Use of PRA in LBB analysis

Probabilistic Leak Before Break of 540 MW Tarapur :3/4 PHWR

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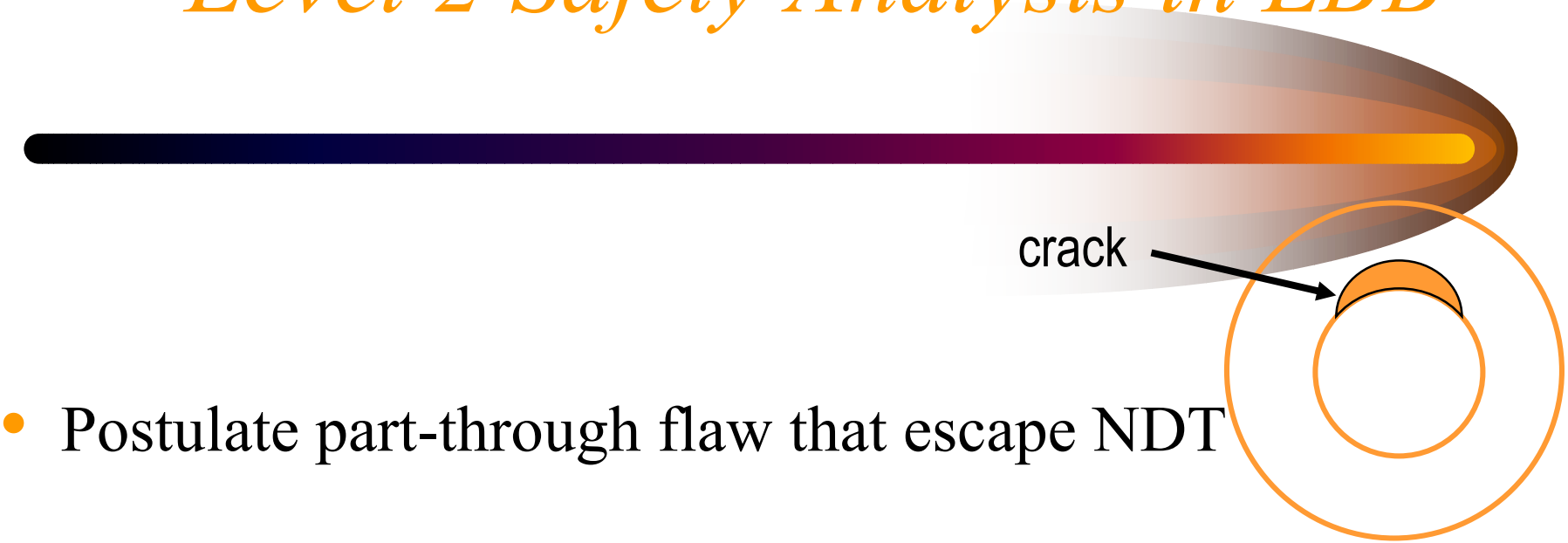
Basic Steps in LBB

- Level 1 : Stringent design criteria
- Level 2 : Fatigue crack growth analysis
- Level 3 : Instability analysis

Level 1 Safety Analysis in LBB

- Design done with a well-defined factor of safety using ASME Sec.III.
- Does not consider the presence of flaw.
- Sufficiently tough material is chosen for piping components.
- Minimize number of weld joints
- 100% radiography/ultrasonic Examination.

Level 2 Safety Analysis in LBB



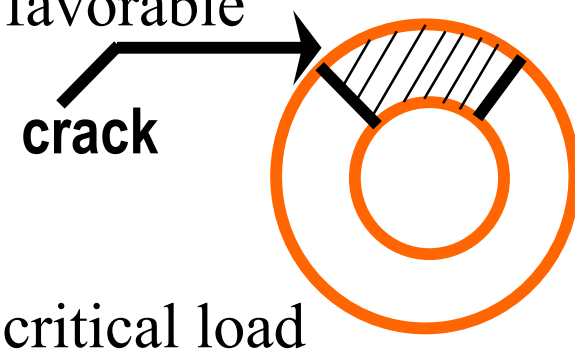
- Postulate part-through flaw that escape NDT

- Perform fatigue crack growth study of the flaw over the entire life period of the reactor.

- Show that the final flaw size is less than 75% of wall thickness

Level 3 Safety Analysis in LBB

- Identify the critical location: Section with less favorable combination of stress and material properties.
- Postulate a through wall crack (LSC).
  that will lead to detectable leakage.
- Perform stability assessment and calculate the critical load (M_c) of the piping component with postulated LSC.
- Calculate critical crack size (a_c) with the maximum credible load on piping component.
- Demonstrate : $M_c/(M_{NOC+SSE}) = 1$ and $a_c/LSC = 1$ for ABS load earthquake combination



Application of LBB requires

- Knowledge of DBA loads
- Geometry of the pipes
- Material properties of pipe
- Leakage size crack

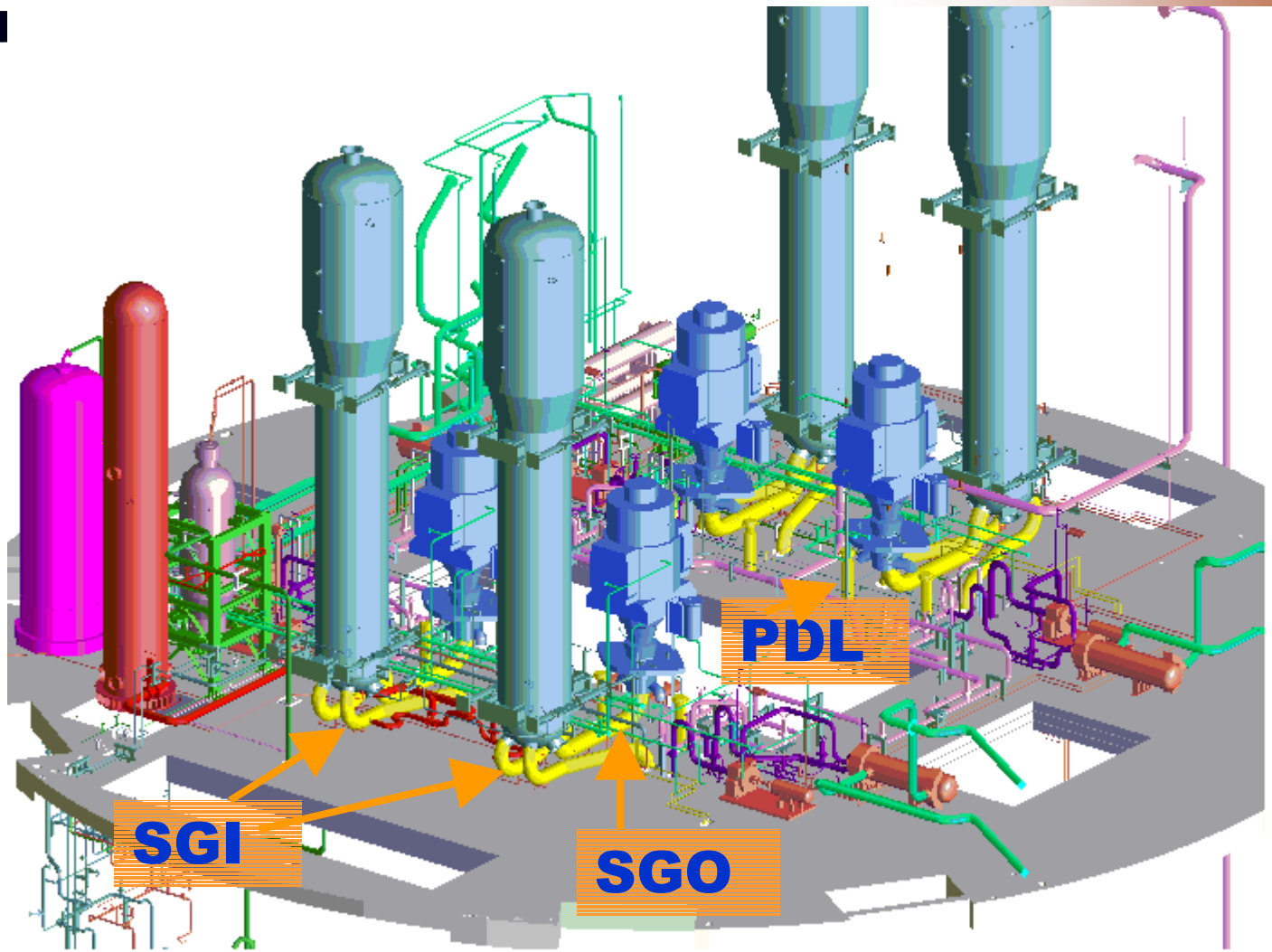
  - Some of these show variability
  - Requires Application of Probabilistic Fracture Mechanics

Probability that LSC is not critical under NOC+SSE

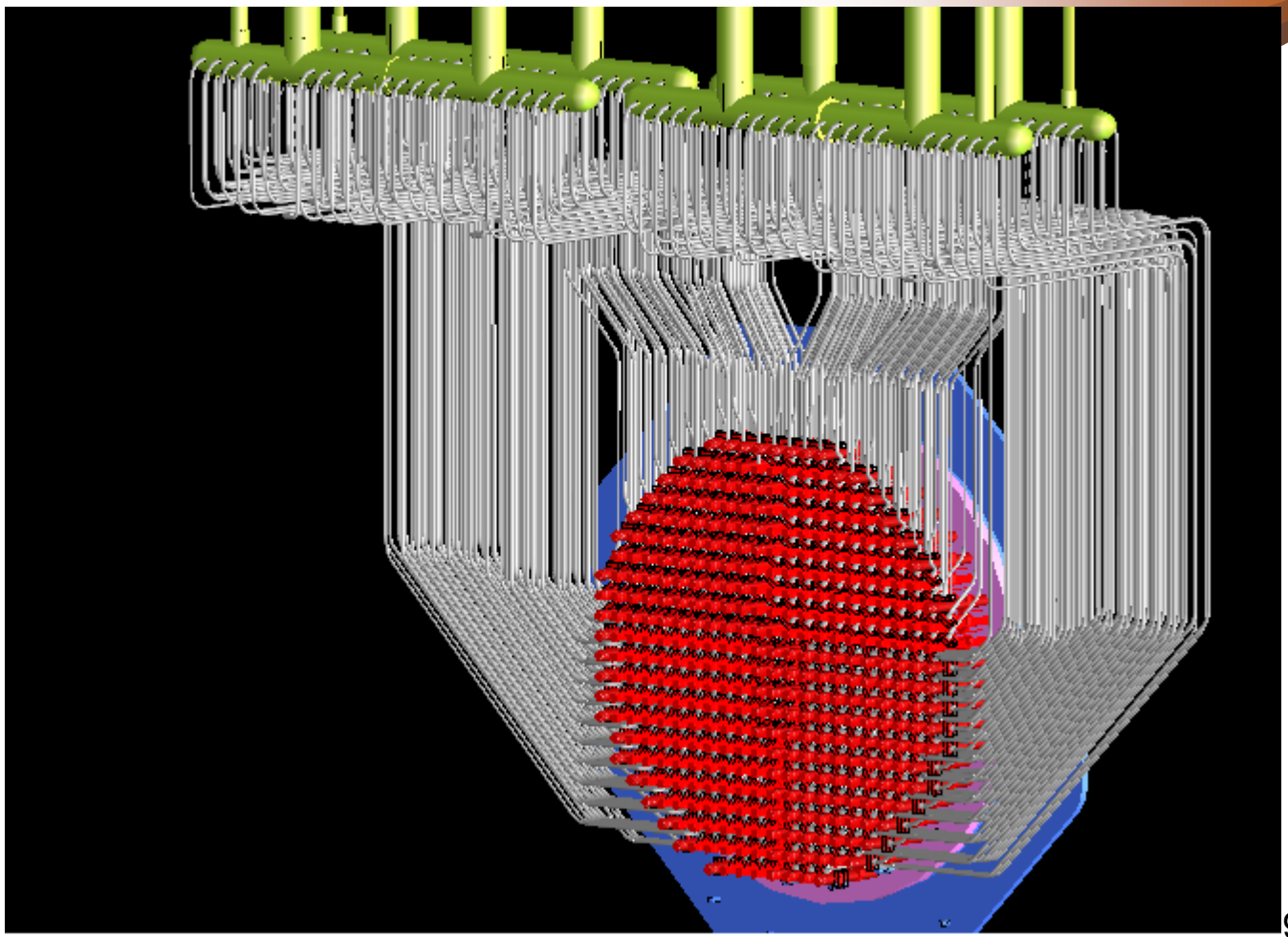
Salient Features of the Analysis

- Critical locations
  - Welds in straight pipe
  - Elbows, Crack at Extrados
    - Steam Generator Inlet (SGI)
    - Steam Generator Outlet (SGO)
    - Pump Discharge Line (PDL)
- Critical Load: NOC + SSE

PHWR Reactor



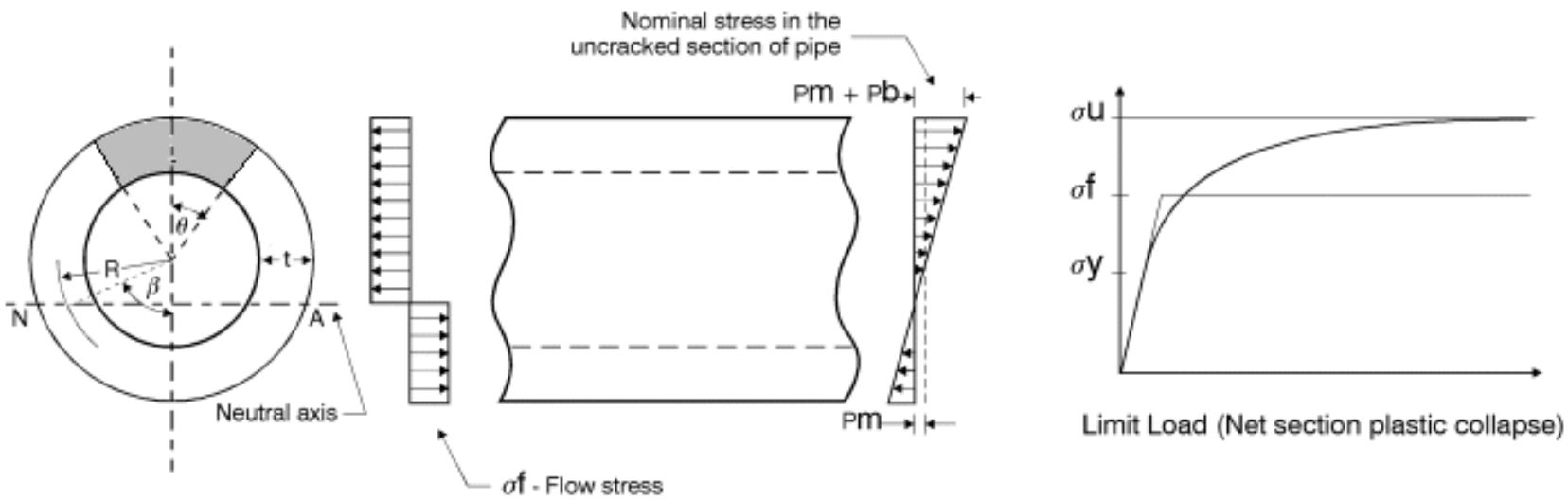
PHWR Reactor



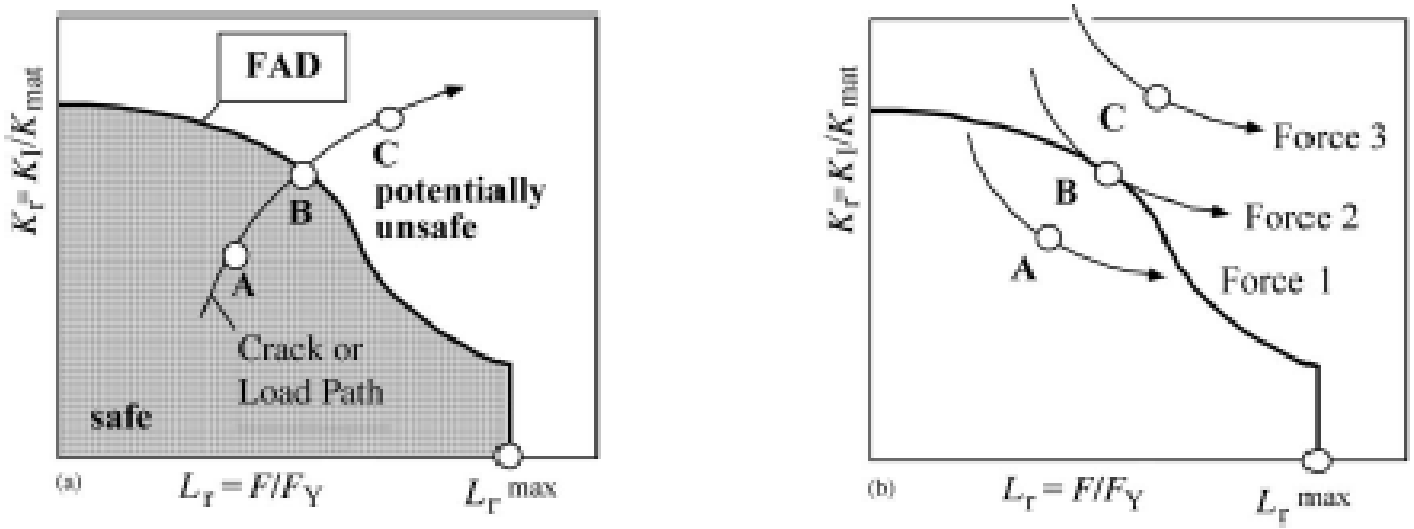
Reliability analysis

- Data for uncertainty quantification
  - Material Properties
    - Fracture Toughness, Fracture Resistance curve
    - Yield Stress, Ultimate Stress, Stress-Strain Curve
  - Leakage size crack
  - Frequency of occurrence of SSE load
- Mechanism of failure
  - Net Section Collapse
  - J-Tearing: Crack Driving Force
  - R6: Failure Assessment Diagram

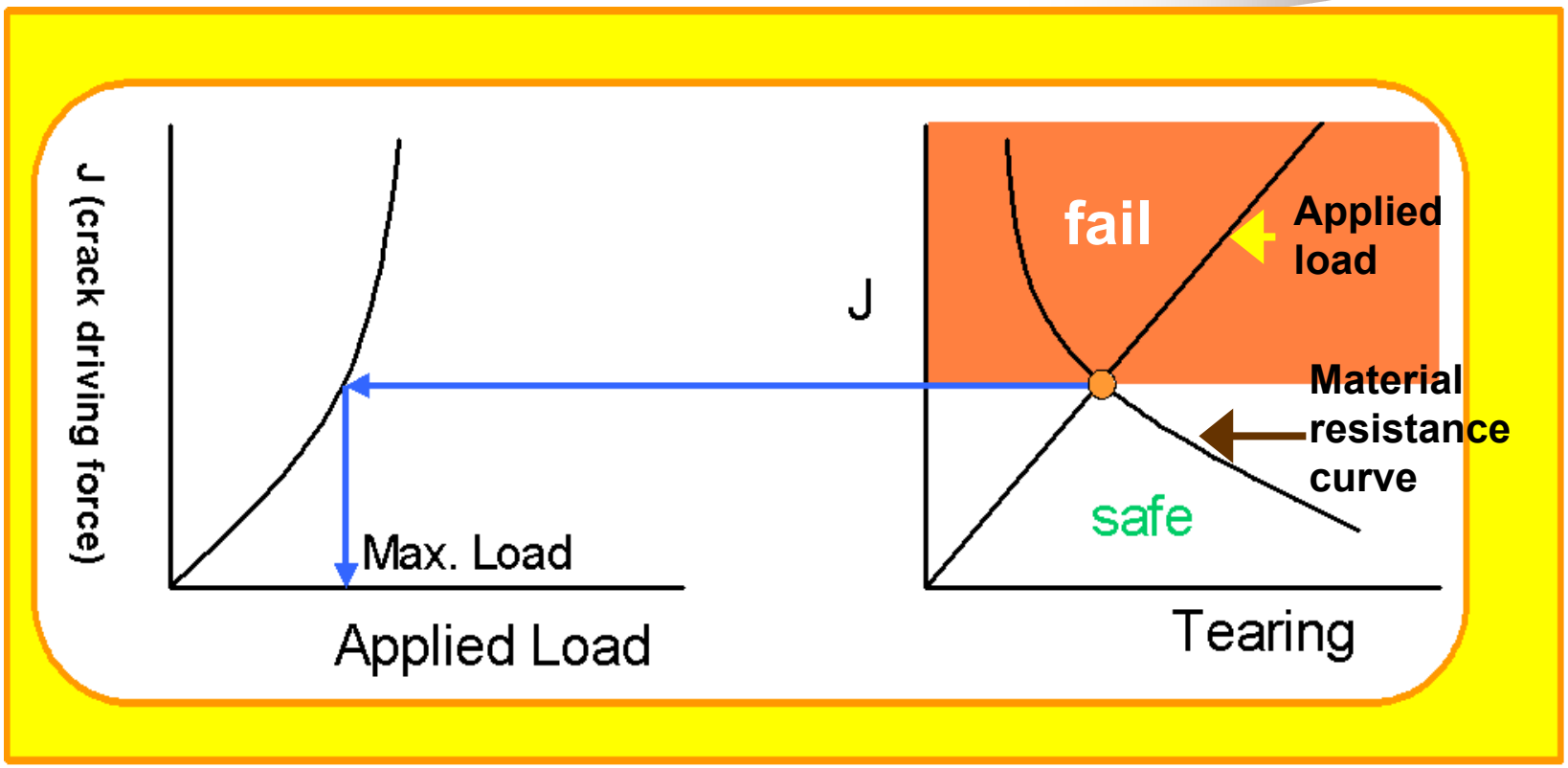
Net Section Collapse (NSC)



R6 Method


FAD
C
potentially
unsafe
B
A
Crack or
Load Path
safe
$K_r = K_I/K_{mat}$
(a)
$L_r = F/F_Y$
L_r max
C
Force 3
B
Force 2
A
Force 1
$K_r = K_I/K_{mat}$
(b)
$L_r = F/F_Y$
L_r max

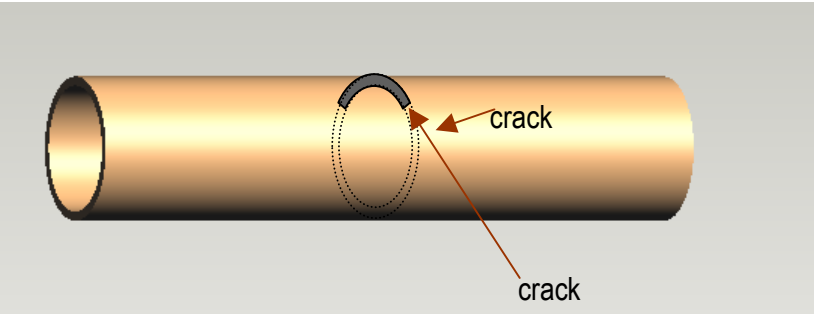
J-Tearing Method



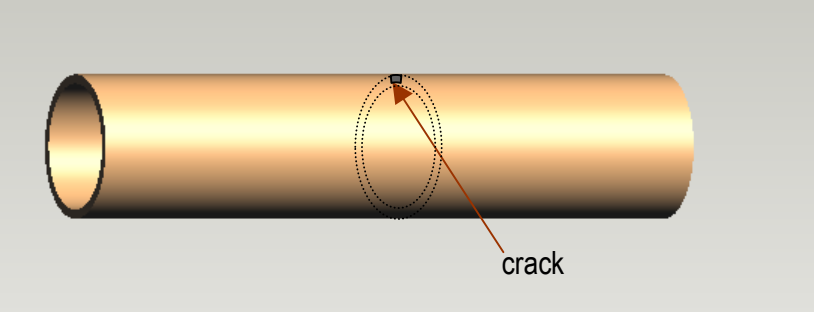
BARC: Comprehensive Component Integrity Test Program

- Fracture tests : 45 (CS) + 14 (SS)
- Fatigue tests : 28 (CS) + 19 (SS)
- Cyclic tearing tests : 24
- Tests carried out on straight pipes and elbows at room temperature
- Sizes : 8” – 16” Nominal Bore (NB)
- Tests also carried out on 100 CT specimens at RT, 200-300°C
- Period of tests : 1999 - 2003

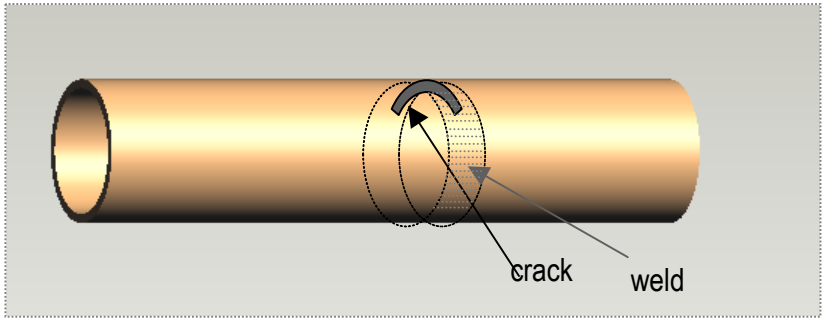
BARC Fracture Tests: Crack Configurations in Piping Components



Through wall circumferential crack

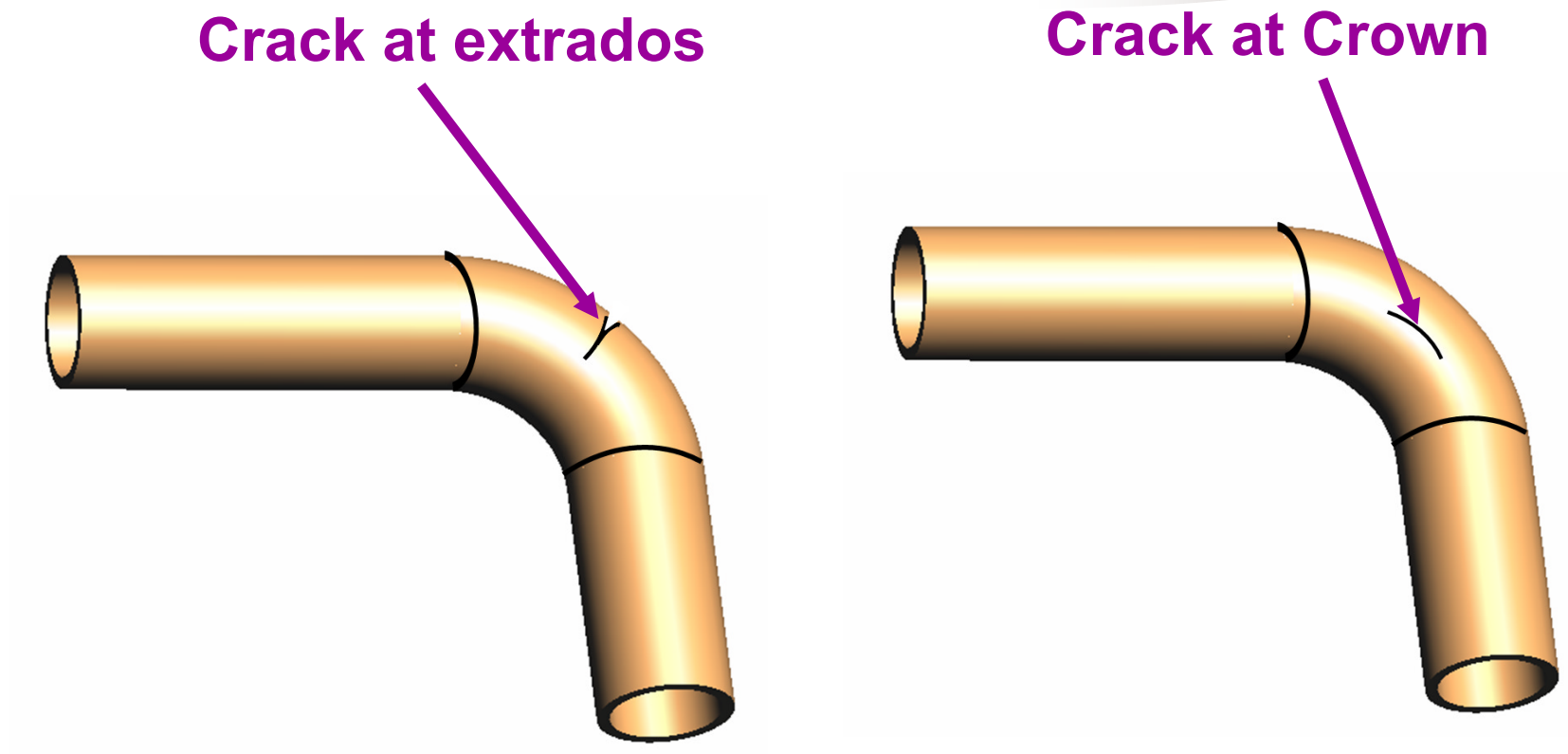


Part through circumferential crack

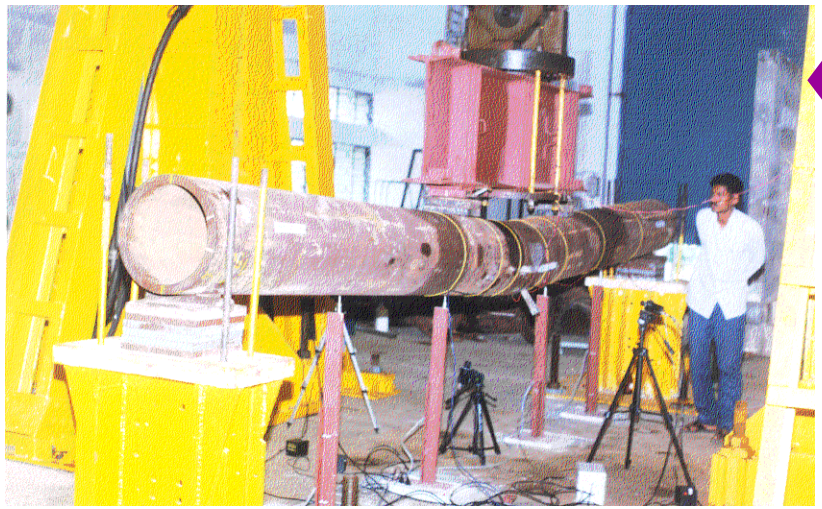


Through wall circumferential crack in weld

BARC Fracture Tests: Crack Configurations in Elbows

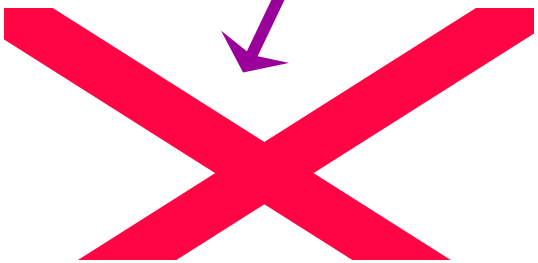


Fracture Test on Through Wall Circumferentially Cracked Pipe

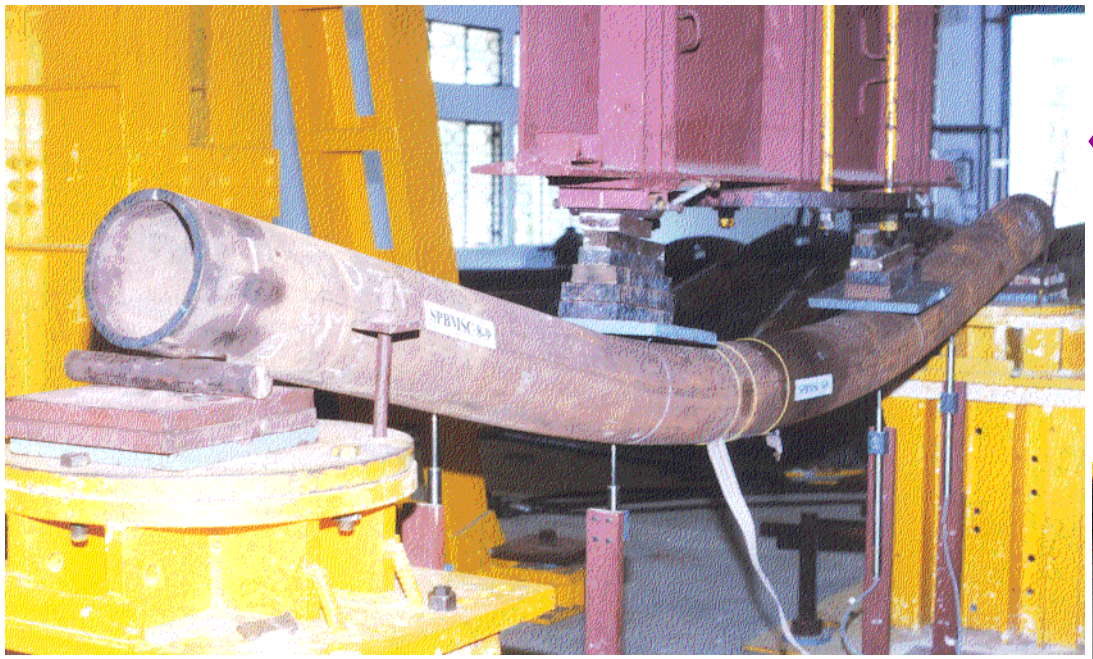


Set-up

Crack growth pattern

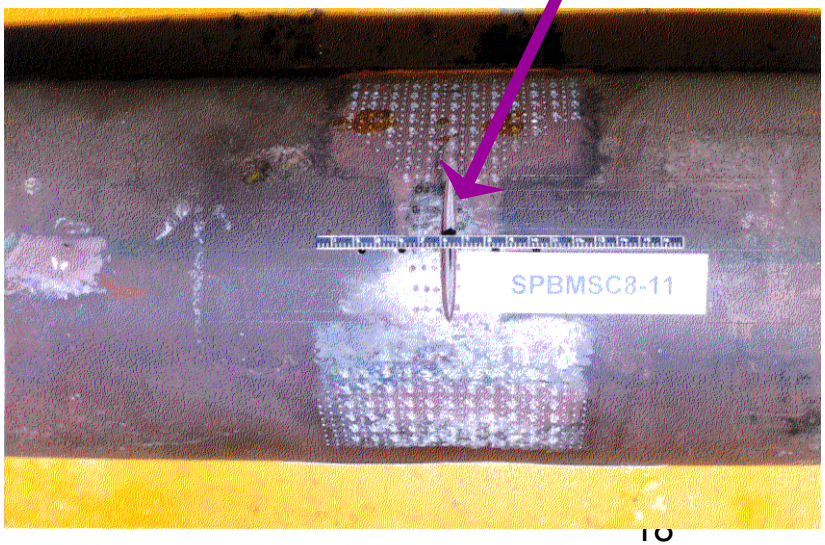


Fracture test on surface cracked pipe



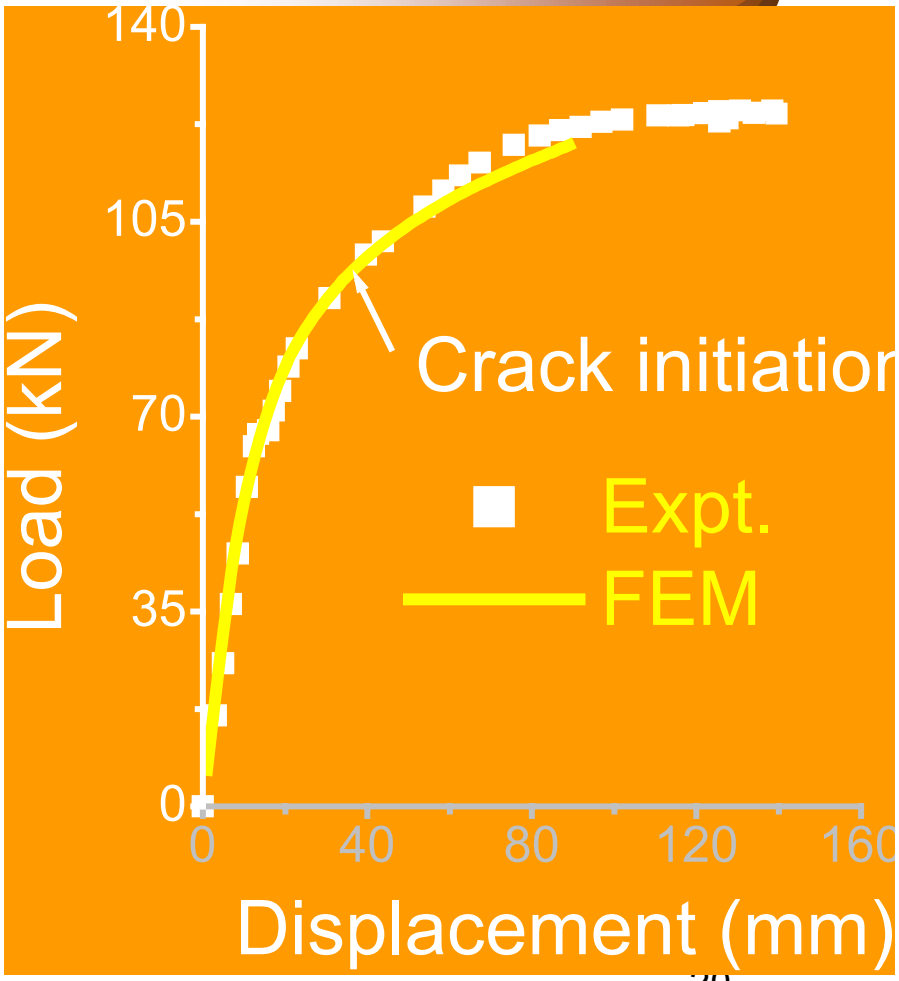
Set-up

Crack growth pattern

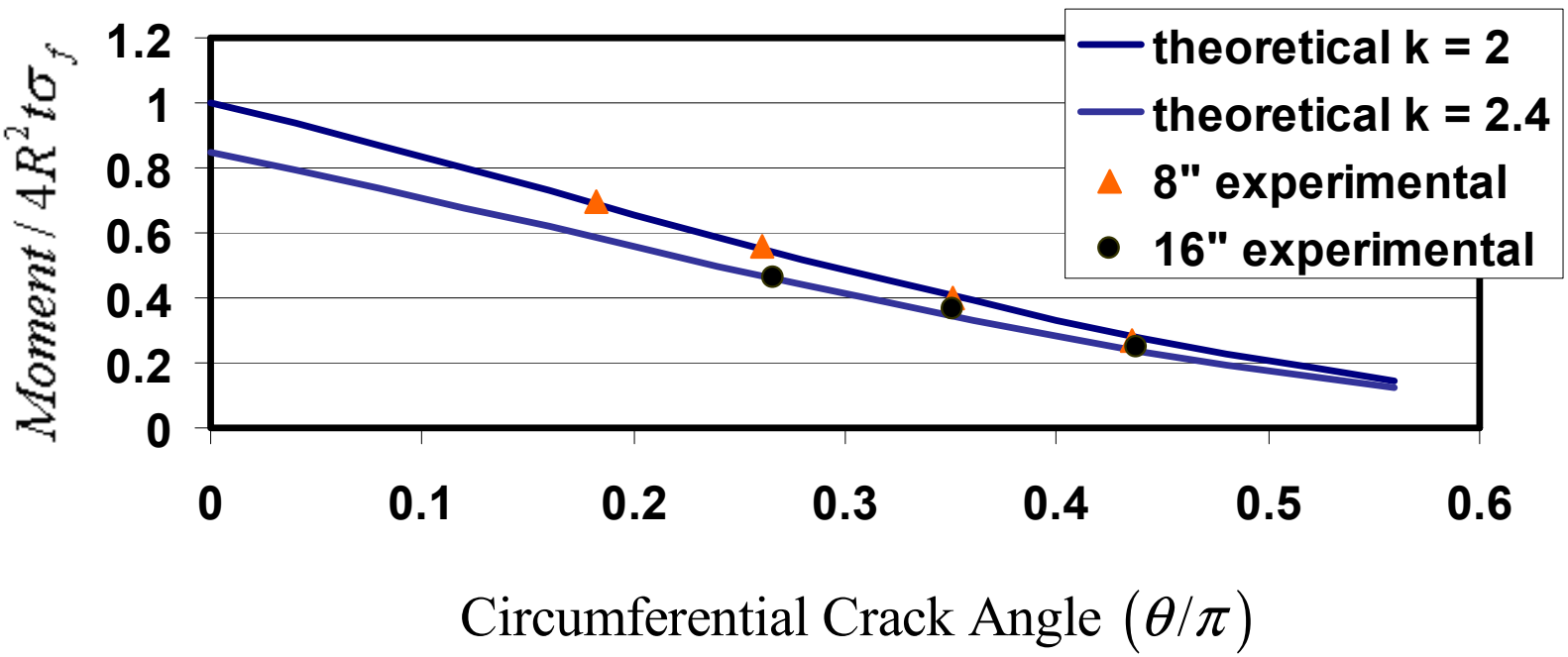


Fracture Tests on Elbows

Comparison of Load Deflection Curve



Net Section Load and Experiments



$$M_l = 4R^2 t\sigma_f \left[\cos(\theta/2) - 0.5\sin(\theta)\right]$$

$$\sigma_f = \frac{(\sigma_u + \sigma_y)}{k}$$

BARC Fracture Tests

- Maximum load observed in pipes up to 8” NB size is nearly same as that based on NSC (using flow stress)
- Maximum load observed in pipes = 12” NB size is less than that based on NSC, hence J-Tearing governs the failure.
- In pipes = 12” NB there is large margin between crack initiation and unstable fracture.
- In all cases maximum load observed is greater than that based on NSC (using σ_y)
- The tests revealed that load carrying capacity under cyclic loads is less. It is compensated by compliance effects of piping system due to which moment redistribution occurs.

Reliability Analysis

- Estimation method
  - Fast Probability Integration
    - FORM
    - SORM
  - Simulation
    - Classical Monte Carlo Method (CMC)
    - Monte Carlo with
      - Importance Sampling (IS)
      - Adaptive Importance Sampling (AIS)
      - Conditional Expectation (CE)
      - Adaptive Stratified-Importance Sampling (VEGAS numerical integration algorithm)

Description of Pipes

Pipe Line	Mean Radius (mm)	Thick. (mm)	Mean LSC Deg.	NOC Load kN-m	SSE Load kN-m
SGI	234	40	34.6	391	339
SGO	280	50	32.4	564	404
PDL	211	35	34.0	242	85.6

LSC has Guassian distribution with cov = 10%

Probabilistic LBB Qualification

Moments in kN-m	SSE Moment	NOC Moment	DBA (NOC + SSE) Moment
SGI	339	391	730
SGO	404	564	968
PDL	85.6	242	327.6

Uncertainty in SSE Moment only (Lognormal Distribution)

Stochastic Treatment of Load

- The distribution of induced moment is considered as lognormal
- The SSE value as computed by piping analysis is considered as Mean Centered
- The SSE moment corresponds to PGA of 0.2g
- The variability [aleatory and epistemic] arises in
  - Piping Dynamic Response (PDR)
  - Building Dynamic Response (BDR)

Piping Dynamic Response Variability

- Floor Spectra
  - Spectral Shape – Peak Broadening
  - Artificial Time History – Enveloping the Design Ground spectra
- Modeling Factors in Piping analysis
  - Boundary Conditions, Geometry/Layout, Modeling.
- Damping Factors
- Model Combination
- Earthquake Component Combinations
  - Vertical and Horizontal (North and South)

$$\delta_{aleatory}^{PDR} = 0.31 \qquad \delta_{epistmic}^{PDR} = 0.27$$

Building Structural Response Variability

- Ground Spectrum Shape
- Damping of RCC
- Modeling: Building, Floors etc.
- Soil Structure Interaction

$$\delta_{aleatory}^{BDR} = 0.25 \qquad \delta_{epistmic}^{BDR} = 0.18$$

Combining

$$\delta_{aleatory} = 0.40 \qquad \delta_{epistmic} = 0.32$$

Lognormal distribution for seismic load

Material Properties
C-Mn Steel (SA333-Gr6)

Random Vector	*Mean Veactor*	*Covariance Matrix*
$\begin{Bmatrix} \sigma_y \\ \sigma_u \end{Bmatrix}$	$\begin{Bmatrix} 240.0 \\ 449.0 \end{Bmatrix}$	$\begin{bmatrix} 282.24 & 113.148 \\ 113.148 & 504.0 \end{bmatrix}$
$\begin{Bmatrix} \alpha \\ n \end{Bmatrix}$	$\begin{Bmatrix} 1.948 \\ 4.898 \end{Bmatrix}$	$\begin{bmatrix} 0.607 & -0.4 \\ -0.4 & 0.406 \end{bmatrix}$
$\begin{Bmatrix} J_{ic} \\ C \\ m \end{Bmatrix}$	$\begin{Bmatrix} 412.0 \\ 587.33 \\ 0.433 \end{Bmatrix}$	$\begin{bmatrix} 2.716\times10^4 & -43.937 & -6.23 \\ -43.937 & 3.105\times10^4 & 8.563 \\ -6.23 & 8.563 & 0.012 \end{bmatrix}$

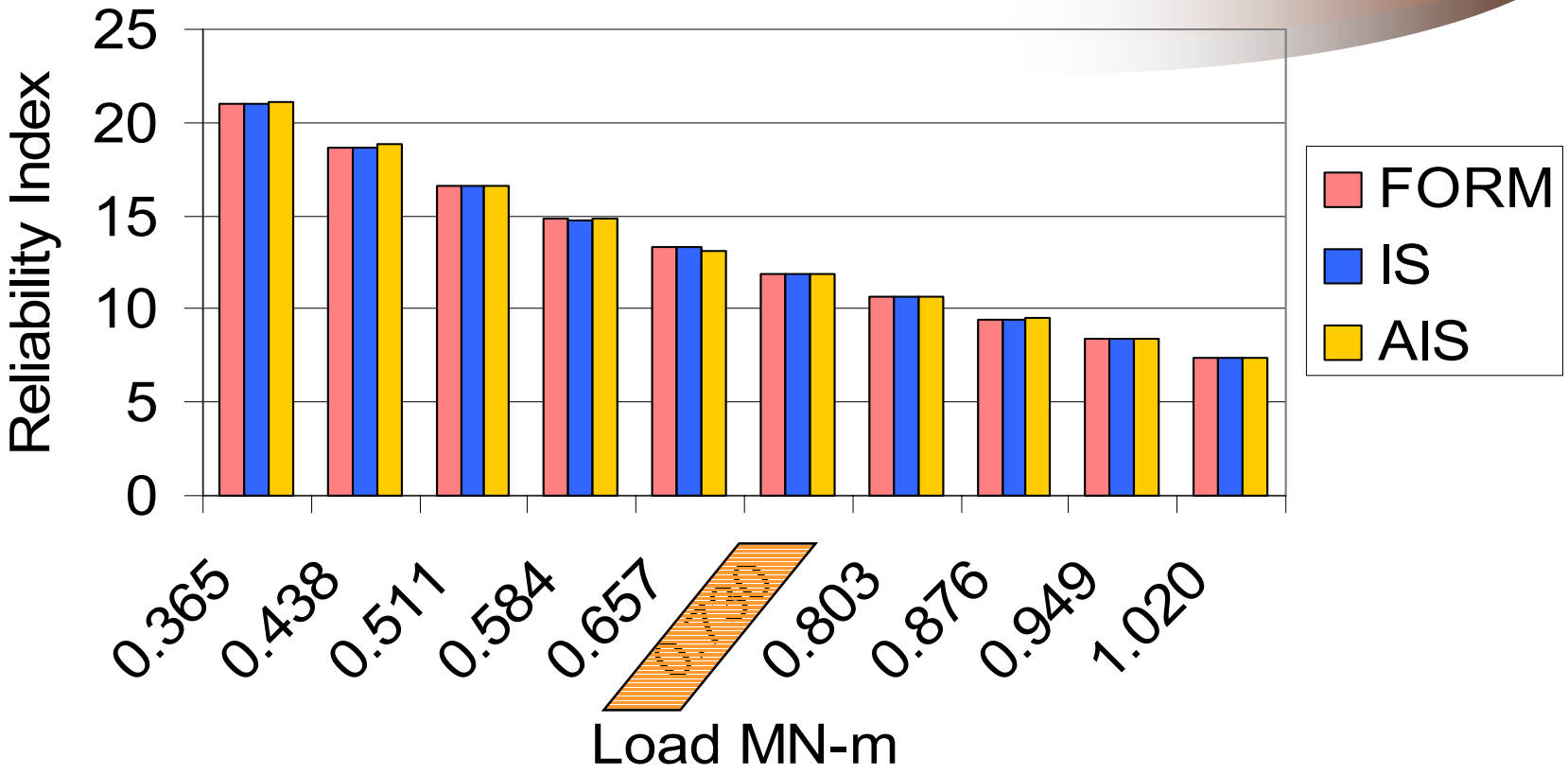
σ_u and σ_y are in MPa,
J_{IC} and C are in kJ/m^2

- Stress-strain curve is represented by Ramberg-Osgood fit (α, n)
- J-R curve is represented by power fit equation (C, m)

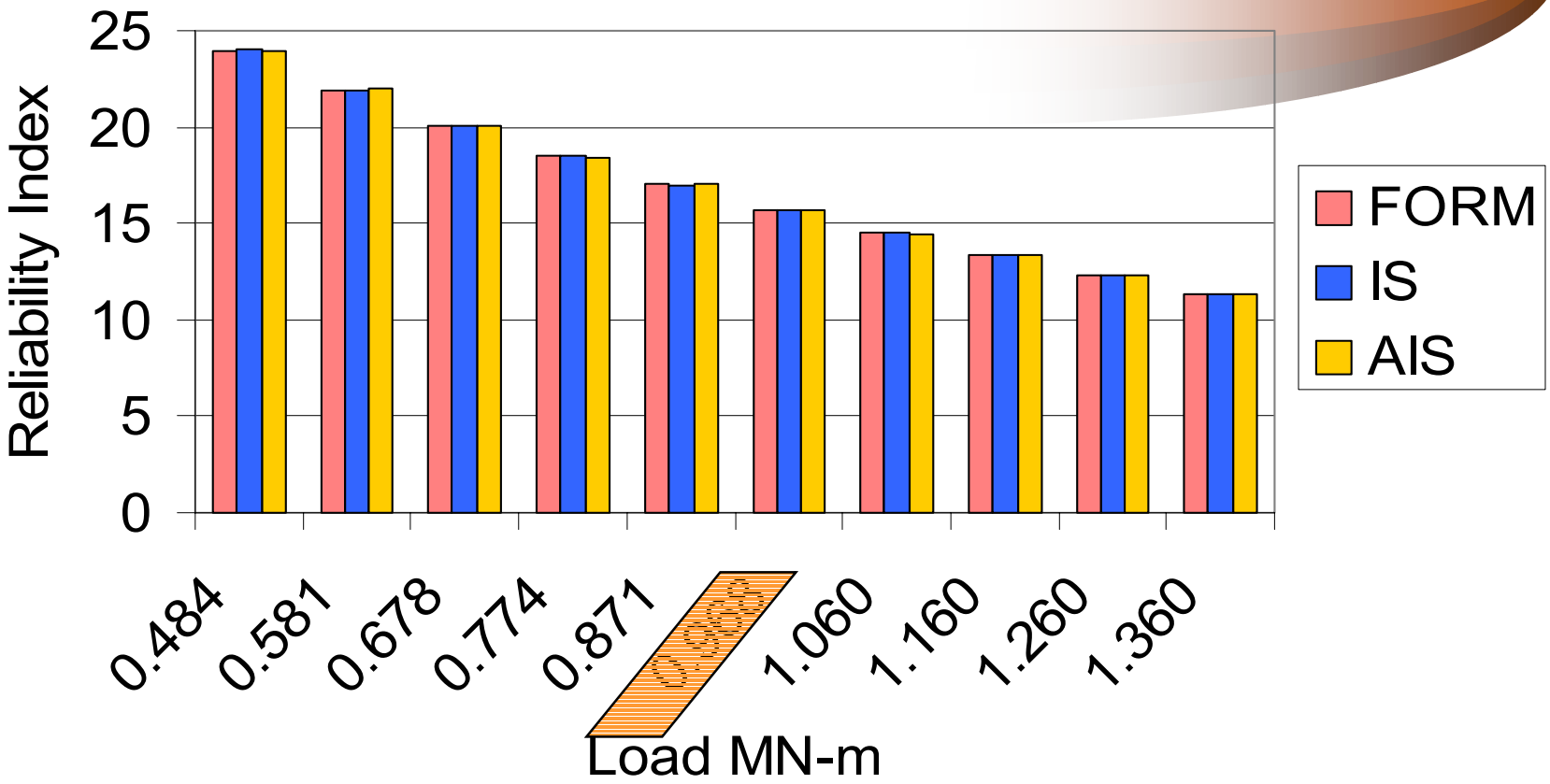
$J_R(\Delta a) = C(\Delta a)^m$

All are lognormally distributed

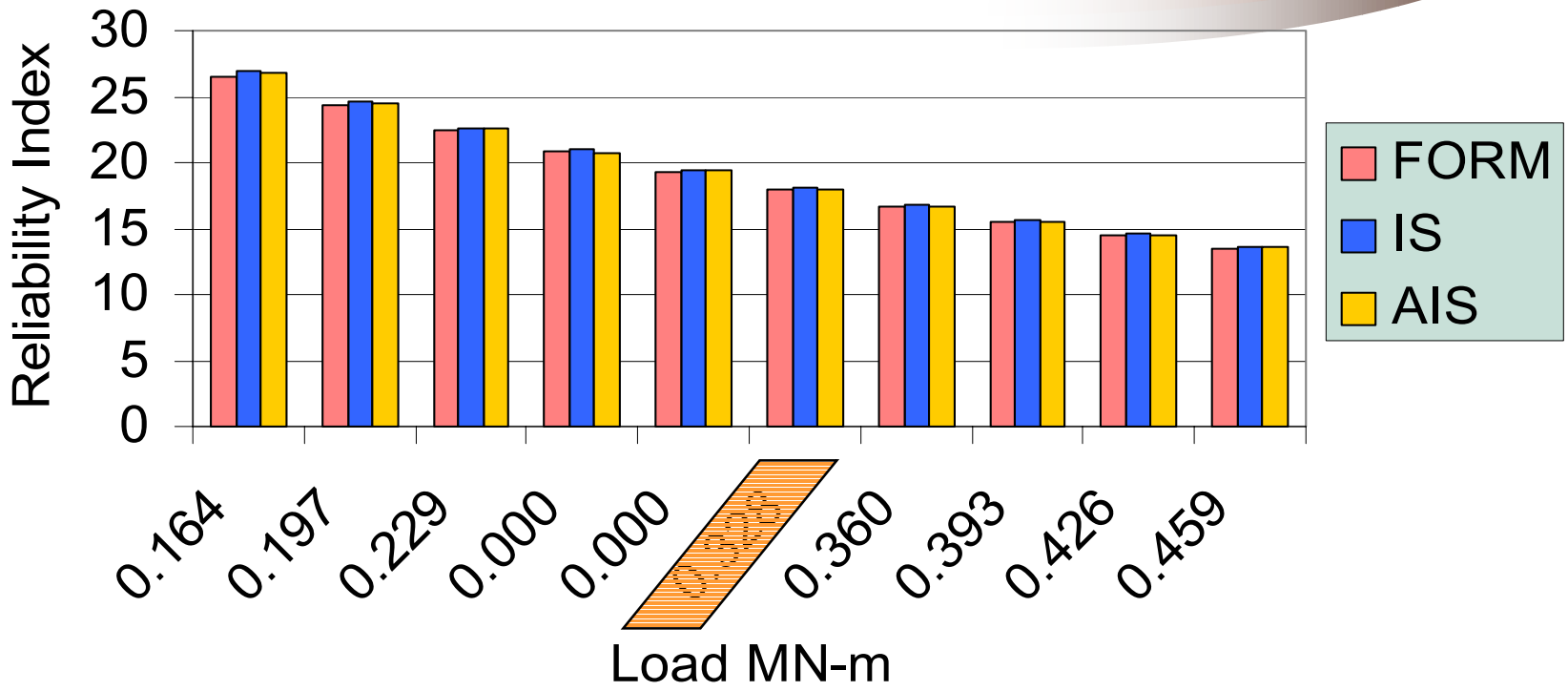
NSC Results: SGI – Constant DBA Load



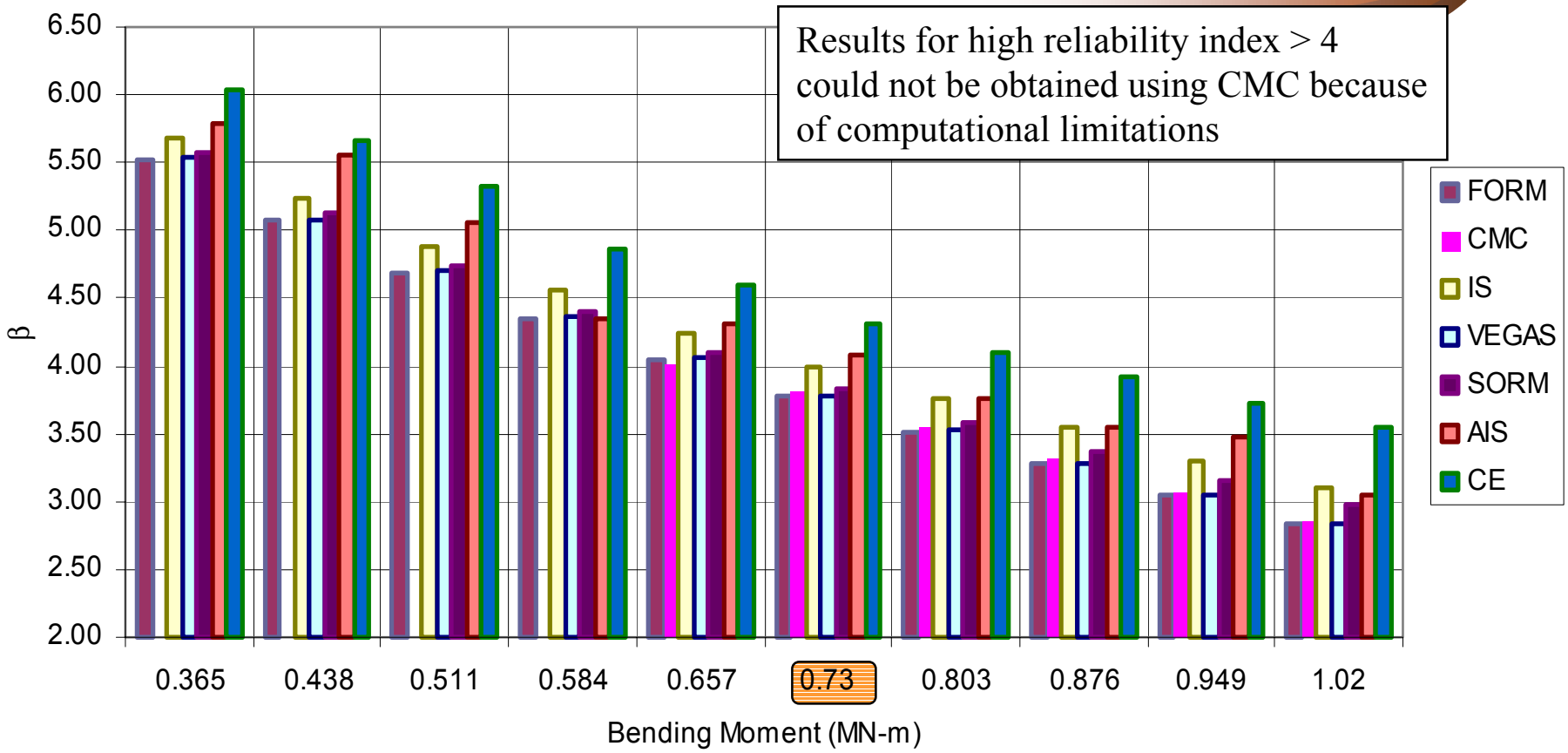
NSC Results: SGO -Constant DBA Load



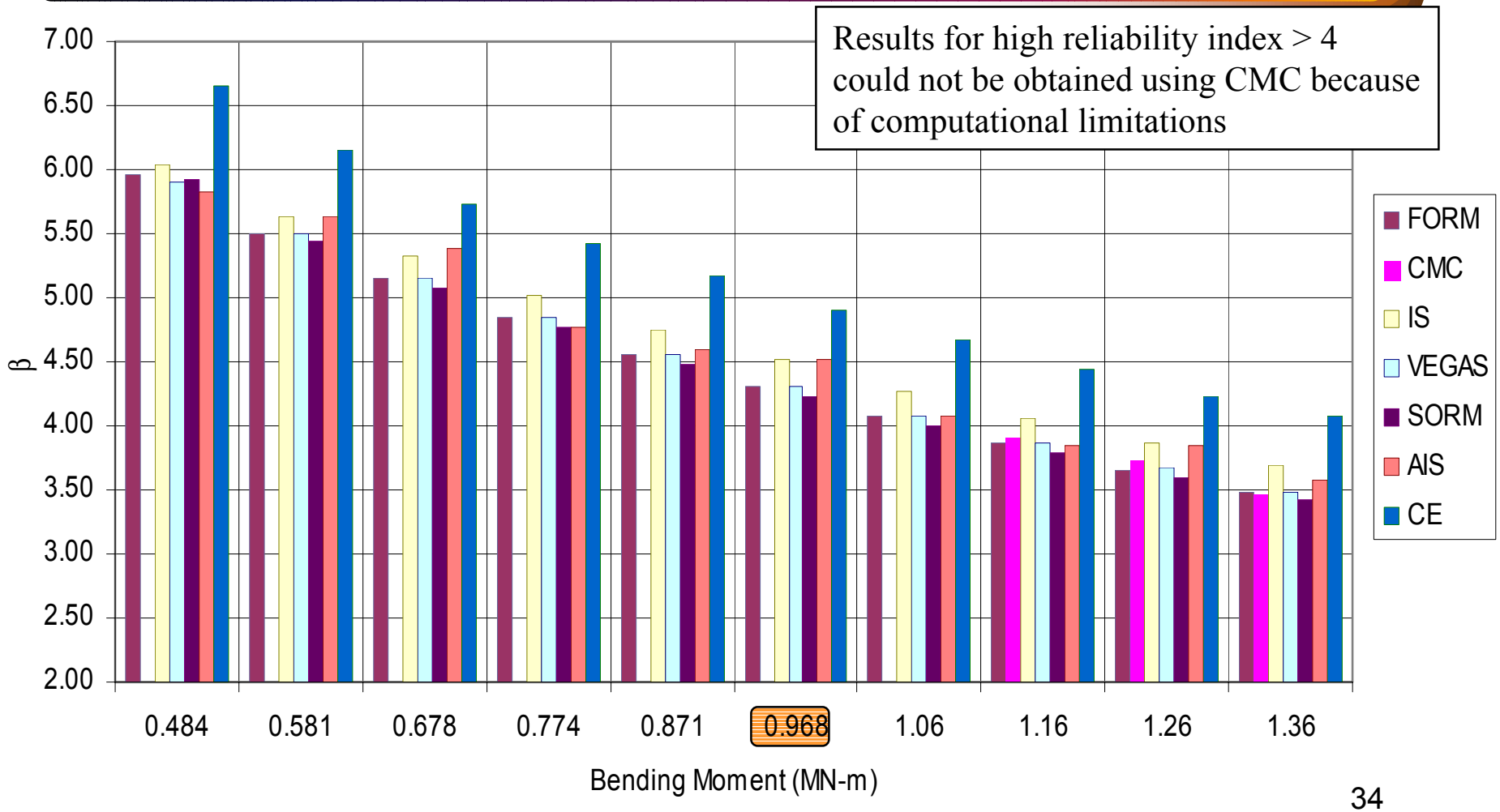
NSC Results: PDL -Constant DBA Load



R6 Results: SGI -Constant DBA Load



R6 Results: SGO -Constant DBA Load



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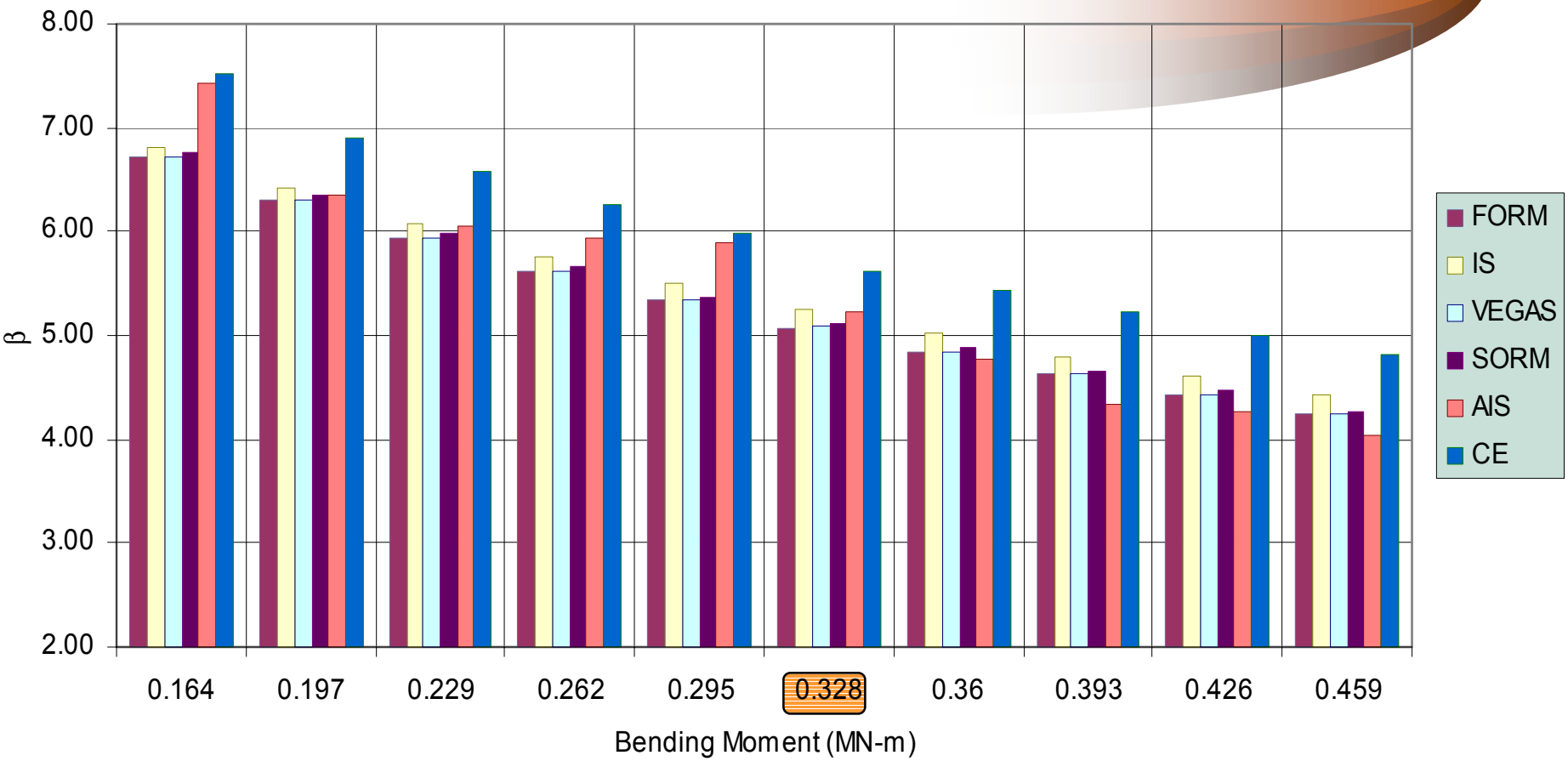
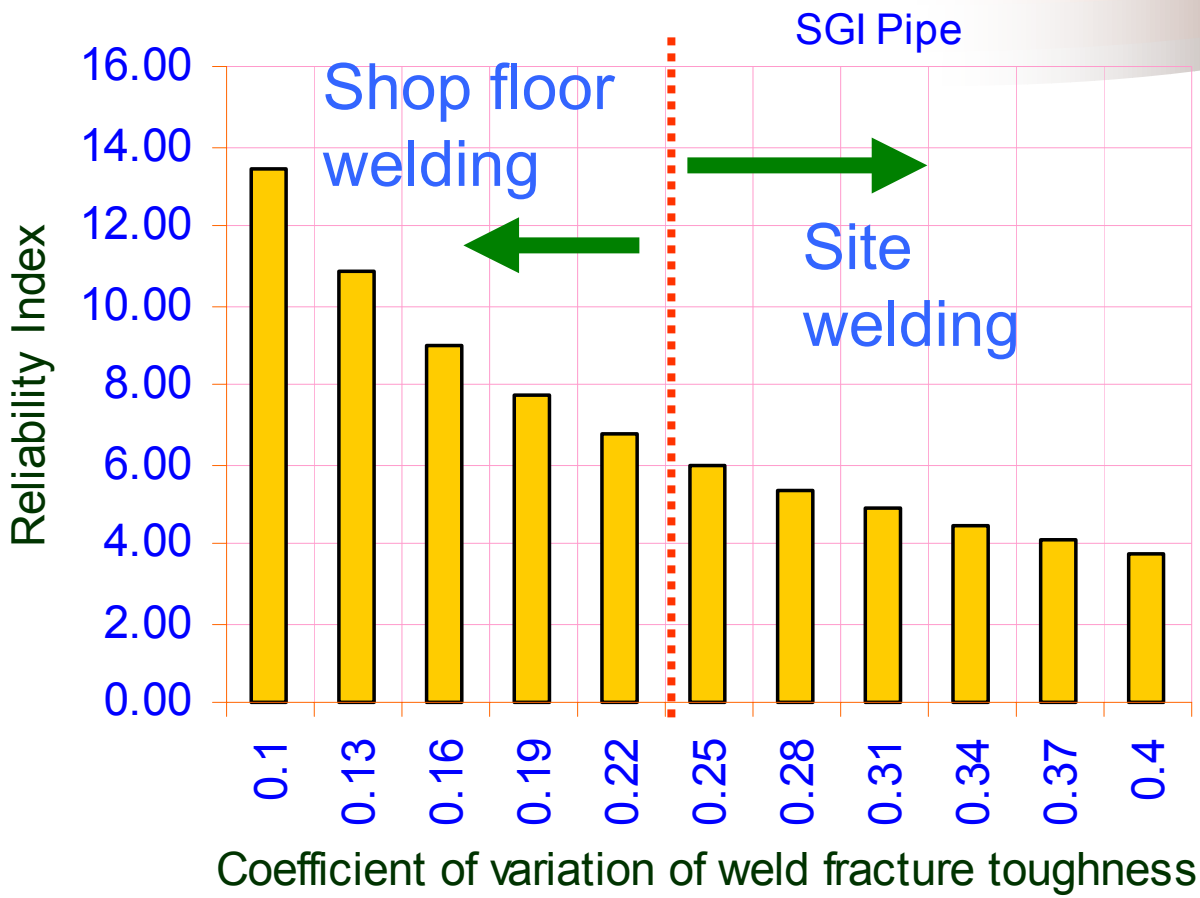


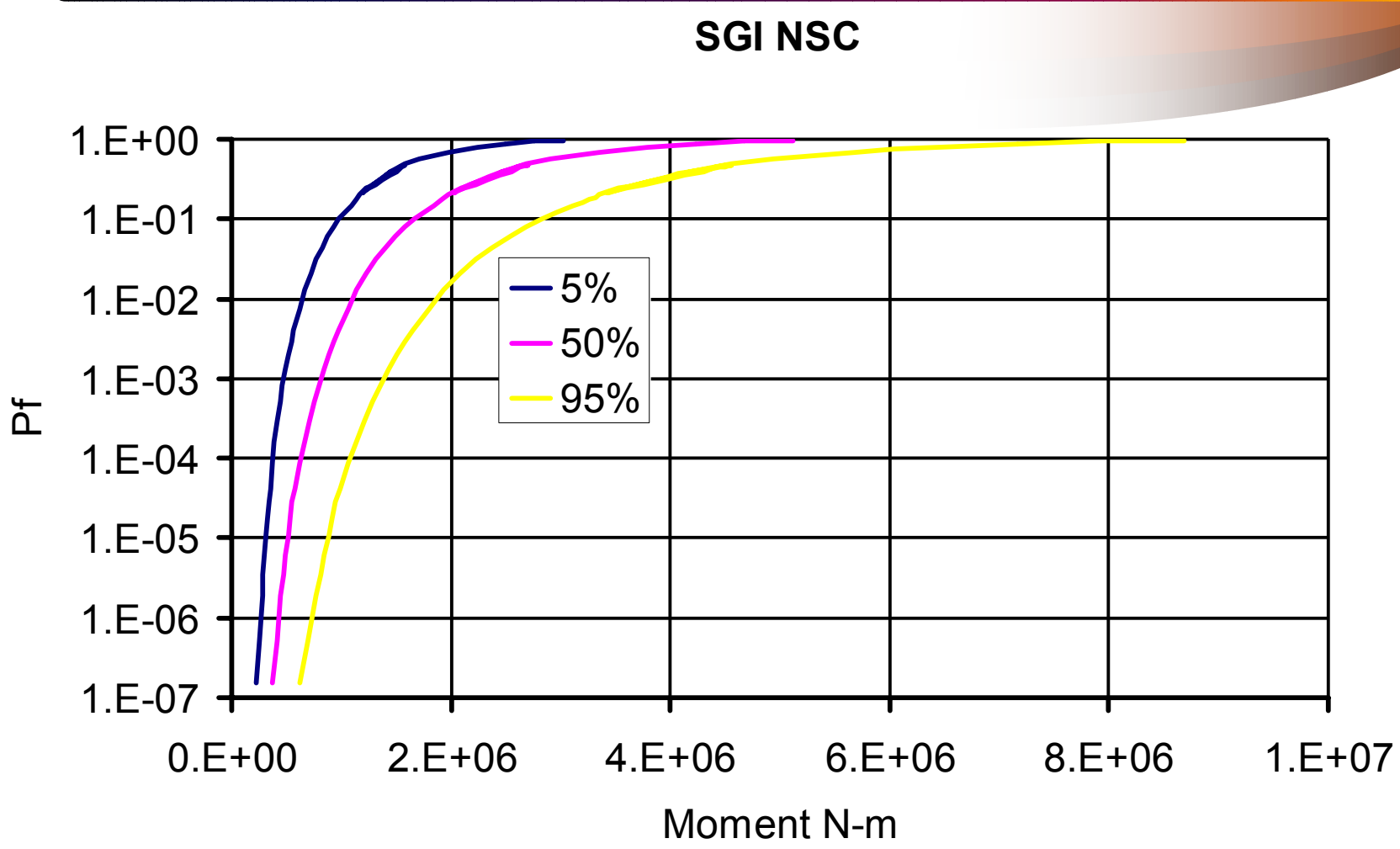
Effect of Variability of Fracture Toughness on Reliability Index



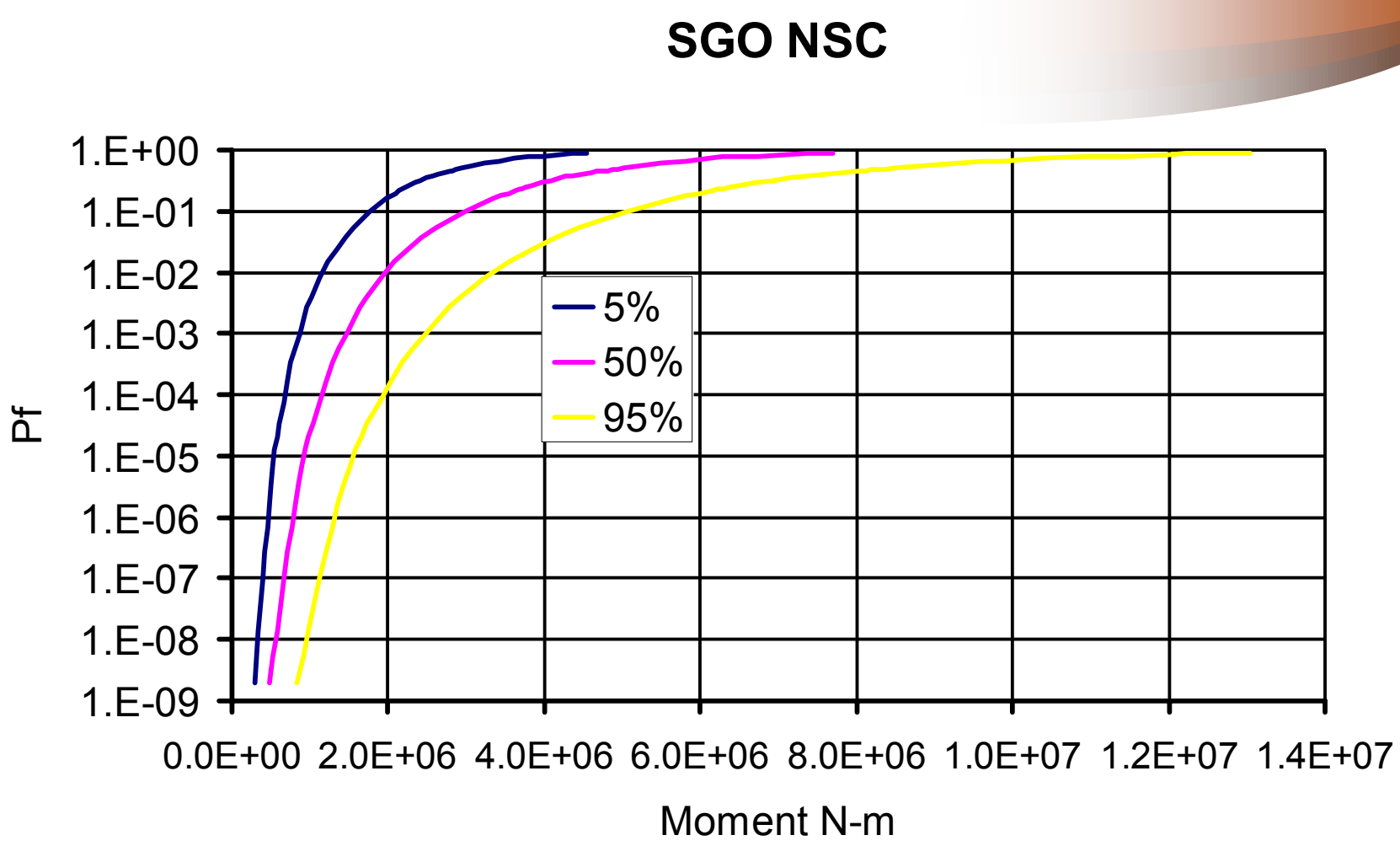
Reliability Index@DBA: Comparing for Different Pipes-constant Applied Load

	NSC	R6 init.	R6 rupture	J-T
SGI	11.9	3.8	8.3	9.8
SGO	15.7	4.3	9.3	10.9
PDL	17.9	5.1	10.3	11.9

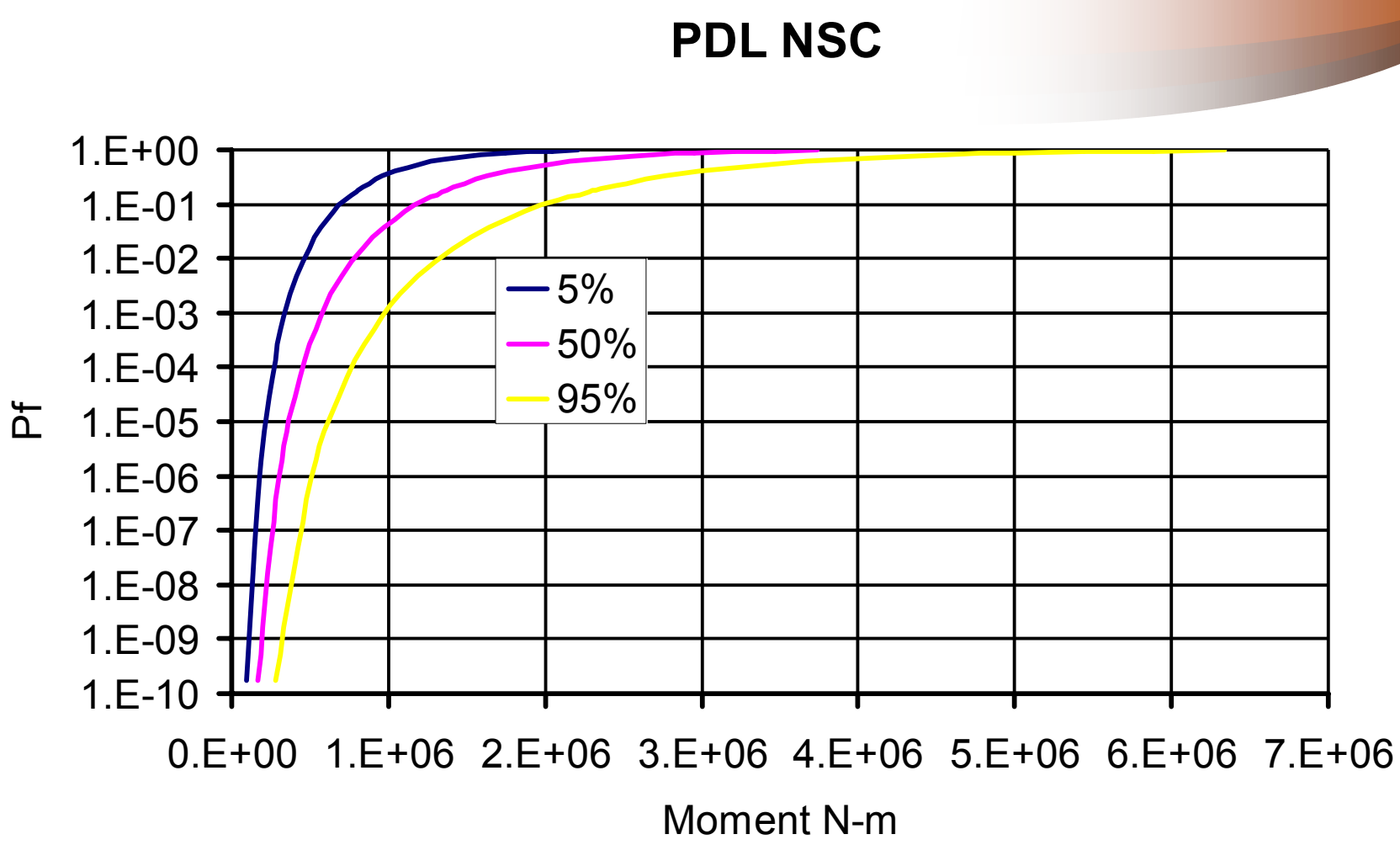
Fragility Analysis-SGI: NSC-Stochastic Load



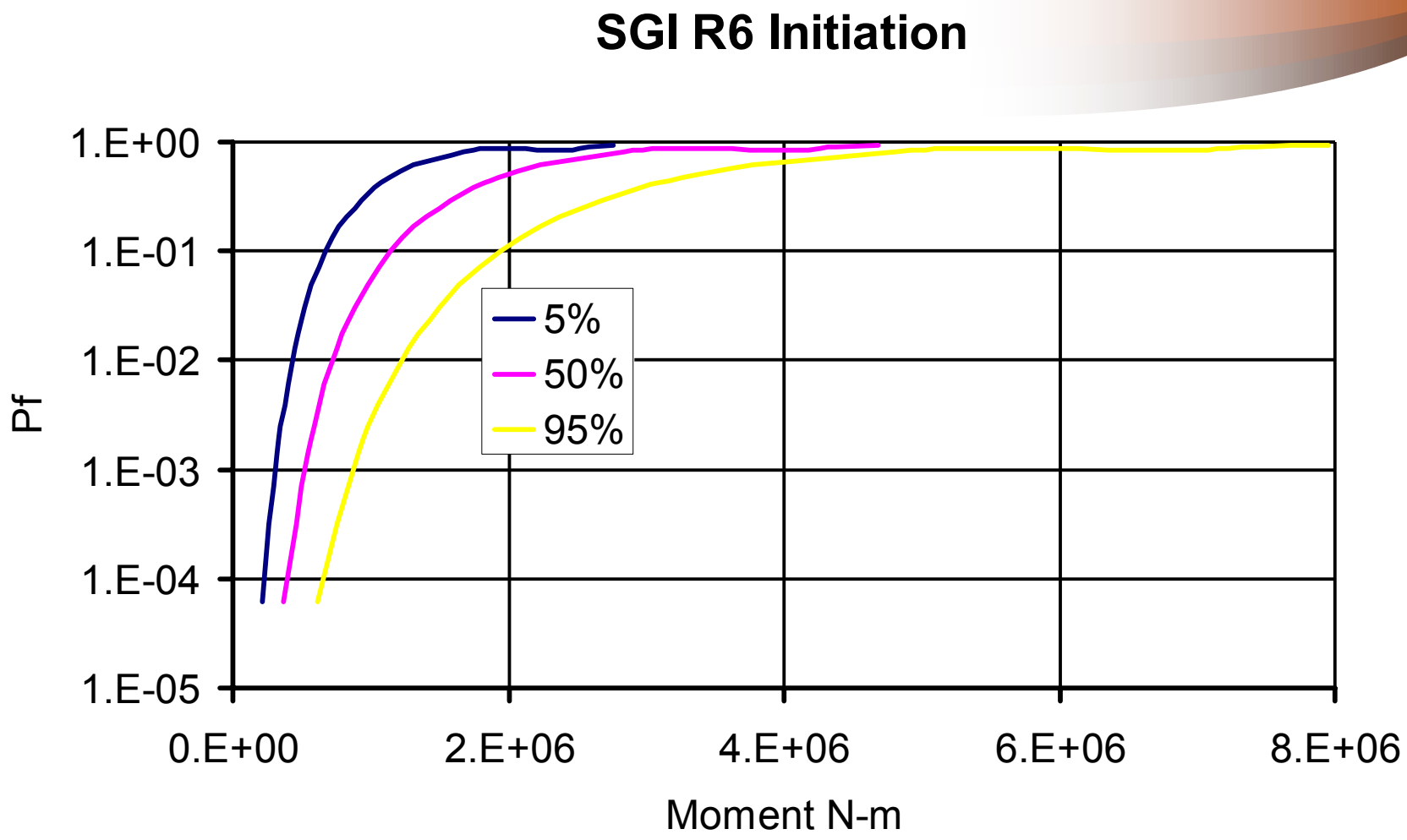
Fragility Analysis-SGO: NSC - Stochastic Load



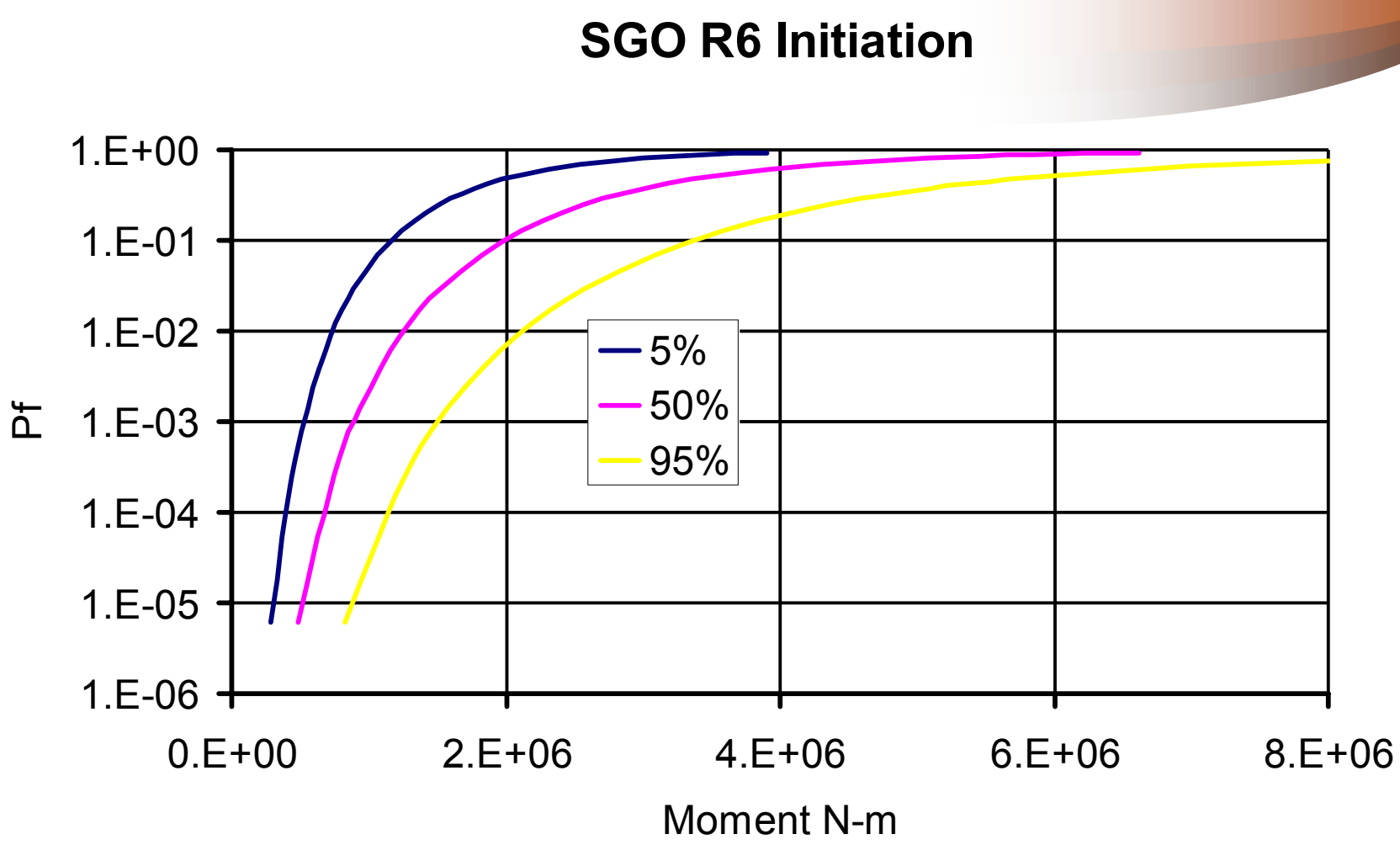
Fragility Analysis-PDL: NSC - Stochastic Load



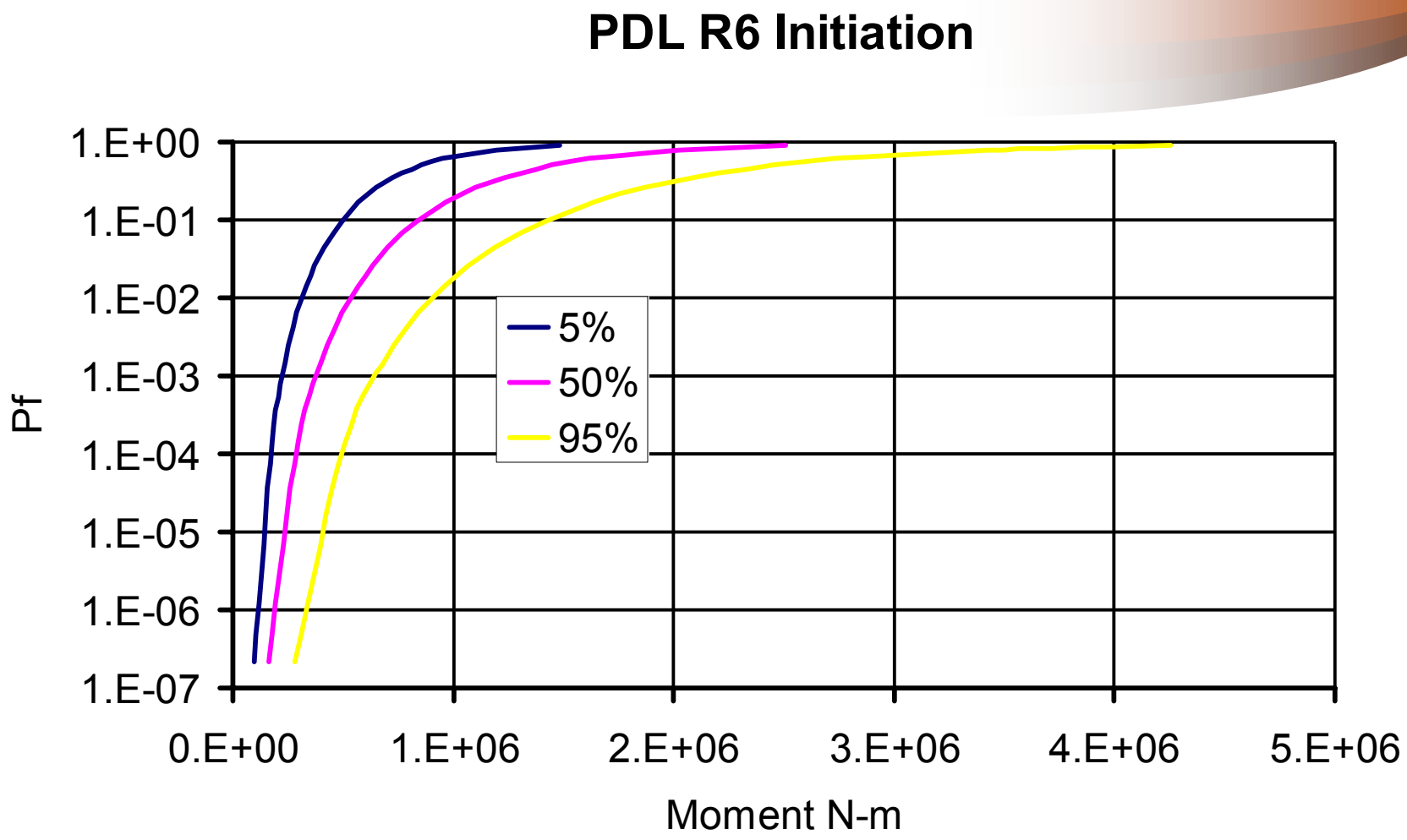
Fragility Analysis-SGI: R6 (INITIATION) - Stochastic Load



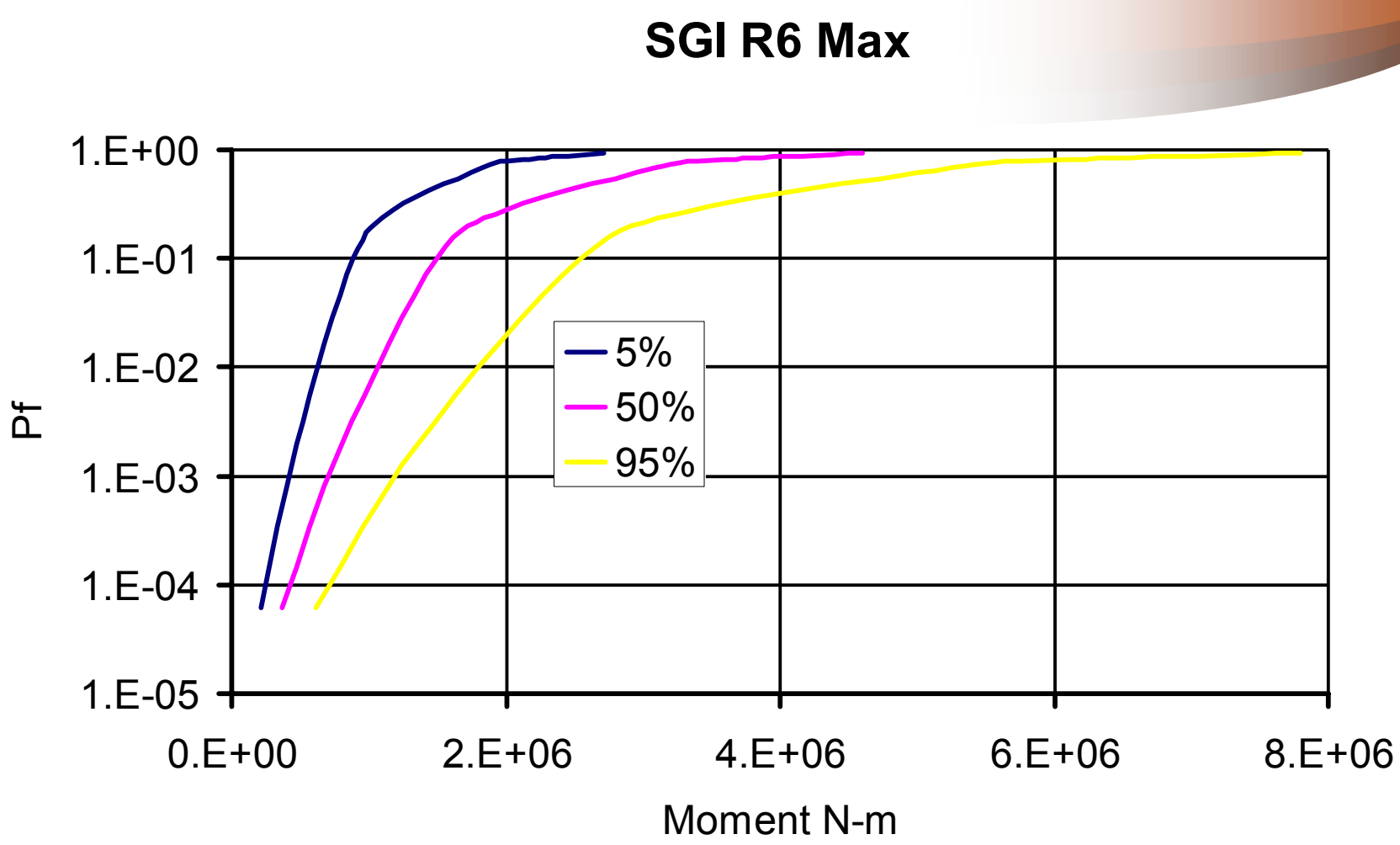
Fragility Analysis-SGO: R6 (INITIATION) - Stochastic Load



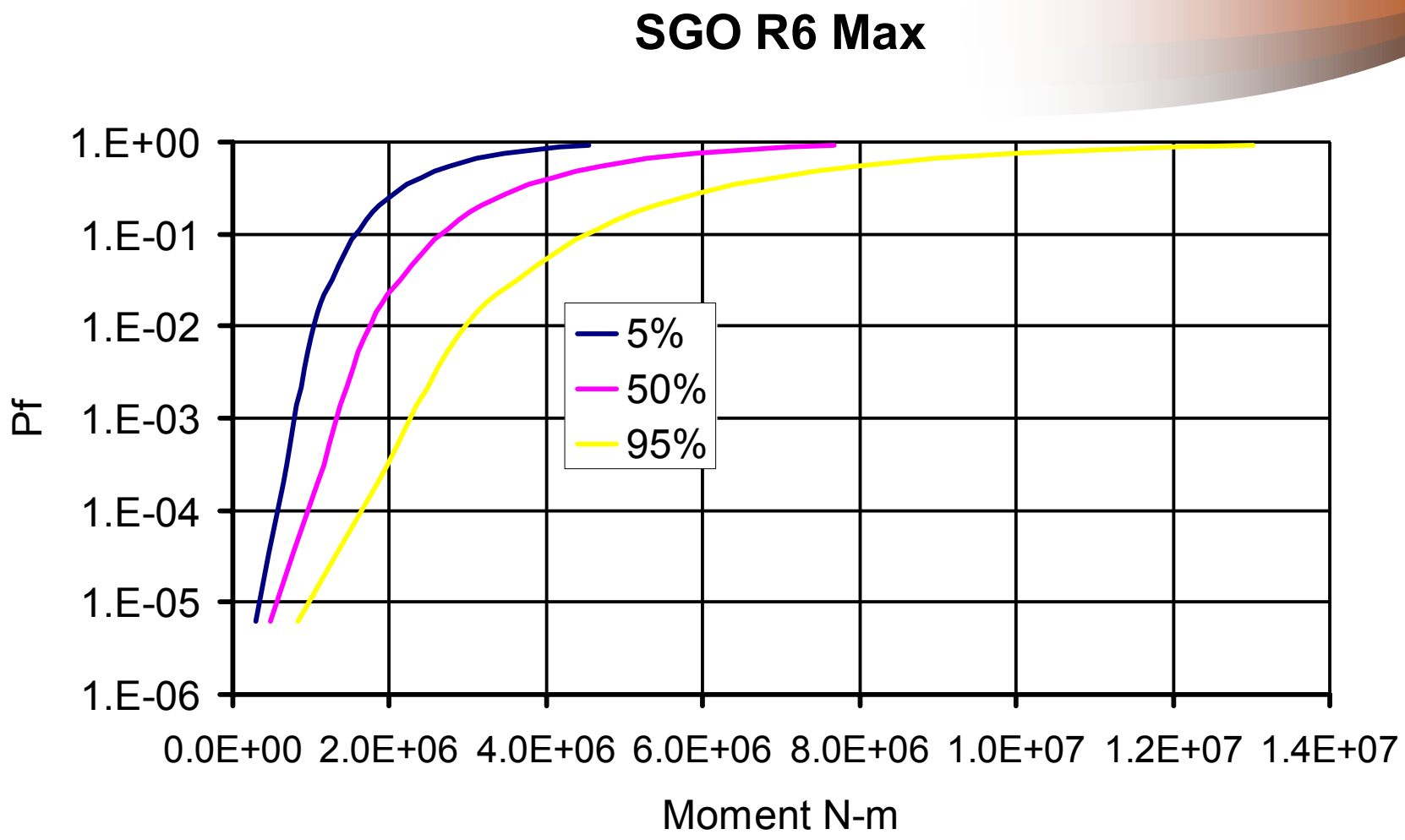
Fragility Analysis-PDL: R6 (INITIATION) - Stochastic Load



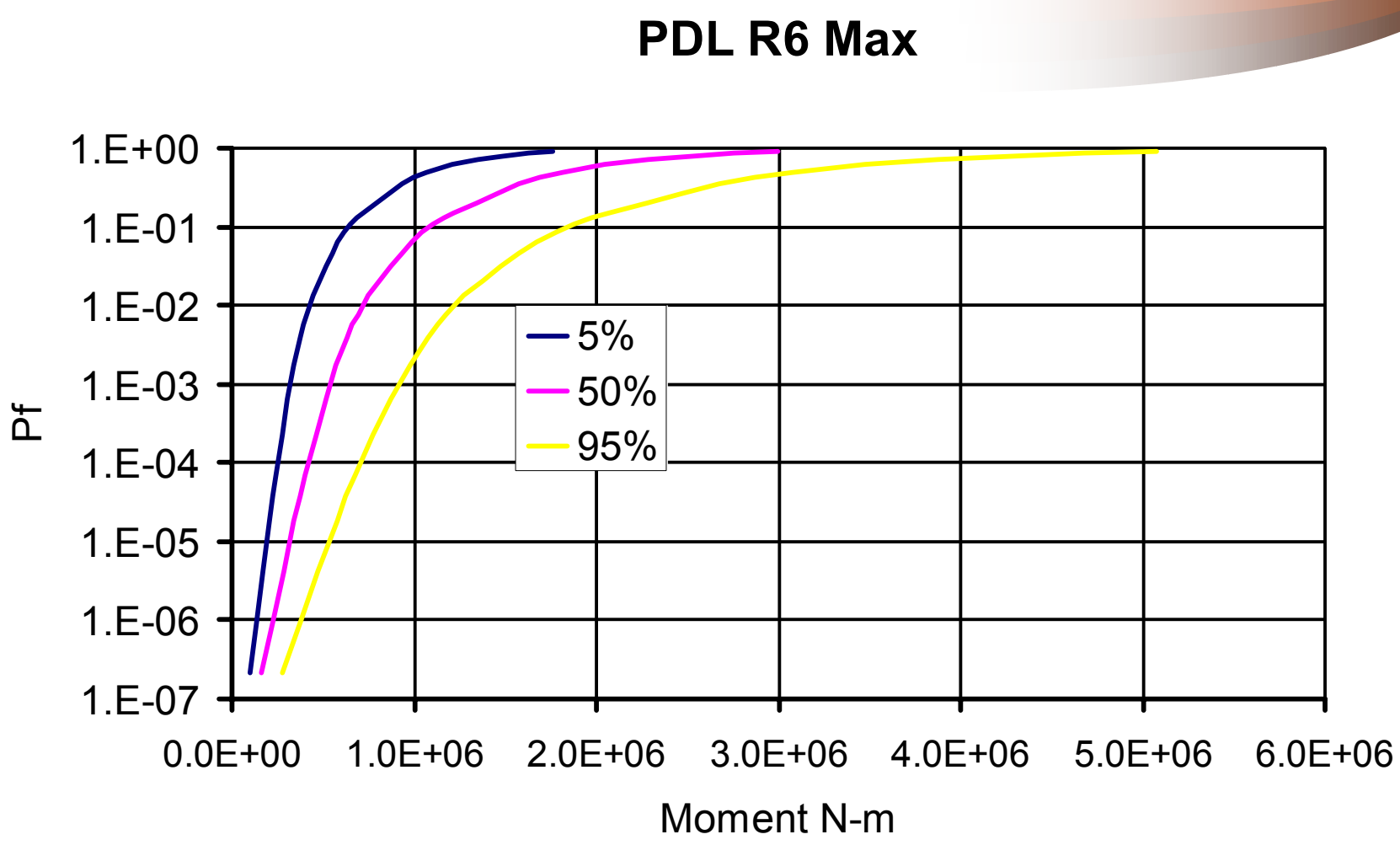
Fragility Analysis-SGI: R6 (UNSTABLE CRACK GROWTH) - Stochastic Load



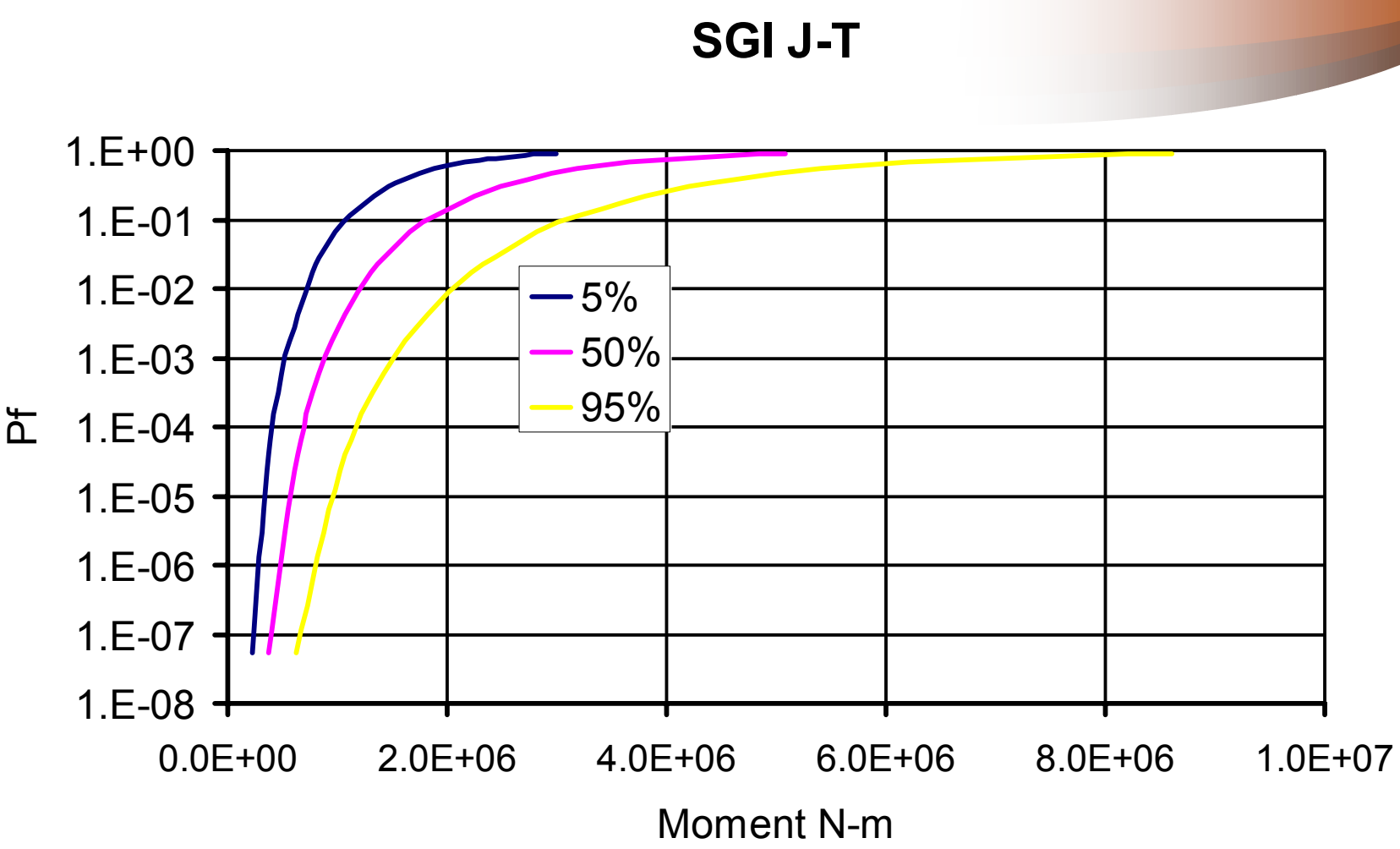
Fragility Analysis-SGO: R6 (UNSTABLE CRACK GROWTH) - Stochastic Load



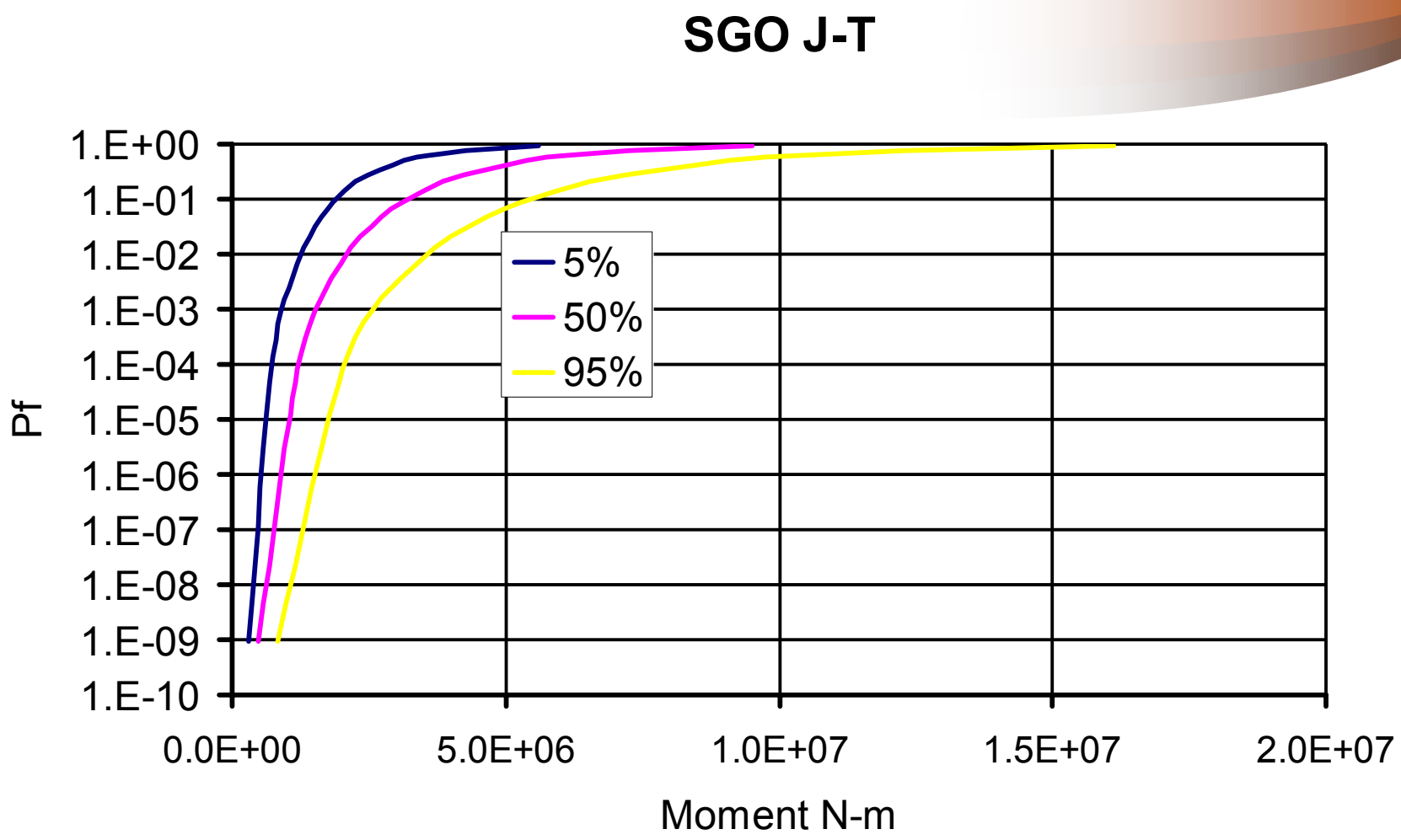
Fragility Analysis-PDL: R6 (UNSTABLE CRACK GROWTH) - Stochastic Load



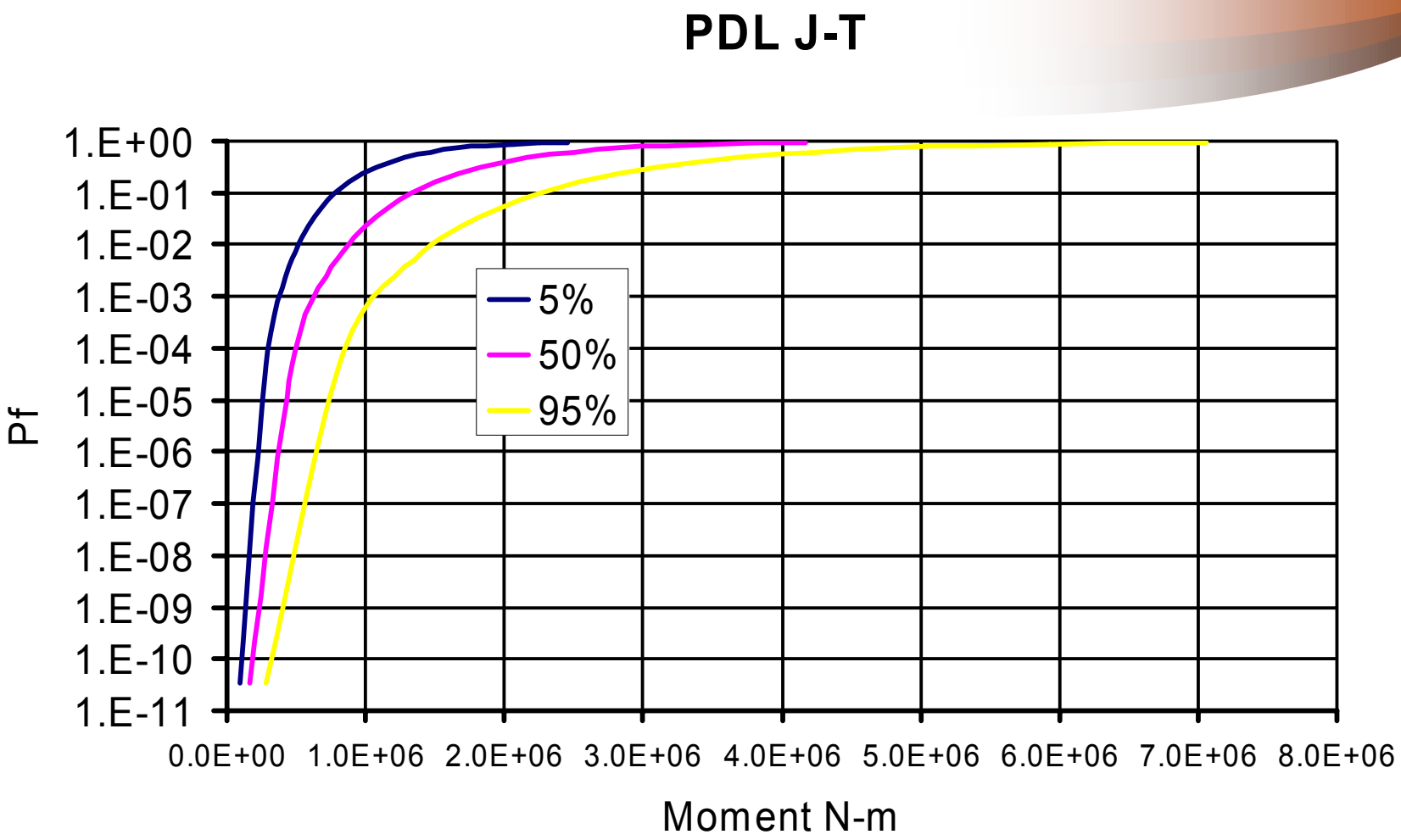
Fragility Analysis-SGI: J-TEARING METHOD - Stochastic Load



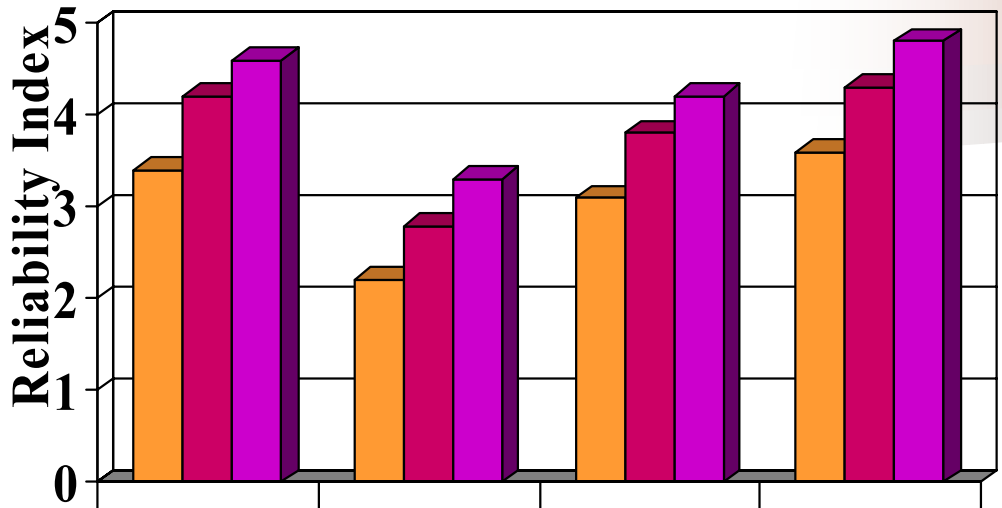
Fragility Analysis-SGO: J-TEARING METHOD - Stochastic Load



Fragility Analysis-PDL: J-TEARING METHOD - Stochastic Load

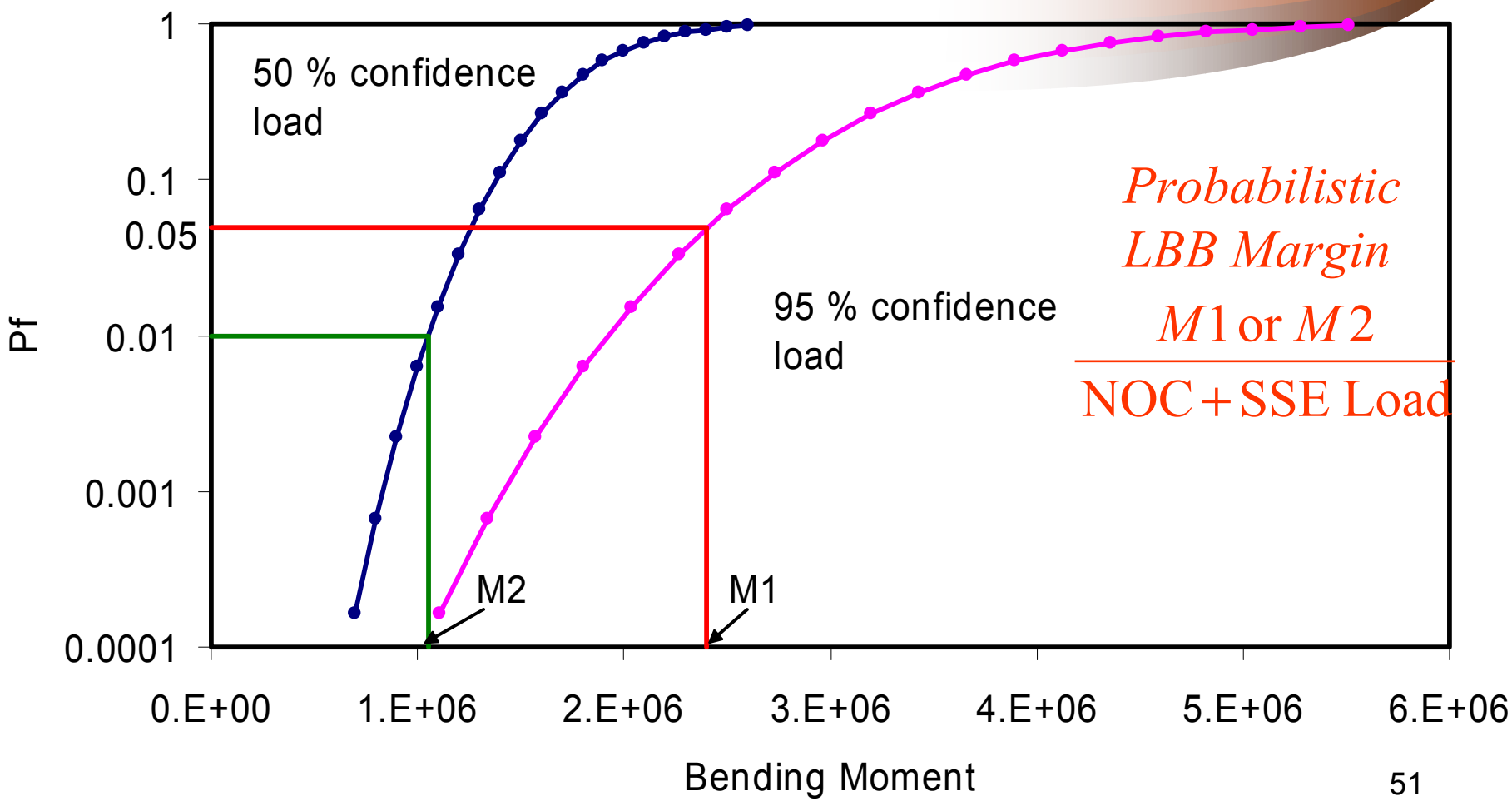


Reliability Index@DBA: Comparing for Different Pipes-Stochastic Applied Load



	NSC	R6 init.	R6 rupture	J-T
SGI	3.4	2.2	3.1	3.6
SGO	4.2	2.8	3.8	4.3
PDL	4.6	3.3	4.2	4.8

Calculation of Margin on Load for LBB



Probabilistic LBB Margin

$$\frac{M1 \text{ or } M2}{\text{NOC} + \text{SSE Load}}$$

LBB Margins at Constant Load (Margin Required :ABS Load Combination=1

	NSC		R6 init.		R6 rupture		J-T	
SGI	2.65	6.60	2.24	3.42	2.40	5.65	2.60	5.64
SGO	3.63	9.34	2.98	4.74	3.20	7.62	3.47	9.06
PDL	4.15	10.8	3.42	9.29	3.82	9.29	4.13	11.1

Deterministic

Probabilistic

Margins calculated at 95% confidence moment (51% cov) with 5% probability of failure (HCLPF)

LBB Margins at Constant Load (margin required :ABS Load combination =1

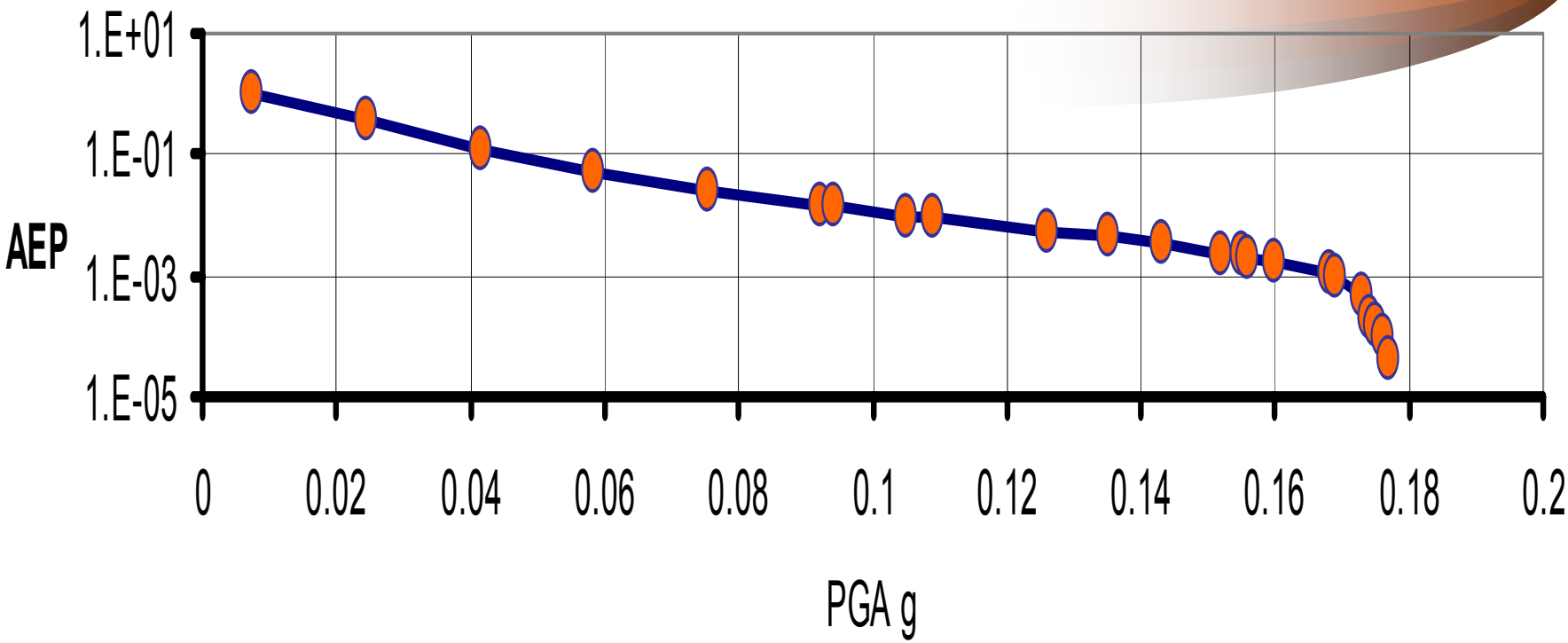
	NSC		R6 init.		R6 rupture		J-T	
SGI	2.65	3.01	2.24	1.51	2.40	2.53	2.60	2.53
SGO	3.63	4.20	2.98	1.96	3.20	3.41	3.47	3.93
PDL	4.15	4.91	3.42	4.12	3.82	4.12	4.13	4.89

Deterministic

Probabilistic

Margins calculated at 50% confidence moment (51% cov) with 1% probability of failure (HCLPF)

Hazard Curve for TAPP



AEP: Annual Exceedance Probability

PGA: Peak Ground Acceleration

Earthquake Induced Probability of Failure

- Probability of DEGB induced by earthquake is extremely low.
- It is consistent with the pipe tests conducted at BARC and international test experience that if material is ductile then maximum load can be approximated by NSC formula
- Probability of crack initiation (per year)

SGI	**$7.91E10^{-07}$**
SGO	**$1.07X10^{-07}$**
PDL	**$5.71X10^{-09}$**

Discussion on Reliability Studies Performed at Constant Load

- Margins required on load for LBB qualification are obtained using probabilistic analysis
- Probability of DEGB of PHT pipe with LSC under DBA load is extremely low
- Mode of failure from experiments
  - Pipe sizes = 8” NB : NSC
  - Pipe sizes > 8” NB : J-Tearing
- Probability of stable crack growth initiation is also very low.
- The reliability calculations were done using a number of methods, (FORM, SORM, Monte Carlo based etc.) All of them gave consistent results

Thank You…