Nuclear Theory - Course 127

REVIEW OF TERMS

So far in this course, consideration has been given to a reactor which is only just critical and the conditions under which this criticality can be achieved. The discussions have been centred around the conditions under which a chain reaction can just be maintained and the contributions made to these conditions by the moderator, reflector and fuel arrangement. No account has been taken of the changes which take place, in a reactor, when it is operated.

For the balance of this Reactor Theory course consideration will be given to disturbances of the steady state, ie, to factors that affect the neutron balance in a reactor and the way in which they are affected. The steady state of a reactor can be disturbed by a variety of causes, which fall into the following general categories:

(a) Power changes brought about by means of the regulating or protective system.

(b) Temperature changes.

(c) Formation of voids.

(d) Build-up of fission product poisons.

(e) Changes in the content of the fuel.

Many of these changes are time dependent, which means that they vary with time in some definite manner.

This first lesson, on this section, will review the terms which will be used in the following lessons.

Neutron Density

The thermal power, (in watts or joules/sec or Btu/min or any other appropriate unit), which is produced in a reactor is directly proportional to rate of fissioning or the fissions occurring per second. Each watt of power produced requires 3.1×10^{10} fissions/sec.

If the power produced is to remain constant, the rate of fissioning must remain constant and, consequently, the total number of neutrons in the reactor must remain constant. The total number of neutrons in the reactor is referred to as the neutron population.

The number of neutrons per unit volume of the reactor is known as the neutron density. Thus, neutron density is measured in neutron/cc.

If the reactor power is steady, the average neutron density remains constant. However, the neutron density may vary from one point to another in the reactor, having its maximum value at the centre and having the same distribution as the thermal neutron flux.

Neutron Power

The thermal power in a reactor is measured from the temperatures and heat transport flow rates, ie, from the thermal energy transported from the core. However, when changes occur in the rate of fissioning, there is some delay before the temperatures settle down. Thermal power changes lag behind changes in neutron density. It is, therefore, desirable that the neutron densities be measured so that a quicker indication, of changes occurring, can be obtained.

This measurement of neutron density is made, at one point in the reactor, with ion chambers and associated equipment. The electronic equipment is usually calibrated, in percent of full power, by comparison with thermal power. This measurement of neutron density is known as NEUTRON POWER. It is an instantaneous measurement.

It must be remembered that the changes in neutron power that will be considered, are not, necessarily, the same as the changes in thermal power that result from them.

Neutron Flux

The neutron flux at a point in a reactor has been defined as the product of the neutron density (n) and the average neutron velocity (v).

ie, $\phi = nv$ ....(1)

Alternatively, the rate at which a particular neutron reaction occurs may be used to define the flux from:

Number of reactions/cc/sec = $\phi \Sigma$ ....(2)

where ϕ is the neutron flux and Σ the macroscopic cross section for that particular reaction.

Thus, the higher the neutron flux, at a point in a reactor, the higher the rate of fissioning, the higher the power produced and the higher the neutron density at that point.

Criticality

Criticality is the reactor state attained when a chain reaction is just being maintained and the power remains constant, ie, the reactor is just critical.

When neutron losses are reduced, so that more neutrons are available for fission than are required just to maintain the chain reaction, then there is neutron multiplication. The power increases and the reactor is said to be supercritical.

When not enough neutrons are available for fission and the chain reaction cannot be maintained, then the power decreases and the reactor is subcritical.

The Multiplication Factor

The multiplication factor, k, is defined as the ratio of the number of neutrons in any one generation to the number of neutrons in the immediately preceding generation.

There are two multiplication factors. The multiplication factor k_∞ is the multiplication factor assuming no leakage, ie, the multiplication factor of a reactor system of infinite size. k_∞ is given by the four factor formula:

$$k_\infty = \eta \epsilon p f \qquad (3)$$

A more practical multiplication factor is k-effective or k_e, which is the multiplication factor of the actual reactor, allowing for leakage.

$$k_e = k_\infty - \text{leakage} \qquad (4)$$

$$k_e = k_\infty - M^2 \left\{ \frac{(2.405)^2}{R_e^2} + \frac{\pi^2}{L_e^2} \right\}$$ for a cylindrical reactor

of extrapolated radius R_e and extrapolated length L_e.

Hence the product $\frac{M^2 (2.405)^2}{R_e^2}$ represents the radial leakage

and the product $\frac{M^2 \pi^2}{L_e^2}$ represents the axial leakage out

of the reactor.

Reactivity

The quantity (k_e - 1) is a measure of how far a reactor is from being just critical. It is, therefore, a quantity which is more significant than k_e itself, particularly where reactor regulation is involved. The REACTIVITY of a reactor is also a measure of how far the reactor is from being just critical. The reactivity, denoted by δk or ρ, is defined in some texts by the equation:

$$\delta k = \rho = \frac{k_e - 1}{k_e} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

and is therefore the fractional deviation of k_e from unity.

However k_e is always close to unity and:

$$\delta k \approx k_e - 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The reactivity, as defined by equation (5), may have to be used for some calculation but, within Ontario Hydro Operations Division, the reactivity will normally be taken as k_e - 1, unless otherwise specified.

When the reactor is just critical	$\delta k = 0$
When the reactor is supercritical	δk is positive
When the reactor is subcritical	δk is negative

Reactivity is normally measured in MILLI-K or one-thousandth of k (0.001 k).

Thus if k = 1.007, δk = 7 milli-k (7 mk).

The reactor is then said to be 7 mk over critical or to have 7 mk positive reactivity.

When k = 0.995, δk = -5 mk

The reactor is then 5 mk subcritical and has 5 mk of negative reactivity.

Neutron Lifetime

The average time between successive neutron generations, in a reactor, is defined as the NEUTRON LIFETIME, $\mathcal{L}$.

The neutron lifetime of prompt neutrons is determined by the time for fissioning, the slowing down time of the fast neutrons and the time taken by the thermalized neutron to be captured (ie, its diffusion time). The lifetime is almost entirely determined by the diffusion time and is about 10^{-3} sec in D_2O moderated natural uranium reactors.

The delayed neutron lifetime is determined by the half-life of its precursor or the fission product from which it originates. Delayed neutron lifetimes vary from 0.07 sec to 80 sec.

Reactor Period

The simplest definition of reactor period is the time required for a reactor to change its neutron density or its power by a factor e (the exponential e = 2.716).

When the reactor is operating at a fixed power level, the period is infinite. A reactor has a finite, measurable period only when its power is changing.

The reactor instrumentation does not measure period directly, but rather the inverse of the period (1/T). It will be shown later that the inverse of the period is equal to the rate of change of the logarithm of neutron power, a quantity which is called the RATE LOG.

$$\text{ie, rate log} = \frac{d\,(\log P)}{dt} = \frac{1}{T}$$

Process Times

Several processes, that go on in a reactor, have already been considered and others mentioned. Each process has its own characteristic rate or time interval which are significant in the present series of lessons. The following table lists the approximate characteristic times of these processes in a D_2O moderated reactor.

	Process	Approx. Characteristic Times
(a)	Fission	10^{-14} sec
(b)	Slowing Down	10^{-4} sec
(c)	Diffusion of thermal neutrons	10^{-3} sec
(d)	Delayed neutron lifetimes	0.07 sec to 80 sec
(e)	Photoneutron lifetimes	1 sec to 2 weeks
(f)	Xenon poison (growth)	10 to 11 hours
(g)	Xenon poison (decay)	14 to 20 hours
(h)	Time constants for thermal effects	few seconds to many minutes
(i)	Fission product accumulation	lifetime of the fuel

3./ Criticality – chain reaction is just being maintained + power level is constant
critical – $\delta k = 0$
supercritical – δk +ve
subcritical – δk −ve

ASSIGNMENT

1. Define neutron density. *no. of neutrons / unit volume n/cm³.*

2. (a) Explain the difference between thermal and neutron power. *measure of neutron density* *Δ temp X flowrate (ΔT·F)*

   (b) What is the advantage of measuring neutron power over thermal power? *neutron power measurements are instantaneous T.P. ∝ N.P. thermal power changes need time to adjust*

3. Define the term "criticality" and explain the terms "critical", "supercritical" and "subcritical".

4. (a) Define the neutron multiplication factor, k. *# neutrons in one gen / # of neutrons in previous gen.*

   (b) In terms of k_e, when is the reactor

   (1) just critical? *$k_e = 0$*

   (2) supercritical? *k_e +ve*

   (3) subcritical? *k_e −ve*

5. (a) Define the term "reactivity" and state the units in which it is measured. *fractional deviation of ke from unity milli-k.*

   (b) When k_e = 1.0075, calculate the reactivity. *$k_e = 1.0075$ $\delta k = k_e - 1.0 = 1.0075 - 1.000$ $\delta k = .0075$ or 7.5 mk 7.5 mk of positive reactivity.*

   (c) In terms of reactivity, when is the reactor

   (1) just critical? *$\delta k = 0$*

   (2) supercritical? *δk +ve*

   (3) subcritical? *δk −ve.*

6. (a) Define "neutron lifetime". *ℓ – average time between successive neutron generations.*

   (b) What is the main factor that determines the lifetime of prompt neutrons and what is the approximate value of this lifetime? *the diffusion time (time for thermalized neutron to be captured ... sec.*

   (c) What determines the lifetime of delayed neutrons and what range of values do they have?

7. (a) Define "reactor period". *time required for a reactor to change its neutron density or power by a factor e.*

   (b) What is the quantity that is normally measured instead of the period and how is it related to the period? *rate log = $\frac{d \log P}{dt} = \frac{1}{T}$*

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