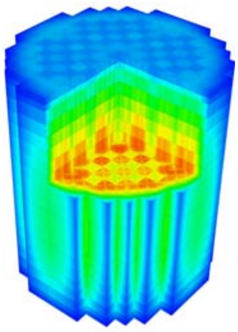
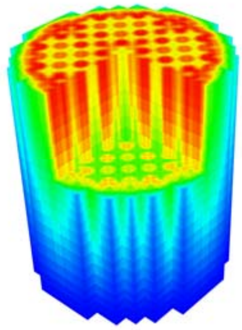
가동원전에 대한 다물리 고신뢰도 해석 현황



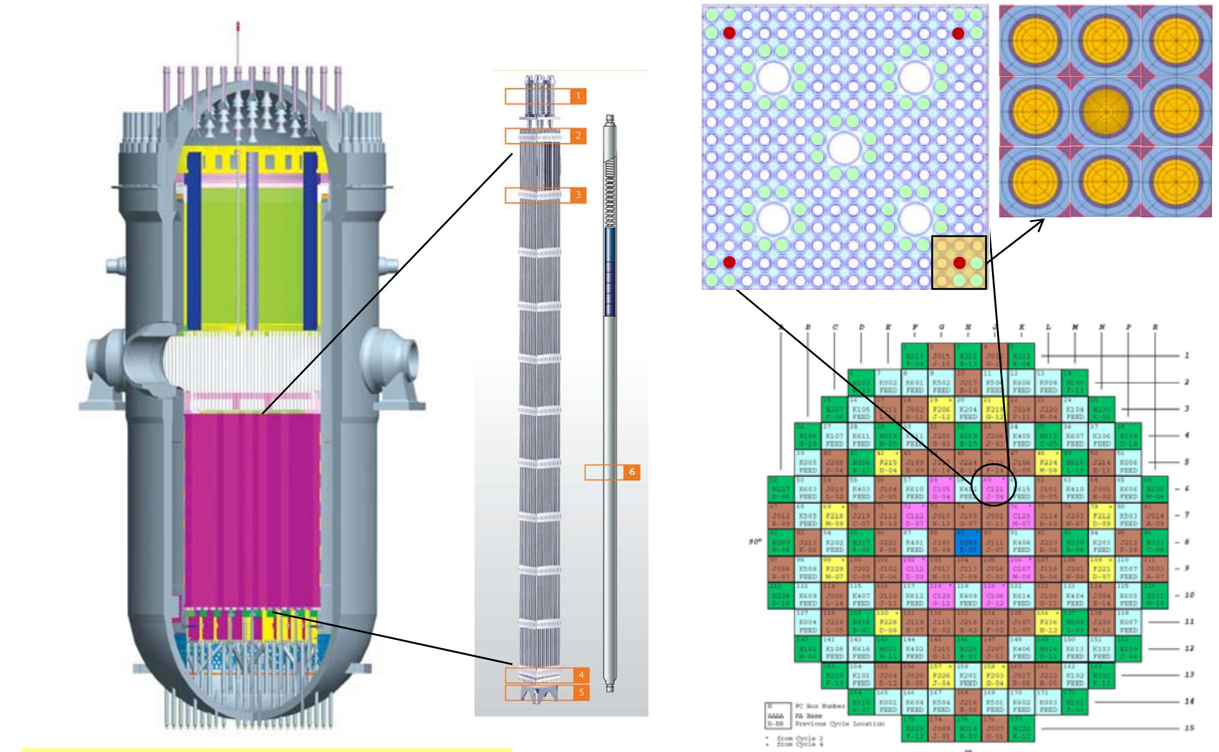
주 한 규
서울대학교 원자핵공학과



목 차

- □ **열유동 연계 고신뢰도 원자로 시뮬레이션의 필요성**
  - 현 노물리 계산 체제의 한계
  - 상세 열유동 모델을 포함한 고신뢰도 원자로 시뮬레이터의 필요성
- □ **nTRACER 직접 전노심 계산 코드**
  - 주요 핵특성 계산 방법
  - 부수로 코드와의 연계
- □ **가동 원전 노심 추적 계산**
  - OPR1000에 대한 수치원자로 계산
  - 핵연료 소자내 온도 분포 형상의 연료온도 계수에 대한 영향
- □ **CASL 팀 크러드 유발 비정상 축방향 출력 분포 해석**
  - SNU-CASL INERI 공동연구
  - MPACT-CTF-MAMBA 연계 CIPS(Crud-Induced Power Shift) 해석
- □ **요약 및 진행 중 연구**

Pressured Water Reactor and Its Constituents
(Korean OPR1000 Reactor w/ CE Type 16x16 FAs)



200 FAs x 300 pins/FA x 50 radial regions/pin x 400 axial regions = 1.2×10^9 Spatial Regions

Different color for different fuel enrichment or burnup

Difficulties of Direct Transport Solution

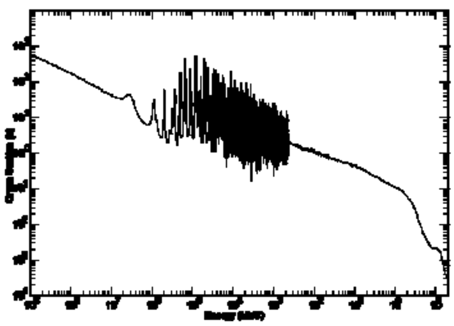
☐ **Boltzmann Transport Equation**

$$\Omega \cdot \nabla \varphi(r,E,\Omega) + \Sigma_t(r,E)\varphi(r,E,\Omega) = \int_{\Omega'}\int_{E'} \Sigma_s(\Omega' \to \Omega, E' \to E)\varphi(r,E,\Omega)dE'd\Omega' + \frac{1}{4\pi}\chi(E)\psi(r)$$

☐ **Complicated Dependence Cross Sections on Conditions**

- Resonance behavior
- Anisotropic scattering
- Temperature dependence of macro Xsec
  - Microscopic cross section: Doppler effect
  - Coolant number density: scattering power

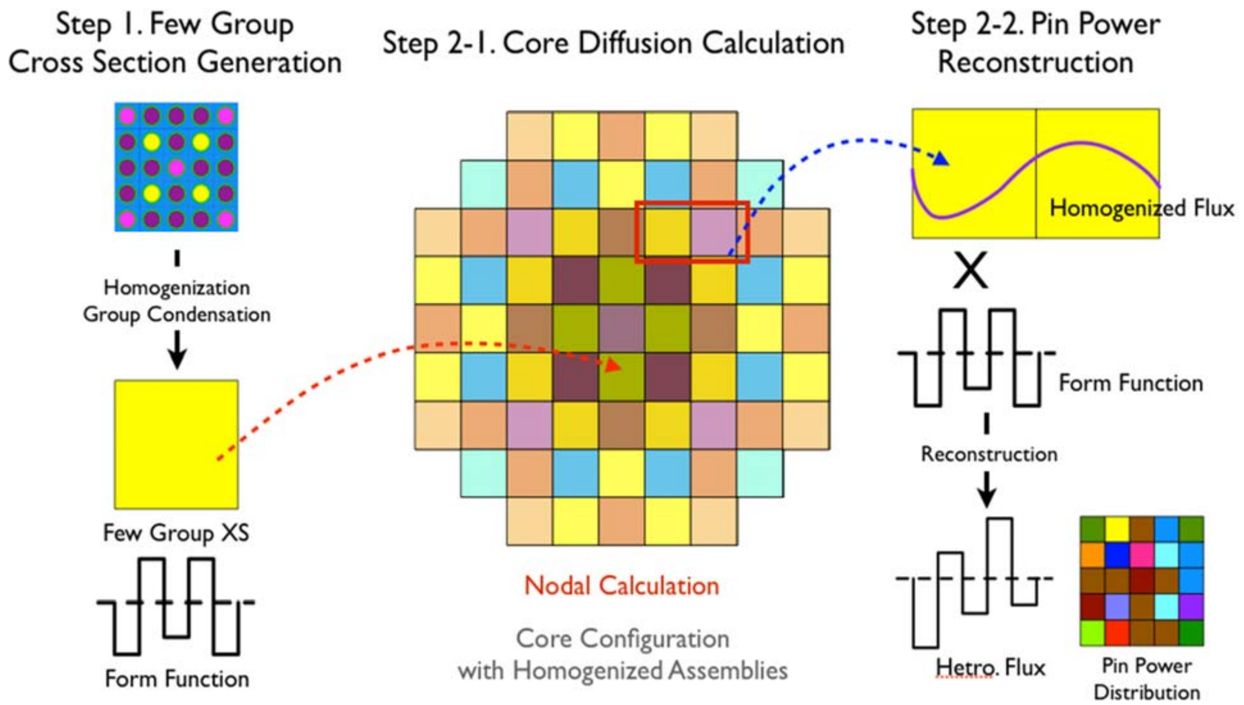
$$\Sigma(\vec{r},E) = \sum_i N_i(\vec{r},T(\vec{r}))\sigma_i(T(\vec{r}),E)$$



☐ **Severe Spatial Dependence**

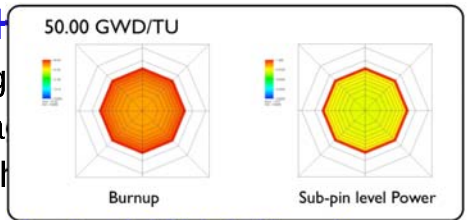
- Large flux gradient across material discontinuity
- Boundary effect determining the global shape of flux

Two-Step Core Calculation Procedure



Problems of Two-Step Procedure

- **Accuracy Loss Due to Homogenization/Condensation**
  - Infinite medium spectrum different from actual spectrum in the core
    - Errors in the homogenized and condensed cross sections
  - Solution for homogenized problem different from heterogeneous sol.
    - Need equivalence parameters such as ADF and SPH factors
    - No thorough theoretical background and thus temporary fixes
- **Inability to Accurately Model Real T/H**
  - Assemblywise flow channels with an averag
  - T/H feedback incorporated only in the avera
  - Pin powers within an FA are determined witl



- **Inability to Accurately Incorporate Detailed BU Effects**
  - Rim effect that lowers pellet interior temperature to give lower average fuel temperatures can not be considered
  - Power defect overestimated

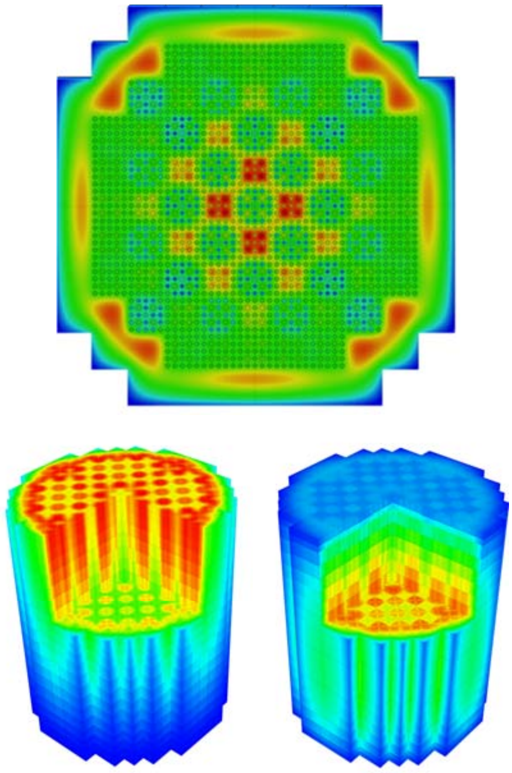
Direct Whole Core Calculation

☐ Requirements

- Transport calculation with explicit geometry and compositions
  - Dimensions of pellet, clad, grid, shroud etc.
  - Intrapellet isotopic inventory
- Fine energy group with more than 40G
- Resonance self-shielding on the fly
  - Composition, configuration and temperature dependence
- Detailed thermo-fluid calculation
  - Subchannel coolant temperature profiles and intrapellet fuel temperature profiles
- Subpin level depletion
- Short and long term transient calculation
  - kinetics calculation and xenon transient

☐ Capabilities

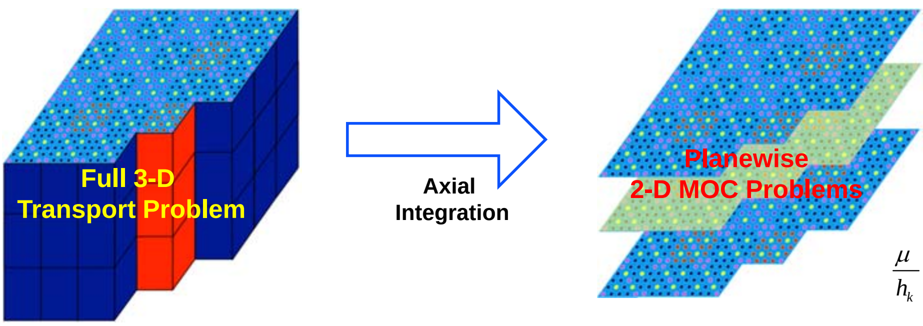
- Subpin level detailed output
  - Flux, power, temperature and isotopic inventory
- Cycle depletion with a single input deck without any prior calculations
- Transient calculation at any burnup point after restart



Planar MOC Formulation

☐ Planar MOC Problem

- Axially Integrated Planar Transport Equation (for Plane k)



$$\frac{\mu}{h_k}\left(\varphi_{km}^{T}(x,y)-\varphi_{km}^{B}(x,y)\right)$$

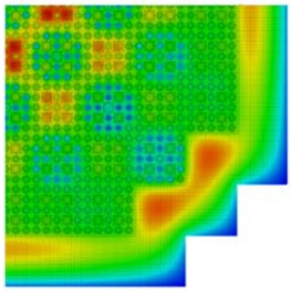
$$\left(\varepsilon_m\frac{\partial}{\partial x}+\eta_m\frac{\partial}{\partial y}+\mu_m\frac{\partial}{\partial z}\right)\varphi_m(x,y,z)+\Sigma_t^k\varphi_m(x,y,z)=Q_m(x,y,z)$$

$$\boxed{\left(\varepsilon_m\frac{\partial}{\partial x}+\eta_m\frac{\partial}{\partial y}\right)\bar{\varphi}_m^k(x,y)+\Sigma_t^k(x,y)\bar{\varphi}_m^k(x,y)=\bar{Q}_m^k(x,y)-\underline{L_m^k(x,y)}}$$

- Each planar MOC is coupled with other planes through axial leakage source Axial Leakage Source
- Given the axial leakage term, each planar MOC problem becomes a source problem
- The axial leakage term can be determined in an approximated manner from a 3-D CMFD result

CMFD Formulation

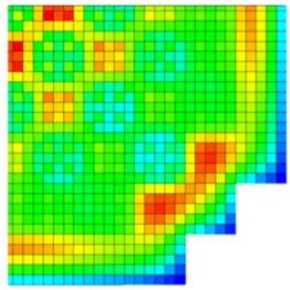
☐ Dynamic Homogenization



Planar MOC Solution

$$\bar{\Sigma}_x = \frac{\sum_i \Sigma_{x,i}\phi_i V_i}{\sum_i \phi_i V_i}$$

Cell-wise Homogenization



Cell-wise homogenized Flux and XS

☐ Construction of CMFD Relation for Net Current

- CMFD relation for the current vs. mesh average flux containing the correction coefficient D-hat is obtained from the base planar MOC soluyion for full consistency between homo and hetro problems

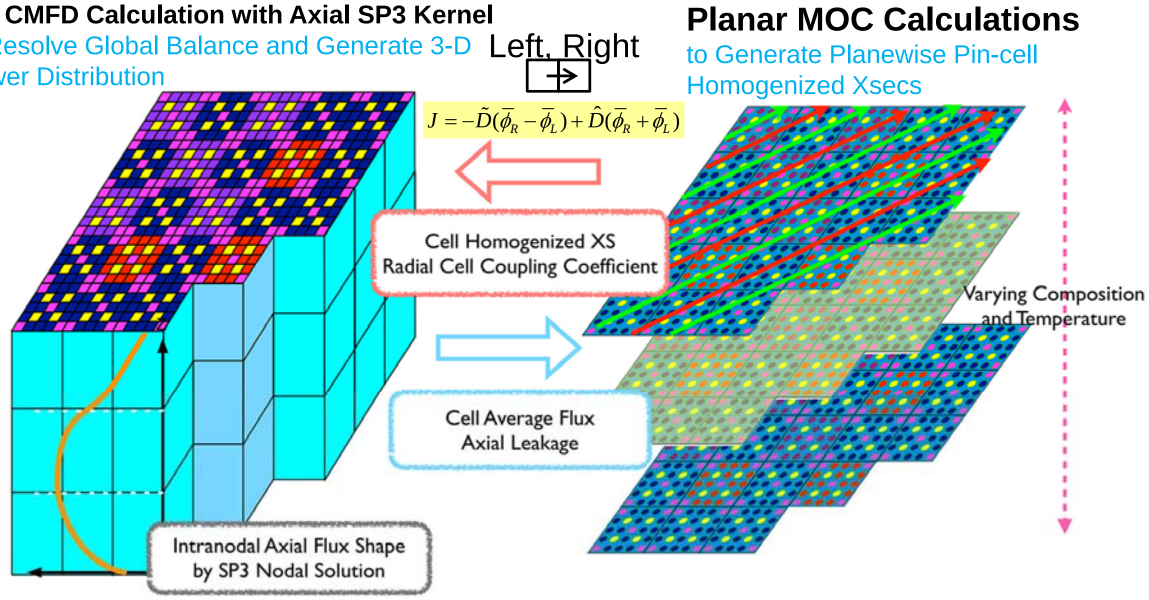
$$J_S = -\tilde{D}_S(\bar{\phi}_R - \bar{\phi}_L) + \hat{D}_S(\bar{\phi}_R + \bar{\phi}_L)$$

- To build the full 3-D CMFD system, the axial CMFD relation is obtained using the axial SP3 nodal calculation solver embedded in the 3-D CMFD module such that cell homogenized cross sections are used in the axial SP3 calculation

Planar MOC Based 3-D CMFD Calculation

3-D CMFD Calculation with Axial SP3 Kernel
to Resolve Global Balance and Generate 3-D Power Distribution

Planar MOC Calculations
to Generate Planewise Pin-cell Homogenized Xsecs



3D CMFD Solver
incorporating with Axial SP3 Nodal Method

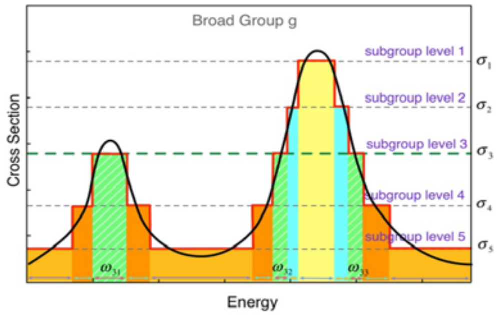
Planar MOC Solver

CMFD=Coarse Mesh Finite Difference

*MOC=Method of Characteristics

Subgroup Method

☐ Subgroup Representation of Resonance and Effective XS



$$\sigma_g = \frac{\int_{E_{g+1}}^{E_g} \sigma(E)\phi(E)dE}{\int_{E_{g+1}}^{E_g} \phi(E)dE} = \frac{\sum_m \omega_m \sigma_m \phi_m}{\sum_m \omega_m \phi_m}$$

☐ Space Dependent Flux Level for Effective XS

$$\phi_m(\mathbf{r}) = \frac{\lambda\Sigma_p(\mathbf{r}) + \Sigma_{esc}^m(\mathbf{r})}{N_R(\mathbf{r})\sigma_m + \lambda\Sigma_p(\mathbf{r}) + \Sigma_{esc}^m(\mathbf{r})}$$

Single Resonance Isotope in medium

☐ Escape XS to Reflect the Heterogeneity Effect due to Leakage

- obtained as a function of subgroup level by solving the following subgroup fixed source problem (SGFSP)

$$\Omega_m \cdot \nabla\varphi_m(\mathbf{r}) + \left(N_R(\mathbf{r})\sigma_m + \lambda\Sigma_p(\mathbf{r})\right)\varphi_m(\mathbf{r}) = \frac{1}{4\pi}\lambda\Sigma_p(\mathbf{r})$$

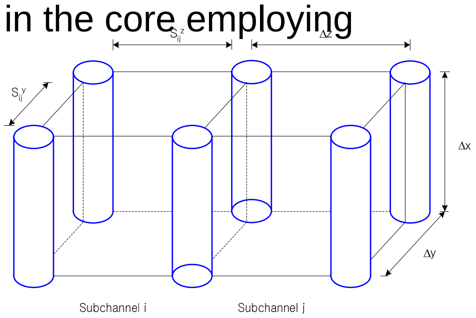
Subchannel Analysis Code MATRA

☐ Functions

- Determine the temperature and flow field in the core employing subchannels
- Estimate DNBR

☐ MATRA Subchannel Code

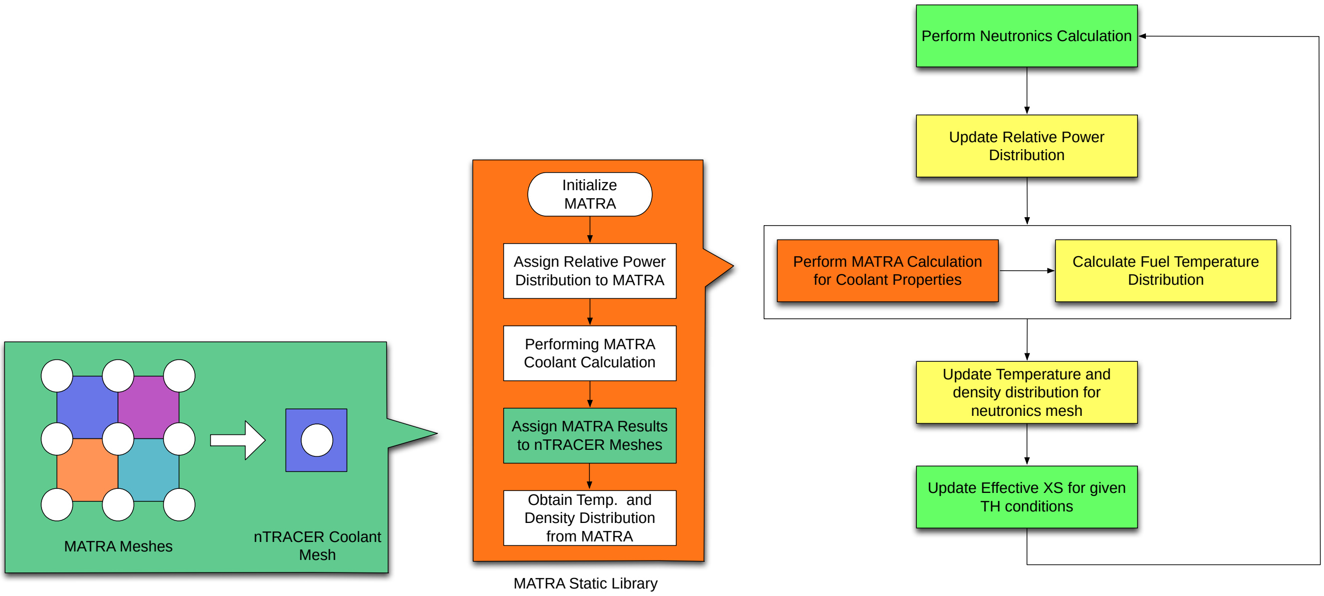
- Based on COBRA-VI-I (HEM Model)
  - Homogeneous mixture of fluid and vapor at thermal equilibrium
- Assumption and Limitations
  - Axially dominant flow
  - Lateral flow has no direction
  - Combined (axial+lateral) momentum equation
  - Two-phase fluid velocity modeled with **slip ratio**
- Applicable Reactors
  - PWR, HTTR, SFR, LFR, SCWR
  - Annular fuel



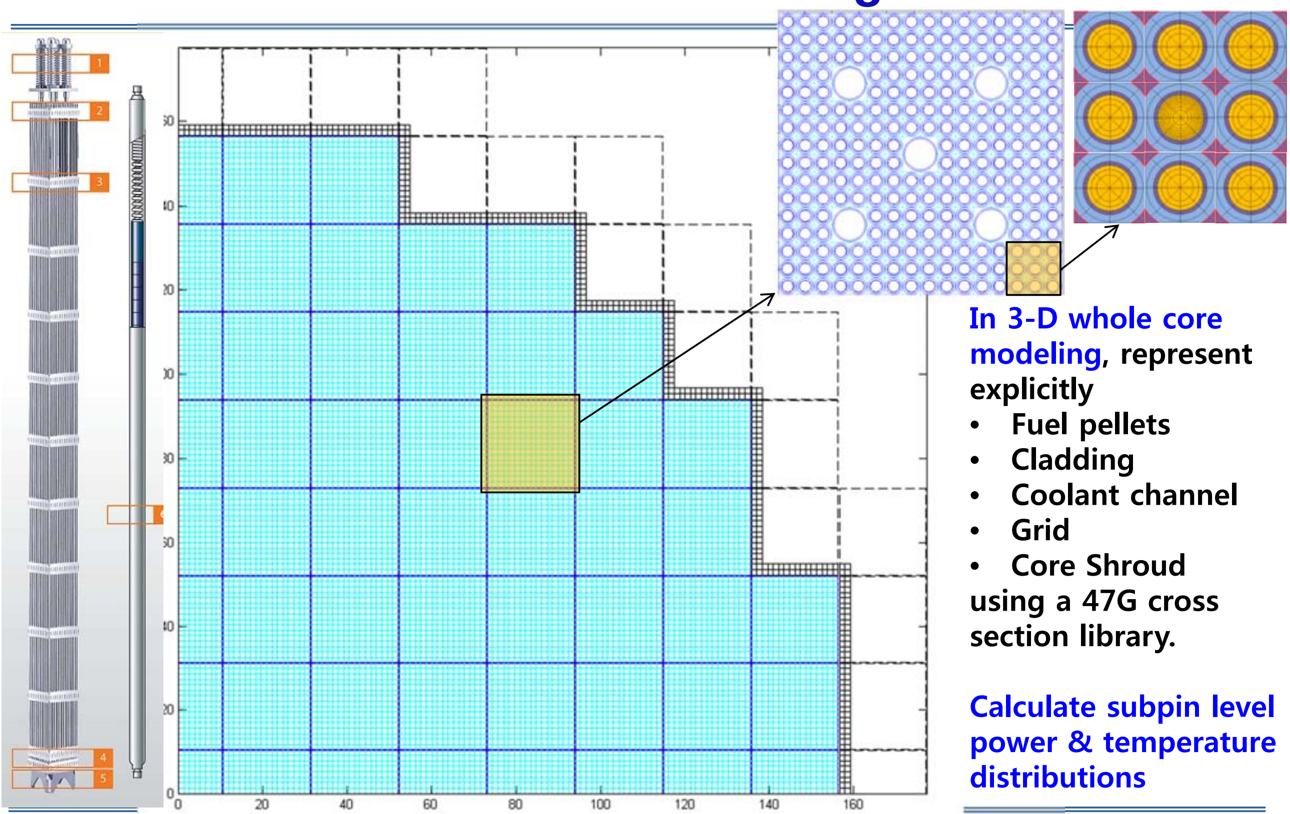
MATRA Features

Governing eq.	Subchannel integral balance (HEM)
Solution scheme	Implicit, marching scheme (B.C.: inlet flow/exit pressure distributions)
Steam table	NIST/ASME Steam DB Ver. 2.21, or TAF
Void correlation	Levy (subcooled), Chexal-Lellouch (bulk)
CHF correlation	SMART specific models
Turbulent mixing	SMART specific models
Pressure loss model	SMART specific models

nTRACER-MATRA Coupling



OPR1000 Modeling

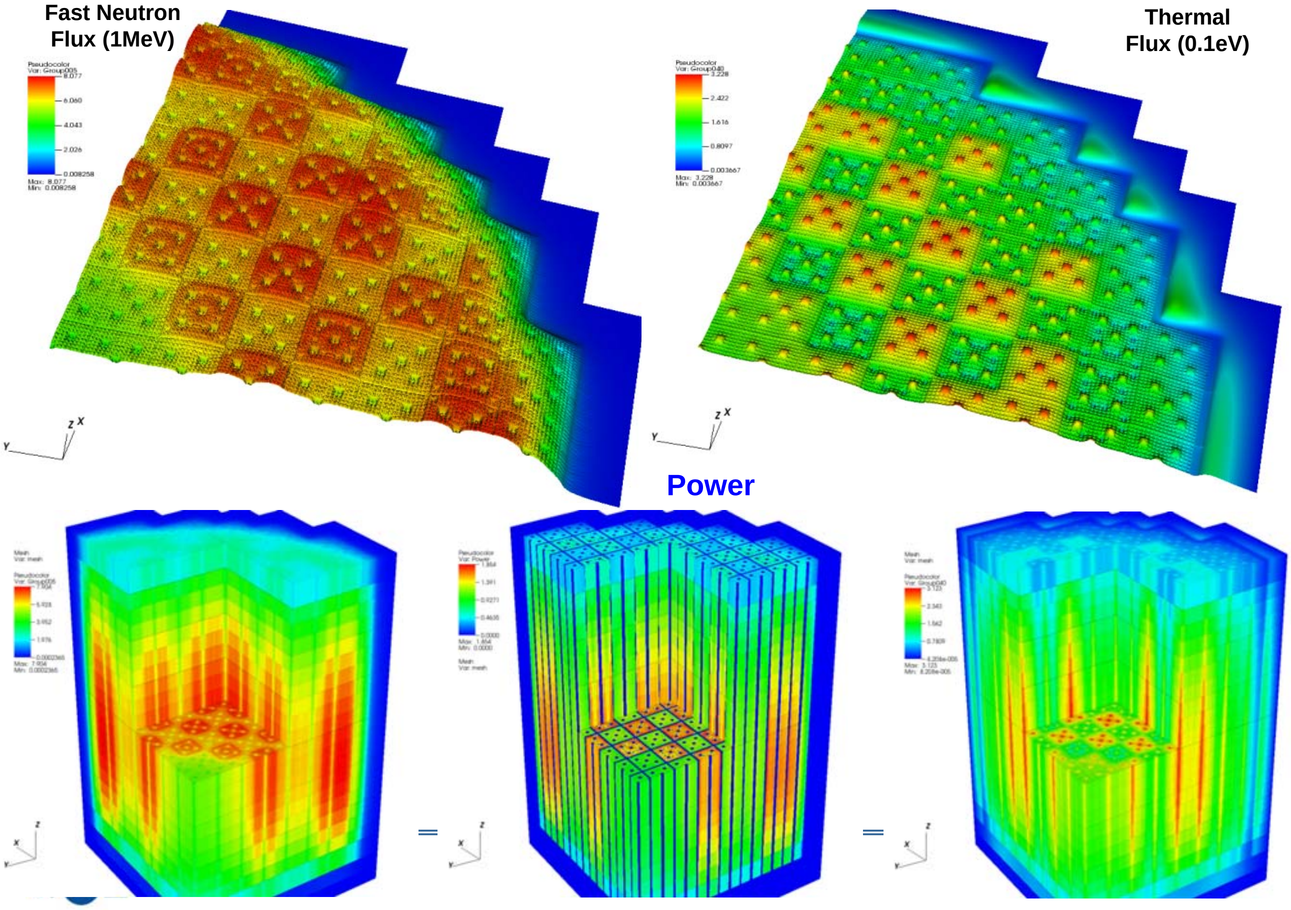


In 3-D whole core modeling, represent explicitly
- Fuel pellets
- Cladding
- Coolant channel
- Grid
- Core Shroud

using a 47G cross section library.

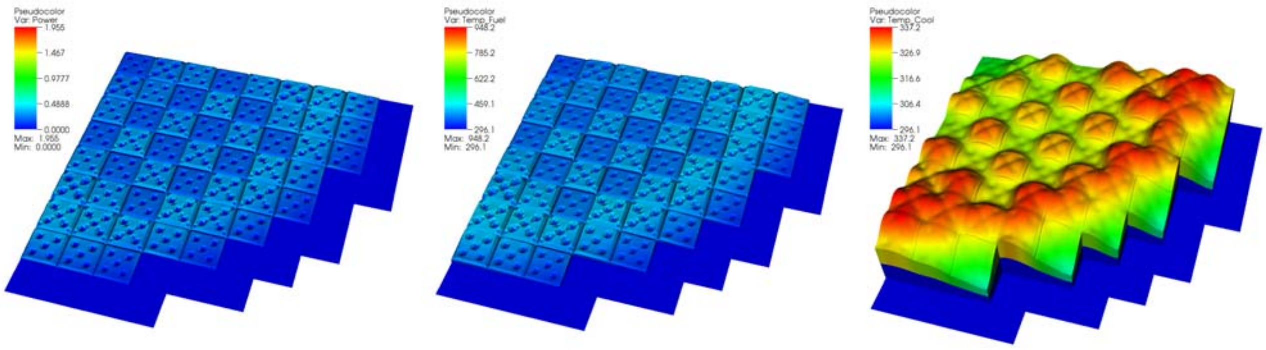
Calculate subpin level power & temperature distributions

Flux and Power Distribution Results

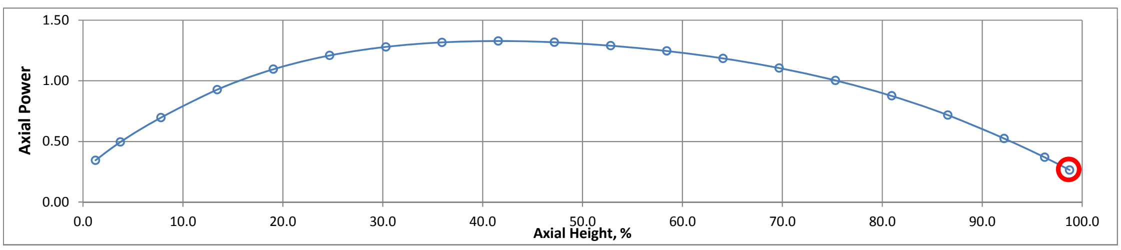


nTRACER-MATRA Coupled Calculation Results

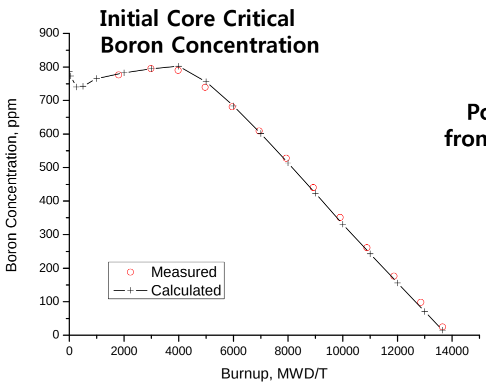
Plane 20



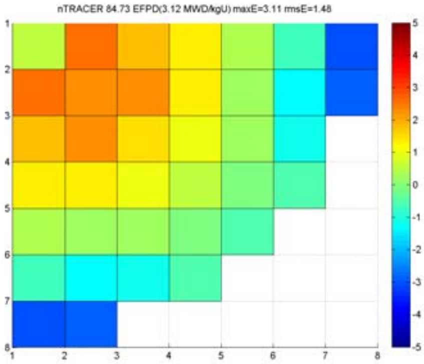
Power | Avg. Fuel Temperature[C] | Coolant Temperature[C]

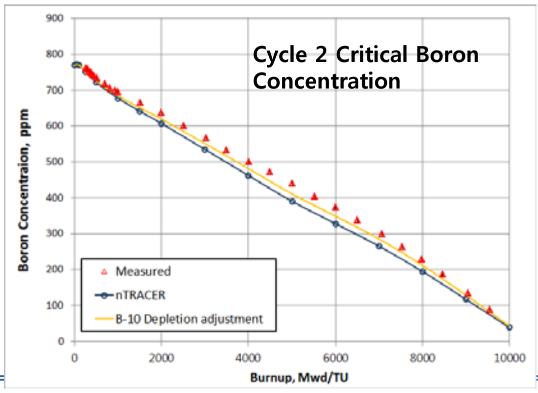


Comparison with Measured Data

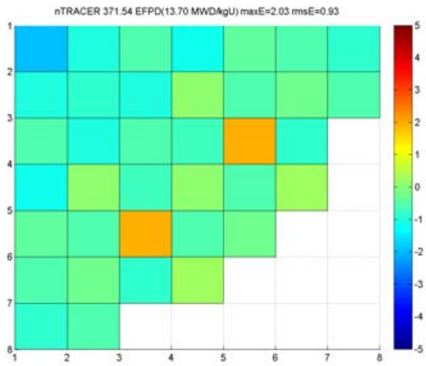


Assemblywise
Power Difference
from Measurement
At 3 GWD/T
(max 3%)

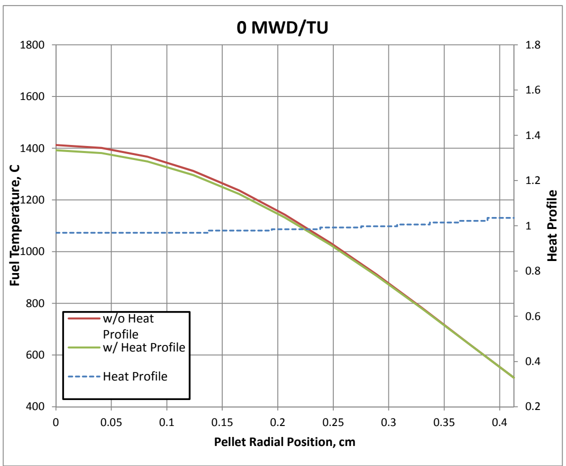


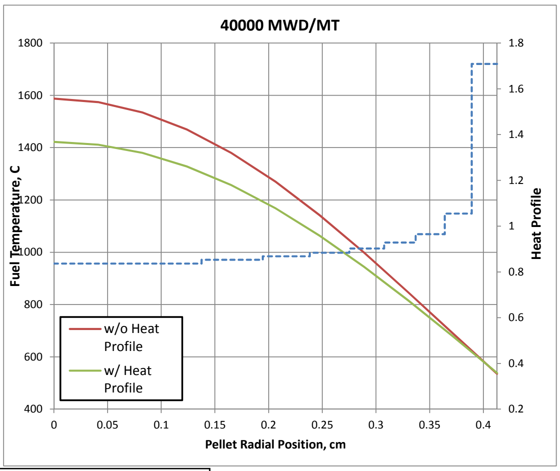


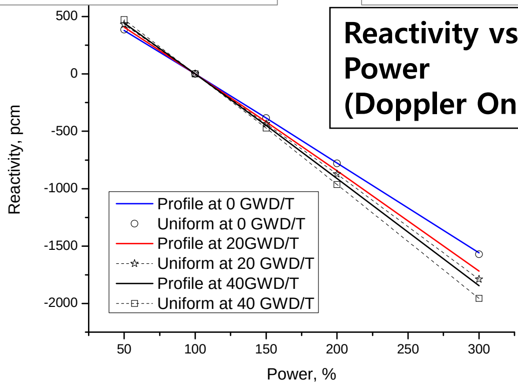
At EOC1
(max 2%)



Effect of Intra-pellet Power Profile on Doppler Power Coeff.



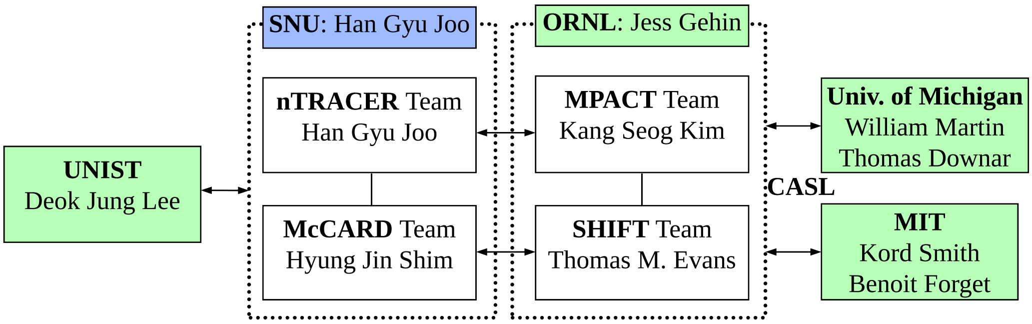




Reactivity vs. Power (Doppler Only)

DPC Reduced by more than 5% at 40GWD/T

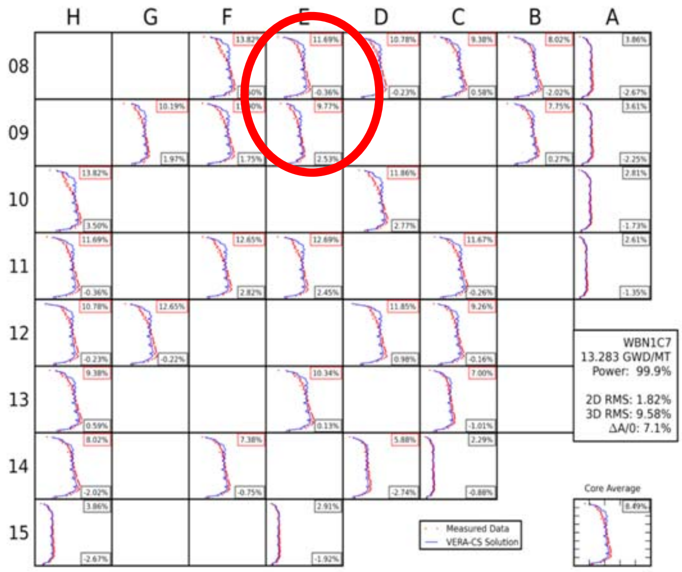
INERI Project Team up

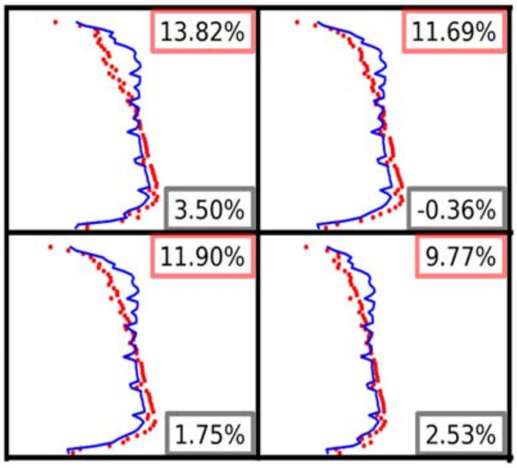


History of High Fidelity Reactor Simulator Development

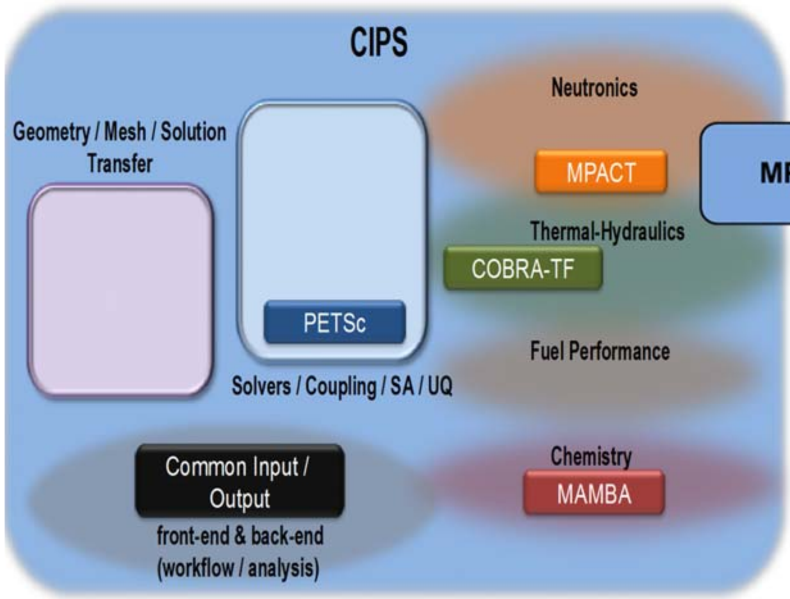
Code	Developer		Neutronics Methods				T/H Code	Application Range
	Institution/ Project/Year	Authors	Transport Methods	Resonance Method	Cross Section Library	Depletion Method		
DeCART	**KAERI** **INERI-1** (with ANL) 2001-2004	**Joo, Han Gyu** **Cho, Jin Young** **Kim, Kang Seog**	2D MOC 1D Diffusion 3D CMFD	Subgroup Method/ Weight Adjustment	ENDF 6 Based HELIOS 47 G	Krylov Subspace Method	**STAR-CD** (CFD)	PWR Only
DeCART2	**KAERI** **INERI-2** (with ANL) 2004-Present	**Cho, Jin Young** Kim, Kang Seog (until 2011) Shim, Cheon Bo (from 2015)	2D MOC 1D SP3 NEM Subplane 3D CMFD	Subgroup Method/ Weight Adjustment	ENDF 7 Based KARMA 47G	Krylov Subspace Method	**GAMMA**	**VHTR** Double Hetero. Treatment XS Generator for Nodal Codes
nTRACER	**SNU** Unique & Competitive Tech. Develop. 2006-Present	**Jung, Yeon Sang** (2006-2014) Ban, Young Seog (2011-Present) **Joo, Han Gyu**	2D MOC 1D SP3 SENM 3D CMFD	Subgroup Method/ Number Density Adjustment	ENDF 7 Based SNU Own 47 G	Krylov Subspace Method	**MATRA** (Sub Channel)	**SFR** Calculation Capability & XS Generator Under Development
MPACT	**U. Michigan/ ORNL** **CASL** 2011-Present	**Kochunas, B (UM)** **Kim, Kang Seog** (ORNL) Collins, Benjamin (UM/ORNL)	2D MOC 1D SP3 Hybrid 3D CMFD	Subgroup Method/ Number Density Adjustment	ENDF 7 AMPX Based ORNL Own 47 G	ORNL ORIGEN Method	**COBTA-TF** (Sub channel)	**BWR** Calculation Capability Under Development

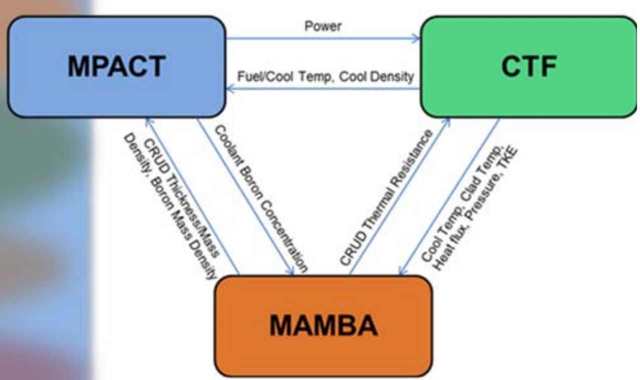
CIPS Impact on Core Power Distribution
Watts Bar Cycle 7





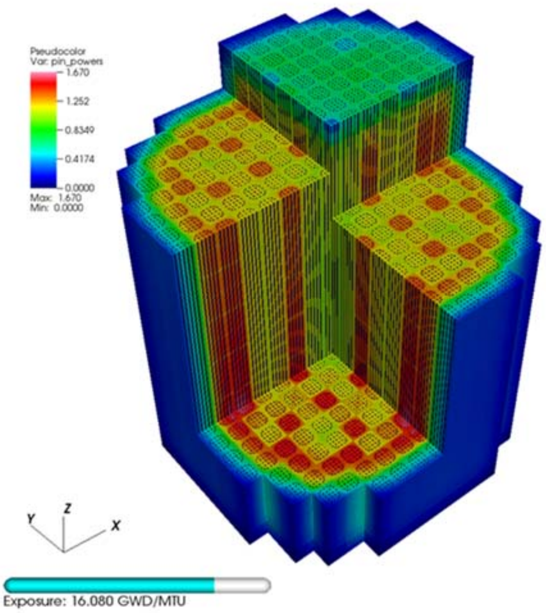
VERA Simulation of CIPS



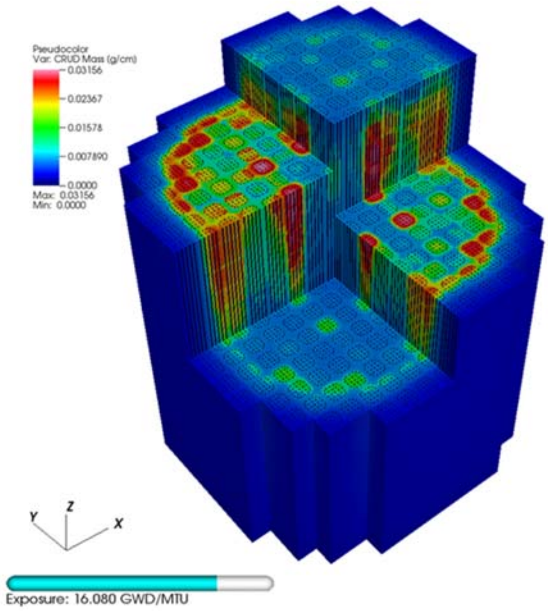


Watts Bar 1 Cycle 7 Predicted Crud Distribution

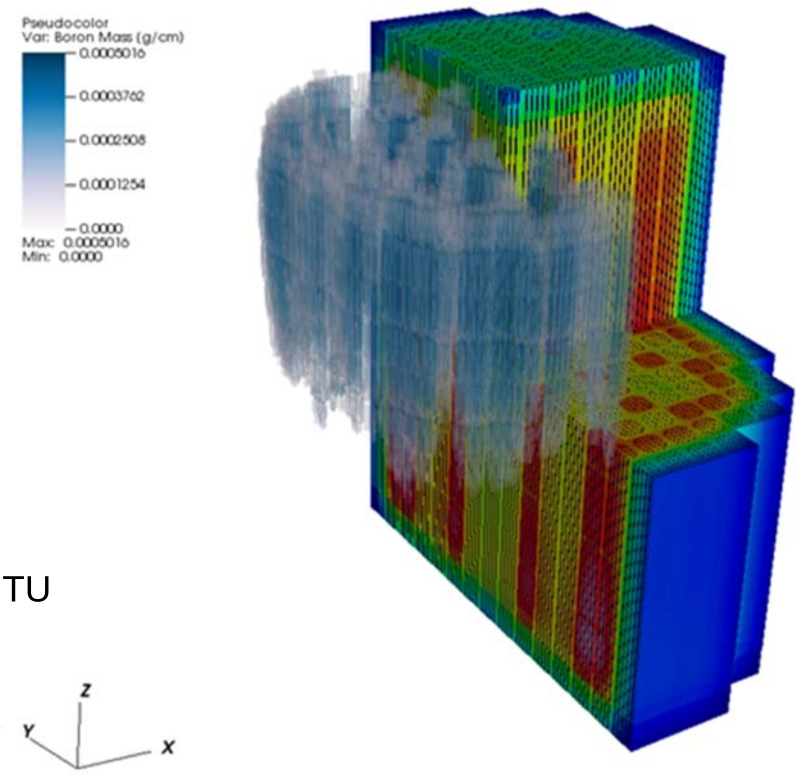
Power Distribution



Crud Distribution

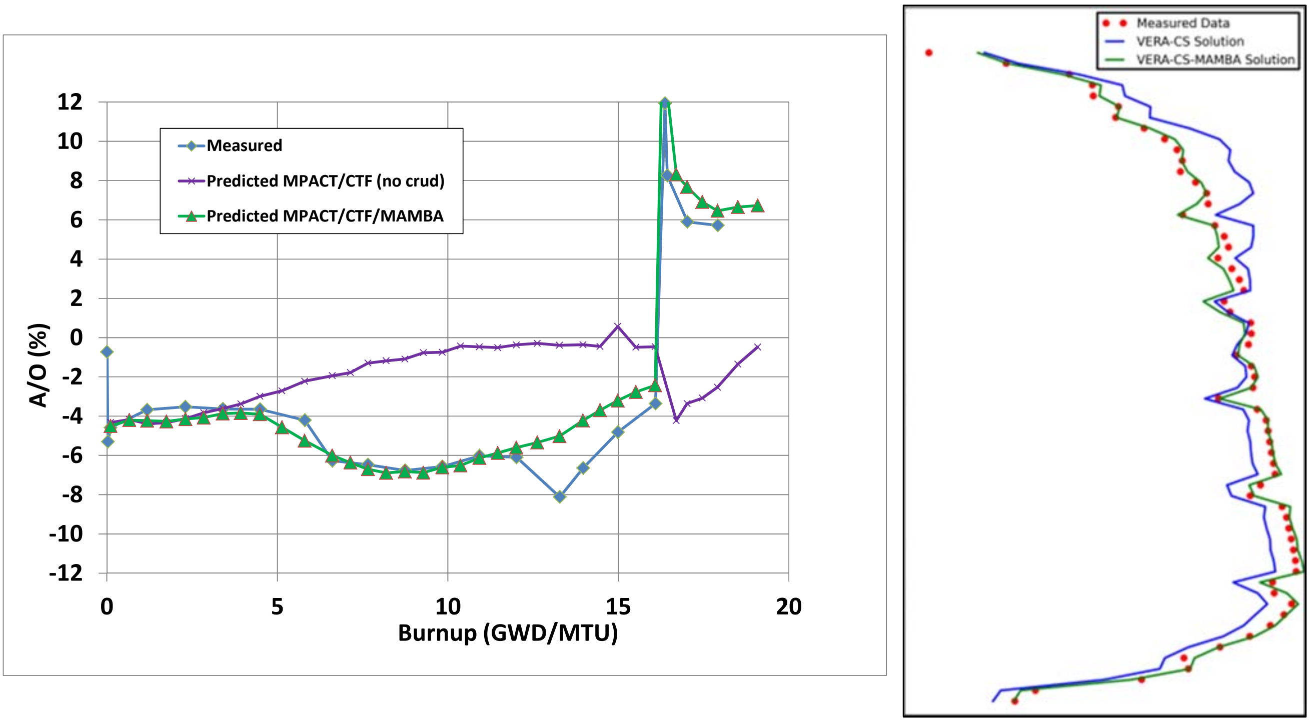


Watts Bar 1 Cycle 7 Predicted Boron Distribution



Boron
Distribution
at 16.08 GWD/MTU

Watts Bar 1 Cycle 7 Measured and Predicted Axial Offset Behavior



요 약

□고신뢰도 다물리 노심해석의 현실화

- 직접 전노심 해석을 가능하게 하는 2차원 MOC/1차원 SP3 계산 기반 3차원 수송해법 구현
- 봉단위 부수로 열유동 계산과 핵연료 소자내 상세 온도 분포의 반영
- Linux 클러스터 상 대규모 병렬 계산을 통한 대용량 계산 현실화

□가동 원전에 대한 다물리 고신뢰도 계산 유용성 입증

- OPR1000 및 Westinghouse 노형 원전 다주기 노심 추적 계산을 통한 고신뢰도 계산 정확성 및 실용성 입증
- 노물리-열수력-수화학 코드 연계 계산을 통한 크러드 유발 출력분포 이상현상 해석으로 다물리 시뮬레이션의 유용성 입증

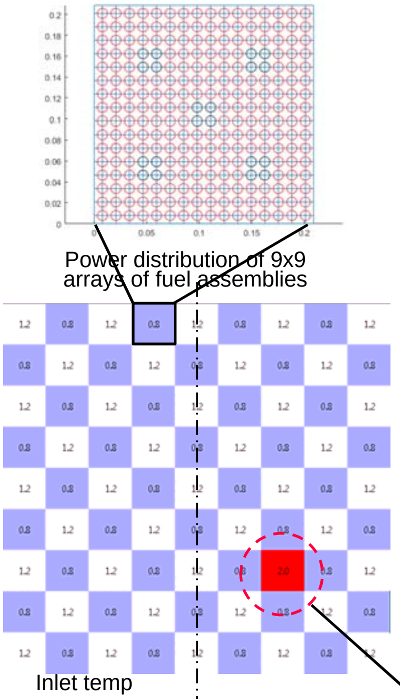
□GPU 등 가속기가 장착된 고성능 컴퓨터상의 가상원자로 개발 추진

- 안전 심사, 정밀 표준해 생산 등의 신속한 처리를 위해 5000 개 이상 코어를 사용하는 대규모 병렬 계산 구현 진행 중
- 열수력 코드 병렬 효율 증진 필요

Drift Flux 모델 기반 봉단위 노심열수력 코드 ESCOT 개발

Typical PWR fuel bundle with 16x16 pins

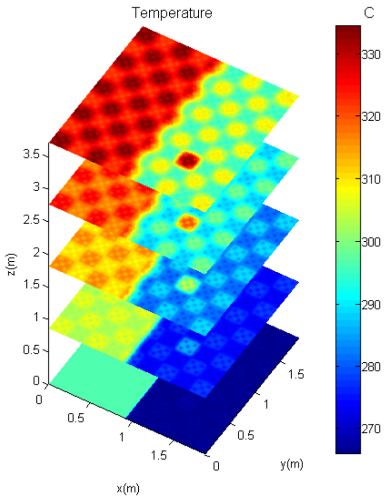
Power distribution of 9x9 arrays of fuel assemblies

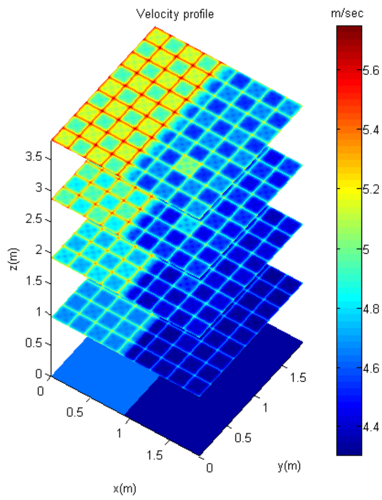


Inlet temp

295.83°C 265.83°C

Stuck control rod position





Axial meshing: 9.525cm x 40 planes = 3.81m (active height length)

# of total meshes: 841,000 (145 x 145 x 40)

Nominal assembly power: 15.904 MW

!