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

UNIT 1: Fundamentals of Reactor Multi-Physics

Lecture 2 : TIME-DEPENDENT PHENOMENA IN NUCLEAR REACTORS
MULTI-PHYSICS INTERACTIONS IN REACTOR CORE
CLASSIFICATION OF MULTI-PHYSICS MODELING AND SIMULATION TOOLS

Time-Dependent Phenomena in Nuclear Reactors

Time-Dependent Reactor: Nomenclature

- Time-dependent phenomena in nuclear reactors may be subdivided into three distinctively different classes, because:
  - *The time constants of the individual phenomena differ by orders of magnitude;*
  - *Different physical phenomena require different set of equations and solution approaches - not just a case of the same phenomenon occurring at different speeds.*

1. Short time phenomena, which typically occur in time intervals of milliseconds to seconds; in special cases, the time intervals may extend to many minutes.

2. Medium time phenomena, which occur over hours or days corresponding to the mean buildup and decay times of certain fission products that strongly affect the reactivity.

3. Long time phenomena, with variations developing over several months or years.

Time-Dependent Reactor: Nomenclature

- These time-dependent phenomena basically include changes in the neutron flux as well as causally related changes in the reactor system, i.e., composition or temperature.

- The causal relationship between the neutron flux and the physical reactor system may occur in either direction:
  1. *changes in the composition or temperature of the system may cause a change in the flux;*
  2. *changes in the flux may alter the composition or temperature and thus the density and absorption characteristics of the system.*

- Changes in the system can also be externally induced - *for example, by the motion of an independent neutron source, or of control rods, resulting in neutron flux changes.*

- If the flux changes cause changes in the reactor and these changes subsequently "act back" on the flux, the phenomenon is termed "feedback“.

Time-Dependent Reactor:
Nomenclature

- The "short time phenomena" include more or less rapid changes in the neutron flux due to intended or accidental changes in the system.
  - *These changes may influence the flux through feedback.*
  - *Short time phenomena include flux transients important for:*
    1. Accident analysis and safety;
    2. Experiments with time-dependent neutron fluxes;
    3. Reactor operation, such as startup, load change, and shutdown (even though some startup procedures may take hours);
    4. Analysis of stability with respect to neutron flux changes.

Time-Dependent Reactor: Nomenclature

- "Medium time phenomena" are generally associated with the buildup, burnup, and beta decay of two fission products (^{135}Xe and ^{149}Sm) in thermal reactors.
  - *These two fission products have very high thermal neutron capture cross sections and thus require special attention in thermal reactors.*

Time-Dependent Reactor: Nomenclature

- "Long time phenomena" include particularly the burnup and buildup of fissionable isotopes, as well as the buildup, beta decay, and burnup of most of the fission products.
  - *In the fast neutron energy range, the cross sections of all fission products are so small that they do not affect the flux and the reactivity as strongly as in thermal reactors.*
  - *Other long time phenomena occurring in reactors, which have only a minimal effect on the neutron flux, include swelling of the structural material, changes in the fuel pellets due to burnup, etc.*

Time-Dependent Reactor:
Nomenclature

- Since short, medium, and long time phenomena are physically different phenomena resulting in different sets of equations, different concepts and solution approaches are utilized.
  - *These are the strongest reasons for separating these time phenomena into three different categories with different names.*

- The nomenclature used for the different categories of time-dependent phenomena in nuclear reactors is not unique:
  - The two basic names in use are kinetics and dynamics:
    - *A few authors subsume all time-dependent phenomena under "dynamics," including burnup and buildup of isotopes;*
    - *Most authors, however, consider long time phenomena to represent a separate category, namely "fuel cycle problems“.*

Time-Dependent Reactor:
Nomenclature

- Essentially three names are in use for this class of short time phenomena:

1. Kinetics, for the entire class of short time phenomena.
2. Dynamics, also for the entire class of short time phenomena.
3. Dynamics, as a general heading for the entire class of short time phenomena, with two subheadings:

    a) *kinetics, for short time phenomena without feedback;*

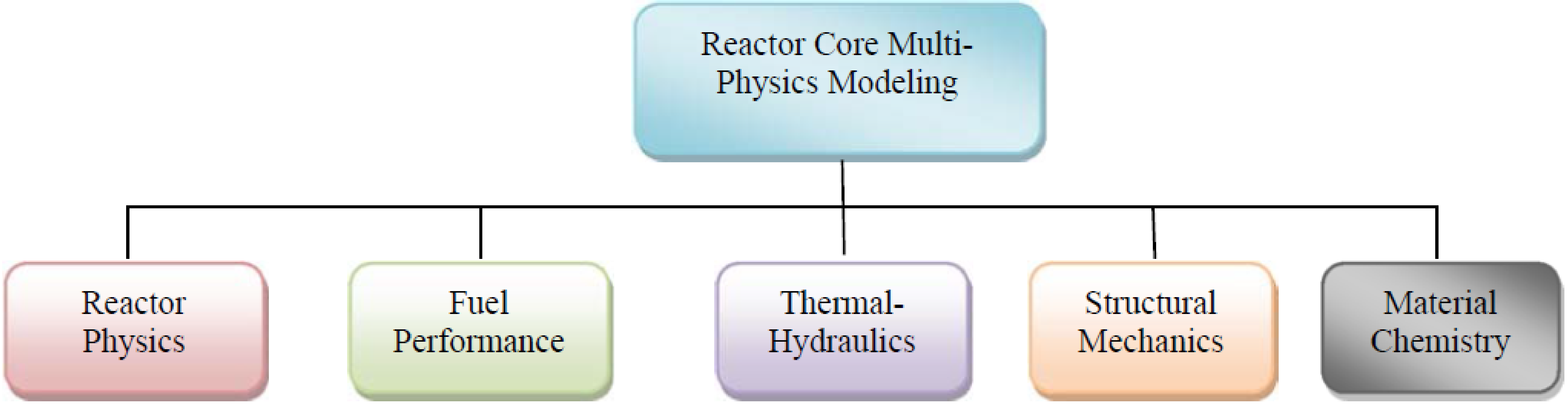
    b) *dynamics, in the narrower sense, for short time phenomena with feedback.*

Time-Dependent Reactor:
Nomenclature

- It is convenient to have a special name for the range of problems in which only the time behavior of neutrons need be considered - kinetics problems, kinetics equations.
- If feedback is important, the system of kinetics equations must be completed by another set of equations describing the various feedback effects.
- It is also convenient to have a different name for this completed set of equations - dynamics equations, dynamics problems.
- Since the completed set of equations describes the general problem, dynamics is also used as a general heading.
- This course is concerned with the short time variations of the neutron flux as a function of time, i.e., with the typical topics of kinetics and dynamics.

Multi-Physics Interactions in Reactor Core

Multi-Physics Interactions in the Reactor Core



Neutronics

- Neutron transport within the reactor core (fuel, cladding, moderator/coolant, structures/reflector);
- Changes in fuel composition with burnup: fuel depletion-transmutation-decay equations (isotopic concentration equations);
- Radiation transport.

Fuel Performance

- Thermal and mechanical properties of the fuel element (fuel, clad, gap) and changes under irradiation:
  - ✓ *fuel and cladding temperatures*
  - ✓ *cladding hoop strain*
  - ✓ *cladding oxidation*
  - ✓ *hydrating*
  - ✓ *fuel irradiation swelling*
  - ✓ *fuel densification*
  - ✓ *fission gas release*
  - ✓ *rod internal gas pressure*
  - ✓ …

Thermal-Hydraulics

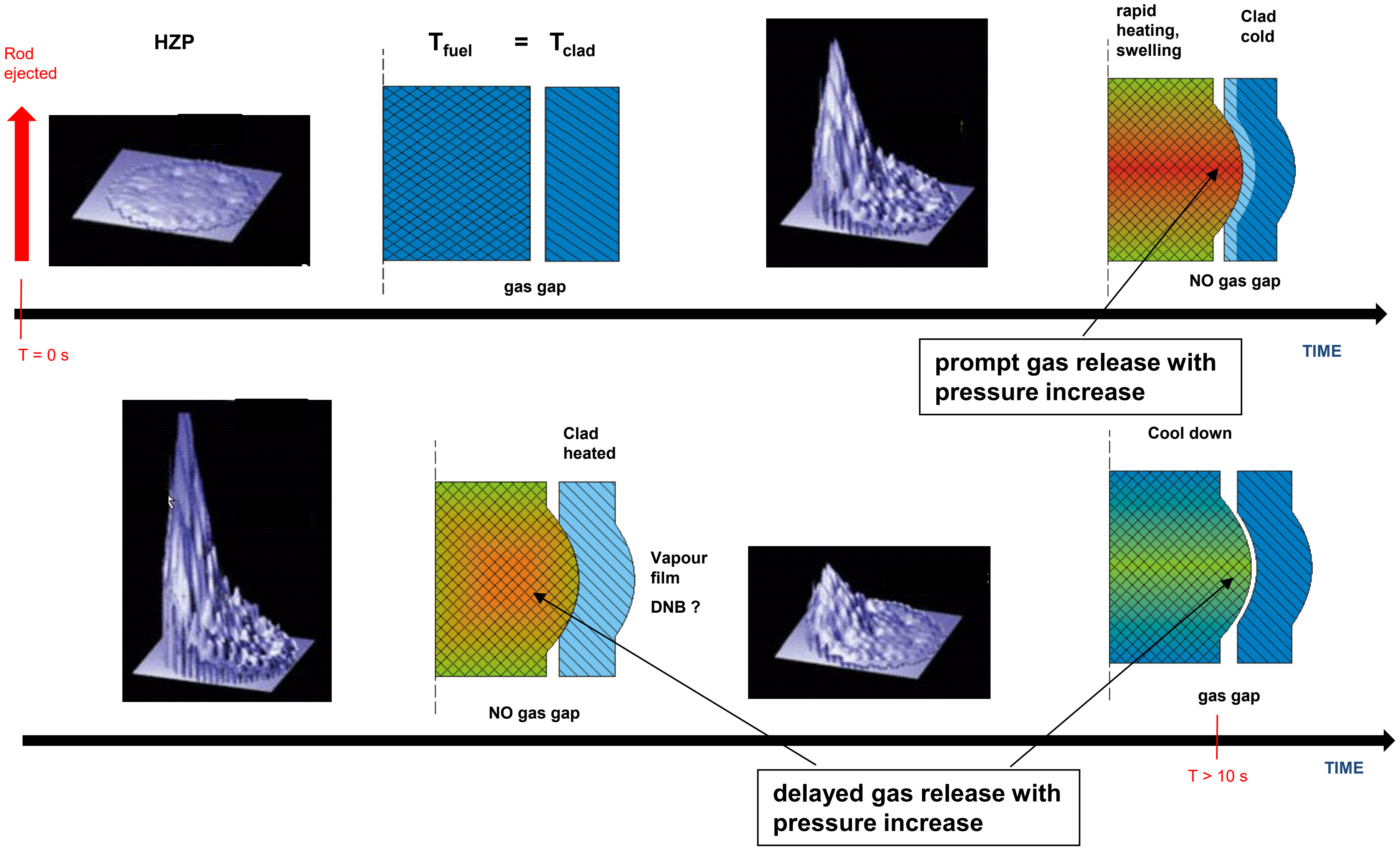
– Coolant flow and heat transfer from the fuel rod cladding:
  - ✓ *coolant (moderator) temperature and density*
  - ✓ *coolant velocity (flow rate)*
  - ✓ *heat transfer coefficients*
  - ✓ *coolant pressure*
  - ✓ *rod cladding temperature*
  - ✓ *onset of boiling*
  - ✓ …

Coolant Chemistry

– Chemical reactions in the interface between the coolant and the cladding
  - ✓ *clad corrosion*
  - ✓ *crud formation, transport, and deposition*
  - ✓ …

Reactor Multi-Physics – Safety Concerns

Reactivity Insertion Accident



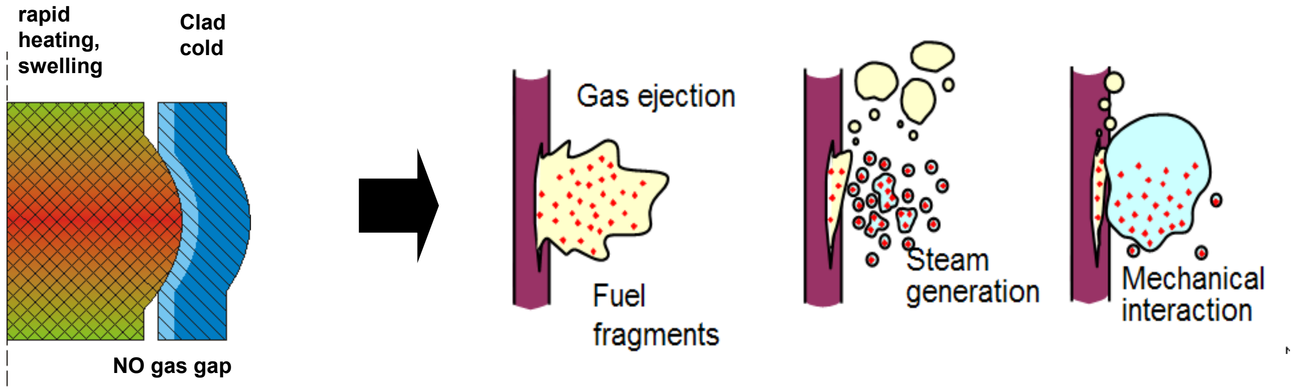
Reactor Multi-Physics – Safety Concerns

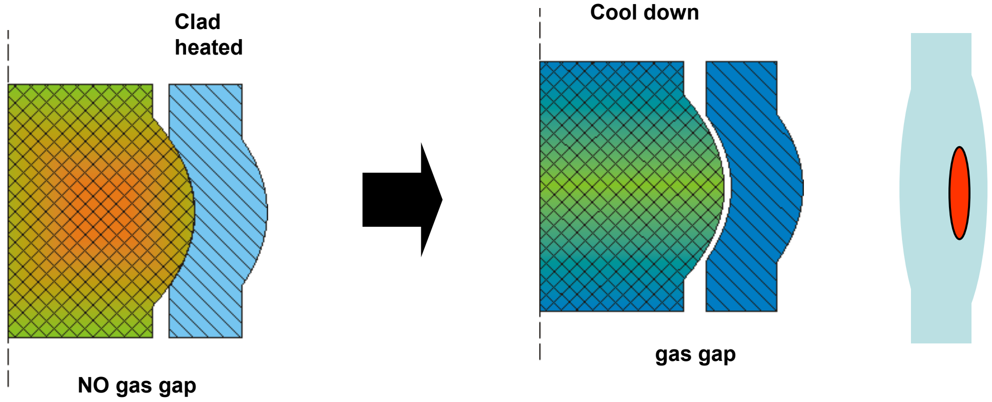
Reactivity Insertion Accident

The two failure modes can lead to a partial (local) destruction of the first safety barrier

Clading brittle failure possible due to loss of ductility (PCMI)

Clading balooning or high temp. oxidation - post DNB failure



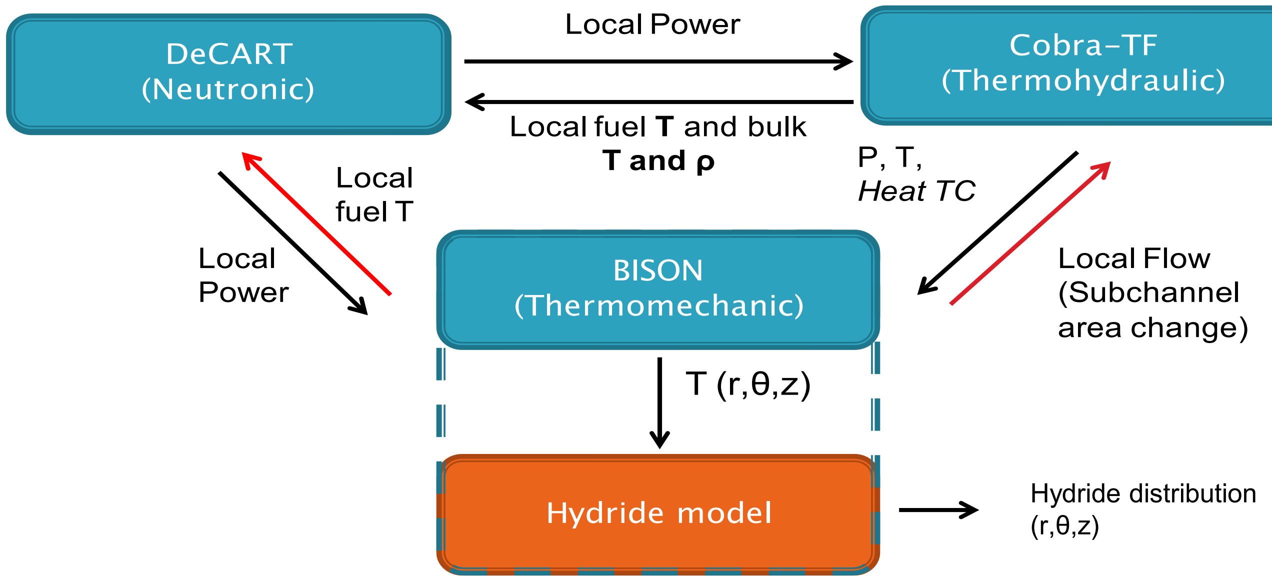


Reactor Multi-Physics – Applications

Prediction of Anisotropic Azimuthal Power and Temperature Distribution as a Driving Force for Hydrogen Redistribution

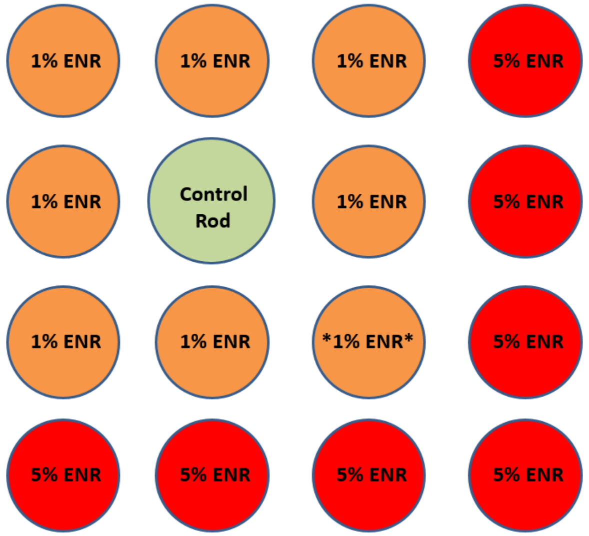
In the high temperature reactor environment, the zirconium in the cladding undergoes waterside corrosion in primary water, releasing hydrogen:

- some hydrogen is absorbed by the cladding;
- hydrogen distribution within the cladding is extremely sensitive to temperature, stress and concentration gradients:
  - → *hydrogen migrates down temperature gradients*
  - → *at a high enough concentration, it precipitates as hydrides which can embrittle the cladding.*



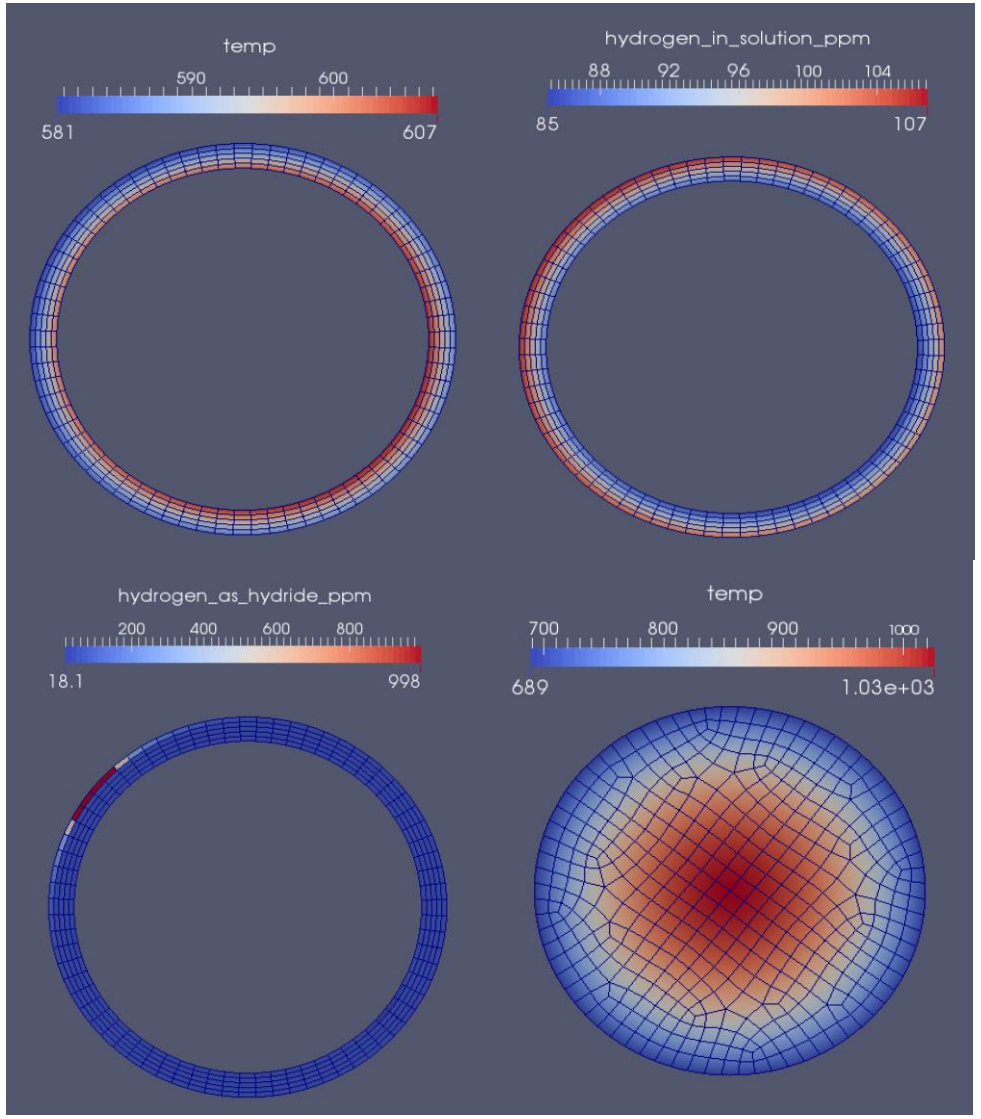
Reactor Multi-Physics – Applications

Prediction of Anisotropic Azimuthal Power and Temperature Distribution as a Driving Force for Hydrogen Redistribution



4x4 Sub-Assembly with Control Rod layout at 0 MWd/kgU Burnup

578.3	578.2	578.0	577.7	576.9	583.9	607.4	614.7
1% Enr.		1% Enr.		1% Enr.		4.95% Enr.	
578.2	578.5	578.3	577.9	577.0	583.8	607.3	614.5
578.0	578.2	566.5	566.1	576.8	583.6	606.7	613.8
1% Enr.		Guide Tube		1% Enr.		4.95% Enr.	
577.6	577.8	566.1	565.7	576.5	583.1	606.2	613.2
576.7	576.8	576.7	576.4	575.7	582.6	604.6	611.6
1% Enr.		1% Enr.		1% Enr.		4.95% Enr.	
583.9	583.7	583.6	583.2	582.5	585.4	607.5	610.6
607.1	607.0	606.4	605.9	604.4	607.3	605.6	608.8
4.95% Enr.		4.95% Enr.		4.95% Enr.		4.95% Enr.	
614.4	614.3	613.7	613.0	611.5	610.5	608.8	608.2



Top Left: **Cladding temperature (K)** ***Top Right:*** **Cladding hydrogen dist.** ***Bottom left:*** **Cladding hydride dist.** ***Bottom Right:*** **Fuel temperature (K)**

Classification of Multi-Physics Modeling and Simulation Tools

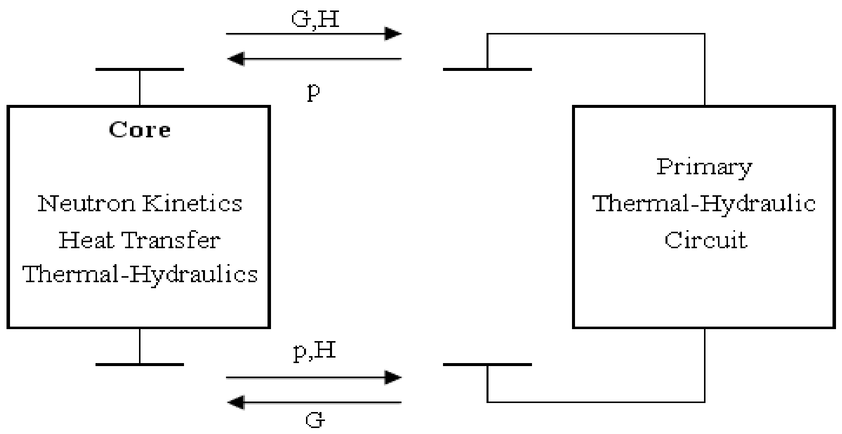
Pre-Traditional (Simplified) Multi-Physics Modeling (Coupling)

- Up to early 1990s, because of the limited computational resources, the multi-physics phenomena in nuclear power plant simulations have been decoupled.
- Only the physics of interest was treated in details and the remaining physics was represented by:
  - *simplified models* - point kinetics and fuel rod models in thermal-hydraulics codes or 1-D thermal-hydraulics models and fuel conduction in core physics simulators; 1-D neutronics and depletion equation in fuel performance codes;
  - *boundary conditions* - tabulated total power and local power distributions in thermal-hydraulics codes;
  - *parameterized or fixed values – fuel temperatures tables (as function of power and burnup) for neutronics codes.*
- We can name these as Pre-Traditional MP coupling schemes.

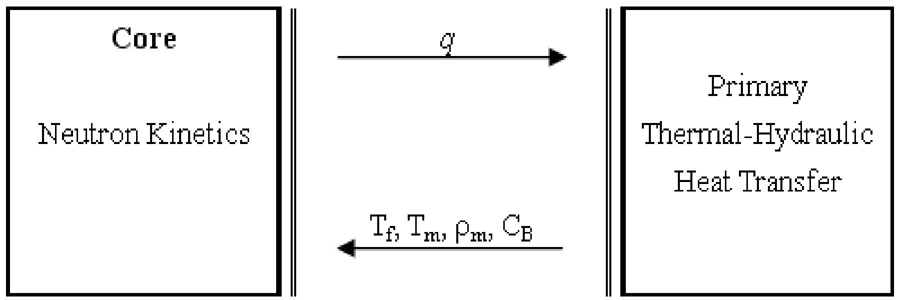
Traditional Multi-Physics Modeling (Coupling)

- The first Traditional MP coupling was performed on coupling 3-D reactor physics (kinetics) with core thermal-hydraulics; and coupling 3-D core models with system thermal-hydraulics.
- Later system models were coupled with containment models.

External Coupling



Internal Coupling

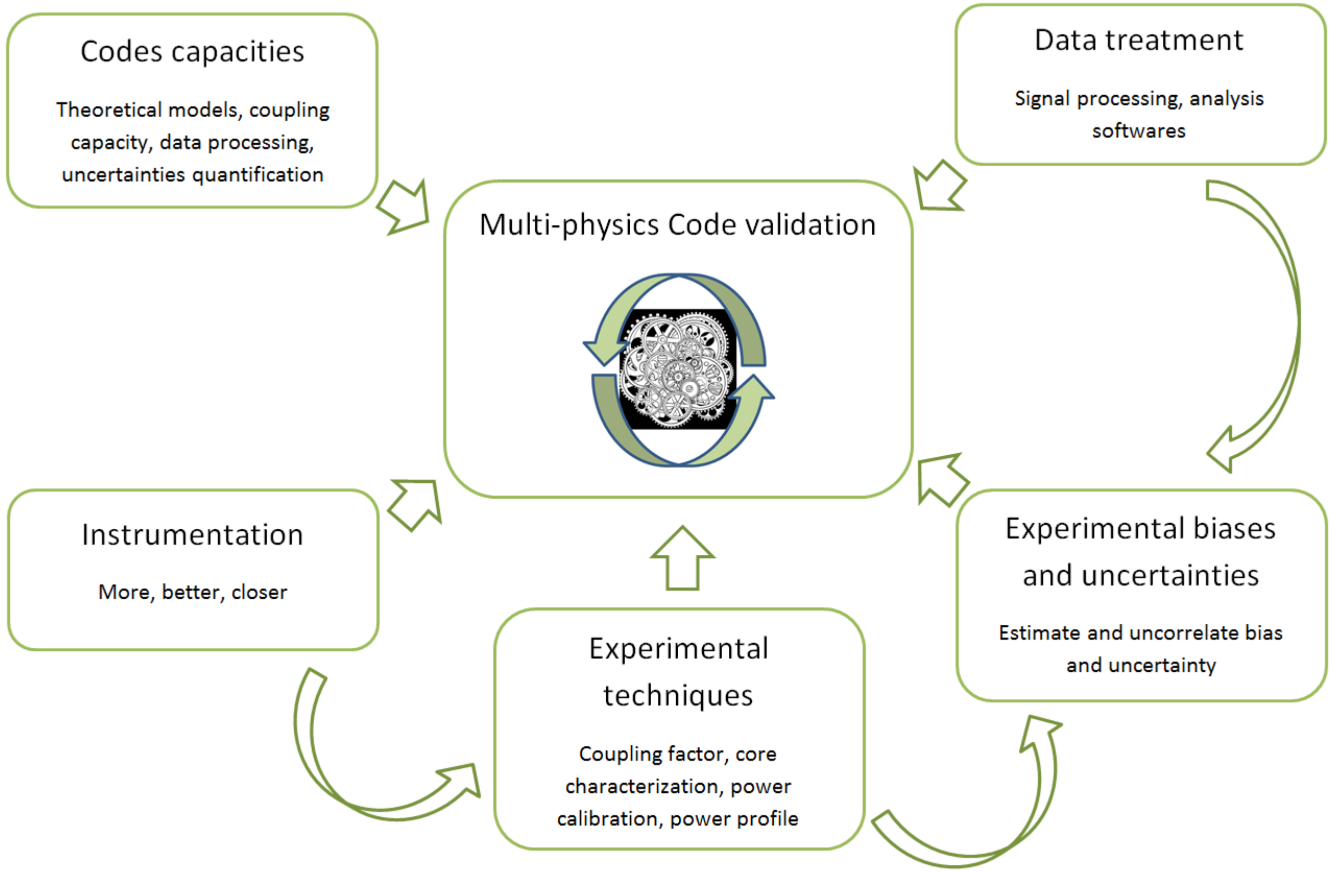


The traditional multi-physics tools usually couple computer codes currently used in nuclear industry and regulatory practice, which are based primarily on empirical models to approximate, or fit, existing experimental data.

These conventional codes have been updated for today's technology, they still suffer from limitations of their original design intent: to approximate or fit existing data by means of empirical models.

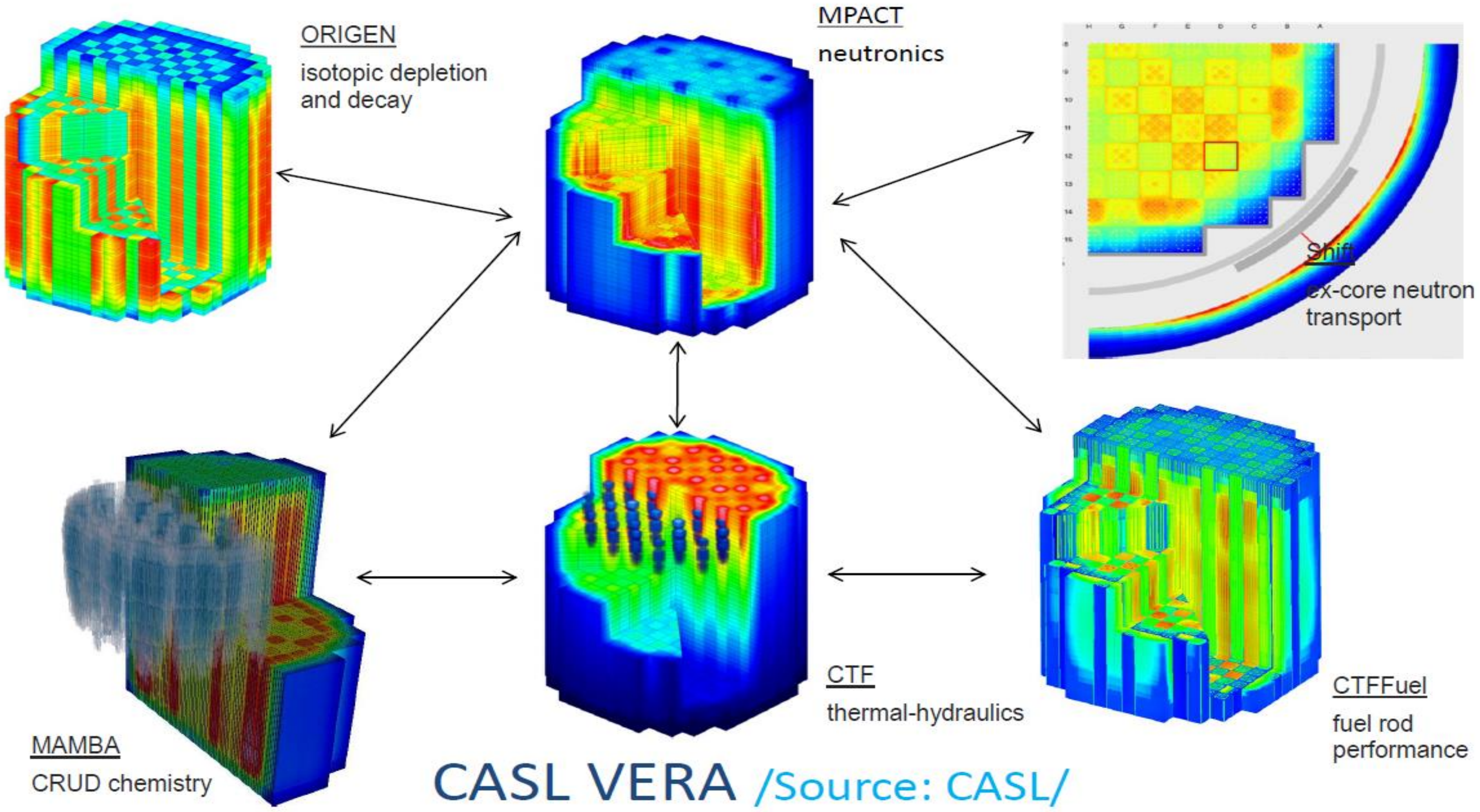
Novel Multi-Physics Modeling (Coupling)

- The novel multi-physics simulations must include all involved (or at least the most important and relevant) physics phenomena.
- The novel multi-physics simulations must be performed in detail – high resolution in space and time.
- They must utilize models which are closer to first-principles physics.
- Need advanced coupling methodologies.
- Need new-philosophy validation experiments.



Source: J.-P. Hudelot (CEA)& Mark DeHart (INL)

Novel Multi-Physics Modeling (Coupling)



CASL VERA /Source: CASL/

Next Class

Short-Time Multi-Physics Phenomena in Reactor Cores -

Dynamic Equation & Simplified Neutron Cycle

Prompt and Delayed Neutron Phenomena

Total Delayed Neutron Yields & Yields of Delayed Neutron Groups

Reactor Multi-Physics and Dynamics

Events: A) Control Rod Ejection/Drop in 0.1sec
& B) 50% coolant flow reduction in 5 sec

Case 1: PWR at HZP

Case 2: BWR at HFP (dropped rod was inserted halfway into the core)

Case 3: Highly enriched (90%) PWR (Navy-type core)