J-PARC Transmutation Experimental Facility Program*)

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The partitioning and transmutation (P-T) technology have promising potential for volume reduction and mitigation of degree of harmfulness of high-level radioactive waste. JAEA is promoting the development of the P-T technology by using an accelerator-driven system (ADS). To facilitate the development, JAEA has a plan to construct Transmutation Experimental Facility (TEF) as one of the experimental facilities of Japan Proton Accelerator Research Complex (J-PARC). TEF consists of two individual facilities: ADS Target Test Facility (TEF-T) and Transmutation Physics Experimental Facility (TEF-P). TEF-T equips with a liquid lead-bismuth spallation target bombarded by a 400 MeV - 250 kW proton beam in which candidate proton beam window materials of the ADS are to be irradiated. TEF-P equips with a critical/subcritical assembly to investigate physical and dynamic properties of the accelerator-driven system by using a low power (10 W) proton beam. Nuclear fuels containing minor actinide are to be loaded to the assembly. Comprehensive R&D activities to support the TEF construction have been conducted, and a technical design report of TEF-T was issued in March 2017.

Keywords: accelerator driven system, nuclear transmutation, J-PARC, Transmutation Experimental Facility, ADS Target Test Facility, Transmutation Physics Experimental Facility, lead bismuth eutectic

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1. Introduction

One of the most critical issues for peaceful uses of nuclear energy is that procedure to dispose of high-level radioactive waste (HLW) has not been established. This issue, as well as the accident at Fukushima Daiichi Nuclear Power Plant in 2011 significantly restricts resuming and operation of nuclear power plants in Japan. For this reason, nuclear energy has been replaced with fossil energy and renewable energy after the accident resulting in the increase in electricity prices and emission of carbon dioxide. Even if we will take the nuclear power phase-out scenario, 17,000 tons of spent nuclear fuel has been accumulated in Japan.

According to the Government of Japan's basic policy, HLW generated by reprocessing spent nuclear fuel is to be solidified to a stable form, stored for 30 to 50 years for cooling, and then disposed of in a deep geological space. However, selection procedure of a candidate geological repository site has not been going on smoothly. Meanwhile, the public has recognized the problem of radioactive waste disposal broadly after the Fukushima accident. Under these situations, the Japanese cabinet decided "the Strategic Energy Plan" on Apr. 11, 2014. It was stated in the plan that "the Government of Japan will promote technology development on volume reduction and mitigation of degree of harmfulness of radioactive waste".

The HLW contains minor actinides (MA) and fission products (FP) having very long half-lives of more than thousands of years. The deep geological disposal has to secure firm confinement of these nuclides for a very long time. One of the ideas to solve this problem is introducing the partitioning and transmutation (P-T) technology. Radioactive nuclides contained in HLW are partitioned according to their half-lives and reuse purposes, and MA and long-lived FP (LLFP) are transmuted to short-lived or stable nuclides. If the P-T technology would be realized in the future, the considerable benefit could be expected; the long-term radiological risk could be reduced by substantial reduction of potential toxicity of HLW, the geological repository site could be used more efficiently, and furthermore, a part of radioactive waste such as platinum group elements could be reused. In addition, when public understanding of nuclear energy would be promoted and nuclear energy would be utilized stably, it could be said that the P-T technology could contribute to low-cost and stable energy supply, and also reduction of carbon dioxide emission to conserve the global environment.

To transmute radioactive nuclides, accelerator-driven system (ADS) is under development in the world, such as an ADS concept [1] developed by Japan Atomic Energy Agency (JAEA), the MYRRHA project [2] in Belgium and the Chinese ADS program [3]. Figure 1 shows a typical example of ADS. A high power proton beam of 30 MW is accelerated by a superconducting linac and injected to a subcritical core. The protons induce spallation reactions with a target material, the lead-bismuth eutectic (LBE) alloy in this case, and produces many neutrons of $10^{18} \sim 10^{19}$ n/s. The neutrons then enter into a reactor core surrounding the

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target and induce fission chain reactions in MA-containing fuel cooled by LBE. The proton beam power of 30 MW is amplified to 800 MW thermal power, and about 270 MW of electric power is generated. A part of the electricity, 100 MW, is fed to drive the accelerator, and the rest of electricity, 170 MW, is provided to an electric power grid. Hence energy balance of the ADS can be positive. The ADS can be used for transmutation of radioactive nuclides and electricity production simultaneously.

A commercial ADS design proposed by JAEA is shown in Fig. 2. In the ADS 2.5 tons of MA are loaded, and 10% of the MA are transmuted per year. This amount of MA corresponds to amount of MA generated in 10 units of light water reactors (LWRs) per year. Thus one unit of the ADS can support 10 LWRs.

To develop the ADS there are a variety of challenges on high power accelerators, a fuel cycle dedicated to ADS, reactor structure and reactor physics for MA bearing cores as indicated in Fig. 2. To undertake challenges on reactor structure and reactor physics, we are proposing to construct the Transmutation Experimental Facility (TEF) as one of the experimental facilities of the Japan Proton Accelerator Research Complex (J-PARC). This paper deals with outlines of TEF with recent progress in research and development (R&D) and design activities.

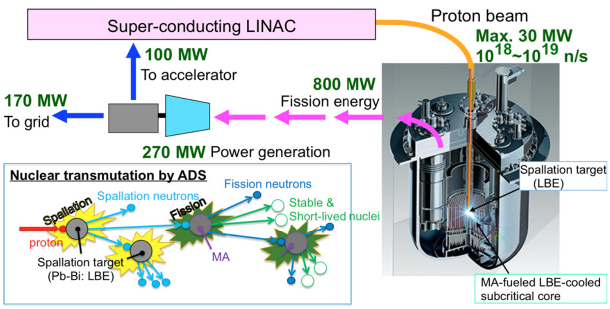

Fig. 1 A typical example of ADS.

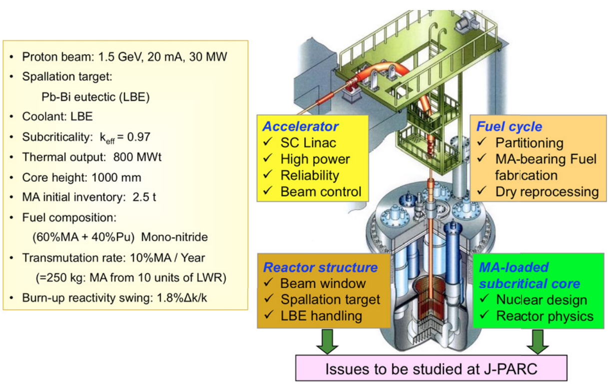

Fig. 2 A commercial ADS design proposed by JAEA with major parameters.

2. Outline of TEF

J-PARC is in operation with three accelerators, i.e., Linac (400 MeV), Rapid Cycling Synchrotron (3 GeV) and Main Ring (30 GeV), and three experimental facilities, i.e., Materials and Life Science Experimental Facility, Hadron Experimental Facility and Neutrino Experimental Facility. TEF (see Fig. 3) has been assigned as the fourth experimental facility of J-PARC since the beginning of the J-PARC project. TEF consists of Transmutation Physics Experimental Facility (TEF-P) and ADS Target Test Facility (TEF-T) where the last characters "P" and "T" denote physics and target, respectively. The Linac is currently being operated with a repetition rate of 25 Hz. When TEF will be constructed, the repetition rate will be doubled to 50 Hz, and proton pulses of 25 Hz out of 50 Hz will be delivered to the existing experimental facilities while the rest of 25 Hz will be provided to TEF. Recent design studies for TEF are found in the literature [4–8].

2.1 TEF-P

TEF-P is a critical assembly, i.e., a zero-power reactor, as illustrated in Fig. 4. A proton beam of 400 MeV is introduced to the reactor core in a sub-critical state to drive it by a spallation neutron source. By replacing central partial matrix tubes with pin-type assembly, MA fuel can be used with cooling and remote handling. Table 1 summarizes TEF-P's major parameters. Reactor physics and nuclear data of transmutation systems including ADS and fast reactors are to be studied. TEF-P is a unique experimental facility in the world on the two points; (1) the reactor core in which MA bearing fuel in kg order can be loaded, and (2) the fast spectrum sub-critical core driven by a spallation neutron source.

Since proton beam power of 10 W at a maximum is enough for experiments to be conducted in TEF-P, a weak proton beam below 10 W is picked up from a high intensity proton beam of 250 kW going to TEF-T by a laser charge exchange (LCE) method [9], and is transported to TEF-P.

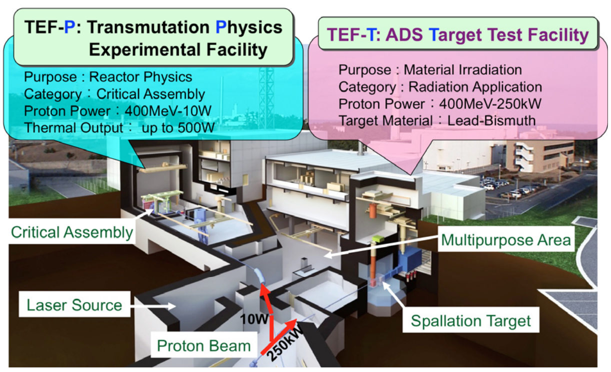

Fig. 3 Conceptual drawing of J-PARC Transmutation Experimental Facility (TEF).

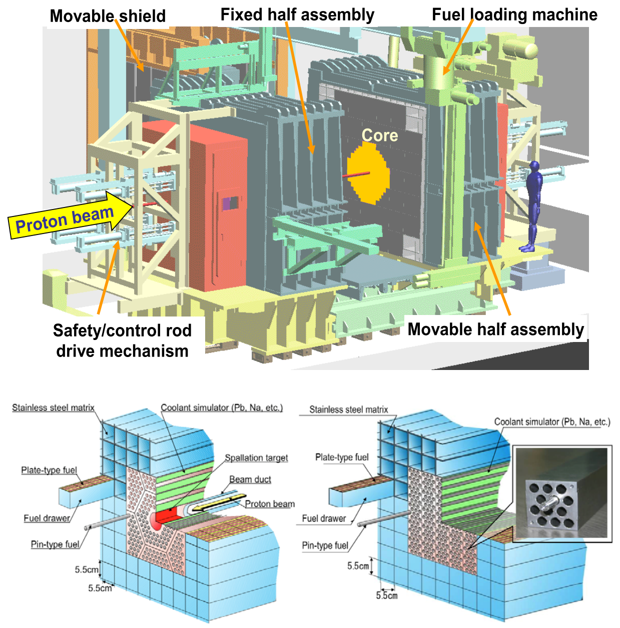

Fig. 4 Schematic view of the critical assembly to be installed in TEF-P.

Table 1 TEF-P's major parameters.

Proton beam	400 MeV, max. 10 W (1.6×10[11] protons/s)
Beam structure	Pulse (repetition rate: 25 Hz, pulse width: 10 ns ~ 500 μs)
Maximum fission power	~500 W (cf. power of the Fast Critical Assembly FCA in JAEA: 2 kW)
Fuel assembly	Horizontal, split-table type Grid tubes: 51×51 (2.8 m (W) × 2.8 m (H) × 2.6 m (D)) Grid tube size: (5 cm × 5 cm: same as FCA)

2.2 TEF-T

As shown in Fig. 5 a vacuum duct is inserted into an ADS's sub-critical core immersed in LBE to introduce a proton beam from an accelerator. An end plate of the duct, i.e., a proton beam window (PBW), is a boundary between high vacuum in the accelerator side and LBE in the reactor core side. The PBW is exposed under very severe circumstances such as pressure difference between the high vacuum and LBE, high temperature around 500°C, corrosion and erosion of materials due to LBE, thermal stress and radiation damage due to the proton beam and spallation neutrons. Since engineering feasibility of the PBW is one of the critical issues for the ADS development, TEF-T is proposed as a materials irradiation facility in which the severe ADS conditions can be simulated. Table 2 summarizes TEF-T's major parameters.

Irradiation sample materials are installed in a target

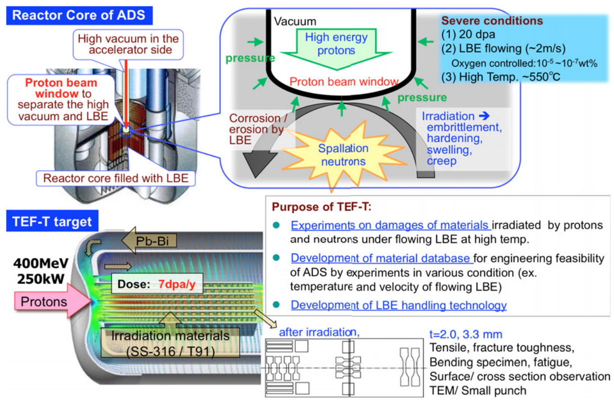

Fig. 5 The proton beam window of ADS under severe circumstances and purposes of TEF-T.

Table 2 TEF-T's major parameters.

Proton beam	400 MeV, 250 kW (3.9×10[15] protons/s)
Beam structure	Pulse (repetition rate: 25 Hz, pulse width: 500 μs)
Beam profile	Gaussian (max. current density: 30 $\mu A/cm^2$)
Target	Liquid lead-bismuth eutectic alloy
Target vessel	Stainless steel SUS316L (for lower T), high-chrome steel T91 (for higher T)

vessel in which LBE is flowing as shown at the bottom left in Fig. 5. A high-power proton beam of 400 MeV - 250 kW is impinged to the target to irradiate the sample materials by the primary protons and spallation neutrons. After the irradiation, the sample materials are taken out from the target vessel. Sample specimens are cut out from the irradiated sample material and served for post-irradiation examination such as tensile test and metallographic observation. Purposes of TEF-T are to study damage of materials under the ADS conditions, to develop a material database for engineering design, and also to develop the LBE handling technology.

TEF-T is also a unique facility in the world because four important ADS conditions for the material testing are realized for the first time; (1) irradiation dose as high as 20 dpa, (2) maximum LBE temperature of 550°C, (3) liquid LBE flowing and (4) controlled oxygen concentration [10] in LBE in a range between 10^{-5} ~ 10^{-7} wt% to suppress materials corrosion.

3. R&D and Design Activities for TEF

Several R&D activities to support the TEF construction are going on [4–9]. Two large LBE loop facilities have been constructed: Integrated Multi-functional MOckup for TEF-T Real-scale TArget Loop "IMMORTAL" and Oxygen-controlled LBE LOop Corrosion tests in HIgh-temperature "OLLOCHI". IMMORTAL reproduces the TEF-T's LBE loop for the demonstration of TEF-T target operation. IMMORTAL is equipped with components such as an electromagnetic pump, a heat exchanger, and an expansion tank as well as instrumentation such as oxygen sensors and an ultrasonic flowmeter. In a commissioning operation, the loop temperature was successfully elevated to 500°C, the maximum operating temperature of TEF-T, and proper circulation of LBE was confirmed. This was achieved by eliminating flange connections that could be a reason for LBE leak in the main LBE loop. Dynamic behavior of heat removal will be tested with simulating heat input due to a proton beam injection by a heater.

On the other hand, the main purpose of OLLOCHI is to obtain material corrosion data under LBE flowing but without irradiation. The material corrosion data are to be compared with those data obtained by TEF-T with irradiation to study irradiation effects on the material corrosion. OLLOCHI equips with three test sections in which sample specimens are installed as well as similar components and instrumentation to IMMORTAL. Upgrading OLLOCHI to add an in-situ stress loading mechanism to samples is underway.

In addition, R&D activities are underway on the following topics;

- control method of oxygen concentration in LBE,
- ultrasonic flowmeter for LBE,
- remote-handling technique to replace TEF-T's target vessel including cutting and re-welding of LBE piping,
- the LCE method [9] to pick up a weak proton beam for TEF-P,
- remote-handling technique to insert/take-out MA containing fuel pins to/from the TEF-P core,
- safety analysis of TEF-P needed for licensing such as assessment temperature increase in the MA loaded core in a case of loss of air cooling, etc.

The basic design of all TEF-T components, such as the LBE target system, target station, post-irradiation examination facilities, waste management systems, proton beam transport system, ancillary facilities, etc. have been made detailed with considering their operation and maintenance procedure. Not only the above-mentioned R&D results but also experience acquired through construction and operation of the existing J-PARC facilities, especially 1-MW spallation neutron source in Materials and Life Science Experimental Facility, are incorporated in the design. The TEF-T building design has been detailed to accommodate all of the TEF-T components as shown in Fig. 6. By compiling these design results a technical design report [11] was issued in March 2017.

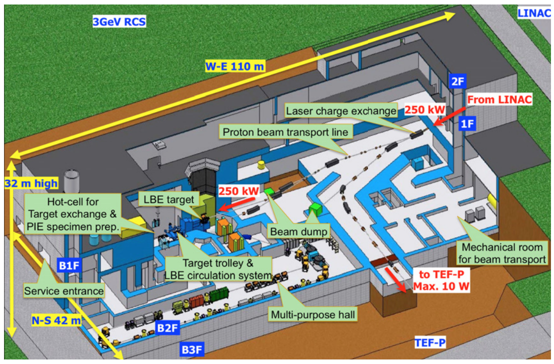

Fig. 6 Cutaway view of TEF-T.

4. Summary

ADS is one of the most beneficial applications of accelerator-based high-power neutron sources. Various R&D activities on ADS development for efficient transmutation of nuclear waste have been implemented in JAEA. To facilitate the development, JAEA has a plan to construct TEF in J-PARC. Comprehensive R&D activities to support the TEF construction have been conducted, and the technical design report of TEF-T was issued in March 2017 to be ready for the construction.

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