

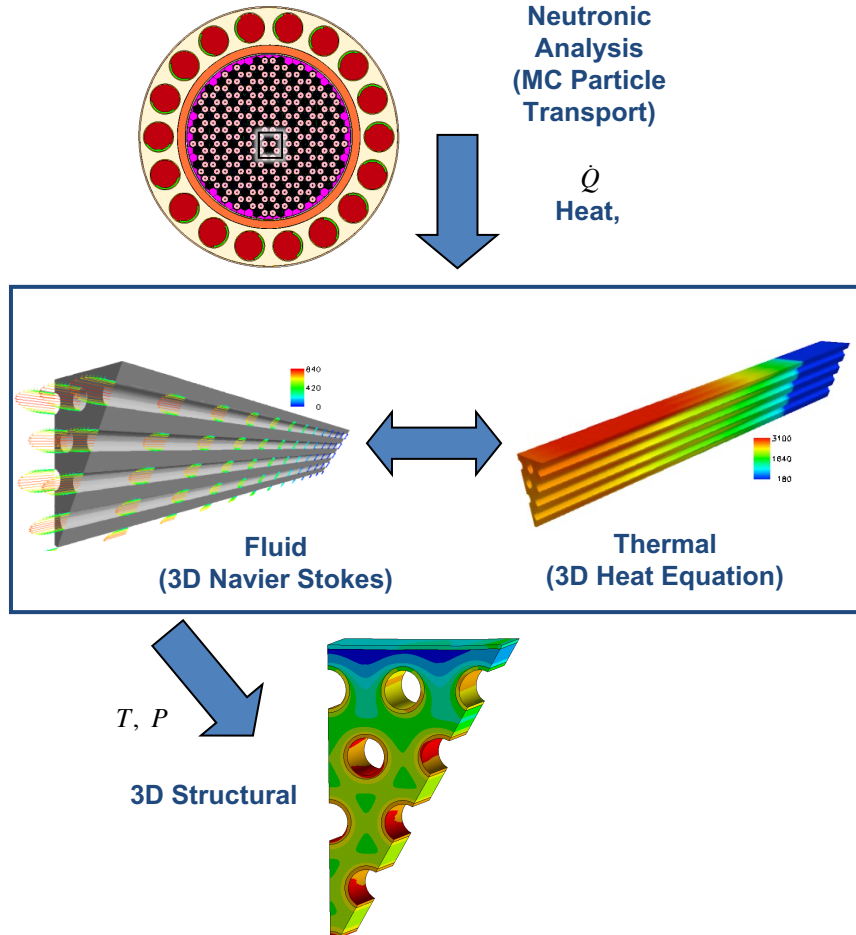


Modeling Validation and Its Design Relevance for NTP Fuel Elements

AIAA Propulsion & Energy
Nuclear Thermal Propulsion: Engine Modeling
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Multidisciplinary NTP Fuel Element Simulations



- "CFD" simulations
 - Detailed geometry
 - Large grids
 - Large computer
- Multidisciplinary: fluid / thermal / structural / neutronic
- Why all together?
- At material, thermal & structural limits:





- **How do we know these multidisciplinary predictions are OK?**
- **Care and check results during development**
- **Validation: compare with an independent solution, typically closed-form**

- **Thermal: fuel element temperatures compare with Sparrow eqn.**
- **Thermal / Fluid: compare HTC correlations with CFD heat tx**
- **Fuel Element Stress / Strain: Compare with closed-form?**
- **Neutronic: MCNP V&V, compare inter-element heating**

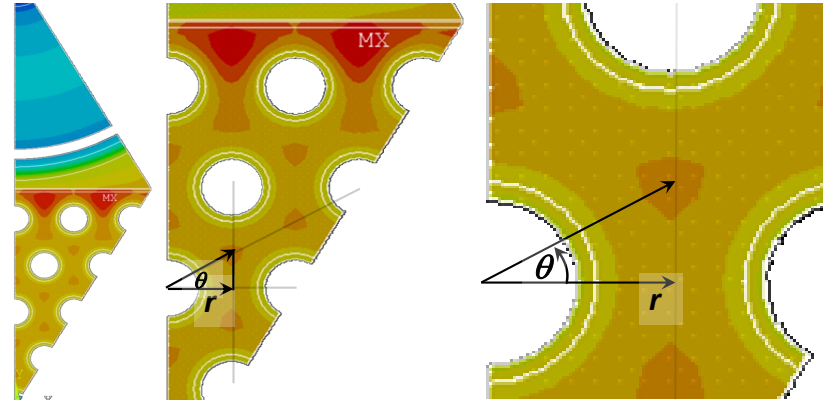
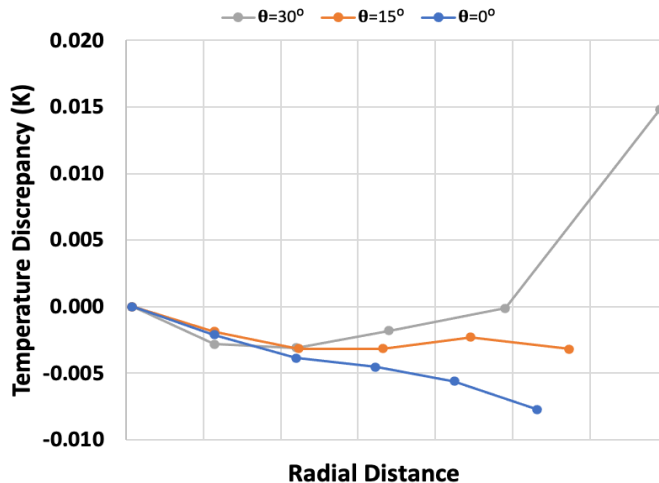
- **Why bother?**
 - Experiments, particularly nuclear, are expensive, time-consuming & radioactive
 - NTP is a challenging design,
 - SNP is emphasizing numerical simulation for design validation



Fuel Element Thermal Validation

- Fuel element temperatures compare with Sparrow eqn:

$$T(r, \theta) - T_{wall} = \frac{Q}{k} s^2 \left[\frac{\sqrt{3}}{\pi} \ln \left(\frac{r}{r_0} \right) - \frac{1}{4} \left[\left(\frac{r}{s} \right)^2 - \left(\frac{r_0}{s} \right)^2 \right] + \sum_{J=1} T_J(r) \cos 6J\theta \right] \quad T_J(r) = \frac{\Delta J}{6J} \left(\frac{r}{s} \right)^{6J} \left[1 - \left(\frac{r_0}{r} \right)^{12J} \right]$$



- Outside the tube array—at the fuel element edges—symmetry fails as does the closed-form temperature prediction.
- Hence detailed analysis needed

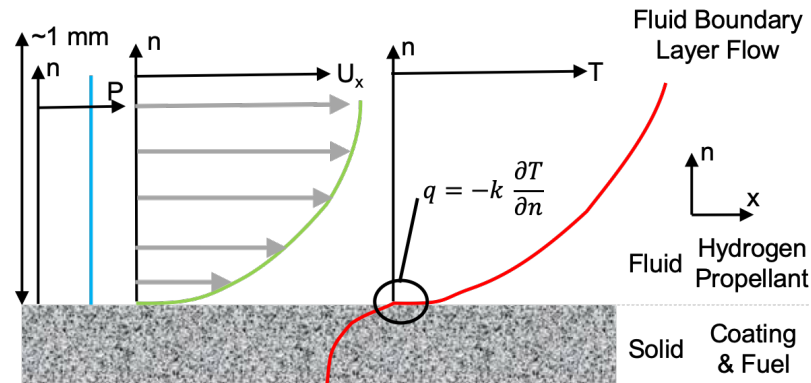


Heat Transfer at Channel Walls

- Wall heat transfer compare with heat transfer correlations,

$$htc = 0.023 \frac{k_b}{D_b} Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b} \right)^{\left[-0.57 - \frac{1.59}{z/D_b} \right]}$$

- Why is it difficult to predict heat transfer?

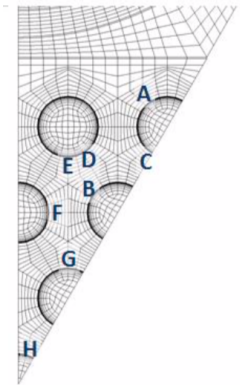
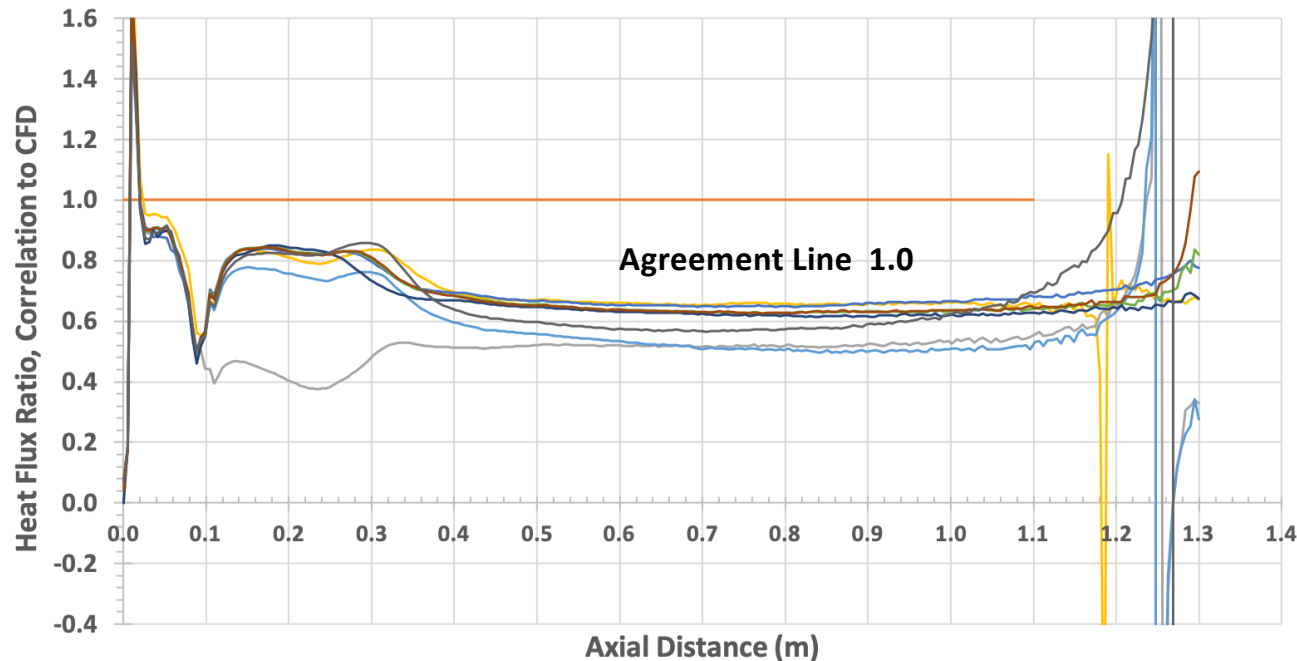


- CFD heat transfer predictions usually $\pm 10\%$



CFD Comparison to Heat Transfer Correlation

- **Measure & plot:** $\frac{q_{wall}^{Corr}}{q_{wall}^{CFD}}$
- **Correlations are conservative, predict ~70% of CFD's heat tx**



- **Could also compare with pressure drop correlations**



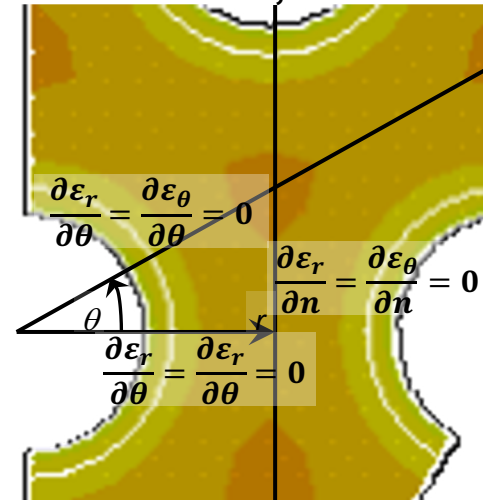
Validation Solutions for Fuel Element Stress & Strain

- Timoshenko gives solutions for arbitrary temperature in polar coords:

$$\begin{pmatrix} \sigma_r \\ \sigma_\theta \\ \sigma_z \end{pmatrix} = \frac{E}{1+\nu} \begin{pmatrix} \frac{1}{1-2\nu} & -\frac{1}{r^2} & 0 \\ \frac{1}{1-2\nu} & \frac{1}{r^2} & 0 \\ \frac{2\nu}{1-2\nu} & 0 & \frac{1+\nu}{E} \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} + \begin{pmatrix} -1 \\ 1 \\ 0 \end{pmatrix} \frac{\alpha E}{1-\nu} \frac{1}{r^2} \int_{r_0}^r (T - T_{SF}) r dr + \begin{pmatrix} 0 \\ -\frac{\alpha E (T - T_{SF})}{1-\nu} \\ -\frac{\alpha E (T - T_{SF})}{1-\nu} \end{pmatrix}$$

- Key terms are clear: thermal stress, CTE mismatch stress, stress free state
- Almost satisfy fuel element B.C.s

- Couples to heat equation solution $T(r)$



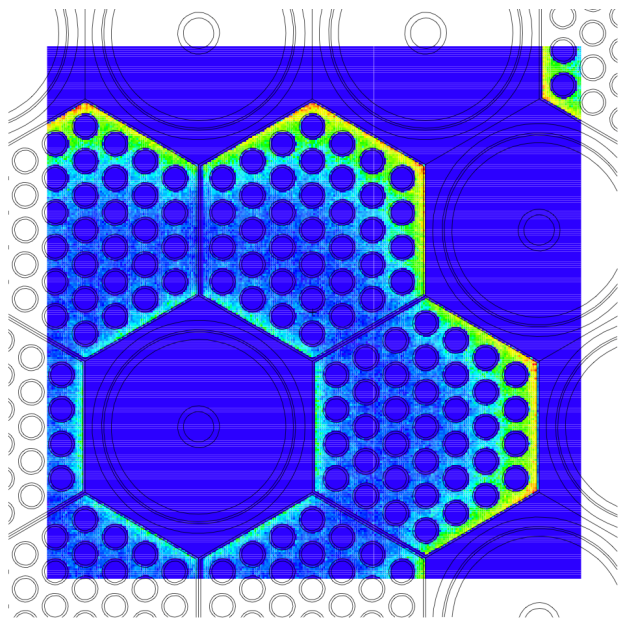


- **Neutronic calculations with MCNP**
- **Extensive validation & verification of MCNP**
- **Realistically, errors are more likely to come from the user, than the code**
- **Independent simulations help to validate**

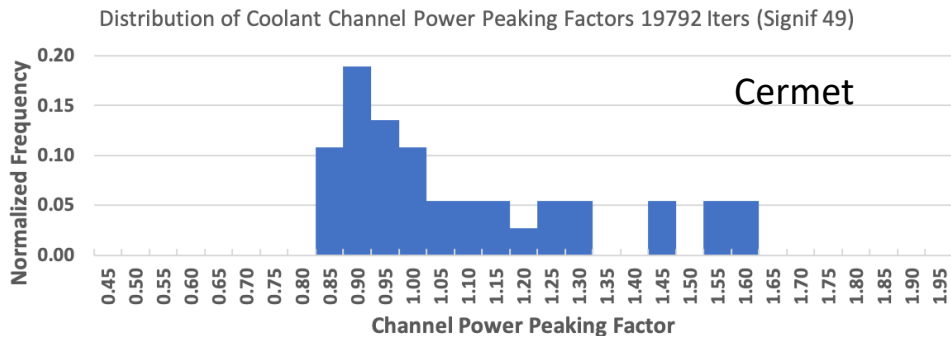
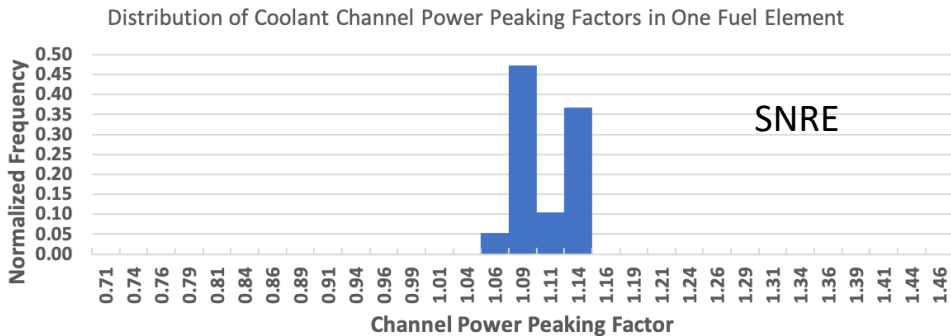


Inter-Element Heating & Validation

- For high I_{sp} performance, all coolant channels have same exit temp
- Otherwise, hot channels at fuel melt limit, cold channels at lower I_{sp}



Radial Heat Deposition

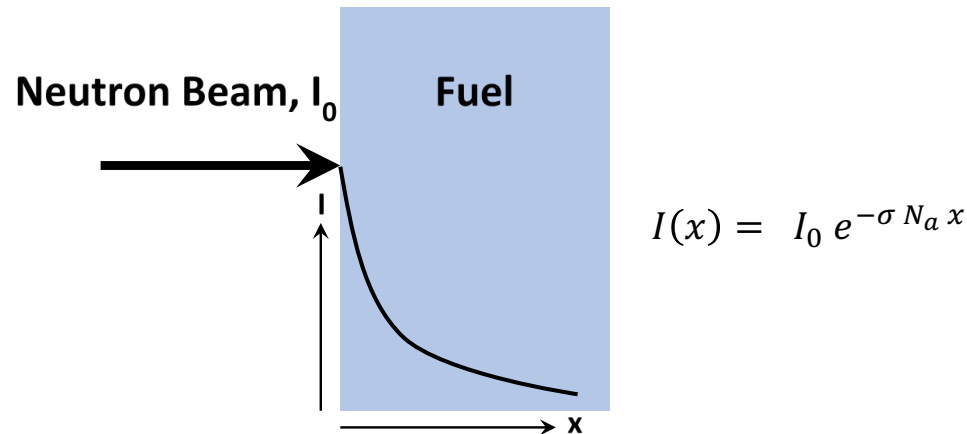


Validation Equation for Inter-Element Heating

- From nuclear cross sections, σ , we get a simple differential eqn:

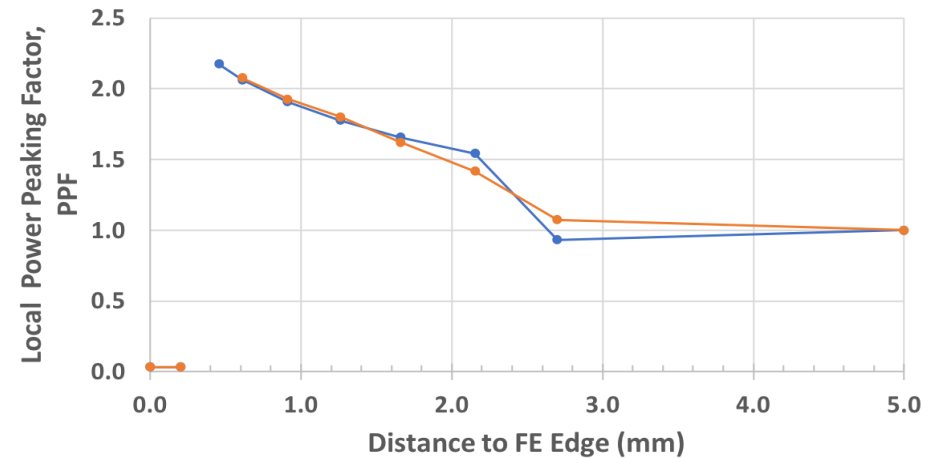
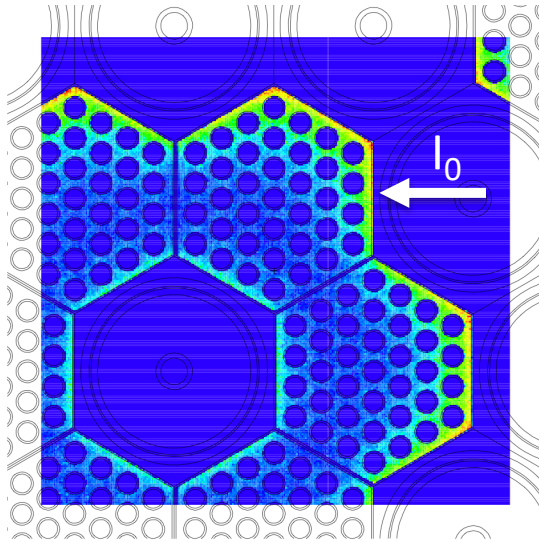
$$I(x) = I_0 e^{-\sigma N_a x}$$

- N_a [Num L⁻³] is the number density of a target
- Characteristic length, $\frac{1}{\sigma N_a}$, of interactions of neutrons with target,
- 63% interact by e^{-1} , or 86% interact by e^{-2} .



Validation Equation for Inter-Element Heating

- What do MCNP calculations show?
- Reactor had a 1-2 mm AVG heating depth, by careful MCNP calcs
- Formula predicts 1.1 mm at 0.025 eV, 6.0 mm at 0.625 eV



Validation Equation for Inter-Element Heating

- What do calculations show about $\frac{1}{\sigma N_a}$?

Reactor	U-235 Nuclei Density, N_a	Heating Depth, D at Energy E (mm)		Neutron Energy Spectrum (%)		
	(atom/cc)	0.025 eV	0.625 eV	< 0.625 eV	0.625 eV < 100 keV	> 100 keV
SNRE HEU	1.14E+21	6.7	35.5	39.2	54.1	6.6
Cermet	6.76E+21	1.1	6.0	59.8	31.6	8.6
Cercer	7.20E+20	10.6	56.3	90.8	7.6	1.6

- Design implications:**
 - Fuel composition is dominant: cermet, cercer, carbide
 - Reactor's neutron spectrum is important: more or less thermal
 - Fuel element size is significant





- **Methods & predictions can be validated by comparing independent methods**
-  **Thermal**
-  **Fluid / Thermal**
-  **Stress / Strain**
-  **Neutronic**
- **Model quickly predicts inter-element heating depth**

