Accelerator-Driven System and Inert Matrix Fuel

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1. Introduction

One of the challenges facing sustainable nuclear power is how to dispose spent nuclear fuel in a way that is safe and satisfactory for the feeling of general citizen. Spent fuel contains radiotoxic trans-uranium nuclear elements such as plutonium and minor actinides, which can survive up to even hundreds of thousands years. This is a universal problem, but Korea is in particularly serious situation, because the country has operated nuclear power plants for more than 30 years and is operating more than 20 light water nuclear reactors. Spent fuel is going to fill the storage in some nuclear plants in a few years. This problem should be solved in the near future.

As a method to solve this problem, the accelerator-driven system (ADS) [1-4] is widely considered as a promising tool for transmutation of plutonium (Pu) and minor actinides (MA). However, smart tactics are required for successful transmutation of those elements and this is particularly so in Korea. For the ADS transmutation, reprocessing of spent fuel is necessary and unlike other such countries as USA, European countries and Japan, where plutonium is regarded as a fuel whereas minor actinides are regarded as toxic waste to be disposed, Korea is supposed to adopt only the pyro-processing scheme in which plutonium cannot be separated from other minor actinides. Plutonium and minor actinides cannot be transmuted separately but should be put into a common reactor. Note that the amount of plutonium is around 10 times more than that of minor actinides. Therefore, Korea needs different transmutation plan from the above countries. Also, as the ADS scheme requires higher cost than a conventional critical reactor due to extra elements such as a high power proton accelerator, heavy metal target system and front-end system, the number of ADS system required for full transmutation of all plutonium and minor actinides generated in Korea.

This paper argues that not only ADS but also the inert matric fuel (IMF) scheme [5-11] is required for successful and efficient operation of ADS for transmutation with minimum number of sub-critical reactors and accelerators. IMF is a type of nuclear reactor fuel that consists of a neutron-transparent matrix and a fissile phase that is either dissolved in the matrix or incorporated as macroscopic inclusions. The matrix plays the crucial role of diluting the fissile phase to the volumetric concentrations required by reactor control, which is the same role U-238 played in the conventional low enriched uranium (LEU) or mixed oxide fuel (MOX) fuel. The key difference is that replacing fertile U-238 with a neutron transparent matrix removes plutonium breeding as a result of neutron capture. IMF is a powerful tool to burn plutonium in a conventional light water reactor (LWR) without further conversion from U-238 to plutonium.

Therefore, this paper claims that L(arge)(Pu) + s(mall)(MA) from a pyro-processing facility should be burned deeply (deep-burn) by a conventional LWR in the form of IMF and then the waste s(Pu) + L(MA) collected from several LWRs after multi-recycling should be transmuted in a transmutation-dedicated ADS system as shown in Fig. 1.

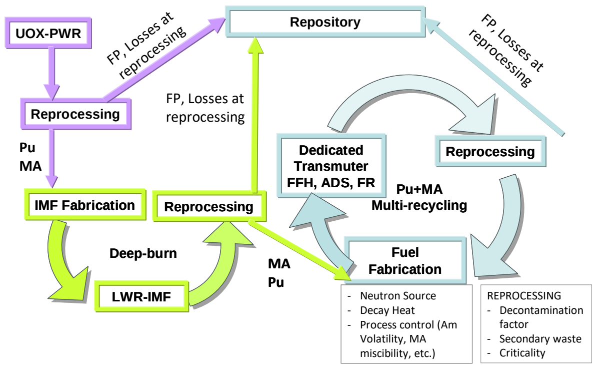

Fig. 1. Schematic figure of deep-burn first and transmutation-dedicated ADS [12].

2. Transmutation by accelerator-driven system

This section explains ADS and transmutation by ADS. Basically, ADS means an accelerator-based sub-critical reactor system (k_{eff}<1) while conventional nuclear reactors operate at the critical condition (k_{eff} =1), where k_{eff} is the effective neutron multiplication coefficient. In ADS, the number of neutrons originating from fission is not sufficient to overcome the neutron losses (due to leaks and absorption of neutrons by materials within the reactor). In order for the fission reaction to proceed, extra neutrons must be supplied from an external source (an accelerator). In principle, ADS is safer than a critical reactor. Neutrons emitted from heavy-metal target hit by high energy protons coming from the driving accelerator are delayed neutrons. Hence, ADS is a system with an external source of delayed neutrons. This feature not only strengthens the safety of ADS substantially but also allows Pu and MAs alone as fuel with no extra U-238. As both Pu and MAs emit small number of delayed neutrons, a critical reactor with a fuel made of Pu and MAs alone would be close to prompt critical and have narrow safety margin. Safety margin means maximum distance from the prompt criticality. The concept of prompt criticality and safety margin is explained by schematic figures in Fig. 2 and Fig. 3. This explains why ADS is safer and more efficient in transmutation of Pu and MAs than a critical fast reactor in which U-238 is added to raise the number of emitted delayed neutrons but U-238 is converted to Pu through neutron capture.

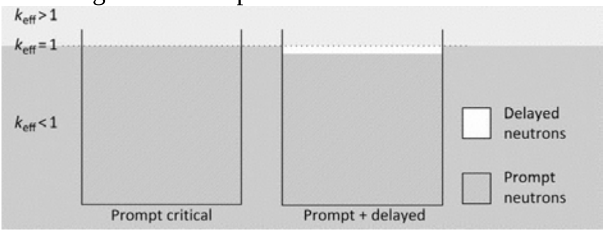

Fig. 2. Radiotoxicity over the course of time for nuclear wastes from the spent fuel.

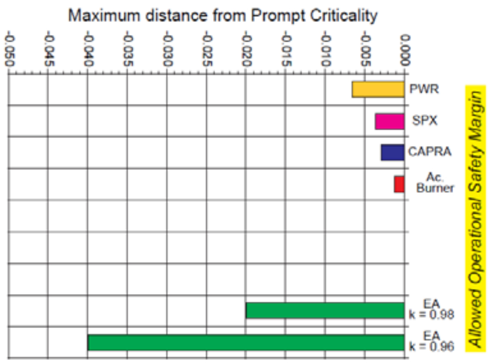

Fig. 3. Safety margin of a few types of nuclear reactors.

ADS is able to reduce substantially half lifetimes of Pu and MAs from hundreds of thousand years to only a few hundred years through the process of nuclear transmutation. Considering that Korea has a relatively small land compared to its population, it is very difficult to construct a permanent storage for spent fuel. Also, considering that a conventional fast reactor is not widely accepted as a safe facility, nuclear transmutation based on accelerator-driven system (ADS) seems to be the most reasonable and promising solution. This is the reason why progress of ADS is so urgent in Korea.

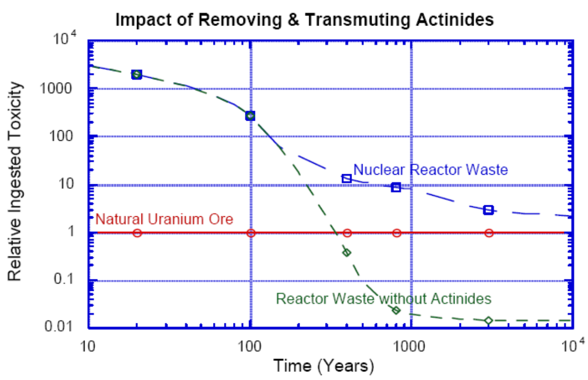

Fig. 4. Radiotoxicity over the course of time for nuclear wastes from the spent fuel

3. Plutonium burning by inert matrix fuel

This section explains plutonium burning by IMF. As mentioned above, IMF has a matrix transparent for neutrons. It is an uranium-free fuel. The aim of IMF is to burn Pu (or MAs) in a thermal (or fast) nuclear reactor with zero conversion from uranium to plutonium. As for the support matrix, rock-like materials or metals are candidate materials. IMF is still under R&D, but its potential as a Pu burner is well illustrated in Fig. 5, according to which the LWR-IMF combination is even better than ADS for Pu-burning. On the other hand, the same figure shows that ADS is the most efficient at MA transmutation. This shows that ADS is best suited as a dedicated MA transmuter.

Therefore, a good transmutation scenario for Korea is to (1) load an IMF containing Pu + MA collected from reprocessed spent fuel into several LWRs, (2) deep-burn and multi-recycle the IMF, (3) transmute the final waste with dominant MAs in a transmutation-dedicated ADS. This scenario is shown in Fig. 1.

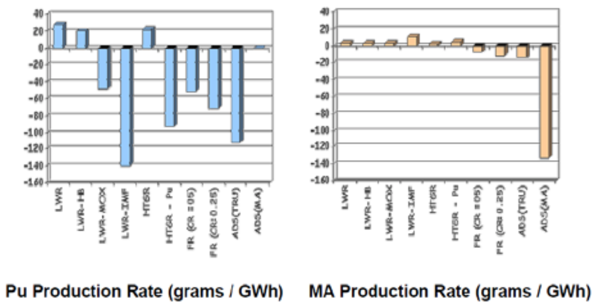

Fig. 5. Pu production rate and MA production rate of several nuclear reactors [13].

- Proton beam : 1.5GeV ~20MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : k_{eff} = 0.97
- Thermal output : 800MWt
- Core height : 1000mm
- Core diameter : 2440 mm
- MA initial inventory : 2.5t
- Fuel composition :
  (60%MA + 40%Pu) Mono-nitride
- Transmutation rate :
  10%MA / Year (**10 units of LWR**)

Fig. 6. Conceptual design of JAEA ADS [14]

This scenario is different from that of those countries where plutonium is separated from minor actinides in reprocessing. For example, Japan regards plutonium as a nuclear fuel. In this case, MAs are the target of transmutation. As shown in Fig. 6, the planned fuel composition is 60% Pu + 40% MA, the planned sub criticality is k_{eff} = 0.97, and the planned transmutation rate is typically 10% MA/year which corresponds to 10 units of LWR/year [7].

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