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Sustainable and Safe Energy Supply with Seawater Uranium Fueled HTGR and Its Economy

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Abstract

Sustainable and safe energy supply with High Temperature Gas-cooled Reactor (HTGR) fueled by uranium from seawater have been investigated and discussed. From the view point of safety feature of self-regulation with thermal reactor of HTGR, the uranium resources should be inexhaustible. The seawater uranium is expected to be alternative resources to conventional resources because it exists so much in seawater as a solute. It is said that 4.5 billion tons of uranium is dissolved in the seawater, which corresponds to a consumption of approximately 72 thousand years. Moreover, a thousand times of the amount of 4.5 trillion tU of uranium, which corresponds to the consumption of 72 million years, also is included in the rock on the surface of the sea floor, and that is also recoverable as seawater uranium because uranium in seawater is in an equilibrium state with that. In other words, the uranium from seawater is almost inexhaustible natural resource.

However, the recovery cost with current technology is still expensive compared with that of conventional uranium. Then, we assessed the effect of increase in uranium purchase cost on the entire electricity generation cost. In this study, the economy of electricity generation of cost of a commercial HTGR was evaluated with conventional uranium and seawater uranium. Compared with ordinary LWR using conventional uranium, HTGR can generate electricity cheaply because of small volume of simple direct gas turbine system compared with water and steam systems of LWR, rationalization by modularizing, and high thermal efficiency, even if fueled by seawater uranium.

It is concluded that the HTGR fueled by seawater uranium with the current technology enables the energy sustainability for approximately 72 million years with superior inherent safety features and lower cost of 6.07 cents/kWh (7.28 yen/kWh) than the 7.34 cents/kWh (8.80 yen/kWh) cost of LWR using conventional uranium.

1. Introduction

Nuclear power is an attractive energy source of clean-air and carbon-free electricity, that produces no greenhouse gases or air pollutants. However, on March 11, 2011, during the Fukushima Daiichi nuclear power plant disaster in Japan, radioactivity in Light Water Reactors (LWRs) released to the environment. The accident occurred even for a LWR that has the inherent safety feature of shutting itself down to a subcritical state during the operation. That is self-regulation feature. However, the decay heat removal from the core, of which system should be designed to work under any circumstance, is failed after the shutdown. It is found from the accident that not only the inherent safety features to shut itself down safely but also the inherent safety feature for heat removal is necessary for the safety of Nuclear Power Plant (NPP). In this context, one of the alternative candidates safer than LWR is High Temperature Gas-cooled Reactor (HTGR).

To achieve the inherent safety feature of self-regulation characteristics, one of the designs is the thermal reactor with under-moderated design (Lweis, 1977). The design concept is employed for LWR to obtain negative reactivity coefficient of coolant temperature for

Pressurized Water Reactor (PWR) and negative reactivity coefficient of coolant void for Boiling Water Reactor (BWR). The most all of HTGRs is designed in under-moderated region even though the spectrum is softer than LWR as described in the Section 2, and the solid moderator of graphite is never voided.

HTGR has outstanding safety features of core heat removal. (Ohashi, et al. 2011) The fuel temperature is maintained under the design limit by the passive heat removal from outside the Reactor Pressure Vessel (RPV) with high thermal conductivity of core graphite and low core power density in both normal operation condition and an accident. The large heat capacity of core graphite moderates the change of the core temperature even in the transient event, such as a depressurized accident and a Reactivity Insertion Accident (RIA). The heat removal from the RPV to the ultimate heat sink, i.e. soil or air, is achieved through radiation and natural convection of air in the reactor cavity at a loss of forced cooling of the core.

Energy supply should be sustained forever by any means. Fossil fuel is limited resources, and nuclear power generation have been expected to be the alternative candidate. Among those, HTGR has a superior safety feature as described above. In general, it is expected that the long term of energy sustainability by nuclear power generation will be achieved by breeding. However, the thermal reactor of HTGR is not preferable to breed fissile fuel material, and the safety features will be lost if the design of HTGR would be changed to a fast reactor, that is Gas-cooled Fast Reactor (GFR), to breed the fissile fuel material.

To ensure nuclear energy sustainability, the uranium resources should be inexhaustible and easy-available. Moreover, the resources must be economical enough to utilize to commercial power generation.

In this paper, we will discuss necessity of uranium resources from the viewpoint of safety, energy sustainability, and economy with HTGR. First, we discuss safety feature of self-regulation in a thermal reactor to elucidate the necessity of utilization of uranium resources in Section 2. The sustainability of the uranium resources is described in Section 3. Finally, the economy of electricity generation is evaluated in Section 4.

2. Safety Feature of Self-regulation for HTGR

In general, thermal reactors, such as LWR and HTGR, have the safety feature of self-regulation for reactor power by the negative reactivity feedback. This feature is achieved with under-moderated design. The moderator plays an important role in criticality for thermal reactors. If sufficient moderator does not exist for criticality, the multiplication factor becomes low. On the contrary, if that exists too much, the multiplication factor becomes low as well because that absorbs neutrons. Therefore, there is the optimum design from the viewpoint of criticality. The design with less moderator is called under-moderated, and otherwise called over-moderated. To achieve the safety feature of self-regulation, the thermal reactors must be designed in the under-moderated region because the negative reactivity feedback occurs when moderator density reduces by thermal expansion and/or moderator void with power increase.

In this context, LWRs are designed in the under-moderated region. In other words, PWR should be designed to make reactivity coefficient of coolant temperature negative, and BWR should be designed to make reactivity coefficient of coolant void negative. HTGRs are also deigned in the under-moderated region, and the design is not determined from the viewpoint of the under-moderation design as described below. In addition, the moderator is never voided and its expansion can be ignored.

In thermal reactor of HTGR, the graphite structure plays a role of moderator. The volume ratio of fuel to moderator is determined by integrity of core structure and a state of the art of fuel fabrication. In general, including LWR, as fuel assembly has more number of fuel pins, the fuel temperature becomes lower because the power sharing decreases per a fuel pin. For HTGR with pin-in-block type fuel, the fuel pins are deployed 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 include 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 burn-up 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 that of light water. The optimum design for criticality is difficult to be achieved because of restrictions described above. Figure 1 shows the criticality of HTGR with change of atomic number density of the graphite block. The criticality is evaluated with cell calculations by assuming representative fuel region of High Temperature engineering Test Reactor (HTTR) (Saito, et al. 1994) by using SRAC code (Okumura, et al. 2007) with evaluated nuclear data library of JENDL-4.0 (Shibata, et al. 2011). The atomic number density in graphite block is virtually varied from 0.1 times to 2.0 times to that in the original design. According to the result, HTGRs are designed in the under-moderated region if the core design is reasonable and realistic from the viewpoint of the heat removal and the integrity of structure.

However, Fast Reactor (FR), which is designed extremely in the under-moderated region, has positive coolant void reactivity caused not by moderation effect but by fast fission effect. In FR, fission reaction increases when coolant is voided and spectrum becomes harder because of the threshold fission cross section of ^{238}U in the fast region from 10^5 MeV to 10^6 MeV (Fukaya, et al. 2009). Then, it should be designed with pancake type core (Fukaya, et al. 2009) and/or sodium plenum concept (Kawashima, et al. 2013) to increase neutron leakage for axial direction when the coolant is voided. With these design approach, the void reactivity coefficient can be improved, but breeding ability is depleted as well at the same time. Then, there are many designs of FR that allow positive coolant void reactivity coefficient. There is also FR design based on HTGR (Okano, et al. 2005). The spectrum is hardened by removing graphite structure from the core, and its coolant of helium has reactivity worth. This design allows positive coolant void reactivity coefficient, and the power increases in depressurized accident by the positive reactivity feedback of 0.3 $ (Okano, et al. 2005).

As a result, to remain the safety feature of thermal HTGR, the energy sustainability should depend not on breeding, but on uranium resources.

Fig.1

3. Energy Resources Sustainability

3.1 Duration Period of Uranium Resources

To ensure the energy sustainability, uranium resources should be inexhaustible compared with its requirement, and energy security is also necessity. For this purpose, the duration period is employed as a measure of the abundance. That is defined as the ratio of available resources to the consumption rate. The consumption rate is estimated to be approximately 60 thousand 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. (OECD/NEA, 2014)

For the available resources, there are two categories: identified resources and undiscovered resources. The identified resources refer to uranium deposits delineated through sufficient direct measurement to conduct pre-feasibility and sometimes feasibility studies. The undiscovered resources refer to expected existence on the basis of geological knowledge of previously discovered deposits and regional geological mapping. 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 are also evaluated to measure the abundance.

The total identified resources in 2013 amounted to approximately 7.6 million tU (7,635,200 tU), which was an increase of 7.6% over 2011 values. (OECD/NEA, 2014) This amount corresponds to a duration period of approximately 120 years (123.2 years). The increase in resources is caused by new discoveries owing to the revitalization of investigations on resources with the recent soaring market price of uranium. Figure 2 shows the relation between the market price and the mine exploration and development expenditure. (OECD/NEA, 2014 and 2006) It is found that the investment for the exploration and development follows the market price. This trend is common for other resources, e.g. petroleum and coal.

Fig.2

The total undiscovered resources in 2013 amounted to 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. (OECD/NEA, 2014) The reason why the resources decreases is that U.S. did not report the amount in 2013. Then, we regards 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 amount of conventional uranium resources recovered from uranium mine and includes 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, non-ferrous 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. (OECD/NEA, 2014) The amount of these sources is 7.3-8.4 million tU (OECD/NEA, 2014), 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 classified as an unconventional resource, amounted to 4.5 billion tU (Tamada, et al. 2006), which corresponds to a duration period of approximately 72 thousand years (72,604 years). The uranium is dissolved in the seawater at a low concentration of 3.3 parts per billion (ppb). (Tamada, et al. 2006) Thus, developing a cost-effective extraction method remains a challenge. Furthermore, the amount of uranium at the surface of the sea floor is approximately a thousand times more than the uranium dissolved in seawater, which is approximately 4.5 trillion tU. (Tamada, et al. 2000) The uranium solved in seawater is in an equilibrium state with the uranium contained in the rock on surface of sea floor. (Tamada, et al. 2000) The concentration of 3.3 ppb is a saturated value and will remain constant. This suggests that almost all of the uranium dissolved seawater and contained in the rock on the surface of sea floor corresponding to the duration period of approximately 72 million years can be recoverable. In other words, the uranium from seawater is almost inexhaustible resource.

3.2 Energy Security of Uranium Resources

From the viewpoint of energy security, the accessibility is important. Accessibility should be discussed about 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 3 shows distribution of identified resources of conventional uranium (OECE/NEA, 2014). The top three countries of 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 and etc. In fact, uranium price in 2007 shown in Fig. 2 soared due to the catastrophic water inflow in Cigar Lake Mine Canada (Cameco. Co, 2006), even though increase of uranium demand in China and India also affected (OECD/NEA, 2015). 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.

Fig.3

Moreover, the uranium requirement exceeds the production in the recent two decades as showed in Fig. 4 (OECD/NEA, 2014). The mass balance has now been achieved by the stock until 1990. In addition, the 1993 US-Russian Highly Enriched Uranium (HEU) purchase agreement was terminated in 2014 (OECD/NEA, 2012). 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. Lack of uranium resources supply compared with the demand will become worse.

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, we discuss a Japanese case as a representative country which is not uranium producing country and dese 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 8 thousand tU (8,091 tU), and the production from own concession is 663 tU in 2007 (Advisory Committee for Natural Resources and Energy, 2009). The fraction is only 8.2 %. Not only companies but also government invest in the exploration and development of the mine to obtain the uranium concession. Table 1 (Advisory Committee for Natural Resources and Energy, 2009) 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.

Table 1

To achieve the ultimate energy security, the resources should exist 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 Fig. 5 (Tamada, et al. 2006). 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 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 1,200 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 about 6.6 times as much as the requirement of 8,091 tU in Japan, and it can occupy the most part of the requirement in the world.

Thus, the utilization of seawater uranium is an effective measure to solve the two problems of geography and concession from the viewpoint of energy security. It is expected that the seawater uranium should be recovered before the exhaustion of conventional uranium resources to solve the problems.

Fig. 5

4. Economy of Electricity Generation using Seawater Uranium

4.1 Recovery cost of uranium resources

To achieve the economic electricity generation, the cheaper uranium recovery cost is preferable. The highest cost category of < 260 $/kgU for conventional uranium resources is added to Red Book 2009 in response to the recent price increase in the market. (OECD/NEA, 2010) On the other hand, the recovery cost of unconventional uranium is higher than 260 $/kgU as mentioned in the previous section. Therefore, the cost of 260 $/kgU is considered as a criterion to determine whether a resource can be recovered economically or not.

The market price of uranium in a past decade is shown in Fig. 6. (International Monetary Fund, 2015) 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 U.S. civilian NPP was 120 $/kgU (46.16 $/lb$U_3O_8$) in 2014. (U.S. Energy Information Administration, 2015) As shown in Fig. 7 (U.S. Energy Information Administration, 2015), the price increased slowly from 2004 and the sharp increase in 2007 was related to the spot market price. In the present study, the representative uranium price of conventional uranium resources is set at current trading price of 120 $/kgU.

Fig.6 and 7

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) (Tamada, et al. 2006). 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 1,200 tU/year, was evaluated. The cost is composed of adsorbent production (69%), uranium recovery (29%), and elution and purification (2%). In this estimation, 6 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 $/kgU with the exchange rate of 120 yen/$ (Tamada, et al. 2006). In the future, a more reasonable cost of 110 $/kgU (Tamada, et al. 2006) can be realized using braids with 60 repeated soaking cycles.

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 Cost Estimation of Electricity Generation using Seawater Uranium

The cost of seawater uranium recovered with current technology is not sufficient low. However, the economy of electricity generation should be assessed not for uranium purchase cost but for the entire cost. In this section, electricity generation cost with seawater uranium is estimated.

The electricity generation cost of HTGR (Takei, et al. 2006 and Kunitomi, et al. 2007) is evaluated based on a Gas Turbine High Temperature Reactor (GTHTR300) (Yan, et al. 2003) 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 4 reactor units in a plant. Total thermal power of the plant is 2,400 MWt, and electric power (gross) is 1,100 MWe. The cost is corrected to take into account the inflation of 3 % (INL, 2012).

In the previous economy study (Takei, et al. 2006 and Kunitomi, et al. 2007), the cost of LWR was compared to evaluate the characteristics of the HTGR cost. The cost of LWR was evaluated assuming the PWR plant with electric power (gross) of 1,300MWe by Federation of Electric Power Companies (FEPC) in Japan (Federation of Electric Power Companies, 2004), and the unit costs of the fuel cost was evaluated by Takei based on the FEPC evaluation. In the present study, LWR cost is also evaluated to compare the HTGR cost change by fueling seawater uranium with the cost by de facto standard of nuclear power generation. The cost of LWR is also re-evaluated in 2011 to take into account the effect of Fukushima Daiichi nuclear power plant disaster (Committee of Electricity Generation Cost Verification, 2011). Major changes of the revised cost for both types of reactor is caused by increase of construction cost. The construction cost shows increase of approximately 30 % for a decade. The reevaluations show consistency.

The electricity generation cost consists of four major parts: 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 Fukushima Daiichi nuclear power plant disaster, social cost, which includes political cost, compensation cost, environmental cost, is considered as a part of the electricity generation cost. Environmental cost is required only for the energy source that release CO_2 gas.

In the present study, the same value of social cost of LWR is also employed for HTGR cost. The political cost is set to 1.1 yen/kWh, and the compensation cost is set to 0.5 yen/kWh for load factor of 80 %. This treatment gives conservative conclusion for HTGR cost because the compensation cost should be reduced due to the outstanding inherent safety feature of HTGR described above.

To evaluate the electricity generation cost variation by using uranium from seawater, the fuel costs are re-evaluated. Moreover, the cost with conventional uranium is also re-evaluated because the conventional uranium price drastically changes in recent years as shown in Fig.2. To estimate the cost, the exchange rate of 120 yen/$ is also employed. In addition, the operation cost of HTGR is also re-evaluated to coincide with the condition of LWR. To evaluate operation cost, the cost rate to the construction cost for the maintenance cost and miscellaneous cost, and the cost rate the operation cost for the head office cost of LWR (Committee of Electricity Generation Cost Verification, 2011) obtained by questionnaires to actual plants is used as listed in Table 2.

The fuel cost was evaluated by uniformly dividing the nuclear fuel cycle cost described in the report of the Organization for Economic Co-operation and Development (OECD)/ Nuclear Energy Agency (NEA). (OECD/NEA, 1994) In this calculation, the fuel cost was evaluated as fuel cycle cost per electric power generation under a condition that the power plant was operated during a specific period. The fuel cycle of HTGR is similar to that of LWR. The unit cost of front-end is determined on the basis of the trial estimation of fuel cycle cost for LWR by the OECD/NEA. (OECD/NEA, 1994) The unit cost of back-end is determined on the basis of the trial estimation of fuel cycle costs for LWRs by the FEPC. (Federation of Electric Power Companies, 2004) For items peculiar to the HTGR fuel, the evaluate assumptions for LWRs were re-examined or other evaluate methods were employed in the previous studies (Takei, et al. 2006 and Kunitomi, et al. 2007). These costs are corrected to take into account the inflation of 3 % (INL, 2012) until 2014. For uranium perchance cost, the current trade price of 120 \$/kgU is employed for conventional uranium. For seawater uranium, the price of 208 \$/kgU, which is the realistically achievable price with the current technology, and the cost with expected price of uranium from seawater is needless to evaluate because the price of 110 \$/kgU is lower than the price of conventional uranium.[†] The conversion price of 8 \$/kgU is the average spot price in 2014. The enrichment price of 366 \$/kgU-SWU is the average price traded by civilian NPP in U.S. in 2014 (U.S. Energy Information Administration, 2015). The unit costs for the fuel cycle cost are listed in Table 3. The unit costs of LWR evaluated by Takei are modified by taking into account inflation of 3 % (INL, 2012) for eight years.

Table 3

[†] (footnote) Tamada concluded that the seawater uranium is too expensive compared with the conventional uranium price of 52 \$/kgU in 2004 for both recovery costs with current technology and expected in the future. However, due to the recent price increase of conventional uranium, the expected recovery cost of sweater uranium become cheaper than that of conventional uranium.

For other conditions, discount rate of 3 %, load factors of 80 % for LWR, 80 % and 90 % for HTGR are set in the evaluation. GTHTR300 is designed to achieve high load factor over 90 % at the price of batch number of core. GTHTR300 employed two-batch core design. However, four-batch core, which also employed in LWR, is also realistic, and the 20 % longer lifetime of fuel is expected according to liner reactivity model. In the present study, the load factor of 80% is also considered to compare with LWR.

The evaluated cost of the fuel and total electricity generation are listed in Tables 4 and 5. 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. The electricity generation cost of HTGR with load factor of 90% increases mere 0.21 cents/kWh, from 5.86 cents/kWh to 6.07 cents/kWh (7.28 yen/kWh), by using seawater uranium. Furthermore, this is lower than the 7.34 cents/kWh (8.80 yen/kWh) for LWR using conventional uranium. The HTGR cost using seawater uranium with load factor of 80% is 6.64 cents/kWh (7.97 yen/kWh), and this is also lower than the cost of LWR with conventional uranium.

Table 4 and 5

4.3 Discussion on Characteristics of the Cost of Electricity Generation

As described in Section 4.1, HTGR can achieve cheaper electricity generation even with seawater uranium than the existing electricity generation by LWR with conventional uranium. Two reasons are considered HTGR to achieve the economic electricity generation.

First, the sensitivity of uranium purchase cost on electricity generation cost is slight~~ly~~. Even though the uranium purchase cost become double, the electricity generation cost shows the small increase of less than 5 %. This is the characteristics of electricity generation cost for NPP. To confirm 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 Fig. 8. As electricity generation cost for NPP, HTGR cost with conventional uranium evaluated in the previous section is employed. The CFPP cost is estimated by the Japanese cabinet secretariat by assuming a plant with electricity generation capacity of 750 MWe (Committee of Electricity Generation Cost Verification, 2011). The cost for NPP consists of capital cost (25.3 %), operation cost (25.3 %), fuel cost (28.7 %), and social cost (20.7 %). 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 4.5 % of the entire cost because 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 6, and the fraction of uranium purchase cost in entire fuel cost is small value of 15.6 %. This is different from fossil fuel power generation, which directly obtains energy from the fuel without fabrication.

Second, the electricity generation cost of HTGR are cheaper than that of LWR especially for the capital cost and the operation cost. Both two costs are proportional to the construction cost. The large part of capital cost is composed of depreciation cost. It can be regarded as construction cost itself. The large part of the operation cost is composed of maintenance cost and miscellaneous cost. It can be intuitively understood that those two costs are proportional to the scale of facilities, which are also proportional to the construction cost. In other words, smaller construction cost per power generation realizes cheaper electricity generation cost.

Fig 8 and Table 6

Fig. 9 shows the construction costs per 1000 kWe of HTGR and LWR. The costs are divided into the category defined by Energy Economic Data Base (EEDB) in U.S. (ORNL, 1987). The cost fraction of LWR was evaluated (Takei, et al. 2006 and Kunitomi, et al. 2007) for the 1,200 MWe class PWR plant of the unit No.4 of Genkai Nuclear Power Station of Kyushu Electric Power Co. The construction cost of HTGR, which is GTHTR300 here, was evaluated with the following assumption.

(1) The reference plant is the Nth plant that allows for learning effects and replacement of a LWR.

(2) A modular method of construction is used.

(3) Equipment can be directly carried into the site from an on-site exclusive port.

(4) Evaluation assumptions for a reactor building and structures are based on those of the HTTR.

(5) Evaluations include design and fabrication of facilities, plant construction cost and test operations (expect for R&D cost, license cost, land price, preparation cost of land, fuel cost

and cost for spare parts).

Fig. 9

Only the reactor component, cost of HTGR is larger than that of LWR due to the lower power density design to offer higher levels of safety. Other parts of 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 is also reduced for direct gas turbine system. Finally, the volume of buildings is also small for HTGR. In addition, higher thermal efficiency of 45.6 % for HTGR (Yan, et al. 2003) than approximately 33 % for LWR also contribute to the cheaper construction cost per unit power generation.

5. CONCLUSIONS

Utilization of uranium resources is investigated to achieve safe, sustainable, and economic energy supply by taking the advantage of safety feature of HTGR. To sustain nuclear energy safely with HTGR, the uranium resources should be inexhaustible and obtained surely because the thermal spectrum reactor of HTGR is not preferable to breed fissile fuel material. Moreover, the cost should be reasonable to be accepted as commercial utilization.

However, the amount of conventional uranium corresponds to consumption of approximately 290 years, and it is not much enough to sustain the energy supply eternally. Moreover, conventional uranium has problems from the view point of energy security, i.e., geology and concession. On the other hand, total uranium from seawater amounted to 4.5 billion tU, which corresponds to a duration period of about 72 thousand years. Seawater uranium is dissolved in equilibrium state with approximately 4.5 trillion tU of uranium at the surface of the sea floor. This suggests that almost all of the uranium resources can be recoverable. The duration period becomes 72 million years. In other words, seawater uranium is almost inexhaustible. Moreover, 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 obtain to fulfill the entire requirement.

The target cost of uranium from seawater is 110 $/kgU, which is lower than the current uranium price of 120 $/kgU. However, with current technology, the achievable cost is 208 $/kgU, which is not reasonable comparing with conventional uranium cost.

The electricity generation costs are also evaluated in the present study for LWR and HTGR. The HTGR reactor used for comparing generation costs is the GTHTR300 designed by JAEA. As electricity generation cost characteristics in NPP, the fraction of uranium purchase cost was only 4.5 % with the uranium price in 2014. Thus, the electricity generation cost in NPP is very stable for the fluctuation of uranium price. Because of this characteristics, the electricity generation cost of HTGR increases mere about 0.21 cents/kWh, from 5.86

cents/kWh to 6.07 cents/kWh (7.28 yen/kWh), by using uranium from seawater. This is lower than the 7.34 cents/kWh (8.80 yen/kWh) cost of LWR fueled by conventional uranium.

As a result, it is concluded that the promising options of electricity generation which has both of the energy sustainability and reasonable economy with superior safety feature are the seawater uranium fueled HTGR. Moreover, the seawater uranium fueled HTGR is cheaper than existing LWR even with the current technology for seawater uranium recovery.

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List of Table and Figures

Table 1 Uranium concession owned by Japanese companies

Countory	Mine	Company	Concession (%)	Condition
Niger	Akouta	Overseas Uranium Resources Develop. Co.	25	Under Operation
Canada	McClean Lake	Overseas Uranium Resources Develop. 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 2 Cost rate of maintenance, miscellaneous, and head office cost

Item	Cost rate (%)
Maintenance cost*	2.2
Miscellaneous cost*	1.9
Head office cost**	13.4

*Cost rate to construction cost.

**Cost rate to operation cost.

Table 3 Unit price of fuel cycle cost

Unit Price	Unit	LWR	HTGR
Conventional uranium purchase	$/kgU*	120	120
Seawater uranium purchase	$/kgU	208	208
Uranium conversion	$/kgU	8	8
Enrichment	$/kgU-SWU	366	366
Fabrication	$/kgU**	887	5933
Storage	$/kgHM***	961	1858
Reprocessing	$/kgHM	3705	11221
Waste disposal	$/kgHM	3536	10398

*The unit is for mass of natural uranium.

**The unit is for mass of enriched uranium.

***The unit is for mass of discharged heavy metal.

Table 4 Fuel cost (cents/kWh)

	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 5 Electricity generation 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 6　Fraction of NPP fuel cost

	Fraction (%)
Uranium Purchase	17.7
Conversion	0.8
Enrichment	29.3
Fabrication	23.9
Storage	1.1
Reprocessing	17.7
Waste Disposal	9.5

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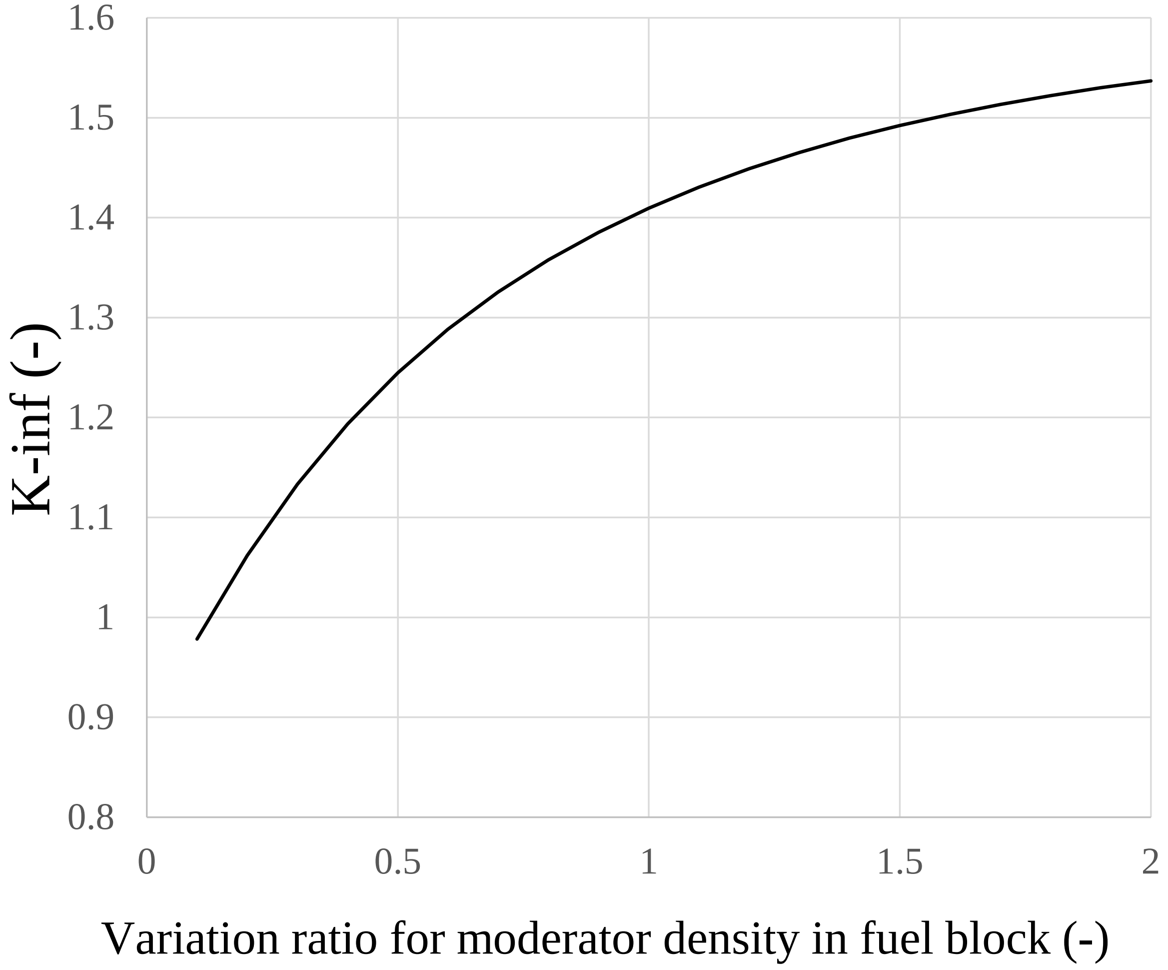

Fig. 1 Change of criticality to moderator density in fuel block

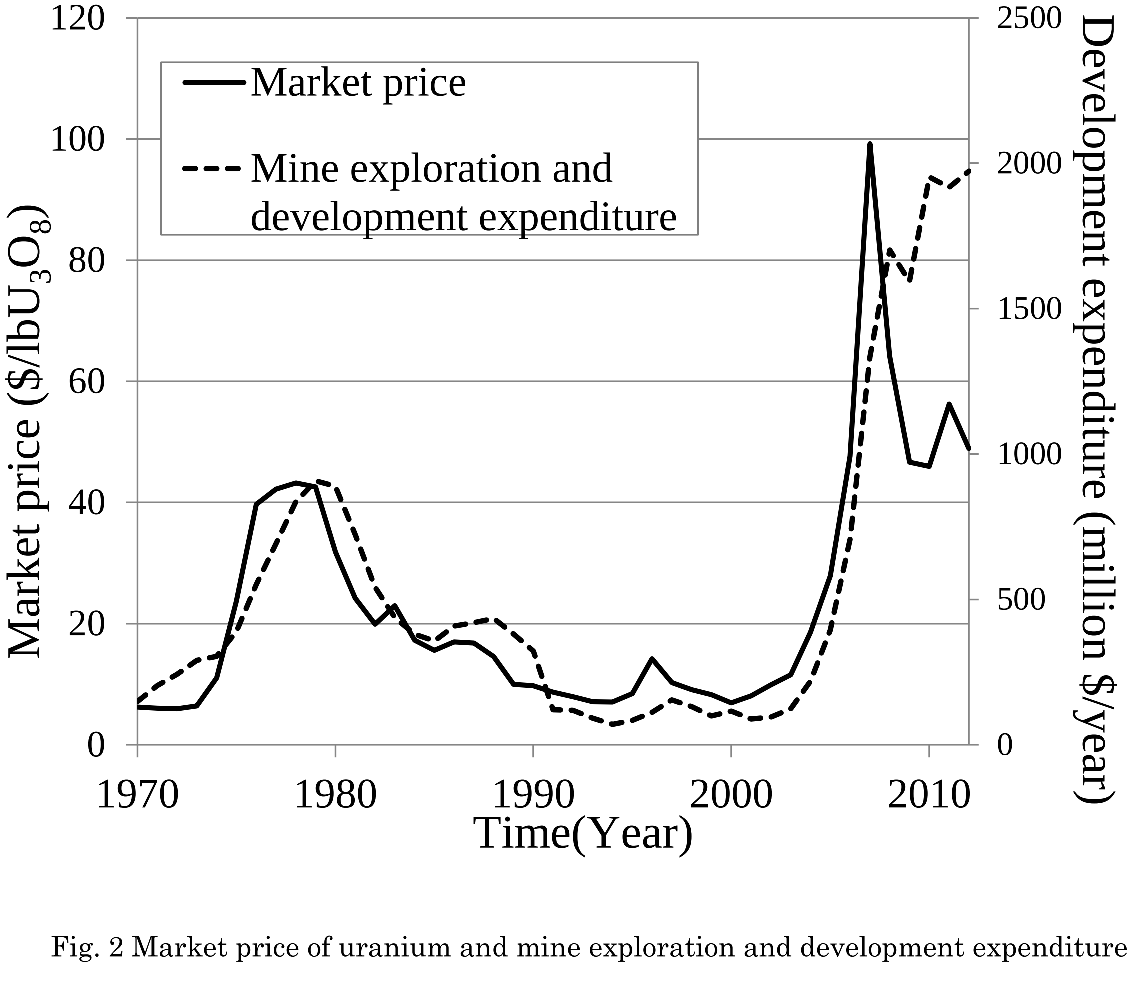

Fig. 2 Market price of uranium and mine exploration and development expenditure

※The uranium resources belong to cost category of < 260 \$/kgU.

Fig. 3 Global distribution of identified resources

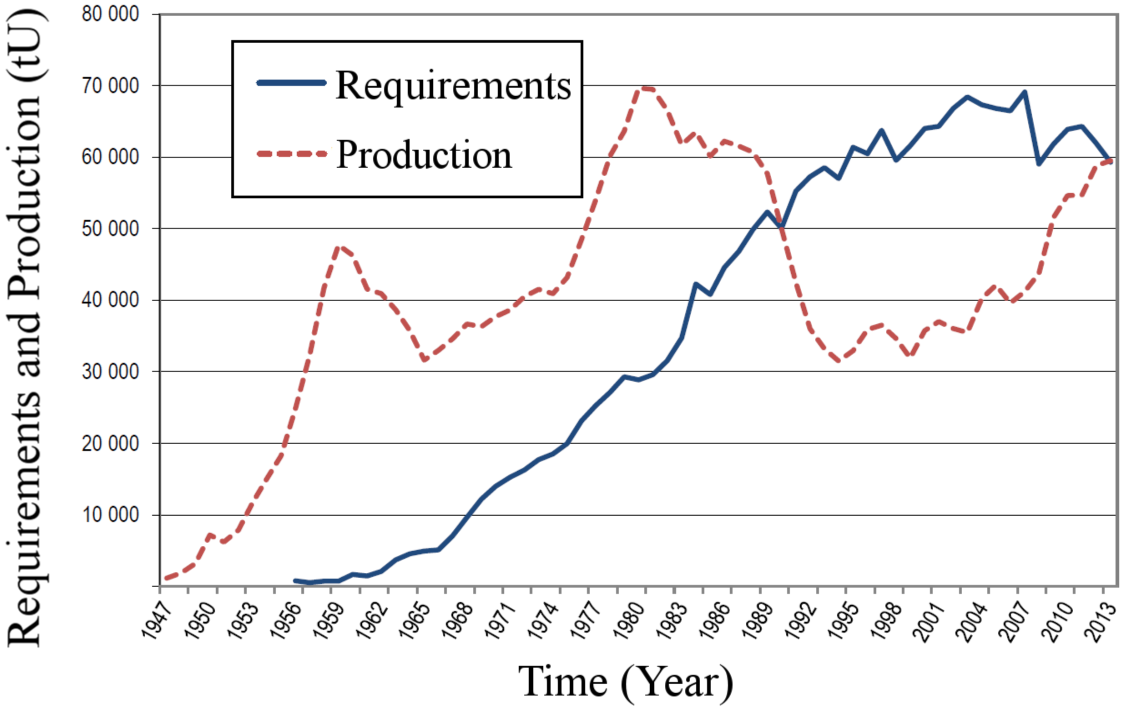

Fig. 4 Annual world uranium requirements and production

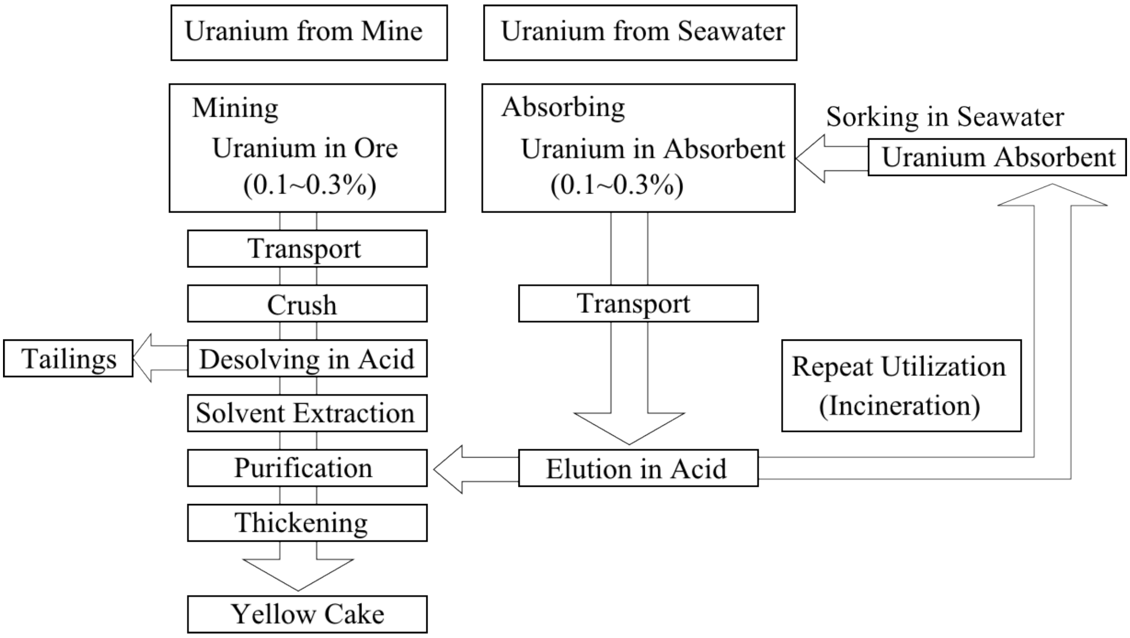

Fig. 5 Process of uranium recovery

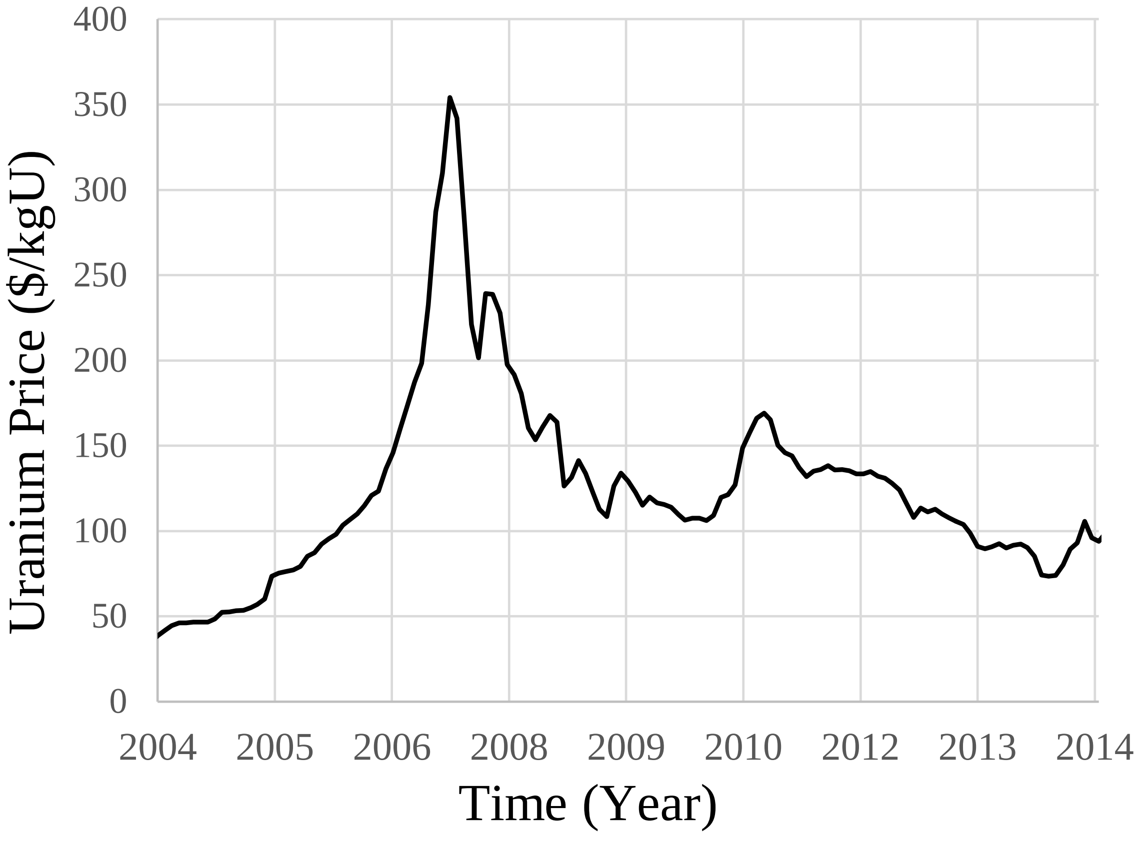

Fig. 6 Spot market price of uranium

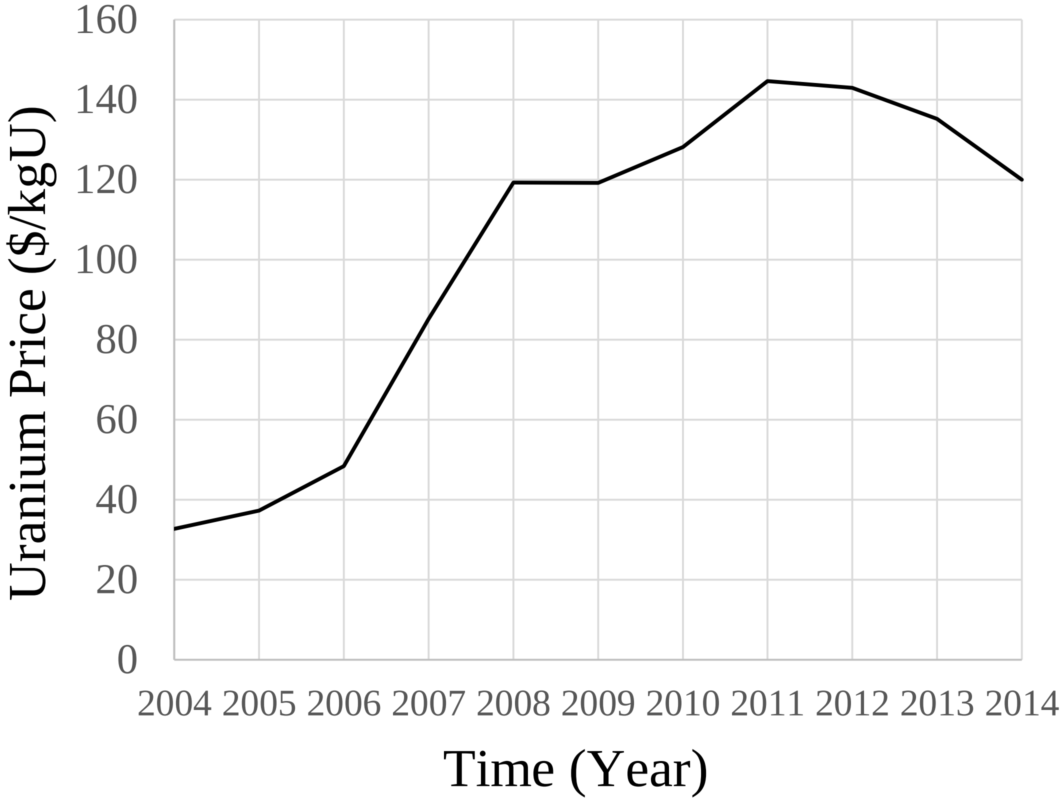

Fig. 7 Weighed-average price of uranium purchased by owners and operators of U.S. civilian NPPs

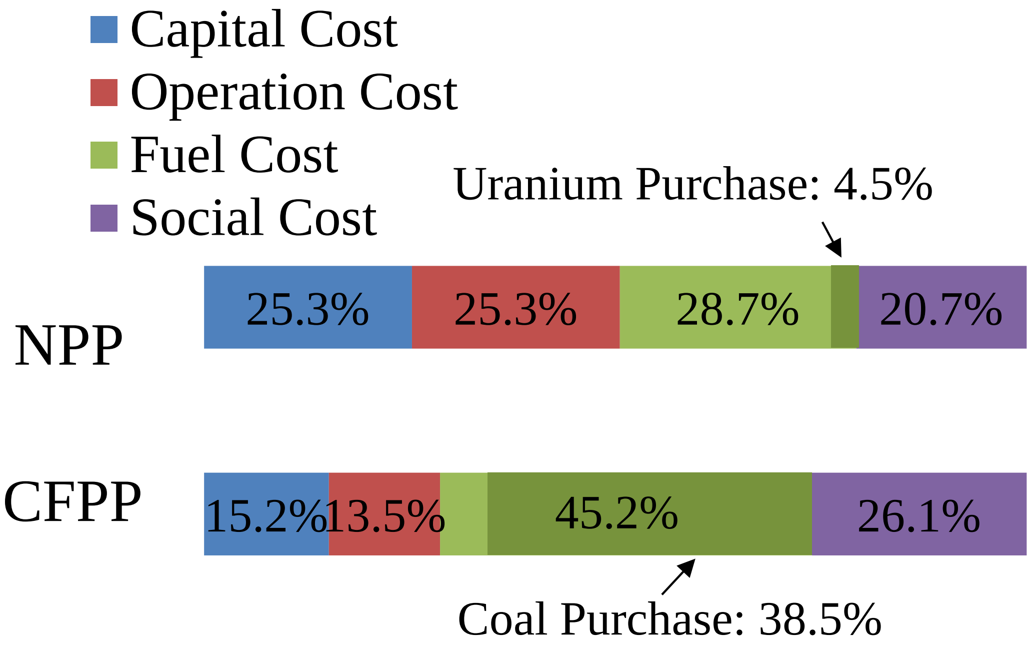

Fig. 8 Fraction of electricity generation by NPP and CFPP

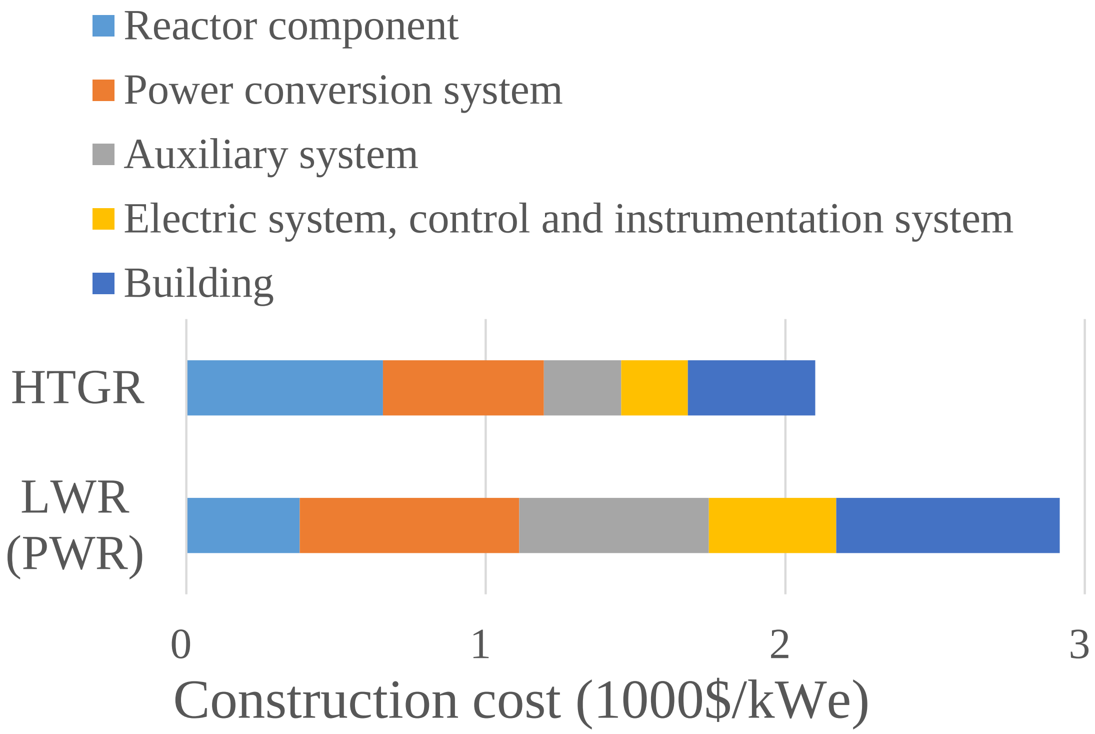

Fig. 9　Construction cost