Development of radiation sources based on CAD models for the nuclear analysis of IFMIF-DONES lithium loop

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A B S T R A C T

IFMIF-DONES is a neutron source designed to irradiate materials to be used in future fusion power reactors such as DEMO. The facility is based on a deuteron beam impinging onto a liquid lithium jet to generate the neutron flux. Lithium and Corrosion Products will get activated and produce Be-7 and Activated Corrosion Products (ACP). These products will be distributed along the lithium loop, both dissolved in lithium and deposited locally. This complex gamma source should be properly represented to perform radiological safety studies. A new tool, called CAD2CDGS, was created to represent these sources. This tool creates decay gamma sources based on CAD geometries and codifies them into CDGS format. Sources are specified in the CAD model, allowing a user-friendly approach. The tool is based on Open-Source tools (FreeCAD) and EUROfusion codes (cR2S European SDDR tool). In this article the CAD2CDGS tool methodology, inputs and workflow are explained. Two verification tests have been done to check the correctness. Finally, it is demonstrated the applicability of the tool to IFMIF-DONES, with the radiological zoning analysis of the rooms surrounding the Lithium Loop Cell impact by the Be-7 and ACP.

1. Introduction

IFMIF-DONES (International Fusion Materials Irradiation Facility – DEMO Oriented NEutron Source) is a neutron source designed to irradiate materials to be used in future fusion power reactors such as DEMO. This facility is an essential part of the EUROfusion roadmap for the realization of fusion energy. One of the IFMIF-DONES systems is the Lithium Systems (LS). This system provides the liquid lithium jet whose interaction with the deuteron beam generates the neutrons to irradiate the test modules. Deuteron beam interaction with the liquid lithium occurs in the Target System and the Heat Removal Loops are in charge of evacuating the heat [1]. Lithium and Corrosion Products (CP) will get activated and produce Be-7 and Activated Corrosion Products (ACP). These products will be distributed along the lithium loop, both dissolved in lithium and deposited locally. This complex gamma source should be properly represented to perform radiological safety studies.

Nuclear analyses in IFMIF-DONES are typically done with MCNP (Monte Carlo N-Particle) radiation transport tool [2]. Particularly, the gamma sources produced from Be-7 and ACP in LS have been typically represented manually with the MCNP SDEF card. It has been found that the manual source representation is tedious and prone to human error.

Also, this card has a limitation of 999 distribution cards which restricts the source complexity. Therefore, a tool is needed to facilitate the source generation without limiting the source complexity.

2. CAD2CDGS source generation tool

CAD2CDGS (Computer-Aided Design to Common Decay Gamma Source) is a new tool to generate gamma sources based on CAD models. These sources are codified into CDGS (Common Decay Gamma Source) format [3] and run with compatible MCNP code extensions. CAD2CDGS source code, manual and examples are available through EUROfusion IDM platform [4].

CAD2CDGS uses CAD models instead of radiation transport geometries to define each source. This method is a user-friendly approach because complex sources can be represented by choosing the groups of CAD solids that form them, allowing an easy source update and revision. CDGS is a decay gamma source exchange format and it is commonly used to store the gamma decay source in Shutdown Dose Rate (SDDR) computations in fusion applications. The use of the CDGS format gives the flexibility to define decay gamma sources with complex shapes and it avoids the source definition with the MCNP SDEF card. Instead, it relies

on the MCNP source subroutine to reproduce the source. The approach of using CAD models to define sources and codify them into CDGS format follows the same approach as [5].

CAD2CDGS tool is based on three main foundations. The first one is Python 3 language [6]. The second one is FreeCAD tool [7]. FreeCAD is used as an interface for Open CASCADE CAD engine [8]. In the tool, FreeCAD is used to manage and process the CAD model. Third one is a set of European tools, called common Rigorous-two-Step (cR2S) European SDDR tool [9], that supports the inter-compatibility of SDDR simulation tools. Part of its cR2S Python code is reused in CAD2CDGS.

2.1. Method description

For the estimation of radiation dose fields at shutdown periods in fusion facilities one of the used approaches is the Rigorous-two-Step (R2S) method [10]. It couples radiation transport and activation calculations, which requires two radiation transport calculations: the neutron and gamma transport. Information for gamma transport is obtained from intermediate activation calculations which estimate the decay gamma source. In R2S simulations, it is used a structured (Cartesian or cylindrical) mesh superimposed to the geometry. In turn, meshes are divided into elementary volumes called voxels. First, voxels are used to record the neutron flux and spectra and, after the activation computation, the decay gamma source.

For the interest of CAD2CDGS tool, the decay gamma source is not given in the same superimposed mesh where the neutron transport (or deuteron irradiation in the specific case of IFMIF-DONES) and the activation simulations are performed. Instead, sources are usually computed by physical system codes that take into account the production rates of radionuclides and the complex processes of corrosion, mass transfer and deposition. Therefore, source term information is given as the radioisotope concentration in each part of the system, in components such as pipes, heat exchangers, storage tanks, etc. and these regions are not necessary in the same space where the activation process takes place.

In order to take advantage of structured meshes of R2S methodology and serve the specific needs of gamma source spatial distribution, meshes are used in a different way. For R2S method, it uses one or several meshes to enclose the region of interest. Whereas for CAD2CDGS it is defined for each source cell a single voxel that encloses completely that cell and independent meshes are defined (one mesh per voxel). With independent meshes, voxel limits can be defined freely and even to overlap. CAD2CDGS uses currently only Cartesian meshes.

For CAD2CDGS, one of the advantages of "mono-voxel" approach over the typical mesh definition is that "mono-voxel" approach does not require users neither to compute the outer boundaries of the mesh (or meshes) nor to set a suitable voxel size. Finally, the CAD2CDGS user should provide the decay gamma information per unit of mass (mass sources) or unit of volume (volumetric sources). Then, CAD2CDGS assigns each source distribution to the corresponding CAD solids, obtaining the gamma intensity that corresponds to each mesh.

2.2. CAD2CDGS inputs

CAD2CDGS input information is structured into four types of input files: a common CAD model, gamma spectrum files, a MCNP cell information file and a configuration file.

2.2.1. Common CAD model

CAD model is used by CAD2CDGS tool mainly to identify the source solids. Definition of source solids is done by the direct modification of the component name in the structure tree. CAD2CDGS tool uses the label of the innermost component (the parent component of the CAD solids) to codify the source information with pair keyword-value separated by underscores. These pairs express the type of source (mass or volumetric)

and the source identification (ID). For mass sources, the component is defined by default with 1 gram of source (e.g. label "msrc1_" sets mass source 1 with 1 gram of source). Each CAD solid inside the component receives a fraction of the component mass (ratio of solid volume and volume sum of all solids inside the component). Other masses (in grams) can be set with an additional pair keyword-value (e.g. label "msrc1_mass1.0e-6_" sets mass source 1 with 10^{-6} grams of source).

For volumetric sources (e.g. label "vsrc2_" sets volumetric source 2), the volume of each CAD solid inside the component is multiplied by the assigned source spectrum (the bigger the solid is, the higher the source intensity is). An optional coefficient can be set to scale volumetric sources (e.g. label "vsrc2_coef0.5_" sets volumetric source 2 and scales by 0.5 the source intensity). This optional coefficient can be useful when a CAD solid is a homogenized component where the source represents a fraction of the volume. So, a coefficient should be applied to not over-estimate the total source.

One of the problems of working with CAD models is that the relative position of components and elements (e.g. CAD solids) in the component tree is not necessarily the same as the ones that CAD tools internally store. This can be a problem when the order of the created MCNP cells obtained by a conversion tool should match the CAD solid order. This problem can be resolved with the creation of a new CAD model, called common CAD model, which guarantees a common CAD solid order maintaining the essential CAD model information. In order to create this common CAD model it has been adapted a SpaceClaim [11] Python script of the SCtools package [12]. The new script not only guarantees a common order between the CAD model and the MCNP cells (original function), but also it maintains the original information in the component tree labels, including the source definition.

2.2.2. Gamma spectrum files

Decay gamma sources are typically represented as a set of discrete photon spectral lines or as a set of energy histograms that reproduce the intensity of each line or bin. Currently, the used CDGS format only supports the bin representation. To obtain the gamma spectrum from nuclear data it is used TAB4 files created by FISPACT-II activation tool [13]. TAB4 files represent the gamma spectrum in bin format in units p/cm^3/s with 24-group format. Volumetric sources in CAD2CDGS tool are defined directly with this format, while mass sources need a more complex preparation. FISPACT-II inputs should define a fictitious material with a source density of one gram per cubic centimeter. With this configuration the TAB4 units in p/cm^3/s equal to p/g/s, allowing the definition per gram. Also, CAD2CDGS tool can be easily adapted to read the gamma spectrum files created by other tools like ACAB activation code [14].

2.2.3. MCNP cell information file

This file contains a list with the MCNP cell IDs and the stochastic volume computation information (volume in cubic centimeters and error) obtained by MCNP. MCNP cell relative order should match with the CAD solid relative order in the common CAD model.

2.2.4. Configuration file

It is a plain text file that stores the paths to common CAD model, MCNP cell information file and generated CDGS file. Properties of gamma spectrum files (type of source (mass or volumetric), source ID and path to TAB4 file) are also defined.

Finally, Fig. 1 presents the CAD2CDGS input preparation summary.

2.3. Code execution

CAD2CDGS tool is launched by calling the Python3 interpreter in a command line terminal with the main Python file and passing the path to the configuration file.
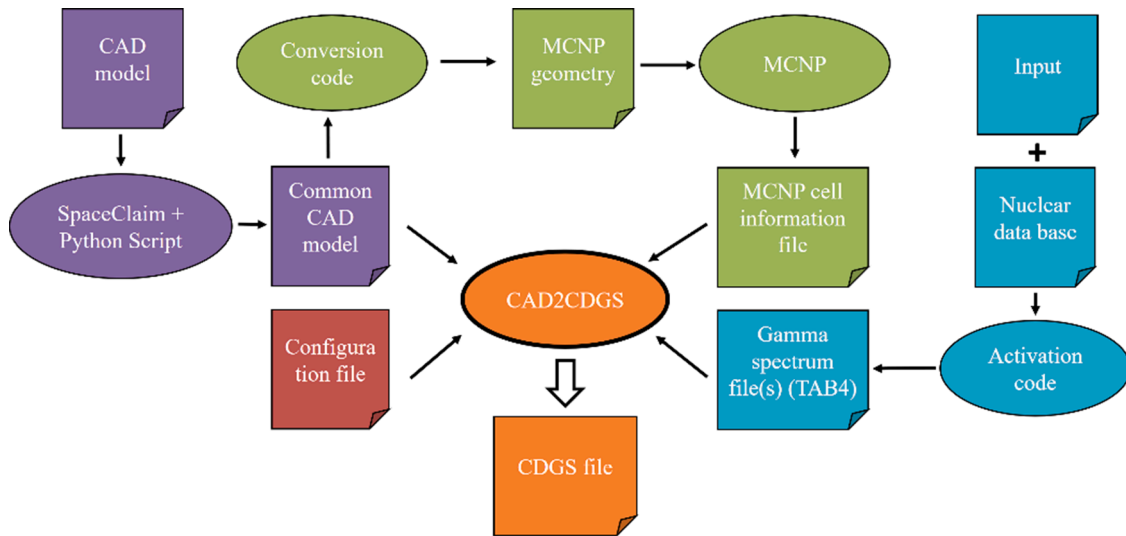
Fig. 1. CAD2CDGS input preparation summary.

2.4. Code workflow

In first step the configuration file is loaded with the information to access and configure the rest of inputs, initialising the variables that stores them. In second step FreeCAD is used to import and store the common CAD model. From it, all solids are stored in a Python list called "Solids" and for each one a bounding box is created to represent the voxels. A bounding box is an orthographic cuboid that describes outer boundaries and default orientation follows the coordinate axes. Then, the component tree is processed to identify the source solids.

In third step MCNP cell information file is read and each CAD solid receives the corresponding MCNP cell ID. A volume comparison between CAD solids and MCNP cells is done and a message is sent if volumes do not match. In fourth step it is read the gamma spectrum file (or

files) and each source distribution is linked with the corresponding source solid.

Fifth step uses the cR2S tool and it iterates over the "Solids" list only considering the source solids (regular solids are skipped). Then, one mesh cell object is initialised and MCNP cell ID, source intensity and other properties are set. For mass sources, the source intensity (in p/s) in each one of the 24 bins is computed as the product of the bin intensity (E_i) by the mass of its corresponding component and by the fraction of the source solid volume and the component volume (volume sum of all solids inside it). For volumetric sources, the source intensity is computed as the product of each bin intensity (E_i) by the source solid volume and by the coefficient. Next, a mesh voxel object is initialised and voxel limits are set. Finally, a mesh object is initialised and cell and voxel are added. Once all meshes are created, they are stored in a CDGS object. Finally, CDGS is stored in a file. CAD2CDGS algorithm workflow is shown in Fig. 2.
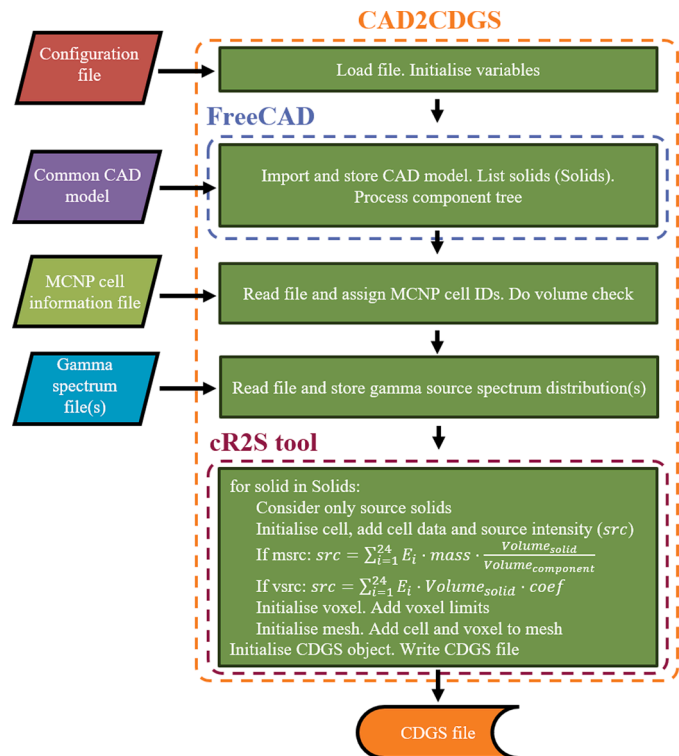
3. Verifications

3.1. R2S simple test case

This study compares the CDGS files created with cR2S and CAD2CDGS tools. This R2S case has been taken from the cR2S tool [9]. Fig. 3 describes the case, the three R2S steps and the used tools.

The first step is the neutron transport. A steel cube and a concrete slab are irradiated with 14 MeV neutrons from a plane source. Then,
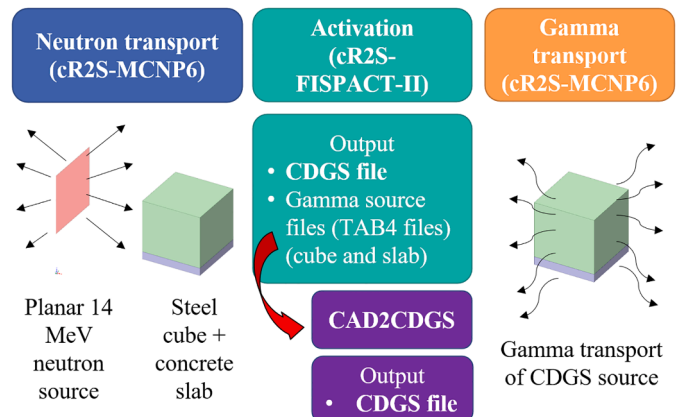

Fig. 2. CAD2CDGS algorithm workflow.

Fig. 3. Steps of the R2S simple case verification test.

tallies are used to record the neutron flux in each component. The second step is the activation of each component with a complex irradiation and cooling scheme. Then, it is obtained the reference CDGS file and additional files (the TAB4 files) with the gamma source spectrums (of both cube and slab). TAB4 files are used to obtain the CDGS file using CAD2CDGS tool.

Both CDGS files are compared with the "diff" Linux tool and after the by-line comparison it is detected only two different lines which correspond to the comments to each mesh. The reason why mesh, voxel and cell match exactly is that CAD2CDGS tool reuses part of the cR2S-FISPACT-II Python code to write the CDGS files, thus almost the same output is produced from the same input. Then, gamma transport (10^9 histories) was performed for each CDGS file and ambient dose rates around the cube and slab recorded. Finally, doses were compared and the same results were obtained as expected.

3.2. IFMIF-DONES lithium loop case with Be-7

In this study an actual IFMIF-DONES simulation done with the native MCNP SDEF source definition was compared with the same case calculated with a CDGS source created using CAD2CDGS tool.

The source term is the Be-7 distributions in the lithium loop due to the deuteron irradiation of the lithium jet in 345 days. Be-7 half-life is 53.1 days and it emits 0.477 MeV gamma rays with an intensity (per atom decay) of 10.44 %. Only precipitated Be-7 (0.132 g) is considered and it is located in the coolest part of the Heat Exchanger (HX) and in the Cold Leg (CL) [15]. Because only a small amount of Be-7 ($2.3 \cdot 10^{-4}$ g) is dissolved in lithium compared to the precipitated Be-7, the Be-7 source inside the Hot Leg (HL) is not considered. Fig. 4 presents the CAD model.

CAD model contains the Lithium Loop Cell (LLC), the HX and the CL. Floor, ceiling and walls are made of concrete. In HX, green solids represent the region with a homogeneous mixture of lithium, oil (hydro-terphenyl) and stainless steel HX inner parts (SS316L). This region is divided into 11 sections and only in the last four (numbered from 1 to 4) there is Be-7. Metallic pipes (SS316L) and liquid lithium represent the CL. CL sources are numerated from 5 to 13. Each source contains a different amount of Be-7.

Three cases are considered. The first case, *Be-7 line*, represents the actual 0.477 MeV Be-7 photon emission while the second case, *Be-7 bin*, represents the photon emission approximation in the 24-group structure with the source defined in the [0.4, 0.6] MeV bin. These sources are easy to define by hand with SDEF card due to the reduced number of isotopes (only Be-7), the source shape simplicity and the small number of sources
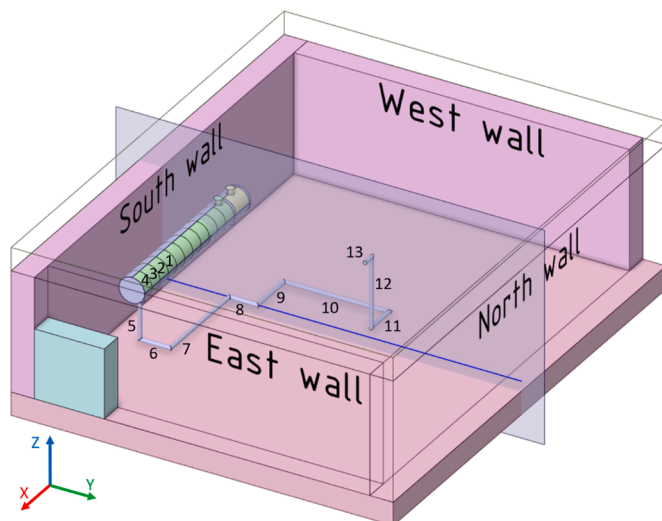
(13). Sources 5 to 13 are cylinders with at least one non-perpendicular base to the axis. To sample this specific shape a surrounding space (a bigger cylinder) is needed. In it, points are picked randomly and only if the point is inside the corresponding cell, the position is accepted. Because all sources are aligned with coordinate axes, defining these surrounding spaces is easy.

For the third case, *Be-7 CDGS*, the 13 source cells are codified into CDGS format with CAD2CDGS. Finally, in each case, ambient dose rates are tallied in a mesh with a mesh cell size of $10 \times 10 \times 10$ cm3 covering the entire LLC. Also, a total of 10^9 histories have been simulated for each case, obtaining good statistics in the inner space of LLC (in the three cases relative errors for further LLC inner regions from the sources are below 3 % while quickly increasing inside the concrete structures). *Be-7 line* and *Be-7 bin* cases used MCNP6 [2], while *Be-7 CDGS* case used the cR2S-MCNP6 [9] to run the CDGS source.

To compare the ambient dose rates, it has been chosen a plane (x = −806.5 cm). This plane is represented by the blue plane in Fig. 4 while Fig. 5 represents the dose maps. These maps are almost equal excepting the regions inside the concrete structures where gammas are strongly shielded and error is higher. Also, to analyse better the results, it has been chosen a preferential set of mesh cells that are aligned with source 8. While blue line in Fig. 4 represents this cell trajectory, results are shown in Fig. 6.

Fig. 6 presents two sets of graphics that share the same horizontal axis. While left vertical axis represents the ambient dose rates (in µSv/h, dotted lines), right vertical axis represents the ratio of ambient dose rates of case *Be-7 CDGS* regarding the other two cases (solid lines). Limits of south wall, source 8 and north wall are included. For dotted
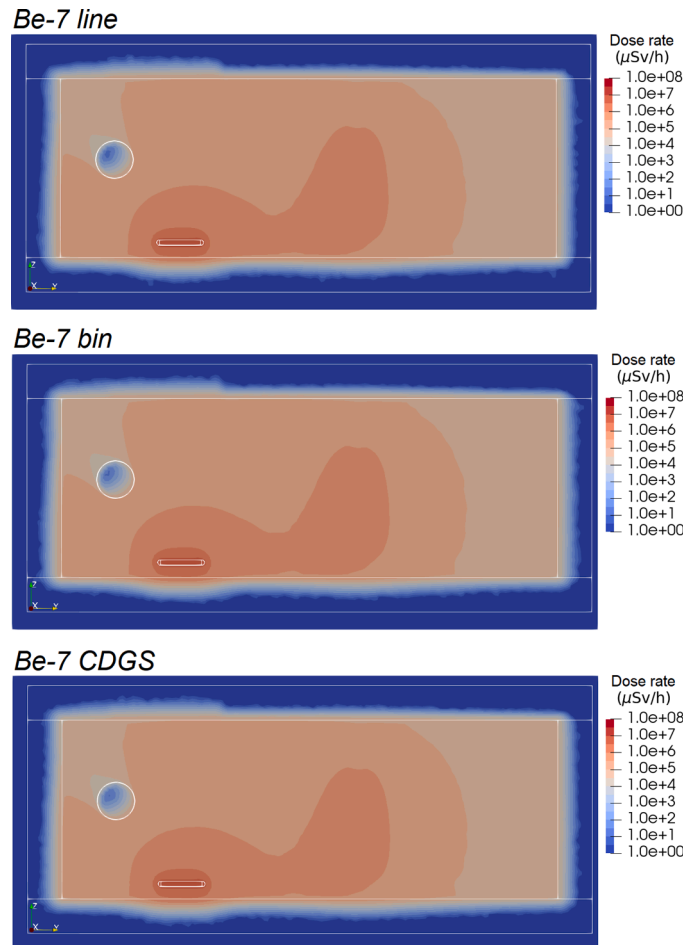

Fig. 4. CAD model of Be-7 cases with Lithium Loop Cell, Heat Exchanger and Cold Leg.

Fig. 5. 2D ambient dose maps at plane x = −806.5 cm of *Be-7 line*, *Be-7 bin* and *Be-7 CDGS* cases.
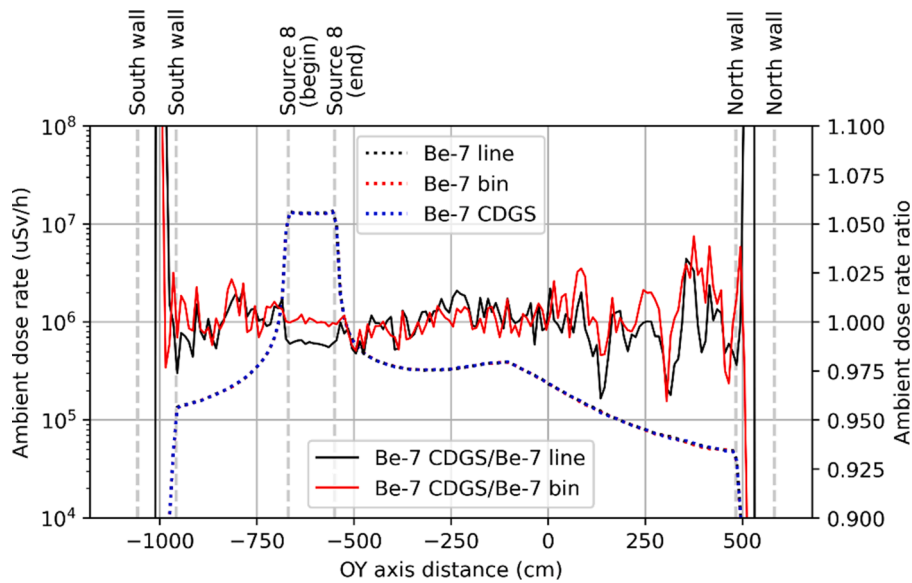
Fig. 6. Ambient dose rates and ratio of ambient dose rates in Be-7 cases.

Table 1
Simulation times of Be-7 cases.

Case	Time (minutes)	Relative difference (regarding *Be-7 line*)
Be-7 line	1644.84	0.0 %
Be-7 bin	1676.97	1.95 %
Be-7 CDGS	1714.59	4.24 %

lines it can be seen that the three cases have very similar ambient dose rates and they follow the same pattern: dose levels take the maximum values inside source 8 and doses decrease as positions are further from that source except in positions near of source 11 (around y = −100 cm) where doses increase. Also, just in both ends of source 8 doses increase slightly due to sources 7 and 9.

Ratio graphics present the small dose differences that are barely visible comparing directly the doses. In graphic *Be-7 CDGS/Be-7 line*, values inside source 8 have a mean value of 0.989 while for *Be-7 CDGS/Be-7 bin* is almost one (0.998). This difference is due to the source intensity correction when a line gamma spectrum is approximated by bin description.

For *Be-7 CDGS* (and also *Be-7 bin*) case the energy is sampled between 0.4 and 0.6 MeV (mean value is 0.5 MeV) while for *Be-7 line* case is 0.477 MeV (actual photon energy). To create the CDGS source, the mean energy per sampled photon should be maintained. Therefore, source intensity is corrected with the term 0.477 MeV/0.5 MeV = 0.954, which explains that values in this region of *Be-7 CDGS* case are smaller than ones of case *Be-7 line*. Finally, for graphics *Be-7 CDGS/Be-7 line* and *Be-7*

CDGS/Be-7 bin mean value inside LLC (excluding concrete structures) is close to one (0.998 and 1.003, respectively), with a small deviation that might come from statistical errors.

Another important aspect of these simulations is the computation time needed for MCNP6 and cR2S-MCNP6 to run. Each case is simulated up to 10^9 histories in a single PC and single core (serial run) with an Intel Xeon 8160 CPU @ 2.10 GHz. Table 1 shows these results.

Table 1 results show that the fastest case is *Be-7 line* while cases *Be-7 bin* and *Be-7 CDGS* are slightly slower. One of the reasons that makes *Be-7 line* faster is that photon energy is constant compared with the other two.

Finally, with this second validation exercise it has been obtained the same ambient dose rates for the three cases. Slightly smaller doses have been obtained in *Be-7 CDGS* case compared with *Be-7 line* case inside source 8 while very similar doses in the three cases have been obtained in rest of LLC. Also, radiation transport times have been very similar.

4. Application to IFMIF-DONES analysis: dose maps in Lithium Loop Cell

4.1. Objective

The applicability of CAD2CDGS tool is demonstrated with the safety analysis of the radiological zoning of the rooms adjacent to the LLC. IFMIF-DONES radiological zoning must be fulfilled and supported by neutronic simulations. Table 2 presents the radiation protection working areas classification under irradiation criteria and Fig. 7 presents the irradiation areas around LLC.

Table 2
Radiation protection working areas. Table taken from [16].

| Area	Colour	Total dose rate due to external exposure Effective dose rate	External exposure of hands, forearms, ankles & feet Dose equivalent rate
		Unrestricted area within the facility	
Unrestricted area	White	< 0.5 μSv/h	-
		Controlled and Supervised areas	
Supervised area	Blue	< 3 μSv/h	< 75 μSv/h
Controlled area. Free permanence	Green	< 10 μSv/h	< 250 μSv/h
Controlled area. Limited permanence	Yellow	< 1 mSv/h	< 25 mSv/h
Controlled area. Specially regulated	Orange	< 100 mSv/h	< 2500 mSv/h
Controlled area. Forbidden	Red	≥ 100 mSv/h	≥ 2500 mSv/h
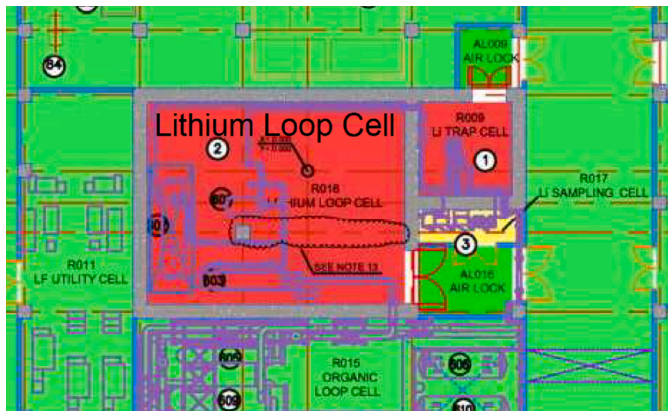
Fig. 7. Irradiation areas around LLC. Figure taken from [16].

In operation, LLC is forbidden accessing radiation-controlled area while most of the surrounding rooms are free permanence radiation-controlled areas (doses below 10 µSv/h). The objective is to evaluate if the one-meter thick concrete floor, walls and ceiling are enough to shield the Be-7 and ACP sources contained in the lithium loop.

4.2. Methodology

LLC, lithium loop, Be-7 and ACP sources are based on the available information. In the year 2022, a new design of LS was proposed and since then it has been implemented [1]. However, at the moment of writing this paper, Be-7 and ACP sources were available only for the old lithium loop design (the year 2021). For the aim of CAD2CDGS tool applicability study, these previous CAD models and sources are still valid.

LLC CAD model is created from the IFMIF-DONES Main Building simplified CAD model [17] while the lithium loop is created from the IFMIF-DONES Heat Removal System engineering CAD model [18]. In order to reduce the time to create the MCNP model, only liquid lithium inside the pipes and HX have been maintained, excluding piping and thermal insulation. This approach is conservative because these elements shield the gamma source, obtaining higher doses.

In Fig. 8 left part, it is shown the original lithium loop while in the right part it is shown the conserved and simplified CAD model. Source is only considered in the part of the lithium loop inside the LLC and therefore the rest of the lithium loop (solids in green colour) and oil pipes are ignored. In Fig. 8 right part, it is shown source 1 (Li-Oil HX),

source 2 (CL) and source 3 (HL). For source 1, lithium represents only 51.93 % of the volume while oil (hydro-terphenyl) represents 29.90 % and metallic parts (SS316L) 16.87 %. So, in the component label of source 1, a scaling coefficient is included (0.5193).

Source information was written on the component labels of the CAD model. A common CAD model was created from the simplified CAD model and then GEOUNED conversion tool [19,20] was used to obtain the MCNP model. After, the MCNP cell information file was obtained from the list of MCNP cells and volumes in the MCNP output. Finally, the lost particle check was done with no lost particle in 10^9 histories.

For source definition, Be-7 concentration ($4.6 \cdot 10^{-4}$ g) includes only dissolved form and production is considered for 345 days [21]. ACPs include only five radionuclides (Fe-55, Mn-54, Cr-51, Co-57 and Co-60) which are generated from neutron irradiation of lithium and CP in the loop. ACPs are presented in dissolved and precipitated form except for Mn-54 (only dissolved form). HL is not expected to have precipitated ACPs due to the impurity trapping in the Cold Trap [22]. Three gamma spectrum files (volumetric source type) were obtained with the help of FISPACT-II. ACP data used in the paper is preliminary and expected to be updated in the near future.

This application case shows the advantages of CAD2CDGS approach face of MCNP SDEF approach. Compared with the Be-7 cases of Section 3.2, first advantage is that updating the geometry or radionuclide concentrations is easier than with SDEF approach where a manual card update is needed. As example, for an ACP definition update, just new FISPACT-II and CAD2CDGS runs are needed. Second advantage is that the definition of the surrounding sampling space (voxels in CDGS format) is done automatically while it should be done by hand with SDEF (analysing the properties of the source cells). Indeed, for the current geometry, there are complex sources (e.g. the simplified elbows) whose surrounding sampling space is hard to determine by hand.

Third argument is that in previous cases there was a constant photon energy (*Be-7 line* case) or only one energy bin (*Be-7 bin* case). Now three different sources should be produced with different quantities of 6 radioisotopes that together sum more than 40 gamma lines. With SDEF card, the user should compute the relative intensity of each gamma line for each source while for CAD2CDGS the same task is done launching 3 times FISPACT-II. Fourth argument is that SDEF sampling frequency is limited to the analogue sampling of the source while with CDGS format additional spatial or energy sampling modes can be set. For the Be-7 and ACP case, the cR2S-MCNP6 uniform sampling was set to improve the sampling. With this option, photons are sampled all over the geometry with the same probability and the weight adjusted based on the gamma intensity.
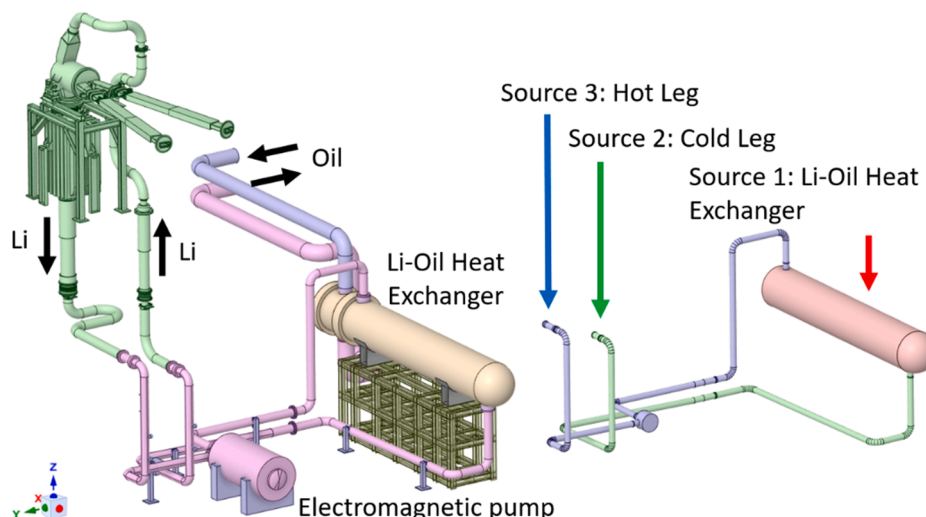

Fig. 8. Engineering CAD model of the lithium loop (left) and CAD solids representing the lithium loop source (right).
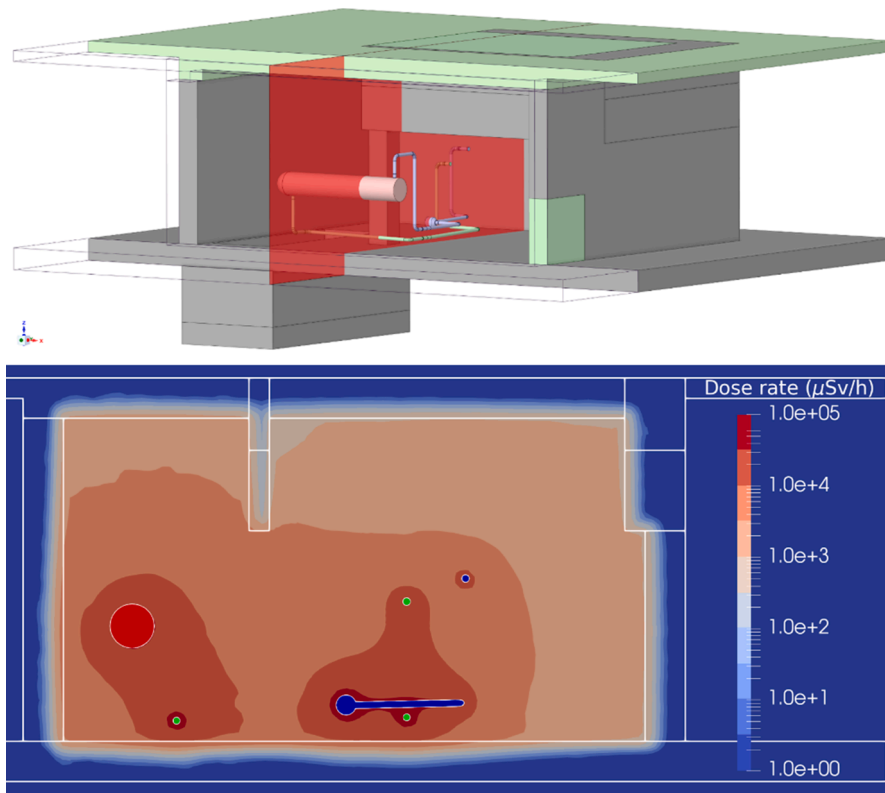
Fig. 9. Inner view of LLC CAD model (upper part) and 2D ambient dose map at plane x = −3.286 m (lower part).

Finally, the configuration file is set and CAD2CDGS tool is launched to obtain the CDGS file. That source is transported in the LLC geometry with cR2S-MCNP6 simulating a total of 10^9 histories. Ambient dose rates were tallied in mesh with a mesh cell size of $20 \times 18 \times 16$ cm3 covering the entire LLC.

4.3. Results

Fig. 9 (upper part) presents the inner view of the LLC CAD model. Part of the room is hidden (wire representation) to show the source solids and the reference plane (in red colour) of the 2D ambient dose map (lower part). This plane cuts HX, HL and CL. A logarithmic scale from 1 μSv/h up to 10^5 μSv/h is set. Higher doses are around the source solids and they decrease at further positions from them, quickly decreasing in the concrete structures. Doses around CL are higher than around HL due to the deposited ACPs in the CL. Also, the limit of 10 μSv/h is always inside the concrete LLC structure, reaching that level approximately at half of the 1-meter thick structure. Indeed, for the rest of the room, it has been checked that the 10 μSv/h limit is always in the concrete structure, again approximately within the first half meter.

Regarding the relative errors, for further LLC inner regions from the sources they are around 6 % while the relative errors quickly increase in the concrete structures, reaching values between 20 % to 50 % in the region of the 10 μSv/h limit. This study confirms that the LLC shielding is thick enough to effectively shield the Be-7 and ACP sources and also that LLC surrounding rooms are free permanence radiation-controlled area.

5. Conclusions

This article presents CAD2CDGS, a new tool to generate decay gamma sources based on CAD models. Tool methodology, inputs and workflow have been explained. Two verification tests, one for the reproduction of a CDGS source and another for a calculation of the ambient dose rates based on an IFMIF-DONES case have been carried out. Good agreement with the reference cases has been demonstrated using CAD2CDGS tool. Finally, tool applicability to IFMIF-DONES has been demonstrated by simulating a detailed Be-7 and ACP gamma source in the lithium loop, which demonstrates that doses outside the LLC are below the limit.

CRediT authorship contribution statement

Juan García: Conceptualization, Methodology, Software, Validation, Visualization, Writing – original draft. **Yuefeng Qiu:** Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Claudio Torregrosa-Martín:** Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] M. Luque, Plant Design Description (PDD) June 2023. IDM Ref. No. EFDA_D_2QW6V3 v2.0, 2023.

[2] C.J. Werner "MCNP users manual - code version 6.2″, LA-UR-17-29981, 2017.

[3] D. Leichtle, A. Turner, Recommendation on a common decay gamma source format for R2S tools. Report For TA WP13-SYS-02, EFDA_D_2JNTCS, v2.0, 2014.

[4] J. Garcia, Y. Qiu, ENS-2.2.2.6-T024-06-N1-Development of a tool for modeling the gamma source from activated Li in the lithium loop. IDM Ref. No. EFDA_D_2Q3MDZ v1.1, 2023.

[5] M. De Pietri, et al., Integral modelling of the ITER cooling water systems radiation source for applications outside of the Bio-shield, Fusion Eng. Des. 171 (2021) 112575.

[6] Python Software Foundation Webpage, https://www.python.org, 2023.

[7] FreeCAD Webpage, https://www.freecad.org, 2023.

[8] Open CASCADE Software Webpage, https://www.opencascade.com, 2023.

[9] D. Leichtle, R. Villari, T. Eade, P. Sauvan, SAE-2.25.3-T001 Deliverable Report Documentation of V&V for European SDDR Tools, IDM Ref. No. EFDA_D_2QDGAQ, v1.0, 2022.

[10] Y. Chen, U. Fischer, Rigorous MCNP based shutdown dose rate calculations: computational scheme, verification calculations and application to ITER, Fusion Eng. Des. 107 (2002) 63–64.

[11] ANSYS SpaceClaim Software Webpage, https://www.ansys.com/products/3d-design/ansys-spaceclaim, 2023.

[12] GitHub, Inc. Webpage, https://github.com/Radiation-Transport/SCtools, 2023.

[13] J.C. Sublet, J. Eastwood, J. Morgan, The FISPACT-II user manual, CCFE-R (11) 11.

[14] J. Sanz, O. Cabelllos, N. Garcia-Herranz, ACAB: Inventory code For Nuclear Applications. User's Manual 2008, 2008.

[15] T. Dezsi, Results of Be7 management parametrical studies. IDM Ref. No. EFDA_D_2N97P7 v1.0, 2020.

[16] E. Fernandez, SC11.D003 - Safety specifications for safety and radiation protection design of DONES. IDM Ref. No. EFDA_D_2PNGFV v1.0, 2022.

[17] C. Prieto, 03.02_Main_Building_CAD_Model_(3D). IDM Ref. No. EFDA_D_2NEVG2 v4.2, 2020.

[18] T. Dezsi, 05.03_Heat Removal System. IDM Ref. No. EFDA_D_2N9TRZ v3.0, 2021.

[19] J.P. Catalán, P. Sauvan, J. García, J. Alguacil, F. Ogando, J. Sanz, GEOUNED: a new conversion tool from CAD to Monte Carlo geometry, Nuclear Eng. Technol. (2024).

[20] J. García, J.P. Catalán, J. Sanz, Development of the automatic void generation module in GEOUNED conversion tool, Fusion Eng. Des. 168 (2021) 112366.

[21] A. Tidikas, ENS-2.2.2.6-T019-02 Shielding analyses supporting the Lithium system design and safety assessments. IDM Ref. No. EFDA_D_2PNU9V v1.1, 2023.

[22] G. Stankunas, et al., Shielding analyses supporting the Lithium loop design and safety assessments in IFMIF-DONES, Nuclear Eng. Technol. 55 (2023) 4.