R&D ACTIVITIES ON ACCELERATOR-DRIVEN TRANSMUTATION SYSTEM IN JAERI

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Abstract

The Japan Atomic Energy Research Institute (JAERI) is conducting the study on the dedicated transmutation system using the accelerator driven subcritical system (ADS) aiming at the reduction of the burden for the final disposal of the high-level radioactive waste. A subcritical reactor with the thermal power of 800 MW has been proposed, where 250 kg of minor actinide (MA) can be transmuted annually. Many research and development activities including the conceptual design study are under way and planned at JAERI to examine the feasibility of the ADS. In the field of the proton accelerator, a superconducting LINAC is being developed. In the field of the spallation target using lead-bismuth eutectic (LBE), material corrosion, thermal-hydraulics, polonium behavior, and irradiation effect on materials are being studied. Moreover, in the framework of the J-PARC project (Japan Proton Accelerator Research Complex), JAERI plans to construct the Transmutation Experimental Facility (TEF) to study the feasibility of the ADS using a high-energy proton beam and nuclear fuel, to accumulate valuable knowledge about reactor physics and operation of ADS, and to establish a database for the LBE spallation target and relevant materials.

Introduction

To reduce the amount of the minor actinide (MA) and the long-lived fission products (LLFP) in the high-level radioactive waste, the Japan Atomic Energy Research Institute (JAERI) has proposed the accelerator-driven subcritical system (ADS). The ADS proposed by JAERI is an 800 MWth, MA-nitride fuelled, Pb-Bi eutectic (LBE) cooled fast subcritical reactor driven by a spallation neutron source using an LBE target and a 1.5 GeV, 20-30 MW proton accelerator [1]. To realize such a large-scale ADS, several technical issues should be studied and resolved. These issues include, for example, reliability of the accelerator, beam transport system, high power spallation target technology, integrity of beam window, reactor physics of subcritical system, controllability, MA transmutation performance, and fuel handling.

To overcome these issues, JAERI is conducting various R&D activities in the fields of the proton accelerator, the LBE technology and the subcritical reactor. Moreover, to promote the R&D on the ADS and the related transmutation technology, JAERI plans to build the Transmutation Experimental Facility (TEF) in the Tokai Research Establishment under a framework of the J-PARC (Japan Proton Accelerator Research Complex) project. This report presents the recent R&D activities on the ADS in JAERI including the plan of TEF.

Design Study of ADS

The ADS proposed by JAERI is an 800 MWth, tank-type subcritical reactor shown in Figure 1, where LBE is used for both the core coolant and the spallation target. It can transmute 250 kg of MA annually.

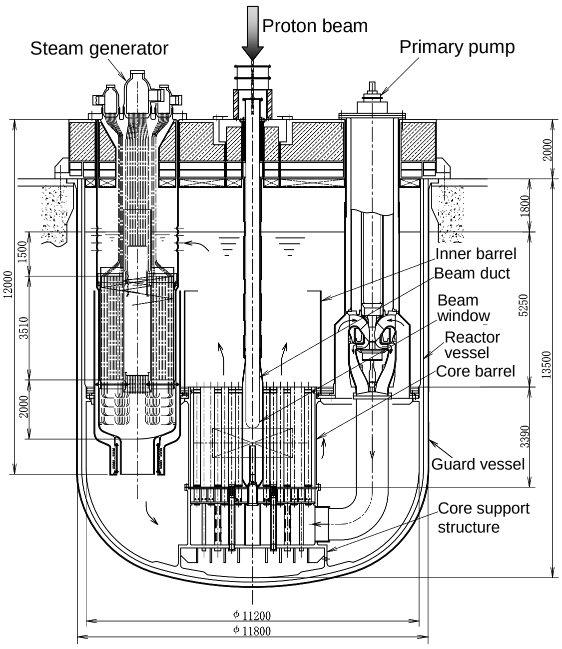


Figure 1. **Concept of 800 MWth, LBE-cooled, tank-type ADS.**

Neutronics Design [1]

In general, the dedicated fuel for MA transmutation without uranium and plutonium shows rapid increase of the effective multiplication factor (k_{eff}) with fuel burn-up because MA acts as a good fertile material. To mitigate this burn-up reactivity swing, plutonium is added at the initial loading, while it is not added on and after the 2nd. cycle. The initial content of plutonium is one of the important design parameters to be optimized. In addition, inert matrix such as ZrN should also be mixed into the fuel to reduce the power density.

The acceptable value of the maximum multiplication factor (k_{max}) is another important design parameter which largely influences the core performance. In the previous neutronics design [2], we had adopted k_{max} = 0.95, taking account of the limitation for the critical safety of existing fuel fabrication and processing plants. Recently, considering the accidental situations of the ADS, we estimated the marginal subcriticality to avoid the critical accident of the ADS, and it was concluded that k_{max} of 0.97 can be adopted [1].

The burn-up reactivity swing and the power peaking factor of the core are shown in Figure 2. After the operation during 600 effective full power days (EFPD), the fuel is unloaded and reprocessed to remove fission products by the pyrochemical process. Then MA is added to compensate the burnt actinides, and nitride fuel is re-fabricated. Table 1 shows the parameters of the reference

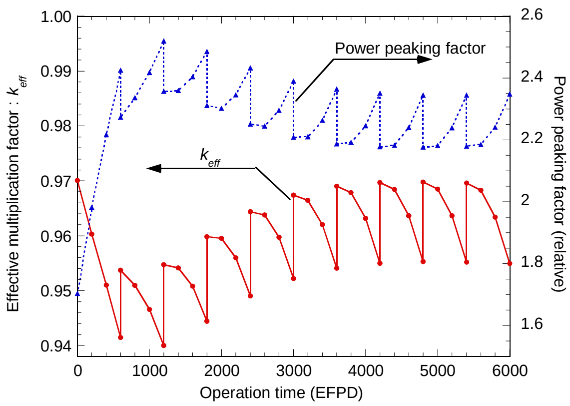


Figure 2. **Change of effective multiplication factor and power peaking factor with burn-up** [1]

core. The k_{eff} changes from 0.970 to 0.940. According to this reactivity swing, the proton beam power should be adjusted from 12 MW to 27 MW. The optimization of the neutronics design is still continued with considering the results of the thermal-hydraulic and structural design study of the beam window and the fuel assembly.

Table 1. **Core physics parameters of 800 MWth, LBE- cooled ADS** [1]

Parameters	Values
Thermal power	800 MW
Cycle length	600 EFPD
Active core diameter	236.6 cm
Active core height	100.0 cm
Inert matrix (ZrN)	49.9 w%
Initial Pu (inner / outer)	30.0 % / 48.5 %
Total heavy metal inventory	4,115 kg
Initial MA inventory	2,500 kg
Effective multiplication factor (k_{eff})	Initial : 0.970 Max. : 0.970 Min. : 0.940
Burn-up reactivity swing	3.01 %Δk/k
Peaking factor (whole core)	Max. : 2.52 Min. : 1.70
Average power density	191 W/cm^3
Proton beam energy	1.5 GeV
Proton beam current	Max. : 17.9 mA Min. : 8.1 mA

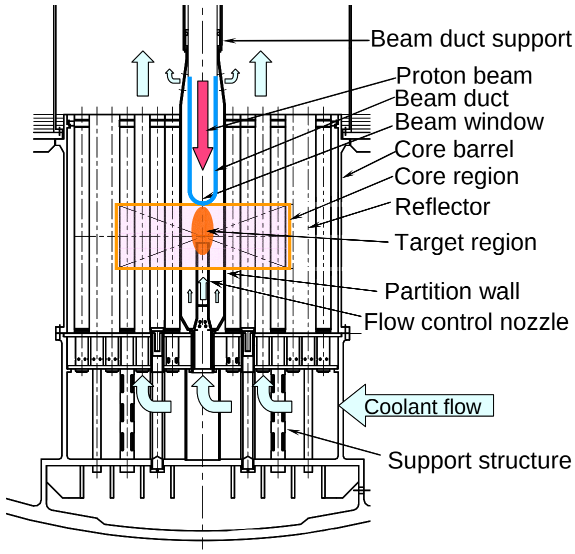


Figure 3. **Preliminary design around beam window and core**

Thermal Hydraulic and Structural Design of ADS

In JAERI's reference design, "ductless type" fuel assemblies are adopted to reduce neutron capture reactions by the structural material and to enhance cooling capability of the decay heat during fabrication, transportation and storage. Figure 3 shows preliminary design around the beam window and the core. The LBE flows into the core bottom structure and it is distributed to the target region and the core region. A "partition wall" is installed between the target and the core regions to avoid the cross flow of the LBE [3].

In terms of thermal-hydraulic and structural design, one of the critical issues for ADS is the engineering feasibility of the beam window for the high power spallation target. To discuss the feasibility of the beam window, two targeted criteria were set: (1) flow speed of LBE should not exceed 2 m/s, (2) outer surface temperature of beam window should not exceed 500 ºC. To satisfy these conditions in the case of the Gaussian beam profile, a "flow control nozzle" was installed aiming at the enhancement of the cooling performance for the beam window. Figures 4 and 5 show the results of the hydraulic analysis and the temperature analysis, respectively, where the inlet temperature of the LBE is 300ºC. It can be seen that the criteria are satisfied.

The material of beam window should be carefully selected with considering many design conditions such as the corrosion / erosion caused by LBE, the strength in high temperature, the creep strength, and the irradiation effect by protons and neutrons. The beam window will be exchanged every one or two years. The partition wall and the flow control nozzle will also be exchanged periodically because they also suffer from heavy irradiation. Further study, therefore, to estimate the life time of the beam window is necessary as the next step. Preliminary analyses on the cooling performance for the hot spot fuel pins and the seismic load of the reactor components are also under way to discuss the feasibility of the ADS.

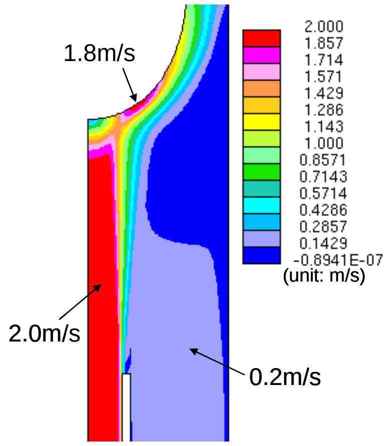


Figure 4. **Result of hydraulic analysis for beam window**

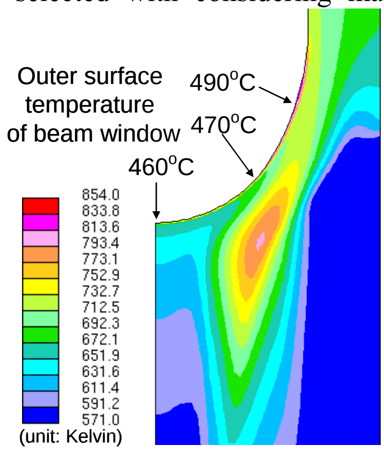


Figure 5. **Result of temperature analysis for LBE target and beam window**

Research and Development on Accelerator for ADS

The proton accelerator for the ADS should have the high power such as more than 20 MW, which is ten times higher than currently existing accelerators. The most crucial issue to achieve such high power is how to reduce the beam loss down to the acceptable level. Moreover, high efficiency should also be achieved to assure the self-sustainability for electricity of the whole system of ADS. Taking account of these conditions, the superconducting linear accelerator (SC-LINAC) is regarded as the most promising choice.

R&D of SC-LINAC

The main part of SC-LINAC consists of a series of "cryo-modules", each of which contains two units of superconducting cavities made of high-purity niobium as shown in Figure 6. In JAERI, a prototype cryomodule was fabricated recently, and the demonstration of its high efficiency in electric field and

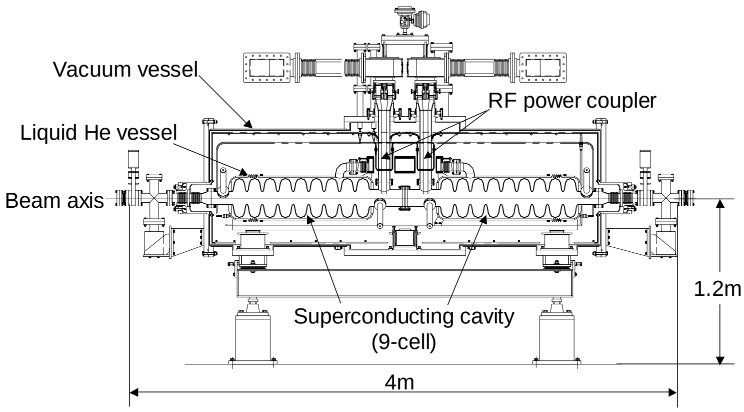


Figure 6. **Schematic view of 9-cell cryomodule**

helium cooling performance is under way. The maximum surface electric field more than 30 MV/m is targeted, though actual acceleration of protons will not be attempted using this prototype cryomodule. The real acceleration of the proton beam by SC-LINAC is planned as the Phase-2 of the J-PARC project described in the next section.

J-PARC Project

In addition to above mentioned development, JAERI has started the high-intensity proton accelerator project, called J-PARC (Japan Proton Accelerator Research Complex), with the High Energy Accelerator Research Organization (KEK) as shown in Figure 7 [4]. As the Phase-1 of this project, a proton LINAC with 0.33 mA x 200 MeV and two proton synchrotrons with 0.33 mA x 3 GeV and 0.015 mA x 50 GeV, respectively, are under construction and scheduled to be completed by 2007. In addition, the energy of LINAC will be upgraded to 400MeV within the framework of Phase-1.

Through the experience of the construction of the 400 MeV LINAC, we can accumulate the technology for the low energy part of LINAC even though it is operated in the pulsed mode. In Phase-2 of the project, the SC-LINAC will be constructed to upgrade the proton energy from 400 MeV to 600 MeV. Then the 600 MeV proton beam will be introduced into the Transmutation Experimental Facility (TEF) to be described in the later section of this report.

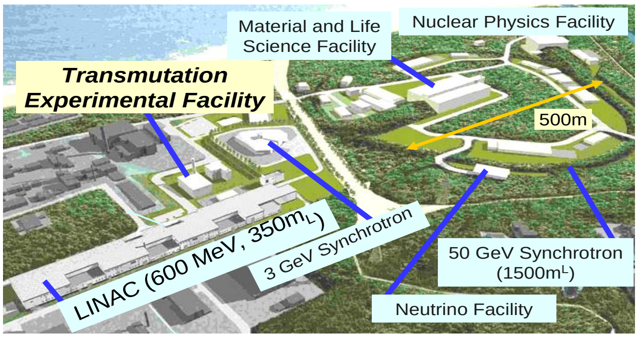


Figure 7. **Site plan of J-PARC**

Research and Development on Lead-Bismuth Spallation Target and Coolant

Lead-bismuth eutectic (LBE) is regarded as the prime candidate for the spallation target and also for the core coolant of the ADS. Advantages to use LBE are in its wide temperature range of liquid state (397K - 1943K), chemical stability in comparison with sodium, large neutron yield as the spallation target, and low neutron capture cross section. The LBE technology for the nuclear system is, however, not well-established except for Russian experience in submarine reactors. In JAERI, four major fields are being studied for the LBE target and related materials: (1) corrosion of structural material, (2) thermal-hydraulics at beam window, (3) behavior of radioactive impurity, and (4) irradiation damage of material exposed by protons and neutrons.

Corrosion of Structural Material

In high temperature region above 450ºC, LBE is known as corrosive liquid against structural material such as austenitic stainless steels. The Russian experience suggests that it can be overcome by controlling oxygen concentration in LBE to form oxide film on the surface of the material. In JAERI, two kinds of activities are under way: the static corrosion test and the loop test.

Using the static corrosion equipment, specimens can be soaked in LBE of 350 ºC to 600 ºC with the oxygen concentration controlled. The first test in oxygen-saturated LBE at 550 ºC for 500 hours showed that the thickness of the corrosion film formed on the surface of the specimens was dependent on the chromium content, i.e. the specimens with high chromium content showed thin corrosion film [5]. Recent test results for 3000 hours suggested the good corrosion resistance of 18Cr-20Ni-5Si steel in oxygen- saturated LBE at 550 ºC because of the formation of silicon oxide film on the surface [6].

The loop test using the JAERI Lead Bismuth Loop -1 (JLBL-1), shown in Figure 8, is also under way. The inventory of LBE is 18 litters. The maximum flow rate is 5 liter/min. and the maximum flow speed at the test tube section is 1 m/s. The maximum temperature is 450 ºC, where the maximum temperature difference between the high-temperature test section and the low-temperature section is 100 ºC. The first 3000-hour operation using oxygen-saturated LBE was carried out with LBE temperature of 450 ºC and the temperature difference of 50 ºC. The inner surface of the test tube made of 316SS was investigated after the operation. Although locally corroded surface was observed, the corrosion depth was not very serious; 0.05-0.1 mm / 3000 h [7, 8]. Up to now, a 3000-hour operation with the temperature difference of 100 ºC was successfully completed without any trouble.

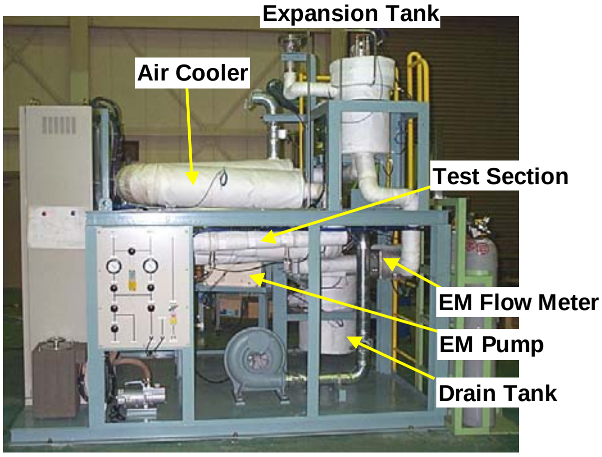


Figure 8. **JAERI Lead Bismuth Loop -1 (JLBL-1)**

In addition to above mentioned tests in JAERI, the material corrosion loop test is also under way at Mitsui Engineering & Shipbuilding Co., Ltd. (MES) as a joint research to accumulate material database for the beam window of the ADS. Two specimens, austenitic steel JPCA and martensitic one F82H, are being tested in the loop. Moreover, to investigate the effect of oxygen concentration on the embrittlement of structural materials, the fatigue test is also under way in the oxygen-controlled LBE circumstance.

Thermal-hydraulics at Beam Window

One of critical problems in the design of the ADS is the feasibility of a beam window that is used under hard conditions: irradiation with protons and neutrons, corrosion and erosion by LBE, heat deposit caused by incident protons, and stress by heavy liquid metal. To overcome these difficulties, the temperature of the beam window should be lowered by appropriate cooling. The cooling performance of LBE for the beam window is, therefore, important issue for the design of ADS.

To investigate the prediction accuracy of heat transfer coefficients at the beam window of hemispherical shape, JAERI and MES recently built a thermal-hydraulic loop at the Tokai Research Establishment of JAERI as a joint research. Figure 9 is a block diagram of the loop. The maximum flow rate of LBE is 500 liter/min. The outer diameter of the test vessel is 8.9 cm and the gap between the test vessel and outer pipe is about 1.3 cm. The maximum flow speed of LBE at the head of the beam window is about 0.8 m/s. A sheathed heater is attached on the inside wall of the hemispherical head of the test vessel. Temperatures at several points on the test vessel will be measured at various flow rates and inlet temperatures, and the heat transfer characteristics will be investigated.

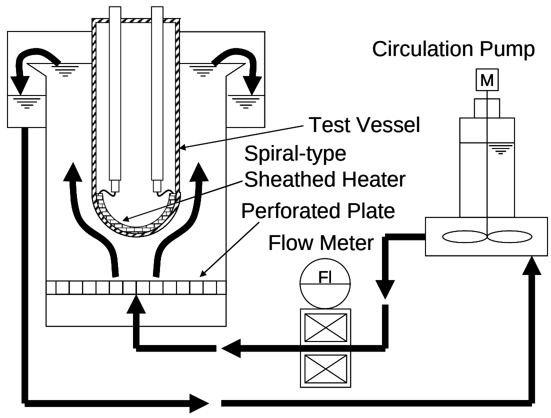


Figure 9. **Block diagram of thermal-hydraulic loop to measure heat transfer characteristics of LBE at beam window**.

Behavior of Radioactive Impurity

When LBE is used as the core coolant, ^{210}Po is produced mainly by $^{209}Bi(n, \gamma)^{210}Bi$ reactions and β-decay. ^{210}Po is an α-emitter whose half-life is 138 days, and has volatile property. It is, therefore, important to know the evaporation rate of Po from LBE in order to evaluate safety of the system.

To know the behavior of ^{210}Po in LBE, JAERI, the Japan Nuclear Cycle Development Institute (JNC), Nippon Nuclear Fuel Development Co. Ltd., and Kaken Co. Ltd. Collaboratively irradiated solid Pb-Bi at the material test reactor JMTR, and are investigating its thermochemical properties. In this collaborative work, the evaporation rates of Po from LBE are being measured by the transpiration method, shown in Figure 10, as a function of the LBE temperature.

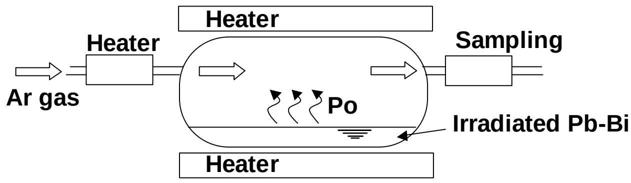


Figure 10. **Transpiration method to measure evaporation rate of Po from LBE**

Irradiation Damage of Material Exposed by Protons and Neutrons

The irradiation damage of the structural material by protons and neutrons, especially for the beam window, is one of the crucial issues for the feasibility of the ADS. Although the material database by the irradiation tests will be accumulated at the ADS Target Test Facility in J-PARC, JAERI is also participating in the irradiation program for the spallation target material using the SINQ facility at the Paul Scherrer Institute in Switzerland. Small pieces of samples irradiated by 580 MeV protons were transported to JAERI, and the tensile test and the fatigue test were done at the hot cell facility. The results for the austenitic steel irradiated up to about 10 DPA (Displacement Per Atom) showed the hardening of the material by the irradiation [9].

Research and Development on Subcritical Reactor Physics

As mentioned in the previous section, “unconventional” fuel will be used in the ADS dedicated to the transmutation of MA. It is therefore important to know the accuracy of neutronics calculation for ADS. In JAERI, the prediction accuracies of the physics parameters such as the criticality, the burn-up reactivity and the coolant void effect are being evaluated by using the sensitivity of nuclear data and the covariance data of MA nuclides. Reactor physics experiments for the subcriticality monitoring and various physics parameters of ADS are also under way at critical assemblies: Fast Critical Assembly (FCA) in JAERI and Kyoto University Critical Assembly (KUCA) as a joint research. Nagoya University is studying the subcriticality monitoring method using the reactor noise technique and trying to demonstrate its applicability at KUCA as a joint study with JAERI.

Transmutation Experimental Facility

To study the basic characteristics of the ADS and to demonstrate its feasibility from viewpoints of the reactor physics and the spallation target technology, JAERI plans to build the Transmutation Experimental Facility (TEF) in the Tokai Research Establishment under a framework of the J-PARC project as already shown in Figure 7. The construction of the TEF is scheduled to start around 2007.

TEF consists of two buildings: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T) as shown in Figure 11. 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 LBE. The outline of TEF-P and TEF-T is presented hereafter [10].

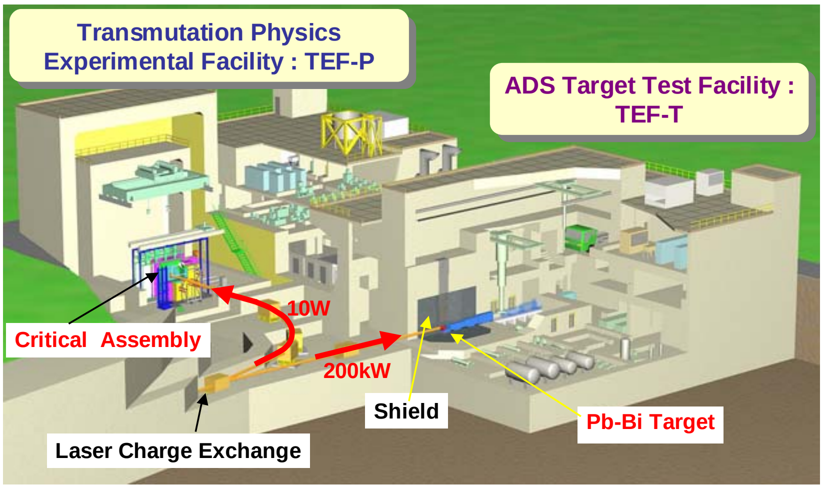


Figure 11. **Concept of Transmutation Experimental Facility**

Transmutation Physics Experimental Facility (TEF-P)

The main purposes of TEF-P are to research the reactor physics of the subcritical core driven by a spallation neutron source, to demonstrate the controllability of the subcritical core and to research the performance of the transmutation system for both critical and subcritical states. For these purposes, a power level of critical experiments such as 100 W is optimal from a viewpoint of accessibility to the core. The TEF-P is therefore designed with referring to the Fast Critical Assembly (FCA) in JAERI, i. e., the horizontal table-split type critical assembly with a rectangular lattice matrix and plate-type fuel. In TEF-P, not only the subcritical experiment but also the critical experiment can be performed, which enhances the experimental accuracy and widens the range of experimental items significantly.

Low current proton beam, less than 10W, is extracted by a laser charge exchange technique from a high-intensity beam line of 200 kW (0.33 mA, 600 MeV), most protons of which are introduced into TEF-T. The maximum neutron source intensity of about 10^{12} n/s can be obtained by this low current beam, which is strong enough to perform precise measurements even in the deep subcritical state (e.g. k_{eff} =0.90) and low enough to easily access to the assembly after the irradiation. The time width of the proton pulse for TEF-P can be adjusted from 1 ns to 0.5 ms by changing the duration of the laser exposure. The proton beam intensity can be also controlled by a collimator.

Using TEF-P, reactor physics parameters such as power distributions, k_{eff} , effective neutron source strength, and neutron spectrum will be measured by changing parametrically the subcriticality and the spallation source position. As for the demonstration of the hybrid system, feedback control of the reactor power will be examined by adjusting the beam intensity. The cross section data of MA and LLFP for high-energy region (up to several hundreds MeV) can be also measured by the time-of-flight (TOF) technique with the proton beam of about 1 ns short pulse width. Ultimate target of the facility is to install a partial mock-up region of pin-type MA nitride fuel with air cooling to measure the physics parameters of the transmutation system for both critical and subcritical states. The conceptual view of the partial pin-fueled assembly is shown in Figure 12.

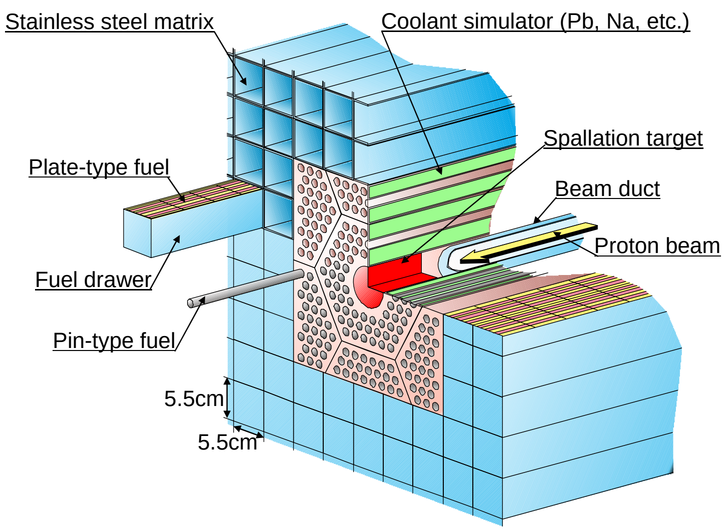
ADS Target Test Facility (TEF-T)

TEF-T is the material irradiation facility using a 200 kW proton beam of 600 MeV and an LBE target. For the demonstration of the feasibility of the beam window, it is important to make the proton density at the beam window identical to that of the future ADS plant. As described in the previous section, a 30MW proton beam of 1.5 GeV (20 mA) at the maximum is used in the 800 MWth ADS, where the diameter of the beam is defocused to about 45 cm. The proton beam density at the beam window becomes about 13 $\mu A/cm^2$ in average and the maximum density will be restricted to about 30 $\mu A/cm^2$. At TEF-T, the proton beam of 0.33mA is focused to 4 cm in diameter, which provides the beam density of 26 $\mu A/cm^2$ in average; this beam density is considered high enough for the demonstration and the material irradiation.

The conceptual design for the LBE target and the whole system of TEF-T is under way. Two types of target concepts are being considered: (a) demonstration type and (b) irradiation type. The former type simulates the LBE target of the future ADS plant in small size, while the latter provides the good field of sample irradiations for the development of the material database.

The principal purposes of TEF-T are to demonstrate the feasibility of the high-power spallation target system and to research the material compatibility in LBE with irradiated circumstances. The irradiated structural material of the target vessel, as well as the irradiated material test pieces, will be examined from viewpoints of tensile strength, ductility, fatigue, fracture toughness, DBTT (Ductile-Brittle Transition Temperature) and so on. In addition to these tests, the effects of the corrosion and the erosion by LBE and the spallation products will be studied by changing the parameters such as the temperature, the irradiation period, the flow speed and the oxygen concentration in LBE. Plenty of experiences to be accumulated at TEF-T will be valuable to learn how to operate and handle the high-power spallation target for ADS.

Figure 12. **Conceptual view of central pin-fueled region of TEF-P**



Concluding Remarks

JAERI is conducting the study on the dedicated transmutation system using the ADS. The design study is under way on LBE-cooled, tank-type ADS with the thermal power of 800 MW. In terms of the thermal-hydraulic and structural design, the feasibility of the beam window is mainly discussed, and a promising design concept was obtained, though further investigation is still necessary on the irradiation effect and so on.

Many research and development activities are under way and planned in parallel at JAERI to examine the feasibility of ADS. In the field of the proton accelerator, the SC-LINAC is being studied by fabricating a prototype cryomodule. In the J-PARC project, the experience for the low energy part of LINAC will be accumulated, and the SC-LINAC will be constructed between 400 - 600 MeV. In the field of the LBE technology to be used for the spallation target and the core coolant of the ADS, material compatibility, thermal-hydraulics and polonium behavior are being studied. The study on the irradiation effect of structural material for the beam window is also under way. In the field of the reactor physics of the subcritical core fueled with MA, the reliability of nuclear data and the subcriticality monitoring technique are being investigated.

In the framework of J-PARC project, JAERI plans to construct the Transmutation Experimental Facility (TEF) to show the feasibility of the ADS with using a high-energy proton beam, to accumulate valuable knowledge about reactor physics and operation of ADS, and to establish a database for LBE spallation target and relevant material.

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