Effect of Power Distribution Change on T/H Parameters with CUPID Alone Calculation

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May 14, 2021

Contents

Background

☐ Power Derating

- **Trip set point decrease**
  - CHF concern due to aging effect
- **Retain Safety Margin**

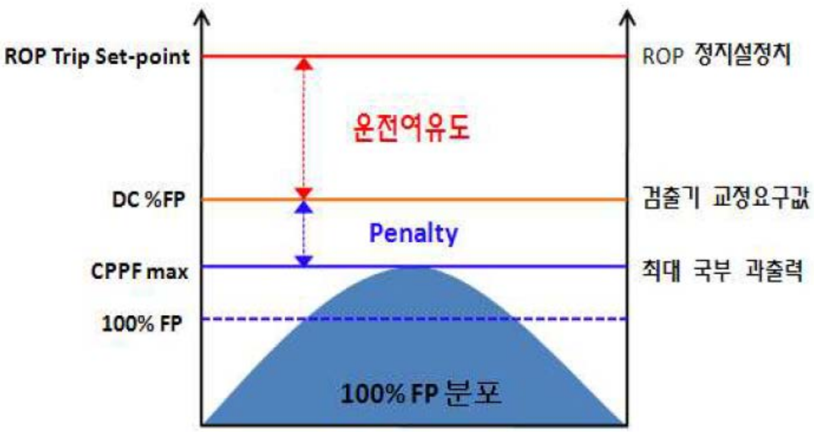

Fig. 1 ROP Trip Set Point and Operational Margin in PHWR

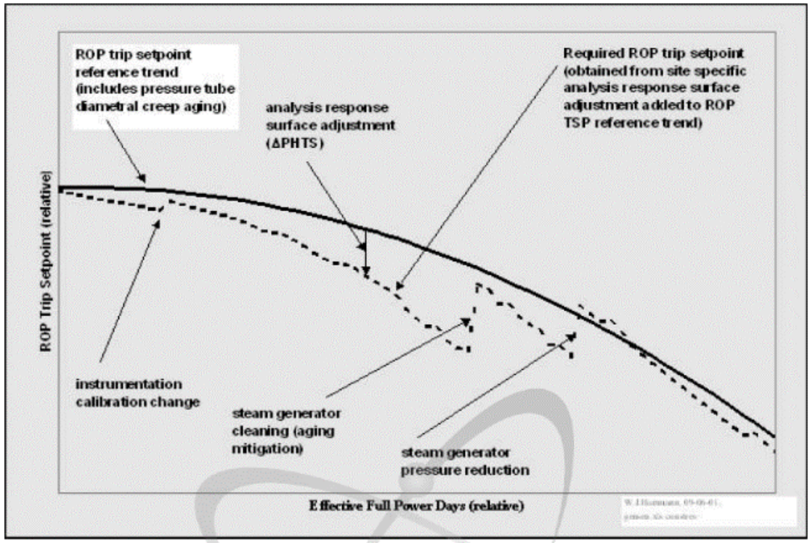

Fig. 2 Reduction Trend of Operational Margin wrt PT diameter expansion

☐ Rough Calculation to Predict CHF

- **Observation of Mass Flow Rate, Quality and Pressure for Virtual Aged Case**
  - Only power distribution change among various factors is consider in this research to confirm the normal operation of the CUPID code and starting point of the work

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Geometry

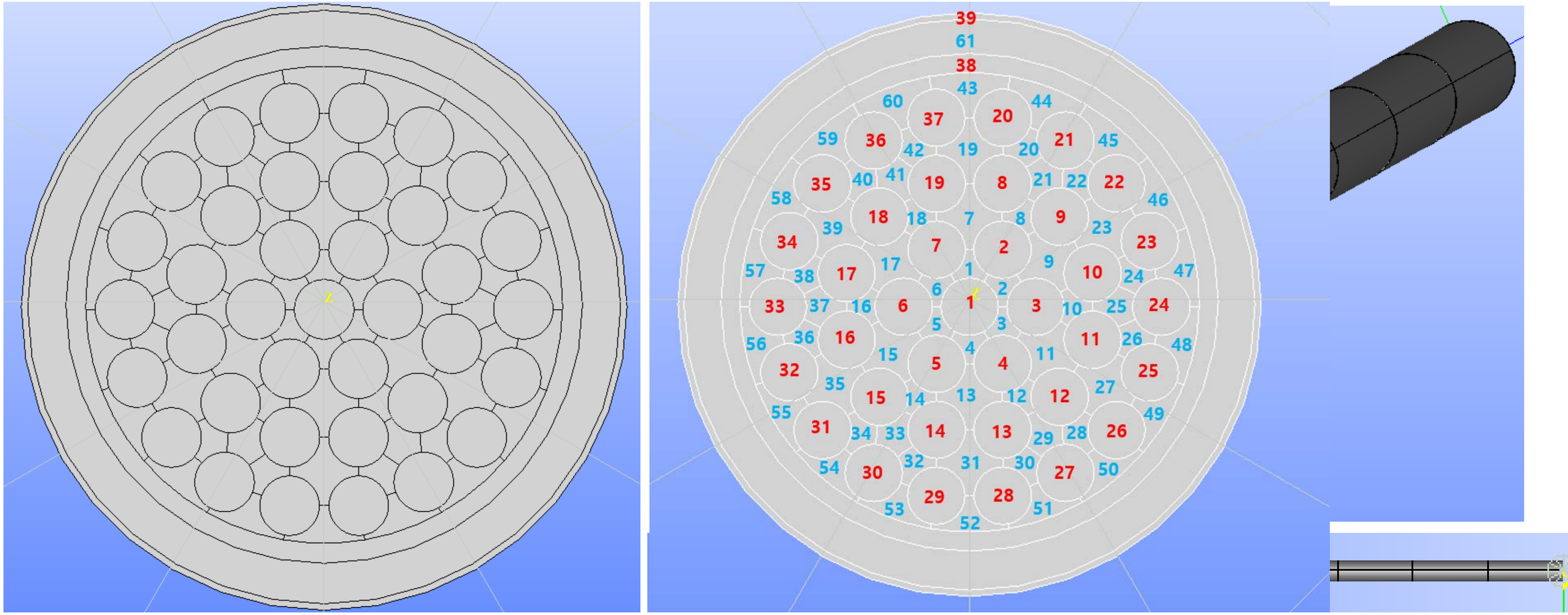


Figure 3. Problem Modeling with CATIA and Salome

❑ Modeling Sequence

- **CATIA modeling**
- **STP file export**
- **Salome import**

Material

Material Assignment

Table 3. Material Assignment of CUPID Calculation

	Reality	CUPID
Fuel	UO_2+He+Zr4	Volume Weighted Material (solid 10)
Coolant	D_2O(99% purity)	D_2O
Pressure Tube	Zr-Nb	Stainless Steel[1)] (solid 4)
Gap	CO_2	Air[2)] (ncg 6)
Calandria Tube	Zr-2	Stainless Steel[1)] (solid 4)

- 1) Stainless Steel will be replaced with Zr in CUPID material list
- 2) It was difficult to CO_2 Related Properties such as rax, dcvax, cvaox and so on. (consulted with Dr. Ha kwi Seok, Dr. Cho Yun Je)

Mesh

☐ 2D Extrusion in Salome

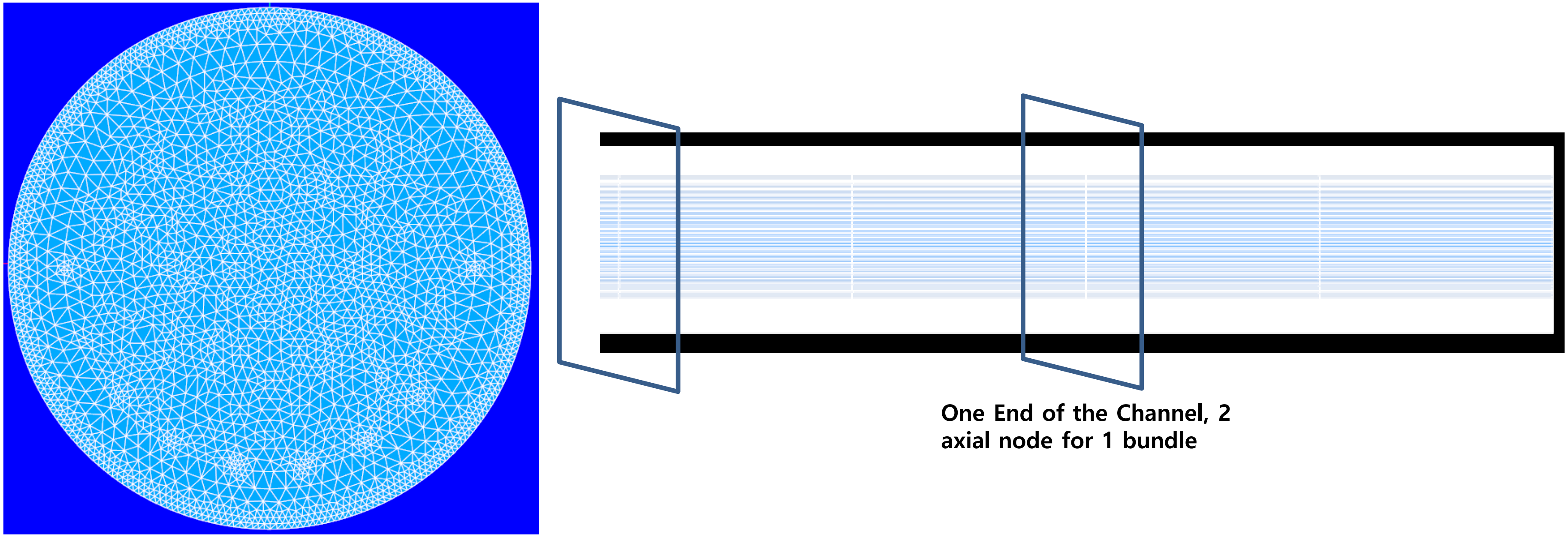
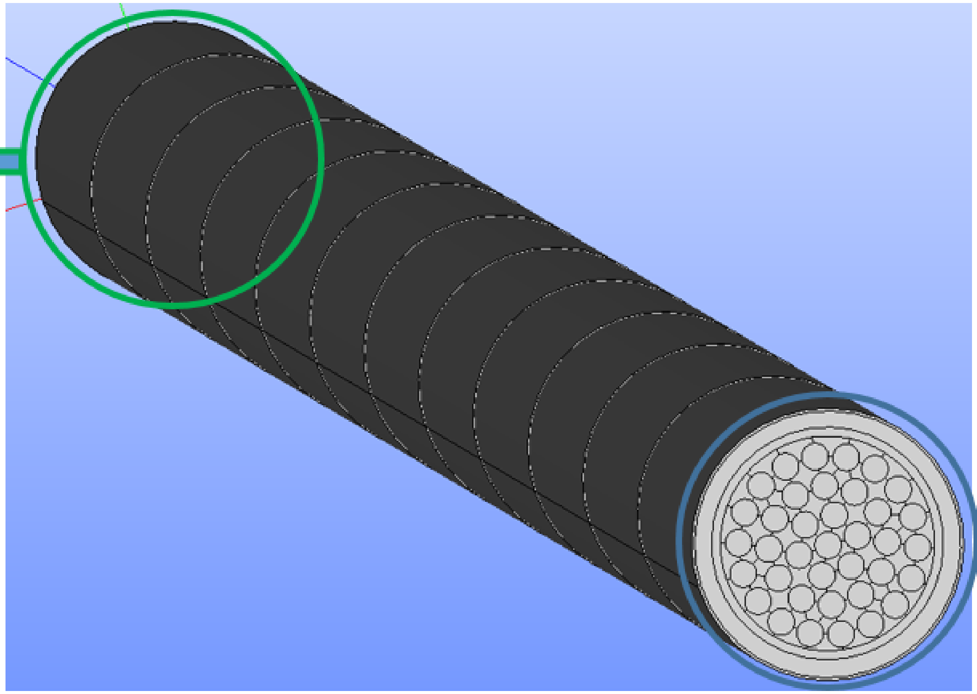


Figure 4. Radial and Axial Plot of the Mesh

- **A total of 65,550 nodes, 119,472 (prism, 4978 X 24) volumes, 24 axial levels in 3-D space**
- **A total of 4,978 triangles in radial cross section**

Boundary Condition

☐ Top and Bottom Surfaces

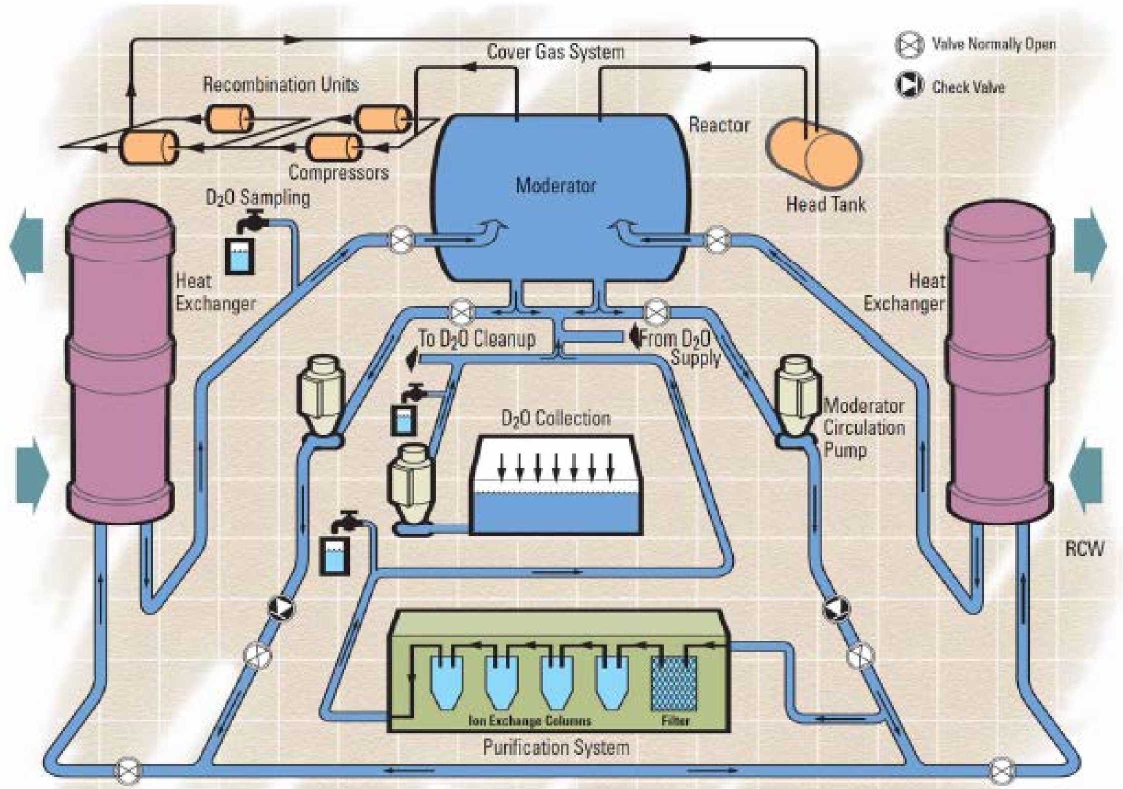


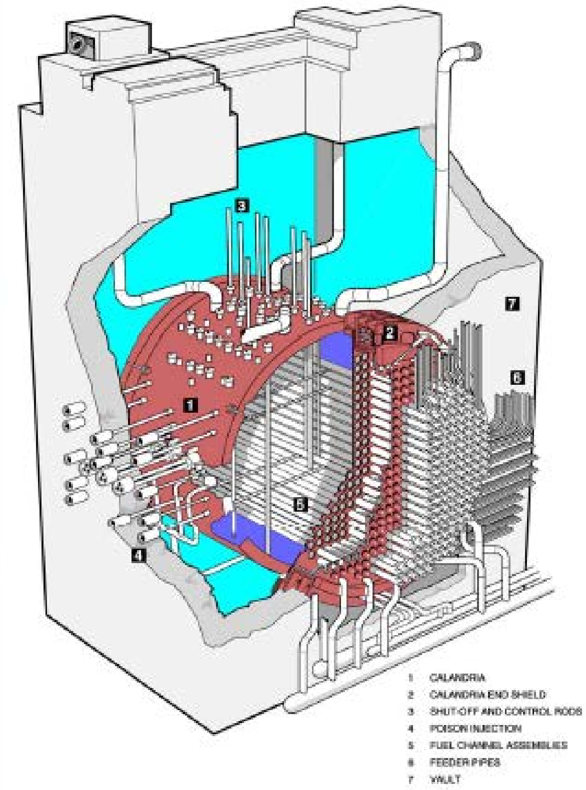
- **No Axial Heat Transfer by Conduction through Solid Surfaces**
  - In reality, the amount of heat loss through axial solid surfaces may certainly exist.
  - But it is assumed that the portion of heat loss through axial solid surfaces is not that big enough to affect to the overall calculation, specially for the purpose of this study
  - In the future, the boundary condition can be consider as constant T, but it should be verified that the CUPID code capable of that boundary condition for axial direction.

Boundary Condition

☐ Side Surfaces

- **Constant T wall**





  – 69 celsius degree in Physics design manual

Power Profile

❑ Axial Profile

- **Channel-wise Averaged Axial Power Profile**

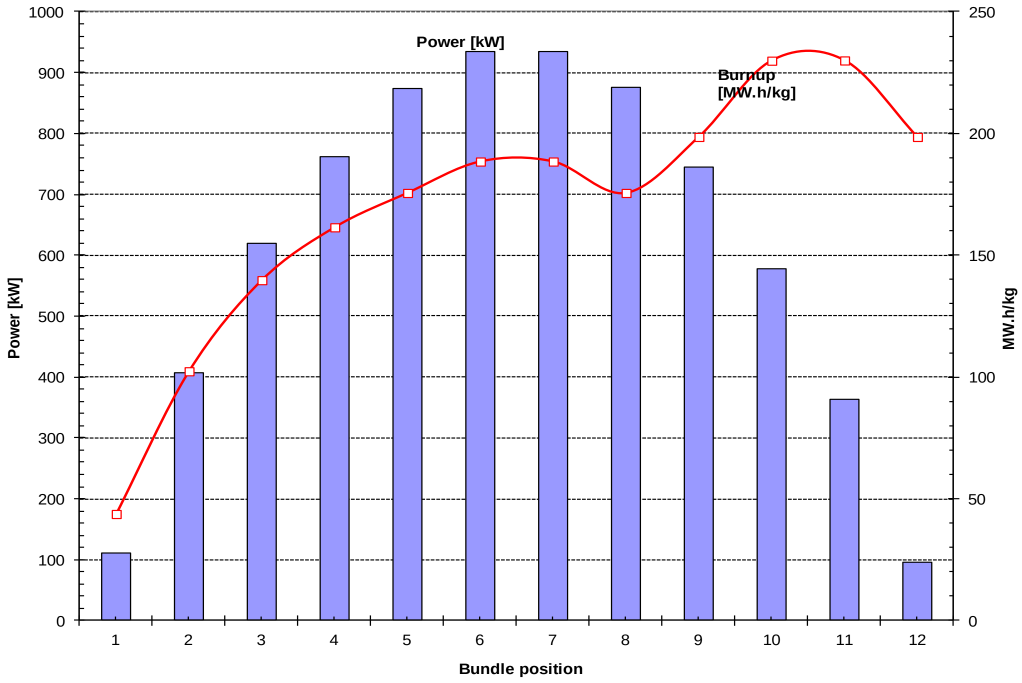


Figure 7. Axial Power and Burnup Profiles

- Almost cosine shape but a little top skewed
- Burnup rise up again at the end of channel because of 8 bundle shift scheme

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Power Profile

- **Estimated Vs. Proposed (Cosine Shape) Powers for Target Channel**

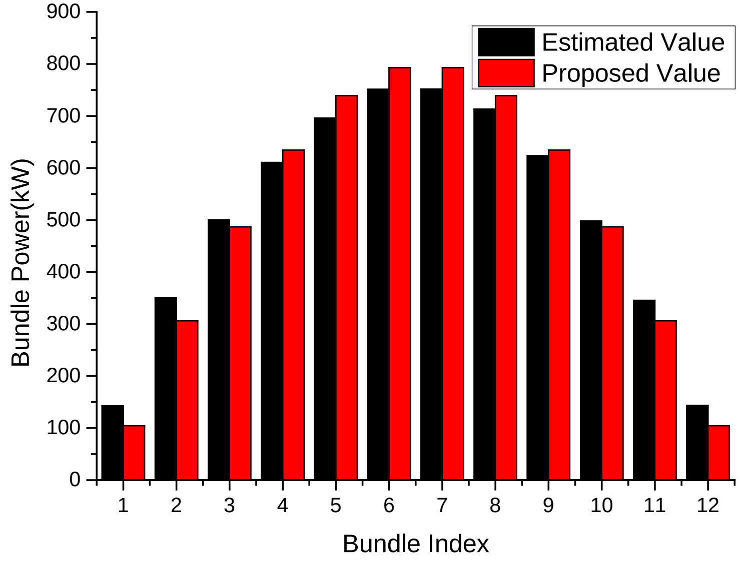


Figure 8. Estimated and Proposed Axial Powers

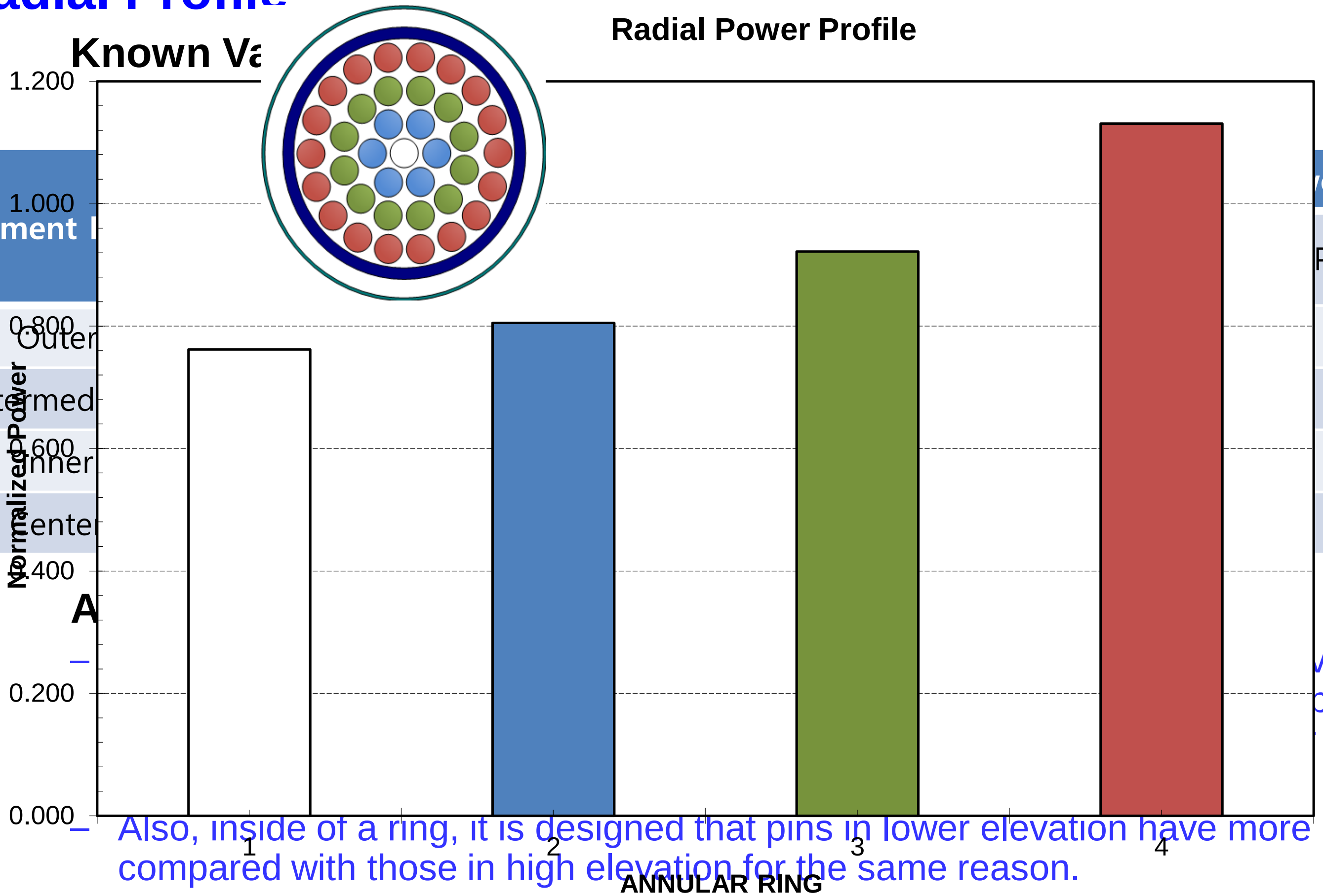
- Wolsong Unit 1, Q07 Channel was selected (procedure omitted, but the magnitude of deformation and channel power were standard for selection)
- Estimated Flux is used instead of Power, it will be corrected in the future, but the results will not be different from each other

Power Profile

☐ Radial Profile

- Known Va

Element	ver
	Per Ring
Outer	54.46
Intermed	30.01
Inner	13.37
Center	2.120



- A
  – vious studies, o, the pin pins will have
  – Also, inside of a ring, it is designed that pins in lower elevation have more power compared with those in high elevation for the same reason.
  – At last, RMS difference between pin powers for ref. and deformed case is set as about 3.6% (previously we found out that aging effect gives us 0.5% power difference)

Fuel Temperatures for Reference Case

Fuel Temperature

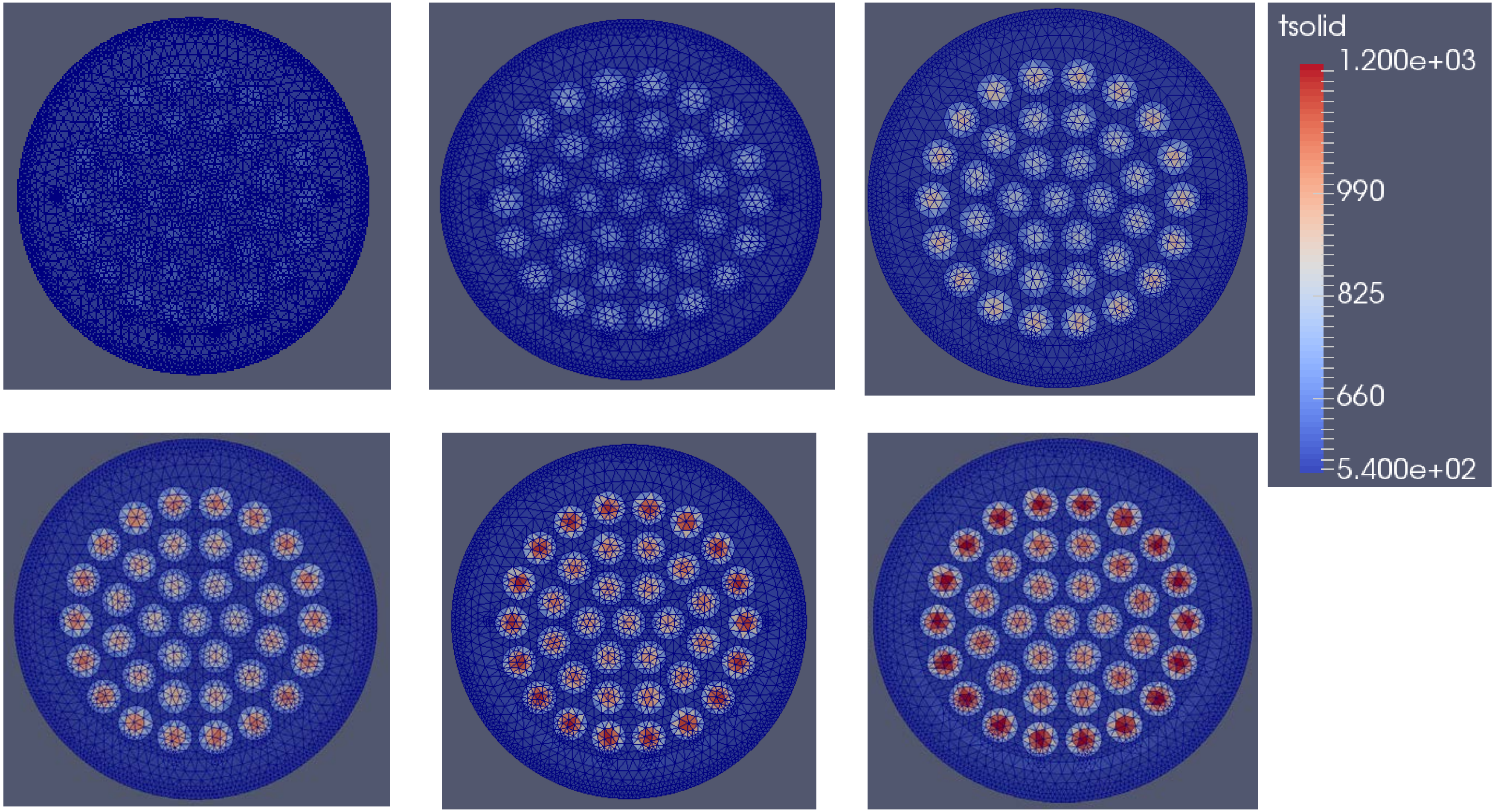


Figure 10. Fuel Temperature for Cross Section 1~6

Fuel Temperatures for Reference Case

❑ Fuel Temperature

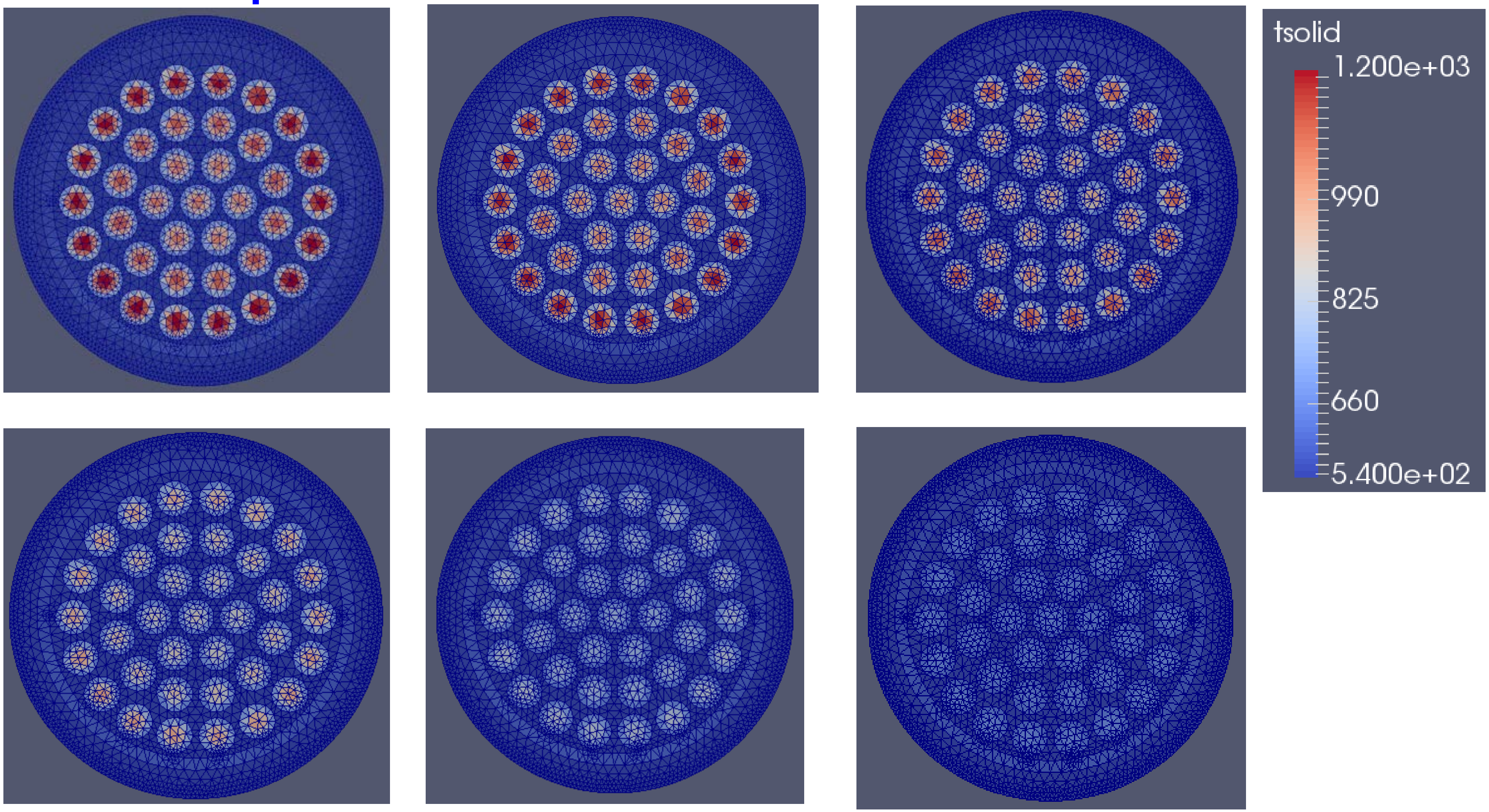


Figure 11. Fuel Temperature for Cross Section 7~12

Pressure Tube and Calandria Tube Temperatures

❑ PT and CT

Table 8. Temperature of PT and CT

Bundle Index	PT (38-th solid region)			CT (39-th solid region)		
	PDM (K)	CUPID		PDM (K)	CUPID	
		Ref. Case (K)	Def. Case (K)		Ref. Case (K)	Def. Case (K)
1	561.15	534.03	534.03	342.15	342.65	342.65
2		535.66	535.65		342.62	342.62
3		538.92	538.88		342.61	342.61
4		543.38	543.29		342.61	342.61
5		548.64	548.50		342.61	342.61
6		554.32	554.12		342.62	342.62
7		559.81	559.58		342.63	342.63
8		565.03	564.75		342.64	342.64
9		569.70	569.33		342.65	342.65
10		573.26	572.93		342.66	342.66
11		575.62	575.24		342.67	342.67
12		576.47	576.04		342.68	342.68
Average		556.24	556.03		342.64	342.64

Coolant Temperatures for Reference Case

☐ Coolant Temperature

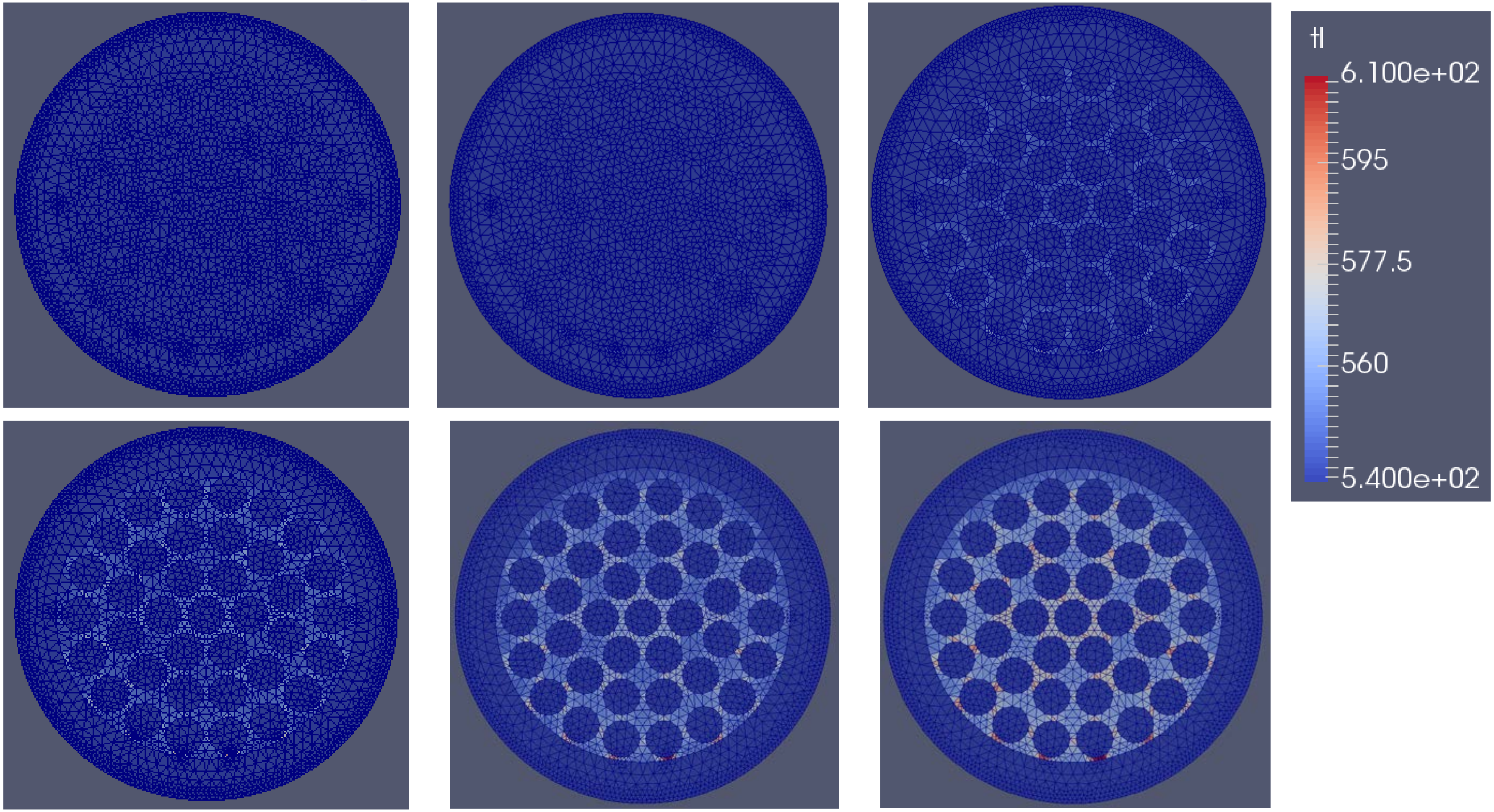


Figure 12. Coolant Temperature for Cross Section 1~6

Coolant Temperatures for Reference Case

☐ Coolant Temperature

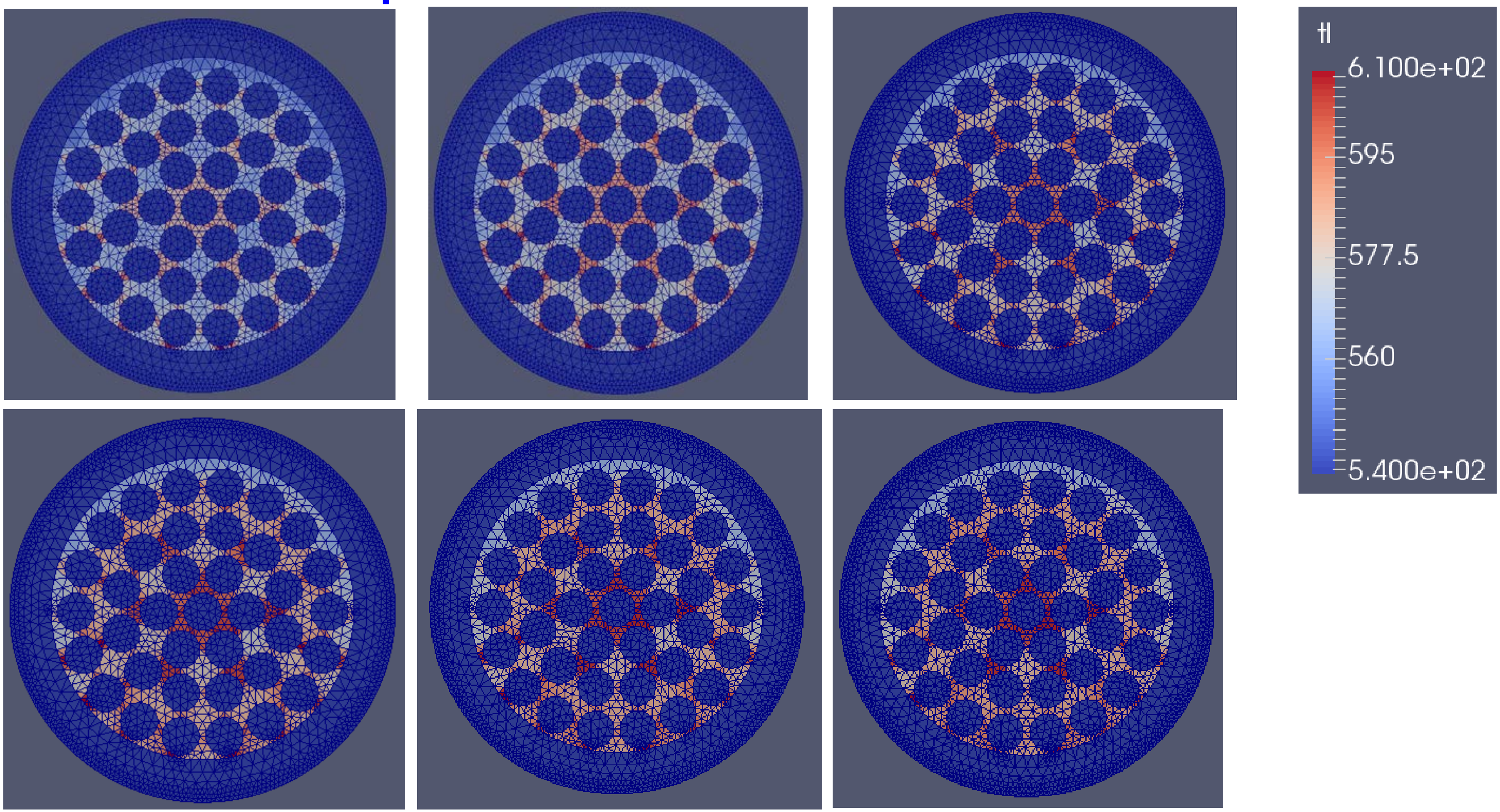


Figure 13. Coolant Temperature for Cross Section 7~12

Coolant Void Fraction for Reference Case

□ Coolant Void Fraction

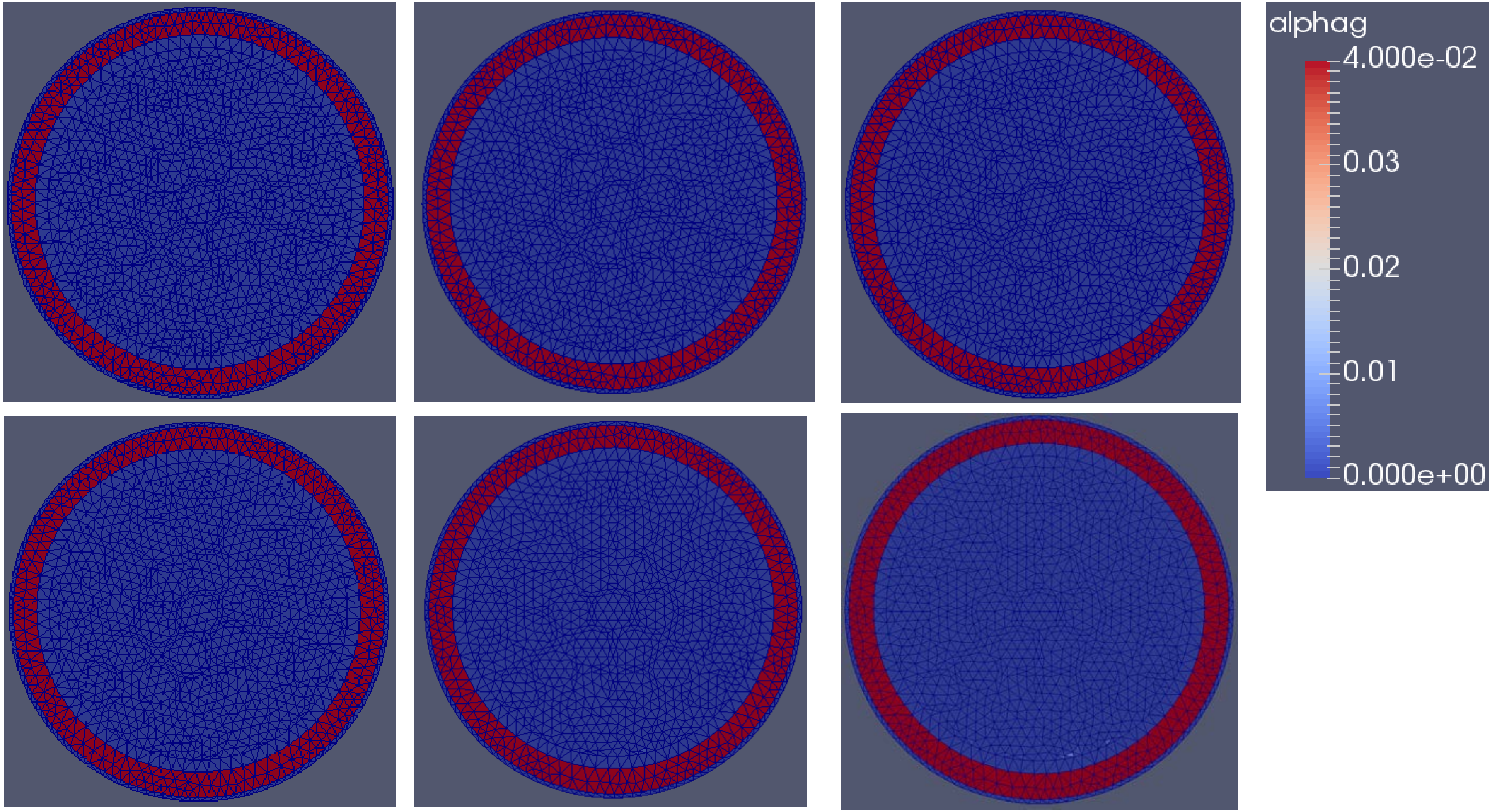


Figure 14. Coolant Void Fraction for Cross Section 1~6

Coolant Void Fraction for Reference Case

☐ Coolant Void Fraction

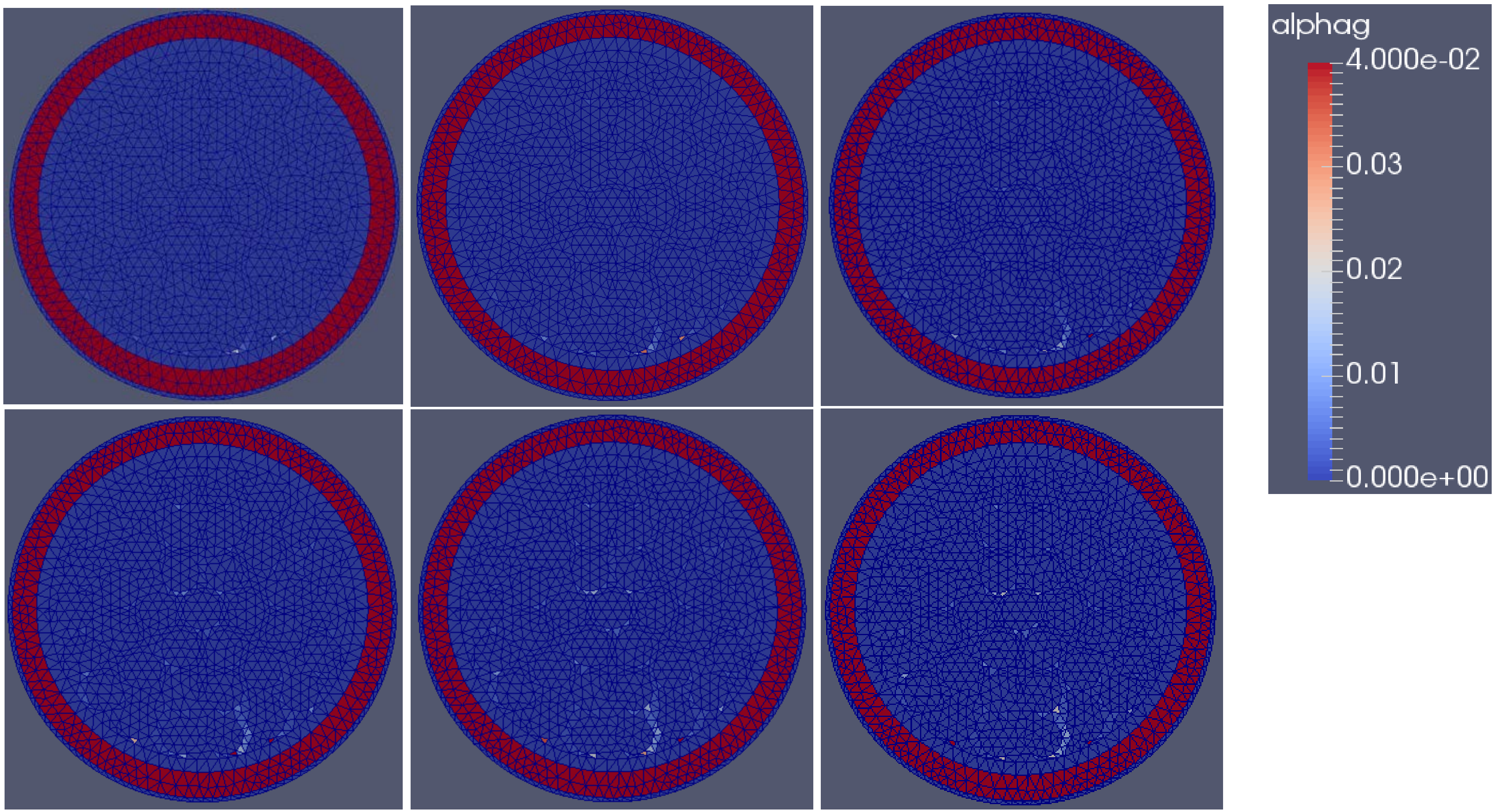


Figure 15. Coolant Void Fraction for Cross Section 7~12

Global Results

RMSE and Relative Errors

Table 9. Various Global Errors for Fuel Temp., Coolant Temp. and Coolant Density

	Fuel Temperature	Coolant Temperature	Coolant Density
RMSE	8.49K	0.99K	2.66kg/m^3
MAXimum Error (MAXE)	4.17% (34.04K)	0.79% (4.63K)	0.33% (2.53kg/m^3)
MAXE Position	7-th Bundle, 1-th Fuel	8-th Bundle, 6-th S.C.	8-th Bundle, 22-th S.C .
MINimum Error (MINE)	-1.03% (-8.66K)	-0.16% (-0.92K)	-1.82% (-13.72kg/m^3)
MINE Position	6-th Bundle, 8-th Fuel	8-th Bundle, 22th S.C.	8-th Bundle, 6-th S.C.

- **By considering that the power change is enlarged compared with the magnitude of real aged channel power, global changes should be approximately divided by 6. Then, we can face that the fuel temperature, coolant temperature, coolant density changes are globally just about 1.4K, 0.16K, 0.44kg/m^3 as well as MAXE and MINE.**
- **By taking into account of small change in magnitude, although there is local issues arising from sub-channel analysis, it seems that impact of pressure tube aging is not a significant threat to the channel in the normal operation.**
- **A cause of worry is that void appear one bundle earlier for the deformed case. If we take a look into cell wise results it may be more earlier. Also, deformed case can have many cells which have fluid temperature over saturation temperature for bundle near from the entrance**

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Conclusions

☐ Solid Temperatures

- **Axially Bottom Skewed Fuel Temperature Distribution**
  - Although we have axial symmetry on power, the coolant temperatures near from the bottom are higher than those around inlet. Thus the magnitude of heat transfer from solid to coolant is smaller because of large temperature difference
- **Global Fuel Temperature Distribution**
  - Globally, fuel temperature distribution follows the power distribution
- **Pressure Tube and Calandria Tube Temperatures**
  - Matched with temperatures in design document such as Physics Design Manual

☐ Fluid Temperatures

- **Monotonic Increase along Axial Direction**
  - Almost reaches to the saturation temperature, in several region fluid temperature exceed the saturation temperature (CUPID problem)
- **High temperatures around Central Region and Gravity Direction**
  - Because of narrow fluid area (or volume), those region encounter danger of CHF.
- **Gap Temperature between Pressure Tube and Calandria Tube**
  - Matched with temperatures in design document such as Physics Design Manual as pressure tube and calandria tube temperatures

Conclusions

☐ Void Fraction

- **Almost Zero during Most of the Simulation Time and Regions**
  - After fuel surface temperature exceed the fluid temperature which is stick with the solid, void can be generated. But the temperature difference should be large enough to generation void
  - Regionally, most of the region is void free for almost time and region, but the sub-channel region around the center pin and end regions along gravity direction has relatively small flow area compared with those of other regions. Due to this reason, the temperature and void fraction in these regions are much higher compared with those of other regions
- **Channel Dependent Property**
  - Although we have almost zero void fraction in this problem, the void fraction varies from channel to channel.

☐ Global Results

- **Negligible Effect from Power Distribution Change**
  - Even though we amplified 6 times the power distribution change compared with real magnitude of change, there were not significant changes in those parameters.
- **Incorporate Other Factors in the Future**
  - Near future, geometric effect, feedback effect will be taken into account to the analysis

References

- KHNP, “CANDU 6 Generating Station Physics Design Manual”, 2009.
- H.K.Cho, “Nuclear Systems Engineering Lecture Material 1-1”, 2017.
- H.K.Cho, “Nuclear Systems Engineering Lecture Material 1-2”, 2017.
- Sunil, “PTCRACK”, documentation, 19 Dec 2019.
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- C.Yoon, J.S.Jeon, J.H.Park, “NUCIRC Single Channel Analysis for Calculating the Power Coefficient of Wolsong Unit 1”, KAERI/TR-3740, 2009.
- J.H.Park, “Introduction to CANDU”, 2011.
- E.H.Ryu, “Introduction to Various Structure Distortions in Nuclear Reactors”

Dimensions

Several Dimensions

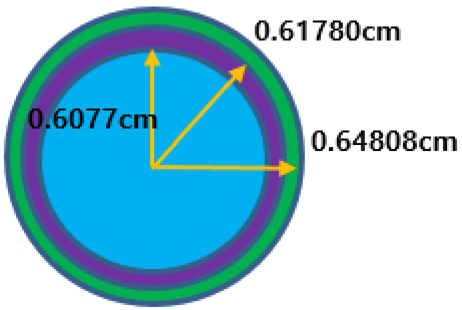

Figure A. Fuel Rod Dimensions

Table A. PT, CT and Bundle

Structure	Value
PT inside Radius	5.1689cm
PT outside Radius	5.6032cm
CT inside Radius	6.4478cm
CT outside Radius	6.5875cm
Bundle Length	49.53cm

Table B. Fuel Rod Center Positions

Rod Index	x (mm)	y (mm)
1	0	0
2	7.4423	12.8904
3	14.8845	0
4	7.4423	-12.8904
5	-7.4423	-12.8904
6	-14.8845	0
7	-7.4423	12.8904
8	7.4418	27.7733
9	20.3314	20.3314
10	27.7733	7.4418
11	27.7733	-7.4418
12	20.3314	-20.3314
13	7.4418	-27.7733
14	-7.4418	-27.7733
15	-20.3314	-20.3314
16	-27.7733	-7.4418
17	-27.7733	7.4418
18	-20.3314	20.3314
19	-7.4418	27.7733
20	7.5202	42.6491
21	21.6535	37.505
22	33.1751	27.8372
23	40.6953	14.8119
24	43.307	0
25	40.6953	-14.8119
26	33.1751	-27.8372
27	21.6535	-37.505
28	7.5202	-42.6491
29	-7.5202	-42.6491
30	-21.6535	-37.505
31	-33.1751	-27.8372
32	-40.6953	-14.8119
33	-43.307	0
34	-40.6953	14.8119
35	-33.1751	27.8372
36	-21.6535	37.505
37	-7.5202	42.6491

Boundary Condition for Radial Direction

☐ Side Surfaces

- **Solid and Fluid Interfaces**

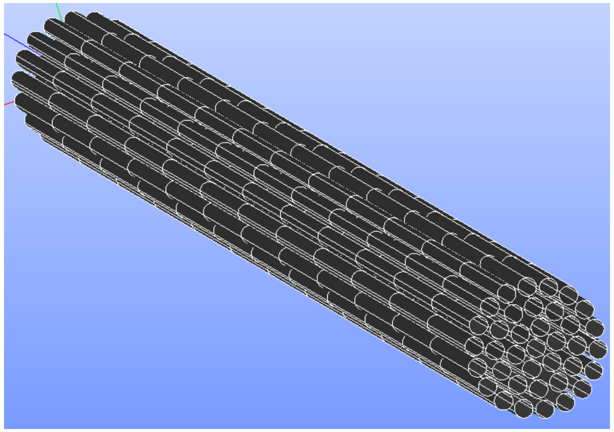

Figure B. Fuel and Coolant Interface(solidf1)

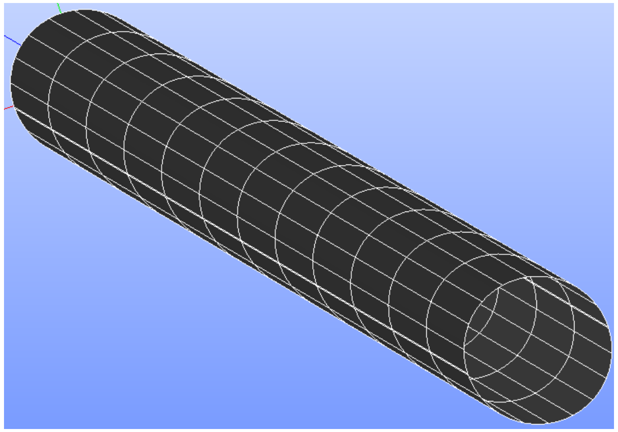

Figure C. Coolant and Pressure Tube Interface(solidf2)

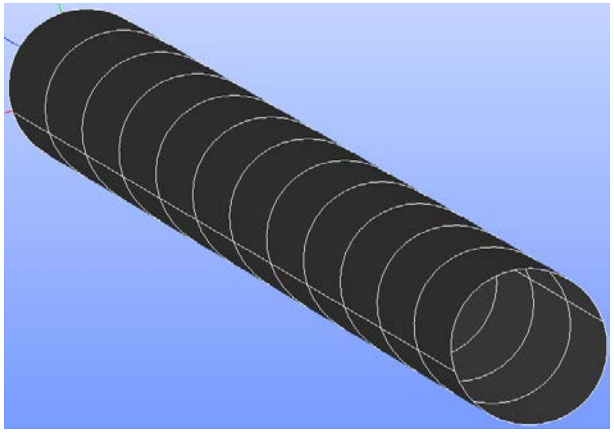

Figure D. Pressure Tube and Gap Interface(solidf3)

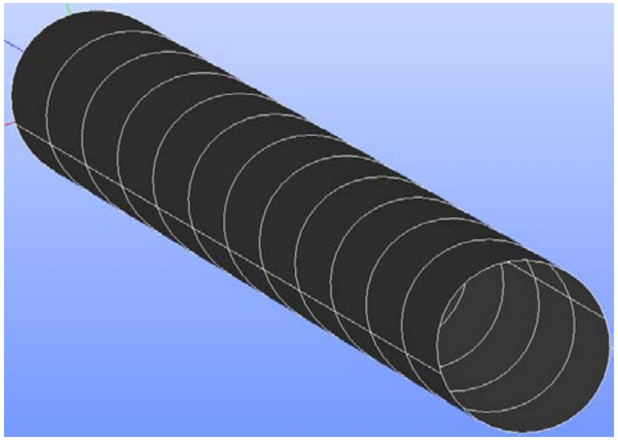

Figure E. Gap and Calandria Tube Interface(solidf4)

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Iteration Condition

Error Condition Definition

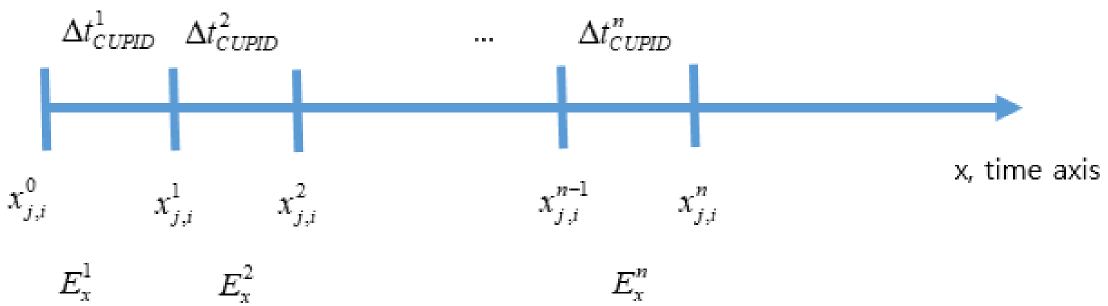

Figure F. Time Axis and Error Condition

$$E_x^n = \frac{1}{\Delta t^n_{CUPID}} \sqrt{\frac{\sum_{i=1}^{12}\sum_{j=1}^{p(x)} V_{j,i}(x)\left(x^n_{j,i} - x^{n-1}_{j,i}\right)}{\sum_{i=1}^{12}\sum_{j=1}^{p(x)} V_{j,i}(x)}}, \left\{x = T_{solid}, T_{fluid}, \rho_{fluid}\right\}$$

$$C_x > E_x^n$$

- **Where, n is time index, i is bundle index, j is radial region index, delta t is size of time interval which is used in the CUPID code, E is self-determined error parameter, C is self-determined convergence criteria which is set as 0.3, 0.2, 0.4 currently.**
- **Speed of solid temperature convergence is most slow. And this is somewhat loosen to see result fast.**
- **Tried to set up parameter which catches global change**

T/H Condition

☐ Values for Two Fluid Zone

Table C. T/H Values for Coolant Region

	Initial Value	Inlet Condition	Outlet Condition
Pressure (Pa)	11.4E6		10.0E6
Liq. Temp. (Kelvin)	535.61		N/A
Gas Temp. (Kelvin)	535.61		N/A
Void Fraction	0.0		N/A
NCG Quality	0.0		0.0
Velocity (m/s)	8.3229		N/A

Table D. T/H Values for Gap(CO_2) Region

	Initial Value	Inlet Condition	Outlet Condition
Pressure (Pa)	221325		201325
Liq. Temp. (Kelvin)	451.65		N/A
Gas Temp. (Kelvin)	451.6		N/A
Void Fraction	1.0		N/A
NCG Quality	1.0		1.0
Velocity (m/s)	16.6458		N/A

- **Pressure drop for gap region is specified well, in the future, maybe we can find exact value, namely 201,325 for outer condition is temporal value.**
- **Basic fluid is D_2O but because void fraction and NCG quality are 1.0 and 1.0 respectively, there is no D_2O actually in the gap region**

Calculation Resource

☐ CPU

- Intel® Core™ i7-8700 CPU @ 3.20GHz 3.19 GHz
- 2 Threads per Core
- Hyper Threading AUTO

☐ MPI

- MPICH2

☐ Command Line

- mpiexec –n 12 CUPID

☐ Results

- 147.019 hours for reference case (over 6 days)
- 147.320 hours for deformed case (over 6 days)

☐ Near Future

Table E. Prediction of Calculation Time Change for a Case

'iheatpart' Usage	Linux compile	Geometry Reflection	Feedback Inclusion	Mesh Quality Control	Increase # of Core	Implicit Option Usage with high CFL	Summation
-	+	-	--	+	++	+	??

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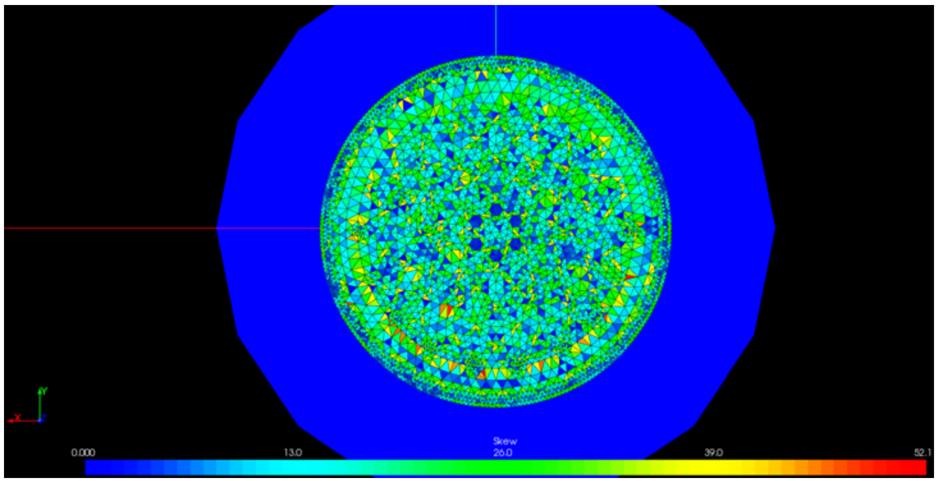
Mesh Quality Control

❑ Mesh Quality

- **Skewness (recommend less than 30)**



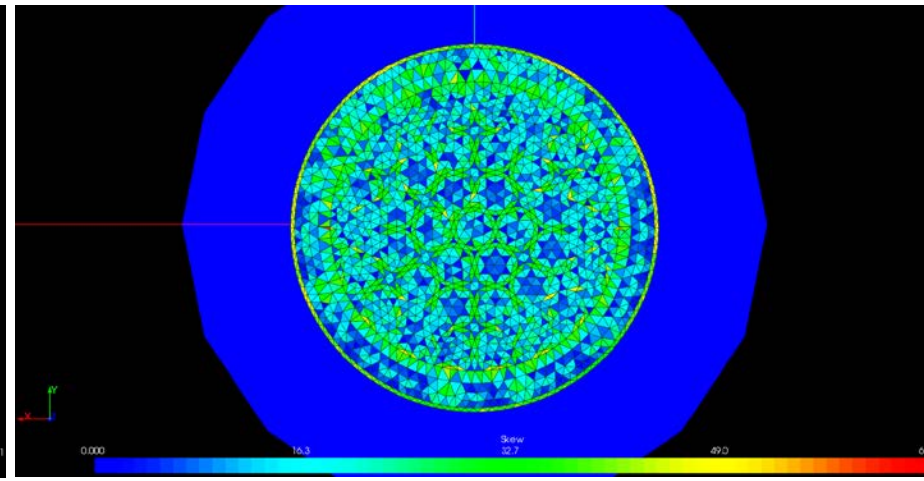


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Figure F. Salome Skewness Plot

- **Growth Rate (recommend less than 5%)**
  - Possible to control in sub mesh option
  - Hypothesis->NETGEN parameters->fineness->moderate to custm