Thermal-hydraulic analysis of our modified annular-fuel-based reactor design

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Acknowledgment

- I would like to thank the rest of my team for their hard work and cooperative nature as well as my professors and doctors for their wise guidance and continuous support:
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  - Prof. Yasser Khalil
  - Dr. Rowayda Fayez
  - Ahmed Ossama abbass
  - Mostafa Ihab
  - Nour Ali

contents

Introduction (design criteria)

- Surveying recent engine designs capable of powering large container ships resulted in the propulsion power requirement being set at 80 MW(e) . (arround 75% ship power requirements and 25% hotel load)
- the total power requirement for the reactor studied in this work was set to 110 Mw(e).
- Considering high efficiency similar to current PWRs of 30-33% the thermal power was set to 350 MWth.

Introduction (design criteria)

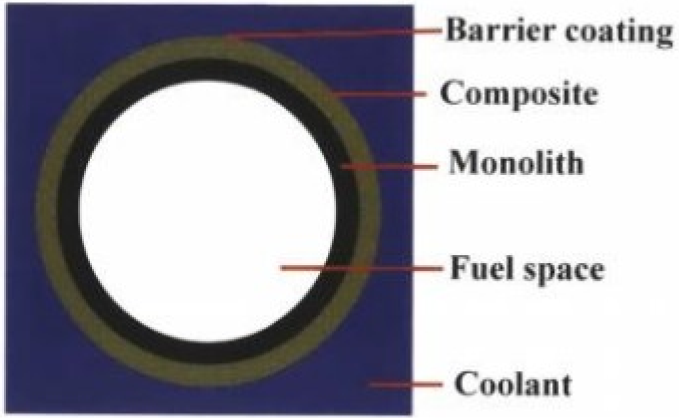
- a 15-year core life can be achievable and was so chosen, assuming 1 as a capacity factor for simplifications.
- Due to the dimensions limitations and due to the fact that annular fuel is significantly larger; lower number of fuel elements per assembly had to be chosen.
- 11x11 assembly is chosen, to retain mechanical stability as well as production feasibility.
- The assembly element dimensions were chosen based on this limitation and on the hydrogen to heavy metal ratio (HHM) which is based on trial and error
- The annular fuel dimensions are based on coupling thermal-hydrauics with neutronics works, lead by trial and error and with the reference MIT's fuel dimensions (as an initial guess)
- Uranium dioxide (UO_2) was chosen as fuel after investigating several other fuel materials also it has several advantages since it is commonly used with a lot of experimental data and manufacturing feasibility.
- we have divided the core into 3-batches of 14%, 13%, 12% respectively with the lower enrichments towards the center to help flatten the power distribution.
- two layers of thorium dioxide (ThO_2) was added to the fuel as thorium helps prolong fuel cycle.

Introduction (design criteria)

- To have a high efficiency PWR, outlet temperature must be high. Normal commercial PWRs have an average 325°C outlet water temperature which corresponds to about 33% efficiency.
- Zircaloy proved to be limited under aggressive working conditions, high power or long fuel cycle leading to allowing fission products into the coolant and therefore a clad failure.
- Oxidation reaction also happens more rapidly over 300 degC
- As the zircaloy temperature increases, its strength decreases about 2% every 100C above 300'C, and the elastic modulus 1% every 100C, The thermal creep rate also increases exponentially with temperature, which causes new challenges with the inner channel.
- Long core life MPRs like ours have low temperatures due to Zircaloy limitations, hence low efficiency ~25%. Since one of our objectives is to reach high efficiency, we overcame this limitation by using triplex SiC as cladding material due to its high-performance capability to achieve higher outlet temperatures and hence high efficiency.

Introduction (design criteria)

- Unlike zircaloy, SiC will retain its strength and will not creep up to 1300°C, and it remains viable to even twice that temperature. SiC is also stable under irradiation, with swelling, which causes a new challenge in the inner channel flow, and changes to strength and thermal conductivity saturating after a few months of typical irradiation. It can also accommodate fission products due to its porous monolith layer and can achieve high burnup up to 100 MWD/kgU.
- In essence such challenges can be avoided by using SiC instead of Zircaloy.

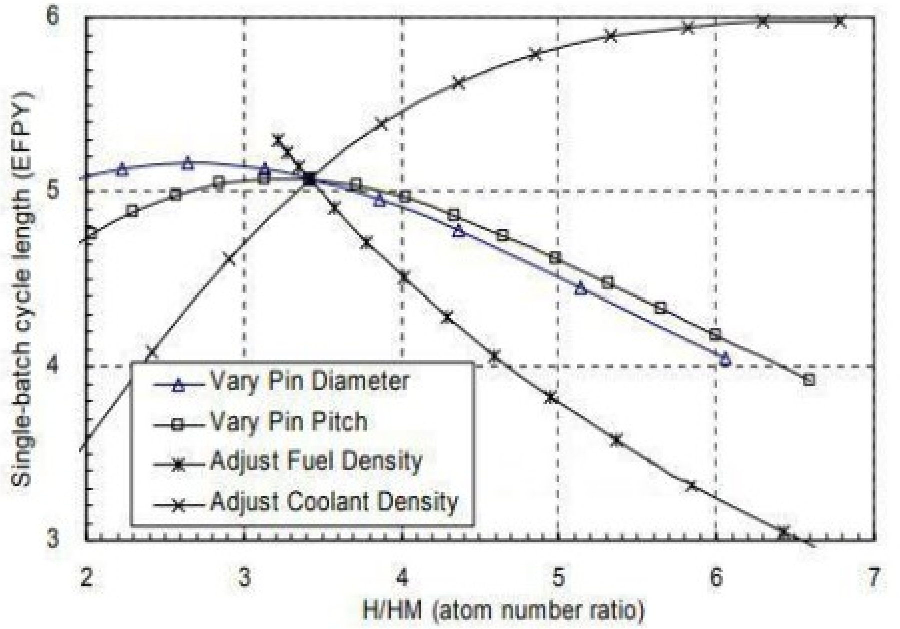


Introduction (why annular fuel?!)

- A transition from solid to annular geometry has two important implications that allow power density increases:
  - reduction of conduction path thickness, which improves margin from peak fuel temperature to melting and,
  - increased heat transfer surface area, which improves the margin for Departure from Nucleate Boiling Ratio (DNBR)
- Main Advantages of annular design:
  - Lower fuel temperature
  - lower thermal fission products production
  - Less temperature gradient
  - Less thermal stresses

Introduction (Our Modifications and fuel structure)

- it's shown that as the H/HM increases fuel cycle length decreases except for coolant density variation which is not an option since many parameters depend on it including efficiency and from Fig.(1)



Introduction (Our Modifications and fuel structure)

- MIT annular fuels were designed with a wet lattice of H/HM ~6 to have higher burnup.
- So, we modified our annular fuel geometry dimensions to have a dry lattice of H/HM ~3.328 taking into consideration the flow area ratio of inner and outer channels to be similar to the ratio of reference design plus having two thorium dioxide (ThO2) layers on outer and inner radius of fuel.

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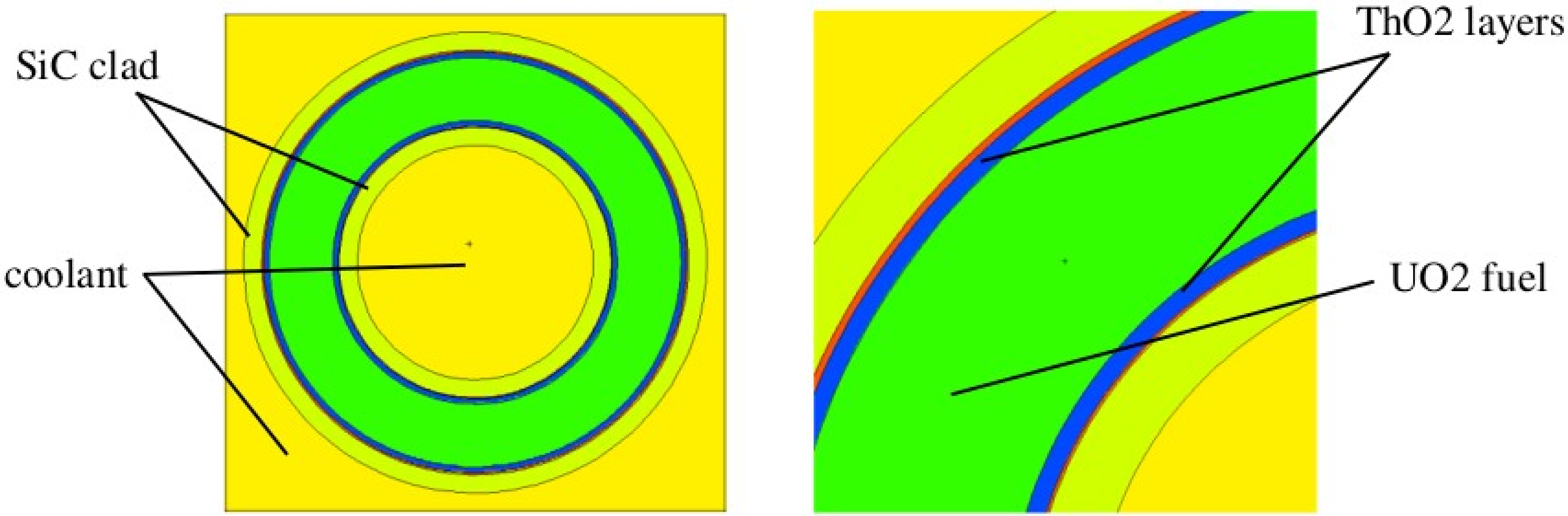
Introduction (Our Modifications and fuel structure)



Annular fuel is good, but it can be better

Thermal-hydraulic analysis goals

- Thermal hydraulic analysis is meant to:
  - Determine the temperature distribution across the fuel
  - Determine the coolant flow rates needed.
  - Determine the Departure from Nucleate Boiling (DNBR) and ensure that the reactor stays within certain limitations
  - Achieve high coolant exit temperature to improve thermodynamic efficiency

thermal-hydraulic limitations.

- That fuel temperature at any point in the core mustn’t exceed its melting point
- Avoid coolant bulk boiling and insuring the stability of the coolant.
- Assuring that we are above 1.3 MDNBR to have sufficient margin away from film boiling.

COMSOL Multi-physics

- The COMSOL code is a finite element, Multi-physics numerical analysis software with diverse physics and engineering applications, including coupled phenomena. This code has an integrated user interface, which allows users to input coupled systems of partial differential equations directly.
- Advantages:
  - COMSOL enables the user to increase the number of meshes only in the core regions with largest numerical errors, without the need to refine the meshes for the whole reactor core. Consequently, reducing the spatial discretization errors, and making the calculation faster.
  - the user is NOT forced to refine the mesh for the whole core to reduce the errors in specific regions, which will affect the core calculation time.
  - It is fast so we can test and try several ideas in a short time making the coupling process, between thermal-hydaulics and neutronics, much easier!

Model Formulation

- It is clear that; the two-fluid mixture model can, in principle, provide us with a full model if we assumed the mixture is (water and vapor) each has its own volume fraction (Ø) and density (ϱ) where the total density is defined as:
- $$\rho = \rho_g \Phi_g + \rho_l \Phi_l$$

  Where, $\Phi_l = 1 - \Phi_g$

- Where the subscript (g) indicates the vapor phase while (l) indicates the liquid phase and that rho without any index is the total density of the mixture. The thermal conductivity (k) and mixture viscosity (μ) are defined as:

$$k = k_l \Phi_l + k_g \Phi_g$$

$$\mu = \mu_l \Phi_l + \mu_g \Phi_g$$

Model Formulation

And we define the mass fraction of the i[th] phase as: $\chi_i = \Phi_i \frac{\rho_i}{\rho}$

Allowing us to define the heat capacity of the mixture in its terms as:

$$C_p = \chi_l C_{pl} + \chi_g C_{pg}$$

- And the enthalpy of a material from a standard reference is given by:

$$H = H_f + \int_{T_R}^{T} C_p dT$$

Where Hf is the standard heat of formation and TR is the standard Temperature.

The enthalpy of a mix is given by:

$$H_{mix} = \sum_i (H_f + \int_{T_R}^{T} C_p dT)_i$$

So, if our standard points as the saturation temperature, and zero and by solving as:

$$\begin{aligned} H_{mix} &= \chi_g(H_g + C_{pg}(T - T_{sat})) + \chi_l C_{pl} T \\ &= \chi_g H_g + \chi_g C_{pg}(T - T_{sat}) + \chi_l C_{pl}(T - T_{sat}) + \chi_l C_{pl} T_{sat} \\ &= \chi_g H_g + C_p(T - T_{sat}) + (1 - \chi_g) C_{pl} T_{sat} \\ &= \chi_g (H_g - C_{pl} T_{sat}) + C_p(T - T_{sat}) + C_{pl} T_{sat} \end{aligned}$$

By defining $C_{pl}T_{sat}$ as H_l

$$H_{mix} = \chi_g(H_g - H_l) + C_p(T - T_{sat}) + H_l$$
$$= \chi_g \Delta H_{gl} + C_p(T - T_{sat}) + H_l$$

Where ΔH_{gl} is the latent heat of vaporization and the thermal conductivity of a fluid under turbulent flow is defined as:

$$k = k_{mix} + k_{turbulent}$$
$$k_{mix} = k_g \Phi_g + k_l \Phi_g$$

And turbulent thermal conductivity known also as the eddy conductivity can be calculated from the k-e model as:

$$k_{turbulent} = \frac{\mu_t C_p}{P_r}$$

Model Formulation

- Where μt is the eddy viscosity, Pr is Prandtl number.
- Using these equations in addition to the phase continuity equation (the conservation of mass), the k-ϵ model and the heat transfer module one can obtain such a model to track and analyze the change in temperature and in phase, if occurred, using COMSOL. And as a solution to the mesh- building problem we have found that defining the meshes as a ratio of 3:1 or 4:1 for gap thickness to length works the best.
- Due to the lack of computational power we decided to work on a sub-channel

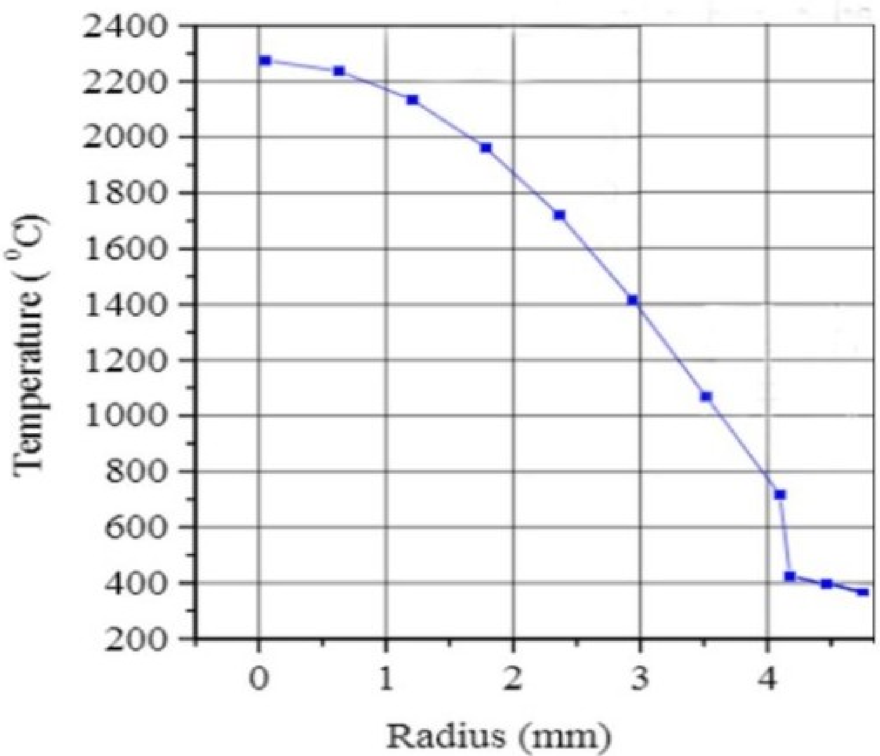
- Benchmarking (Westinghouse typical PWR 4-loops)

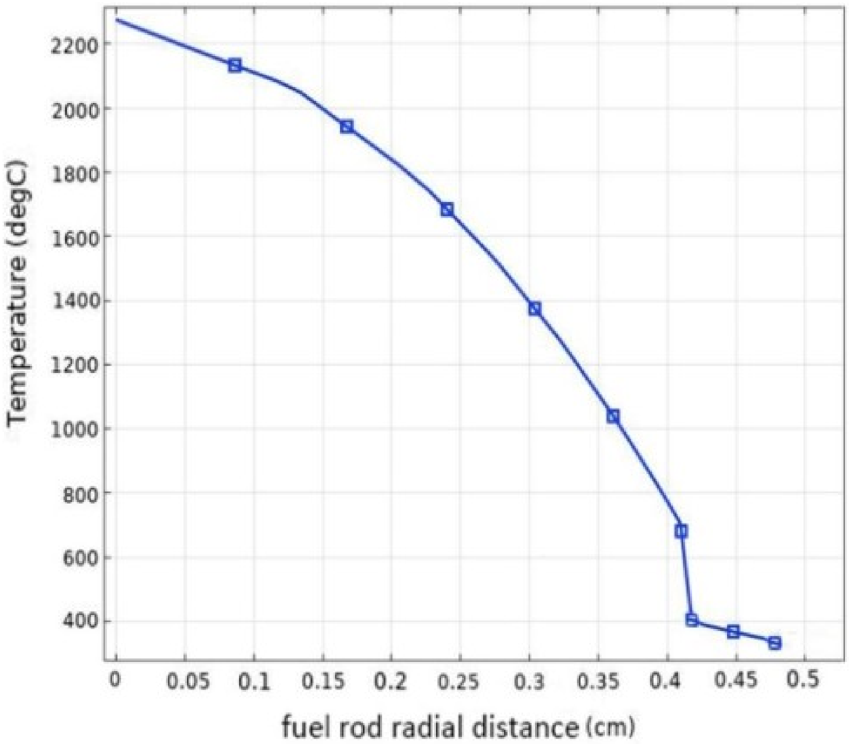
- typical Westinghouse thermal data:

Quantity [unit]	value
Fuel pellet diameter [mm]	8.19
Clad thickness [mm]	0.57
Clad material	zircaloy-4
Fuel rod diameter [mm]	9.5
Rod active length [m]	3.66
Inlet temperature [degC]	292.7
Inlet pressure [MPa]	15.51
Inlet mass flow rate [kg/m^2s]	3.359
Inlet velocity [m/s]	4.572
Water density [kg/m^3]	593.987
steam density [kg/m^3]	102.139
Water viscosity [Pa. s]	6.828E-5
steam viscosity [Pa. s]	2.312E-5
Liquid heat capacity [kJ/kg. K]	8.982
steam heat capacity [kJ/kg. K]	14.099
Ratio of specific heats	2.883
Liquid thermal conductivity [W/ (m.K)]	0.4580
Steam thermal conductivity [W/ (m.K)]	0.122
Prandtl number	0.00139
Power [watt]	164700
Latent heat of evaporation [kJ/Kg]	2248

- Benchmarking (Westinghouse typical PWR 4-loops)

- Temperature profile: Radial Temperature profile of Westinghouse hotspot channel (on the left) Vipre Code (on the right) COMSOL





- Benchmarking (VVER-1000)

- Thermal data used:

Quantity [unit]	value
Fuel pellet diameter [mm]	0.772
Clad thickness [mm]	0.138
Clad material	Alloy E-110
Fuel rod diameter [mm]	9.1
Rod active length [m]	3.53
Inlet temperature [degC]	291
Inlet pressure [MPa]	15.7
Inlet mass flow rate [kg/m^2 s]	1505.3
Inlet velocity [m/s]	2.5609
Water density [kg/m^3]	864.118
steam density [kg/m^3]	7.935
Water viscosity [Pa. s]	0.000133
steam viscosity [Pa. s]	1.573E-5
Liquid heat capacity [kJ/kg.K]	4.496
steam heat capacity [kJ/kg. K]	2.997
Ratio of specific heats	1.356
Liquid thermal conductivity [W/ (m.K)]	0.663
Steam thermal conductivity [W/ (m.K)]	0.0402
Prandtl number	0.90191
Power [watt]	66632
Latent heat of evaporation [KJ/Kg]	1470.4

- Benchmarking (VVER-1000)

I. Heat map

II. Temperature Profile

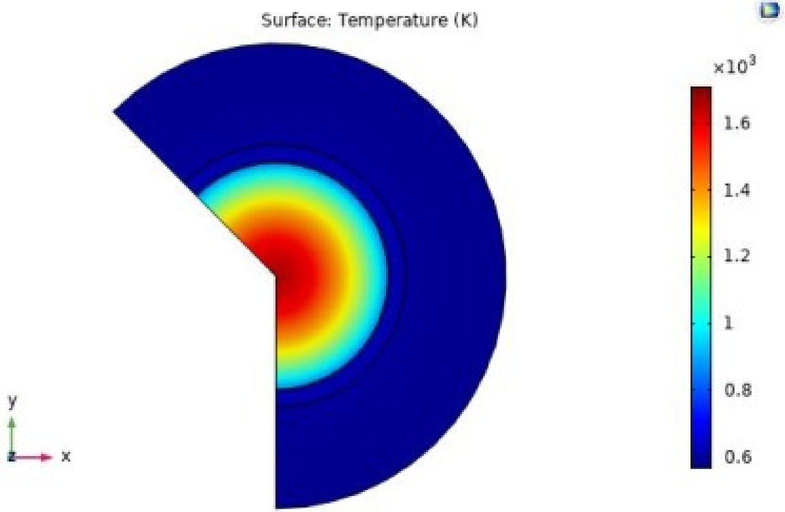


Figure (31): VVER-1000 heat map.

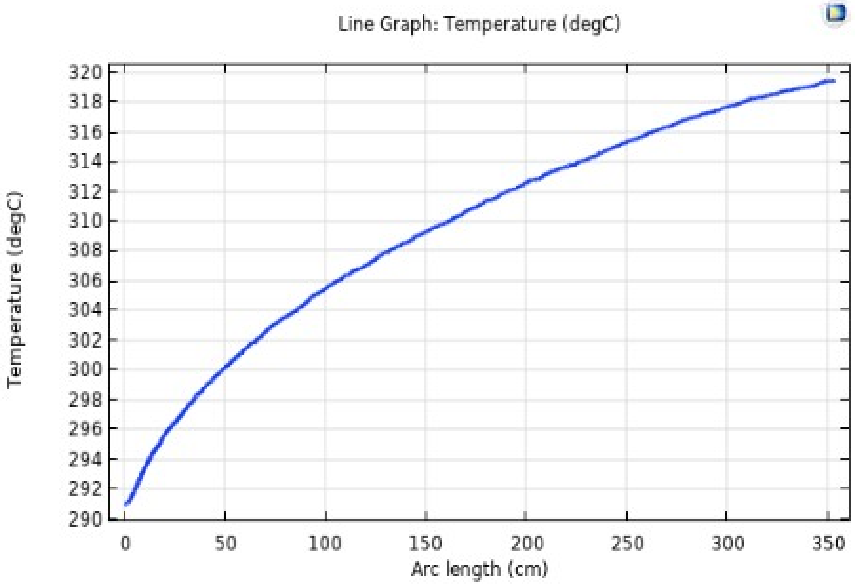


Figure (32): VVER-1000 Temperature profile.

Where we can see clearly that the axial increase in temperature is 30 °C.[4]

Benchmarking (Kazimi's Annular Fuel 13x13)

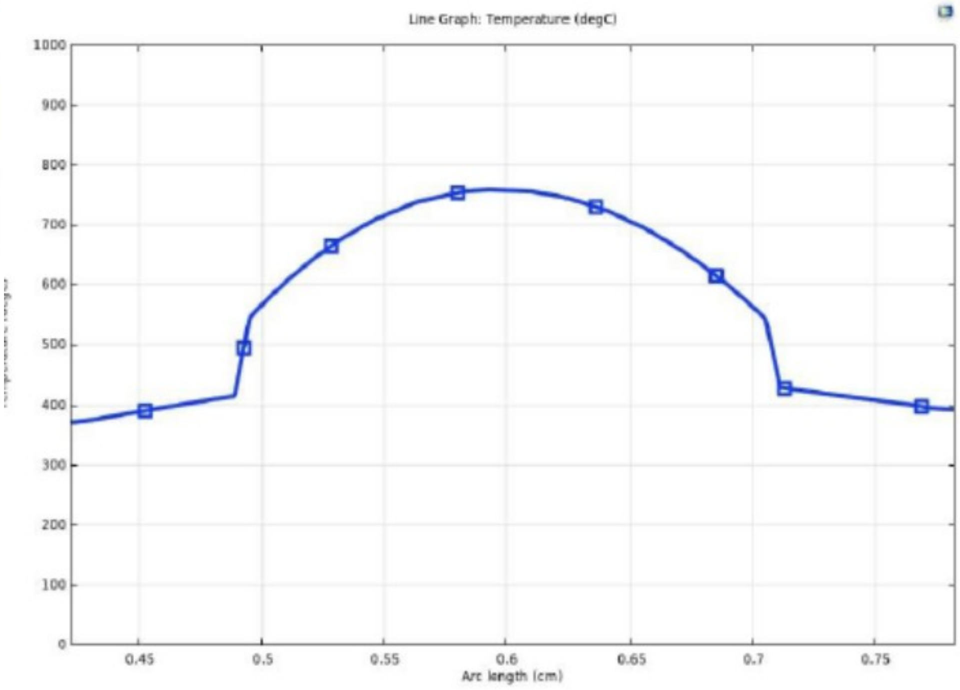
- Thermal data used:
- q'=111 kW/m

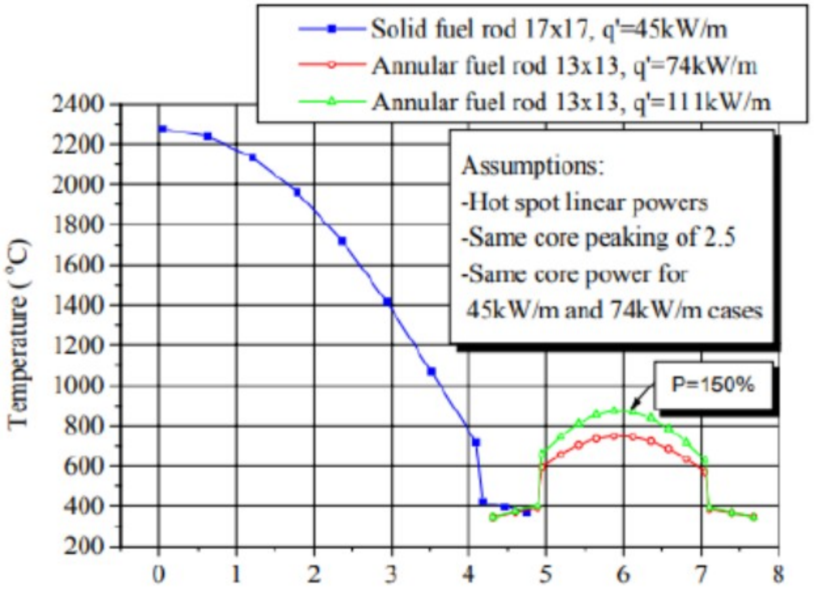
Liquid heat capacity [kJ/kg.K]	8.982
steam heat capacity [kJ/kg.K]	14.099
Ratio of specific heats	2.883
Liquid thermal conductivity [W/(m.K)]	0.4580
Steam thermal conductivity [W/(m.K)]	0.122
Prandtl number	0.00139
Linear power [kW/m]	74
Latent heat of evaporation [kJ/kg]	2248

Quantity [unit]	value
Inner clad inner diameter [cm]	0.8633
inner clad outer diameter [cm]	0.9776
Fuel inner diameter [cm]	0.99
Fuel outer diameter [cm]	1.4100
Outer clad inner diameter [cm]	1.5367
Outer clad outer diameter [cm]	1.651
Clad material	zircaloy-4
Rod active length [m]	3.66
Inlet temperature [degC]	292.7
Inlet pressure [MPa]	15.51
Inlet mass flow rate [Kg/m^2s]	3.359
Inlet velocity [m/s]	4.572
Water density [Kg/m^3]	593.987
steam density [Kg/m^3]	102.139
Water viscosity [Pa. s]	6.828*10^(-5)
steam viscosity [Pa. s]	2.312*10^(-5)

Benchmarking (Kazimi's Annular Fuel 13x13)

- Temperature profile: (the green curve)





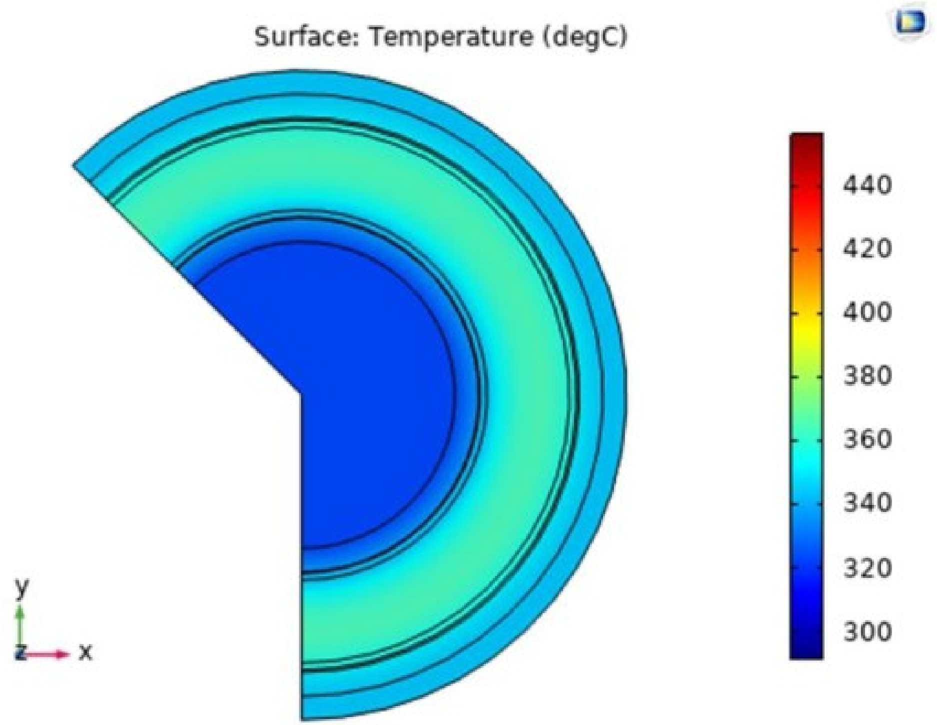
Applying the model to our fuel and parameters determinations

- Our thermal data:

Quantity [unit]	Value
Inner clad inner diameter [cm]	0.39
Inner clad outer diameter [cm]	0.4505
Inner Thorium diameter [cm]	0.4535
Fuel inner diameter [cm]	0.47135
Fuel outer diameter [cm]	0.68115
Outer Thorium diameter [cm]	0.699
Outer clad inner diameter [cm]	0.706
Outer clad outer diameter [cm]	0.76645
Clad material	SiC
Rod active length [m]	2.00
Inlet temperature [degC]	291
Inlet pressure [MPa]	15.5
Inlet mass flow rate (total) [Kg/m2s]	1891.8
Inlet velocity(inner) [m/s]	1.5
Inlet velocity(outer) [m/s]	1.6829
Water density [Kg/m3]	594.357
steam density [Kg/m3]	101.92
Water viscosity [Pa. s]	6.83*10^(-5)
steam viscosity [Pa. s]	2.3108*10^(-5)
Liquid heat capacity [kJ/kg.K]	8.964
steam heat capacity [kJ/kg.K]	14.022
Ratio of specific heats	2.878
Liquid thermal conductivity [W/(m.K)]	0.458
Steam thermal conductivity [W/(m.K)]	0.121
Prandtl number	2.09*10^(-3)
Latent heat of evaporation [KJ/Kg]	1629.85

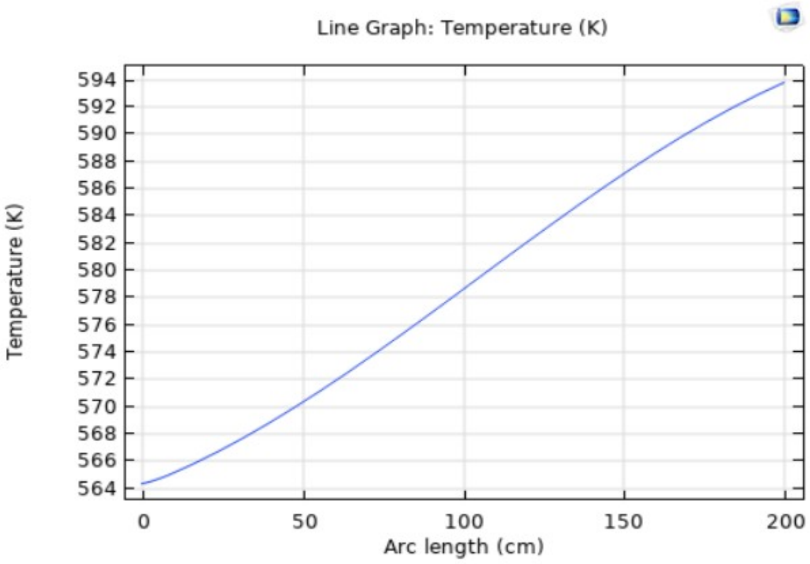
Applying the model to our fuel and parameters determinations

Heat Map

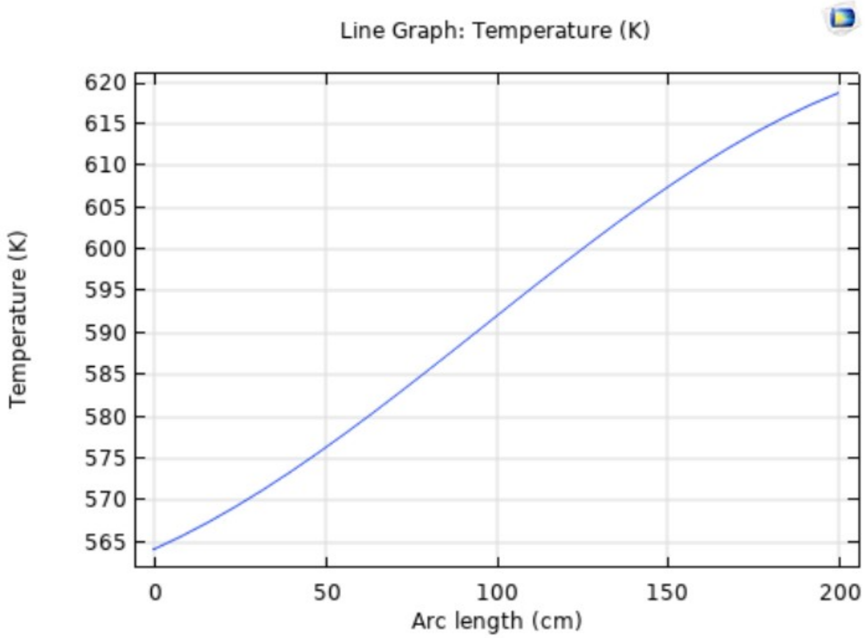


Applying the model to our fuel and parameters determinations

Inner clad axial Temperature profile

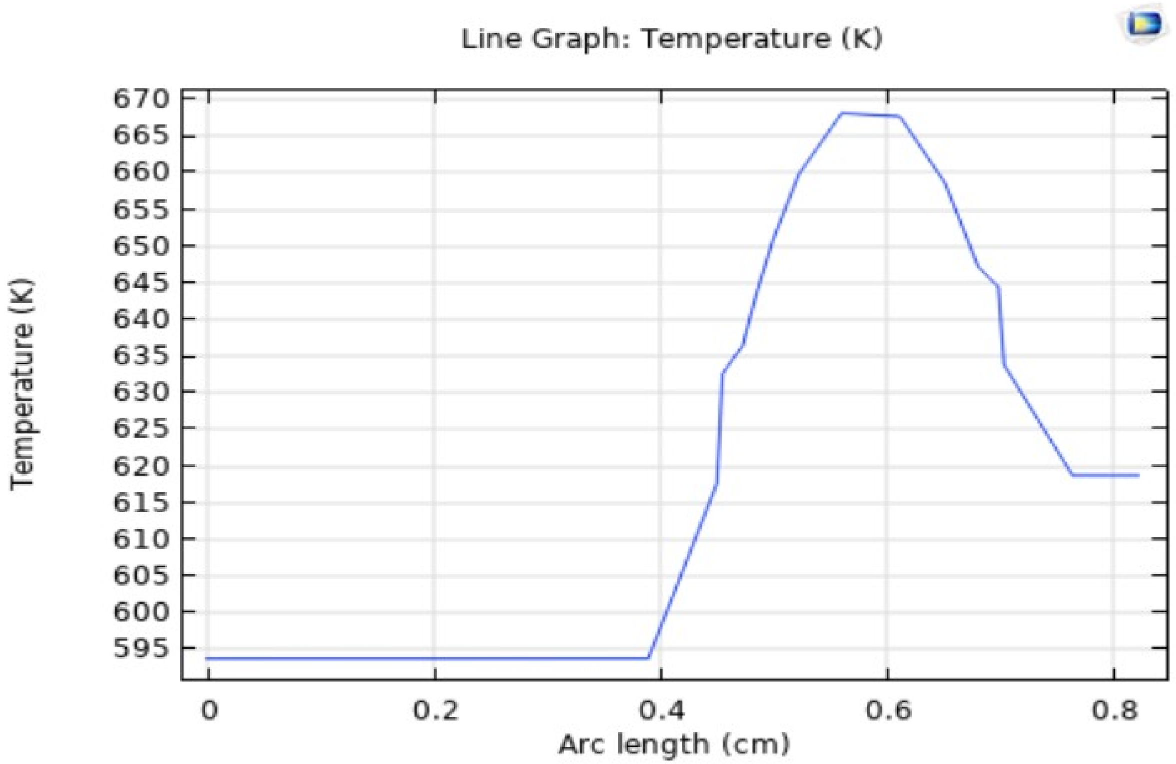


Outer clad axial temperature profile



Applying the model to our fuel and parameters determinations

Radial Temperature Profile at L



Applying the model to our fuel and parameters determinations

- The curve is asymmetric due to the difference in area between the inner channel and the outer channel, according to Forrier’s law the rate of heat flow is proportional to the (area)
- so, the amount of heat transferred in the outer channel is larger than that in the inner channel due to the significant difference in area!
- Larger surface area also made it possible to overcome the fact of lower temperature gradient and the low thermal conductivity of the SiC.

Applying the model to our fuel and parameters determinations

- Evaluated data:

  (via trial and error)

Table 11: Our Design's evaluated thermal data.

Quantity [unit]	value
Average outlet temperature [degC]	333.112
Max. centerline temperature [degC]	320.85
Average fuel temperature [degC]	389.34
Max. fuel temperature [degC]	424.408
Clad average Temperature (inner) [degC]	322.22
Clad average Temperature (outter) [degC]	330.49
Clad average Temperature [degC]	326.36
Max. Clad temperature (inner) [degC]	349.29
Max. Clad temperature (outter) [degC]	361.46
Max. Clad temperature [degC]	361.46
DNBR (inner)	3.18
DNBR (outer)	1.93

Conclusion

- It has been found that none of the components reaches its melting point, as we have determined the operating pressure and temperature of our reactor and other important parameters as the DNBR; we have achieved the goals predefined by the thermal hydraulic analysis

Future work

- To use a more powerful code (like RELAP-SCDAP) to compare our results with, for further verification.
- To extend our work to contain complete channel (assembly) not only a sub-channel (one fuel element) using a supercomputer.

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Thank you!!