Chapter 2
What is nuclear energy?

This chapter will set forth the relationship between humankind and nuclear energy technology. The universe is a system of nuclear reactions. Geothermal energy is obtained from the decay of radioactive materials. Human beings are inevitably connected with nuclear science.

Pierre and Marie Curie and Albert Einstein

The phenomenon of nuclear fission was discovered in a series of research experiments, 40 years later from the discovery of the radioactive element radium by Pierre and Marie Curie in 1898. The ensuing nuclear chemistry study of radioactive elements by the Curies of France, Enrico Fermi of Italy, Otto Hahn of Germany, and Glenn Seaborg of the U.S. led to the discovery of transuranic elements. The enormous quantity of energy produced in nuclear fission can be calculated from Einstein's theory of relativity (1905).

The theory of relativity has immeasurable importance. At first, the assertion that "mutual transformation between mass and energy is possible" was understood only by nuclear scientists. Now it is shared equally by engineers and the public because of the nuclear fission phenomenon. For example, fissile element U-235 (original mass 235) changes through fission into two nuclei and some elementary particles (neutrons and mesons) whose total mass equals 234.8. The mass difference is 0.2. In other words, the vanished mass is converted into 200 MeV of energy (MeV: million electron volt, a unit of energy).

The energy produced from ordinary chemical reactions (e.g., the reaction of hydrogen and oxygen to make water) is on the order of one eV (23 Kcal/mole). By contrast, in a naturally occurring nuclear reaction where a nucleus changes (e.g., C-14 decays to N-14), the order of energy produced is between 0.1 and several MeV. However, the energy from a nuclear fission reaction (200 MeV) is two or three orders of magnitude larger than an ordinary nuclear reaction and eight orders of magnitude larger (a factor of several hundred million) than ordinary chemical reactions. It is our task to use this energy effectively for humankind.

Atomic nucleus, isotopes and radioactivity

To understand the following explanations, it will be helpful to review the fundamentals of nuclear chemistry in some detail. This scientific knowledge is the basis of our understanding.

First, the atomic nucleus consists of elementary particles called the proton (the nucleus of a hydrogen atom with a positive electric charge) and the neutron, with the same weight as the proton but no electric charge. A certain number of protons and neutrons combined to form a nucleus with the aid of mesons (whose existence was predicted and proved by Nobel laureate Hideki Yukawa). The total number of positive charges (i.e., the number of protons) is the atomic number of the nucleus. This determines the element: for example, atomic number six corresponds to carbon, seven to nitrogen, and eight to oxygen. The atomic number is also equal to the total number of electrons, with negative charge, that circle the nucleus. Because the number of protons and electrons is the same, the atom as a whole is electrically neutral. The sum of the protons and neutrons is the mass number of the element. The mass of an electron is negligible (1/1,800 of a proton's mass). The area of the electron movement corresponds to the size of the atom, which is about one hundred-millionth of one centimeter. The diameter of an atomic nucleus is about one ten-thousandth of this value, in other words, one trillionth of a centimeter.

Hydrogen is the lightest atom and consists of a proton (nucleus) and an electron. Its symbol is "H"; its atomic number is one; and its mass number is one, because it has only one proton and no neutrons. Formally, this is written as ${}_1^1H$. The lower and upper numbers indicate the atomic number and the mass number respectively. There are also hydrogen atoms with mass numbers 2 and 3. These are ${}_1^2H$., consisting of a proton and a neutron (called heavy hydrogen, or deuterium, and abbreviated "D") and ${}_1^3H$, consisting of a proton and two neutrons (called tritium and abbreviated "T"). These three kinds of atoms are called the isotopes of hydrogen.

Similarly, many the elements have some isotopes with identical atomic numbers and different mass numbers (i.e., different numbers of neutrons). Taking an example from uranium, which fuels atomic reactors, there are two isotopes with the same atomic number 92 and different mass numbers 235 and 238 (U-235 and U-238). The number of neutrons is 143 for the former and 146 for the latter. Almost all naturally occurring uranium is U-238, and only a very small percentage of it (0.7%) is the fissile U-235. There are other uranium isotopes.

The nucleus of ${}_1^3H$ (T), consisting of a proton and two neutrons, naturally decays with a certain probability and emits electrons "e^-" (with negative charges). The emission of these electrons is called the beta ray. During the decay process, one of the neutrons changes to a proton, and the nucleus of He-3 (${}_2^3He$) consisting of two protons and a neutron, is obtained. In this process, the atomic number changes from 1 to 2, and the element changes from hydrogen to helium. This process is written as

$$ {}_1^3H \rightarrow e^- + {}_2^3He $$

This nuclear reaction is called *beta decay*. As is indicated in Table 2.1, the mass number 3 does not change because the mass of the emitted electron is negligible.

The nucleus's property of emitting electrons, as in the above case, is called radioactivity, and elements with radioactivity are called radioactive elements.

There are several kinds of radioactivity. First, let us explain alpha activity, in which the alpha ray (helium nuclei ${}_2^4He$ flying at high speed) is emitted. In this *alpha decay*, the original nucleus loses two neutrons and two protons (so its mass number is reduced by four) and two positive charges (so its atomic number is reduced by two). Table 2.1 illustrates this point. Because an alpha ray has a far larger mass (in other words, is heavier) than a beta ray (electron), its penetration power is so limited that it can be shielded with paper. However, if it is emitted from a substance that was taken into the human body, it severely affects surrounding living tissues.

Each radioactive nucleus has its own decay time. The time during which the number in the radioactive nuclei reduces to half the initial number is called the half-life. (The units of radioactivity are the becquerel, Bq or curie, Ci.) Changes in radioactive intensity are related to this half-life. After each period equal to the half-life, the intensity of radioactivity decreases by a factor of two.

Radioactivity and radiation

The terms radioactivity and radiation are often confused and erroneously used.

Radioactivity is "the property of emitting radiation spontaneously." Because it is a property, expressions such as "radioactivity leaked" and "be exposed to radioactivity" are erroneous. They should be expressed as "radioactive substance (or radioactive element) leaked" and "be exposed to radiation", respectively. Specialists and journalists in particular should be careful with terminology.

The radiation emitted during a nuclear reaction is divided into the electromagnetic wave and the particle beam. The electromagnetic wave is in the same continuum as light rays, and waves with very short wave length are called gamma rays.

Visible light rays are also electromagnetic waves that are sometimes produced from chemical phenomena or chemical reactions with an energy range on the order of eV. In contrast, gamma rays are produced from nuclear reactions with an energy level of MeV (tens of thousands to a million times larger than the former); and they have energy in the MeV range. X rays (from several to several tens of keV) are also electromagnetic waves.

Other examples are the proton beam and the neutron beam, which consist of protons and neutrons, respectively.

The reality of nuclear energy

What about nuclear reactions? Some important examples the reader should understand are alpha decay and beta-decay, mentioned previously. In these decays, unstable nuclei spontaneously undergo nuclear reactions and change into other nuclei. Strictly speaking, this reaction should be called a nuclear chemical reaction because the atomic number changes and a chemically different element appears. The universe is a system in which atomic nuclei are perpetually changing and moving through nuclear chemical reactions.

One of the other general reactions is a neutron-related reaction. Because neutrons have no electric charges, they are unaffected by electric repulsion and therefore are easily accessible to and absorbed by the nucleus. As a result, the weight of the nucleus (mass number) increases by one but the atomic number does not change. Generally, however, the nucleus becomes unstable and radioactive. In many cases, the element changes as a result of beta-decay or alpha decay.

In nuclear fission reactions, a major concern of this book, uranium (and other nuclides) absorbs neutrons, induces fission, and splits into two nuclei—one with a mass number of around 100 and the other with one of around 140. Generally, both are unstable radioactive elements. Nuclear fission will be further described later.

Actually, nuclear energy is *nuclear (chemical) reaction energy* produced from the nuclear reaction. If the nucleus changes, its mass changes subtly. If the total mass is decreased, then the mass difference is emitted as energy. This is described in Einstein's theory of relativity. Theoretically, if the entire mass of a hydrogen nucleus (a proton) is converted into energy, an energy quantity of 931 MeV will be obtained. (This corresponds to 4.5 times the energy obtained from nuclear fission, but such a conversion has not yet been achieved.)

Not all atomic nuclei are equally stable. The foundation of nuclear chemistry, established in the first half of the 20th century, made it possible to compare the stability of various nuclei. This is shown by the "curve of the nuclear binding energy" in Figure 2.1. The binding energy is divided by the mass number of the nucleus to indicate the binding energy per nucleon (proton and neutron). In this figure, a nucleus plotted in a lower position is more stable than one plotted in a higher position. The most stable nuclei with the lowest positions are iron and nickel, whose mass numbers are about 60. Accordingly, the terminal points of the material changes in the universe are iron and nickel. This is the reason meteorites falling from space are made of iron. They are the result of exploded stars. It is believed that the central part of the earth is composed of iron and nickel.

Generally, nuclear chemical reactions proceed toward stability. Changes in elements and materials occur along these two directions. Various elements are interrelated through these nuclear chemical changes. The fact that nuclear energy is the product of "chemical" reactions is an essential point to bear in mind throughout this book. A nuclear power plant (power plant that uses and produces nuclear energy) is a *facility for chemical reaction*. To remind the readers of the chemical properties of various elements, the periodic table of elements is shown in Figure 2.2.

What is nuclear fission?

Now let us turn our attention to nuclear fission reaction, our main subject.

Nuclear fission is a very peculiar type of nuclear reaction. The heaviest naturally occurring element is uranium (U, atomic number 92), and one of its isotopes with mass 235 (U-235) easily undergoes nuclear fission. Its nucleus is composed of 92 protons and 143 neutrons; these elementary particles are in random motion in the nucleus, just like molecules in a liquid. It is convenient to think of the nucleus as a round drop of liquid.

If another neutron comes in from outside, quite a strange phenomenon occurs. The liquid drop suddenly begins dancing erratically, and then the central part becomes constricted. Figure 2.3 illustrates how the nucleus eventually splits in two and emits two or three neutrons. An atomic nucleus that readily fissions is called a fissile nuclide.

Those two fragments of the split nucleus (fission products) are not exactly the same. They belong to two groups of atomic nuclei, one with a weight of ~85 to 110, and the other, ~130 to 150. As shown on the right side of Figure 2.1, nuclear fission causes the total system to shift towards a more stable state (atomic groups). It should be noted that not all heavy nuclei on the right of the figure are fissionable; those nuclei that easily fission are limited to certain ones like U-235. However, if the energy of the incident neutron is very high, various heavy nuclei become somewhat fissionable.

When U-235 fissions, the emitted neutrons are absorbed by other U-235 nuclei and induce fission chain reactions in the U-235 material. If this chain reaction is controlled so that it repeats continuously, it is called "critical mass" (or a critical state). If each successive reaction is more numerous, it is called super critical. Uncontrolled and explosive chain reactions are utilized for weapons, e.g., atomic bombs. In the process of this chain reaction, artificial radioactive elements heavier than uranium (such as plutonium, Pu, atomic number 94 and americium, Am, atomic number 95) are produced. These are called the transuranic elements. Figure 6.2 depicts the process of U-235 reactions. In addition, transuranic elements have the ability to spontaneously fission without absorbing neutrons. This ability is usually weak; the half-life is longer than a trillion years for many transuranic elements.

However, the half-life Pu-240 is 6,500 years (relatively short), and it provides many neutrons that cause a premature explosion. Thus, the design of a plutonium atomic bomb that contains at least some Pu-240 is more difficult than a uranium bomb. This will be discussed in Chapter 10.

Although the only naturally occurring nucleus that fissions easily with slow neutrons (i.e., low-energy neutrons) is U-235, fissionable nuclides can be produced from nuclear reactions. Thorium, atomic number 90 (Th, Th-232), is the second heaviest naturally occurring element. Although this element is not well known, it is one of the main subjects of this book and a very important resource. Now, if a neutron is absorbed by this Th-232 or by U-238 (the chief ingredient of natural uranium—99.3% share and non-fissionable), the thorium and uranium become Th-233 or U-239, respectively. After two consecutive beta-decays (i.e., successive transformations of two neutrons into two protons, increasing the atomic number by two) they finally become U-233 and Pu-239. These are artificial fissionable nuclides. Figure 6.1 illustrates this transformation. The raw materials Th-232 and U-238 are called *fertile* material.

Materials produced from fission (fission products and neutrons) are emitted at high speed. Furthermore, they are accompanied by a large quantity of gamma rays and other radiation. These materials and radiations gradually lose their speed and energy while influencing surrounding materials through collisions (mechanical momentum exchange or electromagnetic interactions). The surrounding materials acquire energy, and their temperatures rise. Their chemical bonds are broken by the collisions, and atoms are pushed out of their regular positions and affect neighboring atoms. Molecules are broken apart and regular crystal patterns are disrupted. These phenomena are called *radiation damage*.

In explaining nuclear fission, there is one more very important point. In a reactor that uses uranium fuel, for example, some of the neutrons generated from fission of U-235 participate in the continuing chain reaction of U-235 and some of the neutrons are absorbed by non-burnable (non-fissionable) U-238. The absorbed neutron then converts U-238 into a fissile Pu-239. While burning fuel by fission, new fuel is generated. Thus, a part of the fuel consumed from fission is replenished.

The regeneration of the fuel is described by its conversion ratio. The conversion ratio is 1 when the burned fuel equals the replenished fuel. If the conversion ratio is larger than one, the new fuel obtained exceeds self-sufficiency, and *breeding* is attained. A power reactor that can achieve breeding is called a breeder power reactor. In an ordinary nuclear reactor, breeding cannot be achieved because the conversion ratio is low. However, if breeder reactors were built and the regenerated fissile nuclides were gathered through chemical treatment, it would be unnecessary to buy nuclear fuel abroad. To avoid or minimize importing uranium and secure a self-sufficient supply of energy resources, it was argued that breeder power reactors were indispensable. This motivated construction of the prototype fast breeder reactor: MONJU. Some people consider it the ideal power reactor. It is an illusion that breeder power reactors are necessary for the survival of the world. This will be discussed in Chapter 8.

The above section has presented an outline of the nuclear fission reaction. The question of whether we can effectively utilize this phenomenon is the main theme of this book. Let us address nuclear fusion, which is being considered as a substitute for future fission reactors.

The mechanism of nuclear fusion

In nuclear fusion, two nuclei are combined to produce energy. This is exactly the opposite of fission and can be understood from the left-hand part of the curve in Figure 2.1. If light two nuclei combine with each other to make a heavier nuclide, they will become more stable. Energy is produced in amounts corresponding with the degree of improved stability. This is nuclear fusion and can be accomplished with light nuclei.

However, when fusing, the two nuclei approach each other against the strong repulsive force between their positive electric charges. This requires enormous temperature (several or several tens billions of degrees centigrade) and tremendous gravity (pressure), similar to the sun or other fixed stars.

The best fusion reaction for energy production and a low temperature requirement occurs between the nucleus of heavy hydrogen (deuterium—a proton and a neutron: D) and tritium (tritium—a proton and two neutrons: T). This reaction produces a helium nucleus (two protons and two neutrons: He) and is abbreviated as DT nuclear fusion. It requires heating to about 100 million degrees centigrade (10 keV), as shown in Figure 2.4. Unlike nuclear fission reactions, where heating was unnecessary, the required heating energy for fusion reactions is large and poses a serious difficulty. Tritium disintegrates with beta decay at a half-life of 12.3 years. Because only a very small amount of tritium exists in nature, it must be produced from lithium (Li, atomic number 3) using reactions with neutrons, as described in Chapter 5.

In addition, the quantity of heat generated in fusion reactions is only one-tenth of that generated in fission reactions. Though a glance at Figure 2.1 might give the opposite impression, the plotted value in the figure is the energy produced per nucleon (proton and neutron). In the case of DT fusion reactions, because the mass of the formed nucleus helium is four, the energy produced per reaction is 4.4 MeV x 4=17.6 MeV. In the case of U-235 fission, it is about 0.9 MeV x 235= about 210 MeV. Thus, the fusion energy is less than one-tenth of fission energy on a per reaction basis.

Furthermore, the energy of the generated neutrons is 1 to 2 MeV for the fission reaction and about 14 MeV for the DT fusion reaction. In other words, the latter is ten times more energetic than the former, making the design of the reactor more difficult. Radiation damage to a reactor vessel exposed to high-speed neutrons reduces its lifetime.

Super-high temperature deuterium D and tritium T are in a state of ionized gas (plasma) in which the electrons around the nuclei have been peeled off. The nuclear fusion reactions proceed in this state.

After World War II, the U.S. and USSR studied DT nuclear fusion as an adjunct to H-bomb development, to produce plutonium for atomic bombs. The extra fast neutrons generated from nuclear fusion were predicted to be a good way to make plutonium from natural uranium. However, controlled fusion proved difficult. At the opening of the 1955 International the Conference on the Peaceful Use of Atomic Energy, Chairman Bhabha of India put these military studies in perspective. He shook the world by saying, “the peaceful use of nuclear fusion energy will start in 20 years.” However, about 45 years went by without any breakthrough. In 1969, the Soviet Union reported an excellent result from a device (tokamak) that used magnetic fields to confine plasmas.

Thereafter, DT nuclear fusion was widely advertised as being cleaner and safer because it did not use uranium or plutonium and did not produce nuclear wastes, such as fission products. Thus, fusion research investment was made all over the world. However, tritium T, which plays the main part in the reaction, is a radioactive material with a beta decay half-life of 12.3 years. Furthermore, the hydrogen isotope T is difficult to confine. At high temperatures, it easily penetrates various metals. Further, this dangerous radioactive substance is easily absorbed by living bodies.

Nuclear fusion faces pre-technological problems

Nuclear fusion has some fundamental problems. Nuclear fusion researchers claim that if they can successfully confine light nuclei in the plasma state, they will be able to promote nuclear fusion. However, it is worrying that the theoretical basis of plasma physics has not yet been established, and it is not clear when it will be established. This has led to a proposal to build a large device called the International Thermonuclear Experimental Reactor (ITER) with international cooperation at the cost of a trillion yen (the cost has since been halved). A smaller facility would not reveal the basic nature of the phenomena.

From about 1970 to 1980, the author took up the challenge of developing fusion reactors and led studies on the utilization of molten-salt. Molten-salt, one of the subjects of this book, is a kind of liquid, and is described later. However, the authors believe fusion reactors pose excessive problems in plasma physics and reactor chemistry (including structural materials) such as radiation damage and nuclear transmutation. They judged that realization had no prospect for several decades and returned to the study of nuclear fission utilization. Such argument is the general trend worldwide.

Although the Japanese government has spent a large sum of money (850 billion yen) for research, progress has been unsatisfactory and no practical design is near at hand. Over the last ten years, the worldwide investment has steeply dropped for fusion, and fission research as well; Japan is the only exception. How should this be viewed? Although the annual government budget for fission and fusion power is about 300-billion yen (more than ten times that of European countries), the Japanese energy policy lacks focus.

The so-called experimental reactor ITER does not correspond to the pilot facilities of a commercial plant, as defined in the age of fission reactor development. The experimental reactor is not a complete power plant and will require another large facility before a commercial plant is built. Furthermore, such a facility should not be so enormous at the early stage of development. To obtain economical energy, new research approaches are required. Nuclear fusion remains at the research stage.

However, if new inventions and designs should succeed—and neutrons are obtained economically from DT nuclear fusion—it is hoped that they will be used to convert Th-232 to U-233. By about 2030, the new designs could supply fuel for new molten salt reactors. The implication of this will be described in Chapter 8. It must not be forgotten that the study of nuclear fusion started from the fierce covert competition between world powers. Their aim was an effective method for obtaining neutrons and manufacturing nuclear bomb materials. This occurred during an age of nuclear bomb shortage, immediately after World War II.

The universe is a system of nuclear reactions

The universe is a system in which stars emerge and change during nuclear reactions. The source of constant change is nuclear energy. Solar energy is also generated from a nuclear fusion reaction in which hydrogen becomes helium.

Various types of radiation (including light and heat) flow from the universe onto the earth's surface. In addition, the decay of radioactive elements (i.e., potassium, thorium, and uranium) produces radiation that emerges from underground. Usually we receive from one to two milli-sieverts of radiation per year. The intensity of this natural radiation varies from place to place. Creatures on this planet remain healthy with this amount of radiation; indeed, without it, complex physiological abnormalities would result.

The earth's moderate terrestrial heat creates appropriate environments for living things without affecting them adversely. Examples include the alternation of day and night and the seasons. Terrestrial heat is produced from terrestrial nuclear energy. Early in the earth’s creation, almost all the terrestrial heat depended on the decay heat of U-235 and K-40. Since then, the total number of radioactive elements has decreased to about one-sixth. However, even now most terrestrial heat comes from the decay heat of U-238 (with a 4.5-billion-year half-life) and Th-232 (with a 14-billion-year half-life). About 15 % of terrestrial heat is from K-40 (1.26-billion-year half-life). The total amount of decay heat from these terrestrial radioactive elements is about twice as high as the total heat which people generate by burning fuel. Therefore, we already use heat from natural nuclear processes as an energy source.

Once upon a time, there was a natural fission reactor!

We live in a universe that is a nuclear chemical reaction system. Medical facilities and engineering professions benefit from radioactive substances and radiation. There are indeed practical uses for nuclear science.

Some people believe that using nuclear fission reactions is arrogant behavior that defies the natural order. However, once upon a time, natural nuclear fission reactors existed on this earth. They operated about two billion years ago in the Oklo uranium mines of the Gabon Republic, West Africa [“The Oklo Phenomenon”, Proc. Symp. Livreville, 23-27,June 1975 (1975) IAEA].

In 1972, a French mining engineer discovered ore with an abnormally low concentration of U-235. It has been confirmed that reactors had been operating at more than 16 spots. The first cluster discovered (six spots) probably generated heat equaling the current annual capacity of five one-GW nuclear power plants. The total quantity of U-235 consumed by fission was about six tons.

Nuclear fission reactors could exist naturally because the half-life of U-235 is 700 million years (shorter than the 4.5 billion years of U-238). Thus, two billion years ago, the concentration of U-235 in total uranium was 4%, higher than the 0.7% of today. This concentration (enrichment) of U-235 is the same as the 3-4% enrichment of typical light water reactor nuclear fuels. It is possible that rain water penetrated the system and acted as the neutron moderating material (slowing down of neutrons), making the system critical. This would have caused a continuous nuclear fission chain reaction. Proving this hypothesis requires a careful examination of the uranium ore purity. When heat is generated, the water of the moderating material evaporates, and the reactor stops. It is probable that these phenomena were repeated (the meaning of slowing down and moderation will be explained in the middle of the next chapter).

Natural nuclear fission reactors are not science fiction. They are important because they show how easy it is to make nuclear fission chain reactions. Many Japanese know about the chain reactions from the U-compound precipitation tank of a Tokai-Mura factory: the careless criticality accident in September 1999.

The late Kazuo Kuroda, an excellent radio-chemist, predicted the possibility of natural nuclear fission reactors in 1956 [J. Chem. Phys., **25**(1956) 781,1295], 16 years before their discovery. He died at the time of this book writing (April 2001). Though he eventually became a naturalized American, he was educated at Tokyo University, Department of Chemistry, and he hoped that “Japan should be considered the origin of the theory of the natural reactor”[Kuroda, 1977].

Further, the nuclear chemical reaction could be called a modern form of alchemy because it transforms elements. Whenever I say this, I am often asked, “Is it possible to change mercury into gold? Can you do it?” Unfortunately, contrary to the desires of medieval chemists, it is obviously impossible. However, it is quite simple to do the reverse—change gold into mercury. If gold is inserted into the core of a modern nuclear power reactor for a year, about half of it changes into mercury. God seems to be mischievous.