Main Features of the Research Reactor Core Simulator RINNOVO

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Presentation Layout

- Introduction
- RINNOVO Computational Methods
- Engineering Features and Automation
- GUI Example
- Future Efforts and Work

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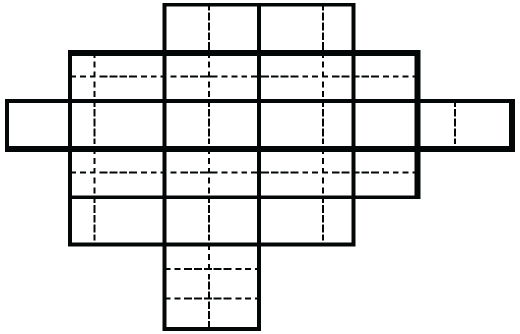
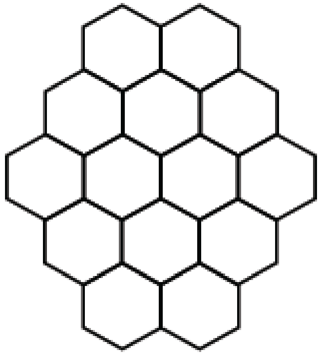
Introduction

- **RINNOVO** is a new **industrial-quality** research reactor core simulator developed by CompuSim AB in Sweden
  - Earmarked **tool** for practical day-to-day applications in support of **reactor operation and planning**
  - Particularly suited to facilities with commercial **radioisotope production**
- **RINNOVO** is a full 3D core simulator and fast core reload tool based on an advanced nodal diffusion theory model
  - Highly **accurate predictions** of core reactivity and power distribution at **low computational cost**
  - Modeling of any facility loaded with rectangular or hexagonal fuel assemblies





RINNOVO Computational Methods

- Nodal flux solver
  - Based on Multi-group Analytical Nodal Method (MANM)
  - **Multi-group** treatment is essential to capture the strong neutron leakage and spectral interaction effects of the small, very heterogeneous, high-leakage research reactor cores
  - Strong spatial variation of flux needs a method of **small discretization error**
  - Application of modern homogenization theory in terms of incorporating **discontinuity factors** in nodal coupling in combination with use of spatially smeared cross sections
  - An advanced nodal method **orders of magnitude faster** than finite-difference methods for the same level of accuracy
  - Use of advanced homogenization methods impractical with finite-difference methods

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RINNOVO Computational Methods

- Nodal flux solver (cont.)
  - Nodal flux solution of both the **eigenvalue** problem and extraneous **fixed source** problems
  - Nodal mathematical **adjoint** solution to the forward eigenvalue problem
    - Assessment of reactivity coefficients
  - Various iteration methods available based on either fission or transverse-leakage source driven schemes
    - Multi-level nested iteration procedure with feedback, outer (eigenvalue) and inner iterations
    - Acceleration by means of Wielandt eigenvalue shift for outers and Cyclic Chebyshev Semi-Iterative (CCSI) or Successive Over-Relaxation (SOR) for inners
    - Slow or divergent convergence addressed by automated switch between schemes

RINNOVO Computational Methods

- Core component depletion and history management methods
  - Adequate data management of individual component depletion histories
    - **Individual tracking** of the full depletion history of each component in the reactor facility
    - Each component tracked using its **own spatial exposure mesh**
    - Use of **HDF5** to store and manage such history data
  - Microscopic depletion of ≈ 35-100 nuclides using a predictor-corrector scheme
    - Depletion of beryllium reflectors
  - Solution of the (very) stiff nuclide transmutation equations without any burnup chain linearization
    - Robust and generic method accounting for feedback reactions (cyclic chain)
    - Matrix exponential by truncated Taylor series with uniformization technique
      - Elimination of catastrophic cancellation/round-off error
      - Numerically stable and controlled by user tolerance

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RINNOVO Computational Methods

- Shutdown cooling and decay heat model
  - Implementation of the latest decay heat model of the American National Standard (ANSI/ANS-5.1- 2014)
  - Based on very detailed tracking of the decay heat precursor concentrations during standard depletion calculations
    - **No use** of any simplified approaches to estimate historical fission rates of fuel
  - Accurate and up-to-date assessment of the decay heat of each individual fuel assembly both within and outside the core (e.g., in the fuel pool)
  - Shutdown cooling assessment by utilizing the regular nuclide decay calculations
    - Nuclide decay during reactor downtime periods
    - Long term fuel pool decay heat estimation

RINNOVO Computational Methods

- Detailed treatment of burnable absorbers
  - Local and heterogeneous depletion of burnable absorbers
    - Essential for tracking **thin wires** with for example cadmium
  - Application of a reconstructed local flux for depletion
    - More representative of the actual neutron flux in burnable absorber locations
  - On-the-fly homogenization of burnable absorber macroscopic cross sections
    - Performed during the nodal core calculation itself
    - Account for the impact of “explicit” burnable absorber depletion on nodal cross sections
  - **Profound impact** on predicted core reactivity and power distribution

RINNOVO Computational Methods

- Nodal cross section representation model
  - Cross section data represented by a **second order polynomial expansion** with dependence on the fuel and moderator temperature, moderator density and xenon concentration
    - **Fitting coefficients** are computed by the data interface code latXS2Nodal currently based on Serpent2 lattice physics calculations and are **tabulated as function of burnup**
  - Additional corrections due to isotopic tracking and intra-nodal cross section variation (spectrum/depletion history effects)
  - An in-line **axial homogenization** procedure invoked to account for any axial material variations
    - Node-average cross sections and axial discontinuity factors for the nodal flux solver
    - Essential for eliminating reactivity cusping effects due to control rod movements
    - Essential for handling follower-type control rods with fuel as follower material

RINNOVO Computational Methods

- Kinetics model
  - Time-dependent diffusion equation solved by means of a **fully implicit** time integration scheme
  - Analytic integration of the delayed neutron precursor equations
  - Time stepping algorithm monitors time variation of the dynamic solution
    - Automated adjustment of kinetics time step size
- Determination of water properties in RINNOVO
  - A water-steam property library implemented based on the latest IAPWS Industrial Formulation for the Thermodynamic Properties of Water and Steam
  - Implementation covers all the specified forward and backward equations

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Engineering Features and Automation

- Shuffling and loading of physically loadable core components
  - Movements of fuel assemblies, reflector assemblies and irradiation rigs
  - GUI tools provide drag-and-drop functionality to perform these actions
- Maintenance of component lifetime history files
  - No user interaction needed besides providing data file paths to RINNOVO
  - Viewing and exporting any component isotopic inventory at any time
- In-cycle reload operations of irradiation rigs
  - Insertion and/or removal, or axial adjustment of position during reactor cycle without need for creating sub-cycle reload and restart simulation cases
  - Automatic update of relevant core load and history files

Engineering Features and Automation

- Exclusion of heat (thermal power) of self-cooled irradiation rigs from core thermal power
  - No manual adjustments to core power and cycle burnup estimations needed
- Automated calculation of reactivity temperature coefficients
- Automated calculation of SDM, core shutdown reactivity and clean excess reactivity
- Automated calculation of integral and differential reactivity worths of control rods
- Automated calculation of in-cycle irradiation rig reactivity worth

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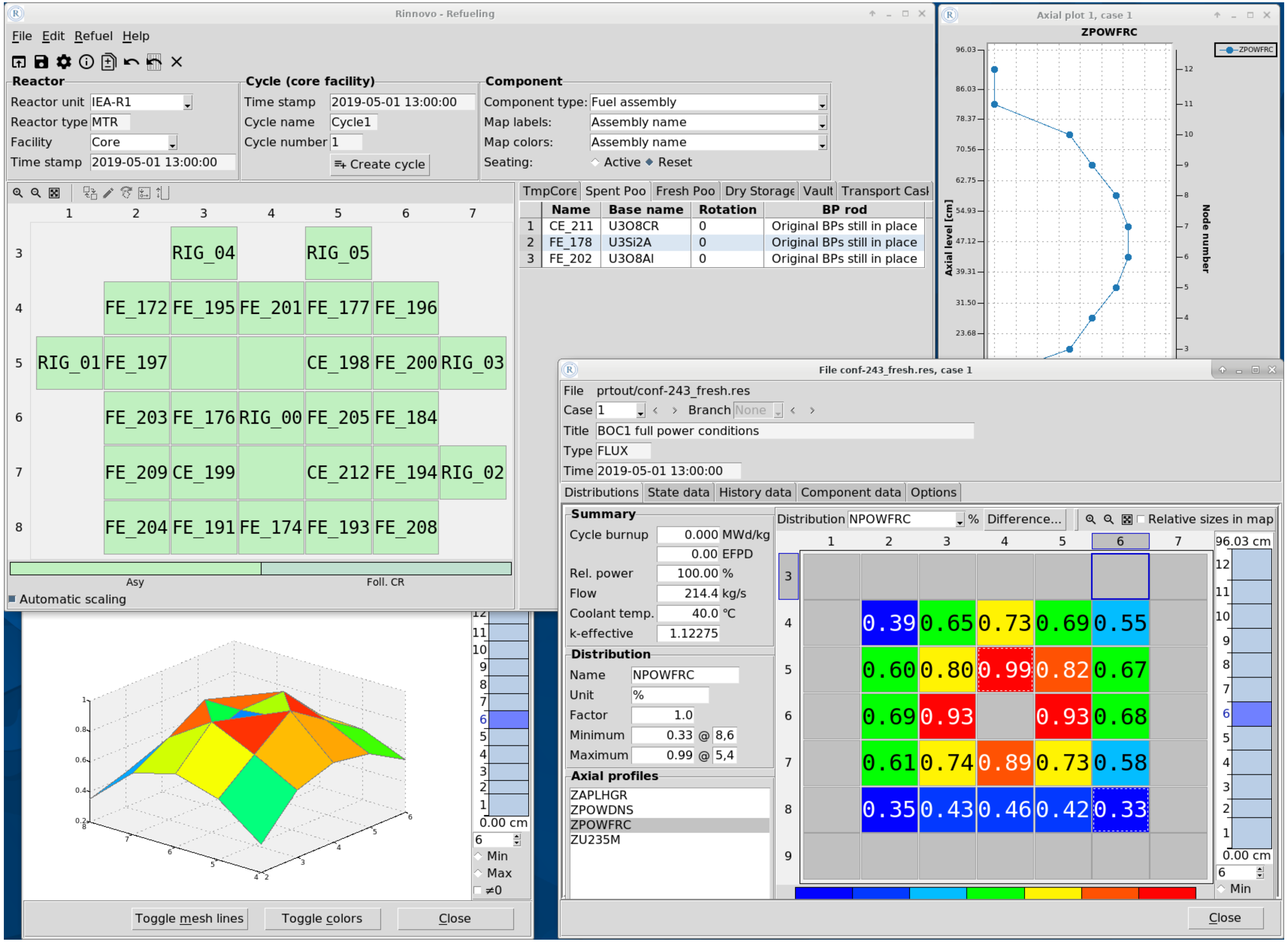
Engineering Features and Automation

- Estimation of End-of-Cycle (EOC) termination based on a user-selected state parameter
  - Target value utilized to determine EOC condition
    - Static multiplication factor
    - Control rod insertion fraction
    - Accumulated cycle energy
  - Useful for core reload design, cycle length estimations and outage planning
- Calculation and visualization of thermal load parameters and peaking factors
  - Core hot spot factor automatically computed and associated fuel assembly identified

GUI Example



Reactor

Reactor unit: IEA-R1
Reactor type: MTR
Facility: Core
Time stamp: 2019-05-01 13:00:00

Cycle (core facility)

Time stamp: 2019-05-01 13:00:00
Cycle name: Cycle1
Cycle number: 1

Component

Component type: Fuel assembly
Map labels: Assembly name
Map colors: Assembly name
Seating: ○ Active ● Reset

	1	2	3	4	5	6	7
3			RIG_04		RIG_05		
4		FE_172	FE_195	FE_201	FE_177	FE_196	
5	RIG_01	FE_197			CE_198	FE_200	RIG_03
6		FE_203	FE_176	RIG_00	FE_205	FE_184	
7		FE_209	CE_199		CE_212	FE_194	RIG_02
8		FE_204	FE_191	FE_174	FE_193	FE_208	

	Name	Base name	Rotation	BP rod
1	CE_211	U3O8CR	0	Original BPs still in place
2	FE_178	U3Si2A	0	Original BPs still in place
3	FE_202	U3O8Al	0	Original BPs still in place

File conf-243_fresh.res, case 1

File: prtout/conf-243_fresh.res
Case: 1
Branch: None
Title: BOC1 full power conditions
Type: FLUX
Time: 2019-05-01 13:00:00

Summary

Cycle burnup	0.000	MWd/kg
	0.00	EFPD
Rel. power	100.00	%
Flow	214.4	kg/s
Coolant temp.	40.0	°C
k-effective	1.12275	

Distribution

Name: NPOWFRC
Unit: %
Factor: 1.0
Minimum: 0.33 @ 8,6
Maximum: 0.99 @ 5,4

Axial profiles

- ZAPLHGR
- ZPOWDNS
- ZPOWFRC
- ZU235M

Distribution: NPOWFRC %

	1	2	3	4	5	6	7
3							
4		0.39	0.65	0.73	0.69	0.55	
5		0.60	0.80	0.99	0.82	0.67	
6		0.69	0.93		0.93	0.68	
7		0.61	0.74	0.89	0.73	0.58	
8		0.35	0.43	0.46	0.42	0.33	
9							

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Future Efforts and Work

- **Efforts up to today** have focused on establishing a functional, industrial-standard core simulator built on robust and state-of-the-art technology
- **Current efforts** focus on lattice physics data coupling functionality
  - RINNOVO coupling to Serpent2 and other lattice physics codes via latXS2Nodal
- **In the future**, attention will be given to
  - Development of a steady-state thermal hydraulics module
  - Coupling of the kinetics module to a system code such as RELAP5
  - Development of advanced homogenization and leakage methods and further improving the cross section representation model of RINNOVO
  - Coupling of RINNOVO to DAKOTA for sensitivity and uncertainty analyses