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A conceptual study on a material irradiation experimental facility with a lead-bismuth spallation target for the accelerator-driven system development

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Abstract

An experimental facility with a lead-bismuth spallation target/coolant is proposed to be built under the JAERI-KEK joint project for high intensity proton accelerator. This facility aims at studying basic physics and technological issues relevant to the accelerator-driven systems (ADS) development. Proton beams of 600 MeV and 0.3 mA (200 kW) are to be delivered to this facility. A frequency and pulse width of the beam are 25 Hz and 500 μs, respectively. The principal objectives of the facility are to accumulate material irradiation database, in particular, for a beam window, fuel cladding candidates and structural material of ADS. The target is designed to be able to irradiate several kinds of materials. A radiation dose over 10 DPA/year can be achieved with a 200 kW proton beam by optimizing the beam profile. The current design study is presented with emphases of target neutronics and thermal properties of the target/coolant system.

1. Introduction

A study of the transmutation of minor actinides (MA) and long-lived fission products (LLFP) has been performed at Japan Atomic Energy Research Institute (JAERI) under the national OMEGA program[1]. JAERI proposes accelerator-driven system (ADS) as a primary option of the transmutation of MA.

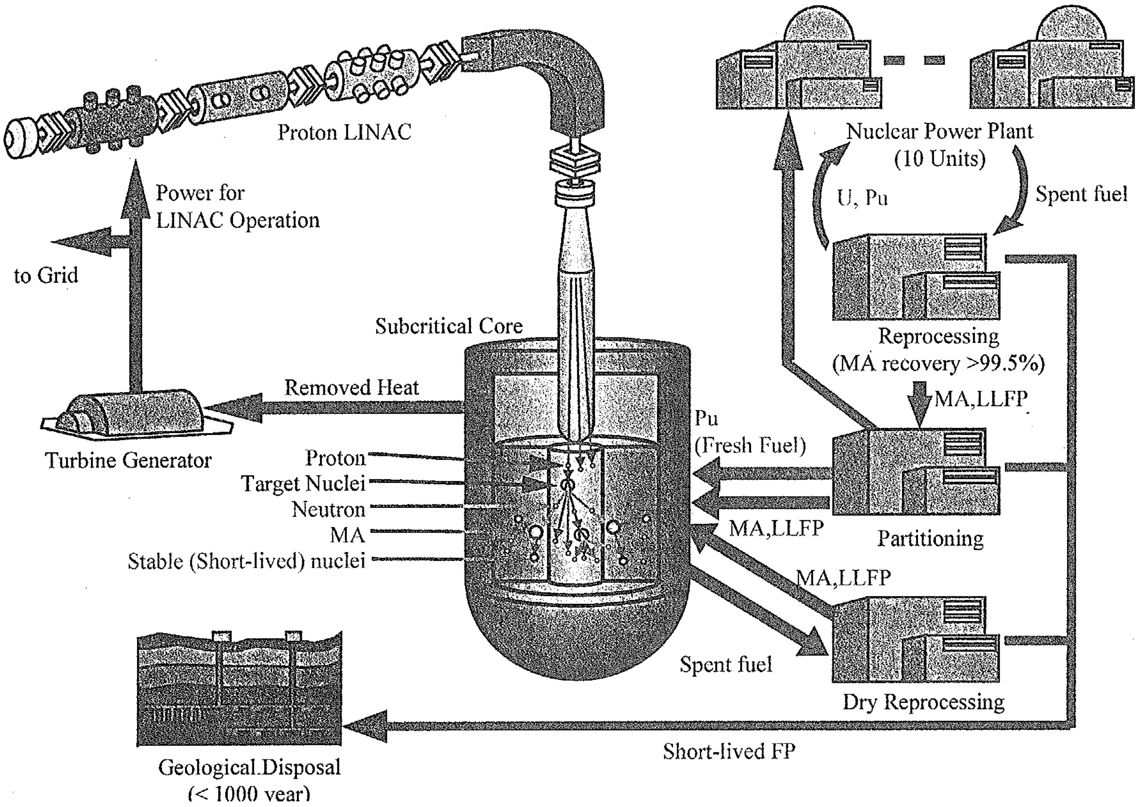

Fig.1 Accelerator-driven transmutation system concept

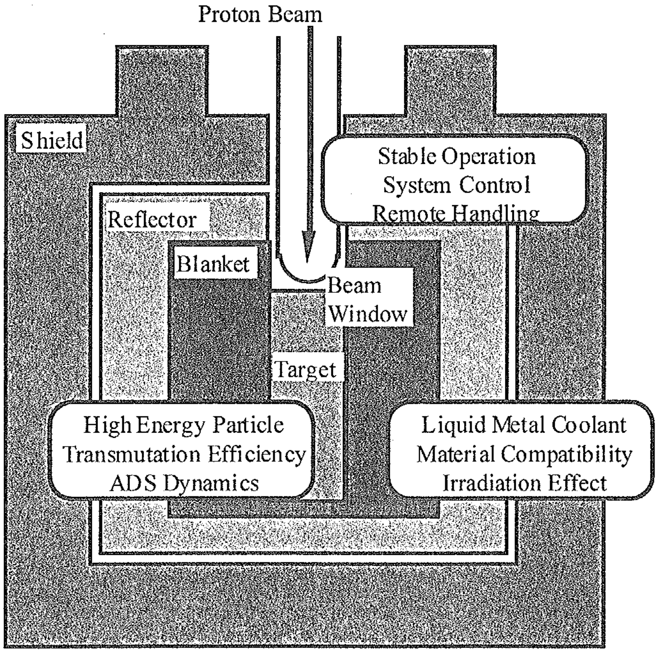

Fig.2 Technical subjects of ADS development

Figure 1 shows a concept of the transmutation system proposed by JAERI. ADS is primarily composed of an intense proton accelerator, a spallation target and a fast subcritical blanket. Because of the subcriticality of the blanket, ADS can accept various composition of MA, which is deeply depend on the burnup profile and cooling time of spent fuel. The chain reaction in the blanket is controled only by the spallation neutron source, ADS is operated in a condition with large safety margins. For a design study of ADS, there are many technical subjects summarized in Fig. 2. In the figure, there are specific issues to ADS in terms of a neutronics of the subcritical blanket driven by spallation neutron, an engineering application of the high power spallation target, a development and operation of the intense proton accelerator and so on. They have been never considered in power reactor development.

In 1998, JAERI and High Energy Accelerator Research Organization launched a joint project to build a research complex with high power proton accelerator[2]. Figure 3 illustrates the latest layout of the research complex.

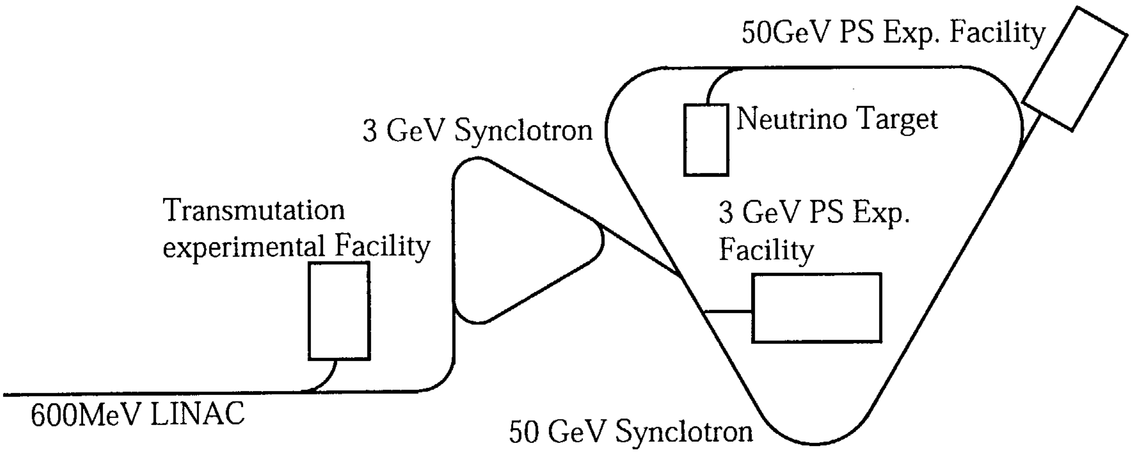

Fig.3 Facility layaout of the JAERI-KEK joint project

The complex is composed of a 600 MeV superconducting proton LINAC, a 3 GeV proton synchrotron, a 50 GeV proton synchrotron and experimental facilities for life science, material science, fundamental particle physics and ADS physics and engineering. The experimental facility for ADS aims at studying basic physics and technological issues relevant to the accelerator-driven systems (ADS) development. Proton beams of 600 MeV and 0.3 mA (200 kW) are to be delivered to this facility. In this paper, a conceptual study of a material irradiation experimental facility with a lead-bismuth eutectic (Pb-Bi) spallation target is summarized.

2. Objective of the facility

ADS is a hybrid system of an accelerator and a subcritical reactor. A beam window acts as a boundary of both components. Beam window receives heavy irradiation of accelerated proton and spallation neutron, thermal stress caused from proton beam operation (i.e. startup, shutdown and beam trip) and external load by the pressure difference between the beam duct and liquid target flow. To satisfy an accuracy of the structure analysis and lifetime estimation of beam window, a detailed design database with reliable experimental data is required. A database must be prepared not only for the beam window but also for the fuel cladding, blanket structure and other components of ADS. Material irradiation for these materials and newly developed material for target/coolant for the ADS has to be performed.

JAERI proposes a lead-bismuth eutectic as a primary cadndidates of the target/coolant of the accelerator-driven transmutation system[3]. By using liquid metal target/coolant, issues associated with temperature and radiation damage becomes not critical. In addition, the neutron economy will be improved by omission of a structure to support the target and a cooling by light element coolant. Furthermore, the technologies for sodium-cooled fast reactor could be applicable to the Pb-Bi because the melting temperature of the Pb-Bi is similar to that of sodium. However, to handle the Pb-Bi in safe, there are limited experimental data as a coolant and no exiperience as a spallation target. Thus, a step by step accumlation of the data and experience is a key element of the facility. A particular interest is placed on providing experimental data of the material compatibility with the Pb-Bi under the proton and neutron irradiation fields at a servicing temperature. Handling technology of the Pb-Bi is also an important subject along with the thermal hydraulic of the Pb-Bi target/coolant system. Table 1 summarizes the experimental items to be studied at this facility.

Table 1 Experimental items of the facility

Subjects	Item
Material Irradiation	Irradiation effect of the material with proton and neutron
	PIE of the irradiation samples
	Data base construction for ADS design
Material Compatibility with Liquid Metal	Corrosion by liquid metal
	Correspondence of irradiation damage and corrosion
System Operation	Heat removal by liquid metal coolant
	Development of the purification system
	Transient analysis at beam on/off and beam trip

As known well, data for Pb-Bi coolant are exist in Russia based on their military application. Part of the data is provided but it is still not enough to construct a database for system design. From the provided data, a quite high solubility of nickel in Pb-Bi eutectic is reported. Erosion of stainless steel, well verified material for sodium-cooled fast reactor, is also observed. To select a structural material for Pb-Bi, irradiation of new material such as Cr-Mo steel and F82H steel and confirmation of the effectiveness of the adjustment of oxygen concentration in Pb-Bi will be examined at this facility.

3. Outline of the transmutation engineering experimental facility

A transmutation engineering experimental facility mainly consists of a Pb-Bi spallation target, a Pb-Bi cooling system (primary loop), a helium gas cooling system (secondary loop), access cells to handle irradiation test pieces, and an emergency beam dump. A facility has one basement floor and two ground floors. A tentative layout of the basement floor is illustrated in Fig. 4.

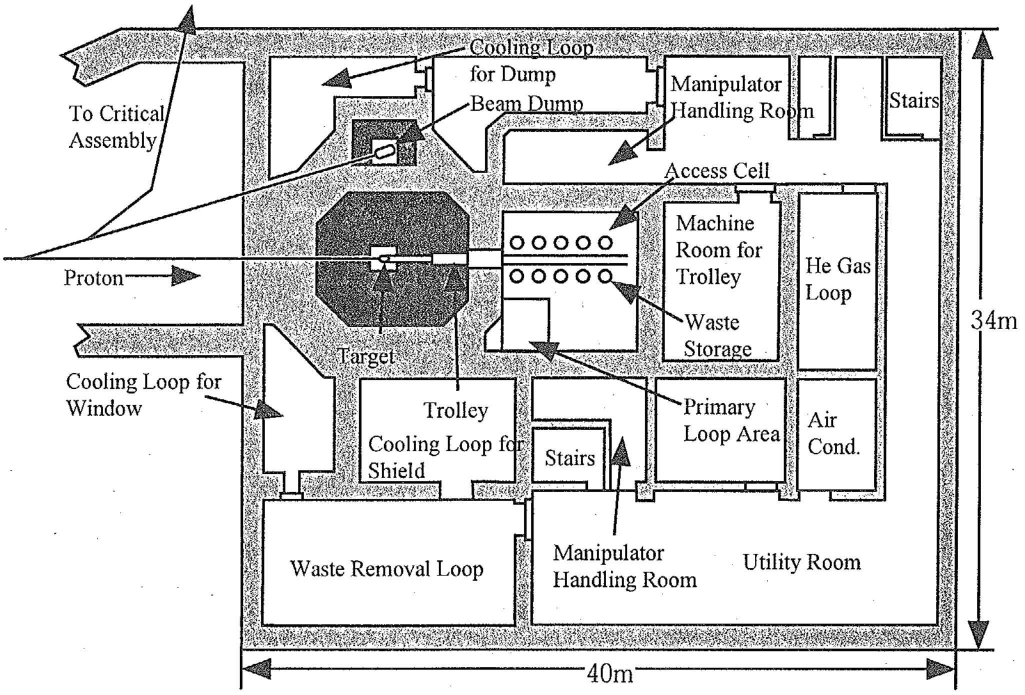

Fig.4 Floor layout of the facility

Pb-Bi eutectic is filled into a cylindrical vessel made by stainless steel. A size of the vessel is 15cm diameter and 60cm long. A number of ten or more irradiation samples can be irradiated simultaneously in the target vessel. The primary Pb-Bi loop is designed to allow Pb-Bi flow with 2m/s of a maximum velocity and 450 degree centigrade of maximum temperature. Though we selected type 316 stainless steel as the structural material of the target vessel, other candidate material can be used according to the result of corrosion test in Pb-Bi cold loop.

A target vessel is installed at the target room surrounded by the iron and concrete shield. Water cooling channels for the heat removal are located at the inside wall of the shield. Target vessel is mounted on a movable trolley and the target vessel is to be extracted to the access cell by the trolley. The access cell has functions of replacing target vessel, cleaning up of residual Pb-Bi to reduce exposure dose by the spallation products, and picking up irradiated material test pieces remotely. The primary cooling devices are also located in the access cell to make a short path of the loop and improve maintainability.

Other components, e.g., the radioactive waste removal circuits, a solid radioactive waste storage, the air conditioners, an electricity and machinery, and a radiation control systems are located in the facility.

4. Neutronic performance of the Pb-Bi target

A preliminary analysis of the Pb-Bi target neutronics was performed. Parameters and a two-dimensional cylindrical analysis model are shown in Table 2 and Fig. 5, respectively. A Pb-Bi eutectic (45%Pb-55%Bi) is filled in a cylindrical vessel made by type 316 stainless steel. Average Pb-Bi temperature is fixed to 400 degree centigrade. Thickness of the vessel is 1 mm. A sample holder for the irradiation materials, which is installed in a real target, is not considered at this analysis. The irradiation room is filled with a helium atmosphere and a target is located at the center of the room. Cooling channel in the wall of the irradiation room is considered.

Table 2 Neutronics analysis parameters

Proton Beam Energy	600 MeV
Proton Beam Current	333 μA
Annual Operation Hours	5000 hrs
Beam Profile	1 to 6 cm diameter, flat distribution
Target Diameter / Length	15 cm / 60 cm
Target Material	45% Pb – 55% Bi
Target Average Temperature	400 ℃
Target Vessel Material, Thickness	316 Stainless Steel, 1mm

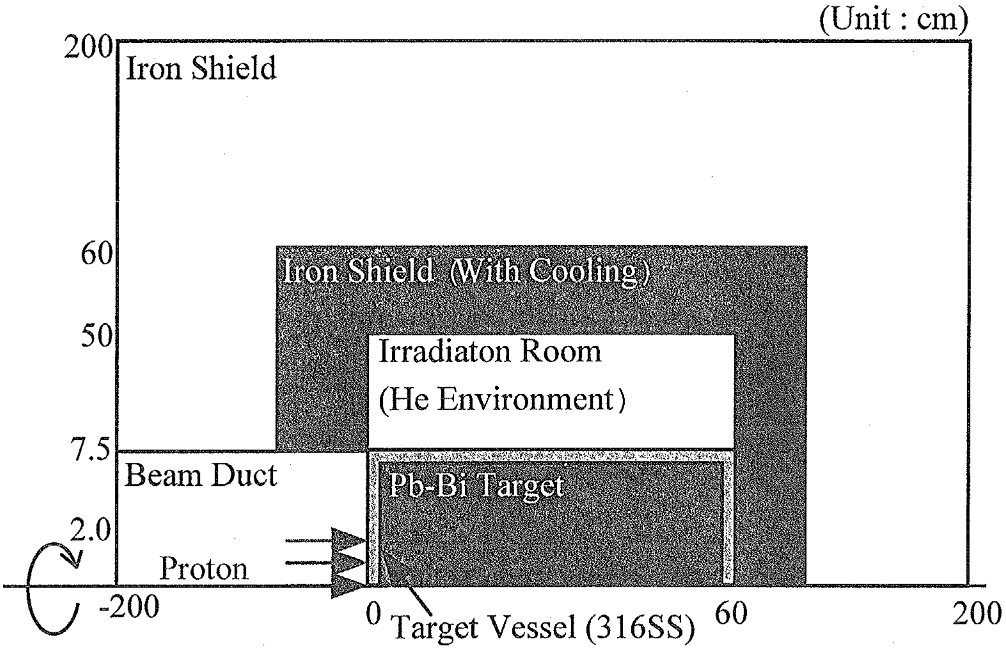

Fig.5 Neutronics analysis model

An ATRAS code system[4] was used for the analysis. ATRAS code system consists of a NMTC/JAM code[5] for the spallation analysis, FSOURCE code for the fixed source file creation, SCALE code[6] for the effective cross section formation, TWODANT code[7] for the low energy neutron transport and BURNER[8] code for the burnup analysis. Pre/post processores for input generation and data tabulation and JENDL-3.2[9] based multigroup cross section library are also included in the code system.

At the analysis, a Bertini model, the nucleon-nucleon cross section given by Pearlstein and the level density parameter given by Ignatyuk were implemented. The cutoff energy of the cascade code for proton and neutron were set at 20 MeV. A transport analysis of the neutrons below 20 MeV was done by TWODANT with P_3-S_8 approximation. Figures 6 and 7 indicates a axial distribution of the total neutron flux and annual DPA (Displacement per Atom) of type 316 stainless steel along to the center of the target, respectively. An axial peak position along the center of the target is seen about 3 cm depth for neutron flux and 6 cm depth for DPA. A radiation dose over 10 DPA is observed at the depth from 2cm to 10cm. Figure 8 shows a radial neutron flux distribution at the axial flux peak point in the target. Figure 9 shows an annual DPA distribution of type 316 stainless steel along the radial axis at an axial DPA peak point in the target. The figures indicate that this target has enough performance to irradiate samples at ADS operating condition by adjusting the beam profile. A maximum neutron flux level is as same order as that of JMTR (Japan Material Test Reactor). Over 10 DPA/y of irradiation can also be done at this facility. And it is also possible to irradiate many samples simlteniously in one operation period by spreading a proton beam.

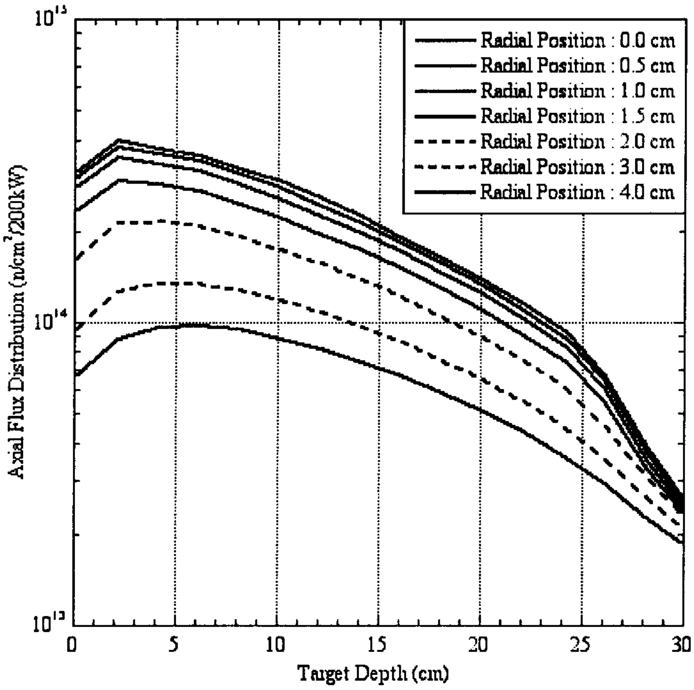

Fig.6 Axial neutron flux distribution along the center of the target

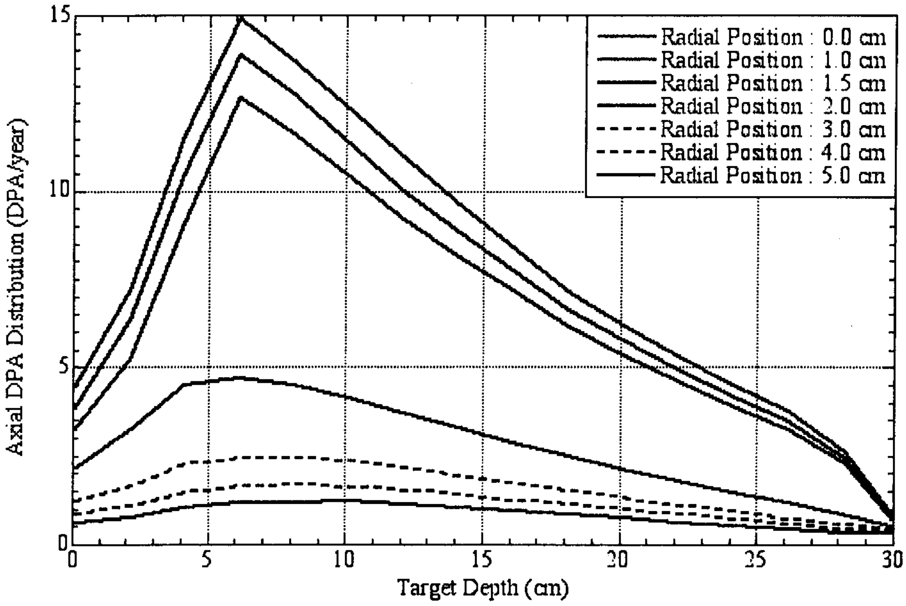

Fig.7 Axial distribution of annual DPA along the center of the target

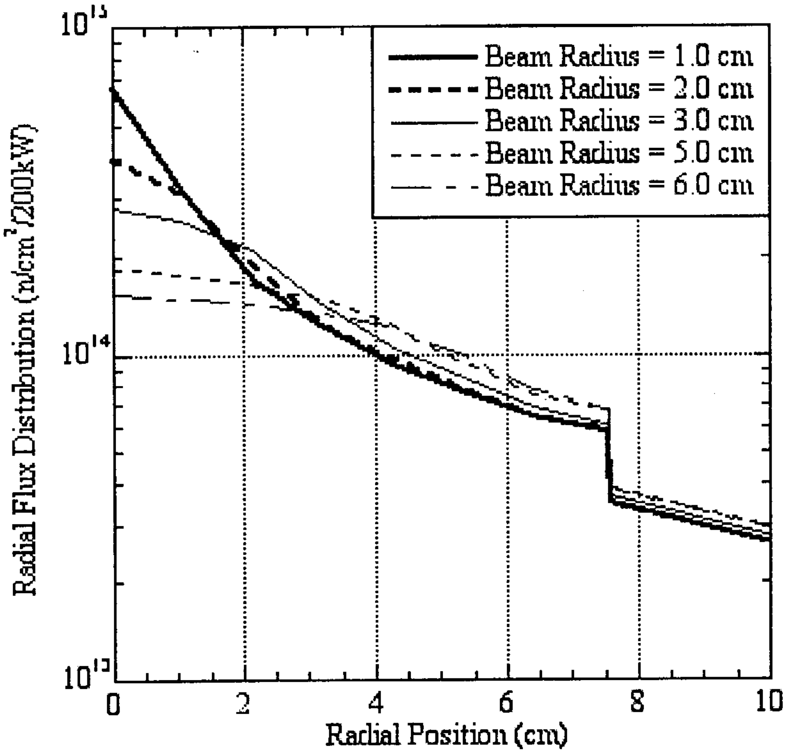

Fig.8 Radial neutron flux distribution at axial flux peak point

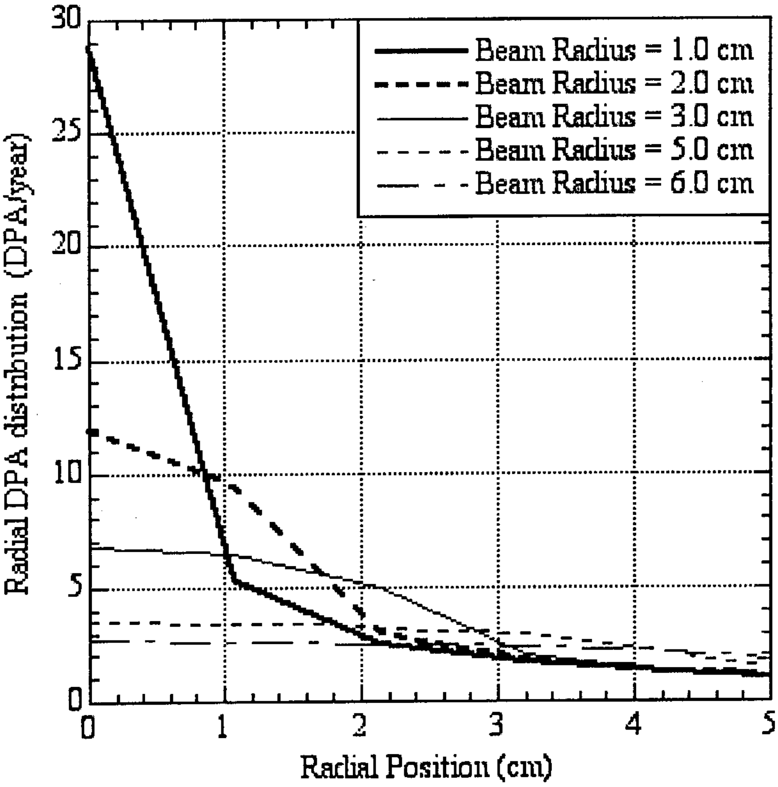

Fig. 9 Radial DPA distribution at axial peak point

5. Thermal-hydraulic performance of the Pb-Bi Target

A beam window of the Pb-Bi target receives heavy irradiation of protons and neutrons and the thermal and mechanical stresses. The thermal stress is occured by the temperature swing at times of the startup, shutdown and beam trips. The mechanical stress is caused by the pressure difference between vacuum in a beam duct and the flowing Pb-Bi eutectic. Shape of the window is a half sphere with an outer diameter of 120 mm. Material of the window is a modified 9Cr-1Mo steel which is assumed to suppress a corrosion of nickel. Maximum allowable pressure and temperature of the window is assumed 0.7 MPa and 600 ℃.

According to the parameters, the required thickness of the window is assumed to 1.15 mm. Considering a margin for erosion by Pb-Bi eutectic, a preliminary window thickness is tentatively determined to be 1.4 mm.

A preliminary estimation of the beam window lifetime was performed.Parameters for beam operation are the same as those of neutronics analysis (600 MeV-200kW, 5000hours/year operation). A model for the hydraulic calculation by the STAR-CD code is shown in Fig. 10. Pb-Bi flows from right side to left side of the figure. An orifis is located in front of the beam window. A temperature map around the beam window and a temperature distribution of the beam window surface is shown in Figs. 11 and 12, respectively. From the results, servicing temperature of 400 ℃ was obtained while the maximum temperature of the beam window was kept less than 600 ℃.

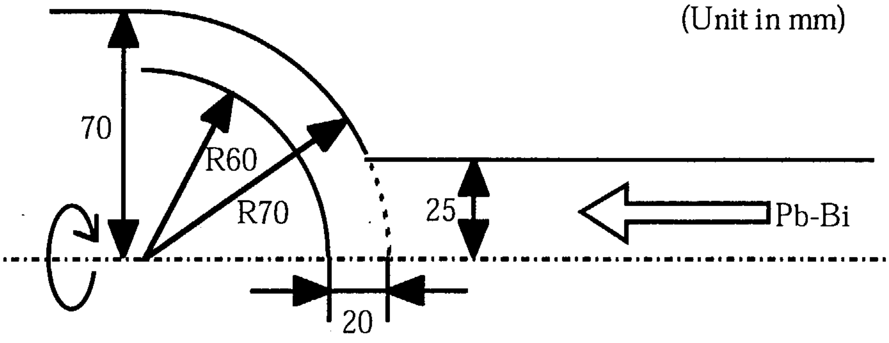

Fig.10 Thermal-hydraulic analysis model

Based on the temperature distribution of the beam window, structure analysis was performed. A maximum stress is about 95 N/mm^2. From the stress analysis, lifetime of the window is about 4000 hours and the maximum cycle of beam on/off (including beam trip) is estimated about 10^4 times. By increasing the heat transfer coefficient, a lifetime can be increases over 10^6 hours. Further optimization of the structure around beam window to improve the heat transfer efficiency must be required.

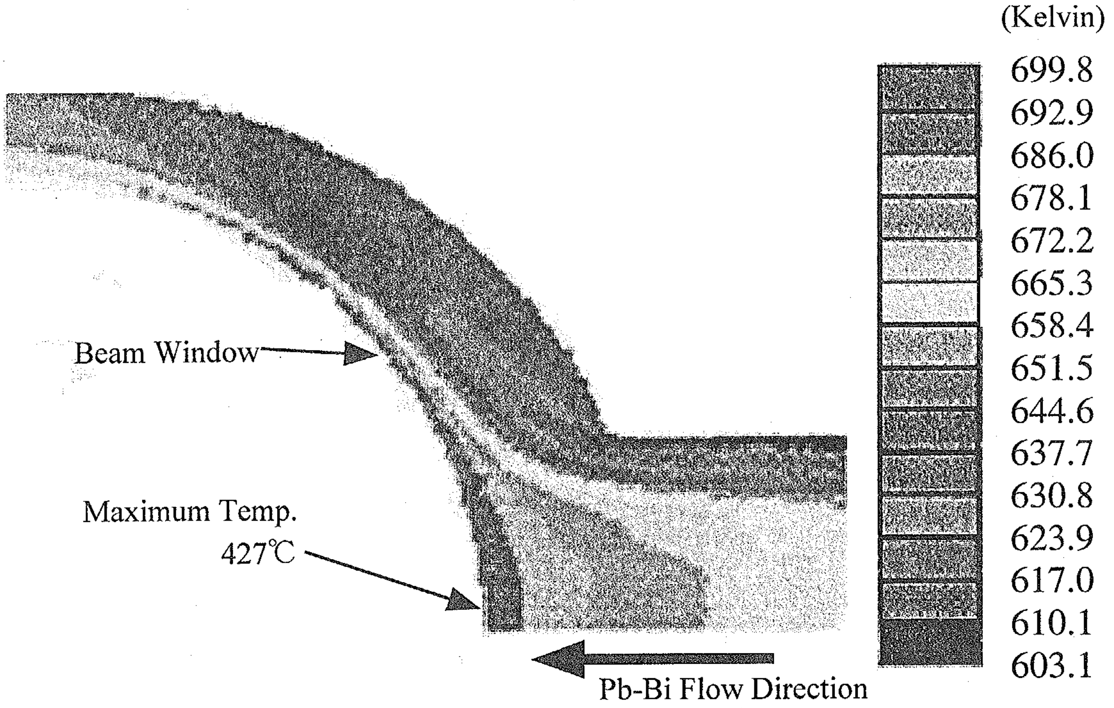

Fig.11 Temperature map around beam window

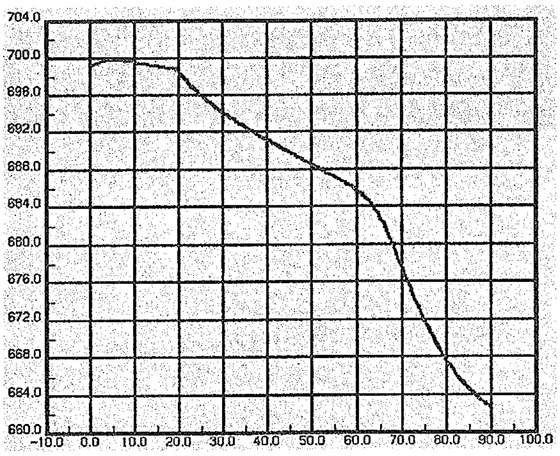

Fig.12 Temperature distribution at the beam window surface

6. Conclusion

The Pb-Bi target is designed to be able to irradiate a number of ten or more test materials simultaneously. Over 10 DPA/year dose can be achieved with a 200 kW proton beam by optimizing the beam profile. According to the thermal-hydraulic analysis further optimization was required to increase a lifetime of the beam injection surface of the target.

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