Tetsuo Tanabe *Editor*

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Preface

After long and significant efforts of researchers on plasma confinement to realize controlled D-T nuclear fusion on Earth, now the International Tokamak Experimental Reactor (ITER) will soon be ready to demonstrate the fusion reaction producing energy. This research has taken a longer time in comparison with the rapid construction of successful nuclear fission reactors following the discovery of energy release in nuclear reactions. Nevertheless, to realize the fusion reactor as an energy source, many engineering–technological issues remain to be solved. It is unnecessary to say that the most important point is that the fusion reactor must be economically beneficial. The initial or capital cost to construct the fusion reactor is unavoidable, and most of the cost estimates so far indicate that a fusion reactor could be economical and repay its capital investment. But additional costs related to tritium fuel, or to sustaining fuel self-sufficiency in a D-T fusion reactor, and the trade-offs between tritium breeding and electricity production (or energy conversion) and tritium safety, are not small, and considerable effort will be required to reduce these costs. The main purpose of this book is to summarize recent efforts to establish fuel self-sufficiency in a D-T fusion reactor with strict regulation of tritium safety.

In 2013, a book entitled *Tritium in Fusion*, edited by S. Tosti and N. Ghirelli (Nova Publishers, NY, ISBN 978-1-62417-270-0) was published. It focused on the production and treatment of tritium in nuclear fusion equipment and aspects of measurements, dose assessment, and safety of tritium. The present book focuses on more practical aspects to realize a fusion reactor as an energy source. There is no doubt that safety is a concern in the tritium handling system described in the book cited above. To realize the fusion reactor as an energy source, however, there are additional issues related to tritium as a fusion fuel, and those are the subjects of the present book.

Although a tritium handling system has been established for military use, the system might not be directly applied to tritium systems for a fusion reactor, because the amount of tritium to be handled in the latter is much larger than in the former. In addition, owing to its limited availability, full recovery of tritium handled in any tritium subsystems in the fusion reactor is mandatory. For safety, tritium removal is

always required in any existing tritium handling system and removed tritium can be disposed of, whereas loss of tritium in the fusion reactor directly influences its fuel self-efficiency. Therefore, a significantly different approach is required in designing tritium handling in the fusion reactor.

This book is devoted to giving readers an idea and understanding of the characteristics of tritium for fusion in Part I, the current status of R&D on tritium fueling (including breeding) systems in Part II, and consideration of tritium safety in Part III.

In Part I (Chaps.1–5), Chap. 1, is an introductory chapter describing a fusion reactor focusing particularly on the use of tritium as a fuel, followed in Chap. 2 by the introduction of characteristics of tritium as a radioactive isotope of hydrogen. Chapters 3–5 summarize present knowledge of fuel (tritium) behavior in a fusion reactor. Because there is no reactor and tritium burning has not been realized yet, we have to extrapolate all present knowledge obtained from experiments and theories on large tokamaks of JET, JT-60U and TFTR, on various medium-size tokamaks, and in laboratory experiments on tritium behavior in reactor-size machines such as ITER and future power reactors. Chapters 3–5 thus describe overall tritium flow, tritium burning, and the behavior of fuel in a reactor, respectively.

In Part II (Chaps. 6–14), details of tritium handling and processing systems for tritium fueling and recycling maintaining tritium safety are described. Fueling is the key to maintaining burning plasma, as explained in Chap. 6. Both for tritium safety and fueling, tritium accountancy and measurements are indispensable, as described in detail in Chaps. 7 and 8. As discussed in Chap. 8, tritium measurement in plasma is not well established, and significant efforts are required. Tritium must be confined in any tritium handling system. Easy permeation by tritium of structural materials resulting in tritium contamination is a serious concern, noted in Chaps. 9 and 10. Isotope separation, explained in Chap. 11, is indispensable for fueling. To establish fuel self-efficiency, tritium breeding, and recovery are major concerns as set forth in Chaps. 12 and 13.

In Part III, major issues related to tritium safety are discussed. Chapters 14 and 15 deal with safety confinement of tritium and behavior of tritium released into the environment, with the important note that tritium safety for the public would be a minor concern in a fusion reactor.

This book is dedicated to the late Prof. Emeritus Masabumi Nishikawa of Kyushu University. During the editing process, we missed him who, as one of the most active tritium scientists in the world, had devoted significant effort to the initial editing of this book. His distinctive works on tritium breeding and tritium fuel systems for a fusion reactor were often referred to by numbers of scientists and engineers in many fields, not only tritium science and technology, but also plasma physics and reactor engineering and design. All authors of this book acknowledge his great work and leadership worldwide in tritium science and technology.

Finally, the editor wishes to thank all the authors for their qualified contributions to this book and acknowledges the support by Grant-in-Aid for Scientific Research, Ministry of Education, Culture and Sports, Priority area 467, “Tritium for Fusion” No. 19055008.

Fukuoka, Japan Tetsuo Tanabe

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Part I
Current Status of R&D on Tritium Fueling (Including Breeding) Systems

Chapter 1
Introduction of a Nuclear Fusion Reactor

Tetsuo Tanabe

Abstract Most of energy resources on the earth are originated from energy given by the sun in which all energy is produced by nuclear fusion reactions. To build a small sun or to realize controlled fusion as an energy source on the earth has been a dream of human being. Owing to extensive research and development, the fusion reaction of Deuterium (D) and Tritium (T) soon comes in burning phase. Nevertheless, to realize a D–T fusion reactor as an energy source, lots of engineering issues still remain to be solved. Among all, T-relating issues are quite important, because T is hazardous due to its radioactivity and its resources are quite limited. In this chapter, after the introduction of nuclear fusion reactions, issues relating T to establish the D–T reactor as an energy source are summarized.

Keywords Fusion reactor · Fuel cycle · Tritium · Deuterium · T processing

1.1 Nuclear Fusion Reactions as an Energy Source

All energy on the earth except geothermal and tidal energies, and nuclear fission is originated from nuclear fusion in the sun. As shown in Fig. 1.1, nuclear fusion reactions in the sun are complicated but, as a whole, are represented by

$$4\mathrm{p} + 2\mathrm{e}^- = {}^4\mathrm{He} + 6\gamma + 2\nu + 26.65\,\mathrm{MeV}, \tag{1.1}$$

where p, e^-, ^{4}He, γ, and ν are a proton (an ionized hydrogen (H) atom), an electron, a Helium atom, gamma ray, and a neutrino, respectively [1]. Ordinary Hydrogen (H)[1]

[1]"Hydrogen" generally represents all hydrogen isotopes which are referred as protium (H), deuterium (D) and tritium (T), and proton (p), deuteron (d) and triton (t) for respective ions.

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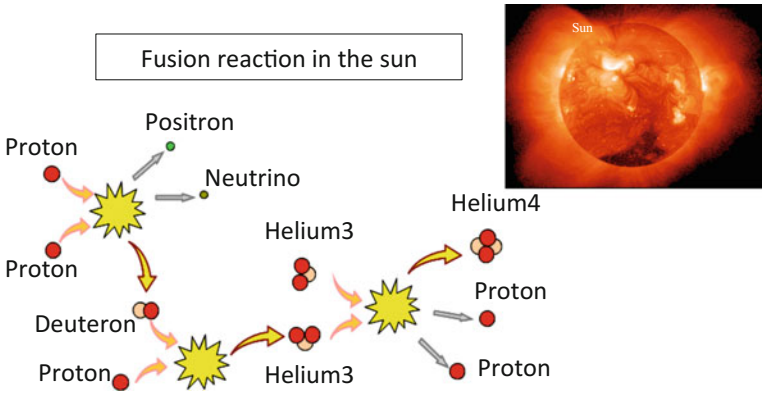

Reaction			Energy	Reaction time
$p + p$	→	$D + e^+ + \nu$	+ 0.4 MeV	14 Billion year
$e^+ + e^-$	→	2γ	+ 1.0 MeV	10^{-19} sec
$p + D$	→	$^3He + \gamma$	+ 5.5 MeV	5.7 sec
$^3He + {}^3He$	→	$^4He + 2p$	+ 12.85 MeV	100 Million year
			Sam	
$4p + 2e^-$	→	$^4He + 6\gamma + 2\nu$	+ 26.65 MeV	

Fig. 1.1 Fusion reactions in the sun

is the most abundant element in the sun (around 75 %) and the universe as well. H exists everywhere on the earth as the tenth abundant element with 0.14 % in weight and the third element in a human body (10 %) essentially as H_2O (water) [2]. Therefore, to realize this nuclear fusion as an inexhaustible source of energy for future or to make the sun on the earth has been a dream. Not only because fossil fuels presently used, such as petroleum, coal and natural gas, are exhaustible but also because the use of the fossil fuels inevitably results in the emission of carbon dioxide (CO_2) and global warming is serious concern. But the dream has not easily come to true.

Various nuclear reactions, both fission and fusion reactions, are energy sources of stellar stars in space. In general, lighter elements can fuse and heavier elements are fissionable, if they are in high-energy state like in the stellar stars, as shown in Fig. 1.2. As depicted in the figure, iron (Fe) is the most stable element and mass differences (ΔM) of reactants and products are converted to energy (E) according to famous Einstein's equation,

$$E = \Delta M \times c^2, \tag{1.2}$$

where c is the velocity of light. Operation of a D–T fusion reactor producing the fusion power of 1 GW for 1 year burns only 55.6 kg of T and 37 kg of D.

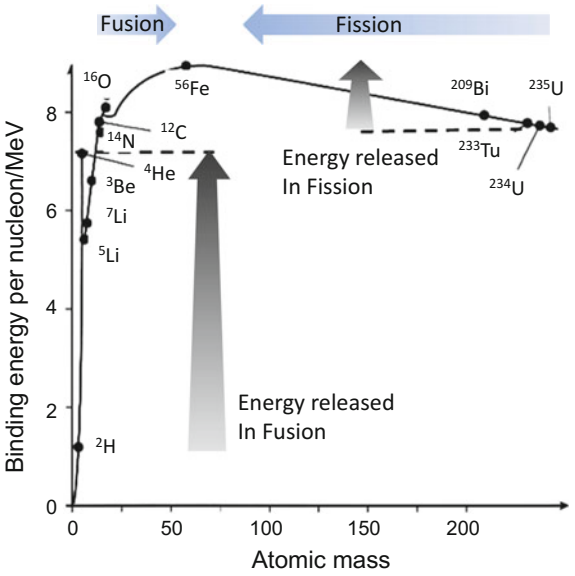

Fig. 1.2 Nuclear energy released as a function of atomic mass

As for fusion reactions, there are quite many different fusion reactions. However, reactions using D, T, ^{3}He, ^{6}Li, ^{7}Li, and ^{11}B as fuels

$$\mathrm{D} + \mathrm{T} = \mathrm{n} + {}^{4}\mathrm{He} + 17.6\,\mathrm{MeV} \tag{1.3}$$

$$\mathrm{D} + \mathrm{D} = \mathrm{p} + \mathrm{T} + 4.03\,\mathrm{MeV} \tag{1.4}$$

$$\mathrm{D} + \mathrm{T} = \mathrm{n} + {}^{3}\mathrm{He} + 3.27\,\mathrm{MeV} \tag{1.5}$$

$$\mathrm{T} + \mathrm{T} = {}^{4}\mathrm{He} + 2\mathrm{n} + 11.3\,\mathrm{MeV} \tag{1.6}$$

$$\mathrm{D} + {}^{3}\mathrm{He} = \mathrm{p} + {}^{4}\mathrm{He} + 18.3\,\mathrm{MeV} \tag{1.7}$$

$$\mathrm{T} + {}^{3}\mathrm{He} = {}^{4}\mathrm{He} + \mathrm{D} + 14.3\,\mathrm{MeV} \tag{1.8}$$

$$\mathrm{p} + {}^{6}\mathrm{Li} = {}^{3}\mathrm{He} + {}^{4}\mathrm{He} + 4.0\,\mathrm{MeV} \tag{1.9}$$

$$\mathrm{p} + {}^{7}\mathrm{Li} = 2{}^{4}\mathrm{He} + 17.4\,\mathrm{MeV} \tag{1.10}$$

$$\mathrm{p} + {}^{7}\mathrm{Li} = {}^{7}\mathrm{Be} + \mathrm{n} - 1.6\,\mathrm{MeV} \tag{1.11}$$

$$\mathrm{p} + {}^{11}\mathrm{B} = 3{}^{4}\mathrm{He} + 8.68\,\mathrm{MeV}, \tag{1.12}$$

seem to be realized on the earth.

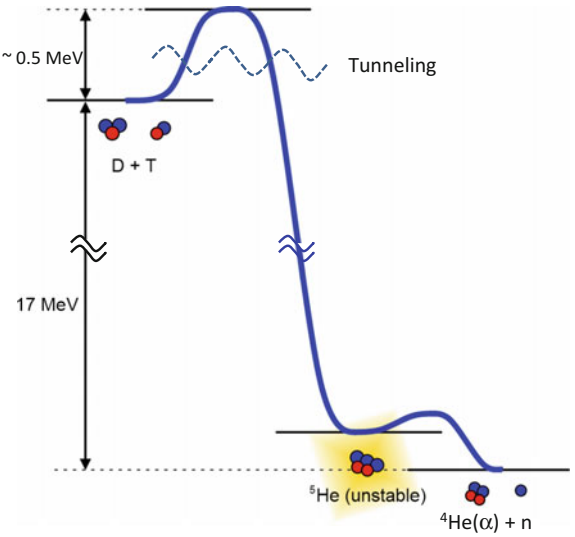

Fig. 1.3 Intermediate energy states of the DT fusion reaction

To induce these fusion reactions, reactants must be in higher energy states to overcome repulsive Coulomb force between them. Figure 1.3 shows energy states of the reactant and product for the D–T reaction (1.3) indicating the existence of around 1 MeV of Coulomb barrier between D and T to be overcome [1]. The reaction cross sections or the reaction rates are energy dependent as shown in Fig. 1.4 which gives 9 reactions having higher cross sections [2, 3]. Among all, the D–T reaction (1.3) requires the least energy to give the highest cross section at around a few tens keV. Because of the tunneling effect, energy required to induce the D–T reaction is much less than the Coulomb barrier of 1 MeV in Fig. 1.3. Therefore, realization of a D–T fusion reactor is the principal goal of the present fusion research.

Unfortunately, however, one of the reactants of the D–T reaction, T, is hazardous owing to its radioactivity. In addition, one of the products, neutron (n), activates structure materials such as ferrite and martensite steels to be radioactive and more hazardous than T. Furthermore, as described in the next chapter, T resources are very limited and artificial production or breeding of T in the reactor to satisfy fuel self-sufficiency is essential.

In the aspect of safety, any fusion reactions in which T and n are not involved would be better than the D–T fusion. In this respect, the D-^{3}He reaction (1.7) which has the 2nd largest cross section as seen in Fig. 1.4 is very much attractive. Although the abundance of ^{3}He, an isotope of ordinary ^{4}He, is very poor on the earth with the abundance ratio of 1.37×10^{-4} %, a fair amount of ^{3}He exists on the surface of the moon and Venus. Hence, there is an ambitious plan to recover ^{3}He from them or build D-^{3}He reactors at their surfaces. In the D-^{3}He reactor, however, a fair amount of T is always produced by D–D reactions (1.4) and accordingly T

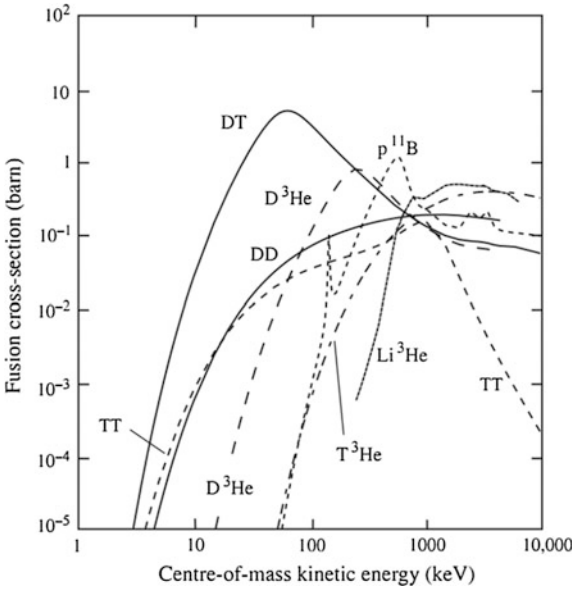

Fig. 1.4 Cross sections of various fusion reactions

handling systems similar to the D–T reactor are required for T to separate from the exhaust and to store safely.

Fusion reactions using Li and/or B as fuels [reactions (1.9–1.12)] are very much attractive. Natural lithium consisting of ^{6}Li (natural abundance ratio of 7.5 %) and ^{7}Li (natural abundance ratio of 92.5 %) is quite abundant in nature when recovery of lithium from the sea water is developed. Natural boron consisting of ^{11}B (natural abundance ratio of 80 %) and ^{10}B (natural abundance ratio of 20 %) is also abundant on the earth. Nevertheless, such fusion reactions require nearly 1000 keVplasma as seen in Fig. 1.4, which is far beyond the present research.

Thus, the establishment of the D–T fusion reactor is the primary goal. Various issues still remain and they are relating to the establishment of burning plasma, plasma materials interactions, materials, fuel cycles, power generation, T breeding, safety, and the reactor construction as the final target. This book focuses on the issues related to the fuel of tritium [4].

1.2 Development of the D–T Fusion Reactor

To induce the D–T reaction, D and T must be heated or in higher energy state as shown in Fig. 1.3. Since energetic particles are usually in ionized states and easily dissipated by electrostatic repulsive forces between them, they must come together over the Coulomb barrier or to be confined to continue the fusion reactions.

In order to overcome the Coulomb barrier between D and T, the fuel particles must be heated to a temperature of around 25 keV or 300 million degrees, under which conditions they are ionized and exist as plasma, a mixture of electrons and ions. To continue the fusion reactions, in addition, sufficient density and energy confinement are required, as specified by the Lawson criterion, or minimum value of [ion density (n_i) multiplied by energy confinement time(τ_E)] for self-heating for fusion reactions. For DT, n_i x τ_E minimizes to be $10^{20}/m^3$ s near the temperature 25 keV. Two different methods have been developed to confine or plasma, i.e., a magnetic confinement fusion (MCF) system and an inertial confinement fusion (ICF) system. Brief introduction of the both systems is given below. It is out of scope of this book to describe details of MCF and ICF.

1.2.1 Magnetic Confinement Fusion (MCF)

In MCF, high-energy plasma is contained in magnetic field by using the electrical conductivity of the plasma. The basic concept can be described by a fluid picture as a balance between magnetic pressure and plasma pressure, or in terms of individual particles gyrating along magnetic field lines. The simplest magnetic configuration is a solenoid, a long cylinder wound with magnetic coils producing magnetic field which forces electrons and ions to run parallel to the axis of the cylinder. The field confines them radially but allows escaping from the ends of the solenoid. To avoid the escaping or loss of them, various confinement schemes are proposed and two major confinements are now extensively studied, a tokamak system and a stellarator system.

Figure 1.5 shows the principle of the tokamak in which a large volume of high-temperature plasma is produced and confined in a toroidal shape by means of strong magnetic fields [5]. The original design principle was developed at the Kurchatov Institute in Moscow in the 1960s, and the tokamak system has become the most advanced magnetically confined fusion concept in the world. Figure 1.6 shows the fusion triple product ($n_i \times \tau_E \times T_i$ (ion temperature)) achieved on different magnetic fusion facilities [6]. Each decade from 1970s to 1990s has given the gain in the triple product more than one order of magnitude to come close to the Lawson condition. Now ITER (International Thermonuclear Experimental Reactor) is under construction at St. Paul Lez Durance, France and will be ready within a several years to attain breakeven for energy production, i.e., the ratio of fusion energy output to input power (Q) is one ($Q = 1$). And $Q = 10$ is the goal for ITER. Now, DEMO (DEMOnstration Power Plant) is designed as a prototype commercial fusion reactor in several countries [7, 8].

The biggest stellarator machine is Large Helical Device (LHD) in National institute of Fusion Science in Japan [9], and the design activity to realize a reactor with the stellarator is under progress [10].

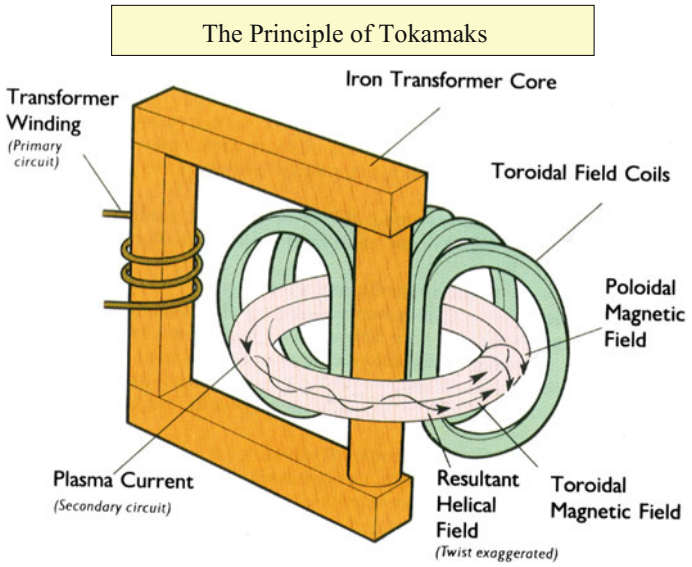

Fig. 1.5 Principle of Tokamak [5]

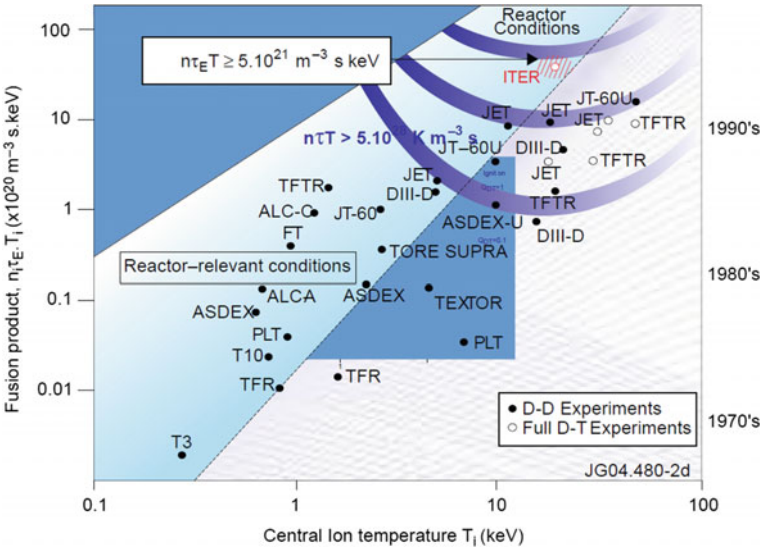

Fig. 1.6 Plasma confinement achieved on different fusion facilities, represented by triple product ($n_i \cdot \tau_E \cdot T_i$); n_i ion density, τ_E Energy confinement time, T_i ion temperature (reprinted with permission from [5]). The fusion triple product achieved on different magnetic fusion facilities. The graph shows clearly that new facilities performed better than previous ones. The present large machines, from the point of view of the fusion product, have now achieved their engineering limits so that only the next step facility, ITER, can bring about decisive progress

1.2.2 Inertial Confinement Fusion (ICF)

In ICF, nuclear fusion reactions are initiated by heating and compressing a fuel target, typically in the form of a pellet which contains fuel, a mixture of D and T (see Fig. 1.7) [11]. To compress and heat the fuel, energy is delivered to the outer layer of the target using high-energy beams of laser light, electrons, or ions. (Most of present ICF devices use lasers.) The heated outer layer explodes outward, producing a reaction force against the remainder of the target, accelerating it inwards, compressing the target. This process is designed to create shock waves that travel inward through the target. When the input power is sufficient enough to compress and heat the fuel at the center, fusion reactions start. The energy released by the reactions will then heat the surrounding fuel to undergo fusion reactions. The principle was realized as a hydrogen atomic bomb in 1952. But the bomb is uncontrolled energy release and cannot be the energy source of the daily life. In ICF, nuclear fusions should be controlled as the energy source. Extensive works have been done to produce a condition known as "ignition" or fulfill the Lawson condition fusing a small fuel pellet, which is a millimeter-sized pinhead and contains around 10 milligrams of D–T fuels. NIF (National Ignition Facility) at Livermore CA, USA, is now under operation to demonstrate ICF being the energy source [12]. At present, its energy gain seems too small for ICF to be energy source.

Tritium technologies required for ICF are very similar to, or a little simpler than those for MCF, and most of tritium systems developed for MCF could be applied to ICF. Therefore, this book focuses on tritium science and technology for MCF. ("MCF fusion" is simply referred "fusion" hereafter.)

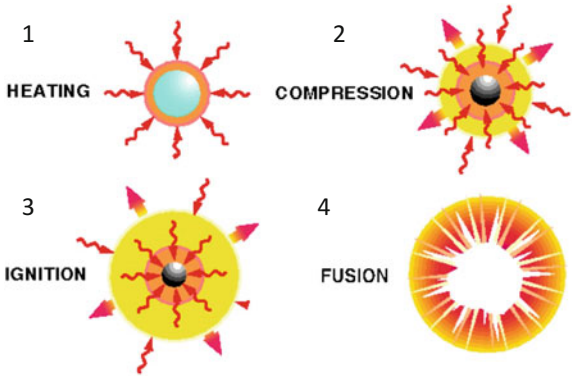

Fig. 1.7 Stages of ICF (reprinted with permission from [11]). *1* Laser beams or laser-produced X-rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope. *2* Fuel is compressed by the rocket-like blowoff of the hot surface material. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 1×10^8 °C. *3* Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy. *4* Fusion

1.3 Energy Conversion in Fusion Reactor and Fission Reactor

Already 60 years have passed after finding that nuclear reactions give energy. Now fission reactors are well established as energy sources, while a fusion reactor seems to need still several tens years to be realized. Why so much longer time has been required for fusion than fission?

To give the answer, principles of energy conversion in a fusion reactor system and a fission reactor system are compared in Table 1.1. Different from any other energy sources, the fusion needs significant amount of energy to start burning or ignition, i.e., to make high-energy and high-dense plasma confined to satisfy the Lawson condition. The initial input power would be 1/3–1/4 of the fusion output power. Since a fusion reactor will be designed to produce the power of a few GW, each reactor may require a power station with the power of a few hundreds MW to

Table 1.1 Comparison of fission reactor and fusion reactor

	Fission reactor	Fusion reactor
Reaction	$^{235}U + n \rightarrow FP_1 + FP_2 + 2–3\ n + \gamma + \sim 200$ MeV	$D + T = n + {}^4He + 17.6$ MeV
Characteristics	– All of energy conversion, fuel breeding, and waste confinement are done in a fuel pin of diameter of ~ 1 cm	– An open tritium handling system with a huge volume
Energy input	– Nearly zero	– Requires huge energy to sustain buring plasma
Energy conversion	– Energy carried by fission products (FP, heavy ions) (~ 170 MeV) is deposited in fuel pins and removed by coolant surrounding the pin	– Energy carried by neutron (14 MeV) must be converted to heat in large volume of blanket system
Fuel and ash	– Both fuels (^{235}U) and ashes (FP) are encapsuled in small fuel pins from the start up—No extra systems for fueling and ash removal are required	– Requires continuous fueling system – Poor efficiencies of fueling and burning require large throughput – Requires continuous exhaust of He ash
Fuel breeding and recovery	– One fission produces 2–3 neutrons, easy to keep chain reactions and to breed fuels – Fuel pins retain both FP and new fissile – Spent fuels are reprocessed to recover them	– To keep breeding ratio more than 1, neutron multipliers (Be, Pb) are required – Tritium breeding and energy conversion must be done simultaneously
Nuclear waste	– Long life radioactive FPs and transuranium elements must be handled with special care and will be reposited deeply underground	– Waste is limited to activated structure materials and could be recycled

start up. In a fission reactor, no such high power is required and only removing control rods from the core could start the reactor.

Energy conversion systems for fission and fusion are completely different. In a fission reactor, energy produced by the fission reaction of U (Uranium) and neutron is carried by fission products (FPs) and transformed to thermal heat of coolant for electric power generation, while in a fusion reactor, energy carried by 14 MeV neutrons must be converted to the thermal heat of the coolant. At the same time, neutron is used to breed T to sustain fuel self-sufficiency as described below. Both fission and fusion leave nuclear wastes. Compared to long life nuclear wastes in fission including FPs and transuranium elements such as U, Np, Pu, which are serious concerns for radiation safety, activated structure materials by fusion neutron irradiation are less hazardous. Of course radioactivity of T requires special care, which is the main subject of this book.

In the following, energy conversion for both fusion and fission is briefly summarized.

1.3.1 Fission Reactor

In most of fission reactors using light water as coolant, energy produced by a nuclear reaction, around $\sim$200 MeV,

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{FP}_1 + \mathrm{FP}_2(\sim 170\mathrm{MeV}) + 2-3\mathrm{n}(\sim 5\,\mathrm{MeV}) + \gamma(\sim 20\,\mathrm{MeV}) \quad (1.13)$$

is distributed to FPs, which are nuclei with atomic numbers of around 40–50, neutrons, and γ rays, as indicated as the numbers in blankets in the equation [13].

Two or three neutrons produced by the reaction sustain chain reactions, and the reaction rate is easily controlled by removing the neutrons by boron (B) encapsulated in control rods with reactions such like,

$$^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He} \quad (1.14)$$

$$^{10}\mathrm{B} + \mathrm{n} \rightarrow 2^{4}\mathrm{He} + \mathrm{T} \quad (1.15)$$

It should be noted that the reaction can be used to produce T. Actually T production in nuclear reactors is considered, due to limited T resources.

Since the fission cross section is higher for lower energy neutrons, the neutrons produced by the fission reaction are decelerated by moderator, for which H_2O is used concurrently as coolant in a light water reactor (LWR). Accordingly, the energy of the neutrons is deposited in the coolant (H_2O). However, its contribution in power generation is not large. The fuel of ^{235}U is included in natural uranium only by 0.7 % and enriched to be a few % as fission fuel for LWR. ^{238}U (99.3 %), the main component of the natural U, absorbs neutrons being transmuted to

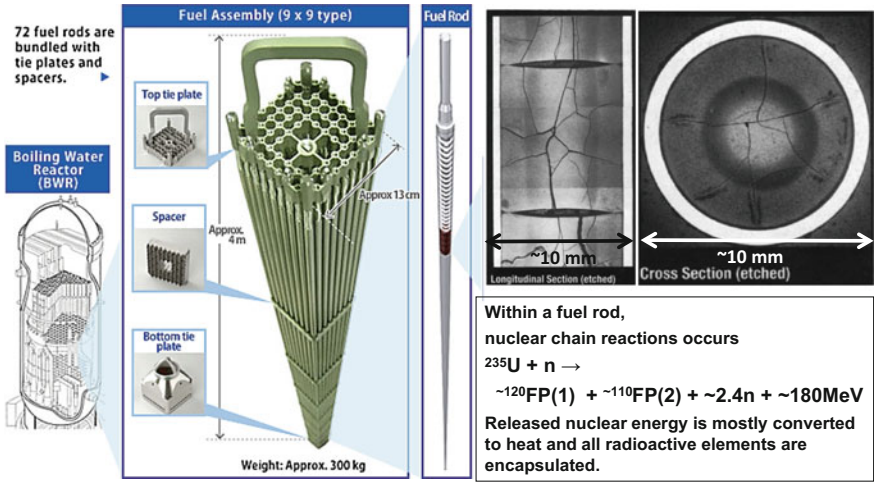

Fig. 1.8 **a** Schematics of a boiling water type reactor and a fuel assembly (reprinted with permission from [14]) and **b** cross sections of a fuel pin (reprinted with permission from [15])

transuranic elements, like Pu, which are fissile and to be used in a fast breeder reactor but very much hazardous.

Because of heavy masses of FPs', their energies are mostly converted to heat in a fuel pin with a diameter of only around 10 mm and transferred to the H_2O coolant in LWR flowing outside of the fuel pins to generate electricity (see Fig. 1.8 [14]). This means that energy conversion from dangerous nuclear energy to heat is done within a very small volume together with the confinement of hazardous FPs in the fuel pins (see Fig. 1.8b [15]). In addition, absorption of neutrons in B in the controlled rods decelerates the reaction rate and hence reaction control is simply done by insertion or extraction of the control rods. These points are all very much beneficial and reasons why a nuclear reactor was accomplished as energy source within rather short time.

One of the disadvantages of the fission reactor is that around 10 % of output power remains in the fuel pins as decay heat of the radioactive FPs just after the reactor shutdown, which requires continuous cooling for rather long time. Otherwise, the reactor core (bundles of the fuel pins) could melt down as such appeared in the Fukushima accident at 2011 in Japan due to the loss of coolant [16].

In this respect, fusion reactors are much safer than fission reactors, in which no fusion power remains after the reactor shutdown, as described below. Although structure materials are activated by neutron irradiation, their overall decay heat after the shutdown would not cause significant damage even at loss of coolant.

1.3.2 Fusion Reactor

As already mentioned, the largest reaction rate appears in the D–T fusion reaction, which produces ^{4}He and neutron having energy of 3.5 MeV and 14.1 MeV, respectively as,

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}(3.5\,\mathrm{MeV}) + \mathrm{n}(14.1\,\mathrm{MeV}). \tag{1.16}$$

Energy carried by ^{4}He is used for plasma heating to maintain burning through its collisions with fuel ions (D^+ and T^+) and electrons, while energy carried by neutron (14 MeV) must be converted effectively to heat or electricity. Consequently, plasma-facing surfaces of a fusion reactor are subjected to high-energy neutrons. However, neutron energy deposition is volumetric and their energy is converted in blankets behind the first wall to thermal energy of the coolant for power generation.

Energy used for plasma heating (1/3–1/4 of the output fusion power) must be also removed; in other words, plasma-facing surfaces are subjected to very high heat load from the burning plasma as shown in Fig. 1.9. The heat load to the surface of divertor, which is installed for removal of He ash and fuel exhaust, becomes intolerably high for any materials. This is the one of the reasons for the selection of tungsten (W) having the highest melting point as plasma-facing materials. Still the heat load is too high and cooling of plasma temperature by impurity seeding is

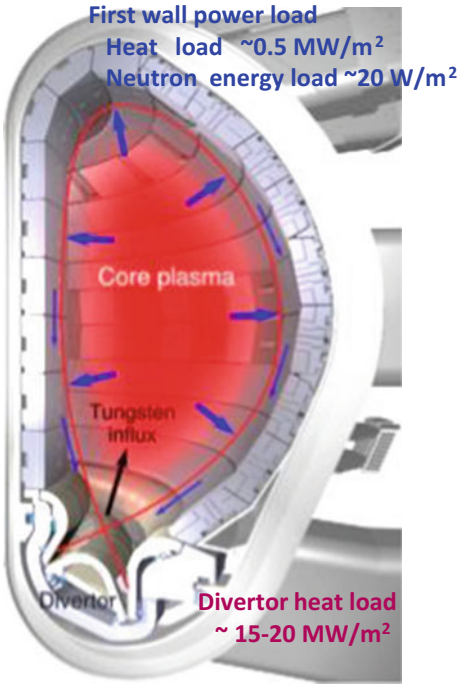

Fig. 1.9 Strucutre of tokamak type reactor core (Torous) and heat load to first wall and divetor

required. Although, plasma heat load to the first wall is much less than that to the divertor, energetic neutrons impinge to the first wall and their energy is superposed.

Furthermore, the neutrons are used to breed T using following reactions.

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + {}^{4}\mathrm{He} + 4.8\,\mathrm{MeV} \tag{1.17}$$

$$^{7}\mathrm{Li} + \mathrm{n} \rightarrow \mathrm{T} + {}^{4}\mathrm{He} + \mathrm{n} - 2.5\,\mathrm{MeV} \tag{1.18}$$

The reaction (1.17) produces one T per one neutron, while the reaction (1.18) produces one neutron which can be used again for both reactions. Since natural Li includes both ^{6}Li and ^{7}Li with their natural abundance ratio of 7.5–92.5, the natural Li can be used to breed T. Although the reaction (1.18) is beneficial for simultaneous production of T and neuron which can be used for T breeding again, the reaction requires energy (2.5 MeV) which in turn reduces the output power. Since the T resources are not enough as described in Chap. 2, the T breeding should have enough margins to compensate inventories of all T handling systems including a reactor vessel, pumps, and fuel processing and recycling systems, i.e., fuel self-sufficiency must be kept. To do this, neutron multiplication using beryllium (Be) or lead (Pb) is employed.

$$^{9}\mathrm{Be} + \mathrm{n} \rightarrow 2\mathrm{n} + 2\,{}^{4}\mathrm{He} - 2.5\,\mathrm{MeV} \tag{1.19}$$

$$^{\mathrm{A}}\mathrm{Pb} + \mathrm{n} \rightarrow 2\mathrm{n} + {}^{\mathrm{A}-1}\mathrm{Pb} - 7\,\mathrm{MeV}, \tag{1.20}$$

where A is a mass number of one of the isotopes of Pb which absorbs a neutron.

In a fusion reactor, the blanket system is set to surround the reactor core, in which conversion of neutron energy to heat must be done simultaneously with the T breeding. Because the neutron energy is very high, very thick materials are required to decelerate neutrons or convert their kinetic energy to heat transferred to coolant. Furthermore, recovering T bred in the blanket requires sophisticated systems. Thus, after confirming D-T burning in ITER, significant effort will be required to establish appropriate blanket systems to attain the energy conversion and T breeding simultaneously, which must be economically efficient [4].

14 MeV neutrons activate materials surrounding burning plasma. And the activated materials, mostly structure materials made of steels, radiate energy as β and γ rays for long after the reactor shutdown. Since the mass of the structure materials of the fusion reactor is much larger than that of the fission reactor, depository of the activated materials is concerned in addition to radiation safety. In this respect, development of low activation steels and utilization of SiC for structure materials is encouraged.

The overall residual energy or decay heat of the fusion reactor is far less than that of the fission reactor. In addition, no fusion power remains in a fusion reactor after shutdown. Thus, the meltdown of the fusion reactor can be avoided by inertial cooling. In this respect, fusion reactors are much safer than fission reactors.

Nevertheless, lots of scientific and technical issues relating T remain to realize the fusion reactor as an energy source. In particular, to keep T safety and to establish fuel sufficiency in T breeding are two of the most important ones. The purpose of this book is to give information relating tritium science and technologies to realize a D–T fusion reactor as an energy source.

Thus, the mechanism of energy conversion from nuclear energy to thermal energy (or to raise temperature of the coolants, whatever they are, any liquids including water, gases, or even liquid metals) is quite different between a nuclear reactor and a fusion reactor. Nevertheless, it should be noted that once the nuclear energy is converted to the thermal energy, there is no large difference in volume energy density between the two reaction systems. In fission reactors, nuclear energy is converted to heat of the coolant in quite small volume with energy density of 0.1–1.0 W/cm^3, while fusion energy is converted in its whole volume of around 1000 m^3 of the reactor with energy density of 0.1–1.0 GW/1000 m^3. Both energy densities are nearly the same.

1.4 Fusion Reactor System—A Huge Open T Handling System

Figure 1.10 shows schematic of electric power generation by a fusion reactor [7]. As described above, energy conversion in the fusion reactor system is quite different from that in the fission reactor system widely used as an energy source.

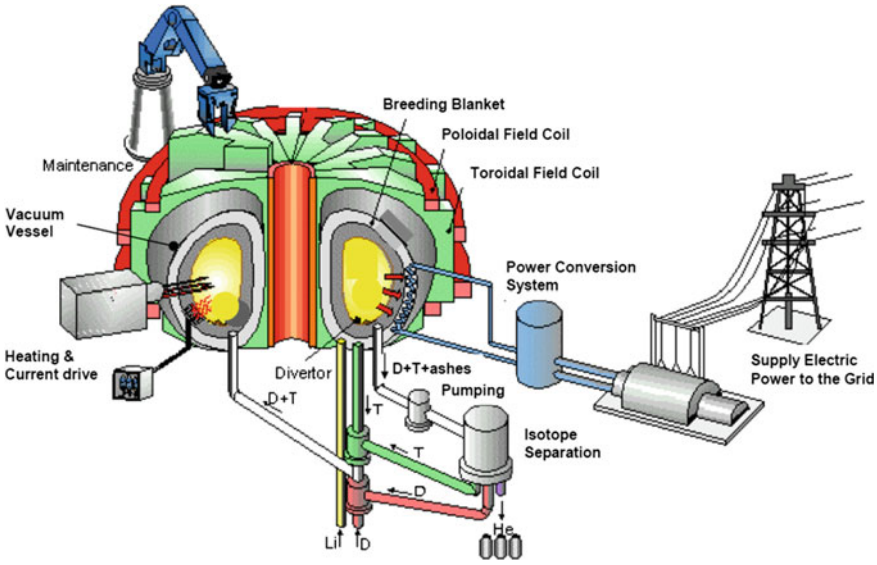

Fig. 1.10 Schematic of electric power generation by a fusion reactor (reprinted with permission from [7])

Moreover, using T as its fuel, safety requirements for the fusion are also quite different from that for the fission.

In the fission reactor, its fuel is simply encapsulated in fuel pins so as the radioactive FPs are also enclosed in the pins. All fuels are loaded in the reactor at the beginning of reactor operation. Any failures of the fuel pins are easily detected by monitoring the radio-activity of cooling water, and removing of the FPs from or cleaning of the cooling water is one of the most important issues during its normal operation. Emergency cooling is one of the key safety features and its failure could cause serious environmental damages such happened at reactors in Fukushima [16] and Three Mile Island [17].

In a D–T fusion reactor, D and T are continuously fueled in its huge reactor vessel or tokamak system and recovered mostly as gaseous form together with He ash and other gases added intentionally or unintentionally. Owing to poor burning efficiency, only a few % of the throughput fuel would be burned, and the amounts of both the fuel throughput and exhaust are quite large.

For safety, T must be contained physically and confined following the regulation law of T in a reactor system specified by ICRP [18]. Because of easily dissipating nature of hydrogen gas, it is hardly possible to avoid leak, permeation, and consequent contamination of T. Therefore, any T handling systems require decontamination of T or detritiation.

T fueling and recycling systems, which use mostly established techniques, can be built for ITER or even a reactor without very high hurdles and, hence, T plant is not likely on a critical schedule path toward the first D–T plasma in ITER [19]. Nevertheless, the amount of T handled in ITER or a reactor will be so large that only tiny amount of T release from any T handling systems by leakage, permeation, and cross contamination is hardly avoidable. Hence, detritiation systems are indispensable and accordingly a D–T fusion reactor will be a huge open T handling system, which we have never experienced, and quite different from small glove box systems for handling small amount of T, for example, tracer usage.

1.5 Safety Issues in a Fusion Reactor

1.5.1 General Safety

Inherent safety and environmental sustainability are key benefits of fusion compared to fission. Because there is no chain reactions like fission and the reaction is thermally self-limiting with limited burning time, a few seconds without refueling. Low residual decay heat of the few-MW level requires no additional external cooling upon system shutdown.

In fission reactors, significant amount of hazardous radioactive FPs and transuranium elements, such as Pu and Np with quite long decay times are produced, while both toxicity and lifetime of T fuel in fusion reactions are much less

than above-mentioned radioactive materials in fission. However, neutrons activate structure materials and the total volume of the activated wastes will be similar or larger than the fission reactor. Currently, materials are not optimized for low activation under neutron irradiation. In future, the activated material can be recycled for reuse after 50–100 years and material optimized for low activation can be readily recycled for use in fusion power plant reactors. In case of active cooling system failure, decay heat from activated materials is low enough that all in-vessel components can be cooled by natural convection and reactor "meltdown" is physically impossible.

Therefore, most of the safety issues are related to radioactivity of T and the activated structure materials. Since the activated materials are not movable, most serious movable hazards involve the T fuel itself and activated dusts containing T resulting from erosion of plasma-facing components, which are discussed in Chap. 5.

The consequence of a "design basis accident" would be suspension of operations and possibly fire. Electricity would cease to be produced, but there would be no offsite impact. The consequences of accidents significantly beyond the design basis are well within the regulatory limits, and radiation dose of radiological workers and of the public can be below the limits specified by ICRP [15]. In ITER, public safety might not be a serious concern. Concerns are mostly for safety of workers in reactor site, and it does not seem easy to keep T contamination below regulatory level, owing to speciality of tritium as a radioactive hydrogen isotope, which can be easily exchanged with H in ubiquitous water on the earth. Thus, the safety concerns of the fusion reactor are quite different from those of fission products mostly metals.

1.5.2 Safety Issues Relating Tritium

In a D-T fusion reactor, only 55.6 kg of T and 37 kg of D are burned (consumed) per 1 GWth year. (GWth is energy released by fusion reactions and GWe for electricity). Since utilization of T is strictly restricted by law with accountancy (or under regulation) of a few tens Bq. T must be physically contained and confined following the regulation law of T in any nuclear systems. Details of T safety in a fusion reactor are described in Part III (Chaps. 14 and 15). Here, it is briefly summarized.

T handling in small scale is well established, and various manuals have been published, such as the Tritium Handbook published by DOE [20, 21], considering to use T as medical diagnostics and sign illumination, especially "EXIT" signs. Few T facilities have handled such large amount of T to be used in ITER and DEMO. In 2007, Savannah River Laboratory has opened a new Tritium Extraction Facility (TEF) [22], in which the amount of T handled is rather large but does not likely exceed 10 kg. We will face to new and never experienced problems to handle such large amount of T used in ITER or a fusion reactor. They are mostly related to T inventory in a reactor vessel and T recycling systems, and precise T accountancy.

As noted in Fig. 2.1 in Chap. 2, the existence of T can be easily detected with β-electrons, while no one method can cover the quantitative analysis in wide range. Moreover, T retained in materials can be detected only within μm range from their surface due to very shallow escaping depth of the β-electron. At very high concentrations, decay heat makes calorimetric measurements of T in the materials possible, but the accuracy of the measurements is only two or three digits. Loss of 0.1 % is never allowed in regulation, but it is quite hard to account T with the accuracy in more than three digits. Ironically, the loss itself can be detected, but it is difficult to determine how large the loss from the total mass handled.

In addition, T handling has been done mostly at room temperature (RT) except for T reservoirs (T stored in metals), and no cooling system has been required. While most of fusion systems as an energy source must be operated at temperatures well above RT with cooling water/gas systems (except for ice pellets manufacturing and isotopes separation). Therefore, absorption, desorption, and permeation of T in materials of any reactor component can be unavoidable. The permeation and leakage result in T contamination of T handling systems and of any coolants or cooling water. Most of those T problems are directly connected to the safety of operators and/or professionals. But, as already mentioned, public safety does not seem to become a significant problem in normal reactor operation, because the T emission to outside of the reactor site can be easily kept below the safety limit. Even in severe accident, T level at the public boundary can be kept below the regulation limit, which is the base for the maximum in-vessel T inventory of 1 kg in ITER.

Nevertheless, T contamination of materials surfaces is one of the most important concerns and understanding of the contamination mechanism is quite important to reduce and/or remove the contamination (decontamination). Because of chemical nature, T can be easily transferred from a highly contaminated surface to lower contaminated or non-contaminated surfaces, leading to cross contamination or multi-step contaminations in T handling systems. In ITER, safety handling of a divertor cassette, which will be the largest component in the reactor vessel, is the most serious concern [23]. The cassette retains very high levels of T on their surfaces, which easily transfers to arms or gloves of remote-handling systems or glove boxes and is highly activated by neutron irradiation. Once the surface of the device/equipment in the systems is contaminated, T can be easily transferred to any materials attaching. Figure 2.8 in Chap. 2 shows an example of cross contamination remaining fingerprints of T activity on metal plates in a glove box, in which heavily contaminated materials were handled [23].

The most important mechanism of the cross contamination is isotope exchange reactions of T with the ubiquitous lighter hydrogen isotope, protium (H), in water to become HTO and hydrocarbons in atmosphere to become OBT (Organic Bound Tritium).

Tritium disintegration at skin is not so important owing to thin penetration depth of the β-electrons, but T can penetrate into a human body by the isotopic exchange reactions with light water in tissues to be very hazardous. Once T is going in human body and tissues, a few weeks are needed to be isotopically replaced by H from

drinking water. In this respect, OBT is more hazardous and requires more time to be removed than HTO. In Chap. 2, mechanisms of isotopic replacement are discussed in detail.

1.6 T Fuel Cycling and Processing Systems

Figure 1.11 is a schematic drawing of T fuel cycling and processing systems with blanket to generate power and to breed T simultaneously. For the safety reasons, T in a reactor will be limited to only a few kg or radioactivity of around 10^{17} Bq [24, 25]. Since burning efficiency is likely to be several % as discussed in Chap. 3, required throughput into the reactor is more than 25 times of T burned. In the figure, fuel throughput is $\sim 10^{14}$ Bq/s, following the maximum fuel throughput of ITER, 200 Pa m^3($\sim$2.5 g)/400 s (one ITER discharge). In present tokamas, 1–10 % ($\sim 1 \times 10^{13}$ Bq/s) of input fuels are retained on/in the plasma-facing walls. Accordingly, $\sim$90 % of the throughput fuel, $\sim 9 \times 10^{13}$ Bq/s, is exhausted and refueled after reprocessing (refinement and isotope separation). In blanket systems, $\sim 10^{12}$ Bq/s must be bred, because the amount of bred T must exceed that of burned T.

In the aspect of T confinement for the safety, there are at least two boundaries, one between the vacuum vessel (or reactor) and the blanket (or tritium processing) systems and the other between the tritium processing system and environment. T is transferred either by permeation and leakage and/or cross contamination through the boundary. Since public exposure to T is regulated at a level as tiny as a few Bq/cm^2, T must be strictly confined in a reactor system with accountancy of an order of pg (picogram). Considering the throughput of $\sim 10^{14}$ Bq/s, each boundary should reduce T level by orders of 10^6.

Passive barriers consisting of process piping, jacketed vessel, guard or second barrier piping [26] are taken into account in ITER tritium systems [25]. Nevertheless, the decommission factor (DF) of 10^{-6} seems hardly possible by a single step. One can apply permeation barriers. Yet, the permeation reduction factor of 3 (orders) has been attained by oxide film coatings, and so on, but the reliability of the barrier effect is rather poor. Since permeation flux of 1/1 to 1/100 of the incidents flux was attained in PDP (plasma-driven permeation) experiments [27], T permeation to cooling channels in the divertor region will be quite large due to extremely large particle fluxes and significant amount of T can be piled up in the cooling systems.

The easy isotopic replacement gives additional problems for T permeated through process piping. The permeated T readily reacts with surface contaminants to produce hazardous tritiated water and/or hydrocarbons. In particular, ferrite, a low activation structure candidate material, has very high T permeability and needs permeation barrier with the permeation reduction of 5-6 orders of magnitude which is not attained yet. For a water-cooling system, permeated T from the plasma-facing surface or blanket to the coolant water easily produces HTO, resulting diluted tritiated water from which T recovery is very cost-consuming.