PART I
FUNDAMENTALS OF REACTOR MULTI-PHYSICS

I-1 Introduction

The nuclear industry has always prioritized the safe, reliable and economically attractive operation of the nuclear power reactor fleet. Given these priorities, the development, validation and application of predictive reliable modeling capabilities for both normal and accident conditions has evolved from the so-called best-estimate calculations to first principle high-fidelity multi-physics simulations.

There are many interactions between different physics phenomena at different scale in different components of Nuclear Power Plants (NPPs). The multi-physics interactions in a NPP are manifested in both global-length-scale behavior and lower-length-scale behavior, as illustrated in Figure I-1 for nuclear fuel, reactor core, and reactor system.

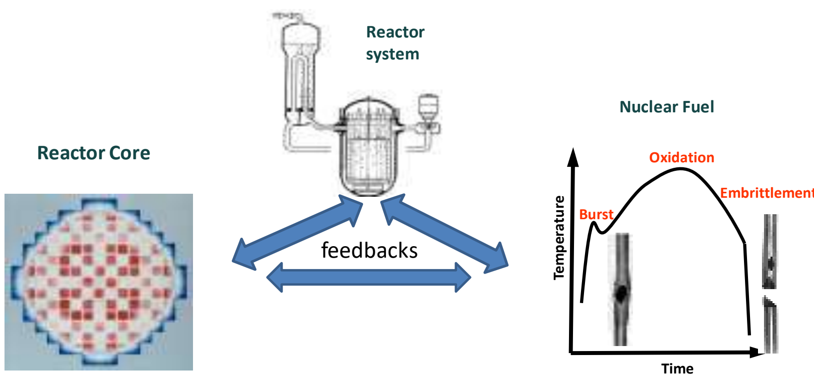

Figure I-1. Multi-physics multi-scale interactions in a NPP

I-2 Basic Topics and Nomenclature

For reader's convenience we will introduce here some basic terms and definitions, which are used in this course. While *integral effects* describe the behavior of a reactor system at nominal, off-nominal or accident conditions, the *separate effects* describe the behavior of single component or characteristics of one phenomenon. *Single physics* modeling (simulation) focuses on single physics phenomenon and takes into account the interactions with other physics phenomena via boundary conditions. *Multi-physics* modeling (simulation) describes nonlinear multi-physics phenomena by on-line treatment of feedback effects of different physics. *Detailed modeled physics phenomena* are the phenomena modeled with the best available models. *Simplified modeled physics phenomena* are the phenomena modeled by simplified models, or boundary conditions, or parameterized values. *Experiment/plant measurable parameters* are integral parameters or local distributions, which can be directly or indirectly measured during the plant operation and/or transient conditions. The obtained measured values have to be supplemented with corresponding experimental/measurement uncertainties.

Before discussing in more detail the multi-physics modeling, the common physical forms of nuclear fuel in a LWR core are introduced as an example. Uranium dioxide (UO_2) powder is compacted to cylindrical pellets and sintered at high temperatures to produce ceramic nuclear fuel pellets with a high density and well defined physical properties and chemical composition. A grinding process is used to achieve a uniform cylindrical geometry with narrow tolerances. Such fuel pellets are then stacked and filled into the metallic tubes. The metal used for the tubes depends on the design of the reactor. Stainless steel was used in the past, but most reactors now use a zirconium (Zr4) alloy which, in addition to being highly corrosion-resistant, has low neutron absorption. The tubes containing the fuel pellets are sealed: these tubes are called fuel rods (or pins). The finished fuel rods are grouped into fuel assemblies that are used to build up the core of a power reactor.

Channel includes fuel pins and coolant area for whole assembly (bundle) or part of the assembly. The subchannel includes much smaller domain – one or few pins and associated coolant area. The *sub-channel* can be defined in two-ways as shown in Figure I-2: fuel pin with surrounding coolant (rod-based sub-channel) and coolant area surrounded by four or three pins depending of the geometry of lattice (coolant-based sub-channel). The geometry and material distribution of a typical LWR single fuel pin (rod) in radial plane is shown in Figure I-3.

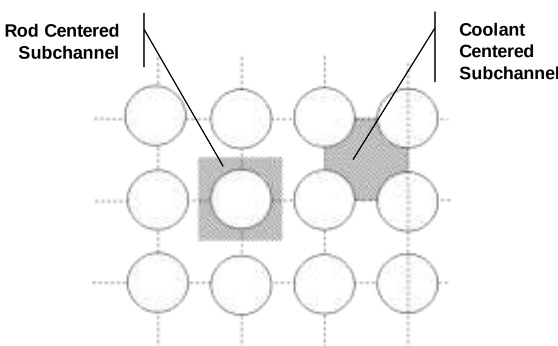

Figure I-2 Definition of two types of subchannels

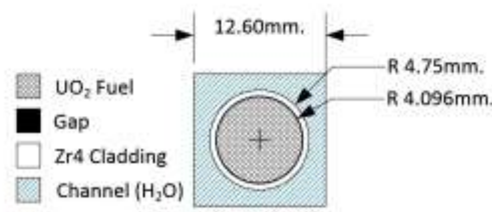

Figure I-3 Single LWR rod centered subchannel geometry and material distribution

The multi-physics coupling can be sub-divided in two groups: *high-level multi-physics coupling*, which is physics coupling between different codes; and *low-level multi-physics coupling*, which is between different models within a code (for example chemistry and boiling flow). Distinction should be made also between *High-Resolution* (HR) and *High-Fidelity* (HF) simulations. 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.

I-3 Basic Time-Dependent Phenomena in Nuclear Reactors

Time-dependent phenomena in nuclear reactors may be subdivided into three distinctively different classes. The time constants of the individual phenomena in the three classes differ by orders of magnitude. In addition, different physical phenomena are treated in each class; it is 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.

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; that is, changes in the composition or temperature of the system may cause a change in the flux, or 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 or shutdown 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".

The "short time phenomena" include more or less rapid changes in the neutron flux due to intended or accidental changes in the system. The latter 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.

"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. Since the treatment of medium time phenomena is methodologically different from kinetics, it is not addressed in this course.

"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 that have only a minimal effect on the neutron flux include swelling of the structural material, changes in the fuel pellets due to burnup, etc.

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.

Kinetics versus Dynamics

The nomenclature used in textbooks and publications 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." The latter widely used practice is followed in this text.

Essentially three names are in use for the 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 and (b) dynamics, in the narrower sense, for short time phenomena with feedback.

The latter nomenclature is used in this book since it is probably in more widespread use and the structure of the problem seems to suggest such a nomenclature. It is convenient to have a special name for the range of problems (kinetics problems, kinetics equations) in which only the time behavior of neutrons need be considered. If feedback is important, the system of kinetics equations must be completed by another, often larger, set of equations describing the various feedback effects. It is convenient to have a different name for the 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 text 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.

I-4 Multi-Physics Interactions in Reactor Core

Especially important are the multi-physics interactions in a nuclear reactor core. A nuclear reactor core is the portion of a nuclear reactor containing the nuclear fuel components where the nuclear reactions take place and the heat is generated. Typically, the fuel will be low-enriched uranium contained in thousands of individual fuel rods (pins). The core also contains structural components in order to sustain and control the reactions as well as to transfer the heat from the fuel to where it is required. Advanced reactor modeling and simulation capabilities are being developed that couple multiple physics phenomena taking place in a reactor core including neutronics (reactor physics), fuel thermo-mechanical performance, thermal-hydraulics, material chemistry, and structural material behaviors – see Figure I-4.

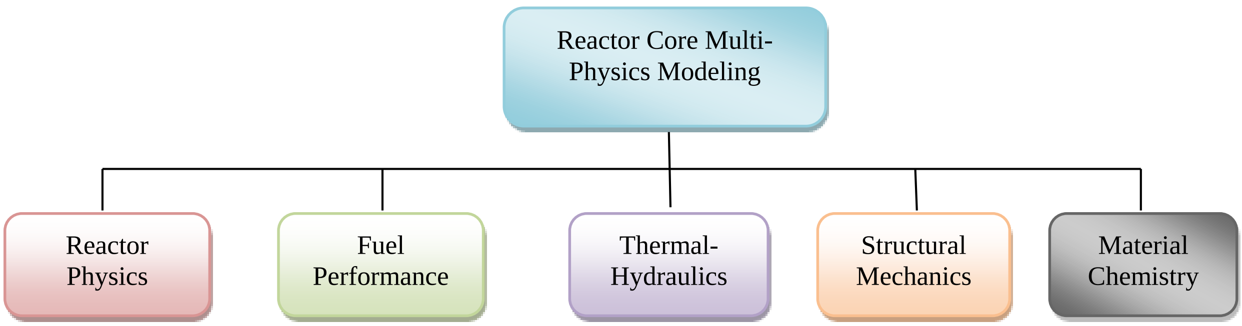

Figure I-4 Multi-physics modeling of reactor core

The Light Water Reactors (LWR) technology dominates the current operating nuclear power fleet around world and is likely to remain dominant for the foreseeable future. In a LWR core the structural mechanics mostly interacts with the coolant flow and these interactions could be neglected in most of the simulations related to operating conditions and most of the transients and accident scenarios. The remaining multi-physics coupling mechanisms and feedback effects in a LWR core are shown in Figure I-5.

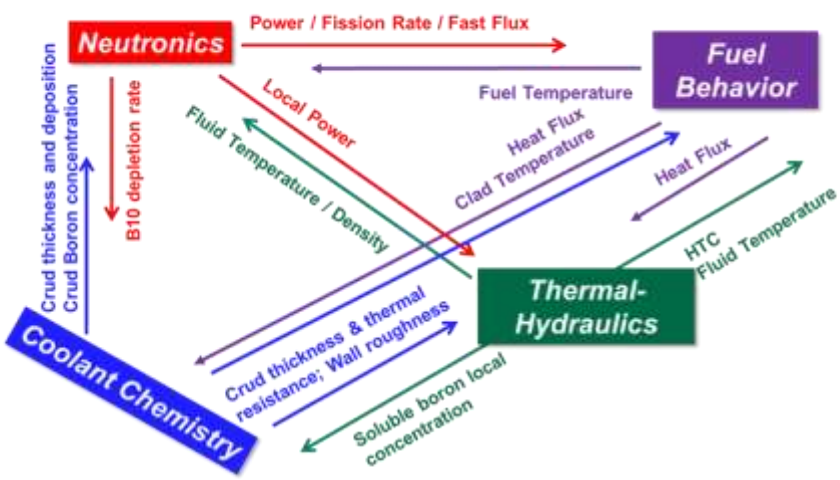

Figure I-5 Multi-physics interactions in a LWR core

The multi-physics interactions in a LWR core as shown in Figure I-5 occur at different time scales, which we can separate (following the classification in Section 1.3) as short (seconds, minutes, and hours) and long (weeks, months, and years) time phenomena. Please note that in a LWR core the material chemistry interactions are actually mostly coolant chemistry interactions with thermal-hydraulics and irradiation environment (reactor physics) and they represent long time phenomena. If we consider the short time phenomena, which is relevant to nuclear reactor transient and accident analysis and thus to nuclear safety, of importance are mostly the interactions between reactor physics, thermal-hydraulics, and fuel performance. The core multi-physics coupling can be carried out at three scales in the spatial domain: 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.

I-5 Classification of Multi-Physics Modeling and Simulation Tools

Historically (up to early nineties), because of the limited computational resources, the multi-physics phenomena in NPP simulations have been modeled in a simplified way. Only the physics of interest was treated in details and the remaining physics was represented by one of the options listed below (we can name these as pre-traditional multi-physics tools):

a) simplified models;

b) boundary conditions;

c) parameterized or fixed values.

With continuing advances in computer technology a more detailed multi-physics modeling of NPPs has been developed along with its validation and application to solution of challenge problems of high importance for NPP's operation and safety.

The multi-physics simulation tools could be further divided in two groups (categories): *traditional* and *novel.* The traditional multi-physics simulations include, usually, no more than two physics phenomena modeled in detail. The most representative example is the neutronics (reactor physics)/thermal-hydraulics coupling for reactor core modeling on assembly/channel basis. The coupling of reactor core to the reactor system and coupling of the reactor system to the containment also belongs to traditional multi-physics simulations. In addition, 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. While 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. The novel multi-physics simulations include all involved (or at least the most important and relevant) physics phenomena modeled in detail. The most representative example is the high-fidelity coupling on pin/sub-pin(pin-resolved)/sub-channel level of several physics phenomena in reactor core such as neutronics (reactor physics), thermal-hydraulics, fuel performance, structural mechanics, chemistry, etc. They utilize models which are closer to first-principles physics and have higher resolution than traditional tools. Novel tools are able to provide insights into physical systems in ways not possible with traditional approaches alone.

Review Questions

1. Describe briefly the three categories of time dependencies occurring in nuclear reactors.
2. State three areas of kinetics or dynamics applications.
3. Considering the nomenclature, what do various authors consider to be the subject of "dynamics" or "kinetics"?
4. What is the main difference in the balance equations for the neutron flux in reactor dynamics and fuel cycle analysis?
5. Describe the multi-physics interactions in a LWR core.
6. How the multi-physics modeling and simulation tools are classified?

REFERENCES

1. H. S. Isbin, *Introductory Nuclear Reactor Theory*, Reinhold Publishing Corp., New York (1963)
2. Milton Ash, *Nuclear Reactor Kinetics*, McGraw-Hill Book Co., New York(1965)
3. D L Hetrick, *Dynamics of Nuclear Reactors*, The University of Chicago Press,
4. G. I. Bell and S. Classtone, *Nuclear Reactor Theory*, Van Nostrand Reinhold Co., New York (1970)
5. Z. Akcasu, G. S. Lellouche, and L. M. Shotkin, *Mathematical Methods in Nuclear Reactor Dynamics*, Academic Press, New York (1971)
6. L. E. Weaver, *Reactor Dynamics and Control*, American Elsevier Publishing Company Inc., New York (1968)
7. K. Ivanov and M. Avramova, "Challenges in Coupled Thermal-Hydraulics and Neutronics Simulations for LWR Safety Analysis," Annals of Nuclear Energy, 34 (6), pp. 501-513 (2007).
8. M. Avramova and K. Ivanov, "Verification and Validation and Uncertainty Quantification in Multi-Physics Modeling for Nuclear Reactor Design", Progress in Nuclear Energy, 52: 601-614 (2010).