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Implementation Strategy of Thorium Nuclear Power in the Context of Global Warming

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1. Introduction

The progress of global warming requires us to construct a sustainable society immediately. At the same time, energy demand in developing countries especially in Asian countries such as China and India is increasing rapidly and at a large scale. In the context of global warming, fossil fuels such as coal and oil should not be used as primary energy sources because they significantly increase concentration of greenhouse gases like carbon dioxide (CO₂) in atmosphere. Therefore nuclear energy can be one of the candidates of carbon-free primary energy source.

However, it is also true that there are concerns relating to the use of nuclear power such as nuclear proliferation, radioactive waste and possibility of severe accident. These concerns make it difficult to apply nuclear power widely in the world even though it does not emit CO₂. We are now in the end of the first commitment period of Kyoto protocol. There are mainly three mechanisms to reduce CO₂ emission from human activity. One of them is called "Clean Development Mechanism (CDM)", which supports implementation of technology and finance for CO₂ reduction in developing countries. Nuclear power is not confirmed as an option of CDM due to its concern of safety issue.

On the other hand, there are many remarkable movements on another nuclear power, which utilizes "thorium" as fuel, in the world recently. Thorium nuclear power becomes to be discussed not only by nuclear specialists but also in the field of global warming. This is because thorium nuclear power has a potential to achieve both production of electricity without emitting CO₂ and reduction of concerns of ordinary nuclear power at the same time. In this chapter, outline of thorium nuclear power will be introduced and its implementation scenario in the global scale from a view of global warming will be demonstrated. In addition, background of recent trend of global warming, which calls thorium nuclear power, will be shown. The focal point of above calculation is mass-balance of fissile materials because implementation amount of thorium nuclear power is mainly governed by supply amount of fissile materials.

2. Necessary understandings on global warming

It is indispensable to know how much CO₂ is emitted from different sectors in order to prepare adequate approaches in technical and economical views. 46 % of CO₂ is coming from energy sectors such as electricity and heat production (International Energy Agency

[IEA], 2009). Governing factor of CO₂ emission from electricity production is coal usage. Coal is a widely spread energy resource and its remaining resource is still large. Its price is also cheap. Recent technological progress of carbon capture and storage (CCS) is expected to reduce CO₂ emission from the whole life of coal usage. Most of technical elements of CCS system have been cleared and some feasibility studies are now carried in Norway, Canada and Australia. However, careful design of total system of CCS will be needed in order to avoid CO₂ leakage during its transportation from its production point to its final disposal area (Kamei, 2008). Solar power is also available for clean electricity supply. But it should be noted that solar power is available only in daytime and its output fluctuates due to weather condition.

One of the practical low-carbon energy sources is nuclear power. Nuclear power has been recognized as an effective way as countermeasure of global warming. But it was not counted as an option of CDM because of its several concerns. These concerns are nuclear proliferation, safety and radioactive waste. As Solana, the high representative for the common foreign and security policy of European Union (EU) said, expansion of nuclear power to developing countries in Asia will cause a concern of nuclear proliferation. We still have the memories of a severe accident of Chernobyl as a possibility relating to the use of nuclear energy. In addition, we are still facing the ongoing severe accident at Fukushima Daiichi nuclear power plant in Japan. Recently, public opinion in the USA revealed that they still have concern against radioactive waste, which contains plutonium (Pu) and trans-uranium materials (TRU).

23 % of world CO₂ emission is coming from transportation sector (IEA, 2009). This is the highest growing sector of CO₂ emission. Road transport sector occupies 73 % of all transportation (IEA, 2007). This trend is estimated to continue because transportation is essentially needed for growth in economy. Therefore, it is indispensable to reduce CO₂ emission from transportation sector. Though there are several candidates of low-carbon transportation, electric vehicle (EV) will rapidly expand its use because infrastructure to supply fuel to EV has already been established. Technological keys for EV and hybrid-vehicles are battery and electric motor using permanent magnet. Historically speaking, EV came to commercial phase earlier than gasoline engine cars. However EV could not obtain major position in the market because it could not have long driving range. Recent progresses of large capacity battery and high power electric motor help commercialize of EV.

Sectoral approach has been suggested by Japan at the 13th Conference of the Parties (COP13) as an effective way to reduce CO₂. We should understand both advantages and disadvantages of this approach to successfully carry out. One of the advantages is that it is easy to determine each country's CO₂ reduction target by this approach. On the other hand, the disadvantage is that some sector's reduction has a possibility to become some other sector's imposition. The most apparent case is transportation sector, which mainly uses oil as its fuel at moment. It is easy for this sector to greatly achieve CO₂ reduction target by electrification. However, power generation sector will be forced to consider additional effort to reduce CO₂ emission, which is not their original responsibility. Therefore, it becomes very important to discuss comprehensive approach, which can avoid such phenomena of emission transition from one sector to other sector, to effectively carry this sectoral approach.

The other important information to design a suitable approach to globally reduce CO₂ emission is nation-based CO₂ emission data. China is now the biggest CO₂ emission country

(IEA, 2009) and it is estimated to emit more CO₂ in near future because of its huge economic growth and its large population. The second biggest CO₂ emitting country is the USA. About 41% of CO₂ emission of the world is occupied only by these two countries. Therefore, it is also necessary to consider a way of CO₂ reduction, which can be applied even by these two great countries as their own countermeasure.

Present accumulation of CO₂ in atmosphere is mainly caused by the previous emission of CO₂ from developed countries such as the USA, European countries and Japan. There are only a few developing countries included in the top 15 ranking of CO₂ emission. However, we have to take care of the future prediction that developing countries are growing now and they will become to emit more CO₂. For example, India is the fourth largest CO₂ emitting country in the world. India is also the second largest country in population at the same time. Therefore, it is necessary to prepare CO₂ emission reduction methods, which can be adopted by these developing countries, too. One of the concerns of national energy security is whether energy is stably supplied or not. From this point of view, energy resource, which can be obtained within its own land area, is most applicable. Even though there are several limitations, but renewable energy such as solar power will be nation's own energy source.

Consequently, there are several points in global scale CO₂ reduction. CO₂ has to be reduced both from power generation sector and transportation sector, but some sector's reduction must not be pushed into other sector. Though there may be some effective method of CO₂ reduction, they should be available even by China and the US. It also should be available by developing countries such as India.

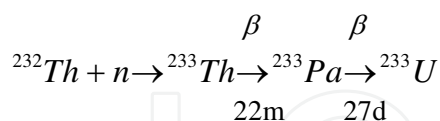
3. Thorium nuclear power

In spite of the concerns mentioned above, nuclear power can play a major role for providing sustainable energy with very low CO₂ emission. One of its advantages is that applying nuclear power will satisfy simultaneous reduction of CO₂ both from power generating sector and transportation sector. That is to say, if newly installed nuclear power plants supply electricity to electric vehicles, it does not disturb efforts of power generating section.

China has already presented that they are going to expand use of nuclear power for providing electricity. Number of nuclear power plant under operation is 11. Number of nuclear plants under construction is 12. Number of plan is 147. Though the super-heated progress was cooled-down after the accident at Fukushima Daiichi nuclear power plant, essential trend is not changed. Even after this severe accident at Fukushima, US's president Obama said that nuclear power will also be used as clean energy source. There are still many countries planning to implement nuclear power in developing countries such as India. However, those concerns relating to nuclear power are still remaining in reality, so it is necessary to overcome these concerns if nuclear power is expanded to the world. For example, nuclear proliferation and radioactive waste must occur essentially as far as only uranium is used as nuclear fuel. Plutonium is the main production from the fertile isotope of uranium (mass number is 238) during the reaction in the nuclear reactor. If spent nuclear fuel is reprocessed, plutonium can be separated. Uranium-235, which is the fissionable isotope of uranium, becomes radioactive waste after nuclear fission. Uranium-238 changes to trans-uranium (TRU) materials such as americium and curium, which govern radioactive waste because of their long half-life. Needless to say, huge earthquakes happen again.

There is a possibility to overcome these concerns relating to uranium usage by adopting thorium as nuclear fuel in parallel to uranium. In this section, outline of thorium nuclear

power will be briefly described and its recent trend in the world will be introduced. Thorium is naturally obtained fertile material. Thorium itself can not make fission reaction, but it transmutes to fissionable uranium-233 by absorbing neutron as shown below.



Thorium is a lighter element than uranium and thus it produces less amount of plutonium and TRU because more than 90 % of uranium-233 fissions without growing heavier nucleus by neutron absorption. Thorium nuclear fuel in a molten-salt reactor (MSR) produces 0.5 kg of plutonium, while uranium fuel produces 230 kg of plutonium in a light water reactor (LWR) during 1 year operation of 1 GWe capacity plant (Furukawa et al., 2008). 8 kg of plutonium is necessary at least for the minimum nuclear explosion, thus it can be said that production of plutonium in thorium MSR is very small. In addition, spent thorium fuel accompanies strong gamma ray, which makes it difficult to fabricate nuclear weapon by using uranium-233 obtained from spent thorium fuel. Tatsujiro Suzuki, a member of Japan Atomic Energy Committee, proposed a new approach toward nuclear non-proliferation and nuclear disarmament in 2009. Here, he suggested using thorium-MOX (mixed oxide) fuel in the present commercially used LWRs (Suzuki, et al., 2009).

Major factors of TRU are americium and curium. Total amount of these elements produced in the same condition mentioned above is 0.3 g from thorium MSR (Furukawa et al., 2008). This value is much smaller than the production amount being 25 kg from uranium LWR. It takes about one million years for the spent uranium fuel without reprocessing to be the same radioactive toxicity of natural uranium. Even with reprocessing, it will need about 100 thousand years. However, it is estimated to be about a few hundred years for the thorium fuel because production amount of americium and curium is very small.

Thorium is about 4 times abundant than uranium and it is widely available even in developing countries such as India, China and Brazil as summarized in Table 1. Developed countries such as Australia, Canada and Norway have large reserve of thorium, too. The U.S. Geological Survey (USGS) announced last year that the USA reserves 915 thousand tons of thorium (USGS, 2009).

We see several notifications on thorium utilization from the side of global warming, not from nuclear industry. Fritz Vahrenholt, CEO of Repower, mentioned in 2001 that conventional LWR will not come back to Germany but safe thorium reactor will be possible. Thorium utilization was recommended as one of the technical approaches to reduce CO₂ emission in the specialist meeting on climate change at Kyoto in 2007. Former Australian Governor-General Major General Michael Jeffrey said that “while solar has the best prospect of a clean and sustainable energy source, thorium should not be discounted, as it is cleaner and can not be used to make weapons grade materials” in 2008 (Future Summit, 2008).

9 papers discussing about thorium fuel in LWR, heavy water reactors (HWR) and MSR were seen in the ANFM IV, which is an international symposium on nuclear power. It was impressive that the general chairman of this symposium wrote as follows; “thorium fuel cycles may be unusual to many of us in the US, but they are important topics internationally, and are subjects that we must carefully study in order to ensure the future success of our industry.” Chinese Tsinghua University in Beijing organized an international workshop on thorium utilization in 2007 (TU2007) collaboratively with international atomic

energy agency (IAEA). China does not have enough amount of uranium but they have huge amount of thorium. Greneche of AREVA said, “It is important to use semi-breeding reactor with thorium fuel. Though CANDU is better than LWR, its conversion ratio (CR) is still smaller than 1. MSR has an attractive feature in this point of view.” Its second workshop, TU2009, was held in Baotou, China. Baotou is the most important city of rare-earth industry, which is indispensable for manufacturing EV. Thorium has already been accumulated as by-product of rare-earth mining in a residual pool.

Country	Reserve [t]	Ratio
Turkey	380,000	14%
India	290,000	10%
Norway	170,000	6%
USA	915,000	33%
Brazil	16,000	1%
Denmark	54,000	2%
Australia	300,000	11%
Egypt	15,000	1%
South Africa	35,000	1%
Canada	100,000	4%
Greenland	54,000	2%
Liberia	1,000	0%
China	388,000	14%
Other	95,000	3%
World total	2,813,000	100%

Table 1. Thorium resource (Nishikawa, 2010)

The Ministry of Petroleum and Energy of Norway published a report of thorium utilization in 2008 (The Ministry of Petroleum and Energy of Norway, 2008). Several private companies such as “Statkraft” and “Thor Energi AS” are carrying R&D of thorium fuel. Former secretary general of IAEA Hans Blix became a board member of Thor Energi AS. In the US, one section titled “study on thorium-liquid fueled reactors for naval forces” was included in the legislation of “National Defense Authorization Act for Fiscal Year 2010”. Finally the description of thorium-liquid fueled reactors was removed, but \$ 61.5 million has been assigned to Oak Ridge National Laboratory (ORNL), which is the origin of thorium-liquid fuel reactor, MSR. There were several movements between private companies of nuclear industries (Peachey, 2009). AREVA, French nuclear company, signed an agreement on collaboration of thorium nuclear fuel with US private company named Thorium Power Co. Ltd (its name has been changed to “Lightbridge” in September, 2009). Canadian nuclear company, AECL signed with Chinese companies group for testing thorium fuel rod in CANDU reactor in Qinshan nuclear power plant at Shanghai.

Many popular magazines are coming to pick up thorium issues. Newsweek presented an article entitled “The Lost Chance” to return to the road not taken 50 years ago – thorium fuel cycle in 2001 (Howard & Graham, 2007). Australian scientific magazine COSMOS reported about the thorium utilization as “green nuclear power” in 2007 (Dean, 2007). Sam Knight reported recent situations on UK’s “Financial Times” in 2008 (Knight, 2008). “U.S. News & World Report” presented thorium utilization in a special issue of green economy in

2009 (Garber, 2009). An international meeting of thorium energy alliance (TEA) was held at Googleplex, the head-office of Google, in March, 2010. Wide range of thorium utilization was discussed including high temperature gas cooled reactor and molten-salt reactor called LFTR (Liquid Fluid Thorium Reactor). The 3rd conference of TEA has successfully organized in May, 2011 at Washington DC. Its sister conference was held at London in October, 2010 by international thorium energy organization (IThEO). Accelerator driven sub-critical reactor (ADSR) was also picked up as a remarkable topic of thorium utilization.

4. Implementation scenario of thorium nuclear power

One of the most attractive reactor types to use thorium is MSR (Weinberg, 1997). The successful R&D program was carried in the USA on MSR for the usage of thorium since 1950's to 70's. Molten-salt reactor experiment (MSRE) was successfully operated during 1965 and 1969. Based on this success, molten-salt breeder reactor (MSBR) was started to develop for targeting commercial power reactor (Rosental et al., 1972). Furukawa et al. have proposed one design of MSR named FUJI (Furukawa, et al., 1990). MSR was chosen among 6 candidates by the Generation IV International Forum (GIF). There are aggressive activities in the US, Canada and France with different types of MSR such as LFTR or tube-in-tube reactor.

Most of MSR has a common technical background. Inner pressure of reactor vessel of MSR is only about 0.5 MPa because it applies molten-salt as coolant, which has very low vapour pressure. Therefore, there is no need to fabricate very high pressure vessel such as necessary in LWR. It reduces risks of bottleneck in its supply chain. Economy of MSR also has been examined (Roy & Robertson, 1971). Comparison between MSBR and LWR indicated that (1) capital cost will be nearly the same, (2) fuel cycle cost will be greatly reduced due to no requirement of manufacturing of fuel rods because MSR is liquid fuel and (3) maintenance cost will be also reduced because there is no necessity of fuel exchange. This is achieved by on-line re-fuelling and re-processing with liquid fuel. There is other recent work showing cost evaluation of MSR and pressurized water reactor (PWR) in view of capital cost, operations and maintenance, fuel, waste disposal and decommissioning (Moir, 2002). The result is summarized in table 2. The fuel cost of MSR was recalculated based on the use of uranium-233. Total cost of MSR will be about 30 % smaller than that of PWR.

	MSR	PWR
Capital cost	2.01	2.07
Operations & maintenance cost	0.58	1.13
Fuel cycle cost	0.12	0.74
Waste disposal cost	0.10	0.10
Decommissioning cost	0.04	0.07
Total	2.85	4.11

Table 2. Cost evaluation of MSR and PWR (cent/kWh)

The most important of thorium usage is that thorium does not contain fissile isotope. Therefore, uranium containing both fissile isotope (uranium-235) and fertile isotope (uranium-238) was used as the first nuclear fuel in the history. Uranium fuel produces fissionable plutonium and some countries are planning to use it as future nuclear fuel in fast

breeder reactor (FBR). However, there is still concern to use plutonium with uranium-238 because it has a possibility to spread plutonium to the world. Total stock amount of plutonium in the world is nearly 2,000 t and it continues increasing in the future. This plutonium can also be used as fissile material with thorium. Thorium is available in any kind of nuclear reactors and many researches are carried now on commercially used reactors, too. Thorium is still not used as nuclear fuel because it is not available for nuclear weapon. Recent global trend of nuclear disarmament also supports starting use of thorium. Disadvantage of thorium containing no fissile isotope can now be solved by applying plutonium in spent nuclear fuel of LWR (Kamei et al., 2008; Kamei et al., 2009). Though it was known that plutonium could be applied as fissile with thorium, there was not enough amount of plutonium in 1970's to start thorium reactors because plutonium is artificially produced material. Now, there is about 200 thousand t of spent nuclear fuel and 2,000 t of plutonium is accumulated. Spent nuclear fuel occurs at least 12,000 tons every year depending on the total capacity of LWR in the world. Czech, Japan and France are studying to use plutonium in spent fuel for thorium MSR. Direct fluorination facility named FERDA has been developed in order to obtain plutonium from spent nuclear fuel (Uhlir, 2008). Outline of possible implementation path of thorium utilization including different types of nuclear reactor such as LWR and new technologies including MSR can be summarized as shown in Fig. 1.

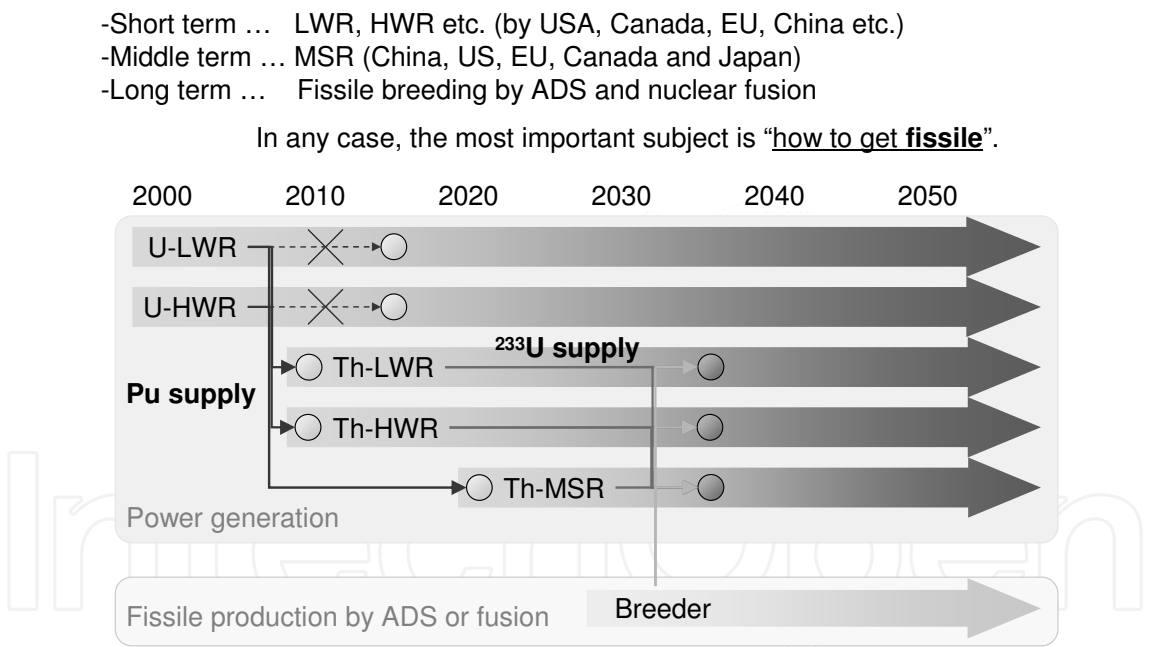


Fig. 1. Implementation path of thorium nuclear power.

The most important point to describe implementation scenario of thorium utilization is fissile supply. Plutonium will be the only fissile material having enough amounts in the very begging of world thorium utilization. Though Plutonium can be used with uranium-238, it is considered here that plutonium will be used with thorium. It is because natural uranium containing uranium-235 can be fed to uranium fuel cycle. As far as present capacity of uranium usage continues in this century, uranium resource is still enough. On the other hand, uranium-235 is also available to be used with thorium. However, it has several limitations. The first point is that in order to be used with thorium, highly enriched uranium-

²³⁵U more than 20% enrichment is necessary. This causes additional concern of nuclear proliferation. The second point is that uranium usage also should be used continuously since it is an established technology emitting no CO₂ during its electricity production. In addition, once uranium usage is terminated in an early stage, plutonium supply will be shortage in order to expand thorium utilization. This will be demonstrated later. Thus, parallel usage of uranium and thorium will be necessary to construct sustainable energy sources available both in developed countries and developing countries.

Once thorium is ignited by plutonium, uranium-233 is artificially produced during operation of thorium fuelled LWR and HWR. This uranium-233 can be used in the following thorium LWR and HWR. Plutonium can also be fed to start MSR. It is estimated to require about 10 years for developing proto-type MSR. Uranium-233 produced from LWR, HWR and MSR will be stored and then can be used as fissile to start following MSR. As presented in the next section, production amount of plutonium and uranium-233 is small. Therefore, production of uranium-233 from thorium by using accelerator or fusion technology will be necessary for large scale implementation. It depends on how design whole view of new nuclear power supply system.

In order to quantitatively evaluate implementation capacity of thorium fuel cycle, mass-balance of fissile material has been calculated. Calculation model is shown in Fig. 2. In this calculation, both uranium fuel cycle and thorium fuel cycle are considered as analysis targets. Fissile material for uranium fuel cycle can be obtained from natural mining. Though

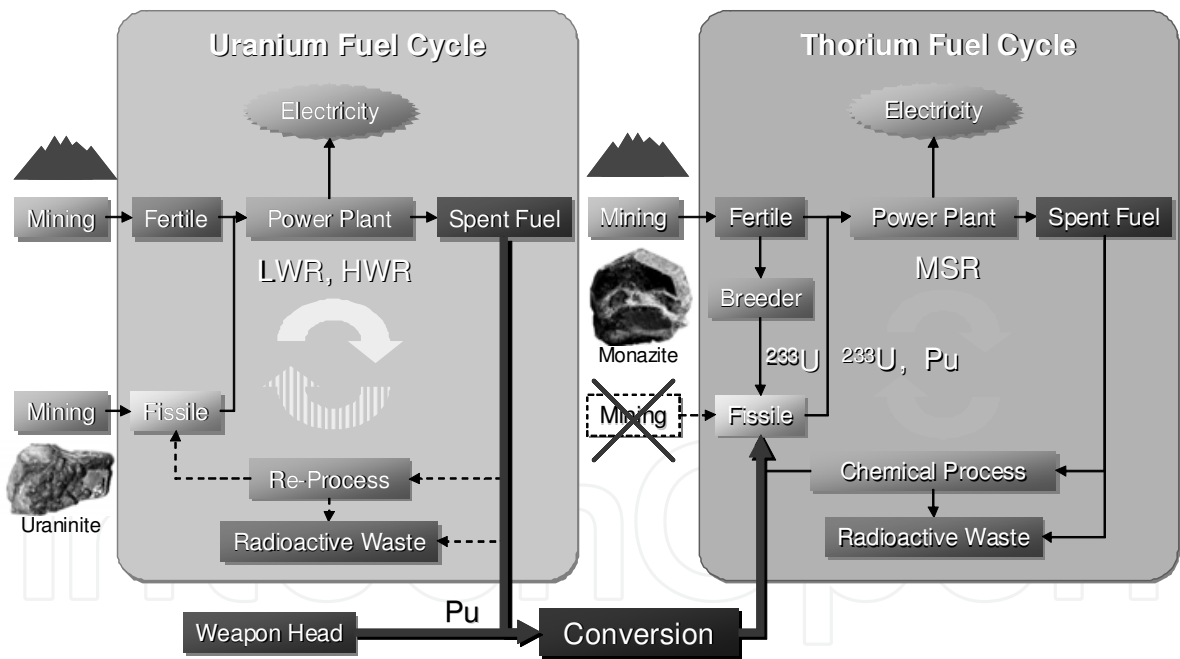


Fig. 2. Calculation model of implementation of thorium fuel cycle

recycled plutonium from spent nuclear fuel can be also fed to uranium fuel cycle as fissile, it is not considered this calculation. Because of the lack of fissile isotope in thorium, it is necessary to obtain fissile material from outside of thorium fuel cycle. Direct production of uranium-233 from thorium by using spallation neutron triggered by accelerator or nuclear fusion neutron can be available inside of thorium fuel cycle without depending on uranium fuel cycle. However, in this calculation, plutonium fed from uranium fuel cycle is considered as fissile material to start thorium fuel cycle. Capacity of uranium fuel cycle is

determined by the prediction of international energy agency (IEA) to be 680 GWe at 2030. In this case, 13 of 1 GWe LWRs will be implemented every year. 1 GWe of LWR generates about 30 t of spent fuel every year.

MSR is considered as a power reactor in thorium fuel cycle because of its high conversion ratio of fissile material. Two designs of MSR, FUJI-Pu2 and FUJI-U3, are applied in this calculation based on different initial fissile. FUJI-Pu2, which uses plutonium as fissile material, will be used for starting the thorium fuel cycle. Spent thorium fuel from FUJI-Pu2 contains uranium-233 and this can be provided to the next generation of thorium MSR. Other design of MSR, FUJI-U3, will be supported by uranium-233 obtained after termination of FUJI-Pu2. Both types of MSR have 200 MWe of electricity capacity and 30 years of lifetime. The performance of these reactors is summarized in Table 3.

	FUJI-Pu2	FUJI-U3
Electricity capacity	200 MWe	200 MWe
Lifetime	30 years	30 years
Pu inventory (initial)	5.78 t	-
Pu feed (total in life)	1.16 t	-
²³³ U inventory (initial)	-	1.132 t
²³³ U feed (total in life)	-	0.344 t
Batch cycle	7.5 years	7.5 years
²³³ U production (batch cycle)	0.295 t	0.029 t
²³³ U production (terminated)	0.295 t	1.505 t
MA production (terminated)	285 kg	5.32 kg
Th inventory (initial)	31.3 t	56.3 t
Conversion ratio	0.92	1.01

Table 3. Specification of MSR

5. Calculation results

Implementation capacity of thorium MSR in a global scale was calculated based on the plutonium supply from uranium fuel cycle. Calculation was carried as follows. At first, capacity of uranium fuel cycle at certain year is determined. Then production of spent nuclear fuel is obtained. It was assumed that MSR will begin to be used around 2024. Its capacity grows gradually and corresponding amount of required plutonium is calculated. This amount is reduced from spent nuclear fuel. Here, capacity of processing spent nuclear fuel to molten-salt fuel is assumed enough high. Calculation result is shown in Fig. 3.

The first Y-axis is referred by electricity capacity. The second Y-axis is referred by storage of spent fuel. Black cross line indicates growth of LWR. The gray line corresponds to the storage of spent nuclear fuel without MSR. The black chain line is the storage of spent nuclear fuel with consumption by MSR. Gray hatching is capacity of FUJI-Pu2. White dot hatching is capacity of FUJI-U3. It is assumed that FUJI-Pu2 begins to be used from 2024. Number of FUJI-Pu2 reactor at 2024 is 32. Plutonium in spent nuclear fuel is rapidly consumed with the growth of FUJI-Pu2. The growing ratio of FUJI-Pu2 decreases at 2029, when stock of spent fuel becomes almost 0. Since then, annual production of spent fuel from uranium fuel cycle is consumed within the same year for new implementation of FUJI-Pu2. After one batch cycle of fuel salt processing of FUJI-Pu2, uranium-233 is extracted and fed to

FUJI-U3. Therefore, two different designs of MSR can be used since 2029. Spent fuel salt from FUJI-U3 is also reprocessed after one batch cycle and fed to next generation of FUJI-U3. Capacity of LWR is 948 GWe and that of MSR including both FUJI-Pu2 and FUJI-U3 is 392 GWe at around 2050. Thorium MSR also produces its own spent fuel. However the amount is considerably smaller than the amount from uranium LWR. This is because spent fuel of thorium MSR comes out of reactor after its lifetime being 30 years. On the other hand, spent fuel of LWR occurs every year. It is estimated here that thorium MSR will be commercialized in 2020's. Therefore, spent fuel of thorium MSR will appear around 2050's. Its quantitative evaluation has been demonstrated in the previous work (Kamei, 2008).

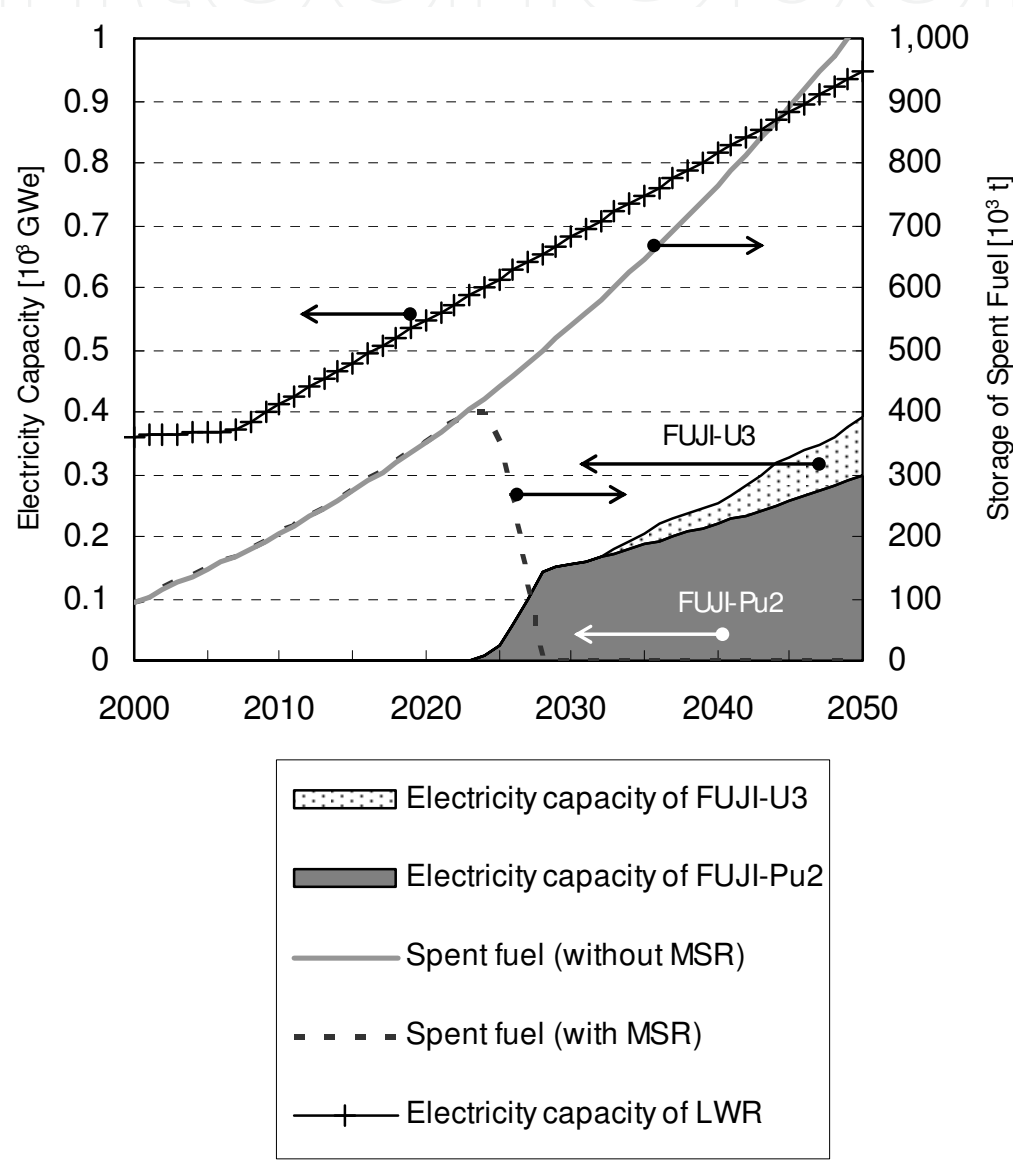


Fig. 3. Calculation result of Implementation capacity of thorium MSR (case 1)

Other result is shown in Fig. 4. It is assumed here that capacity of uranium fuel cycle will be constant within next 40 years by considering the effect of Fukushima Daiichi nuclear power plant accident. In this case, implementation capacity of thorium MSR will be about 258 GWe around at 2050, which is small because supply of fissile plutonium is reduced.

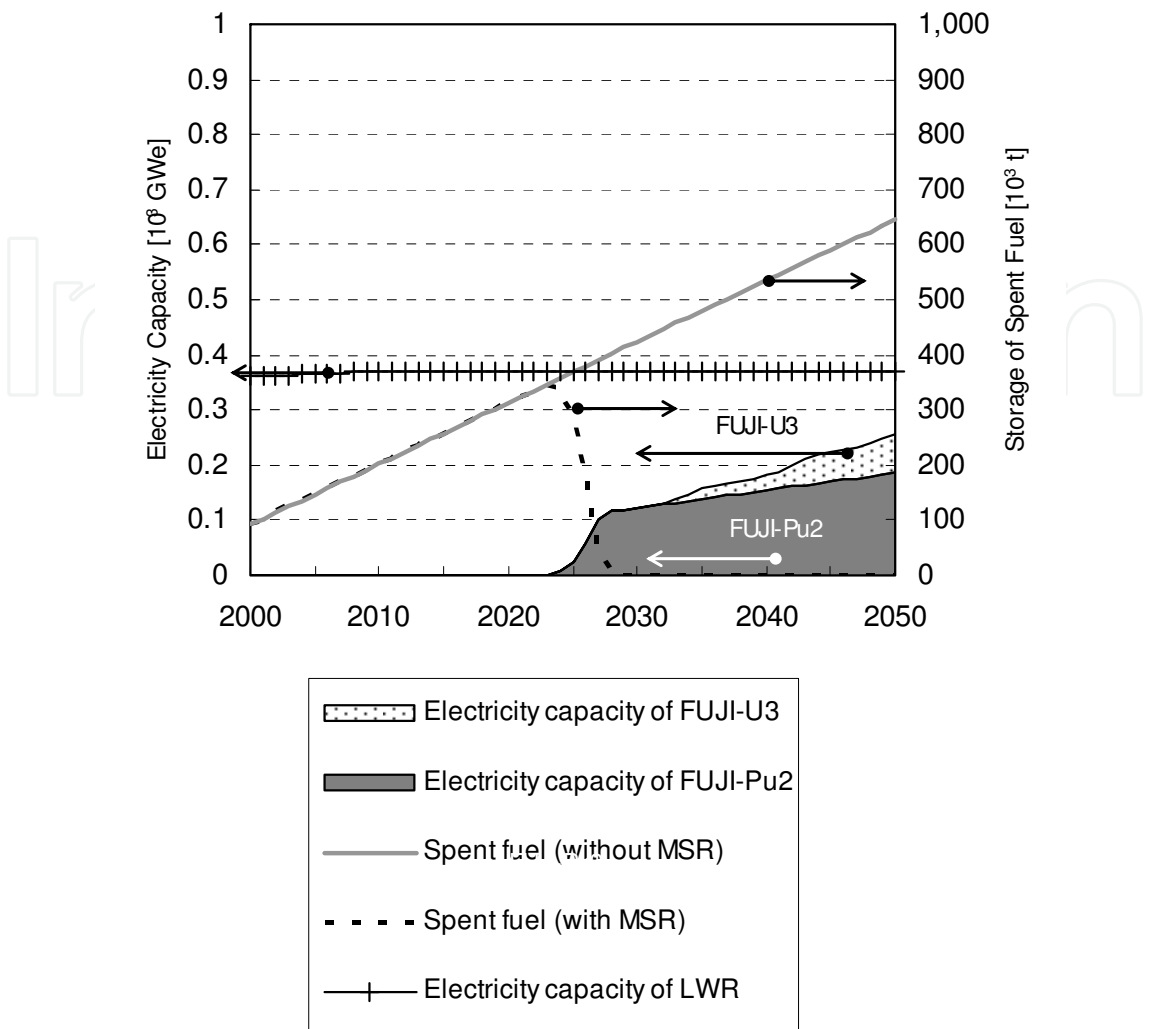


Fig. 4. Calculation result of Implementation capacity of thorium MSR (case 2)

The amount of plutonium from dismantled weapon head is estimated to be about 91.9 t and 145 t for the USA and Russia, respectively (International Panel on Fissile Materials, 2008). Additional 40 t of plutonium can be separated based on the agreement between the USA and Russia to reduce number of nuclear weapons to be 2,000. Briefly speaking, contribution of plutonium from weapon head is about 15 GWe around at 2050 to additionally implement thorium MSR to the implementation capacity by spent nuclear fuel from uranium fuel cycle.

6. Sustainable development with thorium utilization

In this section, relation between thorium utilization and its surroundings will be discussed in a view of comprehensive approach on sustainable development. The key issues are protection of radioactive hazard by thorium, rare-earth production accompanied with thorium, electric vehicle using lots of rare-earth and CO₂ reduction from human activities.

6.1 Production of thorium as by-product of rare-earth

One of the important sectors to reduce CO₂ emission is transportation sector. Many motor companies have presented to supply EV or hybrid-vehicle (HV) recently as summarized in

Table 4. Reborn GM in 2009 put EV for their new backbone like “Chevrolet Volt”. Chevrolet Volt was given the award of 2011 Green Car of the Year. Many new EV companies appeared in China, which became the world largest production and sales of cars. BYD, which was just a battery company, is one of the most famous EV companies in China.

Country	Company	Brand
Japan	Toyota	Prius (HV)
	Nissan	Leaf (EV)
	Honda	Insight (HV), CR-Z (HV)
	Mitsubishi	i-MiEV (EV)
EU	VW	New compact coupe (HV)
	Audi	e-tron (EV)
	BMW	MINI E (EV)
	Daimler	Smart EV (EV)
	Renault	Z. E. (EV)
	PSA	OEM, Mitsubishi (EV)
USA	GM	Chevrolet Volt (EV)
	Ford	Focus EV (EV)
	Tesla motors	Roadster (EV)
Korea	Hyundai	i10 electric (EV)
China	BYD	e6 (EV)
India	Tata	Indica Vista EV (EV)

Table 4. Development of Low-Carbon Vehicle

Rare-earth materials such as neodymium and dysprosium are minerals for fabricating a strong permanent magnetic of electric motor. World annual production of rare-earth materials is about 120 thousands t at 2010 (Watanabe, 2008). The production amount is expected to increase at about 3 or 5 % every year. At moment, China shares 97 % of rare-earth production in the world. These materials can be mined from other Asian countries, too. However, accompanying thorium as by-product of rare-earth mining becomes a radioactive waste having possibility to bring environmental hazard (Nishikawa, 2010). Thorium is not commercially used as nuclear fuel until now. It has been left as radioactive waste, which become environmental and social concerns at the resource countries. Detail investigation is needed but roughly residual thorium is estimated to be produced at least 10 thousand t every year. This makes it difficult for Japanese trade companies to find rare-earth.

6.2 Consumption of thorium

Consumption of thorium has been simulated by using the capacity of thorium fuel cycle demonstrated in the previous section. The result is shown in Fig. 5. Here, it is assumed that 1 % of rare-earth production corresponds to the amount of thorium. It is also assumed that initial value of thorium storage at 2005 is zero. Typical designs of thorium MSR, FUJI-Pu2 and FUJI-U3, require 31.3 t and 56.4 t of thorium as initial value, respectively. Stockpile of thorium will be about 40 thousand t around at 2024, when commercial utilization of thorium MSR begins. Though stockpile of thorium will be accumulated by production of rare-earth, thorium is also consumed and the stockpile will

be about 60 thousand t around at 2050. If there is no utilization of thorium, its stockpile will be more than 130 thousand t.

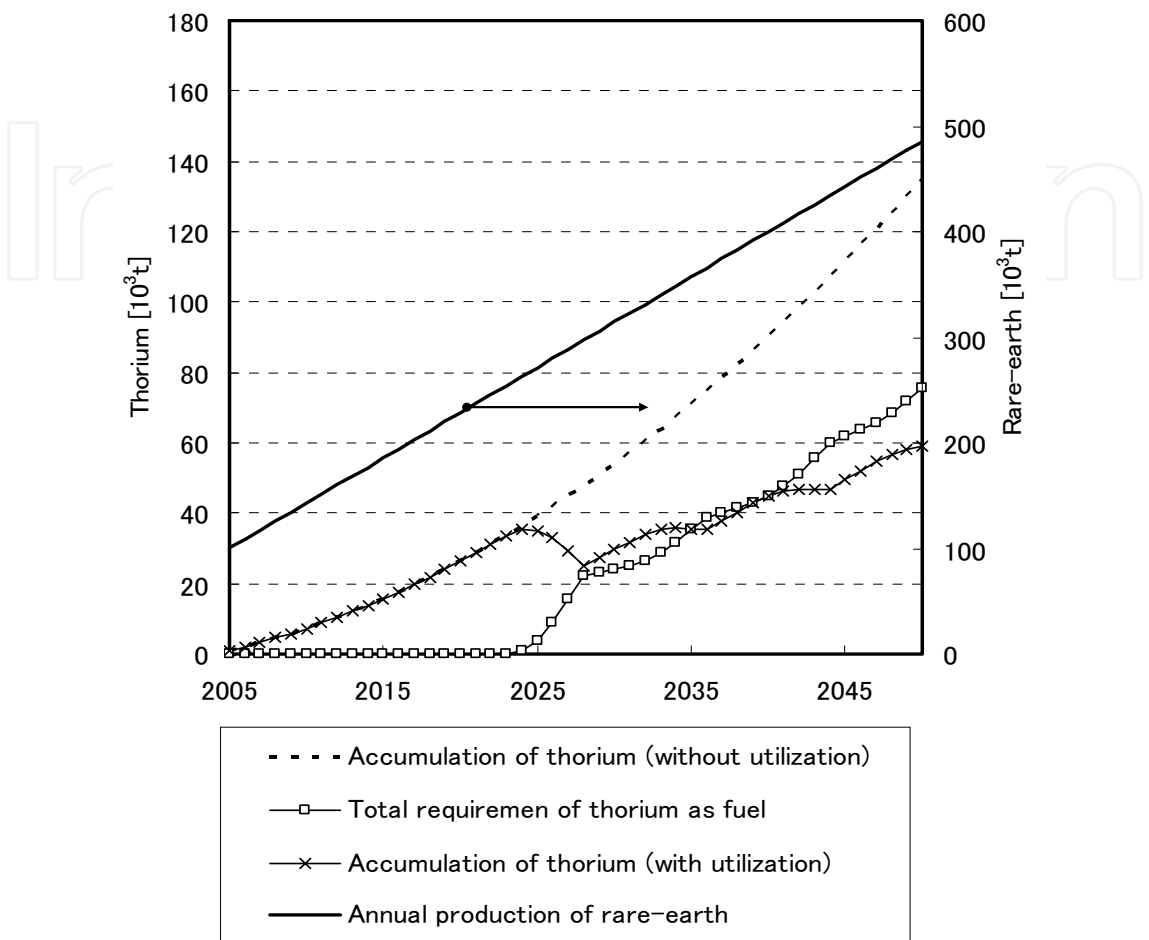


Fig. 5. Consumption of thorium.

6.3 CO₂ reduction from transportation sector

CO₂ emission from transportation sector has been simulated based on the prediction of capacity of thorium MSR also described in the previous section. The result is shown in Fig. 6. It is assumed here that number of vehicles increases with 3.5% of growth rate, which is same to the recent trend (The Japan Automobile Manufacturers Association, 2009). Number of vehicle in the world around at 2005 is about 900 million. This emitted 4.5 Gt of CO₂. Number of vehicle will be about 4 billion around at 2050 emitting 18.6 Gt of CO₂. If 100 million EV are supplied every year since 2010, all vehicles can be replaced with EV at 2050. Even though this estimation is somewhat large, it is assumed in order to evaluate higher case of CO₂ reduction. 392 GWe of thorium MSR can supply electricity to 2.75 billion EV. This is obtained that EV is supplied its electricity by thorium MSR with 80 % of load factor. It is assumed that one EV can drive 10 km per 1 kWh, drives averaged 10,000 km in a year. This corresponds to 60 million t of CO₂ emission from thorium MSR. This was calculated that 1 kWh of nuclear power emits 0.022 kg with its load factor being 80 %. If the rest of 1.25 billion cars are also EV and supplied its electricity by coal fire plant, CO₂ emission is 1.23 Gt. It was assumed that coal fire plant emits 0.975 kg of CO₂ per 1 kWh. Total CO₂ emission is

1.29 Gt both from thorium MSR and coal fire plant. It can be seen that collaborative implementation of thorium MSR and EV has a great potential to CO₂ reduction by solving the problem of sectoral approach.

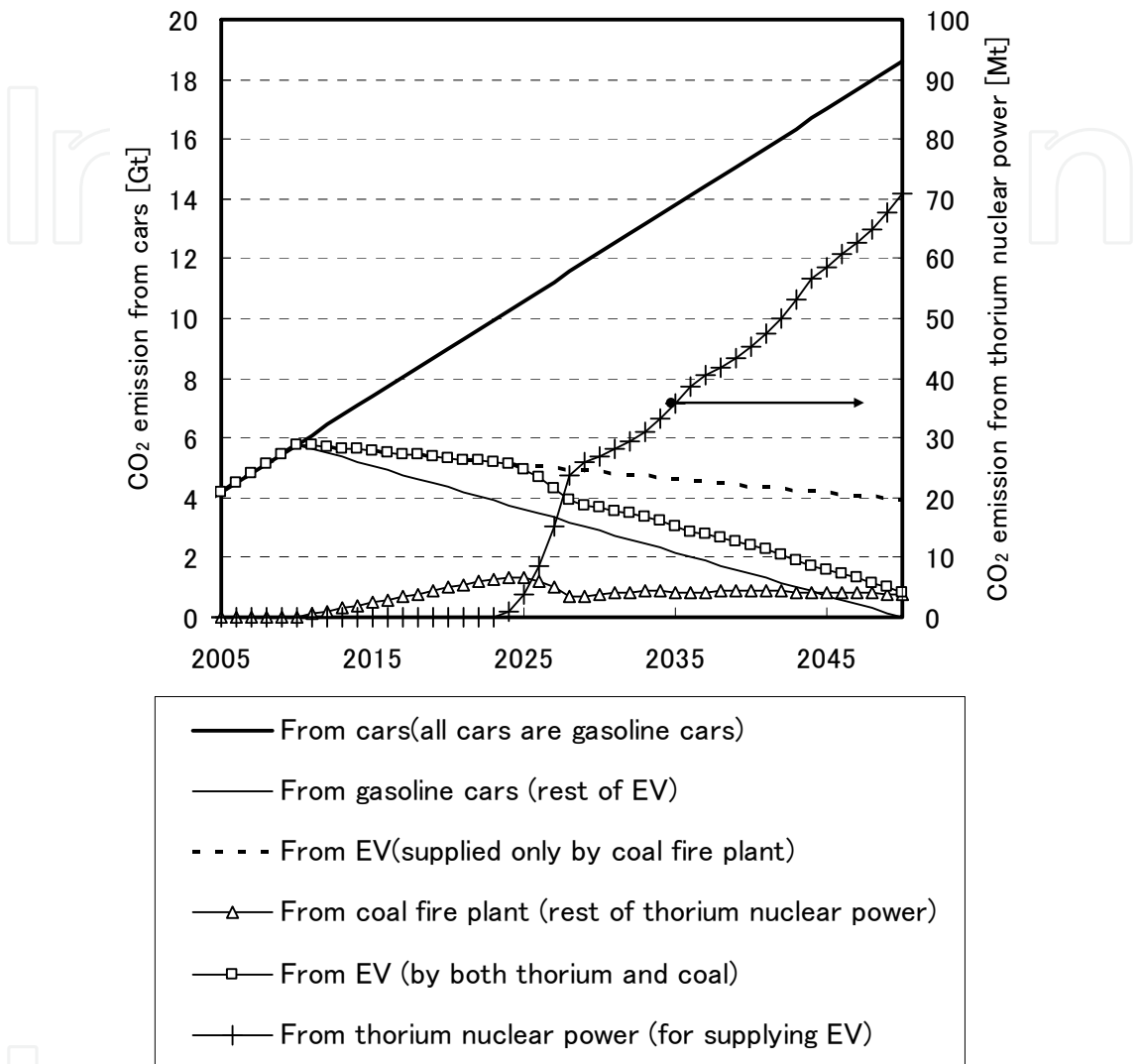


Fig. 6. CO₂ reduction by thorium utilization.

6.4 Concept of “The Bank”

Implementation capacity of thorium MSR is limited by the amount of supply of fissile material. Thorium is recognized as radioactive waste and residual of rare-earth mining. As indicated in the Fig.5, thorium will not be necessarily completely consumed even though it is utilized as nuclear fuel. Therefore, there is a possibility that thorium, which is not managed correctly, cause environmental hazard. In order to promote progress of EV for the reduction of CO₂ emission from transportation sector, rare-earth mining is indispensable. Thus it is also necessary to manage thorium for keeping environment healthy. Estimation of implementation capacity of thorium MSR is based on the supply of fissile material from uranium fuel cycle since thorium does not contain its own fissionable isotope. And the other important point is that it will need more than 10 years for the first commercial implementation of thorium nuclear power. There are several countries, which hold thorium

as future energy source like India, but most of the countries have no plan to store thorium. Therefore it is necessary to storage thorium. Such an idea proposed here is called “The Bank”. This is named from “thorium energy bank”. Outline of “The Bank” is illustrated in Fig. 7.

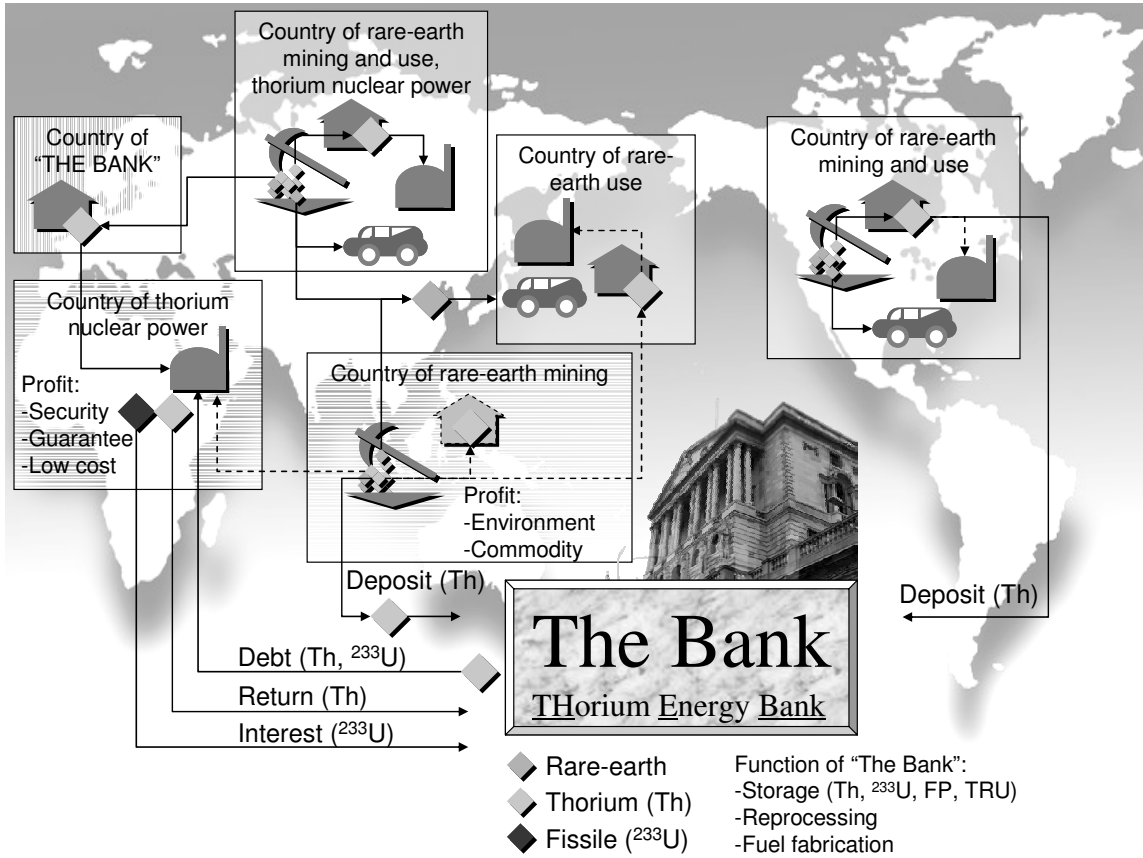


Fig. 7. Concept of “The Bank”.

The most important purpose of “The Bank” is to store thorium obtained as residual of rare-earth mining. This is mainly for protecting environment of mining country of rare-earth from radioactive thorium. The other function is to lend thorium to countries, which does not own its thorium resource. Former US president Jimmy Carter proposed a concept of a nuclear fuel bank. This is to provide fissile material, enriched uranium, in order not to expand the technology of enrichment having fear of nuclear proliferation. Similar proposal was also brought from former director of IAEA, Dr. El Baradei. US President Obama also indicated at the speech in Prague, 2009 that the concept of nuclear fuel bank will be an important role to bring peace nuclear power. “The Bank” accepts both thorium and uranium-233 as fertile material and as fissile material, respectively. However, “The Bank” will not have any uranium- 233 at the beginning of its operation. Thus other fissile material such as plutonium must be provided from uranium fuel cycle. Once thorium fuel is used at some country, the spent thorium fuel will be returned to “The Bank”. Uranium-233 is the interest of debt of thorium. Trend of demand toward rare-earth and thorium will be different. Rare-earth is now eagerly required but thorium is not now. “The Bank” will be an international organization. Head office of “The Bank” can be located in Norway, Sweden, Australia and Japan, which have no risk of nuclear proliferation. It will

be better that the country of the head office has an ability to handle radioactive material. The head office will have several functions. One of the functions is to store separated thorium during the refining process of rare-earth mining. The stored thorium can be lent to countries. These countries have to return both thorium and fissionable uranium-233 in the spent thorium fuel to "The Bank". Uranium-233 is produced by absorption of neutron of thorium. Uranium-233 is the interest against the debt of thorium from "The Bank". As far as the capacity of thorium nuclear power in the world is limited by the supply of plutonium from uranium fuel cycle, amount of produced thorium from rare-earth mining is larger than the consumption of thorium as nuclear fuel. Thus, price of thorium will be kept at low level. The other function of "The Bank" is reprocessing of spent thorium fuel. If LWR or HWR are used as power reactor, solid fuel rod including thorium and fissile materials (uranium-233 or plutonium) will be returned. If MSR is used, frozen fuel salt will be returned. For the former case, direct fluorination method called FERDA will be able to apply obtaining plutonium and uranium-233 from solid spent fuel. For the latter case, dry-process method using molten-salt will be available for reprocessing.

The last function of "The Bank" is to fabricate thorium fuel. If countries plan to implement thorium nuclear power, there is a possibility that it is not allowed to have fuel fabricating facility depending on the international discussion. United Arab Emirates (UAE) can be considered as such a case. UAE has signed with the USA in the agreement of nuclear power. UAE implements nuclear power plant but they do not have enrichment and reprocessing facilities. Nuclear fuel will be fed by the USA and spent nuclear fuel will be sent to France or other countries. "The Bank" will have several branch offices. The function of the branch office will just to store and lend thorium.

It is not necessarily request to all the countries to join this frame of "The Bank". Some countries such as India having thorium resource and functions of re-processing and fuel fabrication can continue their own plans. The function of "The Bank" will be attractive to the countries having rare-earth resources but having no plan to utilize thorium. Countries in the South-East Asia such as Vietnam or Myanmar will correspond to this case.

Recently, there are many researches on breeding of uranium-233 from thorium by utilizing accelerator or fusion technologies. However it is estimated to take more than 20 years to be commercialization. Therefore it is necessary to store thorium until such a wide utilization.

7. Conclusion

In this chapter, emerging tendency of thorium nuclear power has been introduced. It is impossible to describe all information running in the world at this time. However, outline of thorium utilization could be explained. Though thorium utilization has a very attractive feature, quantitative evaluation will be necessary to make a new energy supply vision in the near future. Implementation strategy of thorium fuel cycle discussed in this chapter will be a help for such a purpose. Several results demonstrated here based on the mass-balance of fissile materials show that thorium nuclear power will be available but still be limited. In spite of this result, it should not be said that thorium nuclear power is not enough. The concept of sustainability contains lots of different aspects. If thorium is not correctly used, it becomes an environmental hazard. However, if thorium is used, it produces clean and safe energy. We learned that present uranium LWR has a possibility of severe accident from Fukushima Daiichi nuclear power plant. However, most countries do not have huge earthquake. Therefore, uranium LWR can be used by enhancing its safety. Thorium fuel

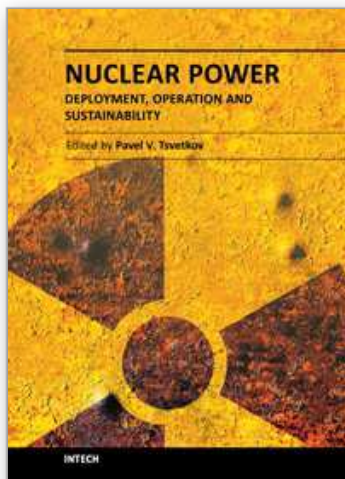
cycle will be introduced with a collaboration of this established uranium fuel cycle which supplies plutonium as fissile material to thorium fuel cycle. Though more detailed scenario for the implementation of thorium fuel cycle will be needed including fuel reprocessing, an international frame work for nuclear safeguard, thorium fuel cycle has an attractive option to provide carbon-free primary energy source.

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We are fortunate to live in incredibly exciting and incredibly challenging time. Energy demands due to economic growth and increasing population must be satisfied in a sustainable manner assuring inherent safety, efficiency and no or minimized environmental impact. These considerations are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. At the same time, catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, design requirements and facilitated growing interests in advanced nuclear energy systems. This book is one in a series of books on nuclear power published by InTech. It consists of six major sections housing twenty chapters on topics from the key subject areas pertinent to successful development, deployment and operation of nuclear power systems worldwide. The book targets everyone as its potential readership groups - students, researchers and practitioners - who are interested to learn about nuclear power.

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