Calculating Residual Dose in Mu2e DS Hall

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Abstract

When physics experiments include particle beams accelerated to relativistic energies impinging upon targets, fluxes of secondary particles are often produced and come into contact with their surroundings. As a result of neutron activation of the walls and other materials, structures will become radioactive even after beams have been turned off. This paper reviews the project of analyzing the downstream hall of the Mu2e experiment at Fermilab. Said analysis was the calculation of radiation residuals in the facility using FermiCORD, a recently developed coding package. The paper will go into detail about the background information, project objectives, stages of the analysis, results, and user feedback.

1. Introduction

1.1 Mu2e

The Mu2e experiment at Fermilab is a project designed to measure the neutrino-less conversion of muons into electrons [1]. Should the experiment find evidence of such a conversion, it would strongly suggest that there are undiscovered particles or forces in our world. Should it result that no instances of a muon to electron were found, the validity of several theory models could be in jeopardy. This would require a serious restructuring in some of our understanding of how the world works.

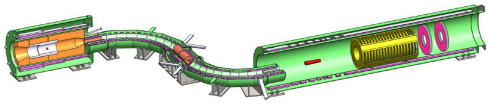


Figure 1: Main apparatus of the Mu2e experiment. On the top left is the production solenoid, middle is the transport solenoid, and the bottom right is the detector.

For the scope of this project, the most important aspect of Mu2e is that to produce the muon sources necessary for the experiment, relativistic proton beams will impinge on a target, producing pions that will decay into muons. Due to this there will be substantial fractions of high-energy stable particles arising in spallation and fragmentation reactions. This results to nuclear transmutations in the structural materials surrounding the target [2].

1.2 MARS15

MARS15 is a Monte Carlo code that allows for inclusive and exclusive simulations of three-dimensional hadronic and electromagnetic cascades and modeling of heavy ion, muon and low energy neutron-photon transport in accelerator, detector, spacecraft and shielding components [3]. Additionally particles can be modeled to have energies from a fraction of an electronvolt up to about 100 TeV.

Nikolai V. Mokhov and colleagues at Fermilab developed this code over the course of several years. It severs as the basis for the coding package that will be used to calculate radiation residuals.

1.3 FermiCORD

FermiCORD is a set of codes based on MARS15 that calculates the accelerator-induced residual doses at experimental facilities of arbitrary configurations. It was largely developed by Vitaly Pronskikh, Anthony Grebe, and Tianyuan Lu.

The package itself can be divided into two stages that will be discussed in more detail later in the paper when the analysis' procedure is explained.

2. Project Objectives

2.1 Residual Dose Calculation

The first project objective is to use the recently developed code package, FermiCORD, to calculate the residual dose in the Mu2e downstream hall. There are several motivators for this objective.

Firstly, the upper stream hall of the Mu2e has already been analyzed meaning that there is no information on the dosage in the other half of the facility – the downstream hall. In order to have a more complete picture of the doses in the facility it is necessary to also analyze the rest of the hall.

Secondly, there is also the desire of quantifying the severity of this radiation hazard in order to comply with Fermilab radiological standards [4]. Since maintenance will eventually need to be done in that area of the building it is important that we can determine how long personnel can work for without needlessly having to be exposed to more radiation than necessary.

2.2 Optimization

The second project objective is to provide feedback intended for new users after having performed an analysis without previous knowledge of the code package. Despite the useful tools FermiCORD has for its users, due to the complicated coding process and limited resources for new users there have not been many users of the package outside of the initial developers and close colleagues.

Therefore, one of the project's goals is to have a new user to the program learn the steps necessary to become proficient in it and then proceed to supply ideas on how to make the package more user-friendly. Additionally, should they think of suggestions to further optimize algorithms in the code itself, recommendations may be made too.

3. Methodology – Stage One

At the very start of the FermiCORD process the user is already supplied with the majority of the executables ready for use. However in order of the algorithm to function properly, the user must first prepare the necessary input files in the correct format. The main processes of stage one will be discussed in depth in the following section.

3.1 Geometry Files

3.1.1 GDML Splitting

To begin, the user must make or obtain GDML files describing the geometry of the space where residual doses are going to be calculated. GDML is a geometry description format that is commonly used to describe geometries between various programs and applications.

Once the user has the desired GDML file, they will need to take into account the sizes of the objects that will be analyzed. In other words, if for example one of the objects in the scenario is a wall then it will likely have to be subdivided into smaller pieces. This division, or splitting, is necessary in order to gather accurate statistics from the program. If there exists a large surface where only a small portion is actually receiving a significant dosage, when averaging out values it would appear that the entire surface is emitting dosage. This kind of situation is undesirable.

The method by which the code splits geometries in the file is through what is known as Delaunay triangulation. These kind of triangles share the properties of the circumcircle of any three points not enclosing any additional points and the smallest angle in the triangulation being as large as possible. This kind of triangulation ensures that the resulting split surfaces aren't so thin that they are unusable. Furthermore, the reasoning for using triangles instead of other shapes like rectangles is because they are able to describe more complex and irregular shapes.

For this analysis, the floors and ceilings where triangulated accordingly but walls were split via rectangular prisms due to imitations in the code. If triangulation of the

walls were desired, it would have required a rewriting of the GDML file or complex method of rearranging extrusions due to the fact that wall triangulation would've needed extrusion to occur in a different axis than everywhere else in the GDML file. See appendix A for figures showing the resulting splitting of the walls, floor, and ceiling.

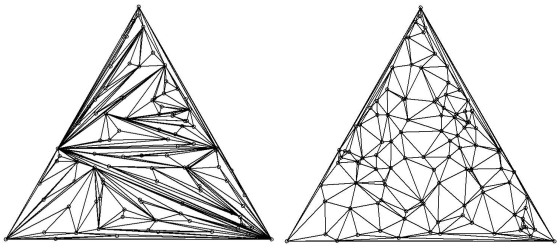


Figure 2: Shows the difference between not using Delaunay triangulation (left) and implementing Delaunay triangulation.

3.1.2 Coordinate Conversion

One of the biggest obstacles when working with the geometry files is that when regarding coordinates (X,Y,Z) the formats between the GDML file (GEANT4) and MARS15 aren't the same. This issue leads to the user having to figure out a method of properly converting between coordinate systems.

After some work, it was noted that the x-axis in G4 is equivalent to the z-axis in MARS15. Similarly the G4 y-axis is the MARS15 negative y-axis. Although there is a z-axis in the GDML file, it's used for extrusions so is not present when defining the bases of objects due to being on an x-y plane.

There is also a main reference object in the GDML file that has to be accounted for. It serves as a sort of origin for the coordinate system in G4 and its coordinate values have to be added during conversion.

Here is an example of how one may go about converting between coordinates:

Reference object coordinates:
$(X_{ref}, Y_{ref}, Z_{ref})$

$Z_{MARS15} = (X_{G4} + Zr_{ef})/10$
$Y_{MARS15} = -[(Y_{G4} + X_{ref})/10]$

**Note: Coordinates are in cm in MARS15 but mm in GDML file, which is why we divide by 10.*

3.2 Contact Dose Histograms

After having completed the geometry splitting, all that was left to do before running stage one is to create histograms. These histograms are required for determining the distribution of nuclide production within the numerous split regions. The main idea of important regarding the histograms is that they are defined by providing X, Y, and Z ranges. Furthermore their placement should be considered too.

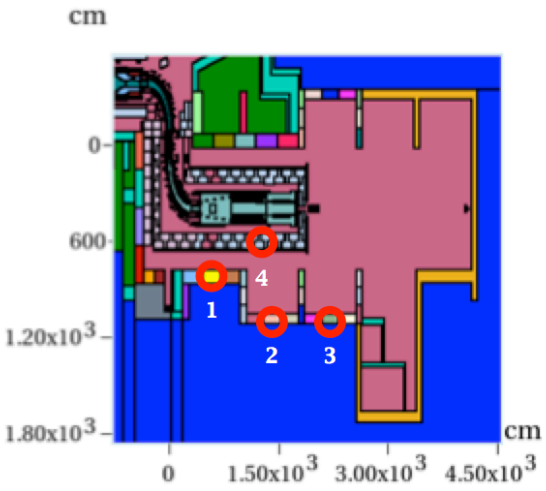


Figure 3: Shows the arrangement of the four histograms used in the analysis. Placement is such that key areas of interest are included.

4. Methodology – Stage Two

Following the completion of the histograms, MARS15 may be run for the first time thus ending stage one. Upon its completion one is left with several files that include the nuclide inventories of each region and other files that fill out the histograms.

4.1 Histogram Check

Before moving one to stage two, it is recommended to check the results of the histograms to ensure that there were no abnormalities that occurred during data production. To do this, we sampled points in the histogram of increasing depth and recorded the dosage at that point. See appendix B for the resulting graphs from this analysis.

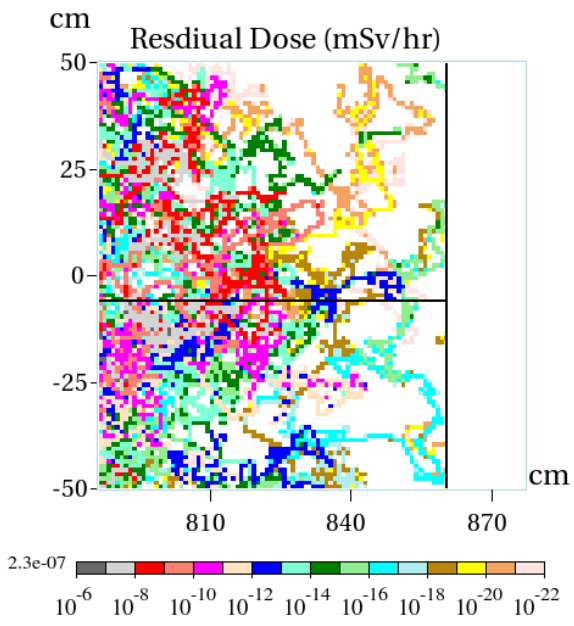


Figure 4: This is the histogram from location #1. Note the tendency for the dosage to degrease as depth increases.

4.2 Running DeTra

In preparation for starting stage two, all the nuclide inventory files made from the previous stage are accumulated and make into a single file that will be read in by DeTra. Furthermore, MARS15 has to be given specific instructions to be run in DeTra mode though the user must simply run some executables to achieve this. In short what DeTra is doing is obtaining the concentration and activities of various isotopes given the specified irradiation and cooling times.

4.3 Gamma Ray Sampling

Once DeTra's output has been processed the last step of the analysis is to run MARS15 for the last time in gamma ray sampling mode. The user must choose appropriate sampling methods depending on the situation and materials. This involves manually making changes to some of the subroutine files in the code.

Unfortunately, for this analysis one of the subroutines in the algorithm was not described in sufficient detail leading to the final step in stage 2 to not be completed. In order to remedy the problem, one will likely need the expertise of the developers of the FermiCORD package itself, which is out of the scope of a new user.

However, in order to get an estimate of the residual dose that would be present in the detector solenoid part of the facility, a small manual sampling was done as a proof of concept.

5. Residual Dosage

To start the manual sampling process, we first looked at the DeTra output file from the beginning of stage 2. In it, one can find

sections divided up into region sections. These sections represent all the geometries that had a nuclide inventory. Within each section is the region number, total activity in the region (given in becquerels, Bq), and a list of the isotopes responsible for the radiation.

We chose to sample region #50, see figure below, which was reported to have a very low activity of 25.067 Bq. A source of Na-24 was placed about 30 cm inside the wall and an area of 3 by 3 meters one meter above the floor was the area the dosage was calculated.

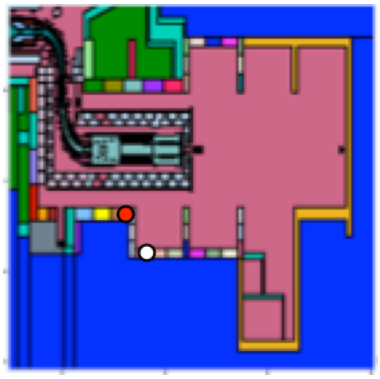


Figure 5: Region #50 is shown as a white dot while the red dot represents region #35 which was reported to have significantly higher activity.

6. Conclusion

The results of the sampling procedure were that the dosage coming from the region was only in the order of $1x10^{-9}$ to $1x10^{-10}$ mSv/hr. For comparison, the average radiation worker will have a dose limit of 50 mSv per year. This corresponds to being exposed to $5.708x10^{-3}$ mSv/hr for every hour of an entire year. As one can see the dosage rate from the wall is relatively low compared to this, which leads one to believe that the residual dosage will not be very significant.

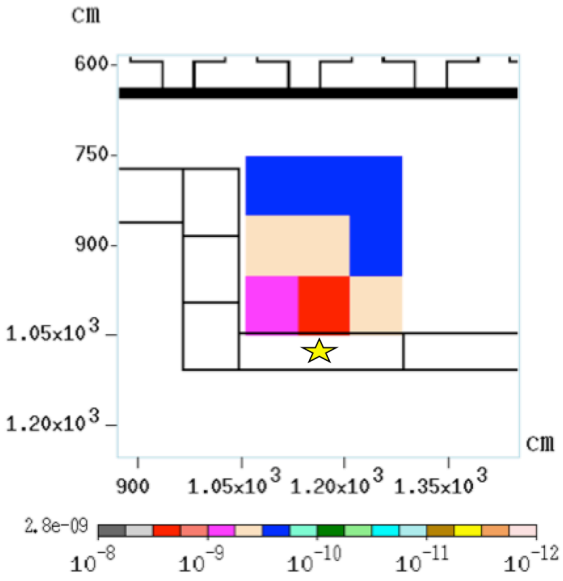


Figure 6: The resulting histogram of the dose from region #50. Note that this was a manual analysis and is not a step in the normal FermiCORD package process.

This kind of conclusion is untrustworthy though due to some factors: firstly, this was a very basic analysis from the wall due to treating the wall as a single point source and secondly the manual sampling ignored the contribution from all all other regions. This can lead to not having a clear picture of the situation due to the fact that other regions in the facility actually have around 1444 times more activity (Bq) than the region we analyzed so those areas may be subject to significant residual dose.

Had the final steps in the second stage of FermiCORD worked as intended a more complete and accurate idea of the residual dosage in the DS hall would've been gleaned. However, the crude analysis done shows that some areas may have a high enough residual dose worth noting while others locations will likely have insignificant amounts.

7. Acknowledgments

I would like to thank my mentor, Vitaly Pronskikh, for his guidance and support throughout the project. Antony Grebe for his advice and help on interpreting his code. David Brown for showing me how to work with GDML files and converting coordinates. Finally, Sandra Charles, Judy Nunez, and Elliot Mccrory for having me in SIST.

8. References

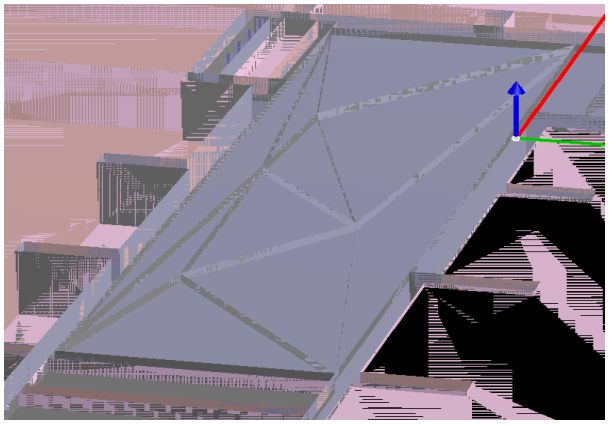
[1] Bartoszek, L., et al. “Mu2e Technical Design Report.” Fermilab-TM-2594. Oct. 2014. http://arxiv.org/pdf/1501.05241v2.

[2] A. Krasa, Spallation reaction physics, Tech. rep., NPI Rˇeˇz (2010). URL http://ojs.ujf.cas.cz/~krasa/ZNTT/ SpallationReactions-text.pdf

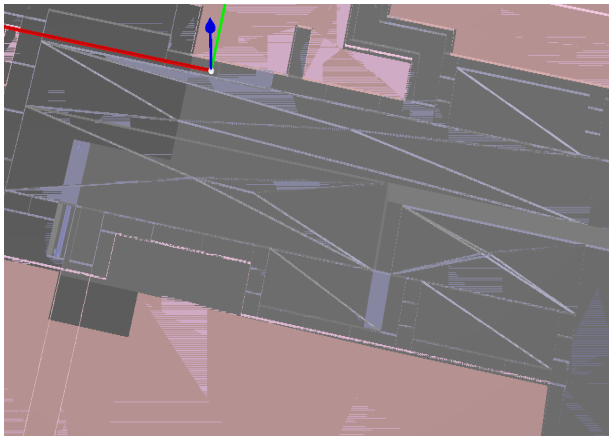
[3] Mokhov N.V., Striganov S.I. “MARS15 Overview” Presented at the Hadronic Shower Simulation Workshop, September 6-8, 2006, Fermilab.

[4] “Chapter 2: Radiological Standards.” Fermilab Radiological Control Manual. Revised December 2007. http://www-esh.fnal.gov/FRCM/ Ch02/ Ch02.pdf.

Appendix A

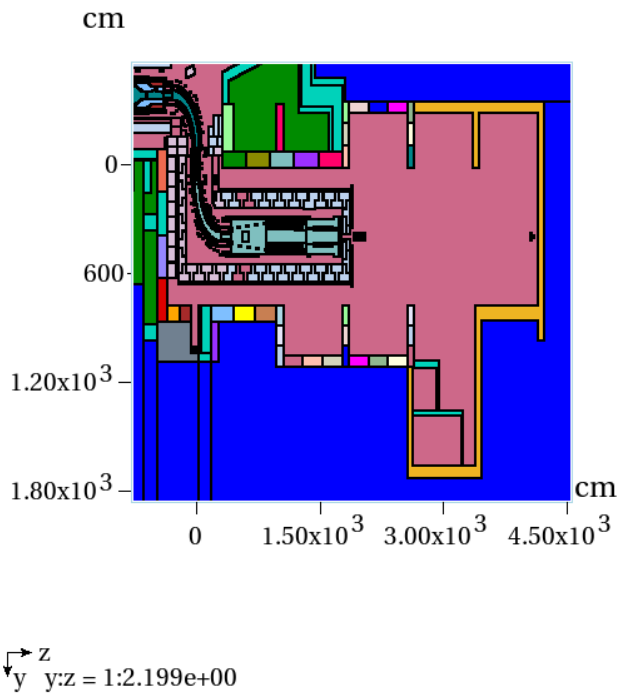


A 3-D view via ROOT of the triangulated downstream hall ceiling.



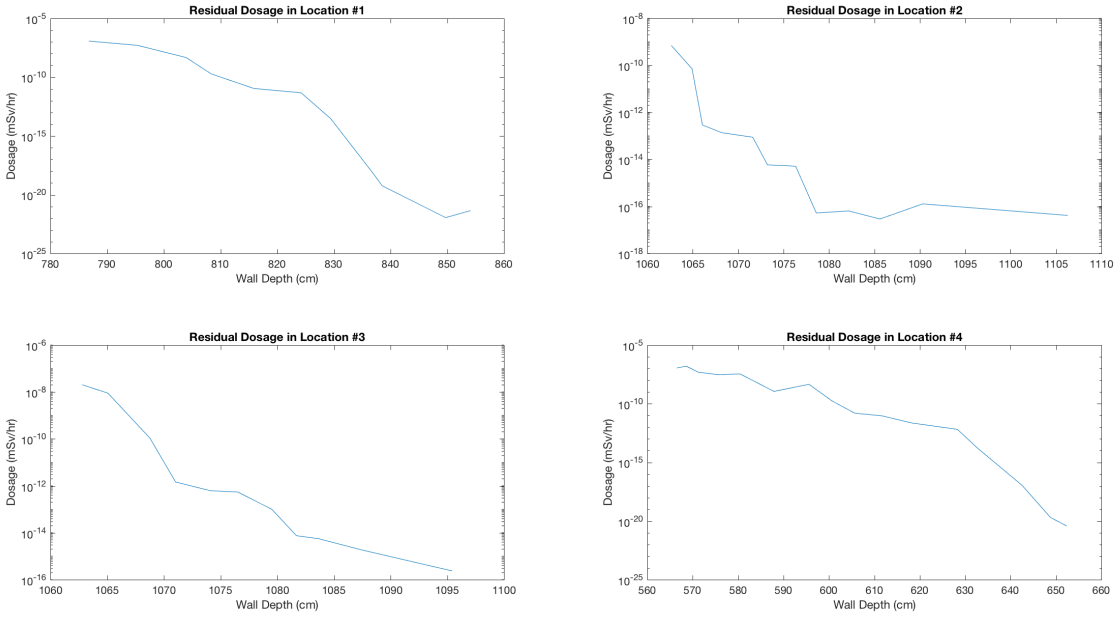
Same view as previous figure only this time showing triangulated floors.

Segmented view of the hall's walls as seen from a top down view on the MARS15 GUI. Recall that these splits are in the form of rectangles rather than triangles like the floor and ceiling.



Appendix B

Dose vs. Depth



The resulting graphs ultimately showed that no abnormalities significant enough to warrant a new data set had occurred. This is due to the fact that all four graphs agreed on the expectation that the dosage would decrease as one went deeper in a material. Clearly this is due to the greater amount of material, or shielding.