CONCEPT OF TRANSMUTATION EXPERIMENTAL FACILITY

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Abstract

Under the framework of the High-intensity Proton Accelerator Project called J-PARC (Japan Proton Accelerator Research Complex), the Japan Atomic Energy Research Institute (JAERI) plans to construct the Transmutation Experimental Facility (TEF). The TEF consists of two facilities: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T). The TEF-P is a critical facility that can accept a 600 MeV, 10 W proton beam. The TEF-T is a material irradiation facility using a 600 MeV, 200 kW proton beam and a Pb-Bi target; however, neutron multiplication by nuclear fuel will not be attempted. This report describes the purpose of the facility, the present status of the conceptual design and the expected experiments to be performed.

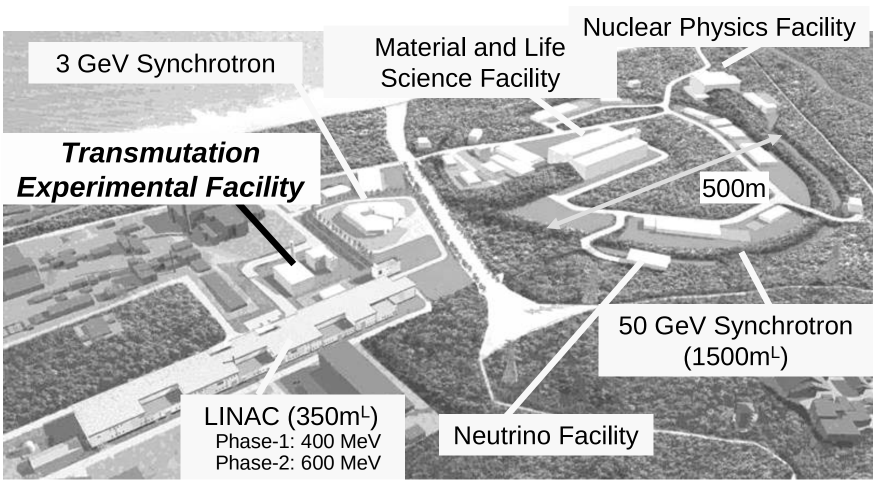
Introduction

To reduce the amount of minor actinide (MA) and long-lived fission products (LLFP) in high-level radioactive waste, the Japan Atomic Energy Research Institute (JAERI) proposed the "double-strata fuel cycle concept", i.e. the dedicated transmutation fuel cycle is established separately from the commercial power generation fuel cycle [1,2]. In the transmutation fuel cycle, nuclear fuel consisting mainly of MA is used to enhance transmutation efficiency. Using such MA fuel, the critical reactor would encounter many difficulties regarding safety and controllability. The accelerator-driven subcritical system (ADS) has potential advantages to manage these difficulties as compared to critical reactors: 1) varying fuel composition is acceptable (within reason) since the small Doppler effect does not seriously affect system safety and 2) a small value of delayed neutron fraction is also acceptable since the margin to prompt critical state and power control by the reactivity adjustment are not necessary. Therefore, the ADS is considered suitable to transmute MA in the transmutation fuel cycle.

The ADS proposed by JAERI is an 800 MWth, nitride fuelled Pb-Bi eutectic (LBE) cooled fast subcritical core driven by a spallation neutron source using an LBE target and 1.5 GeV, 20-30 MW proton accelerator [3]. To realise such a large-scale ADS, some technical issues need to be studied, developed and demonstrated. Issues include, for example, reliability of the accelerator, beam transport system, high-power spallation target technology, integrity of beam window, reactor physics and the controllability of a subcritical system, MA transmutation performance and fuel handling.

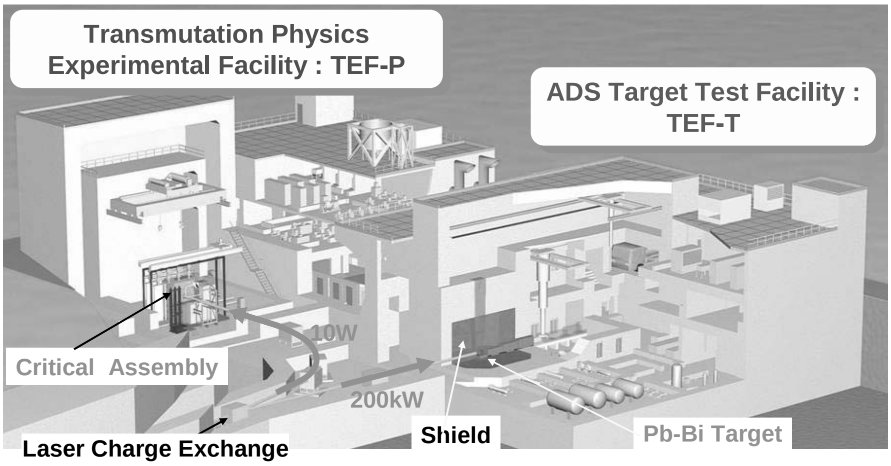
To promote research and development (R&D) for most of the above-mentioned technical issues, JAERI plans to build the Transmutation Experimental Facility (TEF) at Tokai Research Establishment under the framework of the joint project of a high-intensity proton accelerator called J-PARC (Japan Proton Accelerator Research Complex) with the High-energy Accelerator Research Organization (KEK) [4]. Figure 1 shows a site plan of the J-PARC facilities. Phase 1 of J-PARC consists of three accelerators (a 400 MeV linac, a 400 MeV - 3 GeV synchrotron and a 3-50 GeV synchrotron) and three experimental facilities (the Material and Life Science Facility, the Nuclear Physics Facility and the Neutrino Facility). The construction of these Phase 1 facilities is under way and is scheduled to be completed by 2007 (except a portion of the facilities). In Phase 2, construction of the TEF is planned along with an upgrade of the linac from 400 MeV to 600 MeV.

Figure 1. Site plan of the J-PARC facilities



TEF consists of two buildings – the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T) as shown in Figure 2. TEF-P is a zero-power critical facility, which can be operated with a low-power proton beam to investigate reactor physics and ADS controllability. TEF-T is a material irradiation facility, which can accept a maximum 200 kW, 600 MeV proton beam into the spallation target of the LBE. In this paper, the purpose, the present status of the conceptual design and the expected experiments using the facility are reported.

Figure 2. Concept of the Transmutation Experimental Facility (TEF)



Background and purpose of TEF-P

Some experimental research on reactor physics aspects of ADS have been carried out using existing zero-power facilities worldwide. The most systematic is the MUSE program [5] at the Cadarache research centre of CEA (France) where the existing fast critical facility, MASURCA, is connected with a DT (and DD) neutron source called GENEPI. The purpose of the MUSE program is to investigate prediction accuracy of reactor physics parameters in a subcritical core (i.e. power distribution, subcriticality index and source importance in various core configurations). In Japan, basic experiments are underway on JAERI's FCA (fast critical assembly) for the fast neutron subcritical system using a ^{252}Cf neutron source and a DT neutron source [6]. Moreover, at the Kyoto University Critical Assembly (KUCA), an experimental program to connect the thermal neutron subcritical system with a proton accelerator (~150 MeV) is scheduled for a few years from now [7].

On the other hand, many experimental studies have been performed with proton accelerators worldwide to obtain the characteristics of a spallation neutron source using many kinds of target materials such as lead, tungsten and mercury.

However, there has been no experimental work implemented so far that involves research and demonstration of a fast subcritical system combined with a spallation source. Therefore, the main purpose of TEF-P is to research the reactor physics of a subcritical core that is driven by a spallation source using a 600 MeV proton beam. The second purpose is to demonstrate the controllability of a subcritical core; control of reactor power by adjustment of the proton beam current will be attempted in the experimental program. The third purpose is to research the transmutation performance of a subcritical core using a certain amount of MA and LLFP by installing proper shielding, cooling and handling devices.

Specifications of TEF-P

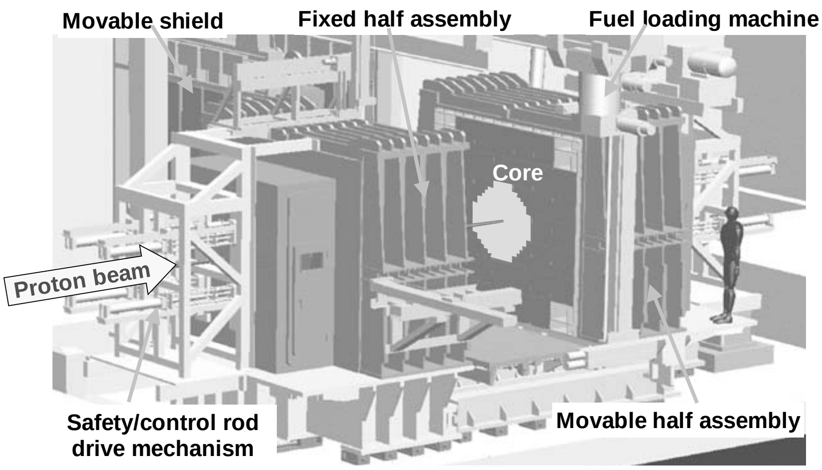
For the above-mentioned purpose, high thermal power is not necessary; a power level of critical experiments (i.e. 100 W) is preferable from the viewpoint of accessibility to the core. Although validation of core thermal feedback effects might be necessary, such experiments can be performed using an electrical heater that simulates reactor power without real fission energy and accompanying fission products. Maximum thermal power of TEF-P was tentatively set at 500 W.

The most important problem in building a new nuclear facility is how to prepare the fuel since tons of low enriched uranium or plutonium are necessary to make the core critical or near-critical (e.g. $k_{eff} = 0.95$) in a fast neutron system. We intend to use the plate-type fuel of the fast critical assembly (FCA) in JAERI/Tokai, or preferably to merge FCA into TEF-P. Metallic fuel of enriched uranium and plutonium will be available as well as natural and depleted uranium. Many kinds of simulation materials such as lead and sodium for the coolant, ZrH for the moderator, B_4C for the absorber and AlN for the nitride fuel will also be prepared.

Therefore, the TEF-P is designed with reference to FCA (the horizontal table-split type critical assembly with a rectangular lattice matrix). Figure 3 shows a conceptual view of the assembly. The fuel is loaded in the fixed and movable half assemblies. The movable assembly approaches the fixed one, and they contact each other for the operation. In the representative experimental configuration, two sets of control rods and six sets of safety rods are installed in total on both assemblies. These control and safety rods are not composed with absorber materials such as B_4C but with enriched uranium fuel to avoid disturbance of the experimental condition.

Low-current proton beam is extracted by a laser charge exchange technique from a high-intensity beam line of 200 kW (0.33 mA, 600 MeV), most of which is introduced into TEF-T. Figure 4 shows the concept of a beam transport system for TEF. The 200 kW proton beam is a pulsed one whose repetition rate and maximum pulse width are 25 Hz and 0.5 ms, respectively. The protons are accelerated as negative ions (H^-). The beam is exposed by a YAG laser, which can strip one of the two electrons so as to change a small amount (below 10 W) of H^- to neutral (H^0). The H^- and the H^0 are then separated by a bending magnet, where H^- is bent into TEF-T and H^0 goes straight/forward in the magnetic field. The other electron of the H^0 is finally stripped by a carbon foil so that the positive protons (H^+) are introduced into TEF-P. The time width of the proton pulse for TEF-P can be adjusted by changing the duration of the laser exposure; a 1 ns - 0.5 ms pulse is expected to be available. The proton beam intensity is controlled by a collimator.

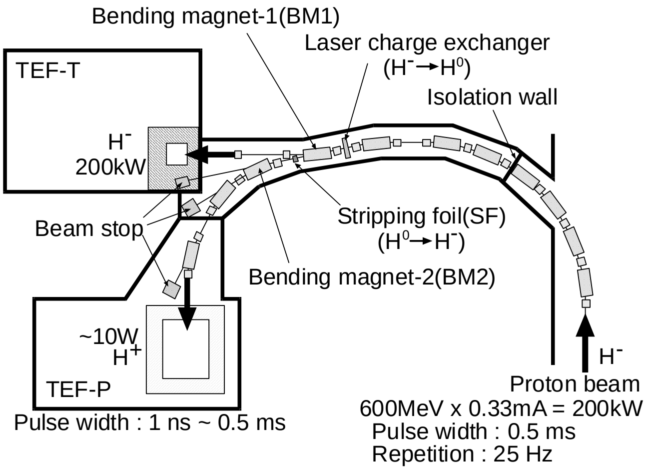
Figure 3. Table-split type critical assembly (TEF-P)



In the experiment with the proton beam, the effective multiplication factor k_{eff} of the critical assembly will be kept less than 0.98. One proton with 600 MeV produces ~15 neutrons via a spallation reaction with a heavy metal target such as lead. The 10 W proton beam corresponds to the source strength of 1.5×10^{12} neutrons/s, which is strong enough to measure power distribution even at a deep subcritical state such as $k_{eff} = 0.90$. A demonstrative test of the laser charge exchange technique is under way using an H^- ion source at JAERI/Tokai.

Safety aspects of the facility are being studied extensively because the TEF-P should be licensed as a nuclear reactor. As for a prompt critical accident, the power excursion can be terminated without fuel melting by the reactor scram system, which has multiplicity and diversity. Unexpected introduction of a 10 W beam into the critical state can also be terminated safely with reactor scram.

Figure 4. Concept of the beam transport system for TEF



Experiments using TEF-P

Many experimental studies are planned using the TEF-P facility. The R&D to be performed is listed by item in Table 1.

Table 1. R&D items to be performed at TEF-P

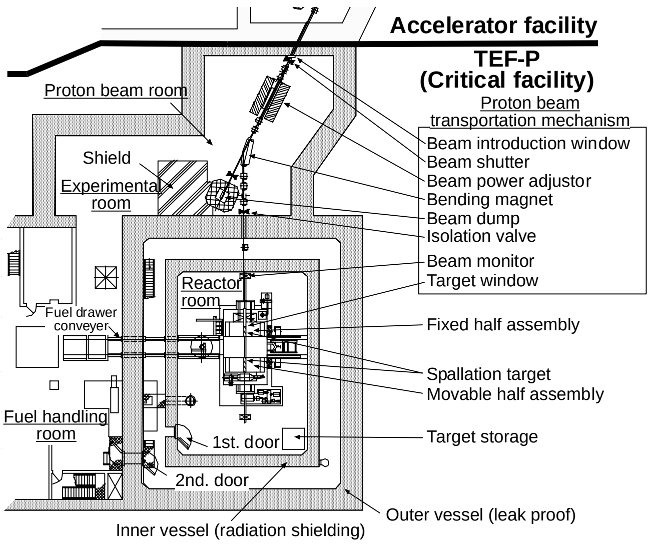
Purpose	Experimental item
Validation of data and method to predict the neutronics in a fast subcritical system with a spallation source	Measurement of power distribution in subcritical system
	Determination of k_{eff} and effective source strength
	Evaluation of influence of high-energy particles
	Evaluation of influence of target, beam window, void in beam duct
Demonstration of controllability of a hybrid system driven by an accelerator	Feedback control of reactor power by beam intensity adjustment
	Investigation of system behaviour at beam trip and restart
	Determination of energy gain factor
Transmutation performance of MA and LLFP	Measurement of MA transmutation rate
	Measurement of MA and LLFP sample reactivity worth
	Study of moderated region for LLFP transmutation
	Simulation of MA-loaded nitride core
	Measurement of cross-section data by TOF technique

As for the neutronics in the subcritical system, power distribution, k_{eff}, effective neutron source strength and neutron spectrum are measured by parametrically changing the subcriticality and the spallation source position. The material of the target will be altered with Pb, Pb-Bi, W and so on. The reactivity worth is also measured for the case of the coolant void and the intrusion of the coolant into the beam duct. It is desirable to make the core critical in order to ensure the quality of experimental data of the subcriticality and reactivity worth.

As for the demonstration of the hybrid system, feedback control of the reactor power is examined by adjusting the beam intensity. Operating procedures at beam trip and restart are also examined.

Regarding 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 the high-energy region (up to several hundreds of MeV) can be measured by the time-of-flight (TOF) technique with a short-pulsed proton beam. By coupling the 1 ns, 10 W proton beam and 5 m of flight path, the neutron flux of 4.7×10^5 n/cm^2/s can be obtained for TOF measurement with a good energy resolution (e.g. less than 1% at 1 MeV). Such cross-section measurements can be performed not only at the reactor room but also at the proton beam room and the experimental room (shown in Figure 5). 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.

Figure 5. Arrangement plan inside TEF-P



The ultimate target of the facility is to install a partial mock-up region of MA nitride fuel with air cooling to measure the physics parameters of the transmutation system. Figure 6 shows a schematic view of the partial loading of pin-type MA fuel around the spallation target. The central rectangular region (28 cm × 28 cm) will be replaced with a hexagonal subassembly. Table 2 shows the heat generation and radioactivity in the central simulation zone with various fuel compositions. The first case in the table, MOX FBR, can be simulated by the existing critical assembly using an air blower to cool the decay heat and a simple radiological shielding for fuel loading by hand. It can be seen from Table 2 that if curium is not contained, decay heat and radioactivity can be managed by strengthening the capability of air blowers and by installing appropriate remote handling devices even for simulating the ADS with (MA + Pu + Zr) mono-nitride fuel. However, in the case with curium, decay heat and neutron emission seem too high to make the experiments.

Figure 6. Illustration of experimental configuration for partial mock-up using pin-fuelled zone

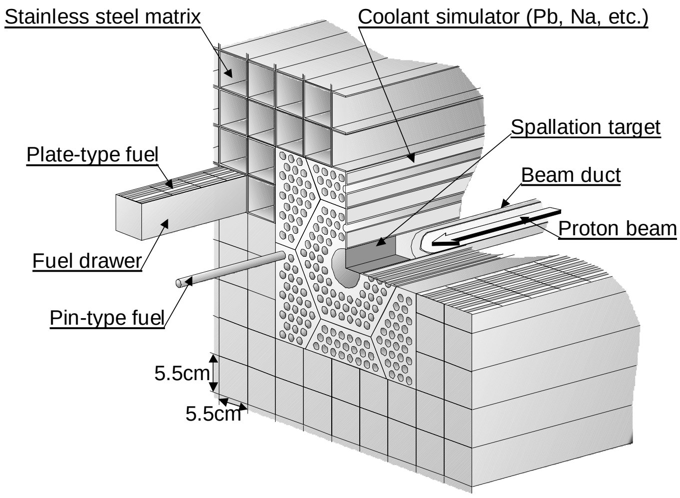


Table 2. Various fuel compositions and their heat and radioactivity

Fuel type to simulate	Actinide composition	Simulation zone: 28 cm × 28 cm × 60 cm		
		Decay heat (W)	γ-ray (γ/s)	Neutrons (n/s)
MOX FBR[a)]	Recovered from UO_2-LWR[d)]	7.1×10^2	3.1×10^{13}	7.5×10^6
MOX FBR with 5% MA[b)]	Recovered from UO_2-LWR[d),f)]	1.1×10^3	3.2×10^{14}	7.1×10^6
	Recovered from MOX-LWR[e),g)]	1.5×10^3	5.3×10^{14}	9.5×10^6
ADS with (MA + Pu + Zr) mono-nitride[c)]	Recovered from UO_2-LWR[d),f)]	1.6×10^3	8.3×10^{14}	3.4×10^6
	Recovered from MOX-LWR[e),g)]	2.6×10^3	1.5×10^{15}	4.5×10^6
	Recovered from MOX-LWR (with Cm)[e),h)]	1.3×10^4	1.3×10^{15}	1.5×10^{10}

a) Pu:U = 17:83, fuel volume ratio = 50.6%
b) MA:Pu:U = 5:16:79, fuel volume ratio = 50.6%
c) MA:Pu:Zr = 23:12:65, fuel volume ratio = 22.9%
d) Pu = 65% fissile
e) Pu = 55% fissile
f) $^{237}Np:^{241}Am:^{243}Am$ = 50:36:14
g) $^{237}Np:^{241}Am:^{243}Am$ = 5:63:32
h) $^{237}Np:^{241}Am:^{243}Am:^{(244+245)}Cm$ = 4:53:28:14

The points that distinguish TEP-P from existing experimental facilities can be summarised as follows: 1) both high-energy proton beam and nuclear fuel are available, 2) the maximum neutron source intensity of ~10^{12} n/s is strong enough to perform precise measurements even in a deep subcritical state (e.g. k_{eff} = 0.90) and is low enough to easily access the assembly after irradiation, 3) a wide range of pulse width (1 ns - 0.5 ms) can be available by the laser charge exchange technique and 4) MA and LLFP can be used as a shape of foil, sample and fuel by installing an appropriate shielding and a remote handling device.

Background and purpose of TEF-T

The beam window of ADS plays an important role as a boundary between the accelerator and the subcritical core. However, it is situated under severe circumstances – heavy irradiation by both proton beam and neutrons, thermal stress by proton beam transients (i.e. startup, shutdown and beam trip), mechanical stress from the pressure difference between the counter flow of the liquid metal target and the vacuum in the beam duct, and corrosion/erosion by Pb-Bi. Thus, feasibility of the beam window should be demonstrated as a top priority in ADS development. Some technical issues are also to be investigated for the high-power spallation target system (e.g. the purification system for spallation products and the polonium, the remote handling device for the Pb-Bi system, etc.).

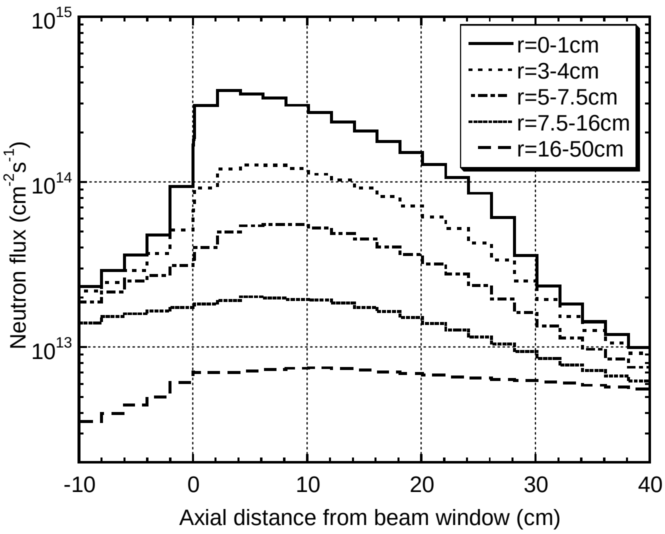
From the above viewpoints, the demonstrative program called MEGAPIE [8] is under way at PSI, Switzerland, where a Pb-Bi spallation target will be operated using a 590 MeV, 1 MW proton beam for several months during 2006. Since this project uses existing accelerators, the duration of the experiment is restricted. Our proposed facility, TEF-T, aims at R&D on spallation target technologies as a proton-neutron irradiation facility dedicated to ADS.

Specification of TEF-T

TEF-T is the material irradiation facility with a 600 MeV, 200 kW proton beam and a Pb-Bi liquid eutectic target. To demonstrate the feasibility of the beam window, the proton beam density at the beam window should coincide with that of the future ADS plant. In the design of an ADS plant, a 30 MW proton beam of 1.5 GeV (20 mA) is assumed to be available, where the diameter of the beam is defocused to ~45 cm. The proton beam density at beam window becomes ~13 $\mu A/cm^2$ on average and the maximum density will be restricted to ~30 $\mu A/cm^2$. At TEF-T, the proton beam of 0.33 mA is focused to 40 mm in diameter, which results in the beam density of ~26 $\mu A/cm^2$ on average; this beam density is considered to be high enough for the demonstration.

The Pb-Bi eutectic is filled into a cylindrical vessel made by stainless steel. The size of the vessel is approximately 150 mm in diameter and 600 mm in length. The neutronics properties of the Pb-Bi target in TEF-T were calculated by the ATRAS code system [9]. The axial distribution of the neutron flux is shown in Figure 7. The neutron flux exceeds 10^{14} n/cm^2/s at the centre of the target and 10^{13} n/cm^2/s at the region of 300 mm in diameter and 300 mm in length, where various materials can be irradiated by fast neutrons.

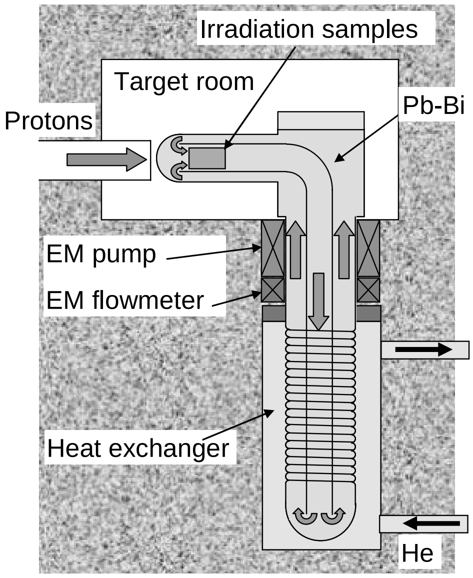
Figure 7. Neutron flux distribution at the Pb-Bi target of TEF-T



The maximum temperature and flow rate of the Pb-Bi target are designed as 450°C and 2 m/s, respectively. Other structural materials such as F82H steel will also be tested as the target vessel. The compatibility of the stainless steel (316SS) with flowing Pb-Bi eutectic is currently being tested by an experimental loop at JAERI/Tokai.

As for the target module, the "double-annular type" Pb-Bi target shown in Figure 8 is under consideration [10]. By this configuration, the electromagnetic (EM) pump and EM flowmeter can be separated from the Pb-Bi loop, and hence the target module can be easily withdrawn for the upper direction in the case of exchange. About 70% of the kinetic energy of the proton beam (140 keV) will be deposited in the target and this heat will be cooled by helium gas of the secondary loop.

Figure 8. Concept of double-annular type Pb-Bi target for TEF-T



Experiments using TEF-T

The principal purpose of TEF-T is to demonstrate the feasibility of a high-power spallation target system and to research the material compatibility in the Pb-Bi with irradiated circumstances. The R&D program to be performed at TEF-T is summarised in Table 3.

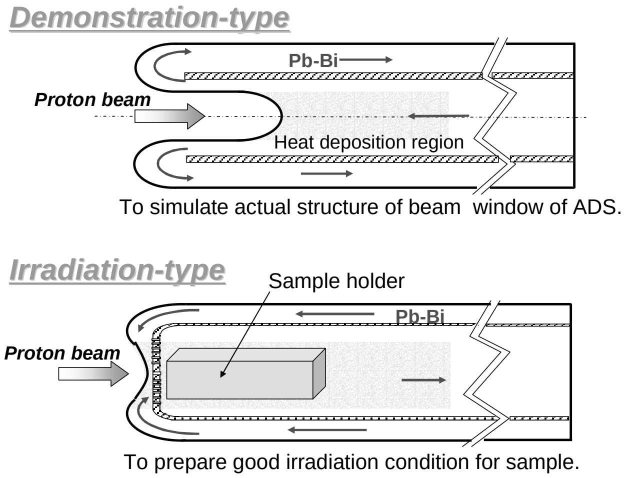
Two kinds of target vessels are being considered – one is a "demonstration-type" and the other is an "irradiation-type" as shown in Figure 9. The demonstration-type vessel simulates the shape of the ADS beam window, where the Pb-Bi heated by the proton beam flows toward the beam window. On the other hand, the irradiation-type vessel is designed to optimise irradiation conditions for samples. The direction of the Pb-Bi flow will be opposite compared to the demonstration-type vessel.

The irradiated structural materials of the target vessel as well as the irradiated samples will be examined from the viewpoint of the following: tensile strength, ductility, fatigue, fracture toughness, DBTT (ductile-brittle transition temperature), etc. In addition to these tests, the effects of corrosion and erosion by Pb-Bi and the spallation products will be studied precisely by changing parameters such as temperature, irradiation period, flow speed and oxygen concentration in Pb-Bi. Plenty of experiences for operation and handling of a high-power spallation target can be accumulated at TEF-T.

Table 3. R&D items to be performed at TEF-T

Purpose	Experimental item
Serviceable lifetime of beam window and structural material under proton and neutron bombardment	Evaluation of soundness and lifetime of beam window
	Duplicated irradiation damage by protons and neutrons
	Establishment of material database for fast neutron irradiation
	Irradiation effect under stressed conditions
Compatibility of material with flowing liquid metal under high-power proton irradiation	Liquid metal corrosion and liquid metal embrittlement under proton and neutron irradiations
	Compatibility of materials with liquid metal as a function of temperature, velocity and oxygen concentration of the liquid metal
	Influence of spallation products
Operation and control of liquid metal spallation target system	Demonstration of performance of pump, flowmeter, heat exchanger and oxygen controller under actual liquid metal spallation target
	Transient behaviour of system at beam trip and restart
	Containment of spallation products and polonium
	Technical issues on system operation and maintenance

Figure 9. Two kinds of Pb-Bi target for TEF-T



Conclusion

To perform R&D of an accelerator-driven transmutation system, the Transmutation Experimental Facility (TEF) was proposed under the J-PARC project. The TEF consists of two facilities – TEF-P and TEF-T. Outlines of the conceptual designs of both facilities were presented in this paper.

TEF-P is a critical assembly that can accept a low current 600 MeV proton beam for the spallation neutron source. The purpose of TEF-P includes experimental validation of the data and method to predict neutronics of the fast subcritical system with a spallation neutron source, demonstration of the controllability of a hybrid system driven by an accelerator, and basic research of reactor physics for transmutation of MA and LLFP. A horizontal table-split type assembly is proposed. The laser charge exchange technique will be used to introduce a 10 W proton beam into the facility.

TEF-T is the material irradiation facility using a 600 MeV, 200 kW proton beam and a Pb-Bi spallation target. The purpose of TEF-T includes R&D for the irradiation damage of the beam window, compatibility of the structural material with flowing liquid metal target and operation of the high-power spallation target. An outline of the target concept was presented.

Combining the experimental results and experiences obtained at both facilities, the feasibility of ADS can be evaluated and demonstrated.

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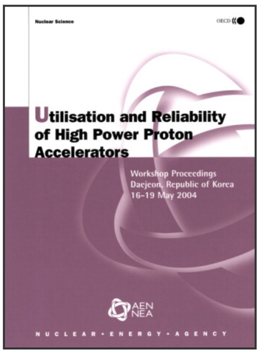

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