Reactor Boiler and Auxiliaries - Course 133

THE FUNCTION OF A REACTOR

In a nuclear electric generating station heat energy is produced by the fissioning of nuclei, such as those of uranium, in a reactor. Thus the source of heat energy is the reactor which is, therefore, equivalent to the furnace in a fossil fired plant. As in thermal electric generating station, it is necessary to transport this energy from where it is produced to the turbine where it is changed to mechanical energy of rotation.

Consideration will be given, in this series of lessons, to the principles involved in the design of the reactor itself and the systems, such as the moderator and heat transport systems, which are associated with the reactor. Separate consideration will be given to reactor fuel, fuel handling, fuel changing, fuel storage and fuel transfer.

Review of Reactor Theory

Energy is produced in a reactor as the result of the fissioning of the nucleus of a fissile material such as Uranium-235, Uranium-238, Uranium-233 or Plutonium-239. The neutrons produced at fission are used to cause further fission and a chain reaction is thus sustained. When the chain reaction is just being maintained, as in Figure 1, the reactor is just critical, the neutron multiplication factor, $k = 1.0$ and the reactivity, $\delta k = 0$. Under these conditions the reactor power is steady.

To raise reactor power the neutron losses by leakage or radiative capture are reduced and more than one fission neutron is used to produce further fissions so that neutron multiplication occurs. k is, therefore, greater than 1.0 and the reactivity is positive. To reduce power k is reduced below 1.0 by increasing neutron losses so that δk is negative. k is only greater or less than 1.0 while the power is being increased or decreased respectively. When the desired power level is reached, k is then maintained equal to 1.0 to keep the power steady.

Fissioning of U-238 will only occur with neutron energies greater than 1.2 Mev and so U-238 is not considered as a nuclear fuel, although U-238 fissions do contribute to the power produced.

However, radiative capture of neutrons of U-238 forms U-239 which decays to Pu-239, a nuclear fuel. The nuclear fuel U-233 is formed by neutron capture in Thorium-232 and the subsequent decay of the Th-233 formed. U-238 and Th-232 are fertile materials.

Fissioning of U-233, U-235 and Pu-239 will occur with neutrons of all energies but the probability of fission occuring increases as the neutron energy decreases. This increase of fission cross-section with decrease in neutron energy occurs because the slower neutron remains in the vicinity of the nucleus for a longer period of time. Neutrons released at fission have an average energy of 2 Mev whereas the neutrons most likely to cause fission would be thermal neutrons with energies comparable to those of molecules (approximately 0.025 ev). It would, therefore, be more efficient if the fission neutrons were slowed down or moderated before being allowed to cause further fissions.

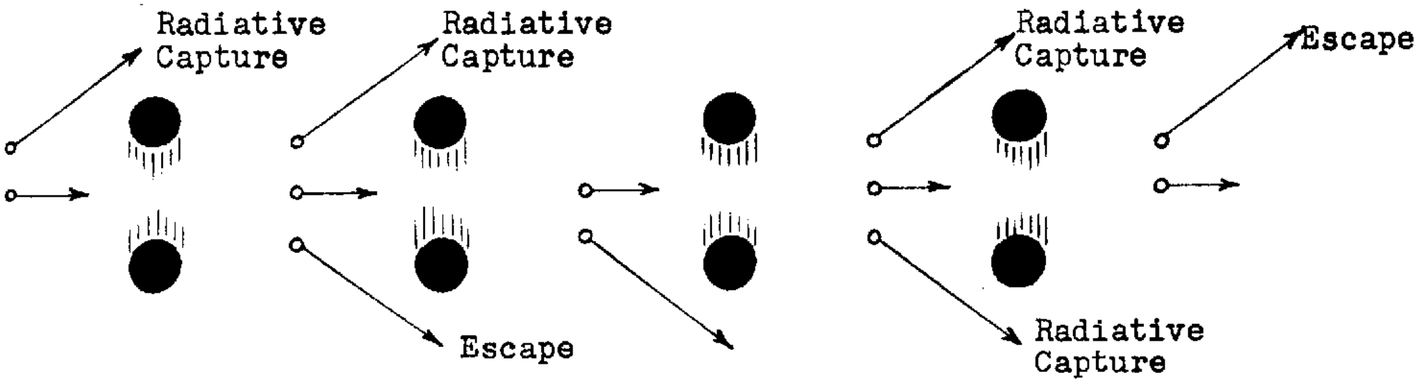

Fig. 1

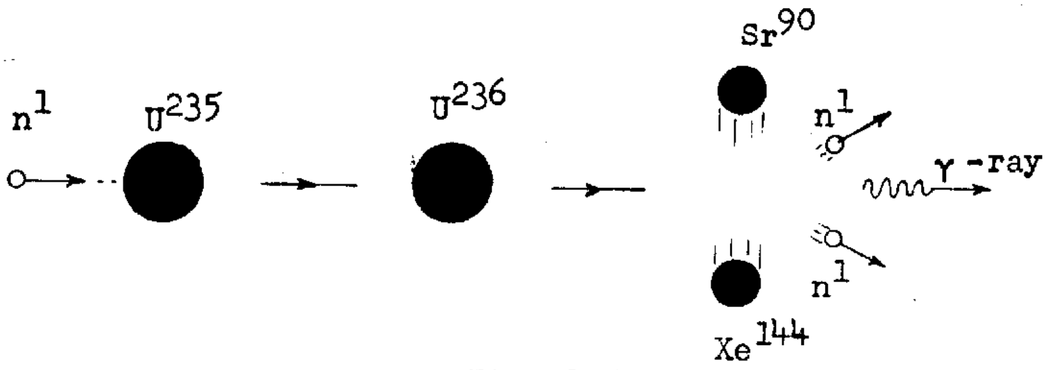

Fig. 2

As shown in Fig. 2, when fission occurs the nucleus divides into two new nuclei called fission products. These are usually unstable and decay into other nuclei, also classified as fission products. If not controlled these fission products could become a radioactive hazard to station personnel. They also absorb neutrons to a greater or lesser degree and are, therefore, known as poisons. The worst poisons that have to be considered are Xenon-135 and Samarium-149.

The Four Factor Formula

A clearer understanding of reactor design requirements and reactor classifications is possible if the factors on which k depends are considered.

k, the neutron multiplication factor is defined by:-

$$k = \frac{\text{Number of neutrons causing fission in any one generation}}{\text{Number of neutrons causing fission in the previous generation}}$$

and the reactivity $\delta k = k-1$.

Now

$$\underline{k = \eta \epsilon p f - \text{neutron leakage}}$$

this relationship being known as the four factor formula.

The neutron leakage depends on the reactor size and shape. The other terms are defined as follows:-

(a) $\underline{\eta}$ represents the number of fast neutrons produced by fission from each thermal neutron <u>captured</u> in the fuel.

It must be remembered that every neutron captured in the fuel does not cause fission since radiative capture is also possible. So η is not the number of neutrons per fission.

If γ is the number of neutrons per fission, then:-

$$\eta = \gamma \times \frac{(\text{neutron captures causing fission})}{(\text{total neutron captures in the fuel})}$$

In pure U-235 for example $\gamma = 2.48$ for thermal neutrons and the fission cross section = 577 barns whereas the radiative capture cross section is 106 barns i.e 577 out of (577+106) neutrons captured in U-235 cause fission.

$$\text{Hence } \eta = 2.48 \times \frac{577}{683} = 2.1 \text{ for thermal neutrons}$$

$$\eta = 2.46 \text{ for fast neutrons}$$

For natural uranium, containing only 0.72% U-235, $\eta = 1.32$ for thermal neutrons.

(b) ϵ, the Fast Fission Factor, is the ratio by which the fast neutron production is increased because of fast fissions in U-238. The value of ϵ is not normally more than 1.02 or 1.03 and it will, therefore, be assumed to be 1.0.

(c) p, the Resonance Escape Probability, is the fraction of neutrons which avoid resonance capture in U-238 while they are being slowed down or thermalized. If the neutrons are not thermalized $p=1$.

(d) The Thermal Utilization Factor, f, is defined as the ratio of neutrons absorbed in the fuel to the total neutrons absorbed in the reactor (i.e in fuel, sheath, structural material, heat transport fluid and moderator if present).

Basic Reactor Design Considerations

The fundamental purpose of a reactor is to continually produce heat energy by fission. It must, therefore, contain fissionable material or fuel. Sufficient fuel must be present so that a chain reaction is sustained or that the reactor is critical. The minimum requirement for this criticality is that $k=1.0$ or that:-

$$\eta \epsilon p f - \text{neutron leakage} = 1.0$$

A further objective is to obtain as much energy as possible from the fuel i.e to obtain as high a burn-up as possible. If just sufficient fuel is provided to make $k=1.0$, then as soon as a little fissile material is used k would become less than 1.0 and the reactor would become subcritical. Thus excess reactivity must be built into the reactor, by providing more fissile material in order to allow for depletion of fuel as it is used up.

As fuel is fissioned, fission product poisons accumulate which absorb neutrons. This decreases either η or f or both and this again reduces k. Hence enough excess reactivity must be available, in the reactor, to compensate for the poison build-up. Some mthod of reactor control must be available to maintain $k = 1.0$ during steady power operation, despite the excess reactivity built into the reactor and to make k greater or less than 1.0 when increase or decrease in power is required.

Suitable choice of reactor material can reduce non-fission neutron captures, increase the value of f and decreases the amount of fuel required.

A third objective which requires consideration, is the necessity of transporting the heat out of the reactor in a useful form, and therefore, at as high a temperature as possible. A heat transport system must be associated with the reactor which will transport the heat, produced in the fuel, to the boiler or turbine. As will be seen later, there are limitations on the temperature of the heat transport system.

If it is decided to thermalize the fission neutrons in order to increase the fission cross-section, a moderator must be provided, in the reactor, for this purpose. Finally the value of k could be increased by decreasing neutron leakage out of the reactor. A reflector may be used in order to decrease this leakage by reflecting neutrons back into the reactor.

Conversion and Breeding

It has been estimated that roughly 8 x 10^{19} Btu of energy are available from the known coal, oil and gas reserves in the world which can be extracted at no more than twice the present cost. At the estimated rate of consumption, these reserves would be exhausted in about 100 years.

If the U-235 fuel alone is utilized in natural uranium to produce energy an estimated 1.2 x 10^{19} Btu are available. However if all the U-238 fissile material could be used to produce Pu-239 and the Pu-239 used to produce energy by fission, then the available energy resources are estimated at 170 x 10^{19} Btu. A further 7 x 10^{19} Btu would be available if all the Th-232 could be used to produce fissile U-233.

Even if these estimates are only accurate within a factor of 2, there appears to be no immediate urgency to produce a reactor system that could utilize U-238 and Th-232 for energy production. The present requirement is the production of economic power by nuclear fission. However, unless other sources of energy are discovered, serious consideration will have to be given, in the forseeable future, to better utilization of available resources.

In nuclear physics, a reactor, in which the fissile material produced from the fertile material is the same as the fissile material consumed, is defined as a breeder reactor. For example if U-233 is used as a fuel and U-233 is also produced from Th-232, then we have a breeder. In a natural uranium reactor, U-235 is used as a fuel and Pu-239 is produced from U-238. This is a converter system. Frequently the term breeder is used loosely to describe both systems.

The effectiveness of a reactor as a breeder or converter is measured by the CONVERSION FACTOR, c. This is defined as the net production of fissile atoms per fissile atom consumed. For there to be a net gain of fissile material which could be extracted and used in another reactor, the conversion factor must be at least equal to 1.0.

An alternative definition of breeder and converter systems can be made on the basis of this conversion factor: -

A converter is a reactor system in which c is less than 1.0

A breeder is a reactor system in which c is greater than or equal to 1.0

Now η is the number of neutrons produced per neutron absorbed in the fuel and 1.0 of these neutrons must be available to cause further fissions and maintain the chain reaction. So, the maximum possible number of neutrons available for breeding or conversion is $\eta - 1$ and this disregards neutron losses by leakage and absorption in reactor material. If w is the number of neutrons lost from the system, per fission, by leakage or absorption,

$$c = \eta - w - 1$$

For good conversion η must be as large as possible and w kept as small as possible. The following table lists the value of η for fast and thermal neutrons for the three fissile materials.

	U-235	U-233	Pu-239
η for fast neutrons	2.46	2.54	2.88
η for thermal neutrons	2.08	2.31	2.03

It may be seen that, in thermal reactors using U-235 or Pu-239 as fuel, $\eta - 1$ is only just greater than 1.0 and, therefore, net breeding or conversion cannot be achieved. It is however **theoretically** possible in a thermal reactor using U-233 fuel and Th-232 as the fertile material.

In a fast reactor, on the other hand, breeding or conversion is possible with all three fissile materials and is particularly attractive with Pu-239.

Other quantities of interest when considering breeding possibilities are:-

The BREEDING RATIO defined as the ratio of the number of fissile atoms produced to the number of the same kind consumed.

The BREEDING GAIN, G, which is the number of fissile atoms gained for each one consumed, ie, the excess of the breeding ratio over unity.

The DOUBLING TIME defined as the time taken for the surplus fissile material produced to equal the total quantity in the fuel cycle.

A short doubling time means a rapid increase in the production of surplus fissile material, which is achieved by having a high breeding gain.

The conversion factor or breeding ratio also affects the fuel burnup. If the factor c is high many fissile atoms are produced while fissile atoms are consumed. These new fissile atoms could, in turn, be fissioned to produce energy and, thus, extend the life of the fuel. The higher the value of c the greater the utilization of fertile atoms.

The maximum or ultimate burnup which can be achieved in the fuel is given by:-

$$U.B. = \frac{100}{1-c} \; \% \text{ original fissile atoms}$$

If $c = 0.8$ $$U.B. = 500\% \text{ original fissile atoms} = 35{,}700 \text{ MWD/ton}$$

which means that the number of fertile atoms utilized is four times the number of fissile atoms present.

If $c = 1.0$ all the fertile atoms will be used up. However, there are other factors which limit the fuel burnup and, so, any net fissile material produced would be extracted if c was high enough to make this worth while.

ASSIGNMENT

1. What is the minimum condition for reactor criticality and what are the values of k and δk under this condition?
2. (a) Define the quantities η p and f in the four factor formula.
   (b) Express the minimum condition of reactor criticality in terms of the four factor formula.
3. Give two reasons for the fact that excess reactivity must be built into a reactor.
4. What non-nuclear objective requires consideration during the design of the reactor-boiler system?
5. What factor will necessitate the use of breeder and converter reactors in the future?
6. Explain the difference between a breeder and a converter.
7. Which reactor systems offer the best possibility of net conversion and breeding? Explain your answer.
8. How does the conversion factor or breeding ratio affect the fuel burnup?

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