Probabilistic Risk Analysis of Reactor Pressure Vessels

Wen-Fang Wu, Chung-Hao Wei
Department of Mechanical Engineering
Institute of Industrial Engineering
National Taiwan University

Jang-Shyong You
National Taipei University of Education

Hou-Chin Chu
Institute of Nuclear Energy Research, Taiwan

May 22, 2008

Not

A PSA System Analysis

but

A Probabilistic Analysis of a Component

Why This Research?

- Current Code-Required Assessment of RPVs:
  - **Deterministic**
  - Defense in Depth

- Things not Considered Appropriately:
  - **Uncertainty** and/or **Variability** of Environment

→ To perform a more appropriate assessment
→ To let the result compatible with Risk-Informed Management

Current Code-Required Assessment of RPV (1/6)

- Based on:
  - 10 CFR50 Appendices G and H of US Regulations
  - NRC Regulatory Guide 1.99, Revision 2

→ To evaluate degrees of Radiation Embrittlement of RPVs

Current Code-Required Assessment of RPV (2/6)

1. Data from Specimens of RPV Material Surveillance Program

2. Aging Assessment Method:

→ Consider Base Metal and Weld Metal respectively

(1) Evaluate Adjusted Reference Temperature (ART)

(2) Evaluate Upper Shelf Energy (USE)

3. Compare Results with Code-Required Threshold Values

Current Code-Required Assessment of RPV (3/6)

$$ART = Initial\ \ RT_{NDT} + \Delta RT_{NDT} + Margin$$

ART : Adjust Reference Temperature of Material

$Initial\ \ RT_{NDT}$: Initial Nil Ductility Transition Temperature of Material

ΔRT_{NDT} : Change of Nil Ductility Transition Temperature

$Margin$: Accounts for Uncertainty

$(^{\circ}\mathrm{F})$

Current Code-Required Assessment of RPV (4/6)

$$ART = Initial\ RT_{NDT} + \underline{\Delta RT_{NDT}} + Margin$$

$$\underline{\Delta RT_{NDT} = (CF)\, f^{(0.28 - 0.1 \log f)}}$$

CF : A Chemistry Factor of Material in °F

= *Cu, Ni* (wt%) + NRC R.G. 1.99, Rev. 2 Tables

f : A fluence factor depending on fast neutron flux the material has been exposed to (measured in 10^{19} n/cm^2)

Current Code-Required Assessment of RPV (5/6)

$$ART = Initial\ \ RT_{NDT} + \Delta RT_{NDT} + \underline{Margin}$$

$$\underline{Margin = 2\sqrt{{\sigma_I}^2 + {\sigma_\Delta}^2}}$$

σ_I : Standard Deviation of $Initial\ \ RT_{NDT}$ (0 if No Data Available)

σ_Δ : Standard Deviation of ΔRT_{NDT}
- Base Metal 17 °F
- Weld Metal 28 °F

Current Code-Required Assessment of RPV (6/6)

$$USE = USE_i (1 - d)$$

USE : Upper Shelf Energy after radiation

USE_i : Upper Shelf Energy before radiation

d : A decreasing factor

⟶ Cu (wt%) + f + NRC R.G. 1.99, Rev. 2 (Figure 2)

Current Criteria set by the Code

- For material at a depth of a quarter wall-thickness counted from the vessel inner-surface
  - **ART < 200℉ during operation**
  - **USE > 50 ft-lb during operation**

→ Beyond Allowable Values?

No → To modify operational curve based on ART

Yes → Further investigation needed

→ Further material treatment or cease operation

Probabilistic Failure Analysis (1/2)

- Current Assessment Method

$$ART' = Initial\,RT_{NDT} + \Delta RT_{NDT}$$

$$USE = USE_i(1 - d)$$

+ Probability and Reliability Methods

→ To find Failure Probability of RPV

Failure Probability:
Probability of ART' and USE of RPV Material
"Exceeds Code-Required Threshold Values"

Probabilistic Failure Analysis (2/2)

1. Randomness due to Uncertainty of Parameters

$$ART' = ART'\left(initial\,RT_{NDT}, Cu, Ni, f\right)$$

$$USE = USE\left(USE_i, Cu, f\right)$$

2. Monte Carlo Simulation and Analysis

3. Probability Papers and Chi-Square Test to find PDF of Results

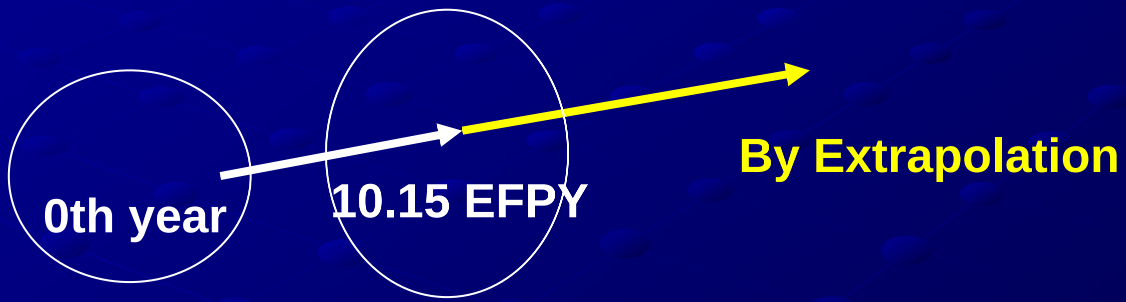
4. Stress-Strength Inference Theory based on Failure Criteria

$$ART' > 200\ ^{\circ}\mathrm{F}$$
$$USE < 50\ \text{ft-lb}$$

→ Failure (Exceeding Code-Required Values) Probabilities of RPV

Case Study

- RPV of a PWR Unit
- Based on Test Results of Specimens from RPV Material Surveillance Program (The Fourth taken at 10.15 EFPY *)



1. Current Deterministic Assessment Result
2. Probabilistic Analysis Result

* EFPY: Effective Full Power Years:
Assuming 80% of operational efficiency

Current Deterministic Assessment Result (1/5)

- ART at End of Design Life (40 years, 32 EFPY)

Parameters	Base metal	Weld metal
Cu **(wt%)**	0.060	0.054
Ni **(wt%)**	0.580	0.130
CF **(℉)**	37.00	42.15
f **(10^{19} n/cm^2)**	3.403	3.403
Initial RT_{NDT} **(℉)**	10	-30
FF	1.32	1.32
$\Delta RT_{NDT} = CF \times FF$	48.85	55.65
Margin **(℉)**	34	56
ART **(℉)**	92.85	81.65

< 200 ℉

Current Deterministic Assessment Result (2/5)

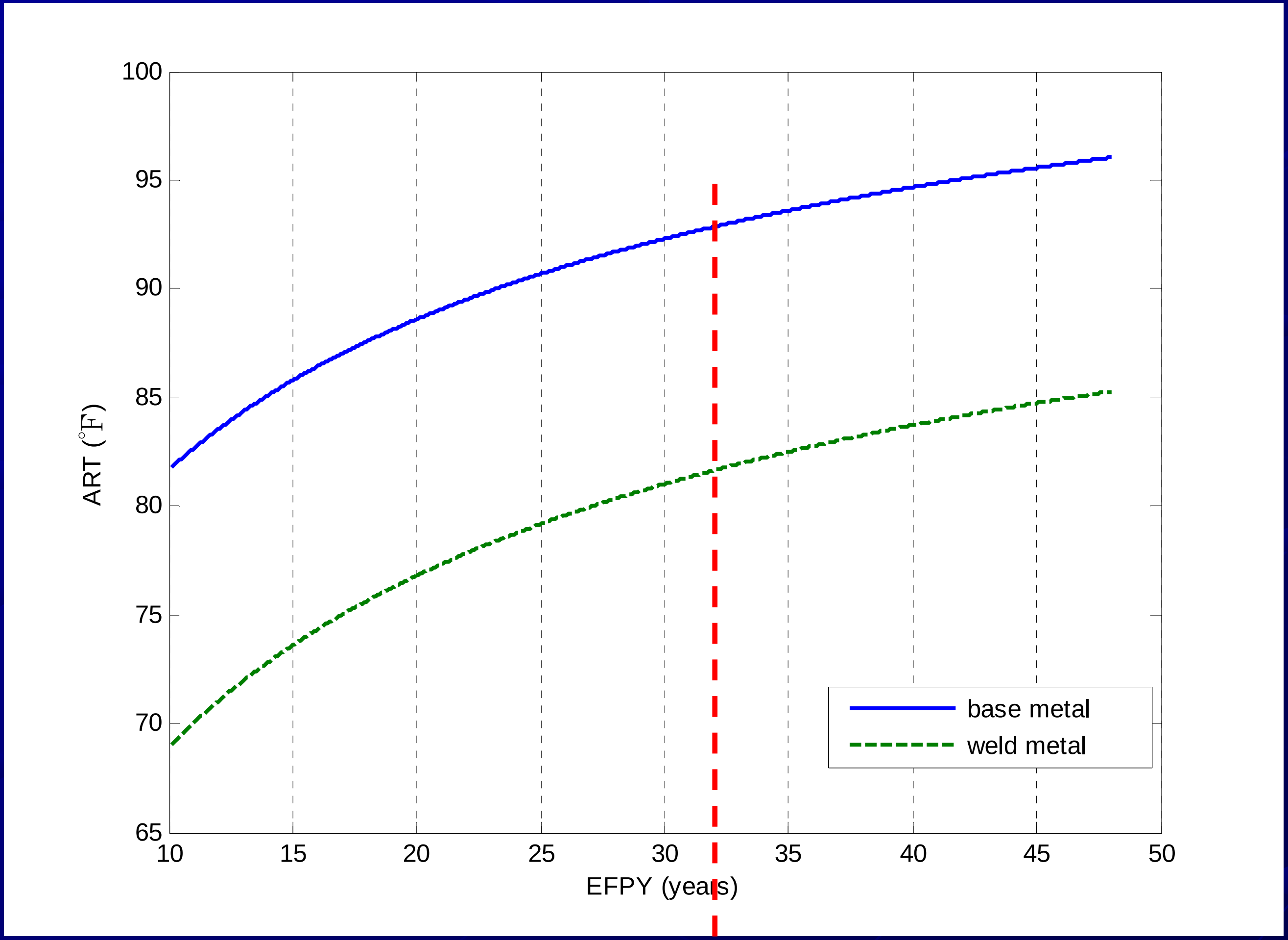
- USE at End of Design Life (40 years, 32 EFPY)

Parameters	Base metal	Weld metal
Cu **(wt%)**	0.060	0.054
f **(10^{19} n/cm^2)**	3.403	3.403
USE_i **(ft-lb)**	78	83
d **(%)**	21.15	25.88
USE **(ft-lb)**	61.51	61.52

> 50 ft-lb

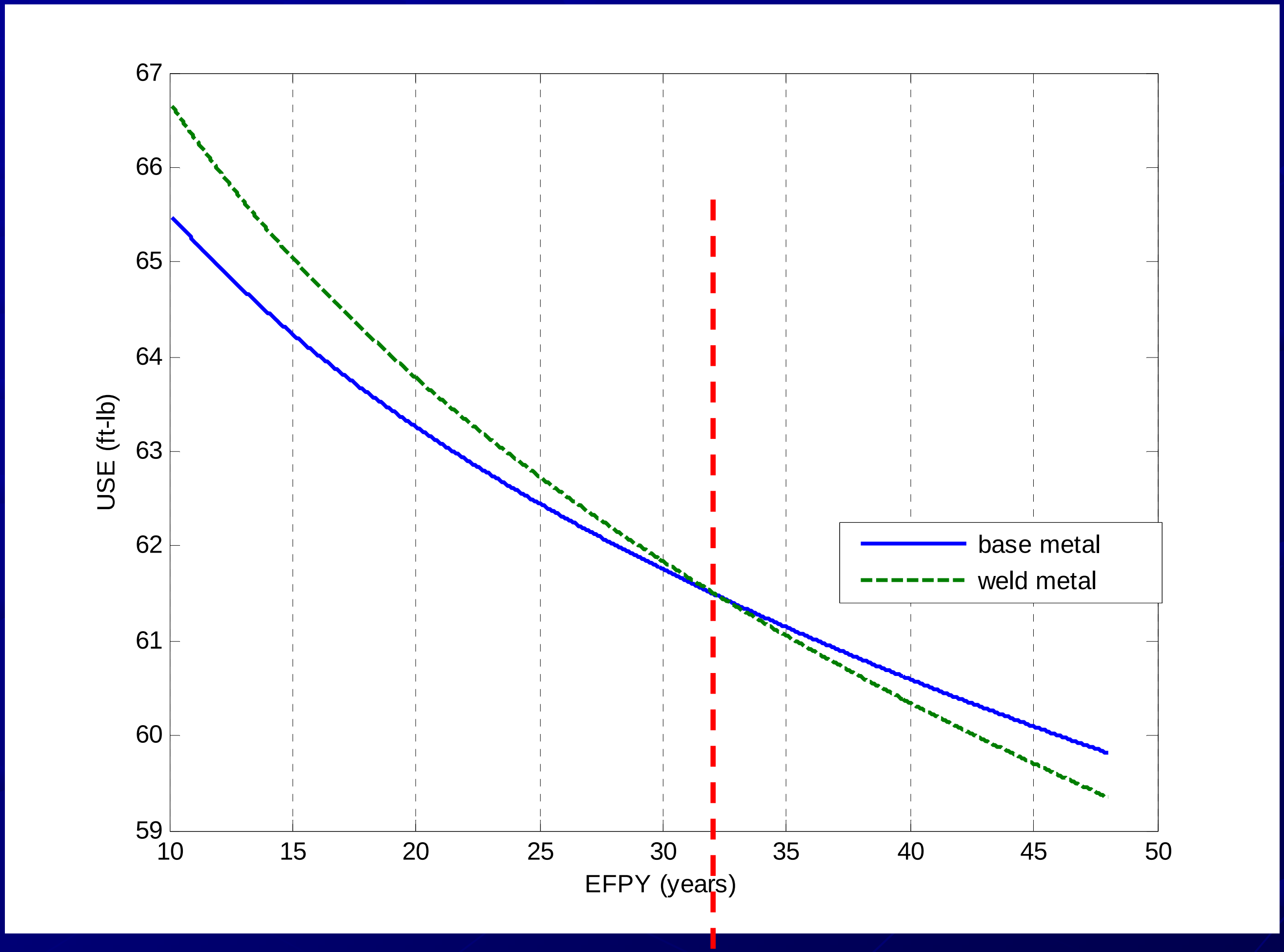
Current Deterministic Assessment Result (3/5)

- *ART* vs EFPY (10.15 ~ 48 EFPY)



Current Deterministic Assessment Result (4/5)

- *USE* vs EFPY (10.15 ~ 48 EFPY)



Current Deterministic Assessment Result (5/5)

→ The RPV is Safe based on the analysis but What is the Probability of Failure & Degree of Risk?

Result of Probabilistic Analysis (1/8)

1. Uncertainty and Randomness of Parameters [13, 25, 26]

Parameter	Mean		Standard deviation		Distribution
	Base	Weld	Base	Weld	
Initial RT_{NDT} (℉) [26]	10	-30	29	29	Normal
Cu (wt%) [13]	0.060	0.054	0.0060	0.0054	Normal
Ni (wt%) [13]	0.580	0.130	0.058	0.013	Normal
f (10^{19} n/cm^2) [25]	0.3403	0.3403	0.0476	0.0476	Normal
USE_i (ft-lb) [25]	78	83	3.90	4.15	Normal

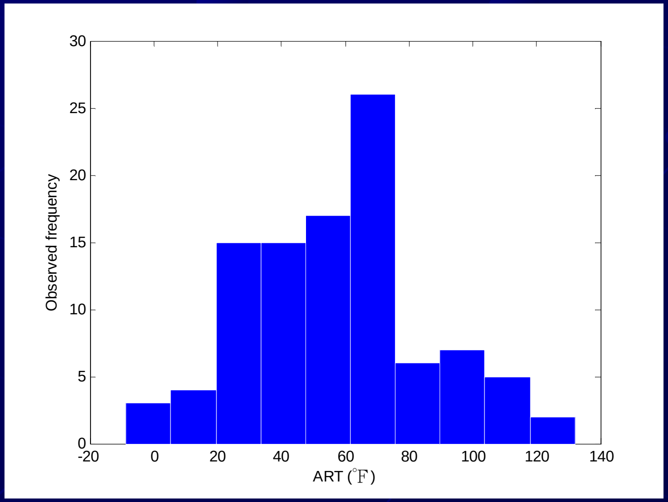
Result of Probabilistic Analysis (2/8)

2. Monte Carlo Simulation

$$ART' = Initial\,RT_{NDT} + \Delta RT_{NDT}$$
$$USE = USE_i(1-d)$$

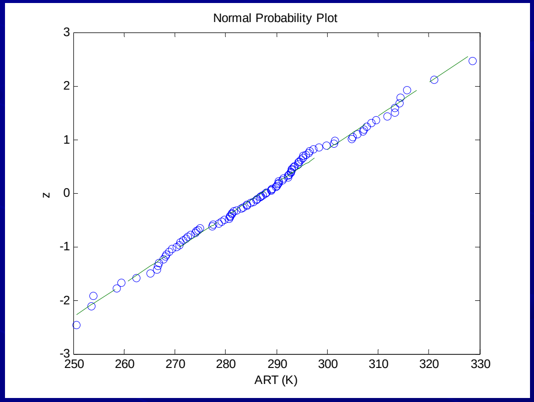
- e.g., *ART' of Base Metal*

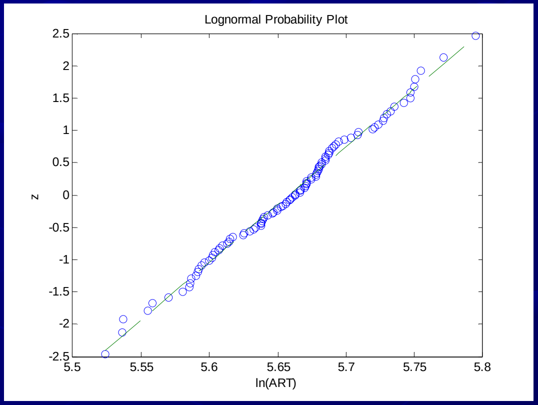
Initilal RT_{NDT} (°F)	*Cu* (wt%)	*Ni* (wt%)	*f* (10^{19} n/cm^2)	ART' (°F)
28.423	0.0574	0.5111	2.9761	74.102
-7.441	0.0500	0.4523	3.4674	33.623
25.984	0.0608	0.6372	3.3368	75.356
-21.895	0.0617	0.5499	2.8487	26.946
12.494	0.0531	0.5990	3.9669	57.017
-48.132	0.0672	0.5936	3.3956	7.297
-4.300	0.0671	0.5813	3.6585	51.829
23.400	0.0598	0.5218	3.0617	71.159
0.691	0.0620	0.5251	3.0907	50.493
45.860	0.0610	0.5583	3.5528	96.045
⋮	⋮	⋮	⋮	⋮

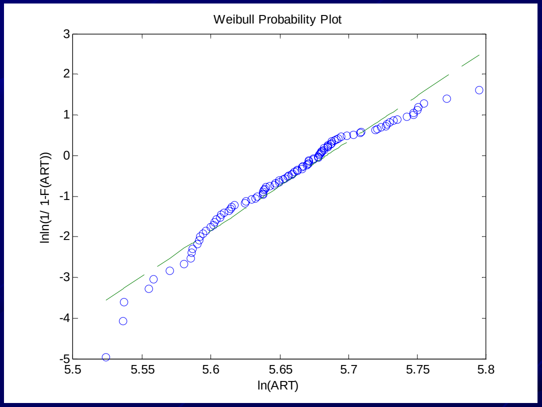


Result of Probabilistic Analysis (3/8)

3. Probability Plots & Chi-Square Tests
   - e.g., *ART' of Base Metal*







Materials	Normal	Lognormal	Weibull
Base	$\mu = 287.04$	$x_{med} = 5.658$	$\beta = 22.19$
	$\sigma = 16.00$	$s = 0.056$	$\theta = 294.04$

Result of Probabilistic Analysis (4/8)

3. Probability Plots & Chi-Square Tests (cont.)

Parameters	Materials	Normal	Lognormal	Weibull
ART'	Base metal	0.3687 ◎	0.7506	5.4231
	Weld metal	0.1277 ◎	0.2188	2.7287
USE	Base metal	1.2921	1.1063 ◎	24.3870
	Weld metal	0.8067	0.4260 ◎	17.1750

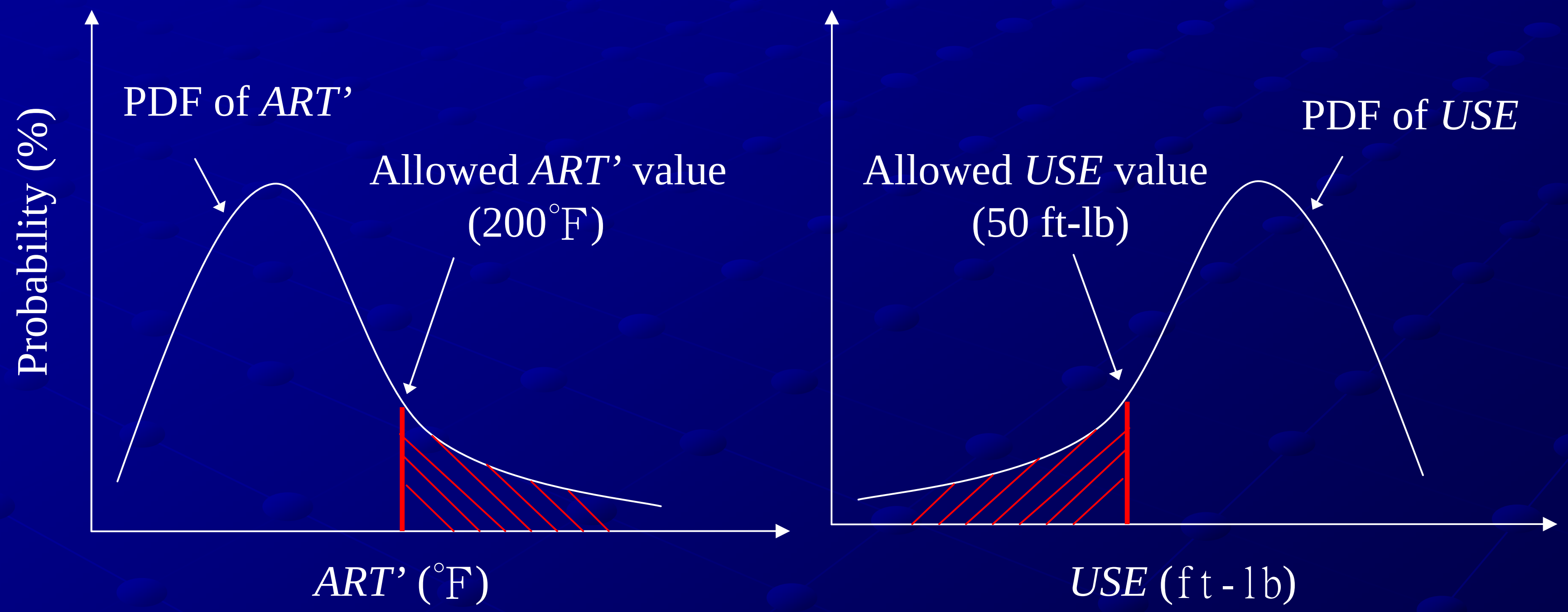
$$\alpha = 0.05 \rightarrow \chi_{\alpha}^{2} = 3.84$$

→ ART' -- **Normal**

USE -- **Lognormal**

Result of Probabilistic Analysis (5/8)

4. Apply Stress-Strength Inference Theory based on Failure Criteria



→ Find the Failure Probability of RPV

Result of Probabilistic Analysis (6/8)

- Failure Probability (P_f) of *ART'* & *USE* at End of Design Life (40 years, 32 EFPY)

Parameters	Materials	P_f
ART'	Base metal	3.42×10^{-7}
	Weld metal	1.16×10^{-7}
USE	Base metal	2.64×10^{-5}
	Weld metal	1.00×10^{-4}

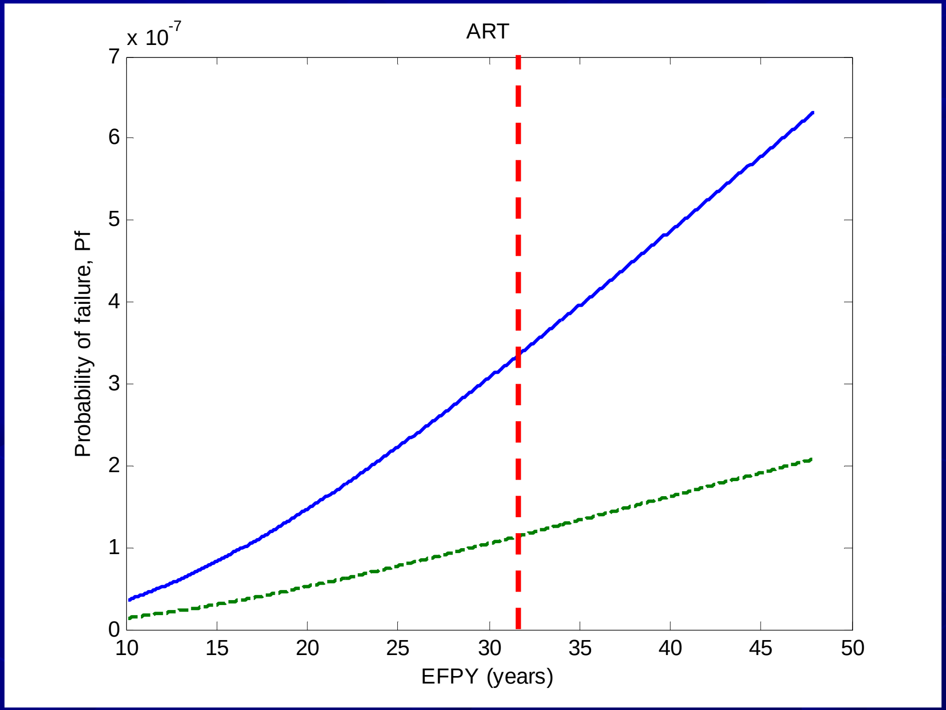
Result of Probabilistic Analysis (7/8)

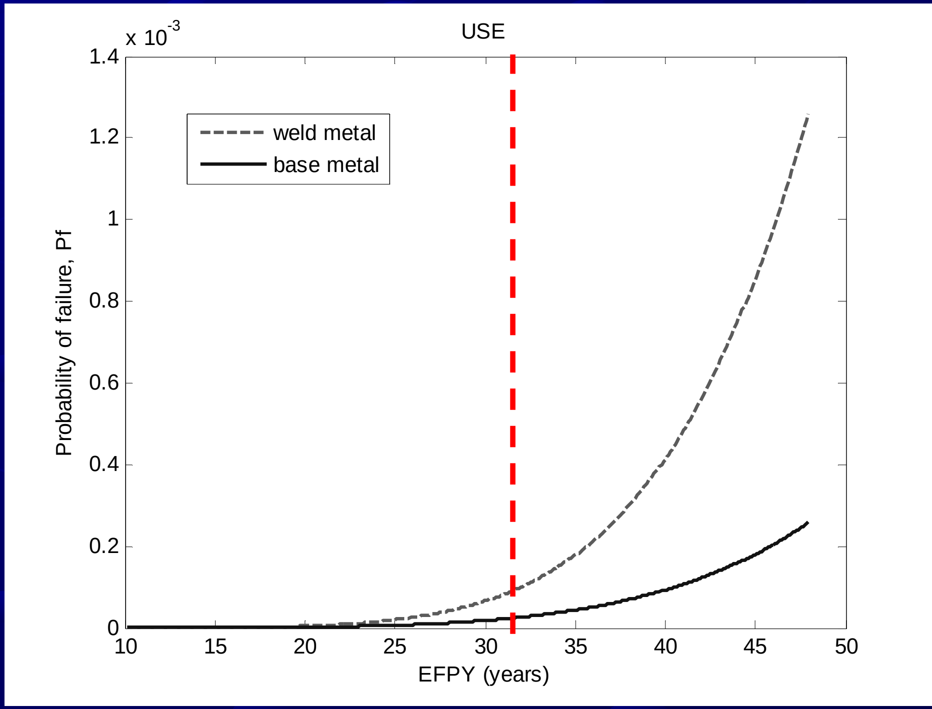
- Comparison between Stress-Strength Theory and Direct Simulation

Parameters	Materials	Probability of failure		
		Stress-Strength interference	**Simulation 10^7 times**	
			Counts	**Probability**
ART'	Base metal	3.42×10^{-7}	3	3.00×10^{-7}
	Weld metal	1.16×10^{-7}	0	0.00×10^{-7}
			Simulation 10^7 times	
			Counts	Probability
USE	Base metal	2.64×10^{-5}	374	3.74×10^{-5}
	Weld metal	1.00×10^{-4}	821	8.21×10^{-5}

Result of Probabilistic Analysis (8/8)

- P_f vs EFPY (10.15 ~ 48 EFPY)





Comparison of Safety Margins based on Art & USE

$$SF_{USE} = \frac{USE}{USE_a} \qquad USE_a = 50 \text{ ft-lb}$$

$$SF_{ART} = \frac{ART_a}{ART} \qquad ART_a = 200\ ^\circ\text{F}$$

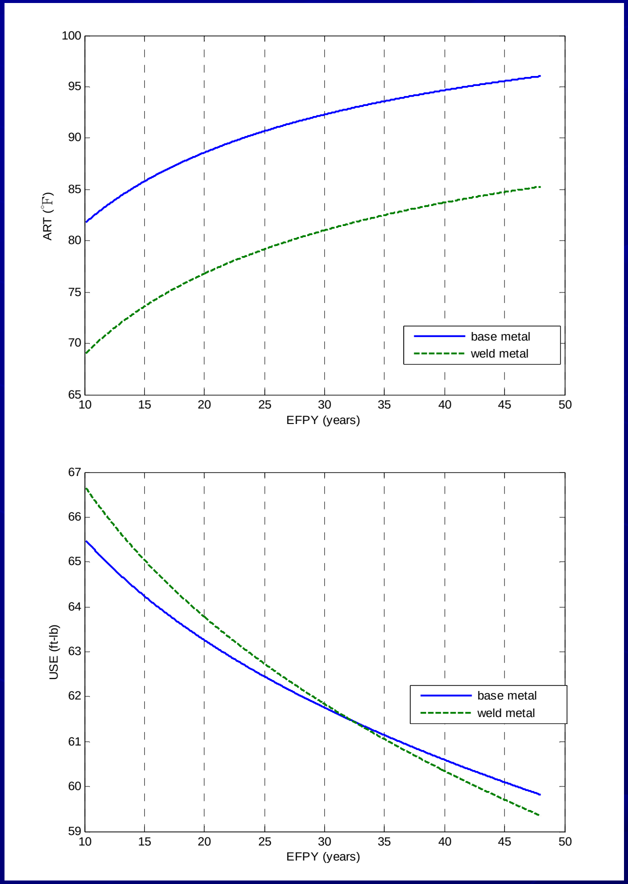
→ Deterministic Analysis $\frac{SF_{ART}}{SF_{USE}} = 2 \sim 3$

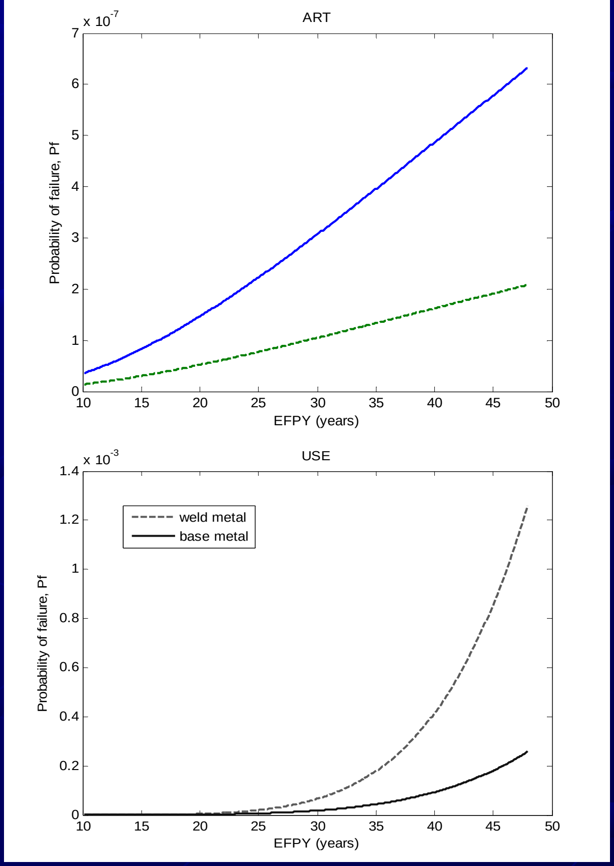
→ Probabilistic Analysis $\frac{P_{f\,USE}}{P_{f\,ART'}} \simeq 10^3$

USE is more critical in this case!

Aging Trends of Studied RPV

Deterministic Analysis   Probabilistic Analysis





Conclusion

- The studied RPV is safe against radiation embrittlement based on deterministic analysis but it still has probability of exceeding code-required threshold values, in particular, at the end of design life (40 years, 32 EFPY)

Parameters	Materials	P_f
ART'	Base metal	3.42×10^{-7}
	Weld metal	1.16×10^{-7}
USE	Base metal	2.64×10^{-5}
	Weld metal	1.00×10^{-4}

- USE is more critical and should be checked more carefully in similar assessments

Thank you for your attention

wfwu@ntu.edu.tw