DESIGN PROGRESS OF ADVANCED FUSION NEUTRON SOURCE FOR JA/DEMO FUSION REACTOR

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Abstract

Based on results from the IFMIF/EVEDA project in the Broader Approach (BA) activities, a conceptual design of the Advanced Fusion Neutron Source (A-FNS) in Rokkasho, Aomori aiming at obtaining material irradiation data for a fusion DEMO reactor is presented in this paper. The A-FNS is composed of an accelerator facility with a 40 MeV and 125 mA deuteron beam, a test facility including a liquid lithium target system and a post irradiation examination facility. The prime objective of A-FNS is the data acquisition of RAFM irradiation data by 2035 and the tritium recovery test on the blanket and durability test on the fusion diagnostic and control devices. A particular attention in the design is paid on an integration of the test facilities by adopting a newly designed for A-FNS. Furthermore, as a unique usage of A-FNS neutron, the multipurpose usage has been investigated. For the mission achievement, the A-FNS/CDA will continue until 2020 and then the EDA will be continuously implement between 2020 and 2024. After the EDA, the A-FNS facility is to start constructing from 2025 toward the neutron operation around 2030. As current activity for A-FNS conceptual design, the analyses and investigations for test module, Li target and loop, remote maintenance, neutron monitor and multipurpose usage has been progressed to solve the design issues.

1. INTRODUCTION

An intense fusion neutron source is generally considered necessary for the irradiation verification of fusion reactor candidate material. The international fusion materials irradiation facility, IFMIF, is just due to the candidate material irradiation test with neutron emitted from deuteron-lithium nuclear reaction. The IFMIF/engineering validation and engineering design activities, EVEDA, has implemented as an JA-EU international collaboration [1]. From 2007, the IFMIF/EVEDA has started to validate the construction of IFMIF based on the Broader Approach (BA) phase. In IFMIF/EVEDA, main three activities have been implemented. The IFMIF engineering design activity has been implemented until 2014. The international development of linear IFMIF prototype accelerator, named LIPAc, has been currently progressed to achieve the beam examination with 125mA and 9MeV deuteron beam in QST/Rokkasho in Japan. This accelerator mainly consists of injector, Radio Frequency Quadrupole (RFQ) and Superconducting Radio Frequency (SRF) linac. The experimental validation of lithium target and loop has been carried out with the use of a large scale EVEDA lithium test loop, ELTL, set up in JAEA/Oarai and the high speed flow and long-term stability operation has been successfully validated [2].
Based on results from the IFMIF/EVEDA project, a conceptual design of intense Fusion Neutron Source, in Rokkasho aiming at obtaining material irradiation data for a fusion DEMO reactor is presented. “Japan’s road map and action plan to promote R&D for a fusion DEMO reactor” decided in 2017 requires that the material irradiation data should be acquired for a decision in the 2030s to start construction of a fusion DEMO reactor [3]. Accordingly, an advanced fusion neutron source based on its construction in Rokkasho, named A-FNS, has been designed at QST on the basis of the results from the IFMIF/EVEDA project in the BA activities.

This paper explains the following issues of A-FNS:

- Objectives of A-FNS for DEMO fusion reactor design;
- Schedule for the construction and operation;
- Basic parameter and components;
- Current activities for CDA.

2. OBJECTIVES

For the evaluation of candidate material for DEMO reactor, the objectives of A-FNS are the following three investigations:

- Helium production and displacement effect of fusion structure material;
- Tritium production and recovery properties of fusion blanket;
- Durability of diagnostics and control devices for fusion reactors.

Furthermore, the A-FNS is to provide unique irradiation modules and beam station for the multipurpose usages of A-FNS neutron. Especially, production of medical and industrial radioisotope is a candidate plan in the A-FNS. The neutron beam station in A-FNS is also to provide for the field of material research and development.

2.1. He production and displacement effect

The first wall material of JA/DEMO is to be utilized with a Reduced Activation Ferritic-Martensitic (RAFM). F82H is the most candidate RAFM. The first wall material will be exposed to fusion neutron flux in the order of 10^{13} cm^{-2} s^{-1}. Since experimental damage investigation under the intense fusion neutron flux has never been implemented, the data acquisition is essential issue to decide the construction of DEMO reactor. Fig. 1 shows the correlation of displacement per atom (DPA) and helium production in case of iron (Fe). It is indicated from Fig.1 that the fusion neutron source like IFMIF is adequate to verify the candidate material irradiation. The past representative DT neutron sources, RTNS-II and JAEA/FNS, are not sufficient to implement the material damage investigate [4, 5]. On the other hands, existing spallation neutron sources, e.g. SNS/SINQ and LANSCE/MTS, are enough neutron intensity [6]. However, the ratio of He per DPA is far from that of DT neutron.

Fig. 2 shows the prediction of loss of elongation of RAFM by irradiation and strategy of testing [7]. From previous neutron irradiation experiments with fission test reactors, it is found that the total elongation of RAFM tend to be harden to around 10% and keep the value of around 7%. On the other hands, the case of fusion neutron irradiation, it is predicted that the tendency is different from that of fission reactor. From the prediction, the start of deviation appears from 10 dpa. To verify the prediction, the first objective of A-FNS is to carry out the neutron irradiation test of F82H/RAFM until 20 dpa and to inspect the fission and fusion neutron correlation.

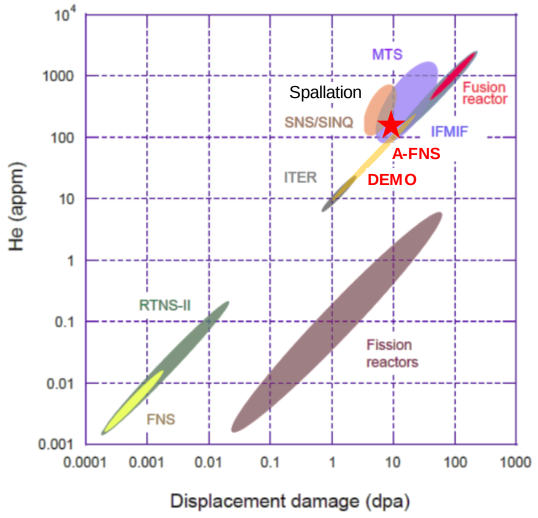


FIG.1. Correlation of DPA and Helium production.

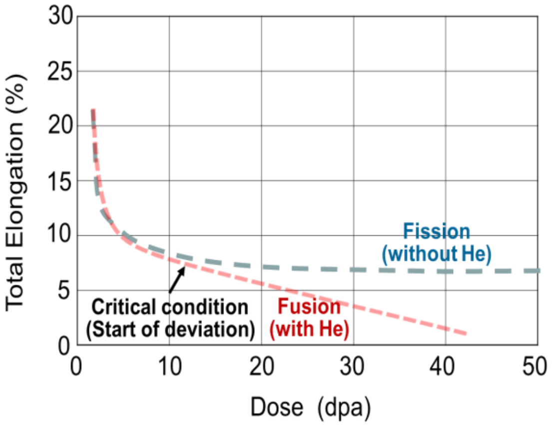


FIG.2. Prediction of loss of elongation of RAFM by irradiation [4].

2.2. Tritium production and recovery properties of fusion blanket

For the investigation of the effective tritium breeding ratio of fusion DEMO reactor, it is quite important to carry out the tritium recovery investigation with fusion neutron irradiation. Especially, in case of JA/DEMO, a type of water cooled ceramic breeding blanket (WCCB) is designed as a main candidate [8]. Since 2009, JAEA/Fusion Neutron Source have performed the tritium release neutronic experiment on the WCCB blanket at JAEA/FNS and then clarified the ratio of tritium release and the recovered tritium chemical form [5]. Since the above previous fusion neutronic experimental investigation was carried out under very low DT neutron flux less than 10^8 cm^{-2} s^{-1}, it was not sufficient to verify the tritium production and recovery properties with. For the precise investigation of tritium production and recovery properties, it is suggested to implement the investigation of these properties with A-FNS.

2.3. Durability of diagnostics and control devices

The functional materials to diagnose and control the fusion plasma will be used near hard dose area. Such materials, for example optical fiber, semiconductor, mirror, magnet coil and insulators, readily tend to be damaged with neutron and gamma-ray. To investigate these life time and replacement period, the durability test should be implement with A-FNS.

3. SCHEDULE

Figure 3 shows the schedule relation of JA/DEMO and A-FNS between the conceptual design phase and operation one. The conceptual design phase of DEMO will be implement until 2025 and then the phase will move into the engineering design phase. The decision of the DEMO construction is set to at 2035. Therefore, the irradiation property data of F82H with A-FNS have to be acquired by 2035. The A-FNS/CDA will be advanced until 2020 and implement the A-FNS/Engineering Design until 2025. A-FNS should be constructed at the latest by 2031. For the acquisition of F82H irradiation data, the irradiation period will be for 2-3 years.

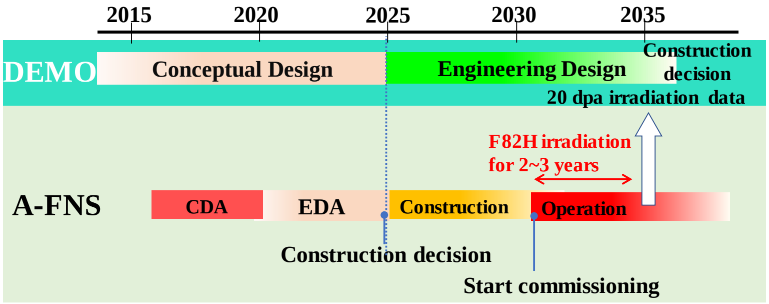


FIG.3. Relation of DEMO design phase and A-FNS design, construction and operation.

4. BASIC PARAMETERS AND COMPORNENTS

From the above-mentioned schedule, the 20 dpa irradiation test of RAFM with A-FNS should be completed before 2035 including the post irradiation experimentation (PIE). That means the irradiation operation for 2-3 years. The A-FNS requires the basic parameters in Table 1. The A-FNS is designed to obtain the material irradiation data up to 20 dpa for a fusion DEMO reactor and is composed of a deuteron accelerator with one beam line, a liquid lithium target test facility in Figs. 4 and a post irradiation examination facility in Fig. 5. In the accelerator facility, deuterons are accelerated up to 40 MeV with a beam current of 125 mA, bombard a liquid lithium target, and generate highly intense neutrons by the *d*-Li splitting reactions with energy spectrum similar to that in fusion reactor and about 7 x 10^{16} neutrons per second (see Table 1). The availability of operation should be more than 33% from the viewpoint of 20 dpa irradiation. The length between the accelerator and the target facility is 50 m to suppress the neutron back streaming and lithium vapor from the lithium target to the accelerator facility. While the accelerator for A-FNS is presently based on the design of the linear accelerator (LIPAc) in the IFMIF/EVEDA project, the result of the LIPAc long operation to be obtained in Rokkasho under the BA activities will be reflected to its design [2]. The test facility is composed of a test cell, lithium target cell and access cell. The design is based on the results of IFMIF/EVEDA lithium target loop (ELTL) test that has achieved high and stable Li flow up to 20 m/s and long operation [3]. The remote handling system, radioisotope and lithium handling cell and temporary storage for radioisotope waste are also installed in the test facility. The remote handling method based on the method developed in the nuclear fuel processing plant is applied. In order to acquire a considerable number of RAFM post irradiation data by 2035, the A-FNS should integrate with the PIE facility. This arrangement scheme of PIE is an essential advantage to achieve the prime mission of A-FNS. Finally, a total area of the A-FNS building is 180 m x 64 m.

TABLE 1. Basic parameters of A-FNS.

Items	Basic parameters	Values
Ion beam	Particle	Deuteron
	Incident energy	40 MeV
	Current	125 mA
	Foot print	200 x 50 mm^2
Target	Material	Lithium (liquid)
	Temperature	250 ºC
	Thickness	25±1mm
	Flow velocity	15 ms^{-1}
Neutron	Intensity	6.8 x10^{16} s^{-1}
	Flux	6.0 x10^{14} cm^{-2} s^{-1}
	He production rate	312 appm/fpy
	Displacement	24.7 dpa/fpy

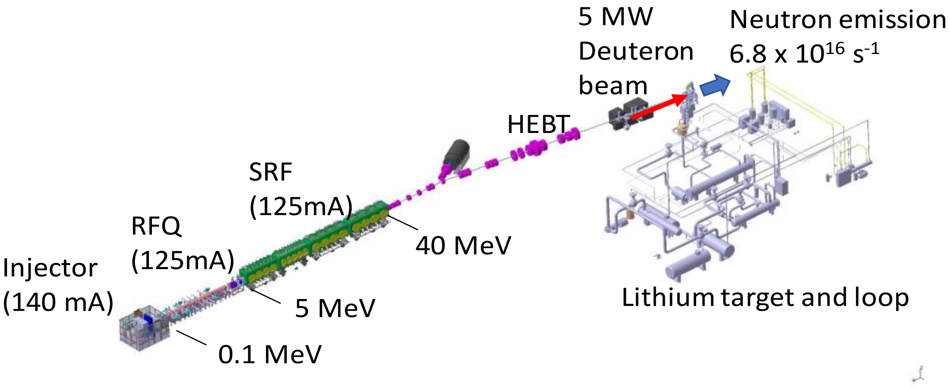


FIG. 4. Schematic view of A-FNS components

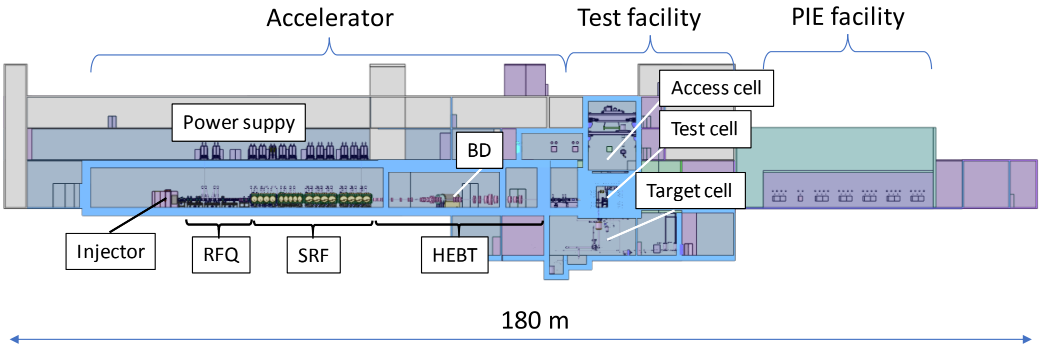


FIG. 5. Vertical cross-sectional view of A-FNS main building. RFQ: Radio Frequency Quadrupole linac for 5MeV, SRF: Superconducting Radio Frequency linac for 40 MeV, HEBT: High Energy Beam Transfer Transport and BD: Beam Dump are installed.

5. SITE

In QST, the A-FNS main building and related buildings are planning to construct at Rokkasho. Fig. 6 is shown the image of location. As the related building and facility, electric power receiving and water supply equipment, lithium facility and storage facility for the activation will be needed. Therefore, its total area needs 300 m x 450 m (13.5 hectares). The amount of electric power and water consumption for A-FNS operation are almost estimated at 60MVA and 1500m^3/day, respectively. From the viewpoint of the application of IFMIF/EVEDA property and resource, it is considerable to construct the A-FNS facility beside the present Rokkasho site in Japan.

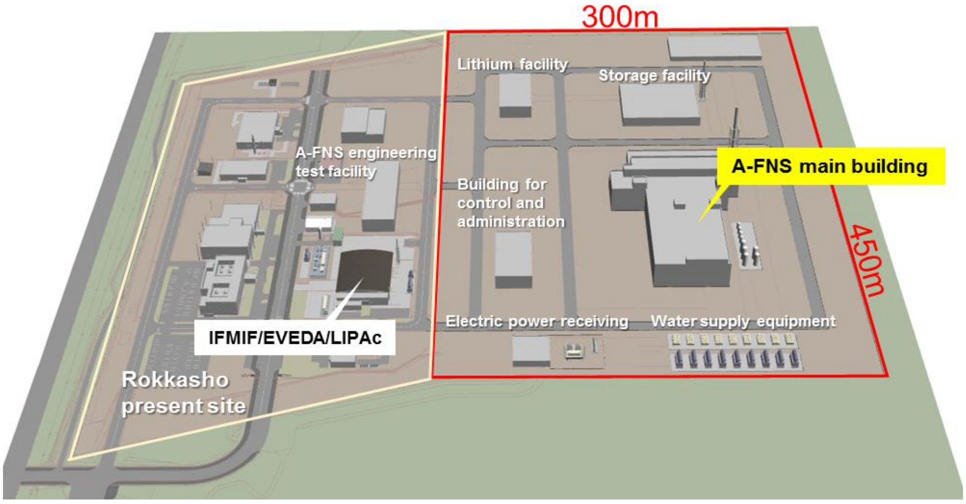


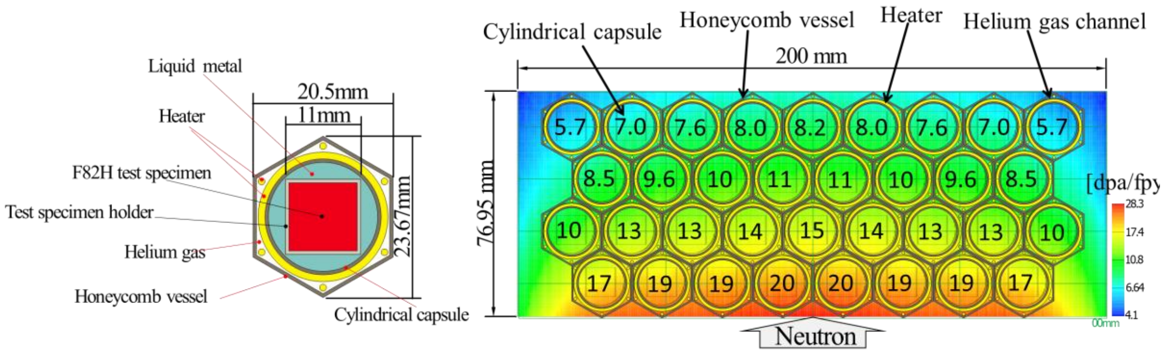
FIG. 6. Image of location of A-FNS site.

6. CURRENT DESIGN ACTIVITIES

It is introduced in session 6 that the present status of A-FNS design activities in QST toward the completion of conceptual design. Some analytical approaches are implementing for material test specimen module, lithium target and loop, remote handling for the replacement of target assembly.

6.1. Material test specimen module

It is principal issue to optimize the conditions of displacement per atom (dpa) and temperature for the test specimen in the capsule. Fig 7(a) shows a horizontal schematic view of the original material test specimen module to be installed in the test facility. The material test specimen module is composed of the honeycomb vessel, the electrical heater and the cylindrical capsule. The small tensile, compact tensile and bending specimens of F82H are installed in the individual capsules, and the liquid metal is packed inside the capsule to hold the prescribed irradiation temperature. The honeycomb vessel and the cylindrical capsule are made of SiC/SiC composite and F82H, respectively. The electrical heater is built in the cylindrical capsule. The helium gas flows in the space between the honeycomb vessel and the cylindrical capsule. Nuclear performance has been evaluated by a Monte Carlo neutron transport calculation with the detailed calculation geometry for the A-FNS material irradiation module. Figure 7(b) also shows the dpa map by neutron irradiation of the A-FNS material irradiation module in



(a) Concept of capsule design

(b) Neutron irradiation damage map

FIG. 7. Concept of the material test specimen module for A-FNS and neutron irradiation damage map in one full power year operation.

one full power year operation. It shows the horizontal map at the center of the capsule. The numerical values show the average dpa in each capsule. The neutron irradiation damage and the helium production are 6 – 20 dpa and 90 – 200 appm, respectively. The ratios of the helium production to the neutron damage are about 15. The irradiation temperature in each capsule is to be controlled between 250 and 550 °C by the electrical heater and the helium gas. From the nuclear analysis, it was clarified that our original module enabled the test pieces to be irradiated uniformly for each capsule. Neutron irradiation experiments with 5 and 20 dpa are to be implemented by three years operation and acquire the irradiation data for construction of a DEMO reactor. As a full remote access machine is required to handle the material test specimen module, a kinematics analysis with the 3D CAD data has been made for the remote handling. Details of the module design, results from the heat flow analysis and an irradiation plan will be presented. To extend application capability of A-FNS, the possibility of the medical isotopes production by using the radioisotope module has been evaluated. It is found that an enough amount of the ^{99}Mo for the medical use can be produced so that the demand in Japan can be fully met by using the radioisotope module.

6.2. Design of lithium target and R&D

A cavitation phenomenon-like acoustic noise was reported in the downstream conduit of Li target assembly of ELTL [2]. To clarify the cavitation, the investigation has been done under the ELTL dismantlement phase (see *FIG.8*). From the investigation, it was found that acoustic emissions due to cavitation occurred in a narrow area near the start of the bend pipe where the Li target impinged by using acoustic-emission sensors. Recently, QST has evaluated the applicability of the proposed numerical method by simulating the cavitation phenomenon occurring in the downstream conduit of the ELTL. A kinematics simulation has been started for the replacement of target assembly and the optimization of quenching tank layout has been implemented for Li target system of A-FNS [9]. Besides the above analysis, a new purification system for lithium loop for A-FNS is considered with the suggestion of the alleviated limits of impurities of nitrogen and hydrogen isotopes in lithium of 400wppm and 550appm, respectively for early realization, and compared with that of IFMIF [10]. As the results, not less than 4-year buffer for R&D of nitrogen trap, which is thought as one of bottle neck. Furthermore, the application of this suggestion would diminish beryllium (a radioactive isotope will generate in A-FNS process) concentration in processing lithium, as well. On the other hand, it is indicated that there would be no fatal problems by application of the suggestion, although some problems are yet unsolved such as corrosion/erosion enhancement due to nitrogen impurity and increase of tritium concentration in processing lithium.

FIG. 8 Discoloration area inside the downstream conduit after disassemblyof ELTL

6.3. Remote maintenance

The remote maintenance (RM) method on A-FNS, newly proposed is aimed at (i) enhancing the modularity of the lithium target assembly (TA) RM and (ii) keeping the compatibility with the materials irradiation tests, compared to the preceding TA RM design of IFMIF [11]. A 3-dimensional kinematics simulation indicates that the clearance of 50 mm between the TA and high flux test module (HFTM), that is 25 times as large as that of the IFMIF engineering design, brings the independent removal from and installation in the test cell, regardless of the presence of the test modules in the test cell. A neutronics performance of the HFTM with the enlarged clearance is also studied (See Fig.9). The gradient of the calculated neutron irradiation damage is found to be decreased and satisfies a users' requirement of the irradiation environment when the clearance is enlarged from 2 to 52 mm. These simulation results suggest that the proposed TA RM method will enhance not only the modularity of the TA, but also improve the materials irradiation test environment.

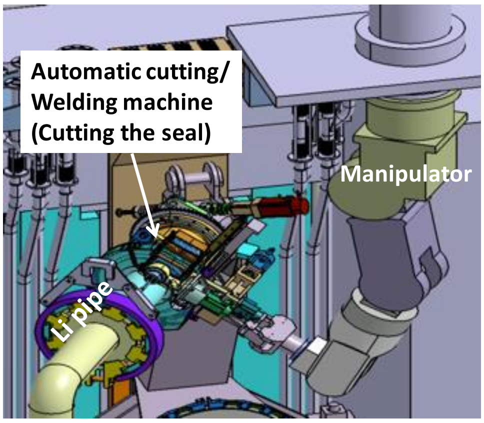


FIG. 9 3D dynamics of the TA removal by the proposed RM method

6.4. Neutron monitor

We have investigated the candidate multi activation foils for A-FNS neutron spectrum measurement system. [12] (See TABLE 2). It is important to evaluate the dosimetry cross section data above 20 MeV neutron due to a lack of experimental data. We measured the dosimetry reaction rates using the activation foils with d-Li neutrons at AVF cyclotron of Tohoku University. The neutrons are generated by the reaction between 40 MeV deuteron and solid Li target of 25 mm in thickness, and the neutron spectrum by the reaction is same as that by A-FNS. We measured the dosimetry reaction rates of ^{59}Co(n,p)^{59}Fe, ^{59}Co(n,2n)^{58}Co, ^{59}Co(n,3n)^{57}Co, ^{93}Nb(n,2n)^{92m}Nb, ^{197}Au(n,2n)^{196}Au, ^{209}Bi(n,3n)^{207}Bi, ^{209}Bi(n,4n)^{206}Bi and ^{209}Bi(n,5n)^{205}Bi reactions as functions of distances from the Li target holder, and angles between the beam line and foils to compare the calculation result of the reaction rate with the experiment ones due to differences of the neutron spectrum. This experiment was analyzed using MCNP5, McDeLicious-11 code, and the latest nuclear data libraries, FENDL-3.1d, IRDFF-1.05 and FENDL/A-3.0. The present dosimetry cross-section data of ^{59}Co(n,3n)^{57}Co, ^{197}Au(n,2n)^{196}Au, ^{209}Bi(n,3n)^{206}Bi, reactions in IRDFF-1.05 can be used for the A-FNS spectrum measurement [13].

TABLE 2. Candidate activation foils for A-FNS neutron spectrum monitor.

Activation foil	**Dosimetry reaction**	**Threshold energy** (MeV)	**Melting point** (°C)	**Half-life of daughter nuclide**	**Energy of decay photons** (keV)**
Manganese (Mn-54)	^{55}Mn(n,2n)^{54}Mn	10.5	1246	312.1 d	835
	^{59}Co(n,p)^{59}Fe	1.75		44.5 d	1099, 1291
Cobalt (Co-59)	^{59}Co(n,2n)^{58}Co	10.63	1495	70.9 d	811
	^{59}Co(n,3n)^{57}Co	19.35		271.7 d	122, 136
Arsenic (As-75)	^{75}As(n,2n)^{74}As	10.5	615*	17.8 d	596, 635
Yttrium (Y-89)	^{89}Y(n,2n)^{88}Y	11.8	1526	106.6 d	443, 1836
Niobium (Nb-93)	^{93}Nb(n,2n)^{92m}Nb	9	2469	10.2 d	935
Thulium (Tm-169)	^{169}Tm(n,2n)^{168}Tm	8.3	1545	93.1 d	198, 816
	^{169}Tm(n,3n)^{167}Tm	15		9.3 d	208
Gold (Au-197)	^{197}Au(n,2n)^{196}Au	8.25	1064	6.2 d	148, 356
	^{197}Au(n,3n)^{195}Au	15		186.1 d	31, 99
	^{209}Bi(n,3n)^{207}Bi	14.6		32.9 y	570, 1063
Bismuth (Bi-209)	^{209}Bi(n,4n)^{206}Bi	23	271	6.2 d	803, 881
	^{209}Bi(n,5n)^{205}Bi	30		15.3 d	703, 1764

6.5. Multipurpose usages of A-FNS

The multipurpose usages of A-FNS has been investigated in QST. The production of medical isotope ^{99}Mo is considered as one of the usages. A conceptual study has been conducted for radioisotope production which was composed of a neutron spectrum shifter and a neutron reflector. It was examined impacts of materials of the shifter and reflector on amounts of the ^{99}Mo production, and their thicknesses. It was concluded that beryllium is the most suitable material both for the shifter and the reflector from the viewpoint of the ^{99}Mo production. It was shown that A-FNS has a possibility to produce enough amount of the ^{99}Mo for the demand in Japan [14].

7. CONCLUSIONS

Based on “Japan’s roadmap and action plan to promote R&D for a fusion DEMO reactor”, the design activity of fusion neutron source, A-FNS has been implemented in QST. The first mission of A-FNS is to complete the irradiation data acquisition of F82H by 2035. It is also being planned at A-FNS to implement blanket irradiation and irradiation durability tests of diagnostics and control devices for DEMO. Furthermore, as multipurpose usage of neutron, A-FNS is to prepare for the medial and industrial test module and neutron beam station. For the mission achievement, the A-FNS/CDA will continue until 2020 and then the EDA will be continuously implement between 2020 and 2024. After the EDA, the A-FNS facility is to start constructing from 2025 toward the neutron operation around 2030. The PIE facility should be integrated in the A-FNS main building to achieve the prime mission of RAFM irradiation data acquisition. The site of A-FNS is planned to be adjacent to the present Rokkasho site. As current design activities, the designs of material test specimen module, lithium target, remote handling, neutron monitor have proceeded for the CDA. Furthermore, the multipurpose usage of A-FNS neutron is being investigated.

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