SAFETY ANALYSIS FOR THE MAINTENANCE OF THE CALORIMETER OF THE FIRST ITER NEUTRAL BEAM INJECTOR

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The Neutral Beam (NB) devices for the International Thermonuclear Experimental Reactor (ITER) are medium energy light particle accelerators. Accelerated particles are negative deuterium ions with maximum energy of 1 MeV. The deuteron beam with a pulse current of 40 A and a duration time of 20 s is stopped on a water-copper alloy calorimeter.

The main features of the NBs will be tested in a Test Facility (NBTF) that will be built in a different site from that of ITER.

In the work presented here the assessment of the radiological safety for the maintenance of the calorimeter of the NBTF is described and the related results are discussed. The activation analysis of NBTF components is performed using MCNP Monte Carlo Code and FISPACT inventory Code in order to predict shutdown dose rates. Starting from a refined description of the D-D neutron source, the induced activation of the NBTF components is calculated, for two realistic operational scenarios. Normal maintenance activities for the calorimeter are identified and the related operator positions are defined. Finally individual and collective doses are assessed for the whole maintenance operation.

I. SCOPE OF THE STUDY

The work described and discussed in the following is part of an international task that is aimed to provide data and tools useful to support licensing, operating and decommissioning phases related to the first neutral beam (NB) for the International Thermonuclear Experimental Reactor (ITER). The ITER NBs are part of a complex system designed to provide energy to the plasma for sustaining the nuclear fusion reactions.

The first ITER NB will be tested in the Neutral Beam Test Facility (NBTF) that will be located in a site different from Cadarache (France) where ITER will be hosted.

According to the opinion of the NB experts an ITER-like NB system has to be built and tested before the ITER NB system is installed at the ITER site. This system has to demonstrate high voltage acceleration at ITER relevant currents, to ensure that reliable NB operation is achieved in ITER and to minimize the time required for on-site commissioning. This is the idea on which the NBTF concept is based.

The NB components and performances have to be tested at the NBTF on a full scale basis, reproducing the pulse length required for ITER NB, until about 1 hour of duration.

The main goal of the facility is to qualify the first ITER NB and the associated high voltage transmission line, but this is not the only mission of the NBTF that is designed to investigate all the aspects related to the NB operation and in perspective it will become a R&D station for these kind of devices. One of the important issues to be considered in the NBTF design is therefore the radiological protection of the workers involved in the maintenance activities. In this frame the studies are under way to setup the maintenance procedures and to assess the related radiation fields and workers exposures.

The current work is devoted to the analysis of the more critical maintenance activity for the NB testing: the repair or the replacement of the calorimeter.

II. THE ITER NEUTRAL BEAM SYSTEM

The NB system for ITER consists of two heating and current drive (H&CD) NB injectors and a diagnostic neutral beam (DNB) injector. The last one will not be considered in the following description. The layout allows a possible third H&CD injector to be installed later. These NB injectors will be connected to equatorial ports of the machine and will be located outside of the ITER cryostat, inside a common enclosure, the NB cell (see Fig. 1).

The ITER H&CD NB injectors are medium energy light particle accelerators. Accelerated particles are negative deuterium ions with maximum energy of 1 MeV.

In each H&CD injector, the D- ion beam of 40 A is neutralized to form a Do neutral beam, which delivers 16.7 MW to the plasma. Thus the NB system provides a H&CD power of 33 MW from 2 injectors, and can be upgraded to 50 MW in total with a third injector. The NB system will be able to operate for long pulses, up to 3600 s.

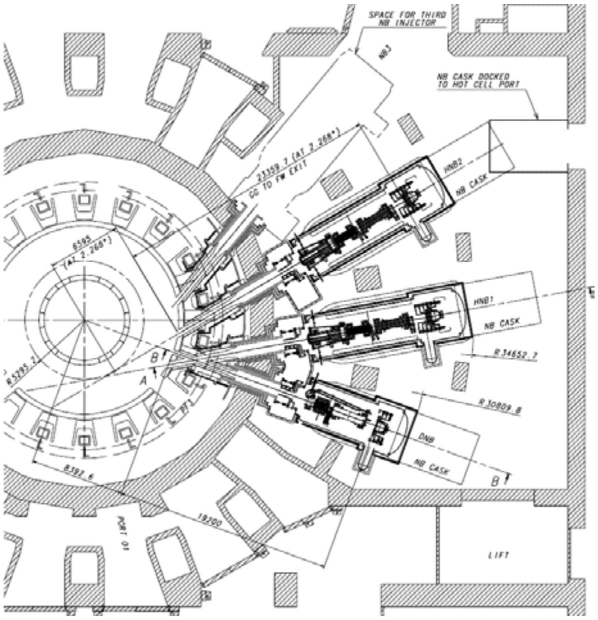

Fig. 1. The ITER NB system.

The ITER H&CD NB components are illustrated in the drawing of Fig. 2.

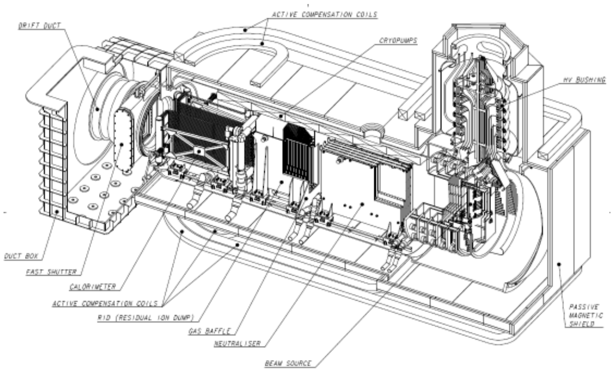

Fig. 2. The components of an ITER H&CD NB.

The reference design for the ITER NB system and for the first ITER NB is described in the ITER Design Description Document (DDD) No 5.3 (Ref. 1). The document contains the detailed description of the system and of the single components in terms of geometry and material composition. In the second part of the DDD 5.3 an extended performance analysis is also presented.

III. NEUTRON FLUX AND DOSE RATE

Nuclear analysis has been applied to the first ITER NB by using a simulation model that was implemented into MCNP computer code.[2]

III.A. The Simulation of the Components

Simple geometrical forms have been defined for the first ITER NB components like the vacuum vessel (VV), the neutraliser, the residual ion dump (RID), the calorimeter and the cryopump.

The materials that have been considered in the simulation are the following: CuCrZr, SS316, Cu, H_2O and Air. CuCrZr-alloy is used for the main panels of Calorimeter and RID; its elemental composition by weight is as follow:

Cu = 0.9930; Cr = 0.0065; Zr = 0.0005

SS AISI 316 is the component of the VV, of the cooling tube walls and of the supporting structures. The elemental composition is the following:

B = 3.08×10^{-05}; C = 3.00×10^{-04}; N = 3.65×10^{-04};
Si = 2.96×10^{-03}; S = 3.45×10^{-05}; Ti = 1.01×10^{-03};
Co = 5.38×10^{-04}; Cr = 1.72×10^{-01}; Mn = 1.74×10^{-02};
Fe = 6.53×10^{-01}; Ni = 1.32×10^{-01}; Cu = 1.00×10^{-03};
Nb = 3.29×10^{-05}; Mo = 1.89×10^{-02}

III.B. The Neutron Source

In the first ITER NB high energy deuterium beam produces neutrons via D-D reactions not only between the beam and the neutralizer gas, but also between the incoming beam particles and deuterium embedded in the copper of the beam dump and/or residual ion dump.

The first aspect to be considered in order to evaluate the neutron emission is the deuteron implantation on the calorimeter and RID surfaces. The surfaces of these components are mainly composed of copper therefore D implantation on this element will be considered. Such aspect was taken into account also in the appendix H of DDD 5.3.

Since the maximum power densities quoted for RID and Calorimeter (8 MW m^{-2} and 22 MW m^{-2} at STE surface) correspond to current densities of 0.8 mA/cm^2 and 2 mA/cm^2 respectively, a reference current densities of 1 mA/cm^2 is an acceptable compromise and it was used in a parallel study[3] to assess deuterium implantation and reactions on the calorimeter surface. According to this parallel study, 80% of the limiting density of implanted D on the calorimeter panels is reached in only 60 pulses of

3600 s at 1 mA/cm^2 - 1MeV and it is therefore reasonable to assume that the target is fully saturated by D from the beginning of the operation. The saturation density of deuterium in copper is known from literature to be 10% of deuterium atoms per copper atoms.[3]

With the above hypotheses the reference work prediction of neutron production from D-D beam-target reactions expressed per Coulomb of incident D particle is 3.78×10^{12} C^{-1}. In the same work also D-T neutrons production has been assessed with a resulting production rate of 5.2×10^{7} C^{-1}.

A detailed source subroutine was implemented for MCNP calculation using a mathematical model already developed for the FNG facility.[4] The following main features were included in the subroutine:

- Only D-D neutron production was considered, D-T neutrons are in fact completely negligible.
- The D(d,n)^{3}He fusion reaction anisotropy in the center of mass (CM).
- Accurate description of D-D reaction was taken form DROSG work (Ref. 5).
- The double differential (energy-angle) CM kinematics has been incorporated and added to the LAB kinematics.
- Source profiles on the STE panels and RID surfaces have been considered.

III.C. Neutron Flux Assessment

Neutron transport starting from the calorimeter and RID plates was simulated with MCNP code,[2] a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/ photon/electron transport.

Two main results were calculated with MCNP code: the neutron flux in each geometry cell and the dose rate at different distance from the NB vacuum vessel due to neutrons only.

III.D. The Reference Operational Scenario

In order to assess the potential components activation in a severe situation an extreme operational scenario was defined for the interim (or normal) campaign, considering 20 s pulses of 40 A each and assuming 100 days campaign with 100 pulses per day.

The scenario was completed with a 14 days final test during which long pulses of 3600 s each are repeated each 4 hours (6 pulses per day) giving a total of 84 pulses.

III.E. The Activation Calculation

FISPACT-2003 code[6] was used to assess neutron activation in the material of the system components. It is an inventory code that has been developed for neutron induced activation calculations for materials in fusion devices.

The main components of the first ITER NB were considered in the FISPACT calculation. The related results are the radioactive inventory and the contact dose rate, that were assessed considering two potential operative scenarios the first one represented by the interim campaign and the second one composed by the interim and a sequential final campaign.

III.F. Dose Rate Assessment

FISPACT calculation gives a limited picture of the dose rate. Only contact dose rates can be assessed with this code, and the doses from the components around the one considered are not accounted for. The worker safety assessment must be based on a dose rate map variable with the time according to the radioactivity cooling down rule. The gamma radiation due to the neutrons activation has to be followed to assess the dose rates in the different points of interest. This process has been implemented in the Direct 1- Step (D1S) computational method[7,8] that is an innovative approach for the evaluation of the dose rate due to the decay of radioactive isotopes produced during neutron irradiation.

In the current application D1S method was used to assess the dose rates around the calorimeter after one interim campaign. The scope was to have a starting point for assessing individual and collective doses to the workers involved in the maintenance of the calorimeter itself. Three reference positions were considered in the calculation by using three detecting rings, located on the same plane that includes the cross section of the calorimeter at its mid length. The application of the D1S method gave the dose rates results reported in Table I.

TABLE I. Dose Rates Related to the Distance from Calorimeter and to the Cooling Time

	Dose Rates (μSv/h)		
Cooling Time (days)	Position A 3 cm from Calorimeter	Position B 3 cm from Vessel	Position C 100 cm from Vessel
1	180	52	10
2	25	10	2
3	16	7	2
4	16	7	2
7	13	7	2

The table shows that after 1 day of cooling time the guideline of 100 μSv/h, set in the ITER radiation protection program,[9] is not observed in every position, i.e. it is not possible for an operator to go close to the calorimeter in a such short time after NB stop. Two days of cooling time are sufficient to fulfil the dose rate guideline and therefore a maintenance operation to be performed close to the calorimeter has to be scheduled at least two days after the NB shut-down.

IV. MAINTENANCE OF THE CALORIMETER

The maintenance of the calorimeter requires disconnection, removal, repairs and connection of the component. These operations are time consuming and need human intervention in many phases of the task.

The procedure for removing and replacing the calorimeter are reported in Table II and in Table III respectively.[9]

In the tables the time required and the number of operators needed are indicated for each subtask. Each operation requires the workers to stay in an average location that can be more or less close to one of the positions reported in Table I.

The operator position is then associated to the dose rate at the time of the maintenance activity. The minimum cooling time to allow the dose rate below the guideline value has been anticipated to be more than 24 hours and for safety reasons a minimum cooling time of 48 hours has been recommended. Dose constraints apply also to the individual dose and to the collective dose values, therefore a parametric study was performed to investigate what could be the optimal cooling time needed for an annual intervention to repair the calorimeter.

In Table IV and Table V individual and collective doses are reported respectively for disconnecting and for connecting the calorimeter. Also after only 48 h of cooling time both the maintenance tasks considered in the tables accrue the individual dose for an amount lower than 0,5 μSv and the collective dose for less than 1 man μSv. The reference limits for the individual dose to the workers allow the maintenance of the calorimeter to be performed by the same two operators without the needing of special staff shifts. Also the constraint values defined in the RPP for individual and collective doses are such that dismounting and remounting the calorimeter could be performed without any additional precaution for reducing the radiological exposure.

Some additional consideration must be issued in the case that the calorimeter maintenance takes place more than once in a year, in this occurrence the dose increment to the exposed workers could lead to an overall individual dose higher than (or very close to) the reference limits or constraints. In both the maintenance activities waiting three days instead of two decreases individual and collective doses by an important amount: about 50% for the disconnection and more than 30% for the connection.

On the other end waiting seven days instead of three does not reduce the doses of an additional significant quantity. In this last case individual and collective doses decrease of about (or less than) 10%, but waiting seven days instead of three could increase the dead time in an unacceptable way. ALARA principle imply therefore that waiting three days of cooling time should be the best solution for the maintenance of the calorimeter.

TABLE II. Procedure for Calorimeter Disconnection

#	Description	Time Estimate (hours)	Number of Operators
D1-2	Disconnection of the Manifold (lower flange metallic seal)	2	2
D2-2	Disassembly of the 3 spacers	1	2
D3-1	Disconnection of the upper vacuum flange from the BLV (Viton or metallic seal)	1	2
D3-2	Disconnection of the lower vacuum flange from the feeding pipe (Viton or metallic seal)	1	2
D3-3	Removal of the large vacuum bellows	2	2
D4-1	Disconnection of the upper hydraulic flange from the calorimeter (metallic seal)	2	2
D4-2	Removal of the feeding pipe	2	2
D5-1	Opening of the BLV front flange (Viton or metallic seal)	3	2
D5-2	Set-up and alignment of the external rails (inside the BLV, partly)	2	2
D5-3	Disconnection of the inner diagnostics: temperature sensors, etc. (inside the BLV)	1	2
D5-4	Disconnection and removal of the lateral jacks (inside the BLV)	1	2
D5-5	Removal of the calorimeter (inside the BLV)	3	2
Total Time Required with Man Access		21	---

TABLE III. Procedure for Calorimeter Connection

#	Description	Time Estimate (hours)	Number of Operators
C1-1	Set-up and alignment of the calorimeter (inside the BLV)	4	2
C1-2	Connection of the lateral jacks (inside the BLV)	1	2
C1-3	Connection of the inner diagnostics: temperature sensors, etc (inside the BLV)	1	2
C1-4	Removal of the external rails (inside the BLV, partly)	1	2
C1-5	Closure of the BLV front flange (Viton or metallic seal)	4	2
C2-1	Connection of the feeding pipes to the component (1 metallic seals)	4	2
C2-2	Leak test of metallic seals under 0.5 Mpa Helium inlet pressure	2	2
C3-1-1	Connection of the lower vacuum flange to the oblong inner flange (Viton seal during phase I)	4	2
C3-1-2	Connection of the lower vacuum flange to the oblong inner flange (metallic seal during phase II)	6	2
C4-1-1	Connection to the upper vacuum flange to the BLV	2	2
C4-1-2	Connection of the upper vacuum flange to the BLV flange	4	2
C5-1	Assembly of the spacers	2	2
C5-3	Helium leak test of the BLV at almost 10^{-5} Pa	3	2
C5-4	High Pressure Helium test of the in-vessel connection flanges (3 MPa)	2	1
C6-1	Connection of the inlet-outlet manifolds (metallic seals)	2	2
C6-3	water pressure test at 3 Mpa, room temperature	1	1
Total Time Required with Man Access		43	---

TABLE IV. Individual and Collective Doses for Disconnecting the Calorimeter, After 2, 3 and 7 Days of Cooling Time

Operation	Operator Position	Gamma Dose Rate (μSv/h)			Individual Dose (μSv)			Collective Dose (man μSv)		
		2 days	3 days	7 days	2 days	3 days	7 days	2 days	3 days	7 days
D1-1	-									
D1-2	B	10	7	7	20	14	14	40	28	28
D2-1	-							0	0	0
D2-2	B	10	7	7	10	7	7	20	14	14
D3-1	B	10	7	7	10	7	7	20	14	14
D3-2	B	10	7	7	10	7	7	20	14	14
D3-3	B	10	7	7	20	14	14	40	28	28
D4-1	B	10	7	7	20	14	14	40	28	28
D4-2	B	10	7	7	20	14	14	40	28	28
D5-1	B	10	7	7	30	21	21	60	42	42
D5-2	A	25	16	13	50	32	26	100	64	52
D5-3	A	25	16	13	25	16	13	50	32	26
D5-4	A	25	16	13	25	16	13	50	32	26
D5-5	A	25	16	13	75	48	39	150	96	78
Total					315	210	189	630	420	378

TABLE V. Individual and Collective Doses for Connecting the Calorimeter, After 2, 3 and 7 Days of Cooling Time

Operation	Operator Position	Gamma Dose Rate (μSv/h)			Individual Dose (μSv)			Collective Dose (man μSv)		
		2 days	3 days	7 days	2 days	3 days	7 days	2 days	3 days	7 days
C1-1	A	25	16	13	100	64	52	200	128	104
C1-2	A	25	16	13	25	16	13	50	32	26
C1-3	A	25	16	13	25	16	13	50	32	26
C1-4	A	25	16	13	25	16	13	50	32	26
C1-5	B	10	7	7	40	28	28	80	56	56
C2-1	B	10	7	7	40	28	28	80	56	56
C2-2	C	2	2	2	4	4	4	8	8	8
C3-1-1	B	10	7	7	40	28	28	80	56	56
C3-1-2	B	10	7	7	60	42	42	120	84	84
C4-1-1	B	10	7	7	20	14	14	40	28	28
C4-1-2	B	10	7	7	40	28	28	80	56	56
C5-1	B	10	7	7	20	14	14	40	28	28
C5-3	C	2	2	2	6	6	6	12	12	12
C5-4	B	10	7	7	20	14	14	20	14	14
C6-1	B	10	7	7	20	14	14	40	28	28
C6-3	C	2	2	2	2	2	2	2	2	2
Total					487	334	313	952	652	610

V. CONCLUSIONS

The study presented here is the first of a series devoted to the setup of the working procedures to be adopted at the NBTF. The work is aimed to help the designers in revising end if possible correcting the technological solutions proposed for the working activities to be performed at the NBTF.

The maintenance of the calorimeter of the first ITER NB after a normal testing campaign has been shown to be a completely affordable task from the radiological protection point of view.

The limits and the consequent constrains for individual and collective doses are easily respected by waiting acceptable periods of time before accessing the experimental hall after the NB shut-down.

Since the calorimeter is the NB component on which the neutron flux is more intense and, also due to its material composition, it is the most affected by the radiological activation, the above results indicate that the technological solutions proposed so far by the NBTF designers are adequate to control the workers exposure.

The result anticipates that also the future studies to assess dose rates and radiological safety of the workers during other working activities at the NBTF should not point out any real difficulty or needing of an important changing in the working strategy.

Optimization process in radiation protection requires anyway a thorough analysis of the procedures and therefore this kind of studies will persist and will constitute one of the basis for the radiation safety report that will be prepared for the NBTF licensing.

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