2019 Basic Nuclear Engineering I Lecture note (4)

- Nuclear fission chain reaction -

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4. Criticality of Nuclear Reactor

4.1 Concept of critical condition of nuclear reactor

Life of neutrons in nuclear reactor

Generation: Born by nuclear fission, scattered with nuclei,

absorbed by nuclei or leak from the reactor

↓ Some of them cause the next fission

The next Generation: Born by nuclear fission, scattered with nuclei,

absorbed by nuclei or leak out

・Multiplication factor (k)

$$k = \frac{\text{(Number of neutrons in a generation)}}{\text{(Number of neutrons in the previous generation)}}$$

$$= \frac{\text{(Number of fission in a generation)}}{\text{(Number of fissions in the previous generation)}}$$

$k = 1$ Critical condition … Number of neutrons in the reactor is constant.

= Reactor power constant

$k > 1$ Supercritical condition … Number of neutrons in a generation

→ increases exponentially

$k < 1$ Subcritical condition … Number of neutrons in a generation

→ decreases exponentially

・Reactivity ρ

Definition $\rho = \dfrac{k - 1}{k}$

Supercritical	$k > 1$	$\rho > 0$
Critical	$k = 1$	$\rho = 0$
Subcritical	$k < 1$	$\rho < 0$

Positive reactivity … Reactor power increases

└ produced energy by fission per unit time

Negative reactivity … Reactor power decrease

・Criticality accident

… The accident that nuclear fuels in storage or in nuclear reactor become supercritical condition accidentally.

If the positive reactivity is large, rapid power increase can occur.

4.2 Prompt neutrons and delayed neutrons

・ Fission neutrons { Prompt neutrons / Delayed neutrons }

Prompt neutrons … Most of the fission neutrons emitted when the fission occurs.

Delayed neutrons … Some fission products (Light nuclei created by fission) emit neutrons after the β-decay.

The emission is delayed by the β-decay.

(Several hundred milliseconds ～ a few minutes)

・Delayed neutron fraction β of fission neutrons

^{235}U	0.64%	The fraction is small.
^{238}U	1.5%	But !! it is important to control
^{239}Pu	0.20%	the fission chain reaction.

・Prompt neutron life time

Life time of a prompt neutron

Fast reactors: $10^{-7} \sim 10^{-6}$ s

Thermal reactors: $10^{-4} \sim 10^{-3}$ s

⇒ Very short

・If all of the fission neutrons are prompt neutrons,

Ex. Assumption

Prompt neutron life time $l = 10^{-4}$s

Time of one generation = Prompt neutron life time

The number of generations in one second

$= 10^4$ generations

If the multiplication factor is $k = 1.001$

$$(1.001)^{10^4} \simeq 22{,}000$$

The reactor power becomes about 20,000 times in one second.

Small deviation from the critical condition results in the rapid increase of the reactor power ⇒ The control is impossible.

Existence of delayed neutrons

⇒ Make the reactor control possible

In general — Fission chain reaction is maintained by both prompt neutrons and delayed neutrons

$\underline{0 < \rho < \beta}$: Slow increase of the reactor power (Normal operating condition)

$\underline{\beta \leqq \rho}$: Rapid increase of the reactor power (Experimental reactor, criticality accident)

Fission chain reaction is possible by prompt neutrons only.

4.3 Control rod

Control rod … A material with large neutron capture cross section is inserted or pulled out by a remote system.

⇒ Control the multiplication factor

Usually partially inserted in the reactor core

· Change of reactor power by control rods

Critical condition → Pull out the control rods

→ Decrease of neutron captures by the control rods

→ Positive reactivity (supercritical)

→ Reactor power increase

→ Insert the control rods

→ Increase of neutron captures by the control rods

→ Negative reactivity (subcritical)

→ Reactor power decrease

· Materials which are used in the control rods

boron, cadmium, hafnium