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Research and Development Activities for Accelerator Driven System at JAERI

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The Japan Atomic Energy Research Institute (JAERI) is developing an Accelerator Driven System (ADS) for transmutation of nuclear waste such as minor actinide (MA) and long-lived fission product (LLFP). To study and evaluate the feasibility of ADS by physical and engineering viewpoints, the Transmutation Experimental Facility (TEF) is proposed under a framework of J-PARC (Japan Proton Accelerator Research Complex) project. The TEF consists of two facilities named as Transmutation Physics Experimental Facility (TEF-P) and ADS Target Test Facility (TEF-T). The TEF-P consists of a zero-power critical assembly which is operated with a low power proton beam to research the reactor physics and the controllability of ADS. The TEF-T is a facility for material irradiation and partial mockup of beam window which can accept a maximum 600MeV-200kW proton beam into the Pb-Bi eutectic target. The purposes, experimental items and the specifications of the facilities are described.

KEYWORDS: Accelerator-driven System, Transmutation, Minor Actinide, Long-lived Fission Product, Lead-Bismuth, Spallation Neutron Source, Critical Assembly

1. Introduction

The Japan Atomic Energy Commission launched a long term research and development (R&D) program named OMEGA (Options Making Extra Gains from Actinides and fission products) for partitioning and transmutation of long-lived radioactive nuclides in 1988. The objectives of OMEGA project are to widen options for future waste management and to explore the possibility to utilize high-level radioactive wastes as useful resources. Under the OMEGA program, the Japan Atomic Energy Research Institute (JAERI) proposed a double-strata fuel cycle concept[1], in which partitioning and transmutation are carried out in a dedicated and small-scale fuel cycle as shown in Figure 1. By the double-strata fuel cycle, no significant modification is required to the current fuel cycle, and long-lived nuclides are confined into the

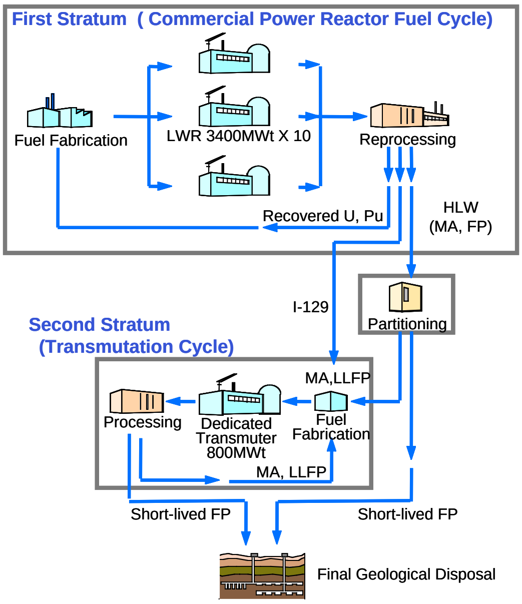

Fig.1 Double-Strata Fuel Cycle Concept

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small cycle that is optimized to the transmutation of MA and LLFP. For a dedicated transmutation system, JAERI has been implementing with the research and development on accelerator-driven system (ADS)[2].

The ADS is a hybrid system that consists of a high intensity proton accelerator, a spallation target and a subcritical fuel region. As a primary option, JAERI proposed a lead-bismuth (Pb-Bi) eutectic target/coolant system[3]. A proton beam of 1.5 GeV - 22 MW is injected and the system is designed to generate 800 MW of thermal power. To realize the ADS, there are many technical subjects: the neutronics of the subcritical core driven by spallation neutrons, the engineering applicability of the high power spallation target, the development and the operation of the intense proton accelerator, and so on. To solve these technical issues relevant to the ADS development, construction of the Transmutation Experimental Facility (TEF) is planned under the Japan Proton Accelerator Research Complex (J-PARC) Project that is directed by JAERI and High Energy Accelerator Research Organization (KEK)[4]. Proton beam of 600 MeV and 0.33 mA (200 kW) is to be delivered to TEF. To cover different fields of research and development, TEF consists of two separated buildings, the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T). In the present work, the reference design of ADS in JAERI is explained, and then the detailed plan of TEF is presented in Chapter 3.

2. Accelerator-Driven Transmutation System Design[3,5]

The reference ADS design proposed by JAERI is the 800MWth fast subcritical core fueled with MA nitride, cooled by liquid Pb-Bi eutectic as shown in Figure 2. The subcritical core is driven by the spallation neutron source using Pb-Bi target and proton accelerator. This ADS can transmute about 250kg of MA annually by fission reactions, which corresponds to the amount of MA produced in 10 units of LWRs whose burn-up is 33,000 MWD/t.

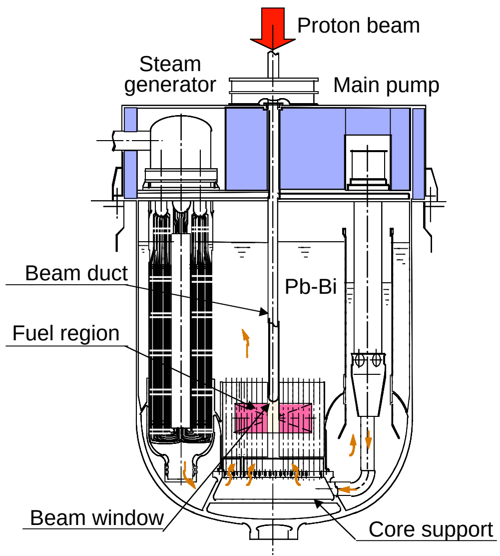

Fig.2 Conceptual design of ADS

In this reference design, maximum value of the effective multiplication factor, k_{eff}, is set to 0.97[5]. To achieve the above mentioned thermal power with this k_{eff}, a high-power proton beam over 20MW is required. This proton beam must be supplied steadily and safely with low cost. To satisfy such requirements, a superconducting linear accelerator is adopted.

As for the spallation target, Pb-Bi was chosen because of its good thermal property; the melting point of 398K and the boiling point of 1943K. Although Pb-Bi is comparatively corrosive to steel at the high temperature above 700K, Russia has a lot of experience to use it as the coolant of reactors in submarines. Many countries have therefore started research and development to establish the technology for the usage of Pb-Bi as the spallation target.

Because of the high MA density and good thermal properties, nitride fuel is suitable for effective transmutation of MA. Nitride fuel also has the advantage to accommodate various MA with a wide range of composition. For avoiding the production of hazardous ^{14}C, however, ^{15}N enriched nitrogen should be used in the nitride fuel.

To realize the ADS, JAERI performed various R&D for superconducting linear accelerator, Pb-Bi eutectic handling, nitride fuel, and subcritical core design and technology.application. Experiments that is indispensable to design the ADS, Transmutation Experimental Facility (TEF) is planned under the framework of JAERI-KEK joint J-PARC project.

3. Transmutation Experimental Facility

3.1 Outline of the facility

To study the basic characteristics of the ADS and to demonstrate its feasibility from viewpoints of the reactor physics and the spallation target engineering, JAERI plans to build the Transmutation Experimental Facility (TEF) in the Tokai site under a framework of the J-PARC Project as shown in Figure 3. The construction of the TEF is scheduled to start since 2007.

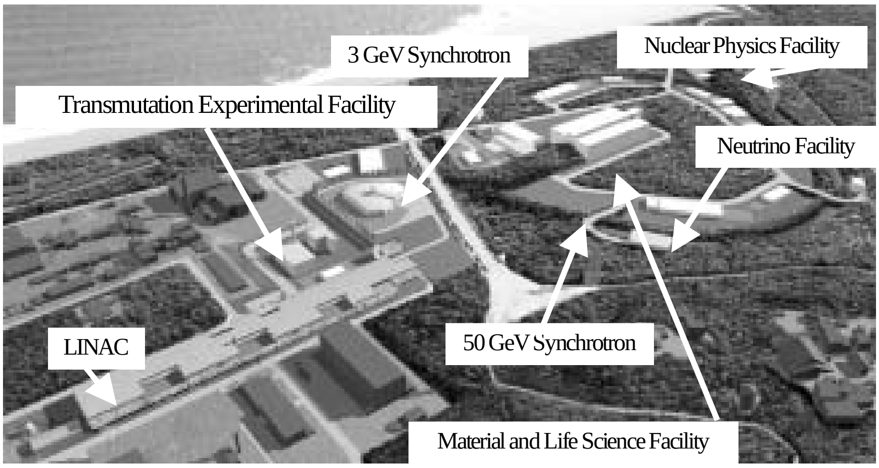

Fig.3 Site plan of the J-PARC project

TEF consists of two buildings: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T) as shown in Figure 4. TEF-P is a zero-power critical facility where a low power proton beam is available to research the reactor physics and the controllability of the ADS. TEF-T is a material irradiation facility which can accept a maximum 200kW-600MeV proton beam into the spallation target of Pb-Bi. Details of TEF-P and TEF-T are presented in the following sections.

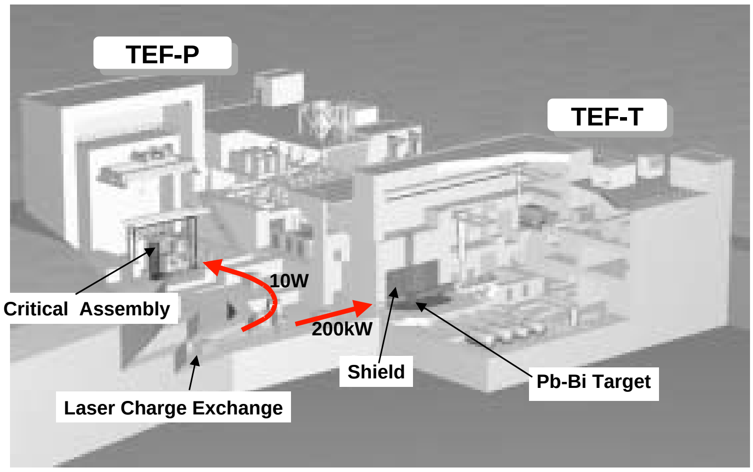

Fig.4 Transmutation Experimental Facility (TEF)

3.2 Transmutation Physics Experimental Facility (TEF-P)

Several kinds of experiments to investigate the neutronic performance of the ADS have been performed using existing facility worldwide. Some of them are for the reactor physics aspects of the subcritical system such as MUSE program[6]. MASURCA, a critical assembly for the fast reactor in France, is used with a newly developed DT and DD neutron source. In Japan, subcritical experiments were carried out at the Fast Critical Assembly (FCA) by using a ^{252}Cf neutron source. Installation of DT neutron source to the FCA is also under way. Moreover, many experimental studies have been performed to the neutronics of the spallation neutron source with various target material such as lead, tungsten, mercury and uranium. These experiments for spallation target are not directly related to the ADS, but they are also useful to validate the neutronic characteristics of ADS.

There has been, however, no experiment aiming at the research and the demonstration of the fast subcritical system combined with a spallation source. Therefore, taking above mentioned situation into consideration, TEF-P is designed to cover the fields of R&D for:

1) 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.

The details of the experimental items are described later.

3.2.1 Specification of TEF-P

For above mentioned purposes, the high thermal power is not necessary; a power level of critical experiments such as 100 W is optimal from viewpoints of accessibility to the core. Although the necessity of thermal feedback effect of the core might be insisted, such experiments can be performed by using an electrical heater which simulates the reactor power without real fission energy nor accompanying fission products. The maximum thermal power is temporarily decided as 500 W.

The most serious problem to build a new nuclear facility is how to prepare the fuel, since tons of low-enriched uranium or plutonium are necessary to simulate the ADS (e.g. k_{eff} = 0.95) in the fast neutron system. We expect to use the plate-type fuel of the FCA in JAERI/Tokai, or preferably to merge FCA into TEF-P. Various simulation materials required to simulate fast reactor and ADS such as lead and sodium for coolant, tungsten for solid target, ZrH for moderator, B_4C for absorber, and AlN for nitride fuel will be prepared.

TEF-P is therefore designed with referring to FCA; the horizontal table-split type critical assembly with a rectangular lattice matrix. Figure 5 shows a conceptual view of the assembly. Proton beam was introduced horizontally from the center of the fixed half assembly.

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 energy of 600 MeV produces about 15 neutrons by the spallation reaction with 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 the power distribution at the deep subcritical state such as k_{eff} = 0.90.

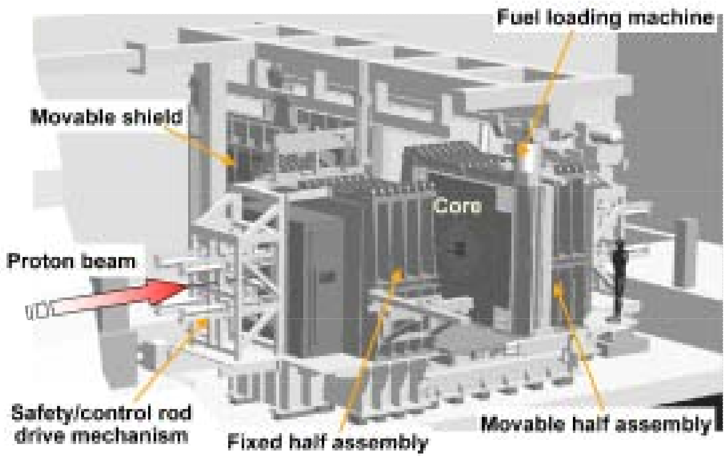

Fig.5 Conceptual view of TEF-P

Low current proton beam is extracted by a laser charge exchange technique from high-intensity beam line of 200 kW (0.33 mA, 600 MeV), most beam of which is introduced into TEF-T. The 200 kW proton beam is pulsed one whose repetition rate is 25 Hz and maximum pulse width is 0.5ms. 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 small amount (below 10 W) of H^- to neutral one (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 straightforward 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; 1ns to 0.5ms pulse is expected to be available. The proton beam intensity can be controlled by a collimator which is installed inside of the facility. A demonstrate test of the laser charge exchange technique is scheduled in the year of 2004 using H^- ion source at JAERI/Tokai.

In the conceptual design of the facility, the shielding property for high energy neutrons is calculated. About 2 m thickness of concrete shield is necessary even when the core is surrounded by about 1m of lead reflector. Safety aspect of the facility is also extensively studied. The prompt critical accident can be terminated without fuel melting by the reactor scram system with multiplicity and variety. The unexpected introduction of the 10 W beam into the critical state also can be terminated safely with the reactor scram.

3.2.2 Experimental Program using TEF-P

Using TEF-P facility, many experimental studies are planned. The R&D items to be carried out at TEF-P are listed in Table 1.

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

Purpose	Experimental items
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 and void in the beam duct
	Simulation of Pb-Bi coolant
Demonstration of controllability of a hybrid system driven by an accelerator	Feedback control of reactor power by beam intensity adjustment
	Investigation of system behavior at beam trip and re-start
	Evaluation of temperature effect for core and target
	Investigation of instability of system caused by the subcriticality and the annular arrangement of the core
	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 changing parametrically the subcriticality and the spallation source position. The material of the target will also 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 the 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 the beam trip and the re-start are also examined.

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. 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.

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 (28cm x 28cm) will be replaced with a hexagonal subassembly.

The distinguished points of TEF-P in comparison with existing experimental facilities can be summarized as follows: (1) both the high energy proton beam and the nuclear fuel are available, (2) the maximum neutron source intensity of about 10^{12} n/s is strong enough to perform precise measurements even in the deep subcritical state (e.g. k_{eff}=0.90), and, is low enough to easily access to the assembly after the irradiation, (3) wide range of pulse width (1ns - 0.5ms) 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 devise.

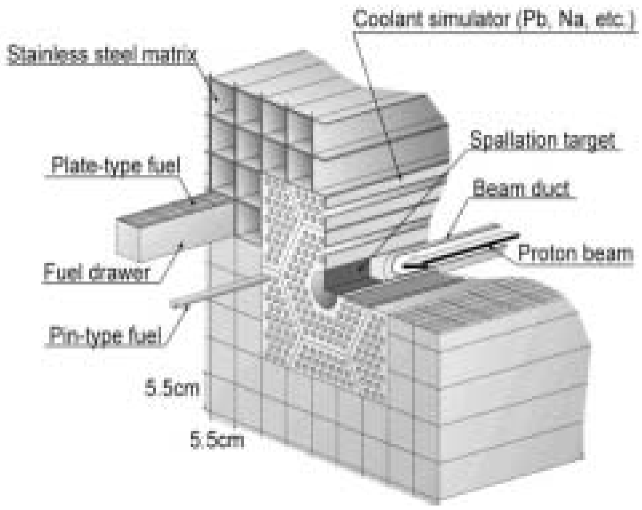

Fig.6 Pin-type fuel partial loading section for TEF-P

3.3 ADS Target Test Facility (TEF-T)

3.3.1 Background and Purposes of TEF-T

JAERI proposes an ADS using Pb-Bi eutectic for both spallation target and coolant of subcritical core. There are, however, many technical issues to use Pb-Bi. To solve them, several R&D programs are proposed. Material irradiation experiment in stagnant Pb-Bi environment has been performed at the SINQ facility in PSI, Switzerland. MEGAPIE project[7] are planned to demonstrate feasibility of Pb-Bi target by using the existing accelerator facilities. According to the limitation of existing equipments of the facility and machine time, experimental data obtained from these programs are limited. Therefore, parametric and systematic experimental data are required to perform the detailed design of the ADS. TEF-T aims at preparation of the database required for ADS design.

One of the most important components for ADS is a beam window. Beam window forms a boundary between an accelerator and a subcritical core. The beam window suffers heavy irradiation of proton and spallation neutron, mechanical stress caused by the pressure difference between the accelerator and flowing Pb-Bi target, thermal stress arising from heat deposition of high energy particles and beam transients (startup, shutdown and beam trip) and chemical interaction with Pb-Bi. It is, therefore, important to prepare the database to estimate a lifetime of the beam window. The experiments to obtain the design database for beam window are also the important mission of TEF-T.

Some technical subjects must be also investigated for the high-power spallation target system, e.g. the purification system for spallation products and the polonium, remote handling device for the Pb-Bi system, and so on. R&D of these items is, also necessary to build TEF-T. Hence, non-radioactive tests have been performed at JAERI.

3.3.2 Specification of TEF-T

TEF-T mainly consists of a Pb-Bi spallation target, a Pb-Bi cooling system (primary loop), a helium gas cooling system (secondary loop) and an access cell to handle irradiation test pieces. Pb-Bi eutectic is filled into a cylindrical vessel made by type 316 stainless steel. An effective size of the vessel is about 15cm diameter and 60cm long. Several kinds of target are planned and designed according to the objective of the experiment. One of the target vessels is designed to irradiate ten or more irradiation samples in the flowing Pb-Bi environment.

A primary Pb-Bi loop is designed to allow Pb-Bi flow with maximum velocity of 2 m/s and of maximum temperature of 723K. Though we selected type 316 stainless steel as a structural material of the target vessel, other candidate material can be used according to the result of corrosion test in Pb-Bi non-irradiated loop. Target vessel is mounted on a movable trolley and is to be withdrawn to the access cell after the irradiation. The access cell has functions to replace target vessel, to clean up residual Pb-Bi to reduce exposure dose by the spallation products, and to pick up irradiated material test pieces remotely. The primary cooling devices are also located in the access cell to make a path of the loop short and improve maintainability.

Neutronic analysis of the Pb-Bi target was performed. Pb-Bi (45%Pb-55%Bi) is filled in a cylindrical vessel made by type 316 stainless steel with 1mm thick. Average Pb-Bi temperature is assumed to 673K. Figure 7 shows a 1 to 1 scale target model. From the neutronics calculation results, the Pb-Bi target of TEF-T has enough performance to irradiate samples at ADS operating condition by adjusting the beam profile.

Fig.7 Pb-Bi spallation target model (1/1 scale)

4. Conclusion

The conceptual design study of ADS is in progress at JAERI under the OMEGA program. JAERI has proposed a concept of a Pb-Bi cooled ADS as a possible option for dedicated transmutation system.

To establish the technical basis for ADS, the construction of TEF is proposed under the J-PARC Project. TEF consists of two buildings: TEF-P and TEF-T. TEF-P is a critical assembly, which can accept the 600 MeV - 10 W proton beam for the spallation neutron source. The purposes of TEF-P are the experimental validation of the data and method to predict neutronics of the fast subcritical system with spallation neutron source, the demonstration of the controllability of a hybrid system driven by an accelerator, and the basic research of reactor physics for transmutation of MA and LLFP. TEF-T is a facility to perform the experiments to prepare the database for engineering design of ADS using 600 MeV - 200 kW proton beam and the Pb-Bi spallation target. The purposes of TEF-T are R&D for the irradiation damage of the beam window, the compatibility of the structural material with flowing liquid Pb-Bi and the operation of the high power spallation target. The neutronic, thermal-hydraulic and structural characteristics of the Pb-Bi target were described. Combining the experimental results and experiences obtained at both facilities, the feasibility of the ADS will be evaluated and demonstrated.

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