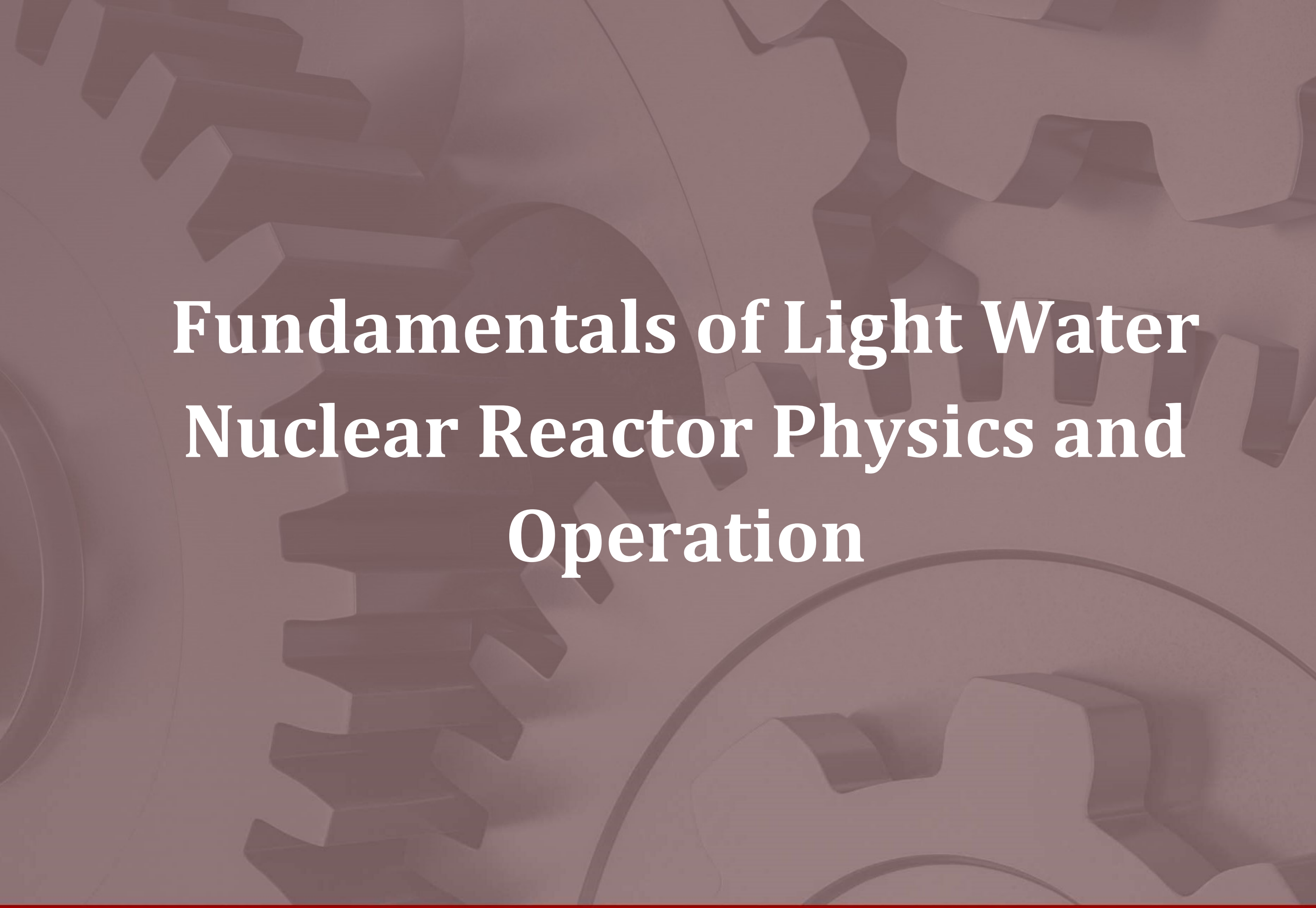

Fundamentals of Light Water Nuclear Reactor Physics and Operation

An Online Continuing Education Course for Engineers

Course Number: R-5002

Credit: 5 Hours / 5 PDH / 5 CPD

Fundamentals of Light Water Nuclear Reactor Physics and Operation

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Introduction

The discovery of nuclear fission, announced by the German scientists Otto Hahn and Fritz Strassmann in January 1939, set the stage for the era of atomic energy development. But the real beginning came 3 years later when a group of scientists led by Enrico Fermi demonstrated that a self-sustaining fission chain reaction could be achieved and, more important, could be controlled.

Fermi's operation of the first nuclear reactor began at 3:25 p.m. on December 2, 1942, in an improvised laboratory beneath the stadium at the University of Chicago. By today's standards, it was a fairly crude apparatus, essentially an assembly of uranium and graphite bricks. The method of assembly, which was simply to place one brick on top of another, gave rise to the name "atomic pile"; "nuclear reactor" is now the preferred term.

Since then, several hundred nuclear reactors have been placed in operation in the United States. Currently, electrical generation by nuclear energy in the United States is second only to the burning of coal. In the world, nuclear energy provides the largest “baseload” of electrical generation capacity. As of this date, nuclear energy is used to produce electricity in 94 operating light water reactors in the United States, with close to 350 worldwide. These light water reactors are of two types – Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs).

Since all nuclear power electrical generating stations rely on nuclear fission, this course will focus on describing the basic concepts of the physics involved in operating and controlling the reactors without the use of complex mathematics that are sometimes used.

Specifically, the course will begin with the basics of nuclear cross-sections, the nuclear chain reaction, the neutron life cycle, and the factors that control that life cycle, and will conclude with how the reactors are started up and controlled. The course will also discuss the reactor physics and parameters that nuclear plant operators use to operate and control the reactors. To ensure a working knowledge of the reactor physics involved in reactor operation (without the complex mathematics), this course will also include the topics of reactivity coefficients, fission product poisons, and reactor period.

Definitions/Important Terms

Beginning of Core Life (BOL) – The first weeks or months of a reactor's fuel cycle (see Fuel Cycle definition)

Boiling Water Reactor (BWR) – In this type of light water reactor, the reactor coolant (which is also the neutron moderator) is allowed to boil. The resultant steam is passed directly to the turbine generator to generate electrical power. Roughly 1/3 of all light water reactors are BWRs.

Chemical Shim – Pressurized Water Reactors use a ***chemical shim*** to aid in the long-term reactivity control of the reactor core as the Uranium-235 (reactor fuel) becomes depleted over the core life. The chemical shim used is ***boric acid*,** dissolved in the reactor coolant/moderator. Boric acid (molecular formula: H_3BO_3) is a white powder that is soluble in water, with ***Boron-10 being the particular neutron absorber isotope***. At the beginning of the specific fuel cycle, the concentration of boric acid is at its highest. At the end of the fuel cycle, the concentration of boric acid is almost zero, at which time the reactor must be refueled.

In certain cases, fine reactor power changes can be controlled by using the chemical shim. For example, if it is desired to increase reactor power, the boric acid concentration must be diluted from the reactor coolant/moderator, removing Boron-10 from the reactor core and reducing its poisoning effect. If a decrease in reactor power is desired, the boric acid concentration must be increased (borate) in the reactor coolant/moderator. Compared with burnable neutron absorbers (long-term reactivity control) or with control rods (rapid reactivity control), the use of boric acid avoids the unevenness of neutron-flux density in the reactor core because it is dissolved homogeneously in the coolant in the entire reactor core.

Because fuel depletion occurs over an 18-24-month period, this method of reactivity control is slow. Normally, it takes several minutes to change the concentration (dilute or borate) of the boric acid in the reactor coolant. For rapid changes in reactivity, control rods must be used.

Criticality – This term refers to the state of the neutron fission chain reaction occurring in the reactor. A reactor is ***critical*** when the nuclear fission chain reaction is self-sustaining. That is, the neutron population density of a nuclear reactor is, on average, invariant from one generation to the next. The power generated by the reactor will be constant.

If the neutron population density decreases over time, the reactor is ***subcritical.*** When the reactor is subcritical, the nuclear fission chain reaction decreases, and reactor power decreases.

If the neutron population density is increasing over time, the reactor is ***supercritical.*** When the reactor is supercritical, the nuclear fission chain reaction is increasing and reactor power will be increasing.

End of Core Life (EOL) – The last few weeks or months of a reactor's fuel cycle (See Fuel Cycle definition)

Excess Reactivity – A reactor core must have enough fuel to form a critical mass at normal reactor operating conditions, achieve 100% power equilibrium conditions, and sustain power levels throughout the entire reactor core life. This additional fuel is termed excess reactivity.

Fissile Material – Fissile material consists of atomic nuclides that **WILL FISSION** with incident neutrons of any energy level. They are the desired nuclides for use in electrical generating nuclear reactors. The advantage of fissile materials is that they can fission with neutrons possessing zero or very low kinetic energies (i.e., thermal neutrons). Common examples of fissile material are Uranium-233, Uranium-235, and Plutonium-239.

Fission – Fission is the splitting apart of a heavy nuclide (such as Uranium-235) into two or more separate nuclei, accompanied by the release of a large amount of energy and additional neutrons. Nearly all of the fissions in a nuclear reactor are generated in the fuel by ***neutron absorption***, which results in the splitting of the fissionable atoms that make up the fuel. The release of neutrons causes additional fissions to occur, causing a self-sustaining fission rate capable of producing sufficient heat for electrical power production.

Fission Product Poisons - Fission fragments generated at the time of fission decay to produce a variety of fission products. ***Fission products are of concern in reactors primarily because they become parasitic absorbers of neutrons and result in long-term sources of heat***. Although several fission products have significant neutron absorption cross sections, Xenon-135 and Samarium-149 have the most substantial impact on reactor design and operation. Because these two fission product poisons essentially remove neutrons from the reactor without causing other fissions, they have a significant impact on the reactivity and operation of the reactor core.

Fissionable Material – Fissionable material is composed of nuclides for which **FISSION IS POSSIBLE**. All fissile materials (see definition) fall into this category as well as those nuclides that fission from only high-energy neutrons. Common examples of fissionable materials are Uranium-238 (natural uranium), Plutonium-240, and Plutonium-242.

Fuel Cycle – Light water reactors are typically loaded with enough fuel to operate at 100 percent power for an 18 or 24-month fuel cycle. The term ***fuel cycle*** describes the core operation between refueling events. A reactor power coast-down (reduction in generated power) may occur at the end of core life (EOL) and will extend the core life.

A typical 1000-megawatt (electric) light water reactor contains approximately 100 tons of uranium in its core, enriched to 3 – 5% Uranium-235. These reactors typically operate on a nominal 18 to 24-month fuel cycle, with one-third of the core replaced with fresh fuel to begin the next 18 to 24-month fuel cycle. Fresh fuel is required due to the depletion of the Uranium-235 content and the accumulation of neutron-absorbing fission products during the previous fuel cycle.

Utilities strive to maximize the fuel cycle in order to achieve the maximum economic benefits from the fuel. These benefits include minimizing downtime (outages) during the fuel cycle as well as extending the time between refueling outages.

Fuel metallurgical limits and installed excess reactivity (extra fuel) determine fuel cycle length and the maximum amount of energy available from the fuel. Metallurgical limits are needed to ensure the integrity of the fuel and its cladding. Maintaining the integrity of the fuel and its cladding ensures fission products, many of which are gases, are contained within the fuel.

Reactivity limits consider shutdown margin (see definition), temperature coefficients, and fuel thermal limits. Fuel thermal limits restrict temperatures to maintain the physical integrity of the fuel.

Pressurized Water Reactor (PWR) – In this type of light water reactor, the reactor coolant (which is also the neutron moderator) is maintained above saturation pressure such that no significant boiling occurs in the reactor. The necessary steam for the turbine generator is produced in a steam generator. Approximately 2/3 of all light water reactors are PWRs.

Reactivity - Reactivity is a measure of the fractional change in neutron population per generation. Reactivity is a function of the ratio of the neutrons produced by fission in one generation to the number of neutrons produced by fission in the preceding generation. Thus, reactivity describes the reactor's deviation from criticality (see definition).

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 fission reaction heat is generated. Typically, the fuel will be low-enriched uranium (typically Uranium-235) contained in thousands of individual fuel pins (or fuel rods). The core also contains structural components, the means to both moderate (slow down) the neutrons and control the fission reactions, and the means to transfer the heat from the fuel outside the core and generate useful electrical power.

Shutdown Margin - Shutdown margin is the amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition, assuming complete insertion of all control rods with the exception of the most reactive control rod fully withdrawn from the core at any time during the core cycle.

Nuclear Cross-sections, Reaction Rate, and Reactor Power

Neutrons resulting from nuclear fission events are emitted or “born” at an average energy of about 2 MeV and interact with reactor core materials (including reactor fuel) in various absorption and scattering reactions. Scattering reactions are useful for thermalizing (slowing down) neutrons. Thermal neutrons may be absorbed by fissile nuclei (i.e., Uranium-235) to produce another fission or absorbed in fertile material (i.e., Uranium-238), resulting in the production of fissionable fuel (i.e., Plutonium-239). Additionally, some neutrons are absorbed in structural components, reactor coolant, and other non-fuel materials, resulting in the removal of neutrons from the fission process.

To determine these neutron interaction rates, it is necessary to identify the number of neutrons available and the probability of interaction. To assist in quantifying neutron availability and reaction probabilities, terms such as neutron flux, microscopic, and macroscopic cross-section are used and discussed.

The complexity of designing, safety, and efficiently operating a nuclear reactor requires the ability to predict that a particular absorption or scattering reaction will occur, both in specific portions of the core and averages throughout the core. Once these probabilities are known, and if the availability of neutrons can be determined, then the rate at which these nuclear reactions take place can be predicted. One example is the calculation of the reactor's thermal output, knowing the fission rate and core volume.

Neutron Energies

There are four classes of neutron energy levels: ***fast, intermediate, and slow***. Neutrons that are in energy equilibrium with their surroundings are called ***thermal neutrons***. These are the most important neutrons for thermal reactors.

Figure 1 illustrates the relative energy levels of neutrons and their flux distribution in a typical fission thermal reactor.

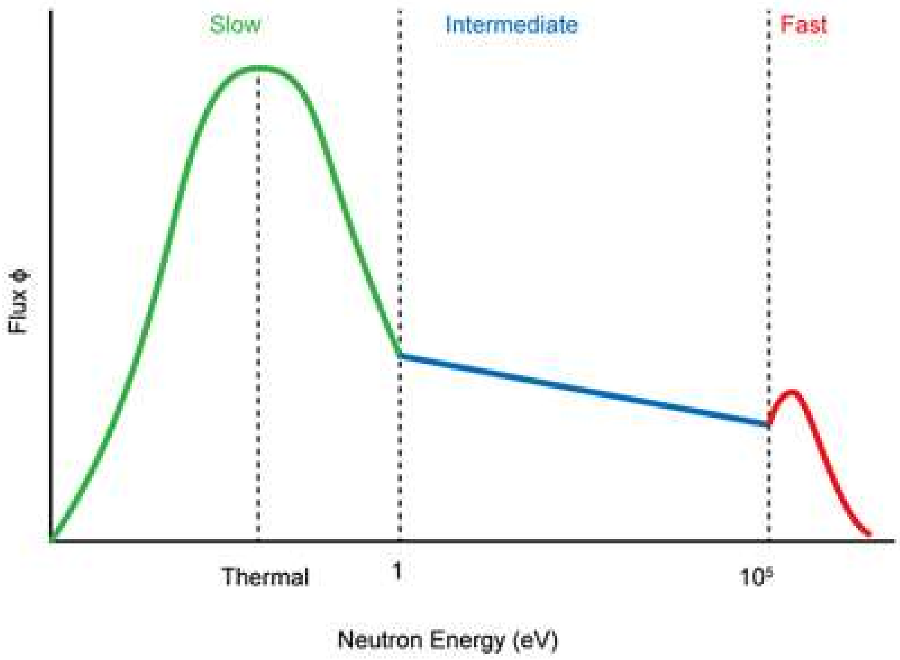

Figure 1: Neutron Flux vs Resulting Neutron Energies

The four classes of neutron energy levels are defined as follows:

Fast neutrons - Fission neutrons are “born” as fast neutrons. They are categorized as neutrons with energy levels greater than 0.1 MeV (10^5 eV); typically, 2 Mev

Intermediate neutrons - neutrons with energy levels between 1 eV and 0.1 MeV

Slow neutrons - neutrons with energy levels less than 1 eV

Thermal neutrons – neutrons with an energy level of 0.025 eV (2.2×10^5 cm/sec. velocity) at 68° F. Velocity and energy increase with temperature.

Atom Density

An important property of a material is its ***atom density***. The atom density is the number of atoms of a given type per unit volume of the material. Using the following equation, one can calculate the atom density of a substance.

$$N = \frac{\rho N_A}{}$$

where:

N = Atom der

ρ = density (g/

N_A = Avogadro'

M = gram atomi

Example:

A block of aluminu m is 26.9815 grams, calculate th

Solution:

Using the equation b

$$= \frac{\;cm^3\left(6.022 \times 10^{23}\,\frac{atoms}{mole}\right)}{26.9815\,\frac{g}{mole}}$$

$$= 6.024 \times 10^{22}\,\frac{atoms}{cm^3}$$

Microscopic Cross-section

When a neutron strikes an atom's nucleus, several reactions can occur. One possibility is that the incident neutron will bounce off the nucleus; this is termed ***elastic scattering***. A second possibility is that the neutron will penetrate the nucleus and form an unstable compound nucleus. If the neutron is then ejected, this is called ***inelastic scattering***. In both cases, the neutron usually will transfer some of its energy to the nucleus. If the nucleus keeps the neutron after the collision, this is called ***neutron capture***. Finally, the captured neutron can cause the nucleus to ***fission***. The probability that a neutron will undergo one of these reactions with a nucleus is measured using terms of ***microscopic cross-section***. The unit of