Welcome to NE 511
Multi-Physics of Nuclear Reactors

North Carolina State University
Dr. Maria Avramova

NE 511: **Multi-Physics of Nuclear Reactors**

UNIT 1: Fundamentals of Reactor Multi-Physics

Lecture 1: INTRODUCTION AND COURSE POLICY
BASIC TOPICS AND NOMENCLATURE

COURSE OBJECTIVES

This graduate level course is focused on reactor multi-physics methods and techniques for multi-dimensional reactor analysis.

TIME-DEPENDENT REACTOR

BWR Instabilities

$$k = k^* + \alpha_f \Delta T_f + \alpha_m \Delta T_m + \alpha_X \Delta_X + \cdots$$

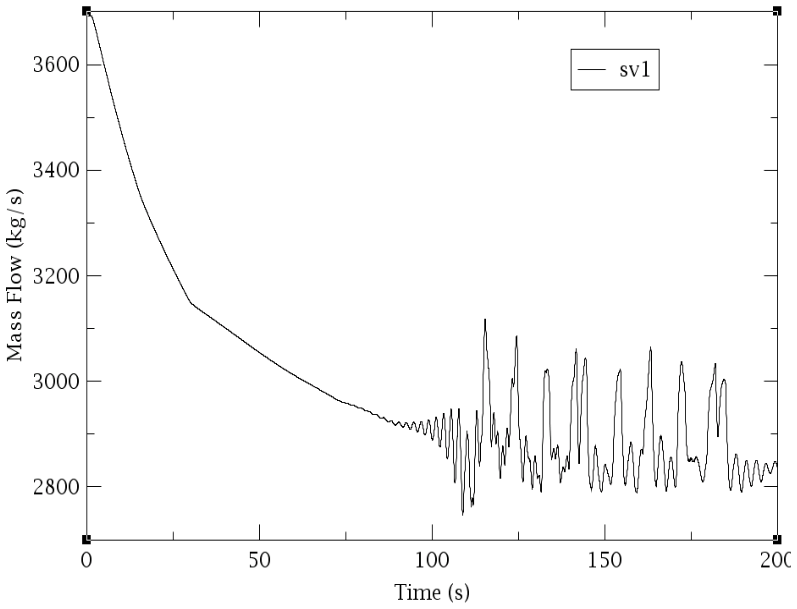
Ringhals-1

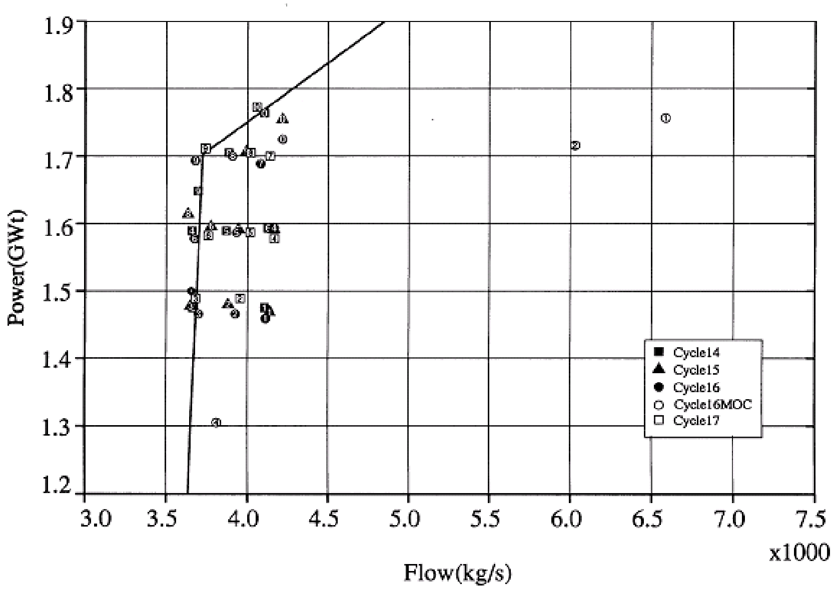
Stability tests at BOC14, BOC15, BOC16, MOC16, BOC17

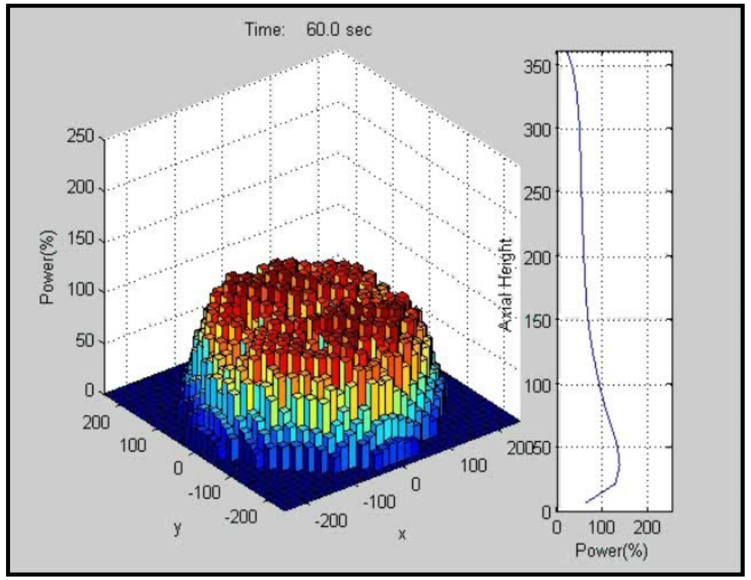
All recirculation pumps lost their torques simultaneously

Feed water temperature coast down to 350 Kelvin in 60 seconds

→ *Core flow and power response:*







TIME-DEPENDENT REACTOR

PWR Control Rod Ejection Accident at Hot Zero Power

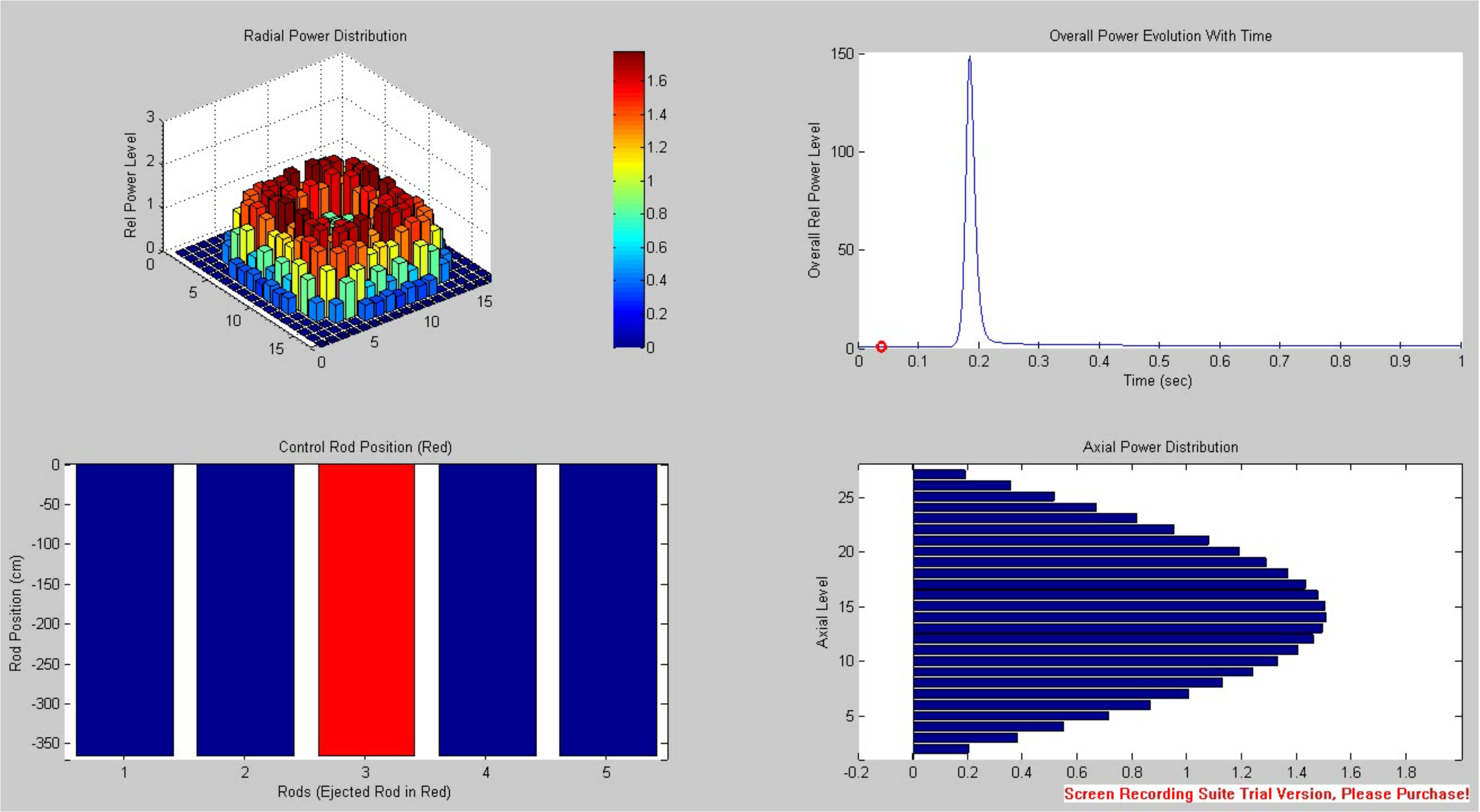
– *The accident scenario is largely based on the OECD/NRC PWR MOX REA benchmark*

– The control rod ejection is performed starting from HZP state where all control banks are in, all shutdown banks are out, and critical boron concentration is achieved with the highest worth rod inserted (which is to be ejected)

– The rod is assumed to be fully ejected in 0.1 second (which means the rod is moved at a rate of 3657.1 cm/s), after which no reactor scram is considered

– During the entire transient calculation, the boron concentration and the position of the other control rods are assumed to be constant

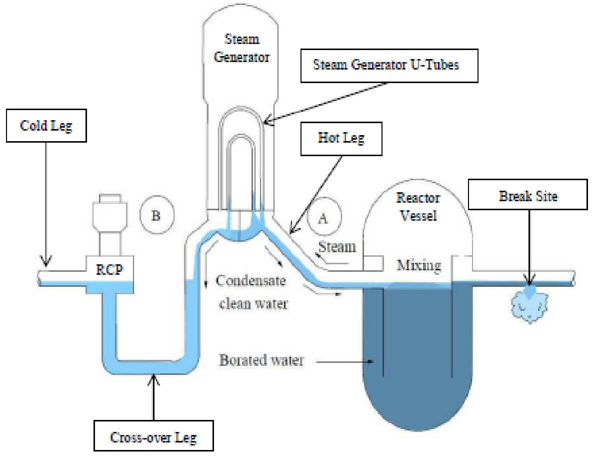
– The transient is to be calculated for 1.0 sec

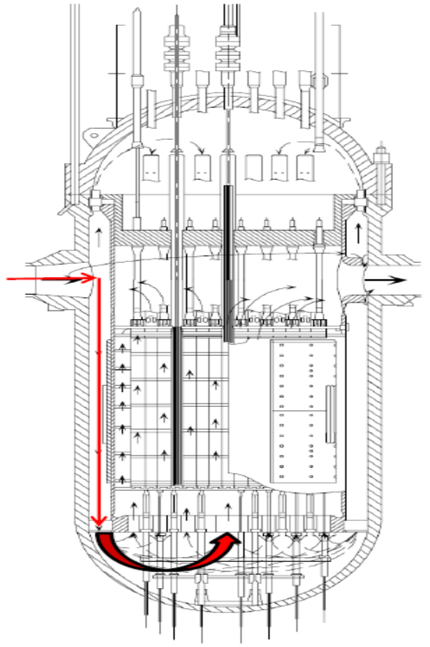


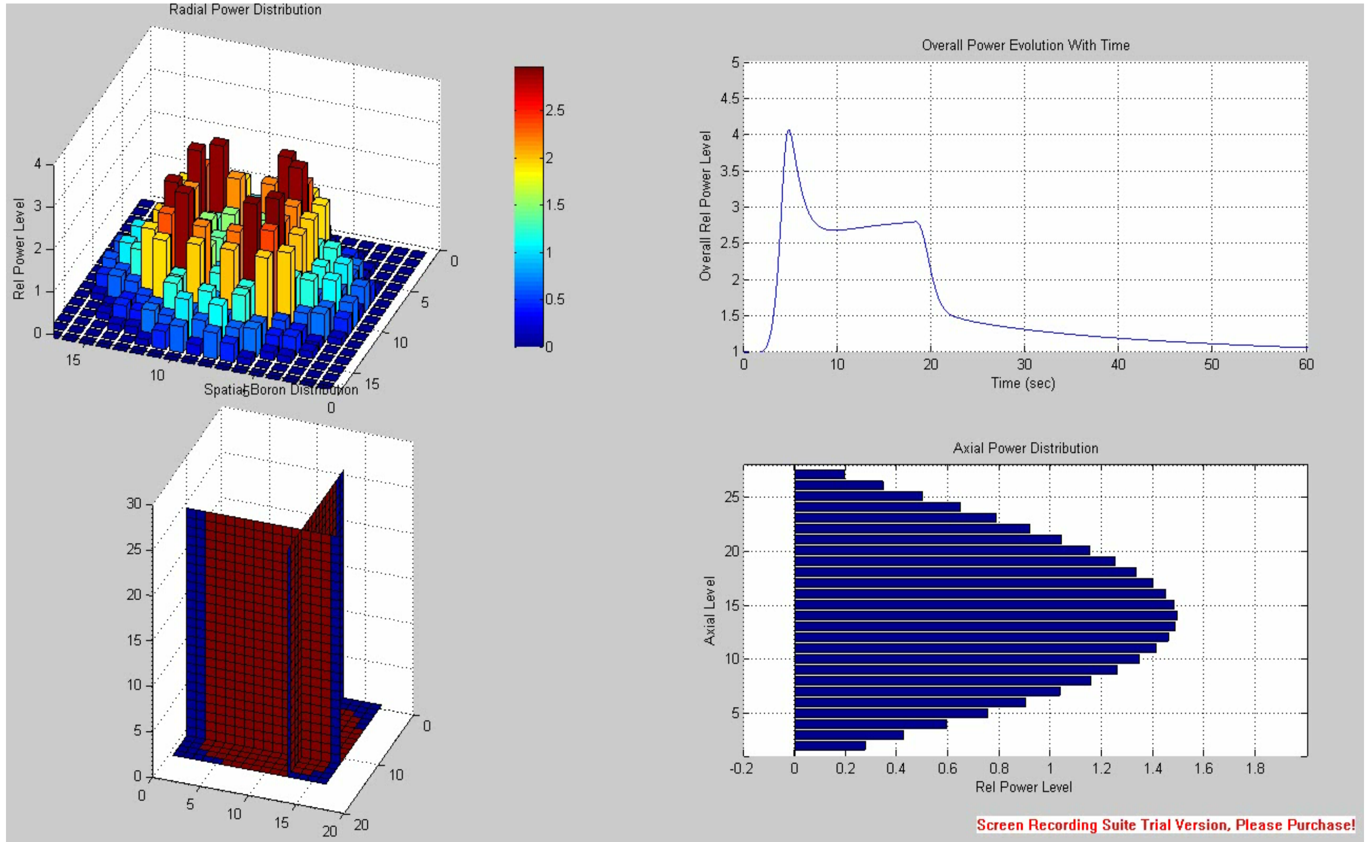
TIME-DEPENDENT REACTOR

Heterogeneous Boron Dilution

- *The accident scenario to be discussed is largely based on the US NRC report "Potential for Boron Dilution During Small Break LOCAs in PWRs" (NUREG / CP-0158, page 328)*
- This boron dilution accident scenario is postulated to occur sometime after a Small Break LOCA
- If there is an interruption in decay heat removal, the core may begin to operate in a boiler/condenser mode and natural circulation would cease
- After accumulation of deborated water in the steam generator cold leg side of the steam generators, it is assumed (either due to operator error or an attempt to recover cooling) that one of the main reactor coolant pumps is started
- Assumptions:
  1. The core initial power is estimated to be 2% of full power rating due to decay heat with a successful full SCRAM
  2. Mass flow rate of the model is uniformly set to 25% of nominal since only one coolant pump is turned on
  3. The forced circulation via the coolant pump is considered to be more conservative since this will result in a much more rapid reactivity insertion than would occur if only natural circulation was restored







COURSE OBJECTIVES

It consists of four major topics:

1. *Fundamentals of Reactor Multi-Physics;*
2. *Short-Time Multi-Physics Phenomena in Reactor Cores;*
3. *Low Fidelity Multi-Physics Modeling;*
4. *High Multi-Physics Modeling;*

The course computer project will provide students with knowledge in multi-physics methods used to model reactor steady-states, cycle depletion, and transients for design and safety evaluations.

COURSE TIME & LOCATION

331 111 Lampe Drive *Tuesday & Thursday 11:45 AM – 1:00 PM*

TEXTBOOKS

Class Notes "Multi-Physics of Nuclear Reactors", NCSU

REFERENCES

1. K. Ott and R. Neuhold, Introductory Nuclear Reactor Dynamics, American Nuclear Society, 1985 (ISBN: 0-894-48029-4) or any new edition of this book
2. W. M. Stacey, Nuclear Reactor Physics, John Wiley & Sons, 2001 (ISBN: 0- 471-39127-1) or any new edition of this book

WEBSITE

Homework problems/solutions and other course materials will be posted on the course Moodle Space.

COURSE INSTRUCTORS

Dr. Maria Avramova
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(919) 513-6354

mnavramo@ncsu.edu
Office Hours: *appointment*

COURSE TEACHING ASSISTANT

TBA
Office Hours: *TBD*

COURSE SCHEDULE

Lectures & assignments schedule and due dates will be available via course Moodle Calendar (minor changes are possible).

GRADING

The grading distributions are approximately as follows:

- Course Project - 30 %
- Mid-term Exam 1 (open book/notes; no proctor) - 20 %
- Mid-term Exam 2 (open book/notes; no proctor) - 20 %
- Homework & Quizzes (closed book) - 30% of the average
- Grading scale:

A+	< 100	A	92 ÷ 100	A-	90 ÷ 91
B+	88 ÷ 89	B	82 ÷ 87	B-	80 ÷ 81
C+	78 ÷ 79	C	72 ÷ 77	C-	70 ÷ 71
D+	68 ÷ 69	D	62 ÷ 67	D-	60 ÷ 61
F	0 ÷ 59				

A grade of C- satisfies all "grade of C or better" prerequisites and other "C-wall" requirements

A+ grades will contribute to the Grade Point Average up to a maximum of 4.000

A grade higher than 100% will be given for an excellent job (more than what is required) or when an innovative treatment of the problem is presented

COURSE TOPICS

Part I: Fundamentals of Reactor Multi-Physics

- *Introduction*
- *Basic Topics and Nomenclature*
- *Basic Time-Dependent Phenomena in Nuclear Reactors*
- *Multi-Physics Interactions in Reactor Core*
- *Classification of Multi-Physics Modeling and Simulation Tools*

Part II: Short-Time Multi-Physics Phenomena in Reactor Cores

- *Dynamic Equation & Simplified Neutron Cycle*
- *Prompt and Delayed Neutron Phenomena*
- *Prompt Reactivity Feedback Phenomena*
- *Delayed Reactivity Feedback Phenomena*
- *General Reactor Stability*

COURSE TOPICS

Part III: Low Fidelity Multi-Physics Modeling

- *Pre-Traditional Multi-Physics Coupling Schemes*
- *Point Kinetics Theory*
- *Thermal-Hydraulics Codes with Point Kinetics Models*
- *Neutronics Core Simulators with 1-D Thermal-Hydraulics Models*
- *Neutronics and Thermal-Hydraulics Models in Fuel Performance Codes*
- *3D Nodal Kinetics Models in Thermal Hydraulic Analysis*
- *Space-Energy Dependent Dynamics*
- *Coupled Thermal-Hydraulics and Neutronics Simulations*

Course Topics

Part IV: High Multi-Physics Modeling

- *High-Fidelity Neutronics, Thermal-Hydraulics and Fuel Performance Models; Feedback Parameters*
- *Spatial and Temporal Coupling Schemes – Multi-Physics Platforms*
- *Verification and Validation of Multi-Physics Simulations*
- *Uncertainty Quantification in Multi-Physics Modeling*

Course Outline

Topic # 1 - Introduction & Fundamentals of Reactor Multi-Physics		
01/13/26	Welcome to NE 511: Multi-Physics of Nuclear Reactors Basic Topics and Nomenclature	
01/15/26	Time-Dependent Phenomena in Nuclear Reactors Multi-Physics Interactions in Reactor Core Classification of Multi-Physics Modeling and Simulation Tools	
Topic # 2 - Short-Time Multi-Physics Phenomena in Reactor Core		
01/20/26	Dynamic Equation & Simplified Neutron Cycle Prompt and Delayed Neutrons Total Delayed Neutron Yields & Yields of Delayed Neutron Groups	
01/22/26	Emission Spectra of Delayed Neutrons Theoretical Background for Calculation of Kinetics Data	*Quiz #1*
01/27/26	No live class; self-work to be assigned	
01/29/26	No live class; self-work to be assigned	
02/03/26	Preliminary Formulation of the Point Kinetics: *Prompt Neutron Balance Equation* *Intuitive Point Kinetics Equation* *One-Group Point Kinetics Equation*	
02/05/26	Reactivity in the Exact PKEs; Effective Delayed Neutron Fractions Point Reactor Model	*Quiz #2* HW1: Prompt and Delayed Neutron Phenomena
02/10/26	Prompt Reactivity Feedback Phenomena: Core Power Models and Fuel Temperature Calculations Course Project Assignment; Discussions & Tasks	
02/12/26	Prompt Reactivity Feedback Phenomena: Transient at Small Times	*Quiz #3* HW1 Due
02/17/26	No classes - Wellness Day	
02/19/26	No live class; self-work to be assigned	
02/24/26	Prompt Reactivity Feedback Phenomena: Asymptotic Transients	
02/26/26	Superprompt-Critical Excursion Following Step Reactivity Insertion	
03/03/26	Superprompt-Critical Excursion Following Ramp Reactivity Insertions	HW2: Reactivity Feedback
03/05/26	Delayed Reactivity Feedback Phenomena: Moderator / Coolant Feedback Effects	
03/10/26	BWR Instabilities; General Reactor Stability	*Quiz #4* HW2 Due

Course Outline

Topic # 3 – Low Fidelity Multi-Physics Modeling		
03/12/26	Simplified Multi-Physics Coupling Schemes Thermal-Hydraulics with Point Kinetics Feedback	
03/12–15/26	**Exam 1 Period: Short-Time Multi-Physics and Delayed Reactivity Feedback**	
03/16 - 20/26	**Spring Break – No Classes**	
03/24/26	Neutronics with 1D Thermal-Hydraulics Feedback Fuel Performance with Neutronics and Thermal-Hydraulics Feedback	HW3: Multi-physics modeling
03/26/26	Thermal-Hydraulics with 3D Nodal Kinetics Feedback Heat Conduction and Fuel Rod Modeling in Thermal-Hydraulic Codes	*Quiz #5*
03/31/26	Space-Energy Dependent Dynamics: General Discussion of the Dynamics Problem; Flux Factorization	*Quiz #6* HW3 Due
04/02/26	Space-Energy Dependent Dynamics: Quasi-Static Methods & Dynamic Reactivity Coefficients	
04/07/26	Course project discussions (students' presentations)	
04/09-12/26	**Exam 2 Period - Traditional Reactor Multi-Physics Modeling**	
Topic # 4 – High Fidelity Multi-Physics Modeling		
04/09/26	High-Fidelity Neutronics, Thermal-Hydraulics and Fuel Performance models; Feedback Parameters	
04/14/26	Multi-Scale Single Physics Modeling Using Hi2Lo Information Schemes and Implementation within Multi-Physics Calculations	
04/16/26	Spatial & Temporal Coupling - Multi-Physics Platforms	*Quiz #7*
04/21/26	No class / Team-work on the project	
04/23/26	No class / Team-work on the project	
04/28/26	Verification and Validation of Multi-Physics Simulations Uncertainty Quantification in Multi-Physics Modeling Course Warp-Up	
04/30 – 05/06/26	Final Exams Period: › No Final Exam › Make-up Quiz (*by request*)	Project Report Due 04/30/2026

Let's have fun!

&

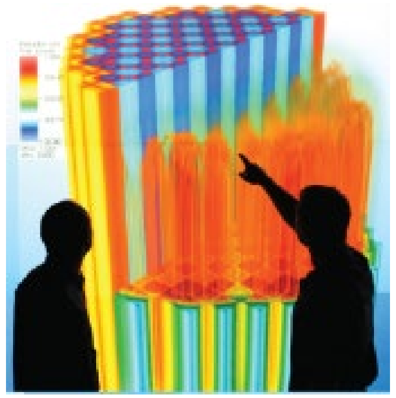
Always can learn more!

Basic Topics and Nomenclature

To recall:

The course is focused on reactor multi-physics methods and techniques for multi-dimensional reactor analysis

Advances in Reactor Simulations



Need for:

- First principles high-fidelity multi-physics methodologies for reactor analysis;
- Extending analysis capabilities by coupling models, which simulate different phenomena;
- Refining the scale of multi-physics coupling;
- Optimal coupling strategies to link neutronics, fuel behavior, fluids and heat transfer software tools;
- Applying advanced modeling and simulation and high-performance computing tools.

Reactor Multi-Physics Modeling
Nomenclature

- Single(Unit)-Physics vs. Multi-Physics Modeling

  - *Single physics modeling focuses on single physics phenomena and any interactions with other physics phenomena are accounted for by applying boundary conditions.*

  - *Multi-physics modeling describes nonlinear multi-physics phenomena by on-line treatment of feedback effects of different physics.*

Reactor Multi-Physics Modeling
Nomenclature

- *Detailed Modeled vs. Simplified Modeled Phenomena*
  - *Detailed modeled phenomena are the phenomena modeled with the best available models.*
  - *Simplified modeled phenomena are the phenomena modeled by simplified models, or boundary conditions, or parameterized values.*

Reactor Multi-Physics Modeling
Nomenclature

- *Separate vs. Integral Effects*
  - *Separate effects describe the behavior of single component or characteristics of one phenomenon.*
  - *Integral effects describe the behavior of a reactor system at nominal, off-nominal, or accident conditions.*

Reactor Multi-Physics Modeling
Nomenclature

- *High-Resolution vs. High-Fidelity*

  - *High-resolution means refined description of space and time at the level of detail dictated by the governing phenomena.*

  - *High-fidelity is a high-resolution supplemented with a confidence level based on capability maturity, which provides potential for truly predictive capability.*

In other words, the high-fidelity simulations are transforming computational science into a fully predictive science.

Reactor Multi-Physics Modeling
Nomenclature

- *Explicit Coupling vs. Implicit Coupling*

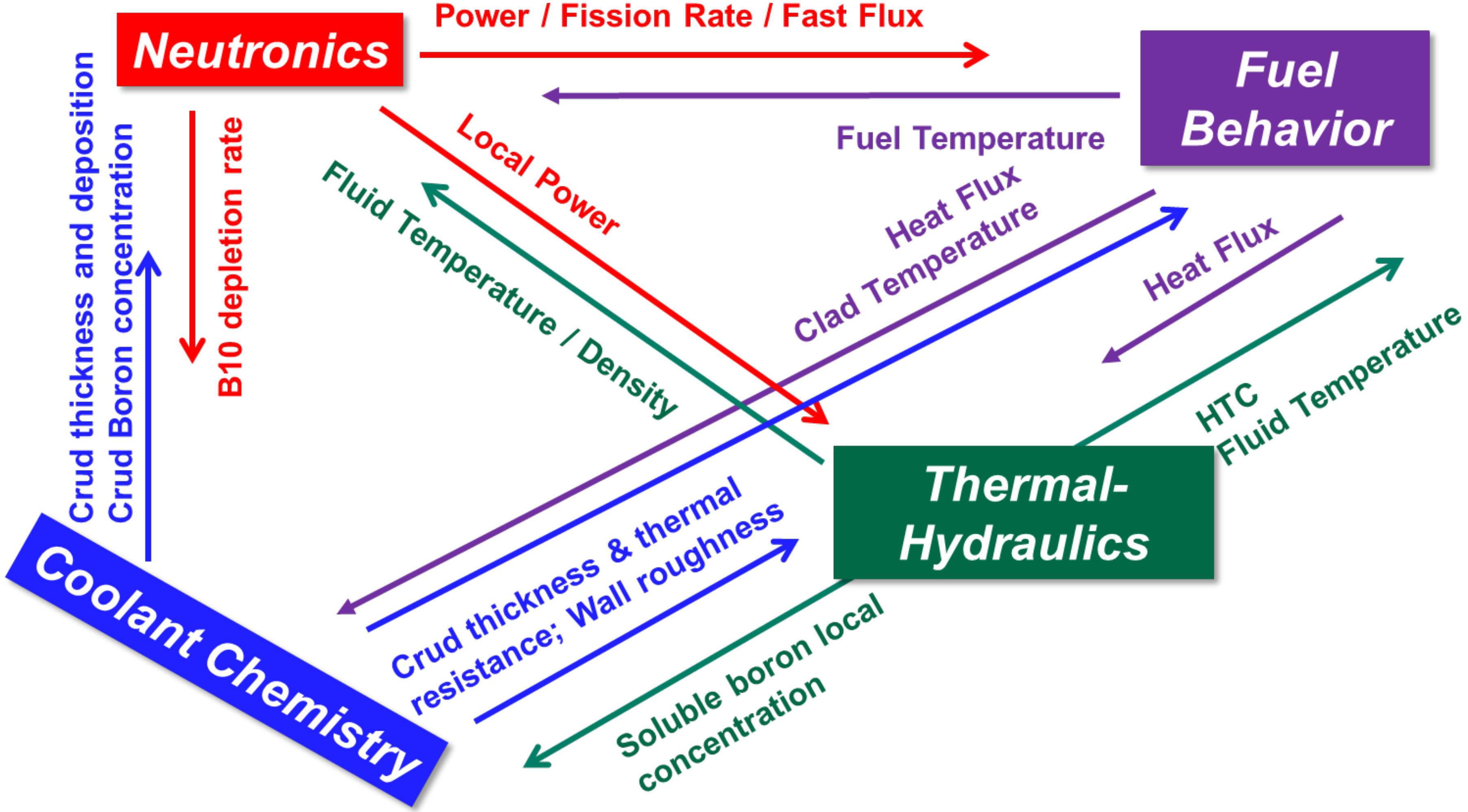
  - *Explicit coupling (operator-splitting) - existing single-physics codes are assembled into an overall coupled simulation code with appropriate interfaces to communicate between the components.*
    - This is generally referred to as a 'bottom-up' framework approach.
    - The exchanged feedback parameters are either not-converged or approximately converged using fixed-point iteration.

  - *Implicit Coupling - an integrated, coupled-physics modeling framework is used, with new code pieces for each relevant physics area developed inside that framework.*
    - This is sometimes referred to as a 'top-down' framework.
    - It requires solving large systems of complex, coupled, nonlinear, stiff equations with simultaneous convergence on all feedback parameters.

Reactor Multi-Physics Modeling
Nomenclature

- *High-Level vs. Low-Level Multi-Physics Coupling*
  - *High-level multi-physics coupling – between different codes (for example neutronics and thermal-hydraulic. codes)*
  - *Low-level multi-physics coupling – between different models within a code (for example chemistry and boiling).*

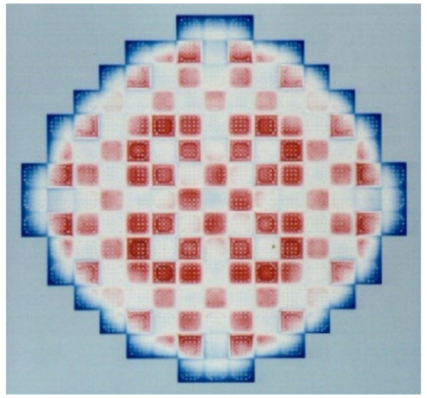
Reactor Multi-Physics Modeling
Feedback



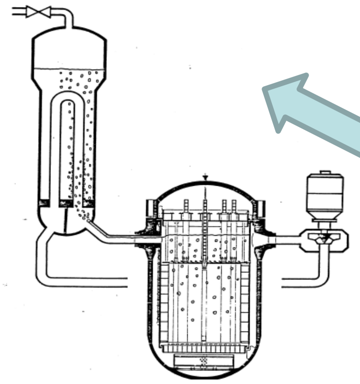
Simplified Case of NO geometry changes

Reactor Multi-Physics Modeling

Reactor Physics

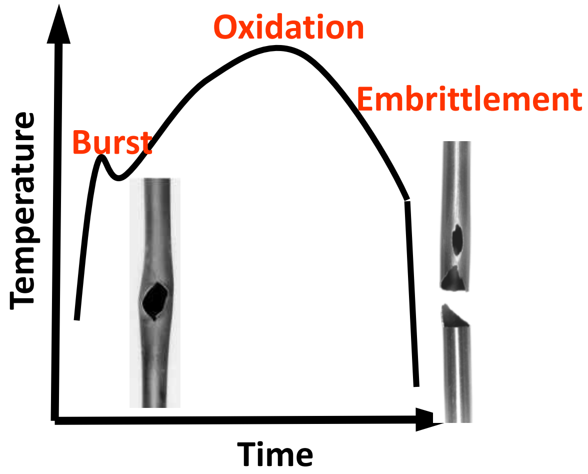


Thermal Hydraulics



feedbacks

Thermal Mechanics

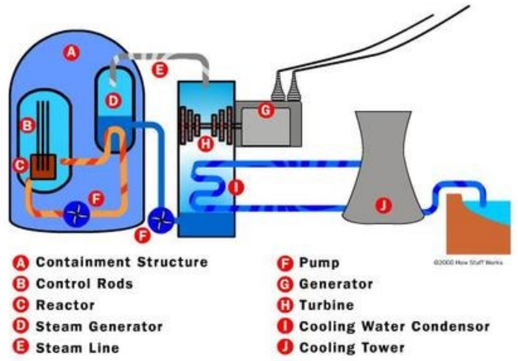


- Effective Multiplication Factor
- Rod Worth
- Shutdown Margin
- Maximum Rod Power
- Hot Channel Factors
- Reactivity Coefficients (Inherent Safety)
- Maximum Burnup
- Decay Heat

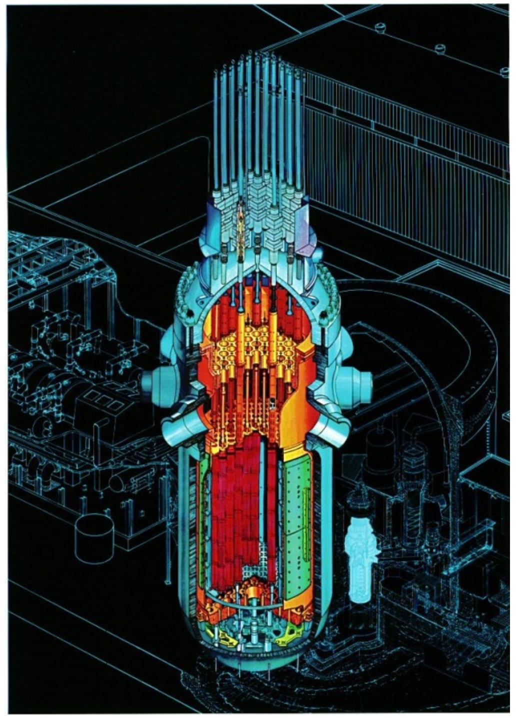
- DNB
- Primary Circuit: Coolant Pressure
- Secondary Circuit: Steam Pressure
- Maximum Forces on FA
- Pressure Losses
- Cladding Surface Temperature
- Pellet Central Temperature
- Maximum Fuel Enthalpy Increase

- Fuel Rod Inner Pressure
- Oxide Layer Thickness
- Hydrogen Uptake
- Tangential Stress
- Guide Tube Stress
- Dynamic Fuel Rod Load

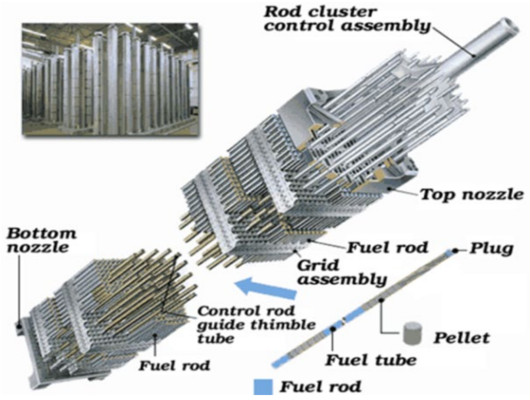
Multi-Scale Modeling in Space



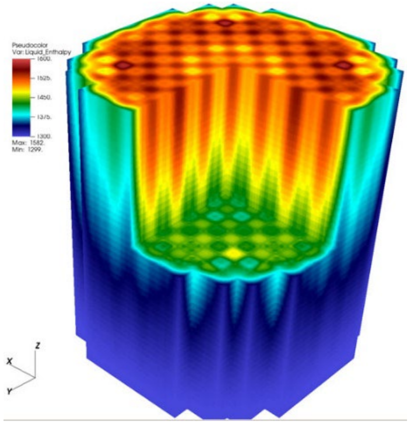
PWR Nuclear Power Plant



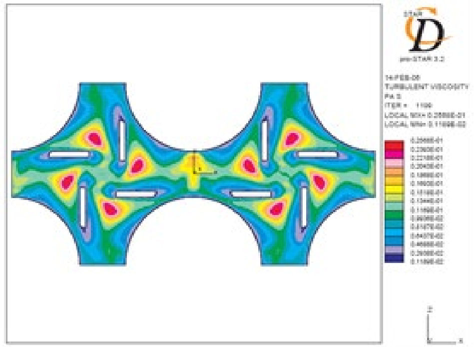
PWR Vessel

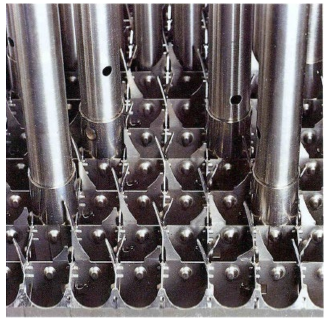


PWR Fuel Assembly

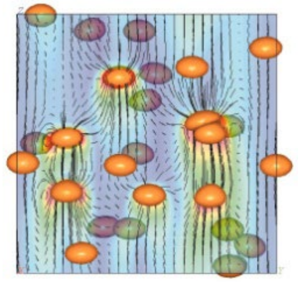


Pin / Subchannel Resolution (Liquid Enthalpy)

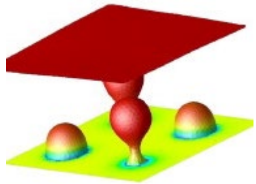




Within Subchannel Resolution (turbulent viscosity at the tip of mixing vanes)

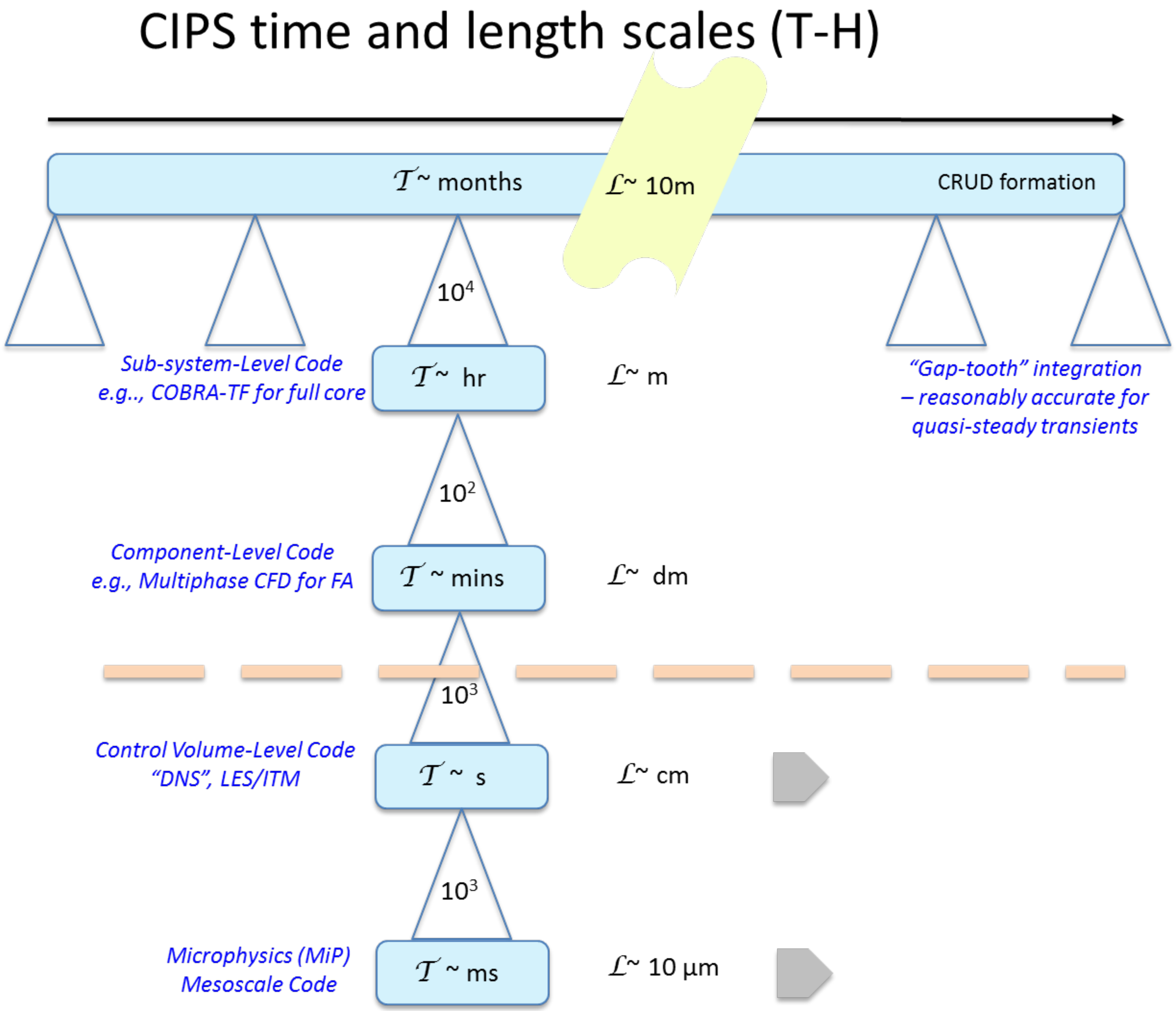


Bubble Dynamics (meso-scale)



Boiling/Condensation (micro-physics)

Multi-Scale Modeling in Time



Source: CASL, Prof. N. Dinh

Reactor Multi-Physics Modeling
Nomenclature

- *In the spatial domain, a reactor core multi-physics coupling can be performed at three scales (levels):*
  - assembly (sub-assembly)/channel scale (level);
  - pin/sub-channel level;
  - and sub-pin (pin-resolved) heterogeneity level as well as combinations; of the above-described scales.

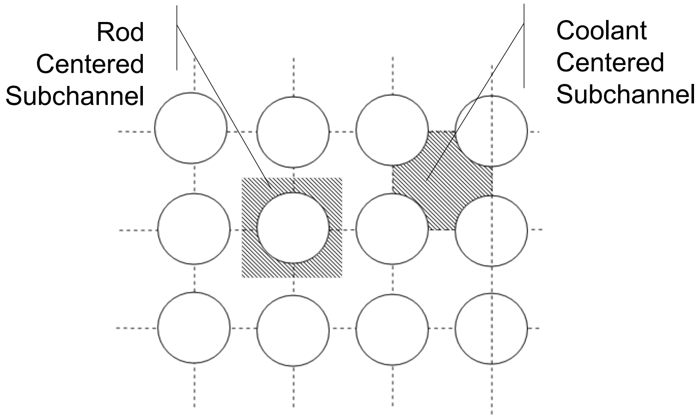
Channel includes fuel pins and coolant area for whole assembly (bundle) or part of the assembly.

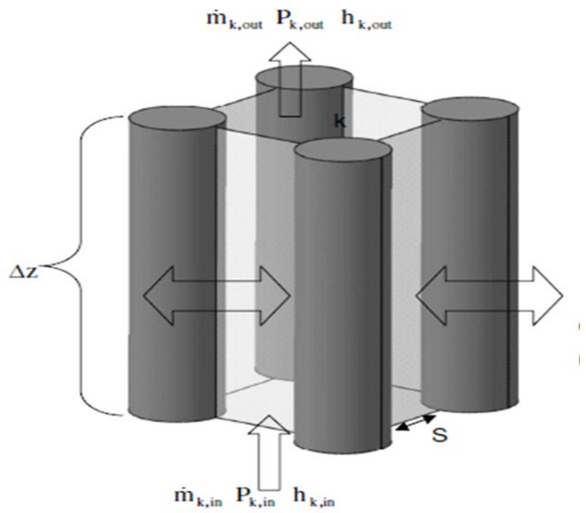
Subchannel includes much smaller domain – one or few pins and associated coolant area.

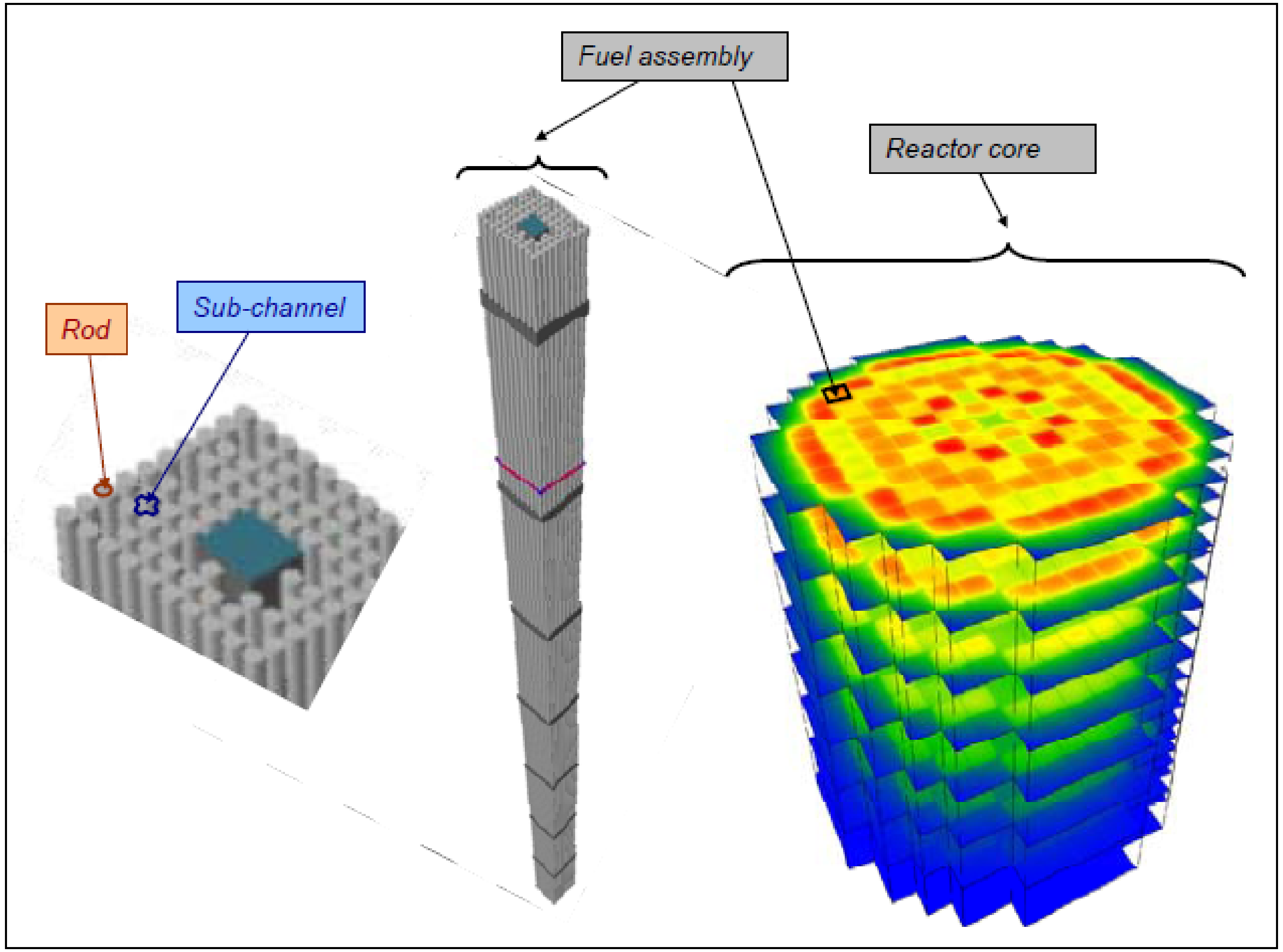
The sub-channel can be defined in two-ways:

- fuel pin with surrounding coolant (rod-based sub-channel);
- coolant area surrounded by four or three pins depending of the geometry of lattice (coolant-based sub-channel).

Reactor Multi-Physics Modeling
Nomenclature







Next Class

Time-Dependent Phenomena in Nuclear Reactors

Multi-Physics Interactions in Reactor Core

Classification of Multi-Physics Modeling and Simulation Tools