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RADIATION ANALYSIS OF THE ITER PELLET INJECTION SYSTEM

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ABSTRACT

The results of neutronics calculations for the pellet injection system of the International Thermonuclear Experimental Reactor (ITER) are described. Hands-on maintenance of components in the pellet injection room results in a considerable simplification of maintenance support equipment and in greater system availability. The basic configuration of the pellet injection system includes small-diameter guide tubes with which the pellet may have several small-angle collisions before reaching the plasma. The pellet injector port through which the guide tubes pass will be shared with ITER plasma diagnostics, so the calculation takes into account penetrations to accommodate numerous channels for a neutron spectrometer and neutron and gamma-ray cameras. The conservative assumption of steady-state operation of ITER for 1000 days was taken as the baseline for calculating the activation of components in the pellet injection room. The plasma configuration is based on the current ITER guidelines, the first wall configuration is based on the most recently updated configuration, and the blanket configuration is based on the U.S. proposal for the blanket. The pellet injection room, following the present design, is located 16.7 m from the center of the machine and 8.5 m from the first wall. The complicated geometry, the large dimensions involved, and the line-of-sight situation make the calculation very difficult. The plasma, coils, and blanket regions were analyzed with the Monte Carlo code MCNP. The transport of neutrons through the penetrations (guide tubes) was also performed with MCNP. The pellet injection room was modeled with the two-dimensional discrete ordinates code DORT, which was also used for the transport of neutrons during operation and of gamma rays caused by activation. The activation calculations were carried out with the REBATE code. Results from this study indicate that restricted personnel access to the pellet injection room is possible, so limited hands-on maintenance can be performed on the majority of the components in the room.

1. INTRODUCTION

The design of a steady-state fusion reactor is a major engineering challenge. A deuterium-tritium (D-T) fusion reactor produces a neutron radiation field that is more energetic and therefore more damaging than those associated with fission reactors. The large dimensions of the device, the large number of penetrations, and the geometrical complexities make the neutronics calculation challenging even with state-of-the-art computational tools.

We present the results of calculations using the most up-to-date computational tools and data available. The objective is to determine the feasibility of hands-on maintenance in the pellet injection room of the International Thermonuclear Experimental Reactor (ITER).¹

The current design of the pellet injector system is discussed in Sect. 2. Section 3 describes the analysis method. Section 4 presents the results, and Sect. 5 provides conclusions.

2. PELLET INJECTOR SYSTEM

The design of the ITER pellet injector system is being performed by the Fusion Energy Division of Oak Ridge National Laboratory (ORNL) and is in a conceptual phase.² Hands-on maintenance is a major issue that must be addressed early in the design process because of the cost, impact on system availability, and design complexities of total remote maintenance. The pellet injection room and injector lines are shown in Figs. 1 and 2. Table 1 lists the major components shown in Figs. 1 and 2. The models used in this analysis are based on the June 1990 reference layouts for ITER. The pellet guide tubes (injection lines) pass from the pellet injection room through shielding materials until they reach the interior of the vacuum vessel through the pellet injector/diagnostics port (port 14). It is assumed that shielding begins 9.51 m from the center of the device (Table 2 shows the composition of the concrete shielding used in this analysis and the composition of the stainless steel guide tube). The five guide tubes have an inside diameter of 6 cm at the entrance to the vacuum vessel, inside the port. The inside diameter decreases to 5.0 cm halfway to the pellet injection room and decreases again, to 4.0 cm, after the modular shielding (component 15 in Fig. 1) inside the pellet injection room. The space between the guide tubes is filled with shielding material from the vacuum vessel to a distance of 14 m from the center of the device. From 14 m to 16.7 m, the

Fig. 1. Plan view of the ITER pellet injection system. Components are identified in Table 1.

Fig. 2. Elevation view of the ITER pellet injection system. Components are identified in Table 1.

Table 1. Components of the ITER pellet injectors
(numbers refer to Figs. 1 and 2)

1. Moderate-velocity injector	22. Rotatable targets
2. Moderate-velocity injector	23. Backing pumps
3. High-velocity injector (HVI)	24. Instrumentation cabinets
4. HVI pump tube	25. Airlock
5. HVI propellant reservoir	26. Crane, 10-ton capacity
6. HVI propellant compressor	27. Crane beam
7. Propellant gas manifolds	28. Crane beam gearmotors
8. Fuel gas manifolds	29. Crane rails
9. High-pressure cage	30. Crane rail columns
10. Low-vacuum chamber	31. Manipulator turret
11. Mid-vacuum chamber	32. Telescoping boom
12. High-vacuum chamber	33. Manipulator and camera
13. Torus isolation valves, breaks, bellows	34. Dual replaceable end effectors
14. Structural shielding wall	35. Manipulator bridge
15. Modular shielding	36. Manipulator bridge gearmotors
16. Normetex 1300-m ³ /h scroll pumps	37. Manipulator bridge rails
17. Normetex control cabinets	38. ITER cryostat
18. Turbopumps, 5000 L/s	39. ITER vacuum vessel port 14
19. Turbopumps, 500 L/s	40. Metal room liner
20. Rotatable shielding drums and motors	41. In-port shielding
21. Flow-limiting fast valves	

space not occupied by the guide tubes and the neutron and gamma-ray cameras is empty. A shielding wall (component 14 in Figs. 1 and 2) extends from 16.7 m to 17.5 m. Figure 2 shows the rotatable shielding drums (component 20) that should reduce the number of neutrons entering the pellet injection room by a factor of about 20. These drums rotate continuously, presenting an opening only for the transit of a pellet. The drums are 0.75 m long and provide almost perfect shielding when closed. During steady-state operation of ITER, only one injection line will be used, and the other four lines will be effectively filled with shielding material, since their rotatable drums will remain in a static shielded position.

Table 2. Material composition

Element	Number density (atoms/cm-barn)	
	Concrete (2.35 g/cm ³)	Type 304 stainless steel (7.86 g/cm ³)
¹ H	7.830×10^{-3}	—
⁶ C	—	1.813×10^{-4}
⁷ N	—	1.284×10^{-4}
⁸ O	4.385×10^{-2}	—
¹¹ Na	1.048×10^{-3}	—
¹² Mg	1.496×10^{-4}	—
¹³ Al	2.389×10^{-3}	—
¹⁴ Si	1.580×10^{-2}	7.921×10^{-4}
¹⁵ P	—	3.974×10^{-5}
¹⁶ S	5.635×10^{-5}	1.772×10^{-5}
¹⁹ K	6.932×10^{-4}	—
²⁰ Ca	2.915×10^{-3}	—
²² Ti	—	2.965×10^{-5}
²⁴ Cr	—	1.611×10^{-2}
²⁵ Mn	—	1.008×10^{-3}
²⁶ Fe	3.127×10^{-4}	5.982×10^{-2}
²⁷ Co	—	8.032×10^{-5}
²⁸ Ni	—	7.499×10^{-3}
²⁹ Cu	—	1.490×10^{-4}
⁴² Mo	—	1.628×10^{-4}

3. ANALYSIS METHOD

The neutron/gamma-ray transport was analyzed with a coupled Monte Carlo/Monte Carlo/discrete-ordinates procedure. The discrete ordinates code DORT³ was used to analyze the pellet injection room. The analysis of the plasma, first wall, blanket, and vacuum vessel regions was performed using the Monte Carlo code MCNP.⁴ The transport of neutrons from the mouth of the port to the modular

shielding inside the pellet injection room was also done with Monte Carlo analysis. The pellet injection line configuration consisted of small-diameter guide tubes penetrating through several meters of shielding material, which constituted a deep penetration problem with streaming and very large length-to-diameter ratios. The use of discrete ordinates for this part of the analysis was not advisable because of the very high ratio between the streaming component through the duct and the radiation transported inside the shielding material—even if highly peaked angular quadrature was used, due to the extrapolation mechanism between spatial meshes (a prohibitively fine mesh would be required to eliminate this anomaly). Accordingly, the Monte Carlo method was used to perform this part of the analysis.

3.1 AREA INSIDE THE PORT

Most of the neutrons entering the pellet injection room are uncollided neutrons. This indicates that the key issue for this problem is the angular distribution of neutrons at the entrance to the penetrations inside the port. Corner effects at the entrances to the ducts require a complete description of the neutron angular flux inside the port. The presence of beryllium as a neutron multiplier in the blanket precludes any simple analytical approximation for estimating the radiation field inside the port. To solve this problem, a detailed three-dimensional (3-D) geometric model of the ITER device was employed. The model comprises one-sixteenth of the complete torus, including the toroidal field coils, the poloidal field coils, the first wall, the blanket, cooling channels, the vacuum vessel, and other features that could affect the final answer. The source term, which consists of the neutrons born within the plasma, was modeled following the ITER physics design guidelines.⁵ Figures 3-5 show different views of the 3-D model obtained with the Monte Carlo code MCNP. Figure 6 is a contour plot of the fusion power density distribution inside the plasma. The angular, spatial, and energetic distributions of the neutrons inside the port were obtained using a boundary-crossing estimator of the current integrated over a surface. The binning for the angular distribution of the neutrons consisted of 19 cosine bins, listed in Table 3, with a strong biasing for angles in the forward direction (the azimuthal dependence was neglected in this calculation). For the spatial distribution, 6 bins were used to represent 15 different surfaces; the symmetry of these surfaces in relation to the plasma and blanket was used to define the 6 spatial bins. The energy distribution was described in terms of 20 energy bins, listed in Table 4.

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Fig. 3. Top view of the model for the plasma, first wall, blanket, and pellet injection port.

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Fig. 4. Side view of the model for the plasma, first wall, blanket, and toroidal field coil.

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Fig. 5. Side view of the model for the plasma, first wall, blanket, and pellet injection port.

Fig. 6. Contour plot of the normalized fusion power density distribution in an ITER D-T plasma. At the center, the normalized power is 6×10^5 , at the edge, 1.

Table 3. MCNP cosine bins used in the first step

Cosine		
bin number	Lower limit	Upper limit
1	-1.0	0.0
2	0.0	0.00873
3	0.00873	0.05234
4	0.05234	0.19252
5	0.19252	0.43339
6	0.43339	0.67940
7	0.67940	0.86506
8	0.86506	0.93937
9	0.93937	0.95003
10	0.95003	0.95968
11	0.95968	0.96832
12	0.96832	0.97593
13	0.97593	0.98251
14	0.98251	0.98805
15	0.98805	0.99254
16	0.99254	0.99598
17	0.99598	0.99836
18	0.99836	0.99968
19	0.99968	1.0

3.2 INJECTION LINES

The pellet injection lines (guide tubes) and the neutron/gamma diagnostics channels share the same vacuum port (port 14). To represent the influences of cross-talk between ducts, the whole cross section of the port was modeled. The model includes 20 channels with a 100-cm² cross section for neutron cameras, 6 with a 115-cm² cross section channels for gamma spectrometer, and 5 guide tubes with a 28.3-cm² cross section. The MCNP code was used to estimate the transport of neutrons from the mouth of the port to the pellet injection room. A special source subroutine was written to accept the input of the information generated in the first part of the calculation. Another special subroutine was written

Table 4. MCNP energy bins used in the first and second steps

Energy bin number	Upper limit (MeV)	Lower limit (MeV)
1	14.1200	14.0900
2	14.0900	13.4990
3	13.4990	12.2140
4	12.2140	11.0520
5	11.0520	10.0000
6	10.0000	8.1873
7	8.1873	6.7032
8	6.7032	4.9669
9	4.9669	3.6788
10	3.6788	2.7253
11	2.7253	2.2313
12	2.2313	1.6530
13	1.6530	1.2246
14	1.2246	1.0026
15	1.0026	0.8208
16	0.8208	0.6721
17	0.6721	0.5502
18	0.5502	0.3020
19	0.3020	0.1657
20	0.1657	0.0001

to estimate the uncollided component of the flux due to the anisotropic source. The radiation flux in the guide tubes at the modular shielding inside the pellet injection room was estimated with the next-event estimator. The complexity of the problem precludes the use of the usual conventional biasing techniques. Studies that preceded the calculation showed that MCNP biasing techniques,⁴ such as the dxtran-sphere and weight-window, and adjoint importance function⁶ biasing were precluded for the following reasons. To use dxtran-spheres it is necessary to be sure that a balance exists between weight produced and weight killed. For this problem, this condition could not be ensured and the answer would probably be

overestimated. Using the weight-window for this type of problem is very difficult because of the large attenuation of the radiation field. Even if a good estimate of the upper and lower limits for the weights for each region could be provided, the existence of particles which can move from regions of low importance to regions of high importance through the duct would make the splitting process very difficult to control. Using adjoint importance information to generate weight-window values would have required an additional calculation, and this was precluded by the tight schedule for this work.

The biasing technique chosen was the standard importance by region with the constraint that a particle would be allowed to split at most ten times at a particular event (through a modification in the MCNP code).

3.3 PELLET INJECTION ROOM

The pellet injection room was modeled with DORT² using two-dimensional (2-D) cylindrical geometry. The calculation starts at the modular shielding (component 15 in Fig. 2) and includes most of the components described in Fig. 2. All of the elements were represented by cylinders preserving their total volumes. The approximated 2-D model is shown in Fig. 7. Because of the large void fraction inside many of the components, the amount of material was uniformly distributed throughout the respective total volumes and the atomic number densities were calculated accordingly. The neutron source was calculated by the MCNP code in the previous steps. The group cross-section structure consisted of 25 neutron groups and 12 gamma-ray groups. The spatial discretization consisted of 8442 mesh spaces, and a 166 discrete angle biased-up quadrature was used in the calculation.

The neutron flux determined by the DORT calculation was input into the activation code REBATE⁷ to evaluate the secondary gamma rays (activation) generated 1 s, 1 h, 12 h, 1 d, and 7 d after shutdown from a 1000-d cycle of full-power operation. These gamma-ray sources were then transported by the DORT code using the same spatial discretization and a quadrature set of 48 angles and 16 gamma-ray energy groups. The equivalent dose in the pellet injection room after each of these five cooling periods was calculated using a special code⁸ developed at the ORNL Fusion Engineering Design Center (FEDC).

Fig. 7. Model of the components in the pellet injection room for calculation of the neutron flux. Letters indicate component locations.

4. RESULTS

The calculation consisted of three steps. In the first step, the neutrons generated in the 3-D plasma were transported to the mouth of the pellet injector port. In the second step, neutrons were transported from the mouth of the port to the beginning of the modular shielding inside the pellet injection room (located beyond the rotating drums). The third step comprised the transport of neutrons inside the pellet injection room, the activation of materials, the determination of the number of gamma rays produced by disintegrations per energy group per second for five different times after shutdown, the transport of the secondary gamma rays, and finally the conversion of the gamma-ray field to an equivalent dose.

The results from the first step show that, in terms of the neutron energy spectrum, two major contributors can be identified: 14-MeV neutrons from D-T reactions that reach the port without suffering a collision and neutrons generated by the beryllium (n,2n) reaction. Figures 8-10 show the estimated angular distribution of

Fig. 8. Estimated angular distribution of neutrons on surface 6 near the mouth of the port, calculated with MCNP.

Fig. 9. Estimated angular distribution α neutrons on surface 3 near the mouth of the port, calculated with MCNP.

Fig. 10. Estimated angular distribution of neutrons on surface 1 near the mouth of the port, calculated with MCNP.

the neutrons at different locations near the mouth of the port for a 1,000,000-particle Monte Carlo calculation. Positions at the center of the port have the most strongly forward-peaked angular distributions. These results were used as the source term for the second step of the calculation.

The second step of the calculation took into account the fact that port 14 used by the pellet injector will be shared with various ITER diagnostics penetrations. The assumed distribution of the penetrations inside the port is shown in Fig. 11. MCNP was used to model the port, shielding, and penetrations from the mouth to the pellet injection room. The major contributors to the detector responses are particles born at or very close to the entrances to the ducts that stream through the penetration. Based on the traditional solid-angle formula, which assumes that the angular distribution of the neutrons is isotropic and that all neutrons are born at the same point, the attenuation factor found for this configuration is 1.25×10^{-10} . The results obtained from the MCNP calculations indicate a lower attenuation factor of 1×10^{-9} , which is what would be expected given the strongly forward-peaked angular distribution of the source neutrons. Figures 12 and 13 show the value for the mean and the associated error at the exit of one of the pellet guide tubes. Figure 14 shows the energy distribution for the same pellet guide tube. The results obtained from this step were used as input into the pellet injection room model.

The first calculation of the third step involves the use of DORT to determine the neutron flux inside the pellet injection room that results from the neutron source obtained in the second step. Figures 15–17 show the neutron spatial flux distribution in the pellet injection room for different energy groups.

The results from this calculation were fed into the activation code REBATE to evaluate the secondary gamma rays generated at five different times after shutdown. The operation scenario used in this calculation was continuous full-power operation of ITER at steady state for 1000 d. The five "cooling periods" used for analyzing the decay of activated materials were 1 s, 1 h, 12 h, 1 d, and 7 d after shutdown. The REBATE results were fed into the DORT code for analysis of the activation gamma rays. Figures 18–20 show the gamma-ray spatial flux distribution for different energy groups. These results were input into a special code developed by the FEDC neutronics group to calculate the dose equivalent (in rem/h) at several locations inside the pellet injection room. Table 5 presents the results obtained for 23 different locations identified in Fig. 7.

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Fig. 11. Assumed distribution of the penetrations inside ITER port 14.

Fig. 12. Fluctuation of the mean of the total neutron count with the number of particles processed for one of the pellet guide tubes.

Fig. 13. Associated error for the mean of the total neutron count in Fig. 12.

Fig. 14. Energy distribution for the total neutron count per energy group for the pellet guide tube in Fig. 12.

5. CONCLUSIONS

The results of this comprehensive study indicate that restricted personnel access to the pellet injection room for maintenance and adjustment tasks is feasible. Table 5 shows that an equivalent dose of 26 mrem/h for 1 h after shutdown was calculated for the location just beyond the modular shielding (component 15 in Figs. 1 and 2). This dose is too high for extended hands-on maintenance, and close monitoring is required. For locations more than 4 m from the modular shield [e.g., the location(s) of the pellet injector(s)], the equivalent doses are within acceptable levels (<2 mrem/h), even at 1 s after shutdown.

The model used for the activation analysis starts at the modular shielding. Thus, gamma rays generated at locations other than those included in the model (i.e., inboard of the modular shielding) were neglected. This approximation does not affect the validity of the results, since the modular shielding provides a strong barrier to those gamma rays. The gamma-ray component that would stream through the duct will be shielded by the rotating drums.

Fig. 15. Total neutron spatial flux distribution in the pellet injection room.

Fig. 16. Group 1 neutron spatial flux distribution in the pellet injection room.

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Fig. 17. Group 25 neutron spatial flux distribution in the pellet injection room.

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Fig. 18. Total gamma-ray flux in the pellet injection room 1 h after shutdown.

Fig. 19. Group 5 gamma-ray flux in the pellet injection room 1 h after shutdown.

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Fig. 20. Group 9 gamma-ray flux in the pellet injection room 1 h after shutdown.

Table 5. Shutdown dose rates in the control room for 1000-d
full-power operation

Position ^a	Dose rate (rem/h)				
	1 s	1 h	12 h	1 d	7 d
A	7.67×10^{-2}	3.78×10^{-2}	1.79×10^{-2}	1.42×10^{-2}	9.75×10^{-3}
B	1.66×10^{-1}	1.07×10^{-1}	4.63×10^{-2}	4.06×10^{-2}	3.48×10^{-2}
C	4.22×10^{-2}	2.62×10^{-2}	1.14×10^{-2}	9.99×10^{-3}	8.54×10^{-3}
D	8.86×10^{-4}	2.37×10^{-4}	9.88×10^{-5}	7.89×10^{-5}	5.81×10^{-5}
E	2.09×10^{-2}	1.53×10^{-2}	6.49×10^{-3}	5.88×10^{-3}	5.36×10^{-3}
F	2.17×10^{-2}	1.60×10^{-2}	6.83×10^{-3}	6.21×10^{-3}	5.69×10^{-3}
G	7.19×10^{-4}	4.78×10^{-4}	1.89×10^{-4}	1.52×10^{-4}	1.15×10^{-4}
H	6.80×10^{-3}	5.05×10^{-3}	2.14×10^{-3}	1.95×10^{-3}	1.80×10^{-3}
I	1.68×10^{-4}	1.22×10^{-4}	5.52×10^{-5}	4.68×10^{-5}	3.77×10^{-5}
J	1.32×10^{-3}	9.78×10^{-4}	4.11×10^{-4}	3.74×10^{-4}	3.44×10^{-4}
K	2.45×10^{-3}	1.82×10^{-3}	7.73×10^{-4}	7.08×10^{-4}	6.57×10^{-4}
L	2.45×10^{-4}	1.84×10^{-4}	7.81×10^{-5}	7.15×10^{-5}	6.64×10^{-5}
M	7.03×10^{-5}	5.25×10^{-5}	2.29×10^{-5}	2.05×10^{-5}	1.82×10^{-5}
N	4.12×10^{-5}	3.01×10^{-5}	1.36×10^{-5}	1.22×10^{-5}	9.13×10^{-6}
O	4.11×10^{-5}	3.03×10^{-5}	1.37×10^{-5}	1.16×10^{-5}	9.46×10^{-6}
P	1.13×10^{-5}	8.04×10^{-6}	3.47×10^{-6}	2.84×10^{-6}	2.19×10^{-6}
Q	8.95×10^{-7}	6.60×10^{-7}	2.05×10^{-7}	1.69×10^{-7}	1.45×10^{-7}
R	1.63×10^{-6}	1.21×10^{-6}	3.58×10^{-7}	2.99×10^{-7}	1.87×10^{-7}
S	2.06×10^{-7}	1.50×10^{-7}	5.36×10^{-8}	4.28×10^{-8}	3.35×10^{-8}
T	2.27×10^{-7}	1.64×10^{-7}	6.54×10^{-8}	5.26×10^{-8}	4.03×10^{-8}
U	8.64×10^{-8}	6.47×10^{-8}	2.62×10^{-8}	2.25×10^{-8}	1.93×10^{-8}
V	5.99×10^{-8}	4.53×10^{-8}	1.51×10^{-8}	1.30×10^{-8}	1.17×10^{-8}
W	1.44×10^{-7}	1.09×10^{-7}	4.53×10^{-8}	4.14×10^{-8}	3.84×10^{-8}

^aThe positions are identified in Fig. 7.

Components on the plasma side of the modular shielding will require remote maintenance or removal. This includes the high-vacuum chamber and pumping manifold (component 12), the torus isolation valve and bellows (component 13), and the rotating neutron shielding drums and motors (component 20). A complementary set of calculations has indicated that 1 h after shutdown the equivalent dose at component 13 is about 1 rem/h and at component 20, 0.4 rem/h. However, most of the components in the pellet injection room can be maintained and repaired using hands-on maintenance, the amount of time available for manual repairs being dependent on location and time since shutdown. The scenario of 1000 days of full-power operation is quite conservative, and more realistic operation cycles will provide even longer exposure times for component maintenance and repair.

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