PROBABILISTIC APPROACH FOR PRESSURISED THERMAL SHOCK (PTS) ANALYSIS

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(EU DuC = N)

- Introduction
- PTS Project
- PETO Code
- Conclusions

Introduction

NRG (Nuclear Research and Consultancy Group)

High Flux Reactor (HFR):

- Radioactive isotopes production
- Nuclear research
- Technical support services

Asset Integrity Team:

- Consultancy services
- Long Term Operation
- TMA
- Research

Introduction

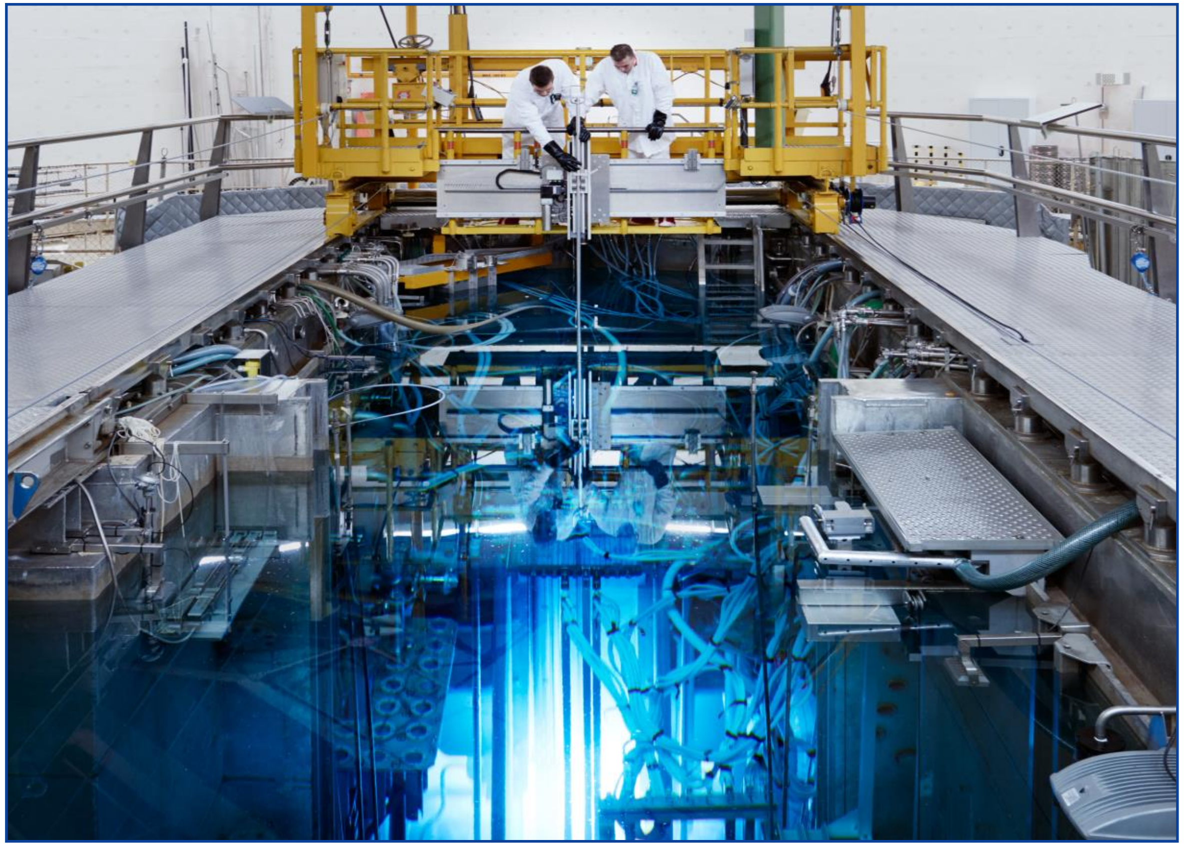
NRG (Nuclear Research and Consultancy Group)

PTS = Pressurised Thermal Shock

During overcooling events structures are under stress because of thermal gradients.

The stress is enhanced by, sometimes, re-pressurisation of the Reactor Pressure Vessel (RPV).

RPV structure can be weakened by the presence of cracks or due to radiation embrittlement.

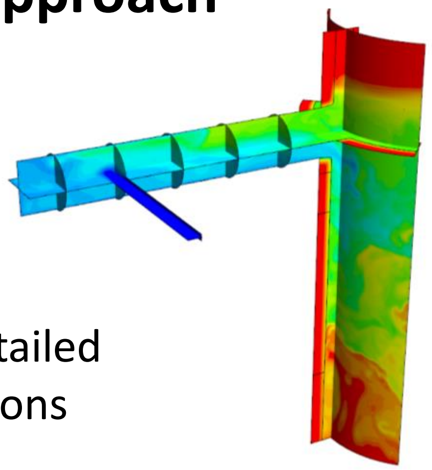


PAST

FUTURE

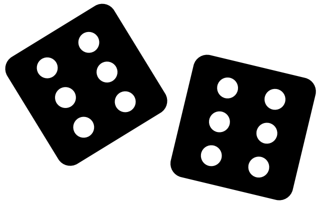
Deterministic approach

- 3D model
- Ansys models
- Complete and detailed transient simulations
- High computing power needed

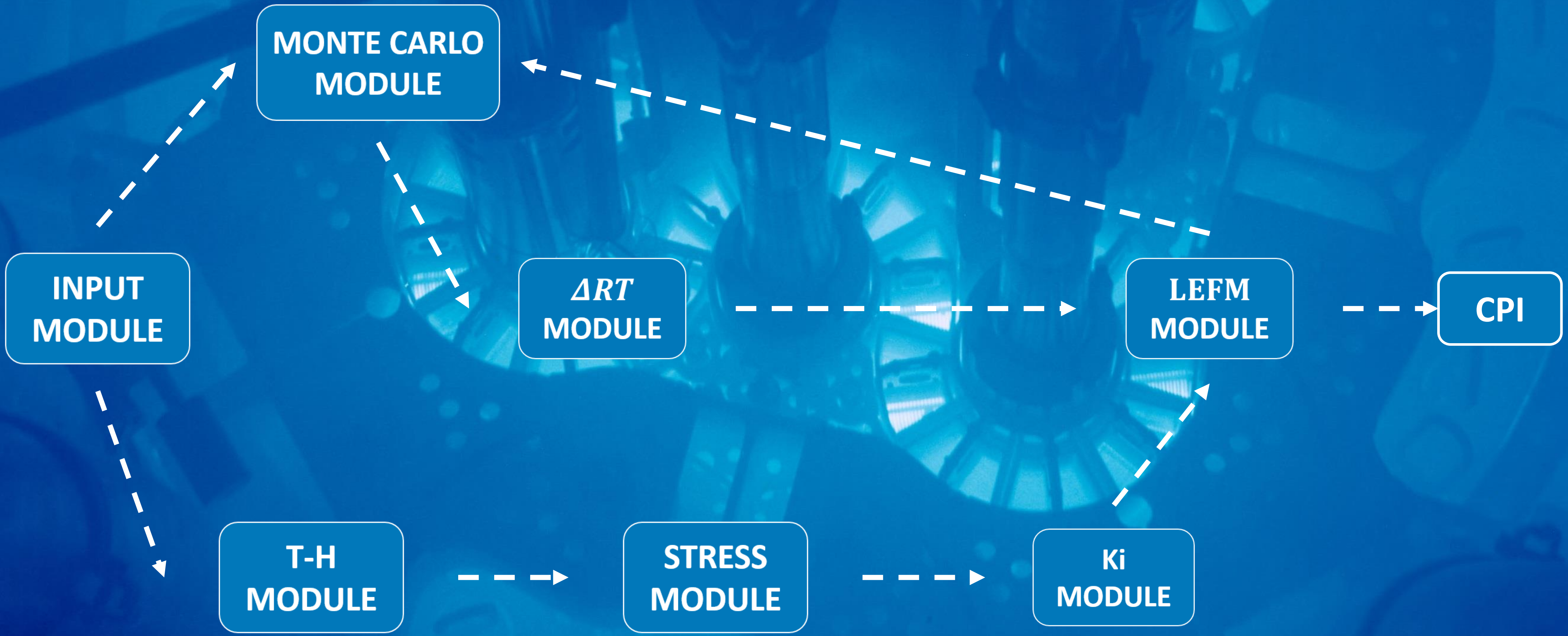


Probabilistic approach

- 1D model
- Python model
- PETO: PTS Evaluation Tool
- Easier to perform several analysis



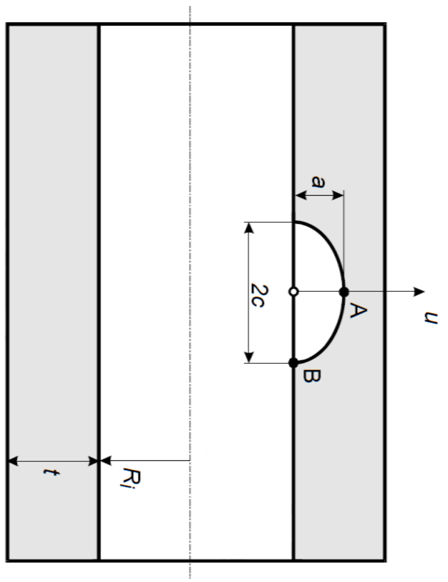
PETO

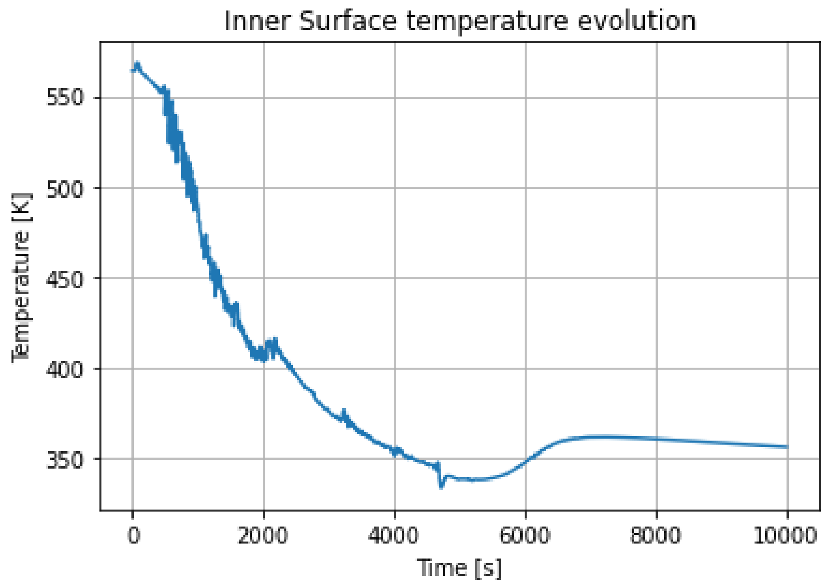

MONTE CARLO MODULE
INPUT MODULE
ΔRT MODULE
LEFM MODULE
CPI
T-H MODULE
STRESS MODULE
Ki MODULE

INPUT MODULE

- **Geometry definition**
- **Material Properties**
- **T-H transient input**
- **Crack type**
- **Chemical composition**
- **N Monte Carlo**
- **Fast Neutron flux**

APAL WP2 RELAP5 Transient



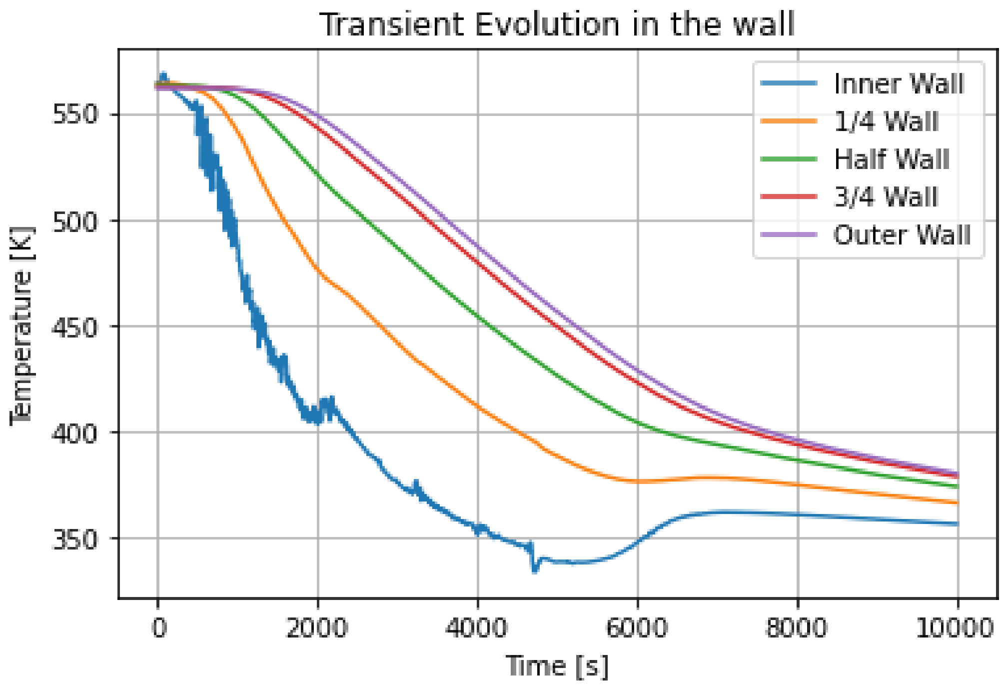


T-H MODULE

T-H Module

$$T(r_j, t_{i+1}) = \frac{\lambda \Delta t}{\Delta r^2}\left[T(r_{j+1}, t_i) + T(r_{j-1}, t_i) - 2T(r_j, t_i)\right] + \frac{\lambda \Delta t}{2 r_j \Delta r}\left[T(r_{j+1}, t_i) - T(r_{j-1}, t_i)\right] + T(r_j, t_i)$$

Fourier's Law solved with time-forward space-centred finite difference method

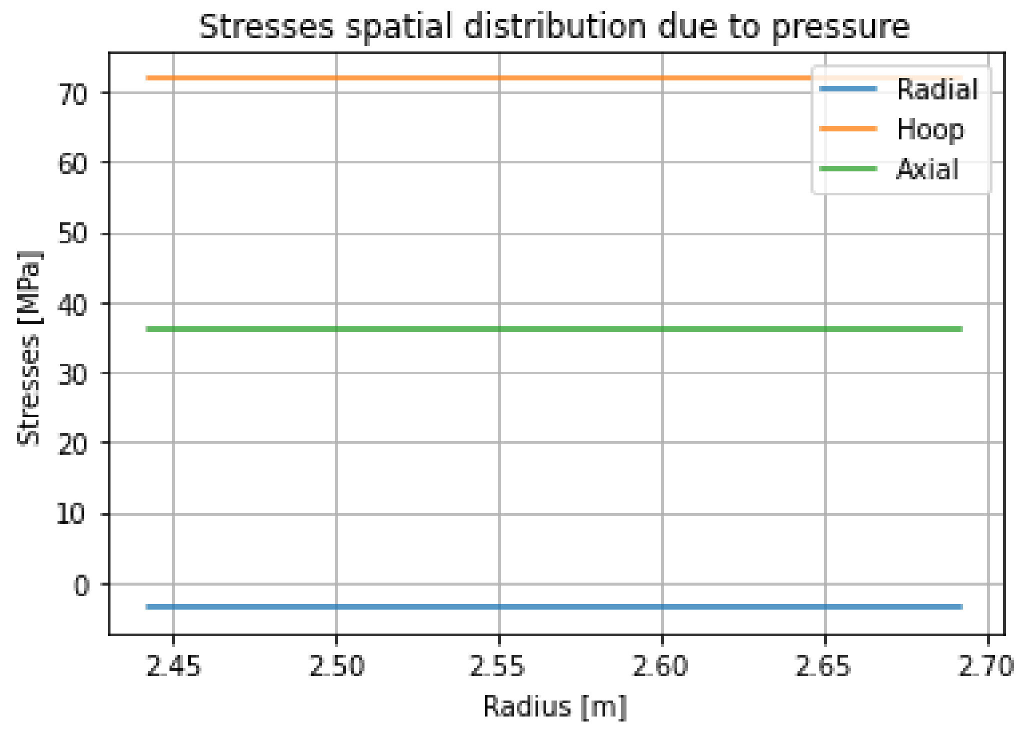


STRESS MODULE

Stress Module

- **RPV approximated as closed cylinder with hemispheric heads (Mariotte's relation)**
- **Pressure stress assumed constant during the transient**

$$\sigma_{rr} \simeq -\frac{P}{2} \qquad \sigma_{zz} = p\frac{R}{2h} \qquad \sigma_{\theta\theta} = P\frac{R}{h}$$



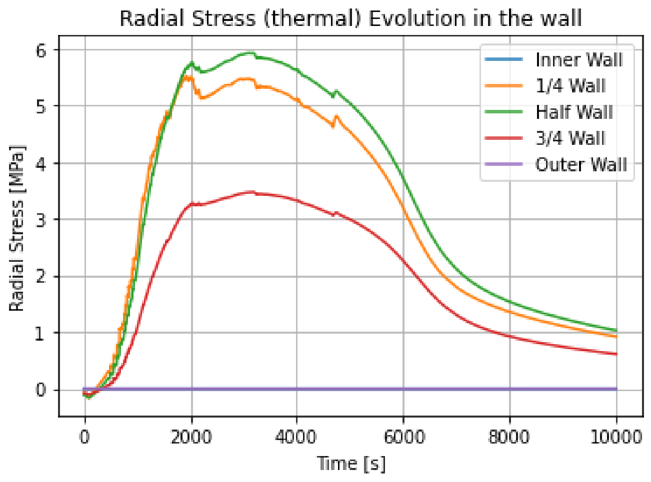
Stress Module

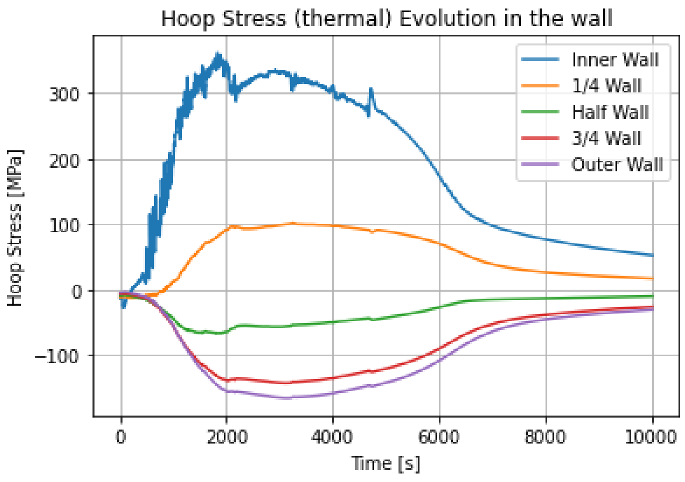
- **Plain Strain**
- **Stress components are derived by Noda et al.**

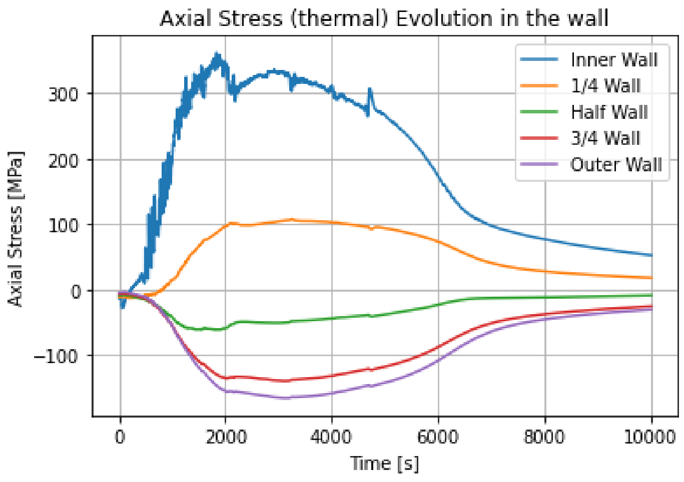
$$\sigma_{rr} = \frac{\alpha E}{1-\nu}\left[-\frac{1}{r^2}\int_a^r \tau r dr + \frac{r^2-a^2}{r^2(b^2-a^2)}\int_a^b \tau r dr\right]$$

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\nu}\left[-\frac{1}{r^2}\int_a^r \tau r dr + \frac{r^2-a^2}{r^2(b^2-a^2)}\int_a^b \tau r dr - \tau\right]$$

$$\sigma_{zz} = \frac{\alpha E}{1-\nu}\left[\frac{2\nu}{b^2-a^2}\int_a^r \tau r dr - \tau\right] \quad for \quad \epsilon_{zz} = \epsilon_0$$







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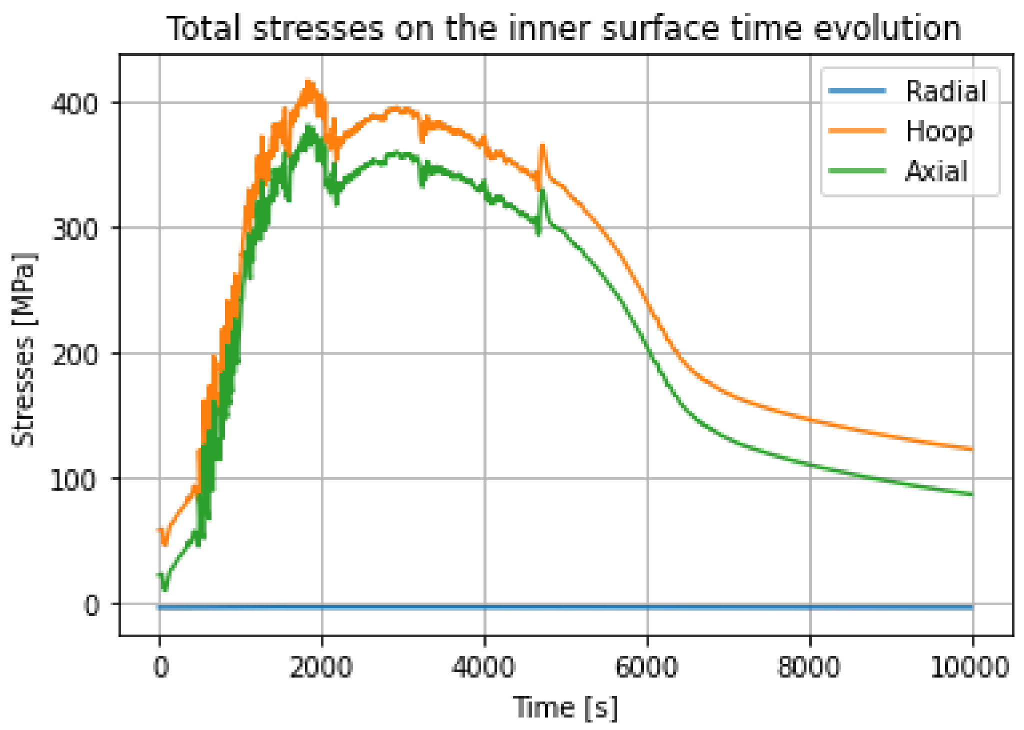


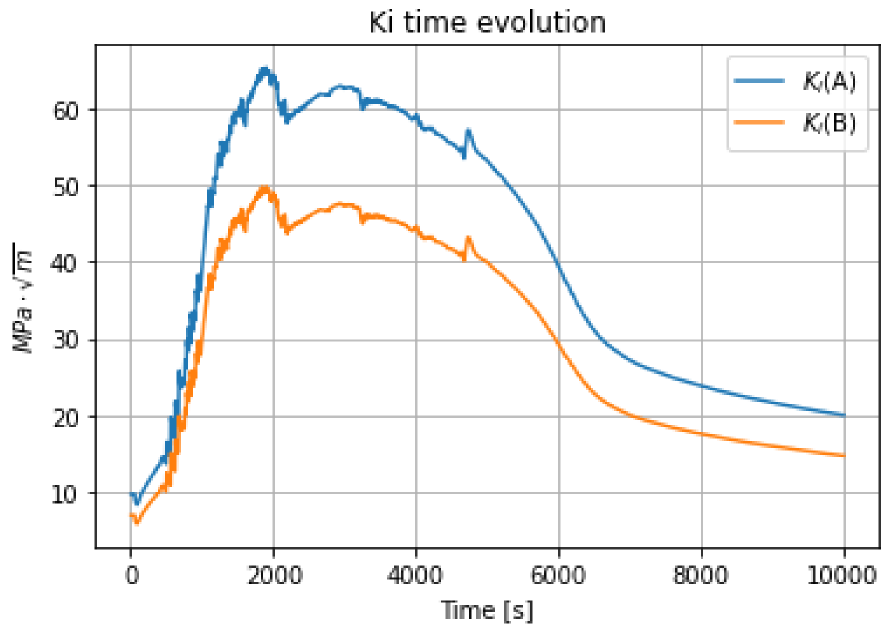
Ki MODULE

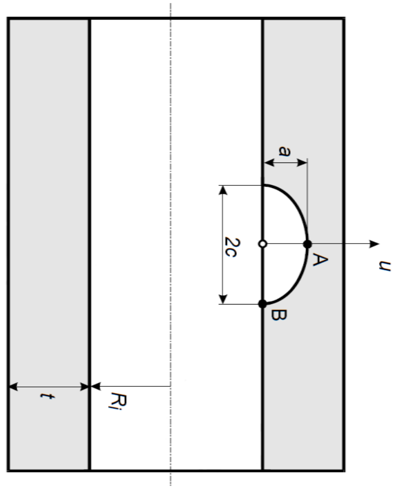
K_i Sub-Module

The intensity factor is obtained by using the relations reported on the British R6 code

$$K_i = \sqrt{\pi a} \sum_{i=0}^{3} \sigma_i f_i \left(\frac{a}{t}, \frac{2c}{a}, \frac{R_i}{t} \right)$$

$$\sigma = \sigma(u) = \sum_{i=0}^{3} \sigma_i \left(\frac{u}{a} \right)^i$$



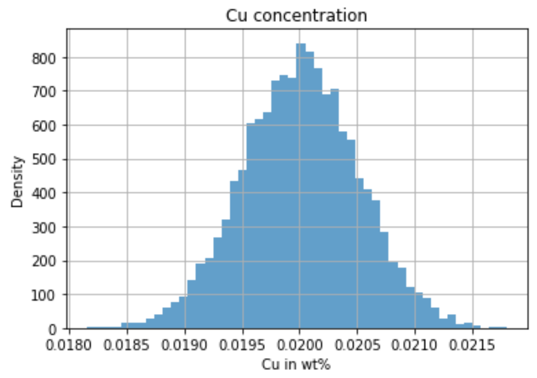


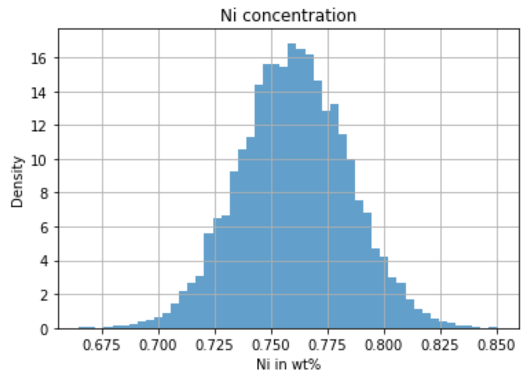
MONTE CARLO MODULE

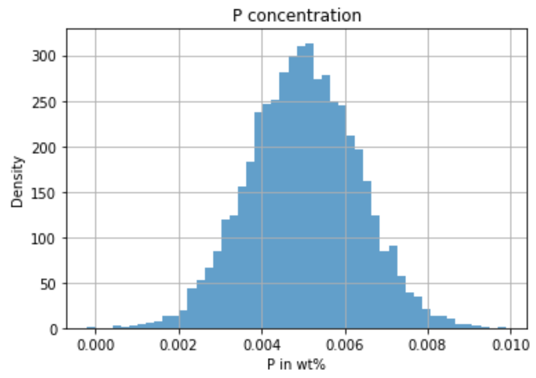
Monte Carlo Module

Material properties are randomly sampled for each Monte Carlo simulation from the material properties in the input module

chemical elements		
Copper mean	0.02	$wt\%$
Copper std	0.0005	$wt\%$
Nickel mean	0.76	$wt\%$
Nickel std	0.024	$wt\%$
Phosphorus mean	0.005	$wt\%$
Phosphorus std	0.0013	$wt\%$







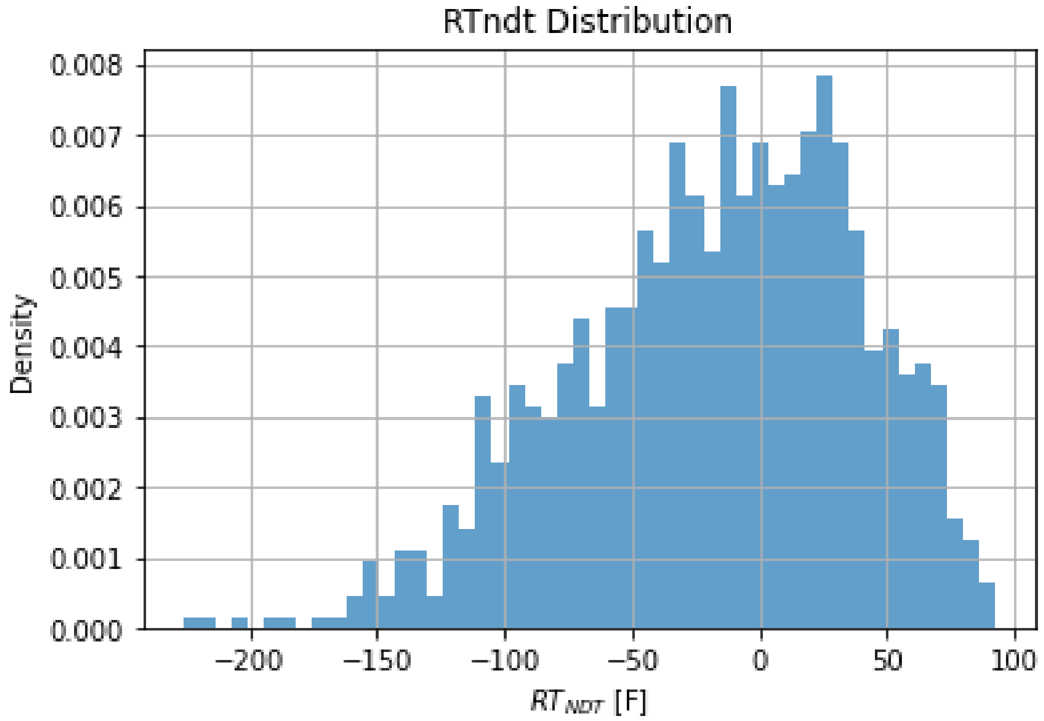
ΔRT

MODULE

ΔRT Sub-Module

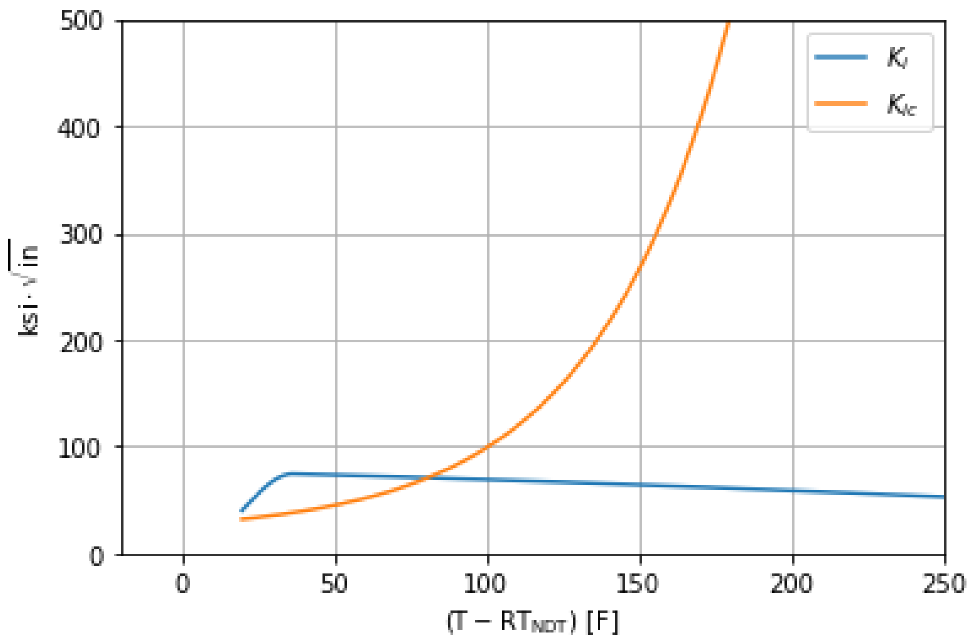
$$\tilde{RT}_{NDT} = RT_{NDT_0} - \Delta \tilde{RT}_{epistemic} + \Delta \tilde{RT}_{NDT}$$

- $\mathbf{RT_{NDT0}}$: Unirradiated Reference Temperature
- $\mathbf{\Delta RT_{NDT}}$: Reference Temperature Shift
- $\mathbf{\Delta RT_{epi}}$: Material variability uncertainties
- **Lower $\mathbf{RT_{NDT}}$ values are safer because the metal is ductile at room temperature**



LEFM
MODULE

Master curve method



Fracture-thoughness data from Charpy-V tests

Fracture-thoughness Weibull distribution as a function of $\mathbf{\Delta T_{relative}}$.

CPI: Conditional Probability of Crack Initiation

To calcualte CPI two LEFM principles are used:

- $K_i > K_{ic}$ then **CPI>0**.
- $\frac{K_i}{dt}$ **< 0, then CPI = 0**

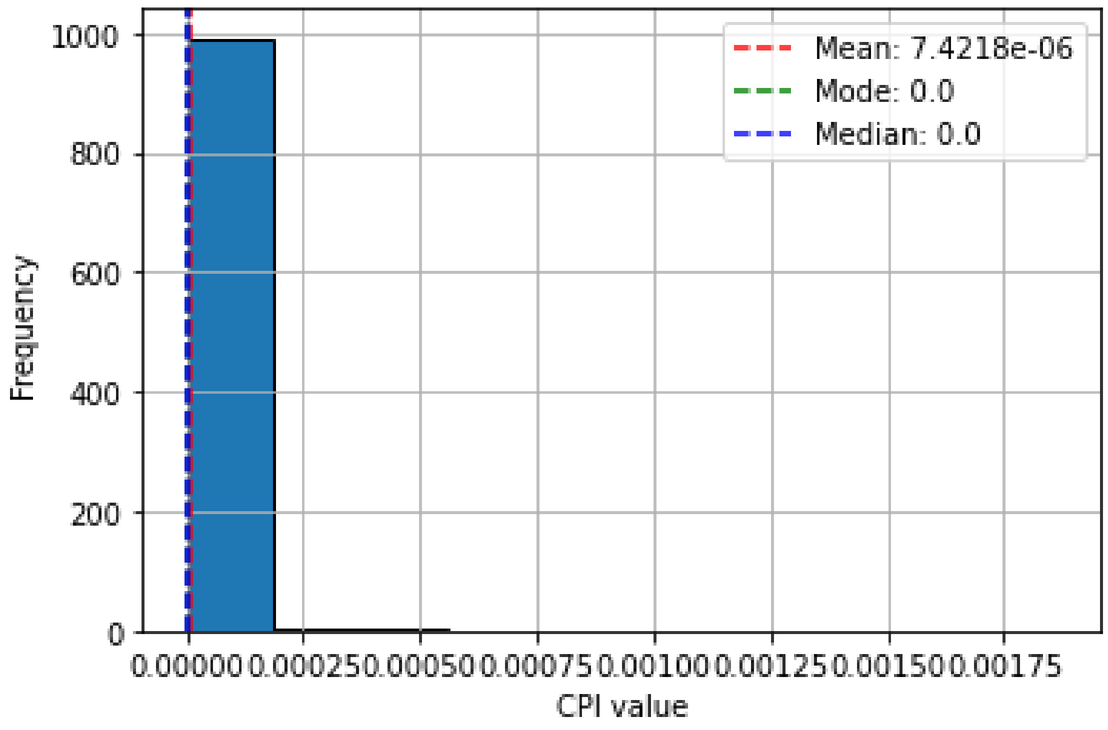
LEFM Module

PALLAS NRG

The highest value **CPI** value obtaiend during each simualtion is extracted and stored

All the **CPI** values stored are then used to get the mean value as final result

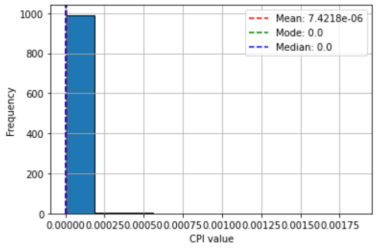
NRC RG1.154 set a first PTS acceptable failure risk less than $\mathbf{5 \cdot 10^{-6}}$ **vessel/year**



Conclusions

INPUT MODULE

PETO CODE



Future Developments

- **Implement crack propagation model**
- **Improve material properties**
- **Differentiate Ki calcualtion methods**
- **Validation with CFD software**
- **Improve the embrittlement model**
- **Embed PETO with Ansys**

Conclusions

Thank you for your attention.