Nuclear Theory - Course 227

NEUTRON REACTIONS

Nuclear reactions can occur as a result of collisions between various particles or gamma photons and nuclei. Charged nuclear particles, such as protons, deuterons (deuterium or H^2) and alpha particles, need to have a large amount of energy (tens of MeV) before they are able to overcome the Coulomb repulsive forces and enter a nucleus.

Neutrons and gamma photons, however, are not charged and are therefore able to interact with nuclei very effectively, even when they have very little energy. In fact, generally speaking, there is a greater chance of a reaction occurring with low rather than high energy neutrons, because the former are in contact with the nucleus for a greater length of time.

The operation of a reactor basically depends on how neutrons react with nuclei in the reactor. It is therefore necessary to look at these reactions, called *neutron reactions*, in some detail. Although there are well over a dozen known neutron reactions, we need only consider the five that are of importance to us.

All neutron reactions can be categorized as either *elastic* or *inelastic collisions*, depending on whether kinetic energy is conserved in the collision or not.

Elastic Collisions

Elastic collisions are those in which the total kinetic energy before the collision is equal to that after the collision.

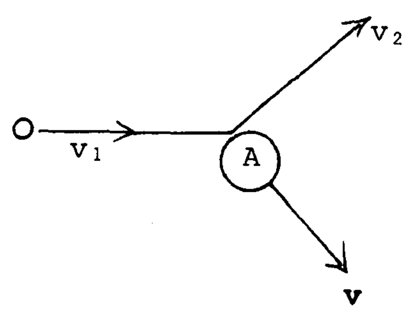

Figure 1
Elastic Collision

For example, in Figure 1 a neutron with speed v_1 strikes a nucleus of mass A and bounces off at lower speed v_2. The nucleus of mass A recoils with speed v, and if kinetic energy is to be conserved, the kinetic energy received by A has to be equal to that lost by the neutron. After the collision the neutron will therefore be moving at a slower speed (ie, $v_2 < v_1$).

The fraction of its initial energy that the neutron loses in such a collision depends on two things:

(a) The angle at which the neutron hits,
(b) The mass A of the target nucleus.

The maximum energy loss occurs when the neutron hits the nucleus head-on, and the least energy is lost in a glancing collision. The pool sharks amongst you will be well aware of this - the difference here is that the angle at which the neutron will hit the nucleus will be quite random. Consequently the angle at which it bounces off is also quite random. That is why we say that the neutron is *scattered* in the process. The term *elastic* implies the conservation of kinetic energy and therefore these collisions are described by the term *elastic scattering*.

The lighter the target nucleus is, the greater is the fraction of the energy that a neutron will lose in these collisions. Since this is the reaction with which fast neutrons are slowed down in the moderator, we want light moderator nuclei (ie, Atomic Mass Number less than 16 or so) if we are going to slow the neutrons down in as few collisions as possible. Otherwise the neutrons will travel large distances before they are slowed down thus making a physically large reactor. To emphasize this point, Table I shows the number of elastic collisions neutrons have to make in various materials to slow down from 2 MeV (the average energy with which they are produced at fission) to *thermal energy* (0.025 eV)*.

Note that for the heavy U^{238} nucleus, a very large number of elastic collisions would have to occur before the neutron would be slowed down to thermal energy.

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*At thermal energy, the neutrons have the same energy as the atoms or molecules with which they are colliding. At room temperature, this is about 0.025 eV.

TABLE I

Number of Elastic Collisions to Thermalize Fission Neutrons in Various Materials

H^1	18
H^2 (deuterium)	25
H_2O (light water)	20
D_2O (heavy water)	36
C^{12} (graphite)	115
U^{238}	2172

Inelastic Collisions

Instead of bouncing off, the neutron may enter a nucleus to briefly form what we call a *compound nucleus*. In such a reaction, kinetic energy is not conserved and it is therefore known as an *inelastic collision*. Basically what happens is that some of the neutron's kinetic energy is taken by the compound nucleus. As a result it becomes unstable in the sense that it cannot exist for very long in this state (ie, for no longer than about 10^{-14} seconds), and the reaction that then occurs will be one of a number of alternatives described below.

1. The compound nucleus may get rid of its excess energy by emitting a neutron and a gamma photon. An example of this is shown in Figure 2. A neutron is shown entering a U-238 nucleus to form a U-239 nucleus. This immediately emits a neutron (any one) and a gamma photon to become U-238 again. The end result is still a slowing down of the neutron because the energy it has lost has been given to the gamma photon.

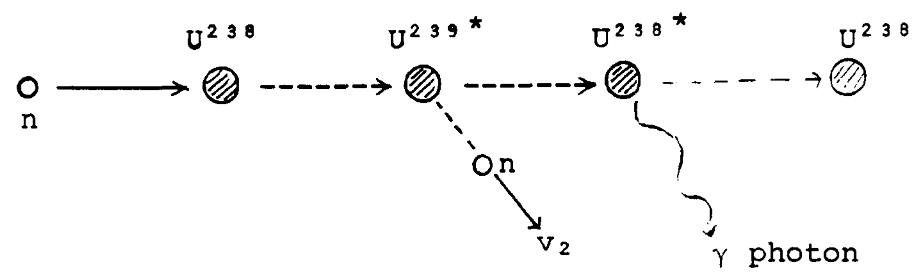


Figure 2

Inelastic Scattering

This reaction is known as *inelastic scattering*; "scattering" because the direction of the emitted neutron is again quite arbitrary. One of the peculiarities of this reaction is that it cannot occur unless the neutron has an initial energy of at least 0.1 MeV (this figure only applies to heavy nuclei like uranium; for lighter nuclei, around 3 MeV or more would be needed before the reaction becomes possible. These figures are based on the possible energy levels discussed in lesson 227.00-1.) From a reactor point of view, we can ignore inelastic scattering everywhere except in the fuel itself, because only there will the neutron energies be large enough for it to happen.

2. An alternative to inelastic scatter is that the compound nucleus may emit either a proton or an alpha particle, and in this way form an entirely new element. Look at Figure 3, which shows such a *transmutation* of oxygen-16.

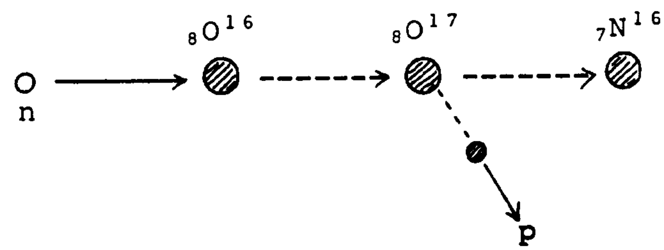


Figure 3

Transmutation (n,p)

This reaction may be written as

$$n + {}_{8}O^{16} \longrightarrow {}_{7}N^{16} + p$$

or you may prefer the short-hand version $O^{16}(n,p)N^{16}$. The N-16 is radioactive and emits high energy gamma radiation. It presents a radiation hazard in any region containing oxygen-16, that has recently been exposed to high energy neutrons. For example, oxygen-16 is present in water (either H_2O or D_2O), and if this water has recently flowed through the reactor, some of the oxygen-16 will have been changed to nitrogen-16, and this will now emit high energy gamma radiation.

Although transmutation reactions - (n,p) or (n,α) - are relatively rare, there are two more which are of interest to us:

$B^{10}(n,\alpha)Li^7$: Reactor instrumentation (ion chambers) for monitoring the neutron population in a reactor operates with this reaction. This reaction releases 2.5 MeV of energy, which shows up as kinetic energy of the helium and lithium nuclei. They lose this energy by producing a large amount of ionization in the counter, and this can easily be detected, even in the high gamma radiation background of a reactor environment. Boron is also used for reactivity control.

$He^3(n,p)H^3$: Very sensitive reactor instrumentation makes use of this reaction, because it occurs much more readily than the one above. He-3 counters were first used in Ontario Hydro for the first start-up of the Pickering and Bruce reactors.

3. The most common neutron reaction of all is also an inelastic type of reaction. It is called *radiative capture*, because the compound nucleus has *captured* a neutron and it then *radiates* a gamma photon. Radiative capture can occur for practically all types of nucleus, and at all neutron energies. Generally speaking, it is more probable for slow neutrons than for fast neutrons.

An example of such a reaction is shown in Figure 4, which explains how tritium (hydrogen-3) is produced in heavy water reactors.

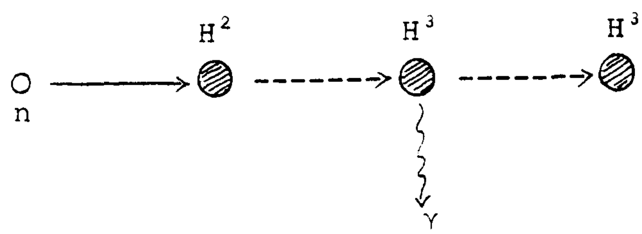


Figure 4

Radiative Capture (n,γ)

Radiative capture is important for two reasons:

(a) Non-fission neutron capture in core materials is, in a sense, undesirable. However, if the non-fission capture is with U-238 (giving U-239) there is a bonus in the subsequent transmutation of the U-239 to Pu-239. Pu-239 is a fissile nuclide and thus extends the fissile component of the fuel.

(b) The product nucleus formed more times than not is radioactive and might present a radiation hazard. For example, corrosion products circulated by the heat transport system will be activated as they pass through the reactor core. When they later plate out in this system, the whole system becomes a radioactive hazard, and will remain so even if the reactor is shut down (ie, if the neutron source is removed). The three most troublesome activation products in our reactors are cobalt-60, manganese-56, and copper-64, and they are produced in this way.

4. The final reaction we are going to consider is called *fission*. The word is borrowed from the biologists, who use it to describe the breaking up of a cell into two new ones.

The Fission Reaction

Production of nuclear power relies on the fact that some nuclei will fission, and that energy is released during this fission process because a loss of mass occurs ($\Delta E=\Delta mc^2$). There are two types of fission; *spontaneous* and *induced*.

(a) Spontaneous Fission

In this reaction, a nucleus fissions entirely spontaneously, without any external cause. It is quite a rare reaction, generally only possible for nuclei with atomic masses of around 232 amu or more. (As the atomic mass number increases, spontaneous fission becomes more and more probable. One could argue that there is an infinite number of heavy elements which do not exist, because they are not stable against spontaneous fission decay). The table on Page 7 shows the spontaneous fission and alpha decay rates of the U-235 and U-238 isotopes.

TABLE II

Spontaneous Fission And Alpha Decay Rates of Uranium

	$t_{\frac{1}{2}}(\alpha)$ (years)	$t_{\frac{1}{2}}$(s.f.) (years)	α decay rate (atoms/s/kg)	s.f. decay rate (atoms/s/kg)
U-235	7.1×10^{8}	1.2×10^{17}	79×10^{6}	0.3
U-238	4.5×10^{9}	5.5×10^{15}	12×10^{6}	6.9

From this table you will be able to appreciate that spontaneous fission has no significance in the production of power. (About 10^{-12}% of full power.) Nevertheless, it is important in that it represents a small source of neutrons in a reactor.

(b) Induced Fission

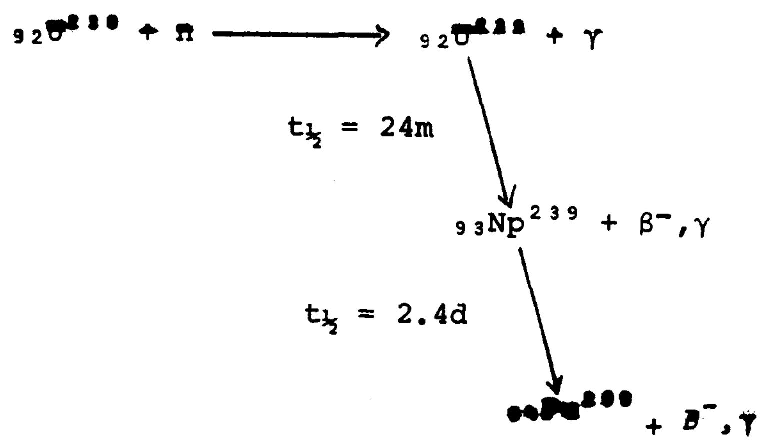
Certain heavy nuclei can be *induced* to fission as a result of neutron capture. In most cases the energy of the captured neutron must be very high before fission can occur, and therefore we can restrict our discussion to those nuclei which can be fissioned by neutron energies likely to be found in a reactor. In practice, we are then dealing with neutrons ranging from 10 MeV down to *thermal energies*.

Practical Fission Fuels

The only nuclei of practical importance to us are the U-235 and U-238 isotopes of uranium, and the Pu-239 and Pu-241 isotopes of plutonium. For all of these, except U-238, fission with thermal neutrons (*thermal fissions*) is much more probable than fission with fast neutrons (*fast fissions*). This is an important (and desirable) nuclear property, and such nuclides are said to be *fissile*. U-238, which will not fission with thermal neutrons, but which will fission with fast neutrons of energy greater than about 1.2 MeV, is merely said to be *fissionable*. It makes a small direct contribution to the power produced in a reactor, (about 3%).

Note: Fissile describes a nucleus that can be fissioned by thermal neutrons but such a nucleus can also be fissioned by neutrons of any energy.

Natural uranium only contains U-235 (0.72%) and U-238. Over a period of reactor operation, Pu-239 and also some Pu-241 will be built up in the fuel as a result of neutron capture:



Pu-239 is fissile like U-235. If it does not undergo fission, it may capture a neutron to form Pu-240. Although this is fissionable it is much more likely to capture another neutron to form fissile Pu-241. A significant fraction of the total power produced by fuel during its life in our reactors is due to fission of the fissile plutonium isotopes. We will deal with this in more detail later on in the course.

Fission Fragments

The fission fragments formed when spontaneous or induced fission occurs are two new nuclei. These may be any two of about 300 nuclides which are known to be formed as a result of fission.

Figure 5 (on Page 9) shows the relative frequency for nuclides of specific mass numbers produced as fission fragments. Such a curve is known as a *fission yield curve* (since two fragments are produced per fission, the area under the curve adds up to 200%). You can see that both fission fragments are likely to consist of a substantial piece of the original nucleus. They are likely to have mass numbers between 70 and 160, with those around 95 and 140 being the most probably. Note that symmetrical fission (equal fragments) is quite rare.

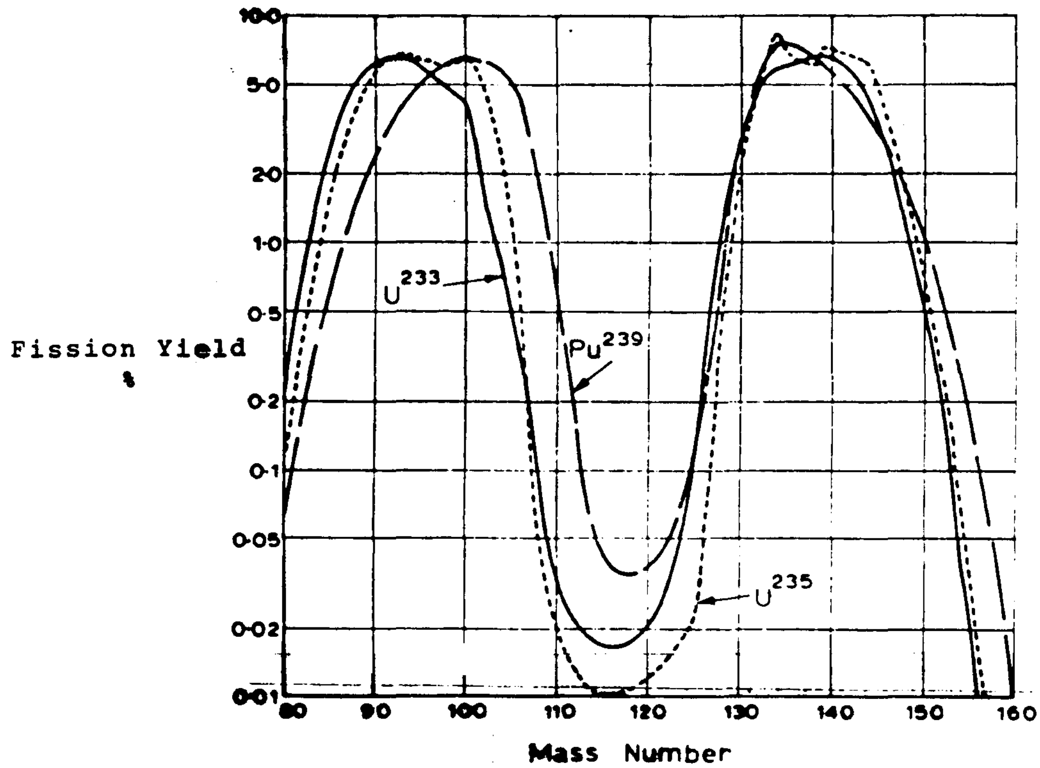


Figure 5

Fission Yield of U-233, U-235 and Pu-239

The fission fragments are almost invariably radioactive. The reason for this is that the neutron/proton ratio of the fragments is about the same as that of the fissioned nucleus, and this is too high for stability at medium mass numbers. The fragments will therefore try to reduce their n/p ratio by successive β^-,γ decays until stability is reached. A typical decay chain is shown in Figure 6 (on Page 10). All the members of such chains are known as *fission products*.

The half-lives of fission products range from fractions of a second to thousands of years. (It is this activity that causes so much concern in atomic bomb fall-out.) There are four important consequences of fission product production in the fuel:

(a) The fission products must be held in the fuel by encasing it in a sheath, so that they do not enter the heat transport system and hence leave the reactor core. As long as the fission products remain in the fuel and the fuel remains adequately shielded there is no biological risk.

$$n + {}_{92}U^{235} \longrightarrow {}_{54}Xe^{139} \xrightarrow[\gamma]{\beta^-} {}_{55}Cs^{139} \xrightarrow[\gamma]{\beta^-} {}_{56}Ba^{139} \xrightarrow[\gamma]{\beta^-} {}_{57}La^{139}$$

$$\longrightarrow n + n + \gamma$$

$$\longrightarrow {}_{38}Sr^{95} \xrightarrow{\beta^-} {}_{39}Y^{95} \xrightarrow[\gamma]{\beta^-} {}_{40}Zr^{95} \xrightarrow[\gamma]{\beta^-} {}_{41}Nb^{95} \xrightarrow[\gamma]{\beta^-} {}_{42}Mo^{95}$$

Figure 6

Fission Product Decay Chain

(a) Continued: Since many of them have long half-lives, their presence in the heat transport system would be a radiation hazard which would prevent access to equipment even when the reactor is shut down.

(b) Heavy shielding is required around the reactor to avoid exposure to the gamma radiation emitted by the fission products.

(c) Fuel must be changed remotely, and special precautions must be taken in handling and storing spent fuel.

(d) Some of the fission products have a high affinity for neutrons and thereby *poison* the reactor. The two most important poisons are Xe-135 and Sm-149. They are produced in a relatively high percentage of fissions, and they capture a significant number of neutrons.

Prompt and Delayed Neutron Emission

The fission fragments are produced in an excited state and will immediately emit perhaps two or three neutrons and some gamma photons. These are called *prompt neutrons* and *prompt gammas*.

Figure 7 (on Page 11) shows the energy distribution of prompt neutrons. The average energy is about 2 MeV, although the most probable energy is only 0.72 MeV.

A very small number of neutrons (less than 1%) appear long after fission occurs, and these are known as *delayed neutrons*. They arise from the radioactive decay of certain fission product daughters. For example:

$$ {}_{35}Br^{87} \xrightarrow[t_{\frac{1}{2}} = 55\ s]{} \beta + {}_{36}Kr^{87} $$

$$ {}_{36}Kr^{87} \xrightarrow[10^{-14}s]{} {}_{36}Kr^{86} + {}_{0}n^{1} $$

The neutron emission is instantaneous (with respect to Kr-87), but obviously occurs some time after the original fission because the Br-87 must decay first. In fact, it appears to be emitted with the 55 second half-life of Br-87.

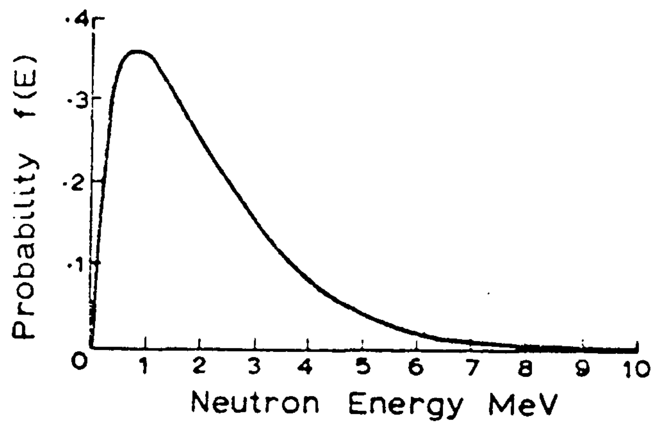


Figure 7

Prompt Neutron Energy Spectrum

Nuclei such as Br^{87} whose production in fission may eventually lead to the emission of a delayed neutron are known as *delayed-neutron precursors*. At the present time, it is believed that there may be as many as twenty precursors, although only about half a dozen have been positively identified. These precursors and their respective half-lives are given in Table II (on Page 12). They are usually divided into six groups according to their half-lives.

TABLE III

Delayed-Neutron Precursors

(Uncertain Quantities are Indicated by Brackets)

Precursor	Half-life and Group (Seconds)	
Br^{87}	54.5	Group 1
I^{137}	24.4	Group 2
Br^{88}	16.3	
I^{138}	6.3	
$Br^{(89)}$	4.4	Group 3
$Rb^{(93\ 94)}$	6	
I^{139}	2.0	
(Cs,Sb or Te)	(1.6-2.4)	Group 4
$Br^{(90\ 92)}$	1.6	
$Kr^{(93)}$	~1.5	
(I^{140} + Kr?)	0.5	Group 5
(Br,Rb,As + ?)	0.2	Group 6

For thermal fission of U-235, the total contribution of all the delayed neutrons (called the delayed neutron fraction; β) is only 0.65% of the total neutrons produced. With Pu-239, the delayed neutron fraction is even less at 0.21%. Despite the fact that these fractions are quite small, they have a very important effect on the time dependent behaviour of thermal reactors. We shall discuss this aspect of delayed neutrons in a later lesson.

Table IV (on Page 13) gives the probability of a particular number of neutrons being emitted in the thermal fission of a U-235 nucleus. This includes both prompt and delayed neutrons.

TABLE IV

Neutron Emission in Thermal Fission of U-235

Number of Neutrons Emitted	Number of Cases per 1000 Fissions
0	27
1	158
2	339
3	302
4	130
5	34

The average number of neutrons emitted per fission is a very important quantity in reactor physics. It is usually denoted by the Greek letter ν ("new"). For thermal fissions of U-235, ν = 2.43. (Fast fissions, ie, fissions caused by fast neutrons, usually produce marginally more neutrons.) It is also interesting to compare the number of neutrons released per thermal fission of Pu-239 and Pu-241 since both of these plutonium isotopes build up in our fuel after a while.

TABLE V

Values of ν for Thermal Fissions

Fissile Nucleus	ν
U -235	2.43
Pu-239	2.89
Pu-241	2.93

Energy Release From Fission

About 200 MeV of energy is liberated when a nucleus fissions. The exact value slightly depends on the fissile nucleus and on the fission fragments produced. The energy can be calculated as follows:

Consider the example given in Figure 6 on page 10:

$$_{92}U^{235} + n \longrightarrow {_{38}Sr^{95}} + {_{54}Xe^{139}} + 2n$$

Total mass before fission	= 235.044 +	1.009		=	236.053 amu
Total mass after fission	= 94.903 +	138.918 +	2.018	=	235.839 amu
			Loss in mass	=	0.214 amu

This corresponds to almost 200 MeV. A summary of how this energy is distributed is given in Table VI.

TABLE VI

Approximate Distribution of Fission Energy Release in U-235

Kinetic energy of lighter fission fragment	100 MeV
Kinetic energy of heavier fission fragment	69 MeV
Energy of prompt neutrons	5 MeV
Energy of prompt γ rays	6 MeV
β particle energy gradually released from fission products	7 MeV
γ ray energy gradually released from fission products	6 MeV
Neutrinos (energy escapes from reactor)	11 MeV
Total	204 MeV

This is not a complete account of all the energy released in the reactor. Some of the neutrons even after losing all their kinetic energy may produce (n,γ) reactions with materials in the reactor, and up to about 8 MeV may be released in such reactions. The total amount of energy produced in a reactor per fission may therefore depend to a slight extent on the form of the reactor, but it is always within a few MeV of 200 MeV.

Not all of this 200 MeV of energy from fission is useful or desirable. The principal useful heat is due to the kinetic energy of the fission fragments. This shows up as heating of the fuel from which the heat is transferred to the heat transport fluid. Most of the neutron and about one third of the gamma energy (≈5-6% of the total) shows up as heating of the moderator. This is essentially wase heat which must be rejected. The energy due to decay of the fission products makes up about 7% of the total fission energy. This has a major effect on reactor design since this energy shows up as heat for a long time after essentially all fissioning has ceased. Because of this decay heat we must have a shutdown cooling system for normal shutdown conditions and an emergency core cooling system in the event that normal cooling is lost. As demonstrated at 3 Mile Island, even when shut down a reactor is still producing about 1% of its full thermal power.

Reactor Power and Fuel Consumption

The 200 MeV released in one fission is not of much practical value because it is minute. In fact, 1 watt of power requires 3.1×10^{10} fission every second.

One Megawatt steady power requires 3.1×10^{16} fissions every second continously. 3.1×10^{16} atoms of U-235 have a mass of:

$$\frac{3.1 \times 10^{16} \times 235}{6.023 \times 10^{26}} = 1.21 \times 10^{-8} \text{ kg}$$

Therefore, to produce 1 Megawatt-day of energy from fission requires the complete fissioning of:

$$1.21 \times 10^{-8} \times 24 \times 3600 = 1.0 \times 10^{-3} \text{ kg} = \underline{1.0\text{g U-235}}$$

The first requirement for producing useful power from the fission process is that enough U-235 nuclei must be available for fissioning. This requirement is met by installing sufficient U-235 in the reactor in the form of fuel rods. If natural uranium is used, of which 0.72% is U-235, then about 140 g of uranium would be used to produce 1 Megawatt-day of energy. This assumes that all the U-235 could be fissioned. In practice this is not so, because some U-235 (∿14%) is consumed in (n,γ) reactions. As a result, 165 g of natural uranium would be used.

For example, a Pickering reactor at full power generates 1744 MW from fission (540 MW gross electrical power). It would therefore use about 290 kg of natural uranium a day on this basis. Because Pu-239 (and Pu241) is produced in the fuel after a while, this contributes substantially to energy production, and the amount of fuel used is consequently smaller.

Production of Photoneutrons

Prompt and delayed neutrons are produced as a result of fission. If no further fissions occur, no more prompt or delayed neutrons will be produced. This is not the case with *photoneutrons*.

Photoneutrons are peculiar to reactors with heavy water moderator or heat transport fluids. They are produced when photons with energies greater than 2.2 MeV are captured by deuterium nuclei:

$$\gamma + {}_1H^2 \longrightarrow {}_1H^1 + n$$

After the reactor has been operating for a while, it will have built up in the fuel an inventory of fission products whose gamma decay photons have an energy greater than 2.2 MeV. Even when the reactor is shut down, this photoneutron source will persist because the gamma rays from decaying fission products can still produce photoneutrons in any heavy water present in the core. Even if the moderator has been dumped, heavy water will always be in the core as heat transport fluid. Therefore in our heavy water cooled reactors we always have a relatively large neutron source (compared to the spontaneous fission source) with which to start the reactor up again after a shutdown.

ASSIGNMENT

1. Explain why we use materials with a low atomic mass for moderators.

2. Table II shows the spontaneous fission rate for U-238 as 6.9 fissions/s/kg. Is this fission rate of any signifigance? Explain your answer.

3. How long will it take delayed neutrons to come into equilibrium after a power change?

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