PROLIFIRATION RESISTANT FUEL CYCLE SYSTEM FOR THE TRANSITION FROM LIGHT WATER REACTOR TO FAST REACTOR

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1. Introduction

For the sustainable electricity generation by nuclear energy, utilization of plutonium (Pu) by fast reactor (FR) is essential and indispensable because of the limited amount of uranium (U) resource and ineffectiveness of Pu usage in light water reactor (LWR) [1]. On the other hand, long period operation of LWR has brought the huge amount of spent fuel (SF) and their storage volume reduction is needed urgently. As LWR produces Pu in SF, long time accumulation of LWR SF means Pu accumulation enough for introduction of FR. Consequently, from the viewpoint of nonproliferation, LWR should be placed as soon as possible by FR which only use the accumulated Pu but not increase Pu amount.

Replacement of LWR to FR will take about 60 years that is the lifetime of LWR. The transition scenario has various unpredictable factors such as introduction speed and time of FR, introduction time and capacity of LWR SF reprocessing plants, and specification of FR SF reprocessing plants. Additionally, there will be significant technology developments such as metal fuel FR and pyro-reprocessing in the transition cycle, which will greatly influence on the economy and nonproliferation of the cycle systems. Thus it is important to investigate how to get the flexible fuel cycle system to accommodate the condition changes including technology development during the transition from LWR to FR.

Considering the above background, the authors propose an innovative nuclear system named “Flexible Fuel Cycle Initiative (FFCI)” compatible for economy and nonproliferation to sustain the nuclear electricity generation by FR [2]. The goals of FFCI are economy, nonproliferation, environmental burden reduction and resource utilization based on the flexibility concept as shown in Figure 1.

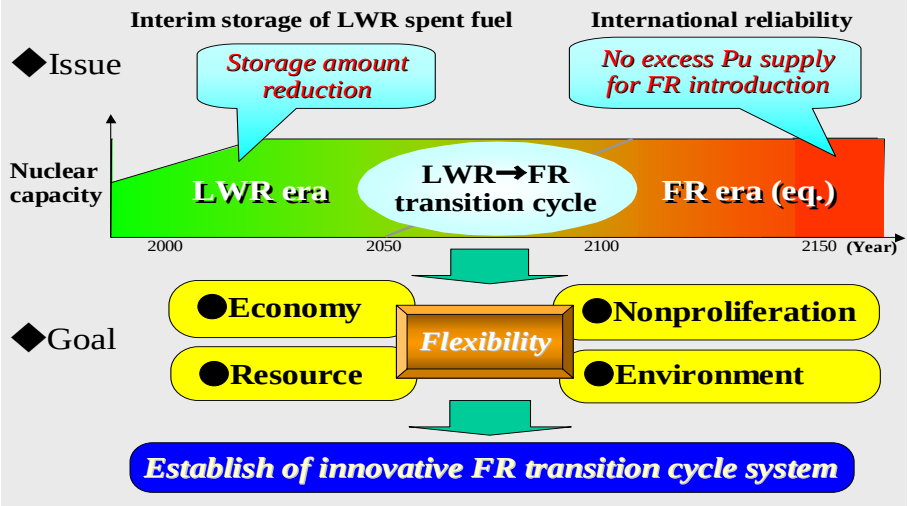


Figure 1 Issue and goal of transition cycle to FR

2. Flexible fuel cycle initiative (FFCI)

The basic concept of the FFCI is shown in Figure 2. In FFCI, LWR reprocessing plant removes about 90% U from LWR SF (UO_2 or MOX fuel). The remaining 10% is dubbed "recycle material (RM)." When the speed of FR introduction is high, (A) it is immediately recycled to the FR; Pu is extracted together with minor actinide (MA) and fuel fabricated by means of FR reprocessing. When the speed is low, (B) simplified fabrication is carried out on some or all of the RM, then it is temporarily stored; when needed,

it is recycled at the FR; Pu is extracted and fuel fabricated by means of FR reprocessing. Thus, it is possible to flexibly respond to the FR status. Under FFCI operation, alternatives A and B are performed independently; they are performed in combination and in parallel. It would also be possible to carry out option B before the introduction of FR; thus the range of choices is broad and the FFCI can make the total system to be flexible.

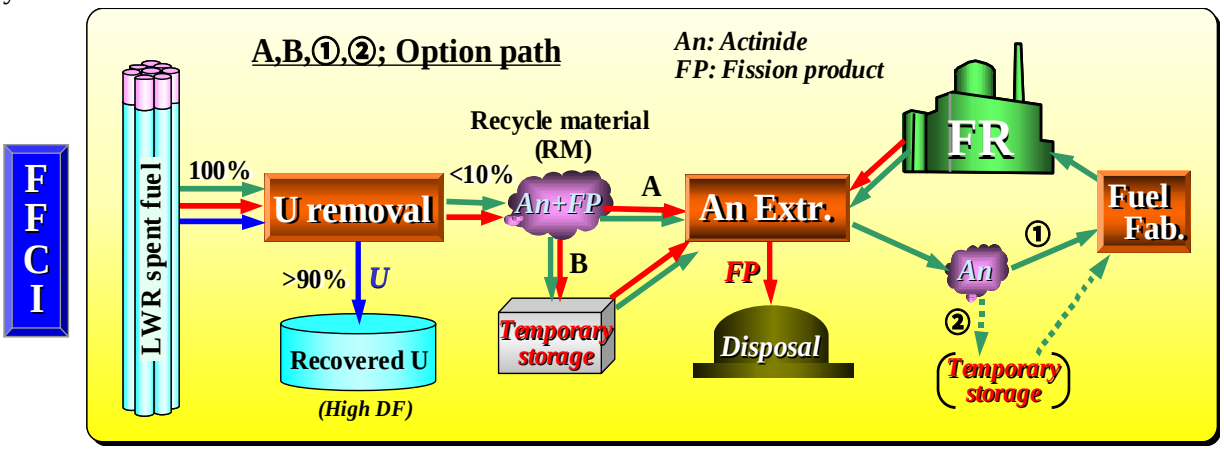


Figure 2 Innovative transition cycle system "FFCI"

In the FFCI, LWR SF reprocessing only performs U removal. Pu extraction and fuel fabrication is performed in FR SF reprocessing. This lowers the cost of LWR SF reprocessing facilities. Moreover, the Pu concentration in RM is the same as that in FR SF. Thus, FR reprocessing plants can also reprocess FR SF. In the FFCI, the weight of the material is reduced to one tenth. For this reason, the load on the FR reprocessing plant is low, and an increase of reprocessing capacity is not required. However, FR reprocessing plants of FFCI must begin operation several years ahead of the start of FR introduction, since they will manufacture the initial-load fuel for initial FR introduction.

Recently, US DOE proposed GNEP as transition cycle from LWR to FR. GNEP cycle could be included as path-A in FFCI. In the case of high speed introduction of FR, there are no difference between FFCI and GNEP as path A-①. However FFCI has more options to accommodate various conditions of transition cycle circumstance including worldwide needs.

Table 1 shows the possible options of FFCI in the case of FR introduction speed delayed, depending on the storage materials. FR introduction speed is important as transition cycle condition, because it causes significant impact to both of economy and proliferation. For example when U-removal facility of 2000 t/y capacity is introduced, actinide as much as 23 t/y could be produced. To burn the actinide of 23 t/y, about 16 GWe FR is necessary to be constructed within 15 years. If such amount of FR construction is not realistic, the capacity factor of U-removal facility of 2000 t/y must be reduced significantly depending on the FR introduction speed and the reduction of LWR SF storage might be gave up. Otherwise storage option of other materials than LWR SF itself should be investigated. Table 1 shows the possible storage materials as countermeasure for FR introduction delay. We omitted the option of LWR MOX fuel use, because it is not suitable to burn actinide with MA in thermal spectrum reactors.

Table 1 Options for FR introduction speed delayed

process / option	U removal	An Extr.	Fuel Fab.	Storage material	Remarks
Option-1	—	—	—	LWR spent fuel	
Option-2	DO (Path B)	—	—	Actinide+FP *(Recycle material)*	FFCI recommend
Option-3	DO (Path A)	DO (Path ②)	—	Actinide	GNEP
Option-4	DO (Path A)	DO (Path ①)	DO(go to FR)	FR fresh fuel	

In these options, option-1 has the problems of low capacity factor of U-removal facility and large amount of LWR SF storage. And option-4 has fear that an international consensus may not be obtained from the

viewpoint of nonproliferation. Furthermore, because option-4 will fix the fuel specification fabricated for 40-60 years, it has less flexibility to accommodate the new technology development results of reactor and fuel cycle in the transition cycle. Therefore, we investigate mainly option-2 and option-3 as the most probable options of FFCI in this paper.

The FFCI FR reprocessing and fuel-fabrication facilities will generally be based on advanced FR recycling technologies. U removal in FR reprocessing does not impact the environment, so the decontamination factor (DF) of removed U is lowered. Although there is a U removal process from SF in the FR reactor core and blanket, removed U is used as replace fuel material again for FR and cannot be used outside that process. If the DF of removed U becomes high, purification facilities will be required, which makes the system less economical. In the case of FR fuel, the DF for U removal is lowered, helping to maintain economy. Note that if there is an overcapacity of FR reprocessing facilities, they can reprocess LWR SF and fabricate FR fuel. In this case, the amount of low-DF removed U generated is small, and can be used in FR-fuel blankets. Consequently, RM and LWR SF can be appropriately combined in accordance with the speed of FR startup, enabling the FR reprocessing facilities to maintain a high availability without creating surpluses or shortfalls in Pu supply.

3. Uranium (U) removal technology in FFCI

The U removal method should be simple, be able to achieve high U recovery ratio, and be able to get high purity in recovered U. As plenty of recovered U is not necessary for FR, it will be stored for a long time or utilized again in LWR after re-enrichment of U-235. The content of U-235 in LWR SF is about 1 wt% and higher than that of natural U (~0.7%), which enables the enrichment cost lower for recovered U than natural U. Simple storage facility and re-enrichment need high purity of recovered U and high DF for U against fission products (FP) and other actinides during U removal process. Many U removal methods are known such as crystallization, solvent extraction, precipitation, molten salt extraction, molten salt electrolysis, and fluoride volatility. The reprocessing systems have been studied widely in Japan including various aqueous and non-aqueous methods, and FR fuel fabrication systems such as pelletizing, vibro-packing and casting methods.

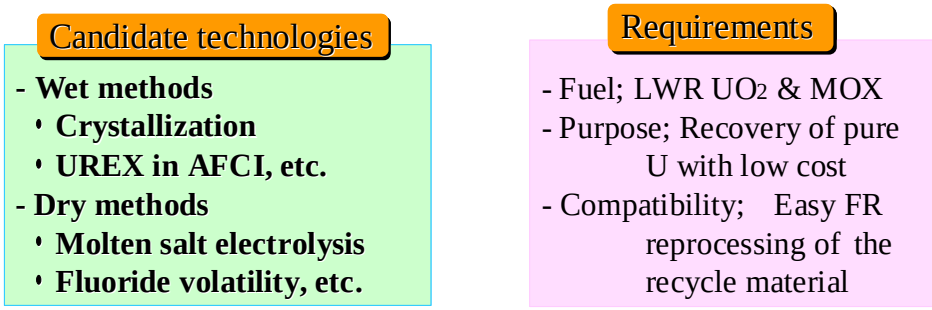


Figure 3 Uranium removal methods for LWR SF

Among U removal methods, one of the desirable candidates is fluoride volatility, which can get high purity U with relatively simple procedures. Preliminary evaluation clarified that fluoride volatility could get the DF of about 10^7 by fluorination, distillation and adsorption processes. Solvent extraction such as UREX developed in US AFCI can also achieve high DF.

The process in the application case of fluoride volatility method for U removal is as follow. Spent fuel from LWR is sheared and the fuel is pulverized and separated from the cladding by a dry oxidation/reduction method such as the AIROX process. Fluorination of most U (90% of SF) to volatile uranium hexafluoride (UF_6) can be achieved by a fluoride volatility method using a compact facility “flame reactor”. Then the volatile UF_6 is purified to high DF (about 10^7) by rectification and passing through adsorbents such as NaF. Pure uranium hexafluoride product is suitable for transferring directly to a re-enrichment process, or for storing for a certain period for future FR in simple storage facilities.

4. Storage of the recycle material (RM) of FFCI

The RM consists of about 10% Pu, 35% U, and 55% FP/MA. Materials with similar compositions include: SF from LWR (UO_2 and MOX fuel); SF from FR; and vitrified high-level radioactive waste (HLW). Among these materials, vitrified HLW has similar property and is most helpful for the design of RM. Table 2 shows a comparison of main properties of RM and vitrified HLW. From these considerations, RM storage facility is based on the vitrified HLW facility.

Table 2 Basic property and condition for storage of recycle material

Item \ Mater.	Recycle M. (estimated)	Vitrified HLW
1. Component	FP,MA, Pu,U	FP,MA, B-Si glass
2. Form	Granule	Lump
3. Density (g/cc)	1-3	2.7
4. Heat (W/cc)	0.01-0.03	~0.01
5. Pu conc. (wt%)	~15	0
6. After-treatment	Reprocessing	Disposal

Concept of RM Storage

- Similar design to vitrified HLW storage facility
- Air cool, natural convection
- Criticality safety by the Pu amount limitation, etc.

Figure 4 shows the structure and example of the RM storage facility. Its fundamental design philosophy and conditions is same as vitrified HLW. That is air-cooling with indirect natural circulation convection. RM is loaded into stainless-steel canisters, which are then placed into containment pipe of storage facility. When the RM is stored in oxide powder form, the weight density is expected to be about 1.0 to 3.0 g/cc. Setting the maximum temperature of the RM rods at 1,000℃, the RM canister have a diameter of 15-45 cm depending on the density and thermal conductivity of RM. Comparing the canister diameter of vitrified HLW of 45 cm, it is smaller corresponding to higher heat source of RM. Containment pipe diameter could be smaller than vitrified HLW to get same cooling air speed and almost same temperature performances of RM as vitrified HLW. The canister height of RM is 1 m same as vitrified HLW. This would give them nearly the same dimensions as the fuel assemblies of LWR and FR, facilitating acceptance into reprocessing facilities.

The RM will be stored temporally in the storage facility for 10-20 years for the typical scenario in Japan FR introduction and will be transported to actinide extraction facility. The maximum stored volume of RM in the facility within 60 years transition cycle is about 1/3 of vitrified HLW produced in that period. Consequently, RM storage facility could be commonly utilized with vitrified HLW facility.

On the other hand, RM storage facility should have the inherent capability to avoid criticality even in the hypothetical accident of RM melting which is not required for vitrified HLW owing to the difference of Pu content.

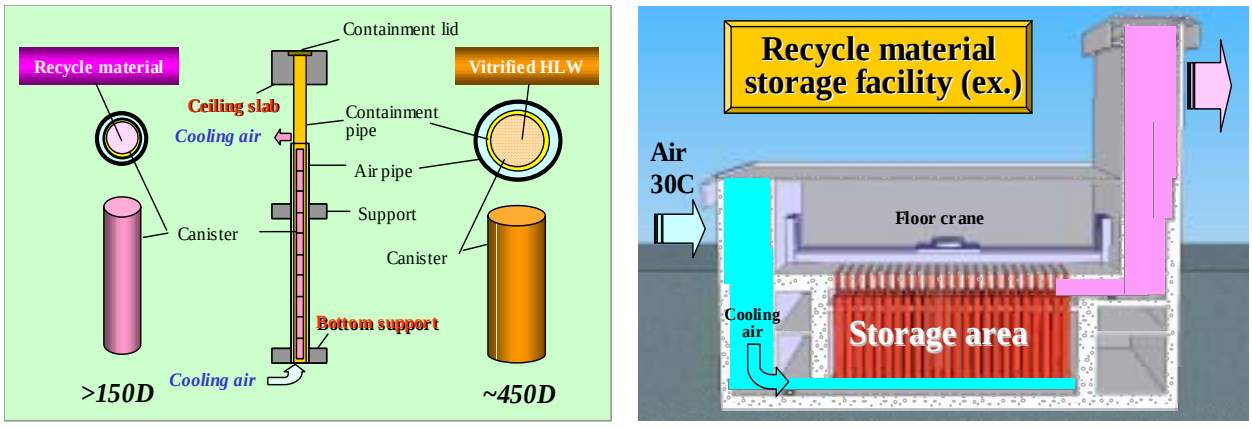
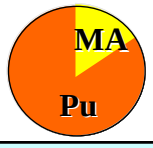
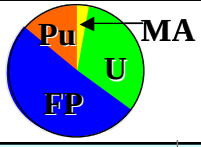


Figure 4 Recycle material storage facility

5. Proliferation resistance, economy and safety of FFCI

We evaluate the performances such as proliferation resistance economy and safety of FFCI. Table 3 shows the comparison of main performance between option-2 and option-3 of FFCI.

Table 3 Performance comparison of options in FFCI

Item		Option-3(An)		Option-2(RM)	
Material composition	Pu	80%		10%	
	MA	20%		3%	
	U	~0%		35%	
	FP	~0%		52%	
1. Proliferation resistance	Physical barrier	Low (no FP)	−	High (with FP)	○
	Pu concentration	High	▲	Low (similar to FR fuel)	−
2. Economy	An extraction availability	Low in case of FR delay	−	High (utilization for FR reprocessing)	○
	Storage facility	An and FP separately	−	No An and FP separation	−
3. Safety	Heat	Low	−	High (consider melting)	▲
	Criticality	Reactivity control needed	−	Reactivity control needed	−

○:Good, −:Base, ▲:Bad

1) Proliferation resistance: FFCI has the following inherent nonproliferation. (1) LWR reprocessing has no Pu extraction, (2) Dirty Pu recovery just before FBR use, (3) Physical barriers of storage materials with high heat and radioactivity. (4) FFCI can respond rapid FBR introduction by reprocessing RM with high Pu content, which enables no need of high breeding ratio (BR) usually effective for high Pu supply. Blanket fuel produces relatively pure Pu-239, especially radial blanket produces Pu-239 separately from core, and causes relatively low proliferation resistance. Coupled with core and fuel design of reactor, FFCI can eliminate radial blanket or both blankets even at high FR introduction speed, and can increase the proliferation resistance. Figure 5 shows the approach to high proliferation resistance FR cycle. Blanketless core of FR with BR of ~1.0 has the advantage of not only nonproliferation but also economy by higher discharge fuel burn-up and small size reactor vessel.

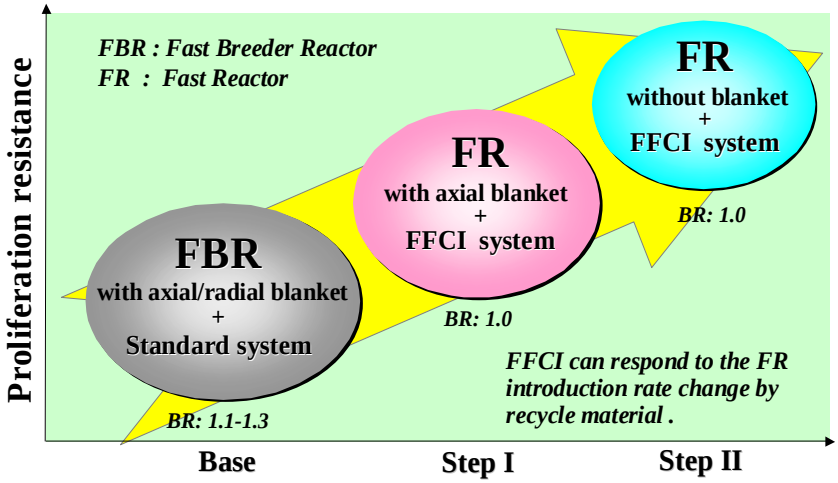


Figure 5 Fast reactor fuel cycle with high nonproliferation

2) Economy: Option-2 of FFCI has the following economical advantage against option-3. (1) Actinide extraction facility could be constructed according to FR introduction timing and have high capacity factor. (2) Single and unified storage facility of actinide and FP is economical comparing to the facilities of actinide and FP separately in option-3.

3) Safety: The RM of option-2 contain heat source of FP and fissile material of Pu. From the viewpoint of criticality safety, RM of option-2 has relatively low Pu content comparing option-3, but heat source isotopes together. As mentioned in previous section, this condition for needs careful study and countermeasure of never critical even in the case of hypothetical accident as melting of RM.

6. Conclusion

The Flexible Fuel Cycle Initiative (FFCI) is in line with Japan's national nuclear energy policy, and is consistent with the Feasibility Study on Commercialized Fast Reactor Cycle Systems. Thus, it will enable the flexible transition from an LWR cycle to an FBR cycle.

Furthermore FFCI has the capability to be applied to other countries scenario of transition cycle from LWR to FR worldwide. Especially for the case of US, FFCI is applicable as a GNEP system.

In the transition cycle from LWR to FR, large capacity of 1000-2000 t/y reprocessing facility for LWR SF will be constructed, and will continue to produce the specific fuel for long time as 40-60 years by its lifetime. This means FR fuel that will be introduced in that period will be affected so long time. Consequently, it is very important to study transition fuel cycle system carefully to accommodate the various condition changes including the technology development, taking the strategy of how to introduce the FR cycle.

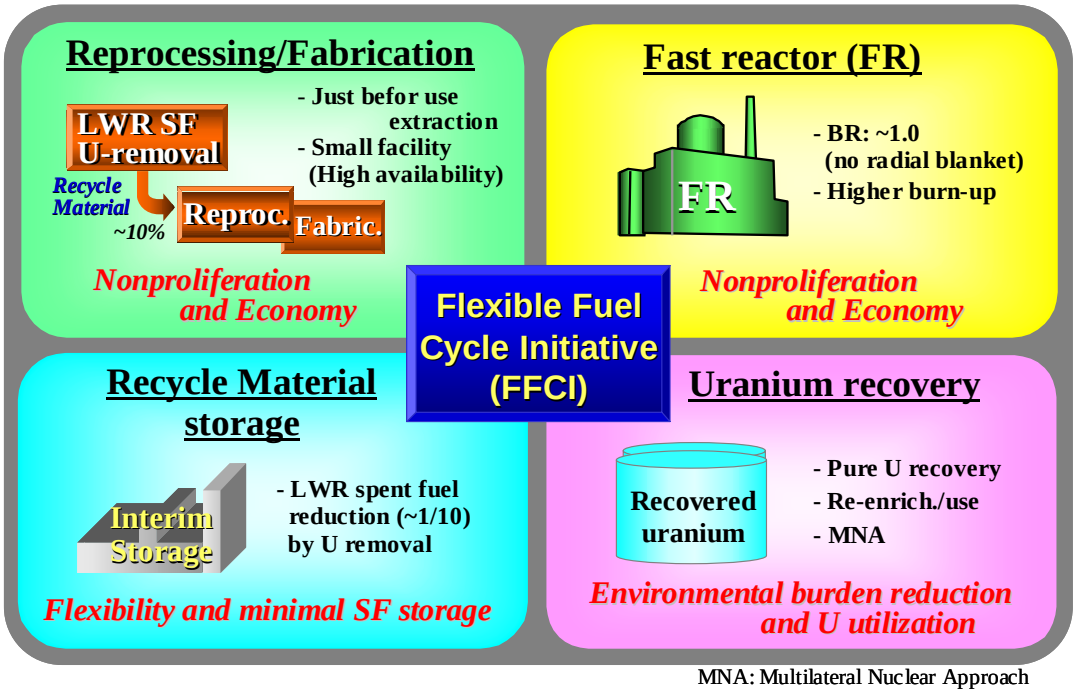


Figure 6 Total concept and characteristics of FFCI

7. References

[1] The Japan Atomic Energy Commission, “Framework for Nuclear Energy Policy”, Oct. 11, 2005
[2] Yamashita J., Fukasawa T., Hoshino K., Kawamura F., Shiina K. and Sasahira A., “Flexible fuel cycle initiative for the transition period from current reactors to next generation reactors”, GLOBAL 2005, Paper No. 562, Oct. 9-13, 2005