

## PROMPT AND DELAYED NEUTRONS

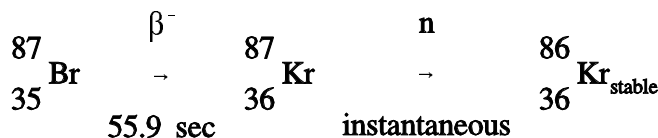
---

*Not all neutrons are released at the same time following fission. Most neutrons are released virtually instantaneously and are called prompt neutrons. A very small fraction of neutrons are released after the decay of fission products and are called delayed neutrons. Although delayed neutrons are a very small fraction of the total number of neutrons, they play an extremely important role in the control of the reactor.*

- EO 3.1**      **STATE** the origin of prompt neutrons and delayed neutrons.
- EO 3.2**      **STATE** the approximate fraction of neutrons that are born as delayed neutrons from the fission of the following nuclear fuels:
- a.      Uranium-235
  - b.      Plutonium-239
- EO 3.3**      **EXPLAIN** the mechanism for production of delayed neutrons.
- EO 3.4**      **EXPLAIN** prompt and delayed neutron generation times.
- EO 3.5**      Given prompt and delayed neutron generation times and delayed neutron fraction, **CALCULATE** the average generation time.
- EO 3.6**      **EXPLAIN** the effect of delayed neutrons on reactor control.
- 

### Neutron Classification

The great majority (over 99%) of the neutrons produced in fission are released within about  $10^{-13}$  seconds of the actual fission event. These are called *prompt neutrons*. A small portion of fission neutrons are *delayed neutrons*, which are produced for some time after the fission process has taken place. The delayed neutrons are emitted immediately following the first beta decay of a fission fragment known as a delayed neutron precursor. An example of a delayed neutron precursor is bromine-87, shown below.



For most applications, it is convenient to combine the known precursors into groups with appropriately averaged properties. These groups vary somewhat depending on the fissile material in use. Table 3 lists the characteristics for the six precursor groups resulting from thermal fission of uranium-235. The fraction of all neutrons that are produced by each of these precursors is called the delayed neutron fraction for that precursor. The total fraction of all neutrons born as delayed neutrons is called the *delayed neutron fraction* ( $\beta$ ). The fraction of delayed neutrons produced varies depending on the predominant fissile nuclide in use. The delayed neutron fractions ( $\beta$ ) for the fissile nuclides of most interest are as follows: uranium-233 (0.0026), uranium-235 (0.0065), uranium-238 (0.0148), and plutonium-239 (0.0021).

<b>TABLE 3</b>			
<b>Delayed Neutron Precursor Groups for Thermal Fission in Uranium-235</b>			
Group	Half-Life (sec)	Delayed Neutron Fraction	Average Energy (MeV)
1	55.7	0.00021	0.25
2	22.7	0.00142	0.46
3	6.2	0.00127	0.41
4	2.3	0.00257	0.45
5	0.61	0.00075	0.41
6	0.23	0.00027	-
Total	-	0.0065	-

### **Neutron Generation Time**

The neutron generation time is the time required for neutrons from one generation to cause the fissions that produce the next generation of neutrons. The generation time for prompt neutrons ( $\ell^*$  - pronounced "ell-star") is the total time from birth to rebirth. Three time intervals are involved: (a) the time it takes a fast neutron to slow down to thermal energy, (b) the time the now thermal neutron exists prior to absorption in fuel, and (c) the time required for a fissionable nucleus to emit a fast neutron after neutron absorption.

Fast neutrons slow to thermal energies or leak out of the reactor in  $10^{-4}$  seconds to  $10^{-6}$  seconds, depending on the moderator. In water moderated reactors, thermal neutrons tend to exist for about  $10^{-4}$  seconds before they are absorbed. Fission and fast neutron production following neutron absorption in a fissionable nucleus occurs in about  $10^{-13}$  seconds. Thus, fast reactors have an  $\ell^*$  of about  $10^{-6}$  seconds, while thermal reactors have an  $\ell^*$  of about  $10^{-6}$  seconds +  $10^{-4}$  seconds, which is about  $10^{-4}$  seconds to  $10^{-5}$  seconds.

On the other hand, the average generation time for the six delayed neutron groups is the total time from the birth of the fast neutron to the emission of the delayed neutron. Again, three time intervals are involved: (a) the time it takes a fast neutron to slow down to thermal energy, (b) the time the thermal neutron exists prior to absorption, and (c) the average time from neutron absorption to neutron emission by the six precursor groups. The average time for decay of precursors from uranium-235 is 12.5 seconds. The other terms in the delayed neutron generation time are insignificant when compared to this value, and the average delayed neutron generation time becomes  $\sim 12.5$  seconds.

A neutron generation time in the range of  $10^{-4}$  seconds to  $10^{-5}$  seconds or faster could result in very rapid power excursions, and control would not be possible without the dependence upon delayed neutrons to slow down the rate of the reaction. The average generation time, and hence the rate that power can rise, is determined largely by the delayed neutron generation time. The following equation shows this mathematically.

$$\mathbf{Time_{average} = Time_{prompt} (1 - \beta) + Time_{delayed} (\beta)} \quad (2-12)$$

Example:

Assume a prompt neutron generation time for a particular reactor of  $5 \times 10^{-5}$  seconds and a delayed neutron generation time of 12.5 seconds. If  $\beta$  is 0.0065, calculate the average generation time.

Solution:

$$\begin{aligned} \mathbf{Time_{average} &= Time_{prompt} (1 - \beta) + Time_{delayed} (\beta)} \\ &= (5 \times 10^{-5} \text{ seconds}) (0.9935) + (12.5 \text{ seconds}) (0.0065) \\ &= \mathbf{0.0813 \text{ seconds}} \end{aligned}$$

This example demonstrates the effect delayed neutrons have on the neutron generation time and thus reactor control. If a reactor were to be operated in a sustained chain reaction using only prompt neutrons ( $\beta = 0$ ), the generation time from the previous example would be about  $5 \times 10^{-5}$  seconds. However, by operating the reactor such that a 0.0065 fraction of neutrons are delayed, the generation life time is extended to 0.0813 seconds, providing time for adequate operator control. Therefore, although only a small fraction of the total neutron population, delayed neutrons are extremely important to the control and maintenance of a sustained fission chain reaction.

## **Summary**

The important information in this chapter is summarized on the following page.

### Prompt and Delayed Neutrons Summary

- Prompt neutrons are released directly from fission within  $10^{-13}$  seconds of the fission event.
- Delayed neutrons are released from the decay of fission products that are called delayed neutron precursors. Delayed neutron precursors are grouped according to half-life. Half-lives vary from fractions of a second to almost a minute.
- The fraction of neutrons born as delayed neutrons is different for different fuel materials. Following are values for some common fuel materials.

Uranium-235	0.0065
Plutonium-239	0.0021

- Delayed neutrons are produced by a classification of fission products known as delayed neutron precursors. When a delayed neutron precursor undergoes a  $\beta^-$  decay, it results in an excited daughter nucleus which immediately ejects a neutron. Therefore, these delayed neutrons appear with a half-life of the delayed neutron precursor.
- The delayed neutron generation time is the total time from the birth of the fast neutron to the emission of the delayed neutron in the next generation. Delayed neutron generation times are dominated by the half-life of the delayed neutron precursor. The average delayed neutron generation time is about 12.5 seconds.
- A prompt neutron generation time is the sum of the amount of time it takes a fast neutron to thermalize, the amount of time the neutron exists as a thermal neutron before it is absorbed, and the amount of time between a fissionable nuclide absorbing a neutron and fission neutrons being released. Prompt neutron generation time is about  $5 \times 10^{-5}$  seconds.
- The average neutron generation time can be calculated from the prompt and delayed neutron generation times and the delayed neutron fraction using Equation (2-12).

$$\text{Time}_{\text{average}} = \text{Time}_{\text{prompt}} (1 - \beta) + \text{Time}_{\text{delayed}} (\beta)$$

- Delayed neutrons are responsible for the ability to control the rate at which power can rise in a reactor. If only prompt neutrons existed, reactor control would not be possible due to the rapid power changes.