PRELIMINARY DESIGN AND DEVELOPMENT OF NEUTRON ACTIVATION SYSTEM ON CN HCCB TBS

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Abstract

A Neutron Activation System (NAS) has been developed for integration with the Helium-Cooled Ceramic Breeder Test Blanket System (HCCB TBS). As an auxiliary system for the CN HCCB TBS, the NAS is primarily responsible for measuring neutron flux and fluence within the HCCB Test Blanket Module (TBM) to support the design validation process. The system comprises Irradiation Ends, capsules containing samples, a pneumatic transfer system, and a counting system. In operation, encapsulated samples are activated by fusion neutrons and subsequently transported via helium through dedicated tubing to a counting station. The pneumatic transfer system includes gas supply mechanisms, transfer stations, connecting lines, disposal bins, and a control subsystem based on Programmable Logic Controller (PLC) technology, which ensures precise monitoring and control of parameters such as temperature, pressure, flow rate, and capsule positioning. Key components, including the transit station and capsule loader, have been successfully manufactured, and a test circuit for the Neutron Activation System (NAS) is currently under construction to assess the performance of the pneumatic transfer system.

The paper provides a comprehensive overview of the preliminary design of the NAS for the HCCB TBS, encompassing system layout, component design, and operational strategies. The progress in manufacturing critical components and constructing the test circuit underscores the achievement of the functional and reliability requirements of the NAS.

1. INTRODUCTION

According to the agreement between ITER Organization and China Domestic Agency (CN DA) signed in 2014, China will fabricate and test the Chinese Helium Cooled Ceramic Breeder Test Blanket System (HCCB TBS) in ITER facility to verify the technologies related to tritium breeding blanket [1][2]. In 2015, the conceptual design of HCCB TBS has been approved by ITER Organization and the preliminary design is expected to be completed in 2025.

Neutron activation system (NAS) is a diagnostic measuring the absolute neutron flux and fluence in the CN HCCB TBM [3]. It utilizes a pneumatic method to send a sample of material in the TBM module, where it gets activated by neutrons. This sample is then retrieved with the same pneumatic technique and the activation of the sample is measured with gamma-gay spectrometers.

A NAS for the TBM has several advantages over other neutron flux measurement techniques. It allows to incorporate several activation materials in one probe and delivers therefore more information on the neutron spectrum and it is radiation hard. Since the primary purpose is to measure the neutron flux in a particular position, it is not required to calibrate the NAS, only the counting station for the induced activity requires calibration. The neutron flux measured in this way is then already an absolute value. The activation probes can be easily replaced; there are no concerns regarding burn-up effects and their compensation.

However, there are some disadvantages and challenges to be faced. The irradiation ends are located in regions of the TBM with temperatures of at above 300℃ while most of the activation probe transportation lines are at room temperature. The transportation lines must penetrate through several interfaces, the TBM is located inside the reactor vessel [4]. The time resolution of the neutron flux measurement is therefore low to moderate. Each measurement position at least in toroidal and poloidal directions requires a separate transportation line so that only a very few measurement positions can be realized.

2. GENERIC DESCRIPTION

The NAS is an ancillary system of CN HCCB TBS. The NAS equipment is located in building 14-L2-24 and 11-L1-C18 (AEU) [3]. The main purpose of the CN HCCB NAS is to measure neutron flux/fluence in HCCB TBM and then evaluate the TBM's performance. The main functions include:

- To transmit sample in cooling loop and measurement loop
- To analysis gamma signal
- To provide confinement for helium and radioactive products
- To receive and discharge service/process fluid

The CN HCCB NAS measures gamma radiation in TBM module from samples activated by fusion neutron flux. Encapsulated samples are transferred between irradiation ends and counting station by the driving of helium gas. Tubes of diameter 12mm will be used for the transfer lines of the capsule.

NAS composed by Irradiation End, Pneumatic transport system, Transit station, Transfer station, Capsule loader and Counting station. Most main components of NAS such as transit station, capsule loader, disposal bin, storage bin, counting station, pumps, tanks, valves, pipes and instrumentation are located in 14-L2-24. Only transfer station, some valves, pipes and instrumentation of NAS are located in 11-L1-C18 (AEU). The irradiation ends located in HCCB TBM.

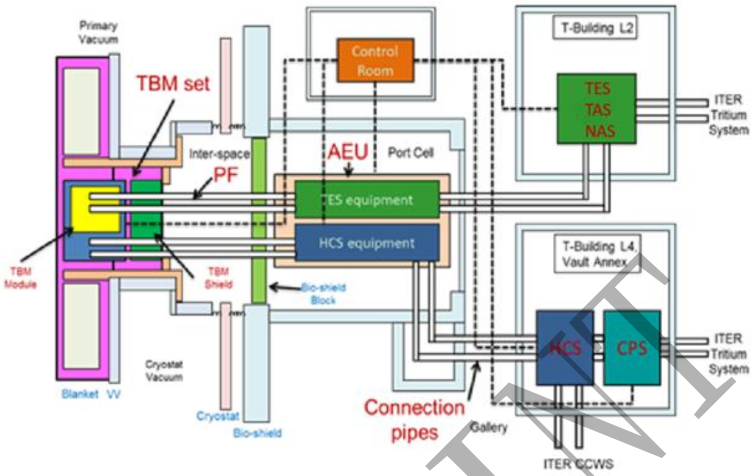

Fig. 1HCCB TBS layout scheme

The capsules with activation samples will be distributed and sent to corresponding irradiation ends in TBM for irradiation, the location is shown in Fig.2[5]. After activated, the capsules will be transported to the counting station for gamma measurement. The capsules transport process has been designed and shown in Fig.3. All transportation action will be performed and controlled by pneumatic transport system. The pneumatic transport system consists of temperature sensors, pressure sensors, flow rate sensor and relevant signal process and transfer units, and it is responsible for temperature, pressure and capsule position monitor and control, also for monitor of operation status of relevant valves, circulator, sensors and transfer system. The PLC-based control system will be harnessed for the accurate operation of the system.

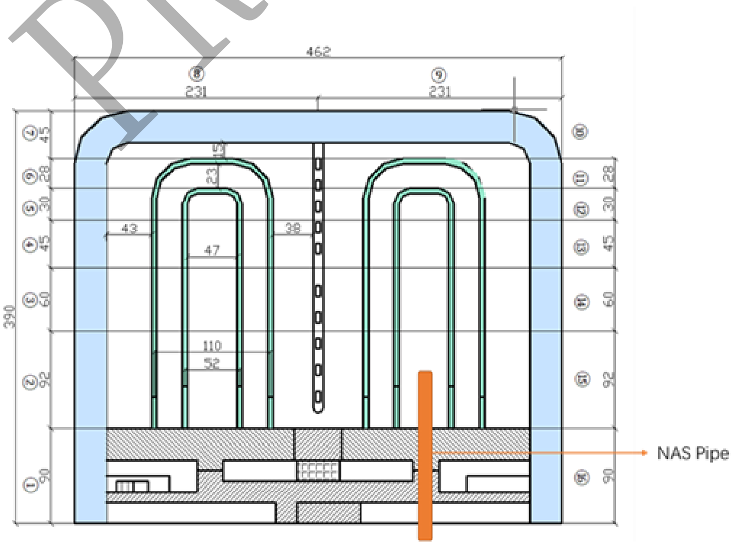

Fig. 2 NAS Irradiation Ends' location in TBM module

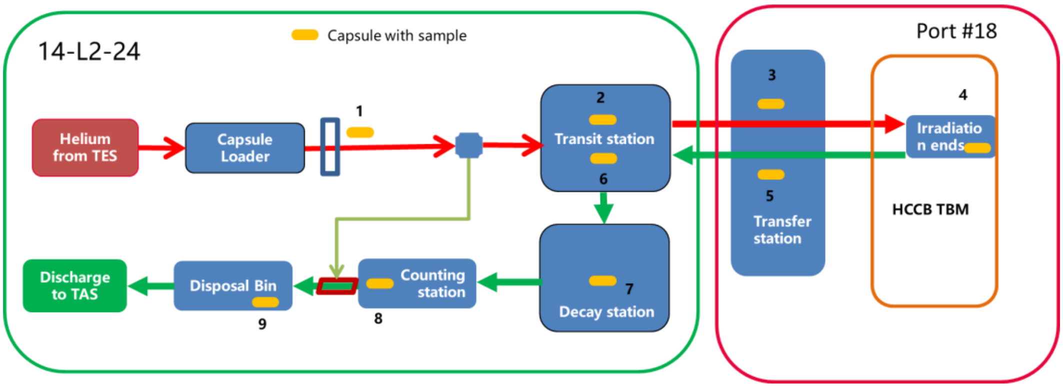

Fig. 3 Capsules transport process

In the counting station, gamma signals will be measured, transported and stored for analysis. The counting station consists of gamma-ray detectors and Data Access, Process Transfer system. Data Access, Process Transfer system consists of electronic devices such as high voltage supplies and amplifiers, and tool for neutron source strength evaluation. It is an integration equipment for the evaluation of the parameters of the NAS by counting gamma-rays from the activated samples. HPGe detector is designed for gamma measurement now and other detector that suitable for gamma measurement is under consideration too.

3. DESIGN OF KEY COMPONENT

3.1. Irradiation Ends

Encapsulated samples are transferred between irradiation ends and counting station by the driving of Helium gas. A double-layer structure tube will be used for the Irradiation Ends. The SS316L is used as the structural material for NAS Irradiation Ends inside TBM set. The heat generation in the NAS tubes and structures in the TBM internal zones is related to the distance from FW, which is calculated by neutronics analysis in TBM, shown in Fig.2.

By switching the high and low pressures at the inlets and outlets of the double - layer pipeline, the transportation and recovery of the capsules can be achieved, the structure and thermal analysis are shown in the Fig. below.

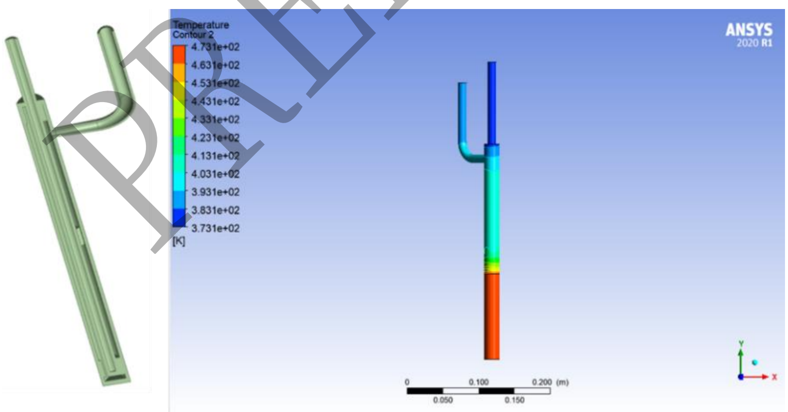

Fig. 4 Irradiation Ends

3.2. Transit station

The goal of transit station is to make the capsule freely choose the destination to be transported. The transit station is composed of turntable, motor, pneumatic valve, linear actuator, etc. After the capsule is transported to the transit station through the loader, the capsule can be delivered to the entrance of the destination through the rotating mechanism. The destinations of the capsule to be transported include: Irradiation Ends, Counting station, Disposal station and Decay station. Therefore, transit station has 4 inlet and outlet capsules, which are respectively connected with other equipment or pipelines through valves. Helium is used to push the capsule in the transfer process and system pipeline. Therefore, there are two helium inlet and outlet in the transfer station. The helium inlet and outlet are connected with the system loop through valves. Currently, a transit station has been designed and manufactured.

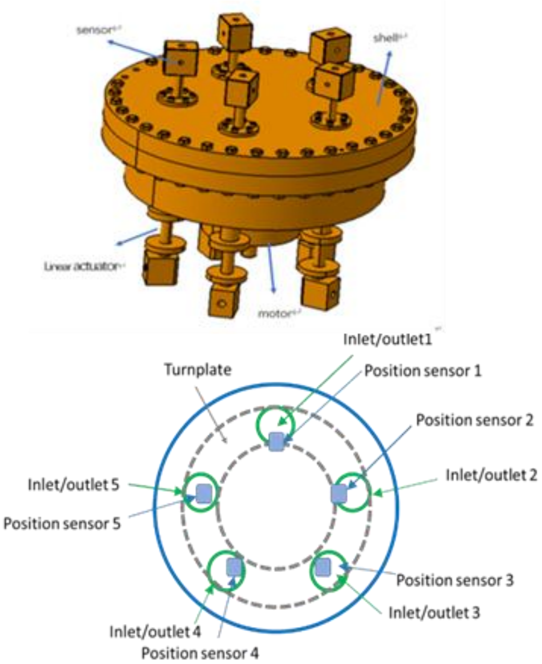

Fig. 5 Transit Station Diagram

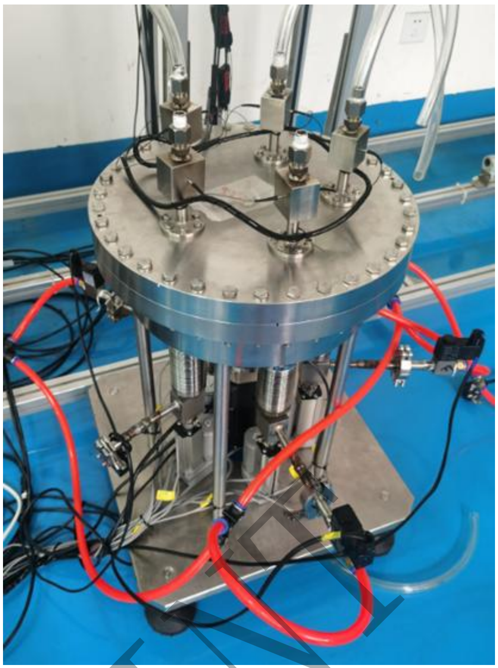

Fig. 6 Transit Station Product

3.3. Capsule loader

Capsule loader is mainly composed of capsule magazine, rotating actuator, linear actuator, gate valve and so on. The shape of capsule loader is similar to that of revolver. The capsule loader has a helium inlet and a capsule outlet. The air inlet is connected with the system loop through a valve; the capsule outlet is connected with the transit station through a valve, and the capsule can be transported to the transit station by entering helium.

Currently, a Capsule loader has been designed and manufactured. The capsule bin can store 300 capsules with dimensions of Φ8mm×25mm.

Fig. 7 Capsule loader Product

3.4. I&C framework

NAS control system consists of a conventional control system, an interlock control system and a safety control system, which are independent in physics. Data exchanging, archiving, communication and the other operations are completed by IO.

The main conventional controllers for NAS are slow controllers, which refers to Siemens PLC from ITER product catalogues specifically, and Siemens PLC 400 series products are preferable. Generally, the remote IO and signal interface modules are also from Siemens, which should match with slow controllers.

The sensors collect the parameters of temperature, flow, pressure, equipment status and so on, transmit data to signal interfaces, then to PLC directly or via remote IO module to PLC. PLC will adjust actuators, and components to reach setting parameters according to CODAC or PSH commands.

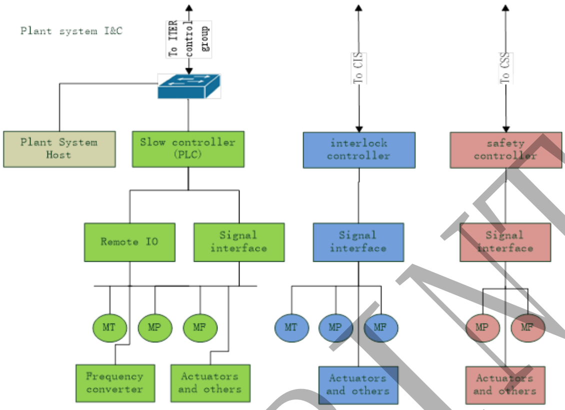

Fig. 8 NAS I&C framework

3.5. NAS test circuit

Currently, a test circuit is being designed and built. The test circuit contains the irradiation End, transit station, capsule loader, disposal bin, storage bin and counting station. The test circuit dimension is the same as the NAS located in ITER site building 14-L2-24, by simulating the actual NAS layout on the ITER site, the transportation and control performance of the current NAS design can be evaluated.

The test circuit is planned to be completed the construction in the second half of 2025 and conduct pneumatic transportation control experiments.

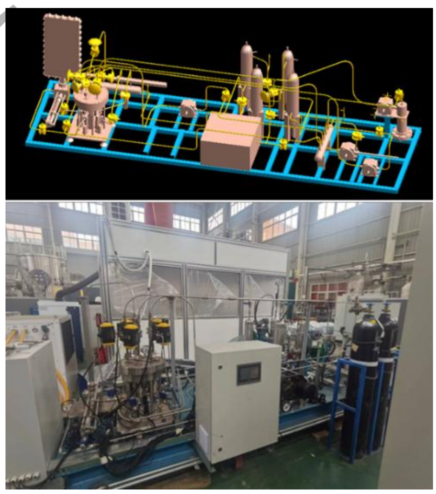

Fig. 9 NAS test circuit

4. PRELIMINARY TRANSFER & MEASURE CONCEPTION OF NAS

4.1. Transfer Conception

A pneumatic transport system was designed to study the translocation of capsules of different sizes and the relationship between transmission speed and air pressure. According to the results of pneumatic transportation experiments on capsules of different lengths and diameters under different pressure, which is shown in Fig.11 and Table 1, the result showed that design of the capsule significantly impacts transport efficiency.

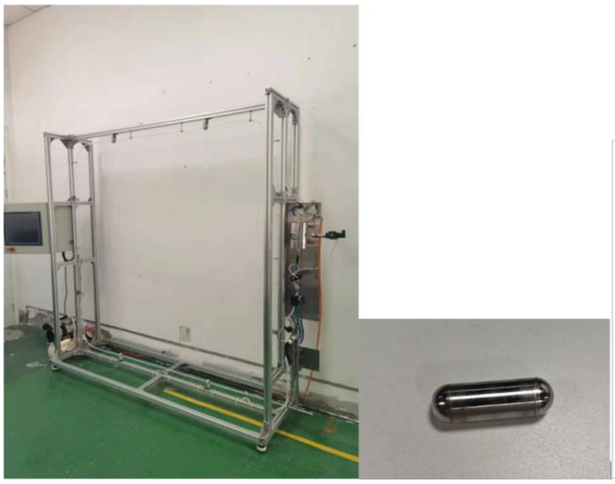

Fig. 10 Pneumatic transport system & capsule

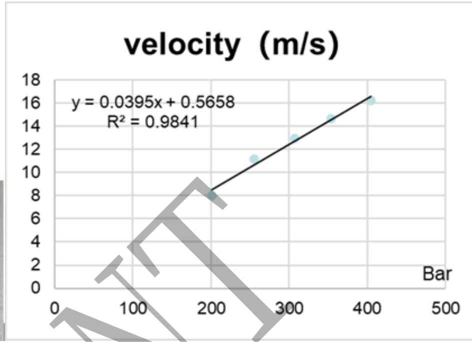

Fig. 11 Velocity and pressure test of capsule

TABLE 1 Passage test of capsule

Chamfer\mm / Length\mm	0	1	2	3	4
10	Spin and beat	Spin and beat	block	block	Spin and beat
15	block	√	Spin and beat	block	√
20	block	√	√	block	Spin and beat
25	√	√	√	√	√
30	×	×	×	×	×

Considering that a speed of about 20 m/s is more suitable for the transportation of capsules in the NAS pipeline, as a result, the capsule dimension is defined Φ8mm*25mm, the pressure difference of NAS is set at 0.5-0.6Mpa.

4.2. Measure Conception

The principle of measuring neutron flux with a high - purity germanium（HPGe) detector is mainly based on the detection of γ - rays generated after the interaction between neutrons and materials. Specifically, when neutrons react with the atomic nuclei in the sample (such as activation, fission, or scattering), characteristic γ - rays are produced. These γ - rays are captured by the high - purity germanium detector and converted into electrical signals. By analysing the energy spectrum and intensity of the γ - rays, the neutron flux can be inferred.

The mass of capsule structure of each one is 1g. The candidate materials for the capsule structure is CFC(CX-2002U). Due to the different half - lives of various nuclides after activation, the cooling duration has a significant impact on some nuclides. Under the conditions of a neutron source strength of 500MW and an irradiation duration of 10s, while also referring to the half - life of the activation products, an appropriate mass of activated nuclides is selected to obtain similar characteristic gamma intensities. Through MCNP analysis, the nuclide mass selection in Table 2 is obtained:

TABLE 2 Activation sample nuclide mass selection

Activated metal	Quality(mg)	isotope	Abundance	gamma energy(keV)	gamma number	Activation products	Half-life(s)
Al	0.059	27Al	1	1369	1.42E+07	24Na	54108
				2754	1.42E+07		
				840	4.41E+01	27Mg	567.48
Cu	0.059	63Cu	0.69	511	1.17E+02	62Cu	584.4
				511	1.07E+07	64Cu	45720
		65Cu	0.31	511	1.11E+06	64Cu	45720
				1039	2.84E-05	66Cu	306
Fe	0.198	56Fe	0.92	846.7	9.56E+06	56Mn	9277.2
		54Fe	0.06	834.8	4.55E+05	54Mn	27017280
				377.9	7.06E-04	53Fe	510.6
Ti	0.396	47Ti	0.26	159	4.19E+06	47Sc	289440
		48Ti	0.74	983	1.44E+07	48Sc	157320
Nb	0.03	93Nb	1	934.5	1.66E+07	92Nb	885600
Co	0.03	59Co	1	1099.2	9.21E+05	56Fe	3853440
				846.7	3.94E+05	56Mn	9288
				810.7	1.56E+07	58Co	6117120
Au	0.03	197Au	1	355.7	1.48E+07	196Au	534211.2
Zr	0.198	90Zr	0.52	909.1	1.40E+07	89Zr	282240

Then the characteristic gamma energy expected to be measured are shown in the following table.

TABLE 3 Characteristic gamma intensity

Gamma energy（keV）	Activated sample	Number of gamma
159	Ti	4.19E+06
355.7	Au	1.48E+07
511	Cu	1.18E+07
810.7	Co	1.56E+07

834.8	Fe	4.55E+05
846.7	Fe、Co	9.95E+06
909.1	Zr	1.40E+07
934.5	Nb	1.66E+07
983	Ti	1.44E+07
1099.2	Co	9.21E+05
1369	Al	1.42E+07
2754	Al	1.42E+07

2 irradiation times (10s and 50s) for the candidate capsule material is evaluated. The analysis model and method referenced HCCB-TBS PD Neutronics Analysis Report [6]. Considering that the high purity germanium detector has a gamma-ray energy resolution (FWHM) of 1.33MeV and a better gamma-ray resolution with lower energy, the expected activity measurement range of the high purity germanium detector is 0.1-10^4 Bq, then some cooling time is needed for capsule.

For the consideration of expected activity measurement range of the high purity germanium detector is 0.1-10^4 Bq, the cooling time for CFC 10s irradiation is about 2 hours (6.65E+04 Bq for 2 hours), for CFC 50s irradiation is much more than 1day (1.60E+05 Bq for 1day). Then only CFC with 10s irradiation and 2-hours cooling time is appropriated for NAS measurement plan, the capsule could be measured within about 2 hours.

Based on the activation assessment, current NAS measure conception was defined maximum 8 samples measurement in one day.

5. SUMMARY

The Early - stage research and development is shown that NAS could work normally in the ITER site environment, but optimal integration design of NAS is still in progress. Methods and possible NAS measure operation are under study. The strategy of neutron diagnostic calibration has been developed but a lot of work in detailed calibration procedure and required hardware development is needed.

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