Chapter 2

Safety and Economics of Uranium Utilization for Nuclear Power Generation

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Additional information is available at the end of the chapter

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Abstract

Safety and economics of uranium utilization for nuclear power generation were investigated and discussed. In order to sustain energy supply with nuclear power generation, uranium resources should be abundant. From the viewpoint of depletion of the resources, fast breeder reactor (FBR), which is breeder reactor of plutonium, has been developed. In this context, the uranium utilization and plutonium utilization with breeding by FBR are compared and discussed from the viewpoint of safety, sustainability, and energy security. In addition, the significance of partitioning and transmutation (P&T), which is one of the advantages of FBR, was also discussed from the viewpoint of environmental burden from radioactive waste.

Keywords: uranium resources, safety, electricity generation cost, plutonium breeding

1. Introduction

Nuclear power is an attractive energy source of clean air and carbon-free electricity that produces no greenhouse gases or air pollutants unlike power generation with fossil fuel. Moreover, it is said that fossil fuels are in danger of running out. Especially for the petroleum resources, the duration period is about 40 years. In this context, nuclear power generation (NPG), whose fuel is uranium, has been installed as alternative energy. However, fast breeder reactor (FBR), which is breeder reactor of plutonium, has been developed from the viewpoint of depletion of uranium resources [1] but not deployed as a commercial reactor yet. Many researchers and engineers believe that sustainable energy supply can be established only with FBR fuel cycle. However, we should reconsider the problem of depletion of uranium resources before coming to a decision because safety of reactor depends on reactor types. Moreover, other problems, e.g., economics and environmental burden, should be considered. To this end, safety of nuclear reactor with uranium utilization and that with plutonium breeding is

discussed in Section 2. Sustainability of uranium resources and that with plutonium thermal use is discussed in Section 3. Economics of electricity generation with conventional uranium, sweater uranium, and plutonium multi-recycling by FBR is discussed in Section 4. Energy security for uranium and plutonium utilization is discussed in Section 5.

2. Safety of nuclear reactor and breeding

Passive safety features are preferred for advanced reactor design, such as Economic Simplified Boiling Water Reactor (ESBWR) [2], Advanced Passive 1000 (AP1000) [2], and European Pressurized water Reactor (EPR) [3], to enhance safety and reliability and to reduce human intervention. In Fukushima Daiichi accident on March 11, 2011, passive safety features were desired especially for isolation condenser (IC) systems in unit 1 [4].

In addition, high-temperature gas-cooled reactor (HTGR) attracts attention after the accident due to the inherent safety features for all safety functions of "shutdown," "cooling," and "containment" [5]. As a result, the development of HTGR was recommended in "strategic energy plan," which is formulated by the government of Japan on April 11, 2014 [6].

The fundamental safety features are composed of the three functions of control of reactivity (shutdown), removal of heat from the reactor (cooling), and confinement of radioactive material (containment). In the Fukushima Daiichi accident, the first function "shutdown" was successfully performed. However, the second function "cooling" failed even with the IC systems, which have enough heat removal function for 8 hours per IC system. For the IC systems, passive safety features were desired as described in the previous section. As a result, the final function of "containment" was lost as well.

The first feature of "shutdown" was performed as the automatic scram by detecting the earthquake. For light water reactor (LWR), if the scram would be failed, the reactor power settles down to zero power by moderator reactivity feedback due to the reduced density of the moderator and the Doppler effect due to the increased fuel temperature when heat removal from core is lost.

That is equivalent to inherent safety feature due to self-regulation of power of LWR for normal operation condition. The negative reactivity feedback is caused by expansion of moderator. The moderator temperature coefficient, void coefficient for boiling water reactor (BWR), is designed to be negative as it depends only on the degree of moderation and not on the core size. In other words, the LWR core is designed to be under-moderated [7] such that the neutron moderation is not sufficient to obtain a maximum multiplication factor. At the same time, the multiplication factor is reduced by a moderator density reduction.

For HTGR, the graphite structure is also employed as moderator. The volume ratio of fuel to the moderator, which is an indicator for degree of moderation, is determined by the integrity of core structure and a state of the art of fuel fabrication. Generally, for almost all nuclear reactors, as fuel assembly has more number of fuel pins, the fuel temperature can be reduced to lower because the power-sharing decreases per fuel pin. For HTGR with pin-in-block type fuel, the fuel pins are allocated into the coolant hole in graphite fuel block. The number of fuel pins is

restricted by the requirement for the fuel block strength against thermal stress. The fuel pins are composed of coated fuel particles (CFPs). The maximum volume fraction is determined by a state of the art of fuel fabrication to restrict initial failure fraction of the CFPs. To obtain high burnup for long life cycle, the volume fraction prefers the maximum value. Moreover, the moderating power and the absorption cross section of graphite are lower than those of light water. The optimized design for criticality is not preferable from the viewpoint of the long life cycle with considering burnup. According to the result, HTGR's design condition is in the undermoderated region when the core design is reasonable and realistic from the viewpoint of the heat removal, the integrity of structure, and the long life cycle. Moreover, the solid moderator of graphite is never voided. To realize a negative power reactivity coefficient, there are two factors, the Doppler effect of fuel temperature and reactivity feedback of moderator temperature due to neutron spectrum shift of Maxwellian distribution peak [8]. As a result, thermal reactor including LWR and HTGR has the inherent safety feature due to self-regulation of power.

On the contrary, many FBR designs allow a positive void reactivity coefficient because of the increase of threshold fission reaction of fertile material with high neutron energy over 1 MeV due to the hard spectrum. **Figure 1** shows the fission and capture cross sections and the ratio of fission cross section to absorption cross section. The ratio stands for the fission probability per neutron absorption reaction. The fission probability also rapidly increases over 1 MeV, and the probability is around unity. Then, when the coolant of sodium is voided, the neutron over 1 MeV increased, and positive reactivity is inserted.

Due to the positive void reactivity coefficient, the coolant is boiled, and the power burst, which melts the fuel pins, occurs upon unprotected loss of coolant flow (ULOF) accident [9]. To prevent the power burst, Integral Fast Reactor (IFR) [10] is designed with a large safety margin for heat removal to avoid coolant boiling instead of inherent safety features of neutronic characteristics for self-regulation due to negative coolant void coefficient. The concept

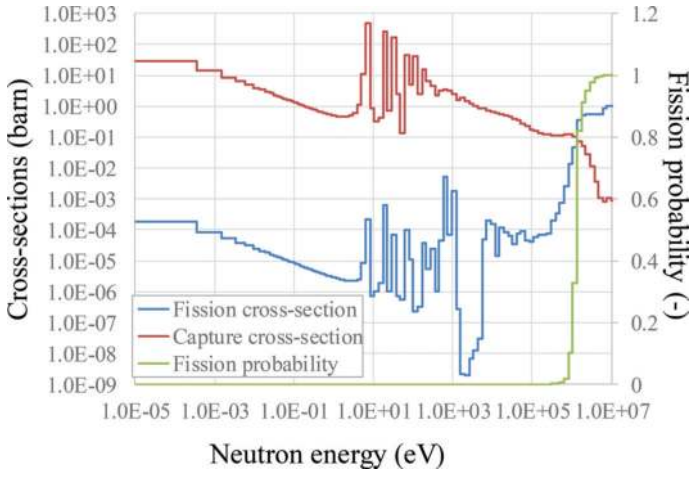

Figure 1. Cross section of ^{238}U and fission probability per neutron absorption.

of the inherent safety feature of IFR was demonstrated using an IFR prototype, Experimental Breeder Reactor No. 2 (EBR-2) [11]. Although IFR allows a positive void coefficient, it was demonstrated that, upon ULOF accident, a reactor operating at full power can be safely shut down using a negative reactivity feedback due to Doppler effect without the need of the scram, other safety systems, or operator actions.

However, the commercial FBRs, such as European fast reactor (EFR) [12], which is one of representative FBRs of Generation IV, have high economy and high breeding ability and cannot have the passive safety feature by the enhanced heat removal function because of its minimal safety margin to obtain high core performance. The safety is guaranteed with a reliable shutdown system in the event of coolant flow loss.

To obtain negative or small positive void coefficient, FBR with large core should be designed with pancake-type core to increase neutron leakage for axial direction when the coolant is voided [13]. However, sodium-cooled FBR cannot obtain the negative void coefficient only with the pancake-type core. Then, the concept of "sodium plenum" [14] was proposed to increase the axial neutron leakage. In this concept, upper axial blanket and upper side of fuel are removed to enhance the neutron leakage when the coolant is voided. Naturally, breeding ability will weaken.

Thus, safety and economy, or breeding ability, are related to the transactions for fast reactors (FRs) including FBR. If core performance is prioritized, the passive safety feature for "shutdown" will be abandoned.

3. Sustainability of energy resources

3.1. Duration period of uranium resources

Uranium resources should be abundant compared with requirement, and energy security is also necessity to ensure the energy sustainability. The duration period, which is defined as the ratio of available resources to the consumption rate, is employed as a measure of the abundance. The consumption rate is estimated to be approximately 60,000 tU/year (61,980 tU/year) by referring to the measured amount required in the world for electricity capacity of 372 GWe at the end of 2012 [15].

The available resources are categorized to identified resources and undiscovered resources. The identified resources stand for uranium deposits delineated through sufficient direct measurement. The undiscovered resources stand for expected existence on the basis of geological knowledge. Usually, only identified resources are employed to estimate the duration period. However, undiscovered resources and other resources described below also exist and will be available. In the present study, the duration periods except for the identified resources are also evaluated to measure the abundance.

The amount of total identified resources in 2013 is approximately 7.6 million tU (7,635,200 tU) [15]. This amount corresponds to a duration period of approximately 120 years (123.2 years). The resources increased by 7.6% from 2011 by new discoveries owing to the revitalization of investigations on resources with the recent soaring market price of uranium. **Figure 2** shows

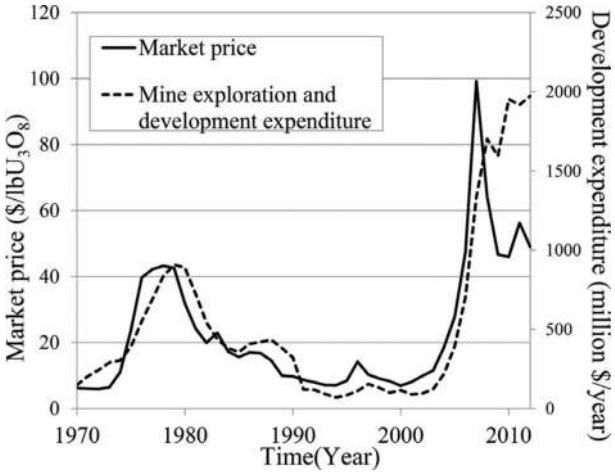

Figure 2. Market price of uranium and mine exploration and development expenditure.

the relation between the market price and the mine exploration and development expenditure [15, 16]. The investment for the exploration and development follows the market price. This trend is common for other resources, e.g., petroleum and coal.

The amount of total undiscovered resources in 2013 is approximately 7.7 million tU (7,697,800 tU), which is a marginal decrease from approximately 10 million tU (10,429,100 tU) reported in 2011 [15]. The reason why the resources decrease is that the USA did not report the amount in 2013. Then, I regard the amount of undiscovered resources as the value of 10,429,100 tU reported in 2011. This amount corresponds to approximately 170 years (168.3 years) of the duration period.

For the estimation of the amount of conventional uranium resources including the identified and undiscovered resources, the highest cost category, i.e., < 260 $/kgU, is used. Furthermore, there are other resources called unconventional resources recovered not from uranium mines as uranium ore. The unconventional resources are recovered as minor by-products such as uranium from phosphate rocks, nonferrous ores, carbonatite, black shale, and lignite. The recovery cost from these products is higher because of the low uranium concentration. In the future, these resources would become a viable source when market price of uranium exceeds 260 $/kgU [15]. The amount of these sources is 7.3–8.4 million tU [15], which corresponds to a duration period of approximately 130 years (117.8–135.5 years). The resources described above can maintain the energy sustainability for the present. However, more resources are needed to achieve the permanent energy sustainability.

Uranium from seawater, which is also categorized to unconventional resources, amounted to 4.5 billion tU [17] corresponding to a duration period of approximately 72,000 years (72,604 years). The uranium is dissolved in the seawater at a low concentration of 3.3 parts per billion (ppb) [17]. Moreover, the amount of uranium at the surface of the seafloor is approximately a thousand times more than the uranium dissolved in seawater, which is approximately 4.5 trillion tU [18]. The uranium solved in seawater is in an equilibrium state with the uranium contained in

the rock on surface of the seafloor [18]. The concentration of 3.3 ppb is remained because of the equilibrium state. This suggests that not only the amount of the uranium dissolved in seawater but also that in the rock on the surface of the seafloor corresponding to the duration period of approximately 72 million years can be recoverable. In other words, the uranium from seawater is almost an inexhaustible resource.

3.2. Utilization of plutonium

Plutonium is generated along with burnup of ^{235}U by conversion of ^{238}U. Suppress plutonium should be incinerated from the viewpoint of nuclear proliferation. Even when the plutonium is disposed, it is problematic and called a "plutonium mine." As time goes on, the plutonium becomes easy to use. Dose from accompanying fission products (FPs) decays, and a fraction of plutonium fissile (Puf) also increases as shown in **Figure 3**. **Figure 3** shows the change on the fraction of the plutonium fissile in spent fuel of LWR. The peak value of around 0.75 appears at 20,000 years near the half-life of ^{239}Pu of 24,000 years. In addition, the ability of conversion is measured by conversion ratio (CR). The conversion ratio is defined as follows [19]:

$$CR = \frac{Average\ rate\ of\ fissile\ atom\ production}{Average\ rate\ of\ fissile\ atom\ consumption} \quad (1)$$

The conversion ratio of LWR is around 0.6 [19]. If the actinoid nuclides are burned as same amount as fissile nuclides in fresh, the conversion ratio coincides with residual ratio (RR), which is defined as the ratio of fissile inventory in discharged fuel to that in fresh fuel. In many designs of LWRs, the fissile inventory and the inventory of burned nuclides are almost same, and conversion ratio can be regarded as residual ratio.

Plutonium can be also used as resources even in thermal reactor, that is, "plutonium thermal use." The duration period increased to 1.6 times, which is the sum of uranium resources of unity and generated plutonium of 0.6, when once-through utilization of plutonium. With considering necessity of reprocessing facility only for spent plutonium fuel, this option can be a realistic candidate.

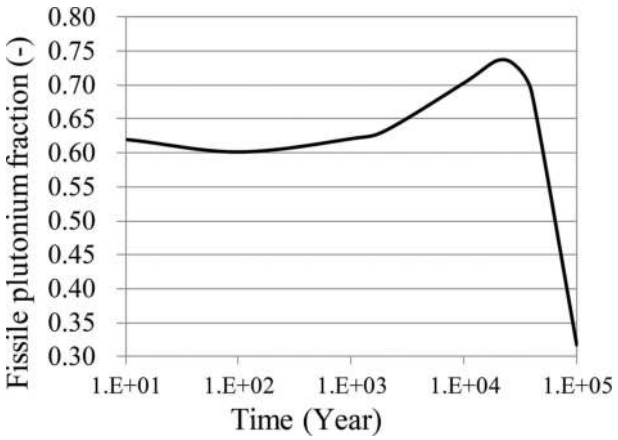

Figure 3. Change on a fraction of fissionable plutonium.

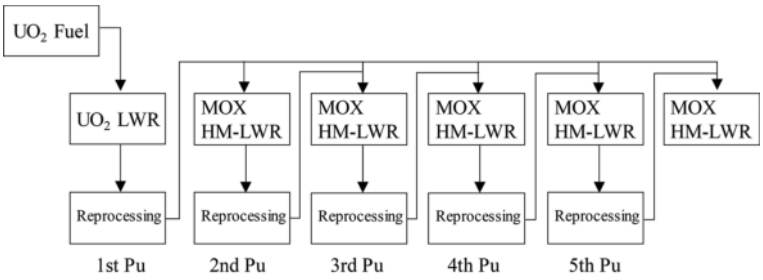

Figure 4. Plutonium multi-recycling scheme for HMLWR.

The residual plutonium can be also used by mixing fresh plutonium to recover the fraction of fissile plutonium. This concept can be realized by high moderation LWR (HMLWR) [20], which is the full mixed oxide (MOX) fuel reactor concept by using exiting advanced boiling water reactors (ABWRs) and advanced pressurized water reactors (APWRs) without changing the plant system. However, the fuel rod diameter is reduced to increase an atomic number ratio of hydrogen to heavy metal (H/HM) value. The H/HM value is changed from 4.9 to 7.0 for BWR concept and from 4.0 to 6.0 for PWR concept. This is the reason why the concept is named "high moderation." The design change concerning to "high moderation" is necessary because the plutonium fuel hardens neutron spectrum.

The concept of plutonium recycling is shown in **Figure 4**. In the recycling process, it has been assumed that UO_2 cores and MOX cores are coexisting and the reprocessing of both UO_2 LWR core and high moderation MOX core provides plutonium. Multi-recycling of Pu in high moderation MOX cores causes degradation of plutonium, while the degradation is prevented by mixing the first plutonium. While repeating this process five times, the plutonium composition is almost saturated and regarded approximately as almost equilibrium state. Using the five times recycled plutonium, the feasibility of reactors was confirmed including safety assessment [20]. This means that multi-recycling of plutonium can be established even in thermal reactor by feeding fresh plutonium from the outside of the cycle.

The Puf consumption rates were evaluated for equilibrium state 39 and 33%, respectively, for the BWR and PWR concept. Those correspond to conversion ratio and/or residual ratio of 0.61 and 0.67, respectively. Here, the conversion ratio is presented by 0.6. With the plutonium consumption of HMLWR, the duration period increases 2.5 times, which can be evaluated as the sum of the infinite geometric series with the ratio of 0.6.

4. Economics of electricity generation

4.1. Recovery cost of uranium resources

For the economic electricity generation, it is preferable that uranium recovery cost is cheaper. With the recent price increase in the market, the highest cost category of <260 $/kgU for conventional uranium resources is added to Red Book 2009 [21]. On the other hand, the recovery cost of unconventional uranium is higher than 260 $/kgU as mentioned in Section 3.1.

Therefore, the cost of 260 $/kgU is considered as a criterion to determine whether a resource can be recovered economically or not.

Figure 5 shows the market price of uranium in the past decade [22]. The price increased abruptly to over 300 $/kgU in June 2007. However, this is a spot price that was not directly employed in trading. Generally, uranium is traded at its forward price. The average price of uranium purchased by owners and operators of US civilian NPP was 120 $/kgU (46.16 $/lb$U_3O_8$) in 2014 [23]. As shown in **Figure 6** [23], the price increased slowly from 2004, and the sharp increase in 2007 was related to the spot market price. In the present study, the current trading price of 120 $/kgU is employed as representative uranium price of conventional resources.

In general, it is believed that unconventional uranium resources such as uranium from seawater are difficult to recover economically. However, an effective recovery method based on a new type of polymer braid has been developed at Japan Atomic Energy Agency (JAEA) [17]. The uranium concentration of 3.3 ppb in seawater is extremely low, but the economic recovery can be achieved with the advantage of efficient absorbents synthesized by radiation-induced graft polymerization and an ocean current. This method can compensate for the difficulty in recovery from low concentration solution. The economic recovery was proved by evaluation with a detailed system design based on the ability to recover confirmed by experiment.

About 1.5 gU/kg adsorbent of uranium was successfully recovered from seawater in Okinawa over a 30-day period. From these tests and trials, the potential cost of uranium recovery, considering a scaled-up annual recovery of approximately 1200 tU/year, was evaluated. The cost is composed of adsorbent production (69%), uranium recovery (29%), and elution and purification (2%). In this estimation, six repeated soaking cycles are assumed. To realize the economic recovery, the duration of absorbent is important because the cost mainly depends on adsorbent production. The realistically achievable cost with current technology using braids with 18 repeated soaking cycles is 208 $/kgU with the exchange rate of 120 yen/$ [17]. In the future, a more reasonable cost of 110 $/kgU [17] can be realized using braids with 60 repeated soaking cycles.

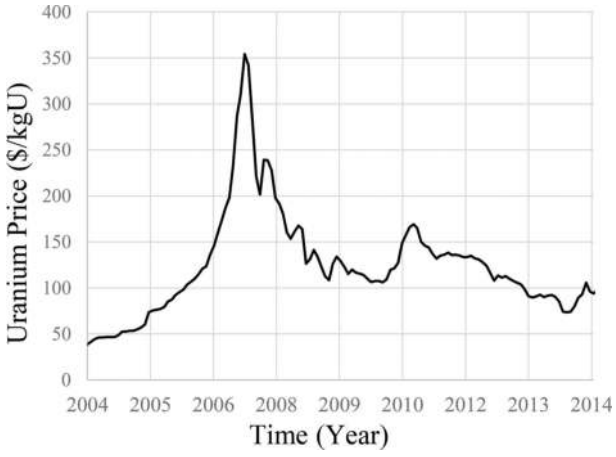

Figure 5. Spot market price of uranium.

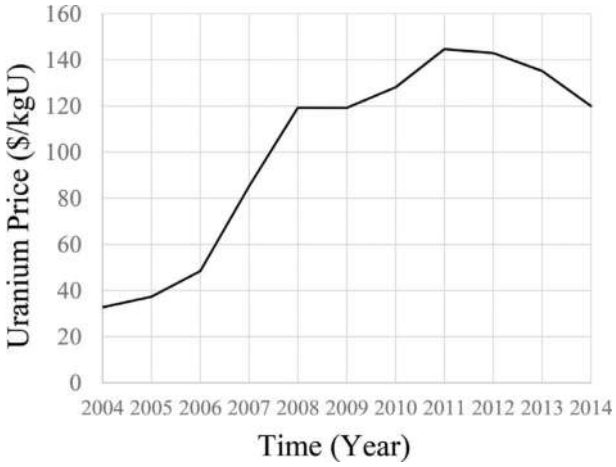

Figure 6. Weighed average price of uranium purchased by owners and operators of US civilian NPPs [23].

The seawater uranium can be extracted economically even by current technology with the cost of 208 $/kgU, which is lower than the criteria of 260 $/kgU. However, the cost is higher than the trading price of 120 $/kgU, even though the lower cost of 110 $/kgU can be achieved in the future. As a result, it is concluded that the cost of seawater uranium with current technology itself is not reasonable even though seawater uranium can be considered as economically recoverable resources.

4.2. Electricity generation cost using seawater uranium recovery cost of uranium resources

The cost of seawater uranium recovered with current technology is not sufficiently low. However, the economy of electricity generation should be assessed not for uranium purchase cost but for the entire cost. In this section, characteristics of electricity generation cost for NPG and the cost with seawater uranium are discussed.

The electricity generation costs of LWR were evaluated with conventional uranium and seawater uranium in Ref. [24] reflecting on the latest condition investigated by the cabinet of Japan [25]. The cost of LWR was evaluated assuming the PWR plant with electric power (gross) of 1300 MWe. In addition, the costs of HTGR were evaluated as well. That is evaluated based on a gas turbine high-temperature reactor 300 (GTHTR300) [26] designed by JAEA as a helium-cooled and graphite-moderated commercial scale HTGR with 600 MWt thermal power and 850°C outlet coolant temperature. The GTHTR300 is combined with four reactor units in a plant. Total thermal power of the plant is 2400 MWt, and gross electric power is 1100 MWe.

The cost of HTGR is cheaper than LWRs due to the cheaper construction cost and higher thermal efficiency of 45.6% [26] than LWRs of approximately 33%. The construction costs are compered in **Figure 7**. The cost of HTGR, only for the reactor component, is larger than that of LWR due to the lower power density design to offer higher levels of safety. Other parts of

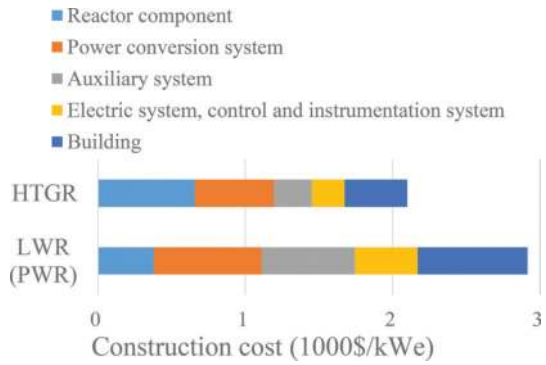

Figure 7. Construction cost of HTGR and LWR.

construction costs of HTGR are cheaper than those of LWR because of the simple direct gas turbine system and rationalization of auxiliary system by modularization. For power conversion system, the direct gas turbine system of HTGR is more compact than the water and steam systems of LWR. The auxiliary system is also more compact for direct gas turbine system. Therefore, the electric system, control and instrumentation system are also reduced for direct gas turbine system. Finally, the volume of buildings is also small for HTGR.

The electricity generation cost is composed of capital cost, operation cost, fuel cost, and social cost. For NPP, the capital cost consists of depreciation cost, interest cost, fixed property tax, and decommissioning cost. The operation cost consists of maintenance cost, miscellaneous cost, personnel cost, head office cost, and tax. The fuel cost consists of each part of the nuclear fuel cycle cost, which includes uranium purchase cost, conversion cost, enrichment cost, fuel fabrication cost, spent fuel storage cost, reprocessing cost, and waste disposal cost. These costs are the sum of yearly costs converted to present values and normalized by the electricity power generation. After the Fukushima Daiichi nuclear power plant disaster, social cost, which includes political cost, compensation cost, and environmental cost, is considered as a part of the electricity generation cost. Environmental cost is required only for the energy source that releases CO_2 gas.

To understand the characteristics, the cost fractions of the NPP are compared with those of a coal-fired power plant (CFPP), which has the largest electricity generation capacity in the world, as shown in **Figure 8**. As electricity generation cost for NPP, LWR cost with conventional uranium is employed. The CFPP cost is estimated by the Japanese cabinet secretariat by assuming a plant with electricity generation capacity of 750 MWe [25]. The cost for NPP consists of capital cost (25.8%), operation cost (32.2%), fuel cost (23.9%), and social cost (18.0%). The cost for CFPP consists of capital cost (15.2%), operation cost (13.5%), fuel cost (45.2%), and social cost (26.1%). The fraction of fuel cost of NPP is less than that of CFPP, which uses fossil fuel. Moreover, most of the fuel cost (38.5%) was spent on coal purchase. On the contrary, the uranium purchase cost for NPP is merely 4.0% of the entire cost because of the proportion of uranium purchase cost for NPP. The fuel cost in NPP consists of several categories from front-end to back-end as listed in **Table 1**, and the fraction of uranium purchase cost in the entire fuel cost is a small value of 16.9%. This is different from fossil fuel power generation, which directly obtains energy from the fuel without fabrication.

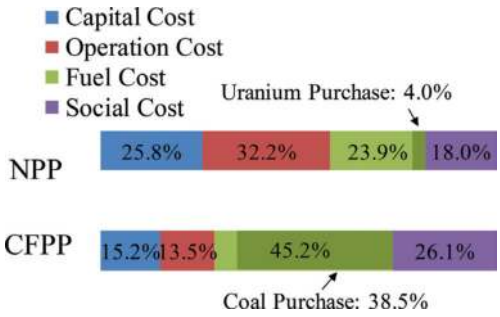

Figure 8. Fraction of electricity generation by NPP and CFPP.

The evaluated cost of the fuel and total electricity generation are listed in **Tables 2** and **3**. The fuel costs increase by approximately 10% by employing seawater uranium for both LWR and HTGR. For electricity generation cost, increases of approximately 3% are observed for LWR and HTGR due to the small fraction of uranium purchase cost as described above. The cost of LWR increases mere 0.21 cents/kWh, from 7.34 to 7.55 cents/kWh, by using seawater uranium. Even with seawater uranium, the cost of HTGR is cheaper than the existing LWR with conventional uranium.

4.3. Electricity generation cost for various fuel cycle schemes

To discuss electricity cost with plutonium utilization including FBR, the cost evaluated by partitioning and transmutation (P&T) working group of OECD/NEA [27] is summarized as follows. In addition, significance of P&T is discussed later because it is said that P&T is an advantage of FR including FBR and accelerator-driven system (ADS). In the report, seven fuel cycle schemes are compared. The schemes are listed as follows. Basically, LWRs mainly generate electricity by using uranium except for the seventh scheme. They are (1) LWR once-through, (2) plutonium burning by LWRMOX, (3) TRU burning in FR, (4) TRU burning in ADS, (5) TRU burning in LWRMOX and ADS, (6) double strata, and (7) closed cycle by FBR, respectively.

	Fraction (%)
Uranium purchase	16.9
Conversion	1.2
Enrichment	25.6
Fabrication	14.5
Storage	2.3
Reprocessing	26.2
Waste disposal	13.4

Table 1. Fraction of NPP fuel cost.

	LWR	LWR (S U*)	HTGR	HTGR (S U)
Uranium purchase	0.29	0.51	0.29	0.50
Conversion	0.02	0.02	0.02	0.02
Enrichment	0.44	0.44	0.55	0.55
Fabrication	0.25	0.25	0.45	0.45
Storage	0.04	0.04	0.02	0.02
Reprocessing	0.45	0.45	0.34	0.34
Waste disposal	0.23	0.23	0.18	0.18
Total	1.71	1.93	1.85	2.06

*SU stands for seawater uranium.

Table 2. Fuel cost (cents/kWh).

	LWR LF*=80%	LWR LF =80% (SU**)	HTGR LF = 80%	HTGR LF = 80% (SU)	HTGR LF = 90%	HTGR LF = 90% (SU)
Capital cost	1.91	1.91	1.63	1.63	1.44	1.44
Operation cost	2.38	2.37	1.63	1.63	1.38	1.38
Fuel cost	1.71	1.93	1.85	2.06	1.85	2.06
Social cost	1.33	1.33	1.33	1.33	1.19	1.19
Total cost	7.34	7.55	6.43	6.64	5.86	6.07

*LF stands for load factor.

**SU stands for seawater uranium.

Table 3. Electricity generation cost (cents/kWh).

The electricity generation costs are listed in **Table 4**. The cheaper option is the once-through option of LWR. The cost of the second scheme of plutonium burning with MOX, where the FR is ignorable, is also cheap. Plutonium utilization in thermal reactor is not problematic from the viewpoint of electricity generation cost. The seventh scheme of multi-recycling by FBR shows the highest cost. That is increased by approximately 40% compared with the cost of LWR. The cost increase is mainly caused by fuel fabrication and reprocessing including MA.

Fuel cycle scheme	1	2	3	4	5	6	7
Electricity generation cost (cents/kWh)	3.80	4.07	4.24	5.35	4.94	4.42	5.69

Table 4. Electricity generation cost for each fuel cycle scheme.

5. Energy security

5.1. Energy security of uranium resources

The accessibility is important from the viewpoint of energy security. Accessibility should be discussed from the viewpoint of geography and concession. The resources should be distributed widely from the viewpoint of geography, and the concession to obtain the resources should be also ensured from the viewpoint both of economy and politics.

Figure 9 shows distribution of identified resources of conventional uranium [15]. The top three countries Australia, Kazakhstan, and the Russian Federation occupy about half of the resources of the world. By the concentration of uranium resources, the risk of damage to sustainable energy supply increases owing to natural disasters, political instability, etc. In fact, uranium price in 2007 shown in **Figure 2** soared due to the catastrophic water inflow in Cigar Lake Mine in Canada [28], even though increase of uranium demand in China and India is also affected [15]. If the production of several mines in a certain region would be damaged simultaneously by large-scale disasters or political instability, the energy sustainability cannot be achieved. It is concluded that the conventional uranium resources have a problem of geography from the viewpoint of energy security.

Figure 9. Global distribution of identified resources.

Moreover, the uranium requirement exceeds the production in the recent two decades as shown in **Figure 10** [15]. The mass balance has now been achieved by the stock until 1990. In addition, the 1993 US-Russia Federation highly enriched uranium (HEU) purchase agreement was terminated in 2014 [15]. According to this agreement, the Russian Federation converts the 500 t of HEU from nuclear warheads to low enriched uranium (LEU) over 20 years from 1993 to 2013. As early as June 2006, the Russian Federation indicated that the HEU agreement will not be renewed when the initial agreement expires in 2013.

In this context, to purchase the uranium securely, mining interest of uranium ore, that is, concession, should be obtained by investing in the exploration and development of the mine. Here, I discuss Japanese case as representative country, which is not uranium-producing countries and does not have enough concession to satisfy the request. Many countries can be applied the similar condition as Japan. In Japan, requirement of uranium is approximately 8000 tU (8091 tU), and the production from own concession is 663 tU in 2007 [29]. The fraction is only 8.2%. Not only companies but also governments invest in the exploration and development of the mine to obtain the uranium concession. **Table 5** [29] lists the uranium concession owned by Japanese companies for mine under operation and development in 2009. Even though all mines under development will start the operation, the production can fill only half of the requirement. It is difficult to obtain the concession corresponding to the entire requirement. It is concluded that conventional uranium resources also have a problem of concession.

To realize the ultimate energy security, the resources should be recovered within the country. Countries facing the sea can utilize seawater uranium as domestic resources. The recovery process of seawater uranium is simpler than mine uranium as shown in **Figure 11** [17]. The extraction process of the recovery system consists only of elution in acid. It can be easy to introduce without any innovative technology. The transportation of absorbent is also realistic because the concentration of uranium in the medium is on the same degree of that in uranium ore. Moreover, the radioactive tailings, which may pollute the environment, are never generated unlike the uranium from mine. The amount of the production is large enough to satisfy the requirement if the current of the sea exists in exclusive economic zone (EEZ). The seawater uranium is effectively recovered with ocean current. The recovery system with capacity of

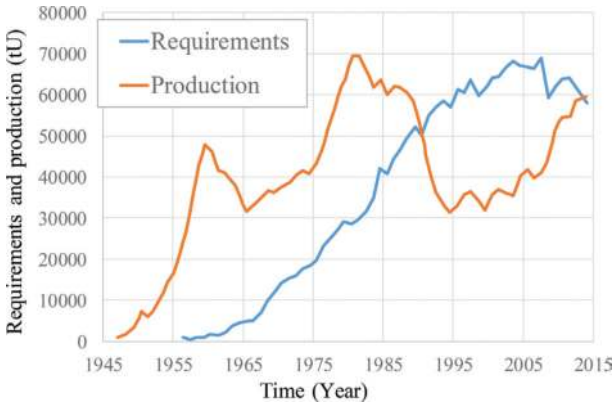

Figure 10. Annual world uranium requirements and production.

Country	Mine	Company	Concession (%)	Condition
Niger	Akouta	Overseas Uranium Resources Development Co.	25	Under operation
Canada	McClean Lake	Overseas Uranium Resources Development Co.	7.5	Under operation
Kazakhstan	West Mynkuduk	Kansai Electric Power Co.	10	Under operation
		Sumitomo Co.	25	Under operation
Canada	Cigar Lake	Tokyo Electric Power Co.	5	Under development
		Idemitsu Kosan Co.	7.9	
Kazakhstan	Kharasan 1–2	Marubeni Co.	13	Under development
		Tokyo Electric Power Co.	12	
		Toshiba Co.	9	
		Chubu Electric Power Co.	4	
		Tohoku Electric Power Co.	2	
Australia	Kintyre	Mitsubishi Co.	30	Under development
	Honeymoon	Mitsui & Co.	49	Under development

Table 5. Uranium concession owned by Japanese companies.

1200 tU/year requires the ocean area of 134 km^2 with a proper current. The Kuroshio Current is proper in Japan, and the ocean area of 6000 km^2 is available to recover the uranium without a conflict of the right of fishing. Annual uranium production of 53,731 tU/year is expected from this area. This is approximately 6.6 times as much as the requirement of 8091 tU in Japan, and it can occupy 87% of the requirement in the world.

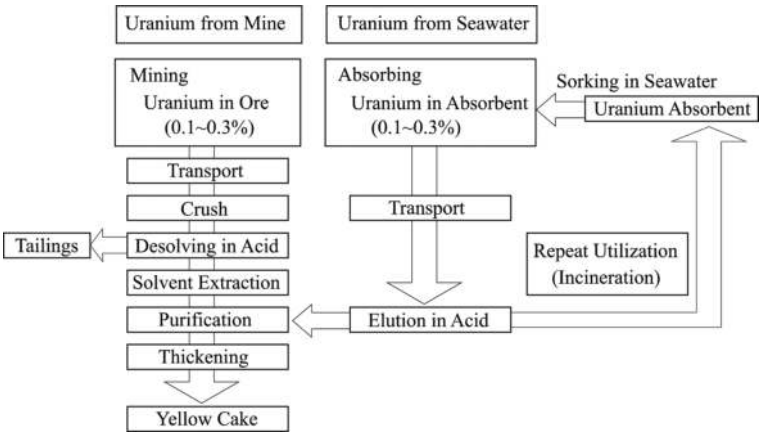

Figure 11. Process of uranium recovery.

Thus, the problems of geography and concession from the viewpoint of energy security can be solved by using seawater uranium. Then, the seawater uranium should be utilized regardless of the exhaustion of conventional uranium.

5.2. Energy security of plutonium utilization

Plutonium composition is depending on the condition of fresh fuel composition, burnup characteristics, and storage period before and after reprocessing. Plutonium composition is always fluctuated. Therefore, in Japan, fuel composition of FBR is managed by equivalent fissile coefficient [30]. The definition is as follows:

$$y = \nu\sigma_f - \sigma_{(n,\gamma)} \tag{2}$$

$$\eta_i = y_i / y_{^{239}Pu} \tag{3}$$

where y is the equivalent fissile value (cm^{-2}), $\nu\sigma_f$ is the microscopic production cross section (cm^{-2}), $\sigma_{(n,\gamma)}$ is the microscopic radioactive capture cross section (cm^{-2}), y_i is the equivalent fissile value of ith nuclide (cm^{-2}), $y_{^{239}Pu}$ is the equivalent fissile value of ^{239}Pu (cm^{-2}), and η_i is the equivalent fissile coefficient ith nuclide (−).

To reserve the product of fuel composition and the equivalent fissile coefficients, plutonium enrichment is determined. However, if fuel loading and/or operation of reactor would be significantly delayed, the fuel should be refabricated and reloaded because of the change on reactivity worth due to the decay of ^{241}Pu, whose half-life is 14.4 years, to ^{241}Am. In Monju, where sodium leakage accident occurred on December 1995 and start-up test is performed on May 2010, the depletion of criticality was observed [31] in the test. After the test, fuel reloading was performed on August 2010 to compensate the reactivity worth. The resilience of fuel cycle system with plutonium is weaker than that of uranium.

Moreover, there is a threat that the spent fuel would be seized in FBR cycle. In general, the Puf ratio of spent fuel is around 60% for LWR and FBR. However, that of FBR blanket is over 90%, that is, weapon-grade plutonium. In this context, the concept of protected plutonium production (PPP) [32] is proposed as an option. By addition of ^{237}Np and/or ^{241}Am, the Puf ratio can be reduced, and the dose rate of spent fuel can increase due to the converted ^{238}Pu in this concept. However, it should be noted that the doping MAs in fuel make working environment severe.

6. Environmental burden and significance of P&T

6.1. Geological disposal and safety

Along with electricity generation, radioactive wastes are generated. Especially, high-level radioactive wastes (HLWs) will be disposed in a deep geological repository. The HLWs, which are spent fuels for direct disposal and vitrified wastes for disposal with reprocessing, are contained into steel canisters and disposed by surrounding buffer material, which delays

migration of radioactive nuclides and is made of bentonite. The waste package, canister, and buffer material are called engineered barrier system (EBS) from the viewpoint of containment and delayed function of radioactive nuclides.

The safety analysis of the geological repository [33] assumes the mechanism as shown in **Figure 12**:

- The canister and waste package failed by corrosion, and the radioactive nuclides dissolve in groundwater.
- The radioactive nuclides migrate through the host rock via groundwater.
- The radioactive nuclides migrate to aquifer through fault.
- The radioactive nuclides flow into river and diffuse into environment.
- The radioactive nuclides are exposed to the public.

Thus, host rock in repository works as barrier as well and is called natural geological barrier. The safety of geological repository is assessed by public exposure by assuming migration of radioactive nuclides due to the corrosion and failure of waste packages.

Moreover, transuranic (TRU) waste [34], which is categorized as low-level radioactive waste (LLW), is also generated when spent fuel is reprocessed and disposed. The dose of public exposure is evaluated for representative geological repository design for LWR wastes as shown in **Figures 13** and **14**, respectively, for HLW and TRU waste.

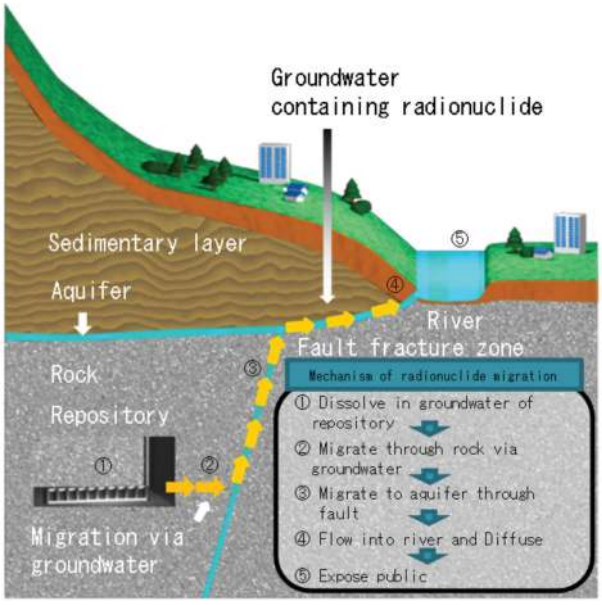

Figure 12. Process of public exposure.

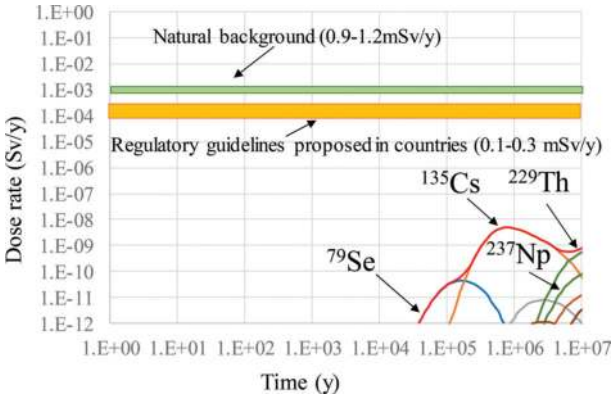

Figure 13. Public exposure from HLW [33].

Basically, the dose rate is limited by the guideline, which is deployed at approximately one order of magnitude lower than the level of natural background. The peak from HLW is composed of ^{135}Cs and four to five orders of magnitude lower than the guideline. The peak from TRU waste is composed of ^{129}I and two to three orders of magnitude lower than the guideline. In addition, the dose rate of HLW for direct disposal of LWR spent fuel was also reported [35]. The peak is composed of ^{14}C and one to two orders of magnitude lower than the guideline. The safety guideline is satisfied enough for exiting LWR waste disposal plans. Especially for HLW disposal with reprocessing, where MA transmutation has been often researched, the safety margin is huge.

With MA transmutation, the electricity generation cost increases as described in Section 4.2. "As low as reasonably achievable (ALARA) principal" [36], which was revised from as low as practical (ALAP), is known as radiation safety policy. Obviously, the necessity to reduce the public exposure is poor because of the huge safety margin. In this situation, the nuclear transmutation with significant cost increases against the ALARA principal. If the nuclear transmutation is plant, we should judge the "reasonability" by considering the benefit and cost.

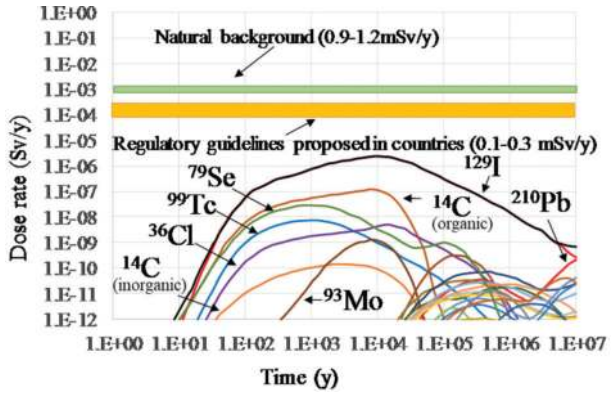

Figure 14. Public exposure from TRU waste [34].

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6.2. Potential toxicity and significance of P&T

Potential toxicity is often used as a hazard index to assess environmental burden. Therefore, it is set up for the objective of nuclear transmutation to reduce the potential toxicity. The definition of potential toxicity is dose of internal exposure by ingestion when all radioactive nuclides are intaken. It is believed that the dose should be lower than that of natural uranium required for the fuel fabrication.

The potential toxicity of LWR spent fuel is shown in **Figure 15** for each element. The burnup is 45 GWd/t, and the enrichment is 4.5 wt%. To fabricate fuel of 1 t with the enrichment of 4.5 wt%, natural uranium of 9 t is necessary. The toxicity of uranium and plutonium, that is almost composed only of plutoniums, needs 100,000 years to decay to the natural uranium level. With reprocessing, uranium and plutonium are recovered, and the toxicity is not problematic. Next, americium needs 2000 years of cooling. If americium is converted by P&T, the cooling time can be reduced to 300 years, by which the dose of FPs decays lower than natural uranium.

From the viewpoint of the potential toxicity reduction under the natural uranium level, it is not necessary for neptunium and curium to convert to FPs. The FPs are composed of long-lived FPs (LLFPs) and other FPs. The toxicity of LLFPs around 1.0×10^3 Sv/tIHM is observed from 1 to 100,000 years. The toxicity of LLFPs is not problematic as well. In addition, the nuclides contributed to the toxicity are different from that contributed to the public exposure described in the previous section. From this comparison, it is found that the actual public exposure strongly depends on mobility characteristics of the nuclides compering with the inventory of the toxicity. Furthermore, the assumption of intaking all radioactive nuclides is not reasonable as a hazard index. In this context, an alternative index of "environmental impact" [37] is proposed by a specialist of geological disposal safety. That is defined as toxicity flowed out from the EBS.

The potential toxicity has also attracted a lot of attention after the Fukushima Daiichi accident in Japan to reconsider the significance of the utilization of nuclear technology. The graph of the potential toxicity is often shown even in television report. Then, nuclear conversion by

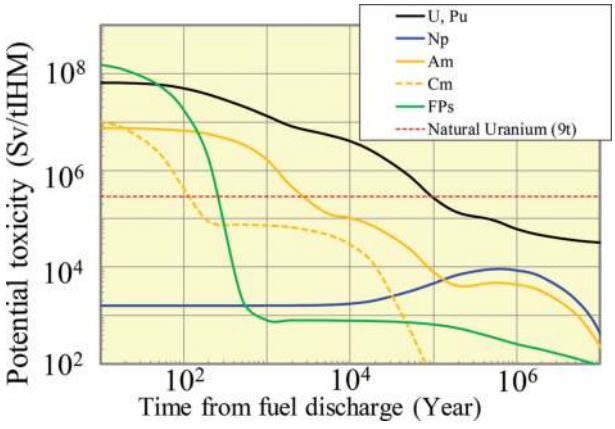

Figure 15. Potential toxicity of LWR spent fuel.

ADS also attracted a lot of attention. In this situation, an expert committee of Atomic Energy Society of Japan (AESJ) published the report for direct disposal [35]. In this report, the safety of geological disposal and public opinion were researched and discussed. It is emphasized that the potential toxicity cannot be the index directly to assess the safety, and the safety of geological disposal should be assessed by public exposure. The expert committee states its own view that the safety of geological disposal tends to be assessed by the potential toxicity in the recent society because it is easy to understand intuitively.

If the potential toxicity would be gotten public support as the hazard index and all MAs and LLFPs would be transmutated, the waste should be managed at least 300 years. Furthermore, if all radioactive nuclides would be transmutated to stable nuclides, the waste should be managed due to the toxicity of heavy metal.

6.3. Waste volume reduction and significance of P&T

P&T is expected to reduce waste volume and repository footprint [38]. However, partitioning and/or transmutation cannot reduce the inventory of waste nuclides itself. P&T reduces waste package volume by conquering the technical problem of vitrified waste fabrication [39].

For vitrified waste fabrication, there are limitations for heat generation (decay heat), waste content (FPs and MAs), platinum group metal (PGM) content, and molybdenum oxide content. The heat generation is limited to remain temperature of waste lower than 500°C during storage to prevent the phase transmutations such as crystallization and liquid-liquid phase separation at elevated temperatures. The waste content is limited to remain characteristics of glass for the confinement of the waste. The PGM content is limited not to shorten the lifetime of liquid-fed ceramic melter (LFCM). The molybdenum oxide content is limited to prevent the formation of molybdenum-rich phase, which is called yellow phase and degrades chemical durability of the vitrified form.

By partitioning [40], the PGM is recovered and used as resources. Strontium and cesium, whose decay heat is dominant, are partitioned and converted to Sr-Cs calcined waste. By employing high-waste-loading glass [41], high content of waste and molybdenum can be contained into the vitrified form.

To confirm the reduction of waste volume by P&T, numbers of waste package generation of four cycle schemes for LWR are compared as shown in **Figure 16**. The schemes are non-P&T, only transmutation, only partitioning, and P&T schemes. To reduce the number, partitioning is the most effective. The effect of high-waste-loading glass is dominant. The P&T scheme generates more waste packages than the partitioning scheme.

However, the partitioning is optimized to minimize the waste package generation and not optimized to minimize the repository footprint because the heat generation from Sr-Cs calcined waste is problematic to dispose. The repository footprint is mainly determined by heat generation from the waste. The buffer material of bentonite should be remained under the temperature of 100°C. The waste package pitches for disposal determined by the limitation of the buffer material temperature. In other words, the waste package with lower heat generation can realize lower footprint. Therefore, to dispose the Sr-Cs calcined waste, long cooling time is necessary.

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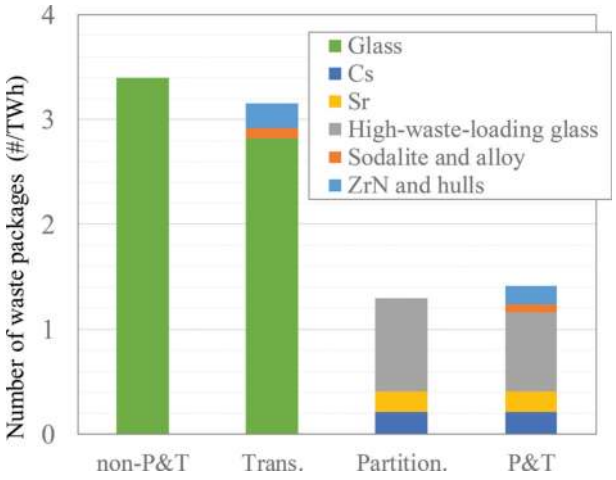

Figure 16. Number of waste packages per electricity generation [38].

There are two representative scenarios for P&T scheme [42]. Those are mainly optimized for the cooling time of Sr-Cs calcined waste. One hundred thirty and 300 years of cooling scenarios are employed. The specifications for LWR-SF (45 GWd/t) of 32,000 tIHM are listed in **Table 6**. Those are evaluated based on Ref. [38]. The P&T with 130 years of cooling can realize

	Cooling time (y)	Configuration	No. of package	Footprint (m^2)
Non-P&T				
Glass	50	V_0	40,000	1,776,000
P&T with 130 years of cooling				
HWL glass	5	V_1	8300	184,260
Sr-Cs	130	V_0	5100	226,440
Total			13,400	410,700
P&T with 300 years of cooling				
HWL glass	45	C	8300	7885
Sr-Cs	300	C	5100	4845
Total			13,400	12,730
Partitioning				
HWL glass	85	V_0	8300	368,520
Sr-Cs	150	V_1	5100	113,220
Total			13,400	481,740

Footprint of emplacement configuration V_0 is 44.4 m^2/cani., V_1 is 22.2 m^2/cani., and C is 0.95 m^2/cani [38].

Table 6. Specifications of disposal for LWR-SF (45 GWd/t) of 32,000 tIHM.

1/4 of footprint compared with that of non-P&T. With 300 years of cooling, 1/100 of footprint can be realized. However, only the partitioning can also realize 1/4 of footprint with 150 years of cooling for Sr-Cs calcined waste and 85 years of cooling for the high-waste-loading glass. The waste package including MAs needs the cooling time to decay ^{244}Cm, whose half-life is 18.1 years. For the rest decay heat, ^{241}Am, whose half-life is 433 years, is dominant and difficult to reduce by cooling. To realize more compact disposal, the transmutation is necessary.

The technology of partitioning is already demonstrated [40, 41]. On the other hand, transmutation should develop many innovative technologies concerning to neutron source by spallation reaction, Pb-Bi FR core, and pyro reprocessing for ADS and reactor core and advanced reprocessing for FBR. The partitioning technology without transmutation is preferable as early introduction option to suit uranium utilization.

6.4. Environmental burden with P&T

As described in the previous section, the safety of waste disposal should not be assessed by the potential toxicity. However, reduction of the potential toxicity is one of the objectives to develop fuel cycle system with FBR in Japan. All TRU nuclide is planned to recycled with the recovery ratio of 99.9% [43] to shorten the cooling time needs to decay the toxicity under the natural uranium level within 300 years.

However, with the recovery, the public dose from MAs would not be reduced. The MAs in 4N+1 decay series are problematic. ^{229}Th is the daughter of ^{237}Np, and other MAs in 4N+1 decay series, that is, ^{241}Pu, ^{241}Am, and ^{245}Cm, are decay to ^{237}Np. These nuclides should be recovered with high recovery ratio. It is said that the recovery ratio should be higher than 99.998% [44]. The relations of the recovery ratio to the molar flux of radioactive nuclide from EBS are shown in **Figure 17**. ^{135}Cs can be reduced with higher recovery ratio because that

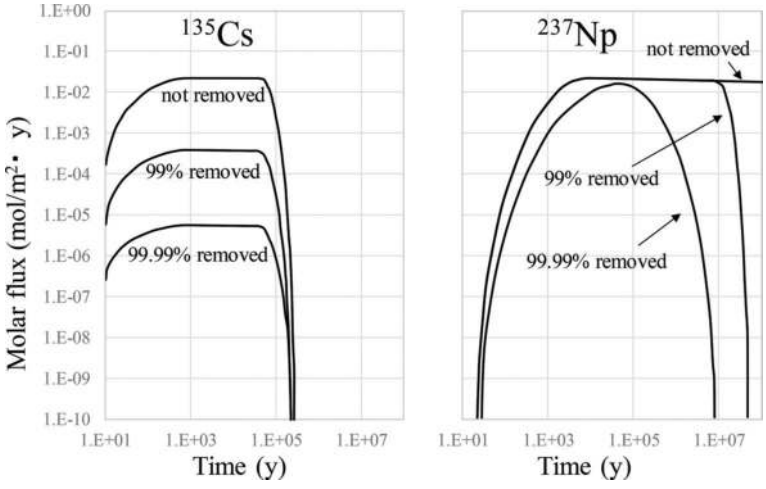

Figure 17. Relation of recovery ratio to the molar flux of radioactive nuclide from EBS [44].

			High decontamination				Low decontamination			
			MOX	MOX	MOX	MOX	MOX	MOX	MOX	MOX
				+Np	+Np + Am	+Np + Am + Cm		+Np	+Np + Am	+Np + Am + Cm
FBR-MOX		Whole body	0.7	0.7	9	60	1000	1000	2000	2000
(114.9 GWd/t)		Hand	0.1	0.1	3	9	300	300	300	300
LWR-UOX	Standard burnup	Whole body	0.8	0.9	3	40	600	600	700	700
	(BWR 45 GWd/t)	Hand	0.2	0.2	3	7	100	100	100	100
	High burnup	Whole body	1	1	4	60	700	700	900	1000
	(PWR 60 GWd/t)	Hand	0.2	0.3	4	10	200	200	200	200
LWR-MOX	Standard burnup	Whole body	2	2	8	100	600	600	700	800
	(BWR 45 GWd/t)	Hand	0.3	0.43	8	20	100	100	100	200
	High burnup	Whole body	2	2	10	400	700	700	900	1000
	(PWR 60 GWd/t)	Hand	0.4	0.6	20	50	200	200	200	200

*The dose rates are normalized by the dose in representative fuel fabrication with spent fuel from Fugen [43].

**Dose rate lower than 1 for the whole body and hand: fabrication in GB is possible with the current technology.

Dose rate lower than two for the whole body and hand: fabrication in GB is possible with the current technology improving the process.

Dose rate lower than 10 for the whole body and hand: automation is necessary for fabrication in GB.

Dose rate higher than 10 for the whole body and hand: fabrication in GB is impossible [43].

Table 7. Feasibility of fuel fabrication in globe box [43].

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dissolved in groundwater congruently with glass form dissolution. On the other hand, the concentration of ^{237}Np is limited by solubility. Then, the inventory of ^{237}Np should be reduced lower than the amount corresponding to the solubility. The MA recycling may not contribute to reduce public dose with the recovery ratio of 99.9%.

Furthermore, MA recycling increases working environment burden like the concept of PPP. MA recycling makes difficulty not only for spent fuel but also for fuel fabrication. **Table 7** lists the feasibility of fuel fabrication in globe box (GB) [43]. MOX fuel and neptunium-doped MOX fuel with high decontamination can be fabricated in GB with the current technology. However, for americium- and/or curium-doped fuel, automation is necessary, or fuel fabrication in GB is impossible. Fuel with low decontamination cannot be fabricated in GB. In this context, there is the opinion that MA recycling should not be performed [45]. For nuclear proliferation, safeguard should be enhanced by increasing the transparency of society instead of MA recycling [45].

7. Summary

Safety and economics of uranium utilization for nuclear power generation were investigated and discussed. To compare the alternative candidate of plutonium breeding by FBRs, P&T technology, one of the advantages of FBRs, was also discussed.

For the safety of reactor, to remain inherent safety feature for "shutdown" function, uranium utilization in thermal reactor is necessary. The safety feature is lost in fast reactor. The core performance, breeding ability, and economy are related to a transaction in fast reactor.

The amount of conventional uranium corresponds to consumption of approximately 290 years, and it is not much enough to sustain the energy supply eternally. On the contrary, the amount of seawater uranium, which is 4.5 billion tU corresponding to 72,000 years and 4.5 trillion tU including the uranium at the surface of the seafloor corresponding to 72 million years, is almost inexhaustible.

Furthermore, by utilization plutonium in spent fuel in thermal reactor, the duration period of uranium can be increased. By once-through utilization, that can be increased to 1.6 times. By multi-recycling, which can by HMLWR, that can be increased to 2.5 times.

With seawater uranium, the electricity generation cost increases by mere 3%. With HTGR, the cost with seawater uranium is cheaper than the cost of existing LWR with conventional uranium. The cost of FBR with multi-recycling increases by 40% compared with the cost of LWR.

From the viewpoint of energy security, conventional uranium has problems, i.e., geology and concession. Therefore, seawater uranium should be recovered before exhaustion of conventional uranium from the viewpoint of energy security because the uranium mining concession, which is necessary to supply the uranium resources sustainably, is difficult to fulfill the entire requirement. Moreover, seawater uranium should be recovered by the countries facing ocean.

Plutonium utilization has problems of energy security due to the decay of ^{241}Pu. When fuel loading and/or reactor operation would significantly delay, the fuel should be refabricated and reloaded. Moreover, weapon-grade plutonium is generated in the blanket of FBR. There is a threat for the spent fuel to be seized.

For environmental burden, the safety of geologic disposal for existing LWR waste is secured by evaluating public dose with a sufficient margin. However, P&T is planned to reduce the potential toxicity, which the index should not be used for safety assessment. To reduce waste volume, P&T is effective. Only with partitioning, the repository footprint is reduced to 1/4 times. However, transmutation of MAs cannot reduce the public dose with the recovery ratio of 99.9% determined to reduce the potential toxicity. MA recycling with FBR increases the working environmental burden due to the increased dose.

As discussed above, uranium utilization in thermal reactor can achieve safe and sustainable energy supply with acceptable environmental burden.

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