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# Conceptual design of DEMO blanket materials test modules for A-FNS

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ABSTRACT

A conceptual design of Advanced Fusion Neutron Source, A-FNS, has been conducted to achieve early realization of fusion-like neutron irradiation test for fusion reactor materials in Japan. A-FNS provides eight test modules to obtain irradiation data for fusion reactor materials. Conceptual design activities on Blanket Functional Materials Test Module (BFMTM), Tritium Release Test Module (TRTM) and Activated Corrosion Products Module (ACPM) were described among the A-FNS test modules. Also, basic concepts of the sub-system cells for the TRTM and the ACPM were also discussed.

## 1. Introduction

Radiation damage that comes from high-energy neutron irradiation, of a fusion DEMO reactor material has to be well-tested and validated. Aiming for that, International Fusion Materials Irradiation Facility (IFMIF) was projected until a few years ago [1].

Advanced Fusion Neutron Source (A-FNS) has been conducted to achieve early realization of fusion-like neutron irradiation test for the fusion reactor materials in Japan [2], in order to overcome resource, time, capability constraints of IFMIF. The IFMIF-DEMO Oriented Neutron Source (DONES) project has been started for the similar reason in Europe [3].

A-FNS reduces two IFMIF-type accelerators to one, thus it is configured one deuteron accelerator, liquid lithium target and test facility. Even though the total neutron flux changes from IFMIF, neutron irradiation data for Reduced Activation Ferritic Martensitic steels (RAFM) such as F82H up to 20 dpa using fusion-like neutrons has prospect for Blanket Structural Materials Test Module (BSMTM) of A-FNS based our previous study [4]. A-FNS provides eight test modules to obtain irradiation data for fusion reactor materials not only for the blanket structural material, but also the blanket functional materials such as neutron multipliers and tritium breeders. In addition, one module for neutron flux measurement before the test modules irradiation and four test modules for other application purposes such as manufacturing medical isotopes, irradiation test for semiconductors are provided. Fig. 1 shows A-FNS test modules for fusion reactor materials with shielding concrete plugs. Conceptual designs of the BSMTM [4], Blanket Nuclear Property Test Module (BNPTM), Diagnostic and Control Device Test Module (DCDTM) and Radio-Isotope Production Module (RIPM) were reported [5]. List of test modules of A-FNS and their output or objective are shown in Table 1.

In this paper, we describe conceptual designs and nuclear responses of three test modules for fusion DEMO blanket materials, Blanket Functional Materials Test Module (BFMTM), Tritium Release Test Module (TRTM) and Activated Corrosion Products Module (ACPM) as shown (bold yellow font) in Fig. 1. All nuclear performances have been calculated using McDeLicious code [6] and FENDL-3.1d library [7]. The TRTM and the ACPM require an exclusive cell for their sub-system to manage tritium quantity and water quality, respectively. Preliminary designs of the sub-system cells are also discussed.

## 2. Blanket functional materials test module, BFMTM

### 2.1. General description

Using the BFMTM, we acquire post irradiation characteristics data of fusion blanket functional materials. The basic structure concept of the BFMTM is almost same as that of the BSMTM [4]. The BFMTM shall be placed at the position just behind the BSMTM. Irradiation specimen shall be set in the cylindrical capsule installed in the irradiation vessel. After the irradiation phase, the specimens are transferred to Post Irradiation Experiment (PIE) facility to acquire physical and mechanical data of the irradiated specimens.

Table 2 shows irradiation conditions of the BFMTM. The purpose of

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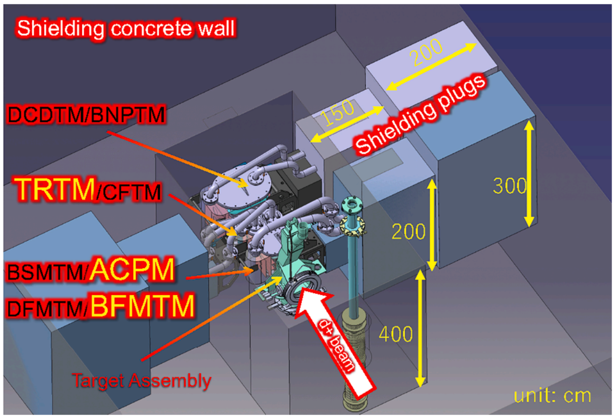

**Fig. 1.** A conceptual view of A-FNS test modules.

**Table 1**
List of A-FNS test modules for fusion purposes (under bar: reported already, italic: to be reported, bold: report here).

| Test Module | Output or Objective |
|---|---|
| Blanket Structural Materials Test Module (BSMTM) | Irradiation data for RAFM |
| **Blanket Functional Materials Test Module (BFMTM)** | **Irradiation data for neutron multiplier and tritium breeder** |
| *Divertor Functional Materials Test Module (DFMTM)* | *Irradiation data for divertor materials, Cu and W* |
| **Tritium Release Test Module (TRTM)** | **Tritium release and recovery property data for neutron multiplier and tritium breeder** |
| **Activated Corrosion Product Module (ACPM)** | **Measurement of ACPs and establishment of water quality standard** |
| *Creep Fatigue Test Module (CFTM)* | *Measurement of in-situ creep fatigue property of RAFM* |
| Blanket Nuclear Property Test Module (BNPTM) | Measurement of detailed distributions of tritium production rate and reaction rates in a blanket mockup |
| Diagnostic and Control Device Test Module (DCDTM) | Evaluation of radiation hardness of diagnostic and control devices for DEMO |

**Table 2**
Irradiation conditions of BFMTM.

| Neutron displacement damage | 2 dpa for neutron multiplier |
|---|---|
| Irradiation temperature (°C) | 300, 400, 500, 600, 700, 800, 900, 1000 |
| Test item for PIE | Physical and Mechanical properties of a ceramic pebble bed for neutron multiplier and tritium breeder materials, such as tensile test, XRD, Nanoindentation, etc. |
| Candidate materials | Neutron multiplier: $Be_{12}V$, $Be_{13}Zr$, $Be_{12}Ti$, Be-Ti-V, BeTritium breeder: $Li_2O$, $Li_2TiO_3$, LTZO20$^{**}$Add $Li_2ZrO_3$ to Li-doped $Li_2TiO_3$ |

data acquisition with the BFMTM is to measure neutron irradiation phenomena of these materials and clarify degradation of their properties due to neutron damage and nuclear transformation. These data shall be used for determination of the lifetime and the replacement schedule for blanket functional materials. Fig. 2 shows a conceptual view of the BFMTM. In the current design, the BSMTM and the BFMTM are installed in the single irradiation vessel, and the BFMTM is placed at the rear location as above mentioned. Honeycomb vessels of the BFMTM are installed in the irradiation vessel. The support frame of the BFMTM is connected to the shielding plug connection structure [4].

### 2.2. Design specification

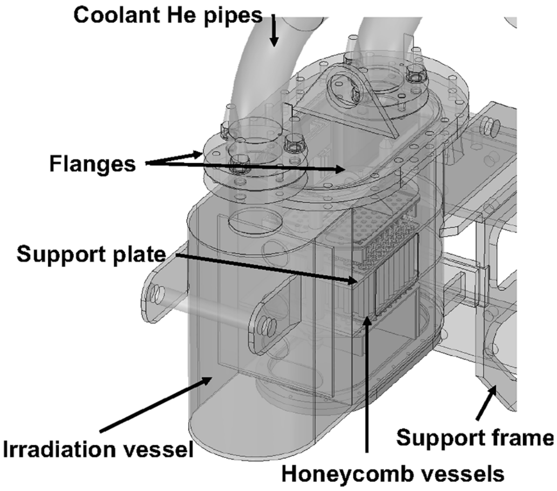

**Fig. 2.** A conceptual view of BFMTM.

The irradiation specimens of the blanket functional materials are loaded into cylindrical capsule in the honeycomb vessel that can be considered a hexagonal tiling as shown in Fig. 3. Instrument lines involves that three sheath heater lines are installed around the cylindrical capsule. The heaters attached on the external surface of the capsule. Helium gas as the cooling medium flows the space between the cylindrical capsule and the honeycomb vessel. All structural features of the BFMTM have been designed based on the BSMTM [4].

The BFMTM is located behind of the BSMTM along the beam direction. The irradiation capsules are arranged in five columns and nine or ten rows. The number of the capsules shall be 47 in maximum in the current design. The irradiation temperatures are from 300 to 1000 °C with 100 °C interval temperature. We are to design the specifications of the heater and helium gas to satisfy the irradiation temperatures and the temperature gradient limits to be considered. Multiple thermocouples, SiC temperature monitors and molten metal thermometers are loaded into each capsule as similar to those of the BSMTM.

### 2.3. Nuclear response

Fig. 4 shows the calculated neutron displacement damage (dpa) per full power year (fpy) in the BFMTM with that in the BSMTM. In the figure, red font values are the DPA rates (dpa/fpy) of Be in the BFMTM, and black ones are those of Fe in the BSMTM. Each value is an average

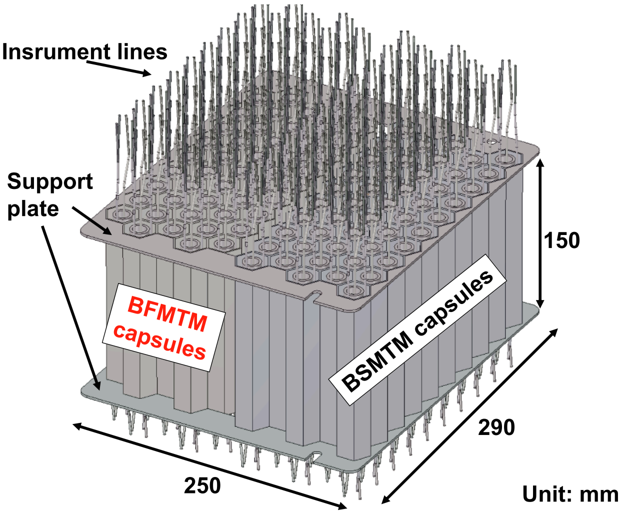

**Fig. 3.** Honeycomb vessels of BSMTM and BFMTM.

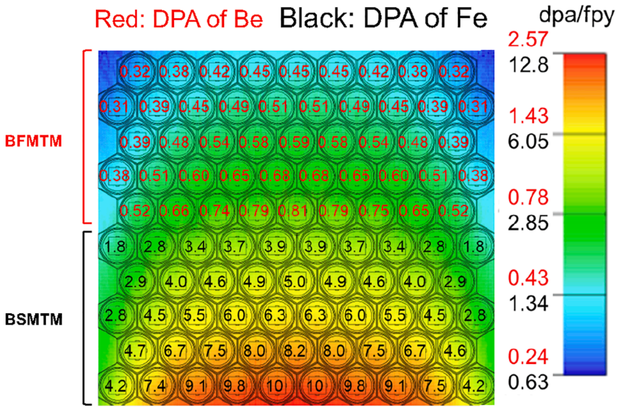

**Fig. 4.** Calculated average of DPA rate (dpa/fpy) in BFMTM.

value of dpa in each capsule. The maximum value of Be is 0.8 dpa/fpy, and the tentative design target of 2 dpa can be achieved by 3 fpy irradiation.

## 3. Tritium release test module, TRTM

### 3.1. General description

The TRTM of A-FNS is used for evaluation of tritium release and recovery properties of fusion DEMO blanket functional materials, tritium breeder and neutron multiplier pebbles, with in-situ tritium measurement. The TRTM shall be located behind the BFMTM as shown in Fig. 1. Neutron flux of the TRTM surface is expected to be ~ $10^{13}$n/cm$^2$/s. The purpose of the TRTM test is to model the tritium release and recovery properties from the pebbles of the candidate blanket functional materials as shown in Table 2.

Although experimental studies related to tritium recovery property of $Li_2TiO_3$ had been carried out using fission and fusion neutrons [8,9], additional data such as long-term irradiation test using various pebbles of the blanket functional material candidates will be performed with the TRTM of A-FNS. Fig. 5 shows a conceptual view of the TRTM. The TRTM capsule unit is installed in the irradiation vessel. All instruments lines are grouped and routed to the contact base which is applied for all electrical cable connections as similar concept to the BSMTM [4]. It is easy way to connect and disconnect by the remote handling. The manifold controls the vacuum supplied and purge gas lines.

### 3.2. Design specification

The tritium breeder and neutron multiplier pebbles are filled in cylindrical capsules. Tritium is produced by nuclear reactions due to neutrons and $^6$Li, $^7$Li and $^9$Be in the pebbles. The tritium is recovered with helium purge gas with hydrogen. In-situ measurement of the tritium shall be performed by using an ionization chamber in the sub-system cell for the TRTM located outside the test cell. Total tritium produced is measured by water bubbler system during and after the irradiation phase. The tritium release and recovery properties from the pebbles shall be assessed with specific parameters such as irradiation temperatures of the pebbles and types of pebble material, and so on.

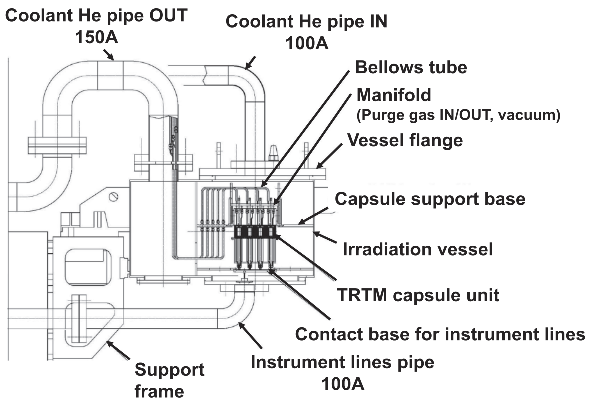

**Fig. 5.** A conceptual view of TRTM.

Fig. 6 shows a horizontal cross-sectional view of the TRTM capsule. The outer diameter of the purge gas cylinder and vacuum cylinder made of F82H are 37.2 mm and 47.2 mm, respectively. The wall of the cylinder is 2.5 mm in thickness. The capsule cylinder is installed in the purge gas cylinder. The pebbles are filled into the capsule cylinder. The capsule cylinder is made of nickel alloy with thickness of 2 mm, inner diameter of 20 mm and outer diameter of 24 mm. Sheath heaters of 1.6 mm in thickness are installed around the capsule cylinder. Void of 2.5 mm in width are installed in the space between the purge gas cylinder and the capsule cylinder to flow helium purge gas with hydrogen. Each TRTM capsules can be extracted one by one using the remote handling. Irradiation temperatures of pebbles are controlled by the sheath heaters and coolant helium gas. The vacuum layer is added for heat insulation, due to the expected difficulty to increase and maintain temperatures such a high temperature up to 1000 °C with only the electrical heater.

We are to acquire the irradiation data for 8 temperature conditions (from 300 °C to 1000 °C, 100 °C intervals) for the tritium breeder and neutron multiplier pebbles. 16 capsules are irradiated at one irradiation phase. Four rows and columns of the cylindrical rigs are arranged in the beam direction as shown in Fig. 7.

### 3.3. Nuclear response

We performed nuclear analyses for tritium production rates in each capsule to assess experimental feasibility, in particular, neutron breeder materials. Because beryllium has very small cross-section for tritium production relative to the lithium isotopes.

Figs. 8 and 9 show the calculated tritium production rates of bulk Li and Be in the TRTM capsules. In the TRTM, enrichment of $^6$Li is not an absolute requirement. Tritium production rates of bulk natural Li and Be are from 1100 to 1600 and from 30 to 190 Bq/s, respectively, where usual ionization chambers (measurement limitation about 10 Bq/s) would be available for online tritium measurements.

### 3.4. Basic concept of TRTM cell

A flow diagram of the TRTM is shown in Fig. 10. A sub-system of the

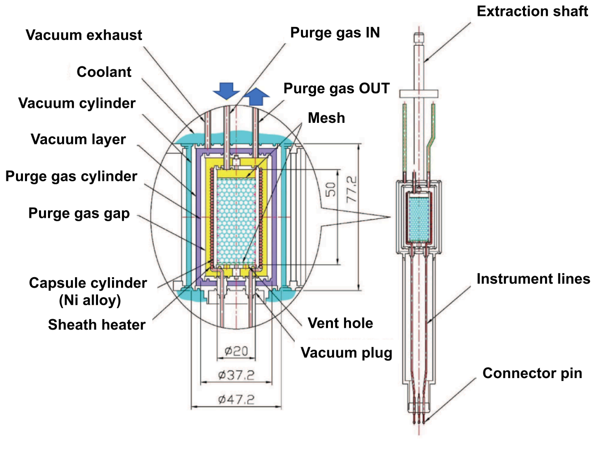

**Fig. 6.** Horizontal cross-sectional view of TRTM capsule.

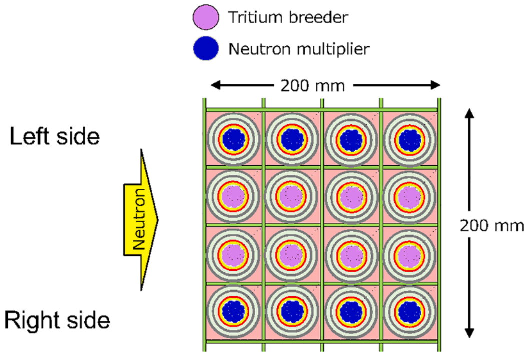

**Fig. 7.** A cross-sectional view of TRTM capsules.

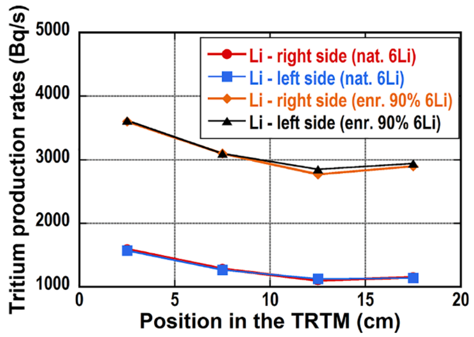

**Fig. 8.** Calculated tritium production rate of bulk Li in the TRTM capsule.

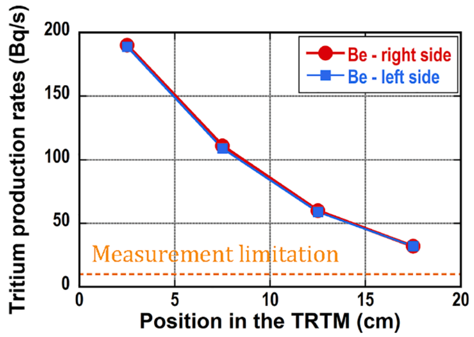

**Fig. 9.** Calculated tritium production rate of bulk Be in the TRTM capsule.

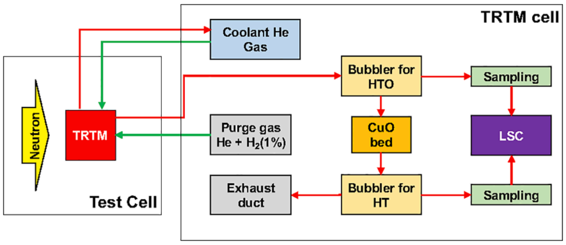

**Fig. 10.** A flow diagram of TRTM.

TRTM is composed of the following five measuring systems; 1) helium cylinders added hydrogen for purge gas, 2) ionization chambers for in-situ measurement of tritium released and recovered, 3) water bubblers for measurement of tritium released and recovered, 4) a copper oxide (CuO) fixed bed to oxidize HT, and 5) a sampling system for the water bubbler to measure tritium concentration directly using liquid scintillation counter (LSC).

Coolant gas of the TRTM is provided from A-FNS central helium gas cell. The sub-system shall be installed in a TRTM cell. Area of about 50 $m^2$ for the TRTM cell is being designed referring to other tritium handling facilities. In order to collect a representative water sampling including tritium, the TRTM cell should be classified to be a controlled area where is limited access for all workers.

## 4. Activated corrosion Products Module, ACPM

### 4.1. General description

Using the ACPM, we are to flow high-temperature and high-pressure water in F82H pipes of inner diameter of 9 mm as shown in Fig. 11, and measure the activated corrosion products under fusion neutron irradiation condition. In one irradiation phase, six F82H pipes are installed. The water conditions in the ACPM are same to those in the DEMO reactor (15 MPa and 300 °C) [10].

The water flowing F82H pipeline is irradiated near the backplate of the lithium target of A-FNS. Neutron flux is about $5 \times 10^{14}$n/cm$^2$/s in the ACPM. Water Cooled Ceramic Blanket (WCCB) of Japanese fusion blanket concept is composed of a box structure of F82H as container with lots of cooling water pipes [10]. It is important to measure an amount of ACP in the cooling water pipe from the point of view of reduction of radiation exposure for workers. Radiolysis of water, degradation of corrosion resistance of F82H due to neutron irradiation and irradiation damage of protective coating such as oxide layer are caused simultaneously in the cooling water pipe of the DEMO reactor, and we are to acquire these ACP data by using the ACPM. These ACP data are required for the safety design of DEMO reactor. The purposes of irradiation test with the ACPM are to establish water quality management guidance of fusion reactor, to acquire corrosion data, and to model corrosion behavior of F82H. An evaluation code to assess ACP shall be developed and validated based on the irradiation data acquired by the ACPM.

### 4.2. Design specification

Fig. 12 shows a vertical cross-sectional view of the ACPM. The F82H pipes to be irradiated are installed in the irradiation vessel on test cell side, in order to prevent leakage of the high-temperature and high-pressure water to the inside of test cell. The irradiation vessel has a main door for the irradiated pipes exchange using the remote control. During the irradiation, the main door is shut tight using mounting screws of the door. SS316L pipes are connected to the F82H pipes in the other irradiation vessel on shielding plug side. The irradiation vessel is cooled using the coolant He gas, due to temperature increase expected by nuclear heating.

Location of the ACPM is same to that of the BSMTM. This is because

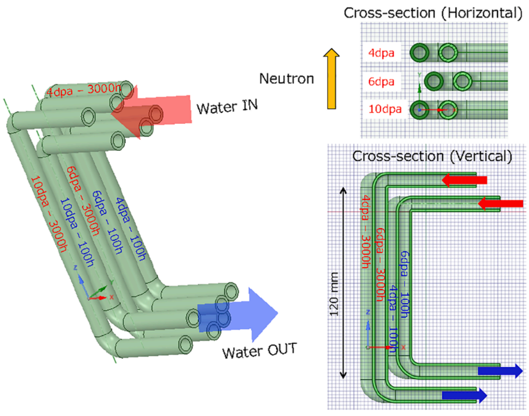

**Fig. 11.** A conceptual view of ACPM.

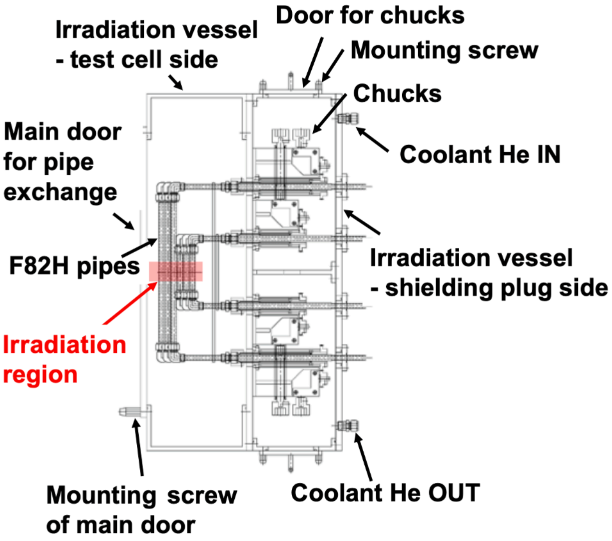

**Fig. 12.** Vertical cross-sectional view of the ACPM.

high and neutron flux field is required for the irradiation of the ACPM to obtain neutron displacement damage rate of 10 dpa/fpy which is the same condition as the rate in the first wall of the DEMO reactor blanket. The irradiation phase of the ACPM and the BSMTM shall be separated, thus the BSMTM is to be replaced with the ACPM. The detailed irradiation campaigns of A-FNS have been determined by different test modules arrangement [4].

Table 3 shows irradiation test conditions in the ACPM. Irradiation conditions are 3 cases of neutron displacement damage rate; 4 dpa/fpy, 6 dpa/fpy and 10 dpa/fpy for each two specimens and 5 cases of irradiation period; 100 h, 400 h, 900 h, 1600 h and 3000 h. Total amount of the specimens is 30 as each irradiation time conditions. During one irradiation period, the six specimens are irradiated in the ACPM. The specimens for the longest irradiation time, 3000 h, are installed at the beginning of the irradiation period. Other specimens for short irradiation time from 100 to 1600 h are successively replaced by unirradiated specimens. Common conditions of the flowing water in the ACPM are shown in Table 4.

### 4.3. Basic concept of ACPM cell

Fig. 13 shows a flow diagram of the ACPM. A sub-system of the ACPM consists of heaters, regenerative heat exchangers, circulation pumps, coolers, a filter, a resin tower, water quality measuring instruments and water quality control tank. The sub-system shall be installed in an ACPM cell. Flowing water with ACPs is sampled and analyzed in an analysis cell of A-FNS/PIE facility. In current irradiation scenario of the ACPM that the target material is F82H, required area of the ACPM cell is estimated about 83 $m^2$ for one target material based on water cooled system (WCS) of WCCB TBM in Japan [11]. In order to in-situ manage the water quality, the ACPM cell also should be classified the controlled area for radiation and contamination to ensure human access and hand-on operation.

**Table 3**
Irradiation test conditions of ACPM.

| Neutron displacement damage rate (dpa/fpy) | Numbers of F82H pipes in an irradiation period | Irradiation time (hour) |
|---|---|---|
| 4 | 2 | 100, 400, 900, 1600, 3000 |
| 6 | 2 | 100, 400, 900, 1600, 3000 |
| 10 | 2 | 100, 400, 900, 1600, 3000 |

**Table 4**
Test conditions of flowing water in ACPM.

| Temperature (°C) | 300 |
|---|---|
| Pressure (MPa) | 15 |
| pH | 5–7 |
| DO (ppb) | < 5 |
| DH (ppm) | 3.5 |
| Flow rate (m/s) | 5 |

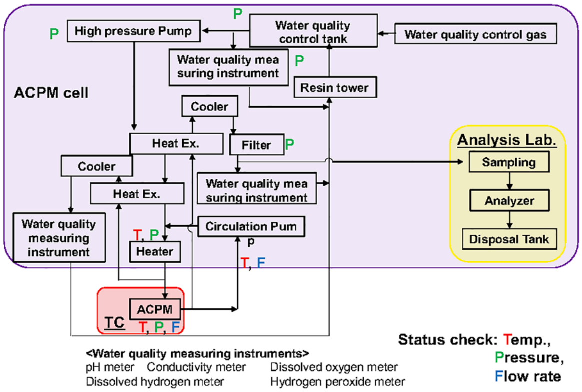

**Fig. 13.** A flow diagram of ACPM.

We have the further irradiation plan to perform with an additional ACPM for another target material, copper alloy which is to be used a lot as a material for discharging the heat in the fusion reactor. Even now is just a kind of potential scenario, we will keep the overall area space of the sub-system adopting a double layer structure in the ACPM cell where the lower layer is prepared for the sub-system of F82H-ACPM and the upper layer for that of copper alloy-ACPM. Because it is difficult to add the area space after establishing the building design of A-FNS.

## 5. Summary

The conceptual designs of the blanket functional materials test module (BFMTM), the tritium release test module (TRTM) and the activated corrosion product module (ACPM) were established. Also, basic concepts of the sub-system cells for the TRTM and the ACPM were given. In the results of the nuclear performance of the modules were discussed as follow:

(1) Using the BFMTM, the tentative design target of 2 dpa irradiation of Be can be achieved,
(2) Using the TRTM, the tritium produced from Be was sufficient to measure,
(3) Using the ACPM, the ACPs under 10 dpa/fpy irradiation condition can be measured.

The current design of the modules above can fulfill the specification requirement as A-FNS test modules.

## CRediT authorship contribution statement

**Saerom Kwon:** Validation, Investigation, Writing - original draft. **Satoshi Sato:** Validation, Investigation, Supervision. **Masayuki Ohta:** Validation, Investigation. **Makoto Nakamura:** Validation, Investigation. **Makoto Oyaidzu:** Validation, Investigation. **Kentaro Ochiai:** Validation, Investigation. **Atsushi Kasugai:** Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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