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Accelerator-Driven System and Other Schemes for Spent Fuel Disposal

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1. Introduction

After the East-Japan earthquake and the subsequent nuclear disaster, the anti-nuclear mood has been wide spread. It is very unfortunate both for nuclear science community and for the future of mankind, which is threatened by a serious challenge, the global warming caused by the greenhouse effect. While the nuclear energy seemed to be one of the important solutions to reduce the emitted carbon dioxide gas, clearly it has its own problems, one of which broke out so strikingly in Japan. There are also other problems including the radiotoxic trans uranium nuclear waste in the spent fuel that can survive up to even hundreds of thousands years. Particularly, Korea faces serious spent fuel problem. The country has operated nuclear power plants for more than 30 years and is now operating 23 nuclear power plants. Spent fuel is going to fill the storage in nuclear plants in a few years. This problem should be solved in the near future. In this paper, as methods to solve this problem, the accelerator-driven system (ADS) for transmutation of toxic elements and disposal of those elements to outer space are discussed.

2. Accelerator-driven system (ADS)

To solve these problems of nuclear fission energy, there can be a few accelerator-based plans and one of them is the accelerator-based sub-critical nuclear reactor [1-4]. In principle, it is safer than critical reactors, because the neutrons emitted from heavy-metal target hit by high energy protons coming from the deriving accelerator are more easily controllable. Also, as the protons from the accelerator are in pulsed bunches in time, the neutrons that are generated by them are delayed neutrons in principle and this can substantially strengthen the safety of the ADS strategy. ADS can also shorten half lifetimes of toxic nuclear waste elements, such as plutonium (Pu) and minor actinides (MA), to only a few hundred years through the process of nuclear transmutation. This is one of the proposed solutions for the spent fuel problem. 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 the 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.

Although the idea of the accelerator-driven nuclear reactor was proposed long time ago, it has not been utilized yet first by technical difficulty and economic reasons. The accelerator-based system needs at least a 1 GeV, 10 MW power proton accelerator and the accelerator operation must be extremely stable.

Conventional nuclear reactors operate at the critical condition. The criticality of a nuclear assembly is determined by the effective neutron multiplication coefficient k_{eff} which is defined as

$$k_{eff} = \frac{\text{Numbner of fissions in any one generation}}{\text{Numbner of fissions in immediately preceding generation}} \quad (1)$$

When $k_{eff} = 1$, number of fissions in each succeeding generation is a constant and the chain fission reaction initiated in the system will continue at a constant rate. Such a system is said to be at a critical conditions. If $k_{eff} > 1$ the number of fission in the system increases with each succeeding generation and the chain reaction diverges; the corresponding condition is referred to as supercritical. On the other hand, if $k_{eff} < 1$ the chain reaction will eventually die out and the system is called subcritical. In a subcritical reactor, 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). Therefore, under no circumstances a chain reaction can be self-sustaining. In order for the fission reaction to proceed, the system must be fed continuously with neutrons from an external source (an accelerator).

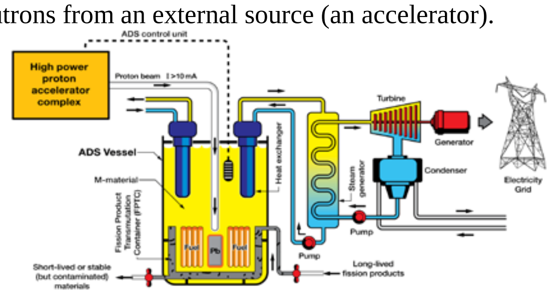

Fig. 1. Basic principles of the operation of accelerator-driven sub-critical reactor.

3. Partitioning and transmutation

Partitioning means 'separating out of the spent fuel the radiotoxic components' and transmutation means 'recycling them in a way to minimize their toxicity and recover their contained energy in a useful way' [5]. Therefore, partitioning and transmutation is necessary to drastically reduce the toxic trans-uranic nuclear waste. Plutonium and minor actinides typically have half time of a few million years and, consequently, a few hundred thousand years are required to reduce their radiation level to the natural uranium ore level as shown in Fig. 2 below. After nuclear transmutation, this number would be reduced to around 2 hundred years. Nuclear transmutation is in general done by fast neutrons and so requires a critical fast reactor or sub-critical accelerator-driven system. But, ADS is more effective in burning those trans-uranic elements because it can run without uranium and consequently would not produce additional trans-uranic elements converted from the uranium. Further, the externally supplied neutrons rom the ADS accelerator ensure higher safety because they are easily controllable.

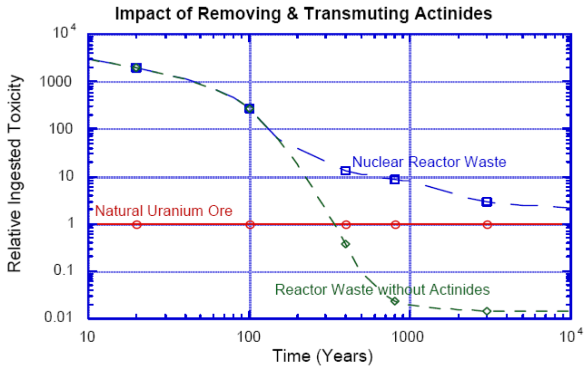

Fig. 2. Radiotoxicity over the course of time for nuclear wastes from the spent fuel

4. ADS accelerator and its requirements

So far, for ADS considerations, a superconducting linear accelerator has mostly been considered as a candidate for the accelerator, mainly because it has a straightforward way of increasing the proton energy and beam power at least in principle. The beam energy can be increased by putting more accelerating columns, which increases its length though, and the beam power can be increased by increasing its current (for example, by increasing the repetition rate). By contrast, a synchrotron has a limitation to increase its repetition rate and thus the current. However, the problem with a linear accelerator is that its construction cost may be huge because it is very long. The 1-GeV proton accelerator of the Spallation Neutron Source is 350 m long (Fig. 3).

However, what is more difficult to achieve is the required accelerator operation stability. Even with modern technology, accelerators frequently stop due to component failures and other reasons. But, ADS requires the highest level of accelerator stability for both stable supply of electricity and durability of reactor components. Required stability (or beam trip frequency) for each component or power plant availability has been discussed in several literatures in slightly different forms. [6]

Fig. 3. Spallation Neutron Source in the Oakridge National Laboratory as an example of superconducting proton accelerator

5. ADS schemes considered

Japan adopts reprocessing of the spent fuel and considers plutonium as a nuclear fuel. In this case, only the minor actinides are the target of transmutation. 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 (light water reactor)/year [7]. On the other hand, Korea cannot separate out of the spent fuel plutonium under its agreement made with US government. Therefore, Korea should separate at most all the trans-uranic elements (Pu + MAs) combined. Typically, MAs/Pu is around 10%. Hence, transmutation should proceed with this trans-uranic elements combined without further uranium addition.

- 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.4. Conceptual design of JAEA ADS

6. Disposal of toxic elements to outer space [8]

The National Aeronautical and Space Administration (NASA) once studied the possibility of disposing high level waste (HLW) using the space shuttle [9], but this requires a large amount of energy. Currently, several commercial companies are developing rocket technologies and the cost of using a rocket will be substantially lower than the time of report. This trend will encourage researches on using outer space for spent fuel disposal.

However, also, instead of using a rocket to generate the escape velocity, by ejecting trans-uranic elements with the escape velocity using an accelerator, we can reduce substantially the energy needed for their disposal. To uniformly disperse the trans-uranic elements into outer solar space from the parking orbit requires an earth escape velocity (VEE) = 42.07 km/sec. Instead of dispersing the trans-uranic elements uniformly in outer space, if we disperse them uniformly in the plane of the earth's orbit, then the velocity required is reduced from 42.07 km/sec to VEE = 12.32 km/sec. When the isotopes are not separated, the power required to dispose uniformly in outer space or in the earth orbit plane of all the trans-uranic elements produced by 1 GW LWR is, respectively, 8.5 kW and 0.73 kW. These energies are much smaller than that required to transmute the trans-uranic elements by spallation neutrons in the subcritical assembly, which is in the order of a few tens of MW [8].

Although the energy required to accelerate the trans-uranic elements is not very great, the current required is large. The total current for the accelerated isotopes and elements is, respectively, about 2.2 and 8.2 A. When the charged ions are ejected into outer space, the magnetic field in solar space might trap the charged ions so that the trans-uranic elements would not be disposed into the outer solar system. To prevent this trapping, the charged ions should be neutralized in the same way as is done for neutral-beam injection in the magnetic fusion reactor. Instead of using a static accelerator with a neutralizer, ions thrusters which were developed for space propulsion have the capability to dispose the trans-uranic elements.

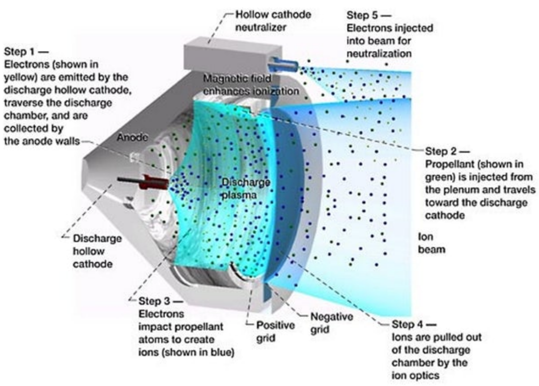

Fig.5. Schematic figure of an ion thruster

There is a possibility of a failure when launching trans-uranic elements from the earth. NASA extensively studied the shielding of the rad wastes which will be loaded into the space shuttle to protect the astronauts. Experiments were performed by dropping the capsule with its heavy shield material on to hard-and soft-ground surfaces. [8]

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