24.331 Fundamentals of NSE

Lesson 2: Introductory Concepts Associated with Nuclear Reactor Design and Operation

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Lesson 2 Objectives

Understand the basic fission chain reaction.

Identify the key products of the fission process.

Compute the approximate uranium requirements needed to produce a given amount of energy.

Discuss the energy density associated with nuclear vs. fossil fuels.

Describe the general neutron life cycle in a thermal reactor.

Define the terms multiplication factor.

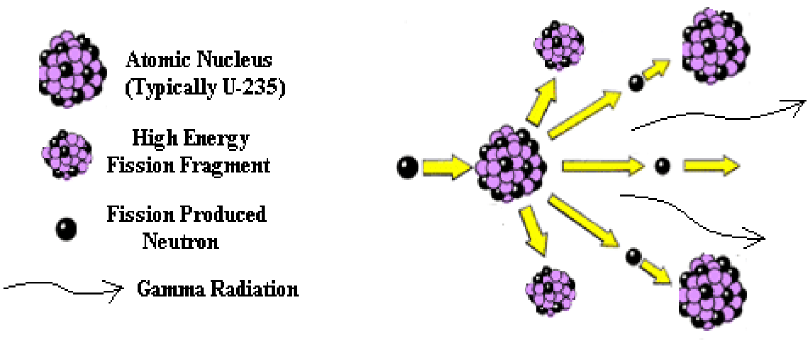
Explain the terms critical, supercritical, and subcritical within the context of a global neutron balance equation and the production and loss rates in the system.

Lesson 2 Objectives (cont.)

Understand the basics of power level and criticality control.

Understand several new terms such as reactivity, enrichment, capture-to-fission ratio, burnup and consumption rates, conversion ratio, etc.

The Fission Process



U235 + n → fission products + 2 or 3 n's + 200 MeV

The Fission Process (cont.)

U235 + n → fission products + 2 or 3 n's + 200 MeV

Items of Interest:

The spatial distribution and amount of U235 loss with time (fuel depletion).

The energy and spatial distribution of the neutrons causing fission are extremely important (e.g. thermal neutrons in a thermal system).

The fission products are neutron poisons and most are highly radioactive (affects the design of the safety systems).

The neutrons given off continue the fission chain reaction. These neutrons have high energy, and a small fraction are given off as delayed neutrons -- allows reactor control.

The energy released (approximately 200 MeV per fission) can be converted into other useful forms (mainly electricity).

U235 Fuel Requirements

$$1\ \mathrm{MW} \times \frac{10^6\ \mathrm{J/s}}{\mathrm{MW}} \times \frac{1\ \mathrm{MeV}}{1.602\times10^{-13}\ \mathrm{J}} \times \frac{1\ \mathrm{fission}}{200\ \mathrm{MeV}} \times \frac{86400\ \mathrm{s}}{\mathrm{day}}$$

$$= 2.7\times10^{21}\ \mathrm{fissions/day}\quad (\mathrm{per\ MW_{th}})$$

due to capture instead of fission

$$2.7\times10^{21}\ \frac{\mathrm{fissions}}{\mathrm{day}} \times \frac{1.17\ \mathrm{atoms}}{\mathrm{fission}}\ \frac{235\ \mathrm{g\ U235}}{6.022\times10^{23}\ \mathrm{atoms}}$$

$$= 1.23\ \frac{\mathrm{g\ U235}}{\mathrm{day}}\quad (\mathrm{per\ MW_{th}})$$

analysis based on 200 MeV/fission

Natural Uranium Requirements

But U235 only occurs at about 0.7 w/o in natural U

$$1.23\ \frac{\text{g U235}}{\text{day}} \times \frac{1\text{ g U}_{nat}}{0.007\text{ g U235}} = 176\ \frac{\text{g U}_{nat}}{\text{day}} \times \frac{1\text{ kg}}{1000\text{ g}}$$

$$\approx\ 0.18\ \frac{\text{kg U}_{nat}}{\text{day}}\quad (\text{per MW}_{th})$$

Energy Equivalents

Energy from Coal (25x10^6 BTU/short ton)

$$1\text{ MW} \times \frac{3.412\times10^6\text{ BTU/hr}}{\text{MW}} \times \frac{2000\text{ lbm}}{25\times10^6\text{ BTU}} \times \frac{1\text{ kg}}{2.205\text{ lbm}} \times \frac{24\text{ hr}}{\text{day}}$$

$$= 2970\ \frac{\text{kg coal}}{\text{day}}\quad (\text{per MW}_{th})$$

Energy Equivalency

$$0.18\text{ kg U}_{nat} \longleftrightarrow 3000\text{ kg coal}$$

$$1\text{ kg U}_{nat} \longleftrightarrow 16700\text{ kg coal} = 16.7\text{ tons coal}$$

Nuclear Benefits

With an energy ratio of almost 17000:1 relative to coal, we see that natural uranium is a very concentrated energy source.

Because of this high energy density, uranium power typically has a very low fuel cycle cost relative to the alternatives. Although capital costs are high, the overall costs associated with nuclear power are quite competitive.

In addition, nuclear power plants do not pollute the air with nitrogen oxides, sulfur oxides, dust, or greenhouse gases like carbon dioxide. Thus, it is an environmentally-friendly large-scale power source (except, of course, for the radioactive waste – which, however, is very concentrated).

The driving force for the interest in nuclear power is simply that, with our current technology, nuclear power is one of only a few viable large-scale environmentally-clean power options…

Neutron Life Cycle (thermal systems)

Fission neutrons are born at high energy, they slow down via elastic and inelastic neutron scattering, and then, as thermal neutrons, they cause additional fissions to continue the cycle…

Scattering only changes the neutron energy level (represents both production and loss in a multigroup formulation).

Parasitic absorption and neutron leakage can occur at all energies. Absorption and leakage are the ultimate loss mechanisms.

Fission is the primary neutron source in nuclear reactors.

When the neutron production and loss rates are in balance, then the neutron population remains constant and the system operates at constant power (power is related to the fission rate).

The Multiplication Factor

The multiplication factor, k, is a term used to describe the neutron balance in a nuclear system.

Reactors are controlled by manipulating the neutron economy such that, on the average, only one neutron produced from each fission causes another fission. When this condition is satisfied exactly, the system is said to be critical. Thus, the effective multiplication factor, k, is a measure of criticality and an indication of how the fission chain reaction is proceeding.

Balance equations are extremely important in all fields of physics and engineering. They can be written in the form

Rate of Change = Production Rate – Loss Rate

where, in the present context, the quantity of interest is the neutron population within the reactor.

The Multiplication Factor (cont.)

$$k = \frac{\text{fissions in one generation}}{\text{fissions in preceeding generation}}$$

$$= \frac{\text{fission neutrons in one generation}}{\text{fission neutrons in preceeding generation}}$$

$$= \frac{\text{neutron production rate from fission}}{\text{neutron loss rate}}$$

$$= \frac{\text{production}}{\text{absorption + leakage}}$$

Critical	→ production = absorption + leakage	**k = 1**
Supercritical	→ production > absorption + leakage	**k > 1**
Subcritical	→ production < absorption + leakage	**k < 1**

Power Level Control

Reactor power can be controlled by regulating the absorption rate via movement of the control rods (these contain neutron poisons – that is, materials with a relatively high absorption cross section).

Power Increase: From steady-state, remove control to decrease the absorption term. This causes production to be greater than loss ($k > 1$). Therefore, the neutron population begins to increase.

Power Decrease: From a stable condition, insert control to increase the relative number of parasitic absorptions. This causes the loss component to be greater than neutron production ($k < 1$). With this situation, the neutron population begins to decrease.

When the new target power level is approached, control is moved towards its previous position until k becomes unity. The reactor is now critical again at the new steady state power level.

A reactor can be critical at any power level…

Reactivity

Note that, in an operating reactor, the value of the multiplication factor, k, is always very close to unity (i.e. near critical) -- thus, it is convenient to quantify the amount of deviation from critical.

To do this, we define the term reactivity, ρ, as a measure of the deviation from critical, or

$$\rho = \frac{k-1}{k}$$

For example, we often talk about the insertion of positive or negative reactivity when the control rods are moved:

-- If the rods are inserted, this adds more absorption, k becomes less than unity, and we say that negative reactivity has been added to the system.

-- If the control rods are moved outward a little, then positive reactivity has been added since the absorption term decreases, and k becomes slightly greater that unity.

Some More Terminology

In completing this introductory lecture, let's define a few additional terms that may help you in understanding some of the basic concepts from the assigned reading…

In particular, you should have a good understanding of the following terms:

The amount of U235 relative to the total uranium content is referred to as the fuel enrichment:

$$\text{enrichment} = \frac{\text{mass of U235}}{\text{mass of total uranium}}$$

There are two different terms used to quantify the number of neutrons emitted in the fission process:

$$\eta = \frac{\text{\# of neutrons emitted}}{\text{absorption in fuel}} \quad \text{and} \quad \nu = \frac{\text{\# of neutrons emitted}}{\text{fission (in the fuel)}}$$

Some More Terminology (cont.)

The thorium, uranium, and plutonium isotopes that can be used as fuel are usually classified into three categories:

Fissile material -- fission can be induced by neutrons with essentially zero kinetic energy (e.g. U233, U235, Pu239, Pu241). Note that only U235 occurs naturally with an abundance of 0.72 a/o (atom percent) in natural uranium.

Fissionable material -- fission can be induced by energetic neutrons (e.g. all heavy elements, Th, U, Pu, etc.). Note that fissile materials are included in the broader class of fissionable material (also includes fertile material).

Fertile material -- fissile isotopes can be produced from fertile material by neutron capture (e.g. Th232, U238, Pu240). Note that Th232 and U238 are naturally occurring and relatively abundant isotopes -- they represent an important potential source of fissile material.

Some More Terminology (cont.)

Examples of some important breeding reactions are:

$$\mathrm{Th232(n,\gamma)Th233} \xrightarrow[22.2\mathrm{m}]{\beta-} \mathrm{Pa233} \xrightarrow[27.0\mathrm{d}]{\beta-} \mathrm{U233}$$

$$\mathrm{U238(n,\gamma)U239} \xrightarrow[23.5\mathrm{m}]{\beta-} \mathrm{Np239} \xrightarrow[2.35\mathrm{d}]{\beta-} \mathrm{Pu239}$$

$$\mathrm{Pu240}\left(\mathrm{n},\gamma\right)\mathrm{Pu241}$$

The conversion ratio (or breeding ratio) is a quantity that is used to quantify the amount of breeding that occurs in a reactor,

$$\begin{matrix}\text{conversion ratio (CR)} \\ \text{[breeding ratio (BR)]}\end{matrix} = \frac{\text{fissile atoms produced}}{\text{fissile atoms destroyed}}$$

For example, for a U235/U238 fueled system at beginning of life (BOL), we have

$$\text{CR or BR} = \frac{\text{capture rate in U238}}{\text{absorption rate in U235}}$$

Some More Terminology (cont.)

As a final set of definitions, let's contrast the difference between the burnup rate and consumption rate.

In particular, the burnup rate is directly proportional to the fission rate (these terms are often used interchangeably).

It is simply a measure of the number of fissions that have occurred over some time interval:

- -- fissions/sec
- -- atoms fissioned per day
- -- energy produced per day (MWD)
- -- MWD per unit mass of initial fuel loading (MWD/MTU), etc.

If you specify the power, then you know the fission rate and burnup rate!!!

The burnup rate is always directly proportional to the fission rate and, as we have seen earlier, this is related directly to the power level.

Some More Terminology (cont.)

The consumption rate, in contrast, refers to the absorption rate, where absorption = fission + capture.

This is the total loss rate of a particular nuclide due to all neutron interactions.

If we define the capture to fission ratio as α, then the consumption rate can be written as

$$\text{consumption rate} = \text{fission rate} + \text{capture rate}$$
$$= \left(1 + \frac{\text{capture}}{\text{fission}}\right)\text{fission rate} = (1+\alpha)\,\text{fission rate}$$

Summary: Fission Rate → Burnup Rate

Absorption Rate → Consumption Rate

Consumption Rate = (1+α)Burnup Rate etc.

Lesson 2 Summary

In this Lesson we have discussed the following topics:

The basics of the fission chain reaction.

The key products of the fission process.

How to compute the approximate uranium requirements needed to produce a given amount of energy.

The energy density associated with nuclear vs. fossil fuels.

The general neutron life cycle in a thermal reactor.

The neutron multiplication factor.

The meaning of the terms critical, supercritical, and subcritical within the context of a global neutron balance equation and the production and loss rates in the system.

Lesson 2 Summary (cont.)

The basics of power level and criticality control.

Several important terms such as reactivity, enrichment, capture-to-fission ratio, burnup and consumption rates, conversion ratio, etc.