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

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Abstract

Conceptual design of the Compact Ignition Tokamak (CIT) is near completion. This short-pulse ignition experiment is planned to follow the operations of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory. The high neutron wall loadings, ~4–5 MW/m^2, 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 and 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 with a radius of ~12 m. The most critical radiation concern in the CIT design process relates to the numerous penetrations in the device. This paper discusses the impact of a major penetration on the design and operations of the CIT pellet injection system. The pellet injector is a major component, which has a line-of-sight penetration through the igloo and test cell wall. All current options for maintenance of the injector require personnel access. A nuclear analysis has been performed to determine the feasibility of hands-on access. Results indicate that personnel access to the pellet injector glovebox is possible.

Introduction

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

The current design of the pellet injector system is discussed in the next section. The analysis methodology is then described, and results of the calculations are presented. The final section contains recommendations for the study of additional computational and modeling issues.

Design Description

The design of the pellet injector system is in a preliminary phase and will not be performed in detail for three years. The configuration used for the present study is based on an injector system similar to the 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. The torus penetration is through a 4-in. schedule 40 pipe. An isolation valve located immediately outside the 1.8-m-thick borated concrete igloo shield connects to a 6-in. schedule 40 pipe. This pipe extends ~0.8 m and connects to an 8-in. schedule 80 pipe that 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 to connect 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 (ID). The space between the guide tubes is filled with shielding material. The nuclear analysis was performed with ordinary concrete as the shielding material; however, other materials with essentially the same radiation attenuation and activation characteristics are available. Reference 2 contains information on composition and cost for borated-lead-polyethelene that can be fabricated in pellet form to facilitate disassembly.

Figure 2 is a schematic representation of the pellet injector glovebox configuration. Because of the lack of existing design information on the specific injector to be implemented for CIT, a representative configuration[3] was adopted for the analysis. Table 1 describes the components modeled and gives the dimensions and material volume fractions used to simulate void spaces.

Analysis Methodology and Results

The methodology for the neutron transport analysis employed 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 pathways with very large length-to-diameter ratios. Because of 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 can be reduced. Individual sections of the analysis are briefly discussed in the following paragraphs, and a more detailed description is given in Ref. 2.

A 10° sector of the tokamak geometry was modeled with the MCNP Monte Carlo code using reflective surfaces. The angular 14-MeV neutron current estimated at 187 cm from the mouth of the port was then used as the source for analysis of the igloo shield penetration. This penetration was analyzed with both DOT 4.3[4] and MCNP (version 3a),[5] but only the DOT results were used as the source for the test cell penetration analysis. The DOT calculation assumed r-z cylindrical geometry, P3 Legendre expansion for the scattering cross sections, a foward-biased 166 angular quadrature set,[6] and a 25-neutron group structure.[7] The MCNP calculation was used to benchmark the DOT calculation. The two solutions are compared in Table 2.

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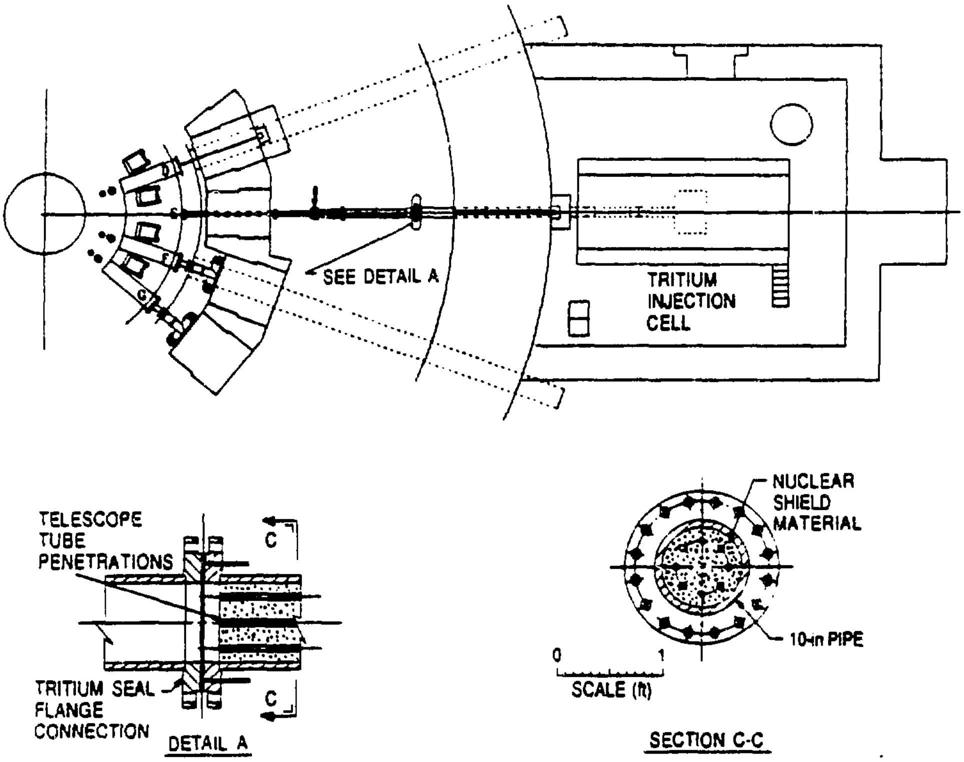

Fig. 1. Plan view of the pellet injector and injection line.

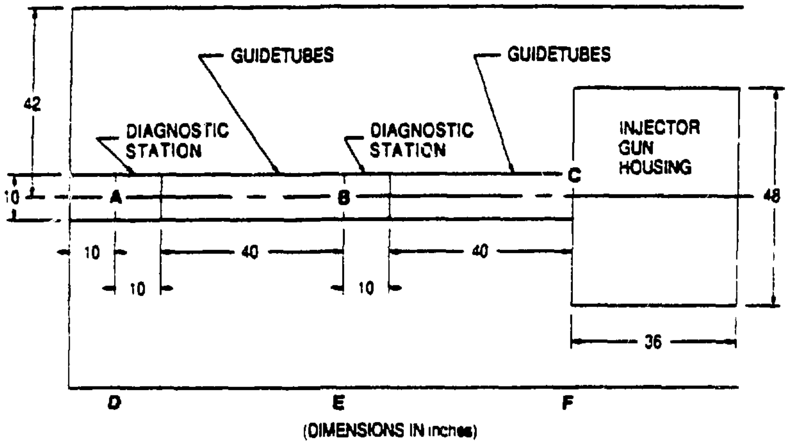

Fig. 2. Schematic representation of the glovebox configuration.

Table 1. Pellet injector glovebox

Component	Material (and volume fraction)	Dimensions (in.)
Diagnostic stations (2)	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

[a] Of the total material volume fraction of 0.25, 94% is SS-304 and 6% is Cu.

Table 2. 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}

[a] Fractional standard deviation.

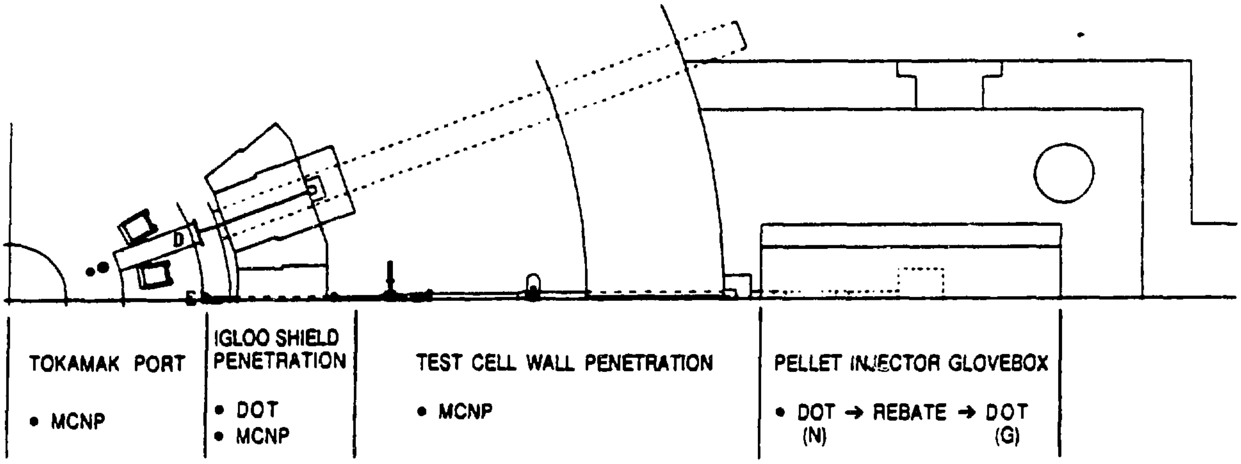

Fig. 3. Relationship between analysis methodology and geometric configuration.

The source for the Monte Carlo analysis of the test cell penetration was sampled from the DOT-calculated angular 14-MeV flux and the scalar fluxes outside the igloo shield. The Monte Carlo results were calculated to a statistical accuracy of 0.03.

The results of this set of calculations indicate that, for practical purposes, only the uncollided 14-MeV neutrons contribute to the detector response outside the test cell wall. This conclusion was demonstrated in part by the very poor particle statistics obtained for the collided neutrons. These results are characteristic for this particular geometry and would not necessarily be true for a larger duct configuration. This is the basis for assumptions made in 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 subtended in this particular geometric configuration, only 7.4×10^{6} neutrons enter the pellet injector cell during each pulse. An analysis was then performed to determine the dose response rates from the 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 provides a detailed representation of the radiation field and easily couples to activation codes. A neutron transport calculation was performed with DOT based on assumptions of r-z cylindrical geometry, a P3 scattering approximation, a foward-biased 166 angular quadrature set, and a 25-neutron group structure. A monodirectional source was placed at the surface of the first diagnostic detector. The DOT solution was then coupled to an activation analysis with REBATE[6] 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 based on assumptions of an S16 symmetric angular quadrature set and a 16-group gamma structure.[7]

The results of these calculations are given in Table 3 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 d, followed by a shutdown period for maintenance.[8] The second scenario corresponds to operating for 200 consecutive d for a total of 3000 pulses. Actual operation will be spread out over a 3.5-year period, so the latter scenario represents a conservative upper bound on the activation. Calculations were performed for shutdown times of 30 min, 1 h, and 1 d. These activation characteristics are discussed in Ref. 2.

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

Table 3. 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	2.4×10^{-2}	2.1×10^{-2}	6.6×10^{-4}	2.8×10^{-2}	2.4×10^{-2}	4.2×10^{-3}
B	1.3×10^{-3}	1.1×10^{-3}	3.5×10^{-5}	1.4×10^{-3}	1.3×10^{-3}	2.3×10^{-4}
C	2.5×10^{-4}	2.0×10^{-4}	7.7×10^{-6}	2.8×10^{-4}	2.3×10^{-4}	4.3×10^{-5}
D	1.8×10^{-4}	1.6×10^{-4}	5.0×10^{-6}	2.1×10^{-4}	1.9×10^{-4}	3.2×10^{-5}
E	7.7×10^{-5}	6.7×10^{-5}	2.1×10^{-6}	8.8×10^{-5}	7.8×10^{-5}	1.3×10^{-5}
F	2.4×10^{-5}	2.1×10^{-5}	6.3×10^{-7}	2.8×10^{-5}	2.4×10^{-5}	3.9×10^{-6}

use of a shielded gate valve[10] 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 complicated coupling of Monte Carlo and discrete-ordinates methods. The dose rates calculated in the pellet injector cell involve both statistical uncertainties and systematic errors. Statistical uncertainties are associated with the Monte Carlo analysis, and systematic errors are associated with the discrete-ordinates analysis. Further, additional systematic errors are caused by the omission of components and simplifications made in modeling and by the approximations made in coupling. The activation analysis of the glovebox is particularly subject to the assumptions made in the materials inventory. Because of these issues and the preliminary nature of the design, the results presented here should be regarded as preliminary.

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