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Overview of Fuel Cycle in Fast Reactor

Chan Bock Lee and Do Hee Hahn
Korea Atomic Energy Research Institute, E-mail : cblee@kaeri.re.kr

1. Introduction

In the fast reactor, fissile elements can be generated while fissile elements undergo fission reactions to produce fission energy[1]. High energy fast neutrons can also burn or transmute the unnecessary elements such as minor actinides and fission products with long half life such as I-129(half life = 1.57 x 10^7 years) and Tc-99(half life = 2.13 x 10^5 years).

Light water reactor(LWR) has been the dominant reactor type for electricity generation since nuclear power was introduced. However, the expected steady increase in the demand of nuclear energy in the coming decades will certainly need the fast reactor, considering the limited resource of natural uranium and buildup of LWR spent fuels.

Breeding capability of fast reactor could increase the utilization of uranium by about 50 times compared with the once-through LWR fuel cycle. Burning or transmutation of harmful radioactive elements in fast reactor, and compact treatment of fission products extracted from the spent fuels could significantly reduce the volume of waste and degree of hazard.

2. Fuel cycle in fast reactor

2.1 Fuel Design

Fuel design includes selection of materials of fuel components, and verification of fuel integrity. In fuel design, safety of the reactor, economy in both the reactor operation and fuel cycle, and effects on waste disposal need to be considered. High fuel discharge burnup is desirable for both the economy and proliferation resistance due to higher radioactivity. The reference fuel in KALIMER developed in KAERI is metallic fuel with ferritic stainless steel cladding under sodium coolant[2]. The maximum fuel discharge burnup is assumed to be 80 MWD/kgU which is limited by the cladding performance.

2.2 Coolant

Selection of the coolant in fast reactor is one of the critical factors in the design of fast reactor and fuel. The candidates of coolant are sodium, lead, lead-bismuth and gases such as helium and carbon dioxide. Table 1 compares characteristics of the coolant candidates[3]. Sodium has by far the most experiences from almost all the fast reactors. The concerns on sodium have been chemical reaction of sodium with air and water, and positive void reactivity coefficient. Lead-bismuth coolant has experience in the Russian submarine reactors[4]. Lead and gas coolant technologies are under development stage. Those coolants are chemically stable to air and water. However, their actual application experiences need to be accumulated and verified. Lead or lead-bismuth has concern of high density and toxicity of lead. Gas coolant has concern of very low heat capacity compared with liquid metal.

Table 1. Characteristics of liquid metal coolants

	Na	Pb(44.5%) /Bi(55.5%)	Pb
Atomic number	11	82/83	82
Density(kg/m^3)	970	10,200	10,700
Melting temperature(^oC)	97.8	123.5	327.4
Boiling temperature(^oC)	892	1,670	1,737
Relative pumping power required	1.0	6.9	6.1

2.3 Fuel Materials

The candidates of fuel materials are oxide, metal and nitride. Table 2 shows irradiation experiences of fuel materials[1]. $(U,Pu)O_2$ fuel has the most irradiation experience from most of the fast reactors operated in the world like France, USA, Japan and Russia. U-Pu-Zr metallic fuel has irradiation experiences in the research reactors such as EBR-II and DFR. Nitride fuel does not have reactor wide experience yet. Fuels containing the minor actinides and some of fission products, which are considered as the primary fuel for the next generation fast reactor are radioactive and therefore they need to be fabricated remotely in the hot cell. There is not much irradiation experience for the minor actinide containing fuels.

Table 2. Irradiation experience of fuel materials

	Oxide	Metal	Nitride
Fuel composition	$(U,Pu,MA) O_2$	U-Pu-MA-RE-Zr	(U,Pu,MA) N
Irradiated fuel pins(Europe, US, Japan)	378,500 $(U,Pu)O_2$	14,609 U-Pu-Zr	108 (U,Pu)N
Maximum burnup(at %)	24.5	20	7
Maximum DPA	200	110	54

2.4 Fuel Cladding

The role of fuel cladding is to contain the radioactive fission products. To maintain fuel integrity up to high burnup, high performance cladding is essential. In the fast reactor, there is high energy and high density neutron flux which the cladding should withstand at high temperature. The performance parameters of concern in the cladding are swelling, creep and corrosion. The radiation damage to the cladding could be up to 250 dpa(displacement per atom) to achieve burnup of 250 MWD/kgU. For the metallic fuel, the peak cladding temperature could be up to 650 ^{o}C which is limited by fuel-cladding chemical interaction. The candidates of the cladding are stainless steel such as ferritic stainless steel and oxide dispersion stainless steel(ODS). Ferritic stainless steel is known for low swelling rate. ODS has good mechanical strength at high temperature. Ceramic cladding such as SiC is under investigation.

2.5 Spent Fuel Processing

Through reprocessing of the spent fuels, uranium, plutonium and minor actinides can be collected and re-used as the fuel. Fission products which consists of only about 5 % in LWR spent fuel are collected for waste disposal, and the fission products of ultra long half life elements such as I-129 and Tc-99 can be separated and be transmuted in the fast reactor fuel.

There are two different fuel reprocessing processes. One is PUREX process which has been widely used in reprocessing of LWR UO_2 fuel to produce MOX fuel. Since it separates plutonium from the spent fuel, there is high concern on the proliferation. There has been developed the PUREX plus process which does not separate plutonium alone and collects plutonium together with minor actinides such as neptunium, americium and curium[1]. Therefore, it could be considered proliferation resistant.

The other is pyroprocessing process which is operated at high temperature under the salt electrolyte. It can be applied to both oxide and metallic fuels. Pyroprocessing was demonstrated extensively for the metallic fuel in the EBR-II reactor. Since uranium, plutonium and minor actinides are collected altogether, it is considered as proliferation resistant process.

2.5 Proliferation Resistance

Nuclear proliferation has been a critical factor in the application of fast reactors. A new paradigm may come in the management of spent fuels. There is an argument that removal and burning of plutonium as a fuel in the reactor may be more proliferation resistant than storage of the spent fuels with plutonium. There are successful examples of countries where IAEA safeguards make it possible to operate the spent fuel reprocessing to keep proliferation resistance.

2.6 Technical Issues for Next Generation Fast Reactor

The primary targets of the fuel for the next generation fast reactor could be sustainability, proliferation resistance and economy. High burnup fuel is desirable to get better economy and high proliferation resistance. The peak target burnup could be 250 MWD/kgU. The key technologies in fuel cycle which need to be demonstrated are as follows[5].

Selection of fuel materials such as metal and ceramic, and selection of coolant such as sodium and lead base coolant are directly related with reactor design. Each has different advantages and different depth of experiences. Safety and performance of fuel material composition with uranium, plutonium and minor actinides need to be demonstrated up to high burnup.

The remote fuel manufacturing processes to handle radioactive plutonium, minor actinides and fission products need to be demonstrated in the areas of facility engineering, radioactivity shielding and criticality.

The cladding is one of the key components which could limit the fuel burnup and control the coolant operating temperature and reactor thermal efficiency. Therefore, development of cladding materials which can be irradiated up to high burnup is necessary and has a good commercial potential.

Reprocessing method of the spent fuels from both LWR and fast reactor needs to be demonstrated. It should satisfy the requirements for proliferation resistance as well as engineering practicality such as efficiency, effluents and wastes treatments.

3. Conclusion

Application of fast reactor seems to be inevitable considering growing demand of nuclear power, limited resource of uranium, and buildup of spent fuels from LWRs. Fast reactor could generate fissile elements and burns the unnecessary elements while generating the fission energy. Thorium resource can be also used in the fast reactor as fuel. Through the technology development for the next generation fast reactor, nuclear power could be much more productive, sustainable, proliferation resistant and environmentally friendly.

REFERENCES

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