 22.9 | 5056 |
| 4 | 1.116 | 22.9 | 1411 |
| 5 | 1.204 | 22.9 | 1044 |
| 6 | 1.028 | 7.6 | 669 |
| 7 | 1.028 | 2.3 | 201 |
| 8 | 1.028 | 68.7 | 6022 |
| 9 | 1.028 | 229.0 | 20073 |
| 10 | 0.852 | 2.3 | 506 |
| 11 | 0.852 | 229.0 | 50558 |
| 12 | 1.204 | 2.3 | 104 |
| 13 | 1.204 | 229.0 | 10440 |



# Initiation Sensitivity Study – Results

| Case | $\beta$ | $t_1$ | $\theta$ |
|---|---|---|---|
| 1 (base) | 1.028 | 22.9 | 2007 |
| 2 | 0.940 | 22.9 | 3051 |
| 3 | 0.852 | 22.9 | 5056 |
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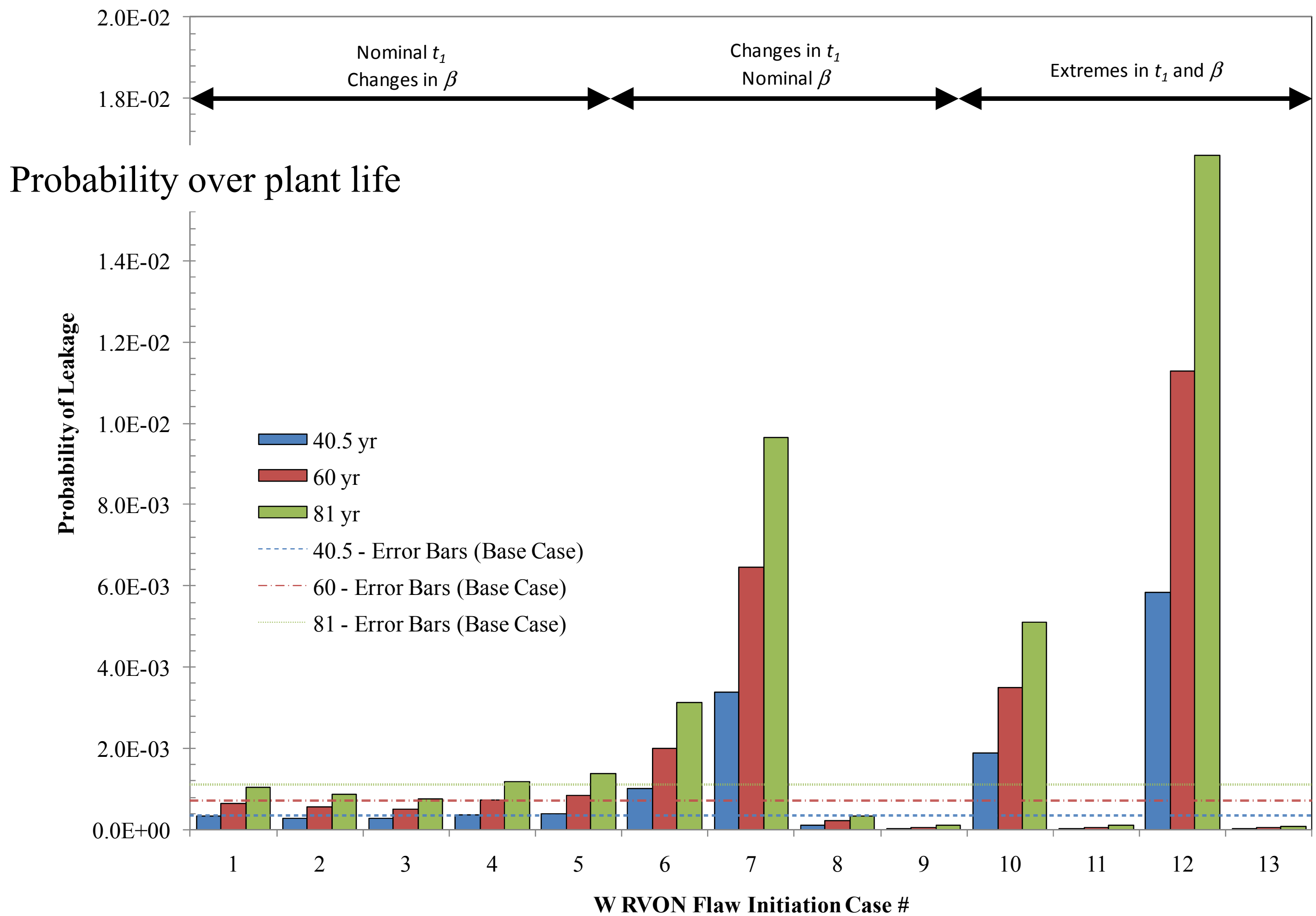
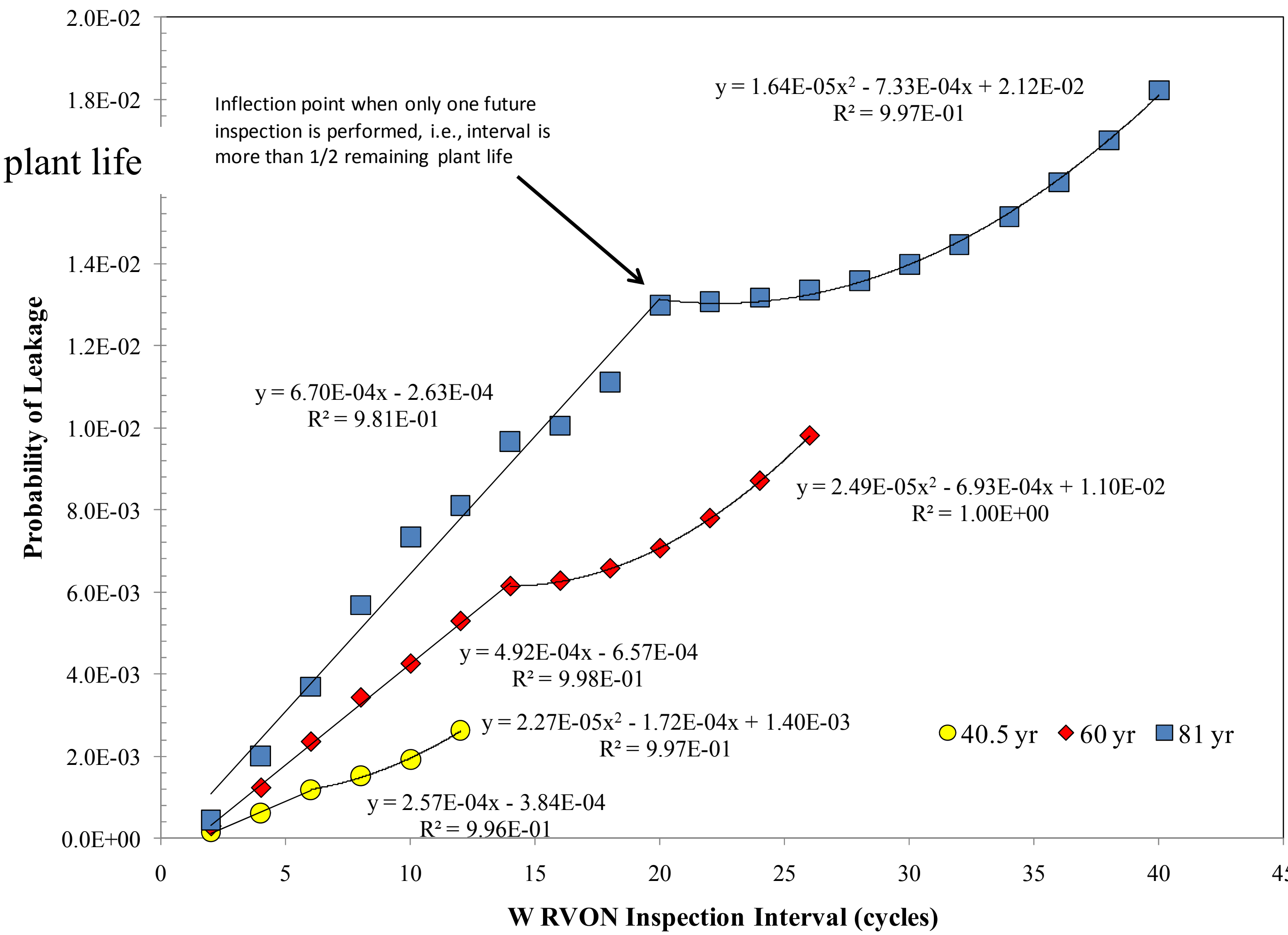


# Dependence on Inspection Interval

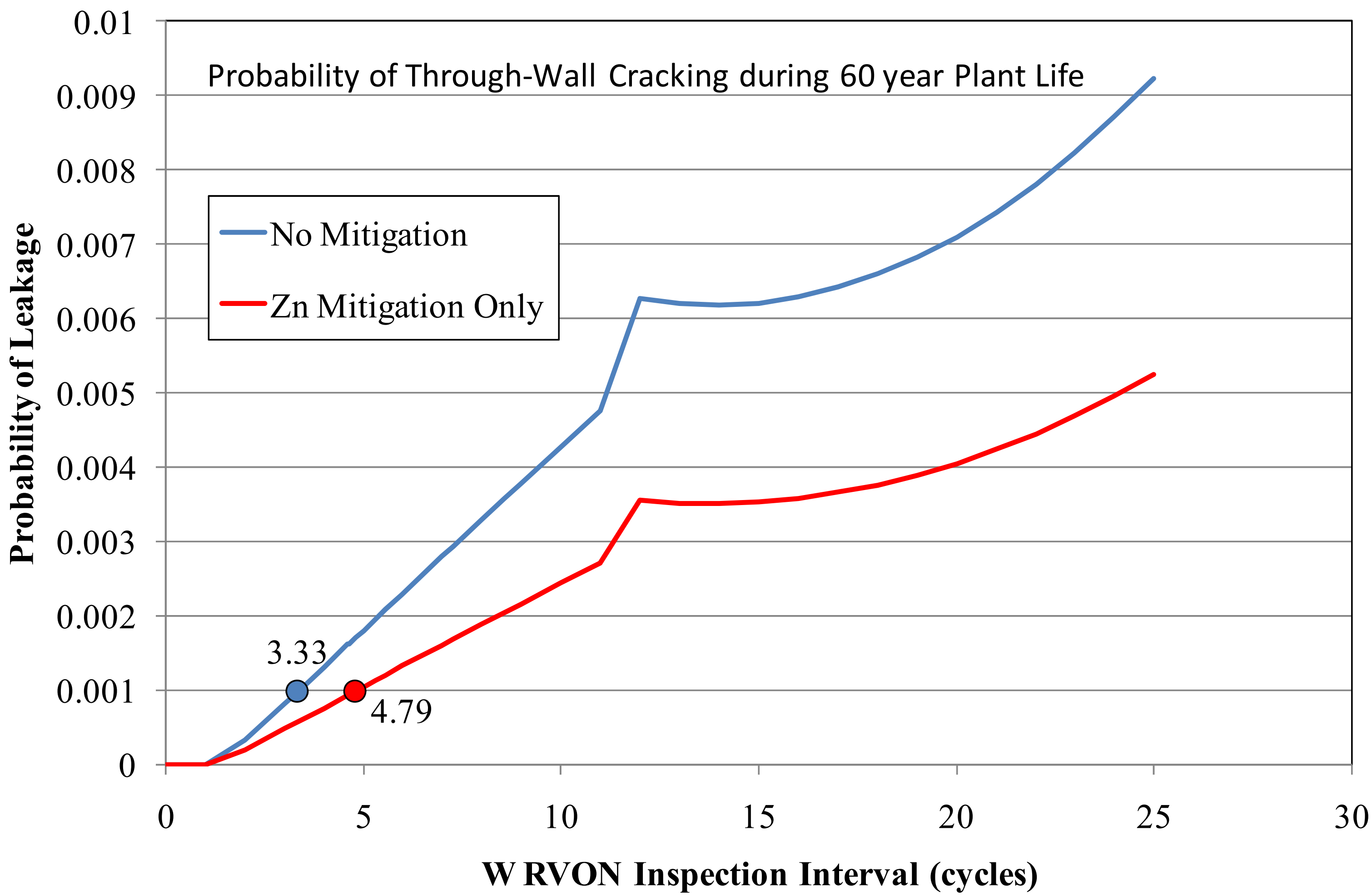
*No Mitigation*

Probability over plant life



# Dependence on Inspection Interval

*Comparison of No-Mitigation with Mitigation – Zinc Only*



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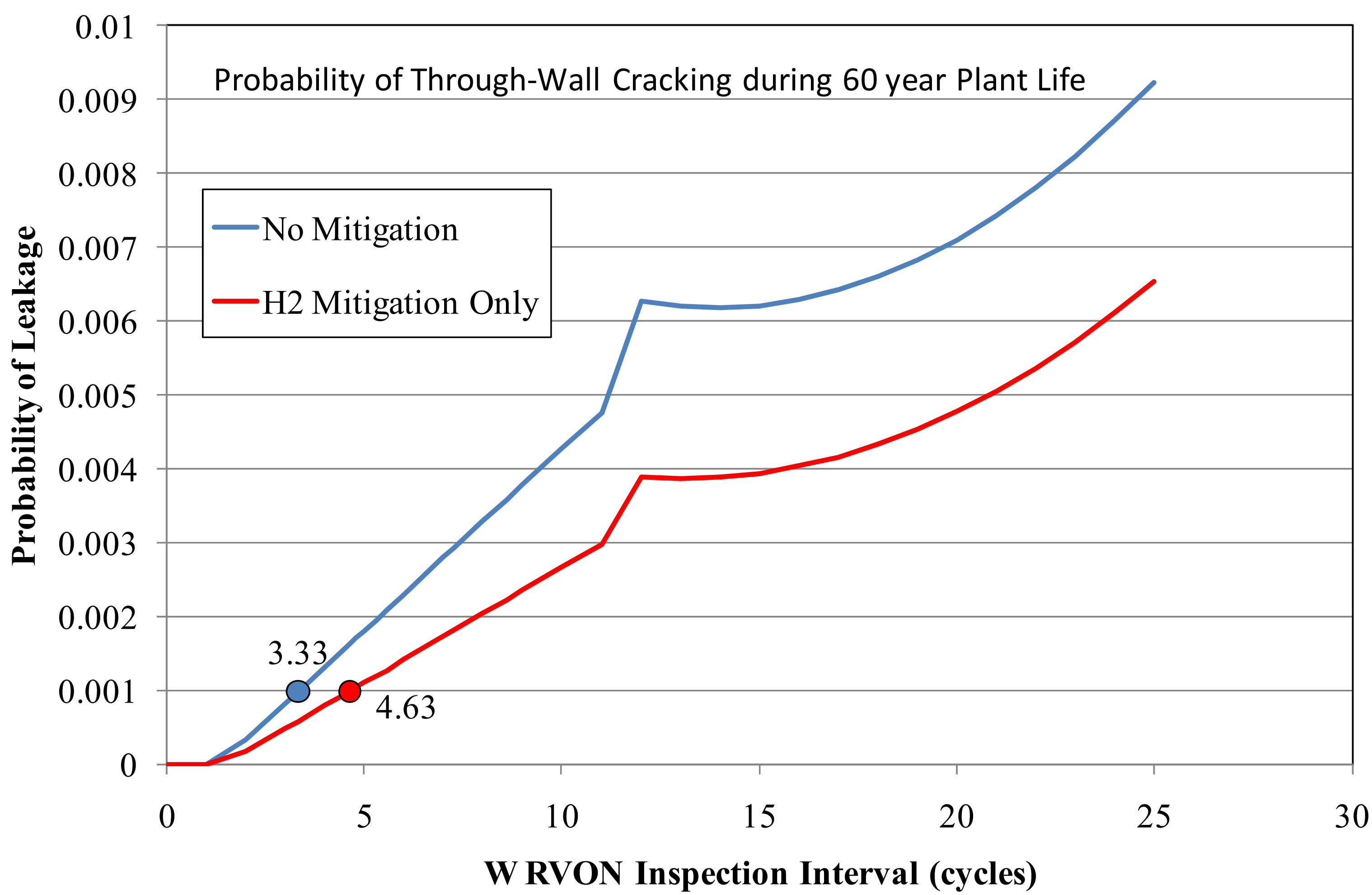
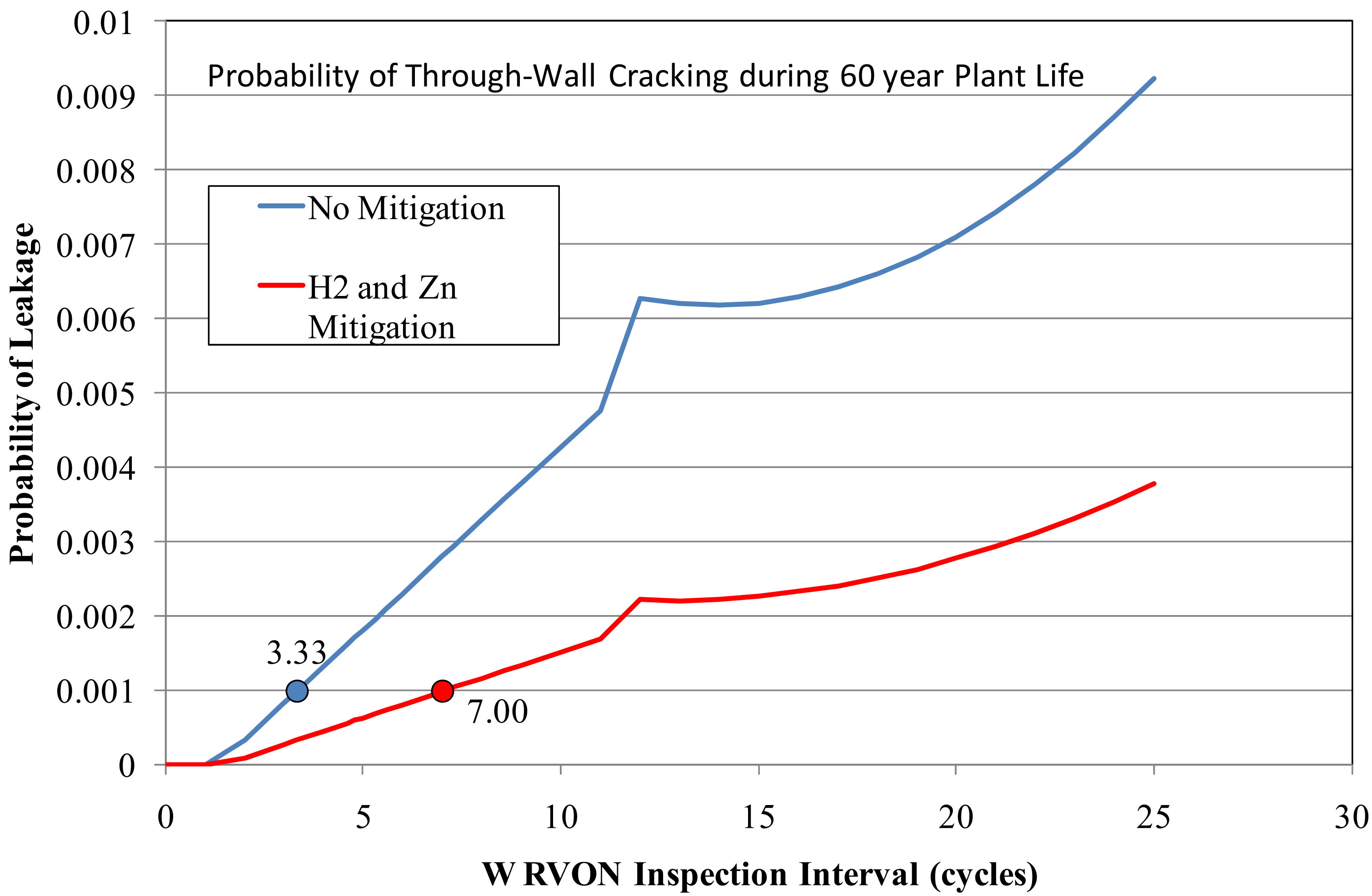
# Dependence on Inspection Interval

*Comparison of No-Mitigation with Mitigation – Hydrogen Only*



# Dependence on Inspection Interval

*Comparison of No-Mitigation with Mitigation – Hydrogen and Zinc*



# Conclusions

- Framework for quantitative incorporation of chemical mitigation (initiation and propagation) developed
- Results are favorable
- Industry considering best path forward