

J-PARC Transmutation Experimental Facility Programme

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Abstract

Since the Fukushima accident, nuclear transmutation is considered as an option for waste management. Japan Atomic Energy Agency proposes the transmutation of minor actinides (MA) in accelerator-driven system (ADS) using lead-bismuth eutectic alloy (LBE) as a spallation target and a coolant of subcritical core. To obtain the data required for ADS design, we plan the building of a transmutation experimental facility (TEF) is planned within the J-PARC project. TEF consists of an ADS target test facility (TEF-T), which will be installed 400 MeV-250 kW LBE spallation target for material irradiations, and a transmutation physics experimental facility (TEF-P), which set up a fast critical/subcritical assembly driven by low power proton beam with MA fuel to study ADS neutronics. At TEF-T, various research plans to use emitted neutrons from LBE target are discussed. The paper summarises a roadmap to establish the ADS transmutor and latest design activities for TEF construction.

Introduction

After to the great East Japan Earthquake and ensuing tsunami, the Fukushima-Daiichi nuclear power plant was seriously damaged and many nearby residents are still forced to be evacuated. Following the accident, the public interest in nuclear waste management has increased. The Cabinet of Japan decided on a new strategic energy policy in April 2014 to promote “a decreasing the radiation dose remaining in radioactive waste over a long period of time and enhancing the safety of processing and disposal of radioactive waste, including nuclear transmutation technology using fast reactors and accelerators”.

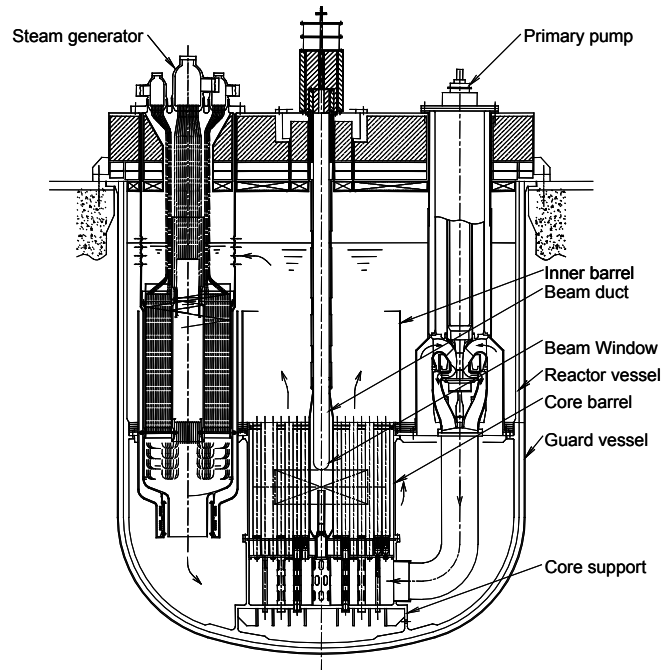
Japan Atomic Energy Agency (JAEA) precedes R&Ds to reduce the radiological hazard of HLWs by partitioning and transmutation (P&T) technology [1]. As for the transmutation of radiological waste, the accelerator-driven system (ADS), which combines a high intensity proton accelerator and a fast subcritical core, is discussed from a viewpoint of transmutation efficiency and compatibility with a power generation cycle. Within the framework of the J-PARC project, JAEA is preparing to construct the transmutation experimental facility (TEF) to study minor actinides (MA) transmutation in both MA-loaded fast reactors and ADS [2]. TEF is located at the end of LINAC, which is also important components to be developed for future ADS, and shares the proton beam with other experimental facilities in J-PARC. R&Ds for important technologies required to build the TEF are also performed, such as application methods of MA bearing fuel in the critical/subcritical assembly, spallation product removal method especially for the polonium, and so on. The objectives, the latest design concept, and key technologies to construct TEF are described in this paper.

JAEA proposed ADS

JAEA's reference design of ADS is a tank-type subcritical reactor, where lead-bismuth eutectic (LBE) alloy is used as both the primary coolant and the spallation target (Figure 1). The spallation target region is located at a central part of the core. In the target region, LBE is flowing from the core bottom along to the dedicated wrapper tube and flow guide. A proton beam with about 1.5 GeV-30 MW proton beam is

supplied from the accelerator to operate the ADS. The rated power, which is controlled by adjusting the injected proton beam current of the accelerator, is $800 \text{ MW}_{\text{th}}$.

Figure 1: ADS for transmutation of MA proposed by JAEA



A tank-type system is adopted to eliminate the necessity of heavy primary piping. All primary components, including two primary pumps and four steam generators, are set up in the reactor vessel. The heat generated in the target and the core is removed by forced convection of the primary LBE, and transferred through the steam generators to a secondary water/steam system for power conversion. The inlet and outlet coolant temperatures were set to 300 and 407°C respectively, which are low enough to prevent material corrosion by LBE.

Nitride fuel was selected as a fuel for dedicated MA transmutation, suitable for reprocessing for ADS. To minimise the burnup reactivity change and the power peaking, the fuel region is divided into several zones with a different fuel composition. About 2 500 kg of MA is loaded in the core and 10% of them can be transmuted annually. The maximum k_{eff} during whole burnup cycles was set to 0.97. The burnup swing in whole cycles is about 3% $\Delta k/k$.

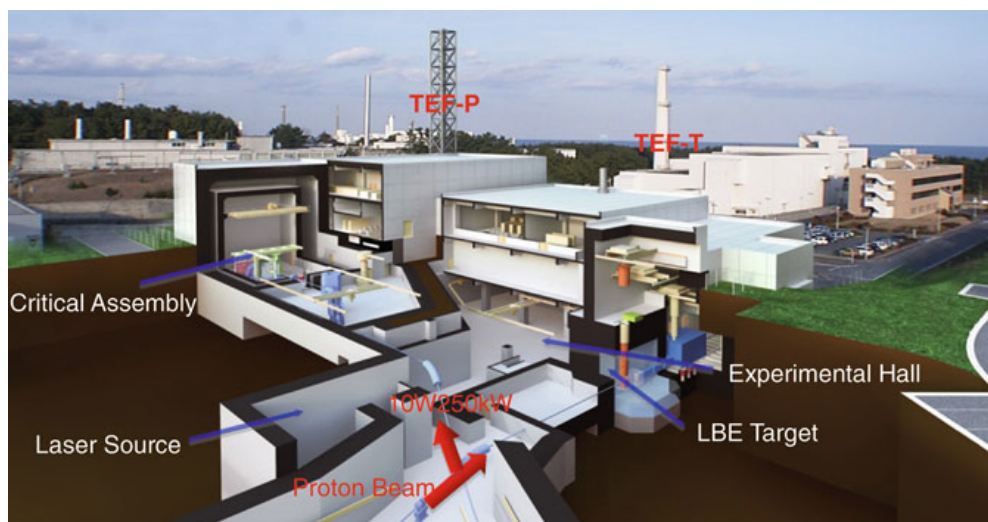
Transmutation experimental facility

As shown in Figure 2, TEF consists of two individual buildings: ADS target test facility (TEF-T) [3] and transmutation physics experimental facility (TEF-P) [4].

The two buildings are connected by a beam transport line with a low power beam extraction mechanism using a laser beam. TEF-T is planned as a material irradiation facility which can accept a maximum 400 MeV-250 kW proton beam on a LBE spallation target. It can also be used for various purposes such as measurement of the reaction cross-sections of MA and structural materials, semiconductor development, etc. TEF-P is a facility with critical/subcritical assembly to study neutronics and controllability of ADS. Using these two facilities, basic physical properties of subcritical system and engineering tests of spallation target will be studied. R&Ds for several important technologies required to build the facilities are also performed, such as laser charge exchange technique to extract a very low power

beam for reactor physics experiments, a remote handling method to load MA bearing fuel into the critical/subcritical assembly, the spallation and activation product removal method especially for the polonium, and so on.

Figure 2: Transmutation experimental facility



Design studies for TEF-T

The main purpose of TEF-T is to obtain the data to evaluate the actual lifetime of beam window. TEF-T mainly consists of a spallation target, a cooling circuit, and hot cells to handle the spent target and irradiation test pieces. A proton beam current density of $20 \mu\text{A}/\text{cm}^2$, which is almost the same as the future ADS design, was adopted as a reference. The irradiation performance of the reference case was evaluated around 8 DPA/yr by 400 MeV-250 kW beam irradiation. This value is about 20% of DPA considered in the beam window of JAEA-ADS. Further optimisation of the target design to increase DPA is underway.

To operate LBE loop with high temperature condition above 400°C , the mockup of the primary circuit is under manufacturing and will be operated to develop the technology for target loop maintenance. The measurement and operation devices of the oxygen concentration in LBE are attached to suppress the corrosion by LBE. Remote handling techniques for maintenance of irradiated LBE loop is also under development including replacement of spent target and other loop components with preheating systems.

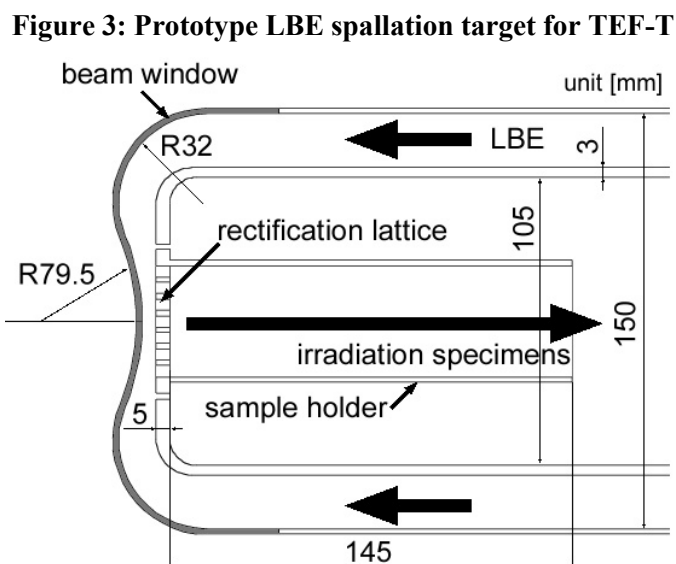
When LBE is irradiated by high-energy protons or neutrons, polonium isotopes will be accumulated and they should be carefully controlled. The removal method of polonium was studied for the design of exhaust circuit of TEF-T. An equilibrium vaporisation test of polonium from liquid Pb-Bi was performed and equilibrium vaporisation characteristics were measured by transpiration method with LBE, which was irradiated at the JAEA/JMTR [5]. It was shown that at the low temperature around 450°C , considered as a standard operational condition of TEF-T and future ADS, most accumulated polonium remained in LBE as a chemical compound with Pb or Bi which is much harder to evaporate than elemental polonium. Another experiment to recover evaporated polonium in the exhaust circuit was performed [6]. LBE samples were irradiated at the JAEA/JRR-4 and were heated in a special vacuum vessel up to 690°C . By adopting the multi-layered filter, which consists of the stainless steel meshes with two different finenesses, escaping polonium can be decreased to 1/400.

Design of high power spallation target for TEF-T

A high power spallation target, which will be mainly used for material irradiation of candidate materials for a beam window of full-scale ADS, is an essential issue to realise a TEF-T. To set up the beam parameters, future ADS concepts are taken into account. In the reference case of the target, proton beam current density of $20 \mu\text{A}/\text{cm}^2$, which equals to the maximum beam current density of JAEA proposed $800 \text{ MW}_{\text{th}}$ ADS, was assumed.

To evaluate a feasibility of a designed beam window of TEF target, numerical analysis with a 3D model was performed. The analysis was done by considering a current density and shape of the incident proton beam into the target, and the thermal-fluid behaviour of LBE around the beam window as a function of flow rate and inlet temperature of LBE. The thickness of the beam window is also considered parametrically. After the temperature distribution analysis, structural strength of the beam window is determined to evaluate a soundness of the target.

A concave shape beam window was used for this analysis. The prototype design of the beam window for TEF target system was shown in Figure 3.



The material of beam window would be a type 316 stainless steel as a primary candidate for operation temperature below 450°C . The concave section in the centre part of the target was connected to the convex section in the terminal part, and finally, it was connected to the straight tube. In the analysis, the thickness of beam window was parametrically set from 3 to 2 mm. A straight tube part has coaxially arranged annular and tube type channels. The inner diameters of the outside tube and inside tube were set to 150 mm and 105 mm, respectively. The total length of the analysis region was 600 mm, which corresponds to an effective target depth for 400 MeV proton injection and primary beam suppression. An irradiation sample holder, which was installed in the inner tube, holds irradiation specimens. The size of each specimen was set to $40 \times 145 \times 2$ mm, tentatively. The rectification lattice having the aperture of the plural squares type was installed at the front-end of the sample holder. A slit of 2 mm in width was arranged along the side of the rectification lattice to cool off the sample holder by flowing LBE.

The thermal-fluid behaviour of the target was calculated by the STAR-CD with a detailed three-dimensional model. The quarter-part model was set to tetra metric type and the divided face was set to a reflected image condition in the CFD analysis. In this calculation model, a hexahedral element was used and the total number of the elements was about 220 000. At first, LBE flowed through the annular region

and it joined in the centre of the beam window, and then, turned over and flowed in the inner tube after having passed a rectification lattice and an irradiation sample. In a default condition, the flow rate at the inlet of annulus region was 1 *litre/sec*, and this was equivalent to the flow velocity of 0.125 m/sec. LBE flow is easy to form a complicated turbulent flow. Therefore, the standard k- ϵ model for high Re number type was used for a turbulence model. A heat deposition given by the incident proton beam, which was analysed by the hadronic cascade code PHITS [7], was used for CFD analysis. The internal pressure to the inside of the beam window was set to 0.3 MPa in consideration of the flowing LBE and the cover gas. On the outer wall of the beam window and the border of the atmosphere, release of the radiant heat was considered. In this analysis, the embrittlement of the structural materials by the irradiation was not considered. Based on the results provided by CFD analysis, the analysis to verify the feasibility of the beam window was performed by ABAQUS code, the computational code for the finite element method. The operating conditions for the first stage of material irradiation in TEF were decided by a result of the analysis on each condition.

The CFD analyses were performed by changing flow rates. The maximum velocity of LBE was confirmed at the rectification lattice part and was approximately 1.2 m/sec in the case of the inlet flow rate of 1 *litre/sec*. When the inlet flow rate increases much higher value, the maximum velocity in the target increases more and cannot be applied because the fluid vibration by LBE was concerned as well as the acceleration of erosion and/or corrosion of the material. So, the design limitation of this target is set to 2 m/sec.

The temperature profile on the beam window, by changing the thickness of the window, was performed with 1 *litre/sec* of LBE flow. The maximum temperature is 544°C in the case of 3mm thick stainless steel window. In the case of 2 mm thick window, the peak temperature decreases to 477°C. The temperature differences between outside and inside, at the centre of the window were 65°C and 37°C in the case of 3 mm thick window and 2 mm thick window, respectively. From these results, it was disclosed that a condition of 2 mm was desirable for design parameter.

The temperature and thermal stress for the steady state was estimated using ABAQUS code. In the ABAQUS code, only a beam window was modelled as the cylinder-slab geometry. The model consisted of 1 896 4-node axial-symmetric elements. For the analysis, results by STAR-CD were converted to the temperature of each node. From the analysis result, the stress strength reached the maximum value of 190 MPa on the outer surface of the beam window. When the maximum temperature of the beam window is adapted to 470°C from the result of STAR-CD, these stresses were lower than the tolerance level of the stress strength of the materials for a fast reactor, which sets less than 294 MPa, and hence, the feasibility of a designed beam window was confirmed.

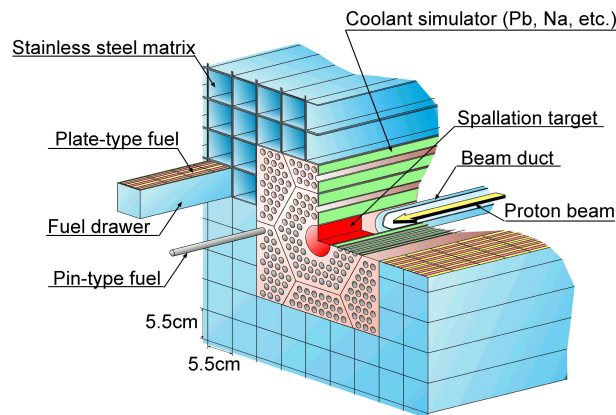
Outline of TEF-P

Several neutronic experiments for ADS have been performed in both Europe [8,9] and Japan. In Japan, subcritical experiments were performed at the Fast Critical Assembly (FCA) in JAEA/Tokai with a ^{252}Cf neutron source and a DT neutron source. Subcritical experiments with a thermal subcritical core driven by 100 MeV protons are being performed at Kyoto University Research Reactor Institute. There have been, however, no subcritical experiments combined with a spallation source installed inside the subcritical fast-neutron core. The purposes to build TEF-P are (1) Study on reactor physics aspects of the subcritical core driven by a spallation source, (2) Demonstration of the controllability of the subcritical core including a power control by the proton beam power adjustment, and (3) Investigation of the transmutation performance of the subcritical core using certain amount of MA and LLFP.

TEF-P is designed with referring to FCA as shown in Figure 4, the horizontal table-split type critical assembly with a rectangular lattice matrix, to utilise operation experiences and existing experimental data of FCA. In this concept, the plate-type fuel for FCA with various simulation materials such as lead and

sodium for coolant, tungsten for solid target, ZrH for moderator, B₄C for absorber, and AlN for simulating nitride fuel, can be commonly used at TEF-P. The proton beam will be introduced horizontally at the centre of the fixed half assembly and various kinds of spallation targets can be installed at various axial position of the radial centre of the subcritical core.

Figure 4: TEF-P critical/subcritical assembly with Pin-type MA fuel



In the experiment with a proton beam, the effective multiplication factor (k_{eff}) of the assembly will be kept less than 0.98. One proton with energy of 400 MeV produces tens of neutrons by the spallation reaction with a heavy metal target such as lead. The 10 W proton beam corresponds to the source strength of 10^{12} neutrons/sec, which have enough strength to measure the neutronic characteristics.

From the viewpoint of the neutronic analyses for subcritical systems, it is desirable to make the core critical in order to ensure the quality of experimental data of the subcriticality and the reactivity worth. So, the subcritical core can make critical condition when the proton beam is suppressed.

As for the transmutation characteristics of MA and LLFP, fission chambers and activation foils are used to measure the transmutation rates. The cross section data of MA and LLFP for high energy region (up to several hundreds MeV) can be measured by the Time of Flight (TOF) technique with the proton beam of about 1ns pulse width which can be delivered by a special beam extraction device using an Nd:YAG laser source [10]. Several kinds of MA and LLFP samples are also prepared to measure their reactivity worth, which is important for the integral validation of cross section data.

One of the main purposes of TEF-P is to perform integral experiments using MA because the present accuracy of nuclear data is not sufficient for ADS design [11]. To improve the accuracy of the nuclear data especially for MA, both the differential experiments and the integral experiments are necessary, while the integral experiments on MA are more difficult than those on the major actinides. The effectiveness of MA-loaded experiments with a certain amount of MA was discussed [12]. In the procedure, data of virtual experiments using TEF-P are determined to estimate the reduction of the errors in the effective cross sections. The data by TEF-P was assumed to be equal to the calculation result, and experimental error was taken from the past experiments in FCA. By using a certain amount of MA, which is about order of kg, typical improvement was observed.

When the highly MA contained fuel is used with critical assembly, remote handling operation and constant heat removal should be required. The development of the technologies to handle the high MA contained fuel with effective heat removal, during storage, transport, and loading of the MA fuel, is underway.

Conclusion

JAEA has been promoting various R&Ds on ADS to reduce the burden of spent nuclear fuels and high-level radioactive wastes. For the basic experimental studies necessary for future ADS design and construction, a plan to build Transmutation Experimental Facility has been proposed. The design optimisation of TEF-T to improve irradiation performance, including R&D for polonium management, was carried out. The effectiveness of TEF-P experiments using a certain amount of MA was assessed quantitatively.

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