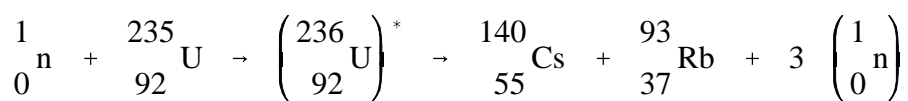

ENERGY RELEASE FROM FISSION

Fission of heavy nuclides converts a small amount of mass into an enormous amount of energy. The amount of energy released by fission can be determined based on either the change in mass that occurs during the reaction or by the difference in binding energy per nucleon between the fissile nuclide and the fission products.

- EO 4.8** **CHARACTERIZE** the fission products in terms of mass groupings and radioactivity.
- EO 4.9** **Given** the nuclides involved and their masses, **CALCULATE** the energy released from fission.
- EO 4.10** **Given** the curve of **Binding Energy per nucleon versus mass number**, **CALCULATE** the energy released from fission.
-

Calculation of Fission Energy

Nuclear fission results in the release of enormous quantities of energy. It is necessary to be able to calculate the amount of energy that will be produced. The logical manner in which to pursue this is to first investigate a typical fission reaction such as the one listed below.



It can be seen that when the compound nucleus splits, it breaks into two fission fragments, rubidium-93, cesium-140, and some neutrons. Both fission products then decay by multiple β^- emissions as a result of the high neutron-to-proton ratio possessed by these nuclides.

In most cases, the resultant fission fragments have masses that vary widely. Figure 21 gives the percent yield for atomic mass numbers. The most probable pair of fission fragments for the thermal fission of the fuel uranium-235 have masses of about 95 and 140. Note that the vertical axis of the fission yield curve is on a logarithmic scale. Therefore, the formation of fission fragments of mass numbers of about 95 and 140 is highly likely.

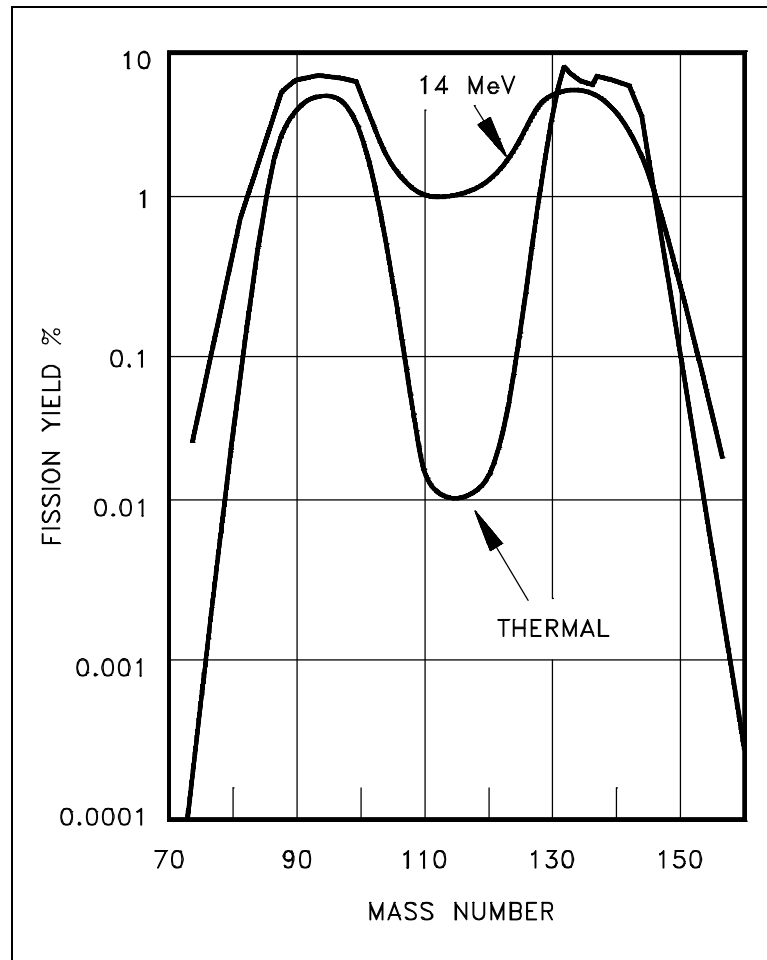


Figure 21 Uranium-235 Fission Yield vs. Mass Number

Referring now to the binding energy per nucleon curve (Figure 20), we can estimate the amount of energy released by our "typical" fission by plotting this reaction on the curve and calculating the change in binding energy (ΔBE) between the reactants on the left-hand side of the fission equation and the products on the right-hand side. Plotting the reactant and product nuclides on the curve shows that the total binding energy of the system after fission is greater than the total binding energy of the system before fission. When there is an increase in the total binding energy of a system, the system has become more stable by releasing an amount of energy equal to the increase in total binding energy of the system. Therefore, in the fission process, the energy liberated is equal to the increase in the total binding energy of the system.

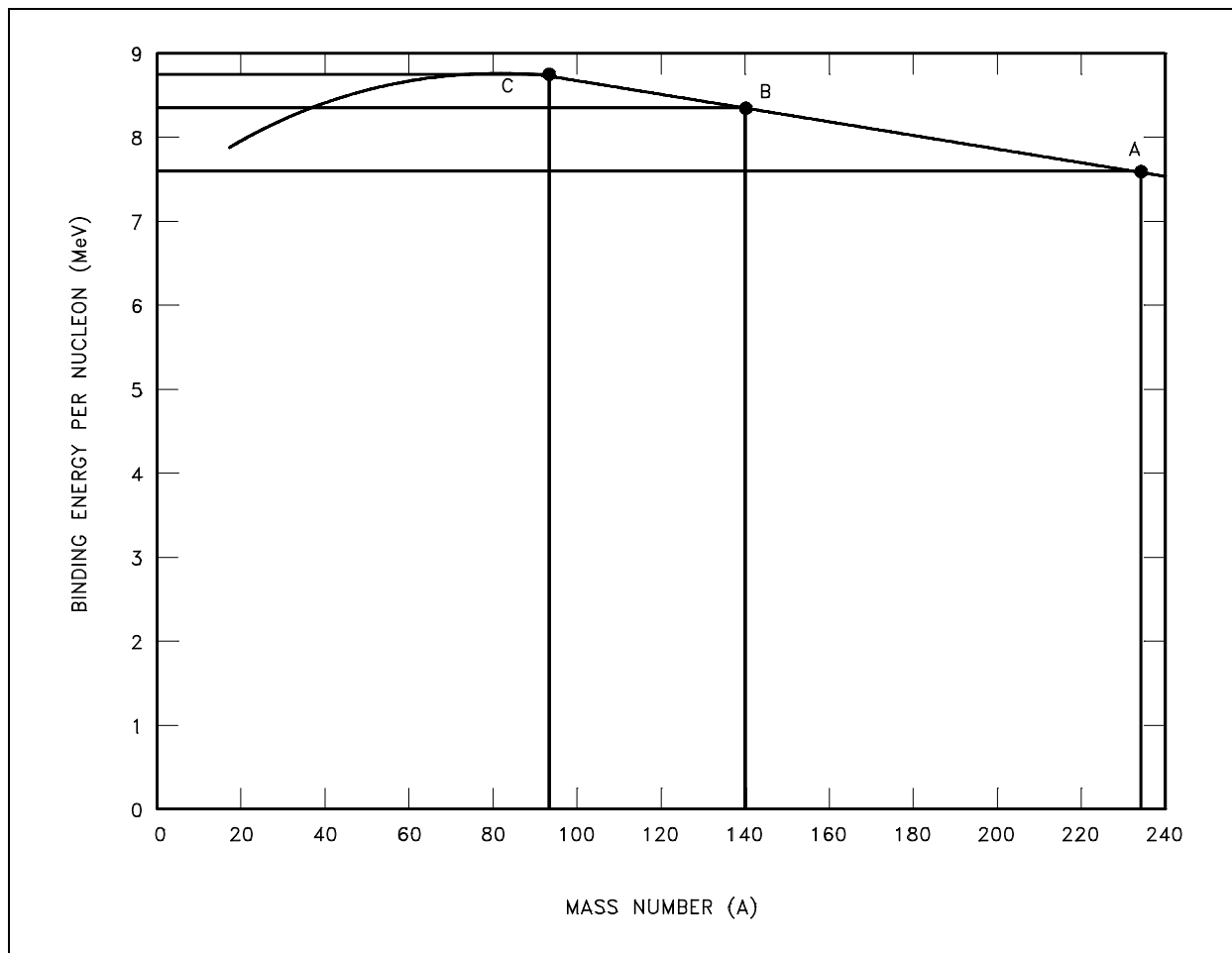


Figure 22 Change in Binding Energy for Typical Fission

Figure 22 graphically depicts that the binding energy per nucleon for the products (C, rubidium-93 and B, cesium-140) is greater than that for the reactant (A, uranium-235). The total binding energy for a nucleus can be found by multiplying the binding energy per nucleon by the number of nucleons.

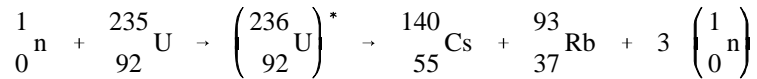
<p style="text-align: center;">TABLE 5 Binding Energies Calculated from Binding Energy per Nucleon Curve</p>			
Nuclide	B.E. per Nucleon (BE/A)	Mass Number (A)	Binding Energy (BE/A) x (A)
⁹³ ₃₇ Rb	8.7 MeV	93	809 MeV
¹⁴⁰ ₅₅ Cs	8.4 MeV	140	1176 MeV
²³⁵ ₉₂ U	7.6 MeV	235	1786 MeV

The energy released will be equivalent to the difference in binding energy (ΔBE) between the reactants and the products.

$$\begin{aligned}\Delta BE &= BE_{\text{products}} - BE_{\text{reactants}} \\ &= (BE_{\text{Rb-93}} + BE_{\text{Cs-140}}) - (BE_{\text{U-235}}) \\ &= (809 \text{ MeV} + 1176 \text{ MeV}) - 1786 \text{ MeV} \\ &= 199 \text{ MeV}\end{aligned}$$

The energy liberation during the fission process can also be explained from the standpoint of the conservation of mass-energy. During the fission process, there is a decrease in the mass of the system. There must, therefore, be energy liberated equal to the energy equivalent of the mass lost in the process. This method is more accurate than the previously illustrated method and is used when actually calculating the energy liberated during the fission process.

Again, referring to the "typical" fission reaction.



E_{Inst} , the instantaneous energy, is the energy released immediately after the fission process. It is equal to the energy equivalent of the mass lost in the fission process. It can be calculated as shown below.

<u>Mass of the Reactants</u>		<u>Mass of the Products</u>	
${}_{92}^{235}\text{U}$	235.043924 amu	${}_{37}^{93}\text{Rb}$	92.91699 amu
${}_0^1\text{n}$	1.008665 amu	${}_{55}^{140}\text{Cs}$	139.90910 amu
		$3 \left({}_0^1\text{n}\right)$	3.02599 amu
236.052589 amu		235.85208 amu	

$$\begin{aligned}\text{Mass difference} &= \text{Mass of Reactants} - \text{Mass of Products} \\ &= 236.052589 \text{ amu} - 235.85208 \text{ amu} \\ &= 0.200509 \text{ amu}\end{aligned}$$

This mass difference can be converted to an energy equivalent.

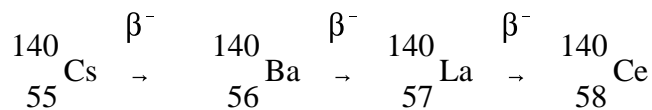
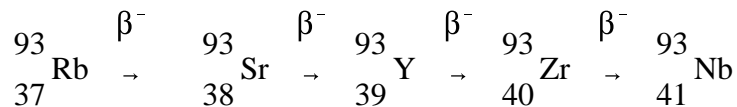
$$\begin{aligned}E_{\text{Inst}} &= 0.20059 \text{ amu} \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\ &= 186.8 \text{ MeV}\end{aligned}$$

The total energy released per fission will vary from the fission to the next depending on what fission products are formed, but the average total energy released per fission of uranium-235 with a thermal neutron is 200 MeV.

As illustrated in the preceding example, the majority of the energy liberated in the fission process is released immediately after the fission occurs and appears as the kinetic energy of the fission fragments, kinetic energy of the fission neutrons, and instantaneous gamma rays. The remaining energy is released over a period of time after the fission occurs and appears as kinetic energy of the beta, neutrino, and decay gamma rays.

Estimation of Decay Energy

In addition to this instantaneous energy release during the actual fission reaction, there is additional energy released when the fission fragments decay by β^- emission. This additional energy is called decay energy, E_{Decay} . The decay chains for rubidium-93 and cesium-140 are shown below.



The energy released during the decay for each chain will be equivalent to the mass difference between the original fission product and the sum of the final stable nuclide and the beta particles emitted.

The energy released in the decay chain of rubidium-93 is calculated below.

$$\begin{aligned} E_{\text{Decay}} &= [m_{\text{Rb-93}} - (m_{\text{Nb-93}} + 4 m_{\text{electron}})] \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\ &= [92.91699 \text{ amu} - (92.90638 \text{ amu} + 4 (0.0005486 \text{ amu}))] \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\ &= 0.008416 \text{ amu} \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\ &= 7.84 \text{ MeV} \end{aligned}$$

The energy released in the decay chain of cesium-140 is calculated below.

$$\begin{aligned}
 E_{\text{Decay}} &= [m_{\text{Rb-93}} - (m_{\text{Nb-93}} + 3 m_{\text{electron}})] \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\
 &= [139.90910 \text{ amu} - (139.90543 \text{ amu} + 3 (0.0005486 \text{ amu}))] \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\
 &= 0.000202 \text{ amu} \left(\frac{931.5 \text{ MeV}}{\text{amu}} \right) \\
 &= 1.89 \text{ MeV}
 \end{aligned}$$

The total decay energy is the sum of the energies of the two chains, or 9.73 MeV.

Distribution of Fission Energy

The average energy distribution for the energy released per fission with a thermal neutron in uranium-235 is shown in Tables 6 and 7.

TABLE 6	
Instantaneous Energy from Fission	
Kinetic Energy of Fission Products	167 Mev
Energy of Fission Neutrons	5 MeV
Instantaneous Gamma-ray Energy	5 MeV
Capture Gamma-ray Energy	10 MeV
Total Instantaneous Energy	187 MeV

TABLE 7	
Delayed Energy from Fission	
Beta Particles From Fission Products	7 Mev
Gamma-rays from Fission Products	6 MeV
Neutrinos	10 MeV
Total Delayed Energy	23 MeV

Because the 10 MeV of neutrino energy shown in Table 7 is not absorbed in the reactor, the average value of 200 MeV per fission is still accurate. Note in Table 6 that some fission neutrons undergo radiative capture and the resultant gamma ray emission provides an additional 10 MeV of instantaneous energy, which contributes to the total of 187 MeV instantaneous energy.

All of the energy released, with the exception of the neutrino energy, is ultimately transformed into heat through a number of processes. The fission fragments, with their high positive charge and kinetic energy, cause ionization directly as they rip orbital electrons from the surrounding atoms. In this ionization process, kinetic energy is transferred to the surrounding atoms of the fuel material, resulting in an increase in temperature. The beta particles and gamma rays also give up their energy through ionization, and the fission neutrons interact and lose their energy through elastic scattering. Of the 200 MeV released per fission, about seven percent (13 MeV) is released at some time after the instant of fission. When a reactor is shut down, fissions essentially cease, but energy is still being released from the decay of fission products. The heat produced by this decay energy is referred to as "decay heat." Although decay energy represents about seven percent of reactor heat production during reactor operation, once the reactor is shut down the decay heat production drops off quickly to a small fraction of its value while operating. The decay heat produced is significant, however, and systems must be provided to keep the reactor cool even after shutdown.

Summary

The important information in this chapter is summarized below.

Energy Release From Fission Summary

- Fission products have some general characteristics in common.
They generally decay by β^- emission.
The most common mass numbers are grouped near 95 and 140.
- The energy released by fission can be calculated based on the difference in mass between the masses of the reactants before fission and the fission fragments and fission neutrons after fission.
- Another method to determine the energy released by fission is based on the change in binding energy per nucleon between the fissile nuclide and the fission products.