

## NEUTRON SOURCES

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*Neutrons from a variety of sources are always present in a reactor core. This is true even when the reactor is shut down. Some of these neutrons are produced by naturally occurring (intrinsic) neutron sources, while others may be the result of fabricated (installed) neutron sources that are incorporated into the design of the reactor. The neutrons produced by sources other than neutron-induced fission are often grouped together and classified as source neutrons.*

**EO 1.1**      **DEFINE the following terms:**

- a.      **Intrinsic neutron source**
- b.      **Installed neutron source**

**EO 1.2**      **LIST three examples of reactions that produce neutrons in intrinsic neutron sources.**

**EO 1.3**      **LIST three examples of reactions that produce neutrons in installed neutron sources.**

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### Neutron Sources

In addition to neutron-induced fission, neutrons are produced by other reactions. The neutrons produced by reactions other than neutron-induced fission are called *source* neutrons. Source neutrons are important because they ensure that the neutron population remains high enough to allow a visible indication of neutron level on the most sensitive monitoring instruments while the reactor is shutdown and during the startup sequence. This verifies instrument operability and allows monitoring of neutron population changes. Source neutrons can be classified as either intrinsic or installed neutron sources.

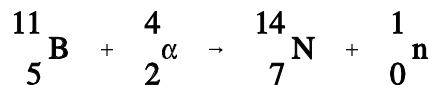
### Intrinsic Neutron Sources

Some neutrons will be produced in the materials present in the reactor due to a variety of unavoidable reactions that occur because of the nature of these materials. *Intrinsic neutron sources* are those neutron-producing reactions that always occur in reactor materials.

A limited number of neutrons will always be present, even in a reactor core that has never been operated, due to spontaneous fission of some heavy nuclides that are present in the fuel. Uranium-238, uranium-235, and plutonium-239 undergo spontaneous fission to a limited extent. Uranium-238, for example, yields almost 60 neutrons per hour per gram. Table 1 illustrates a comparison of the rate at which different heavy nuclides produce neutrons by spontaneous fission. Californium-252 is not an intrinsic neutron source, but will be discussed in the section on installed neutron sources.

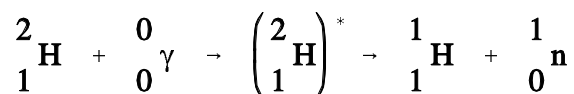
Nuclide	$T_{1/2}$ (Fission)	$T_{1/2}$ ( $\alpha$ -decay)	neutrons/sec/gram
${}^{235}_{92}\text{U}$	$1.8 \times 10^{17}$ years	$6.8 \times 10^8$ years	$8.0 \times 10^{-4}$
${}^{238}_{92}\text{U}$	$8.0 \times 10^{15}$ years	$4.5 \times 10^9$ years	$1.6 \times 10^{-2}$
${}^{239}_{94}\text{Pu}$	$5.5 \times 10^5$ years	$2.4 \times 10^4$ years	$3.0 \times 10^{-2}$
${}^{240}_{94}\text{Pu}$	$1.2 \times 10^{11}$ years	$6.6 \times 10^3$ years	$1.0 \times 10^3$
${}^{252}_{98}\text{Cf}$	66.0 years	2.65 years	$2.3 \times 10^{12}$

Another intrinsic neutron source is a reaction involving natural boron and fuel. In some reactors, natural boron is loaded into the reactor core as a neutron absorber to improve reactor control or increase core life-time. Boron-11 (80.1% of natural boron) undergoes a reaction with the alpha particle emitted by the radioactive decay of heavy nuclides in the fuel to yield a neutron as shown below.



The boron-11 must be mixed with, or in very close proximity to, the fuel for this reaction because of the short path length of the alpha particle. For a reactor core with this configuration, this ( $\alpha, n$ ) reaction is an important source of neutrons for reactor startup.

In a reactor that has been operated, another source of neutrons becomes significant. Neutrons may be produced by the interaction of a gamma ray and a deuterium nucleus. This reaction is commonly referred to as a photoneutron reaction because it is initiated by electromagnetic radiation and results in the production of a neutron. The photoneutron reaction is shown below.



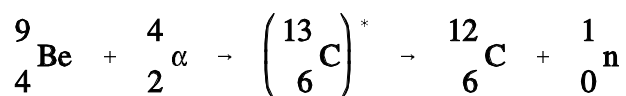
There is an abundant supply of high energy gammas in a reactor that has been operated because many of the fission products are gamma emitters. All water-cooled reactors have some deuterium present in the coolant in the reactor core because a small fraction of natural hydrogen is the isotope deuterium. The atom percentage of deuterium in the water ranges from close to the naturally occurring value (0.015%) for light water reactors to above 90% deuterium for heavy water reactors. Therefore, the required conditions for production of photoneutrons exist. The supply of gamma rays decreases with time after shutdown as the gamma emitters decay; therefore, the photoneutron production rate also decreases. In a few particular reactors, additional D<sub>2</sub>O (heavy water) may be added to the reactor to increase the production of photoneutrons following a long shutdown period.

### **Installed Neutron Sources**

Because intrinsic neutron sources can be relatively weak or dependent upon the recent power history of the reactor, many reactors have artificial sources of neutrons installed. These neutron sources ensure that shutdown neutron levels are high enough to be detected by the nuclear instruments at all times. This provides a true picture of reactor conditions and any change in these conditions. An *installed neutron source* is an assembly placed in or near the reactor for the sole purpose of producing source neutrons.

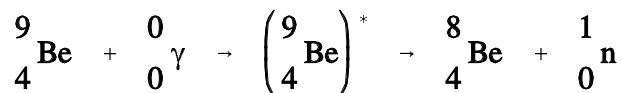
One strong source of neutrons is the artificial nuclide californium-252, which emits neutrons at the rate of about  $2 \times 10^{12}$  neutrons per second per gram as the result of spontaneous fission. Important drawbacks for some applications may be its high cost and its short half-life (2.65 years).

Many installed neutron sources use the ( $\alpha$ ,n) reaction with beryllium. These sources are composed of a mixture of metallic beryllium (100% beryllium-9) with a small quantity of an alpha particle emitter, such as a compound of radium, polonium, or plutonium. The reaction that occurs is shown below.



The beryllium is intimately (homogeneously) mixed with the alpha emitter and is usually enclosed in a stainless steel capsule.

Another type of installed neutron source that is widely used is a photoneutron source that employs the ( $\gamma$ ,n) reaction with beryllium. Beryllium is used for photoneutron sources because its stable isotope beryllium-9 has a weakly attached last neutron with a binding energy of only 1.66 MeV. Thus, a gamma ray with greater energy than 1.66 MeV can cause neutrons to be ejected by the ( $\gamma$ ,n) reaction as shown below.



Many startup sources of this type use antimony and beryllium because after activation with neutrons the radioactive antimony becomes an emitter of high energy gammas. The photoneutron sources of this type are constructed somewhat differently from the ( $\alpha$ ,n) types. One design incorporates a capsule of irradiated antimony enclosed in a beryllium sleeve. The entire assembly is then encased in a stainless steel cladding. A large reactor may have several neutron sources of this type installed within the core.

## **Summary**

The important information in this chapter is summarized below.

### **Neutron Sources Summary**

- Intrinsic neutron sources are sources of neutrons from materials that are in the reactor for other purposes such as fuel, burnable poison, or moderator.
- Installed neutron sources are materials or components placed in the reactor specifically for the purpose of producing source neutrons.
- Examples of intrinsic neutron sources are listed below.

Spontaneous fission of heavy nuclides in fuel, such as uranium-238, uranium-235, and plutonium-239, results in fission fragments and free neutrons.

Boron-11 mixed with the fuel undergoes an alpha-neutron reaction and becomes nitrogen-14.

Deuterium present in the reactor coolant undergoes a gamma-neutron reaction and becomes hydrogen-1.

- Examples of installed neutron sources are listed below.

Spontaneous fission of californium-252 results in fission fragments and free neutrons.

Beryllium-9 undergoes an alpha-neutron reaction (alpha from the decay of plutonium, polonium, or radium) and becomes carbon-12.

Beryllium-9 undergoes a gamma-neutron reaction (high energy gamma from decay of antimony-124) and becomes beryllium-8.