

SCHEMES FOR THE ACCELERATOR-DRIVEN SYSTEM*

Tae-Yeon Lee[†], Seunghwan Shin, and Hee-Seock Lee, PAL, Pohang, Korea

Abstract

Accelerator-Driven system (ADS) is considered the future nuclear reactor. In principle, it is safer and creates less waste than the conventional nuclear reactor, and provides the transmutation function that converts spent fuel into short-lived elements. However, to fully realize this system, a huge proton accelerator (typically, 1 GeV beam energy and over 10 MW beam power) with extremely high operational stability is necessary. This paper discusses how the currently available technology can be applied for nuclear transmutation.

INTRODUCTION

The accelerator-driven system (ADS) [1][2][3] had long been considered to be an absolutely safe nuclear power generation system. In ADS, nuclear reactor is set up sub-critical and extra neutrons required for sustainable power generation is provided by neutrons emitted from high energy proton beam hitting a heavy metal target. The accelerator plays the role of safety key; turning off the accelerator, which is very sensitive to perturbations, leaves the reactor in shortage of neutrons and the nuclear chain reaction would immediately stop. The ADS is safe especially when an accident such as earthquake occurs, because this type of accident would quickly stop the accelerator making the chain reaction be unable to sustain. However, the nuclear disaster of Fukushima turned off people's interest in ADS as well as in conventional nuclear power plant (NPP), because even ADS would not have avoided the Fukushima accident which occurred due to failure of cooling system after the reactor became sub-critical. Perhaps, future power generation by ADS will have to block any possibility of Fukushima type accidents. In this regard, that the thorium molten salt reactor adopts air cooling and, therefore, there will be no chance of Fukushima-type accident has been pointed out.

However, in spite of the Fukushima accident, nuclear power plants are still being constructed as several countries including Vietnam, Bangladesh, United Arab Emirates, Turkey and Belarus began to build the first NPP of each country in 2012 while Jordan and Saudi Arabia began in 2013. Hence, nuclear power will continue to be used because of merits it has, and the serious problem of disposing spent fuel will continue to exist. The ADS proposes so far the best method of disposal, transmutation of minor actinides having hundred thousand year level half lifetime to nuclear species having 2~3 hundred year half lifetime. The original concept of ADS covers from transmutation of spent fuel to power generation but, with the current technology level, only the transmutation seems feasible. Korea is one of the countries that face impeding

spent fuel problem and ADS can be a serious candidate for solving the problem.

This paper discusses possible schemes of ADS for transmutation of spent fuel. Focus will be put on economic aspect and using currently available technologies.

ACCELERATOR-DRIVEN SYSTEM

The ADS scheme was proposed long time ago, but has not been realized yet mainly because the accelerator technology is not sufficiently matured. The ultimate goal of ADS, generation of electricity, requires an unprecedented proton beam power (up to several tens of MW while the highest proton beam power achieved is only 1.3 MW) and unprecedented accelerator operation stability. The important milestones to the ultimate goal were classified to the 4 phases shown below in Table 1 [4] and the corresponding technical requirements were specified through studies. In particular, the accelerator stability requirement is such a challenge that its achievability is even unclear at this moment. The primary purpose of these stability requirements is to prevent components of ADS, such as proton beam window and reactor vessel, from being damaged by frequent interruptions. The availability of electricity transmission can be secured by energy storage system.

On the other hand, the issue of proton energy and beam power seems more realizable. Linear accelerators based on superconductor technology are expected to deliver even 100 MW proton beam in the future, but the required proton beam power may greatly vary depending on the neutron multiplication factor k and proton energy, as shown in Fig. 1, from 6 MW to over 50 MW. In the case of transmutation, k may be able to get closer to 1 than power generation without higher risk. Anyway, the currently achievable goal is certainly the first phase, transmutation demonstration, and possibly the second phase, industrial scale transmutation. Hence, the goal right now should be transmutation of long-lived nuclear waste.

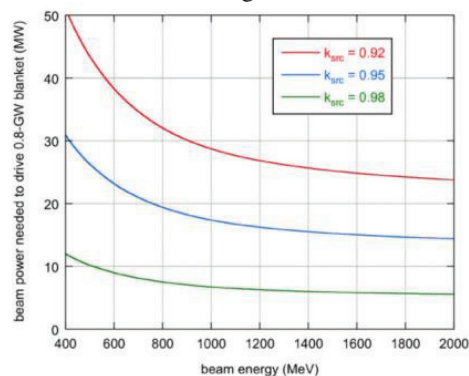


Figure 1: Beam power needed to drive a 0.8-GW ADS sub-critical core as a function of beam energy, for several values of k . [4].

* Work supported by Ministry of Science, ICT & Future Planning

[†] Email address: tylee@postech.ac.kr

Table 1: Range of Parameters for Accelerator-driven Systems for Four Missions

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1 – 2 MW	10 – 75 MW	10 – 75 MW	10 – 75 MW
Beam Energy	0.5 – 3 GeV	1 – 2 GeV	1 – 2 GeV	1 – 2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam Time ($t < 1$ sec)	N/A	<25000/year	<25000/year	<25000/year
Beam Time ($1 < t < 10$ sec)	<2500/year	<2500/year	<2500/year	<2500/year
Beam Time ($10 \text{ s} < t < 5 \text{ min}$)	<2500/year	<2500/year	<2500/year	<250/year
Beam Time ($t > 5$ min)	<50/year	<50/year	<50/year	<3/year
Availability	>50%	>70%	>80%	>85%

Accelerator

The issue for accelerators in ADS is proton energy and beam power. As can be seen from Fig. 2, 1.2 GeV proton energy is most effective for producing neutrons. However, the figure also shows that proton energy above 0.5 GeV can be fairly effective for neutron production. A few accelerator types, such as the linear accelerator, cyclotron or FFAG, have been studied as a candidate for the ADS accelerator. But, considering that the FFAG is still an accelerator being studied rather than a matured type widely used, the linear accelerator and cyclotron are the two accelerator types that can be used. Synchrotrons cannot supply sufficiently high beam power.

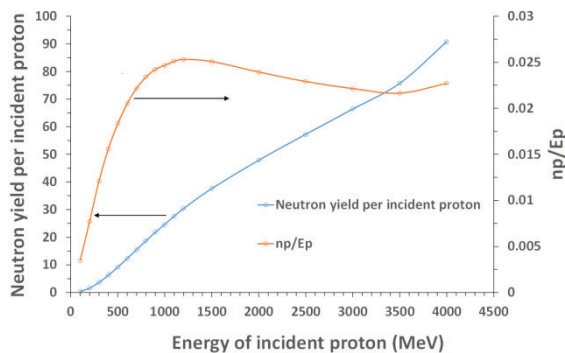


Figure 2: Neutron multiplicity np , and neutron yield per unit energy of the incident proton (np/E_p) as a function of incident proton energy, based on calculation using MCNPX code [5].

The advantage of using the linear accelerator is its directness in increasing the proton energy and beam power. This is particularly so in the superconducting linear accelerator. The superconducting linear accelerator seems to be the only viable accelerator for producing even 100 MW beam power which may be required in the future for in-

dustrial scale power generation. The superconducting linear accelerator has no theoretical limitation put on the energy and power of the accelerator. The disadvantage of using the linear accelerator is its high cost in construction and maintenance, and this is particularly so in Korea where land costs high. A typical GeV-scale linear accelerator is longer than 300 m.

By contrast, raising cyclotron energy is difficult. However, note that the highest beam power in the world is delivered by the 590 MeV cyclotron at Paul Scherrer Institute (PSI), Switzerland which boasts 1.3 MW beam power. This cyclotron has a plan to be upgraded to 1.8 MW [6]. And, higher proton energy and higher power cyclotrons have been proposed such as an 800 MeV and 2.4 MW cyclotron [7] or a 1 GeV and 10 MW cyclotron [8]. Authors of this article will design a cyclotron for ADS in the energy range of 0.5~1.0 GeV and beam power range of 2 ± 0.5 MW. Note that the PSI cyclotron can certainly take responsibility for the first stage of demonstrating nuclear transmutation, and a CW cyclotron with the energy and beam power of PSI cyclotron can be used for industrial transmutation by forming a cyclotron complex of 5-6 identical cyclotrons. This multi-beam ADS scheme, discussed in [9], can be not only economical but also realizable with current technology.

Linear accelerators may be the ultimate ADS accelerator to be used in the future, but cyclotrons can certainly be used for transmutation demonstration and possibly for the industrial scale transmutation.

Multi-beam Scheme

As far as accelerator stability is concerned, using several accelerators is both advantageous and disadvantageous. To explain this, suppose a fictitious accelerator complex of 5 identical accelerators (e.g., cyclotrons).

Suppose also that $p \ll 1$ is the accelerator trip probability at each instant. Note that the probability that all 5 cyclotrons are in trip will be p^5 , which is much smaller than p depending upon how small p is. Hence, the probability of zero proton flux is much lower with several accelerators than with only one high power accelerator, and there will almost always be a few accelerators operational. On the other hand, the probability that all 5 accelerators are operational (i.e., the probability of full proton power) is $(1 - p)^5$, which is also lower than $(1 - p)$, the probability of full proton power when only one accelerator is used, but not much lower because $(1 - p)$ is not substantially lower than 1. That is, the probability of full proton power is lower with several accelerators than with an accelerator, but not substantially. Hence, using several small accelerators, you can always get proton beam but the proton power may sometimes be lower than with one big accelerator.

CONCLUSION

Cyclotrons can be used for ADS transmutation demonstration or possibly even for the industrial scale transmutation. A cyclotron complex several equivalent cyclotrons may have potential for ADS not only because of the added beam power but because of the stability issue.

ACKNOWLEDGEMENT

Authors thank Mr. Dong-Hyun Kim and Dr Mokhtari Oranj for their help in running MCNPX.

REFERENCES

- [1] K. D. Tolstov, "Some aspects of accelerator breeding", Joint Institute for Nuclear Research, Dubna, Russia, Preprint 18 - 89 - 778, 1989.
- [2] C. D. Bowman et al. (1992, Aug.). "Nuclear energy generation and waste transmutation using an accelerator-driven intense thermal neutron source", *Nucl. Instr. Meth. A*, vol. 320, pp. 336-367, 1992.
- [3] F. Carminati, R. Klapisch, J. P. Revol, C. Roche, J. A. Rubio, and C. Rubbia, "An energy amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator", CERN, Geneva, Switzerland, Preprint, CERN/AT/93-47-ET, 1993.
- [4] H. Ait Abderrahim et al., "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production", ADS White Paper, Department of Energy, USA, Sep. 2010.
- [5] J. S. Hendricks, et al., "MCNPX, VERSION 2.7.0.", Report LA-CP-11-00438, Los Alamos National Laboratory, Los Alamos, NM, USA, 2011.
- [6] M. Seidel and P. A. Schmelzbach, "Upgrade of the PSI cyclotron facility to 1.8 MW", in *Proc. of 18th Inter. Conf. on Cyclotrons and Their Applications*, Giardini Naxos, Italy, October 2007, pp. 157-162.
- [7] F. Meot, T. Roser, W. Weng, and L. Calabretta, "MW-Class 800 MeV/n H_2^+ SC-Cyclotron for ADS Application, Design Study and Goals", in *Proc. of 3rd Int. Particle Accelerator Conference (IPAC'12)*, New Orleans, Louisiana, USA, May 2012, paper THPPR064, pp. 4121-4123.
- [8] Th. Stambach et al., "The feasibility of high power cyclotrons", *Nucl. Instr. Meth. B*, vol. 113, pp. 1-7, 1996.
- [9] W. T. Weng, H. Ludewig, D. Raparia, D. Trobjevic, M. Todosow, P. McIntyre, and A. Sattarov, "Comparison of Accelerator Technologies for Use in ADSS", in *Proc. of 2011 Particle Accelerator Conference*, New York, USA, March 2011, paper MOOBN3, pp. 4-6.