INL/MIS-23-75661

December 2023

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Analysis of SiC ATF Reliability in Accident Conditions

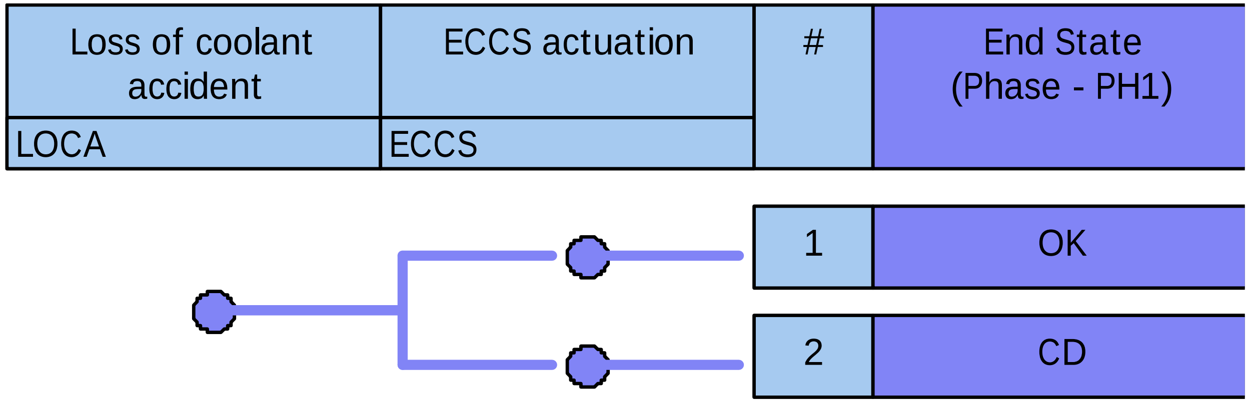
Idaho National Laboratory

Background

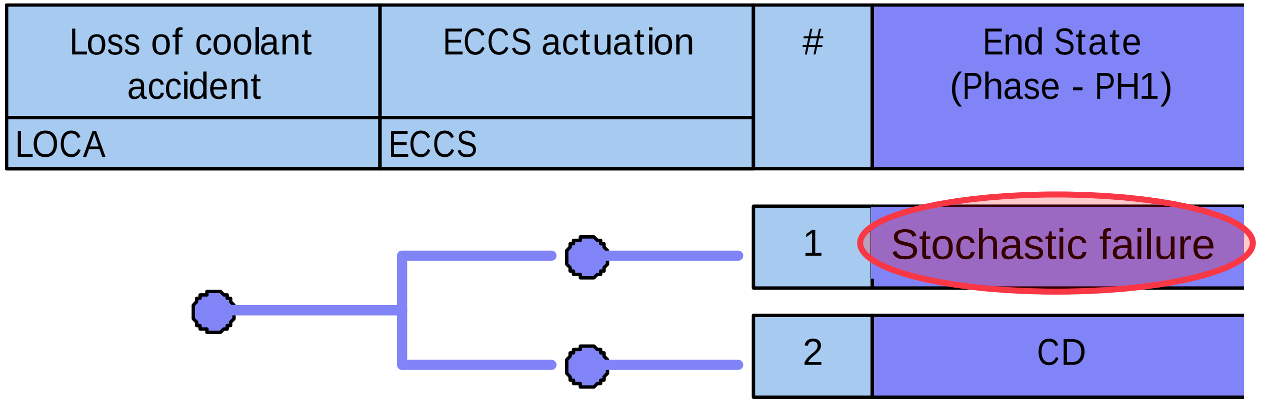
- Draft rule 10 CFR 50.46c
  - Emergency Core Cooling System (ECCS) criteria for LWR reactor
  - Any fuel or cladding

- Design ECCS performance criteria for SiC clad

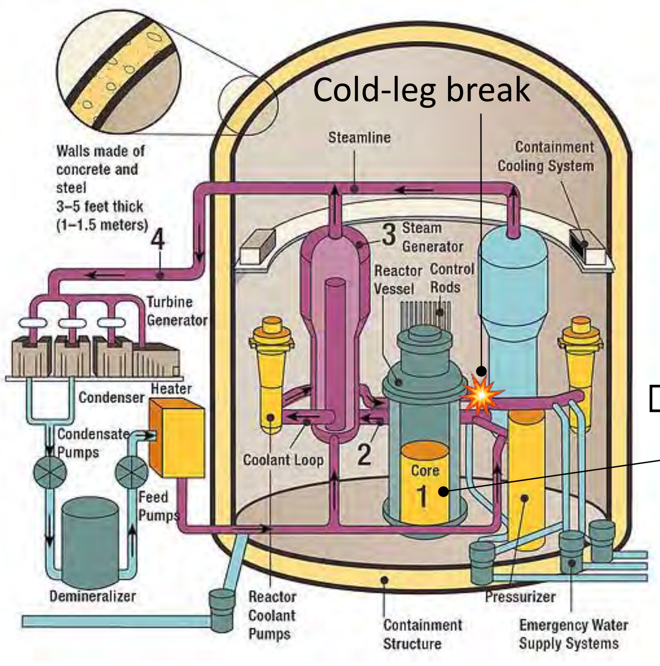
Zr cladding



SiC/SiC composite cladding

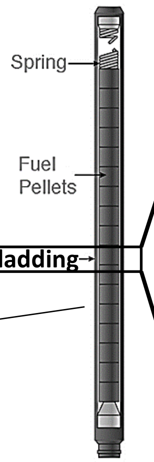


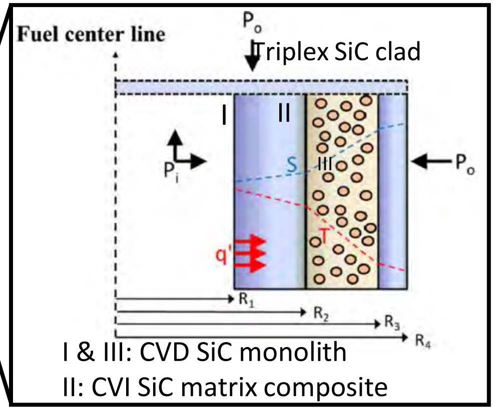
Clad Reliability in LOCA Accidents



PWR 1000 MWe model
2 Primary loops @ 2 ECCS systems
ECCS @ 1 passive tank & 1 active HP & LP systems

Fuel rod





Triplex SiC cladding

Fuel performance code (MATLAB)
High-fidelity fuel model

- Initial condition: P(0), T(0)
- P(t), T(t)
- Thermomechanical stresses
- Clad fracture probability

Plant model (RELAP5) of PWR
1000 MWe
Low-fidelity fuel model

- Steady-state parameters
- Transient parameters (Primary cold-leg LBLOCA)

* PWR sketch from U.S. NRC, https://www.nrc.gov/reactors/pwrs.html

Code Validation

- Steady-state

$$-\frac{1}{r}\frac{d}{dr}\left(k_{eff}\, r\frac{dT}{dr}\right) = 0$$

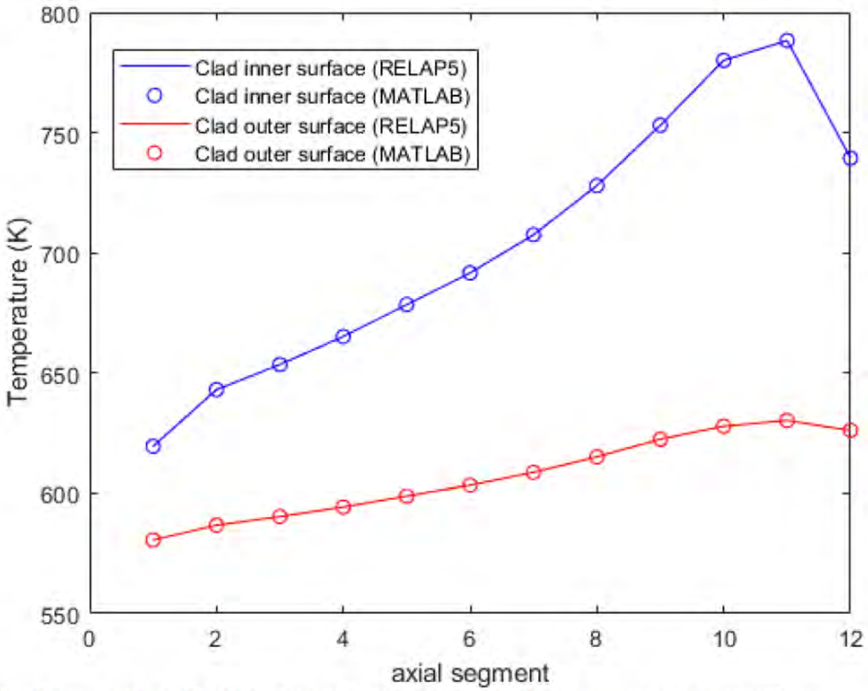


Figure 3.7. Validation of steady-state heat transfer equations

- Transient

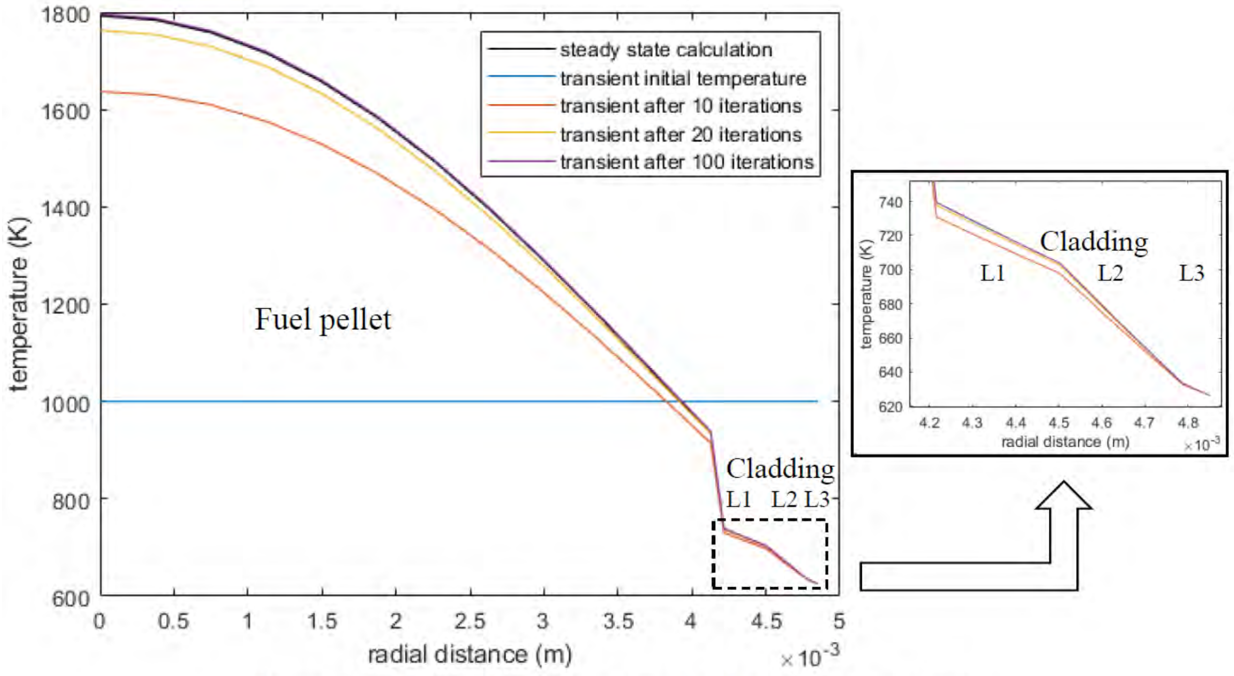
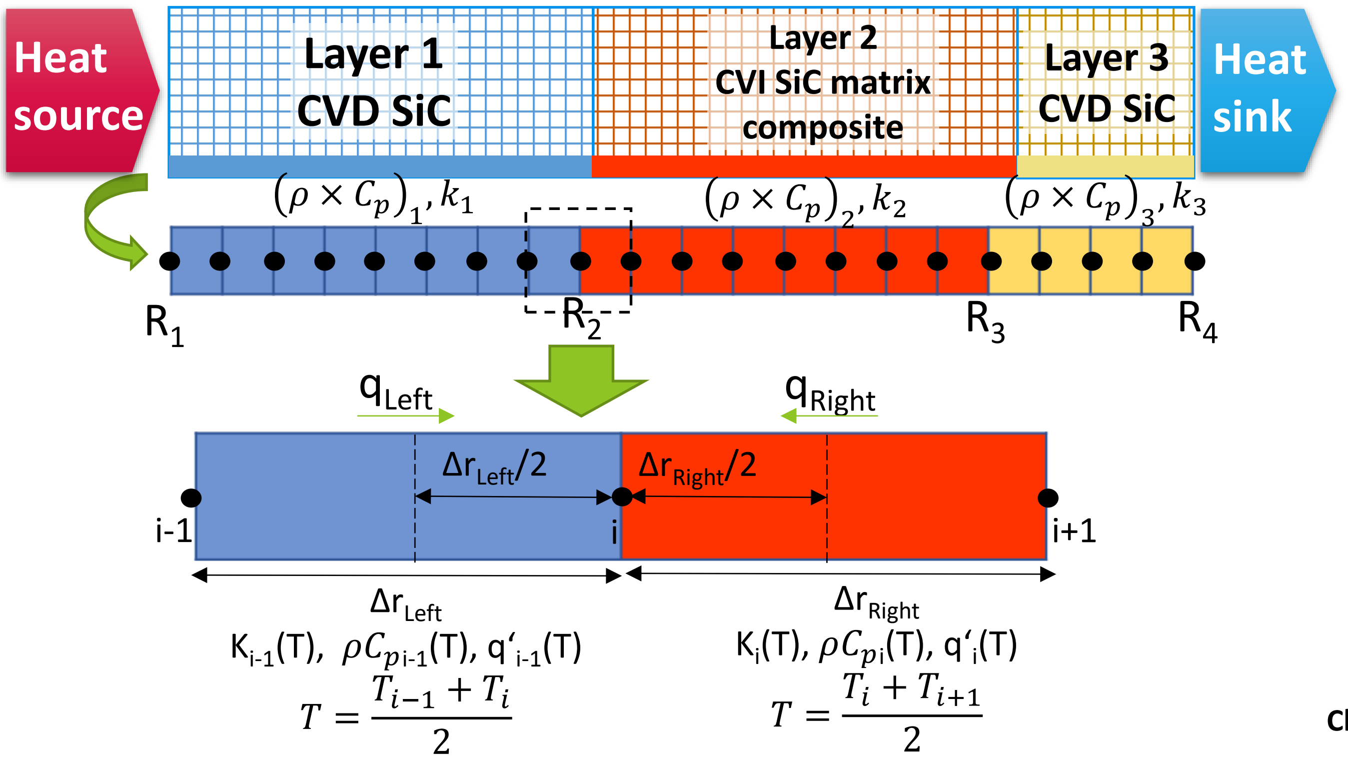


Figure 3.8. Validation of transient heat transfer equations

Cladding Temperature

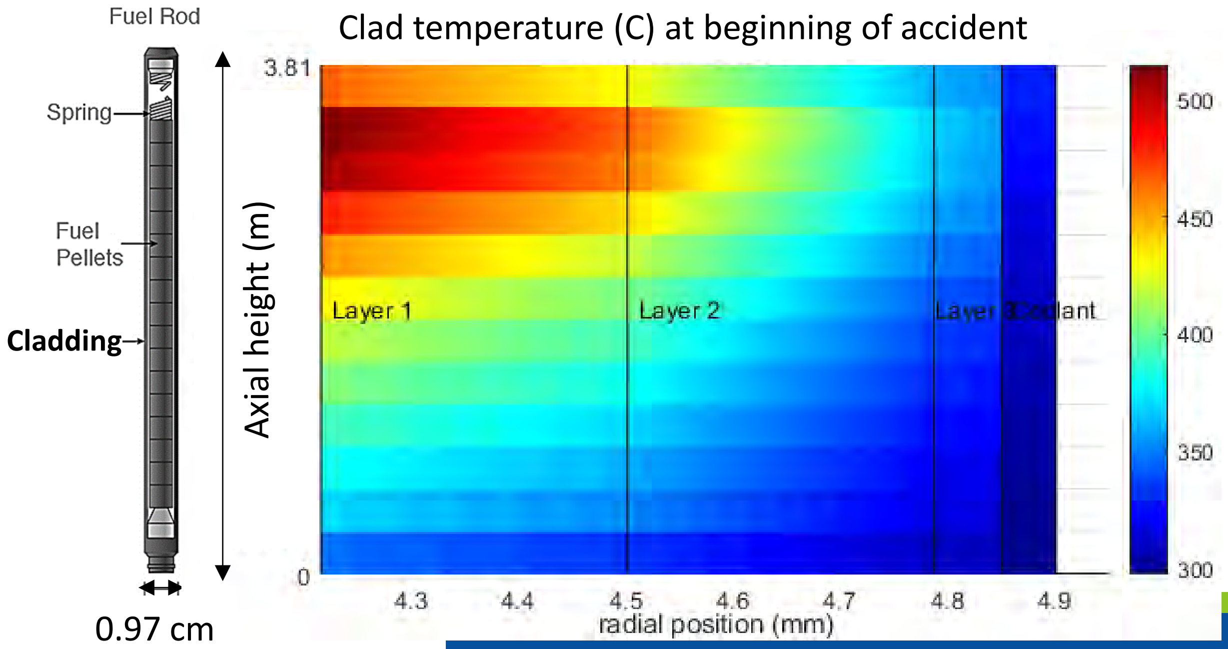
- Spatial mesh for triplex clad model:



- Substitutive parameters for single-layered clad model:

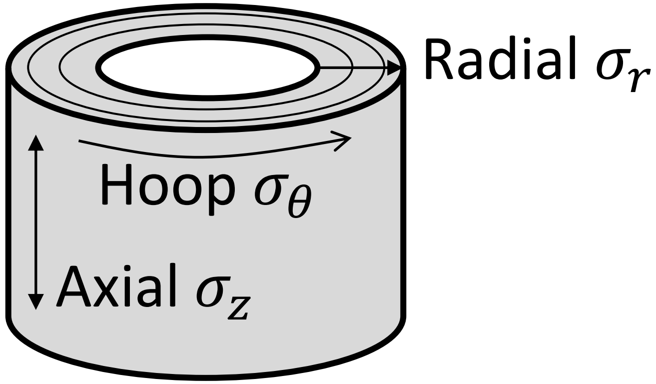
$$k_{eff} = \frac{\ln \frac{R_4}{R_1}}{\sum_{i=1}^{3} \frac{ln\left(\frac{R_{i+1}}{R_i}\right)}{k_i}} \qquad \left(\rho C_p\right)_{eff} = \frac{\sum_{i=1}^{3} \left(\rho C_p\right)_i \left(R_{i+1}^2 - R_i^2\right)}{R_4^2 - R_1^2}$$

- Boundary conditions from **RELAP5**:
  - Heat source: Linear heat generation rate history q'(t)
  - Heat sink: Pressure P, T_{liquid}, T_{gas}, Void fraction, $h_{convection}$

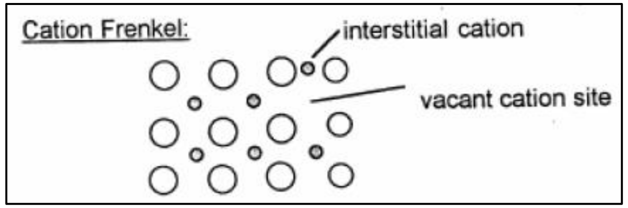


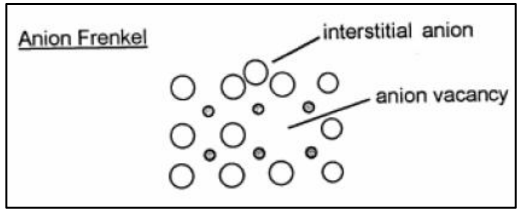
Cladding Stresses

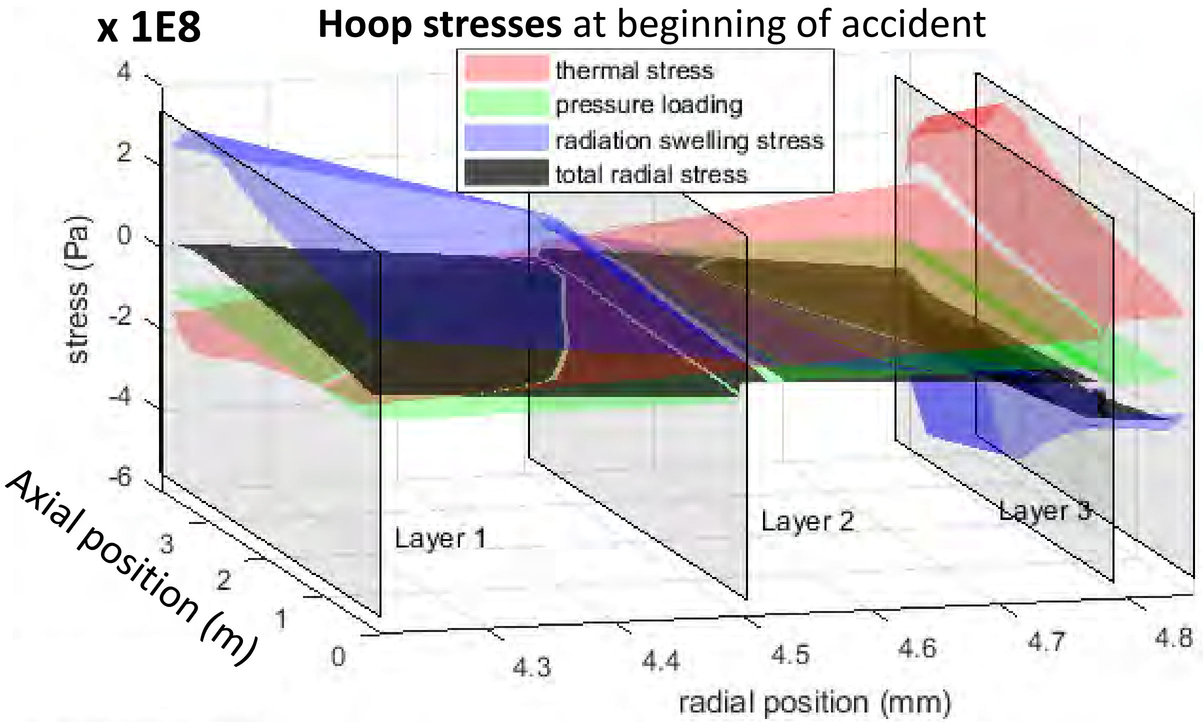
- 3 stress directions:

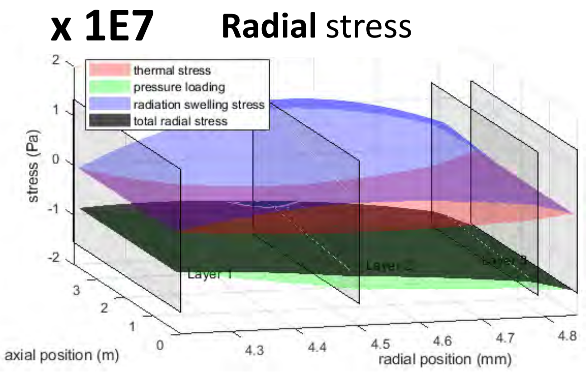


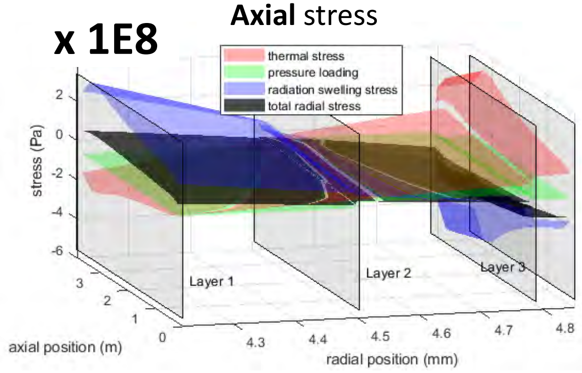
- 3 stress components:
  - **Thermal** expansion (T)
  - **Mechanical** pressure loading (P)
  - **Irradiation** swelling (T) → Conservative assumption: no annealing
- Equations in Appendix slides





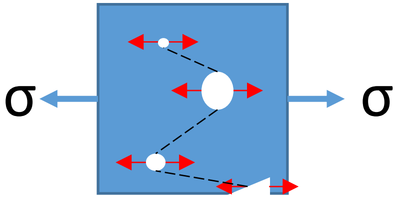






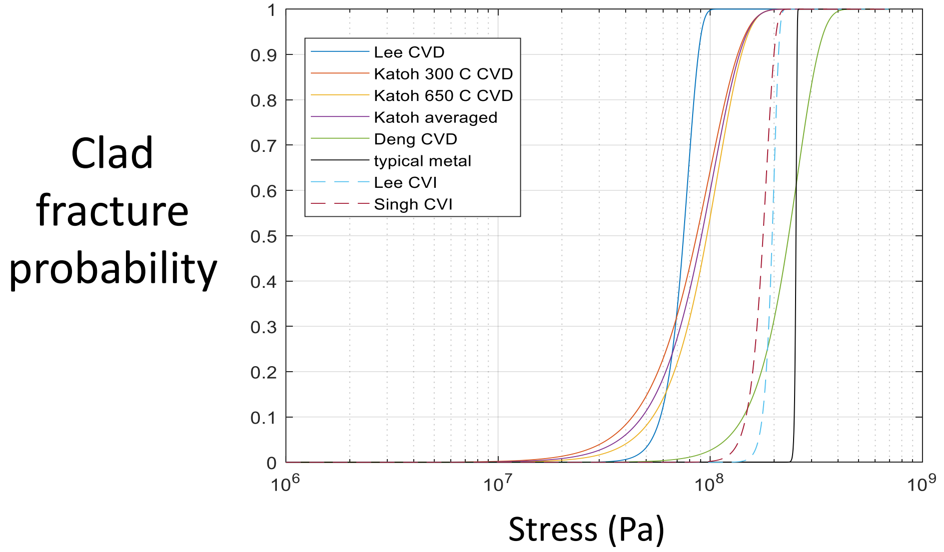
SiC Clad Failure

- Brittle fracture



- Weibull reliability function:

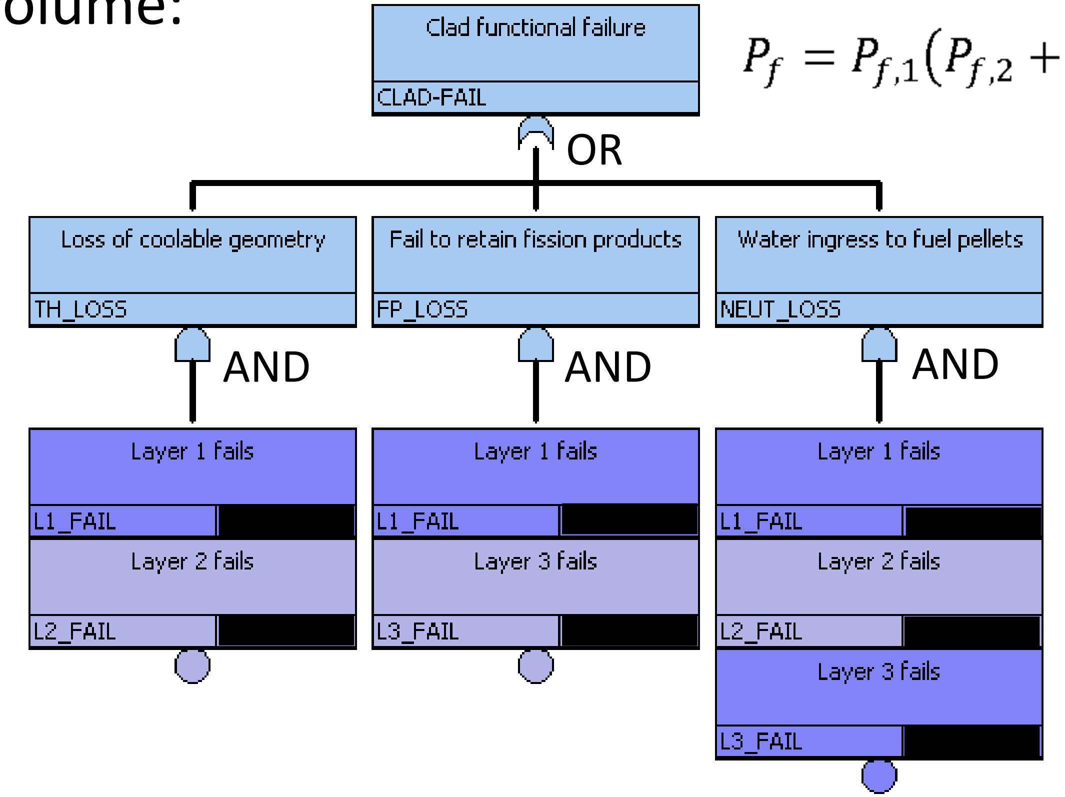
$$P_s(V) = \exp\left[-\frac{1}{V_0}\int_V \left(\frac{\sigma_r(\vec{r})}{\sigma_0}\right)^m + \left(\frac{\sigma_\theta(\vec{r})}{\sigma_0}\right)^m + \left(\frac{\sigma_z(\vec{r})}{\sigma_0}\right)^m dV\right]$$



- Time-dependent fracture probability:

$$P_f | 0 \le t \le t_1 = P_f\left(\max\left(\sigma_{(t)} | 0 \le t \le t_1\right)\right)$$

- Clad functional failure at each axial unit volume:



$$P_f = P_{f,1}\left(P_{f,2} + P_{f,3}\right)$$

- Clad fails if any axial unit-volume fails:

$$P\left(\bigcup_{i=1}^{n_z} A_i\right) = 1 - P\left(\bigcap_{i=1}^{n_z} A_i\right) = 1 - \prod_{i=1}^{n_z}(1 - A_i)$$

Multi-Layered SiC Cladding

Triplex Clad	Inner: CVD-SiC Monolith	Middle: CVI SiC Composite Matrix	Outer: CVD SiC Monolithic
Properties	Solid & brittle	Porous & pseudo-ductile	Solid & brittle
Function	Fission gas retention and load sharing	Primary load-bearing structure and catastrophic shatter prevention	SiC fiber separation from H_2O
Failure mode	A fast fracture without a sign of plasticity	Quasi-ductile failure and carbon fiber degradation by H_2O	Fast fracture and high-temperature steam oxidation
Failure Effect	**Status**		
Fail to retain fission products	Fail		Fail
Fail to maintain coolable geometry	Fail	Fail	
Water ingress to fuel pellets	Fail	Fail	Fail

Duplex Clad	Inner: CVI SiC Composite Matrix	Outer: CVD SiC Monolithic
Function	Primary load-bearing structure and catastrophic shatter prevention	SiC fiber separation from H_2O
Failure Effect	**Status**	
Fail to retain fission products		Fail
Fail to maintain coolable geometry	Fail	Fail
Water ingress to fuel pellets	Fail	Fail

Reference LBLOCA Scenario

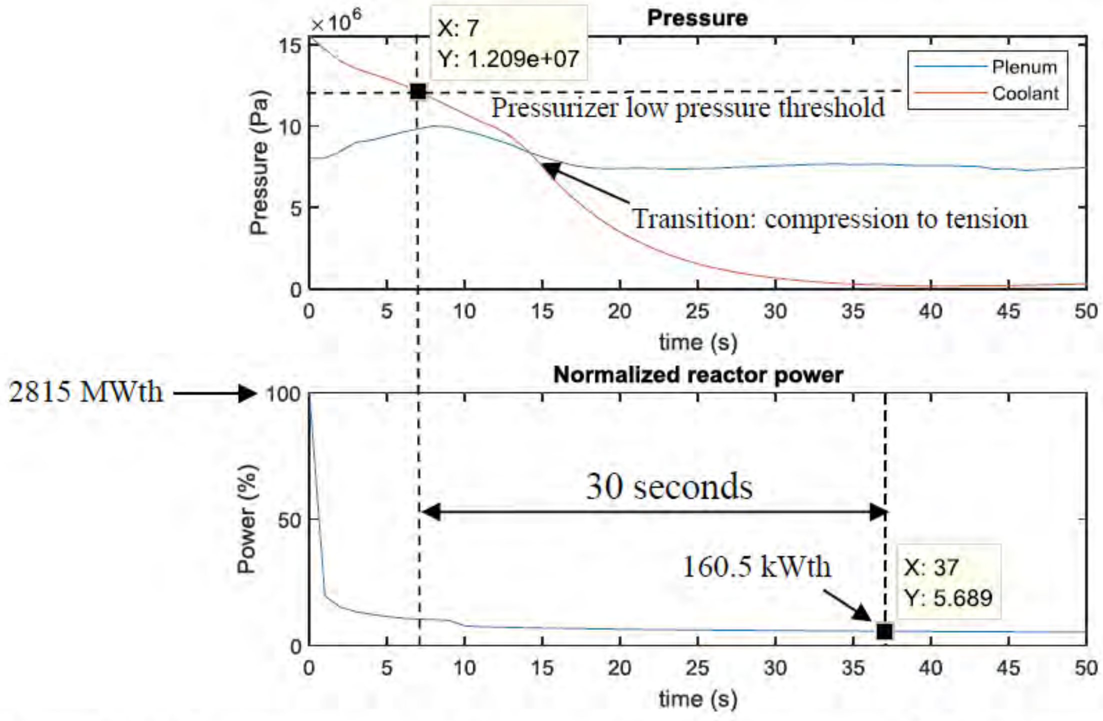


Figure 3.19. Reactor power and pressure during reference LBLOCA scenario

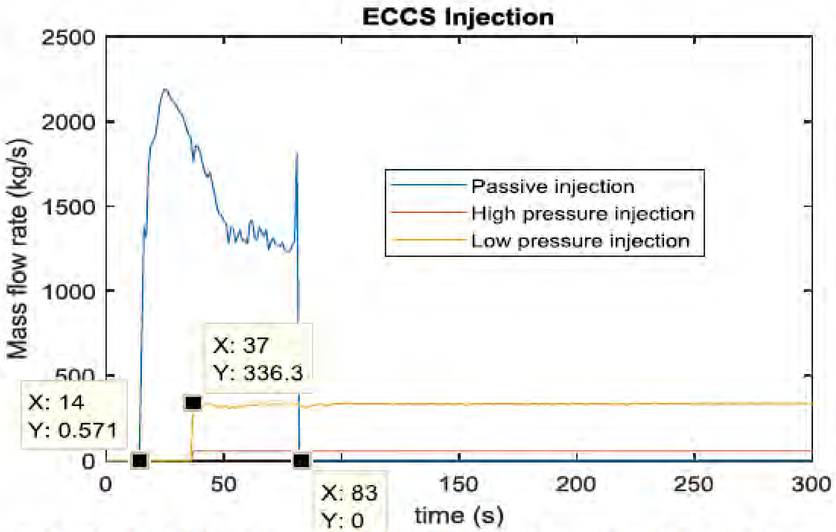


Figure 3.20. ECCS injection in the reference LBLOCA scenario

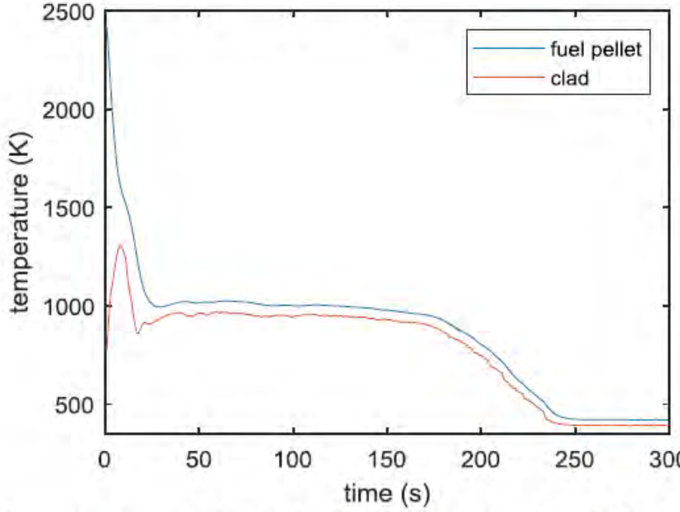
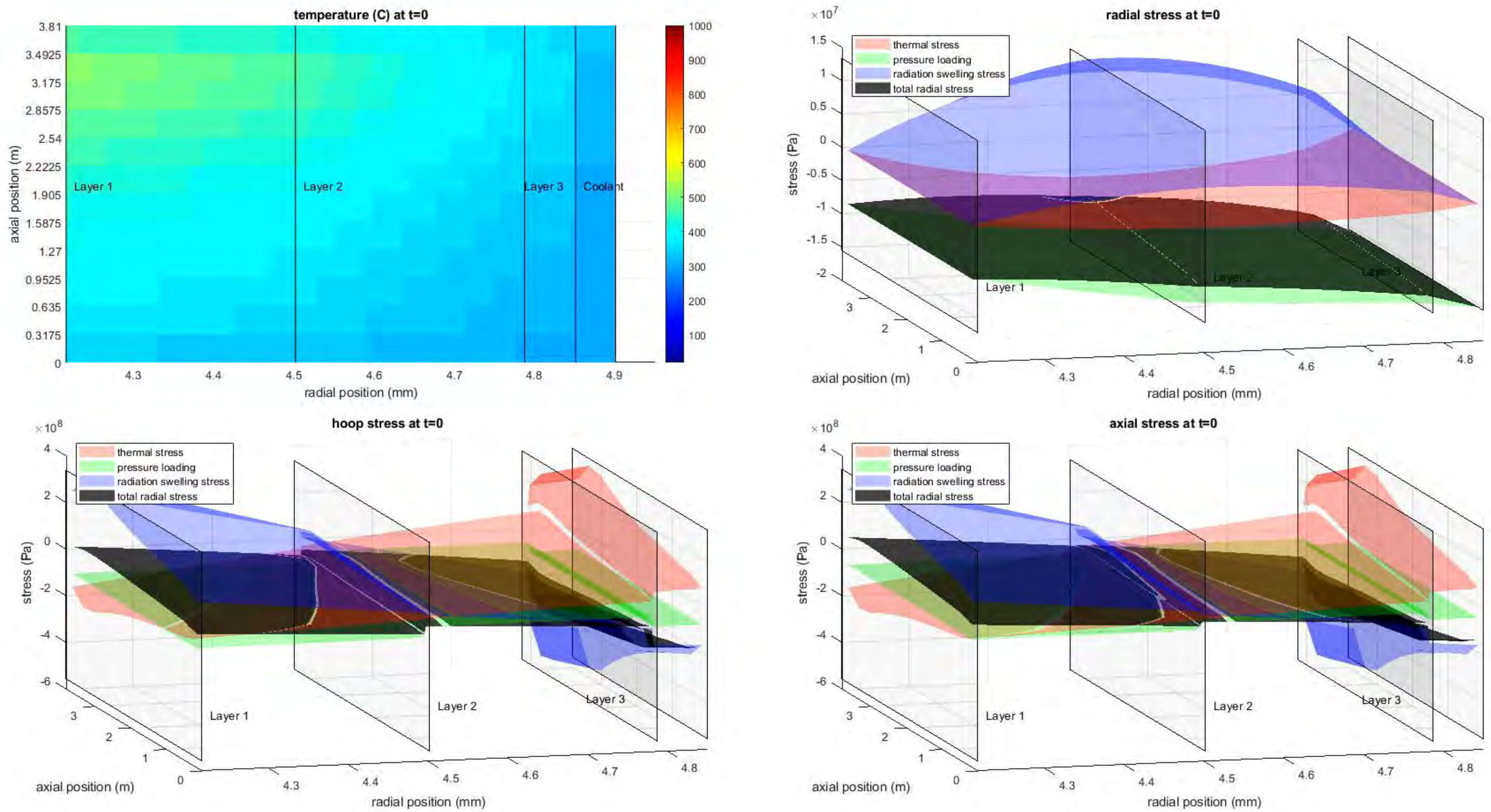
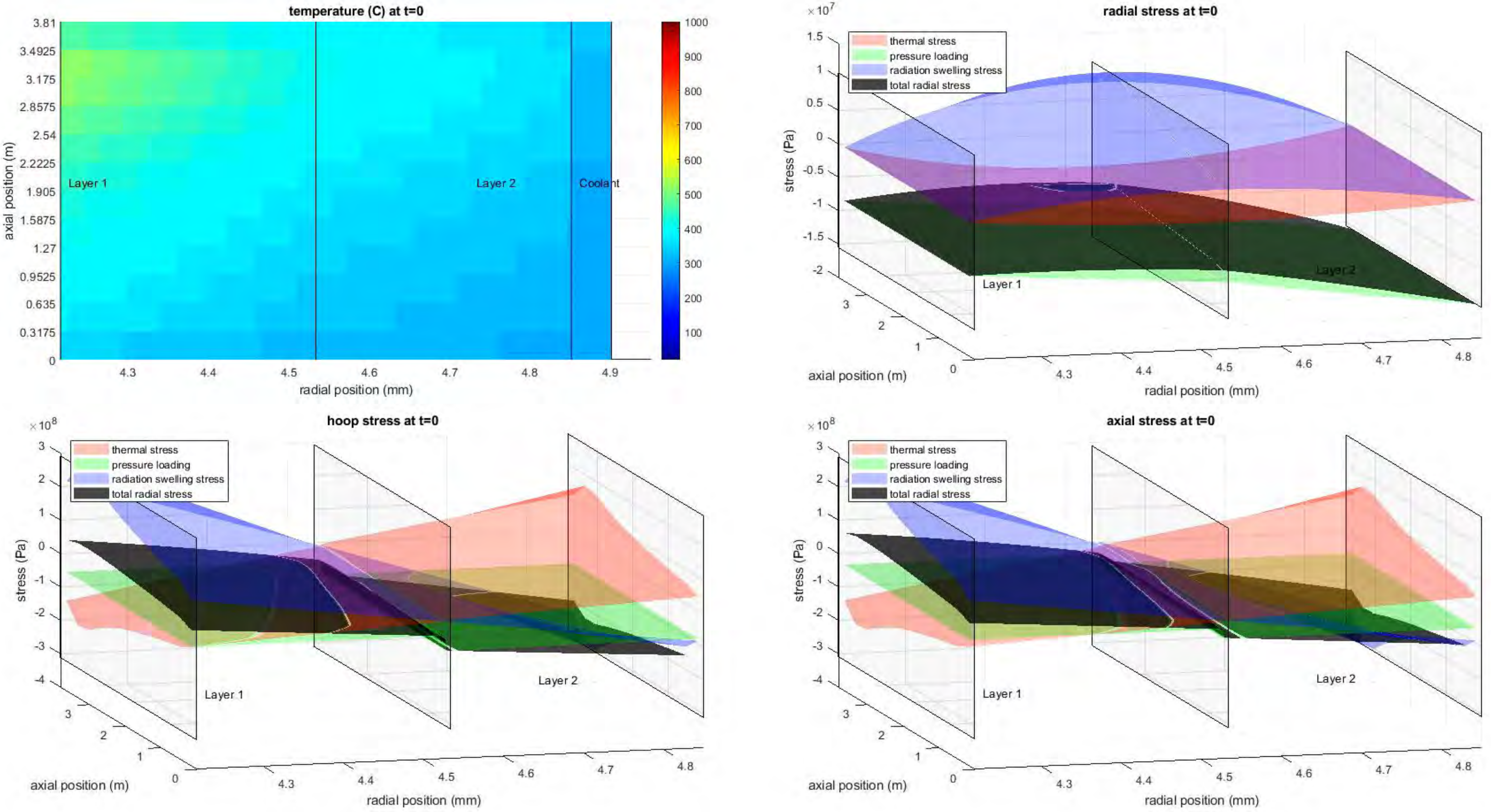


Figure 3.23. Maximum temperatures in the hottest fuel rod during LBLOCA scenario

Triplex SiC parameters in Reference LBLOCA scenario

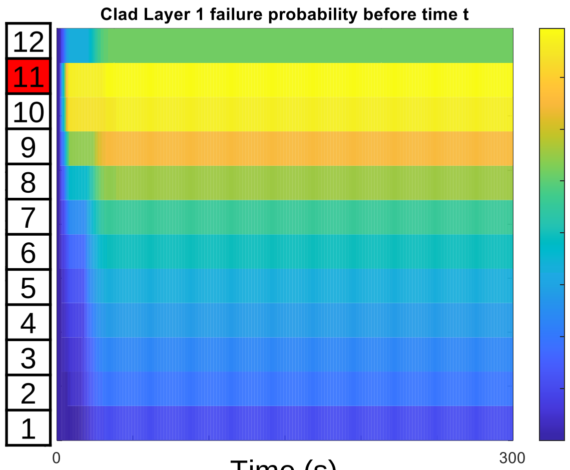


Duplex SiC parameters in Reference LBLOCA scenario

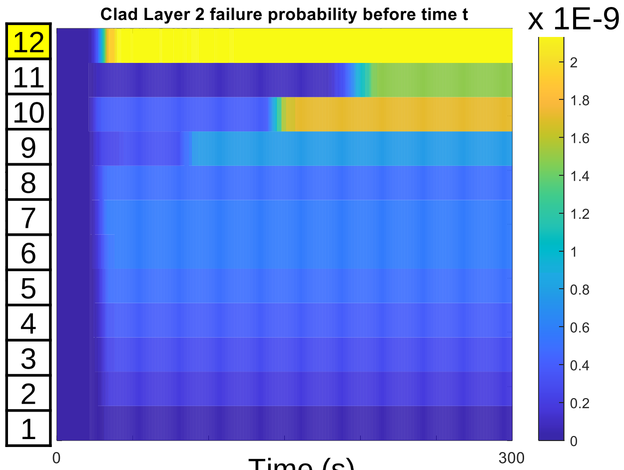


Clad Failure Probability

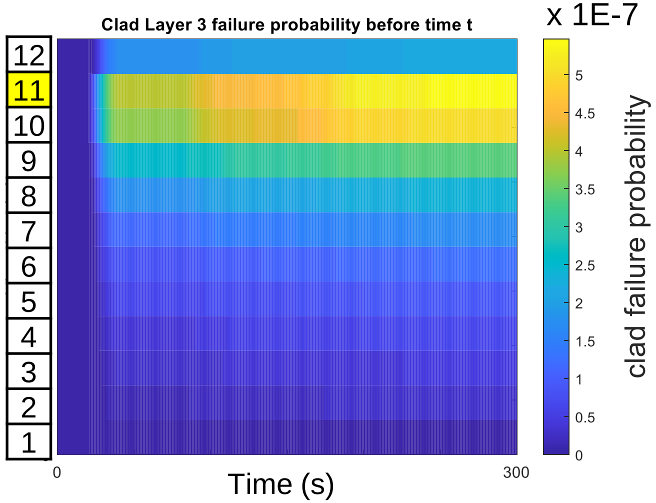
Triplex



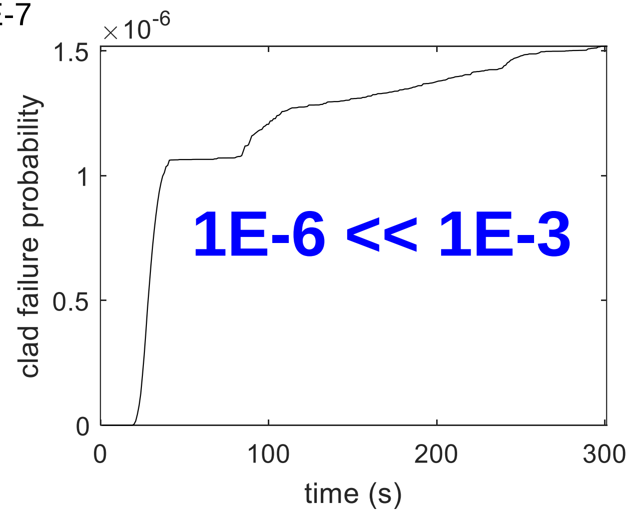
(a) Layer 1 failure probability



(b) Layer 2 failure probability

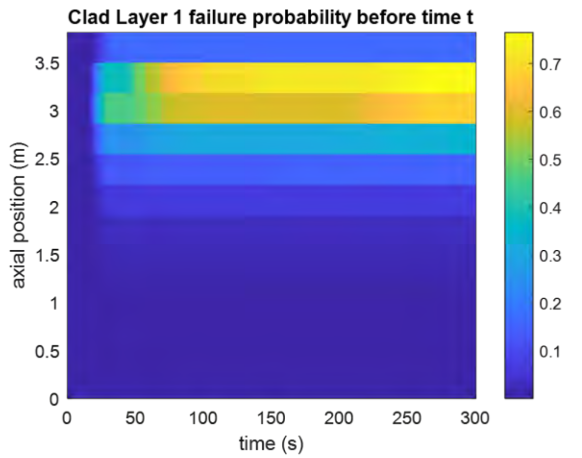


(c) Layer 3 failure probability

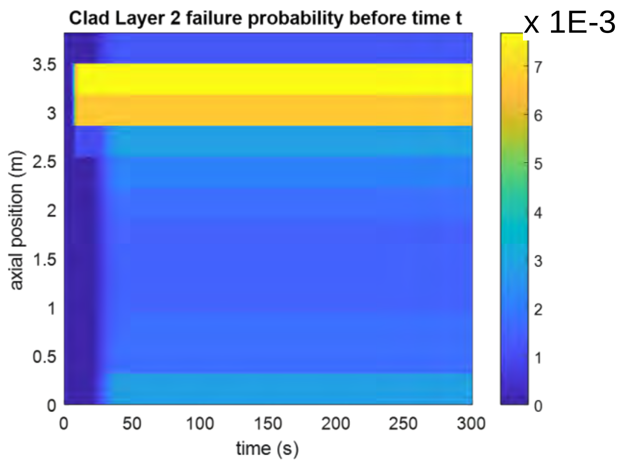


(d) Clad functional failure probability

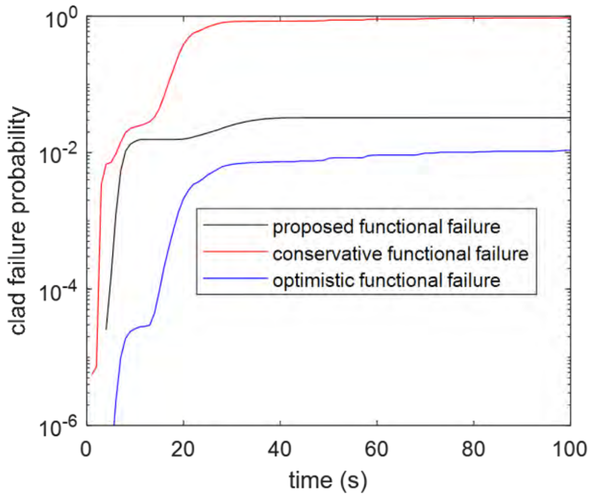
Duplex



(a) Layer 1 (matrix composite) failure probability



(b) Layer 2 (CVD mSiC) failure probability

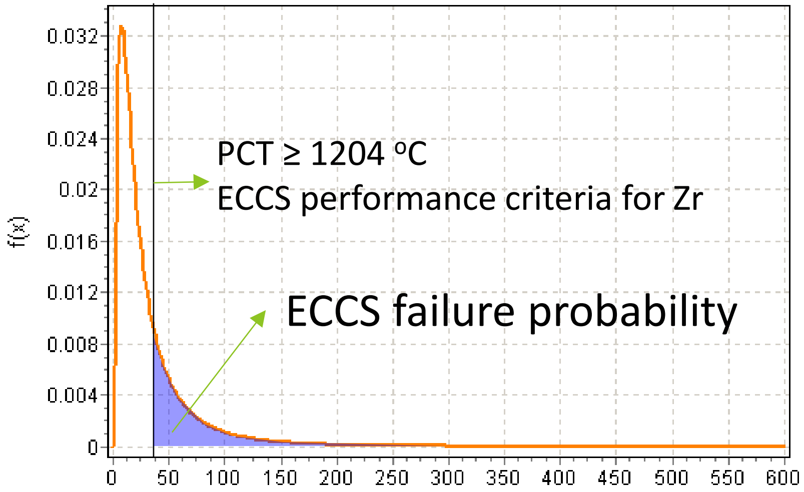


(c) Duplex SiC clad functional failure probability

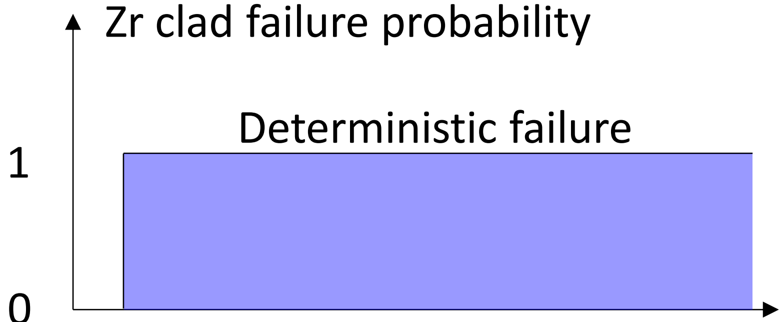
Objective Statement

UO2-Zr system

ECCS actuation probability distribution



ECCS actuation timing (s)



$$P_{CD-SiC} = \int_{t=0}^{\sim} P_{ECCS} \times P_{clad}$$

Optimize ECCS criteria for SiC:

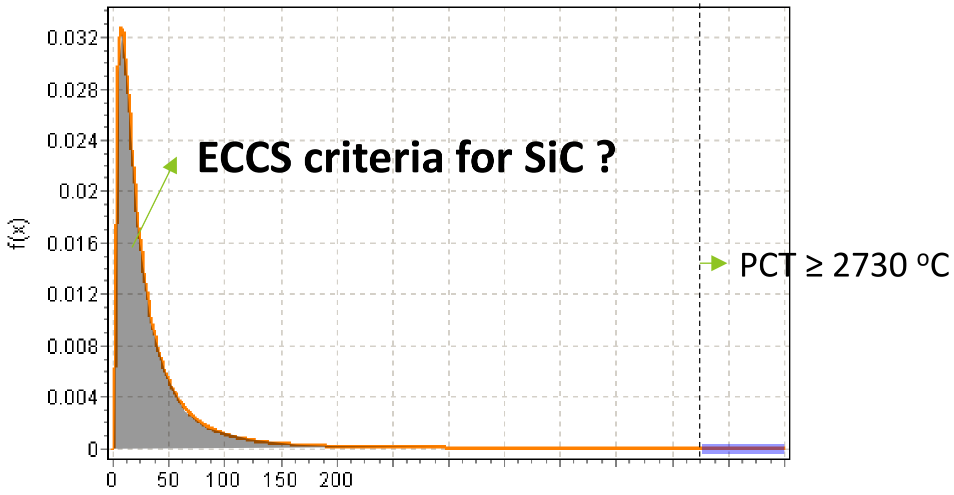
$$\mathbf{P_{ECCS} \mid P_{CD\text{-}SiC} < P_{CD\text{-}Zr}}$$

Cumbersome to simulate many scenarios

Use **surrogate model** for time-efficiency

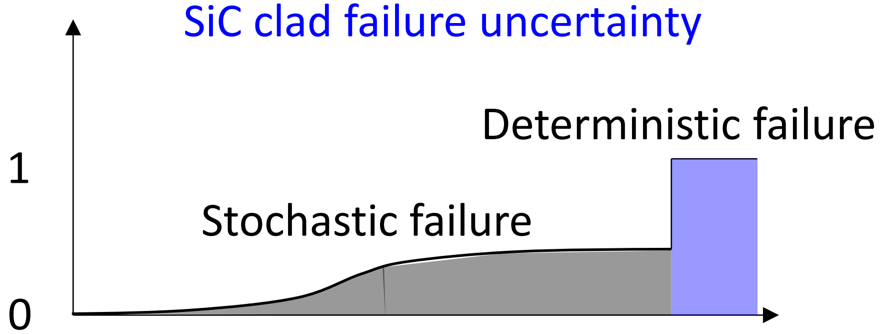
UO2-SiC system

ECCS performance uncertainty

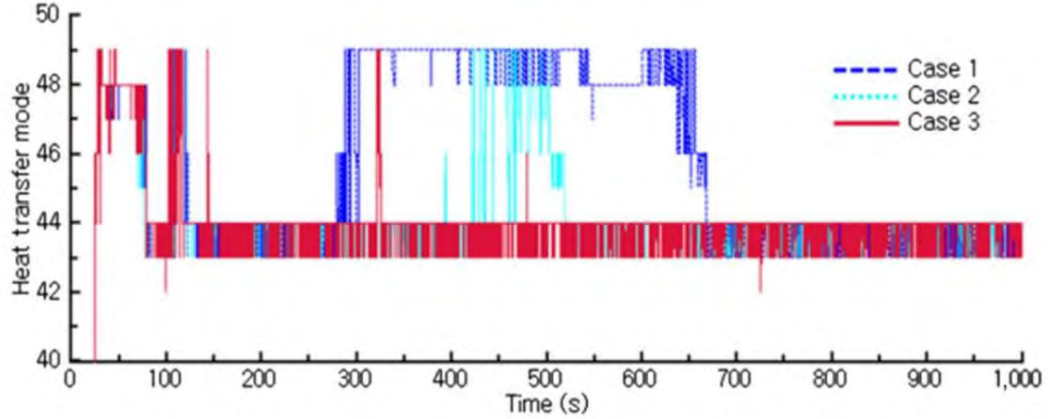


ECCS actuation timing (s)

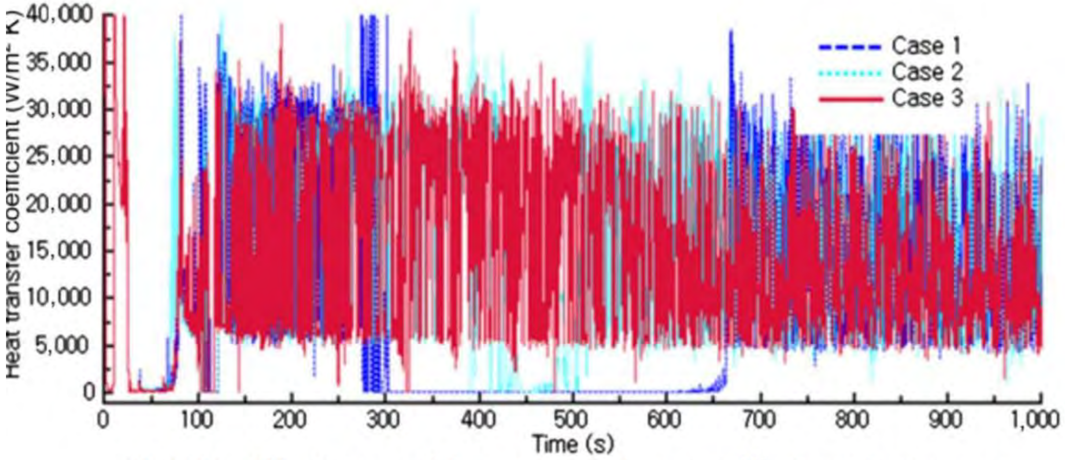
SiC clad failure uncertainty



RELAP5 Uncertainties



(a) Discrete modes of heat transfer between clad and coolant in accident scenarios



(b) Oscillations of heat transfer coefficient between clad and coolant in accident scenarios

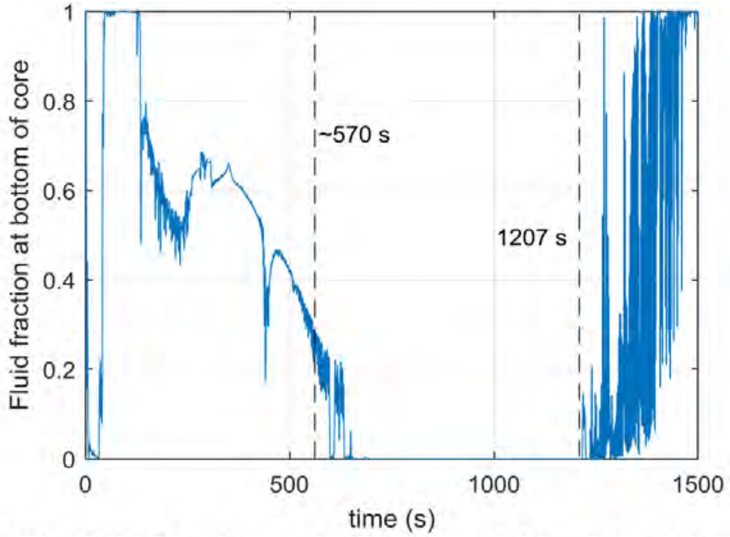
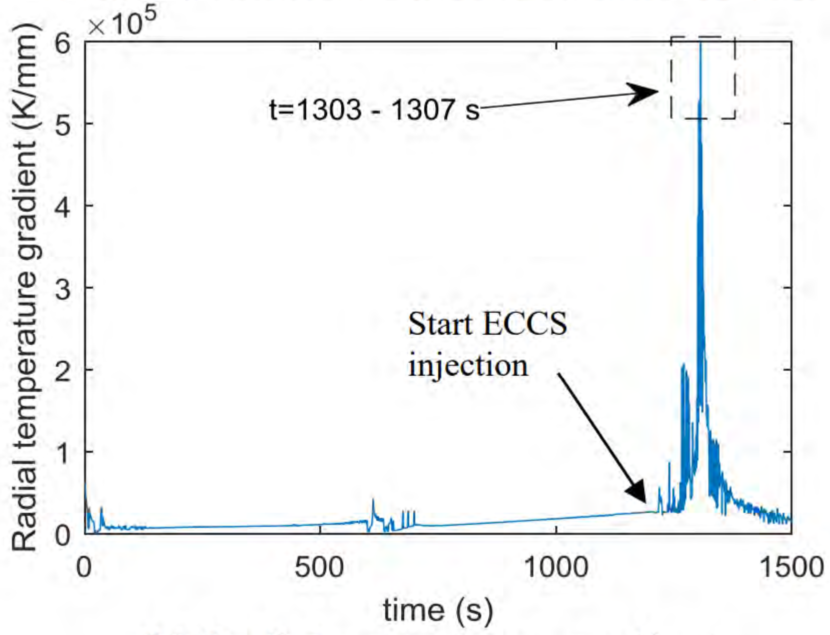


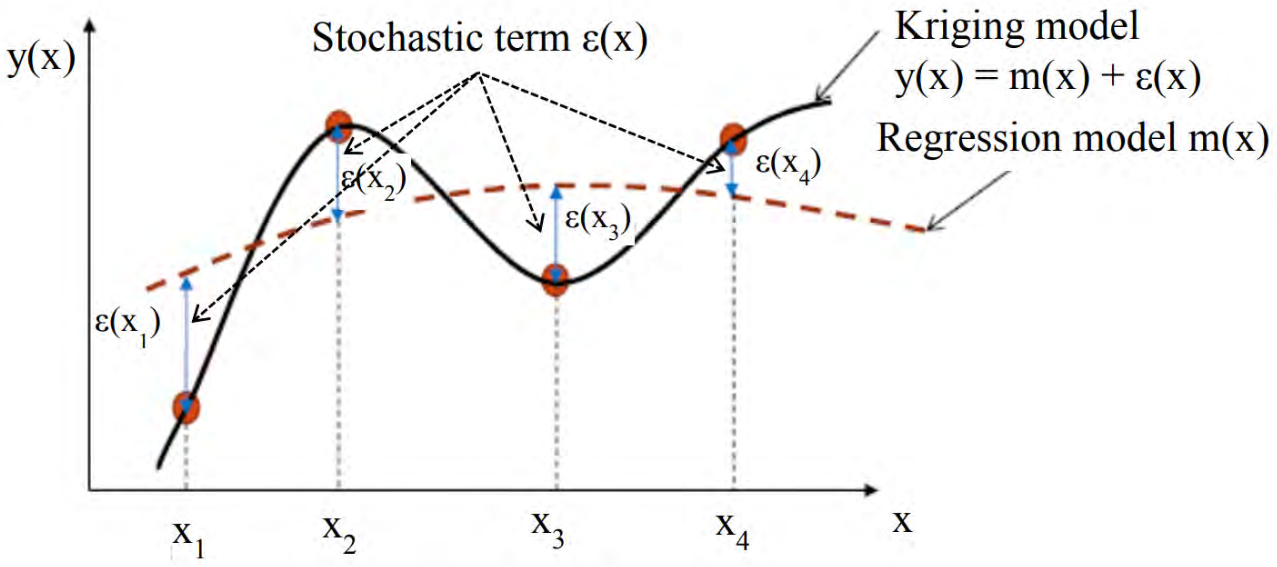
Figure 4.7. The fluid fraction at the bottom axial section of the reactor core

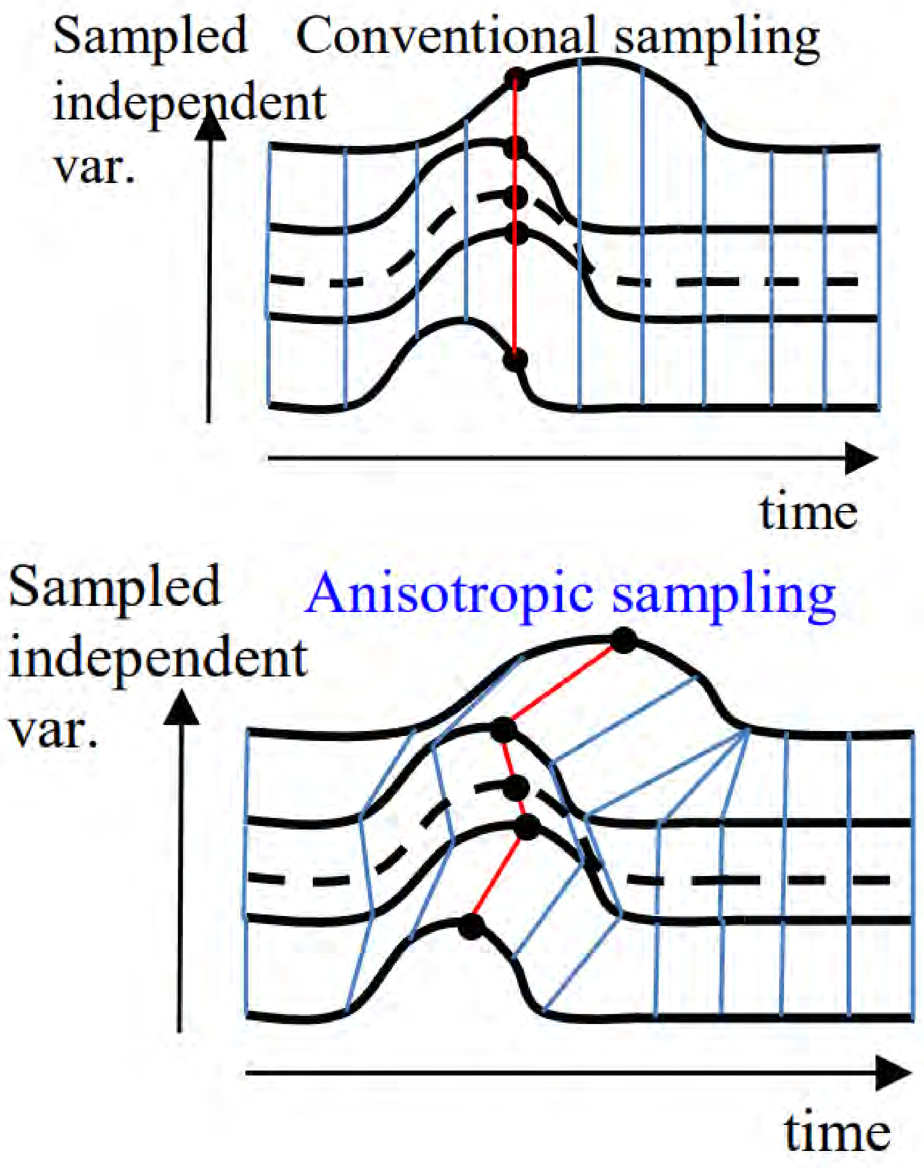


(b) Radial temperature gradient

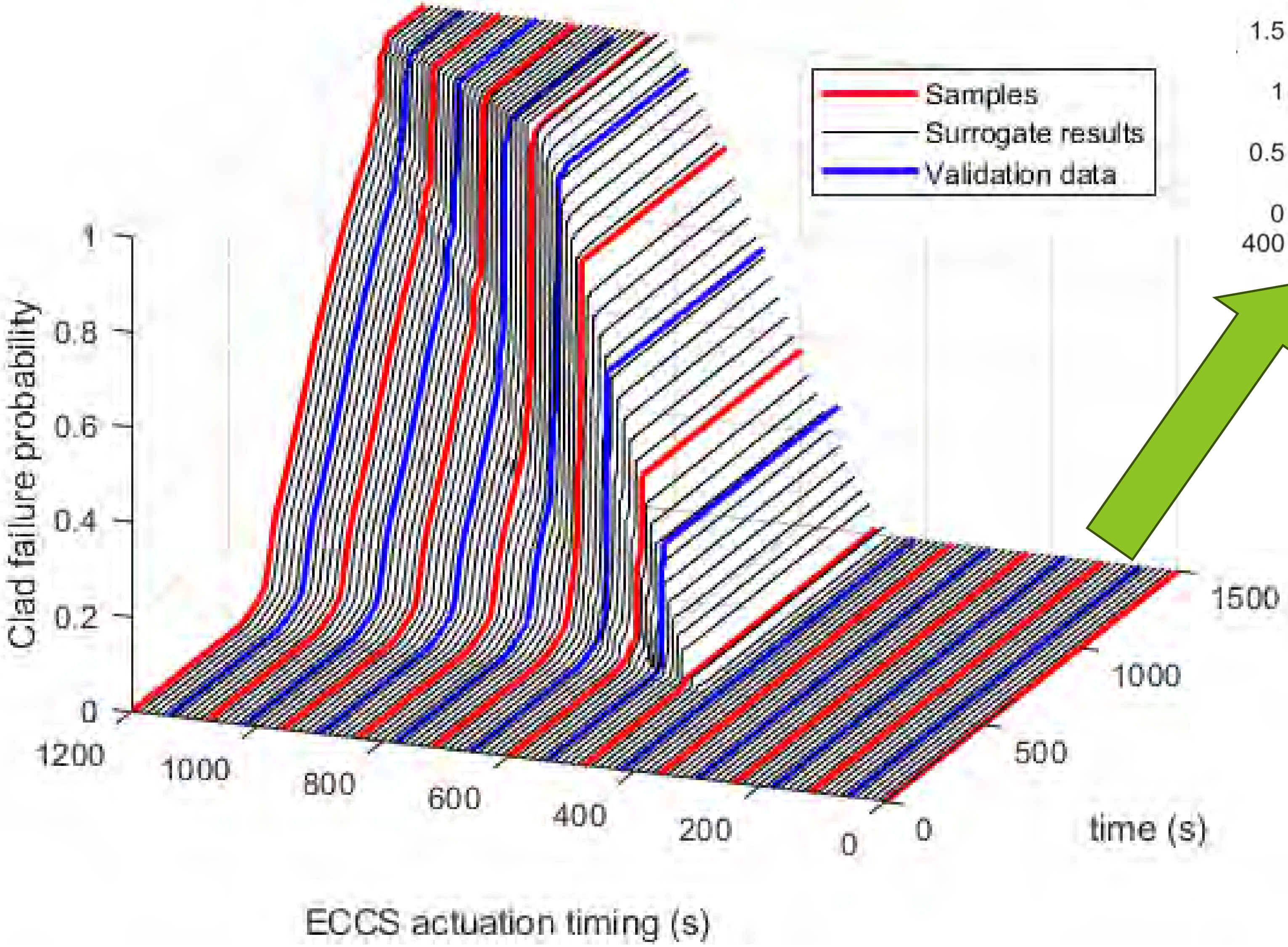
Surrogate Design

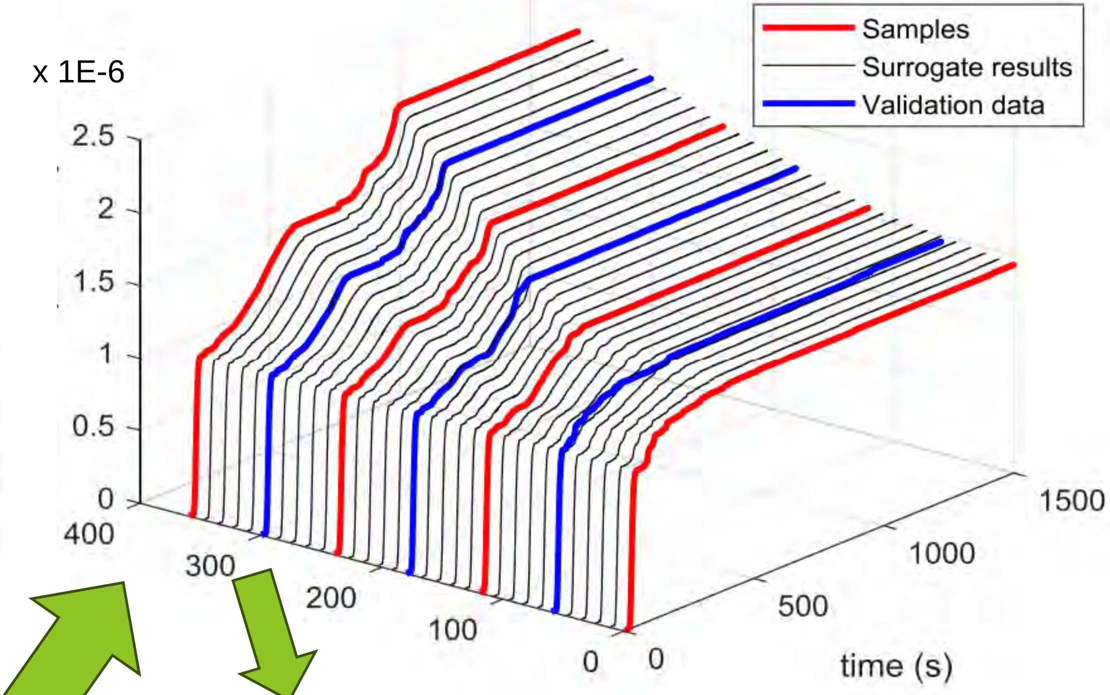
- Global trendline + uncertainty term

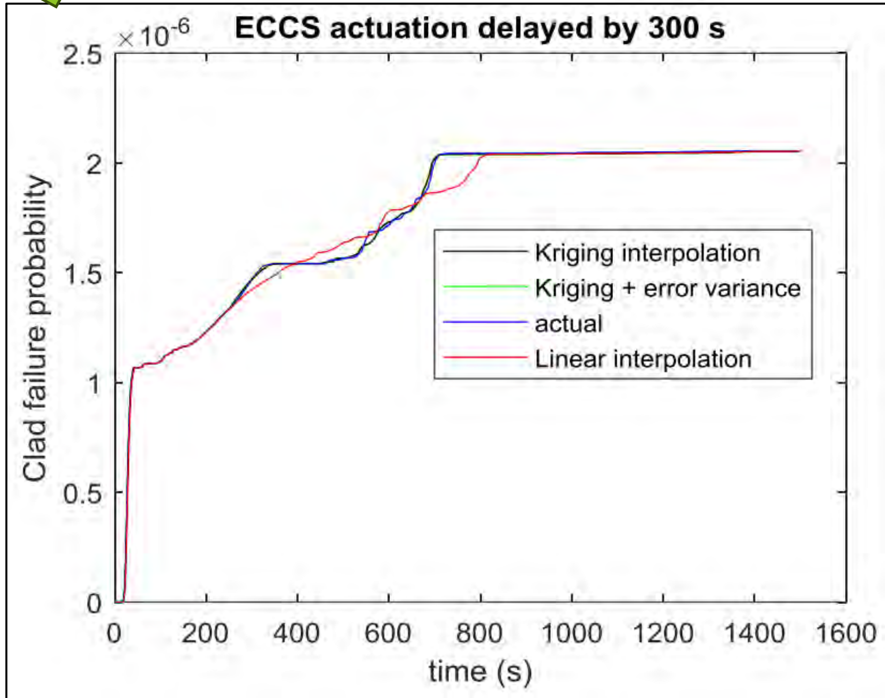




Response Surface Surrogate

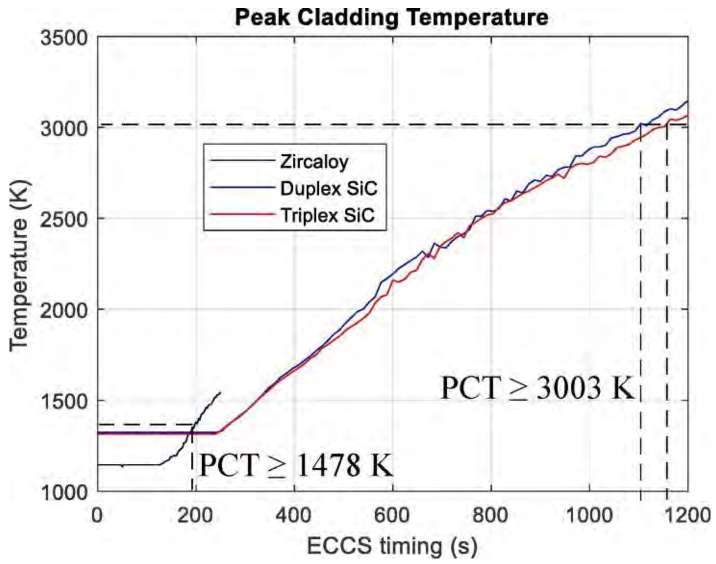




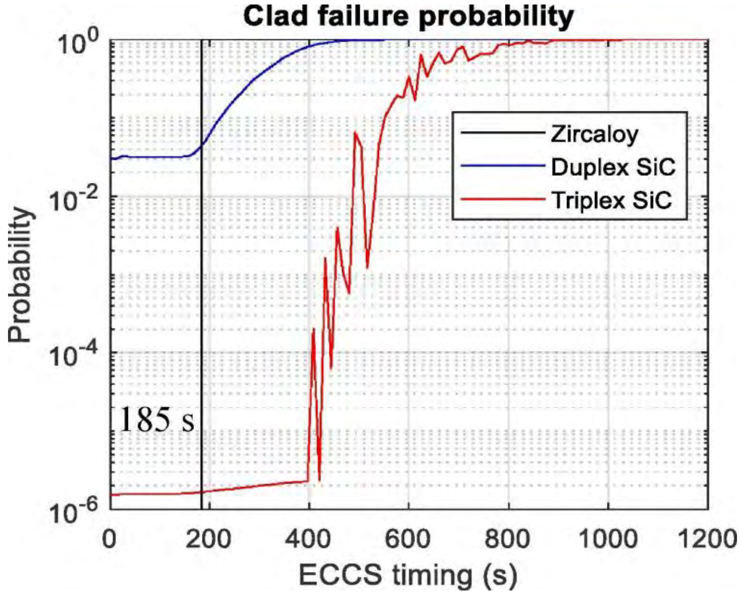


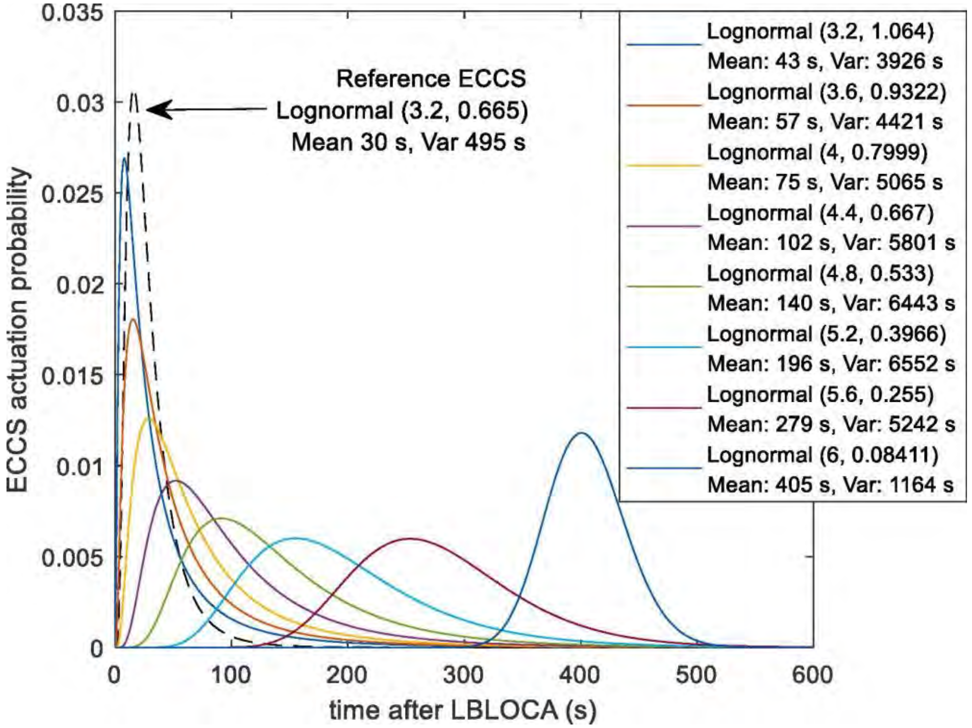
ECCS Performance

Deterministic criterion



Probabilistic criterion





ECCS relaxation provides more time window for DGs & pumps to start, reducing components' failure probability.

ECCS may be re-classified from safety-significant to low safety-significance following 50.69, eliminating special treatment requirements and reducing O&M costs.

Publications

1. **R. Christian**, A.U.A. Shah, H.G. Kang, "Dynamic PRA-based Estimation of PWR Coping Time Using a Surrogate Model for Accident Tolerant Fuel", Nuclear Technology 207, 3, 376-388, 2021, https://doi.org/10.1080/00295450.2020.1777035
2. **R. Christian**, Y. Lee, H.G. Kang, "Emergency core cooling system performance criteria for Multi-Layered Silicon Carbide nuclear fuel cladding", Nuclear Engineering and Design, Volume 353, 2019, https://doi.org/10.1016/j.nucengdes.2019.110280
3. A.U.A. Shah, **R. Christian**, J. Kim, J. Park, H.G. Kang, "Dynamic Probabilistic Risk Assessment Based Response Surface Approach for FLEX and Accident Tolerant Fuels for Medium Break LOCA Spectrum". Energies 2021, 14, 2490, 2021 https://doi.org/10.3390/en14092490
4. A.U.A. Shah, **R. Christian**, H.G. Kang, "Coping Time Estimation for Accident Tolerant Nuclear Power Plant", 2020 ANS Virtual Winter Meeting, November 2020. https://epubs.ans.org/?a=48868
5. **R. Christian** and H.G. Kang, "Code surrogate development for dynamic PRA", presented at ANS International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2019), Charleston, SC, USA, April 28 – May 3, 2019. https://epubs.ans.org/?a=45708
6. **R. Christian** and H.G. Kang, "Emergency core cooling system criteria for triplex silicon carbide cladding", presented at NPIC&HMIT 11, Orlando, FL, USA, Feb. 9-14, 2019. https://epubs.ans.org/?a=45766
7. **R. Christian** and H.G. Kang, "Code surrogate development for dynamic PRA using anisotropic Taylor Kriging methodology", presented at PSAM 14, Los Angeles, CA, USA, Sept. 16-21, 2018. https://www.iapsam.org/psam14/proceedings/paper/paper_87_1.pdf
8. **R. Christian** and H.G. Kang, "Surrogate development for dynamic risk assessment using anisotropic Taylor Kriging methodology", presented at International Symposium on Future I&C for Nuclear Power Plants (ISOFIC), Gyeongju, ROK, Nov. 26-30, 2017.

Idaho National Laboratory

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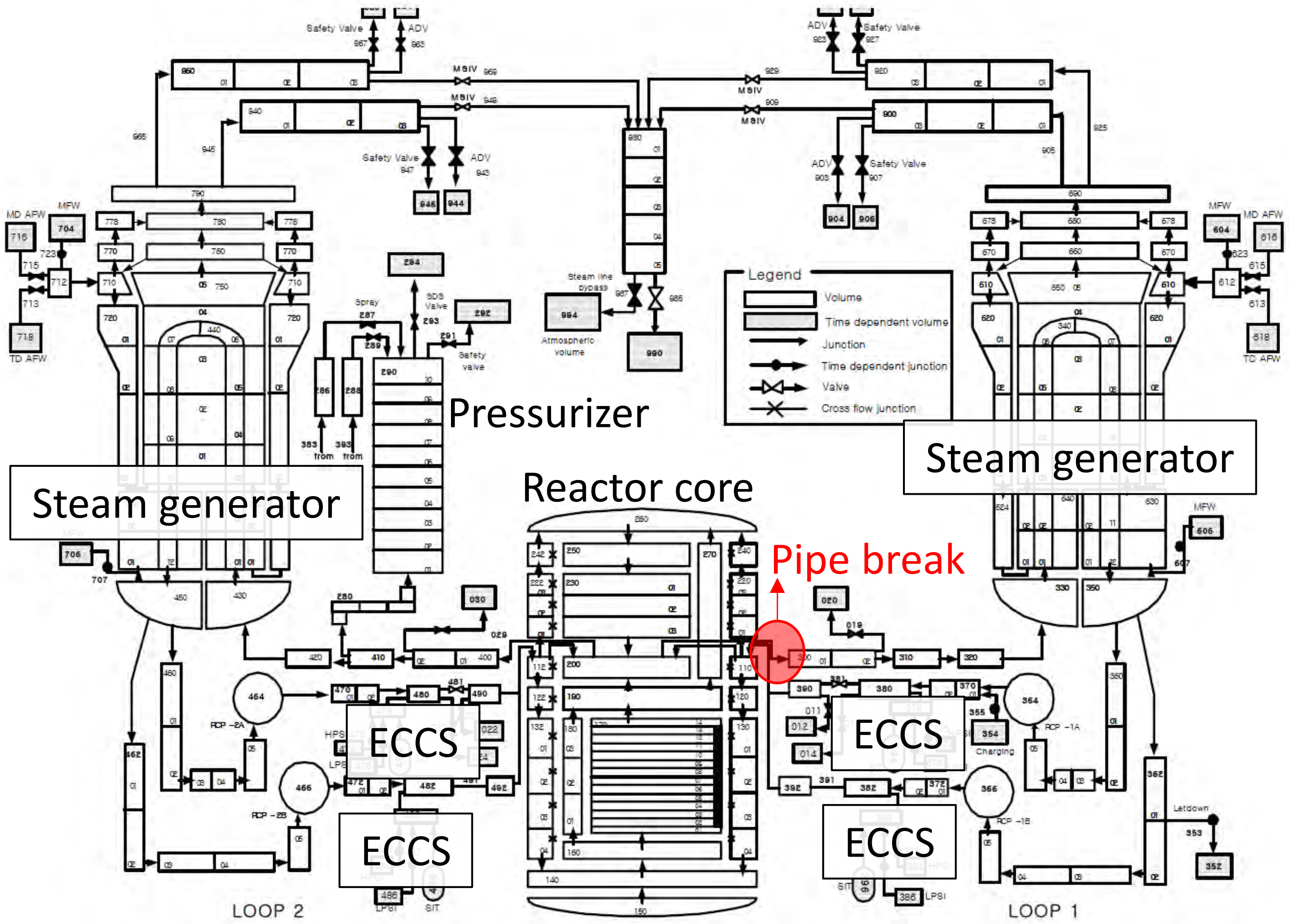
Nodalization



PWR 1000 MWe model
2 Primary loops @ 2 ECCS systems
ECCS @ 1 passive tank & 1 active HP & LP systems

Equations

- Underlying equations:
  - Lamé equations → cylinder stress from pressure
  - Hooke's Law → stress-strain proportionality

$$\sigma_h = A + \frac{B}{r^2} \qquad \sigma_r = A - \frac{B}{r^2} \qquad \sigma_a = p_i \frac{r_i^2}{r_o^2 - r_i^2}$$

- Assumptions:
  - Plane-strain assumption → negligible axial displacement
  - Isotropic elasticity → Constant elastic modulus for all directions
- BCs:
  - Continuity at layer boundaries
  - Constant axial strains

Stress from pressure-loading

$$\sigma(r)_{\theta,i} = A_i + \frac{B_i}{r^2}, R_i \le r \le R_{i+1}, i = 1,2,3$$

$$\sigma(r)_{r,i} = A_i - \frac{B_i}{r^2}, R_i \le r \le R_{i+1}, i = 1,2,3$$

$$\vec{X}_p = A_p^{-1}\vec{b}_p \tag{3.3}$$

$$A_p = \begin{bmatrix}
1 & -\frac{1}{R_1^2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & -\frac{1}{R_2^2} & -1 & \frac{1}{R_2^2} & 0 & 0 & 0 & 0 & 0 \\
\frac{1-v_{r\theta,1}}{E_{\theta\theta,1}} & \frac{1+v_{r\theta,1}}{E_{\theta\theta,1}R_2^2} & \frac{v_{r\theta,2}-1}{E_{\theta\theta,2}} & \frac{-1-v_{r\theta,2}}{E_{\theta\theta,2}R_2^2} & 0 & 0 & -\frac{v_{z\theta,1}}{E_{\theta\theta,1}} & \frac{v_{z\theta,2}}{E_{\theta\theta,2}} & 0 \\
0 & 0 & 1 & -\frac{1}{R_3^2} & -1 & 1/R_3^2 & 0 & 0 & 0 \\
0 & 0 & \frac{1-v_{r\theta,2}}{E_{\theta\theta,2}} & \frac{1+v_{r\theta,2}}{E_{\theta\theta,2}R_3^2} & \frac{v_{r\theta,3}-1}{E_{\theta\theta,3}} & -\frac{1+v_{r\theta,3}}{E_{\theta\theta,3}R_3^2} & 0 & -\frac{v_{z\theta,2}}{E_{\theta\theta,2}} & \frac{v_{z\theta,3}}{E_{\theta\theta,3}} \\
0 & 0 & 0 & 0 & 1 & -\frac{1}{R_4^2} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & A_{c,1} & A_{c,2} & A_{c,3} \\
-\frac{2v_{\theta z,1}}{E_{zz,1}} & 0 & \frac{2v_{\theta z,2}}{E_{zz,2}} & 0 & 0 & 0 & \frac{1}{E_{zz,1}} & -\frac{1}{E_{zz,2}} & 0 \\
0 & 0 & -\frac{2v_{\theta z,2}}{E_{zz,2}} & 0 & \frac{2v_{\theta z,3}}{E_{zz,3}} & 0 & 0 & \frac{1}{E_{zz,2}} & -\frac{1}{E_{zz,3}}
\end{bmatrix} \tag{3.4}$$

$$\vec{b}_p = [-P_i \quad 0 \quad 0 \quad 0 \quad 0 \quad -P_o \quad P_i\pi R_1^2 - P_o\pi R_4^2 \quad 0 \quad 0]^T \tag{3.5}$$

$$\vec{X}_p = [A_1 \quad B_1 \quad A_2 \quad B_2 \quad A_3 \quad B_3 \quad \sigma_{z,1} \quad \sigma_{z,2} \quad \sigma_{z,3}]^T \tag{3.6}$$

where r is the radial distance from the fuel centerline, R is cladding radius, v is the Poisson ratio, E is elastic modulus, and Ac is cross-sectional area of clad.

Thermal expansion stresses (1)

$$\sigma(r)_{r,i,Th} = -\frac{\alpha_i E_i}{(1-v_i)r^2}\int \Delta T r dr + \frac{E_i}{1+v_i}\left(\frac{C_1^j}{1-2v_i} - \frac{C_2^j}{r^2} + \frac{v_i \varepsilon_0}{1-2v_i}\right), \tag{3.7}$$

$$R_i \le r \le R_{i+1}, i = 1,2,3, \qquad j = I, II, III$$

$$\sigma(r)_{\theta,i,Th} = \frac{\alpha_i E_i}{(1-v_i)r^2}\int \Delta T r dr - \frac{\alpha_i E_i \Delta T}{1-v_i} + \frac{E_i}{1+v_i}\left(\frac{C_1^j}{1-2v_i} - \frac{C_2^j}{r^2} + \frac{v_i \varepsilon_0}{1-2v_i}\right), \tag{3.8}$$

$$R_i \le r \le R_{i+1}, i = 1,2,3, \qquad j = I, II, III$$

$$\sigma(r)_{z,i,Th} = E_i \varepsilon_0 - \frac{\alpha_i E_i \Delta T}{1-v_i} + \frac{2 v_i E_i C_1^j}{(1-2v_i)(1+v_i)} + \frac{2 v_i^2 E_i \varepsilon_0}{(1-2v_i)(1+v_i)}, \tag{3.9}$$

$$R_i \le r \le R_{i+1}, \qquad i = 1,2,3, \qquad j = I, II, III$$

$$\vec{X}_{Th} = A_{Th}^{-1} \vec{b}_{Th} \tag{3.10}$$

$$\vec{X}_{Th} = [C_1^I \quad C_2^I \quad C_1^{II} \quad C_2^{II} \quad C_1^{III} \quad C_2^{III} \quad \varepsilon_0]^T \tag{3.11}$$

where α is the thermal expansion coefficient, $\Delta T = T(r) - T_{ref}$ is the radial temperature deviation from the strain-free temperature T_{ref}, ε_0 is the constant axial strain

Thermal expansion stresses (2)

$$
A_{Th} = \begin{bmatrix}
\frac{E_1}{(1-2\nu_1)(1+\nu_1)} & -\frac{E_1}{(1+\nu_1)R_1^2} & 0 & 0 & 0 & 0 & \frac{E_1\nu_1}{(1+\nu_1)(1-2\nu_1)} \\
\frac{E_1}{(1-2\nu_1)(1+\nu_1)} & -\frac{E_1}{(1+\nu_1)R_2^2} & -\frac{E_2}{(1-2\nu_2)(1+\nu_2)} & \frac{E_2}{(1+\nu_2)R_2^2} & 0 & 0 & \left(\frac{E_1\nu_1}{(1+\nu_1)(1-2\nu_1)} - \frac{E_2\nu_2}{(1+\nu_2)(1-2\nu_2)}\right) \\
1 & \frac{1+\nu_1}{(1+\nu_1)R_2^2} & -1 & \frac{-1-\nu_2}{(1+\nu_2)R_2^2} & 0 & 0 & 0 \\
0 & 0 & \frac{E_2}{(1-2\nu_2)(1+\nu_2)} & -\frac{E_2}{(1+\nu_2)R_3^2} & -\frac{E_3}{(1-2\nu_3)(1+\nu_3)} & \frac{E_3}{(1+\nu_3)R_3^2} & \left(\frac{E_2\nu_2}{(1+\nu_2)(1-2\nu_2)} - \frac{E_3\nu_3}{(1+\nu_3)(1-2\nu_3)}\right) \\
0 & 0 & 1 & \frac{1+\nu_2}{(1+\nu_2)R_3^2} & -1 & -\frac{1+\nu_3}{(1+\nu_3)R_3^2} & 0 \\
0 & 0 & 0 & 0 & \frac{E_3}{(1-2\nu_3)(1+\nu_3)} & -\frac{E_3}{(1+\nu_3)R_4^2} & \frac{E_3\nu_3}{(1+\nu_3)(1-2\nu_3)} \\
\frac{2\nu_1E_1\pi(R_2^2-R_1^2)}{(1+\nu_1)(1-2\nu_1)} & 0 & \frac{2\nu_2E_1\pi(R_3^2-R_2^2)}{(1+\nu_2)(1-2\nu_2)} & 0 & \frac{2\nu_3E_3\pi(R_4^2-R_3^2)}{(1+\nu_3)(1-2\nu_3)} & 0 & \pi\left(\begin{matrix} E_1\left(1+\frac{2\nu_1^2}{(1-2\nu_1)(1+\nu_1)}\right)(R_2^2-R_1^2)+ \\ E_2\left(1+\frac{2\nu_2^2}{(1-2\nu_2)(1+\nu_2)}\right)(R_3^2-R_2^2)+ \\ E_3\left(1+\frac{2\nu_3^2}{(1-2\nu_3)(1+\nu_3)}\right)(R_4^2-R_3^2) \end{matrix}\right)
\end{bmatrix} \quad (3.12)
$$

$$
\vec{b}_{Th} = \begin{bmatrix}
0 \\
\frac{E_1\alpha_1}{(1-\nu_1)R_2^2}\int_{R_1}^{R_2}\Delta T r dr \\
-\frac{\alpha_1(1+\nu_1)}{(1-\nu_1)R_2^2}\int_{R_1}^{R_2}\Delta T r dr + \Delta T(\alpha_1\nu_1-\alpha_2\nu_2) \\
\frac{E_2\alpha_2}{(1-\nu_2)R_3^2}\int_{R_2}^{R_3}\Delta T r dr \\
-\frac{\alpha_2(1+\nu_2)}{(1-\nu_2)R_3^2}\int_{R_2}^{R_3}\Delta T r dr + \Delta T(\alpha_2\nu_2-\alpha_3\nu_3) \\
\frac{E_3\alpha_3}{(1-\nu_3)R_4^2}\int_{R_3}^{R_4}\Delta T r dr \\
2\pi\left(\int_{R_1}^{R_2}\frac{E_1\alpha_1\Delta T}{(1-\nu_1)}r dr + \int_{R_2}^{R_3}\frac{E_2\alpha_2\Delta T}{(1-\nu_2)}r dr + \int_{R_3}^{R_4}\frac{E_3\alpha_3\Delta T}{(1-\nu_3)}r dr\right)
\end{bmatrix} \quad (3.13)
$$

Radiation swelling stresses

$$\sigma(r)_{r,i,s} = -\frac{E_i}{(1-\nu_i)r^2}\int \frac{S_i(T)}{3} r dr + \frac{E_i}{1+\nu_i}\left(\frac{C_{1,s}^j}{1-2\nu_i} - \frac{C_{2,s}^j}{r^2} + \frac{\nu_i \varepsilon_{0,s}}{1-2\nu_i}\right), \tag{3.19}$$

$$R_i \le r \le R_{i+1}, \quad i = 1,2,3, \quad j = I, II, III$$

$$\sigma(r)_{\theta,i,Th} = \frac{E_i}{(1-\nu_i)r^2}\int \frac{S_i(T)}{3} r dr - \frac{E_i S_i(T)}{3(1-\nu_i)} + \frac{E_i}{1+\nu_i}\left(\frac{C_{1,s}^j}{1-2\nu_i} - \frac{C_{2,s}^j}{r^2} + \frac{\nu_i \varepsilon_{0,s}}{1-2\nu_i}\right), \quad R_i \le r \le R_{i+1}, \tag{3.20}$$

$$i = 1,2,3, \quad j = I, II, III$$

$$\sigma(r)_{z,i,Th} = E_i \varepsilon_{0,s} - \frac{E_i S_i(T)}{3(1-\nu_i)} + \frac{2\nu_i E_i C_{1,s}^j}{(1-2\nu_i)(1+\nu_i)} + \frac{2\nu_i^2 E_i \varepsilon_{0,s}}{(1-2\nu_i)(1+\nu_i)}, \tag{3.21}$$

$$R_i \le r \le R_{i+1}, \quad i = 1,2,3, \quad j = I, II, III$$

$$\vec{X}_S = A_{Th}^{-1}\vec{b}_S$$

$$\vec{X}_S = \begin{bmatrix} C_{1,S}^{I} & C_{2,S}^{I} & C_{1,S}^{II} & C_{2,S}^{II} & C_{1,S}^{III} & C_{2,S}^{III} & \varepsilon_{0,S} \end{bmatrix}^T$$

$$\vec{b}_S = \begin{bmatrix} 0 \\ \frac{E_1}{3(1-\nu_1)R_2^2}\int_{R_1}^{R_2} S_1\, r dr \\ -\frac{(1+\nu_1)}{3(1-\nu_1)R_2^2}\int_{R_1}^{R_2} S_1\, r dr \\ \frac{E_2\alpha_2}{(1-\nu_2)R_3^2}\int_{R_2}^{R_3} S_2\, r dr \\ -\frac{(1+\nu_2)}{3(1-\nu_2)R_3^2}\int_{R_2}^{R_3} S_2\, r dr \\ \frac{E_3}{3(1-\nu_3)R_4^2}\int_{R_3}^{R_4} S_3\, r dr \\ 2\pi\left(\sum_{i=1}^{3}\int_{R_i}^{R_{i+1}} \frac{E_i S_i}{3(1-\nu_i)} r dr\right) \end{bmatrix}$$

where S(T) was taken as the temperature-dependent dose-saturated volumetric swelling

Radiation swelling (2)

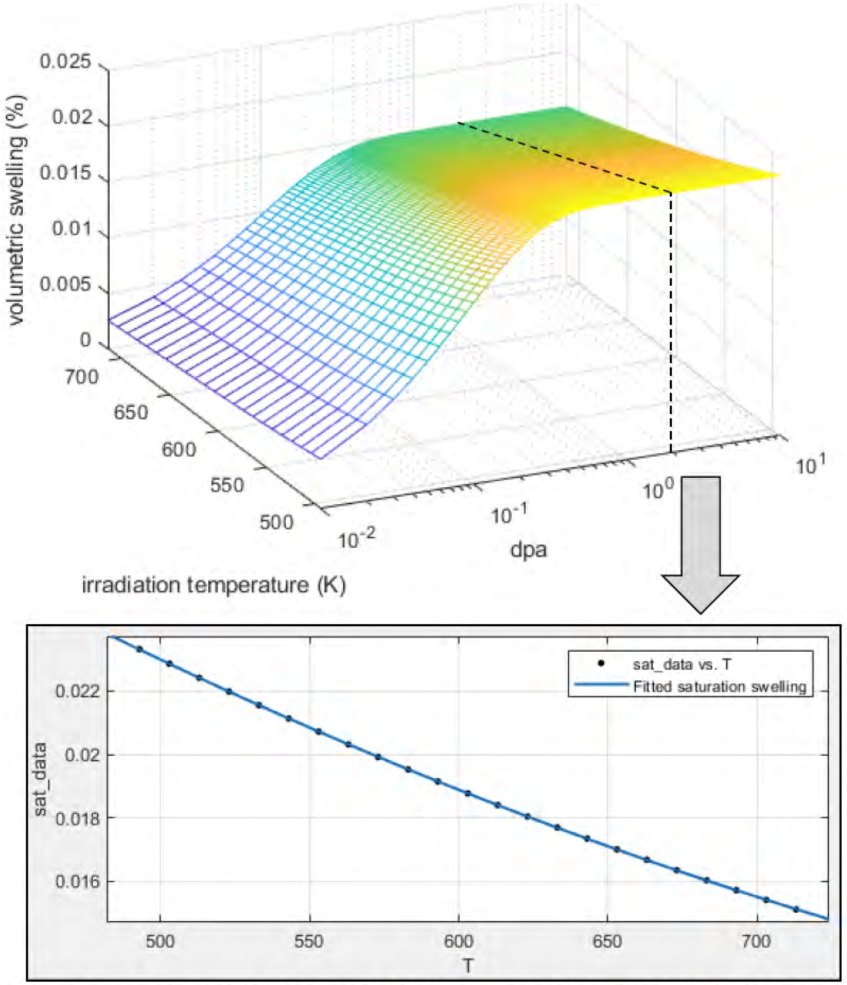


Figure 3.12. Fitting of dose saturated volumetric swelling from different irradiation temperatures (top) to a second order polynomial at 2 dpa (bottom)

$$S\left[\frac{\Delta V}{V} \times 100\%\right] = 3.653 \times 10^{-8}T^2 - 8.123 \times 10^{-5}T + 0.05447 \qquad (3.51)$$