Overview of Transmutation Fuels for Sodium Fast Reactor

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1. Introduction

To solve accumulation of light water reactor(LWR) spent fuels, recycling of LWR spent fuels in Gen-IV sodium-cooled fast reactor (SFR) is investigated through international collaboration[1]. Extraction of trans-uranic(TRU) elements from LWR spent fuel and their transmutation or burning in SFR can decrease radioactivity hazard of LWR spent fuel significantly. In this work, status of transmutation fuels for recycling in SFR is reviewed.

2. Transmutation Fuels for SFR

2.1 Trans-uranic elements in LWR spent fuel

In the LWR spent fuel, trans-uranic(TRU) elements such as plutonium(Pu) and minor actinides, like neptunium(Np), americium(Am) and curium(Cm) are contained as shown in Table 1. Among TRU elements, Am and Cm can decay by spontaneous fission, followed by high energy fission neutron and gamma radiation. Therefore, those need to be handled under radiation-shielded environment like hot cell. On the other hand, α-decay radiation from Pu and Np can be shielded by using glove box.

Table 1. TRU elements in LWR spent fuel[2]
(initial U-235 4.95 %, 60 MWD/kgU, 3 yr. cooling)

	Kg/t-HM-SF	Half Life (yr)	γ-rad. E (Kev)	Spont. fission
Np-237	0.9	2.14×10^6	29.4	no
Am-241	0.3	4.33×10^7	59.5	yes
Am-243	0.3	32	74.7	yes
Cm-244	0.1	18.1	42.8	yes
Pu	12.8	24390 (Pu-239)	0.07	no

2.2 Recycling of TRU in SFR

There are two approaches to recycle TRU from LWR spent fuels in SFR, homogeneous and heterogeneous[3]. Homogeneous recycling is to collect all TRU elements together from LWR spent fuel through recycling processing and to make TRU fuel for SFR. Heterogeneous recycling is to separate α-decaying Pu and Np from Am and Cm which can decay by spontaneous fission. Then, SFR fuel is fabricated using Pu and Np, and target element is fabricated using Am and Cm, to be transmuted separately in SFR core. Heterogeneous recycling allows Pu/Np fuel fabrication under glove box environment, and only concentrated Am/Cm target is fabricated in heavy-shielded hot cell, and irradiated in SFR for longer period to transmute up to 90 %. In homogeneous recycling which is more proliferation resistant, all TRU fuels are fabricated in hot cell.

The candidate transmutation fuel materials for SFR are oxide ($(U,Pu,MA)O_2$), metal (U-Pu-MA-Zr), nitride ((U,Pu,MA)N) and carbide ((U,Pu,MA)C). Oxide fuel, $(U,Pu)O_2$ has the most irradiation experience from most of the fast reactors operated in France, USA, Japan and Russia. Metallic fuel (U-Pu-Zr) has irradiation experiences in the research reactors such as EBR-II and DFR. Nitride and carbide fuel do not have reactor-wide experience yet. For the minor actinide containing fuel, there is not much irradiation experience for all type of fuel materials.

2.3 Recycling process of spent fuel

LWR spent fuels are processed to separate the recyclable elements from disposable waste. Recyclable elements are used as SFR fuel, and later spent SFR fuel is also processed to extract the recyclable elements. There are two processes such as aqueous and pyroprocessing. Combination of both processes could be also possible, if necessary.

PUREX(Plutonium Uranium Refining by Extraction) process extracts TRU after dissolving LWR spent fuel in nitric acid. It is commercially used in reprocessing of LWR spent fuels to produce MOX fuel for LWR. However, extraction of Pu in PUREX process causes proliferation concern. Therefore, more proliferation resistant aqueous process which does not extract pure Pu is investigated, such as UREX+(Uranium Extraction) and COEX(Co-Extraction), etc. And, for SFR spent fuel, PUREX process needs to be developed to accommodate high fissile contents of SFR fuel without criticality concern.

Pyroprocessing or pyrometallugical processing extracts TRU in molten salt electrolytes at high temperature. Fuel recycling through pyroprocessing was demonstrated in EBR-II fast reactor. Metallic fast reactor fuels were reprocessed by pyroprocessing and TRU metallic fuel was fabricated in radiation-shielded hot cell. Since in pyroprocessing, TRU are extracted together, it has high proliferation resistance. Pyroprocessing of LWR spent oxide fuel to extract TRU to be recycled in SFR is under development stage.

2.5 Evaluation of fuel recycling method

To select the fuel recycling route, fuel recycling process and fuel materials for SFR need to be decided. In the evaluation, sustainability, safety, economy and proliferation resistance are considered. First, fuel recycling meets the sustainability by decreasing radioactive waste and increasing the uranium utilization efficiency. Fuel material and fuel recycling process depends upon each other.

Selection of fuel materials is directly related to SFR design. As fuel performance influences safety and economy of SFR, irradiation performance of TRU fuel, metal or oxide should to be demonstrated before design and construction of SFR using TRU fuel.

As SFR fuel, metal fuel has more merits than the oxide fuel due to better compatibility with sodium coolant and high thermal conductivity which makes the SFR inherently safe[4]. Metal fuel has advantage over oxide fuel due to simply casting of long fuel slug, compared with multi-processes of oxide fuel pellet. Hot cell fabrication of metal fuel was demonstrated in EBR-II. For metal fuel, pyroprocessing of SFR spent metal fuel needs to be developed, while pyroprocessing or aqueous processing could be applied to LWR spent oxide fuel. Pyroprocessing of LWR spent fuel through oxide to metal reduction and electro-winning to extract TRU and TRU fuel fabrication in large scale need to be demonstrated.

Aqueous process of oxide fuel is more established than pyroprocessing, as demonstrated in commercial PUREX process of LWR spent fuel. Heterogeneous recycling is possible through aqueous process since Pu/Np and Am/Cm can be separately extracted. As oxide fuel is more suitable to aqueous process, the complexity of oxide fuel fabrication can be compensated through heterogeneous recycling. However, low compatibility of oxide with sodium and lower thermal conductivity are still the significant concern in SFR safety. And proliferation resistance of advanced aqueous process needs to be confirmed.

Decision of fuel recycling methods such as SFR TRU fuel materials, recycling process of LWR spent oxide fuel and recycling process of SFR spent fuel is a complex task as they are interrelated. Solid research results are necessary in the critical areas such as hot cell fuel fabrication, SFR safety and recycling process of both LWR and SFR spent fuels. In the end, economy will be a key factor for the commercialization of fuel recycling while proliferation resistance should be maintained and acceptable.

3. Conclusion

Status of investigation on recycling of LWR spent fuel as transmutation fuel in Gen-IV SFR was reviewed. There are many factors to be considered such as sustainability, safety, economy and proliferation resistance. More works need to be done in fuel qualification and fuel recycling process to provide the reliable information for the final decision on fuel recycling methods such as recycling process and fuel materials. As more results are expected to come out in near future, the best fuel recycling route will be selected for Gen-IV SFR.

REFERENCES

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