# Studies for Accelerator-driven System in J-PARC/JAEA

T.Sasa

J-PARC Center, Japan Atomic Energy Agency (JAEA), Ibaraki, Japan

*E-mail contact of main author: sasa.toshinobu@jaea.go.jp*

**Abstract**. The management of radioactive waste is one of the critical issues for sustainable nuclear energy application especially after the Fukushima accident. In the latest strategic energy policy of Japan express to enhance a research and development to reduce the burden of long-lived nuclides in spent nuclear fuel using both fast reactors and accelerator-driven systems (ADS). Japan Atomic Energy Agency (JAEA) proposes a transmutation of minor actinides (MA) by ADS. A lead-bismuth eutectic alloy (LBE) is used as a spallation target and a coolant of subcritical core because LBE has a good spallation neutron production performance and a chemically inert characteristic. However, the compatibility with steels is unfavourable for the typical structural materials such as a 316 stainless steel. To obtain the data for ADS design, JAEA plans to construct the Transmutation Experimental Facility (TEF) within the framework of the J-PARC project, which consists of two buildings, an ADS Target Test Facility (TEF-T) and a Transmutation Physics Experimental Facility (TEF-P). A 250kW LBE spallation target will be installed in TEF-T to prepare the irradiation database for candidate ADS structural materials in flowing LBE environment. Engineering tests for LBE loop operation and experiments to determine the effective lifetime of proton beam window will be also performed. Spallation neutrons from LBE target will be used for multi-purpose applications. A critical/subcritical assembly with a certain amount of MA fuel will be set up in TEF-P to perform the neutronic experiments for MA-loaded core. To realize both TEF-T and TEF-P, various studies are being carried out. Test loops for the TEF-T LBE target were manufactured and are ready for operation. One is a loop for TEF-T target mock-up and the other is that for collection of material corrosion characteristics in flowing oxygen controlled LBE environment. Sensor systems for LBE flow and oxygen potential have been also developed. Remote handling tests for TEF-T LBE target loop maintenance are underway to fix a design of the loop and the spallation target trolley. The activities to realize the TEF are summarized.

**Key Words**: Transmutation, Accelerator-driven system, J-PARC, Transmutation Experimental Facility

## 1. Introduction

Due to the Great East Japan Earthquake and the ensuing tsunami, the Fukushima-Daiichi Nuclear Power Plant was seriously damaged and then, many nearby residents are still forced to be evacuated. After the accident, the Science Council of Japan suggested prioritizing research and development (R&D) to reduce the radiological burden of high level wastes (HLW) as recommended by the Atomic Energy Commission of Japan. In 2014, the cabinet of Japan decided on a new strategic energy policy enhancing R&D to reduce the burden of radioactive waste in spent nuclear fuels by using a fast reactor and/or accelerators.

The Japan Atomic Energy Agency (JAEA) promotes R&D to reduce the radiological hazard of HLWs by Partitioning and Transmutation (P-T) technology [1]. For the transmutation of radioactive nuclides in HLW, the management of minor actinides (MA) is significantly important. By using P-T technology, MA can be transmuted effectively by using the accelerator-driven system (ADS), which combines a high intensity proton accelerator and a fast subcritical core. It is also important that the P-T using ADS be compatible with various power generation cycle scenarios, because ADS can be established independently from the nuclear fuel cycle for power generation.

To realize ADS, the innovative nuclear system, there are many issues to be solved. Within the framework of the J-PARC project, JAEA plans to construct a Transmutation Experimental Facility (TEF) to study MA transmutation by both MA-loaded fast reactors and ADS [2]. TEF is located at the end of the LINAC, which is also an important component to be developed for ADS, and shares the proton beam with other experimental facilities in J-PARC. R&D for important technologies required to build the TEF are also performed, such as design and operation of lead-bismuth spallation target, application methods of MA bearing fuel in the critical/subcritical assembly, spallation product removal methods especially for polonium, and so on. The objectives of the TEF, the latest design concepts, and key technologies to construct a TEF are described.

## 2. Impacts of P-T Technology Introduction

To introduce the P-T cycle, a double stratum concept was proposed by the JAEA. In the double-strata fuel cycle, the power generation cycle including the Fast Reactor is the first stratum and the ADS is installed as the second stratum cycle. In the first stratum, uranium and plutonium are recycled and MA is partitioned to send to the second stratum for transmutation. At the reprocessing and partitioning plant in the first stratum, fission products (FP) are separated into three groups: the Sr-Cs, the platinum group metals (PGM: ruthenium, rhodium and palladium) and the other elements including lanthanides. Strontium and cesium are calcined, and stored to decrease their decay heat. The separated PGM may be utilized as a catalyst. Iodine is separated in a reprocessing plant, and disposed of as low-level long-lived waste or transmuted in ADS. The other waste elements from the first stratum are supposed to be vitrified with higher density (~35 wt. %) than is conventional (~15 wt. %) because of the low heat generation and the extraction of PGM, which is undesirable for the glass melting process.

In the second stratum, MA-based fuel is loaded into the ADS to maximize the transmutation amount of MA. Spent MA fuel is reprocessed by dry reprocessing process. Since the wastes from the second stratum are relatively low, because the actinide’s inventory is smaller than that of the power generation cycle, the wastes from the second stratum give a limited impact to the entire nuclear fuel cycle.

The conventional reprocessing process for spent fuel from light water reactors forms about 3.4 pieces of vitrified waste packages per 1 TWh of electricity generation, and therefore the area of geological repository for 1 TWh is about 150 $m^2$. If the MA is recovered and recycled, the required space for one vitrified waste package will be kept at 44 $m^2$, and therefore the area per unit of electricity generation can be reduced by about 40%. In addition, if MA is recycled and Sr-Cs is cooled separately for about a hundred years, the total repository area will be reduced to 1/4 of the non-P-T case because the decay heat from the Sr-Cs is decreased significantly. If the Sr-Cs is stored and cooled for a much longer period, for example about 300 years, the heat generation from the Sr-Cs is no longer influential to the repository structure, and hence it can be disposed of in a very compact manner [3].

## 3. JAEA Proposed ADS

The JAEA's reference design for ADS is a tank-type subcritical reactor, where lead-bismuth eutectic (LBE) alloy is used as both the primary coolant and the spallation target, as shown in Figure 1. The spallation target region is located at a central part of the subcritical core. In the target region, LBE flows from the core bottom along to the dedicated wrapper tube and to the flow guide tube. About a 1.5 GeV - 30 MW proton beam is supplied from the linear accelerator to operate the ADS. The rated power, which is controlled by adjusting the injected proton beam power from the accelerator, is 800MW$_{th}$. Therefore, the maximum neutron multiplication factor during the whole burn-up cycle was set at 0.97.

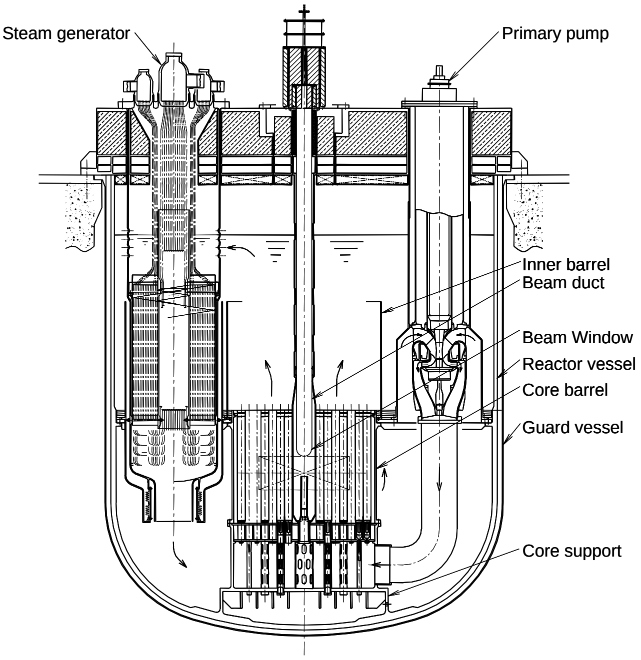

*FIG. 1. ADS for transmutation of MA proposed by JAEA*

A tank-type system was adopted to eliminate the necessity of heavy-weighted 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 ºC, respectively, which are low enough to prevent material corrosion by LBE.

## 4. Transmutation Experimental Facility in J-PARC

As shown in Figure.2, TEF consists of two individual buildings: the ADS Target Test Facility (TEF-T) [4] and the Transmutation Physics Experimental Facility (TEF-P) [5].

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 also has the possibility of being used for various research purposes such as measurement of the reaction cross sections of MA and structural materials, basic science studies and so on. TEF-P is a facility with a critical/subcritical assembly to study the neutronic performance and the controllability of ADS. Using these two facilities, basic physical properties of the subcritical system and the engineering tests of the spallation target will be studied. R&D for several important technologies required to build the facilities are also performed, such as the laser charge exchange technique to extract a very low power beam (less than 10W) 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.

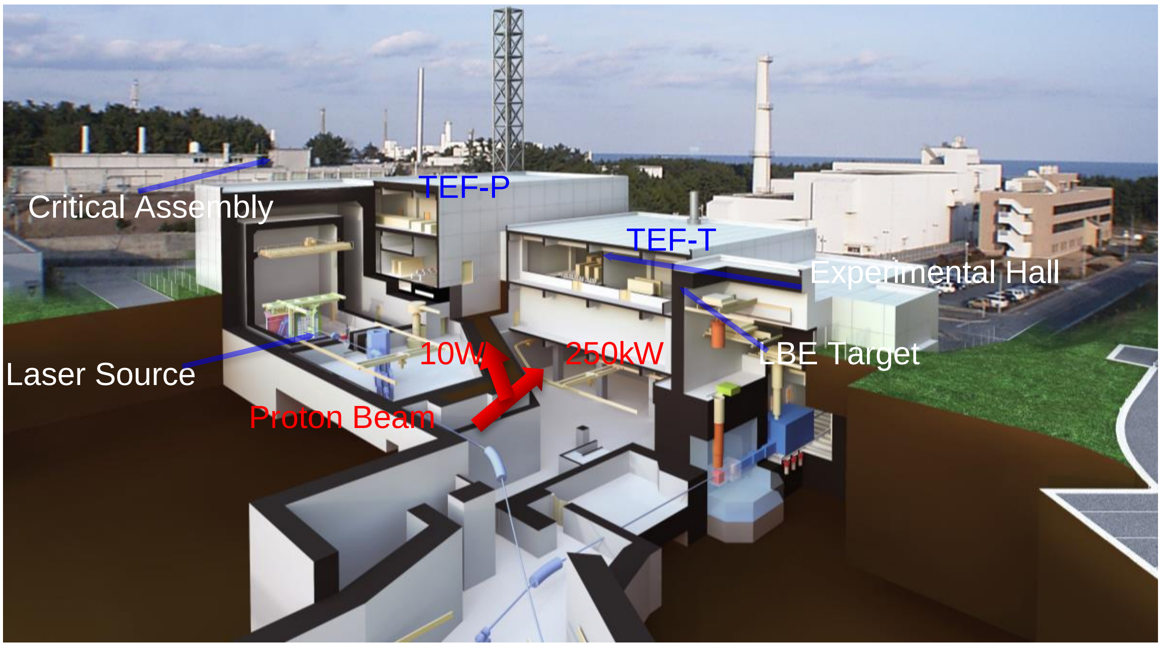

*FIG. 2. Transmutation Experimental Facility*

### 4.1.Outline of TEF-T

The main purpose of TEF-T is to obtain the data to evaluate the actual lifetime of the beam window. TEF-T mainly consists of a spallation target, a LBE cooling circuit, and hot cells to handle the spent target and irradiation test pieces.

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 realize a TEF-T. To set up the beam parameters, future ADS concepts will be taken into account. In the reference case of the target, the proton beam current density of 20 $\mu A/cm^2$, which equals the maximum beam current density of the JAEA-proposed $800MW_{th}$ ADS, was selected. The material of the irradiation target would be a type 316 stainless steel for temperatures below 450ºC and a T91 steel for higher operation temperatures. The irradiation performance of the reference case was evaluated at around 8 DPA/yr by 400MeV-250kW protons of irradiation. This value is about 20% of the DPA considered in the beam window of the JAEA-ADS. Further optimization of the target design to increase the DPA is underway.

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 the exhaust circuit of TEF-T. An equilibrium vaporization test of polonium from liquid Pb-Bi was performed and equilibrium vaporization characteristics were measured by the transpiration method with LBE, which was irradiated at the JAEA/JMTR [6]. It was shown that at a low temperature of around 450ºC, which is considered 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 [7]. LBE samples were irradiated at the JAEA/JRR-4 and were heated in a special vacuum vessel up to 690ºC. 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.

### 4.2.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) of the JAEA 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 for building the TEF-P are (1) to study reactor physics aspects of the subcritical core driven by a spallation source, (2) to demonstrate the controllability of the subcritical core including the power control by the proton beam power adjustment, and (3) to investigate the transmutation performance of the subcritical core using a certain amount of MA and long-lived FP (LLFP).

TEF-P was designed with reference to the FCA, the horizontal table-split type critical assembly with a rectangular lattice matrix, to utilize the operation experiences and existing experimental data of the FCA. In this concept, the plate-type fuel for FCA with various simulation materials such as lead and sodium for coolants, tungsten for the solid target, ZrH for the moderator, $B_4C$ for the absorber, and AlN for the simulating nitride fuel, can be commonly used by the TEF-P. The proton beam will be introduced horizontally at the center of the assembly and various kinds of spallation targets can be installed at various axial positions off the radial center of the subcritical core.

In the experiment with a proton beam, the effective multiplication factor of the assembly will be kept less at than 0.98. One proton with the 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, and has enough strength to measure the neutronic characteristics. From the viewpoint of the accuracy of neutronic analyses for subcritical systems, it is desirable to make the core critical in order to ensure the quality of the experimental data of the subcriticality and the reactivity worthwhile. So, the subcritical core will be made to have a 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 regions (up to several hundred MeVs) can be measured by the Time of Flight (TOF) technique with a proton beam of about a 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 being prepared to measure their reactivity value, which is important for the integral validation of the 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 the ADS design [11]. To improve the accuracy of the nuclear data especially for MA, both the differential experiments and the integral experiments are necessary, even though 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]. By using a certain amount of MA, which is on the order of a kg, typical improvement can be obtained.

## 5. Development of High Power Spallation Target for TEF-T

### 5.1.Design of the LBE Spallation Target Head

A spallation target in TEF-T is mainly used for material irradiation and also for the feasibility tests for ADS beam window. For the material irradiation, target should suffer the focused proton beam up to 20 μA/cm$^2$ of beam current density. 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.

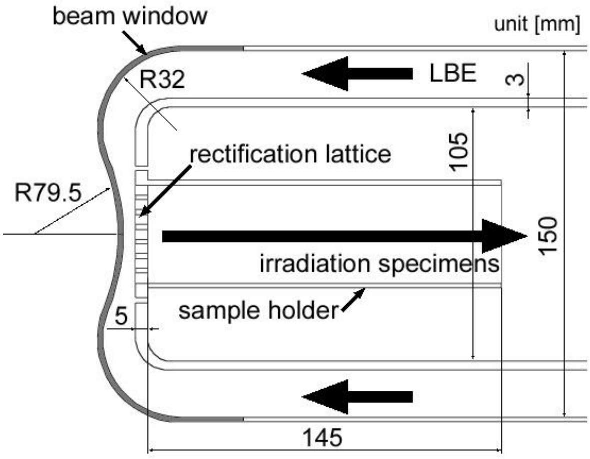

*FIG.3.Prortotype LBE Spallation Target Head*

The material of beam window would be type 316 stainless steel as a primary candidate. The concave section in the center 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 to 3 or 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. An irradiation sample holder, which was installed in the inner tube, holds eight irradiation specimens in the horizontal direction. The size of each specimen was 40×145×2 mm. The rectification lattice having the aperture of the plural squares type was installed at the front-end of the sample holder. A slit of 2mm in width was arranged along the side of the rectification lattice to cool off the sample holder by flowing LBE.

The thermal-fluid behavior of the target was calculated by the STAR-CD [13] 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 center 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 *liter*/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 analyzed by a hadronic cascade code PHITS [14], 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 [15], 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 from 1 to 4 *liter*/sec. In each case, a dead region was commonly formed in the center of the inside of beam window. 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 *liter*/sec. When the inlet flow rate increases to 4 *liter*/sec, the maximum velocity in the target reached 4.8 m/sec 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.

One of the results, which are shown in Figure 4, was the temperature profile on the beam window by changing the thickness of the window from 2mm to 3mm with 1 *liter*/sec of LBE flow.

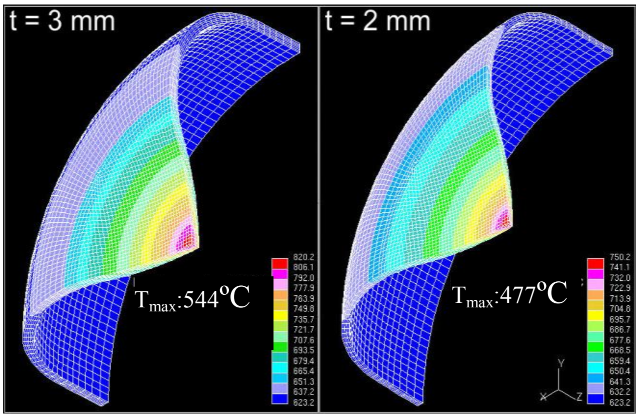

*FIG.4 Temperature profile in beam window*

The maximum temperature is 544 ºC in the case of 3mm thick window. In the case of 2mm thick window, the peak temperature decreases to 477 ºC. The temperature differences between outside and inside at the center of the window were 65 ºC and 37 ºC in the case of 3mm thick window and 2mm thick window, respectively. From these results, it was disclosed that a condition of 2mm was desirable.

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 adopted to 470 ºC 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.

## 5.2.Design of TEF-T LBE Spallation Target Loop

The trolley type target system is adapted to TEF-T LBE spallation target. The existing J-PARC spallation neutron source, 1MW mercury target, is also mounted on horizontal trolley. The TEF-T target system is designed based on the mercury target system. Figure 5 shows a TEF-T target system with target trolley. To improve the gas tightness, several pillow-seal type joints are substituted to metal O-ring joints. In TEF-T, vacuum vessel is selected instead of safety hull and helium vessel, to catch irradiated LBE in the case of LBE leakage accident around target head. Inside the vacuum vessel is kept in deepest negative pressure in TEF-T building and then, acts as a barrier to confine radioactive reaction products in LBE. For effective cooling of the target system, pressurized water is selected as a secondary coolant. To prevent the accidents by contacting high-temperature LBE and water, double-annular tube is used for the heat transfer pipe for heat exchanger. Helium gas is selected as a filler gas between LBE and water. Basic design is underway and trial production of double-annular heat transfer pipe will be performed.

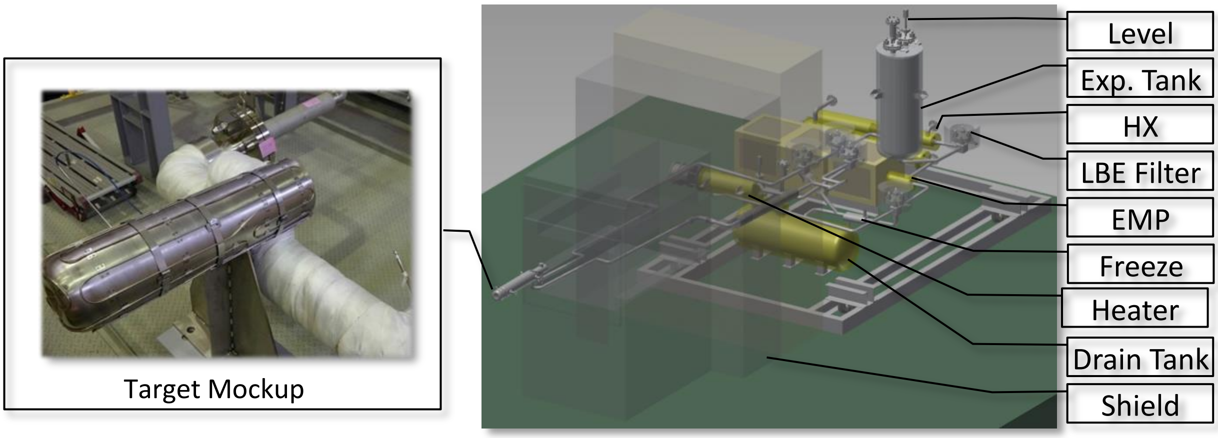

*FIG. 5. TEF-T LBE Spallation Target Loop with Trolley*

## 5.3.Basic R&Ds to Realize LBE Spallation Target System

To operate LBE loop with high temperature condition above 400°C, the mockup of the primary circuit is manufactured and start operation since March, 2015. The mockup loop named IMMORTAL (**I**ntegrated **M**ulti-purpose **MO**ckup for TEF-T **R**eal-scale **TA**rget **L**oop) is aimed at developing the technologies for safe operation and reliable maintenance. 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. In order to operate the target in high temperature, it is difficult to use flanges to replace the spallation target, especially with the remote handling systems. The target replacement scenario by using pipe-cutter and automatic welding machine is under discussion and will be tested using IMMORTAL. After the establishment of TEF-T, IMMORTAL will be used to prepare the non-irradiated samples to clarify the effect of proton irradiation by comparing TEF-T irradiated samples, because all other operation parameters (temperature difference, LBE flow rate, oxygen concentration, etc.) can be adjusted with TEF-T irradiated samples.

Establishment of measuring techniques for LBE loop system is one of the key issues of the safe operation of LBE loop. The measurement and operation devices of the oxygen concentration in LBE are developed to suppress the corrosion by LBE. Two kinds of oxygen sensors, platinum electrode type and bismuth electrode type were tested and then, platinum electrode type was selected because of the higher output signals compared to the bismuth electrode type. In the case of platinum electrode type, open hole should exist to supply the air into the sensor. To prevent the leakage of irradiated LBE through the air hole, freeze seal design was installed in the sensor housing. Leakage test of the sensor housing was performed and confirmed that there are no LBE leakage even in the case of maximum design pressure of LBE cover gas. Figure 6 shows the platinum type oxygen sensor fabricated by JAEA.

*FIG. 6. Oxygen sensor fabricated by JAEA*

Flow rate of LBE is another important parameter for both irradiation experiment and loop operation. However, the electro-magnetic flow meter, which is one of the most popular measuring methods, requires a complicated calibration procedure by lifting/draining LBE. Moreover, the output signal from electro-magnetic flow meter is highly affected by the wettability of the LBE to the electrode. By applying sodium-cooled fast breeder reactor technology, we developed the ultrasonic flow meter to measure the flow rate of LBE, which can work with required high temperature range below 500°C. Durability test of the flow meter was successfully performed with temperature of 400°C up to 5,000 hours. Further improvement to increase the maintainability is underway.

The corrosion tests of the candidate structural material for TEF-T and ADS is also planned as a fundamental research to realize LBE cooled ADS. A high-temperature material corrosion test loop OLLOCHI (**O**xygen-controlled **L**BE **LO**op for **C**orrosion tests in **HI**gh-temperature) were manufactured and installed in JAEA. OLLOCHI has three independent test sections, that can change flow rate and temperature of LBE to correct material corrosion date efficiently. Construction of OLLOCHI was finished except the third test section, which plans to install special test device for corrosion with mechanical stress, and functional tests of the loop is underway.

## 6. Summary

The JAEA has been promoting various types of R&D on P-T fuel cycles including a dedicated ADS transmutor. As for the basic experimental studies necessary to establish an innovative system like the ADS, a plan to build a Transmutation Experimental Facility has been proposed within the framework of the J-PARC project. The design optimization of TEF-T to improve irradiation performance to simulate ADS operation conditions, including R&D for LBE loop development, clod material tests, oxygen sensor development and polonium management, was carried out. The effectiveness of TEF-P experiments using a certain amount of MA was assessed quantitatively.

## References

[1] T. Sasa, et al., “Research and development on the accelerator-driven transmutation system at JAERI”, Nuclear Engineering and Design 230, 209-222 (2004).
[2] K. Tsujimoto, et al., “Feasibility of a Lead-Bismuth-Cooled Accelerator-Driven System for Minor-Actinide Transmutation” ,Nuclear Technology, 161, 315-328 (2008).
[3] H. Oigawa et al., “Current status and future plan of research and development on partitioning and transmutation technology in Japan”, Proc. 11th OECD/NEA Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation”, San Francisco, USA (CD-ROM, 2012).
[4] T. Sasa, et al., “Conceptual Study of a Transmutation Experimental Facility (2) Study on an ADS Target Test Facility” (in Japanese), JAERI-Tech 2005-021 (2005).
[5] H. Oigawa, et al., “Conceptual Design of a Transmutation Experimental Facility”, Proc. Global2001, Paris, France (CD-ROM, 2001).
[6] S. Ohno, et al., “Equilibrium Evaporation Behavior of Polonium and Its Homologue, Tellurium, in Liquid Lead-Bismuth Eutectic”, Journal of Nuclear Science and Technology, 43:11, 1359-1369 (2006).
[7] T. Obara, Y. Yamazawa, T. Sasa “Polonium decontamination performance of a stainless steel mesh filter for lead alloy-cooled reactors”, Progress in Nuclear Energy, 53, 1056-1060 (2011).
[8] R. SOULE, et al., “Neutronic Studies in Support of the ADS: The Muse Experiments in the MASURCA Facility”, Nuclear Science and Engineering, 148, 124-152 (2004).
[9] W. UYTTENHOVE, et al., “The neutronic design of a critical lead reflected zero-power reference core for on-line subcriticality measurements in Accelerator Driven Systems”, Annuals of Nuclear Energy, Vol.38, No.7, 1519-1526 (2011).
[10] T. TOMISAWA, et al., “Investigation of the Photo Neutralization Efficiency of High Intensity H- Beams with the Nd:YAG Laser in J-PARC”, Proceedings of the 7th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 2005), 275-277 (2005).
[11] T. Sugawara et al., “Analytical Validation of Uncertainty in Reactor Physics Parameters for Nuclear Transmutation Systems,” J. Nuclear Science Technology 47(6), 521-530 (2010).
[12] T. SUGAWARA, et al.,”SND2006-V.10-1: the Design of MA-loaded Core Experiments using J-PARC”, Proceedings of the 2006 Symposium on Nuclear Data, Jan. 25-26, 2007, (2007) [CD-ROM].
[13] CD-Adapco “STAR-CD”, CFD Commercial Code.
[14] K. Niita, et al., “PHITS: Particle and Heavy Ion Transport code System, Version 2.23”, JAEA-Data/Code 2010-022 (2010).
[15] Dassault Systems “ABAQUS”, FEM Commercial Code.