Probabilistic Evaluation of BWR Core Shroud Weld Inspection Intervals

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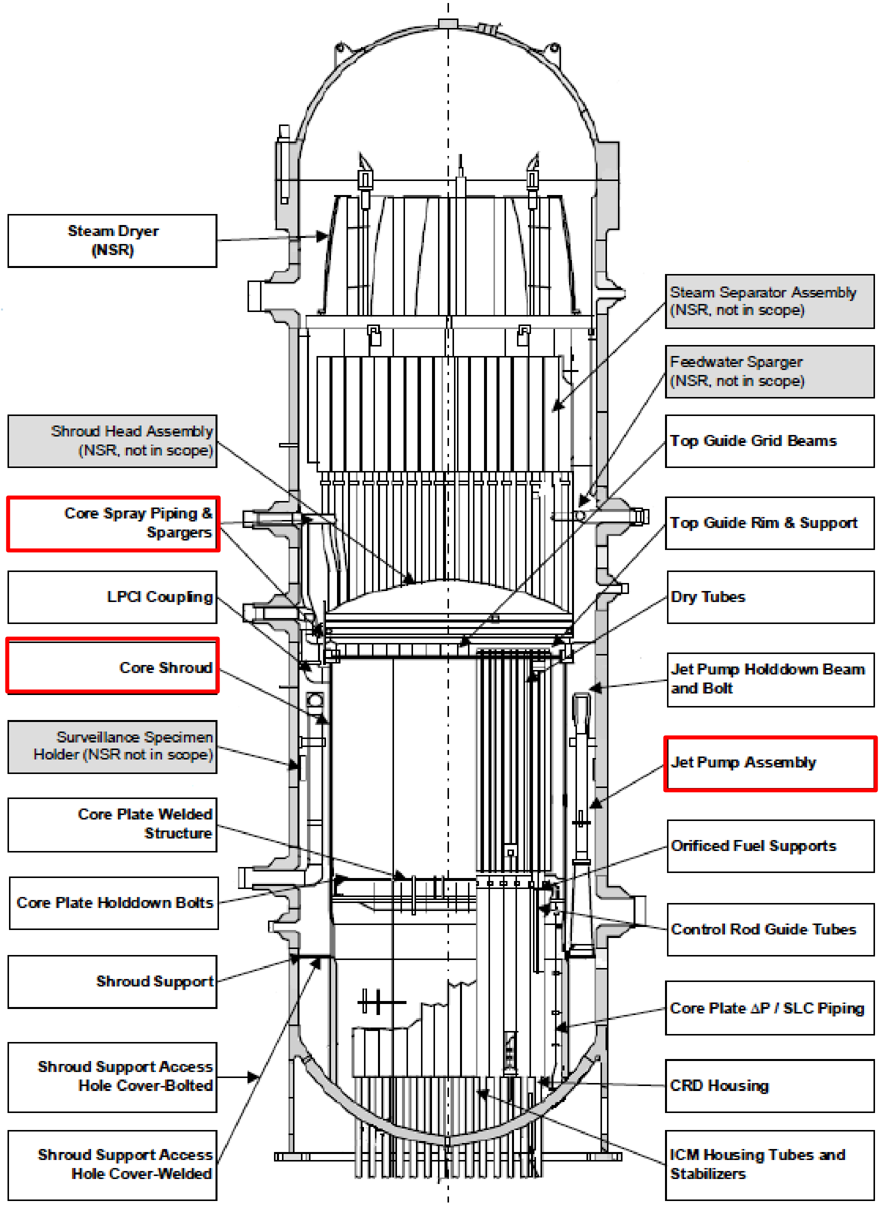
Background

- IGSCC of reactor internals has been an ongoing aging management issue for BWRs since the early 1990s
- Stainless steel reactor internals with significant IGSCC occurrences include the core shroud, jet pump assemblies, and core spray internals
- Almost all operating U.S. BWRs have identified IGSCC in the core shroud
- Although some core shrouds were repaired with tie rods in the 1990s, current best practice is to manage cracking thru water chemistry control, periodic inspection, and flaw tolerance evaluation



Typical BWR RPV Internals Components

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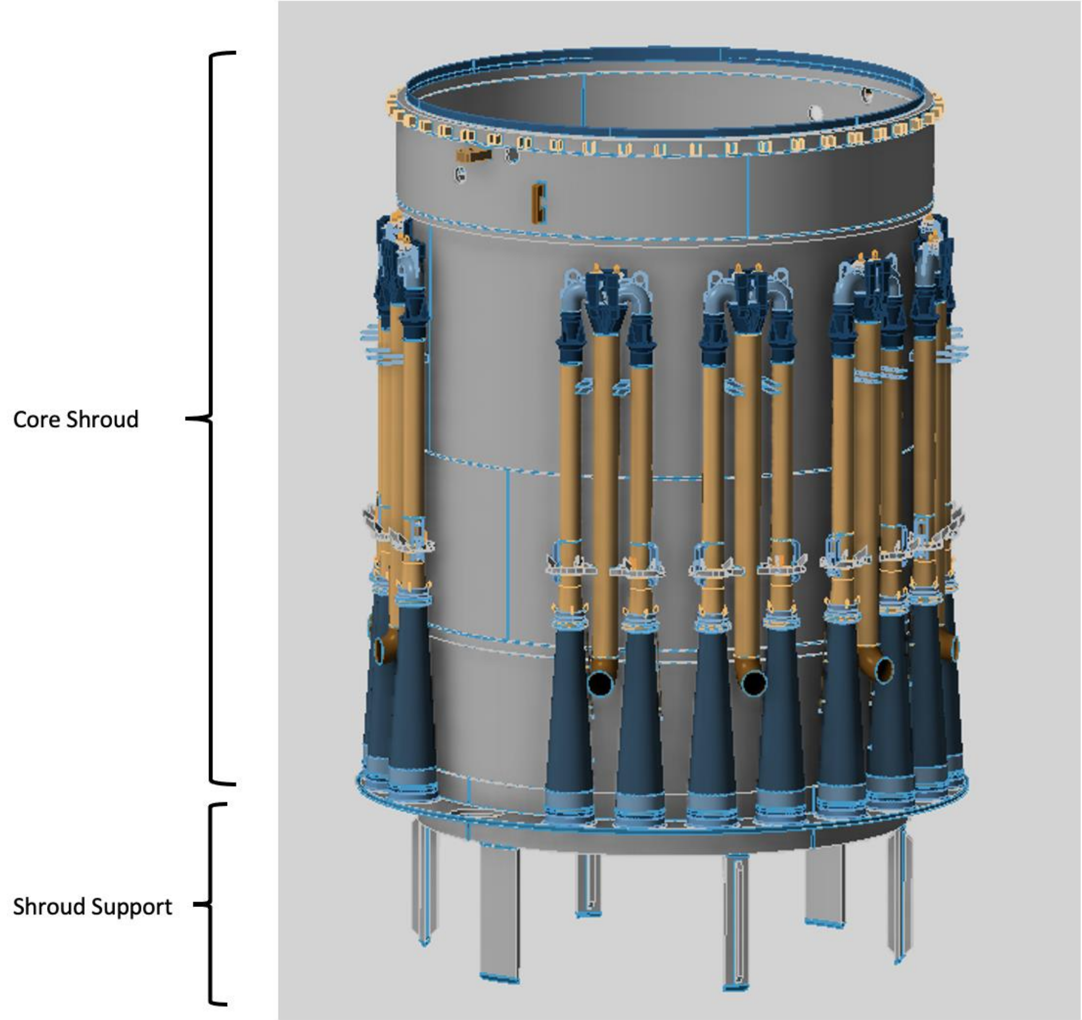
Core Shroud Design and Function

- Welded stainless steel cylindrical structure located inside the pressure vessel and surrounding the reactor core
- Safety functions include core support and providing a refloodable volume post LOCA
- In U.S. BWRs, core shrouds were fabricated from rolled and welded stainless steel plates with thicknesses ranging from 1.25” to 2.0” [32mm to 51mm]



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Evaluation Objective & Focus

- In the U.S., core shroud welds have generally been examined on 10-year frequency
  - Interval capped at 10 years - even if structural evaluation results indicate much longer inspection intervals can be justified
  - Appropriate at the time given the limited state of knowledge regarding progression of IGSCC in BWR reactor internals
- PFM evaluation focused on assessing the relative change in risk associated with 20-year inspection intervals (vs. 10-year intervals)
- Initial evaluations showed that the limiting welds in a core shroud are the irradiated beltline welds
  - As a result, the PFM analyses focused on evaluating irradiated welds

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Evaluation Inputs

- Material properties
  - Fracture toughness: typical of irradiated end-of-life condition, a lower end value of K_{IC} = 50 ksi√in generally considered
- IGSCC CGRs:
  - Depthwise crack growth: statistical distributions derived from ASME Code Case N-889 technical basis crack growth data
  - Lengthwise crack growth: Based on EPRI BWRVIP core shroud inspection database (see following slide)
- Loads: Evaluation considered a range of loads typical of irradiated beltline core shroud horizontal welds (1 to 4 ksi)
- Weld residual stress: Based on work described in BWRVIP-14-A with sampling from a multivariate normal distribution calculated from the means, standard deviations, and correlation of the ID and OD WRS parameters
- Inspected fraction of circumference: 50% and 80% coverage evaluated to assess relative differences
- Initial cracked fraction of circumference selected to investigate cases where deterministic structural analyses results would predict end-of-intervals at or near 20 years

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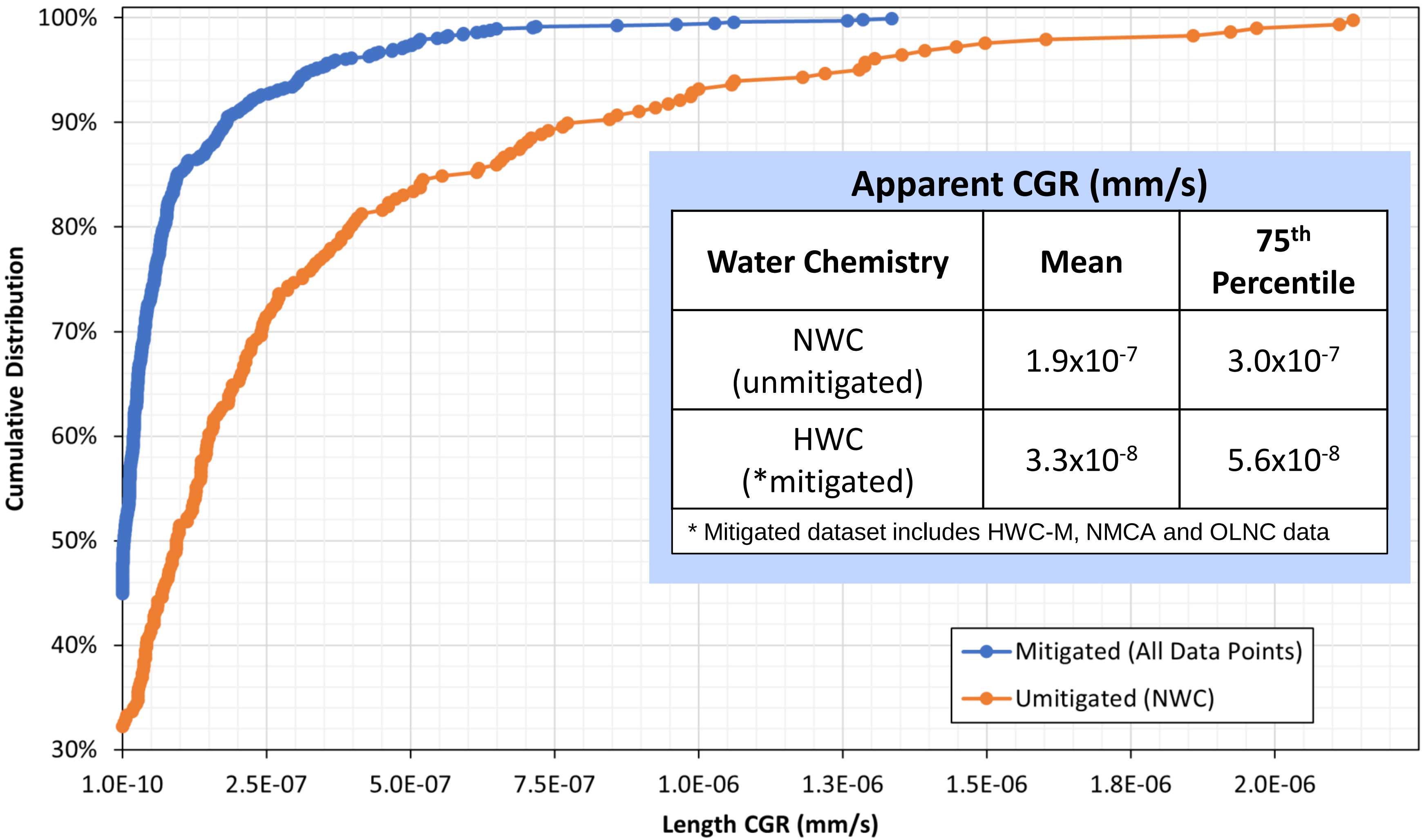
Lengthwise CGRs – As Estimated from Field Data

- EPRI BWRVIP database contains over 3,500 CGR data estimated from repeat inspections of individual indications
- The HWC CGR dataset (blue data) was used in the PFM assessment



Apparent CGR (mm/s)

Water Chemistry	Mean	75th Percentile
NWC (unmitigated)	1.9×10^{-7}	3.0×10^{-7}
HWC (*mitigated)	3.3×10^{-8}	5.6×10^{-8}

* Mitigated dataset includes HWC-M, NMCA and OLNC data

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Applicability of Results

- Results are used to understand relative <u>conditional</u> probability of failure (CPOF) considering changes in relevant parameters:
  - Inspection interval
  - Inspected fraction of circumference
  - Initial cracked fraction of circumference
  - Load
  - Material properties
- Actual probability of failure (POF) is product of frequency of occurrence per year (Freq) and CPOF:

$$POF = Freq \times CPOF$$

  - Service Level A/B: Freq = 1 event/operating year
  - Service Level D: Freq << 1×10^{-3} event/operating year

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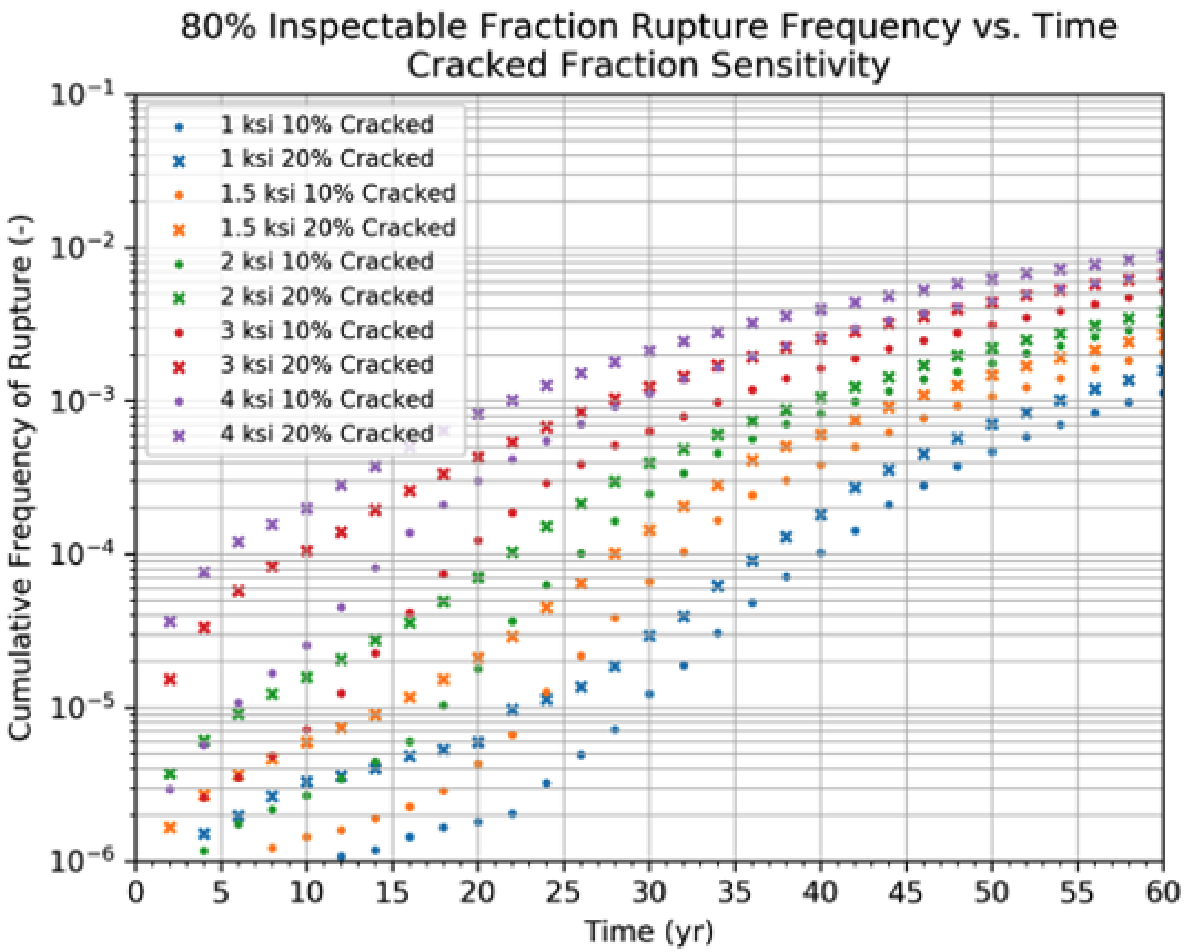
Shroud Horizontal Weld Probabilistic Fracture Mechanics Results



- **Conclusion: Results show that increasing inspection intervals has minimal impact on overall risk of failure**
  - Service Level A/B CPOF ~ 1E-5 at 20 years (1 & 1.5 ksi stresses)
    - POF ~ 1E-5 yr^{-1}
  - Service Level D CPOF ~ 1E-3 at 20 years (3 & 4 ksi stress)
    - POF ~ 1E-6 yr^{-1}

1 ksi and 1.5 ksi results generally applicable to Service Level A/B (Frequency of Occurrence ~ 1 event/operating year)

3 ksi and 4 ksi results generally applicable to service level D (Frequency of Occurrence << $1x10^{-3}$ event/operating year)

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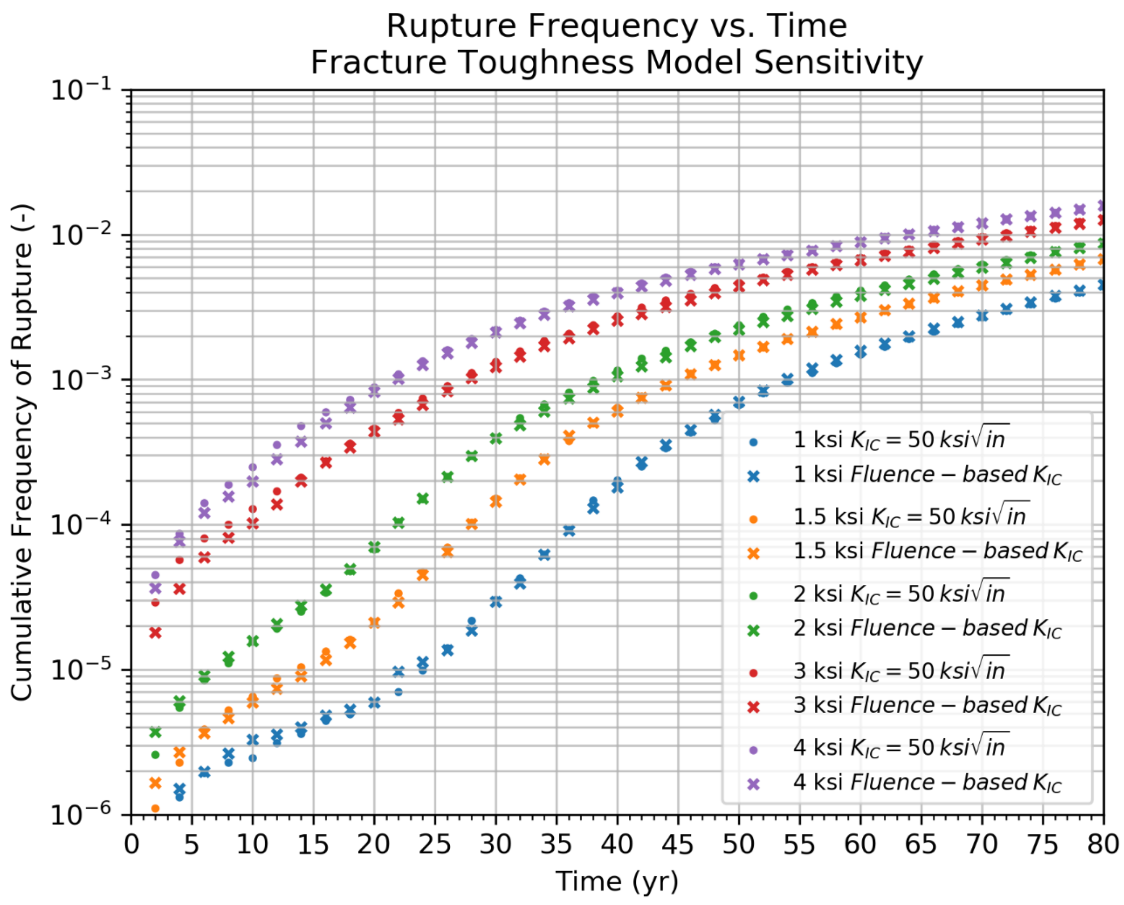
Fracture Toughness Sensitivity

- "*Fluence-based*" model evaluated mixture of K_{IC} = 112 ksi√in and K_{IC} = 50 ksi√in values (based on BWRVIP-100)
- Marginally lower rupture frequency for fluence-based K_{IC} vs K_{IC} = 50 ksi√in
- **Conclusion: Differing fracture toughness models result in effectively no difference in frequency of rupture**



1 ksi and 1.5 ksi results applicable to Service Level A/B (Freq ~ 1 event/operating year)

3 ksi and 4 ksi results applicable to service level D (Freq << 1x10^{-3} event/operating year)

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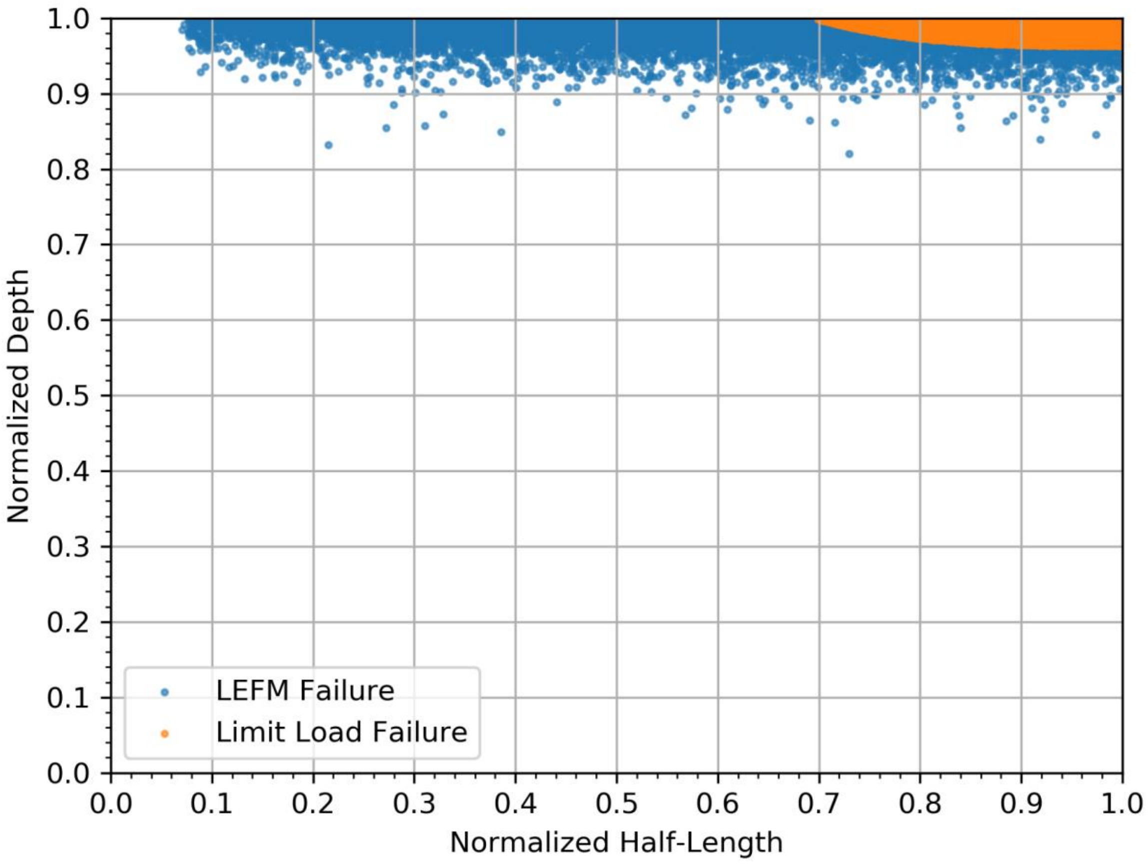
Single Crack Failure Study

- 1 crack per realization at the outer diameter (more conservative)
- Depths between 0.1% and 99.9% shroud thickness
- Lengths between 1% and 99.9% circumference
- 4 ksi load, all cracks centered at maximum bending moment, K_{IC} = 50 ksi√in
- Very deep (>82% TW) cracks required for any failures to occur
- **Conclusions:**
  - **Length of surface cracking not correlated with failure beyond 10% circumference**
    - **Very deep or thru-wall cracks are the main risk associated with shroud failure**



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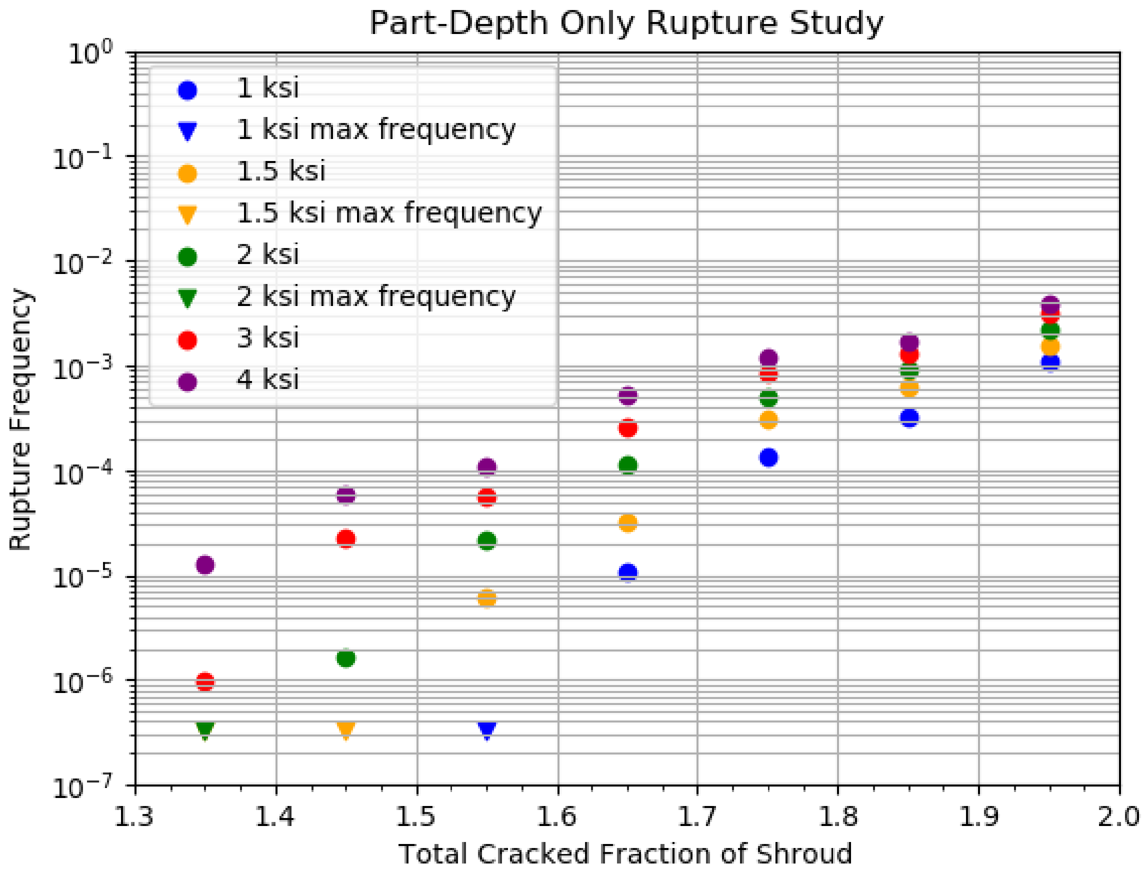
Surface Crack Failure Results

- Rupture frequency for realizations with cracked fractions in each 0.1 interval
- Exclusively Limit Load failures
- Significant drop-off in rupture frequency at low loads and lowest cracked fractions
- **Conclusion: part-depth cracks do not result in failure cases**



$$Cracked\ Fraction = \frac{length\ of\ cracking\ at\ ID + length\ of\ cracking\ at\ OD}{Shroud\ Circumference}$$

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Conclusions

- Analyses show insignificant change in CPOF when increasing inspection intervals from 10 years to 20 years (or much longer)
- Core shroud CPOF driven by “failures” occurring from brittle fracture of through-wall flaws
  - However, experience has shown that thru-wall cracking is extremely unlikely in circumferential welds
    - In 25+ years of inspections of over 30 BWR core shrouds, only 1 potentially thru-wall flaw in a circumferential weld has been reported
    - Reanalysis of the UT data for this case showed that the vendor uses conservative procedures for assessing flaw depth and that the actual flaw depth is 75% or less
- Results are conservative due to the conservative interpretation of CGRs used in the analyses
  - All cracks assumed to grow continuously (i.e., crack arrest never assumed) even though nearly half of cracks in U.S. BWR shrouds are not growing at detectable rates
  - Field data not used for thru-thickness CGRs (ASME Code Case N-889 basis data are used instead)

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