Feasibility of Hands-On Maintenance of the Ion Sources in the NBI of MARS

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FEASIBILITY OF HANDS-ON MAINTENANCE OF THE ION SOURCES IN THE NBI OF MARS

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ABSTRACT

The problem of the radiation in penetrations was solved in the MARS sloshing beam line by providing several bends through the penetration shield to efficiently attenuate the streaming radiation. The design of the shield within the NBI penetration and the off-axis arrangement of the ion sources along with the selection of low activation materials for the NBI help reduce the biological dose to an acceptable level at the back of the injector where hands-on maintenance is highly desirable.

INTRODUCTION

The study was carried out for the tandem mirror power reactor MARS.[1] Its end cells require a number of heating systems to produce the necessary potential, pressure, and density profiles that ensure stability, confinement, and overall desirable operating characteristics. The heating systems include the ECRH, ICRH, and the high energy neutral beam injector (NBI). These penetrations connect the reaction chamber to the functional equipment located outside the shield and thus, present a variety of problems for the designers. The NBI was selected for radiation analyses as it has the largest streaming radiation among the MARS end cell penetrations[2] and, therefore, the radiation problems in the other systems seem to be less severe.

Recently, the acceptability of NBI heating based on positive-ion sources for fusion reactors has been seriously questioned because of the engineering complications and the low overall efficiency of this scheme. On the other hand, NBI heating based on negative-ion beams is an area in which recent advances improve the prospects for a system with high efficiency and significantly reduced neutron streaming. An attractive and practical solution to the streaming problem is to provide several bends in the penetrations and strong transport structures capable of transporting the heating particles around bends in channels through the penetration shield. This option has proven to provide effective attenuation for the streaming radiation.[3,4] These combined factors dictated the choice of the Berkeley version as the baseline design for the MARS sloshing ion beam line. One important achievement is the installation of the ion sources and the high-voltage sections in a low neutron environment off the direct line of sight of the streaming radiation by employing a rather long and curved beam transport system penetrating the shield, thus adding to the reliability, reducing radiation damage and simplifying maintenance of the vital components of the injector.

GENERAL FEATURES OF THE NBI

The NBI is required to deliver a total of 14.75 A at 475 keV and is based on negative ions which can be efficiently converted to neutrals at such high energy. Figures 1 and 2 show the main components of the 15 m long sloshing ion beam line. Multiple sources in each beam line form ribbon beams for the accelerator. The LBL (Lawrence Berkeley Laboratory) self-extraction negative ion sources[5,6] produce negative ions on the surface of a cesiated electrode in contact with a deuterium plasma. The source ions are pre-accelerated to 80 keV by a standard DC multiple grid set before being injected into a four stage Transverse Field Focussing (TFF) accelerator. The TFF system uses transverse electrostatic fields alternating in direction to focus and control the beam. It consists of properly shaped and oriented grids that offer the possibility of bending the ribbon beam with a short enough radius (~ 0.4 m) that the beam can be transported through a sinuous path of reasonable length surrounded by a shield to greatly attenuate the streaming radiation through the NBI duct and alleviate problems of activation of the ion sources and accelerators. The accelerated negative ions are converted to neutral atoms by passing the ion beam through a folded resonator laser photodetachment neutralizer; a conversion efficiency of 95% or more is possible. The beam then passes through a sweep magnet where the remaining ions are removed from the neutral beam. A considerable amount of this ion energy is recovered by the ion-beam dump. The cryopumps distributed along the beam line

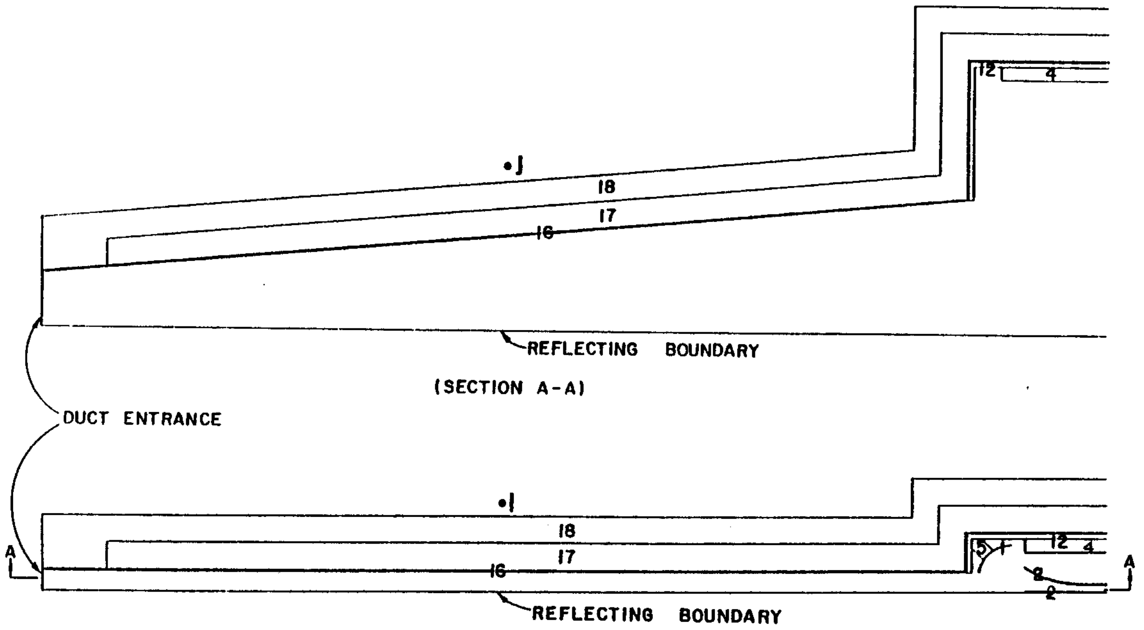

Fig. 1. Vertical and horizontal cross sections of the NBI for axial zone 0-8 m (output from MCNP[7] plotting routine); numbers on the figure are for the regions identified in Table I.

remove most of the gases emerging from the neutralizer and the ion-beam dumps, and maintain the pressure at a sufficiently low value so that very little of the neutral beam is reionized.

STUDY GOALS

The aim of this study is to design a suitable radiation shield for the NBI, select low activation materials for the different components, evaluate the radiation effects on the high voltage insulators, the nuclear heat loads on the cryopanels and magnetic shield, the heating effects for the laser neutralizer mirrors, and calculate the biological dose rate at the back of the injector where hands-on maintenance is highly desirable. Until recently, it was assumed that the injector would become activated by the streaming neutrons and that the maintenance must be by remote procedures. The new concept of hands-on maintenance of the injector has been brought on by a better design and off-axis arrangement for the most sensitive components of the NBI. The criterion for hands-on maintenance is to have a dose rate not greater than 2.5 mrem/h at the end of a cooling-off period of 48 hours after reactor shutdown to be able to maintain the ion sources without a special radiation shield. To assess the feasibility of hands-on maintenance, detailed 3-D neutronics calculations are required to compute the neutron flux at the various components of the NBI. These are followed by activation analyses to produce the decay gamma ray sources at the end of a one full power year (FPY) irradiation period. Then, 3-D gamma transport calculations are performed and the dose is determined two days after shutdown at various locations outside the NBI.

ACTIVATION CONSIDERATIONS

To keep the radiation around the NBI to reasonable levels, the materials and thicknesses of the components (Table I) were chosen based on activation considerations while meeting the structural and functional demands. In general, the use of copper was avoided and the HT-9 structural material is used in the hard neutron spectrum region of the straight beam duct (starting from the injector entrance up to the beginning of the HEBT section). In this region the use of Al was excluded to avoid the production of ^{24}Na by the energetic neutrons[8] ($E > 5$ MeV). In the accelerator region, where the neutron spectrum is relatively soft, Al is preferable[8]. The electrodes are chosen as thin as possible as well as their supports to meet the activation constraints. The 304-SS steel alloy is less activated[9] than Fe1422 steel. Accordingly, the 304-SS was selected as the structural material of the NBI penetration shield. Even though the HT-9 would be less activated[9] than 304-SS, its well known DBTT problem at low temperatures characteristic of the water cooled shield has led to its exclusion. Alumina

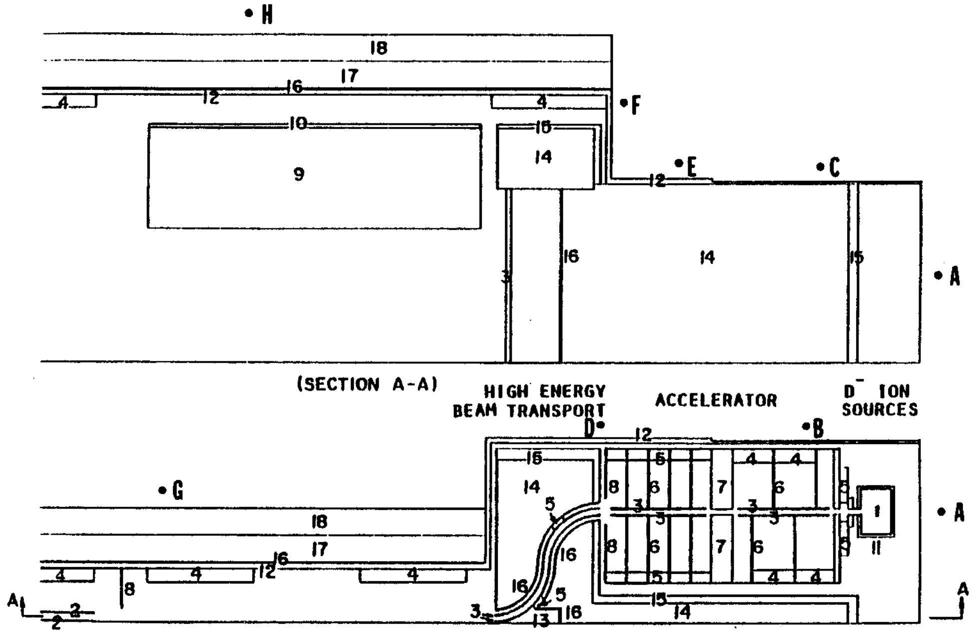

Fig. 2. Vertical and horizontal cross sections of the NBI for axial zone 8-14.6 m (output from MCNP[7] plotting routine); numbers on the figure are for the regions identified in Table I.

(Al_2O_3) is used as the high-voltage insulator in the NBI. It is a well developed ceramic insulator and can tolerate[10] a neutron fluence up to 5 x 10^{24} n/m^2 (E_n > 0.1 MeV).

PENETRATION SHIELD DESIGN

Special attention was paid to the design of the NBI shield as the amount of radiation which leaks through the penetration can be controlled to some extent by proper choice of material, composition, and arrangement of the radiation shields. The high energy beam transport (HEBT) consists of two TFF stages, each with a right angle bend and 0.4 m radius of curvature. The transverse spacing between the 0.01 m thick electrodes is 0.04 m. To effectively attenuate the streaming radiation, tungsten is used to surround the double-bend penetration at the HEBT section. The W-shield [80 vol.% W (90% d.f.), 10 vol.% 304-SS, and 10 vol.% H_2O] which is effective in slowing down the high energy neutrons, is backed by several centimeters of B_4C-shield [8 vol.% B_4C (87% d.f.), 10 vol.% 304-SS, and 82 vol.% H_2O] to further moderate the neutrons and absorb the low energy neutrons. The promising results of other studies[4,11,12] suggested the installation of a flux trap, designated 13 in Fig. 2, in the W-shield to improve the attenuation by trapping most of the particles streaming up the straight beam duct. Boral (B_4C and Al) as a penetration shielding material was found[4] to reduce the thermal group flux around the penetration by two to three orders of magnitude, and is recommended as a duct lining material for penetrations. In this regard, the NBI penetration is completely lined with 0.01 m boral sheets. Normally the beam duct is lined with an electrical conductor to avoid the buildup of surface charges. Since boral is a conductor, it is not expected to cause any problem in this regard. However, the outgassing and vacuum properties of the boral in this position need to be examined.

In the region surrounding the straight beam duct, the expensive W-shield was avoided in favor of a less effective lower cost shield since space utilization is not a constraint. The shield there is made of two layers, each 0.2 m thick. The first layer is mainly water with 10 vol.% structural content. The water is almost transparent for the high energy neutrons but it is a good moderator in the intermediate energy range. Therefore, the water layer reduces the backscattering into the penetration by providing a relatively clear path for the energetic neutrons and thermalizing the lower energy neutrons. In addition, the water layer offers the advantage of easily draining the water from the containing tank for easy personnel access to the laser neutralizer for maintenance, adjustment, or replacement. The radiation leaked from the water layer is intercepted by a 0.2 m thick layer made of a homogeneous mixture of the magnet radiation shield used in the end cell.

Table I. Dimensions and Compositions of the Material Zones in the NBI

Region*	Identification	Dimension (m)	Material
1	ion dump	0.06 thick	Al
2	electrostatic plates	0.01 x 1 x 1.1	HT-9
3	electrode	0.01 thick	Al
4	cryopanel	0.1 thick	18 vol.% Al, 2 vol.% HT-9, 80 vol.% void
5	electrical insulator	0.1 thick	Al_2O_3
6	electrode support structure	0.01 x 0.5 x 1.3	Al
7	vacuum valve	0.15 x 0.51 x 1.3	HT-9
8	vacuum separator	0.01 thick	HT-9 or Al
9	neutralizer	0.03 x 2.5 x 0.75	25 vol.% Al, 75 vol.% void
10	mirror	0.03 x 2.5 x 0.03	75 vol.% Mo, 25 vol.% H_2O
11	ion sources	see Ref. 5	
12	magnetic shield and vacuum vessel	0.02 thick each	Al
13	flux trap	0.1 x 0.2 x 1.3	void
14	W-shield	~ 0.75 x 1.22 x 1.75	80 vol.% W, 10 vol.% 304-SS, 10 vol.% H_2O
15	B_4C-shield	~ 0.05 thick	8 vol.% B_4C, 10 vol.% 304-SS, 82 vol.% H_2O
16	boral lining	0.01 thick	36.6 vol.% B_4C, 63.4 vol.% Al
17	water layer	0.2 thick	90 vol.% H_2O, 10 vol.% 304-SS
18	shield	0.2 thick	65.4 vol.% 304-SS, 29.2 vol.% H_2O, 2.1 vol.% B_4C, 3.3 vol.% Pb

*See Figs. 1 and 2.

Admittedly, extra shield can be added if the shield thickness is not sufficient to reduce the biological dose to an acceptable level.

CALCULATIONAL PROCEDURES

The model shown in Figs. 1 and 2 was entered into the MCNP input to treat the problem of the radiation effects on the NBI components. The 18 regions of the NBI are identified by Table I. Due to symmetry, one-fourth of the NBI was modeled with reflecting boundaries at the injector axis. Only those components which have significant effects on the activation of the ion sources are included in reasonable detail. The material cross sections were taken from the RMCCS library based on the ENDF/B-V evaluation.[7] The problem employs neutron and gamma surface sources at the duct entrance of 2.2×10^{16} and 3.75×10^{15} particles/s, respectively, as obtained from the previous model of the end cell shield and penetrations.[2] The source particles are sampled according to their energy and angular distributions (see Ref. 2 for the plots). The neutron spectrum shows that approximately 24% of the crossing neutrons are source neutrons at 14.1 MeV. A significant number of lower energy secondary neutrons that have been moderated in and reflected from the end cell shield also stream through the duct, and ~ 70% of the neutrons have energies below 1.35 MeV. The angular distribution of the particles peaks at normal incidence and most particles stream along the beam line. This serves as a warning to carefully shield the NBI system in order to protect the vital components located at the back of the injector. To improve the statistical accuracy of the results, the source angular distributions were biased toward the injector axis by sampling from biased cumulative distribution functions and adjusting the weights of the source particles to reflect this effect. Moreover, the particle transport through the NBI relied heavily on geometry splitting coupled with the Russian Roulette variance reduction technique.[7]

To evaluate the effectiveness of the flux trap and the arrangement of shielding for the straight beam duct, the perturbation version of the MCNP code was utilized. The current version handles a maximum of two perturbed problems simultaneously. The use of this version has the advantage that particle histories are correlated and the computation effort is typically less than that required for independent calculations. The geometric perturbation is treated by changing the material and/or densities in the desired perturbed geometry. For instance, to evaluate the effect of the flux trap, all histories are followed once with the exception that for particles entering the flux trap the history is followed twice: once with void in the flux trap, and once with this region filled with the W-shield. A similar treatment is carried out for the second perturbed problem where the consequences of placing a water layer in the straight beam duct were investigated, in comparison to filling this layer with shielding material.

RESULTS

The 100,000 histories run of MCNP results in the neutron fluxes at several components of the NBI. The flux at the ion source is as low as 10^5(±50%) n/cm^2 s. Since the flux at the duct entrance is ~ 10^{13} n/cm^2 s, we conclude that a neutron attenuation of about eight orders of magnitude is achieved. This is mainly attributed to the design of a narrow and bent beam channel through the ~ 0.7 m thick W/B_4C shield, in addition to the $1/r^2$ geometrical attenuation of the flux. It is worth mentioning that each bend attenuates the streaming radiation through the double-bend penetration by about an order of magnitude. This was evident by examining the current across surfaces located at the beginning and end of each bend. The shield surrounding the double-bend helps attenuate the high energy neutrons and the neutrons at the accelerator and ion sources have energies below 1 MeV.

The MCNP results indicate a reduction of up to 45% in the neutrons backscattered from the shield wall of the straight beam duct in the case of water filling the front 0.2 m of the shield. About 40% reduction in the number of neutrons crossing a surface located at the end of the double-bend was obtained as a result of using the flux trap and an even greater reduction of 65% was achieved in the case of using the water layer in the shield of the straight duct. Evidently, the installation of the flux trap and the water layer substantially reduces the streaming radiation beyond the double-bend penetration.

The computations also include some results of interest. The first insulating support of the electrodes in the double bend penetration has the highest neutron fluence of 10^{22}(±15%) n/m^2 (E_n > 0.1 MeV) compared to the other insulators. It appears that the alumina insulator would last the 24 FPY reactor life as far as radiation is concerned. If the MACOR[13] insulator is prefered because of its machinability, it can still be used without any expected problems during the reactor life although it tolerates a relatively lower fluence level[10] of ~ 5 x 10^{22} n/m^2. The nuclear heat loads on the cryopanels and magnetic shield seem acceptable with maximum values of 0.023(±8%) and 0.012(±10%) mW per cm^3 of the solid material, respectively, which are not expected to cause an excessive cryogenic load. The volumetric heating rate in the laser neutralizer mirror is 0.03(±45%) mW/cm^3 and may not need additional cooling except as required for the removal of the heat resulting from the surface absorption of the laser beam.

Table II. Biological Dose Rate Around the NBI at the End of One Full Power Year Irradiation Period and Two Days After Reactor Shutdown

Region*	Dose Rate (mrem/h)	
A	0.088	(± 4%)
B	0.038	(± 7%)
C	0.183	(± 10%)
D	30.75	(± 15%)
E	3.98	(± 30%)
F	130.27	(± 15%)
G	12.42	(± 16%)
H	17.06	(± 32%)
I	2170	(± 6%)
J	341	(± 20%)

*See Figs. 1 and 2.

The activation analyses were carried out using the DKR code[14] and its data library. The analyses employ the neutron fluxes and energy spectra at every material zone as obtained from the previous MCNP run. The analyses result in the decay gamma rays at each component in the NBI at the end of a 1 FPY irradiation period and a cooling-off period of 2 days after shutdown. The analyses show that the decay gamma photons have energies below 3 MeV and are emitted at a rate ranging from ~ 7 x 10^{11} γ/s in the regions adjacent to the NBI entrance to < 0.5 γ/s at the back of the injector.

The activation analyses were followed by a final run of MCNP which included the transport calculations of the gamma rays and the computation of the biological dose rate at various locations outside the NBI. Enough histories were run to ensure that the statistical uncertainty in the dose at the ion sources was less than 10%. The results are reported in Table II and the gamma flux-to-dose conversion factors were taken from Ref. 7 (Appendix G). The biological dose at the ion source is ~ 0.1 mrem/h two days after shutdown. This is well below the limit and it is now assured that the routine maintenance of the ion sources can be completed in a hands-on fashion rather than remotely. However, the radiation level elsewhere around the NBI is quite high and to reduce it to an acceptable level additional Pb-shield (a good gamma absorber) is required especially near the duct entrance. On the basis of ~ 0.1 m of Pb-shield reducing the flux by an order of magnitude, the estimated shield thicknesses needed are 0.3, 0.2, and 0.1 m at the regions designated I, (F,J), and (D,G,H) in Figs. 1 and 2, respectively.

CONCLUSION

The 3-D neutronics and activation analyses of the MARS NBI show that the biological dose rate at the back of the injector is reasonably low so that the routine maintenance of the ion sources can be completed in a hands-on procedure. This is mainly attributed to the combined effect of choosing low activation materials in the NBI and the off-axis arrangement of the ion sources and the design of highly efficient penetration shield. The analyses also indicate that the nuclear heat loads on the various components are not expected to cause any problems and the insulators will last the reactor life as far as radiation is concerned.

While there is no problem with the NBI of the MARS design, it could become a problem in reactors with high entrance wall loadings such as tokamaks where the incident radiation is about two orders of magnitude higher. The designer will then have to provide either more bends in the penetration shield, or maintain the ion sources in a remote fashion.

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