FIGURE 31–5 Color painting of the first nuclear reactor, built by Fermi under the grandstand of Stagg Field at the University of Chicago. (There are no photographs of the original reactor because of military secrecy.) Natural uranium was used with graphite as moderator. On December 2, 1942, Fermi slowly withdrew the cadmium control rods and the reactor went critical. This first self-sustaining chain reaction was announced to Washington, by telephone, by Arthur Compton who witnessed the event and reported: "The Italian navigator has just landed in the new world." Gary Sheahan, "Birth of the Atomic Age," Chicago (Illinois); 1957. Chicago Historical Society, ICHi-33305.

Fermi and his co-workers (at the University of Chicago) showed it was possible by constructing the first **nuclear reactor** in 1942 (Fig. 31–5).

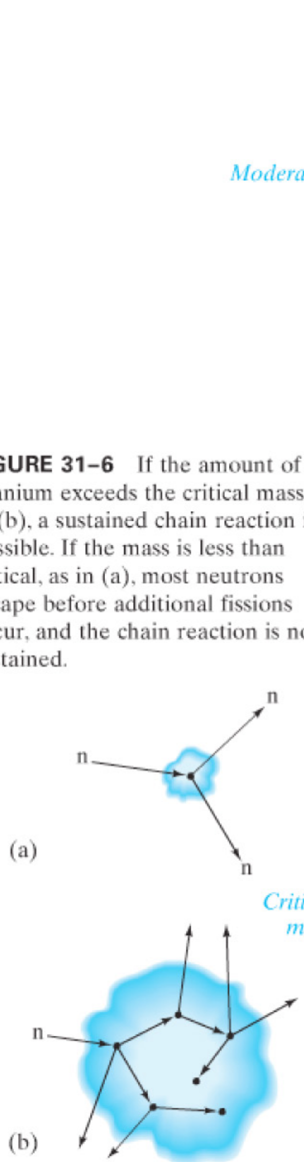
Nuclear Reactors

Several problems have to be overcome to make any nuclear reactor function. First, the probability that a $^{235}_{92}\text{U}$ nucleus will absorb a neutron is large only for slow neutrons, but the neutrons emitted during a fission, and which are needed to sustain a chain reaction, are moving very fast. A substance known as a **moderator** must be used to slow down the neutrons. The most effective moderator will consist of atoms whose mass is as close as possible to that of the neutrons. (To see why this is true, recall from Chapter 7 that a billiard ball striking an equal mass ball at rest can itself be stopped in one collision; but a billiard ball striking a heavy object bounces off with nearly unchanged speed.) The best moderator would thus contain $^{1}_{1}\text{H}$ atoms. Unfortunately, $^{1}_{1}\text{H}$ tends to absorb neutrons. But the isotope of hydrogen called *deuterium*, $^{2}_{1}\text{H}$, does not absorb many neutrons and is thus an almost ideal moderator. Either $^{1}_{1}\text{H}$ or $^{2}_{1}\text{H}$ can be used in the form of water. In the latter case, it is **heavy water**, in which the hydrogen atoms have been replaced by deuterium. Another common moderator is *graphite*, which consists of $^{12}_{6}\text{C}$ atoms.

Moderator

A second problem is that the neutrons produced in one fission may be absorbed and produce other nuclear reactions with other nuclei in the reactor, rather than produce further fissions. In a "light-water" reactor, the $^{1}_{1}\text{H}$ nuclei absorb neutrons, as does $^{238}_{92}\text{U}$ to form $^{239}_{92}\text{U}$ in the reaction $n + {}^{238}_{92}\text{U} \rightarrow {}^{239}_{92}\text{U} + \gamma$. Naturally occurring uranium† contains 99.3% $^{238}_{92}\text{U}$ and only 0.7% fissionable $^{235}_{92}\text{U}$. To increase the probability of fission of $^{235}_{92}\text{U}$ nuclei, natural uranium can be **enriched** to increase the percentage of $^{235}_{92}\text{U}$ using processes such as diffusion or centrifugation. Enrichment is not usually necessary for reactors using heavy water as moderator since heavy water doesn't absorb neutrons.

FIGURE 31–6 If the amount of uranium exceeds the critical mass, as in (b), a sustained chain reaction is possible. If the mass is less than critical, as in (a), most neutrons escape before additional fissions occur, and the chain reaction is not sustained.



The third problem is that some neutrons will escape through the surface of the reactor core before they can cause further fissions (Fig. 31–6). Thus the mass of fuel must be sufficiently large for a self-sustaining chain reaction to take place. The minimum mass of uranium needed is called the **critical mass**. The value of the critical mass depends on the moderator, the fuel ($^{239}_{94}\text{Pu}$ may be used instead of $^{235}_{92}\text{U}$), and how much the fuel is enriched, if at all. Typical values are on the order of a few kilograms (that is, not grams nor thousands of kilograms).

Critical mass

To have a self-sustaining chain reaction, on average at least one neutron produced in each fission must go on to produce another fission. The average number of neutrons per fission that do go on to produce further fissions is

† $^{238}_{92}\text{U}$ will fission, but only with fast neutrons ($^{238}_{92}\text{U}$ is more stable than $^{235}_{92}\text{U}$). The probability of absorbing a fast neutron and producing a fission is too low to produce a self-sustaining chain reaction.