Probability of Leakage and Critical Flaw Size

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Topics

- Probability of Leakage
  - Weibull slope
  - Weibull distributions based on plant data
- Critical Flaw Size
  - MRP-44, Part 2 methodology and inputs
  - Comparison with EMC^2 presentation of November 8, 2001

Probability of Leakage

Weibull Modeling

- Probability of future leakage is modeled using the two-parameter Weibull distribution:

$$\text{Probability of Leakage} = F\left(EDY\right) = 1 - e^{-\left(\frac{EDY_{600^\circ F}}{\theta}\right)^{b}}$$

- The accrued effective degradation years (EDYs) is the plant effective full power years (EFPYs) normalized to a head temperature of 600°F:

$$T_{ref} = 617^\circ\text{F} + 459.67 = 1076.67^\circ\text{R}$$

$$Q_i = 50 \text{ kcal/mole}$$

$$R = 1.103 \times 10^{-3} \text{ kcal/mole} \cdot {}^\circ\text{R}$$

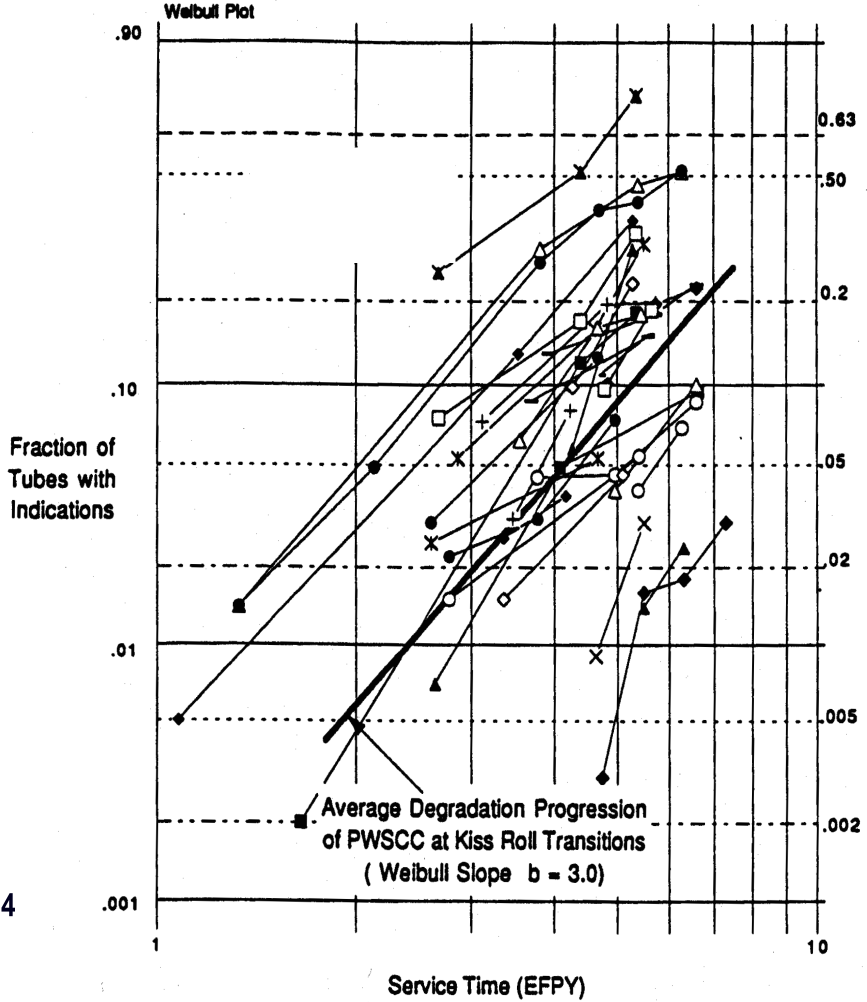
$$EDY_{600^\circ F} = \sum_{j=1}^{n} \left\{ \Delta EFPY_j \exp\left[-\frac{Q_i}{R} \left(\frac{1}{T_{head,j}} - \frac{1}{T_{ref}} \right) \right] \right\}$$

Probability of Leakage
Weibull Slope

- Practically no multiple inspections (i.e., at the same plant) have been performed for RPV head leakage
- In the absence of available data for the specific application, Abernethy recommends that "library" values of the Weibull slope for similar applications be used
- This approach is preferable to pooling data for multiple plants because differences in susceptibility will distort the apparent Weibull slope
- Experience with PWSCC of Alloy 600 materials in nuclear power applications indicates that a slope of 3 is appropriate for head nozzle leakage
  - Plant PWSCC in steam generator tubes at various locations
  - PWSCC lab tests (e.g., MRP-68, April 2002, best fit slope of 2.73 for 127 test sets)
- Using the slope of 3, a Weibull characteristic time may be calculated based on head nozzle leakage inspection results

Probability of Leakage
Available Plant Data from Multiple Inspections

Time-to-PWSCC for
Steam Generator
Hot Leg Kiss Roll
Expansion Transitions



Source:
EPRI TR-103696, July 1994

Probability of Leakage
Available Plant Data from Multiple Inspections

Typical Weibull Slopes for Steam Generator Tube PWSCC

Type of PWSCC	**Number of Plants**	**Median**	**Average**	**Standard Deviation**
At Kiss Roll Transitions (full depth rolled)	14	2.74	3.01	1.4
At Full Depth Roll Standard Transitions	7	4.09	3.72	1.74
Above F* Distance (standard roll transitions plus roll overlaps)	9	3.14	3.04	1.03
At Wextex Transitions (full depth expansion)	7	4.2	3.72	1.64
At Part Depth Roll Standard Transitions	3	4.48	4.14	0.96
At TSP Dents (slope for only one plant)	1	2.66	2.66	None
At Row 1 and 2 U-bends (pooled data for many plants)	--	About 4.4	--	--

Source:
EPRI TR-104030, July 1994

Probability of Leakage
Weibull Distributions Based on Plant Data

- Head nozzle inspection results evaluated assuming a Weibull slope of 3
- The following tables and Weibull plots reflect inspection results through the end of 2001
- Several types of distributions considered
  - B&W plants versus all domestic plants
  - Fraction of nozzles leaking at a plant
  - Fraction leaking in pooled population of nozzles for several plants
  - Fraction of units that have at least one leaking nozzle
- Some distributions treat “non-leaking” nozzles or heads as suspended items

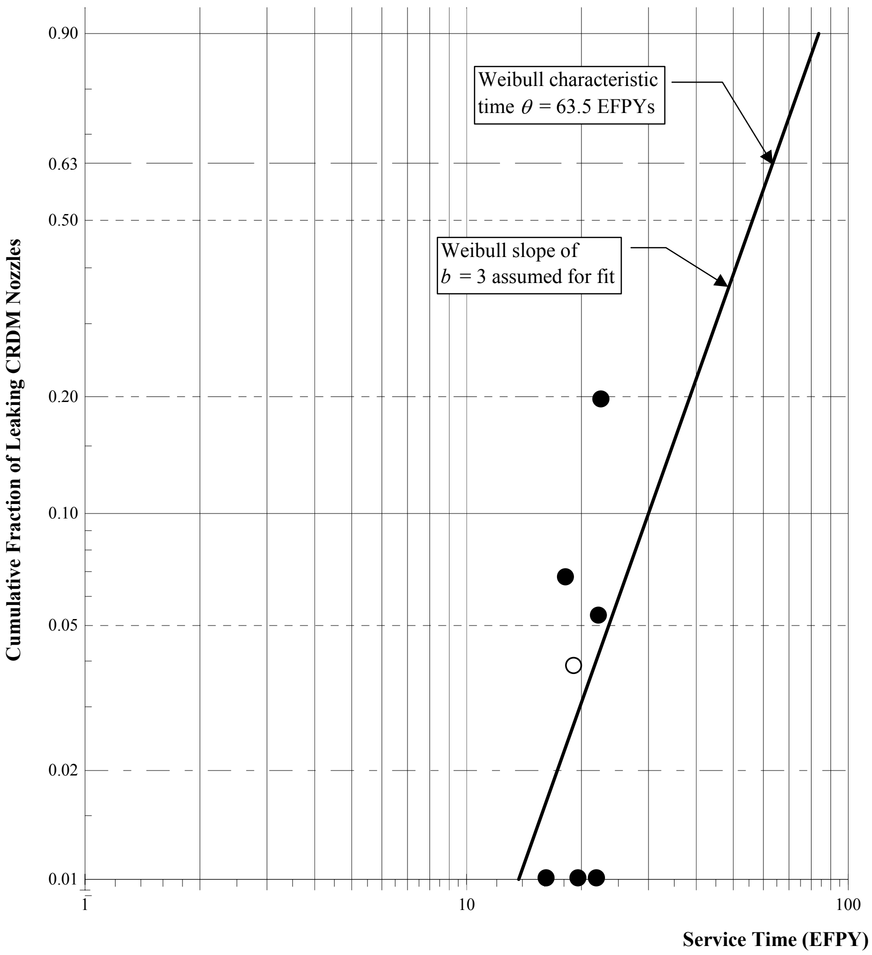
Probability of Leakage
Weibull Plot for B&W Units

- Fraction of nozzles leaking at each B&W unit
- Weibull characteristic time for fit is 63.5 EDYs
- Equivalent Weibull characteristic time for time to first leaking nozzle is 15.5 EDYs

$$\theta_{1st\ leak} = \frac{\theta}{\sqrt[b]{n}}$$

- Figure reflects data through end of 2001

All inspection data adjusted to 600 °F (Q = 50 kcal/mole)

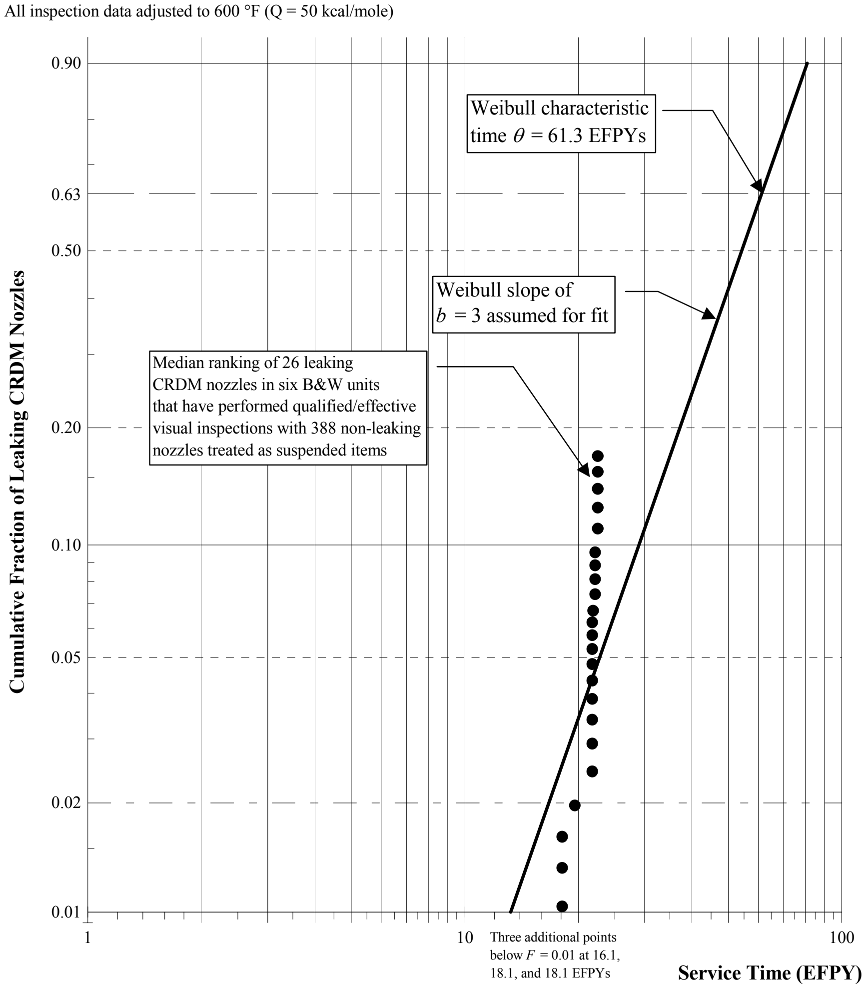

Weibull characteristic time θ = 63.5 EFPYs

Weibull slope of b = 3 assumed for fit

Probability of Leakage

Weibull Plot for B&W Units

- Pooled data for all inspected B&W plants
- Non-leaking nozzles treated as suspended items
- Figure reflects data through end of 2001



All inspection data adjusted to 600 °F (Q = 50 kcal/mole)

Weibull characteristic time θ = 61.3 EFPYs

Weibull slope of b = 3 assumed for fit

Median ranking of 26 leaking CRDM nozzles in six B&W units that have performed qualified/effective visual inspections with 388 non-leaking nozzles treated as suspended items

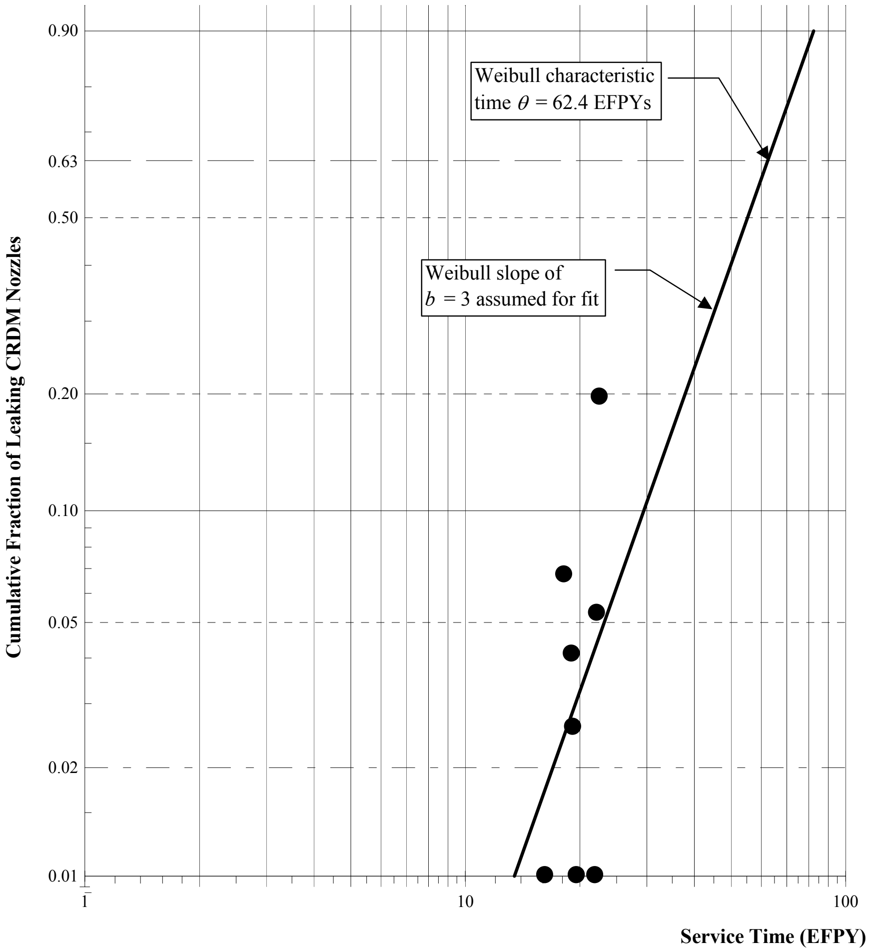
Three additional points below F = 0.01 at 16.1, 18.1, and 18.1 EFPYs

Probability of Leakage

Weibull Plot for All Domestic Units

- Fraction of nozzles leaking at each unit
- Plants that found no leaking nozzles cannot be included in the fit
- Figure reflects data through end of 2001

All inspection data adjusted to 600 °F (Q = 50 kcal/mole)



Weibull characteristic time $\theta = 62.4$ EFPYs

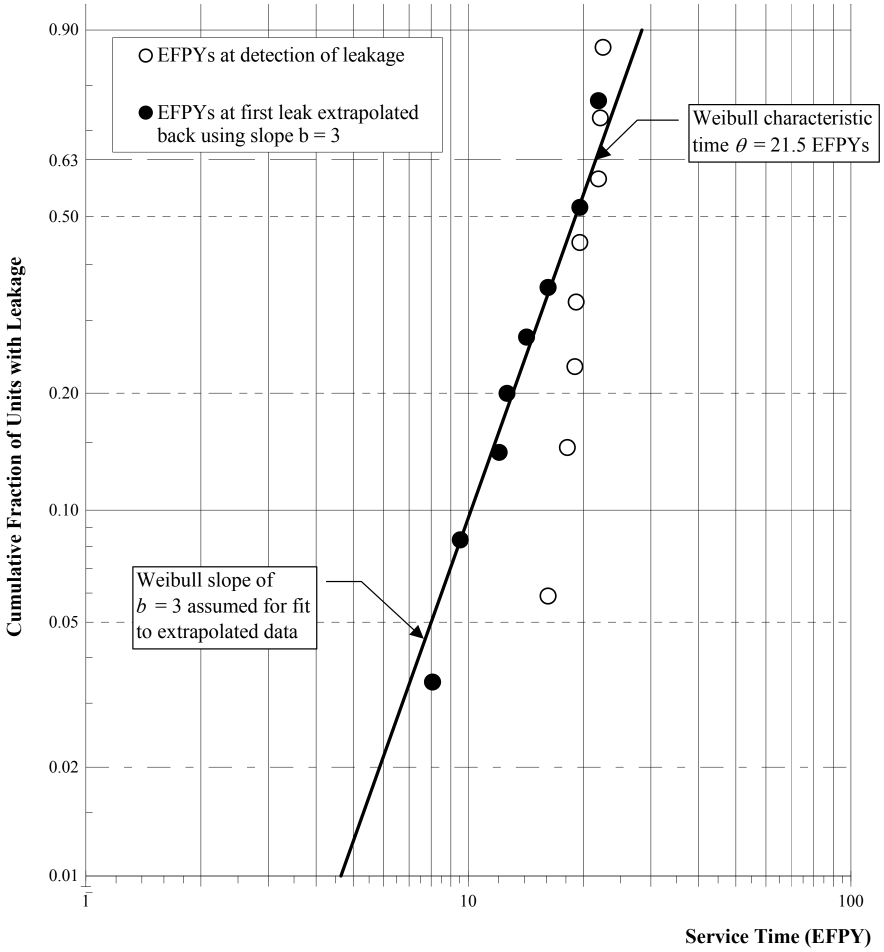
Weibull slope of $b = 3$ assumed for fit

Probability of Leakage

Weibull Plot for All Domestic Units

- Fraction of units with leakage
- 12 units with no leakers treated as suspended items
- Time to first leakage based on slope of 3
- Figure reflects data through end of 2001

All inspection data adjusted to 600 °F (Q = 50 kcal/mole)



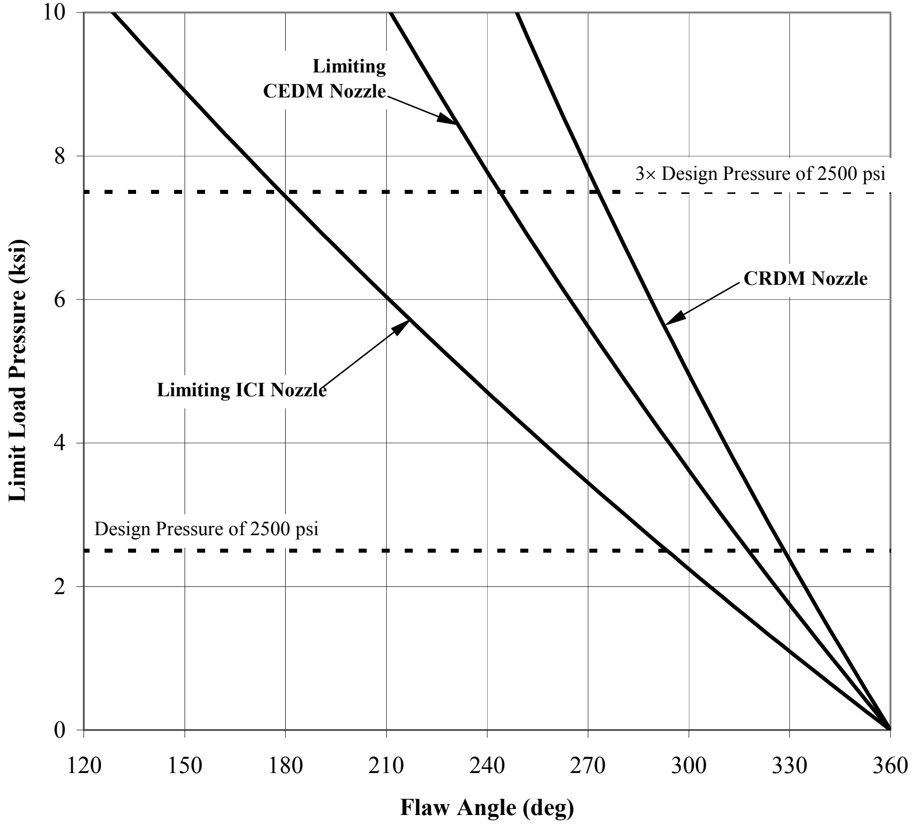
Critical Flaw Size

Critical Flaw Size
MRP-44, Part 2 Methodology

- Because of tight fitting annulus and high ductility of nozzle material, bending loads do not affect the required minimum ligament
- Critical flaw size may be calculated by equating ligament axial stress due to 2500-psig pressure with material flow stress
- Pressure load assumed to act on crack face as well as nozzle bore area
- Flow stress taken as average of yield and ultimate strengths at 650°F for applicable material specs
- Full range of nominal nozzle diameters and thicknesses at the 69 PWRs considered
- MRP-44 calculations are limiting and individual plants may perform less restrictive plant-specific calculations

Critical Flaw Size

MRP-44, Part 2 Results



Nozzle Type	Nozzle Geometry	Flow Strength S_f (ksi)	Flaw Angle θ for P_{flow} = 2500 psi (deg)	Flaw Angle θ for P_{flow} = 7500 psi (deg)	Limiting Nozzle of Type
CRDM	CRDM 1	54.85	330.2	277.9	
		51.95	328.7	273.9	
	CRDM 2	51.95	328.4	273.1	X
CEDM	CEDM 1	54.85	331.4	281.2	
	CEDM 2	54.85	331.3	280.7	
	CEDM 3	51.95	323.4	259.5	
	CEDM 4	51.95	317.7	243.8	X
	CEDM 5	54.85	333.5	286.9	
ICI	ICI 1	47.45	293.5	178.6	X
	ICI 2	47.45	308.6	219.9	
	ICI 3	47.45	313.4	232.9	

$$\theta = 360\frac{1-\dfrac{P_{flow}}{S_f}\dfrac{A_{bore}}{A_{wall}}}{1+\dfrac{P_{flow}}{S_f}}$$

Critical Flaw Size
Comparison with EMC^2 Presentation of 11/8/01

- Flow stress difference
  - MRP-44: $S_f = (S_y+S_u)/2.0$
  - EMC^2: $S_f = (S_y+S_u)/2.4$
- Used code properties at slightly different temperatures
  - MRP-44: 650°F
  - EMC^2: 600°F
- Results for CRDM nozzles are similar (at 3 times 2500 psig):
  - MRP-44: 273°
  - EMC^2: 262°
- MRP-44 also includes critical flaw sizes for limiting CEDM and ICI nozzles

Critical Flaw Size

Comparison with EMC^2 Presentation of 11/8/01

Parameter	EMC^2 Calc (CRDM)[1]	MRP-44 (Limiting CRDM)	MRP-44 (Limiting CEDM)	MRP-44 (Limiting ICI)
Design Pressure (psig)	2500	2500	2500	2500
Material Condition	——	SB-167 (hot-worked annealed; <5" OD)	SB-167 (hot-worked annealed; <5" OD)	SB-167 (hot-worked annealed; <5" OD)
Yield Strength, Sy (ksi)	——	23.9	23.9	19.9
Ultimate Tensile Strength, Su (ksi)	——	80.0	80.0	75.0
Basis for Sy and Su Values	Code properties at 600°F	Code properties at 650°F	Code properties at 650°F	Code properties at 650°F
Flow Stress, Sf (relationship)	Sf = (Sy+Su)/2.4	Sf = (Sy+Su)/2	Sf = (Sy+Su)/2	Sf = (Sy+Su)/2
Flow Stress, Sf (value, ksi)	——	51.95	51.95	47.45
θ (1xPdesign) (deg)	——	328	318	293
θ (3xPdesign) (deg)	262	273	244	179

1. Wilkowski et al., NRC-Funded CRDM Critical Crack Size Analysis, presentation by Engineering Mechanics Corporation of Columbus, 11/08/01.