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Feasibility of Accelerator-Driven System in Korea

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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 contained in 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.

To solve these problems of nuclear fission energy, accelerator-based sub-critical nuclear reactor was once proposed [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. It 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.

2. Accelerator-driven system (ADS)

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).

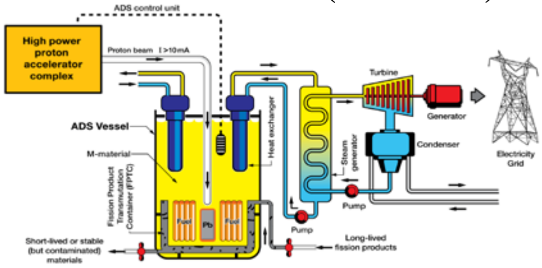

Fig. 1. Basic principles of the operation of accelerator-driven sub-critical reactor.

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 (ADS). 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.

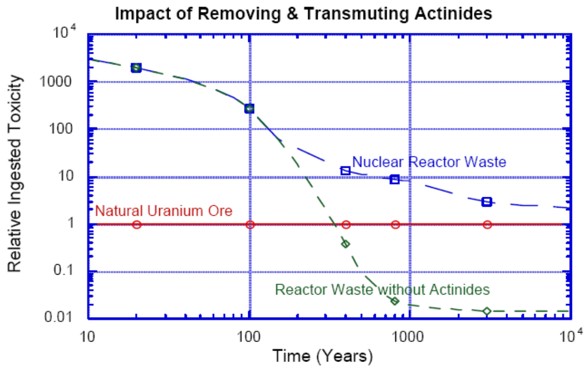

Fig. 2. Radiotoxicity over the course of time for nuclear wastes from the spent fuel

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).

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

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, and one of them is summarized in the table below.

Table I: Acceptable frequency of beam trips for each beam trip duration [6].

Criteria	Acceptable value (times/year)	Component that imposed limits
0 sec $\leq$ T $\leq$ 10 sec	20,000	Beam window
10 sec $\leq$ T $\leq$ 5 min	1,000	Reactor vessel
T $\geq$ 5 min	50	Plant availability

On the other hand, beam trip frequencies, as recorded in SNS, allowed by JAES and accepted for MYRRAH are shown in Fig. 4 below.

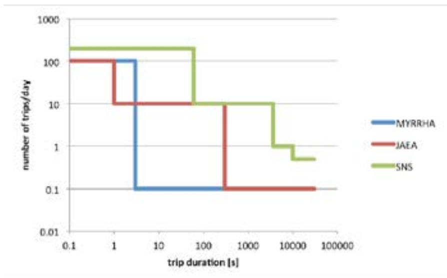

Fig. 4. Beam trip frequencies: recorded in SNS, allowed by JAEA, accepted for MYRRHA.

5. ADS schemes considered

5.1. ADS scheme in Japan

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].

- 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.5. Conceptual design of JAEA ADS

5.2. ADS scheme in Korea

On the other hand, Korea cannot separate out of the spent fuel plutonium under its agreement made with US government. Therefore, Korea can 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.

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