Chapter 14

NUCLEAR FUSION

For the longer term, the National Energy Strategy looks to fusion energy as an important source of electricity-generating capacity. The Department of Energy will continue to pursue safe and environmentally sound approaches to fusion energy, pursuing both the magnetic confinement and the inertial confinement concepts for the foreseeable future. International collaboration will become an even more important element of the magnetic fusion energy program and will be incorporated into the inertial fusion energy program to the fullest practical extent.

(*National Energy Strategy*, *Executive Summary*, 1991/1992)

Research into fundamentally new, advanced energy sources such as [...] fusion energy can have substantial future payoffs... [T]he Nation's fusion program has made steady progress and last year set a record of producing 10.7 megawatts of power output at a test reactor supported by the Department of Energy. This development has significantly enhanced the prospects for demonstrating the scientific feasibility of fusion power, moving us one step closer to making this energy source available sometime in the next century.

(*Sustainable Energy Strategy,* 1995)

Nuclear fusion is essentially the antithesis of the fission process. Light nuclei are combined in order to release excess binding energy and they form a heavier nucleus. Fusion reactions are responsible for the energy of the sun. They have also been used on earth for uncontrolled release of large quantities of energy in the thermonuclear or ‘hydrogen’ bombs. However, at the present time, peaceful commercial applications of fusion reactions do not exist. The enormous potential and the problems associated with controlled use of this essentially nondepletable energy source are discussed briefly in this chapter.

Fusion Reactions

The concept of nuclear fusion has been described in Chapter 12. It is summarized in Figure 14-1, which is analogous to Figure 13-2 for nuclear fission. As the nuclei of two light atoms are brought closer to each other, they become increasingly destabilized, due to the electric repulsion of their positive charges. Work must be expended to achieve this and so the energy of the two nuclei increases. If this “activation energy” is provided to overcome the repulsive forces, fusion of the two nuclei into a stable heavier nucleus will take place and a large amount of energy will be released. The net energy output is potentially larger in the case of fusion than in the case of fission.

The reaction described in Illustration 14-1 (fusion of deuterium and tritium into helium) is only one of the possible reactions that could be the basis for the fusion power reactors of the future. The others are the following:

$${}_1H^2 + {}_1H^2 = {}_1p^1 + {}_1H^3 \ (+\,4.0\ \text{MeV})$$

$${}_1H^2 + {}_1H^2 = {}_0n^1 + {}_2He^3 \ (+\,3.3\ \text{MeV})$$

$${}_1H^2 + {}_2He^3 = {}_1p^1 + {}_2He^4 \ (+\,18.3\ \text{MeV})$$

$${}_3Li^6 + {}_0n^1 = {}_2He^4 + {}_1H^3 \ (+\,4.8\ \text{MeV})$$

Deuterium and tritium are the main ingredients in most fusion reactions. Deuterium is a stable form of hydrogen; it is found in ordinary water. Tritium is a radioactive form of hydrogen, not found in nature. In contrast to the situation with fission, where tritium is produced (and thus contributes to radioactivity), here it is consumed. As shown above, it can be obtained from lithium, Li-6, a relatively abundant metal found in mineral ores. A simple calculation, based on the fact that there is one deuterium atom in every 6500 atoms of hydrogen, shows that in 65,000 pounds of water there is about one pound of deuterium. Now, water is in general an abundant resource on our planet. This fact, together with the fact that enormous amounts of energy are released in fusion reactions, makes fusion an essentially nondepletable energy source. To quote a physicist at the Princeton University's Plasma Physics Laboratory, the leading fusion research center in the U.S., “the top two inches of Lake Erie contain 1.6 times more energy than all the world's oil supplies" (*Business Week*, October 15, 1990, p. 62). The reader can easily become convinced that such comparisons are not exaggerated. Another simple calculation shows that if only 1% of the deuterium in world's oceans – equivalent to 10^{40} atoms of deuterium – is used to produce tritium, this would be equivalent to using up all the world's fossil fuel reserves 500,000 times. These are impressive numbers. Unfortunately, however, significant technical difficulties stand in the way of commercial development of this technology.

Illustration 14-1. Calculate the energy released in the following fusion reaction:

$$\underset{\text{(deuterium)}}{{}_1H^2} \quad + \quad \underset{\text{(tritium)}}{{}_1H^3} \quad = \quad \underset{\text{(helium)}}{{}_2He^4} \quad + \quad \underset{\text{(neutron)}}{{}_0n^1}$$

Compare this energy with that calculated in Illustration 13-1 for the fission of uranium-235.

Solution.
Knowing the masses of the individual nuclei involved in this fusion reaction allows us to calculate the mass decrease.

$$\begin{array}{ccccccc} {}_1H^2 & + & {}_1H^3 & = & {}_2He^4 & + & {}_0n^1 \\ (2.014102) & & (3.016050) & & (4.002603) & & (1.008665) \\ & 5.030152 & & > & & 5.011268 & \end{array}$$

So, 0.018884 a.m.u are converted to energy for every nucleus of deuterium (or tritium) that undergoes fusion. Therefore,

$$\Delta E = \Delta m\, c^2$$

$$= (0.018884 \text{ a.m.u.}) \left(\frac{1.66056\text{x}10^{-27}\text{ kg}}{1\text{ a.m.u.}}\right) \left(3\text{x}10^{8}\,\frac{\text{m}}{\text{s}}\right)^2 =$$

$$= (2.82\text{x}10^{-12}\text{ J}) \left(\frac{6.242\text{x}10^{12}\text{ MeV}}{1\text{ J}}\right) = 17.6 \text{ MeV/nucleus}$$

$$= \left(17.6\frac{\text{MeV}}{\text{nucleus}}\right) \left(\frac{1\text{ nucleus}}{2\text{ nucleons}}\right) = 8.8 \text{ MeV/nucleon (of deuterium)}$$

This energy is one order of magnitude higher than the energy (per nucleon) released in the fission of U-235.

FIGURE 14-1. Schematic representation of a fusion reaction. The net energy output is larger here than in fission, but so is the energy input required to get the reaction started.

A Fusion Reactor

Fusion offers several advantages over fission. One advantage is that the reserves of fusionable isotopes are much larger than those of fissionable isotopes; in fact, they are essentially unlimited. Another advantage is that the products of fusion reactions are less radioactive then the products of fission reactions. Among the products of the fusion reactions listed above, only tritium and the neutrons are radioactive. The last advantage of fusion lies in its inherent safety. There would be very little fusionable material at any given time in the reactor and the likelihood of a runaway reaction would thus be very small. Furthermore, the reaction is so hard to achieve in the first place that small perturbations in reactor conditions would probably terminate it.

The basic challenges of fusion are the following:

(a) heating of the reacting mixture to a very high temperature, to overcome the repulsive forces of positively charged nuclei;

(b) compressing the mixture to a high density so that the probability of collision (and thus reaction) among the nuclei can be high; and

(c) keeping the reacting mixture together long enough for the fusion reaction to produce energy at a rate that is greater than the rate of energy input (as heat and compression).

The first challenge is that of providing a huge amount of energy to the reactants. This is why fusion is called a *thermonuclear* reaction. Table 14-1 shows the mind-boggling temperature thresholds ("ignition temperatures") needed to accomplish some of the fusion reactions shown above.

TABLE 14-1

Heating requirements for selected fusion reactions

Fusion Reaction				Threshold Temperature (°C)
D + D	=	$_2He^3 + n$	+ 3.3 MeV (79 MJ/g)	400,000,000
D + D	=	T + p	+ 4.0 MeV (97 MJ/g)	400,000,000
D + T	=	$_2He^4 + n$	+ 17.6 MeV (331 MJ/g)	45,000,000
D + $_2He^3$	=	$_2He^4 + p$	+ 18.3 MeV (353 MJ/g)	350,000,000

D=deuterium; T=tritium; p=proton; n=neutron.

The second and third challenges are collectively referred to as the *confinement* problem. It is easily understood that the reacting mixture – called 'plasma' at the high temperatures involved – cannot be brought together (or confined) in ordinary vessels. The presence of solid vessels is ruled out because they would carry away the heat necessary to reach the very high ignition temperatures. Magnets (magnetic confinement) and lasers (inertial confinement) are used instead (in designs that are too complicated to concern us here).

Current research efforts in the development of nuclear fusion technology are focused on achieving the so-called *breakeven point*. The production of a plasma at sufficiently high temperature and particle density, held together long enough to produce at least as much energy as is being consumed in this process, is being pursued. In addition to the temperature requirement, the so-called *Lawson criterion* must be met, meaning that the product of particle density (in nuclei per cubic centimeter) and confinement time (in seconds) must exceed 10^{14}. This criterion can be satisfied, for example, by having 10^{14} nuclei/cm^3 held together for one second (using magnetic confinement), or by having 10^{25} nuclei/cm^3 held together for 10^{-11} seconds (using inertial confinement).

Although the ultimate objective is still elusive, a number of important milestones have been reached. In late 1991 a group of European scientists made perhaps the most significant one. They successfully fused tritium with deuterium, thus releasing a 2-second pulse of energy equivalent to 2 megawatts (see “Breakthrough in Nuclear Fusion Offers Hope for Power of Future,” NYT of 11/11/91; “Hot Fusion Test Using New Fuel Shows Promise,” WSJ of 11/11/91; “Europeans ahead of U.S. efforts to tap fusion energy, experts say,” PI of 11/12/91; “Fusion needs an infusion,” *USA Today* of 11/12/91; “Harnessing the physics of the sun,” USNWR of 11/25/91). More recently, at the Tokamak reactor in Princeton, NJ, a record-breaking one-second 10.7 MW burst – mentioned on p. 257 – was achieved with a 50-50 deuterium-tritium fuel (see “Experimental Fusion Reactor At Princeton Sets a Record,” NYT of 11/9/94).

Bringing fusion to the level of technological viability for electricity production and to commercial scale will take several decades and billions of dollars of further research and development. Even with support from the Department of Energy, a demonstration plant is not expected to be built in the U.S. until 2025. This support has not been as large in recent years as it was in the late 1970s and early 1980s, as Figure 14-2 shows. According to (probably) optimistic estimates, the construction of a commercial plant might be achieved by 2040, but only if this R&D support is increased substantially. Given the tremendous costs involved, international collaboration is being pursued. Design and construction of the International Thermonuclear Experimental Reactor (ITER), which will go beyond short fusion bursts, is being financed by the U.S., Japan, Russia and the European Union; it is expected to cost some $10 billion and the jury is still out regarding its successful completion (see “U.S. joins other nations hoping for better nuclear plants,” NYT of 7/28/92; “Dunkin' dough: Nuclear fusion can ill afford the managerial turmoil surrounding its most prominent experiment,” *Economist* of 7/30/94; and “Cold Calculations Chill the Hot Pursuit of Cheap Fusion Power,” NYT of 12/10/96).

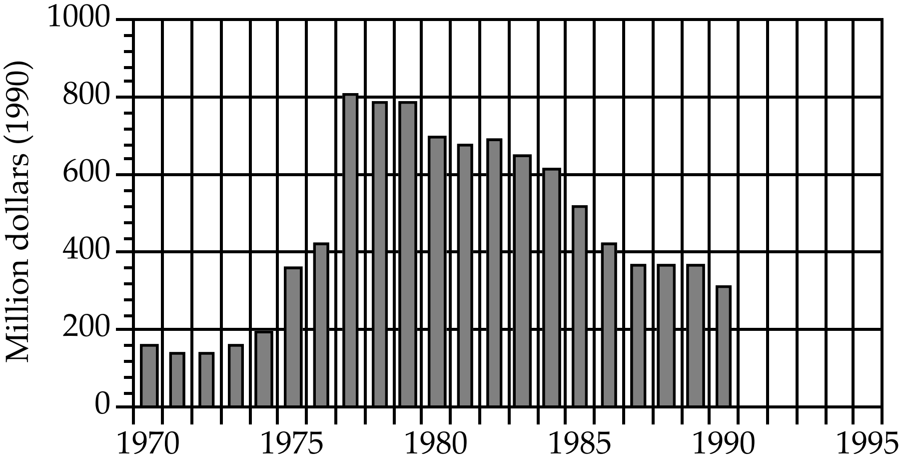

FIGURE 14-2. Federal budget appropriations for fusion research.
[Source: “The Ups and Downs of Harnessing the Sun,” NYT of 10/9/90.]
(The 1996 appropriation is $244 million, according to M.W. Browne, NYT of 4/23/96.)

The “Cold Fusion” Confusion

In March of 1989, two chemists called a press conference at the University of Utah to announce a startling discovery which had eluded physicists for decades. They claimed to have produced “fusion in a jar.” This reaction was claimed to have occurred at room temperature within a palladium electrode immersed in a beaker of deuterium-containing water:

$$ {}_1H^2 + {}_1H^2 = {}_2He^4 + 23.85\ \text{MeV} $$

This new nuclear reaction – if indeed possible at such extremely low temperatures – would produce a larger amount of energy than the traditional ones (see Table 14-1). It is not surprising, therefore, that a frenzy or activity followed this announcement. For their media coverage, see Investigation 14-1. Many months of frantic research activity were spent by scientists, in dozens of laboratories all over the world, to reproduce these results. The scientists themselves got caught up in the media ‘show’ and there were almost daily claims and counter-claims about the validity of this new approach to harnessing fusion. The final verdict, at least for the time being, was disappointing: the claims were too good to be true. Bursts of heat were indeed detected, suggesting that some unusual process is taking place within the palladium electrode, but no characteristic byproducts of the possible reactions (neutrons, gamma rays or enough tritium) were detected.

There is no question that, if indeed possible, this reaction would rank as one of the major discoveries in the history of mankind and would solve most of world's energy problems. This idea has probably led the two scientists to announce their results before verifying them thoroughly.

Society will thus have to continue to seek more complicated – and more expensive – solutions to its energy problems.

INVESTIGATIONS

14-1. Find out about the media ‘hoopla’ around the announcement of “cold fusion.” See “2 Report Nuclear Power Gain But Experts Express Doubts,” NYT of 3/24/89; “Breakthrough seen in nuclear energy,” PI of 3/24/89; “Fusion in a Jar: Announcement By 2 Chemists Ignites Uproar,” NYT of 3/28/89; “Second Fusion Discovery Comes to Light,” WSJ of 3/29/89; “Heat Source in Fusion Find May Be Mystery Reaction,” WSJ of 4/3/89; “Fusion Claim Is Put to the Test Worldwide,” NYT of 4/4/89; “Frenzy Over Fusion in Hundreds of Labs,” NYT of 4/18/89; “Italian Researchers Report Achieving Nuclear Fusion,” NYT of 4/19/89; “In hot pursuit of cold fusion,” USNWR of 4/24/89; “Fusion May Keep the Continents in Motion,” NYT of 4/25/89; “The Utah Fusion Circus,” NYT of

4/30/89; “Physicists Challenge Cold Fusion Claims,” NYT of 5/2/89; “Fusion Illusion?,” *Time* of 5/8/89; “Putting the Heat on Cold Fusion,” *Time* of 5/15/89.

14-2. Reports about “cold fusion” continue to appear in the media. Summarize the latest developments. See “Cold Fusion Still Escapes Usual Checks of Science,” NYT of 10/30/90; “Turning Up the Heat on ‘Cold Fusion’,” WSJ of 11/7/90; “Fusion Researcher Discusses Findings,” NYT of 11/9/90; “There Still May Be Something Scientific About Cold Fusion,” NYT of 4/14/91; “Power in a Jar: The debate heats up,” BW of 10/26/92; “Cold Fusion, Derided in U.S., Is Hot In Japan,” NYT of 11/17/92; “Cold Fusion: The controversial dream of cheap, abundant energy from room-temperature fusion refuses to die,” *Popular Science* of 8/93.

14-3. In order for fusion to become a commercially viable energy source within the next 3-4 decades, very large research and development (R&D) funding will be required. (This is also true for the renewable energy sources to be discussed in Chapters 16 and 17.) Find out about some of the initiatives and costs associated with fusion R&D. See “U.S. Losing Ground In Worldwide Race For ‘Hot’ Fusion,” NYT of 6/20/89; “Future of Hot Fusion Is Boiling Down To the Behavior of a Few Helium Atoms,” WSJ of 8/31/90; “Revival of Fusion Energy Program Sought,” WSJ of 9/20/90; “Next Bold Step Toward Fusion is Proposed,” NYT of 10/9/90; “Hot Fusion Is Burning Dollars–and Little Else,” BW of 10/15/90; “Reactor Passes Point of No Return In Uphill Path to Fusion Energy,” NYT of 12/7/93; “Blinded by the Light,” *Time* of 12/20/93; “U.S. Will Build Laser to Create Nuclear Fusion,” NYT of 10/21/94; “Bang: The former weapons scientists who study nuclear fusion are learning new political skills as they try to build the world's largest laser beam,” *Economist* of 10/29/94; “At the going down of the nuclear sun,” *Economist* of 9/16/95.