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RADIATION ANALYSIS OF THE CIT PELLET INJECTOR SYSTEM AND ITS IMPACT ON PERSONNEL ACCESS

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FUSION ENGINEERING DESIGN CENTER

OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

The conceptual design of the Compact Ignition Tokamak (CIT) is nearing completion. The CIT is a short-pulse ignition experiment, which is planned to follow the operations of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory (PPPL). The high neutron wall loadings, 4-5 MW/m², associated with the operation of this device require that neutronics-related issues be considered in the overall system design. Radiation shielding is required for the protection of device components as well as personnel. A close-in igloo shield has been designed around the periphery of the tokamak structure, and the entire experiment is housed in a circular test cell facility that has a radius of 12 m. The most critical radiation concerns in the CIT design process relate to the numerous penetrations in the device. This report discusses the impact of a major penetration on the design and operation of the pellet injection system in the CIT. The pellet injector is a major component, and it has a line-of-sight penetration through the igloo and test cell wall. All current options for maintenance of the injector require hands-on access. A nuclear analysis has been performed to establish the feasibility of hands-on access. A coupled Monte Carlo/discrete-ordinates methodology was used to perform the analysis. This problem is characterized by deep penetration and streaming with very large length-to-diameter ratios. Results from this study indicate that personnel access to the pellet injector glovebox is possible.

1. INTRODUCTION

The design of a nuclear fusion device requires close interface between system designers and analysts. Early in the design process, it is particularly important to establish specific requirements for remote maintenance equipment. These considerations can then be factored into the overall design and cost projections. The objective of this study was to determine the feasibility of hands-on access to the pellet injector system glovebox.

The current design of the pellet injector system is discussed in Sect. 2. Section 3 describes the analysis methodology and presents the results of the calculations. Section 4 provides recommendations for the study of additional computational and modeling issues. This report was summarized in a paper published in the proceedings of the 12th Symposium on Fusion Engineering.

2. DESIGN DESCRIPTION

The design of the pellet injector system is in a preliminary phase and will not be performed in detail for about three years. The injector configuration used for the present study is based on a system similar to the Oak Ridge National Laboratory (ORNL) developed TFTR tritium pellet injector [1], which includes an eight-barrel pneumatic gun. Figure 1 is a plan view of the pellet injector and injection line. This analysis was based on the 0601-87 design of the CIT device, which had a major radius of 1.75 m. Although the present design has evolved to a major radius of 2.1 m, the conclusions presented here remain applicable. The torus penetration is through a 4-in. schedule 40 pipe at the horizontal midplane. An isolation valve is located immediately outside the 1.8-m-thick borated concrete igloo shield and connects to a 6-in. schedule 40 pipe. This pipe extends 0.8 m and connects to an 8-in. schedule 80 pipe, which extends 2.5 m into the test cell. A 10-in. schedule 120 pipe begins inside the tritium vault facility, penetrates the 2.8-m-thick test cell wall and extends 1.1 m into the test cell facility, connecting with the 8-in. pipe. The 10-in. pipe contains eight guide tubes configured around a 6-in. diam centerline circle; each guide tube has a 0.5-in. inside diameter. The space between the guide tubes is filled with shielding material. The nuclear analysis was performed with ordinary concrete as

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Fig. 1. Plan view of the pellet injector and injection line.

the shielding material; however, other materials with essentially the same radiation attenuation and activation characteristics are available. Table 1 gives the elemental compositions of ordinary concrete and of two candidate materials that could be fabricated in a pellet form to facilitate disassembly.

Figure 2 is a schematic representation of the pellet injector glovebox configuration. Because of the lack of design information on the specific injector to be implemented for CIT, a representative configuration [5] was adopted for the analysis. Table 2 describes the components modeled and gives the dimensions and material volume fractions used to simulate void spaces. The glovebox is assumed to be filled with argon.

Table 1. Composition of ordinary concrete and two candidate shielding materials for space between guide tubes

Material	Element	Number densities (atom/b-cm)
Ordinary concrete (PPPL type 4 [2])	H	7.830×10^{-3}
	O	4.385×10^{-2}
	Na	1.048×10^{-3}
	Mg	1.486×10^{-4}
	Al	2.389×10^{-3}
	Si	1.580×10^{-2}
	S	5.635×10^{-5}
	K	6.932×10^{-4}
	Ca	2.915×10^{-3}
	Fe	3.127×10^{-4}
Borated-Pb-polyethylene (Reactor experiments [3])	H	2.561×10^{-2}
	B	1.461×10^{-3}
	C	1.300×10^{-2}
	O	3.416×10^{-3}
	Na	2.245×10^{-4}
	Mg	1.187×10^{-4}
	Al	2.814×10^{-5}
	Si	2.217×10^{-4}
	Ca	4.016×10^{-4}
	Pb	5.960×10^{-3}
NS-1 (Bisco [4])	H	1.614×10^{-2}
	b	2.934×10^{-3}
	C	6.078×10^{-3}
	O	8.465×10^{-3}
	Si	5.343×10^{-3}
	Pb	4.580×10^{-3}

Fig. 2. Schematic representation of the glovebox configuration.

Table 2. Pellet injector glovebox

Component	Material (and volume fraction)	Dimensions (in.)
Diagnostic stations (two)	SS-304 (0.3)	10 × 10 × 10
Guide tubes	SS-304 (0.05)	10 (diameter) × 40
Injector gun housing	94% SS-304, 6% Cu (0.25) ^a	36 × 36 × 48

^aOf the total material volume fraction of 0.25, 94% is SS-304 and 6% is Cu.

3. ANALYSIS METHODOLOGY AND RESULTS

The methodology for the neutron transport analysis consisted of a coupled Monte Carlo/discrete-ordinates approach. Figure 3 shows the relationship between the various methods employed in terms of the geometric configuration. The problem is characterized by deep penetration and streaming with very large length-to-diameter ratios. Because of deep penetration and the small solid angle subtended at the injector glovebox, statistical considerations preclude a complete Monte Carlo analysis of the entire pellet injection line. By performing part of the calculation deterministically, the statistical errors of the overall solution will be reduced. In this analysis, MCNP (version 3a) [6] was employed for the three-dimensional Monte Carlo calculations and DOT 4.3 [7] was employed for the two-dimensional discrete-ordinates calculations. The individual sections of the analysis are described in Sects. 3.1 through 3.4.

3.1 TOKAMAK PORT

A 10-degree sector of the tokamak geometry was modeled by using reflective surfaces. This modeling approximation, which assumes specular reflection at these surfaces, is useful for more efficiently estimating the local radiation field near a

Fig. 3. Relationship between analysis methodology and geometric configuration.

port. This is particularly applicable during the conceptual design phase, when all of the asymmetries in the device have not been clearly defined, and the concept of repeating sectors can be employed. A similar technique was employed for the lithium blanket module (LBM) neutronics calculations for TFTR [8].

The angular 14-MeV neutron current estimated at 187 cm from the mouth of the port was used as the source for the analysis of the igloo shield penetration. Two cases were analyzed, corresponding to configurations representing large and small ports. The large port configuration had an internal void area of 44 cm by 108 cm, and the small port configuration is described in Sect. 2. The normalized 14-MeV scalar responses for the two cases agreed to within statistical error limits. However, to improve the statistical quality of the differential responses obtained, the larger port configuration was used to generate the source for the igloo shield penetration. This choice will not affect responses of significance at the detector location inside the pellet injector cell—this will be discussed later. The scalar 14-MeV flux per deuterium-tritium neutron was calculated to a fractional standard deviation (fsd) of 0.017. The 14-MeV currents corresponding to six angular bins were then converted to a form compatible with a DOT external boundary source. This conversion involved a manipulation of the angular weighing functions associated with the discrete-ordinates analysis.

3.2 IGLOO SHIELD PENETRATION

The igloo shield penetration was analyzed with both DOT and MCNP, but only the DOT results were used as the source for the analysis of test cell penetration. The DOT calculation assumed r - z cylindrical geometry, P3 Legendre expansion for the scattering cross sections, a forward-biased, 166-angular-quadrature set [9], and a 25-neutron group structure [10]. The spatial mesh structure corresponded to 96 axial and 25 radial meshes. The MCNP calculation, which used a surface crossing detector, was used to benchmark the DOT calculation. The two solutions are compared in Table 3. The difference in response values may be attributed to systematic errors associated with the DOT modeling of the streaming configuration.

The importance information used in the MCNP calculation was derived from an adjoint discrete-ordinates solution. The adjoint flux, which is the direct output from

Table 3. Comparison of MCNP and DOT analysis of igloo penetration

(14-MeV flux per unit source particle—
average in 4-in. pipe just outside igloo)

MCNP	2.37×10^{-6} (0.061) ^a
DOT	3.55×10^{-6}

^aFractional standard deviation.

the DOT calculation, may require intermediate processing before implementation into the Monte Carlo analysis. This is to remove any sharp gradients in the adjoint scalar flux, which could result in excessive splitting in localized areas. Such splitting could prematurely terminate a given MCNP calculation because one particle history would then take an excessive amount of time. This automatic termination is a feature of the MCNP code.

Both the forward and adjoint calculations assumed a P3 approximation for the scattering cross sections and a forward-biased, 166-angular-quadrature set. To avoid occasional problems with negative fluxes, a negative source repair option was invoked in DOT. This problem arises because of truncation errors associated with the finite Legendre polynomial expansion of the scattering-cross-section data. This repair procedure, which sets the source in a given region to zero if negative fluxes are found, has been widely used in the discrete-ordinates solution of a variety of radiation transport problems [11].

Note that the highly biased angular-quadrature set employed in this analysis may not have been an optimum selection. This set contains a fine angular mesh in regions representing the transport of the highly forward-peaked streaming neutrons and a much coarser mesh in other regions. However, too many angular directions are represented in the coarse-mesh regions for this problem, which results in an unnecessary expenditure of computer time. The use of the first-collision-source method may have further reduced the angular-quadrature requirements for the transport analysis.

3.3 TEST CELL PENETRATION

The source distribution for the Monte Carlo analysis of the test cell penetration was obtained from the DOT-calculated angular 14-MeV flux and the scalar fluxes outside the igloo shield. An adjoint discrete-ordinates solution was the importance information used in the MCNP calculation, as discussed above. The Monte Carlo results were calculated to a statistical accuracy (fsd) of 0.03. Next-event estimation was employed in the calculation.

The coupling employed between DOT and MCNP is analogous to the function of the DOMINO code, which couples DOT and MORSE. This code analyzes the DOT-generated boundary fluxes and produces normalized cumulative surface source distributions in space, energy, and angle. Because of the limitations of MCNP, only two levels of source dependency are provided in the code. A tri-level dependency, as would be required to produce the analogy of DOMINO, would have to be developed by the user. Time constraints precluded accomplishing this during the course of this analysis. Consequently, only the 14-MeV angular flux and the scalar fluxes were used to describe the source for the test cell penetration analysis.

The results of this set of calculations confirm that, for practical purposes, only the uncollided 14-MeV neutrons contribute to the detector response outside the test cell wall. These results are characteristic of this particular geometry and would not be necessarily true for a larger duct configuration. This is the basis for the assumptions made at the interfaces between the partitioned calculations.

The neutron source in the plasma corresponds to a production of 5×10^{20} neutrons per pulse. Because of the small-solid-angle cell penetration in this particular geometric configuration, only 6.9×10^9 neutrons enter the pellet injector cell during each pulse. For comparison, a hand calculation that considered only the uncollided component from a point isotropic source yielded 7.6×10^9 neutrons. This further justifies the interface assumptions made in this analysis.

This study has used a complex coupling of techniques for analyzing a difficult neutron streaming problem. The specific assumptions made in this work cannot be applied to the analysis of larger straight-duct configurations or to non-line-of-sight configurations, where the detector may receive significant contributions from first

and second collisions. Modifications to the interface analyses would permit a more generalized treatment.

3.4 PELLET INJECTOR GLOVEBOX

An analysis was performed to determine the dose response rates from neutron-induced activation inside the glovebox at several times after shutdown.

The glovebox configuration was modeled according to the schematic shown in Fig. 2. The dose calculations were carried out with the discrete-ordinates method, which gives a detailed description of the radiation field and easily couples to activation codes. A neutron-transport calculation was performed with an r - z cylindrical version of DOT, a P3 scattering approximation, and a 25-neutron group structure. A monodirectional source was placed at the surface of the first diagnostic detector. A forward-biased, 166-angular-quadrature set was used to resolve the monodirectional source and narrow distribution of materials. The DOT solution was then coupled with REBATE [12] to calculate the energy and spatial distribution of the decay gamma ray production in the glovebox. This distributed gamma source was input into a gamma transport analysis to determine the dose response rates. The gamma transport analysis was carried out with DOT using an S16 symmetric angular quadrature set and a 16-group gamma structure [10]. A symmetric quadrature set is appropriate in the gamma transport analysis because of the softer spectrum and more isotropic angular distribution.

The results of these calculations are given in Table 4 for six different positions identified in Fig. 2. Two operational scenarios were assumed with a 5-s pulse width, a 1-h interval between pulses, and operation with 15 pulses/d. The first scenario corresponds to operating for 10 consecutive days, followed by a shutdown period for maintenance [13]. The second scenario corresponds to operating for 200 consecutive days for a total of 3000 pulses. The REBATE code [12] is able to explicitly model the above-mentioned scenarios. In general, the code can simulate a specified number of pulsing groups with a given period of repetition. Within each pulsing group, the pulse width, period, and total number of pulses can be specified. Actual operation of the device will extend over a 3.5-year period, so the latter scenario represents

**Table 4. Shutdown dose rates in the glovebox
(mrem/h)**

Position	10-d scenario			200-d scenario		
	30 min	1 h	1 d	30 min	1 h	1 d
A	2.3×10^{-1}	2.0×10^{-1}	6.3×10^{-3}	2.6×10^{-1}	2.3×10^{-1}	4.0×10^{-2}
B	1.2×10^{-2}	1.0×10^{-2}	3.3×10^{-4}	1.4×10^{-2}	1.2×10^{-2}	2.2×10^{-3}
C	2.3×10^{-3}	1.9×10^{-3}	7.3×10^{-5}	2.6×10^{-3}	2.2×10^{-3}	4.0×10^{-4}
D	1.7×10^{-3}	1.5×10^{-3}	4.7×10^{-5}	2.0×10^{-3}	1.8×10^{-3}	3.0×10^{-4}
E	7.3×10^{-4}	6.3×10^{-4}	1.9×10^{-5}	8.3×10^{-4}	7.3×10^{-4}	1.2×10^{-4}
F	2.3×10^{-4}	2.0×10^{-4}	5.9×10^{-6}	2.6×10^{-4}	2.3×10^{-4}	3.7×10^{-5}

a conservative upper bound on the activation. Calculations were performed for shutdown times of 30 min, 1 h, and 1 d. Many of the isotopes contributing to the activation at the times considered here have short half-lives and hence reach saturation conditions after a short operating period. The 30-min responses are characterized by the decay of S-37, which has a half-life of 5.05 min and emits 3.1-MeV gammas. The 24-h responses are dominated by the decay of the 2.56-h half-life Mn-56, which emits 0.85-MeV gammas.

It is meaningful to compare the dose response rates given in this table with the occupational dose limits prescribed in the Code of Federal Regulations. Under the ALARA (as low as reasonably achievable) principal, a recommended guideline for continuous exposure during a 40-h work week is 0.5 mrem/h. The dose responses computed at the pellet injector glovebox are within occupational exposure limits.

4. CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that the shutdown dose rate levels from the neutron-induced activation inside the glovebox do not present a concern for personnel access.

The major assumption in this analysis has been that the only source of radiation is the neutron-induced activation of the glovebox. The contribution from activation of the test cell wall was not considered. Further, the contribution from streaming gammas from the activation of the tokamak structure and the injector line piping

was not assessed because the use of a shielded gate valve [14] on the injector line inside the test cell would reduce the gamma-streaming component. The use of lower-activation materials such as aluminum in the piping structure would also be beneficial; these issues require examination.

This analysis of the pellet injector system has involved a coupling of Monte Carlo and discrete-ordinates methods. A complete Monte Carlo analysis of the entire pellet injection line would have required significantly more sophisticated biasing techniques and/or increased computational effort. This could be a subject of further investigation. The dose rates calculated in the pellet injector cell involve both statistical uncertainties (associated with the Monte Carlo analysis) and systematic errors (associated with the discrete-ordinates analysis). Additional systematic errors are caused by the omission of components and the simplifications made in modeling and by the approximations made in coupling. The activation analysis of the glovebox is particularly sensitive to the assumptions made in the materials inventory. Because of these issues and the preliminary nature of the design, the specific numerical results presented here should be regarded as preliminary. Significant design changes, particularly with regard to the geometric configuration and proximity of the glovebox to the plasma source, could alter conclusions about the feasibility of personnel access.

A comparison of the results of this analysis with those predicted by a simplified analytic expression has shown that the specific geometric configuration of this problem can be adequately represented with a simplified model. This problem was characterized by deep penetration and streaming with unusually large length-to-diameter ratios. For penetration configurations with smaller length-to-diameter ratios, where the contributions to detector response from first and second collisions may be significant, this modeling approximation may not be valid. The more general problems of streaming analysis require use of the methods discussed in this report.

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