Key Points of *Introduction to Nuclear Engineering*

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October 28, 2023，Xi'an Jiaotong University

ABSTRACT

I am an idiot.

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Nuclear Engineering

1.1 | Introduction

Nuclear engineering is an endeavor that makes use of radiation and radioactive material for the benefit of mankind.

- $E = mc^2$ *Einstein*, theoretical basis
- Chicago Pile 1 *Fermi*, the first nuclear reactor
- EBR-I *USA*, the first nuclear reactor to produce electricity
- Obninsk *USSR*, The first nuclear reactor for commercial power generation
- Shipping Port *USA*, The first large-scale nuclear power plant
- Three-Mile-Island *USA*, Level-5
- Chernobyl *USSR*, Level-7
- Fukushima *Japan*, Level-7

Chinese percentage of electricity from nuclear power is 5.02% in 2021.

Nuclear energy is a thousand-year energy resource.

1.2 | Nuclear Reactor

A nuclear reactor is an engineering device, in which nuclear fuel and structural materials are arranged such that a self-sustained fission chain reaction can occur in a controlled manner.

The nuclear energy (in the form of kinetic energy of fission fragments, neutrons and gamma rays) released during chain reaction is to be utilized.

In a reactor, neutrons are produced by fission and lost through capture and leakage.

Usually, we remove the heat generated in the reactor core through

1) Heat conduction
2) Heat convection
3) Heat radiation(Negligible)

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Nuclear Reactors and Nuclear Power

2.1 | The Fission Chain Reactions

Neutrons emitted by fissioning nuclei induce fissions in other fissile or fissionable nuclei; the neutrons from these fissions induce fissions in still other fissile or fissionable nuclei; and so on.

Definition 2.1 | The effective multiplication factor is defined as

$$k_{\text{eff}} = \frac{\text{number of fissions in one generation}}{\text{number of fissions in preceding generation}} = \frac{\text{neutron production rate}}{\text{neutron loss rate(absorption + leakage)}} \tag{2.1}$$

$\square$

About k_{eff},

$$k_{\text{eff}} \begin{cases} > 1 & \text{Supercritical, the number of fissions and energy increases with time.} \\ = 1 & \text{Critical, fissions at a constant rate, energy is released at a steady level.} \\ < 1 & \text{Subcritical, the number of fissions and energy decreases with time.} \end{cases} \tag{2.2}$$

2.2 | Nuclear Reactor Fuels

Definition 2.2 | Reproduction Factor (or Number of effective fission neutrons) is defined as the number of fission neutrons produced per absorption by a fissile or fissionable nucleus in the fuel, which is denoted by the symbol η (energy dependent). $\square$

Fact 2.3 | Nuclides that can be induced to fission ($\eta > 1$) by neutrons of any incident energy are called *Fissile Nuclides*, such as ^{233}U, ^{235}U, ^{239}Pu. However, for the *Fissionable Nuclides*, only neutrons with much higher incident energies could guarantee that the $\eta > 1$ (fission thresholds). $\square$

In nature, only one fissile nuclide, ^{235}U, is found. Its natural isotopic abundance is 0.72%.

Conversion & Breeding

It is possible to manufacture certain fissile isotopes from abundant nonfissile material, a process known as *Conversion*.

$$^{232}\text{Th} \longrightarrow {}^{233}\text{U} \tag{2.3}$$

$$^{238}\text{U} \longrightarrow {}^{239}\text{Pu} \tag{2.4}$$

Definition 2.4 | The average number of fissile atoms produced in a reactor per fissile fuel atom consumed is called *Conversion Ratio*, which is denoted by the symbol C, when $C > 1$, it is called *Breeding Ratio*. □

About C,

$$C \begin{cases} > 1 & \text{Breeder, more than one fissile atom is produced for every fissile atom consumed.} \\ < 1 & \text{Converter, reactors that convert but do not breed.} \\ = 0 & \text{Burner, reactors that neither convert nor breed but simply consume fuel.} \end{cases} \tag{2.5}$$

- Conversion, $\eta > 1$;
- Breeding, $\eta > 2$.

For ^{233}U, ^{235}U and ^{239}Pu, above about 100 keV, η rises to values substantially above 2, reactors that can produce such high-energy neutrons ($E > 100\,\text{keV}$) are called *Fast Reactors*.

Definition 2.5 | The net increase in the number of fissile atoms in a reactor per fuel atom consumed is called *Breeding gain*, which is denoted by the symbol G. Obviously, $G = C - 1$. □

Breeding is also described in terms of *Doubling Time*.

Definition 2.6 | The hypothetical time interval during which the amount of fissile material in a reactor doubles, there are *The Linear Doubling Time*, t_{Dl} and *The Exponential Doubling Time*, t_{De}. □

$$m_0 + GwP_0 \cdot t_{Dl} = 2m_0 \Rightarrow t_{Dl} = \frac{m_0}{GwP_0} \tag{2.6}$$

$$\frac{\mathrm{d}m}{\mathrm{d}t} = GwP = Gw\beta m \Rightarrow t_{De} = \frac{m_0 \ln 2}{GwP_0} \tag{2.7}$$

$$t_{De} = t_{Dl} \ln 2 \quad (\text{Since} P_0, m_0) \tag{2.8}$$

- t_{Dl} ⇔ New fuel continually is extracted and used for further breeding (More commonly);
- t_{De} ⇔ New fuel left in reactor.

The actual doubling time is greater than computed doubling time (Removed, Chemically Separated and Fabricated were omitted).

Definition 2.7 | The total energy released in fission by a given amount of nuclear fuel is called the *Fuel Burnup* (MWd). □

Definition 2.8 | The fission energy released per unit mass of the fuel is termed the *Specific Burnup* (MWd/t). □

Definition 2.9 | (Fractional burnup) The equation form is

$$\beta = \frac{\text{number of fissions}}{\text{initial number of heavy atoms}} \tag{2.9}$$

□

2.3 | Non-Nuclear Components of Nuclear Power Plants

Two main ways to circumvent the droplets problem (excessive erosion of the blades and hence to reduce turbine lifetime) :

- By superheating the steam before it enters a turbine;
- By removing the wet steam from the turbine when the water content has reached a specified level (moistture separator).

Definition 2.10 | The overall efficiency of a nuclear power plant is defined as

$$\mathrm{eff} = \frac{W}{Q_R} \approx 1 - \frac{Q_C}{Q_R} \tag{2.10}$$

□

2.4 | Components of Nuclear Reactors

Moderator, Coolant, Blanket, Reflector, Control Rods, Pressure Vessel.

2.5 | Power Reactors & Nuclear Steam Supply System(NSSS)

PWR

Pressure Vessel

- inlet ≈ 290 °C
- inside ≈ 15 MPa
- outlet ≈ 325 °C

At this pressure, the water will not boil, at least not to any great extent.

U-tube Steam Generator

Steam ≈ 293 °C, 5 MPa.

This gives an overall efficiency of between 32% or 33% for a PWR plant.

Pressurizer

- top pressure-actuated spray nozzle
- bottom pressure-actuated immersion-type heaters

Fuel

Uranium dioxide (abundance ≈ 2% – 5%), small cylindrical pellets.

Zircaloy-4 fuel tubes,

1) Provide mechanical support
2) Prevent the escape to the passing coolant of fission products, especially fission product gases.

Loading Pattern: Out-In and low-leakage.

BWR

- Steam generators in separate heat transfer loops are required for a PWR, while they are in the same loops for a BWR.
- Control rods are always placed at the bottom of the reactor in a BWR.

> **Tip**
>
> The coolant at the bottom of core has low steam content, high reactivity and high power density, and the control rods insert from the bottom of core can make the axial power distribution even.

- Less water must be pumped through a BWR per unit time than through a PWR for the same power output.

> **Tip**
>
> There is two-phase water in BWR, and no heat transfer loss between the first and second loops, the average enthalpy value of water is higher, when the heat power is constant, the high-enthalpy-value fluid needs lower mass flow.

- The pressure in a BWR is approximately 7 MPa (about one-half the pressure in a PWR).

CANDU

- Pressure-Tube type
- Heavy water as moderator and coolant
- Nature Uranium
- On-line refueling

LMFBR

Loop Type and Pool Type.

Others

VHTR, MSR, SFR, SCWR, GFR, LFR.

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Nuclear Reactor Theory

3.1 | One-Group Reactor Equation

$$D\nabla^2\phi - \Sigma_a\phi + S = \frac{1}{v}\frac{\partial\phi}{\partial t} \tag{3.1}$$

Since, $S = k_\infty\Sigma_a\phi$, use multiplication factor k_{eff} to balance the equation, time-independent neutron diffusion equation is

$$D\nabla^2\phi - \Sigma_a\phi + \frac{k_\infty}{k_{\text{eff}}}\Sigma_a\phi = 0 \tag{3.2}$$

The form is Helmholtz equation,

$$\nabla^2\phi + B^2\phi = 0 \tag{3.3}$$

the solution depends on the shape of the reactor.

When the reactor is critical, $k_{\text{eff}} = 1$, by equation 3.2 and 3.3, we have *Material Buckling*

$$B^2 = \frac{k_\infty - 1}{L^2} = B_m^2 \tag{3.4}$$

At any time, *Geometric Buckling* equals to Material Buckling,

$$B_g^2 = B_m^2 \tag{3.5}$$

must be satisfied for the reactor to be critical.

Alternative expression of critical equation is

$$\frac{k_\infty}{1 + L^2 B_g^2} = 1 \tag{3.6}$$

Modified: $L^2 \longrightarrow M^2 = L^2 + \tau$.

3.2 | Thermal Reactors

Definition 3.1 | (Thermal Reactor) A nuclear reactor with a large fission rate by thermal neutrons. ☐

Six quantities

1) The fast fission factor

$$\varepsilon = \frac{\text{number of fast neutrons}}{\text{number of fast neutrons produced by thermal fissions}} \tag{3.7}$$

2) The fast non-leakage probability
   P_s is the fraction of the fast neutrons that do not leak from the reactor.
3) The resonance escape probability
   p is the fraction of neutrons that pass through the resonance region without being absorbed.
4) The thermal non-leakage probability
   P_t is fraction of the thermal neutrons that do not leak from the reactor.
5) The thermal utilization factor

$$f = \frac{\text{number of neutrons absorbed in the fuel}}{\text{total number of thermal neutrons absorbed}} \tag{3.8}$$

6) The number of effective fission neutrons

$$\eta = \frac{\text{average number of fission neutrons released}}{\text{number of neutrons absorbed in the fuel}} \tag{3.9}$$

$$k_{\text{eff}} = \varepsilon p f \eta P_s P_t = k_\infty P_L \tag{3.10}$$

3.3 | Reflected Reactors

Reflector

- Flatten the radial neutrons flux density distribution
- Improve core edge fuel efficiency
- Reduce neutrons leakage and critical core radius
- Usually use the same material as the moderator

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Nuclear Fuel Cycle

4.1 | The Nuclear Fuel Cycle

Definition 4.1 | The nuclear fuel cycle, also called nuclear fuel chain, is the progression of nuclear fuel through a series of differing stages.

- FRONT END: the preparation of the fuel
- BACK END: safely manage, contain, and either reprocess or dispose of spent nuclear fuel

- not reprocessed: *Open Fuel Cycle*
- reprocessed: *Closed Fuel Cycle*

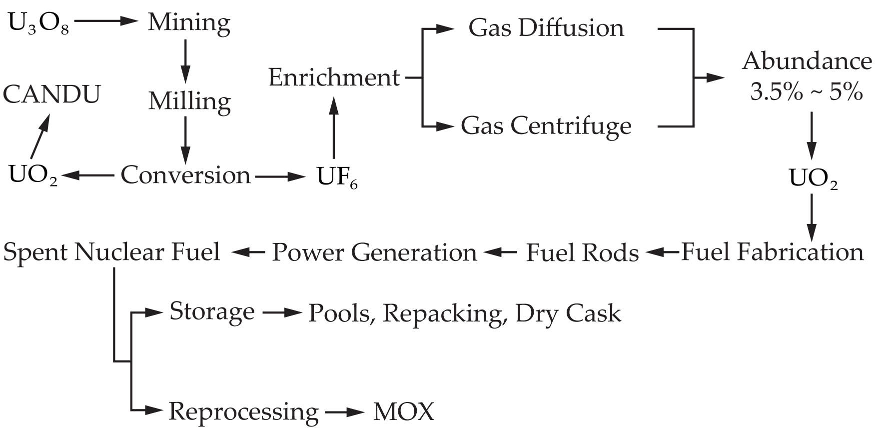

Figure 1: The Nuclear Fuel Cycle

4.2 | Isotope Separation

Definition 4.2 | Isotope separation is the process of concentrating specific isotopes of a chemical element by removing other isotopes.

Isotope separation method:

- Gas diffusion
- Gas centrifuge

- Aerodynamic processes
- Laser techniques
- Chemical methods
- Plasma separation process
- Thermal diffusion method

Gas diffusion

When mixed gas reached the thermodynamic balance. The $^{235}UF_6$ and $^{238}UF_6$ have the same average kinetic energy but different velocity (**Semi-Permeable Membranes, Micropores**).

Conditions:

1) Low pressure
2) Keep aperture small

The process is easy but economics is low.

Gas centrifuge

The gas centrifuge process uses a large number of rotating cylinders in series and parallel formations.

High efficiency, Very economic, but highly depend on the strength of material.

Others

- Aerodynamic processes: Gas mixture expand through the slit nozzle, different centrifugal forces to partially separate isotopes
- Laser techniques: Selective excitation of isotopic atoms or isotopic containing compound molecules by a laser beam (Low cost but low efficiency)
- Chemical methods: The isotopic distribution in each reaction molecule is not equal probability during the isotopic chemical exchange reaction
- Plasma separation process: Plasma rotation and ion cyclotron resonance in the electromagnetic field
- Thermal diffusion method: When there is a temperature gradient in a homogeneous mixture of gases or liquids, the light components will be concentrated in hot regions and the heavy components will be concentrated in cold regions

4.3 | Nuclear Fuel Reprocessing

Fuel Reprocessing & Radioactive Waste Disposal

- 😊: Recover fissile material for energy extraction
- 😅: Economic disadvantage and political risks

Fuel Reprocessing

- Solvent extraction
- Plutonium and Uranium Recovery by Extraction, *PUREX*

Radioactive Waste Disposal

- High-level waste
  - Without reprocessing: place in suitable containers and bury in some stable geological settings

  - Be reprocessed: liquid form can be made into glass or surround beads of waste with layers of ceramic, then place in suitable containers and bury
- Transuranic (TRU) waste
- Low-level waste
  - Place in drums and shipped off-site to waste depositories
- Mine and mill tailings

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Heat Removal from Reactor

5.1 | General Thermodynamics Considerations

Design Principles

1) Fuel maximum temperature < its melting temperature at corresponding burn-up (2200 – 2450°C)
2) No boiling crisis (MDNBR > 1.3)
3) Sufficient cooling
4) No flow instability

Nuclear Limits

1) Hot spot factor
   - Peak power in pin
   - Prevent fuel melting
2) Hot channel factor
   - Assure heat removal from pin
   - MDNBR: Minimum Departure from Nucleate Boiling Ratio
3) Design considerations
   - Limits on power
   - Materials

Heat Removing

- Fuel pin power production
  - Heat conduction
  - Fourier law
  - Poisson's equation
- Gap to clad: Heat conduction
- Clad heat transfer: Poisson's equation (no heat source)
- Clad to coolant: Newton's law of cooling

When heat is added to a substance at constant pressure, essentially all of the heat is used to increase its enthalpy.

5.2 | Heat Generation in Reactors

Energy Released in Fission

For the fission of ^{235}U,

- More than 90% of the recoverable fission energy deposited in the fuel rods
- About 5% deposited in the moderator

- Less than 5% deposited in the blanket, reflector, and shield

Power Distribution

According to the *Uniform Bare Pile* hypothesis, the heat release rate per unit volume is a cosine function distribution in axial direction and a zero-order Bessel function distribution in radial direction.

Fission Products Decay Heating

- About 7% of the total thermal power output of the reactor
- Due to the Fission Products decaying heat, a means for cooling the reactor core after shutdown must be provided in all reactors

5.3 | Heat Conduction

Definition 5.1 | Heat is transmitted from one location in a body to another as a result of a temperature difference existing in body (there is no macroscopic movement of any portion of body). □

Differential equation of heat conduction:

$$\rho c_p \frac{\partial t}{\partial \tau} = \nabla \cdot \kappa \nabla t + q_v \tag{5.1}$$

5.4 | Heat Transfer to Coolant

Definition 5.2 | Heat is transferred to a moving liquid or gas, as the result of a temperature difference as well. □

Newton's law of cooling:

$$q = h\Delta t \tag{5.2}$$

Influent factors of h:

- Cause of flow
- Phase transition of fluid
- The flow state of a fluid (Laminar or Turbulent Flow)
- Geometric factor
- Nature of the coolant fluid

Most of the heat produced in the fuel flows directly to the coolant in a direction normal to the axis of the fuel rod.

Equivalent Diameter

$$D_{\mathrm{e}} = \frac{4A}{P_w} = \frac{4 \times \text{cross-sectional area of coolant channel}}{\text{wetted perimeter of coolant channel}} \tag{5.3}$$

For liquid metals, it is strikingly different from ordinary coolants,

1) High thermal conductivity

$$\kappa_{\mathrm{Na}} = 122\kappa_{\mathrm{H_2O}} \tag{5.4}$$

2) Heat conduction dominates heat transfer even in turbulent flow

5.5 | Boiling Heat Transfer

Distinct advantages

1) The coolant pressure is much lower
2) Require lower cladding and fuel temperature for a given flow rate and heat flux

TIP

PWR permits boiling of restricted nature.

Boiling Heat Transfer Curve of Large Volume

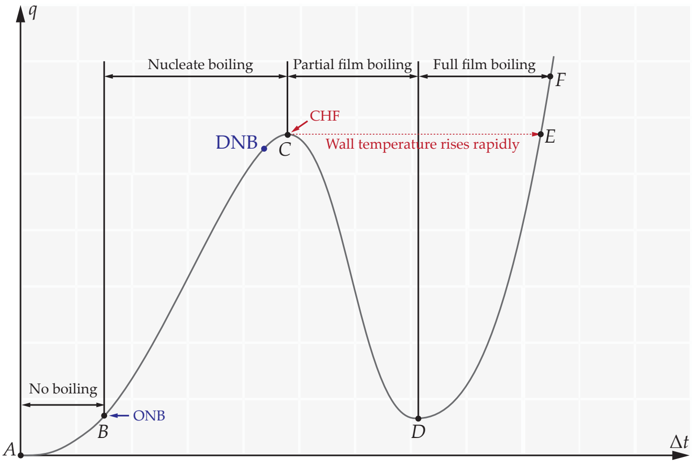

Figure 2: Boiling Heat Transfer Curve of Large Volume78694532

5.6 | Thermal Design of a Reactor

1) Determine the thermal parameters
2) Fuel rod parameters
3) compute Δp, MDNBR, t and so on
4) Technical and economic evaluation
5) Thermal and hydraulic experiment