ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/324457492

The ITER tokamak neutronics reference model C-Model

Article *in* Fusion Engineering and Design · April 2018

DOI: 10.1016/j.fusengdes.2018.04.002

CITATIONS
8

READS
109

10 authors, including:

Bethany R Colling
Culham Centre for Fusion Energy
20 PUBLICATIONS **78** CITATIONS
SEE PROFILE

Michael J. Loughlin
ITER
146 PUBLICATIONS **2,203** CITATIONS
SEE PROFILE

Arkady Serikov
Karlsruhe Institute of Technology
124 PUBLICATIONS **804** CITATIONS
SEE PROFILE

Andrew Turner
Culham Centre for Fusion Energy
24 PUBLICATIONS **158** CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project Neutronics analyses for the ADS systems, Tritium Breeding Modules (TBM) in ITER & DEMO, and hybrid fusion reactors View project

Project Alternative radiation transport codes View project

All content following this page was uploaded by Arkady Serikov on 03 October 2019.

The user has requested enhancement of the downloaded file.

ARTICLE IN PRESS

Fusion Engineering and Design xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

The ITER tokamak neutronics reference model C-Model

Dieter Leichtle[a,*], Bethany Colling[b], Marco Fabbri[a], Rafael Juarez[c], Michael Loughlin[d], Raul Pampin[a], Eduard Polunovskiy[d], Arkady Serikov[e], Andrew Turner[b], Luciano Bertalot[d]

[a] Fusion for Energy, Josep Pla 2, Barcelona 08019, Spain
[b] UK Atomic Energy Authority (CCFE), Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[c] UNED, Depart. Ingeniería Energética ETSII, Calle Juan del Rosal 12, 28040, Madrid, Spain
[d] ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France
[e] Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany

ARTICLE INFO

Keywords:
ITER
Neutronics
MCNP
Shielding analysis

ABSTRACT

The ITER Organization maintains neutronics reference models for nuclear analysis. The "lite" series of tokamak sector models has progressed over many years to the C-lite V1 model released at the end of 2013. Since then several model updates have been continuously implemented in various C-lite V2 models. The latest release, C-Model represents the 40° regular sector of the tokamak up to the bioshield with central upper, equatorial and lower ports, i.e. an even-port configuration.

C-Model, as previous C-lite models, is based on a modular concept of model envelopes which fill all space of the torus sector. This envelope block structure has been adopted to facilitate model update management on the basis of single standalone models, which can be easily replaced in the model assembly. C-Model has been significantly improved with respect to C-lite in terms of specific system model design status and level of detail, focused on in-vessel and vessel components. The development of those updated system models was conducted according to the quality standards of ITER reference models. Modelling instructions, documentation and verification formed an essential part of the related activities.

1. Introduction

The decree of creation of the Nuclear Basic Installation INB 174 related to the ITER project was signed in 2012. Nuclear analyses are required to assess the impact of radiation sources, most prominently the 14-Me V neutrons from the DT plasma, and radiation fields on system design, licensing, plant operation and maintenance, and decommissioning by providing a variety of nuclear responses. In many cases, such analyses involve Protection Important Components and are classified as Protection Important Activities in application of the French regulatory framework.

To facilitate the provision of validated input data for a wide range of nuclear analysis applications reference inputs and standards are provided which are utilized to the extent required by the respective application. Among those input data the reference geometry models for radiation transport and shielding applications are the most important. They are considered to be part of the technical baseline documentation and accordingly are applicable for any related work which is in need for such a reference model. As radiation transport is inherently a highly transversal problem, the problem space in many applications is extending well beyond the region of interest. Therefore, reference models provide the required boundary conditions based on the technical configuration baseline. They serve as a framework to establish valid configurations of radiation sources and structures for a particular radiation transport problem.

Reference models are currently provided for the tokamak (a regular 40° sector model) and for some of the nuclear buildings (e.g. Tokamak Complex Building, [1]). The "lite" series of tokamak sector models has progressed during many years from A-lite, [2], over various B-lite versions to the C-lite V1 model release in 2013. Several new partial models have been developed since then which have been used to create variants of C-lite V2 for different applications.

The aim of the paper is to provide an overview of the collaborative development of C-Model (Fig. 1), the new regular sector ITER tokamak reference model, in 2016 based on formalized modelling and quality standards. Key features of the model will be described and guidance to ITER shielding analyses is given, taking into account the need to identify the appropriate baseline configuration of sources, shields and structures and, as needed, well defined and justified deviations.

* Corresponding author now at: Karlsruhe Institute of Technology, Germany.
E-mail address: dieter.leichtle@kit.edu (D. Leichtle).

https://doi.org/10.1016/j.fusengdes.2018.04.002
Received 26 September 2017; Received in revised form 1 April 2018; Accepted 2 April 2018
0920-3796/ © 2018 Elsevier B.V. All rights reserved.

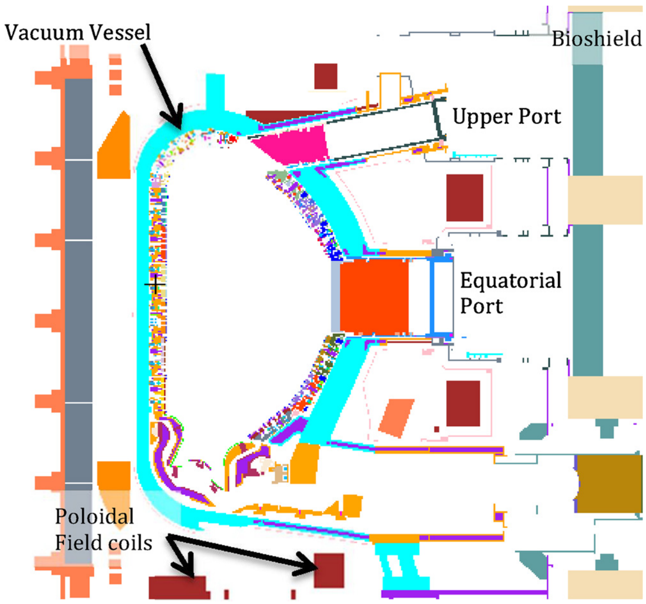

Fig. 1. ITER tokamak sector C-Model.

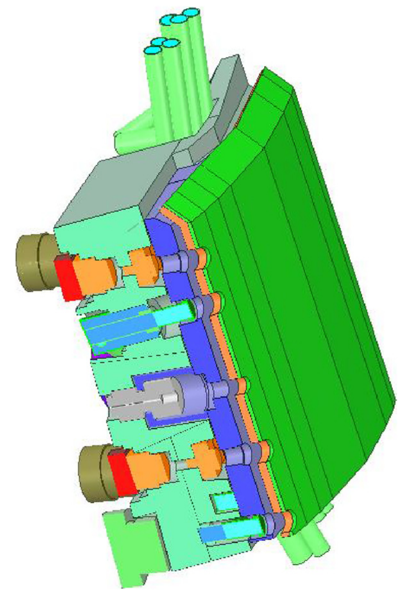

Fig. 2. Neutronics CAD of a single blanket model (semi-detailed representation of C-Model).

2. Description of C-Model release

C-Model is a major update of the previous ITER neutronics reference model C-lite. It represents a 40° regular sector of the tokamak up to the bioshield with central upper, equatorial and lower ports, i.e. an even-port configuration. The neutronics model is based to a large extent on configuration and design models of the respective tokamak systems of sector 1. To be noted is the 30° clockwise rotation of C-Model around the z-axis with respect to the Tokamak Global Coordinate System which is required to center the x-z-plane in the sector.

Further, it contains specific port configurations based on Diagnostic Generic Upper and Equatorial port plugs (including port interspace structures) and a Torus Cryopump Lower port, as well as an In-Vessel Viewing System port. The half ports at upper and equatorial level at each side are filled by default with the respective central port models. Reflective boundary conditions are applied to the torus sector planes to account for the quasi-toroidal symmetry. The bioshield plugs are modelled as simple concrete reflectors.

The model is made available as an input file for the MCNP code, [3]. It contains the respective material definition cards based on reference material specifications for both radiation transport and activation analyses. In addition, it contains the reference plasma neutron source and some parameters for the radiation transport simulation. An extensive set of standard tallies is provided for a variety of nuclear responses, like nuclear heating to vacuum vessel (VV) and toroidal field coils (TFC).

In addition to the MCNP model, which is the ITER reference model, a CAD model assembly has been prepared as a complementary model, which is not supposed to be used directly for ITER nuclear analysis. Typical application is for visualization and inspection purposes. It is based on the simplified CAD representations of all system models making up the full model.

The release package of C-Model (currently: Version 1 Release 2.1) includes a set of documents, which in turn provide several further references to specific model documentation.

3. Modelling approach and quality standards

Generally the modelling approach is based on available Configuration Management Models (CMM), Design Models (DM) and Manufacturing Design (MD) Models and additional design information, typically, such as information about material allocations and masses/volumes of components. CATIA engineering models (in STEP format) are modified for nuclear analysis applications by removal of unnecessary parts, defeaturing, geometry simplifications and homogenisation of materials, as appropriate. These so called neutronics CAD models (Fig. 2) were converted by automated software to produce nuclear analysis models in MCNP format.

This standardized modelling approach requires a huge investment in manpower as well as in suitable modelling tools. During the C-Model development the use of ANSYS/SpaceClaim, [4], for preparing CAD models and of SuperMC, [5], for the automatic conversion step have been essential to undertake and secure the tremendous efforts.

3.1. Block structure

C-Model is based on a modular concept of model envelopes which fill all space of the torus sector. This envelope block structure has been adopted already at B-lite to facilitate model update management on the basis of single standalone models (see Section 3.2), which can be easily replaced in the model assembly. Those are universe fillers to be integrated in the respective envelope cells.

One of the main applications of C-Model is the set of radiation shielding analyses for port systems. To this end, the envelope structure allows the complete replacement of the default port system fillers by the appropriate models of other port systems. This scheme has been implemented for all the major ports, including the lower port, where the switching between the default TCP port and the Diagnostics/Remote Handling port is considerably facilitated.

3.2. System specific models

C-Model has been significantly updated in terms of specific model design status and level of details. Recently approved Project Change Requests (PCR) to its baseline, important for nuclear analysis applications, have been incorporated. Major improvements and additions to the C-lite V1 release are blanket manifold pipes in the upper port, TFC detailed model of straight inboard leg, VV detailed models, complete blanket/in-vessel detailed models, cryopump lower port shielding, and upper and equatorial port plug gap configurations.

Due to those major updates and the significantly increased complexity of the specific models included in C-Model a complete restructuring of the final MCNP model was required. To this end, additional universe numbers had to be introduced. New cell, surface and material number range allocations have been implemented which necessitated a complete renumbering of all available universe filler models. Tools like numjuggler, [6], have proven very effective for these purposes.

3.3. Model verification

An important part of the investment in C-Model development was in quality assurance. Respective modelling guidelines have been applied to ensure the reliability of the resulting nuclear analysis models in terms of criteria like geometrical and mass accuracy as well as limited material mixing. The methodology for the production of many of these representations, specifically for in-vessel models, was standardized, documented and validated, and the representations themselves were commented, documented and independently verified.

Stand-alone universe filler models were checked to ensure the geometry was sufficiently accurate, according to the modelling guidelines, and clean. This was tested with void runs to control the lost particle rate, both in the stand-alone as well as in the integrated model, to values generally below 1 in 10^7. The conversion from CAD was verified to yield an equivalent number of cells with the expected volumes, and that there were no unintended void cells or cells with importance zero assigned. These checks ensure the resulting system-specific MCNP models faithfully represent the CAD models.

3.4. Model integration

To assist the assembly of C-Model all universe filler models have been treated separately to follow the instructions on C-Model integration, in terms of proper documentation and appropriate renumbering of cells/surfaces/materials. The complete set of those standalone models is available in MCNP format.

During integration of all universe filler models several issues leading to lost particles have been detected and resolved. Respective changes in the as-assembled C-Model were implemented and documented.

4. C-Model highlights

There are several main achievements associated with the C-Model development. Most obvious are the updated system specific in-vessel and vacuum vessel models (see Fig. 3), providing a considerably enhanced and detailed representation of the most recent configuration, design and manufacturing models, as appropriate, with reduced levels of material homogenisation. This has been supported by updates on the block structure model to account for a clearer separation between system models (related to the Plant Breakdown Structure).

In the same way modifications at port levels have been introduced to accommodate interfaces with in-vessel system models. Port system models provided now standard port interspace equipment in upper and equatorial ports. Details of the most important model improvements are described in the following sections.

Material specifications have been revised and updated according to a PCR on material selection and impurity control e.g. reducing Cobalt and Tantalum content in non-procured material to 0.05 wt% (or 0.03 wt % in DGUPP/DGEPP) and 0.01 wt%, resp. Several new material specifications have been added, including a wide range of several homogenized material mixtures in blanket and other in-vessel models.

C-Model has reached a high level of configuration and design compliance with a respective increase in model complexity and computational demands. The current release version V1 R2.1 features more than 70,000 cells and 100,000 surfaces with a MCNP input file of ca. 42 MB. It has been successfully tested and applied with MCNP5.160 and MCNP6.1 Due to its complexity it takes roughly 2 h to initialize a MCNP transport run.

4.1. In-vessel models

The set of updated in-vessel component models encompasses the blanket modules, the blanket manifolds, the in-vessel coils (IVC), and the divertor cassettes. Due to the long development history they are based on a mixed set of CMM with some later updates, incorporating recent PCRs.

First Wall (FW) and Shield Block (SB) are consistently modelled with appropriate material mixtures (so-called semi-detailed representation) with layers of the First Wall (Beryllium, CuCrZr or steel fingers, beam and waterbox) and a single steel/water mix for the SB. Thicknesses of the FW layers are chosen according to the Normal or Enhanced Heat Flux variants. It should be noted, that only parts of the FW water piping is modelled explicitly, whereas in particular cooling channels inside the SB are not available in these semi-detailed models. Further specific components, e.g. blanket attachments (no homogenisation applied) and electrical straps (homogenised materials) are added. For a limited number of FW and SB main variants dedicated DM exist and have been utilized both in geometrical modelling (shapes of SB rear sides) and in final volume and mass adjustments. Where DM information was not available or judged unreliable, the final SB masses have been conservatively reduced corresponding to 95% of the CM volumes.

Blanket manifold pipes with supports are available with separate water volumes, except in the manifold coaxial connectors in blanket rows 7–9 and 12.

The IVC, i.e. Upper and Lower vertical stabilisation coils and ELM coils, models are represented with coil and structure material mixtures.

The divertor cassette model provides, similar to the blanket FW, layered Plasma Facing Units (Tungsten, Copper, CuCrZr, water) for dome and Inner/Outer Radial Plates, whereas the Inner/Outer Vertical Target (IVT/OVT) elements are represented by approximated and homogenised cooling channels embedded in the tungsten blocks. Explicit water volumes, as available in the DM, have been introduced within the main structures, like cassette body, dome and IVT/OVT structures.

4.2. Vacuum vessel models

Vacuum Vessel models consist of the double shell vessel with field joints, the triangular support and the in-wall shields (IWS). They are based on approved MD models of several parts for vessel sectors 4, 5, and 6.

The model is fully heterogeneous, i.e. no material mixtures have been applied. The IWS components of borated steel plates, ferromagnetic inserts, brackets and bolts are modelled as separate parts. The VV structure also distinguishes the flexible support housings, ribs and field joints. Cooling water is modelled explicitly. The total volume of all material groups has been retained during the model preparation.

4.3. Port system models

Generic Diagnostic port system models have been integrated into C-Model as default fillers of UP (DGUPP, see Fig. 4) and EP (DGEPP, see Fig. 5). Both systems are comprised of the Port Plug with dummy Diagnostic FW and Diagnostic Shield Module (DSM), generic Interspace Support Structures with maintenance rails and diagnostic bioshield plugs. DFW and DSM are using a representative homogenised material mixture (steel, water, boron-carbide and void). Port gap configurations have been updated compliant with recent PCRs. This includes in the case of DGEPP the shims to establish double doglegs at the VV interface and narrower gaps near the closure flange.

5. Shielding analyses with C-Model

C-Model is used for neutron/photon transport and shielding

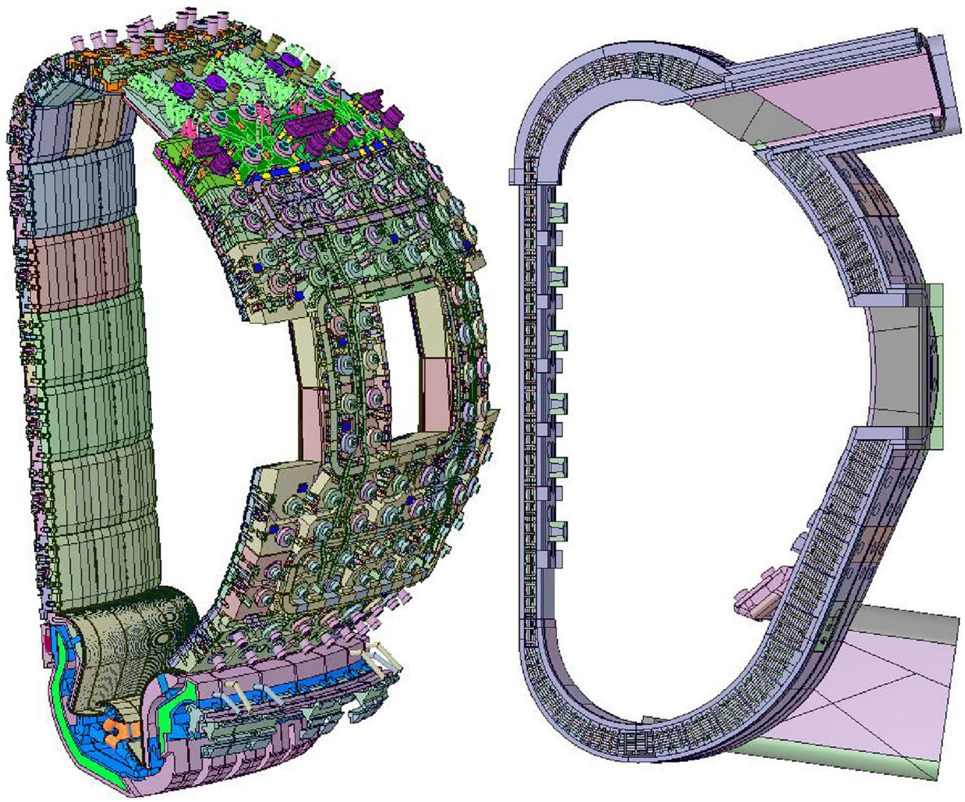

Fig. 3. In-vessel and vessel models of C-Model.

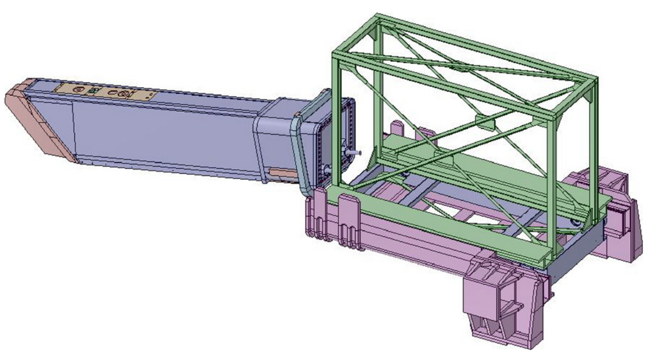

Fig. 4. Generic Diagnostic UPP model with interspace equipment.

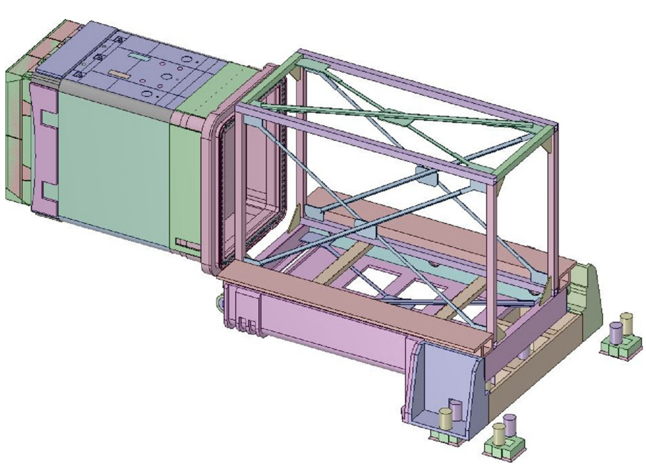

Fig. 5. Generic Diagnostic EPP model with interspace equipment.

calculations in the ITER tokamak up to the bioshield. Depending on the objective of a particular shielding analysis, such as protection of radiation sensitive equipment or radiological protection of workers, and the associated required nuclear responses the analysis methodology has to take account of specific requirements. In all cases it is essential to identify the appropriate baseline configuration of sources, shields and structures and, as needed, well defined and justified deviations. The analysis methodology has to take into account model errors, approximations and assumptions to estimate the uncertainties of a particular shielding calculation. Conservative estimates have to be applied whenever a rigorous quantification of errors is not possible or impractical.

Several distinct approximations are introduced in the various system specific models which are in C-Model. In all cases there will be an impact on the nuclear responses calculated within a particular part (direct sensitivity) as well as due to the affected flux density relevant for that response (indirect sensitivity). This impact gives raise to associated systematic uncertainties which need to be carefully assessed for the specific application. Generally, homogenisation of components as well as geometrical simplifications will cause significant effects on local responses. Global responses and far responses, however, tend to be more accurate in comparison. The impact on radiation streaming paths (void or weakly absorbing/scattering media) requires particular attention.

In this respect it is to be noted, that C-Model is not meant to represent each specific configuration in a 40° segment of the ITER tokamak. It serves as a generic regular sector (i.e. 7 out of 9 sectors) model centered at an even port of the VV. Due to its intrinsic asymmetry and adoption of default reflective boundary conditions at the sector planes, artefacts at those boundaries may deteriorate nuclear responses in this area. Also radiation cross talk contributions from neighbor ports will be impacted by the given boundary conditions. Similarly, C-Model cannot represent accurately an odd-port centered tokamak 40° segment.

ARTICLE IN PRESS

Other reference models are available or under development which are to be used when extending the domain of transport simulation beyond C-Model. This refers to the models for an odd-port centered regular sector, the 80° tokamak sector in the NBI cell and the Tokamak Complex Building. As regards the link to the irregular tokamak sectors in the NBI cell, this needs to be accounted for in radiation transport simulations and the calculation of nuclear responses affected by the presence of the 80° sector. Typical examples are port system analyses of neighboring ports in sector 1 and 4 (port numbers 3 and 7). Transport through the bioshield (including bioshield plugs) into the Tokamak Complex Building requires the implementation of appropriate specific bioshield plug models.

The C-Model MCNP input file contains a reference description of the plasma neutron source; therefore, it can be used directly for the calculation of nuclear responses from the fusion plasma in inductive H-mode (10 MA/5.3T, 500 MW fusion power). Any other radiation source has to be properly validated for the use with C-Model (i.e. the geometry model). In particular, secondary radiation sources such as activated cooling water, activated corrosion products and dust or activated structures need to have both a valid source characterization (e.g. particle type, energy, spatial distribution) and a valid geometry model (e.g. water piping) which need to be implemented into C-Model.

As C-Model is not a complete nuclear analysis design model, missing items or partial models need to be added when and where appropriate. This refers obviously to nuclear analysis for systems which are not or not completely available in C-Model, but also to systems which can affect the nuclear responses of interest. Typical examples are port plug analyses which have to account for the close environment, including in-vessel model, (affecting e.g. gap streaming) as well as neighboring port systems (affecting the global radiation field). Similarly, there might be the need to replace existing models by more detailed or extended models. Respective instructions have been issued for the integration/modification within C-Model; in particular, specific guidance on port system integration is provided.

6. Conclusions and further considerations

C-Model, the new regular sector ITER tokamak reference model, has been developed based on standardized and formalized modelling approaches. It has reached a high level of configuration and design compliance by, most prominently, major updates on in-vessel and vacuum vessel models and by adherence to quality assurance procedures for providing validated neutronics reference models. The overall effort for this new major release is estimated at roughly 5 PPY. It is probably one of the most complex MCNP models used in fusion neutronics with more than 70,000 cells and 100,000 surfaces.

The release features not only the reference MCNP model but also a complete CAD model (for visualization) and an extensive set of model records and user instructions, thus supporting ITER nuclear analysis work adopting C-Model for radiation transport and shielding analyses.

A continuous effort is put in place to ensure the maintenance, user support and configuration control of this ITER reference model.

Disclaimer

A major part of the work leading to this publication has been funded by Fusion for Energy under several contracts (OMF-466-02-03, OMF-466-01-04, OMF-466-03-05, OMF-466-03-07, OMF-466-03-08, OMF-466-01-09) and by ITER Organization under contracts IO/4300000896 and IO/CT/4300001299. This publication reflects the views only of the author, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

The views and opinions expressed herein do not necessarily reflect the views of the ITER Organization. The content of the paper does not commit the ITER Organization as nuclear operator.

Acknowledgements

C-Model was developed as a collaborative effort between AMECFW (International), UKAEA (UK), ENEA Frascati (Italy), F4E (Spain), INEST-FDS Team (PRC), IDOM (Spain), ITER Organization (France), QST (Japan), KIT (Germany), UNED (Spain), University of Wisconsin-Madison (USA).

Model preparation, integration and testing were facilitated by several software packages, such as ANSYS SpaceClaim, INEST-FDS SuperMC and KIT numjuggler. Many stimulating discussions with several colleagues from CCFE and Fusion for Energy during the integration activities were particularly helpful for the preparation of the paper.

References

[1] A.J. Lopéz-Revelles, J.P. Catalan, A. Kolsek, et al., MCNP model of the ITER Tokamak Complex, to appear in Fus. Eng. Des.
[2] M.J. Loughlin, et al., ITER nuclear analysis strategy and requirements, Fusion Sci. Technol. 56 (2009) 566–572.
[3] X-5 MONTE CARLO TEAM, MCNP – A General Monte Carlo N-Particle Transport Code Overview and Theory (Version 5, Vol. I), National Laboratory, Los Alamos, 2003 Report LA-UR-03-1987, 24 April 2003 (Revised 10/3/05).
[4] ANSYS SpaceClaim [Computer Software], Retrieved from http://www.spaceclaim.com.
[5] (a) Y. Wu, FDS Team, CAD-based interface programs for fusion neutron transport simulation, Fus. Eng. Des. 84 (2009) 1987–1992;
(b) Y. Wu, J. Song, H. Zheng, et al., CAD-based monte carlo program for integrated simulations of nuclear svstem superMC, Ann. Nucl. 82 (2015) 161–168.
[6] KIT Numjuggler [Computer Software], (2016) Retrieved from https://github.com/inr-kit/numjuggler.

View publication stats