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# STUDY AND IMPLEMENTATION OF THE CADIS METHODOLOGY TO RESEARCH REACTOR SHIELDING DESIGN

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## ABSTRACT

The Consistent Adjoint Driven Importance Sampling (CADIS) is a methodology that basically uses source biasing and a mesh-based importance map. Therefore, to make the best use of an importance map, the map must be consistent with the source biasing. To achieve this consistency, a Sn calculation could be made to improve the importance map and the computational performance. The MAVRIC (Monaco with Automated Variance Reduction using Importance Calculations) code does that and this work intends to study the code options to generate the importance map. A pool type 10 MW research reactor was designed in a simple way just to study the prompt gamma rays penetration in the concrete and therefore study the CADIS methodology applied to point detectors and mesh tallies. By keeping constant the simulation time and the CPU (central processing unit) power a significant improvement was achieved in the relative errors for the point detectors and for the mesh tally.

## 1. INTRODUCTION

For deep penetrations problems where it is hard to achieve meaningful results using analog Monte Carlo simulations the CADIS methodology has been shown to be a good tool to help achieve good results in reasonable CPU time.

The SCALE 6[1] package is a set of codes to perform nuclear systems modeling and simulations, and as a part of this package there is a recent sequence added to the MONACO radiation shielding code. The MAVRIC sequence uses the CADIS methodology to generate an automated importance map that optimizes the Monte Carlo simulation giving better results in the same CPU time. To establish the CADIS methodology a research nuclear shielding problem will be analyzed.

## 2. METHODOLOGY

### 2.1. CADIS and FW-CADIS

In a typical source-detector model, with emission probability distribution function $\boldsymbol{q}(\vec{\boldsymbol{r}},\boldsymbol{E})$ and a detector response function $\boldsymbol{\sigma_d}(\vec{\boldsymbol{r}},\boldsymbol{E})$ to calculate the total detector response $\boldsymbol{R}$, the forward scalar flux $\boldsymbol{\phi}(\vec{\boldsymbol{r}},\boldsymbol{E})$ must be calculated first and then the response is given by:

$$\boldsymbol{R} = \iint\limits_{E\,V_D} \boldsymbol{\sigma_d}(\vec{\boldsymbol{r}}, \boldsymbol{E})\, \boldsymbol{\phi}(\vec{\boldsymbol{r}}, \boldsymbol{E}) \boldsymbol{dVdE}. \tag{1}$$

Where $\boldsymbol{V_D}$ is the detector total volume and if the adjoint scalar flux $\boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E})$ is known from the adjoint problem with the adjoint source $\boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E}) = \boldsymbol{\sigma_d}(\vec{\boldsymbol{r}}, \boldsymbol{E})$ the response is now given by:

$$\boldsymbol{R} = \iint\limits_{E\,V_S} \boldsymbol{q}\,(\vec{\boldsymbol{r}}, \boldsymbol{E})\, \boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E}) \boldsymbol{dVdE}\,. \tag{2}$$

Where $\boldsymbol{V_S}$ is the source total volume. Wagner [2] demonstrated that if an estimate of the adjoint flux is found, then an estimate of $R$ can be found using Eq. (1), and a biased source distribution for source sampling in the following form:

$$\hat{\boldsymbol{q}}(\vec{\boldsymbol{r}}, \boldsymbol{E}) = \frac{\boldsymbol{1}}{\boldsymbol{R}} \boldsymbol{q}(\vec{\boldsymbol{r}}, \boldsymbol{E}) \boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E}). \tag{3}$$

With this biased source it is possible to generate the following weight window target values for the particle transport:

$$\bar{\boldsymbol{w}}(\vec{\boldsymbol{r}}, \boldsymbol{E}) = \frac{\boldsymbol{R}}{\boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E})}. \tag{4}$$

So, when a particle is sampled from the biased source distribution (Eq. 3), its initial weight is adjusted to

$$\boldsymbol{w_0} = \frac{\boldsymbol{q}(\vec{\boldsymbol{r}}, \boldsymbol{E})}{\hat{\boldsymbol{q}}(\vec{\boldsymbol{r}}, \boldsymbol{E})} = \frac{\boldsymbol{R}}{\boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}}, \boldsymbol{E})}, \tag{5}$$

and in this way, the particle’s position and energy matches the target weight value.
The CADIS methodology is suitable for classical source/detector problems, but when multiple tallies are need to be found with low uncertainties (ex. mesh tallies), some parts in the phase space are of great importance to one tally and at the same time of little importance to another tally.

To deal with this situation an adjustment of the CADIS methodology needs to be done in order to converge several tallies to the same relative uncertainty. This adjustment consists in weighting the adjoint source inversely by the expected forward tally of that region, so that areas with low flux/dose rate can have more adjoint source strength than areas with high flux/dose rate. This adjustment is called FW-CADIS [3,4].

### 2.1. Problem characterization

A typical research nuclear reactor was designed to analyze the CADIS methodology performance[5,6]. Its core volume (20cm x 20cm x 30cm) was placed centered in a cylindrical heavy water tank which is in the middle of a 400cm deep light water pool. To demonstrate this geometry Fig. 1 presents a plot for the simulation geometry.

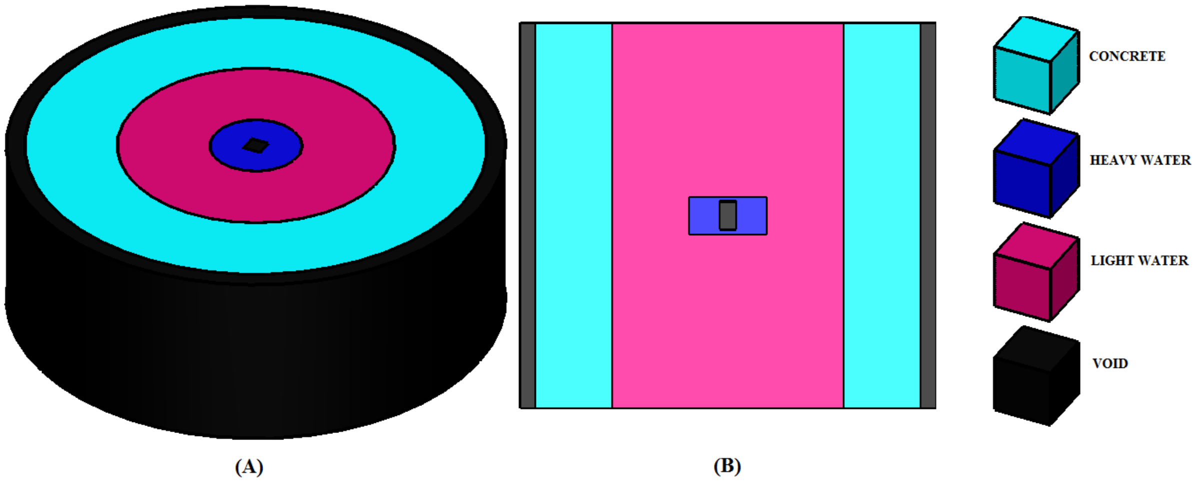

**Figure 1: Plot of the problem geometry: a horizontal (A) and vertical (B) cut.**

The source energy distribution considered is of prompt gamma rays due to the fission of the $U^{235}$ and the source strength corresponds to a 10 MW power evenly distributed in the core volume. The core is at the center of the geometry, the heavy water tank has a height of 40 cm and a diameter of 100 cm, the pool diameter is 300 cm and the concrete thickness is about 100 cm.

### 2.2 MAVRIC (Monaco with Automated Variance Reduction)

Monaco with Automated Variance Reduction using Importance Calculations (MAVRIC) [7] is a sequence of the well know Monaco shielding code that uses the monte carlo (MC) method to solve the transport equation.. In this sequence the CADIS methodology is applied to generate an importance map to optimize the Monte Carlo simulation.

Like other shielding codes the user must supply a geometry situation which involves a radiation source and a physical quantity of interest to be calculated, which differs MAVRIC from other shielding codes is the ability to create a mesh grid to be called the importance map.

To use the CADIS methodology the adjoint scalar flux $\boldsymbol{\phi}^{+}(\vec{\boldsymbol{r}},\boldsymbol{E})$ must be know from the corresponding adjoint problem and to use the FW-CADIS the forward scalar flux $\boldsymbol{\phi}(\vec{\boldsymbol{r}},\boldsymbol{E})$ must be also know. MAVRIC does both of these calculations using a built-in discrete ordinates code called DENOVO [8], and then the MC simulation is done using the CADIS biased source distribution and the weight window targets.

## 3. RESULTS AND DISCUSSION

To analyze the CADIS methodology performance a four point detector situation was inputted. Two are placed in the $x$ axis and the other two in the $y$ axis, both of them are in $z = 0$ and the ones that are in the same axis are diametrically opposed to each other. A 24h simulation time was established for comparison purposes between two simulations: one using the CADIS methodology and another with no reducing variance technique (analog). The response function utilized to convert the gamma flux (particle/cm$^2$s) to equivalent dose (Sv/h) was the recommended in the ICRU report nº57 [9]. With a little variation, the results from the four point detectors results are the same. Table 1 presents the total gamma flux ($\phi_t$) and the total dose ($D_t$) results for one of these point detectors.

**Table 1: Point detector results for the analog simlation and for the CADIS simulation**

| | $\phi_t$ *(particle/cm2/s)* | *Uncertainty(%)* | $D_t$ *(Sv/h)* | *Uncertainty(%)* |
|---|---|---|---|---|
| **Analog** | 1.83E+07 | 0.45029 | 8.33E-01 | 0.44227 |
| **CADIS** | 7.25E+07 | 0.00282 | 1.55E+00 | 0.00284 |

As it can be seen from table 1 the results when the CADIS methodology is applied are sensitively better. One now is encouraged to analyze the figure of merit (FOM) for each simulation; this quantity means how efficient the simulation is and it is mathematically expressed as: $FOM = 1/t.\sigma^2$. Table 2 presents the FOM for these both simulations.

**Table 2: Figure of merit**

| | *Analog* | *CADIS* |
|---|---|---|
| **FOM** | 0.00355 | 86.09954 |

For different simulations of the same physical situation, the one with the biggest FOM is preferred since for a fixed simulation time it produces the smallest relative error. The ratio of these FOMs is about 24253.4 and this value gives an idea of how much effectiveness is gain by using the CADIS methodology when possibly.

Jointly with the point detectors calculations for gamma flux and dose a mesh tally was requested over the entire geometry for both simulations. The main idea of these mesh tally is to demonstrate visually the relative error distribution and the particle's range along the mesh. Figure 2 presents these mesh tallies for the total gamma flux.

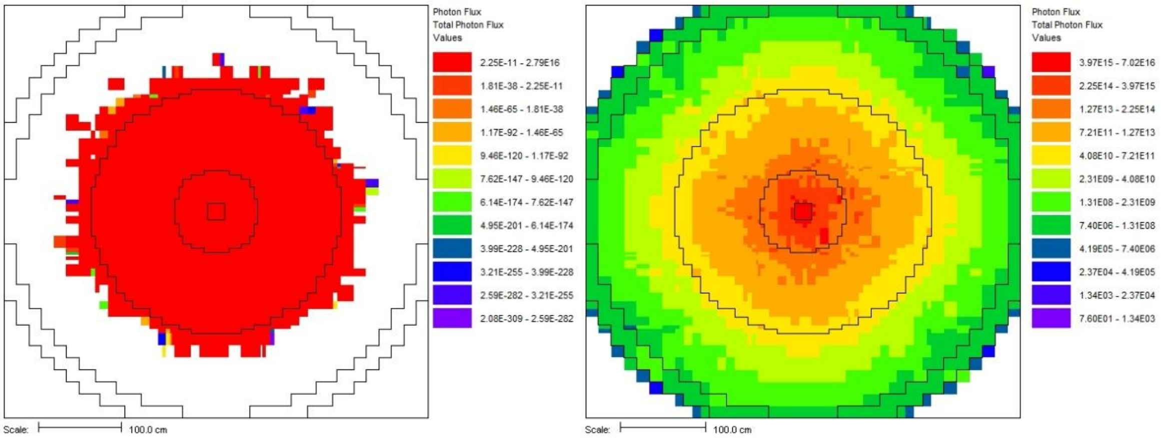

**Figure 2: Mesh tallies (total gama flux) for the analog (left) and for the CADIS (right) simulations.**

As it can be seen from Fig. 2 the particles from the CADIS simulation has a deeper penetration than the particles from the analog simulation and as expected these particles are forced to reach the point detectors using the importance map. However, if it is of interest also knowing the flux or dose in regions other than the point detectors locations, the relative error distribution has to be analyzed to make sure that these results for these regions are acceptable. Fig. 3 presents the relative error distribution for the mesh tallies presented in Fig. 2.

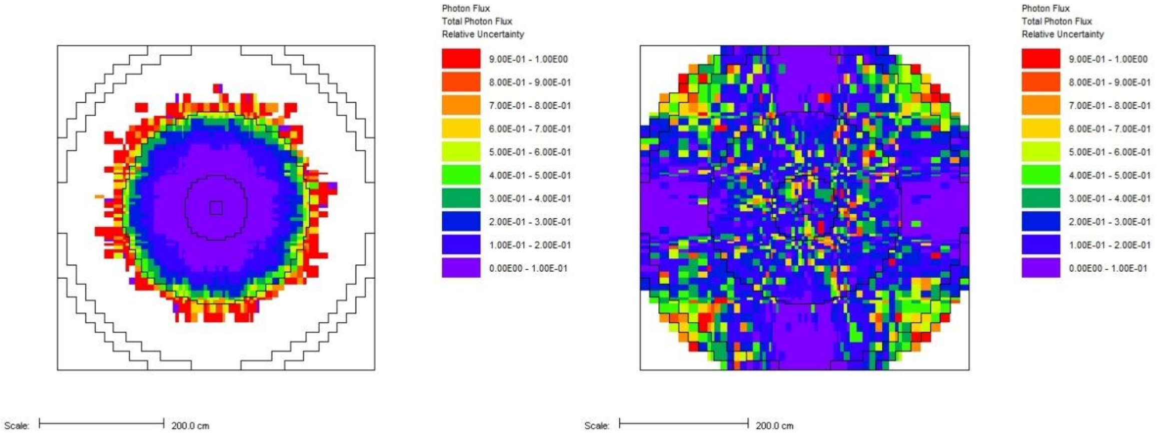

**Figure 3: Relative error distribution (total gama flux) for the analog (left) and for the CADIS (right) simulations.**

In these relative errors distributions it can be seen that for the analog case, the distribution is as expected, the higher values are uniform in the circumference of the light water/concrete interface. And it is in this interface that particles have trouble keeping their history due the change for a material with higher density, as the absorption/attenuation grows in the medium the Monte Carlo calculation needs more particles to keep the uncertainty at small values.

However the error distribution for the CADIS it is not uniform, the relative error has smaller values around the point detectors locations. In Fig. 3 it is evident these locations. Unlike the analog simulation the core region has non uniform relative error distribution. Consequently, nothing can be affirmed about the flux/dose in regions with non uniform and large relative error distributions.

To deal with this situation, where it is important to have low uncertainty over a large area other than only in point detectors locations the FW-CADIS approach must be used. To emphasize this ability the concrete thickness was increased to 250 cm, a larger mesh was created and 24h simulation time was performed. Fig. 4 presents this mesh tally for the total gamma flux along with the correspondent analog simulation.

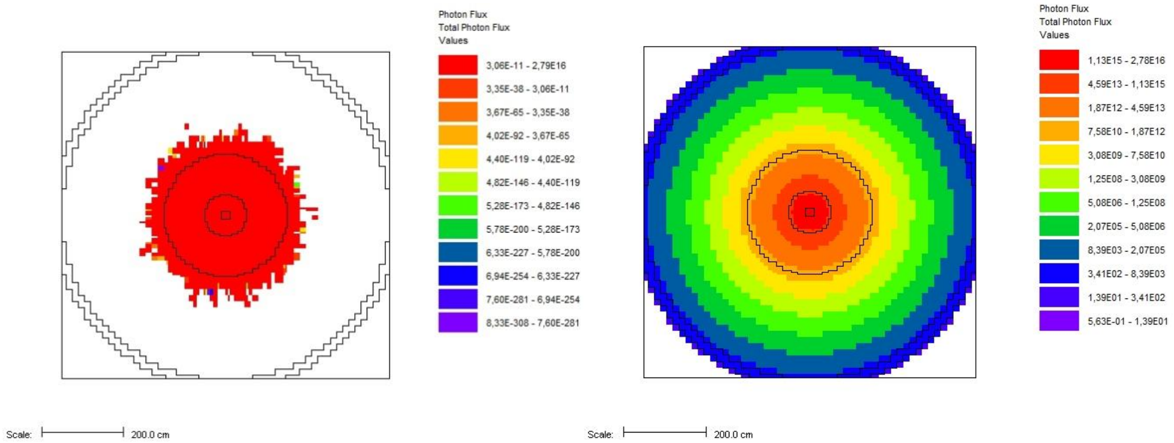

**Figure 4: Mesh tallies (total gama flux) for the analog (left) and for the FW-CADIS (right) simulations.**

The analog simulation for this situation is as expected and the particles cannot penetrate the concrete while the particles from the FW-CADIS simulation can. Yet again, it demonstrates that the use of the importance map in deep penetration problems is crucial for achieving better results in lesser CPU time. However it is in the relative error distribution that the difference is remarkable when using the FW-CADIS approach. Fig. 5 presents the relative error distribution for the mesh tallies presented in Fig. 4. Note that is less than 0.1% for the whole problem domain.

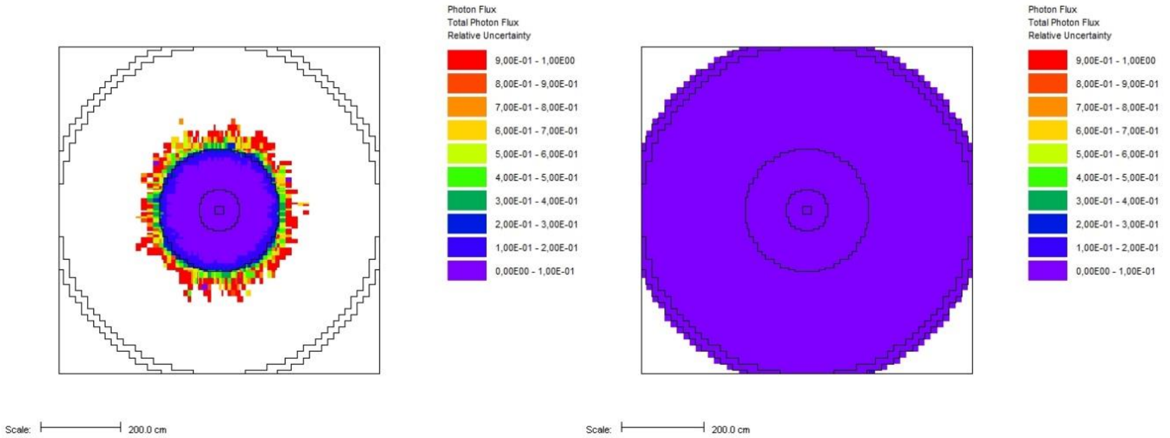

**Figure 5: Relative error distribution (total gama flux) for the analog (left) and for the FW-CADIS (right) simulations.**

## 3. CONCLUSIONS

After evaluating the CADIS methodology for a point detector situation and the FW-CADIS methodology for a mesh tally situation, keeping the simulation time fixed a significant improve in the relative error was achieved when compared to the analog case. The use of the importance map feature in the MAVRIC code can speed up significantly shielding calculations for biological shielding in research reactors.

The CADIS methodology along with others shielding methodologies (SN, Point Kernel, etc) can improve the shielding analyst judgment, and it can be also employed to any deep penetration problems like ex-core detectors, well-logging instruments, cask shielding studies, hot cell shielding studies and spent fuel storage facilities.

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