Journal of Energy

VOLUME 72 Number 1 | 2023

journal homepage: http://journalofenergy.com/

Graphical Visualisation of the MCNP Mesh Tally File

Mario Matijević, Krešimir Trontl, Domagoj Markota

***Summary* — This paper presents an updated version of the MTV3D (Mesh Tally Visualization in 3D) program with Windows graphical user interface for visualization of the MCNP-based mesh tally files. Several improvements over the previous program version are addressing better figure export functionality (»Save as« option), switching between linear and logarithmic values on axes, dynamic figure scaling in active window, inversion of relative errors from "max" to "min" values, etc. MCNP is a well known and widely used general purpose Monte Carlo computer code for neutron, photon and electron transport simulation through arbitrary three-dimensional configurations. An important feature of the MCNP code is a graphical display of the simulation model using auxiliary program, such as X-window server, which is useful for geometry error-checking during model setup and visualisation of Monte Carlo results from a mesh tally file (i.e. meshtal file) over a structured xyz mesh. Such inspection of the model is useful for the end user, providing an insight of the Monte Carlo convergence process in a phase space and effectiveness of the selected variance reduction parameters in shielding calculations. Basic features and functionalities of the updated MTV3D program are presented on some selected hybrid-shielding problems involving ADVANTG3.0.3 and MCNP6.1.1b codes.**

***Keywords* — mesh tally, hybrid shielding, Monte Carlo, MCNP, ADVANTG**

I. Introduction

This paper presents new features and capabilities of the graphical visualization tool MTV3D [1] (Mesh Tally Visualisation in 3D) for displaying the mesh tally ASCII file of the Monte Carlo (MC) program MCNP [2]. The MTV3D was developed several years ago and this updated version contains several improvements over the original version addressing some shortcomings in practical usage. The mesh tally file of the MCNP program (meshtal file) contains user-defined superimposed structured mesh, independent from Monte Carlo problem geometry. It is developed as a special tally type, covering desired portions of user's model for capturing particle flux or any other response with relative errors. The MCNP program is distributed without a built-in tool for displaying a mesh tally, so standard approach is plotting with X server for Windows [3], such as Cygwin [4] or Xming [5] free tools. The same X server tools can be used for plotting MC model geometry and eventual weight windows (WWINP file) when variance reduction (VR) approach is needed. Using such tools for visualization of mesh-based objects is very useful for MCNP user, since they provide a useful insight in several phases of work:

1. geometry inspection during input checking;
2. weight windows quality inspection;
3. mesh tally flux convergence inspection, i.e. effectiveness of VR parameters.

The X server graphical emulators on Windows for mesh tally plotting are very useful but are essentially basic in their nature, so custom development of similar mesh-based graphical tools can be useful for practical applications. This paper presents such an effort to develop a graphical visualization tool for displaying the mesh tally file of MCNP program. Several improvements over the previous program version are addressing better figure export functionality (»Save as« option), switching between linear and logarithmic values on axes, dynamic figure scaling in active window, inversion of relative errors from "max" to "min" values, etc. Hopefully, this graphical tool will find its place in a daily work with MCNP at the Faculty of Electrical Engineering and Computing.

The rest of the paper is organized as follows. Chapter 2 gives a short description of a well known Los Alamos National Laboratory (LANL) MCNP code. Chapter 3 gives a short overview of the mesh tally file which can be generated using the FMESH card of MCNP code. Chapter 4 gives an overview of the program tools (modules) used for the MTV3D application development: MS Windows SDK (WinAPI, DirectX, GDI+), C++, and Microsoft Visual Studio. The MTV3D structure in C++ language for native Windows platform is presented in Chapter 5. Basic features and functionality of MTV3D are presented in Chapter 6 for real-life shielding problems, such as stationary cask for PWR spent fuel assemblies and spent fuel dry storage building dose distributions. Conclusions and referenced literature are given at the end of the paper.

II. MCNP Code of the LANL

The MCNP [2] is a general-purpose Monte Carlo N-Particle radiation transport code that simulates neutrons from 0-20 MeV, photons and electrons from 1 keV to 100 GeV. Several nuclear engineering applications of MCNP are nuclear criticality safety, oil-well logging, radiation shielding, medical radiation modelling, aerospace, etc. MCNP features detailed continuous-energy physics to provide a near-predictive model of how radiation interacts with matter. It has been continuously developed for over 60 years and has been widely used internationally for over 40 years. Regardless of the problem nature, many statistical trials or particle histories are required for MC simulation to converge to an acceptable solution. For that purpose, the variance reduction techniques (VR)

(Corresponding author: Mario Matijević)

Mario Matijević, Krešimir Trontl and Domagoj Markota are with the University of Zagreb Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia (e-mails: mario.matijevic@fer.hr, kresimir.trontl@fer.hr, domagoj.markota@gmail.com).

https://doi.org/10.37798/2023721468

are standard tools for biasing a normal random walk of simulation particles, so important parts of the phase space are sampled more often at the expense of the less important ones. In particular, a well-known VR technique weight windows (WW) controls the particle population in space, time and energy by splitting particles into many low-weighted samples and, at the same time, rouletting unimportant particles into few high-weighted samples. MCNP code has a stochastic WW generator (WWG card) for generating WW over a user-defined superimposed structured mesh. This generates an auxiliary WWINP file, containing WW space-energy data, used to accelerate the final MCNP run. Alternatively, the user can construct deterministic WW using ADVANTG [6] code, based on the method of discrete ordinates (so called SN method) [7][8]. The ADVANTG has been successfully applied to neutron, photon, and coupled neutron-photon simulations of real-world radiation detection and shielding scenarios [9].

III. Mesh Tally Data Structure

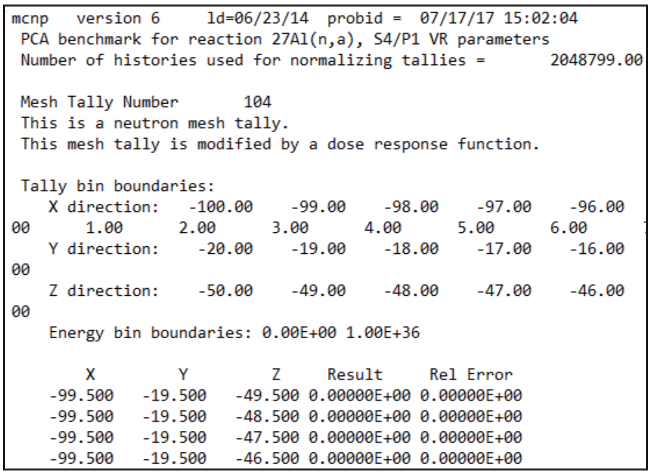
The mesh tally file was initially introduced in MCNP5v1.6 and is created with the FMESH card containing description of a superimposed structured mesh covering the problem geometry while the results are written to a separate ASCII file with the default name »meshtal« [2]. The track length estimate of the particle flux averaged over a mesh cell is the default MC estimator, but user can change this flux solution to any desired response, such as dose rates or reaction rates, typically by using an energy-dependent response function (DE+ DF cards) or with tally multiplier (FM card). The MCNP results are always normalized to unit source intensity, corresponding to a source which emits one particle per second. This can be properly scaled with an optional keyword »factor« in the FMESH card. A simple definition of the neutron mesh tally, with 100 cells (or bins) per x, y and z axis would look like the following:

```
c simple FMESH tally example in MCNP input
fmesh04:n     geom=xyz  origin=xmin ymin zmin  factor=1.0
              imesh=xmax  iints=100 $ number of x bins
              jmesh=ymax  jints=100 $ number of y bins
              kmesh=zmax  kints=100 $ number of z bins
```

When projecting mesh tally results over the MCNP model geometry, the particle tracking routines are used to march through the model geometry in the plane of the plot frame, while the plotting algorithm reads and puts cell-based flux value. The ASCII meshtal file contains the following information:

- MCNP version number,
- title of the simulation problem from the MCNP input,
- number of histories simulated (for normalizing tallies),
- mesh tally ID number,
- particle type for tracking with mesh tally,
- information about optional response function to modify tally results,
- structured mesh dimensions (tally bin boundaries in x, y, z),
- cell-wise results as MC average with relative error.

A mesh tally file sample from the PCA benchmark [10][11] is depicted in Figure 1, where one can notice aforementioned information about the LWR simulation model.



```
mcnp   version 6     ld=06/23/14  probid =  07/17/17 15:02:04
 PCA benchmark for reaction 27Al(n,a), S4/P1 VR parameters
 Number of histories used for normalizing tallies =      2048799.00

 Mesh Tally Number       104
 This is a neutron mesh tally.
 This mesh tally is modified by a dose response function.

 Tally bin boundaries:
    X direction:   -100.00     -99.00     -98.00     -97.00     -96.00
00      1.00      2.00      3.00      4.00      5.00      6.00
    Y direction:    -20.00     -19.00     -18.00     -17.00     -16.00
00
    Z direction:    -50.00     -49.00     -48.00     -47.00     -46.00
00
    Energy bin boundaries: 0.00E+00 1.00E+36

        X          Y          Z      Result     Rel Error
    -99.500   -19.500   -49.500 0.00000E+00 0.00000E+00
    -99.500   -19.500   -48.500 0.00000E+00 0.00000E+00
    -99.500   -19.500   -47.500 0.00000E+00 0.00000E+00
    -99.500   -19.500   -46.500 0.00000E+00 0.00000E+00
```

Fig.1. Mesh tally file structure

IV. Modular Structure of MTV3D Program

Interactive 3D graphics (zoom, rotation, cut plane, elevation, etc.) of MTV3D program were developed for MS Windows operating system. An overview of the program tools used for MTV3D development is presented next, including MS Windows SDK (WinAPI, DirectX, GDI+), C++, and Microsoft Visual Studio.

A. Microsoft Windows SDL Module

The MS Windows SDK (Software Development Kit) is a set of Operating System (OS) native tools for software development, while variety of APIs (Application Programming Interface) allows complete supervision of all resources, including CPU, Graphical Processing Unit (GPU) and RAM. The WinAPI is a primary tool for GUI (Graphical User Interface) development and has many visual elements, such as buttons (radio/check/click), textbox, select box, etc. Drawing of basic shapes is provided with GDI+ while more demanding graphical rendering is based on specialized DirectX libraries, i.e. Direct3D performs 3D graphics rendering, while Direct2D takes care of 2D graphics. DirectWrite is quite helpful for text incorporating into D3D/D2D frames, as there is no exact tool to perform such operation in DirectX11. DirectXMath library's methods simplify work of mathematical operations with vectors and matrices.

B. The C++ programming language

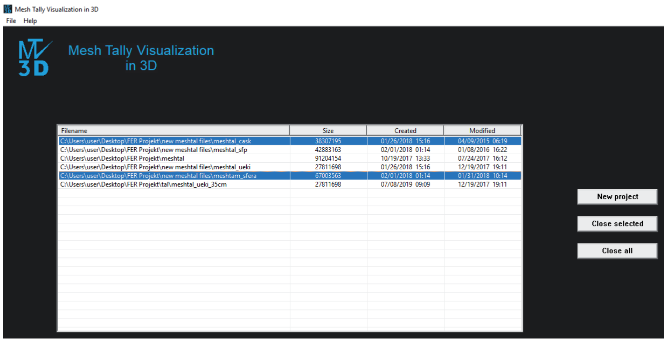
The C++ is an object-oriented programming language of third generation [12] created by Bjarne Stroustrup in the early 1980s as an extension of C language, the so called »C with classes«. The language has gone through process of standardization and became the most important programming language in the whole computer industry. The C++ has been modernized to keep up with other similar languages and has also been enriched with elements of functional programming paradigm. For that reason, the standard C++ v.17 has smart pointers, lambda expression, data type deduction, etc. It also has Standard Template Library (STL) which makes easier to manipulate data.

C. The Microsoft Visual Studio Environment

The MS Visual Studio is an IDE (Integrated Development Environment) for MS Windows OS. Within the IDE it is possible to develop applications for Windows OS, Xbox, Linux distributions, Android OS and to integrate various technologies, of which C# with .NET and C++ are the most significant ones. The MS Visual Studio possesses its own compiler Visual C++. Web development is also part of offered possibilities. This IDE contains extremely useful debugger, code autocompletion, language syntax checker, insight into executable assembly code, etc. Important part of IDE is Remote Debugger with ability to build the software on one machine and to deploy and debug on another, even with different versions of OS.

V. MTV3D Program Improvements

The graphical visualization software is created under the acronym MTV3D (Mesh Tally Visualization in 3D) with a targeted platform of MS Windows 7. Accordingly, MS Windows SDK 8.1 is used to cover Windows versions 7, 8, 8.1 and 10. Native MS Windows SDK tools requiring C++ language are preferred to achieve all intended features without any unwanted limitations, which would very likely to happen if a third party SDKs were used. The DirectX11 graphics APIs in this case are preferred to their counterparts like OpenGL API. Though OpenGL rendered graphics may result in a slightly better performance regarding the frame rate, the lack of platform support via Windows SDK represent an emerging issue in creation of a unique Windows cross-version (7 upwards) executable file. Starting with Windows 7, DirectX11 is contained within Windows OS. Considering that, the final executable file will not have any platform dependencies that are pre-required, such as runtime redistributables and DLLs (Dynamic Link Libraries). The MTV3D program has a user interactive GUI with the main window shown in Figure 2, offering a list of projects that are currently open by the user.


Mesh Tally Visualization in 3D
File
Help
MT 3D
Mesh Tally Visualization in 3D
New project
Close selected
Close all

Filename	Size	Created	Modified
C:\Users\user\Desktop\FER Projekt\new meshtal files\meshtal_cask	38307195	01/26/2018 15:16	04/09/2015 06:19
C:\Users\user\Desktop\FER Projekt\new meshtal files\meshtal_sfp	42883163	02/01/2018 01:14	01/08/2016 16:22
C:\Users\user\Desktop\FER Projekt\meshtal	91204154	10/19/2017 13:33	07/24/2017 16:12
C:\Users\user\Desktop\FER Projekt\new meshtal files\meshtal_ueki	27811698	01/26/2018 15:16	12/19/2017 19:11
C:\Users\user\Desktop\FER Projekt\new meshtal files\meshtam_sfera	67003563	02/01/2018 01:14	01/31/2018 10:14
C:\Users\user\Desktop\FER Projekt\tal\meshtal_ueki_35cm	27811698	07/08/2019 09:09	12/19/2017 19:11

Fig. 2. Selection of a project inside the Main Window

The list shows filenames, size of files, creation date and last modification time of projects. The user can load a new project or close any of already opened. When loading a "meshtal" file, it is assumed by default that the file is UTF-8 encoded. Each loaded project has its own execution thread and main window consisting of MCNP data: MC average values (left window) and associated relative errors (right window). This is shown in Figure 3 for a point gamma source ($1.85 \cdot 10^7$ phot/s with 1 MeV) located inside a 4 cm thick spherical iron shield, with mesh tally consisting $0.5 \cdot 10^6$ cells (cut plane z=0 cm). The default plot is with linear scale and zero-valued cells are depicted in white (label "irrelevant"). The logarithmic scale is depicted in Figure 4, giving a more inuitive flux distribution over the same cut plane.

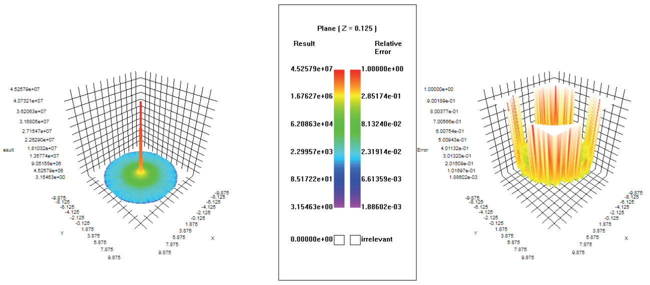


Fig. 3. Mesh tally gamma flux (phot/cm2/s) from point source inside an iron shield (lin scale)

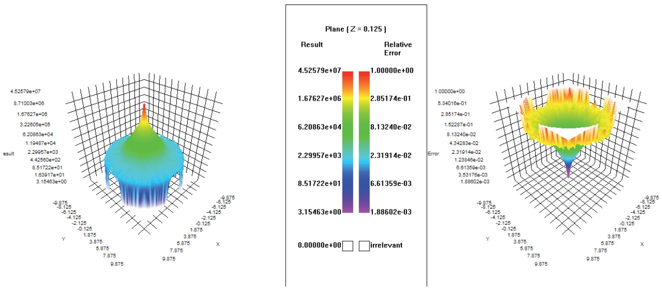


Fig. 4. Mesh tally gamma flux (phot/cm2/s) from point source inside an iron shield (log scale)

The selection of a cut-plane is done within the active window by selecting orthogonal plane and intersection value (x, y or z). This creates a new execution thread and a new window with MCNP results corresponding to a selected cut-plane. The plane values are then automaticaly elevated in z-axis to produce a surface plot effect in 3D. Top view of this surface plot is shown in Figure 5, giving classical 2D flux distribution in z=0 cm plane.

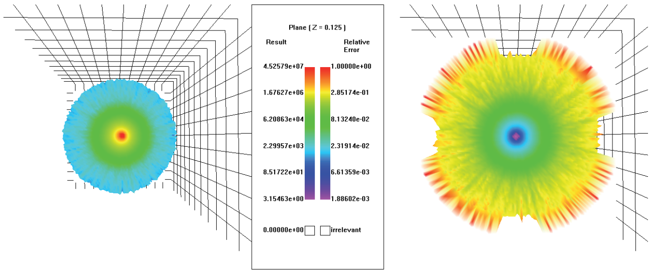


Fig. 5. Top view of the gamma flux surface plot in z=0 cm plane

Surface plot generally gives a better insight into a MC convergence process and effectiveness of the employed VR parameters. Inside this surface plot window it is further possible to select an independent axis, after which a new window is created showing the curve plot of MC results as a function of selected axis. This option is shown in Figure 6 for an independent x-axis, where one can notice gamma flux in yellow and relative errors in pink.

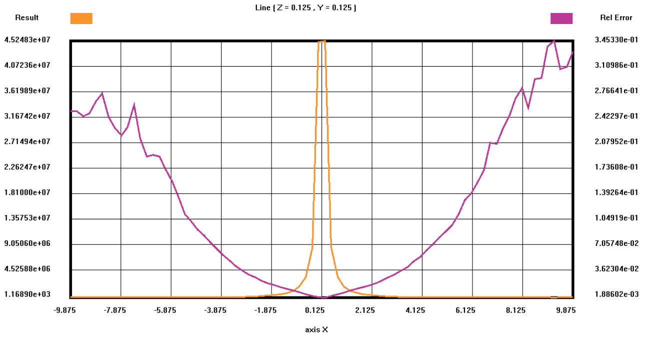


Fig. 6. Curve plot of gamma flux (phot/cm2/s) with relative errors in x-axis (cm)

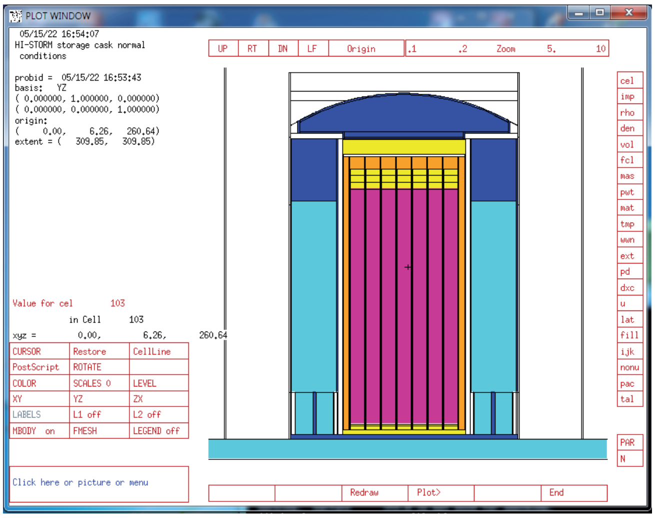
It is possible to dynamically interact with a model by means of rotation and zooming. The rotation is a two-step process: the first step is around the vector from the centre of the viewport and the second step is around the vector orthogonal to the mouse pointer vector, observed from the centre of the viewport. The rotation steps are then combined to form a final rotation. The zooming is performed with a mouse scrolling option. Another useful feature is a visibility of grid lines and axes values, which can be turned on/off by selecting the appropriate checkboxes.

VI. Selected MTV3D Applications

Basic features and functionality of MTV3D program for visualization of MCNP mesh tally are presented next for some selected shielding results of the Spent Fuel Dry Storage Project of the NPP Krško [13]. The presented intermediate results are taken from an early stage of the project and are not reflecting the final updated design of spent fuel casks nor a dry storage building. The intention is only to demonstrate capabilities of MTV3D program in visualization of MC neutron flux distributions and assocciated errors. The final Independent expert Evaluation Report (IER) providing all model details and MC results of the transport cask (HI-TRAC) [14], storage cask (HI-STORM) [15] and dry storage building (DSB) can be found in report [13].

A. HI-STORM Storage Cask

The MCNP model of the HI-STORM storage cask is depicted in Figure 7 [15]. The multipurpose canister (MPC), housing 37 spent fuel assemblies from NPP Krško, is inserted in a thick concrete structure with upper and lower ventilation openings. The point detectors at cask surface are placed at inlet vents, cask midplane, outlet vents, and top lid (centre, annulus, edge). The hybrid shielding methodology of ADVANTG code was used for variance reduction (VR) preparation which optimized MCNP neutron dose rates (in rem/hr) at detector locations. The mesh tally had 1.2 million cells covering cask with surrounding air. The point detector neutron dose rates in cask midplane are shown using MTV3D in Figure 8 (surface plot), while 2D distribution (top view) is depicted in Figure 9.



```
 05/15/22 16:54:07
HI-STORM storage cask normal
 conditions

probid =  05/15/22 16:53:43
basis:   YZ
( 0.000000, 1.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
(     0.00,     6.26,   260.64)
extent = (   309.85,   309.85)

Value for cel        103
            in Cell      103
xyz =        0.00,         6.26,       260.64
```

Fig. 7. MCNP model of the HI-STORM cask

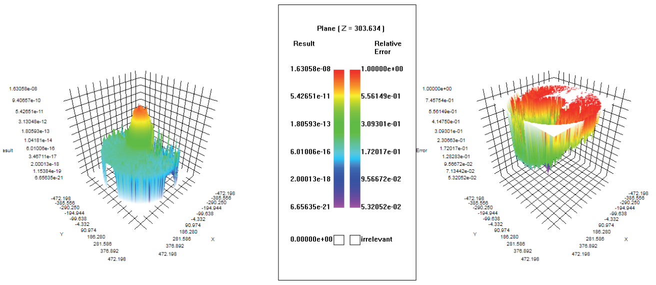


Fig. 8. Neutron dose rates (rem/hr) in cask midplane

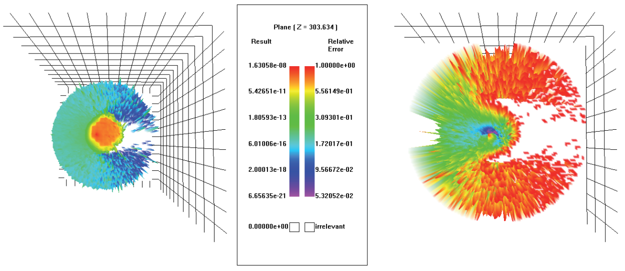


Fig. 9. Top view of neutron dose rates (rem/hr) in cask midplane

One can notice location of small relative errors corresponding to a point detector on the left side of the cask while unimportant regions have high errors (in red) or don't have any results at all (in white). Additional rotation of surface plots in different cut-plane can assist user in VR effectiveness inspection. The curve plot of neutron dose rates in x-axis is shown in Figure 10 using MTV3D, where cells with small MC error correspond to point detector surroundings.

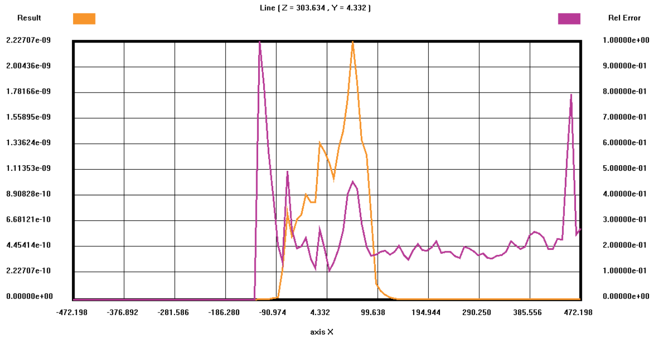
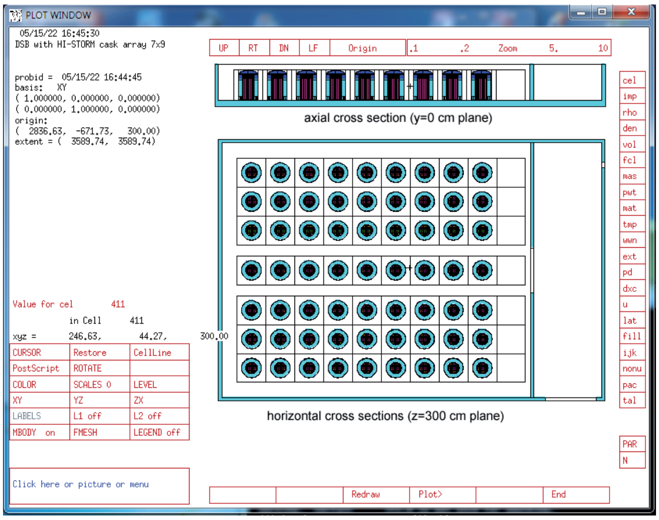


Fig. 10. Curve plot of neutron dose rates (rem/hr) with relative errors in x-axis (cm)

B. Dry storage building for HI-STORM casks

The MCNP model of the DSB (Figure 11) contains a HI-STORM cask array 7x9 located in a concrete building with thick foundations. This tentative model had 63 casks filled with the same averaged neutron-gamma source, corresponding to a spent fuel cooling period of 59 years. The steel roof for gamma skyshine was introduced in the later phase of the model together with a detailed source of the individual cask depending on real simulated Campaign. The hybrid shielding methodology was used to optimize neutron dose rates (in rem/hr) inside and outside the DSB. The location and dimensions of the cask transfer doors proved to be an important path for particle streaming inside the building. The mesh tally showing global neutron dose rates over DSB is shown in Figure 12 (values omitted), while neutron dose rates in cask midplane are shown in Figure 13 and Figure 14 (top view). These initial solutions demonstrated a need for VR refinement and insufficient MC histories over 1.1 million cells since statistical noise proved to be quite high in the desired regions. This notorious slow convergence of the neutron-gamma dose rates at distant regions, well below background radiation level, was thoroughly investigated in [13][14][15] with different tally objects, until satisfactory MC errors were achieved.



```
 05/15/22 16:45:30
DSB with HI-STORM cask array 7x9

probid =  05/15/22 16:44:45
basis:   XY
( 1.000000, 0.000000, 0.000000)
( 0.000000, 1.000000, 0.000000)
origin:
(  2836.63,  -671.73,    300.00)
extent = (  3589.74,  3589.74)

Value for cel        411
          in Cell      411
xyz =        246.63,        44.27,
```

Fig. 11. MCNP model of the DSB

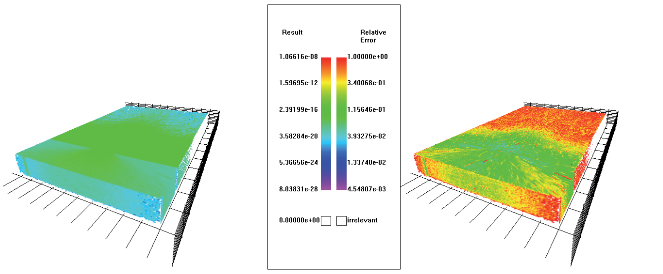


Fig. 12. DSB neutron dose rates (rem/hr) with relative errors (global)

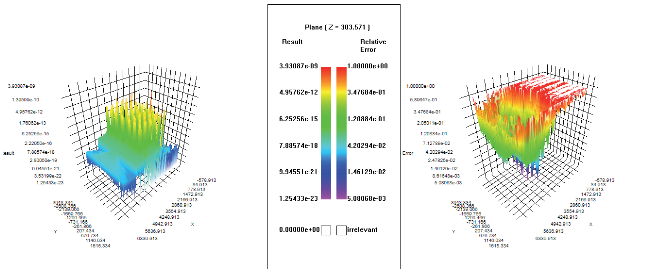


Fig. 13. DSB neutron dose rates (rem/hr) with relative errors (cask midplane)

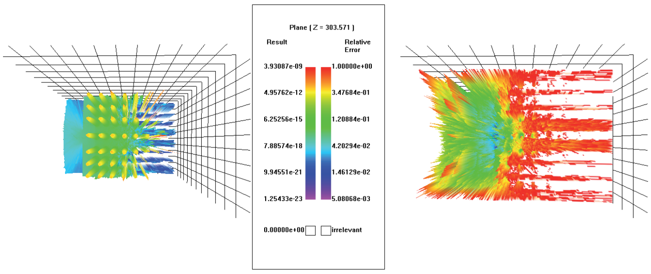


Fig. 14. DSB neutron dose rates (rem/hr) with relative errors (top view)

Results of neutron dose rates (in rem/hr) outside of DSB are shown in Figure 15 and Figure 16 (top view), showing the necessity for improved VR parameters and more CPU time for increased number of MC histories.

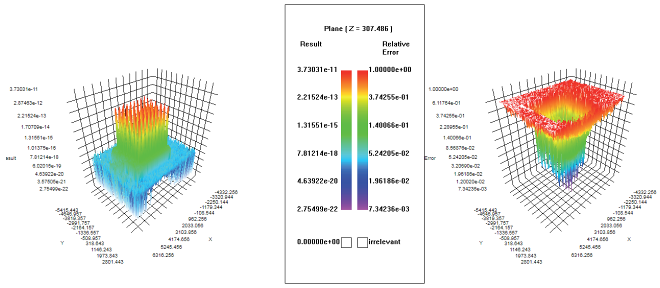


Fig. 15. DSB external neutron dose rates (rem/hr) with relative errors (cask midplane)

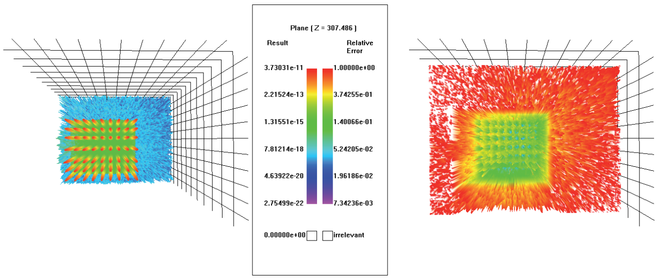


Fig. 16. DSB external neutron dose rates (rem/hr) with relative errors (top view)

VII. Conclusions

This paper presents an updated version of MTV3D program for visualization of the MCNP mesh tally file. The main features of the MTV3D program are 3D visualization of mesh-based results (MC mean values and relative errors), cut-plane results with elevate transformation producing surface plots, and curve plots for selected independent axes. The choice of program modules used for MTV3D development was determined by Windows operating system. The MS Windows SDK 8.1 was used which supports Windows versions from 7 to 10. Application controls are implemented using procedures from Win32 interface and Windows Controls library. Graphical unification of points was done via DirectX11 API collection, including DirectWrite on text rendering. Transformations over matrices and vectors were done using DirectXMath library, while 2D rendering is based on GDI+ class-based API. The MTV3D supports multicore CPU architecture, multithreaded environment processing, and simultaneous work with several open projects. The capabilities of MTV3D were demonstrated for several real-life shielding problems, namely spent fuel dry storage building of NPP Krško. Future work on MTV3D will introduce additional options for mesh tally plotting and possibility to read external WWINP file of MCNP.

References

[1] M. Matijević, D. Markota, D. Grgić, »Software Development for Visualization of Monte Carlo Results Based on the MCNP Program«, Proceedings of the International Conference Nuclear Energy for New Europe, Portorož, Slovenia, September 9-12, 2019.

[2] T. Goorley, »MCNP6.1.1-Beta Release Notes«, LA-UR-14-24680, 2014.

[3] X.Org Foundation website: https://www.x.org/wiki/

[4] Cygwin website: https://www.cygwin.com/

[5] Xming website: http://www.straightrunning.com/XmingNotes/

[6] S. W. Mosher, S. R. Johnson, A. M. Bevil, et al, »ADVANTG – An Automated Variance Reduction Parameter Generator«, ORNL/TM-2013/416, Rev. 1, August 2015.

[7] G. I. Bell, S. Glasstone, Nuclear Reactor Theory, Van Nostrand Reinhold Company, Litton Educational Publishing, 1970, pp. 252-273.

[8] J. C. Wagner, A. Haghighat, »Automated variance reduction of Monte Carlo shielding calculations using the discrete ordinates adjoint function«, Nucl. Sci. and Eng., 128(2), 1998, pp. 186-208.

[9] M. Matijević, R. Ječmenica, D. Grgić, »Spent Fuel Pool Dose Rate Calculations Using Point Kernel and Hybrid Deterministic-Stochastic Shielding Methods«, Journal of Energy: Energija, Vol. 65, No. 1, 2016, pp. 151-161.

[10] J.A. Kulesza and R.L. Martz, »Evaluation of the Pool Critical Assembly Benchmark with Explicitly Modeled Geometry Using MCNP6«, Nuclear Technology 197(3), 2017, pp. 284-295.

[11] M. Matijević, D. Pevec, K. Trontl, B. Petrović, »PCA Benchmark Analysis with ADVANTG3.0.1. and MCNP6.1.1b Codes«, Journal of Energy: Energija, Vol. 68, No. 2-3, 2019, pp. 171-183.

[12] B. Stroustrup, The C++ Programming Language, 4th Edition, Addison-Wesley, 2013.

[13] »Independent Expert Evaluation Report of Spent Fuel Dry Storage Modification Documentation for Spent Fuel Cask Criticality and Dose Assessment«, Report number: FER-ZVNE/SA/SO-FR01/19-3, commissioned by: Nuclear Power Plant Krško, executed by: University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Energy and Power Systems and Department of Applied Physics, 2019.

[14] D. Grgić, M. Matijević, P. Dučkić, R. Ječmenica, »Analysis of the HI-TRAC VW Transfer Cask Dose Rates During Nuclear Power Plant Krsko Spent Fuel Dry Storage Campaign One«, Journal of Nuclear Engineering and Radiation Science (2021) doi:10.1115/1.4051447.

[15] D. Grgić, M. Matijević, P. Dučkić, R. Ječmenica, »Radiation shielding analysis of the HI-STORM FW storage cask«, Nuclear Engineering and Design, 396 (2022) 111878, pp. 1-13, doi: 10.1016/j.nucengdes.2022.111878.