Research Status of the Effects of the Pressure Tube Deformation on the Power Derating

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Contents

Channel Modeling Correction

☐ Shield Plug

- Material : Stainless steel
- Position : Between the closure plug and the fuel
- Role : Completes the radiation, prevents fuel movement
- Length : 91.4cm (based on the google)

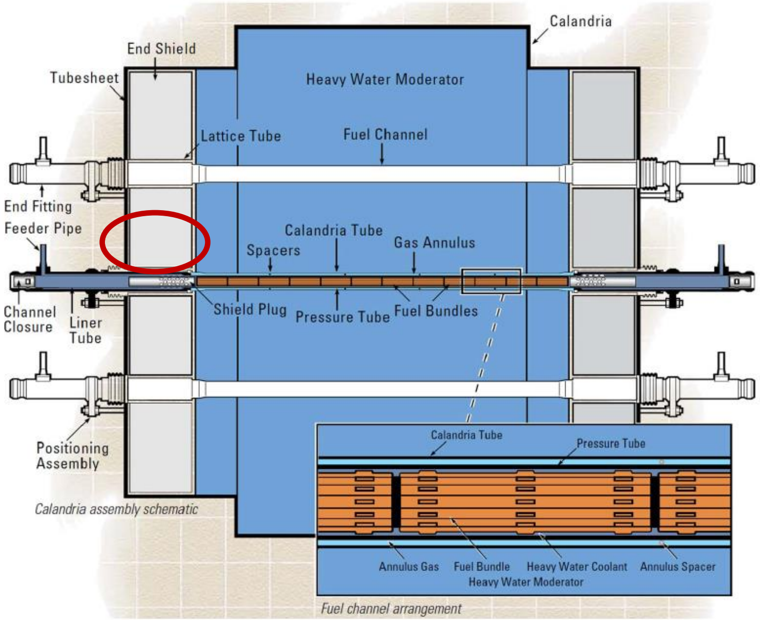

Fig. 1 Channel Structure

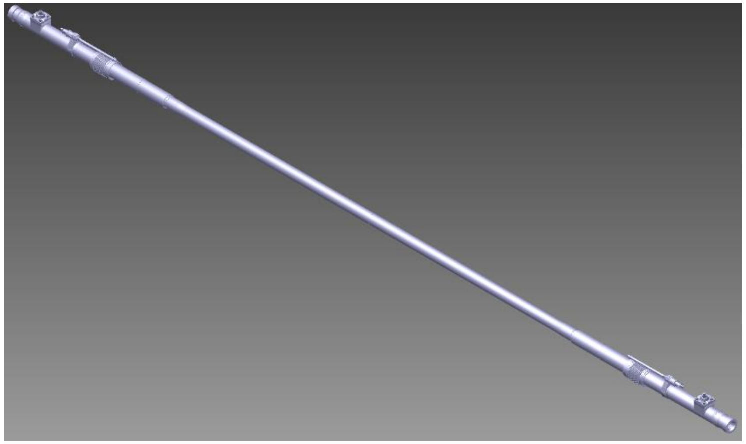

Fig. 2 Pressure Tube with CAD

Channel Modeling Correction

☐ Gap Sealing and Material Composition at the Channel End

- **Large Neutron Leakage though Gap**
- **A kind of Effort to Capture Real Geometry**

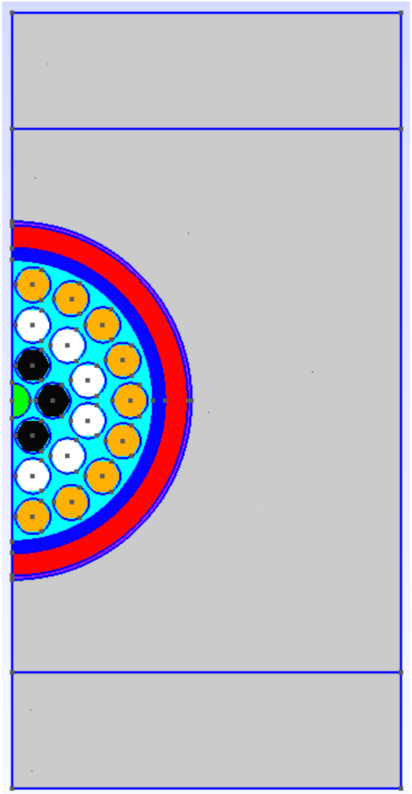

Fig. 3. Cross Sectional View for Half Lattice

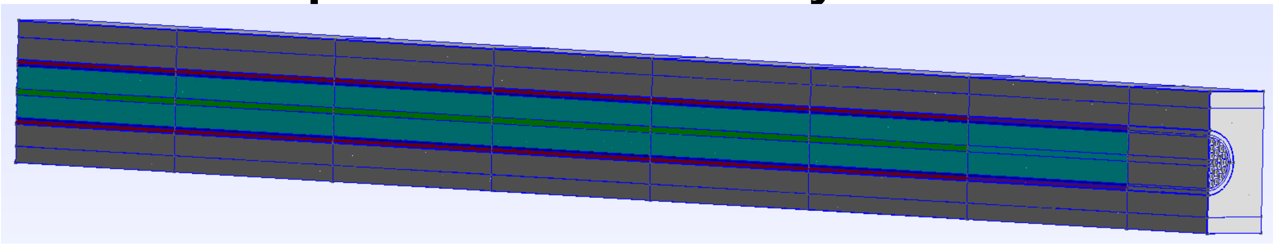

Fig. 4. Previous Modeling of Channel

-7 layer including end shield CT material except for PT and GAP regions
-7 layer extended.

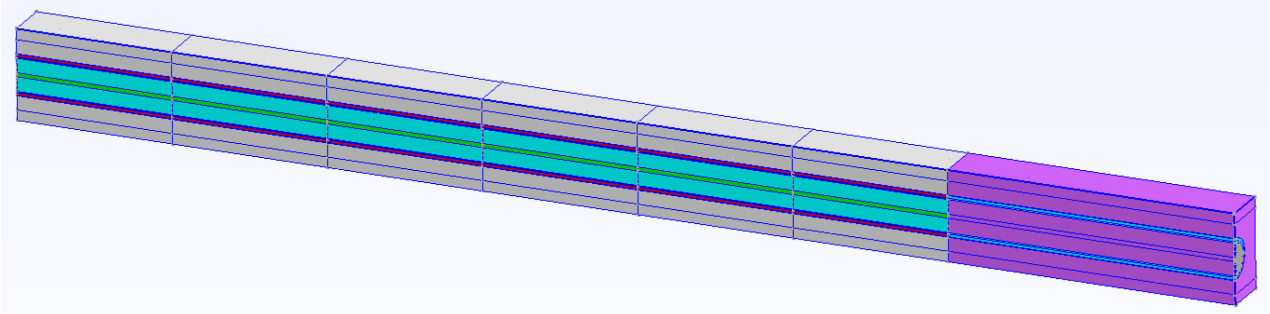

Fig. 5. Current Modeling of Channel

Analysis Flow Modification

❑ Flow Chart

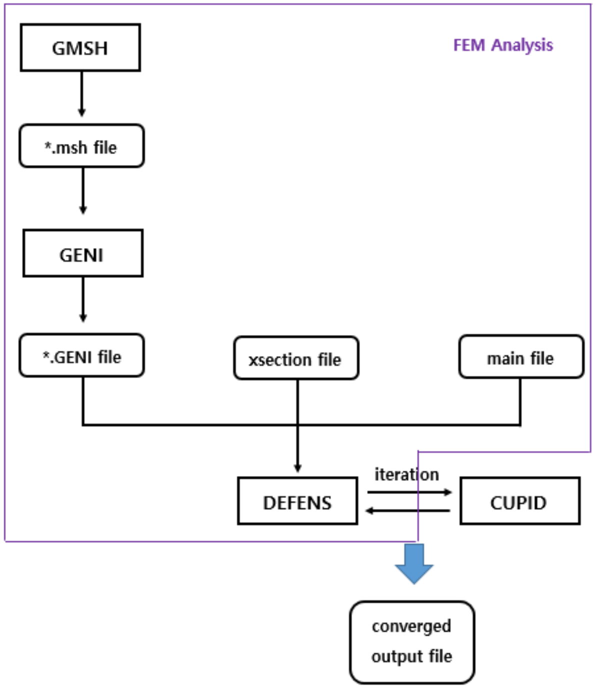

Fig. 6. New Flow Chart of Pressure Tube Deformation Analysis

- **GENI is newly made to separate mesh works from original version. (MPI is used for better performance)**
- **DEFENS is newly rewritten with PETSc library.**

Performance of the GENI Code

☐ Speed-up Ration and Parallel Efficiency with the Number of Processors

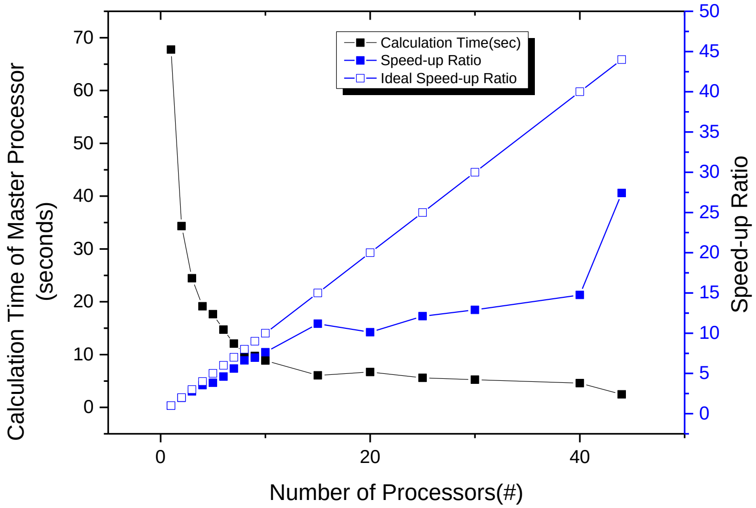

Fig. 7. Speed-up Ratio of the GENI Code

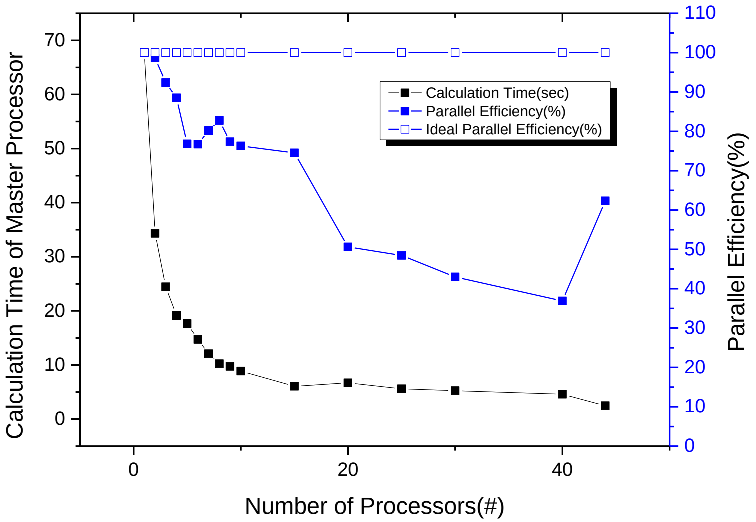

Fig. 8. Parallel Efficiency of the GENI

- **Node : 43,568, Elements : 250,636, Periodic Nodes : 4110**
- **Results in PC Environment is excluded because of speed**
- **Pre-processing time of original code is 84.67 seconds**

Performance of FEM Main Body with PETSc

☐ Speed-up Ratio and Parallel Efficiency with PETSc Solve Time per # Iterations

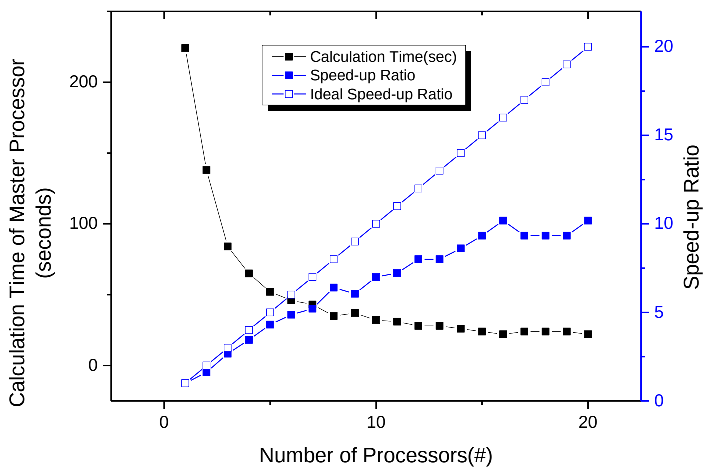

Fig. 9. Speed-up Ratio of FEM Main Body

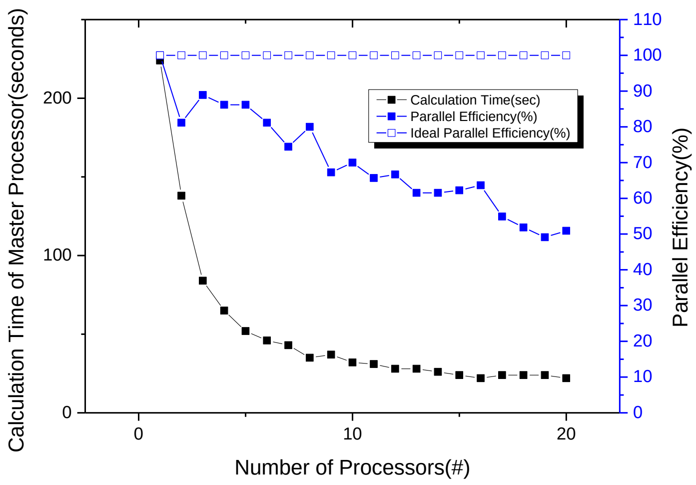

Fig. 10. Parallel Efficiency of FEM Main Body

- **Node : 688,951, Elements : 3,877,528**
- **Verification is done(Result Consistency Confirmed)**
- **Pre-processing time of the GENI code is 1207seconds with 20 processors**
- **Original Version Never Ends**

Other Issues

ILU Preconditioned CG VS Block Jacobi Preconditioned CG(Original Code VS PETSc)

- **Nodes 147,899, Elements 836,506: 438, 57 for power iteration part respectively (Same Iterations)**

Convergence Problem

- **Multiplication Factor Comparison with Problem Size**

Difficulty on Mesh Size Control exists

Table 1. Multiplication Factors for No Deformation Case with Mesh Size

Case	K_{eff} (error in PCM)	# Nodes	# Elements	Avg. Pitch(cm)	Avg. Vol.(cm^3)
McCARD (Muli-group)	1.09851	N/A			
CASE 1	1.11986	298,572	1,653,050	0.51	0.096
CASE 2	1.11428	591,582	3,340,268	0.40	0.047
CASE 3	1.11937	724,388	4,082,106	0.38	0.039
CASE 4	1.11853	885,009	5,007,368	0.35	0.032

Other Issues

- **Region Volume for Each Cases**

Table 2. Multiplication Factors for Ballooning Only Case with Mesh Size

Region	Real Volume (cm^3)	Case 1	Case 2	Case 3	Case 4
중심봉(1)	256.4	230.9	231.8	231.6	233.4
나머지연료봉(2~19)	512.7	428.9	474.2	438.3	444.9
연료합계	9485.2	7951.3	8775.6	8121.7	8240.5
냉각재(20)	6886.9	7565.9	7565.9	8222.0	8107.8
압력관(21)	2855.5	2854.1	2853.1	2854.8	2857.7
GAP(22)	6164.0	6174.1	6167.0	6167.1	6165.5
CT(23)	1111.5	1109.5	1110.8	1111.2	1111.0
MODER UP(24)		18251.7	18251.7	18251.7	18251.7
MODER CENTET(25)		95687.4	95668.1	95663.4	95657.9
MODER DOWN(26)		18251.7	18251.7	18251.7	18251.7
MODER합계	132140.6	132190.7	132171.4	132166.7	132161.2
전체	158643.7				

– Multiplication factor decreases as fuel volume increases and coolant volume decreases

Other Issues

☐ Solver Dependency

- By considering the structure of matrix(Symmetric and Positive Definite) generated using FEM, Conjugate Gradient is chosen in this research.
- Dependency on solver will be examined in the near future

☐ Preconditioner Dependency

- Production of Preconditioner is limited because of parallelization
- Only three of them, point Jacobi, block Jacobi, generalized additive Schwarz were examined without using IB, namely in 1 node
- ILU and ICC were not able to be generated with parallel algorithm, currently.
- Lc : 0.85, Nodes : 298,572, no deformation case, CG was used

Other Issues

Table 3. PETSc Time per Power Iteration with varying Preconditioner

# Processors	Point Jacobi (PCJACOBI)	Block Jacobi (PCBJACOBI)	Generalized Additive Schwarz (PCGASM)
1	78.6	52.7	57
2	52.9	33.8	36.2
3	34.4	24.2	25.3
4	25	18.8	19.5
5	21.5	15.8	16.5
6	18.5	14	14.7
7	16.7	12.8	13.3
8	14.1	11	11.5
9	13	9.7	10.2
10	11.7	9.2	9.5
11	11	9.1	9.4
12	10.3	8.1	8.3
13	9.9	7.8	8.2
14	8.9	7.3	7.7
15	8.7	6.7	7
16	8.4	7	7.4
17	8.1	6.2	6.7
18	7.7	6.2	6.3
19	8.1	6.8	6.8
20	8	6.3	6.3

Other Issues

☐ IB Band Test

- **Cluster in KAERI, 미래ITS, 임희영, last year, IB installed, 10 nodes are prepared**
- **Cluster in KAERI(LIFE Building), HPC KOREA, 송명환, Giga bit communication, no IB, 3 are nodes prepared**
- **Various OPENMPI versions were tested with PETSc**
- **Additional option required to use IB above version 4.0 of OPENMPI**
- **LAPACK was installed manually**

Other Issues

Table 4. Various Calculation Time in LIFE and RPL Clusters for Different Processors

# Processors	LIFE동 NODE 1 Only	LIFE동 NODE 1 + NODE 2	RPL Cluster	RPL Cluster PETSc 관련	RPL Cluster Coefficient Matrix 관련
2	228.7		202.6(177.7)	171.2(0.4,170.7)	15.9(15.5,0.9)
4	113.5	294.2	96.9(79.0)	75.5(0.3,75.1)	8.8(8.5,1.4)
6	87.6		79.2(61.8)	59.2(0.3,58.8)	7.3(6.9,1.9)
8	78.6		71.5(55.8)	53.5(0.3,53.1)	5.9(5.6,1.7)
10	67.6		62.5(47.2)	45.1(0.3,44.6)	5.6(5.3,2.2)
12	60.0		59.3(44.2)	42.0(0.2,41.6)	5.0(4.8,2.2)
14	57.0		57.6(43.0)	40.8(0.2,40.4)	4.8(4.6,2.3)
16	54.1		56.8(42.8)	40.5(0.3,40.1)	4.1(3.9,1.9)
18	53.3		57.0(42.6)	40.3(0.2,40.0)	4.4(4.2,2.4)
20	52.6		56.8(42.4)	39.9(0.3,39.3)	4.4(4.1,2.4)
22	149.8	613.8	58.3(44.1)	41.4(0.3,40.8)	4.3(4.1,2.5)
24			59.2(44.7)	41.9(0.3,41.3)	4.2(4.0,2.5)
26			60.6(45.9)	42.9(0.3,42.3)	4.3(4.0,2.6)
28			61.9(47.6)	44.4(0.2,43.8)	4.2(4.0,2.6)
30			59.7(44.7)	41.6(0.3,40.9)	4.8(4.5,3.2)
32			59.9(44.1)	41.0(0.3,40.3)	4.8(4.5,3.2)
34			51.3(35.9)	32.8(0.3,32.1)	5.4(5.1,3.9)
36			48.0(32.6)	29.6(0.3,28.9)	5.0(4.7,3.5)
38			46.6(30.5)	27.6(0.3,26.9)	5.6(5.2,4.1)
40			45.1(29.4)	26.5(0.3,25.8)	5.4(5.1,4.1)

Ballooning with the McCARD Code

☐ Ballooning Effect with the McCARD Code

- Coolant volume in real geometry : 6886.9041cm^3
- Coolant volume increment in current modeling : 532.726cm^3
- Modified pressure tube outer radius : 5.2627cm
- Every thickness of structure is maintained
- Multi-group calculation is done, the McCARD calculation with continuous cross sections will be done in the future
- High burn-up cross section is not used. It will be done in the future, too.
- Sagging cannot be modeled in the McCARD code
- 1 million particles were simulated with 1000 cycles including 200 inactive cycles.

Ballooning with the McCARD Code

- **Multiplication Factor**
  - Reduced from 1.09851(2pcm) to 1.09723(2pcm)
- **Pin Power Distribution Change**
  - RMS Error : 0.01%
  - Max Relative Error : Pin 1, 0.04%

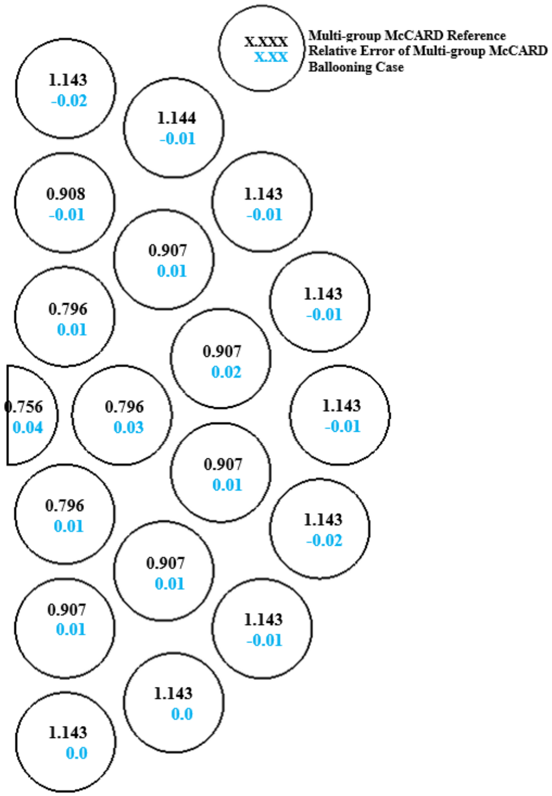

Fig. 11. McCARD Powers with Ballooning

Multiplication Factor and Power Distribution Change with Deformation

☐ Multiplication Factor

Table 5. Multiplication Factor for Deformations from Finite Element Analysis

McCARD Base Case	Base	Ballooning Only	Sagging Only	Ballooning with Sagging
1.09851 (2pcm)	1.11936 (2085pcm)	1.11740 (1889pcm) (-196pcm)	1.11948 (2097pcm) (12pcm)	1.11746 (1895pcm) (-190pcm)

- **1 million particles were simulated with 1000 cycles including 200 inactive cycles for the McCARD Calculation**

☐ Pin Power Errors

Table 6. Pin Power Errors for Deformations for Finite Element Analysis

Errors	Ballooning Only	Sagging Only	Ballooning with Sagging
RMSE(%)	0.02	0.23	0.22
MAXE(%)	0.038	0.44	0.41
MAXE Position	Pin 1	Pin 19	Pin 19

Multiplication Factor and Power Distribution Change with Deformation

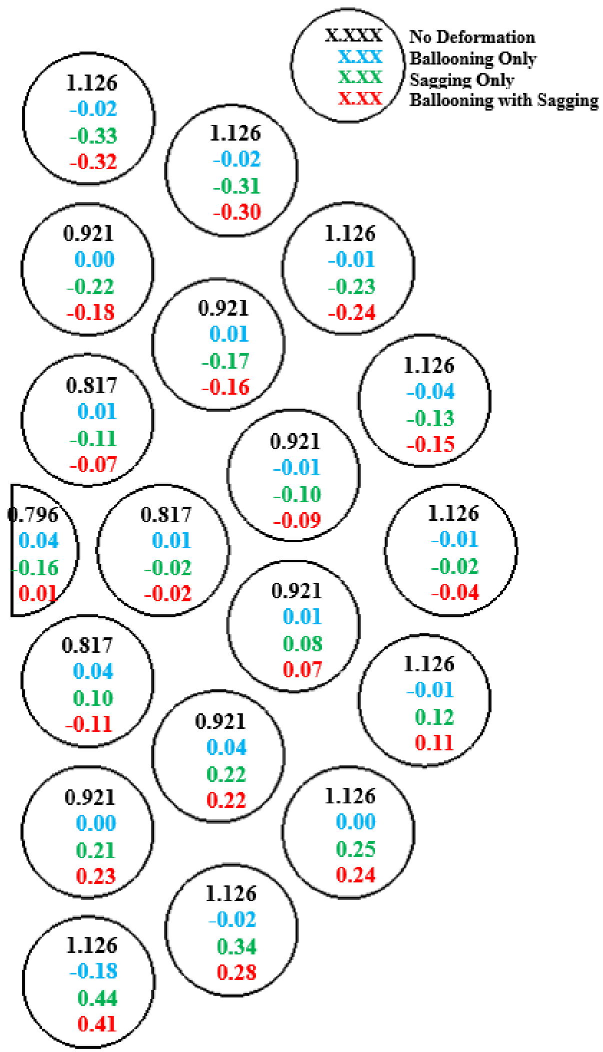

Fig. 12. FEM Powers with Deformations

2 Group Cross Sections and Incremental Cross Sections

□ Characteristics

- **High burn-up cross sections**
  - Average exit burn-up of CANDU reactor is about 7000MWD/tonU
  - Dimensions used in modeling are those of aged core with conservative views
- **Assumptions**
  - Cross sections do not vary with pressure tube deformation (Impossible to reflect and it is supposed that the variations is negligible)
  - (n,2n), (n,3n) reactions are treated as absorption cross section, thus the multiplication factor will decrease in multi-group calculation
  - 0.625eV is used as cut off value for 2 group
  - P1 equation was solved even though this is channel problem. P1 equation is possible to see the difference between deformations in the aspect of multiplication factor and pin power distribution. Also, its pin power distribution is trustable, thus it can be coupled with sub-channel code such as CUPID

2 Group Cross Sections and Incremental Cross Sections

☐ Sub-channel Division

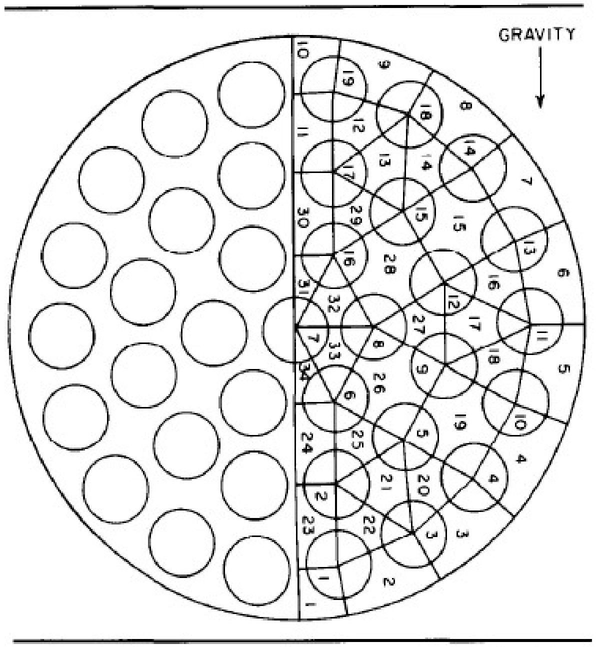

Fig. 13. Sub-channel and Rod Numbering in ASSERT

- CUPID sub-channel analysis in the CANDU reactor have never been done before
- Incremental cross section production is done for every sub-channels using symmetry

CAD Modeling for CUPID Input

☐ Sample Modeling without Deformation

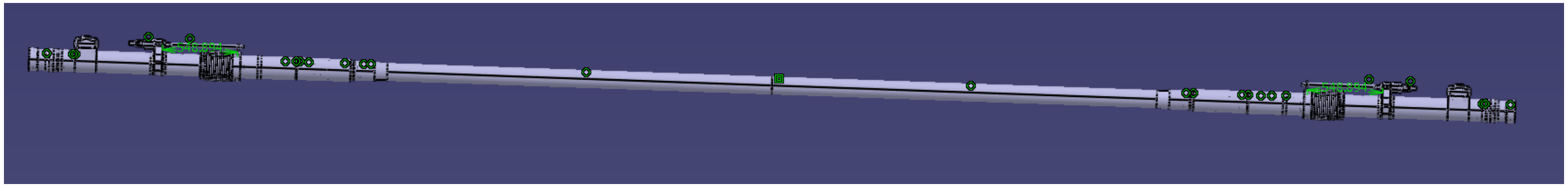

Fig. 14. Pressure Tube with Catia

☐ Sample Modeling with Deformation

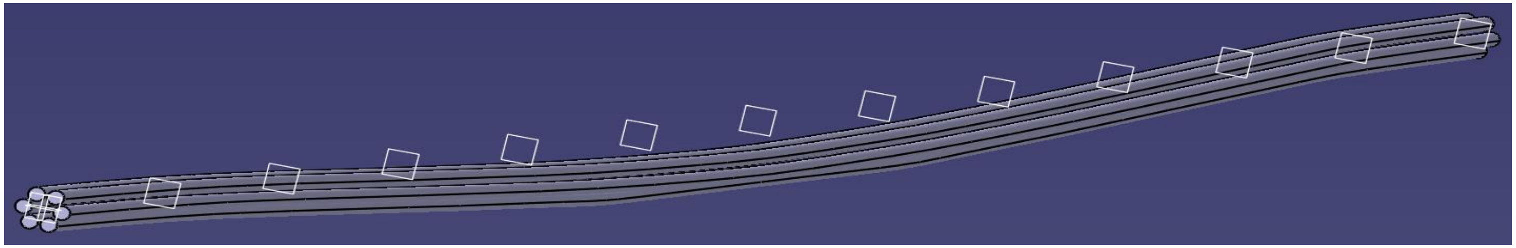

Fig. 15. Deformed Fuel Array 2 with Catia

☐ CUPID Workbench Test Running

- Solved simple problems to get familiar with the workbench including preprocessing and postprocessing
- Communication with CUPID team

Summary and Future Work

☐ Summary

- Channel model was modified to reflect real geometry more than before
- Strategy of FEM analysis was changed into two parts, mesh arrangement part and power iterations part
- The performance of the GENI code was examined
- The performance of the FEM main body which incorporated the PETSc library was studied
- Improvement for 1 processor was examined
- Convergence behavior with region volume was examined
- Preconditioner dependency of the PETSc library is tested a little
- Ballooning effect by using the McCARD code is introduced
- GMSH is fully capable of modeling and meshing until now
- Current status of cross section work is introduced
- Current status of works related with the CUPID code is introduced

Summary and Future Work

☐ Future Works

- Change GENI output format to binary, change FEM Main Body input format to binary to enhance the speed of reading and make more room in memory
- Cross Sections Production
- CUPID Input Production
- Solver Dependency Test
- IB band Test(Error Fix in RPL Cluster with Lee Jae Jin)
- Phenomenological explanation why the multiplication factor increases with fuel increase and coolant decrease
- Numerical result with finer mesh
- Addition examinations
- Mesh ordering like the CUPID code for better performance

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