FUNDAMENTALS OF PFM ANALYSES

PFMの概要とPFM解析の標準的な流れ

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What is PFM?

- Integrity Assessment
- Dispersion of Data
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- Typical Flow of PFM Analysis

How to use it?

INTEGRITY ASSESSMENT

Loading Factor < Strength

- SIF < Fracture Toughness
- Stress < Yield Stress

- Normalized Crack Size > 0.8 ?

DISPERSION OF DATA -1

- Dispersions of

Yield Stress

Fracture Toughness

Temperature & its History

Fast Neutron Irradiation

RT-NDT

- affect Strength directly or indirectly

DISPERSION OF DATA -2

- Dispersions of

Thickness

Crack Size & Aspect Ratio

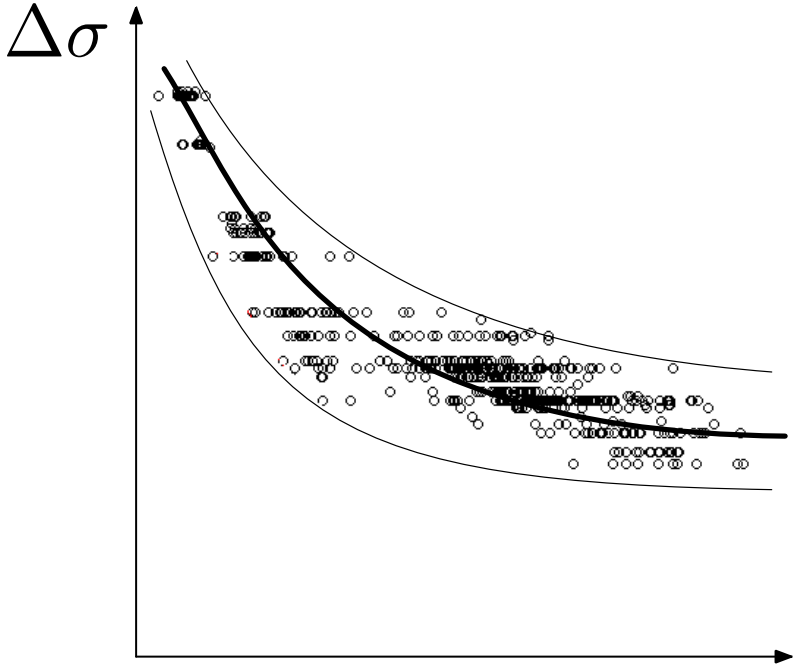
Loading

- affect Loading Factors
- Stress, SIF & etc.

DETERMINISTIC APPROACH

Conservative Value

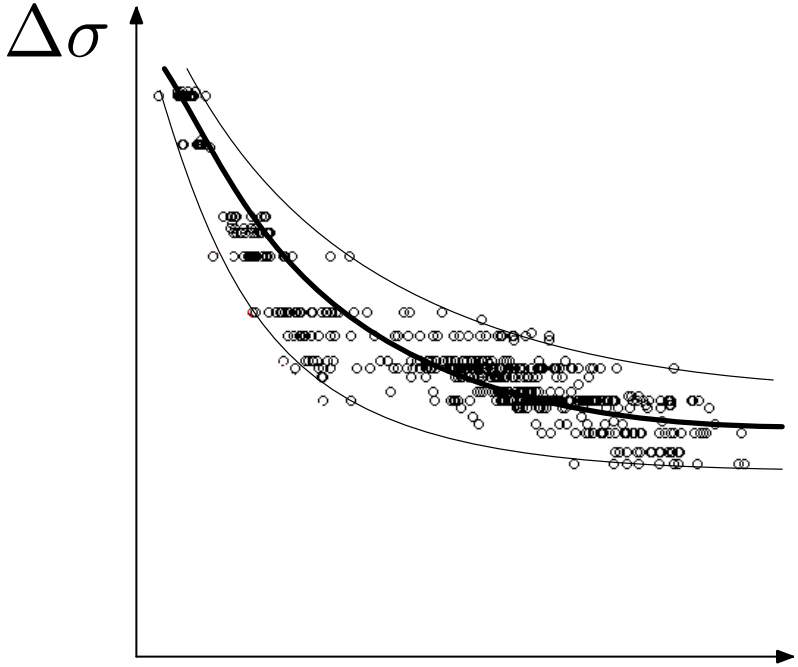
Safety Factor



PROBABILISTIC APPROACH

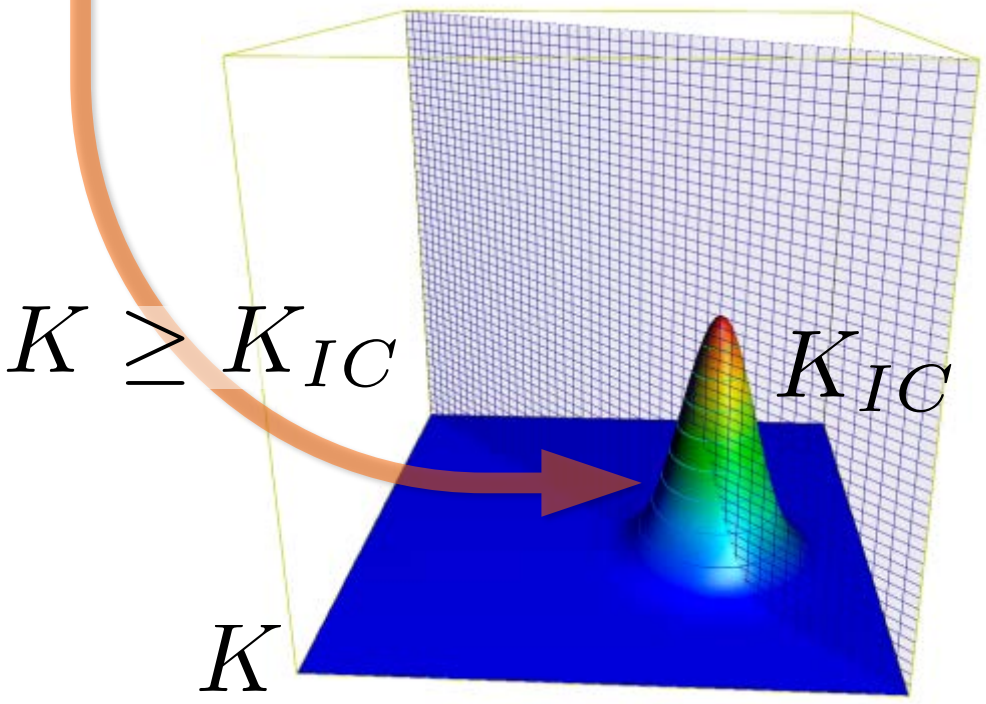
Mean Value & Deviation

Dispersion itself



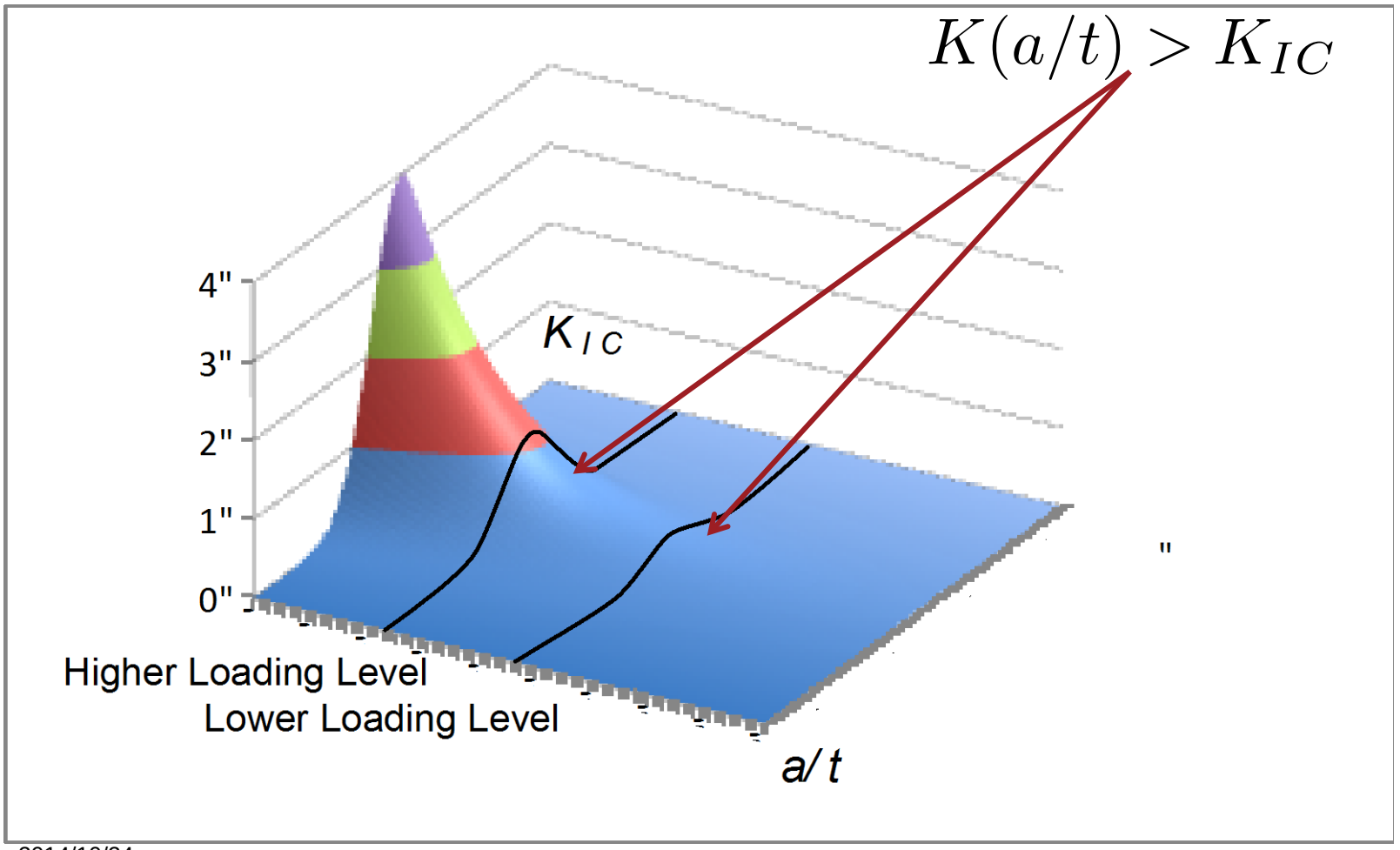
FAILURE PROBABILITY

$$P_f = \int_0^{\infty} \left\{ \int_{K_{IC}}^{\infty} f(K_I) dK_I \right\} f_C(K_{IC}) dK_{IC}$$



Probability Distribution Function

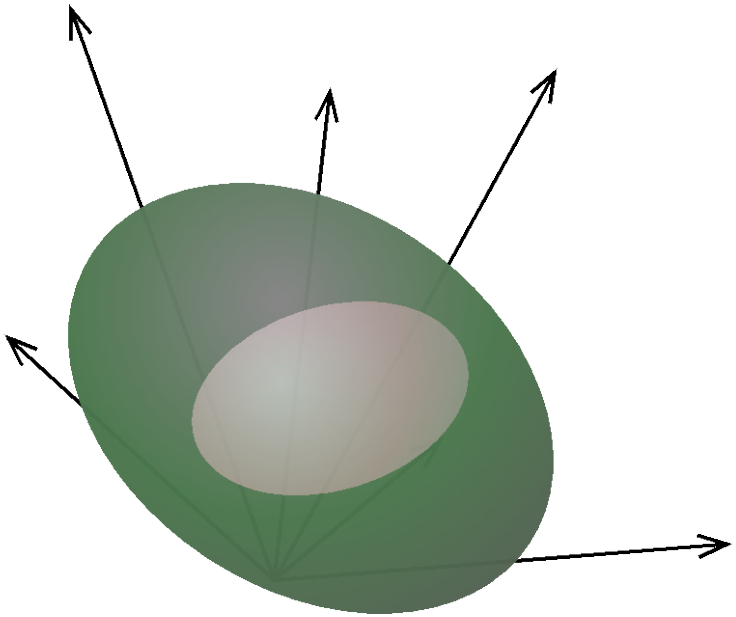
FAILURE PROBABILITY



MULTI-DIMENSIONAL SPACE PROBLEM

Related Factors

- Material Contents (Cu, Ni)
- Crack Size
- Neutron Irradiation
- Loading
- Fracture Toughness
- etc.



MONTE CARLO SIMULATION

Numerical Integration Method for Multi-dimensional space

$$P(x > c) = \int_{c}^{\infty} f(x)dx$$

$$P(x > c) = \int_{-\infty}^{\infty} I_c(x) f(x)dx$$

$$I_c(x) = \begin{cases} 1 & (x > c) \\ 0 & (x \leq c) \end{cases}$$

$$P(x > c) \cong \frac{\sum_{i=1}^{N} I_c(x_i)}{N}$$

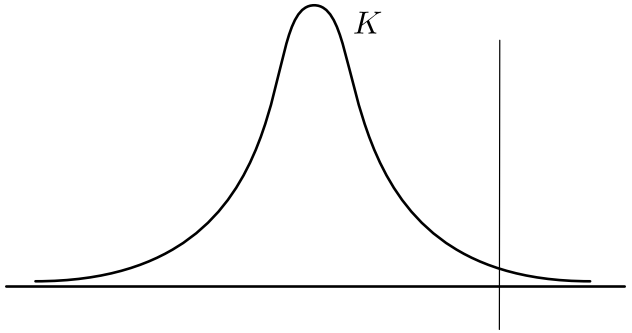
ERROR OF MC METHOD

$$P = \int_c^{\infty} f(x)dx \qquad P_N = \frac{\sum_{i=1}^{N} I_c(x_i)}{N}$$

$$E_N = |P - P_N| < C\sqrt{\frac{\log\log N}{N}}$$

$$\frac{E_{1,000,000}}{E_{10,000}} \cong 0.109$$

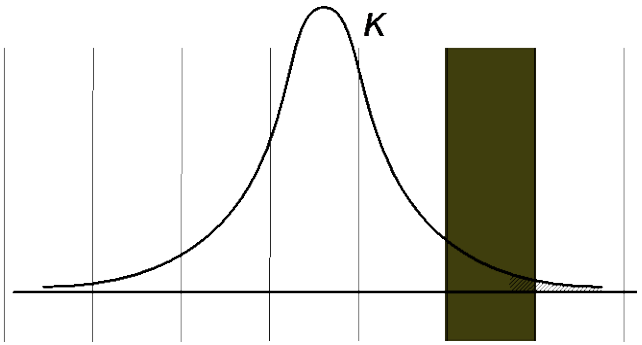
STRATIFIED SAMPLING



Sampling Points

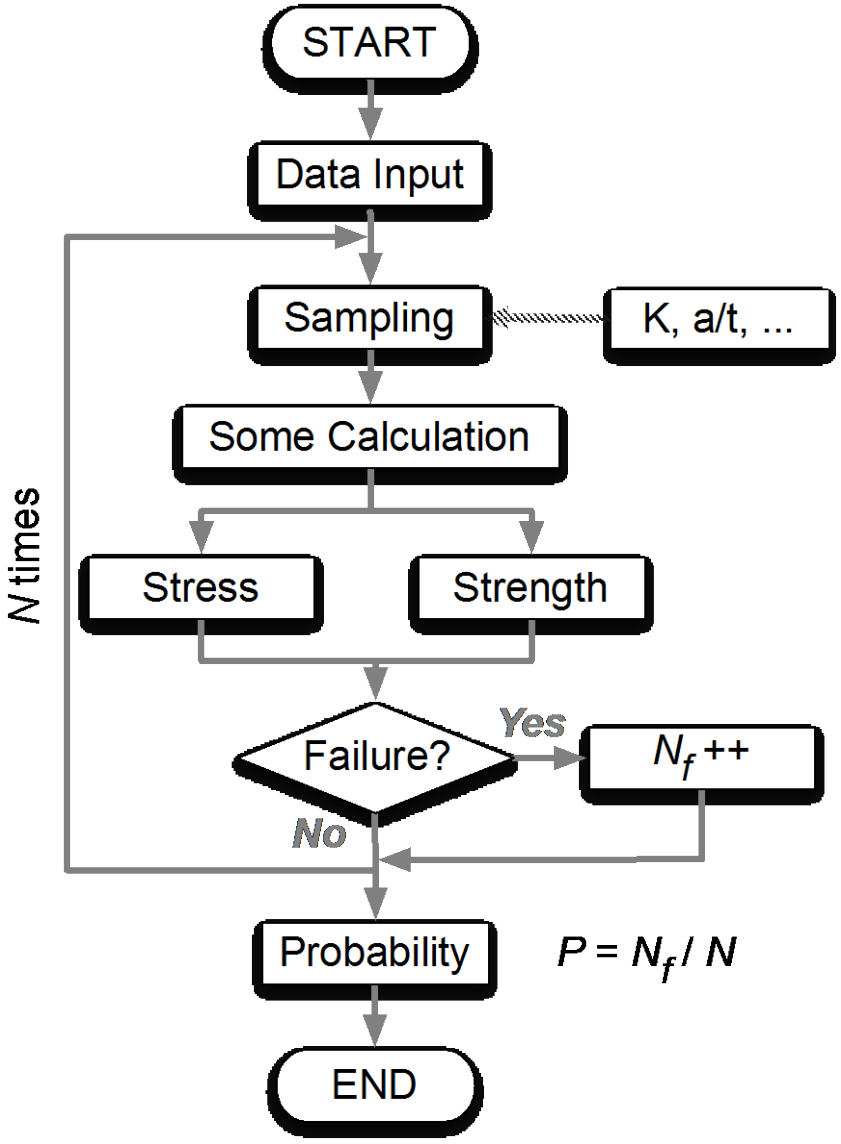
- Many points are in “Safe” region.
- Very few points are in “Break” region.

Stratified Sampling



- Many points from Boundary Region.
- Few points from other regions.

SIMPLE FLOW OF PFM ANALYSIS



PASCAL CODE

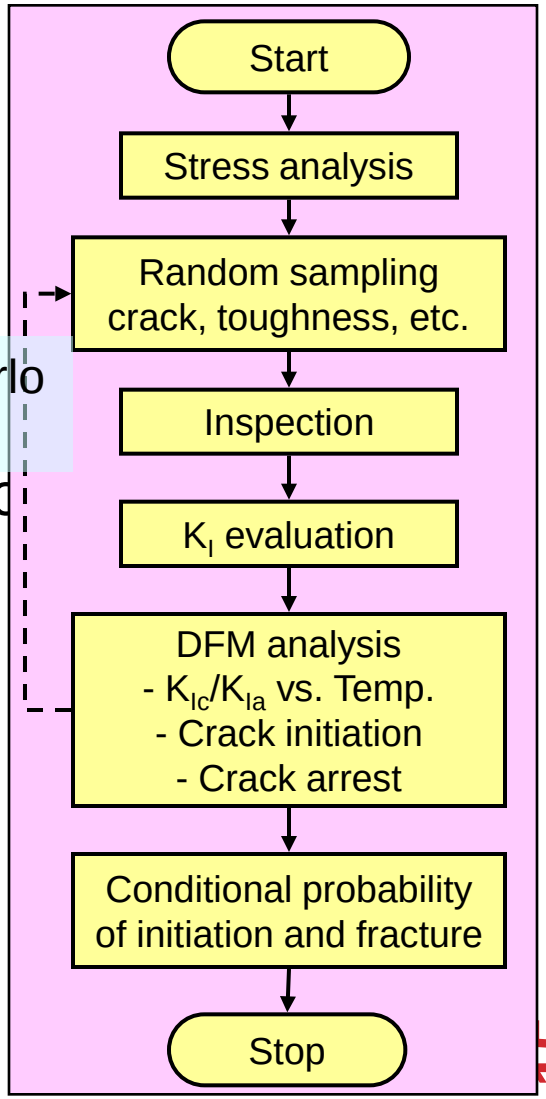
FRACTURE PROBABILITY ANALYSIS BY MONTE CARLO SIMULATION

- *PASCAL* Ver. 1 is available at OECD/NEA Databank.
  - ICAS PFM benchmark

***PASCAL* Ver. 1 → Ver. 2 (PASCAL2)**

Main Improvements **(added to ver. 1)**

- **Geometry of crack**
  - Surface crack (Long & Circum)
  - Embedded crack
- **K_I calculation**
  - Influence function, ASME method, etc
- **Fracture toughness (initiation and arrest)**
  - IPTS (NRC) K_{Ic}/K_{Ia}, JEAC K_{Ic} (Normal)
  - Master curve, ORNL Weibull-type
- **Irradiation embrittlement**
  - Japanese equation, USNRC R.G.1.99 r2
  - ASTM E900, NUREG



MAJOR PFM SOFTWARE

Name	Developer	Target	Remark
PASCAL3	JAEA, MRI	PV	PTS
PASCAL-SP	JAEA, MRI	Pipe	SCC
PASCAL-EC	JAEA, MRI	Pipe	Thinning
MSS-REAL	JAEA, JRI	FBR	Creep-Fatigue
PEPPER	Tepco Systems	Pipe	Linear/Non-Linear
PEPPER-M	Tepco Systems	Pipe	SCC
WinPRAISE	Eng. Mech. Tech.	Pipe	Seismic Load
FAVOR	ORNL	PV	
SPEC	Tepco Systems	Pipe	MS Excel
Dr. Mainte	UT, JNFL, INSS, Allied Engineering	PV, Pipe and etc.	Economical Evaluation Integrated Simulator

EXAMPLE OF PFM ANALYSIS

Round Robin Analysis

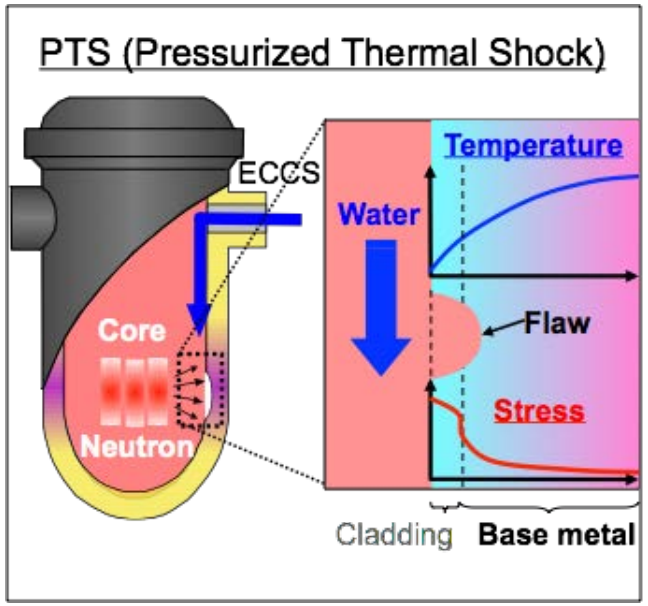
- Verification & Validation of Software
- Improvement of Method, Input Data …

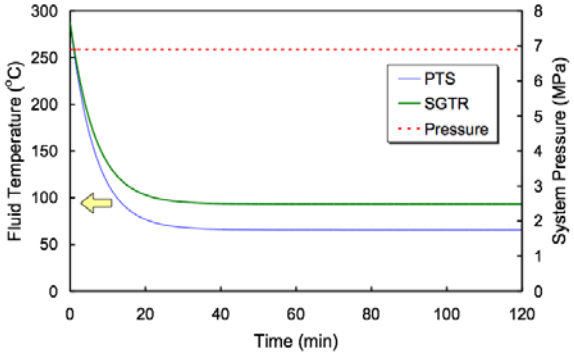
International RR program

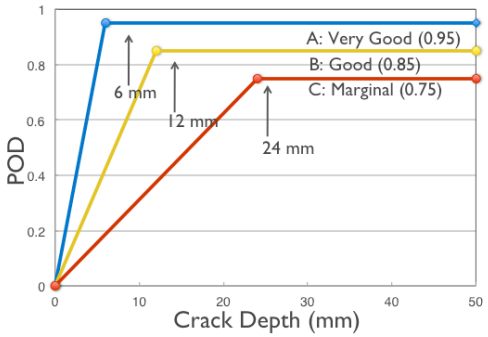
- Exchange of Information

PROBLEM OF RR ANALYSIS

- **RPV failure probabilities with a single crack located inside of the belt line for PTS and SGTR transients**
- **Sensitivity analyses for inspection performance**
- **Sensitivity analyses for copper contents and initial RT_{NDT}, which effect fracture toughness**

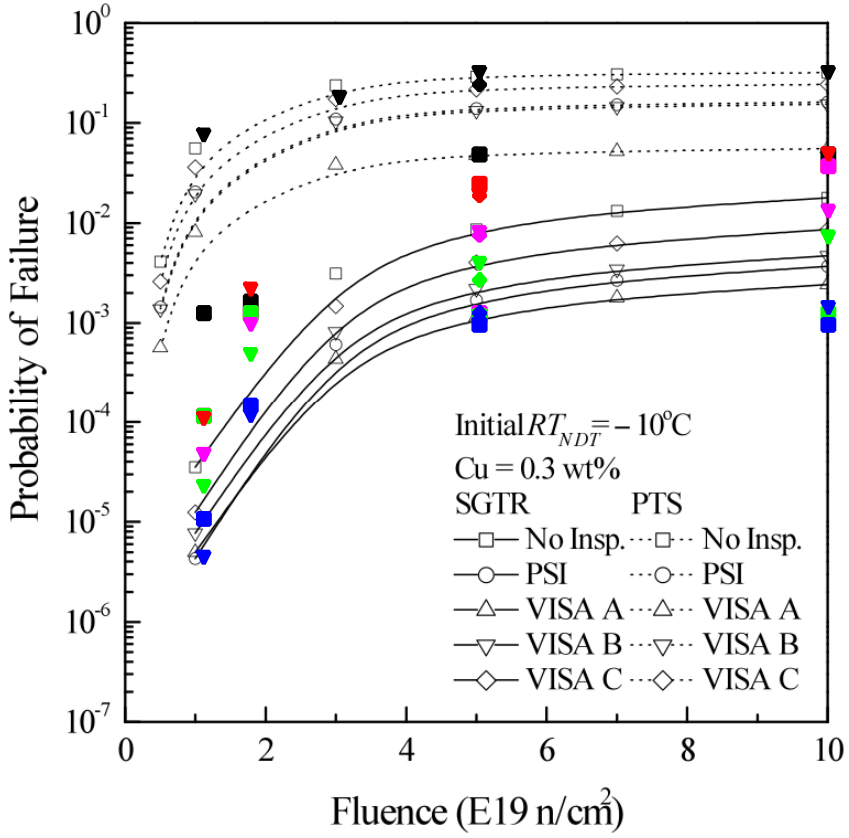






RESULTS OF RR ANALYSIS

Effect of Inspection Performance



USAGE OF PFM

Absolute Value

- Regulation

Relative Value

- Measure of Safety
  - Difference of Design
  - Difference of Maintenance