

Study of nuclear environment & material strategy

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Abstract: There is a concern about the environmental hazard caused by radioactive materials coming with the expansion of nuclear power and even by renewable energies, which are used as countermeasures against global warming to construct a sustainable society. A concept to internalize the pollution caused by radioactive materials, which are directly or indirectly related to nuclear power, to economical activities by adopting externality is proposed. Energy and industrial productions are strongly related to the supply of material. Therefore material flow is also part of this internalization concept. The concept is named "NEMS (Nuclear Environment & Material Strategy)". Fission products and transuranic isotopes from nuclear power such as plutonium are considered in this concept. Thorium, which comes from the material flow of rare-earth production to support the elaboration of renewable energies including electric vehicles on the consumer side, is considered as an externality of the non-nuclear power field. Fission products contain some rare-earth materials. Thus, these rare-earth materials, which are extracted by the advanced ORIENT (Optimization by Recycling Instructive Elements) cycle, are internalized as rare-earth supplier in economy. However, the supply quantity is limited. Therefore rare-earth production itself is still needed. The externality of rare-earth production is thorium and is internalized by using it as nuclear fuel. In this case, the demand of thorium is still small within these few decades compared to the production of thorium as byproduct of the rare-earth production. A thorium energy bank (The Bank) is advanced to regulate the storage of the excess amount of thorium inside of an international framework in order to prevent environmental hazard resulting from the illegal disposal of thorium. In this paper, the material flows of thorium and rare-earth are outlined. Their material balance are demonstrated based on the prediction of rare-earth mining and an implementation of thorium nuclear power.

Keyword: thorium; rare-earth; material balance; externality

1 Introduction

A sustainable society is strongly needed nowadays. Though there are many aspects to consider in order to satisfy this request, energy supply is one of the major pillars. Presently, energy consumption affects our society and obstructs sustainability. This is caused by the disposal of waste originating from energy production in the environment in which our society exists. Economy has always considered that our environment has an infinite capacity of waste disposal. For example, fossil fuel, which is still important as a form of energy supply, emits carbon dioxide (CO₂) as waste into the atmosphere. The atmosphere could be considered to have an infinite capacity as CO₂ sink. However it has a limited volume in reality. As a result, global warming is caused by an increase of CO₂ concentration in the atmosphere. If CO₂ becomes a valuable commodity, some market mechanism will be spontaneously created, but so far it has not been.

On the other hand, the social loss caused by global warming represents a significant monetary value. Though this value is not directly related to the CO₂, it can be used to determine the value of CO₂ emission. This way of thinking is called "externality" or "external diseconomy" in economy. Externality has been studied mainly in Europe since 1980's to overcome environmental hazards such as acid rain. The project called ExternE is a famous example ^[1]. Social loss by externality can be avoided not by separating the waste itself from the society, but by implementing it into economic activities. This is called internalization.

Nuclear power is still one of the established carbon free energies. Nuclear power has been increasingly favored due to the recent increase of energy demand, the predicted oil-peak, and the progress of global warming. Even though the accident at Fukushima Daiichi nuclear power plant on the 11th of March 2011 affected some countries' nuclear energy policy, most countries having large economic growth have

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not changed their plans to expand nuclear energy (e.g. China). Radioactive waste from nuclear energy becomes external diseconomy. Because of this and other features such as safety and nuclear proliferation, nuclear power is not recognized as an efficient technical option as clean development mechanism (CDM) defined in the Kyoto protocol in 1997. Therefore, it is necessary to internalize wastes from nuclear power for further expanding their utilization.

In order to efficiently handle global warming, the activity on the demand side is also required to reduce CO₂ emission. The transportation sector has the most important role because automobile represents about 20 % of the world CO₂ emission [2]. There are several different approaches to reduce CO₂ emission from the transportation sector, among which electric vehicles (EV) are thought to be the main pole. What is required for the expansion of the EV market is rare-earth supply. This is because thorium, which is a radioactive material, derives from the rare-earth refining process. Thorium is now disposed in the environment, which represents a severe externality.

An outline of the recent trend in thorium utilization was summarized and a preliminary quantitative evaluation of thorium production was discussed in a previous work [3]. A new concept called “The Bank (Thorium Energy Bank)” has been proposed, but this concept functions just to store and use thorium. In the new study reported in this paper, the above-mentioned environmental hazards were studied and a strategy called NEMS (Nuclear Environment & Material Strategy) has been designed by including the previous idea of “The Bank” as a concept to solve these externalities in a relation between nuclear power and global warming. This concept has been quantitatively evaluated and the results are reported hereafter.

2 Internalization of externality

2.1 Externality of the uranium fuel cycle

Nuclear power supplies electricity and represents 15 % of the world’s electricity. This complex system can be simply modeled as shown in Fig. 1. The nuclear power system consists of the uranium mining, its processing to become fuel, the usage of uranium for electricity generation, and the reprocessing of

spent nuclear fuel to extract usable plutonium. Radioactive waste is disposed outside of this system.

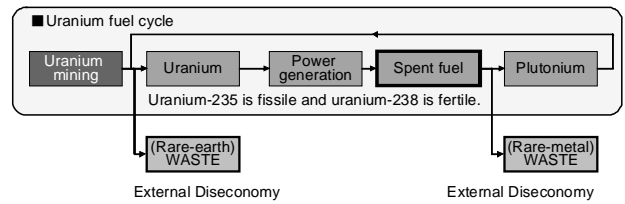


Fig. 1 Model of the uranium fuel cycle in view of externality.

In the case of the once through utilization of uranium fuel, spent nuclear fuel is generated and becomes radioactive waste. In this study, the reprocessing of spent nuclear fuel was assumed by considering the value of plutonium as energy source. In addition, the uranium tail derives from the process of uranium refining. If this tail is disposed in the environment, it becomes external diseconomy.

2.2 Internalization of the externality of radioactive waste from uranium spent nuclear fuel

An object is considered as waste when it has no value at the given time for the system to which it belongs. However, this object also generates additional or external cost after its disposal. There are several methods to internalize such externalities.

One of them is tax. Carbon-tax has been recently discussed to reduce the CO₂ emission from motor cars. Some regulations are often applied. Giving incentive is also a technique to attribute a value to

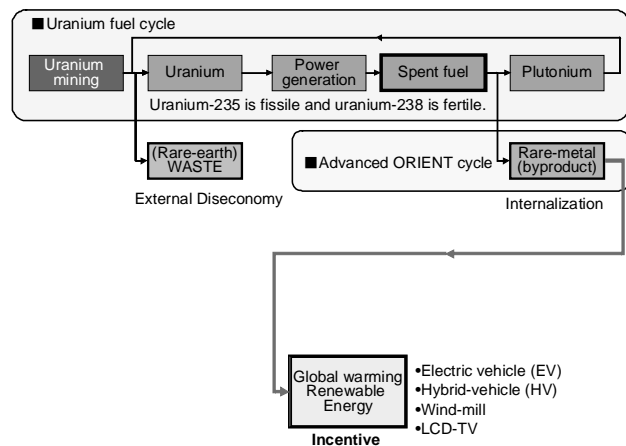


Fig. 2 Internalization of the externality of radioactive waste from uranium spent nuclear fuel by an incentive of global warming.

some object. One example is shown in Fig. 2.

Radioactive waste does not have any value inside of the nuclear power system. (Plutonium is extracted because of its own value as nuclear fuel.) There is a possibility that other systems in the same society of nuclear power will see an unexpected value in radioactive waste.

There are many possibilities to counter global warming. EV and hybrid vehicles (HV) are two important transportation methods. Renewable energies such as wind-mills and photo-voltaic cells are low-carbon energy sources. In addition, liquid crystal display (LCD) and light emitting diode (LED) are widely used for devices with low energy consumption. These machines need rare-earth elements for their production. And the supply of rare-earth is becoming significantly important as resource strategy^[4, 5].

Radioactive wastes consist of fission products and contain rare-metals including rare-earth. Therefore, extracting these rare-earth materials from radioactive waste can be an additional source to provide rare-earth materials as far as their radioactivity is reduced. This means that global warming can be treated as an incentive to internalize radioactive waste into society. In Japan, advanced ORIENT (Optimization by Recycling Instructive Elements) cycle research is one of these activities^[6].

2.3 Internalization of the externality of uranium tail

Uranium-tail derives from the process of uranium refining and has also no value inside of the nuclear power system. However, this uranium-tail also contains rare-earth elements. This enables the internalization of uranium-tail inside society by determining an incentive of material supply. This is illustrated in Fig. 3.

For example, Toshiba and Sumitomo Corporation have started to extract rare-earth from uranium-tail in Kazakhstan since 2008^[7].

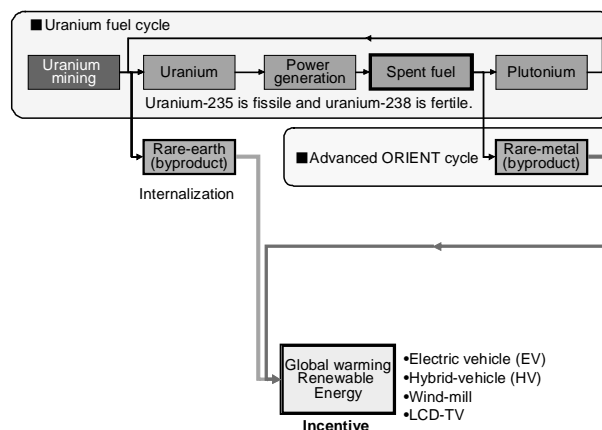


Fig. 3 Internalization of the externality of uranium tail by an incentive of global warming.

A monopoly by China in rare-earth supply serves as the backdrop of rare-earth extraction from radioactive waste and uranium-tail. 97 % of the world’s production of rare-earth is occupied by China. Thus rare-earth consuming countries seek alternative ways of rare-earth supply. If rare-earth elements can be obtained from spent nuclear fuel that exists inside of the demanding country, it becomes an incentive as a way to enhance resource security.

2.4 Externality of rare-earth mining, “Thorium”

The EV production industry is independent from the nuclear power industry. Still, it requires rare-earth as material. In order to obtain this, rare-earth ores are refined and rare-earth tails are generated. The main component of this tail is thorium, which is a radioactive material. This process is outlined in Fig. 4.

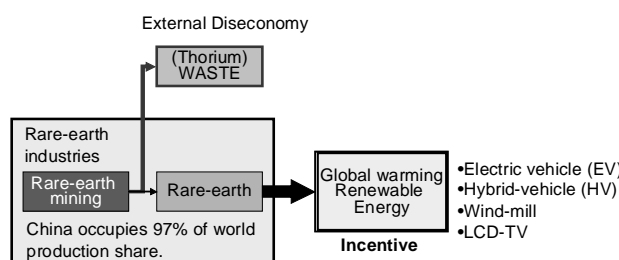


Fig. 4 Material flow of rare-earth production.

The volume of rare-earth production was about 10,000 t in 1960’s and mostly supplied by India. It became 30,000 t in 1980’s and then expanded to 80,000t at the beginning of this century. This expansion was supported by the US. Thus, this period was called the “Mountain Pass Era”, based on the

name of the famous rare-earth deposit in the Rocky Mountains. The world production of rare-earth is about 120,000 t nowadays and 97% of it is generated by China. The reason why China occupies such a huge share is that environmental protection was not seriously considered when refining rare-earth. One inherent environmental hazard is thorium. Global warming did not necessarily act as an incentive to expand the production of rare-earth. Rare-earth begun to be supplementary used to fabricate small machinery or enhance specific features of devices. Mobile phones or lap-top computers are representative products. Rare-earth is used as material of permanent magnet to make small and high-power electric motors.

The recent rapid growth of the rare-earth demand mainly emerged because of the estimation of the increase in EVs. The consumption of rare-earth by one EV is larger than that of any mobile phone. The automobile industry has showed a tendency to shift from fossil fuels to EVs by an incentive of global warming. As a result, radioactive thorium is stored in the rare-earth tail on the production site of rare-earth in China. In August 2010, China announced its intent to reduce the exportation license of rare-earth and stopped exporting rare-earth in September. It hit Japanese high-technology industries and Japanese companies tried to develop other supply sources outside of China. Sumitomo corporation made an agreement with US Molycorp and Sojitz contracted with Australian Lynas at the same time on October 19th 2010. But the agreement between Sumitomo and Molycorp was canceled in September 2011^[8]. Lynas is going to build a new rare-earth refining facility in Malaysia, but there is a serious opposition because of the radioactive byproduct that thorium represents.

2.5 Internalization of “Thorium”

The reason why radioactive waste and uranium-tail can be internalized is that rare-earth included in these wastes has a significant value as means to counter global warming. In the case of thorium, it has been used to produce crucibles because of its very good thermal characteristics. However, it is difficult to use it widely as material for ordinary constructions because thorium is radioactive. One of the most attractive ways for consuming thorium is nuclear fuel.

The application of thorium to nuclear power can be considered as an incentive to internalize the externality of thorium in the context of global warming because it does not emit CO₂. Possible internalization processes are outlined in Fig. 5.

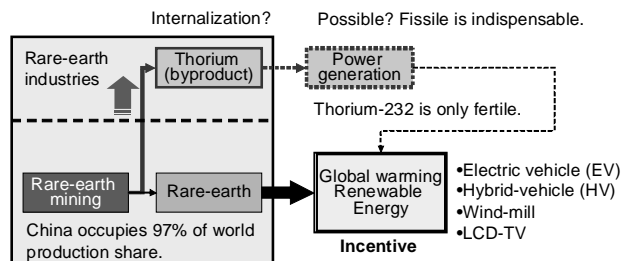


Fig. 5 Possible ways of internalizing thorium.

In this figure, an interrogation remains on the internalization of thorium as nuclear fuel. This is because thorium does not act as nuclear fuel. Thorium consists of isotope having mass number of 232, which is only fertile. Once thorium absorbs a neutron, it transmutes to uranium-233, which is fissionable. Therefore, some fissile material is necessary to start this reaction in a nuclear reactor.

In Fig. 1, radioactive waste refers to waste from the uranium fuel cycle. In the case of the once through utilization of uranium fuel, plutonium existing in the spent fuel becomes externality because of the risk of it being stolen and contributing to nuclear proliferation. Additional costs for the disposal management will then be needed compared to the recycling of plutonium. The internalization of this externality can be performed by adding value to plutonium as usable fuel for nuclear power because plutonium is an artificial fissile material.

As already reported in the case of carbon capture and storage (CCS), which internalizes CO₂ into our society^[9], the sustainability of some systems is not necessarily automatically achieved simply by internalizing the externality. Even though the externality is internalized, the system still faces the possibility of a catastrophe due to a lack or overflow of internalized commodity inside of the system. In the case of the uranium fuel cycle shown in Fig. 1, separated plutonium may overflow from its storage if a fast breeder reactor is not operated based on the original plan.

This kind of overflow is sometimes solved by extending the capacity of storage. However, it means that additional costs are needed for the extension. Therefore, it is necessary to evaluate whether such a commodity (*i.e.* plutonium in the above-mentioned case) will be used in the future. A second option is to add another value that was not considered before to consume the commodity and reduce its stock. The most important value of plutonium in the uranium fuel cycle is its fissionability. The reason why plutonium is not necessarily consumed is because there are other cheaper fissile materials obtained from natural sources, such as uranium-235, which is considered as sufficiently available. This indicates that a material valuable as fissile material like plutonium can possibly lead to catastrophic events in its internalized system because of a discrepancy between demand and supply.

If another system based on thorium is assumed, the fact that thorium is only fertile calls for new valuation of plutonium as fissile material. Then both values of thorium and plutonium can be realized and exceed the internalization of thorium. This is shown in Fig. 6. Here, it is assumed that thorium spent nuclear fuel is also reprocessed to extract both fissionable uranium-233 and rare-earth materials. It should be mentioned that this additional value of plutonium serves the internalization of the externality of thorium in our society to avoid environmental and social hazards caused by thorium. The possibility of the utilization of thorium as additional (not alternative) nuclear fuel represents a supplementary low-carbon energy source. It does not contribute to CO₂ reduction in the energy sector if thorium serves as alternative to uranium.

The whole vision of internalization relating both to nuclear power and rare-earth production mentioned above is summarized in Fig. 7.

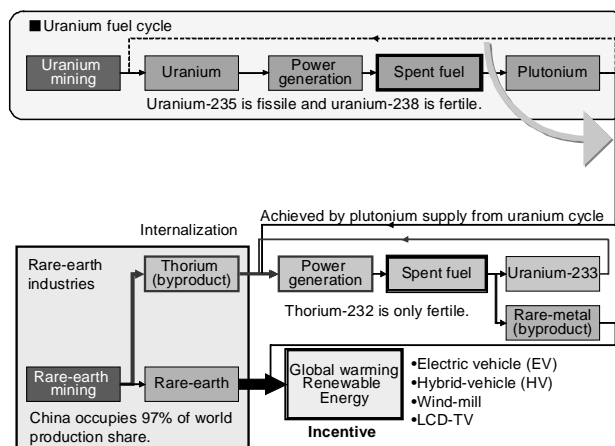


Fig. 6 Internalization of thorium by adopting plutonium as fissile material from the uranium fuel cycle.

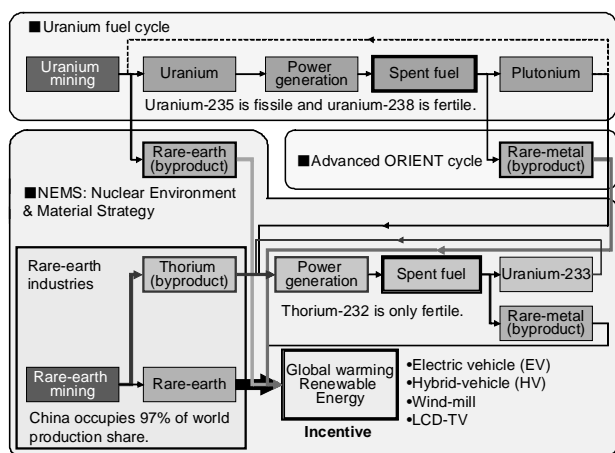


Fig. 7 Framework of internalization of nuclear power and rare-earth production by incentive of global warming.

The newly internalized area, except the advanced ORIENT cycle, is named “Nuclear Environment & Material Strategy (NEMS)”. This is a proposal to determine the potential of the nuclear industry not only as energy source but also as optimal material supply source. This can be achieved by transmuting some hazardous material to other materials in nuclear chain reactions.

3 Thorium utilization

3.1 Outline of thorium utilization

In this section, the utilization of thorium as nuclear fuel will be briefly explained. Thorium has been known as nuclear fuel since the 1940s. Thorium can be used in any type of reactor including light water reactors, heavy water reactors, *etc.* There are many advantages of thorium. One of them especially in the

scope of sustainability is its reduced radioactive waste. Also, the fact that it comes with a small production of plutonium is attractive for countries who do not want to make nuclear weapons but take advantage of energy sources. Thorium's main drawback is that strong gamma ray of 2.6 MeV from its daughter product thallium-208 appear once it is exposed in a nuclear reactor. The concept of Molten-salt reactors (MSR) has been proposed to use thorium [10]. MSR uses liquid fuel, therefore remote operation is possible to avoid the hazard inherent to the exposure to gamma ray. MSR is also efficient to burn nuclear fuel. There are remarkable new researches on MSR in several countries such as France [11], Indonesia [12], and others. The author himself has published many articles about the utilization of thorium from rare-earth residuals [13-15]. The most important characteristic of thorium is that this is only fertile. Uranium-233 transmuted from thorium is the best fissile material but it cannot be observed in nature. Artificial plutonium from uranium-238 and natural uranium-235 are also available to start the thorium fuel cycle to produce uranium-233.

3.2 Expected capacity of the implementation of the thorium fuel cycle

The electrical capacity furnished by an implementation of the thorium fuel cycle based on plutonium supply from the uranium fuel cycle is simulated here. MSR is considered in this calculation for thorium utilization. There are two typical design of thorium MSR. One of them is named FUJI-Pu2 using plutonium as initial fissile material [16]. The other one is FUJI-U3 using uranium-233 as fissile material [17]. Their characteristics are summarized in Table 1.

Table 1 Specifications of MSR

	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

It is assumed here that the commercialization of thorium MSR will start in 2023. The capacity of the uranium fuel cycle is given by a prediction from the international energy agency (IEA). The result is shown in Fig. 8.

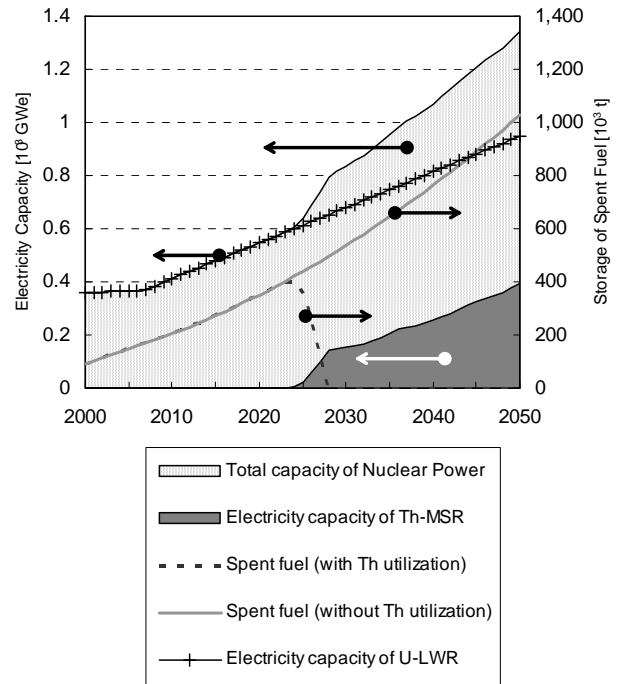


Fig. 8 Expected electrical capacity of an implementation of the thorium fuel cycle (case 1).

After the Fukushima accident, some express the opinion that it would be appropriate to bring an end to nuclear power plants that use older generation reactors. Some also think about stopping the usage of uranium because thorium can be used as described above. Hereafter, another result is presented. It is based on a smaller capacity of the uranium fuel cycle, which is considered as equal to the present capacity until 2050 (Fig. 9). As can be seen from Fig. 9, the capacity of the thorium fuel cycle will be about 258 GWe in 2050. The total capacity of nuclear power both from uranium and thorium fuel will be limited to less than 628 GWe.

This is simply because the introduction of the thorium fuel cycle depends on plutonium supply from the uranium fuel cycle. Of course, there are ideas to artificially produce uranium-233 by using the nuclear fusion reaction or an accelerator driven system. The

author has examined several cases, in which accelerator system are used, to estimate the potential capacity of the implementation of the thorium fuel cycle integrating artificial uranium-233 [18]. The results showed that more than 1,000 accelerator driven systems will be needed in order to supply 2 TWe of thorium nuclear power in 2050. Significant progress would be needed to achieve this capacity in order to develop high power accelerators.

On the other hand, nuclear weapon is one of the other important issues to determine the sustainability of the system. The author also demonstrated the contribution of dismantled nuclear weapons to enhance the capacity of the thorium fuel cycle [18]. The amount of additionally implemented thorium nuclear power will be limited to 10 GWe based on the usage of plutonium coming from the US and Russian agreement on nuclear disarmament in 2010. High enriched uranium (HEU) is not considered in this calculation because it should be used for low enriched uranium fuel.

Although the impact of the Fukushima accident was huge, it triggered no drastic global change to the diffusion of nuclear power except in Germany. Egypt

announced on the 17th of March that their plan on nuclear power will not be affected by the Fukushima accident. This seems like a rational choice because there is no significant earthquake in the North African region including Egypt. Light water reactors will also be available in these regions. On the contrary to Japan, there are many places in China and India where no earthquake happens.

However, it should be noted here that it is not necessarily possible to provide a large number of light water reactors because the production capacity of reactor pressure vessels is limited. In the case indicated in Fig. 8, about 14 light water reactors of 1 GWe class will be supplied every year in the world. Recently, 80 % of the production of reactor pressure vessels is performed by Japan steel works (JSW). In fact, currently several countries are able to build pressure vessels of the 1GWe class NPP, but only Japan can produce pressure vessels of bigger classes such as the 1.4, 1.7 GWe classes NPP. JSW's annual production capacity was 4 units until March 2008. They decided to invest 80 billion yen in March 2010 and said that they would expand their capacity up to 12 units/year by March 2012. If they keep 80 % of the world share with 12 units/year, the total world supply in pressure vessels will be 15 units/year. That is to say, the capacity of the uranium fuel cycle based on light water reactors cannot exceed the prediction made by the IEA and shown in Fig. 8.

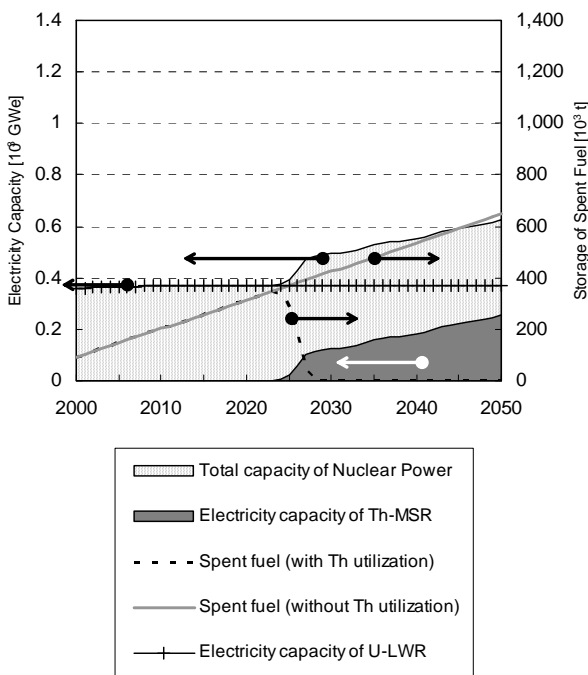


Fig. 9 Expected electrical capacity of an implementation of the thorium fuel cycle (case 2).

4 Results

4.1 Quantitative evaluation of the internalization of the uranium fuel cycle

In section 2, a framework to internalize several externalities related to nuclear power and rare-earth production was proposed in the context of a countermeasure to global warming. It is also important to evaluate this quantitatively. In this section, quantitative evaluations are discussed in the case in which the internalized system is managed without catastrophe by adopting a method of supply chain management (SCM). This method estimates the size of the stock of commodities in each process of the system. If the stock faces a lack or overflow, we consider that the system enters a catastrophic state [9]. At first, rare-earth recycling from radioactive waste is quantitatively evaluated. One light water reactor of 1

GWe capacity produces 33 t of spent nuclear fuel in a year. Therefore, the annual total production of spent nuclear fuel from 370 GWe reactors can be estimated as about 12,210 t. 3 % in weight of spent nuclear fuel corresponds to fission products. Therefore the total amount of fission product in spent nuclear fuel obtained in every year is 366 t. Only the rare-earth in fission products is needed as material to use as countermeasure to global warming. Rare-earth only represents a few percent of the fission product. It means that rare-earth originating from fission products of spent nuclear fuel can only reach up to 10 t in a year in the world.

Second, rare-earth recycling from uranium tail is quantitatively evaluated. One light water reactor of 1 GWe capacity requires 33 t of fresh nuclear fuel in a year. Therefore, the total annual requirement of fresh nuclear fuel from 370 GWe reactors represents about 12,210 t. This low enriched uranium reaching about 3 % enrichment, it corresponds to 50,875 t of natural uranium (as only 0.72 % of natural uranium is uranium-235). The World Nuclear Association (WNA) announces that the world production of uranium was 43,853 t in 2008.

It can be estimated that the amount of rare-earth contained in uranium-tail will be about 8,770 t annually in the world. This is calculated based on the content of uranium in ore, which is about 1%, and its ratio of rare-earth, which is about 0.2 %. The above figure corresponds to 7 % of the current annual production of rare-earth in the world. These values indicate that it is insufficient to support the world demand of rare-earth. Therefore, the direct production of rare-earth from mining will be indispensable.

4.2 Quantitative evaluation of the internalization of “Thorium”

All the thorium is now deriving from residuals of rare-earth refining, except in India, which targets specifically the production of thorium. The production of rare-earth is monopolized by China with 97 % of the world market. Therefore almost all the thorium is stored in China’s rare-earth tails. In reality, thorium is not stored in warehouses after adequate refining but disposed into rare-earth tails in

Baotou, the largest rare-earth production center in the inner Mongolian territory of China. Rare-earth tail containing radioactive thorium has been causing significant environmental and social hazard in Baotou. The estimation of the world thorium production by rare-earth refining is plotted in Fig. 10.

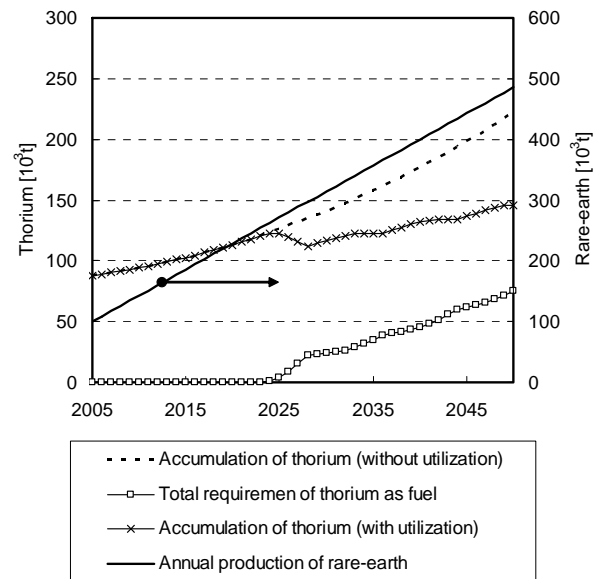


Fig. 10 Mass balance of thorium (case 1).

Solid line is rare-earth production. The amount of rare-earth production is estimated to increase more and more since it is indispensable to manufacture EVs or wind-mills, photovoltaic cells and liquid crystal displays which are very important commodities for overcoming global warming.

In this prediction, 1 % of the rare-earth production corresponds to thorium. It is indicated by the dotted line. The world thorium storage in 2005 (without distinguishing its form of stockage, refined or residual in rare-earth tail) is determined on the basis of the previous total production of rare-earth in the world. India and Brazil have been producing rare-earth and deriving thorium since the 1950’s. Their average annual production amounts to about 5,000 t. For example, nowadays the Indian share in the world production of rare-earth is about 2 %. The main source of rare-earth in India and Brazil is monazite and the ore contains about 20 % thorium. Thus, the accumulation of thorium from 1950 until 2005 represents about 55,000 t. The USA has also produced thorium since 1965 for nearly 40 years with an average amount of 10,000 t. Their major ore is

carbonatite containing about 5 % of thorium. Therefore it can be estimated that the US has about 20,000 t of thorium stock until 2005. China has been expanding their production of rare-earth nearly linearly since 1985 and their total production is about 120,000 t in a year. Their main ore is also carbonatite but the percentage of thorium in the rock tends to be about 1 %. As a consequence the total stock of thorium accumulated in China until 2005 should be about 12,000 t. Through these calculations, it was determined here that the total world stock of thorium in 2005 may have amounted to about 87,000 t.

The expected consumption of thorium related to the internalization of thorium is also plotted with a rectangular line in Fig. 10. The crossed-line indicates the remaining stock of thorium. As can be seen here, the consumption of thorium is still smaller than the production even though thorium is internalized. This is a great characteristic in the scope of energy resource. If thorium is recognized as a reliable energy source in terms of safety, radioactive waste and nuclear non-proliferation, it often happens that some countries or mining companies disclose all thorium mining in the world because they think that the thorium price will increase and expand their business. However, it also often brings additional damage to the environment through the development of new mining. What differs with the usage of thorium is that it cannot be used alone and needs a complementary

fissile material such as plutonium. And its supply is limited. Therefore, the thorium already stored in the world and thorium extracted in the next 40 years will satisfy the implementation of the thorium nuclear fuel.

If the usage of uranium does not expand in the next 40 years as mentioned in Fig. 9, the consumption and storage of thorium will be as plotted in Fig. 11. Due to the lower capacity of thorium nuclear power, which is governed by a smaller supply of plutonium from the uranium fuel cycle, more thorium will remain unused than what is represented in the case of Fig. 10.

4.3 Mechanism of thorium storage, “The Bank”

It should be discussed how the remaining thorium should be treated. In recent years, most of the thorium has been stored in rare-earth tail within China. The US’s Molycorp, Inc. and Australian Lynas Corporation are going to start rare-earth mining at Mountain path and at Mount Weld, respectively. Separated thorium will also be stored in rare-earth tails at both plants. Thorium could be used as nuclear fuel in the future, but so far there has been no fixed decision on this subject except in India. In addition, India will not import any thorium because the importation of fuel weakens one country’s energy security. India has enough thorium within its own land. This political tendency regarding thorium means that refining and storing thorium would not benefit private companies but would just generate additional costs. Usually, private companies would not pay such additional costs without regulation or incentive to store thorium.

On the contrary to the rare-earth that exists in uranium spent fuel and uranium tails, thorium itself is hazardous for the environment due its radioactivity. Therefore, the illegal disposal of thorium may cause significant external costs. This is of importance for the internalization of thorium.

However, the question still remains how to prepare the budget for the safe storage of this thorium and how to store thorium without letting emissions of this radioactive material escape and pollute the environment. It requires the design of an adequate

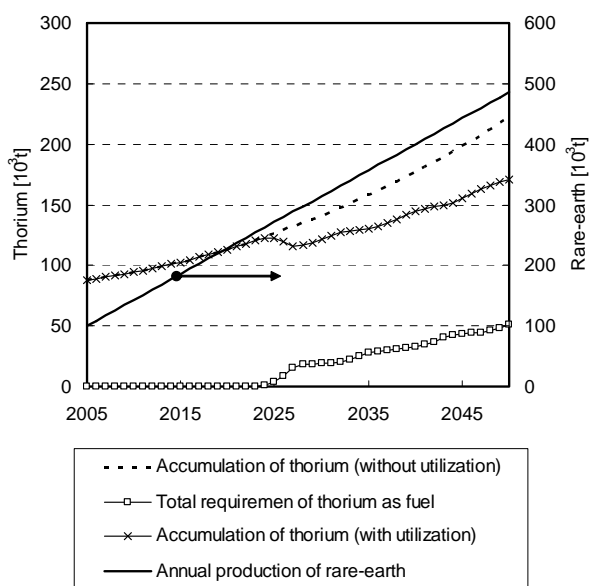


Fig. 11 Mass balance of thorium (case 2).

framework to prepare the budget for the storage of thorium. The author has already proposed such an international mechanism named “The Bank (Thorium Energy Bank)” [13], which was detailed in a previous paper [3]. It is implemented in the NEMS and enables thorium storage as shown in Fig. 12.

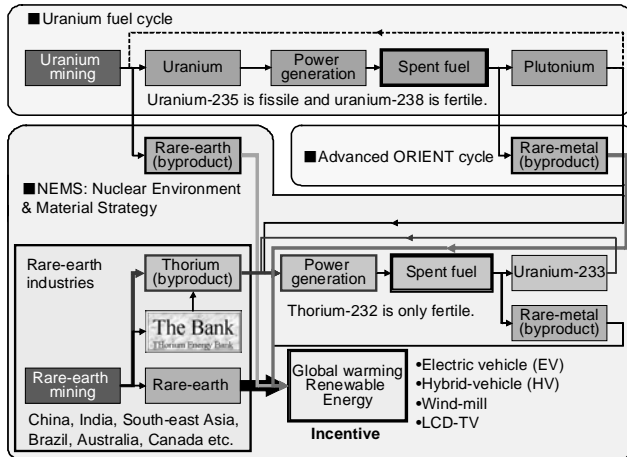


Fig. 12 Storage function of thorium (The Bank) in the NEMS.

Generally speaking, energy sources such as oil are stored by the country from which they originate and not by an international organization. India has been storing thorium as energy source in its own land and also China has declared its wish to promote research and development of molten-salt reactor to use thorium [19]. China will soon start to build warehouses for thorium storage.

What should be noted here is that the motivation to store thorium will quickly disappear if thorium is actually not used. For example, the US, which produced rare-earth in the 1950's, stored thorium as national stockpile based on the possibility of using it in the future as nuclear fuel. But the national stockpile was stopped in 1959 once uranium became the only nuclear fuel in the US.

If the rare-earth mining industry expands from a Chinese monopoly to numerous countries, thorium will be disposed to the environment as far as there is no chance for it to be used in society. This would happen because of the differences between countries producing rare-earth and thorium (Australia or Vietnam), countries making use of thorium (India,

China or Middle-East countries) and rare-earth (Japan). Therefore, some international framework will be needed to prevent that the environmental hazard caused by radioactive thorium goes beyond each nation's benefits.

5 Conclusion

A framework named NEMS (Nuclear Environment & Material Strategy) to internalize the externality related to nuclear power and rare-earth mining was proposed in the context of countermeasures against global warming. Its quantitative analysis was carried out. The contribution of the advanced ORIENT cycle to the recycling of rare-earth from uranium spent nuclear fuel will be limited in a quantitative manner. Though the contribution of rare-earth extraction from uranium tails of the refining process is still small, it will enable to supply nearly 7 % of the world's demand. In both cases, it has significance as an incentive to reduce the environmental load related to nuclear power. The production of rare-earth will increase in the near future and there is a concern about the radioactive residuals caused by thorium. It can be considered that an incentive to utilize thorium as nuclear fuel is an effective way to internalize this externality. The electric capacity generated by the utilization of thorium depends on an additional supply of fissile material and should reach about 392 GWe in 2050 as long as plutonium issued from the uranium fuel cycle is used for this purpose. The consumption of thorium is still small in this case and, as a result, the storage of thorium becomes indispensable. Consequently, a concept named “The Bank (Thorium Energy Bank)” has been proposed to form an international framework. Additional studies are necessary to research how to prepare a budget to support this international storage cost.

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