SAND2019-4197PE

A Transient Thermal and Structural Analysis of the Fuel in the Annular Core Research Reactor

Thesis Defense by Elliott Pelfrey
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THE UNIVERSITY OF NEW MEXICO

OUTLINE

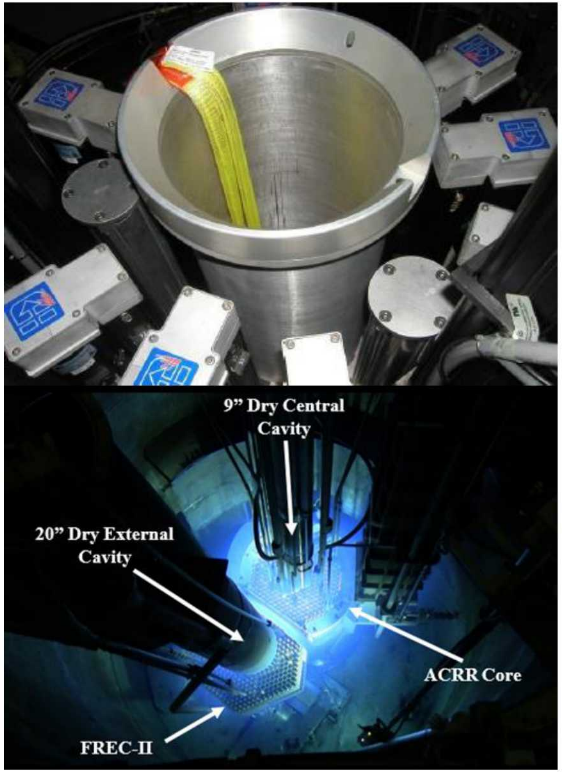
- **Introduction**
- Previous Work
- Burnup and Radiation Effects
- Material Properties
- Transient Thermal Analysis
- Transient Structural Analysis
- Material Sensitivity
- A Fracture Mechanics Perspective
- Conclusion

INTRODUCTION: Motivation

- Health of the fuel pellets in the ACRR
- Two contradictory unfinished reports recently resurfaced
  - A report in 1982 and in the 1990's reported contradictory conclusions
- A new facility that would include the ACRR
- Desire to use modern tools to perform a more in-depth analysis
  - Previous work used analytical solutions or basic FEA codes
  - None of the previous work modeled the true geometry of an ACRR fuel element

INTRODUCTION: ACRR

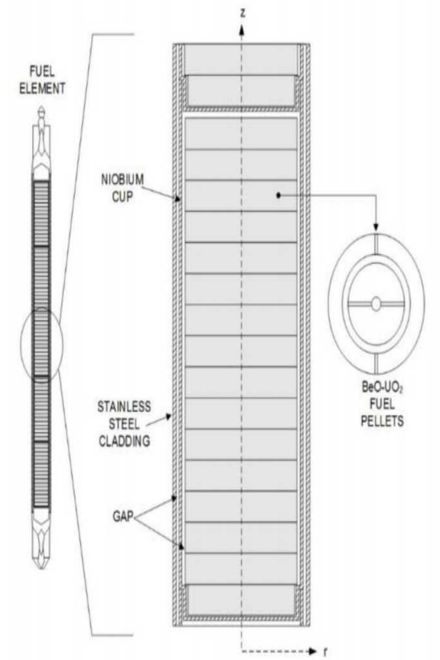
- Annular Core Research Reactor (ACRR)
- Located within TAV of SNL
- Came online in 1978
- Has performed 12000+ operations
- Used primarily for electronic component testing
- 236 fuel elements arranged in annulus around 9" central cavity
- Capable of operating at 4MW and pulsing up to 50GW with energy depositions of >300MJ



[1]

INTRODUCTION: Fuel Elements

- Operated using 11 moveable fuel elements
  - Boron-carbide upper
- Each normal element is made of:
  - SS cladding
  - 5 fluted Nb cans
  - 16 fuel pellets per Nb can
  - Back filled with He



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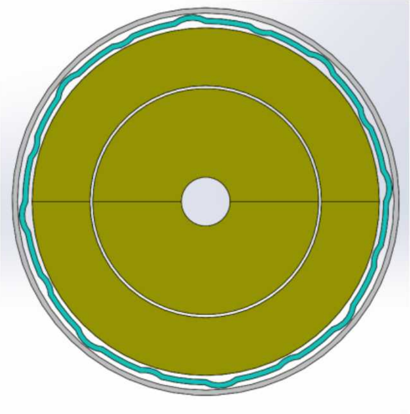
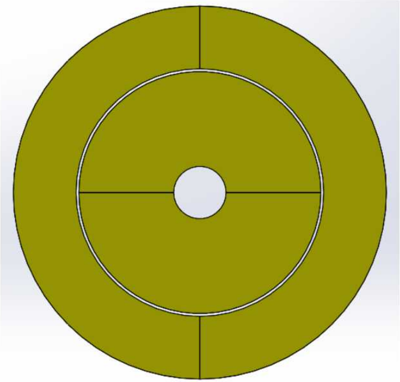
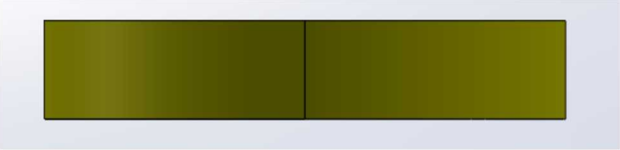


INTRODUCTION: Fuel Pellets

- Geometry and materials are unique
- Split dual annuli
- UO_2-BeO
- 6.9 v/o UO_2 that is 35% enriched
- Cold-pressed and sintered to 99% TD
- UO_2 dispersions are not to exceed 1 μm
- No traditional materials testing was performed on the fuel pellets
- Literature on the material is sparse and none directly relates to the ACRR's fuel





INTRODUCTION: Pulse Operation

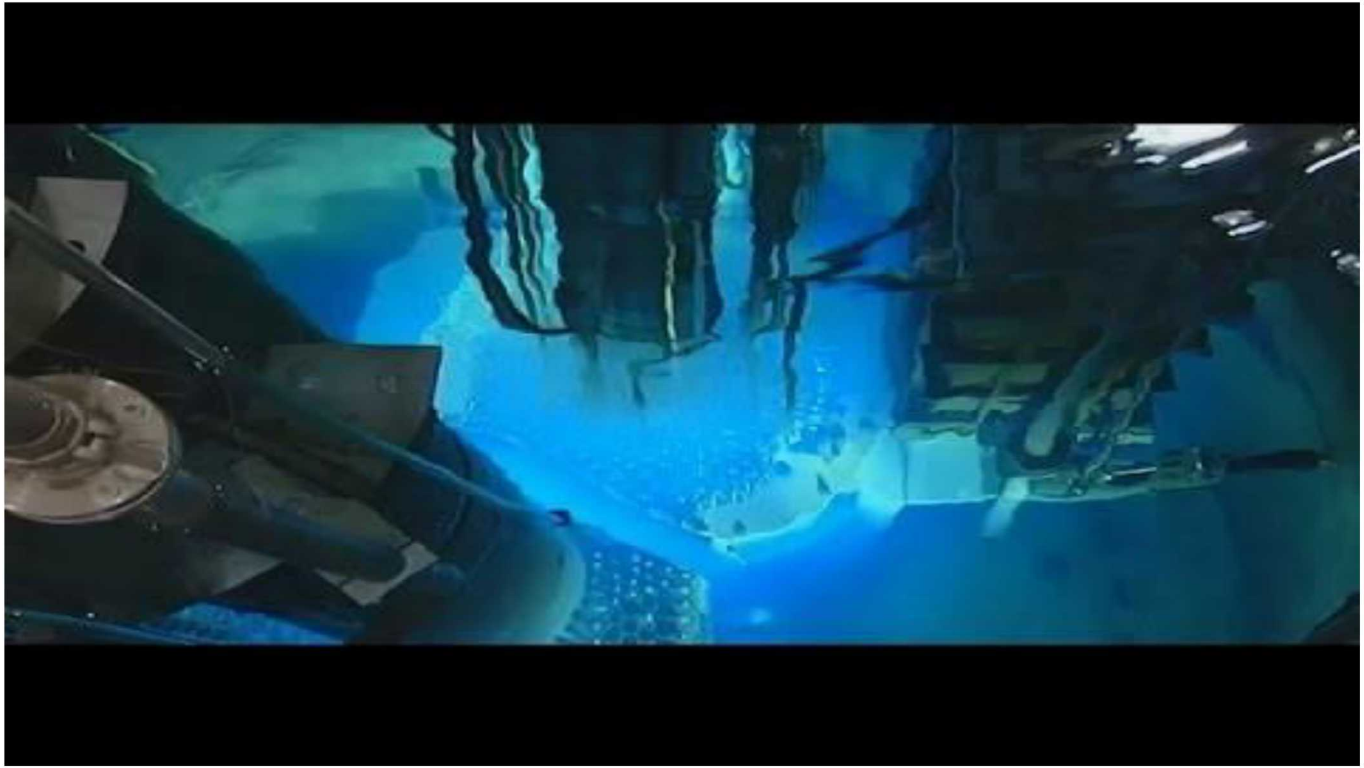
Safety rods are removed → Control rods are adjusted to operate at SS → Reactor operators determine worth of package → Transient rods are ejected to induce pulse

↓

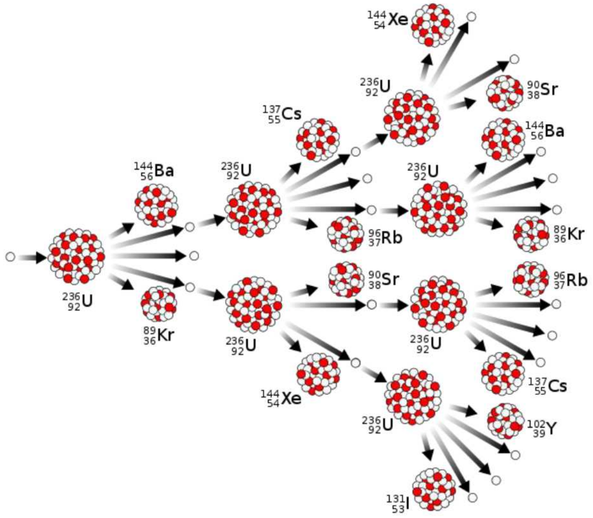
PULSE

← Doppler broadening in the fuel shuts reactor down ← Transient rods are released back into reactor

INTRODUCTION: ACRR's 10,000th Operation



INTRODUCTION: Fission



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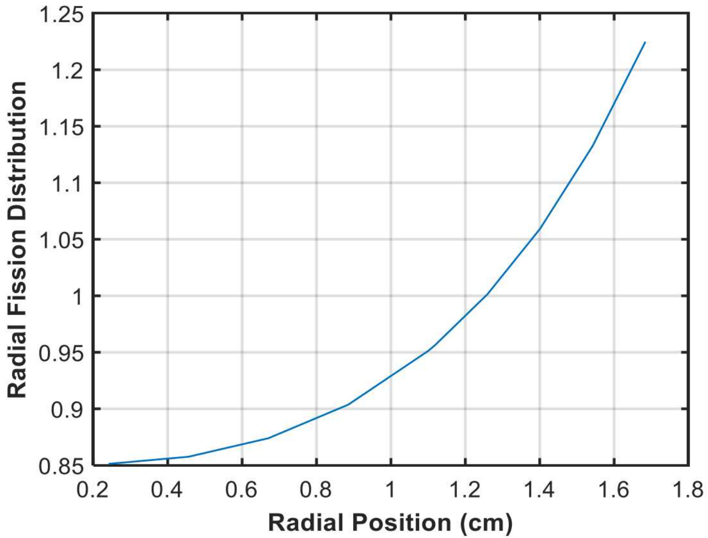
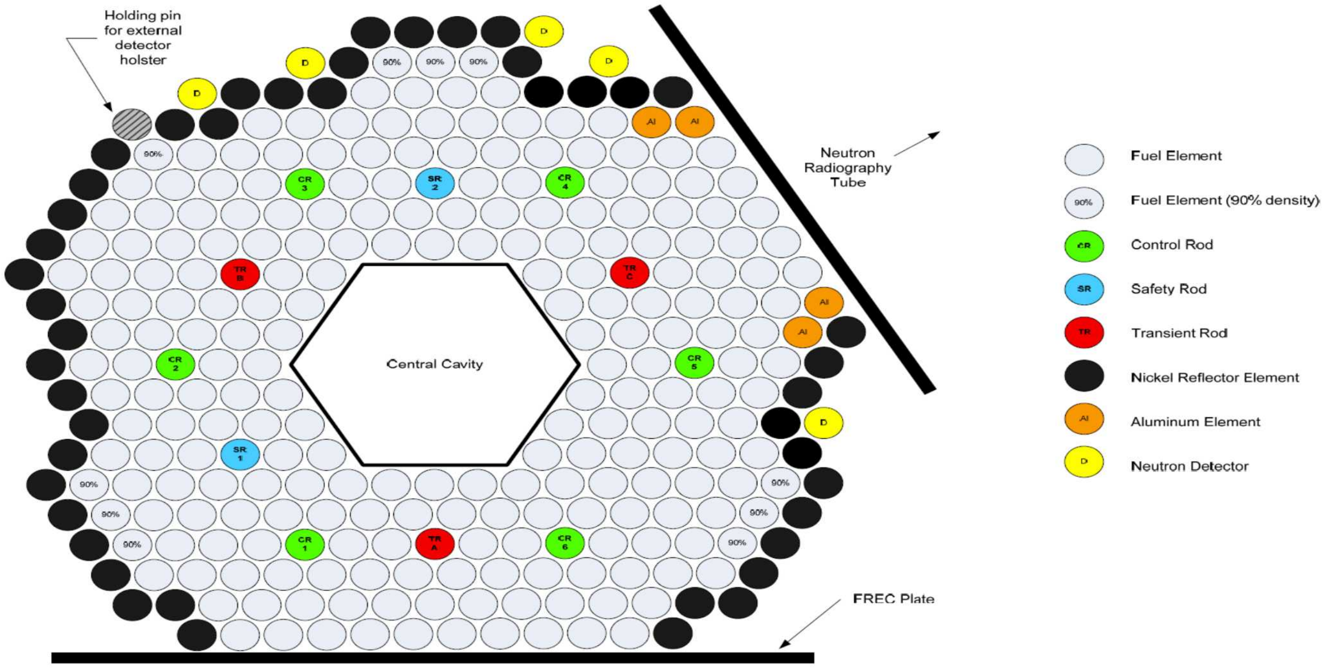


INTRODUCTION: Reactor Layout



[4]

INTRODUCTION: Burnup and Radiation Effects

Impurity Buildup

- Transmutation

$$\mathbf{n + {}^{9}_{4}Be \rightarrow [{}^{10}_{4}Be] \rightarrow 2n + 2{}^{4}_{2}He}$$

$$\mathbf{n + {}^{9}_{4}Be \rightarrow [{}^{10}_{4}Be] \rightarrow {}^{6}_{2}He + {}^{4}_{2}He}$$

$$\boldsymbol{\gamma} + \mathbf{{}^{9}_{4}Be \xrightarrow{n} [{}^{8}_{4}Be] \rightarrow 2{}^{4}_{2}He}$$

$$\boldsymbol{{}^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu}$$

- Fission Fragments
  - I, Ba, Xe

Lattice Defects

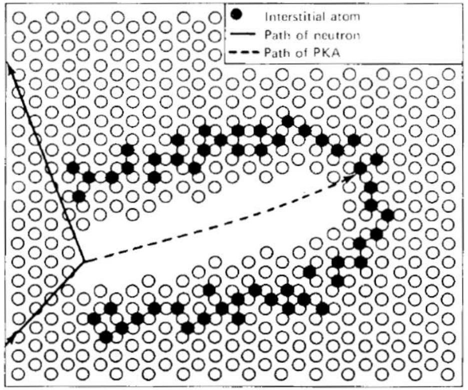


Fig. 17.24 Original version of the displacement spike. [After J. A. Brinkman, *Amer. J. Phys.*, 24: 251 (1956).] [5]

INTRODUCTION: Work Performed

- Estimated the effects of burnup in the ACRR
- Estimated the material properties of fuel
- Performed transient thermal and structural analysis of pulse
- Performed a material property sensitivity study
- Examined the effects of the stresses

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PREVIOUS WORK: Timeline

Quarterly Reports

- In-pile experiments
- Fuel pellets were 93% enriched
- Multi-pulse and single-pulse experiments

[6,7]

Wright's Report

- Estimated burnup
- Correlated in-pile experiments to fracture using Boley-Weiner
- Determined fracture strength was 179 MPa
- Determined the pellets have a very small probability of failing

[9]

1974 1977 1982 1990's 2019

Tills' Report

- Correlated stresses during in-pile experiments to transient thermal analysis
- Determined pellets begin to fracture at ~88 MPa
- Suggested the pulses in the ACRR should be further limited

[8]

PREVIOUS WORK: Summary

- None of the reports included true fuel element geometry
- No experimental materials testing was ever performed
- The analyses did not include temperature dependent material properties
- The Tills and Wright reports had contradictory conclusions

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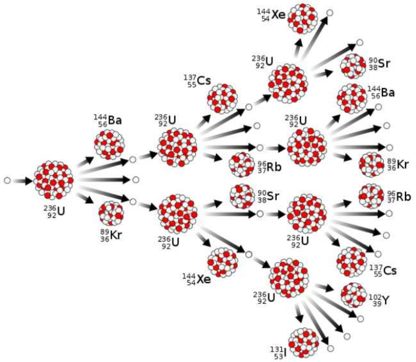
ESTIMATION: Current Burnup

Element	Mass (g)
^{238}U	10.00
^{235}U	150.0
^{239}Pu	15.57

[10]



Total Mass (g) ^{235}U	Mass (g) ^{235}U per Element	% ^{235}U	Fissions/cm^3	% Heavy Atom Burnup	MW-Day
150	0.64	0.63	4.4E18	0.16	167

ESTIMATION: Estimated Effects

Property	Percent Change in Property (%)
Strength	-1.5
Modulus of Elasticity	-14
Thermal Conductivity	-70
Gap Thermal Conductivity	Negligible
Change in Volume	0.37

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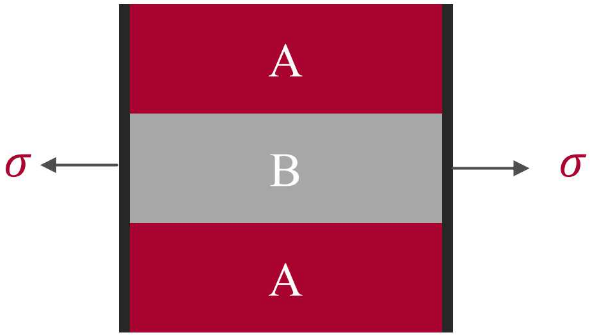
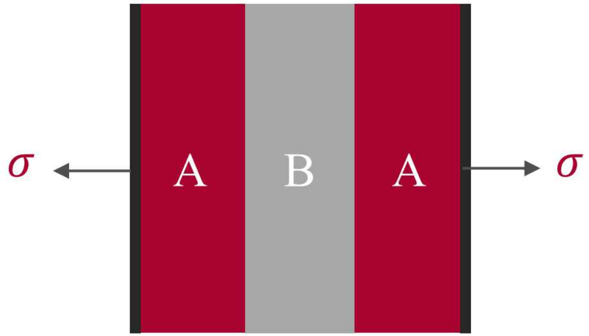
MATERIAL PROPERTIES: Modulus of Elasticity

- Used Voigt-Reuss-Hill Approximation

Voigt



Reuss



$Voigt - Reuss - Hill$

$$E = \frac{(E_{Voight} + E_{Reuss})}{2}$$ [11]

MATERIAL PROPERTIES: k, α, C_p

- Used Maxwell's expression for thermal conductivity

$$k_{eff}=k_m\left[1+\frac{3V_p}{\frac{k_p+2k_m}{2(k_p-k_m)}-V_p}\right]$$ [12]

- Used "refined" rule of mixtures for CTE

$$\alpha_{eff}=\alpha_m-V_p\theta(\alpha_m-\alpha_p)$$

$$\theta=\frac{3E_p(1-\nu_m)}{[(1+\nu_m)+2V_p(1-2\nu_m)]E_p+2V_mE_m(1-\nu_m)}$$ [13]

- Used the rule of mixtures for specific heat

$$C_{eff}=V_mC_m+V_pC_p$$

MATERIAL PROPERTIES: Fracture Strength

- Dependent on microstructure, stress state, temperature, and flaw size
- Estimated using in-pile experiments
- Tills simulated two in-pile experiments: 364 cal/g and 429.4 cal/g
- Wright calculate thermal stresses of two in-pile experiments as well: 1150°C and 1410 °C

Tills

$$\text{Peak/Avg}= 0.79985971 + .34048928r - 1.2141774r^2 +1.939536r^3 - 1.2757009r^4 +.32146363r^5$$

[8]

Wright

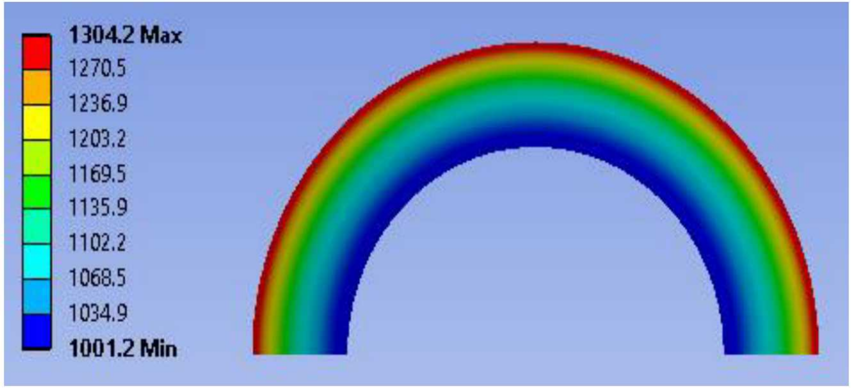
$$T(r)=1150\left[0.5004+0.0187\exp\left(\frac{r}{0.4997}\right)\right]$$

$$T(r)=1410\left[0.4928+0.008058*\exp\left(\frac{r}{0.3962}\right)\right]$$

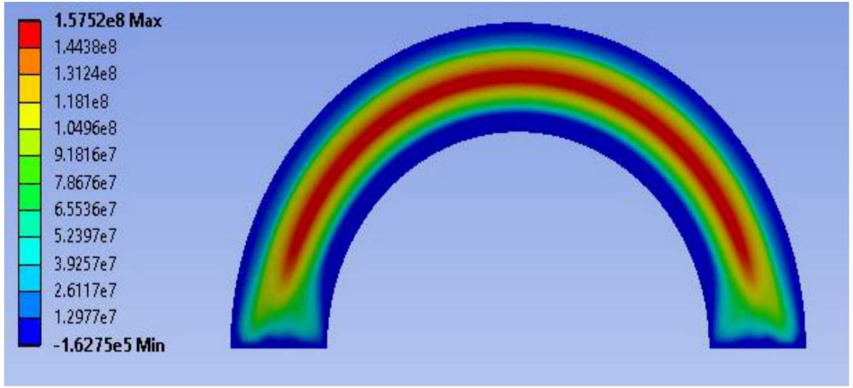
[9]

MATERIAL PROPERTIES: Fracture Stress Cont'd

- Temperature and stress contour plots of 429.4 cal/g experiment



Temperature (°C)



Stress (Pa)

MATERIAL PROPERTIES: Fracture Stress Cont'd

	Tills		Wright	
Experiment	364 cal/g	429.4 cal/g	1150°C	1410°C
Max Experimental Temperature (°C)	1182.9	1340	1189.8	1491.7
Reported Thermal Stresses	74MPa (10.8ksi)	88MPa (12.8ksi)	68MPa (9.98ksi)	108.9MPa (15.8ksi)
Pelfrey's Thermal Stresses	134.7MPa (19.53ksi)	153.5MPa (22.2ksi)	174.0MPa (25.2ksi)	271.4MPa (39.4ksi)
# of Pellets Fractured	0/40	10/40	2/8 @ 101 Pulses	6/10 @ 71 Pulses

MATERIAL PROPERTIES: Conclusion

- Material properties for He, Nb, and SS are all readily available
- Material properties for fuel pellets were derived from basic relations
- Material properties were adjusted for burnup by simply scaling them
- Because the properties were derived and not measured, they introduced uncertainty

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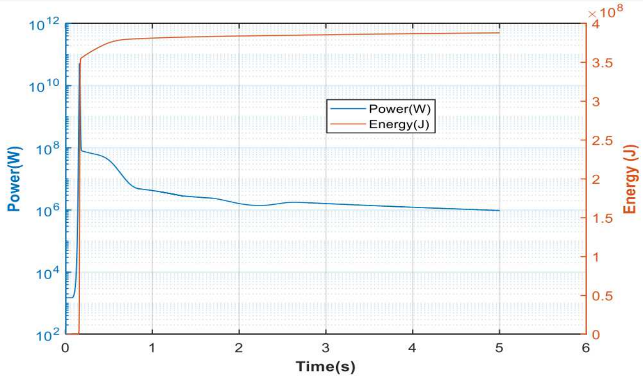
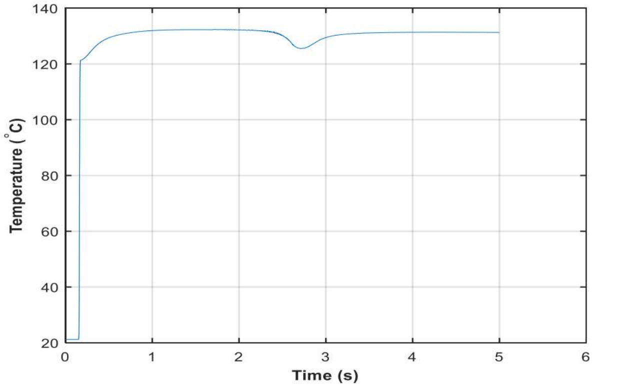
THERMAL ANALYSIS: Loads and Boundary Conditions

- Used RAZORBACK to simulate a max pulse operation
- Simulated a \$3.16 pulse
- Power of 52 GW and energy generation of 388 MJ
- This is a very large pulse

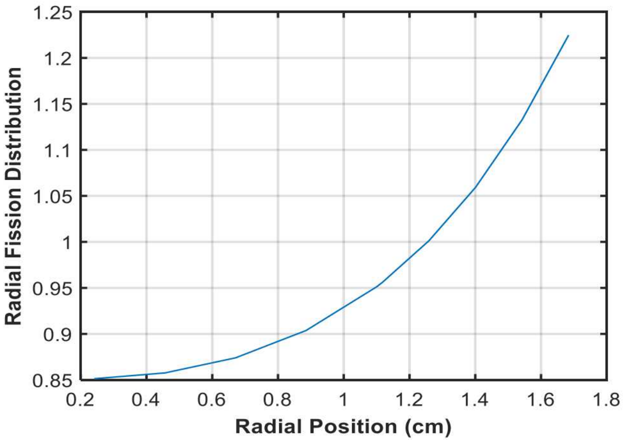




THERMAL ANALYSIS: Loads and Boundary Conditions Cont'd

- Volumetric heat generation applied in areas where fission and radiation deposit heat
- Neutron and gamma heating accounted for in Nb

Axial Peaking Factor (peak/average)	1.24
Core Peaking Factor (peak/average)	1.52
Peak Fission Profile	$F_{peak}(r)=0.7962e^{-0.1299*r}+0.0570e^{1.382*r}$



THERMAL ANALYSIS: Loads and Boundary Conditions Cont'd

Time Stepping

$$Fo = \frac{k\Delta t}{\rho C(\Delta x)^2}$$

Gap Conduction

Convection is assumed to be negligible in the small gaps

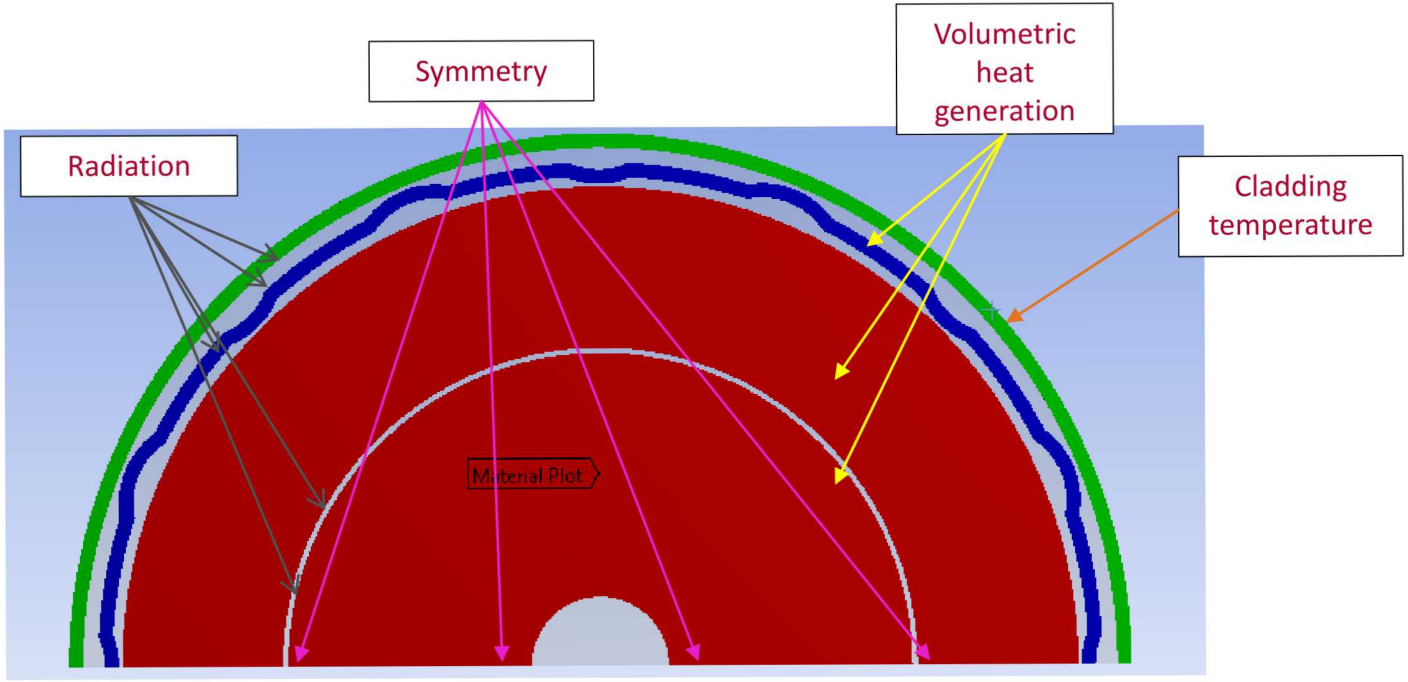
Outer Cladding

Used results from RAZORBACK

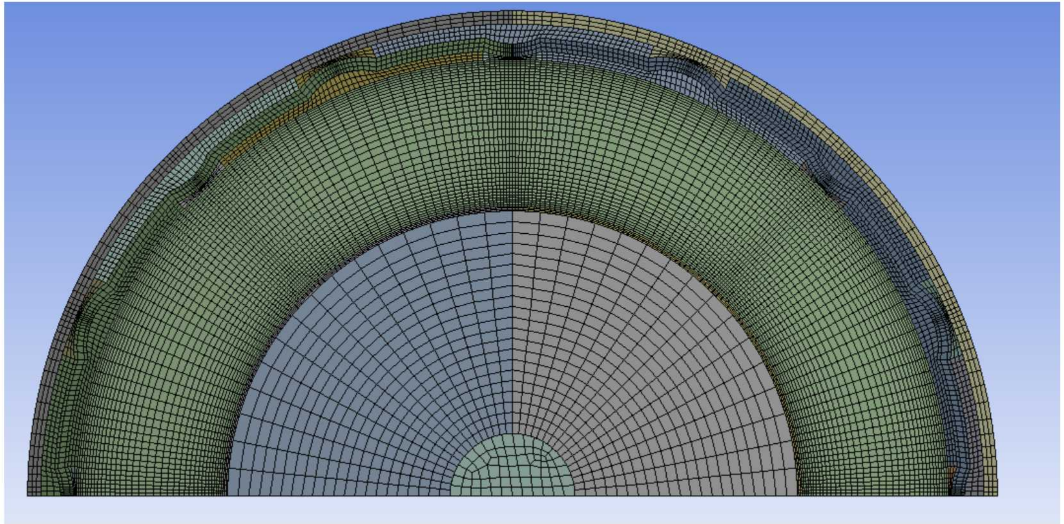
Gap Radiation

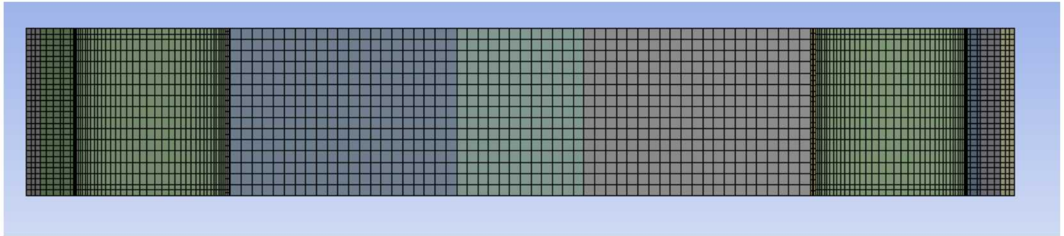
Material	Emissivity	Source
SS	0.67	[51]
UO_2-BeO	0.37	[6]
Nb	0.22	[52]

THERMAL ANALYSIS: Loads and Boundary Conditions Cont'd

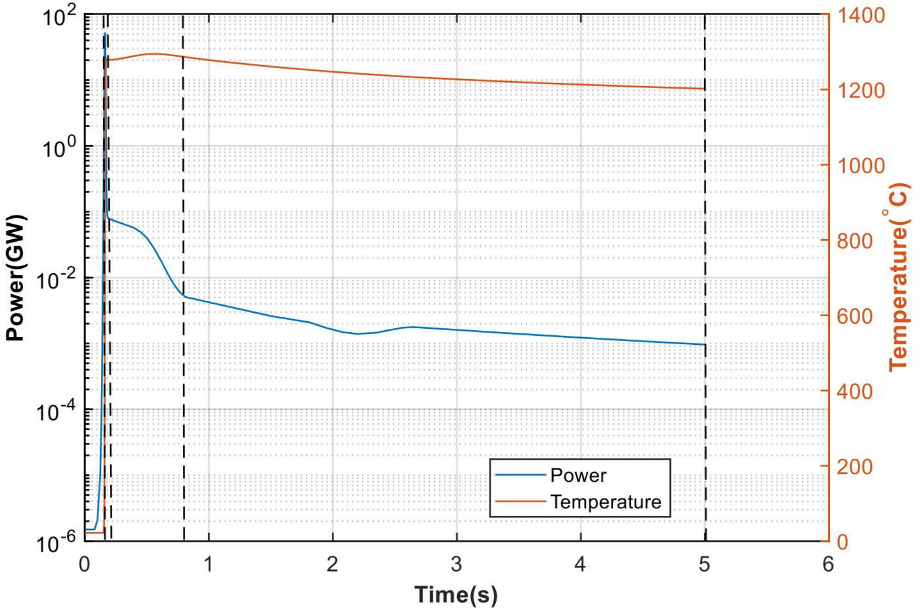


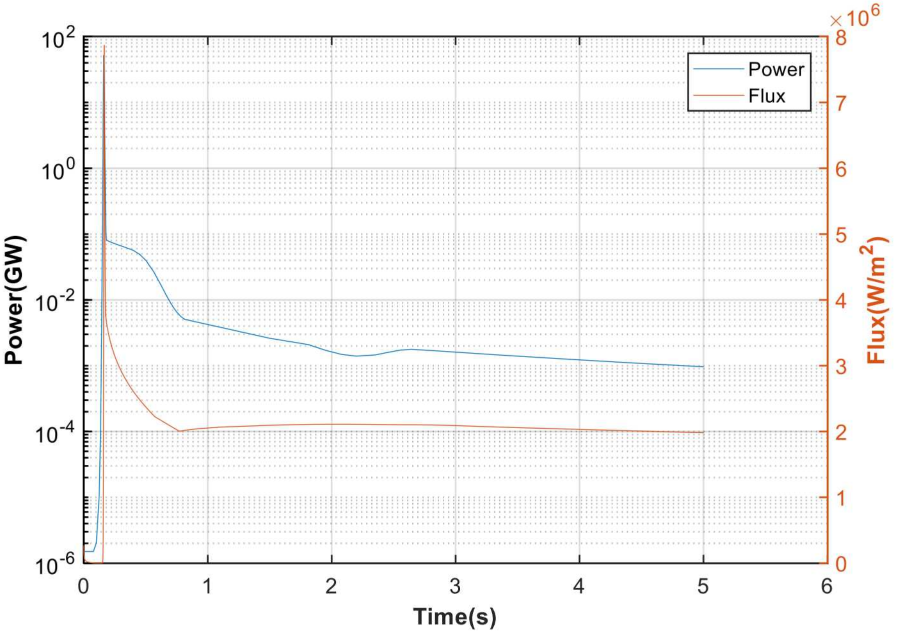
THERMAL ANALYSIS: Mesh





THERMAL ANALYSIS: Results





THERMAL ANALYSIS: Results

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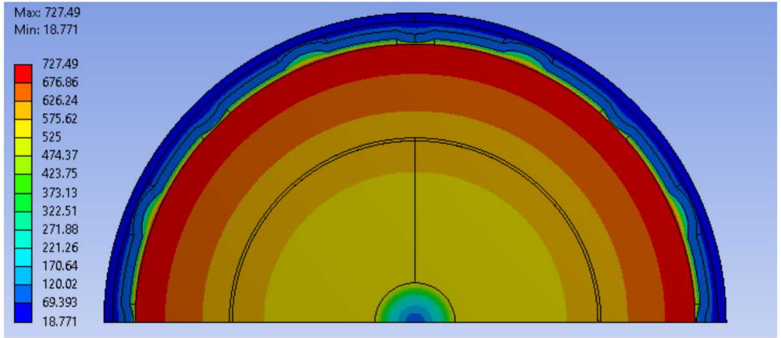

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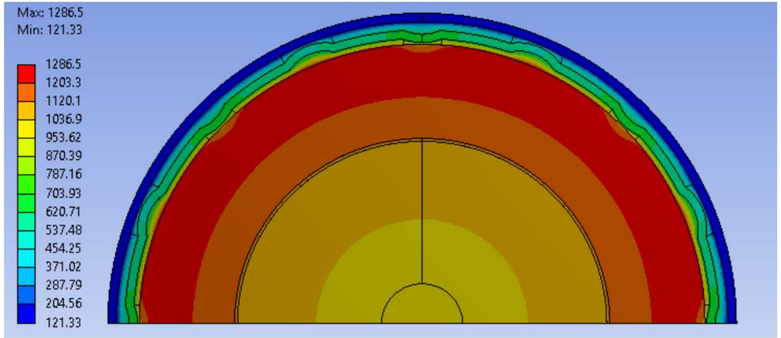

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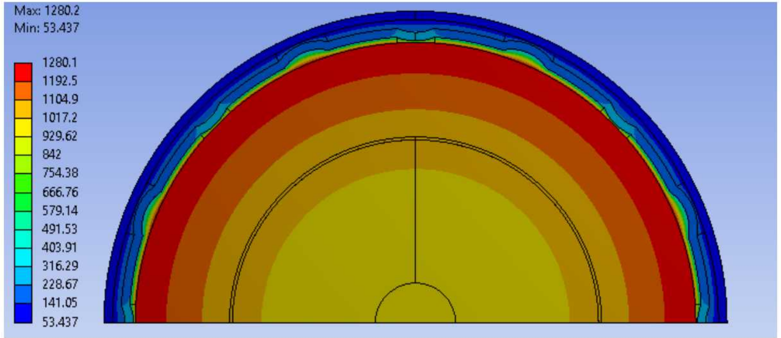

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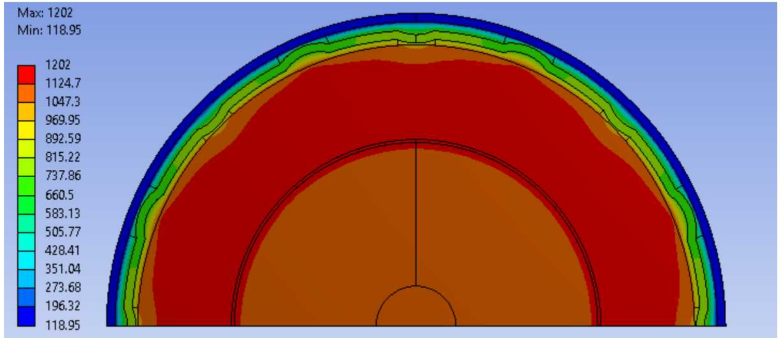

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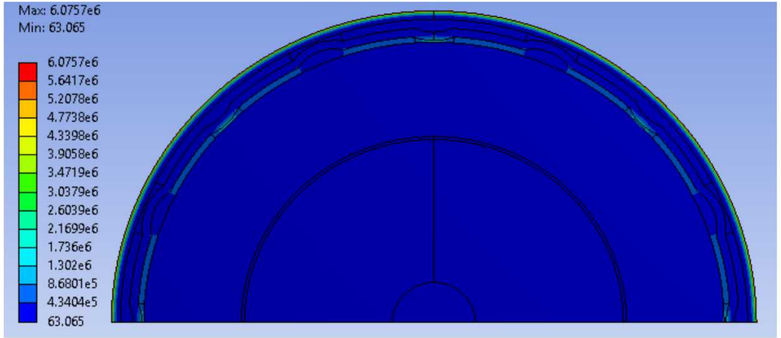

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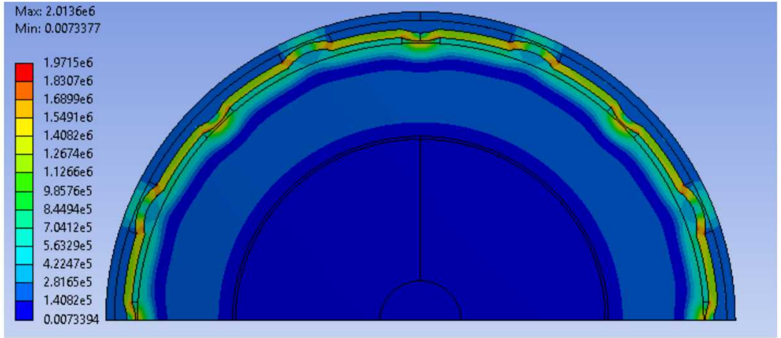

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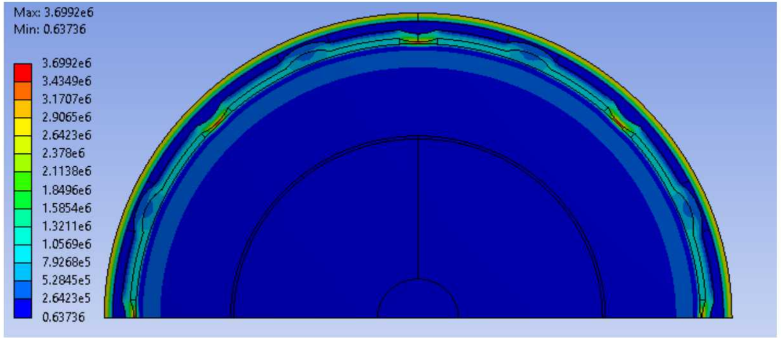

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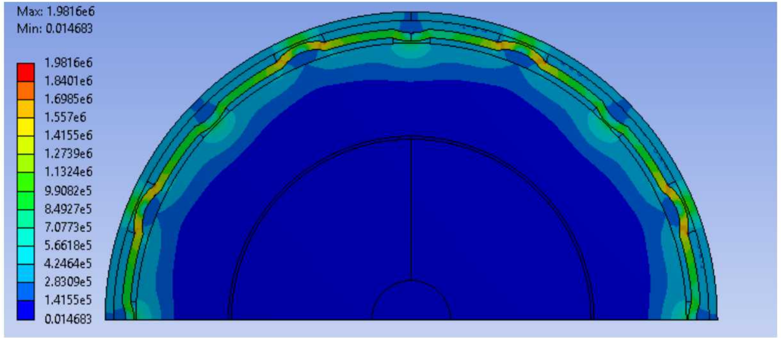

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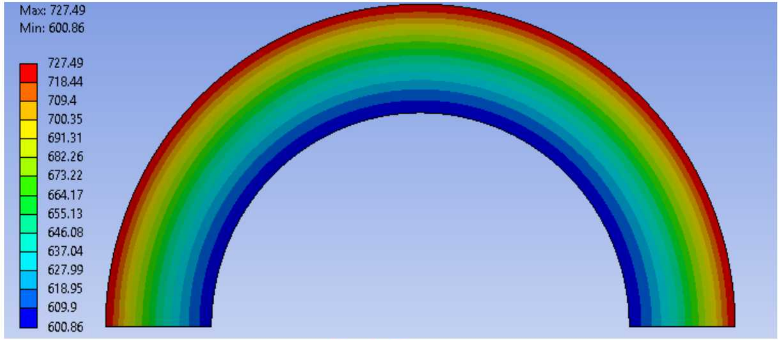

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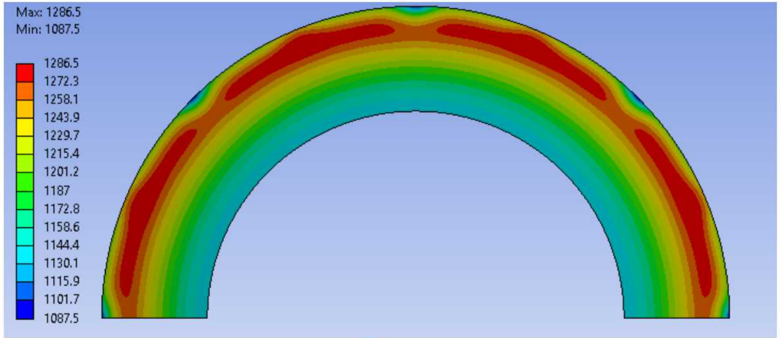

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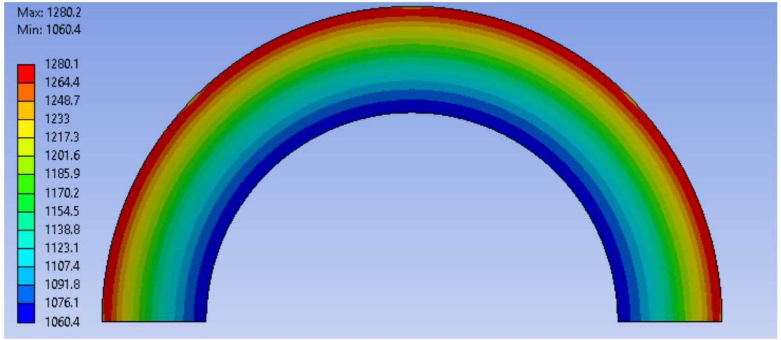

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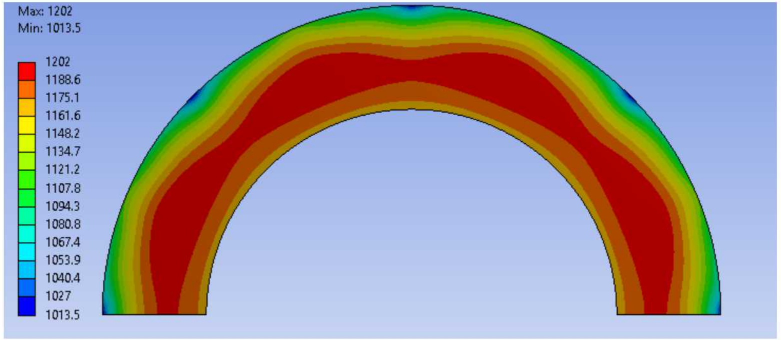

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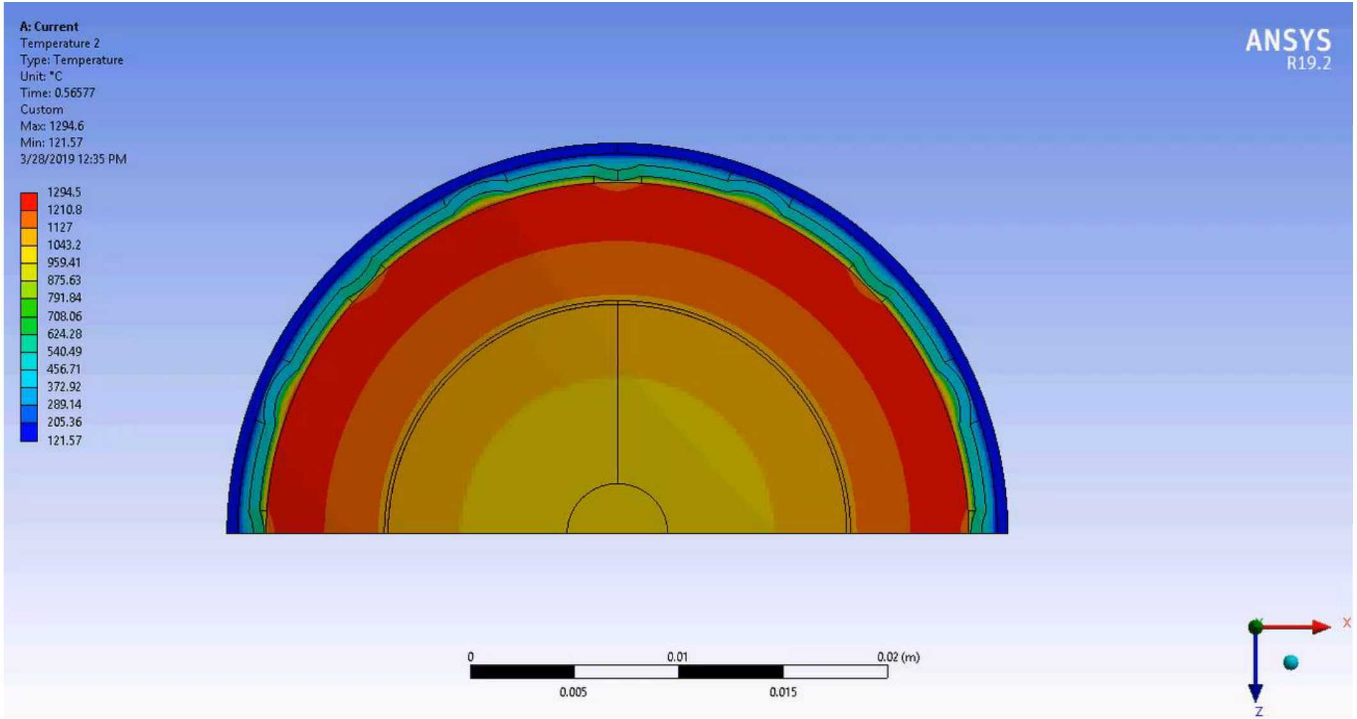

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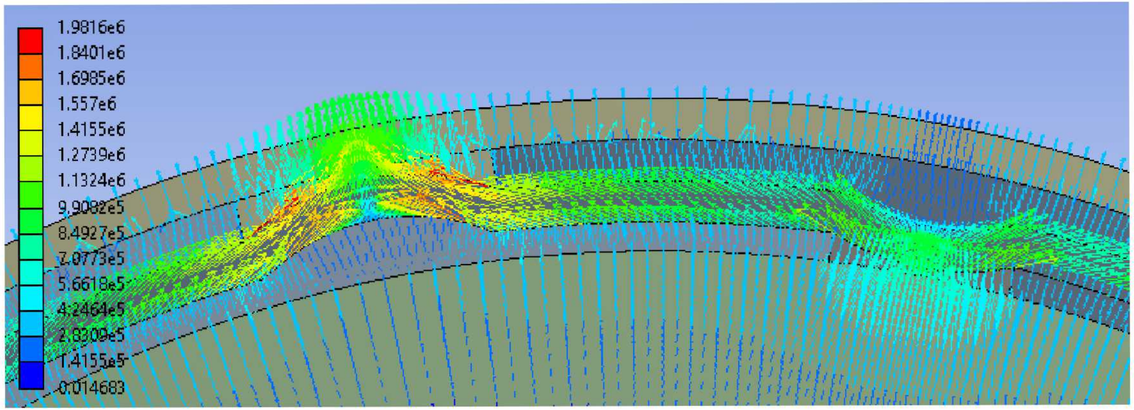

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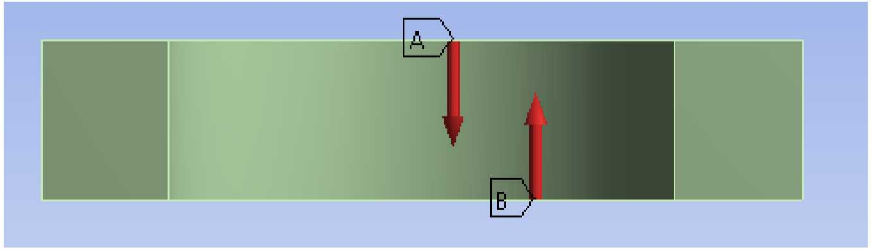
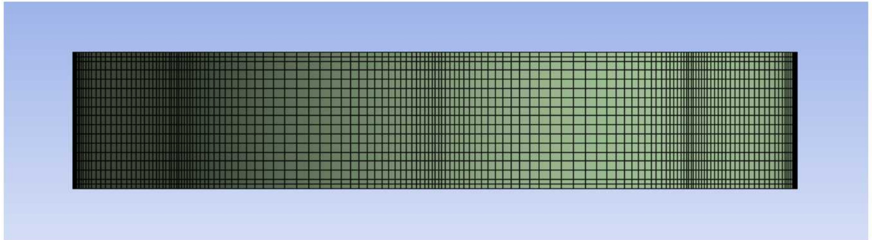
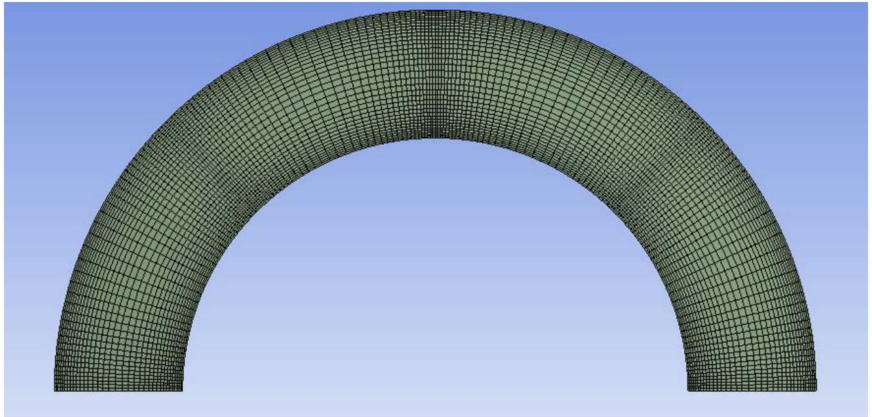
STRUCTURAL ANALYSIS: Loads and Boundary Conditions

- Weak spring boundary condition was applied to the body
- Weight of fuel pellets above and below were accounted by applying 0.4431 N loads
- Temperature gradients from transient thermal analysis were inputted







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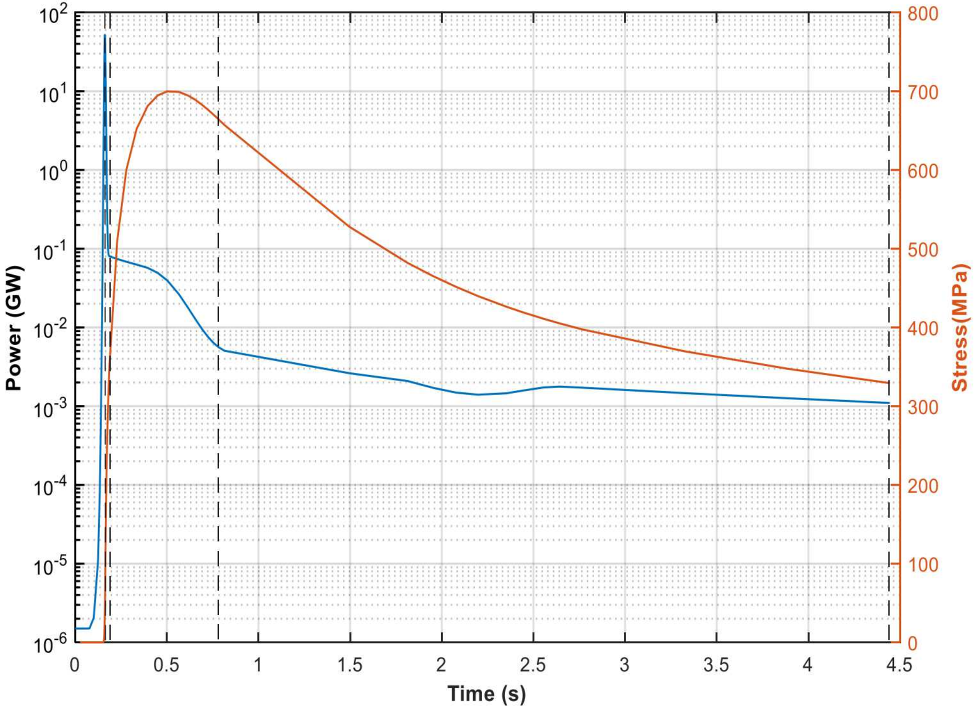

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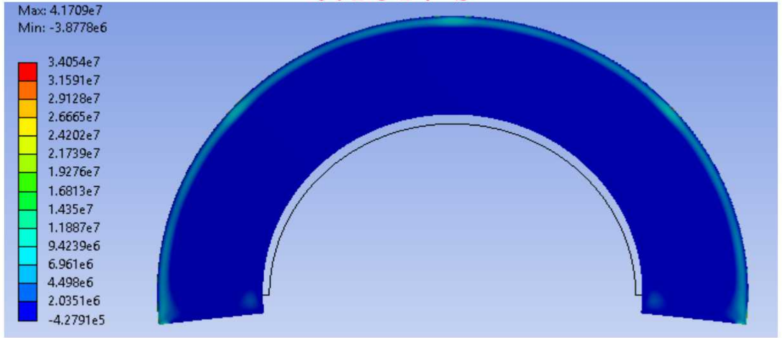

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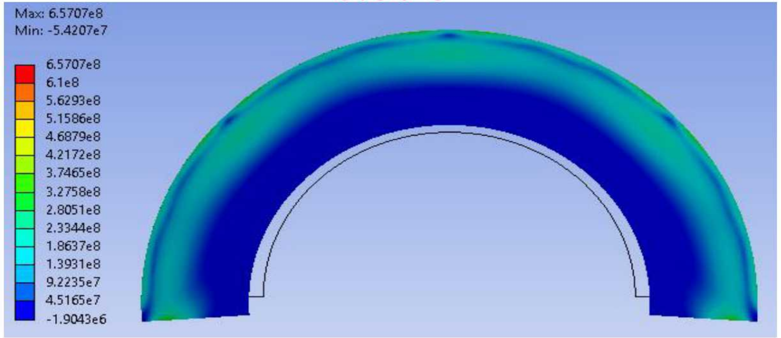

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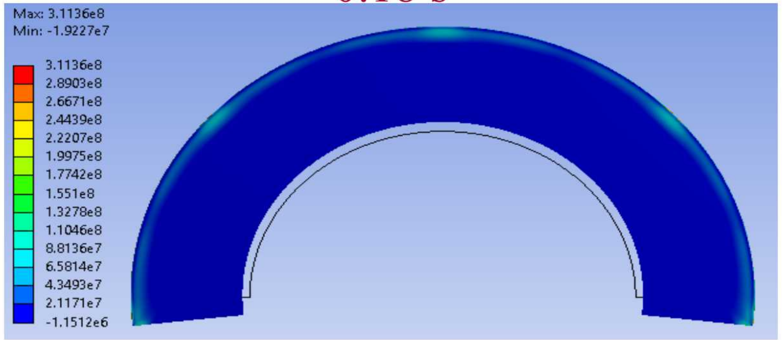

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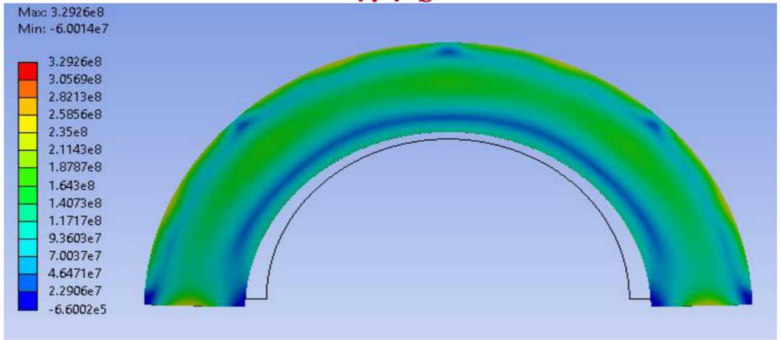

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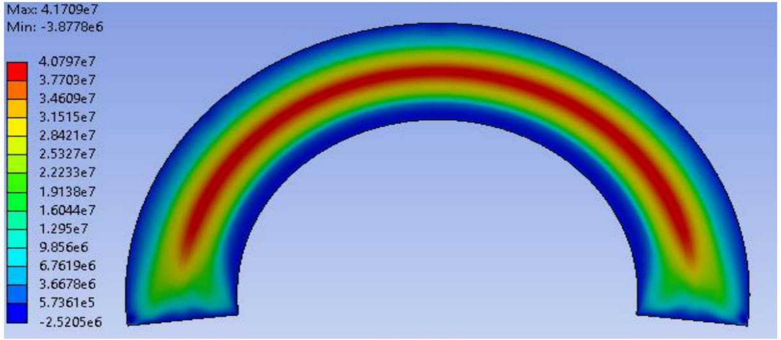

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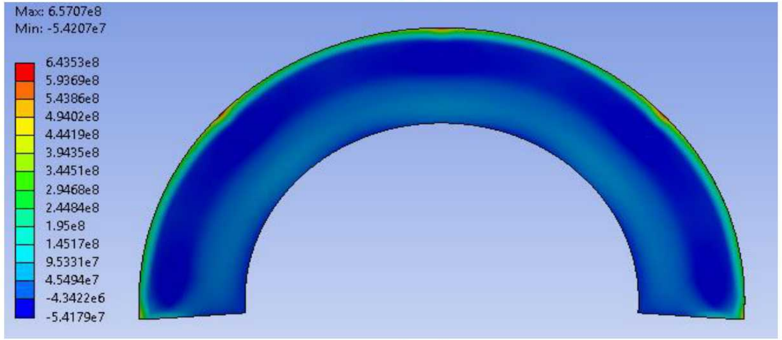
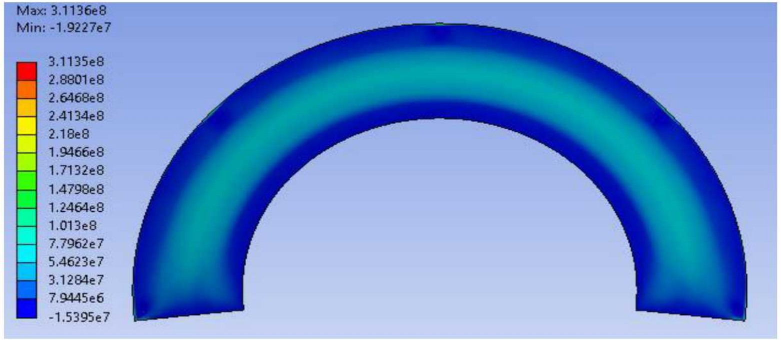
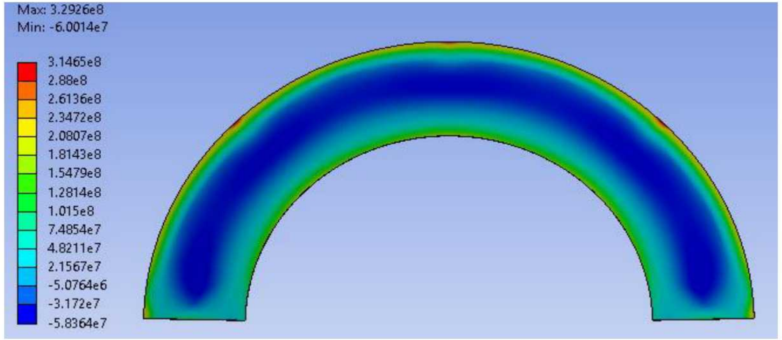


0.18 s

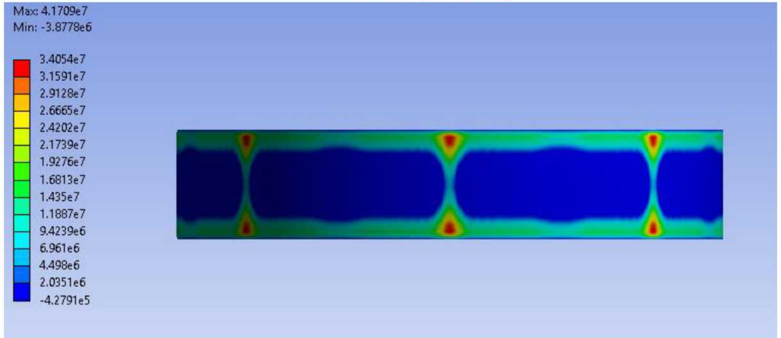


4.4 s

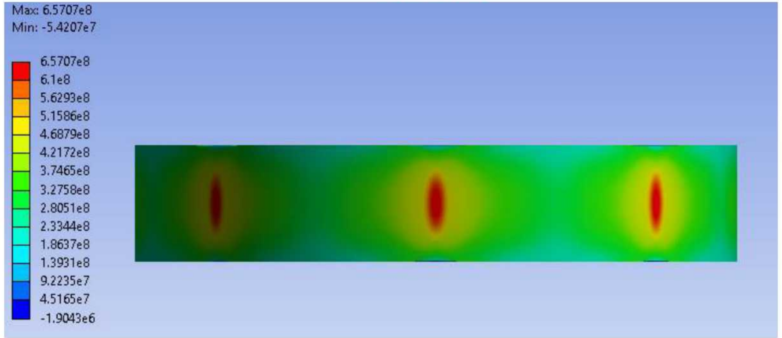


STRUCTURAL ANALYSIS: Results

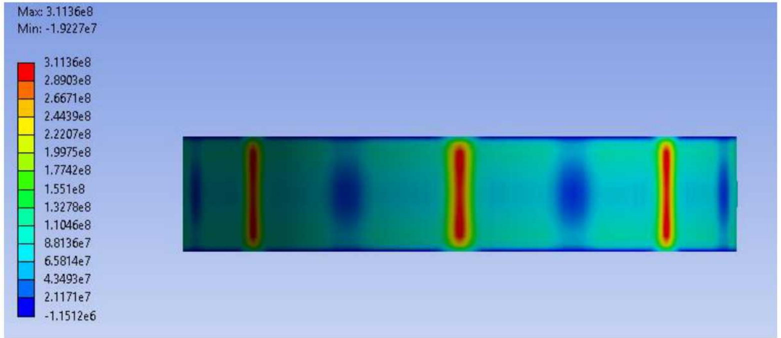
0.1617 s



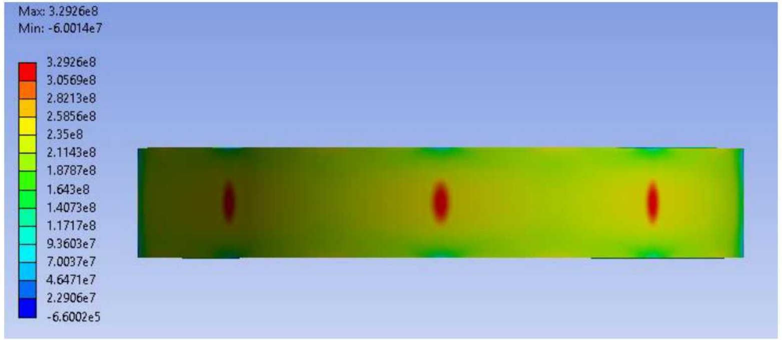
0.80 s



0.18 s

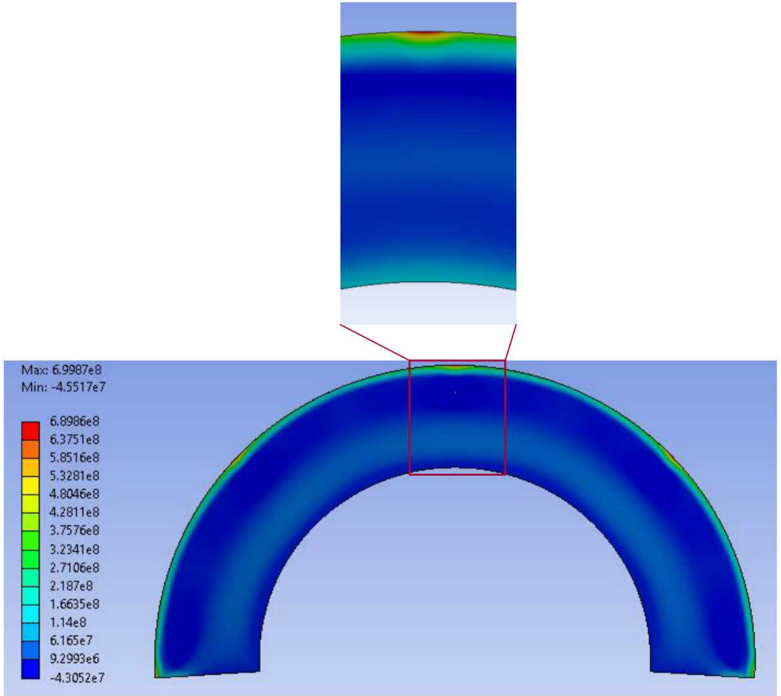


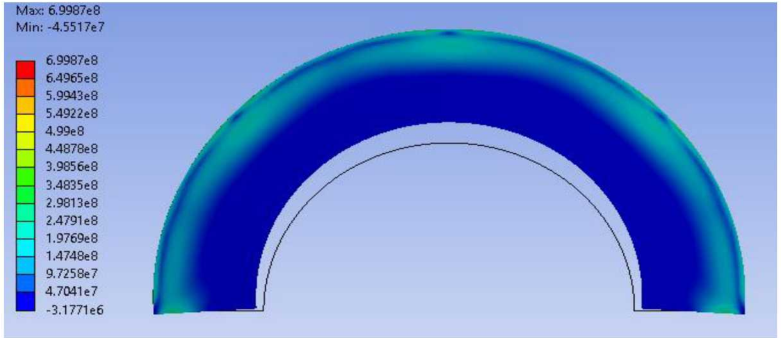
4.4 s

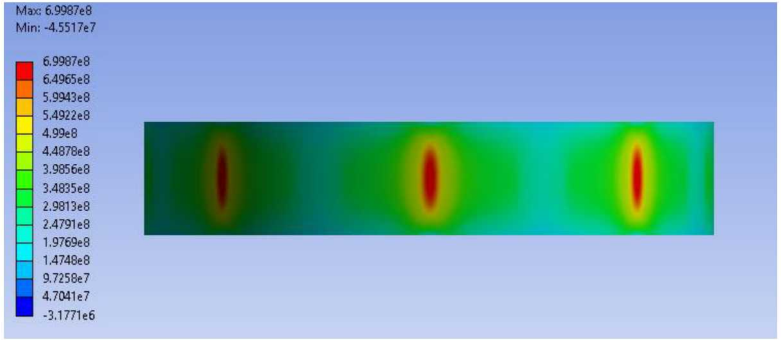


STRUCTURAL ANALYSIS: Results

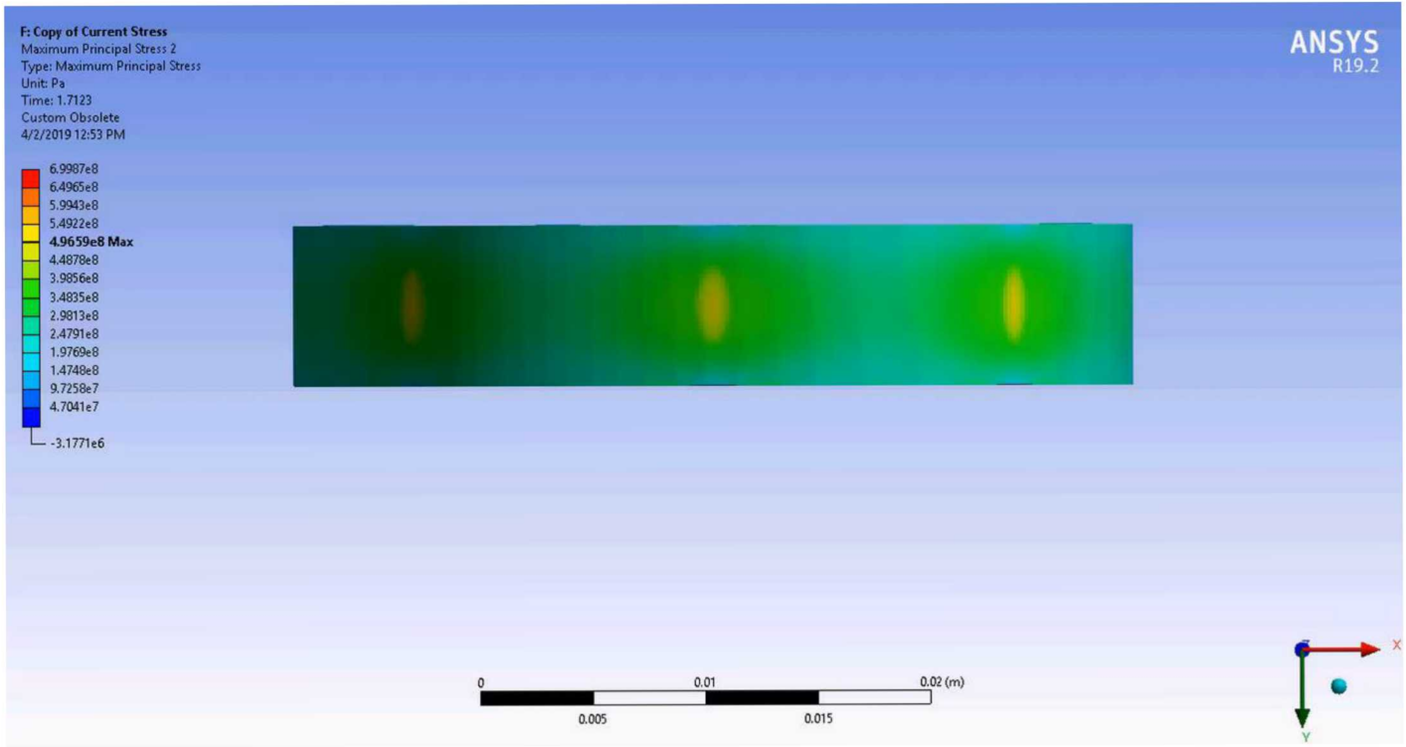
Maximum Stresses (0.5 s)





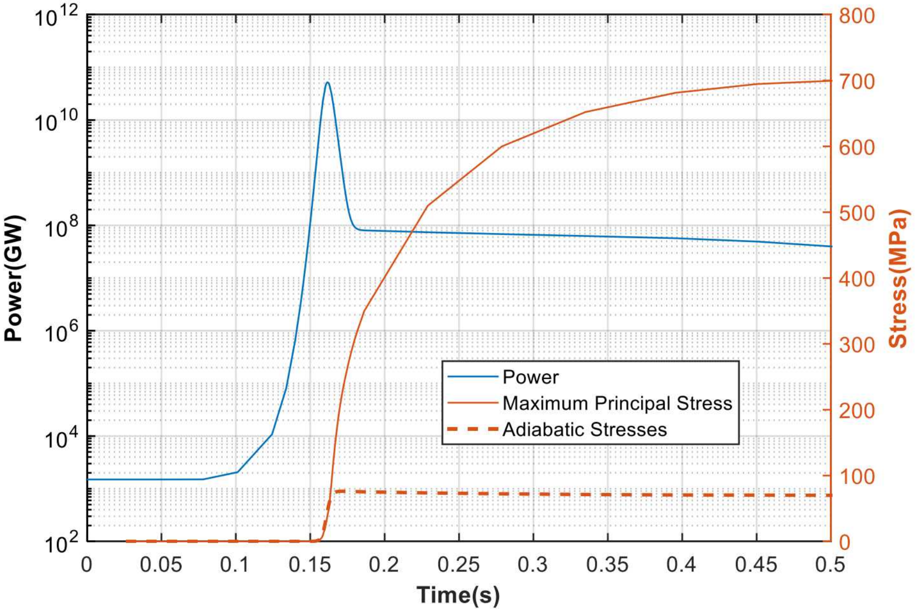


STRUCTURAL ANALYSIS: Results



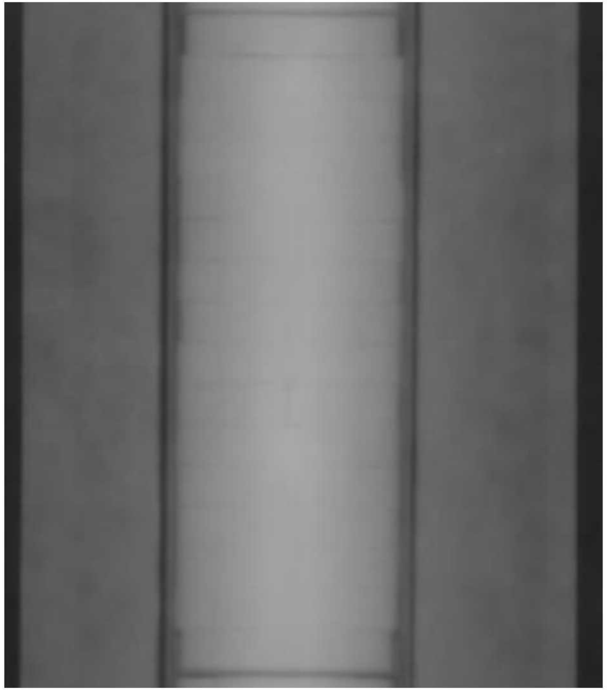
TRANSIENT ANALYSIS: Discussion

- The fluted Nb increases heat flux
- Increased heat flux causes localized cooling
- Localized cooling causes large thermal stresses
- Stresses can be described in two phases
  - Stresses caused by the fission distribution
  - Stresses caused by heat loss



TRANSIENT ANALYSIS: Discussion

- It would seem that pellets would fracture due to large localized stresses
- Neutron radiography performed in 1989 showed fuel pellets were intact
- Analysis was performed with fresh fuel properties to insure stresses were not due to burnup
  - Showed stresses increased but calculated stresses for fresh fuel still far exceeded stresses that cause fracture during in-pile experiments



TRANSIENT ANALYSIS: Discussion

- Reasons for discrepancy
  - Derived properties could cause over estimations of the stresses
  - Neutron radiographs may not have enough resolution to detect cracks
  - The small volumes that stresses occupy do not induce fracture

OUTLINE

- Introduction
- Previous Work
- Burnup and Radiation Effects
- Material Properties
- Transient Thermal Analysis
- Transient Structural Analysis
- **Material Sensitivity**
- A Fracture Mechanics Perspective
- Conclusion

PROPERTY SENSITIVITY: TC & E

Thermal Conductivity	Maximum Principal Stress (MPa)	Percent Change (%)
25% ↑	614	-12
-	700	-
25% ↓	823	+18

Modulus of Elasticity	Maximum Principal Stress (MPa)	Percent Change (%)
25% ↑	875	+25
-	700	-
25% ↓	525	-25

PROPERTY SENSITIVITY: CTE

Coefficient of Thermal Expansion	Maximum Principal Stress (MPa)	Percent Change (%)
25% ↑	875	+25
-	700	-
25% ↓	525	-25

- Thermal stresses are most sensitive to E and CTE

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FRACTURE MECHANICS: Maximum Strength

- Assumptions
  - Plane strain
  - Minimum crack size of 1 μm
  - Fracture toughness is that of the BeO
- Max fracture strength of 782 MPa

Plane-Strain Fracture Toughness

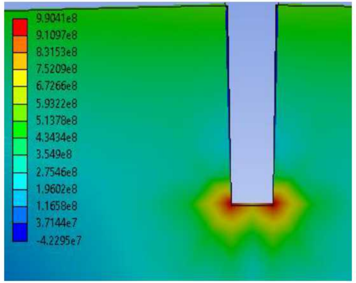
$$K_{IC} = Y * \sigma_O \sqrt{a * \pi}$$ [14]

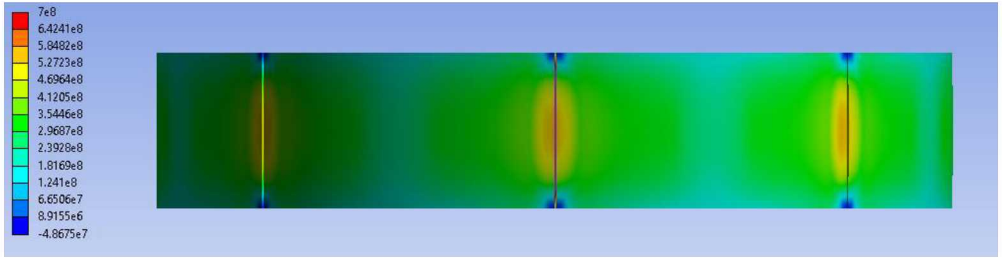
Fracture Toughness

$$K_{IC} = \sqrt{G_C * E}$$

FRACTURE MECHANICS: Cracking

- Cracks introduced using element death
- Singularities were neglected
- Reduced max stress to 555 MPa

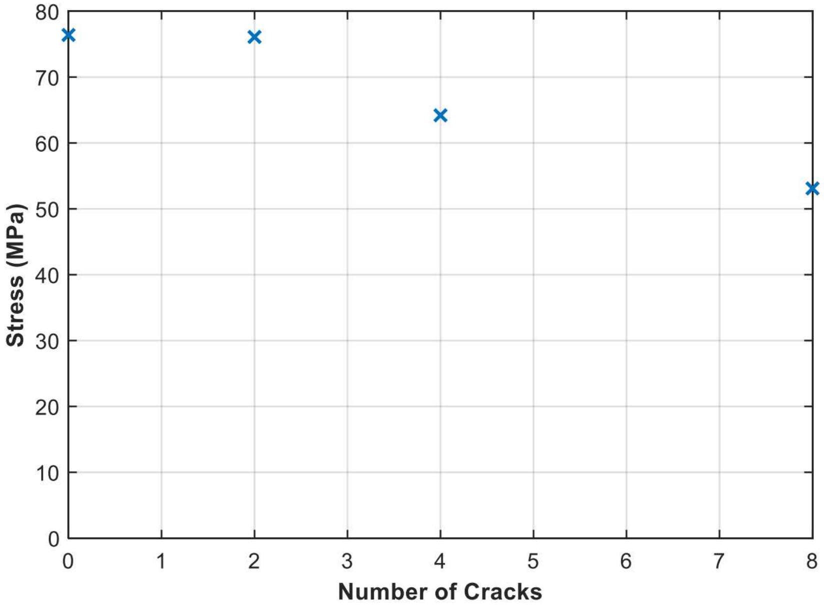




FRACTURE MECHANICS: Fracture

- Assumptions
  - Pellets fracture
  - Fission profile causes fracture

- Stresses are reduced as pellet fractures



OUTLINE

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- **Conclusion**

CONCLUSION

- Nb fluting does play a role in heat transfer and induces thermal stresses
- Neutron radiography indicated that the stresses would not induce fracture
- Thermal stresses caused by fission profile are well below the estimated fracture strength
- If fracture occurs, it will lower the stresses
- Cracks could also lower the thermal stresses
- Without proper material properties, neutron radiography should be performed to know the state of the fuel

CONCLUSION: Future Work

- Fully coupled thermal-structural analysis
- Further investigations into properties of the fuel
- Neutron radiography

QUESTIONS?

Sources

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