# A Method of Automatically Converting General Sources to Mesh-Based Sources for CADIS

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## 1. Introduction

When calculating and analyzing large-scale system problems with deep penetration by Monte Carlo program, the results are difficult to converge and the RSD (relative statistical deviation) is large. In order to reduce variance, CADIS (Consistent Adjoint Driven Importance Sampling) method is used for research. When CADIS method is applied, due to the requirement of source biasing, the fixed source must be in the mesh-based form, which is different from the form of the general source SDEF (Source Definition). SDEF-form source is applied in MCNP by defining the characteristics of source, including position, energy, angle, etc. The application of this definition is widespread. In this work, a new module for generating mesh-based source by converting SDEF sources is developed in NECP-MCX, which is a Monte Carlo deterministic coupling program. The development of this module in NECP-MCX expands the application scenarios of the original CADIS method and simplifies the usage, as users do not need to convert a SDEF source to a mesh-based source manually. In nuclear facilities, areas with a large number of fissile isotopes must be equipped with a critical accident alarm system (CAAS) to provide timely alarms to avoid critical accident. In this work, a typical problem in the CAAS is calculated to verify the application of the source converting module in NECP-MCX.

## 2. Methods and Results

### *2.1 Source biasing in CADIS method*

The CADIS method achieves variance reduction through a two-step process. In the first step, weight window suitable for deep penetration environments are generated, allowing for more particles count in low-dose areas. In the second step, the source particle weight is adjusted to match the distribution of the weight window, avoiding excessive particle splitting at the beginning of the simulation. Source biasing is introduced to ensure the consistency between source particle weight and weight window.

In CADIS process, the source distribution adjusted by source biasing is

$$q(\boldsymbol{r},E,\boldsymbol{\Omega}) = \frac{\phi^*(\boldsymbol{r},E,\boldsymbol{\Omega})q(\boldsymbol{r},E,\boldsymbol{\Omega})}{<\phi^*(\boldsymbol{r},E,\boldsymbol{\Omega}),q(\boldsymbol{r},E,\boldsymbol{\Omega})>} \qquad (1)$$

where $q(\boldsymbol{r},E,\boldsymbol{\Omega})$ is the distribution of original source, $\phi^*(\boldsymbol{r},E,\boldsymbol{\Omega})$ is adjoint flux distribution obtained from deterministic calculations.

To ensure the simulation is unbiased, the particle weight needs to be modified before sampling from biased distribution. The particle weight after biasing is

$$wgt(\boldsymbol{r},\boldsymbol{E},\boldsymbol{\Omega}) = \frac{<\phi^*(\boldsymbol{r},\boldsymbol{E},\boldsymbol{\Omega}),\boldsymbol{q}(\boldsymbol{r},\boldsymbol{E},\boldsymbol{\Omega})>}{\phi^*(\boldsymbol{r},\boldsymbol{E},\boldsymbol{\Omega})} wgt_0 \qquad (2)$$

where $wgt_0$ is the particle weight before biasing.

The source form must be discrete distribution because the adjoint flux calculated by deterministic is discretely represented, so the highly versatile SDEF definition can't be applied to the CADIS method. In the CADIS method previously developed in NECP-MCX, space-energy coupled discrete source was used for source sampling and source biasing, which required users to manually generate mesh-based sources consuming a large amount of time. To solve this problem and expand the application scenarios of the CADIS method, an automatic converting general sources to mesh-based source module has been developed in NECP-MCX.

### *2.2 Conversion from SDEF source to mesh-based source*

The figure 1 shows the flowchart of describing the process of conversion from SDEF source to mesh-based source.

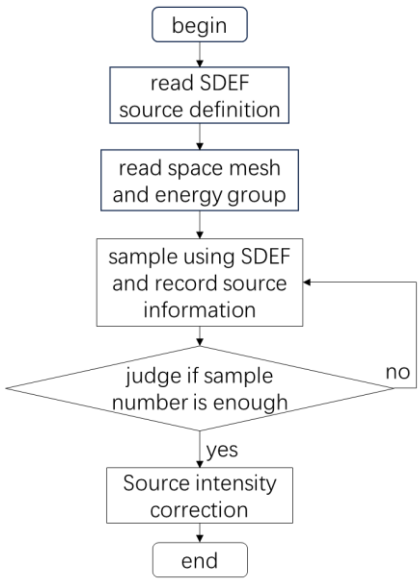


Figure 1. The process of conversion from SDEF source to mesh-based source

In order to approximate the distribution of the SDEF sources, partition the source region into intensive meshes and energy groups encompassing its space and energy. Represent the quantity of spatial meshes as $N$ and the quantity of energy groups as $G$ .The total discrete count is $N \times G$ . Due to many common source situations is isotropic, the division does not involve angles. Employ the previously defined SDEF source for a sufficient number of samplings, the quantity of particles sampled in each mesh and energy group could be recorded.

A coarse mesh-based source distribution can be obtained by the recorded quantity of sampled particles. Represent the quantity of particles sampled by the SDEF source as $n$ and the quantity of particles in a specific energy group of a specific mesh $i$ as $n_i$ , the proportion of the source particles intensity in this energy group of the mesh relative to the total source particles intensity is $n_i/n$ . Assuming the total source intensity of 1, then the source intensity in this energy group of the mesh is $n_i/n$ . It can be considered that the source intensity distribution obtained through sampling is similar to the source intensity distribution of SDEF.

Due to the quantity of particles sampling to generate mesh-based sources is unknown, a limit is necessary to determine whether the sampled particles are sufficient. Represent the quantity of particles sampled in a specific mesh $j$ as $m_j$ . According to the central limit theorem, the error between simulated source strength and actual source strength is

$$\varepsilon = \sqrt{\frac{n - m_j}{n \times m_j}} \tag{3}$$

Setting an error limit, when $\varepsilon$ does not reach the error limit, the number of particles continues to increase until the error limit is reached. Requiring every mesh to reach the error limit is unrealistic. Setting proportion of meshes that reach error limit. As long as sufficient proportion of meshes meet the error limit, the quantity of sampled particles is sufficient.

Because the total volume of the mesh containing the source is greater than the volume of the SDEF source, source converting has errors. In order to reduce errors, it is necessary to correct the source intensity. Represent the volume of a specific mesh as $D_i$ and the source volume of the mesh as $V_i$ . The sampling originally done in $V_i$ is now being carried out in $D_i$ . A same source intensity will be sampled in a larger volume, increasing the sampling proportion of this area and causing errors. Set the correction factor to be

$$\eta_i = \frac{V_i}{D_i} \tag{4}$$

Multiplying each mesh by corresponding correction factor can effectively reduce the error caused by volume changes.

The volume $D_i$ of a specific mesh can be directly determined through a user-defined mesh distribution, but the internal source volume $V_i$ of the mesh cannot be directly obtained. When sample uniformly for meshes that can completely encompass the source, the fluctuation of sampling error is minimal. On one hand, the volume of these completely encompassed meshes can be calculated, on the other hand, the proportion of source sampling in these meshes can be calculated. This enables the determination of the total volume of the sources, followed by the calculation of the source volume $V_i$ within each mesh based on the proportion of sampled particles in each mesh.

When utilizing the source converting module, the deterministic calculation mesh is directly employed as the source converting mesh. However, due to the extensive quantity of deterministic computation meshes, the number of meshes used during source converting is large, which leads to a considerable memory consumption. The array that holds each spatial mesh and energy group is configured as a one-dimensional array, with its element content being $N \times G$ . Given the fact that the majority of spatial areas lack source distribution, this array comprises numerous zeros, resulting in a significant memory wastage. To solve that, transform this one dimensional array into two small one-dimensional arrays. One array retains non-zero values, while the other array stores the positions corresponding to these values within the large array. Both of these arrays can subsequently serve operations like source sampling and source bias, substantially curtailing computational memory usage.

### *2.3 Verification in circular stretching source*

A circular stretching source model is established by sdef in NECP-MCX. The circular stretching source’s inside diameter, outside diameter, and height are 91cm, 120cm and 100cm. 10000 particles is sample in NECP-MCX.

Figure 2 shows the position information of the generating mesh-based source (red dots) and SDEF source(blue dots). It can be observed that the positions of the two sources are in good agreement.

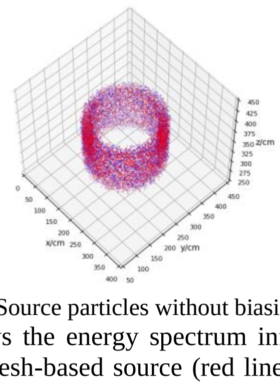


Fig. 2. Source particles without biasing

Figure 3 shows the energy spectrum information of the generating mesh-based source (red line), as well as the energy spectrum information of SDEF source (blue line). It can be seen that the energy of the two sources are in good agreement.

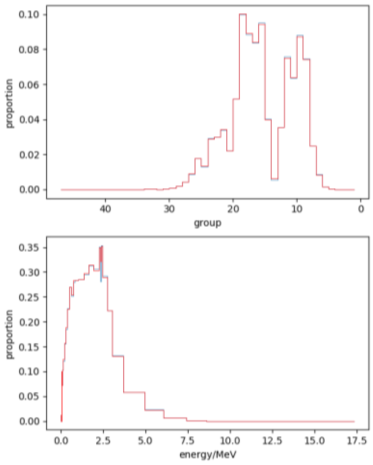


Fig. 3. Source energy spectrum without biasing

Figure 4 shows the position information of the generating mesh-based source after biasing(red dots) and SDEF source after biasing(blue dots). Compare to figure 1, the source biasing is obvious.

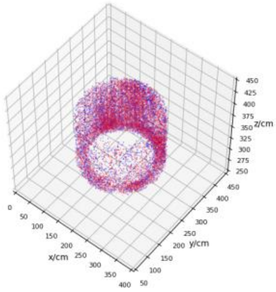


Fig. 4. Source particles with biasing

*2.4 Verification in CAAS*

In various nuclear facilities of the nuclear fuel cycle, a considerable number of regions contain fissile isotopes. Thus, a critical accident alarm system (CAAS) must be set up to provide timely alarms to avoid critical accident. The physical dimensions of nuclear facilities' factories and equipment rooms are relatively large, and the installation location of CAAS detectors is relatively far from the equipment with the smallest critical accident (to achieve detection coverage for the most remote equipment), with neutron flux density attenuation of several orders of magnitude or more. This work verifies the application of the CADIS module for automatically converting general sources to mesh-based sources in CAAS design through a typical nuclear facility plant CAAS calculation problem.

A calculation model for a virtual factory building has been established, which is a rectangular body with a length, width, and height of 500cm × 530cm × 700cm, and is covered with 50cm thick concrete. There is a box source with dimensions of 50cm, 30cm, 50cm in the factory building, which is covered with 1cm thick stainless steel. Figure 5 and figure 6 show the model. The aim is to calculate the flux of one detector inside the concrete wall. The NECP-MCX program was used to calculate the models above.

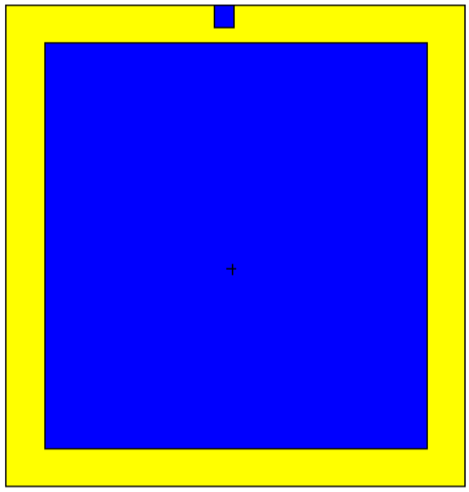

Figure 5. Model xy section view

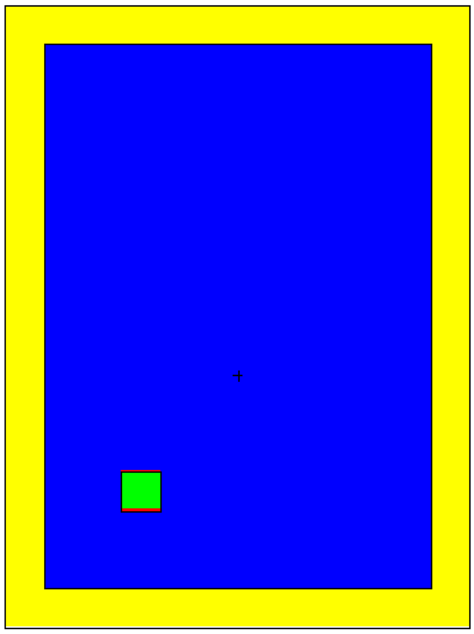

Figure 6. Model xz section view

MCX sets 500 batches of particles, with $10^6$ number of particles per generation, totally $5 \times 10^8$ number of particles. The meshes size divided for deterministic calculations, weight window settings, and fixed source generation are all about 5cm. When converting SDEF sources into mesh-based sources, more than 90% of meshes exhibit an error limit of less than 5%.

The flux comparison between mesh-based source with CADIS and SDEF source without CADIS is as follows. 500 batches of particles are sampled in the SDEF source without CADIS method, with $10^6$ number of particles per batch. Table I shows the result compare between SDEF source without CAIDS and mesh-based source with CAIDS. The flux difference is 1.16%. The

FOM(figure of merit) shows that the mesh-based source with CADIS has higher efficiency in this problem.

Table I. Result compare between SDEF source and Mesh-based source

| | Mesh-based source with CADIS | SDEF source without CADIS |
|---|---|---|
| Flux | 2.62E-03 | 2.59E-03 |
| RSD | 1.49E-03 | 5.07E-03 |
| Time/s | 1.01E+03 | 9.88E+02 |
| FOM | 444.53 | 39.43 |

## 3. Conclusions

This article describes a method for automatically converting general sources to mesh-based sources for the CADIS method, and applies this method to the system of critical accident alarm devices to verify the feasibility of this method, improve the convenience of software usage, and create better conditions for the application of the CADIS method in large-scale problems in the future.

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