Efficiency of an LBE spallation target in an accelerator-driven molten salt subcritical reactor

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1. Introduction

An Accelerator-Driven System (ADS)[1] combined with a subcritical Molten Salt Reactor (MSR) is a type of hybrid reactor originally designed to breed uranium from thorium or to incinerate long-lived minor actinides in nuclear wastes. In an MSR, the salt material is used not only as a nuclear fuel but also as a primary coolant. In addition, this material is used as a target for inducing spallation neutrons in most AD-MSR concepts.

A subcritical reactor cannot sustain fission chain reactions, and therefore needs an external neutron source. External neutrons are usually produced by a high power accelerator. A high energy proton beam impinges on a heavy metal target to induce spallation reactions and produces neutrons. Accordingly, a reliable proton accelerator is needed to feed the source neutrons. As ADSs have been criticized for requiring high power accelerators, minimization of beam power is an important aspect of ADS design. A primary concern associated with ADS development is stable high-power accelerators. We therefore studied the neutron source efficiencies of an AD-MSR involving chloride fuels by including a Pb-Bi eutectic (LBE) spallation target.

1.1. Source efficiency and energy gain

Optimization of the accelerator beam power amplification (Gain) in an ADS is related to two types of source efficiencies. They are called a neutron source efficiency(φ^*) and proton source efficiency(ψ^*)[2]. These quantities are useful in determining the effect of a spallation target in an AD-MSR system.

Proton source efficiency refers to the number of fission neutrons generated by a source proton. It is independent of the definition of the external neutron source. The proton source efficiency(ψ^*) can be expressed through the number of fissions(f_p) per source proton as

$$\psi^* = -\rho\,\bar{\nu}\,f_p, \quad (1)$$

where ρ is the reactivity of the reactor system and $\bar{\nu}$ is the average total number of fission neutrons produced per fission. Normally, the reactivity ρ of a subcritical system is determined by considering the safety of the reactor, and ν is nearly constant. Thus, maximizing f_p can maximize the proton source efficiency.

When the proton source efficiency is optimized, a required beam current for a certain subcritical reactor power can be determined by

$$i_p = \frac{eP}{f_p\,\overline{E_f}} = -\rho\,\bar{\nu}\,\frac{eP}{\psi^*\,\overline{E_f}}, \quad (2)$$

where P is the reactor thermal power E_f is the average recoverable energy per fission. Finally, the energy gain can be expressed through the proton source efficiency as

$$G = f_p\,\frac{\overline{E_f}}{E_p} = -\psi^*\,\frac{\overline{E_f}}{\rho\,\bar{\nu}\,E_p}, \quad (3)$$

where E_p is the incident proton energy.

2. Modeling and Methods

2.1. Molten salt fuels

The fuel material considered in this work is based on sodium chloride with U/Pu. This fuel cycle is considered important for future applications of nuclear energy. With regard to long-term sustainability.

	LBE target	*Molten salt fuel [3]*
Composition	PbBe 44.5-55.5 (wt.%)	$NaCl$-UCl_3-$PuCl_3$ 55-38-7 (mol. %)
Atomic number > 80 (Atom %)	100	15.51
Temperature (K)	700	900
Density (g/cm^3)	10.169	3.6

Table I : Compositions, temperatures and densities of the molten salt fuel material and those of LBE target considered in this work.

Table I presents the molten salt fuel composition and target material used in this work. A spallation target with an LBE was implemented to increase the neutron production in the reactor. This LBE was extensively studied at PSI (MEGAPIE)[4] and is well known as a candidate material for a MW power target. The LBE can induce a high neutron production because of its high atomic fraction of heavy elements in comparison with molten salt fuels.

2.2. Reactor Modeling

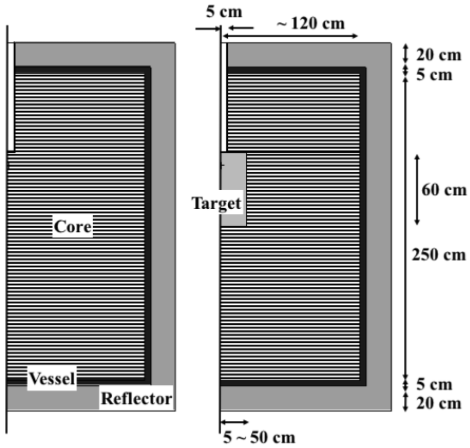

Fig. 1. Schematic diagrams of reactor models considered here. The left one shows an AD-MSR without a spallation target and the right one shows an AD-MSR with an LBE target.

To evaluate the spallation target effect, simple cylindrical reactor models with or without a target were assumed, as shown in Fig. 1. The core height is fixed as 250 cm, and the core radius is approximately 120 cm. The thickness of the vessel is 5 cm, and the vessel is made of Hastelloy-N as was used for MSRE. The thickness of the lead reflector is 20 cm. The accelerator-beam line tube is made of Hastelloy-N with a 1 cm thickness and outer radius of 10 cm. The beam line extended to 65 cm below the top of the reactor core. The LBE spallation target length is 60 cm.

2.3. Monte Carlo calculations

The Monte Carlo code MCNP6.1[5] was used for all the calculations. The MCNP6.1 is a new version of MCNP by merging MCNP5 and MCNPX code. In addition, the INCL physics model for nucleons and pions coupled with the ALBA evaporation model was used. The evaluated nuclear data library ENDF/B-VII.1 was used for the neutron energies below 20 MeV.

3. Results

3.1. Proton source efficiency

The proton source efficiency (ψ^*) has been studied for different molten salt fuels, with or without an LBE target by treating the target radius (R_T) as a variable parameter. The proton efficiency is defined as the total number of fission neutrons produced in a system by each source proton, and is thus a good indicator of the optimization of an ADS combined with a spallation target.

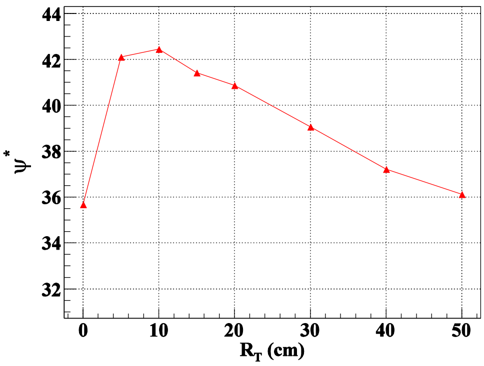

Fig. 2 The proton source efficiencies (ψ^*) as a function of the target radii (R_T) when the incident proton is 1 GeV. The zero radius means the absence of LBE target.

The proton efficiency for the molten salt fuel as a function of the target radii is shown in Fig. 2. The proton efficiency increases significantly when the LBE target is adopted. (Note that there is no LBE target at a radius of zero.) The maximum proton source efficiency is achieved at ~ 10 cm. When the target radius is increased over 10 ~ 20 cm, the proton source efficiencies decrease slightly. It is expected because the ratio of the number of neutrons in the target system to that in the reactor core increases as R_T increases.

3.2. Beam current and Gain

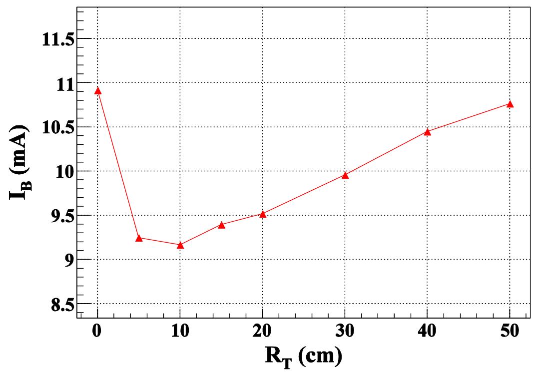

Fig. 3. The proton beam current required for a 500 MW_t subcritical reactor as a function of the spallation target radius.

The proton beam current (I_B) required for a 500 MWt power reactor have been estimated and is shown in Fig. 3. We assumed a proton energy of 1 GeV. When the reactor power and the reactivity are fixed, the beam current is proportional to $1/\psi^*$ as shown in Eq. 2. If the target radius is chosen so that ψ^* becomes maximum, the beam current can be minimized. The current required for a target radius of 10 cm is 84 % of that required without a target. If the radius increases further to 50 cm, the current required increases to almost 99 % of that without the target system. The required beam power is about 9.2 MW for a 500 MW_t reactor. If k_{eff} is changed from 0.95 to 0.98, then the beam power can be significantly further reduced.

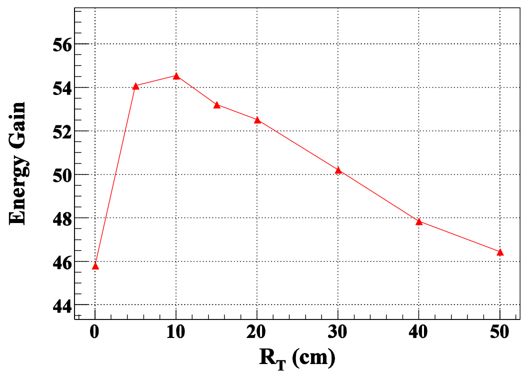

Fig. 4. The beam power amplification (energy gain) as a function of the target radius

An ADS reactor generates energy by fission and it feeds back part of the generated energy to be used for accelerator operation. The energy gain is defined by the generated reactor power over the accelerator beam power. The reference reactor model has a power of 500 MWt and the proton energy is 1 GeV, and thus the energy gain can be optimized by reducing the beam current. Fig. 4 shows that the maximum gain is approximately 55 for a 10 cm radius. It is inverse of the beam currents shown in Fig. 3. Thus, the increase in the gain by the presence of an LBE target is 1.2 times for Type 2, in comparison with the absence of a target.

4. Conclusion

The proton source efficiency and the accelerator beam power required have been studied for an AD-MSR. Adoption of an LBE spallation target induces an increase in proton source efficiencies in comparison to the case without a spallation target. Thus the presence of an efficient spallation target is useful in the reduction of the beam power of an accelerator. Almost 16 % of the beam power can be reduced in comparison to the case without the target for NaCl-U/Pu fuel. The beam power amplifications increase by for NaCl-U/Pu in comparison with the no target AD-MSR. Although the spallation target is useful in the reduction of the accelerator beam power, it might possibly increase the system complexity and increase the construction and management costs. Such economic considerations will require further studies.

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