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Radiation levels in the ITER tokamak complex during and after plasma operation

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HIGHLIGHTS

- Neutronics and 3-D activation simulations of the ITER complex.
- Simulated radiation sources included D–T fusion neutrons exiting the cryostat.
- Modelling work also includes gamma rays arising from activation of cooling water.
- Novel capabilities include a secondary neutron cylinder source representation.
- Smeared source and moving geometry capabilities created for cask transfer modelling.
- Results have been incorporated into the ITER radiation maps tool.

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ABSTRACT

Extensive neutronics and 3-D activation simulations were carried out to assess the levels of radiation throughout the ITER tokamak complex. The simulated radiation sources included D–T fusion neutrons exiting the cryostat and gamma rays arising from the activation of cooling water, activated pipe chases and cask transfers. Resultant biological dose rates, dose rates to silicon and particle fluxes, for both neutrons and gamma rays, have been calculated.

Results of on-load simulations of activated water show photon biological dose rates approaching 3.2 kSv/h near the upper cooling pipes, and dose rates on the B2 level of the tokamak complex are typically of the order of 0.1 μSv/h or less inside the diagnostics and tritium handling buildings. On-load neutron dose rates are calculated to be less than 1 Sv/h inside the port cells. The dose rate resulting from activated steel pipe chases, 10^6 s after shutdown was typically a few μSv/h. Simulations of integrated dose to electronics for multiple divertor cask transfers show a dose to silicon inside the north-east electronics cubicle of 9.8×10^{-5} Gy and inside the tritium handling building is shown to be of the order of 1×10^{-7} Gy.

1. Introduction

The ITER organisation has produced a web-based radiation mapping tool intended to communicate information on radiation fields within the ITER complex to end users in a straightforward and comprehensible manner. The utility requires a database of information on the radiation fields of interest throughout the ITER complex. The work presented here shows in broad terms the calculations carried out in order to produce these maps from a comprehensive range of sources and responses, with sample results illustrating the available maps.

The ITER complex itself comprises the tokamak, diagnostics and tritium handling buildings (Fig. 1). The size of the tokamak complex is ~118 m × 80 m × 73 m and presents an extremely challenging radiation transport problem, largely due to its scale, deep shielding aspects and numerous streaming paths. Various methods have been implemented to improve the simulation statistics by careful implementation of variance reduction and approximate secondary sources to reduce the complexity of the simulations.

The information drawn from the radiation mapping of the complex is essential for assessing radiation hardness of electronics during operation, and safe working dose limits to staff during routine maintenance.

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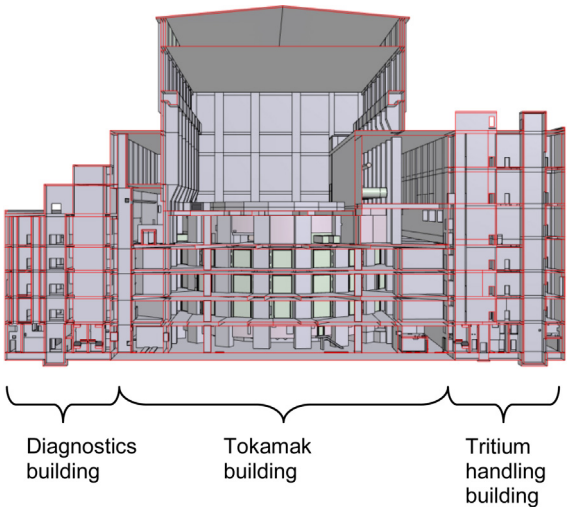

Fig. 1. Illustration of the three buildings constituting the ITER complex.

1.1. Building model, penetrations and fills

Initial ITER operation will start in low power D–D and hence significant shielding is not required until the device starts to operates at 500 MW D–T. The ITER CAD and MCNP geometry models relate to the building as it will be initially constructed, with open penetrations for pipes and diagnostics. As the neutron fluxes increase later in the life of the experiment, the shielding will need to be improved with the inclusion of shielding doors and more significant penetration fills. The current work is primarily concerned with modelling an ITER D–T experimental campaign, thus the model required numerous geometry updates so that the simulated geometry reflects the latter D–T irradiation scenario.

With this in mind, updated and corrected building models have been developed by integrating old and new models, with desired model changes as per instructions from IO [2]. As expected the results of preliminary calculations showed large radiation streaming paths in open penetrations between the buildings in the ITER complex, and in-between walls and floors of the tokamak building.

In order to more realistically represent the various penetrations, detailed advice was sought from IO [2] and penetration fills applied to approximate the state during D–T operations. Since this was approximating shielding which is not yet designed, a simplistic approach was chosen, selecting from either unfilled, a 50% dense fill, or a 100% dense fill concrete or surrounding material, depending on the penetration.

Concrete bioshield port plugs were added in order to fill all the bioshield port plug penetrations; these were modelled as 45 cm thick concrete, to approximate the concrete/lead plugs which are yet to be designed. Port cell doors have been modified to provide a total thickness of 35 cm of steel.

Large gaps above the port cell doors, intended for lintels, service pipes and cabling are assumed to eventually be backfilled, however in the absence of these details it was agreed to leave these gaps open in order to ensure dose estimates are conservative.

2. Methodology and tallies

Neutron and photon fluxes, biological dose rates and doses to silicon were calculated for neutron and gamma radiation arising from the neutrons produced inside the vessel and the subsequent neutron activation of cooling water and pipe work resulting from the capture and decay of oxygen in water molecules. Mesh tallies were scored on 50 cm resolution voxels spanning the entirety of the complex up to the roof level.

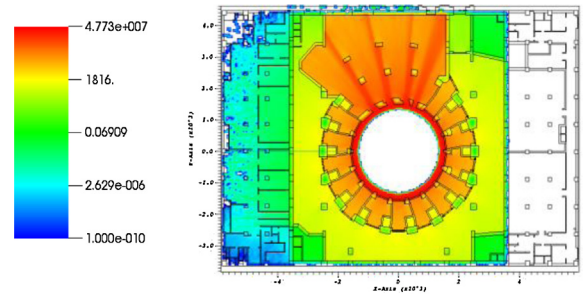

Fig. 2. Biological dose rate μSv/h, neutrons during plasma operation – example results, level L2.

Dose rates were deemed insignificant below 0.1 μSv/h, and a cut-off criteria was defined to determine acceptability of the calculations, which required dose rates at one-tenth of this value to known to less than 10% statistical uncertainty.

3. On load radiation sources

3.1. Neutrons

A spectrum of neutrons is emitted from the tokamak plasma during operation. It is at present extremely computationally challenging to model the full plasma neutron source, transport through the internals of the tokamak, and then track particles throughout the ITER complex.

As an alternative, a custom MCNP cylindrical neutron grid source routine was created. This routine takes an MCNP cylindrical mesh tally scored on the cryostat cylindrical surface using the ITER reference B-lite, 40° standard sector model, with dummy port plugs. The sector tally is tiled through 360° to model all neutrons entering the bioshield from the tokamak internals and is normalised to the outgoing neutron flux.

The secondary source thus captures the variable neutron flux intensity and spectrum as a function of space and only the angular information is approximated by selecting an angular distribution chosen from a selection of power laws or cosine distributions. For the present work it was found that a normal-radial distribution is likely to be conservative and most closely approximated the B-lite angular distribution [2].

This secondary neutron source term was implemented in the tokamak complex model, at the cryostat. Global variance reduction (GVR) [3] was required to transport particles through shielding coupled with long computation times in order to obtain statistically acceptable results throughout the building. Preliminary analysis showed neutron biological dose rate levels in the tritium handling and diagnostics building were below the specified cut-offs, i.e. less than 0.1 μSv/h; there was no need to further map these buildings. Fig. 2 shows a sample neutron dose map on the L2 level of the complex. Biological dose rates of ~0.2 Sv/h are evident inside the port cells, but rapidly falling to hundreds of μSv/h outside the port cell doors and below 0.1 μSv/h into the diagnostics building.

Note that the cylindrical surface source approximation does not provide accurate dose maps inside the neutral beam injector (NBI) cell, as the 40° B-lite sector model, upon which the secondary source is based, does not contain the NBI port. The large streaming paths of the NBI port are thus neglected in the surface source approximation. Radiation maps of the NBI region of the building have been mapped by IO in separate analysis.

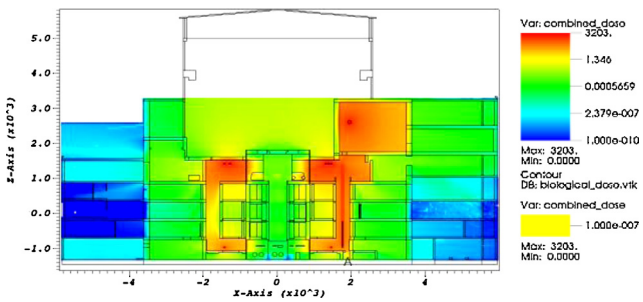

Fig. 3. Total photon dose rate (Sv/h), during plasma operation.

3.2. Activated cooling water

The most intense photon sources of interest in the building model during plasma operation are the result of the activation of cooling water producing short-lived nitrogen isotopes:

$$^{16}\mathrm{O} + \mathrm{n}(10.2\,\mathrm{MeV threshold}) \rightarrow {}^{16}\mathrm{N} + \mathrm{p}$$

$$^{17}\mathrm{O} + \mathrm{n}(8.4\,\mathrm{MeV threshold}) \rightarrow {}^{17}\mathrm{N} + \mathrm{p}$$

These products subsequently undergo beta decay:

$$^{16}\mathrm{N}(t_{1/2} = 7.13\,\mathrm{s}) \rightarrow {}^{16}\mathrm{O} + \gamma(69\%6.13\,\mathrm{MeV}, 5\%7.12\,\mathrm{MeV})$$

$$^{17}\mathrm{N}(t_{1/2} = 4.17\,\mathrm{s}) \rightarrow$$
$$^{17}\mathrm{O}^{*} \rightarrow {}^{16}\mathrm{O} + \mathrm{n} + \gamma(95\%0.901\,\mathrm{MeV neutron}, 3.7\%0.871\,\mathrm{MeV}\gamma)$$

These two short-lived products' decay time is sufficiently long for water to travel far enough from the activation source to cause distant pipe chases to become activated. The water and water pipes thus act as intense gamma sources during plasma operation and after shutdown [1].

Only the ^{16}N radioisotope is considered during plasma operation as it is by far the more dominant of the two activation sources. Individual modelled sources of activated water comprised of the lower pipechase (level B2), divertor outlet – vertical shaft 17 (level B1 to L2), upper pipechase (level L3), heat exchangers (level L4) and the Outlet vault manifold (OVM) (level L4). The ^{16}N isotope is simulated as not having undergone decay in the cooling circuit, except in the heat exchangers and OVM, where two half-lives are assumed to have elapsed. This approach ensures that the simulated results remain conservative.

GVR was applied to the transport calculations and in order to efficiently solve sampling issues and poor statistics on the central floors of the building model a dual meshing methodology was adopted, whereby optimal results were calculated on the B2 and B1 levels spanning the three buildings of the tokamak complex and a further set of results calculated, again using GVR, spanning several floors in only the tokamak building. Results were combined based on selecting the voxels with the least relative uncertainty for any given voxel. This method thus allowed for the running of a larger numbers of histories on smaller, targeted, sections of the geometry.

Fig. 3 shows results of on load simulations of activated water in a vertical cross section through the tokamak complex. Photon biological dose rates were 3.2 kSv/h near the upper cooling pipes, and dose rates on the B2 level of the tokamak complex exceeded 0.1 μSv/h inside the diagnostics and tritium handling buildings.

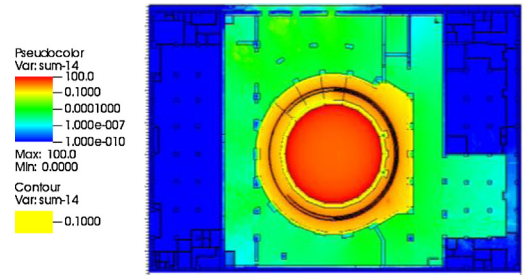

Fig. 4. Biological dose rate activated pipe chases and cryostat μSv/h, at 10^6 s after shutdown – example results.

4. Photon dose maps 10^6 s after shutdown

4.1. Activated pipework

Following shutdown, activated cooling water in the pipes will rapidly decay away. However, the neutrons produced in the pipes, by the decay of ^{17}N, activate the pipework, which decays on longer timescales after shutdown.

The neutron activation of pipes has been modelled based on FISPACT calculations performed by ENEA [4], from which source volumetric intensity and spectra were obtained and source terms modelled. The previous pipe chases, which were modelled carrying the activated water, were then simulated as activated pipe chases.

Fig. 4 shows an example of a biological dose map in a horizontal plane through the upper pipe chase of the tokamak complex, hot spots demark the upper pipe chase and cryostat sources. Calculated dose rates in close proximity to the activated upper pipe chase source are ~11 μSv/h.

4.2. Activated cryostat

ITER safety requirement state that the dose rate at the port interspace (where maintenance is to be carried out) are required to be less than 100 μSv/h 10^6 s after shutdown [5]. In order to include the activated tokamak internals as a gamma source term in the shutdown dose maps a cylindrical surface source was generated at the cryostat which captured the gamma field from tokamak internals, based on SS304 steel activation. The gamma spectrum and intensity were calculated using the FISPACT inventory code. The neutron spectrum used in FISPACT was calculated in the standard B-lite model at the inner cryostat location at height $z = 0$. A normalised intensity of the gamma source was set to achieve 100 μSv/h contact dose rate at the cryostat.Fig. 5 shows shut down dose rates from the cryostat can be seen reaching the normalised value of 100 μSv/h.

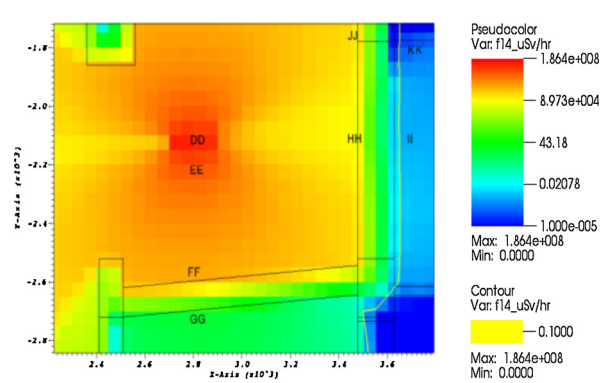

Fig. 5. Total photon dose rate (μSv/h).

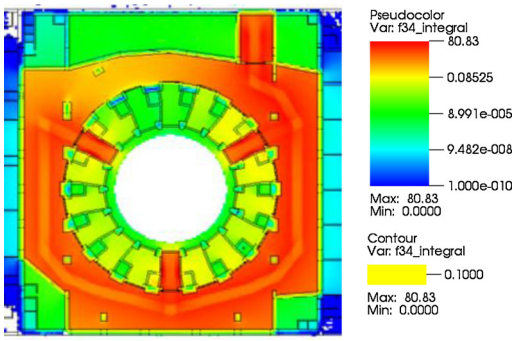

Fig. 6. Integral dose to silicon from 54 cask transfers (from three port cell locations), in units of Gy.

5. Three weeks after shutdown

5.1. Stationary cask

Work has been carried out to assess radiation fields during cask transfer movements containing activated divertor and blanket modules, for a three weeks post operation maintenance scenario.

The simulated radiation source comprised of a single divertor module loaded into a thin-walled cask with a 7 cm thick steel base plate. Three stationary point simulations were carried out, representative of worst-case transfer scenarios in the event of the cask remaining stationary for a prolonged period of time. These comprised: a location close to the south-east cubicle containing sensitive control electronics; in the port cell during loading and outside the lift shaft en-route to the hot cell.

Dose rates were calculated in the south-east cubicle with the divertor source positioned sideways-on (to give the worst-case dose to the cubicle); these were 8.95 μSv/h and 1.16 Sv/h inside and outside the cubicle respectively, points GG and FF in Fig. 5. Thus the shielding wall provides more than 5 orders of magnitude reduction to the dose rate.

The dose rate calculated at a point adjacent to the cask, inside the tritium handling building, are 2.09×10^{-3} μSv/h with an estimated relative uncertainty of 7.2% (point II).

5.2. Integral cask transfers

The previous stationary point calculations provided conservative estimates of peak dose rates foreseeable during cask transfers. However, in the case of sensitive electronics the quantity of greatest interest is the accumulated absorbed dose to silicon. In order to quantify this, simulations were carried out to assess the typical dose to silicon that would be observed during 'moving' cask transfers. A 'boxed source' methodology [6] was adopted for cask transfer simulations. The source, being independent of the cell geometry, permits position sampling and smearing of the source along routes of arbitrary complexity and is much more efficient at mapping distributed radiation fields over large areas. A custom Fortran MCNP source routine was written to read in the route data and sample the cask position on the chosen path. The cask direction was calculated such that the cask is rotated to point in the direction of motion. The simulated cask transport properties can be found in Ref. [2].

Dose rate maps to silicon were calculated for single cask transfers, containing a single divertor cassette, at representative speeds and dwell times, the results of which can be readily scaled for an integral number of casks transfers which will follow identical routes. Further simulations have also been carried out to assess integral radiation levels from a complete set of divertor cassette transfers from differing port cells.

Fig. 6 shows sample results for a cask route simulating the transfer of 54 divertor cassettes, over three equi-probable routes, leading to the lift shaft and through to the hot cell. Doses to silicon inside the north east electronics cubicle are 9.79×10^{-5} Gy, 7.66 Gy outside the cubicle, 41.5 Gy inside the port cell and 1.12×10^{-7} Gy inside the tritium handling building.

6. Discussion/conclusion

Detailed radiation maps of the ITER complex have been produced during plasma operation and after shutdown to the required dose rate cut-off criteria. A variety of neutron and photon sources have been modelled with simulations through shielded regions of the ITER complex proving to be extremely challenging and computationally demanding. In lieu of this a number of novel capabilities have been developed through this work including a secondary neutron cylinder source representation, smeared source and moving geometry capabilities for cask transfer simulations. Separate developments have also lead to the improved secondary RSSA source capabilities used for 'boxing' cask sources.

On-load dose rates from neutrons were shown to be below 1 Sv/h inside the port cells, whilst on load photon dose rates near the upper cooling pipes reached 3.2 kSv/h. Off-load photon dose rates from activated pipe chases, 10^6 s after shutdown, were of the order of a few μSv/h near the cooling pipes.

It was noted that both the secondary source terms and integral (smeared) cask dose rates have separate uncertainties associated with each calculation. In the current implementation these uncertainties are not currently propagated through to the final statistical error that is quoted in the calculations. The full quantification of this compounding uncertainty was beyond the scope of the presented work in this paper. It is however recognised as a limitation and an important aspect to report on as part of further developments

Acknowledgments

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organisation.

References

[1] M. Loughlin, Shielding for gamma rays from activated water in ITER, Trans. Am. Nucl. Soc. 109 (2013) 1176–1179.
[2] Task report on ITER Radiation Maps, ITER Organisation, private communication.
[3] A. Davis, A. Turner, Comparison of global variance reduction techniques for Monte Carlo radiation transport simulations of ITER, Fus. Eng. Des. 86 (9–11) (2011) 2698–2700.
[4] Dose rates in tokamak building due to the ^{16}N and ^{17}N isotopes in ITER PHTS cooling water, ITER Organisation, private communication.
[5] N. Taylor, et al., ITER safety analysis update, Fus. Eng. Des. 87 (5–6) (2012) 476–481.
[6] A. Turner, J. Naish, Box Source Routine, ARP Technical Note ARP-022, CCFE, February, 2014.