Nuclear Theory - Course 227

NEUTRON BALANCE DURING STEADY REACTOR OPERATION

We have seen, in the previous lesson, what type of neutrons are produced and how they are produced in a reactor. We now take a look at this neutron population in a reactor, how this population varies, if at all, during steady power operation and the factors that can affect this neutron population. For the moment we will disregard the photo-neutrons since they form a very small fraction of the total. We will also group the prompt and delayed neutrons together and consider them both to be produced as a result of fission.

Maintaining a Chain Reaction

We have seen that the energy released during one U-235 fission is not of any practical significance and that, to produce useful power, this one fission has to be duplicated millions of times over. Fig. 1, illustrates how each individual fission releases a minute quantity of energy locally, but when millions of these small amounts of energy are all released at the same time in a small volume of uranium the total amount of energy released becomes significant.

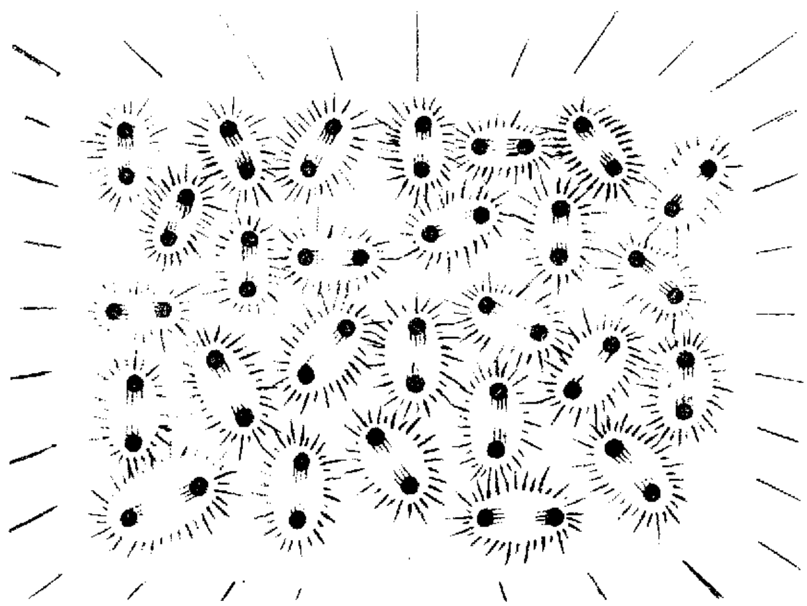

Fig. 1

The bulk of the fuel then heats up and the heat can then be used to produce useful power. It would require 3.1×10^{10} (thirty one thousand million) of these fissions to occur every second to produce 1 watt of power.

We have also seen that, to produce steady power, the fission process must be continuous. It would be of no value to have thirty thousand million fissions occurring in one second and no fissions occurring after that. The number of fissions occurring per second must remain constant second after second, day after day while the reactor is producing steady power. Such a continuous repetition of the fission process is known as a chain reaction. Such a chain reaction can be maintained if one of the neutrons, produced at fission, is used to cause a further fission.

On the average, $2\frac{1}{2}$ new neutrons are produced during each fission and one of these must be used to cause a further fission. A typical chain reaction is therefore a continuous series of fissions each one caused by a neutron from the previous one. Diagramatically a chain reaction would be as in Fig. 2. Here, one neutron from each fission is being used to cause a further fission. The other neutrons are lost by one of the following processes: -

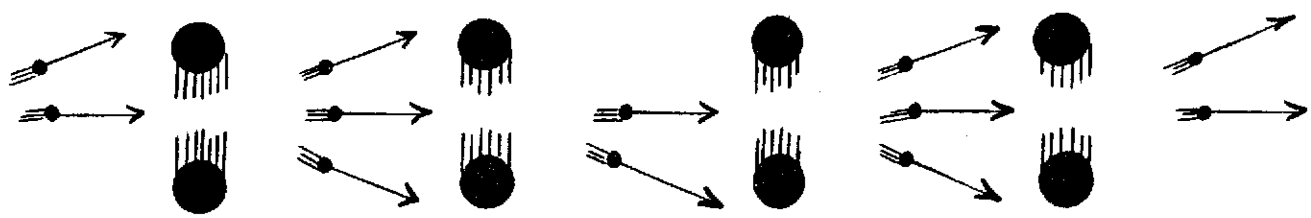

Fig. 2

(1) Capture in U-235, U-238, or the nuclei of other materials in the reactor without causing fission.

(2) Leakage or escape out of the reactor.

Non-fission captures can be reduced and fission made more likely by: -

(1) using a moderator to slow down the fission neutrons to thermal energies (0.025 ev)

(2) suitable arrangement of fuel in the reactor

(3) suitable choice of reactor material to minimize capture of neutrons.

Neutron leakage can be decreased by using a reflector around the reactor core. Let us now consider the neutron balance in more detail.

A neutron, shown in Fig. 2, may go through a typical cycle which can be described briefly as: -

Neutron Balance and a Typical Neutron Cycle

A neutron, shown in Fig. 2, may go through a typical cycle which can be described briefly as: -

Neutron born or released, as a fast neutron, at fission → Neutron slowed down in the moderator until it becomes a thermal neutron → Neutron captured by U-235 to cause fission

From each fission the only neutron that goes through this cycle is the one that maintains the chain reaction. The others are lost by some means of other during the cycle. However, it is useful to know how they are lost since the knowledge will enable losses to be reduced and will also indicate how reactor power can be regulated. We therefore consider the histories of a number of neutrons. Fig. 3 shows a typical neutron balance cycle when losses are considered. The continuous line (——>——) show what happens to the neutrons that contribute to the chain reaction whereas the dotted line (---->) show what happens to the neutrons that are lost.

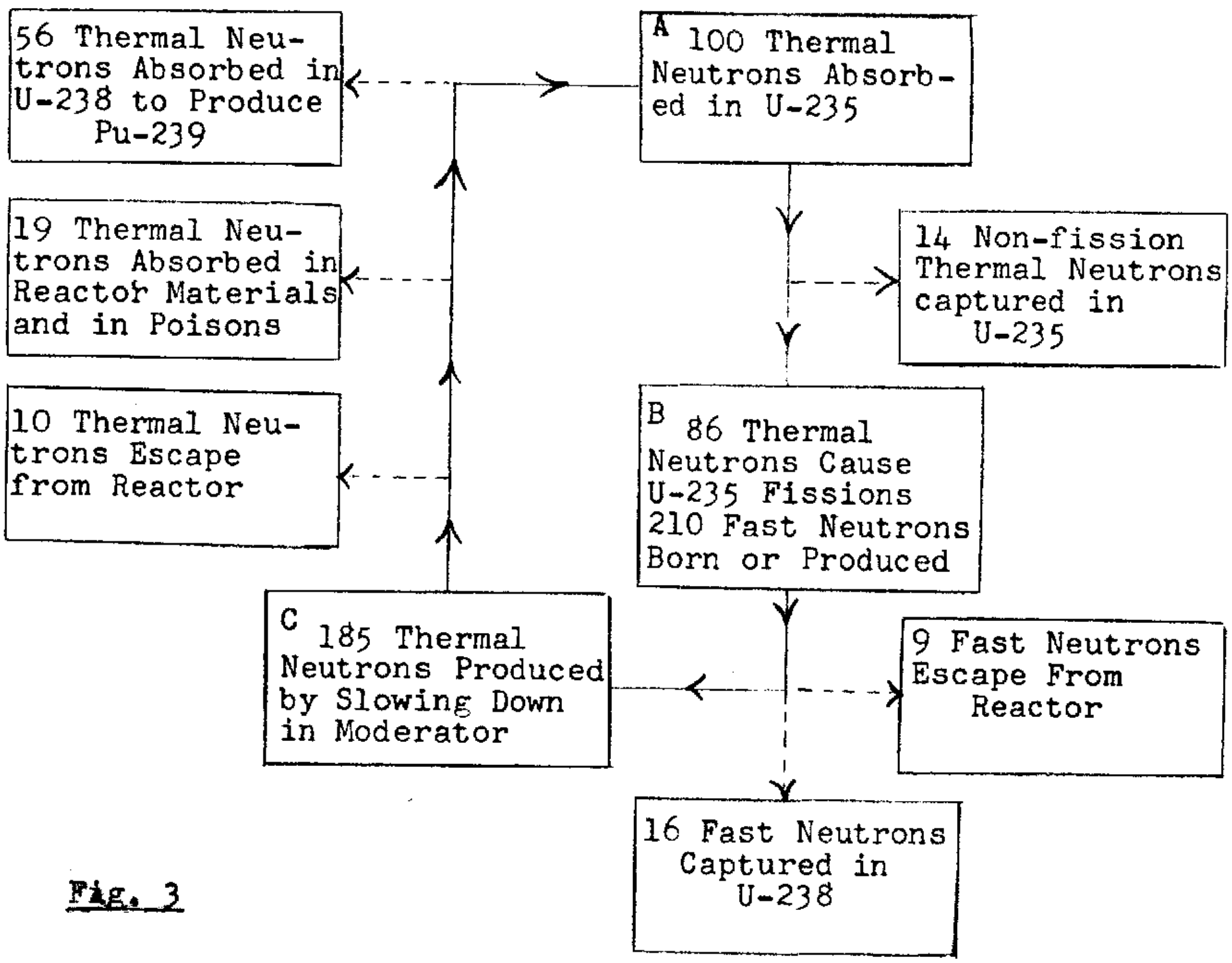

Fig. 3

The cycle can be started from any of the boxes marked A, B or C. If the cycle is to be continuous and the chain reaction just maintained (i.e. steady power operation), then, on completing the cycle back to the starting box, the same number of neutrons must appear in the box as were there at the beginning of the cycle.

For instance suppose we start at B and go around one cycle. Fig. 4 shows the same cycle in a different way and may help to follow the cycle.

86 Thermal Neutrons Cause U-235 Fissions ← First Generation

↓

210 Fast Neutrons Produced

9 Fast Neutrons Escape ← → 16 Fast Neutrons Absorbed in U-238

↓

185 Thermal Neutrons Produced

10 Thermal Neutrons Escape ← → 16 Absorbed in Reactor Material
3 Absorbed in Poisons
56 Absorbed in U-238

↓

100 Thermal Neutrons Absorbed in U-235

→ 14 Non-Fission Thermal Neutron Captures in U-235

↓

86 Thermal Neutrons Cause U-235 Fissions 2nd Generation

Fig. 4

At B, 86 thermal neutrons cause fission. These 86 fissions will be referred to as the FIRST GENERATION of neutrons. Since 2.5 fast neutrons are produced at each fission a total of 210 fast neutrons are produced. 9 of these are lost by leakage out of the reactor and 16 are lost by capture in U-238. Thus, only 185 become thermal neutrons. Before these 185 thermal neutrons can be used to cause fission, 10 of them escape and 75 are lost by non-fission captures. The remaining 100 are captured in U-235 nuclei but 14 of those captured do not cause fission. Therefore 86 fissions occur and these are referred to as the SECOND GENERATION of neutrons. At the end of a further cycle there would be a THIRD GENERATION of neutrons and so on.

If the number of fissions, in each succeeding generation remains the same, the chain reaction is just being maintained and the reactor is operating at steady power. If the number of fissions in succeeding generations decreases, because the neutron losses are greater, then the reactor power decreases and the chain reaction will eventually stop. If the number of fissions in succeeding generations increases, reactor power increases. This last condition is known as neutron MULTIPLICATION.

Factors Affecting Neutron Balance

Let us now examine how the number of neutrons, in the various boxes in the cycle, could be changed:

(1) Fast and thermal neutron leakage or escape. Neutron leakage can be decreased by increasing the size of the reactor core or by placing a reflector around the core to reflect the escaping neutrons back into the core. The reactor size is generally determined only once but a reflector is something that can be varied. Here, then, is a possible method of changing neutron leakage and therefore reactor power i e , a possible method of reactor regulation.

(2) Fast neutron capture in U-238. Since the U-238 is in the fuel, the only method of decreasing fast neutron capture in U-238 is to keep the neutrons away from the fuel while they are being slowed down. The fast neutrons, produced by fission, must be allowed to escape quickly from the fuel into the moderator and then slowed down to thermal energies before being allowed back into the fuel. This, then, is a neutron loss which can be reduced by suitable choice of moderator and fuel arrangement. The fuel arrangement is fixed in a reactor but the amount of moderator may be variable and is, again, a possible method of reactor regulation.

(3) Neutron absorption in reactor material is, of course, a loss that is kept to a minimum by suitable choice of materials. Substances with low neutron capture should be used for structural, moderator and heat transport materials, but these are basically design considerations.

(4) Neutron absorption in poisons. Poisons in a reactor may be substances which accumulate as a result of reactor operation, such as fission products, or substances deliberately introduced into the reactor to absorb neutrons. In either case the poisons are good absorbers of neutrons. Little can be done about the fission product poisons except to allow for them in the design of the reactor. However the introduction or removal of absorbers in the form of boron or cadmium rods provides another method of reactor regulation.

(5) Thermal neutron absorption in U-238. The U-238 forms 99.3% of the uranium in the fuel if natural uranium is used. Thus, if a system is committed to using natural uranium fuel, nothing can be done about thermal neutron absorption in U-238. However, absorption in U-238 can be decreased and absorption in U-235 increased by artificially increasing the U-235 content of the fuel. This is known as ENRICHMENT.

(6) Non-fission captures of thermal neutrons in U-235. The percentage of neutrons, captured by U-235, which do not cause fission does not vary except for a slight variation with temperature.

ASSIGNMENT

1. What is a chain reaction and what is the minimum condition required to maintain it?

2. (a) Starting with fast neutrons produced at fission state how they can be lost while being thermalized?

   (b) Explain briefly, the factors that would decrease these losses.

3. (a) By what methods, other than leakage, can thermalized neutrons be lost?

   (b) Which of these form the basis for reactor regulation? Explain.

   (c) Which of them can be decreased by enrichment?

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