The effect of tripartite fuel on the heat transfer quality and reactor safety in the case of pressurized water reactor

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New reactor concepts and safety analyses for the Polish Nuclear Energy Program
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Presentation outline

1- Nuclear Power Plant.

2- Fuel assemblies.

3- Surface area effect.

4- Power limitations.

5- Case study description.

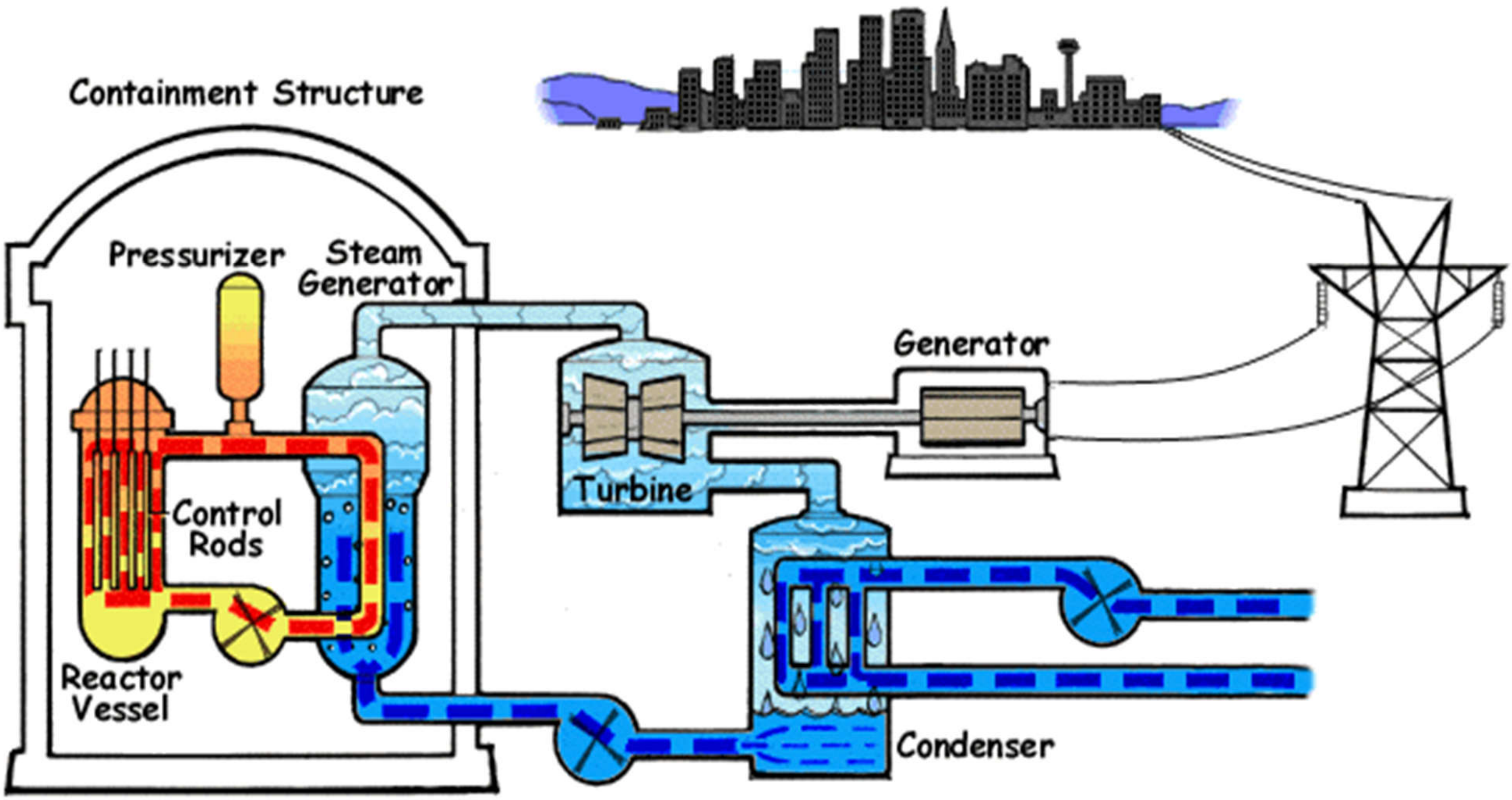
6- Cylindrical and tripartite geometries.

7- Methodology.

8- Results.

9- Conclusions.

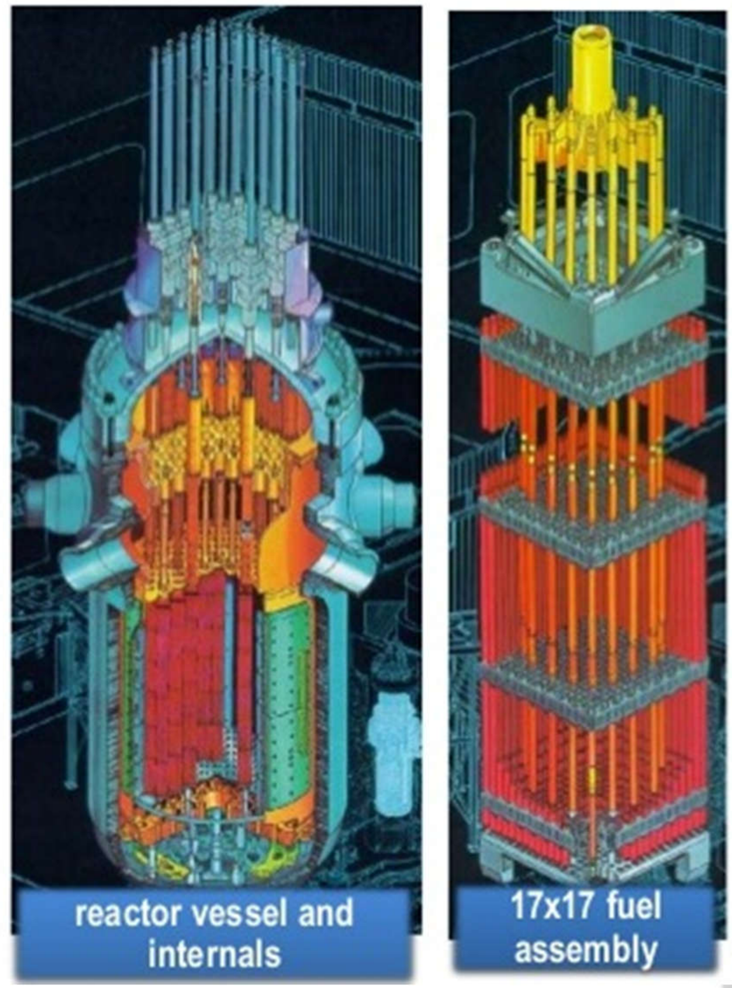
Nuclear power plant (PWR) (1)



Fuel assemblies (1)

- Heat transfer from the fuel pellets to cladding through the gas gap.

- Then from Cladding outer surface to the fluid (H_2O).



Surface area effect (1)

$$Q = A\ h\ (T_{clad} - T_{water})$$

Q' *is heat transfer per unit time*

A *is the heat transfer contact area*

H *is the heat transfer coefficient*

T_{clad} *is the outer clad surface*

T_{water} *is the water temperature*

C- Surface area effect (2)

$$Q' = A\,h\,(T_{clad} - T_{water})$$

As the area increases **A ⇧**

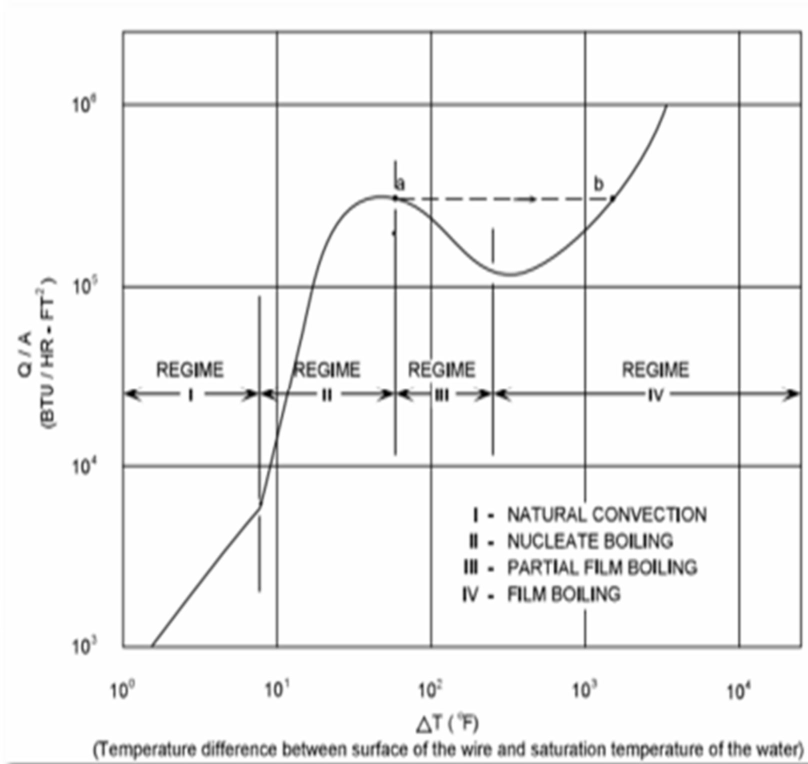
The Q' increases **Q' ⇧**

Power limitations (1)

1- Thermal hydraulics limitations

$Q_{critical}$ is reached once the departure from nucleate boiling starts to occur.

$$\textbf{DNBR} = \frac{Heat\ flux\ required\ to\ reach\ DNB}{The\ actual\ local\ heat\ flux}$$



Power limitations (2)

1- Thermal hydraulics limitations

$$q''(r) < q''_{CHF}$$

The power generated per unit area must be less than the critical heat flux to avoid departure from nucleate boiling.

Power limitations (3)

<u>2- Fuel Melting temperature</u>

$$q' < q'_{max}$$

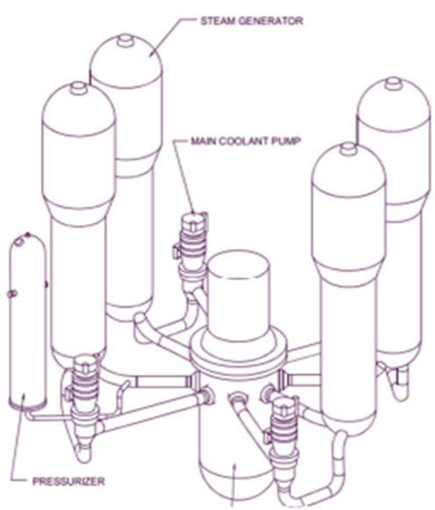
The linear power generation must be less than the max allowed power to avoid fuel overheating and melting.

q'_{max} = 0.446 kW/cm

lowered for safe operation to **0.357 kW/cm**.

Case study description (1)

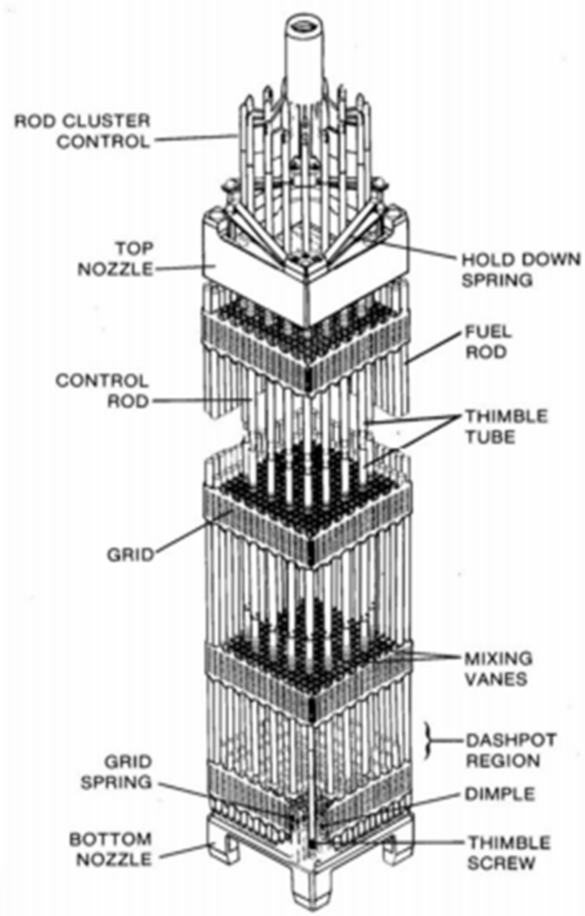
Four-loops,
Westinghouse PWR
412 core
parameters



Total heat output, MWt	3411
Heat generated in fuel, %	97.4
Nominal system pressure, psia (bar)	2250 (155)
Total coolant flow rate, lb/hr (kg/sec)	~138.4×10^6 (17438)
Coolant temperature	
Nominal inlet, °F (°C)	557.5 (291.9)
Average rise in vessel, °F (°C)	61.0 (33.9)
Outlet from vessel, °F (°C)	618.5 (325.8)
Equivalent core diameter, ft (cm)	11.06 (338)
Core length, between fuel ends, ft (cm)	12.0 (365.8)
Fuel type	17x17 OFA
Fuel weight, uranium in core, kg	81,639
Number of fuel assemblies	193

Case study description (2)

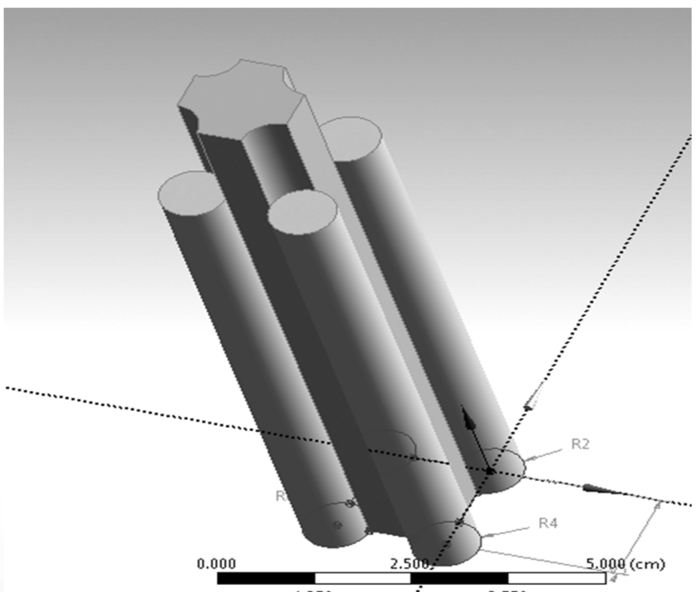
Fuel rods and assembly parameters

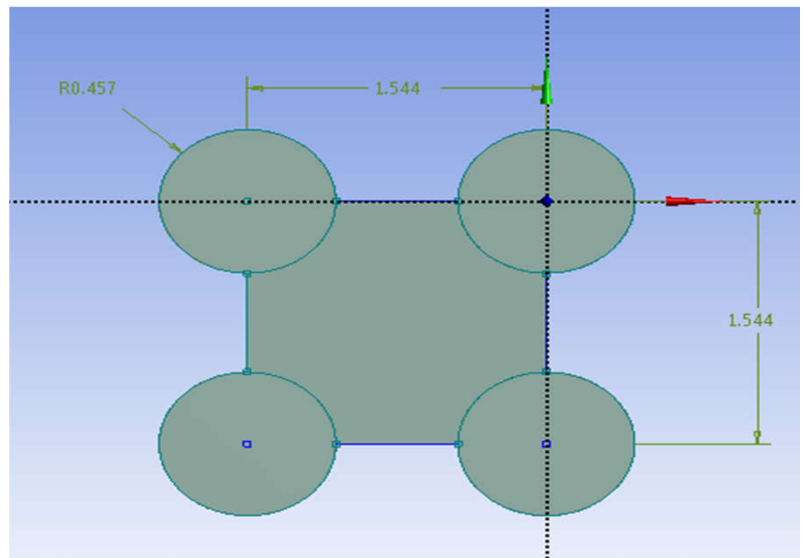


FUEL ROD PARAMETERS (Four-Loop Plant)	
Fuel rod length	12 ft (365.8 cm)
Outside diameter	0.360 in. (0.914 cm)
Cladding thickness	0.0225 in. (0.0572 cm)
Cladding material	Zircaloy-4
Diametrical gap	0.0062 in. (0.0157 cm)
Pellet diameter	0.3088 in. (0.7844 cm)
Lattice pitch	0.496 in. (1.260 cm)
Rods array in assembly	17 x 17
Rods in assembly	264
Total number of fuel rods in core	50,952

Cylindrical and tripartite geometries (1)

1- Cylindrical geometry (rods and sub-channel)

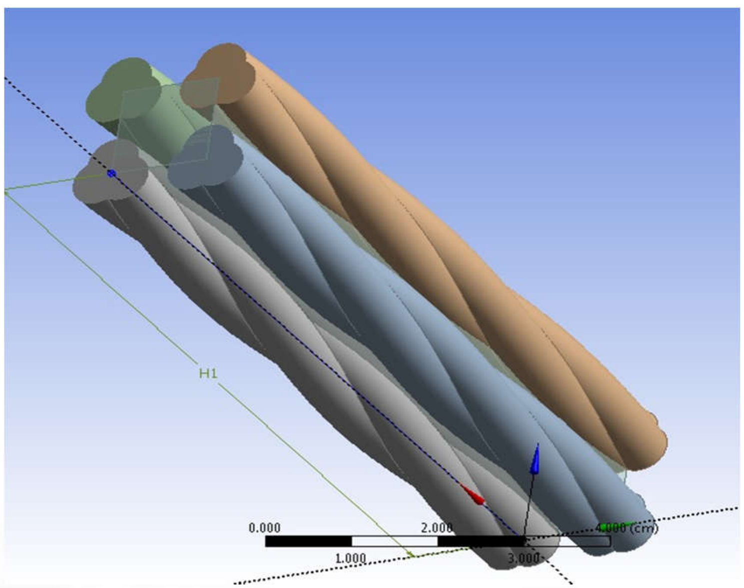


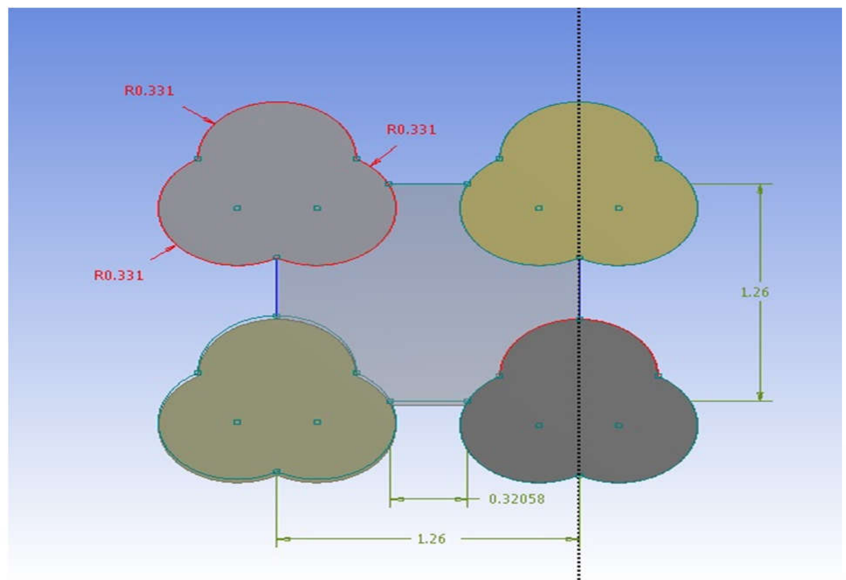


Full rod outside area = 1050.36 cm^2

Cylindrical and tripartite geometries (2)

- 2- Tripartite geometry with helical shape (rods and sub-channel)



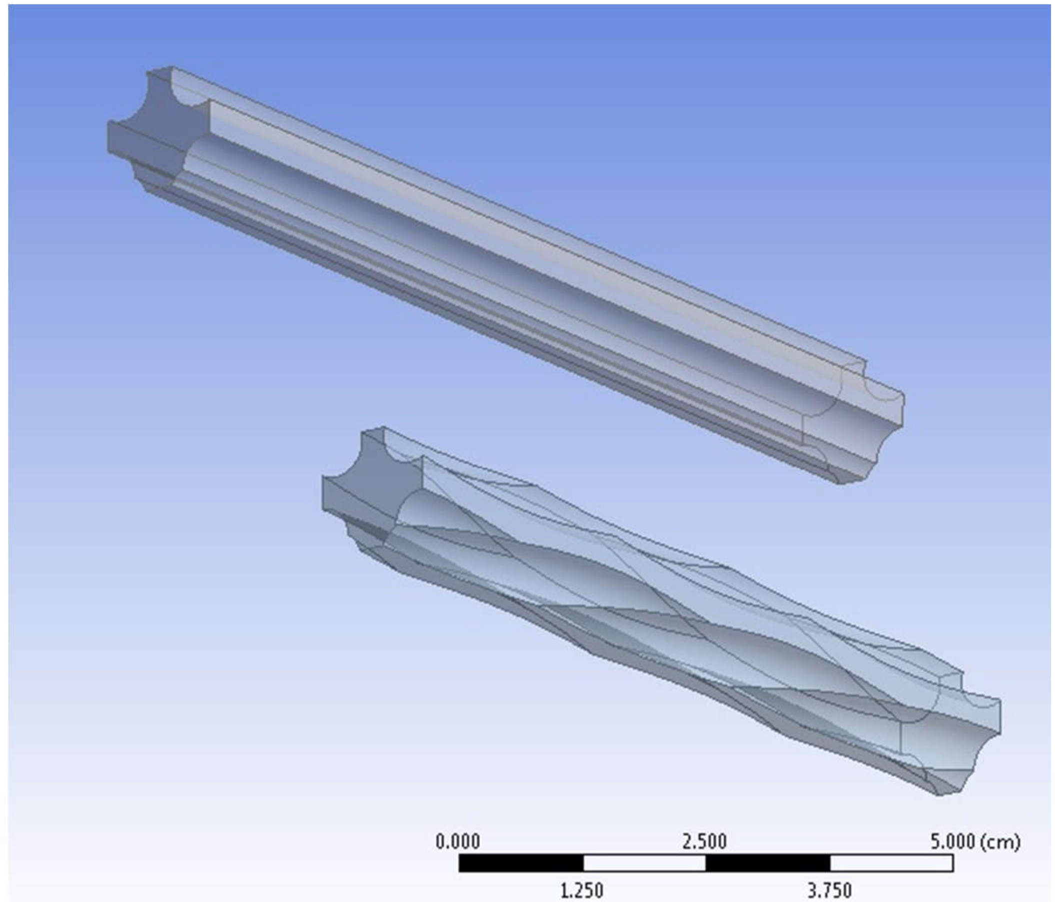


Full rod outside area = 1100.03 cm^2

Area Increased by 5%

Cylindrical and tripartite geometries (3)

Sub-channels in case of straight tripartite and helical tripartite geometries



Methodology (1)

Calculations are based on the sub-channel analysis method using Ansys Fluent software as a modeling effective tool, in 3-D dimensional analysis, the following input data have been considered:

Sub-channel mass flow = **0.31263 kg/s**

Coolant outlet pressure = **154 bar**

Coolant inlet temperature **= 564 K**

Results (1)

Case 1: Cylindrical rods (traditional)

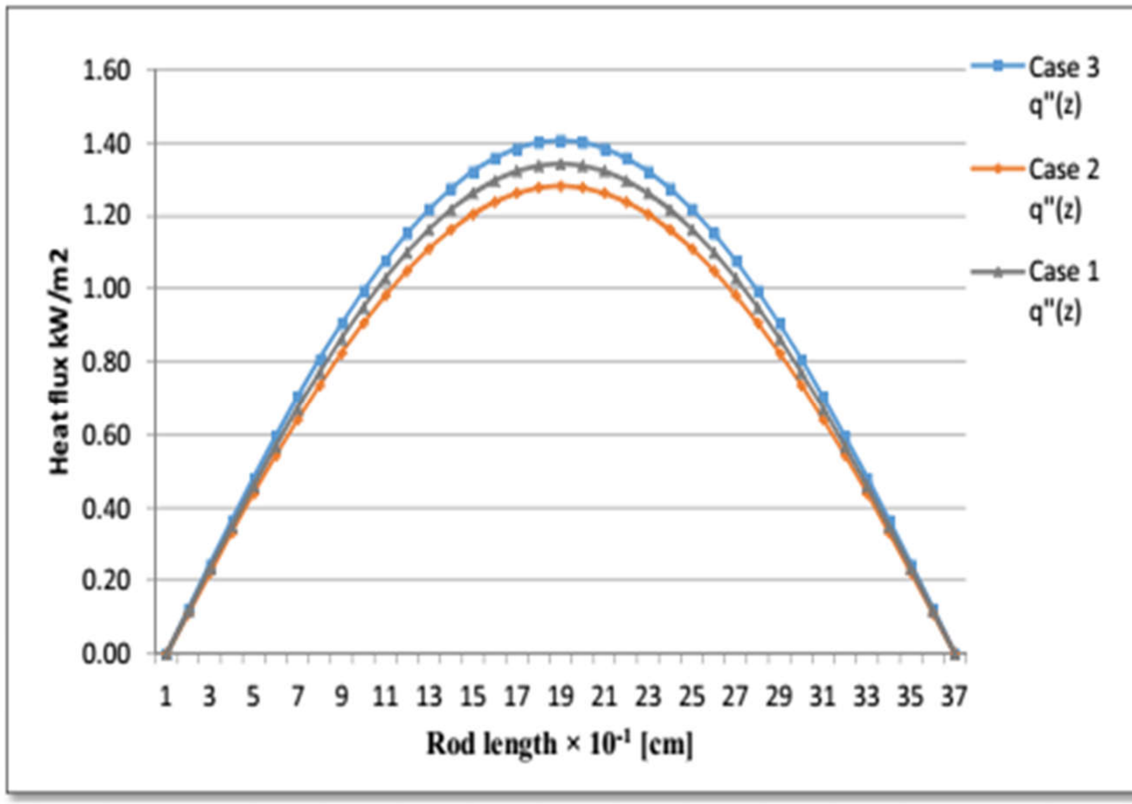
Case 2: Tripartite rod (constant heat per length)

Case 3: Tripartite rod (Increased heat flux)

Results (2)

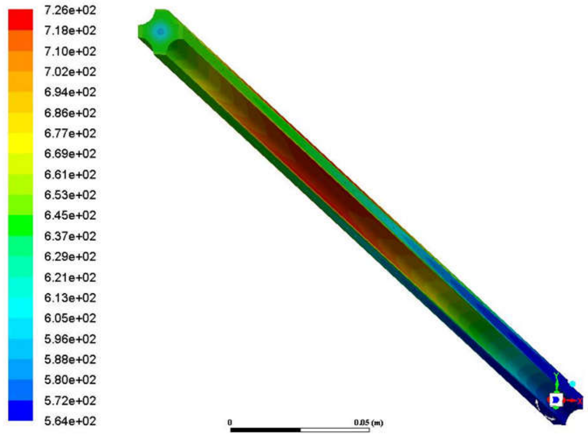
1- Power distribution profile

Case 2 (The Constant flux per length) shows lower peak power which increases safety of operation.

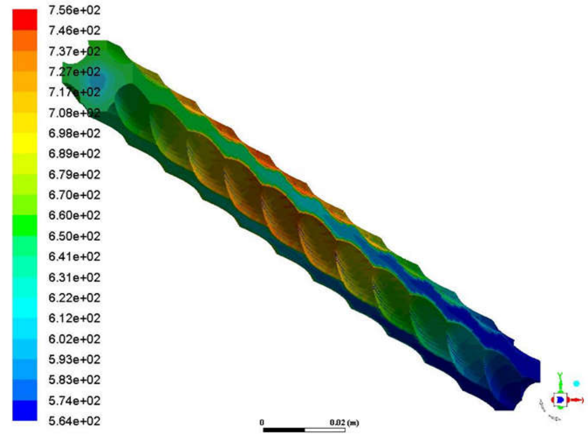


Results (3)

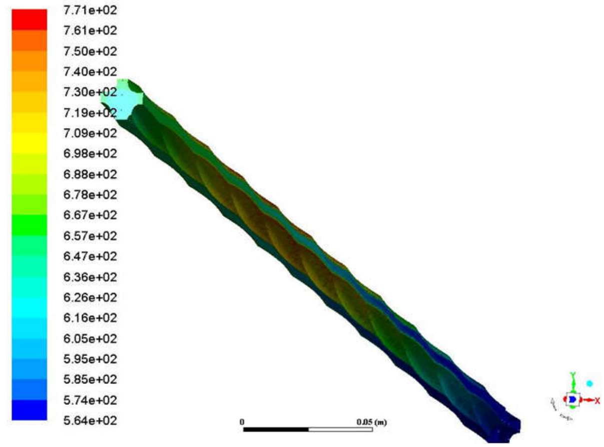
2- Temperature distribution



Case 1



Case 2



Case 3

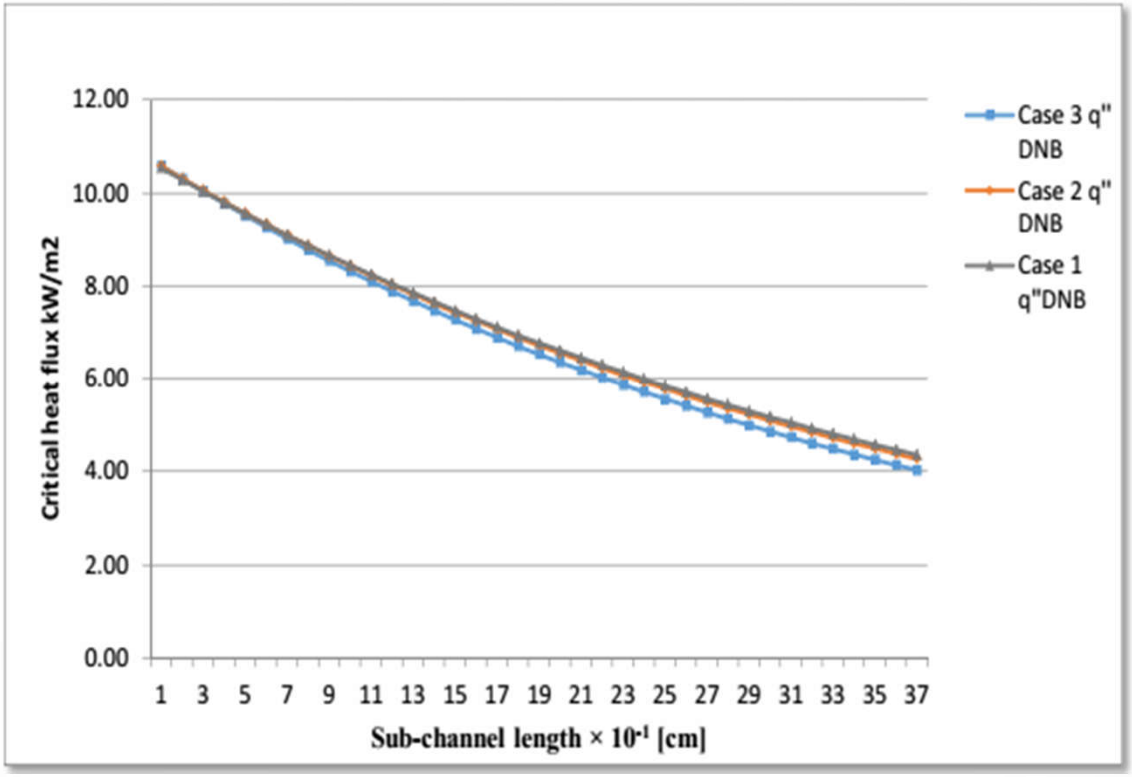
Maximum temperatures are higher in case 2 and case 3 but tinny and scattered due to the good mixing.

Results (4)

3- Critical heat flux

Case 1 and Case 2 (cylindrical and constant q per length) have pretty equal values for the critical heat flux vales

While case 3 (increased q per area) has a slightly lower values



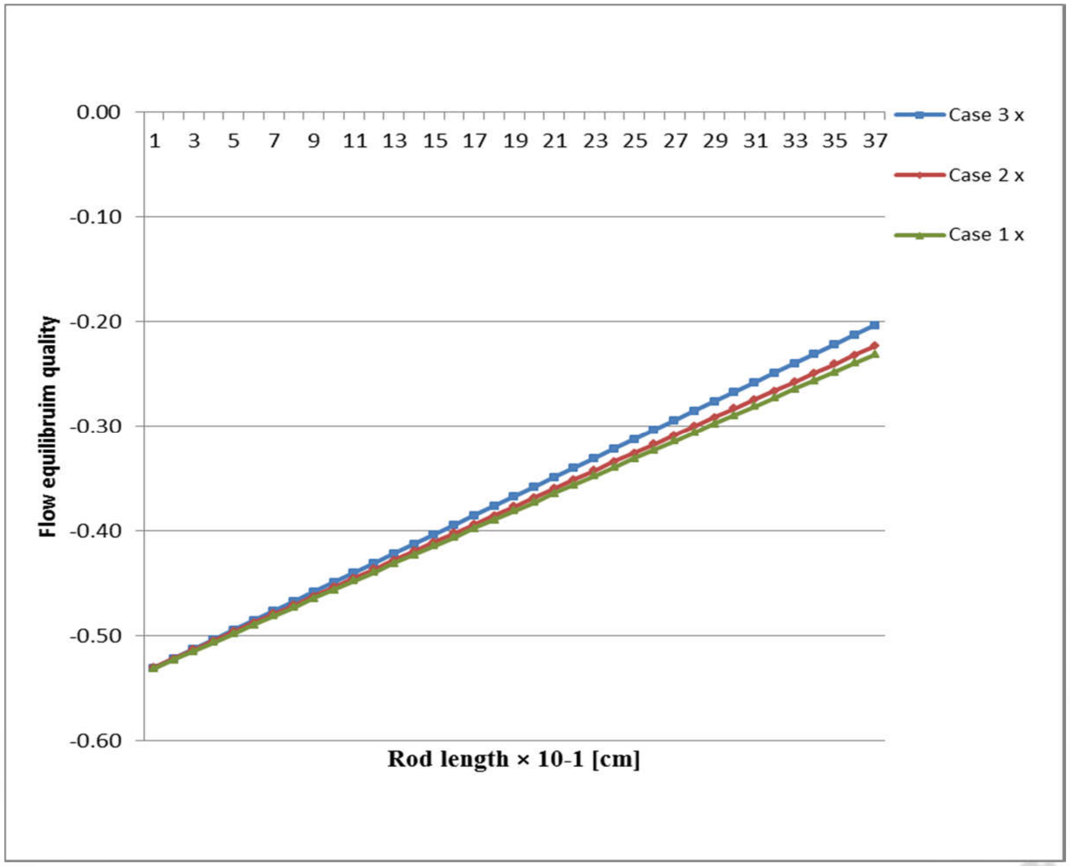
Results (5)

4- Flow quality

The steam quality is higher in case 3 (increased q per area)

While,

almost equal in cases 1 and 2

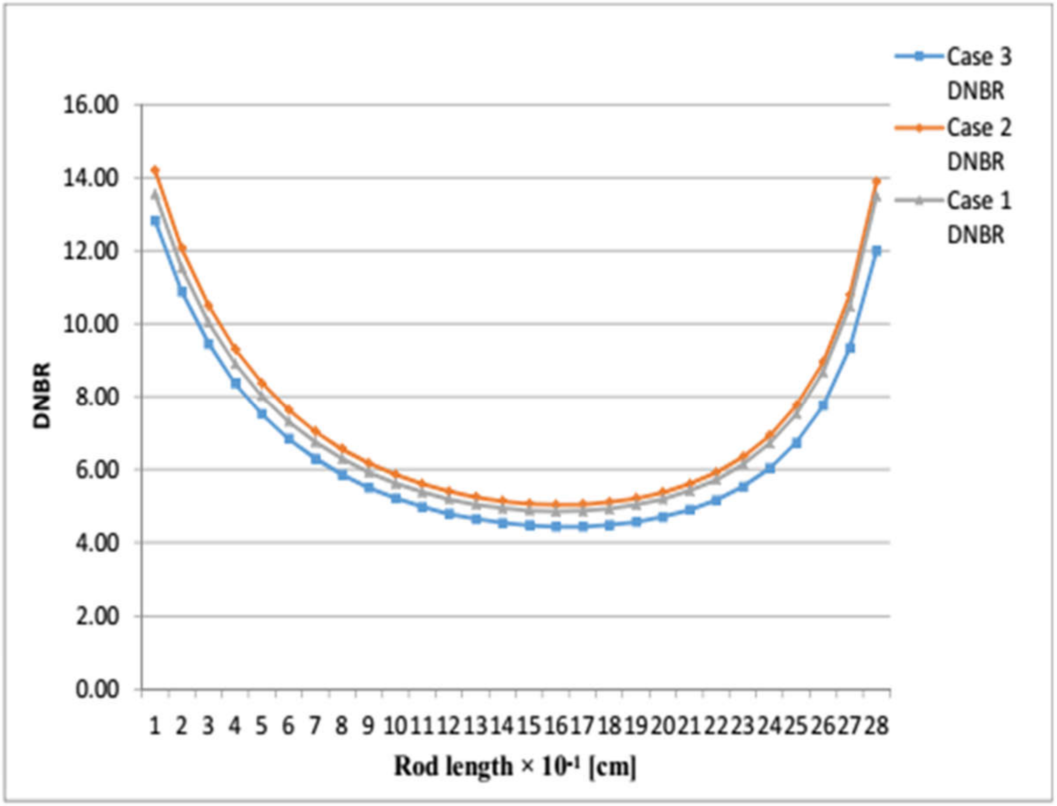


Results (6)

5- DNBR

Case 2 (constant per length) has the highest DNBR.

Case 3 has the lowest DNBR values.



Results (7)

6- Parameters observed

Hot channel		Cylinderical design	Helical Tripartite	
			q / length *constant*	q / area *increased*
Inlet pressure		154.42402	154.30381	154.39883
X_in		-0.531543175	-0.530598618	-0.53134508
Outlet pressure		154	154	154
X_out		-0.231	-0.227	-0.204
Area of 1 cm length	**cm^2**	2.871	3.007	3.007
Power Average/length	**kW/cm**	0.178	0.178	0.196
Avg Q added/subchannel	**kW**	89.76	90.20	98.07
Average T-inlet	**°K**	564	564	564
Average T-outlet	**°K**	633.0	634.5	639.5
Average net T-increase	**°K**	69.0	70.5	75.5

Conclusions (1)

1- The increase in the outer surface area of a fuel rod will increase operation safety.

2- The outer surface increase will allow the operator to generate larger power with the same safety considerations.

3- The helical shape of a fuel rod will result in a better mixing and better heat transfer accordingly.

4- The increase in the thickness of the rod in three diagonals will increase the rod resistance to buckling and bending.

5- The change in the thickness position along the fuel rod due to the helical shape, this will increase the resistance to buckling and bending stresses and lower any possible strain occurrence.

[redacted]

Thank you!