CONCEPTUAL DESIGN OF NEUTRON ACTIVATION SYSTEM FOR IN-LLCB TBM

S. TIWARI
Institute for Plasma Research
Bhat, Gandhinagar, India
Email: shailja@ipr.res.in

ARVIND KUMAR1, DEEPAK SHARMA1, VILAS CHAUDHARI1, ATIK MISTRY1, H.L. SWAMI1, C. DANANI1, E. RAJENDRA KUMAR1
1 Institute for Plasma Research
Bhat Gandhinagar, India

Abstract

Neutron Activation System (NAS) is the primary neutron diagnostics for Indian Lead-Lithium Ceramic Breeder (LLCB) Test Blanket Module (TBM) in ITER. The main objective of NAS is to measure spatial distribution of neutron flux and energy spectra and in-situ measurement of tritium production rate inside the TBM. These measurements will be utilized for validation of neutron transport tools (software codes) and tritium breeding predictions used for breeding blanket systems design. NAS for LLCB TBM mainly consists of transfer station, capsule loader, transfer lines, foil gamma activity measurement system and irradiation ends. The irradiation locations of capsules consisting of foils are positioned inside the LLCB TBM at mid-plane location. The conceptual design of TBM along with NAS irradiation transfer line has been developed and its engineering design is in progress. All the ancillary system components of NAS such as transfer station, capsule loader, foil gamma activity measurement system will be located at tritium building level L-2 of ITER building. The capsules are pneumatically transferred to irradiation end of transfer line located inside the TBM. After irradiation, the capsules are transferred back to counting station for foil activity measurement. This paper will present the conceptual design of NAS system along with preliminary engineering analysis and sequence of operations.

1. INTRODUCTION

India is testing its own breeding blanket module technology in ITER through Test Blanket Module (TBM) program. The TBM program has six different invariants of tritium breeding blanket technology in ITER. India is developing its own blanket concept based on its experience in both liquid breeder as well as solid breeder for getting maximum tritium reproduction rate (TPR) named as LLCB TBM[1]. One of the specific objectives of LLCB TBM testing in ITER is validation of neutron transport tools (software codes) and tritium breeding predictions. This can be achieved through neutron diagnostics which are suitable to work in TBM like harsh environment. Neutron Activation System (NAS) is one of the techniques suitable to measure radial neutronic profile as well as average TPR during a plasma pulse inside TBM to compare the capability of codes used. Such a system is being designed and developed at preliminary scale for LLCB TBM and described in next pages.

Neutron Activation System (NAS) is a passive neutron diagnostics where simultaneous signal measurement is not possible. It is based on foil activation method. NAS is a pneumatic transfer system designed to carry metal samples to neutron irradiation location using a driving gas and after irradiation metal samples (foils) are transferred to another location for gamma activity measurement system. The activity induced in foils is corresponding to various daughter nuclide and gamma formed (prompt or delayed gamma) due to nuclear reactions from neutrons with metal isotopes. Threshold reactions and the representative gammas are chosen to calculate corresponding neutron energy and neutron flux information.

2. BASIS AND CONCEPTUAL DESIGN OF NAS

Neutronic analyses were performed as a first step to design NAS inside LLCB TBM to determine its location. The poloidal-toroidal middle zone of TBM is found appropriate due to flat spectral response causing less uncertainty due to fluctuations [2]. A pneumatic system is developed to facilitate metal foil samples to move to irradiation location and return back to measurement locations. NAS for LLCB TBM mainly consists of transfer station, capsule loader, transfer lines, foil gamma activity measurement system and irradiation ends. The irradiations of capsules consisting of foils are positioned inside the NAS transfer lines in mid-plane of LLCB TBM, called as irradiation ends. NAS transfer lines inside TBM are enclosed within a housing which isolates NAS transfer lines from rest of the TBM.
structure. The complete layout of NAS transfer lines in LLCB TBS is shown in Figure 1. Capsules sent through these transfer lines at irradiation locations inside TBM are clearly shown in two NAS operation in Figure 1 in section (a) and (b).

Figure 1 Layout of NAS inside TBM (a) NAS irradiation end 1 in first operation (b) NAS irradiation end 2 in second operations during one pulse

The two NAS transfer lines are located inside a housing which is extended up to back plate of TBM. During plasma operation, one batch of capsules will be pushed by gas in transfer line-1 to cover radial length from first Ceramic Breeder (CB) canister up to middle of the housing and transfer line-2 will work as driving gas vent pipe. After irradiation, capsules will return through same transfer line-1 when driving gas sent through transfer line-2 in reverse direction. The same procedure is repeated during same plasma shot by sending other capsules in transfer line-2 and using transfer line-1 as driving gas vent pipe. Capsules are spherical and made of Carbon Fiber reinforced Carbon (CFC) with diameter 13 mm. There is a hollow space of dimension 3x4 mm² inside the capsule to keep foils and pellet samples. Figure 2 shows preliminary process flow diagram of NAS with the main components.

Figure 2 Preliminary Process Flow diagram of NAS for LLCB TBM
2.1. Main components of the NAS

**Transfer lines:** Two no. of NAS transfer lines are carrier of foil sensor carrying capsules as well driving gas from Transfer station (located inside tritium building) to irradiation ends inside TBM. Considering space restrictions inside Tokamak building the both lines are designed so that they can work as capsule transfer as well for driving gas lines in alternate operations. These transfer lines are actually standard pipe of entire length ~ 100 m with outer diameter of 18 mm with thickness 1.5 mm. The operating pressure range is less than 1 MPa and working temperature outside TBM will be 100-RT. Only part of NAS inside TBM will see high temperature due to radiation effect although it will be enclosed inside housing (Figure 1).

**Capsules:** Foil sensors are encapsulated inside spherical capsules to move in-between irradiation end and counting station located inside tritium building. NAS is using a train of capsules to map radial neutronic profile. One of the most suitable materials taken for capsule fabrication is Carbon Fiber reinforced Carbon (CFC) [3]. Fabricated capsules are shown in Figure 3. Capsules can be locked and unlocked through a screw mechanism (Figure 3) and has facility to store metallic foils, and Li$_2$CO$_3$ pellets. Testing of these capsules has been carried out in test loops of transfer lines to check integrity and optimization of system parameters.

![Figure 3 CFC Capsules with screw-lock arrangement and space for foil sensors](image)

**Irradiation ends:** NAS has two irradiation ends, each inside transfer lines in TBM as shown clearly in Figure 1, and Figure 2. The basis of this arrangement is to measure whole radial neutronic profile in two consecutive operational steps during one plasma pulse. The irradiation end is perforated at the ends to facilitate driving gas passage through other transfer line while capsules stay in the previous transfer line.

**Transfer Station:** The transfer station serves the purpose of capsules to and fro to transfer lines as well directing train of capsules to its different channels connecting for purpose of counting, disposal or cooling. Transfer station utilizes dedicated gas supply and tank to discharge used gas for driving capsules as shown in Figure 2.

Design of NAS transfer station is different for LLCB TBM but serves similar functioning as in ITER NAS [4] however design and automation are evolving as per LLCB TBM functioning and requirements. Detailed design of transfer station is out of scope of this paper.

**Counting station:** It consists of mainly gamma detectors to measure induced gamma activity from capsules. HPGe detectors are one of the most widely used detectors. The process of handling all capsules one by one for counting will be automated. The measurement performed will be simultaneous measurement of all the foil sensors inside capsule without opening it. The time required before a capsule goes to measurement referred as cooling time and measurement i.e. time record to get sufficient gamma counts will be dependent on foil samples as well activity estimation by FISPACT activation calculations.

Cooling bin and Disposal bin are equipment’s where capsules are stored before counting as well before disposing them respectively. There are provisions of isolation and safety valves in each of the line as per requirements. A vacuum pump is attached to the transfer station in order to evacuate gas from system and its components before one complete operation.
3. DETAILED MECHANICAL AND NEUTRONIC ANALYSIS OF NAS

3.1. Thermal and thermo-structural analysis of NAS housing and pipes in LLCB TBM set

The two NAS transfer lines are attached to LLCB TBM set flange through a pipe-flange interface. The simplified model used for the analysis consists of NAS housing and pipes along with poloidally reduced back plates manifolds. Back plates are also included in this model to apply the realistic boundary conditions. The finite element model in ANSYS for the analysis is shown below in Figure 4, section (a). The IN-RAFMS [7] is used as the structural material for NAS inside TBM set. Transient thermal analysis has been performed for the model using the ITER burn cycle during normal inductive operation with full power. Heat generation was applied in the structures as per ITER pulse to simulate nuclear heating. The HTC average value of 2300 W/m²-K for Lead Lithium-2 to Lead Lithium-6 zones in TBM has been used for housing surface in contact with lead lithium.

![Figure 4](image)

*Figure 4 Mechanical analyses of NAS transfer lines and housing (a) Finite element model of NAS (b): Temperature distribution in NAS piping and housing (c): Displacement of NAS piping and housing*

The temperature results with temperature time history are shown in section (b) of Figure 4. The maximum temperature of NAS pipe is 501°C which occurs at 4190 seconds. The maximum temperature of NAS housing is 343°C which occurs at 4110 seconds. The total displacement results in the model are shown in section (c) of Figure 4. The maximum displacement on NAS pipe is 2.25 mm and the maximum displacement of housing is 1.6 mm both in radial direction. The analysis shows that dimension taken for NAS transfer lines and housing are suitable w.r.t. design parameter (pressure and temperature) of NAS.

3.2. Neutronic analysis of NAS inside TBM

Neutronic analyses have been carried out to assess the impact of NAS arrangement inside TBM on the nuclear responses. The estimation of tritium production rates in lithium carbonate pebbles is carried out at 7 irradiation ends inside TBM, with & without NAS arrangement. Neutron spectra were also estimated at irradiation ends with & without NAS arrangement for comparison and to assess the impact of NAS arrangement in measurements. Details can be found in reference [2].

3.3. Estimated activities in capsule material and foils

A preliminary study for activation induced in capsule material (CFC) has been performed 10s, 400 s and 3600s as shown in Figure 5. Neutron flux of $1.33 \times 10^{14}$ n/(cm$^2$.s) during DT plasma pulse at irradiation end inside TBM is considered for the calculation.

FISPACT-2007 [5] and European Activation Libraries [6] are used for estimation of foil activities shown in Figure 6 during D-T plasma pulse for irradiation time of 10s, 400 s and 3600. Activities of candidate foils V, Al, Cu, Fe, Co, Au, Ni, Zr, Nb, Mg, In, Zn are calculated inside CB-1 zone inside TBM. It is found that 10 minutes cooling time is sufficient for most of the foils to reach below maximum activity of 100 micro Curie which corresponds to safe limit for manual handling [4].
4. DEVELOPMENT OF A NAS TEST FACILITY

In order to demonstrate the proof of principle of NAS functionality for LLCB TBM, a small scale experimental facility is developed in IPR shown in Figure 7. The test facility contains an arrangement of long transparent plastic tube suitable for capsule movement inside it from one end to another end. Transparent tube makes position measurement of capsules feasible through fiber optic sensors installed at two different locations. Total length of the tube is kept around 38 meter including various bends (bend radius 150 mm) and vertical height 3 meter. The bend radius is sufficient to move spherical capsules without being stuck and vertical height provided in this mock up to observe gravity and induced pressure drop effect on capsule movement. The system is operated in between 0.1-0.6 MPa with mass flow rate 0.09-2.06 g/s. Driving gas used are Ar and He both for capsule transfer tests.

During movement when capsules are passed through thru-beam type fiber optic sensor installed at particular locations each of the capsule obstruct light and gives a voltage signal which is recorded by using a Cathode Ray Oscilloscope (CRO). Based on the measured time difference between start to finish of each of the capsule, speed was determined for each run. A database was generated for average capsule speed with various applied pressure to get hands on experience with probable design and operating parameters for NAS operations in ITER.
Spherical shaped capsules (Figure 8) of diameter 10 mm were used for this mock up facility which are made of stainless steel. All the ten capsules are put together inside the tube at one end. This end is then connected to a gas distribution system. The gas distribution system has number of manifolds and one of its inlet line is connected to the helium gas source. Two no. of position sensors (Figure 9) are installed at the two ends to determine the average speed over the entire length of the tube. The experienced gained from these steel capsules transfer was utilized to in experiment with actual CFC capsules in next pages.

4.1. Position sensor measurement

Applied gas pressure moves the capsule’s train inside the tube. Since other end of the tube is open to the atmosphere for gas exit, after travelling the total tube length, capsules stop when they reach to the other end (irradiation end). Observations recorded are shown in Figure 10, when capsules cross the sensor regions. Each peak of voltage signal represents to the individual capsule. With increase in pressure, the capsules speed also increases due to increase in the thrust force. The speed is then estimated by measuring time of capsule between two sensor regions.

It is observed that, SS capsules moves at a speed of around 5 m/sec at a gas pressure of around 1.7 bars as shown in Figure 11. With increase in applied pressure, capsules speed increases due to increase in the net applied force and at a pressure of 6 bars it reaches up to 11 m/sec. It is observed that to obtain 10 m/sec capsules speed, a pressure of around 5 bar is required for this experimental setup made of Polyurethane (PU) flexible plastic tube. However in comparison to actual NAS, this required pressure will be less due to the use of steel tube (less friction than PU tube) and CFC capsule (less force required to move capsules as density ratio between CFC and steel material is ~ 1: 3.5).
5. DEMONSTRATION OF PRELIMINARY MOCK-UP OF NAS WITH TRANSFER STATION

Section 4 of this paper describes the proof of principle of NAS design using only one plastic tube for movement of SS capsules and different small tubes for facilitating gas transfer. In this arrangement transfer station is not used as movement is within ends of one tube only. However as per actual Indian NAS design, demonstration of the same having two transfer lines along with transfer station is must to be performed. A scaled down mock-up of NAS is shown in Figure 12. In this arrangement transfer station is connected to different channel i.e. transfer lines (made of Poly Vinyl Chloride (PVC) plastic tubes), capsule activation measurement (counting station), disposals and gas transfer lines. The transfer station is used in manual mode although designed for automated stage. Actual CFC made capsules (4 nos.) are used for movement in this arrangement. Position sensor measurement similar to section 4 are used at two locations in these transparent transfer line-first at irradiation end and second in the transfer station from where capsules emerges to the transfer lines. He gas is used for transferring capsules.

In this demonstration a bit difference in movement of capsule is observed in forward and backward direction in the same transfer line at same pressure.

In Figure 13, observation are recorded (for first and last capsules) when capsules are sent from transfer station towards irradiation end in transfer line-1 in forward direction. It is very clear that capsule movement is deflected near to irradiation end and capsules reaches with different velocities in comparison to their source place. Figure 14 shows observation of position sensor for the backward movement of capsules from irradiation ends to transfer station. Again same trends can be observed that capsule starts with almost same velocity (near irradiation end as source) while reaching to the destinations they have different velocities shown by voltage spikes different times as measured from position sensors.
6. CONCLUSION AND FUTURE WORK

The conceptual design of NAS for LLCB TBM is analyzed with mechanical and neutronic simulation tools. The small scale mock-up of NAS is realized by demonstrating the feasibility of its operation with available capsules and piping. Position sensing of capsule is also performed which is most crucial part of this system to predict uncertainty in measurement location which affects predictions of TBM neutronic parameters. In next stage, an upgraded test facility, actual 1:1 mock-up of NAS loop with actual materials for LLCB TBM NAS will be designed having its own automated transfer station and gas distribution system. It will be demonstrated and tested for CFC Capsule impact test and provision to direct capsules to multi destination.

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