Severe Accident Gamma Dose Mapping of PWR Nuclear Island Using FW-CADIS Methodology and Contributon Flux

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ABSTRACT

The FW-CADIS hybrid deterministic-stochastic shielding methodology was used to find global gamma dose distribution in case of station blackout (SBO) with small loss of coolant accident (LOCA) scenario in a realistic PWR nuclear island model. The MAVRIC shielding sequence of SCALE6.2.4 program package is controlling the hybrid FW-CADIS methodology that uses deterministic forward-adjoint flux solution over a large computational mesh to produce variance reduction (VR) parameters for accelerating the final Monte Carlo (MC) simulation. Such shielding problems, with massive flux attenuation by many orders of magnitude, can be solved only by an efficient computational workflow. This paper presents numerical trade-offs and influence of discrete ordinates (SN) solution on global MC convergence via space-energy VR parameters (importance map and biased source) that closely work in a tandem. In this way it is possible to prepare a rather detailed and large MC model to analyse gamma flux attenuation from the PWR containment interior to external auxiliary buildings in case of hypothetical SBO accident. The accident source was calculated using RADTRAD3.03 code and prepared for SCALE6.2.4 by ORIGEN2.2 code, representing gaseous effluents with uniform distribution over all air-regions inside the containment. The gamma source corresponding to activity 2h after the SBO accident gives the largest gamma dose rate in auxiliary buildings, so it was used for subsequent MAVRIC calculations. The resulting gamma flux distribution was examined through different sections and compartments to pin-point possible streaming paths important for radiological assessment. MAVRIC auxiliary routines were used for folding forward and adjoint multigroup fluxes into a normalized contributon flux, giving an extra insight how the global response propagates throughout the computational phase space. The adjoint source location was varied to investigate possibility of uniform particle distribution in heavy-shielded areas of the simulation model.

Keywords: *FW-CADIS, shielding, Monte Carlo method, gamma dose, severe accident, contributon flux*

1 INTRODUCTION

A hybrid deterministic-stochastic shielding methodology of SCALE6.2b4 code package [1] was used for calculations of accident gamma-dose field map through typical NPP containment building and auxiliary buildings (AB). This hybrid approach is nowadays preferred for complex models with deep penetration shielding problems, since shortcomings of classical Monte Carlo (MC) variance reduction techniques (VR) are well known. The methodology is based on deterministic transport theory and the concept of adjoint flux (i.e. importance function) which is the solution of the adjoint Boltzmann transport equation [2]. The typical deterministic solver is based on discrete ordinates method (SN) [3], approximating the space-energy adjoint flux for preparation of VR parameters which will bias MC simulation towards one specific region. This is known as the

Consistent Adjoint Importance Sampling (CADIS) [4] formalism and it is used for optimization of localized results, such as point detectors. Generalization of this methodology for optimizing global MC distribution is a more complicated process which involves additional SN forward calculation needed for redistribution (forward weighting) of the adjoint source in phase-space. This FW-CADIS [5] methodology has been successfully applied to real life shielding problems resulting in MC simulations with nearly uniform relative errors over large problem domains [6].

In this paper we have used the FW-CADIS methodology implemented in MAVRIC sequence of the SCALE6.2b4 code package to obtain gamma dose distribution map throughout PWR facility with containment and auxiliary buildings. The objective of this paper was accomplished by a two-step approach: the accident source preparation using the RADTRAD [7] code linked to a hybrid shielding calculation with the SCALE6.2b4 code package. This task represents a challenging shielding problem which can be solved only by an efficient hybrid methodology with automatic preparation of the mesh-based VR parameters [8]. The hybrid shielding calculations are thus focused on MAVRIC capabilities to produce global, well-converged gamma dose rates over the nuclear island originating from the containment source.

The SCALE6.2b4 general geometry package (SGGP) of the KENO-VI code [1] was used for MC model preparation of the PWR nuclear island, with detailed description of the containment interior while the auxiliary, intermediate and turbine building contain only concrete floors and walls. Typical industrial and text-book data were used for the necessary dimensions and material compositions, together with NPP Krško data [9][10]. Part of the activity is performed to support NPP Krško equipment survivability project where thermal-hydraulic and radiological parameters should be determined in so called design extended conditions.

This paper is organized as follows. Section 2 gives description of the SCALE6.2b4 code package with focus on MAVRIC hybrid shielding capabilities. Section 3 provide basics of the contributon theory. Section 4 shows MAVRIC model of the PWR nuclear island housing reactor, primary loop elements, containment, and the rest of the external buildings. Section 5 gives MAVRIC gamma dose rates over different sections of the model using variable adjoint source positioning. The correlation of contributon streamlines to gamma dose relative errors is presented in Section 6. Section 7 gives discussion and conclusions while the referenced literature is given at the end of the paper.

2 SCALE6.2.4 HYBRID SHIELDING METHODOLOGY

The SCALE6.2.4 code package from ORNL was developed for the U.S.NRC as a standardized tool for nuclear safety analysis and reactor design. The modular structure of the code enables comprehensive evaluation of nuclear facilities and radioactive waste characterization, covering eigenvalue criticality, radiation shielding, source term characterization through fuel depletion/decay, general reactor physics, cross section processing, and sensitivity/uncertainty analyses. This paper present MAVRIC hybrid shielding capabilities applied to large model of the PWR nuclear island, posing significant shielding problem. The hybrid shielding includes a relatively novel paradigm of combining the SN mesh-based solution to effectively accelerate the final MC simulation. The space-energy dependent VR parameters are generated with FW-CADIS method, a well-known technique in radiation shielding community. The method is based on the concept of particle's importance function, which is obtained by solving the adjoint Boltzmann transport equation by a fast SN solver Denovo [11]. The Denovo is using orthogonal structured SN mesh over which nonstationary Krylov methods are applied for solving the within-group equations. The VR parameters working in a tandem are called weight windows (or importance map) and biased source distribution, giving a calculational "recipe" how to perform splitting and Russian roulette of MC particles in Monaco transport code. For that purpose, a global mesh tally with millions of cells is covering the MC simulation model to demonstrate the gamma dose convergence and effectiveness of VR parameters. The FW-CADIS should ideally ensure near-uniform MC particle density in important regions of the simulation model, but this proved to be a rather specific point.

The steady-state transport equation can be written in the operator form as [2][3]

$$H\phi = q\,, \tag{1}$$

where H is the linear transport operator, ϕ is the forward flux and q is the total forward source. The solution to Eq. (1) by Denovo SN solver is used for forward-weighting the global adjoint source $q^{\dagger}(\vec{r},E)$, defined to be all air-regions of the auxiliary buildings external to containment with energy spectrum $\sigma_d(E)$ corresponding to conservative ANSI-ANS 1977. gamma dose rates [1]. The adjoint problem is then formulated as an operator equation

$$H^{\dagger}\phi^{\dagger} = q^{\dagger}\,, \tag{2}$$

where $H^{\dagger}$ is the linear adjoint transport operator, $\phi^{\dagger}$ is the adjoint flux, and $q^{\dagger}$ is the total adjoint source. The adjoint flux is also called the importance function due to physical interpretation as a "measure" of a particle contributing to the response of the detector [2][3]. This property can be easily seen by multiplying Eq. (1) and Eq. (2) with $\phi^{\dagger}$ and ϕ, respectively, integrating over the whole phase-space variables (Dirac brackets) and subtracting the obtained expressions as:

$$\left\langle \phi^{\dagger}, H\phi \right\rangle - \left\langle \phi, H^{\dagger}\phi^{\dagger} \right\rangle = \left\langle \phi^{\dagger}, q \right\rangle - \left\langle \phi, q^{\dagger} \right\rangle. \tag{3}$$

Since the adjoint transport operator is defined using the following property [2]

$$\left\langle \phi^{\dagger}, H\phi \right\rangle = \left\langle \phi, H^{\dagger}\phi^{\dagger} \right\rangle, \tag{4}$$

one can see that response of the detector R can be obtained with the choice of adjoint source as $q^{\dagger} = \sigma_d(\vec{r},E)$, i.e. corresponding to some reaction cross section. However, the choice of the forward source q is arbitrary and could be a Dirac delta-function at some phase point $q(\vec{r},E) = 1\cdot\delta(\vec{r}-\vec{r}_0)\delta(E-E_0)$ in which case the physical interpretation of the importance function follows from reciprocity relation:

$$R = \left\langle \phi^{\dagger}, q \right\rangle = \left\langle \phi, q^{\dagger} \right\rangle \equiv \phi^{\dagger}(\vec{r}_0, E_0)\,. \tag{5}$$

The reciprocity relation in Eq. (5) is quite common in radiation shielding and shows how response rate functional R can be calculated easily from the known adjoint flux, eliminating repetitive forward calculations for a changing forward source.

The spatial domain $g(\vec{r})$ of the adjoint source will be limited to users' region of interest where optimized MC results are searched, and in the case of total gamma dose rates this weighting will be performed as:

$$q^{\dagger}(\vec{r},E) = \frac{\sigma_d(E)g(\vec{r})}{\int_E \sigma_d(E)\phi(\vec{r},E)dE}\,. \tag{6}$$

The way to control the MC particle weight w, so not to become too low or too high, is by weight windows which will perform splitting and Russian roulette to correct particle's weight during the MC transport. The average weight of MC particle is inversely related to the adjoint flux solution as

$$\bar{w}(\vec{r},E)=\frac{R}{\phi^{\dagger}(\vec{r},E)}=\frac{\iint q(\vec{r},E)\phi^{\dagger}(\vec{r},E)d\vec{r}dE}{\phi^{\dagger}(\vec{r},E)}, \tag{7}$$

where R is the total response approximated with Denovo (integration goes over the source region). It is important to note this inverse relationship between particle weight and adjoint source since it ensures consistency between MC source biasing and MC transport biasing. In that way the detector location will have a high importance and a low particle weight. For importance calculations the broad shielding library “v7.1-28n19g” was used for SN memory-demanding Denovo and fine group library “v7.1-200n47g” for Monaco MC particle transport. Primary data for both libraries originate from the ENDF/B-VII.1 nuclear data library [12].

The biased source distribution [1] used for source particle sampling is constructed as

$$\hat{q}(\vec{r},E)=\frac{\phi^{\dagger}(\vec{r},E)q(\vec{r},E)}{R}, \tag{8}$$

so real physical interaction of particles is preserved as a fair game:

$$\bar{w}(\vec{r},E)\hat{q}(\vec{r},E)=q(\vec{r},E). \tag{9}$$

3 APPLICATION OF THE CONTRIBUTON THEORY

The concept of spatial channel theory [13] was developed in ORNL in the late 1970-ies as a useful tool in radiation shielding problems to identify important spatial paths or “spatial channels” through which particles stream easily and contribute to the response of interest. Initially, the spatial coupling of the 2D SN forward-adjoint flux solution was considered, but over the time the theory was further generalized [14] and showed to be a special form of generalized reciprocity relations. The coupling of forward-adjoint flux has a meaning of so called contributon flux, containing deeper information not contained solely in forward or adjoint part:

$$C(\vec{r},E)=\phi(\vec{r},E)\phi^{\dagger}(\vec{r},E). \tag{10}$$

The contributons represent a special form of pseudo particles in phase space flowing from the source region and sinking into the detector, showing a response continuum propagating throughout the phase space. These particles (and their progeny) form a small subset of entire particle population and always produce a desired response without any absorption or leakage from the observed system. Inspecting the contributon flux distribution in space and energy can provide useful information to the user about possible streaming paths or “energy windows” inside the shield [15].

The fluxes produced by Denovo (forward and adjoint) in FW-CADIS method are space-energy functions and as such can be used in the extended channel theory incorporating additional energy aspect of the particle contribution. Using the MAVRIC auxiliary tools for Denovo flux files (*.dff), such as integration and normalization, the user can manually construct the scalar contributon flux by folding forward-adjoint multigroup fluxes over the computational SN mesh. After that, the data filtering can be applied with a threshold operator to fine-tune the contributon flux level and thus visualize important streaming paths in the model. This information can then be used in the next iteration of the computational strategy to proceed with a SN mesh rebalance or local refinement which will ideally result in even faster MC convergence. Some authors have successfully used contributon theory for obtaining large memory savings within SCALE6.1/MAVRIC by using different block-structured SN grids over energy groups for storing weight windows maps [16].

4 MAVRIC MODEL OF THE PWR NUCLEAR ISLAND

The MAVRIC shielding sequence of the SCALE6.2.4 code package was used for preparing a rather detailed model of the PWR nuclear island, significantly extending the previous explicit PWR containment model with primary loop elements [17]. For the present purpose, all auxiliary buildings were modelled as empty (air filled) with bulk gamma flux attenuation coming from solid concrete walls and floors. The RADTRAD code was used for the gamma source preparation for the case of hypothetical Station Black Out (SBO) accident with small loss of coolant accident (LOCA) scenario, while the gamma dose mapping was carried out by the FW-CADIS methodology.

4.1 Geometry preparation

A well-established MAVRIC simulation model of the PWR facility was done for the previous containment irradiation analyses [17]. A fairly detailed model of the reactor with concrete compartments housing primary pumps and steam generators was developed using as-built dimensions. The input file was partially rewritten and ported to SCALE6.2.4 with final geometry extension to include auxiliary, intermediate and turbine buildings, forming a complete PWR nuclear island. The NPP Krško documents [9][10] were used for containment and other civil structures dimensions and typical industrial and text-book data were used for definition of material mixtures. The SketchUp model was drawn from the available data (Figure 1) and then used to manually construct KENO-VI computational model to be used with MAVRIC sequence (Figure 2).

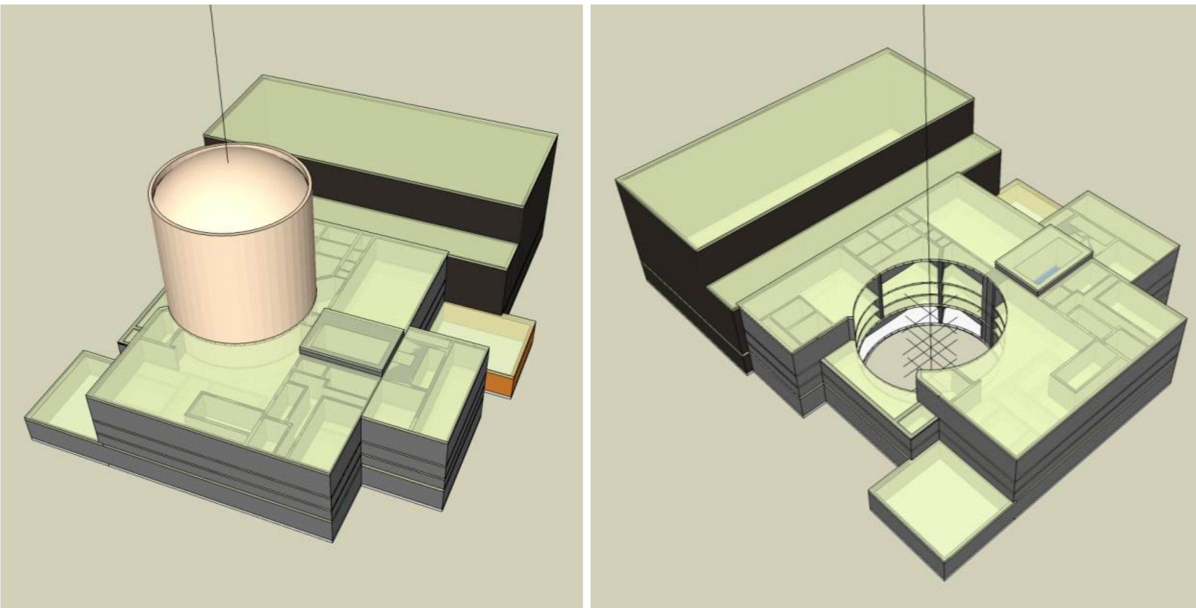

Figure 1: SketchUp model of the nuclear island with containment and auxiliary buildings

Figure 2 shows MAVRIC nuclear island model with many walls, floors and roofs removed from the containment and auxiliary buildings, to reveal the explicit modelling of the nuclear island. The spent fuel pool (SPF) was represented by homogenized mixture of spent fuel assemblies, structural materials of the spent fuel racks (steel and B_4C) and borated water.

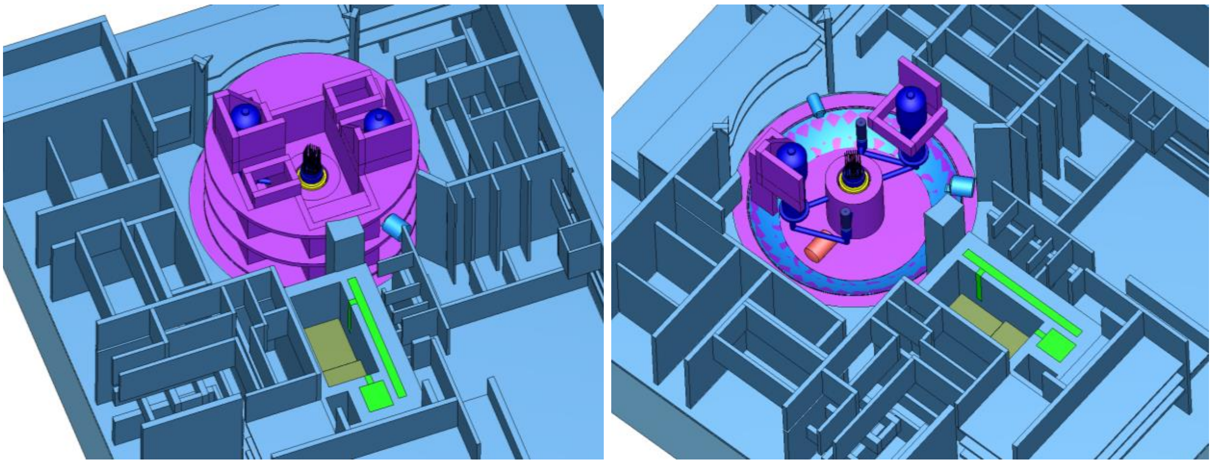

Figure 2: MAVRIC model of the nuclear island with external air removed

An aerial view of the MAVRIC model is shown in Figure 3, with characteristic intermediate and auxiliary buildings around the containment, including spent fuel building and turbine building.

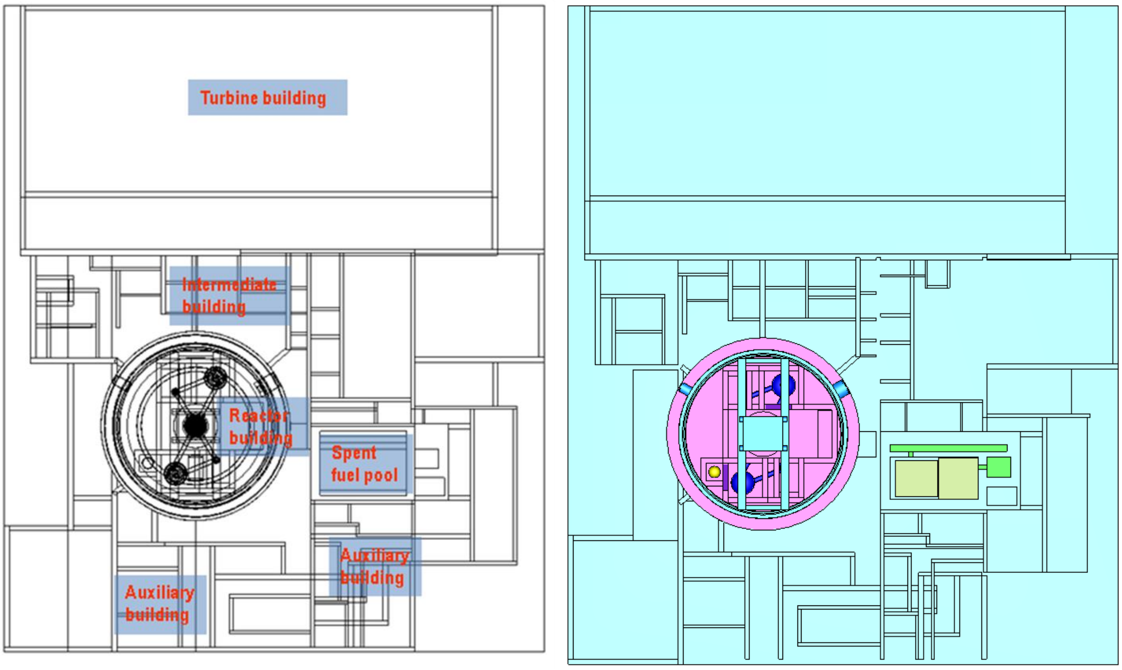

Figure 3: Top view of the MAVRIC model: transparent wireframe (left); roof, some walls and containment structure removed for clarity (right)

4.2 Accident source parameters

The accident gamma source was prepared using the isotopic concentrations calculated with RADTRAD3.03 code and 18-group ORIGEN energy structure [18]. The source is homogenous and uniformly distributed over all air regions inside the containment. The influence of melted material in reactor cavity is not considered at the moment. Under such conditions, the aim was to calculate gamma dose rates through different floors, sections and buildings, posing a significant shielding problem. Special attention was given to gamma doses inside the containment and in AB rooms with close proximity to determine environmental conditions for operation of accident mitigation equipment.

RADTRAD3.03 code was used to calculate the activity of the source term released in the containment during "nothing works" SBO sequence. The model has just one compartment (containment) and environment. Containment sprays are not available, and natural deposition is not taken into account to maximize the activity available in the containment atmosphere. The design containment air leakage is assumed until Passive Containment Filtered Vent (PCFV) actuation (about 11.87 hours after SBO initiation). The time of opening and subsequent volumetric flow from the containment atmosphere are based on SBO MAAP4.0.7 calculation [19]. The explicit MAAP calculation covers first 5000 min and RADTRAD calculation was performed up to 30 days using conservative assumptions. Any material removed from the containment atmosphere decreases doses in containment and shine doses from the containment and surrounding buildings. The representative nuclide inventory was calculated for NPP Krško Cycle 26 using the ORIGEN 2.2 [18] and realistic depletion based on fuel assembly power and burnup data. The release fractions, timing for release of radioactive materials from the reactor core and assumed Iodine chemical fractions were based on PWR severe accident recommendations from the NUREG-1465. The RADTRAD code was modified to make time dependent isotopic activities released to containment atmosphere available for further use. Using these isotopic activities and small auxiliary program based on 18-groups ORIGEN gamma library spectrum, the energy dependent photon source was obtained for MAVRIC input. The source intensity of $1.673 \cdot 10^{19}$ phot/sec corresponding to activity 2 hours after the accident initiation gives the largest dose rate in AB and it was used for the MAVRIC calculations.

4.3 MAVRIC shielding parameters

The MAVRIC sequence was used with FW-CADIS methodology on the workstation with 32 GB RAM and Core i-5 CPU. The volumetric adjoint source was investigated with different spatial domain while the spectrum of the adjoint source was set to conservative ANSI-ANS standard (1977) gamma flux-to-dose-rate factors in rem/h. In the first case, the adjoint source was defined as all air regions external to containment, defining phase-space locations for optimized gamma dose rates of uniformly small uncertainties. In the second case, the adjoint source was reduced only to the right part of auxiliary buildings, proved to be problematic due to massive attenuation of thick concrete walls, like the SFP building. The mesh tally was kept the same in both cases, to capture the MC gamma dose convergence over the simulation model. The accuracy of Denovo SN fluxes is generally not a paramount for VR calculations, since approximation to space shape will sufficiently accelerate the final MC calculation. Denovo was used with options: QR quadrature set, 4 polar and 4 azimuth angles per octant, P1 Legendre expansion for cross section, multigroup flux tolerance of 10^{-6}, and step characteristic spatial differencing. To improve the quality of SN solutions, the macromaterial option was turned on and resulted in 5049 cell-weighted materials from basic 30 mixtures. The broad shielding library "v7.1-28n19g" was used for importance calculations, while Monaco MC used finer "v7.1-200n47g" library to capture effects of low-energy photon transport important for MC biasing scheme.

4.4 Krylov Space Size

The main features of Denovo SN solver are speed, flux positivity and numerical robustness coming from modern Generalized Minimum Residual (GMRES) Krylov method for solving group equations [1], proved to be more efficient than traditional source (Richardson) iteration [20]. Krylov restart vectors are new starting vectors used in restarted Krylov subspace methods, which are algorithms that address the memory and round-off errors of standard Krylov methods by periodically restarting the process. Instead of discarding all previous information, these methods use a technique called polynomial filtering to identify the most significant components of the Krylov subspace and encode them into a new starting vector. This allows the method to continue its convergence toward a desired subspace. As Krylov methods iterate, the subspace dimension can grow, leading to memory issues and potential round-off errors, so restarting is a technique to keep the subspace dimension bounded, creating a new intermediate starting vector, but it can slow down convergence. A common approach is to use a polynomial filter, where the new starting vector is an action of a polynomial on the original starting vector. The polynomial filter is designed to “dampen out” or select for certain parts of the spectrum of the matrix, effectively steering the new Krylov space towards a desired invariant subspace. There are different ways to implement restarting, each with its own advantages [20]. Implicit restarting, for example, avoids throwing away information by replacing the old basis with a new one that spans the same subspace but incorporates the filter information. Restarting keeps the size of the Krylov basis at a manageable level, which is crucial for large-scale problems and memory management. In this work, the number of Krylov vectors to store for the GMRES within-group solver in Denovo was set to 20, which proved to be well balanced with the size of SN mesh used in importance calculations. Reducing the number of vectors can relax memory requirements but can prolong convergence.

5 GAMMA DOSE MAPS OF THE ACCIDENT SCENARIO

Two volumetric adjoint sources with focus on external air (mixture 32) have been used to test the FW-CADIS methodology in case of SBO accident: auxiliary buildings just around the containment spanning smaller circular area and strictly right portion of the model covering the SFP region. However, both adjoint sources are defined over the same computational SN mesh including containment as the forward gamma source. The importance map[1] represents the region(s) for which VR parameters will be generated to bias Monaco simulation with optimized MC results on desired locations. The gamma source sampling is also done from the biased source distribution, determined from the adjoint SN solution, to work in tandem with the importance map. The Denovo representation of the SBO source is shown in Figure 4 where one can notice uniform volume density (in red) with excluded concrete structures (in white).

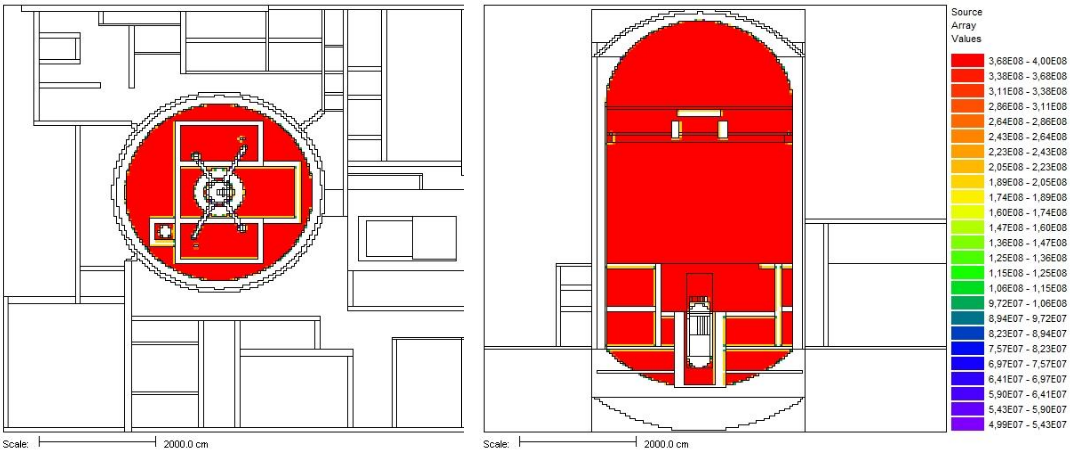

Figure 4: Discrete ordinates representation of the accident source (uniform intensity)

5.1 FW-CADIS gamma-maps with global adjoint source

This approach used focus on all air regions external to containment building, aiming at photon extraction through empty concrete structures, resulting in variable attenuation power over different floors and compartments. The structured SN mesh of 8 million cells (40 cm side) covered somewhat

[1] This concept is very similar to Weight Windows (WW) from MCNP code, but in MAVRIC each cell of importance map represents average particle weight by arithmetic mean. MCNP uses lower weights in mesh-based WWINP file.

reduced model with bulk dimensions of (7920 x 7770 x 7900) cm. The coarse mesh tally was defined over the same volume but used 4.1 million cells (50 cm side). The Monaco MC code used 4000 batches with $2.5 \cdot 10^5$ photons per batch giving total $1 \cdot 10^9$ photon histories. The short importance map option was turned on to spatially limit our calculation only to AB rooms in the vicinity of the containment. The Figure 5 shows adjoint source distribution on the elevation z=342 cm, relative from the reactor midplane *z*=0 cm, which is primary pipes plane (hot leg). Every material different from air is excluded from the adjoint source and depicted in white (floors, walls, containment interior). Most difficult regions for photon transport are the ones with the highest adjoint source strength to ensure the same number of particles as in regions close to the accident source. Forward Denovo took 2.4 h, adjoint Denovo 2.6 h, while Monaco took 6.2 days of CPU time on Core i5-3090K 3.2 GHz processor.

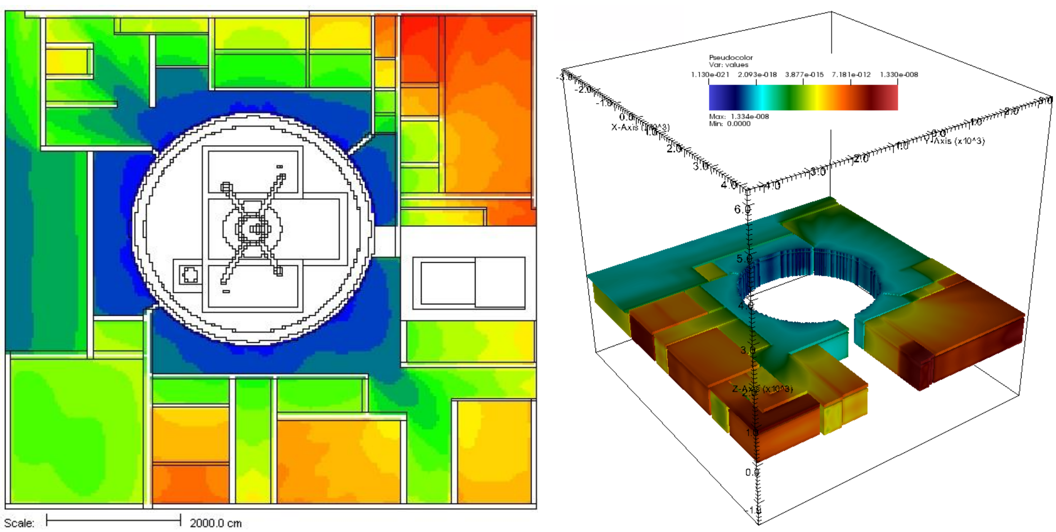

Figure 5: Forward-weighted adjoint source distribution (elevation 342 cm)

The gamma dose maps 1 m above the operating third floor deck (elevation z=1625 cm) of the NPP model are shown in Figure 6. The VisIt software was used for producing all surface plots [21]. The values in the south-east part outside of the containment (control room area) are on the order of several rem/hrs. Compared to dose rates inside the containment, it is clear how gamma flux attenuates by factor of 10^5.

The associated MC relative errors at one sigma level are shown in Figure 7, where purple areas designate satisfactory errors below 10%. As expected, better MC statistics can be found inside large air regions closest to the containment, while thick concrete walls and floors are preventing photon penetration deeper inside the building interior. If one is interested in very focused results, like parts of the control room, then point detector approach can be an alternative MC biasing at expense of losing results in other regions of the model. Additional penalty with point detector estimator inside large MC models comes through ray tracing algorithm and long CPU simulation time for estimating the probability of particle striking a detector on each photon emission and interaction site.

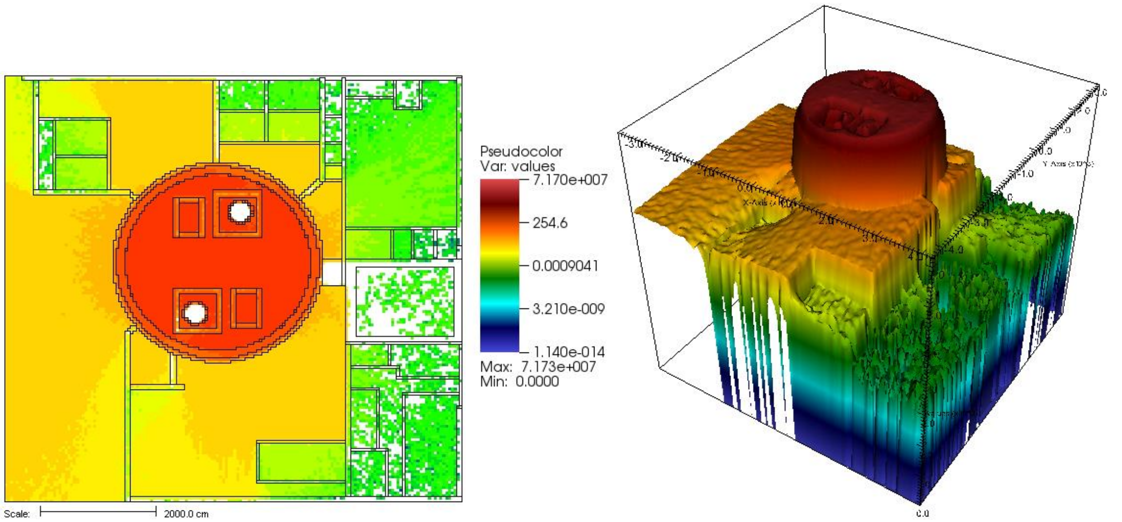

Figure 6: Gamma dose rates (rem/hrs) at elevation 1625 cm

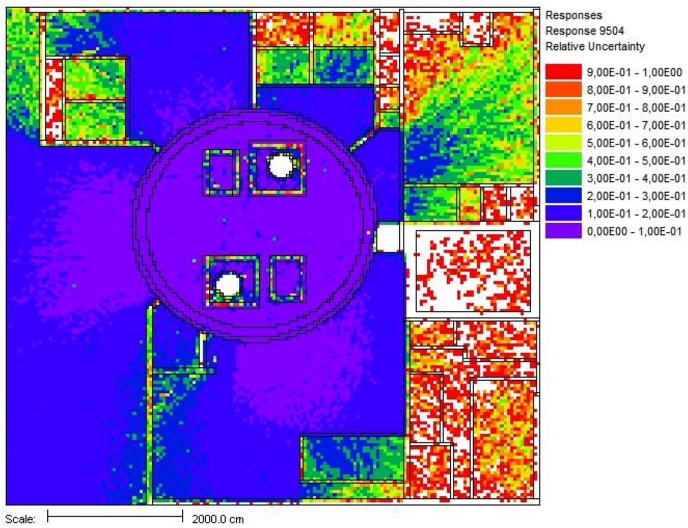

Figure 7: Relative errors of gamma dose at elevation 1625 cm

Results of gamma dose rates through reactor axial midplane (x=0 cm) are shown in Figure 8 with associated relative errors. Satisfactory results indicate that most of the AB structures and air-regions outside of the containment will receive photons. Using more MC histories will generally improve the overall flux convergence, but this “brute force” will not assure satisfactory results in distant, heavy shielded regions. Point detectors, region detectors and small volumetric adjoint sources would be a better choice of computational strategy in such cases. Point detector tallies are however computationally costly, since ray tracing routines through MC geometry must be utilized for every site of particle interaction to compute pseudo flux contribution to the detector.

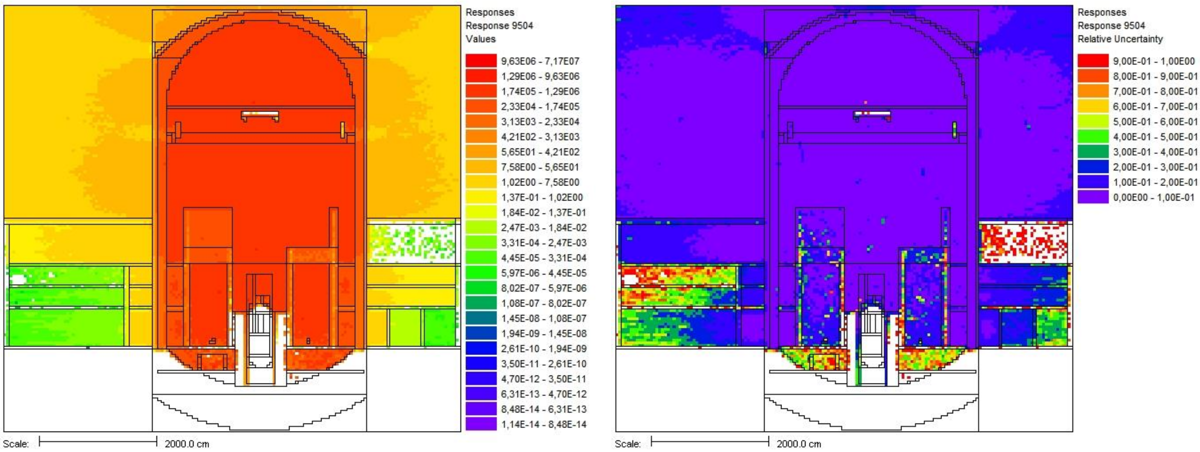

Figure 8: Gamma dose rates (rem/hrs) and relative errors in axial midplane *x*=0 cm

The gamma dose rates as a function of *x*-axis are shown in Figure 9 at elevation of 2750 cm, going through containment axial midplane. It is easy to notice the shielding efficiency of the containment concrete structure, bringing rapidly the millions of rem/hrs in the interior to external values below 10 rem/hrs.

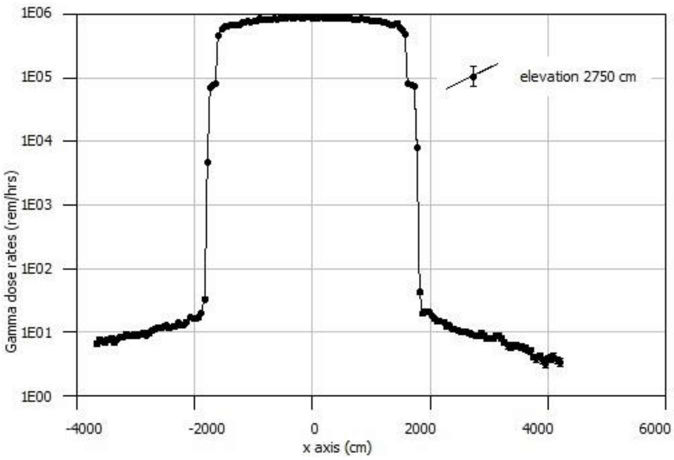

Figure 9: Containment gamma dose rates at elevation z=2750 cm

5.2 FW-CADIS gamma-maps with reduced adjoint source

The previous chapter presented MC results of the global adjoint source, rendering auxiliary building on the right to the containment as the most problematic for particle transport. This result is in accordance with amount of concrete in thick walls and floors, especially around the SFP region. The FW-CADIS method was again applied but using the reduced adjoint source covering the problematic region, to see for possible improvement in MC gamma dose distribution. All computational parameters for Denovo SN and Monaco MC were kept the same as in previous run to allow direct comparison. The forward Denovo run took 2.9 hrs, similar to the adjoint run of 3 hrs, amounting to 6.1 hrs for deterministic VR preparation. The Monaco MC simulation took total of 5.8 days.

The following pictures show selected results in primary pipes plane (z=342 cm) and third floor operating deck (z=1625 cm). The forward-weighted adjoint source in Figure 10 was again focused on air-regions only, excluding concrete objects, showing increased strength for distant and heavy-shielded parts of the model. Despite the smaller and more "focused" volumetric adjoint source, the MC gamma dose map errors presented in Figure 11 show difficulty for gamma ray penetration. Considering massive flux attenuation, it is safe to say how these interior portions of the auxiliary building will not be significantly exposed areas compared to the third floor and open free space above it, receiving much higher gamma dose rate due to streaming gamma rays from the containment building.

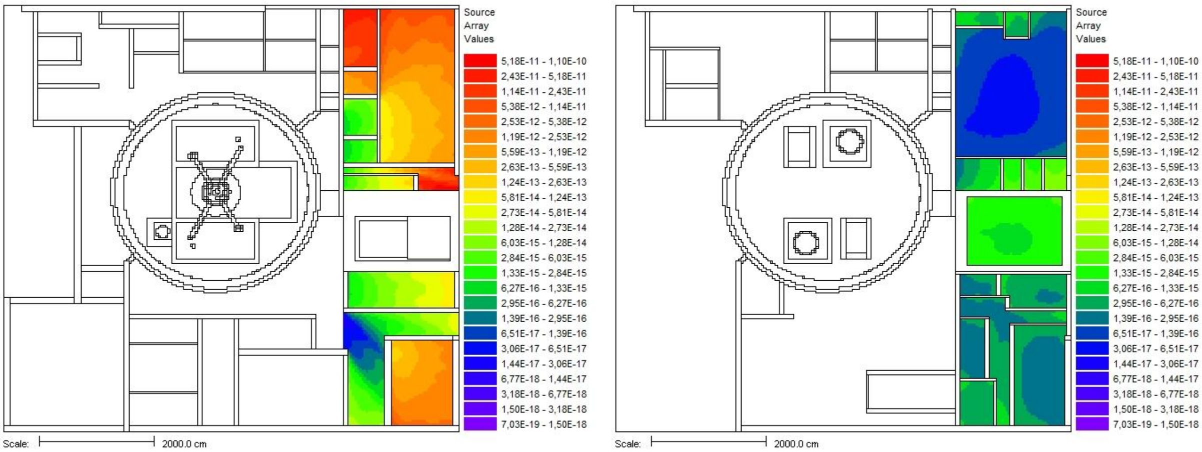

Figure 10: Forward-weighted adjoint source in planes 342 cm and 1625 cm

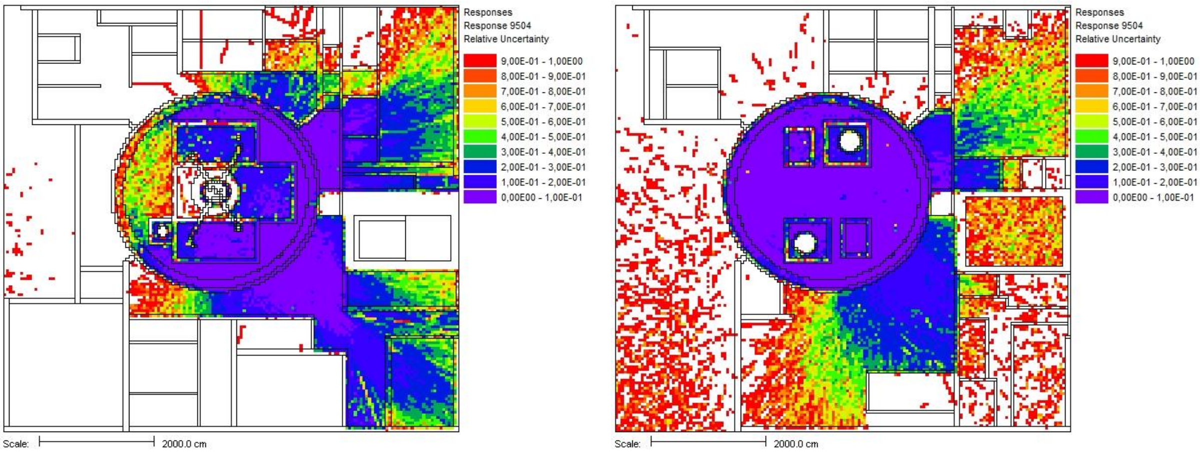

Figure 11: Gamma dose error maps in planes 342 cm and 1625 cm

The level of dose rate on operating deck south-east (elevation 1625 cm) approximated from the mesh tally is ranging from 5 to 1 rem/hrs, while the central point in containment at elevation 2750 cm has a dose rate of $8.86 \cdot 10^5$ rem/hrs. These results are in accordance with the previous MAVRIC run. However, smaller adjoint source with FW-CADIS did not result in more uniform gamma dose rates as expected, but rather indicated which areas are heavy shielded by concrete structures and thus less important for radiological impact. It is also interesting to notice how VR parameters are preferentially forcing photons to right part of the model, leaving other areas less populated with high MC error. This asymmetry in gamma dose map can be clearly seen in Figure 12 for axial plane y=0 cm.

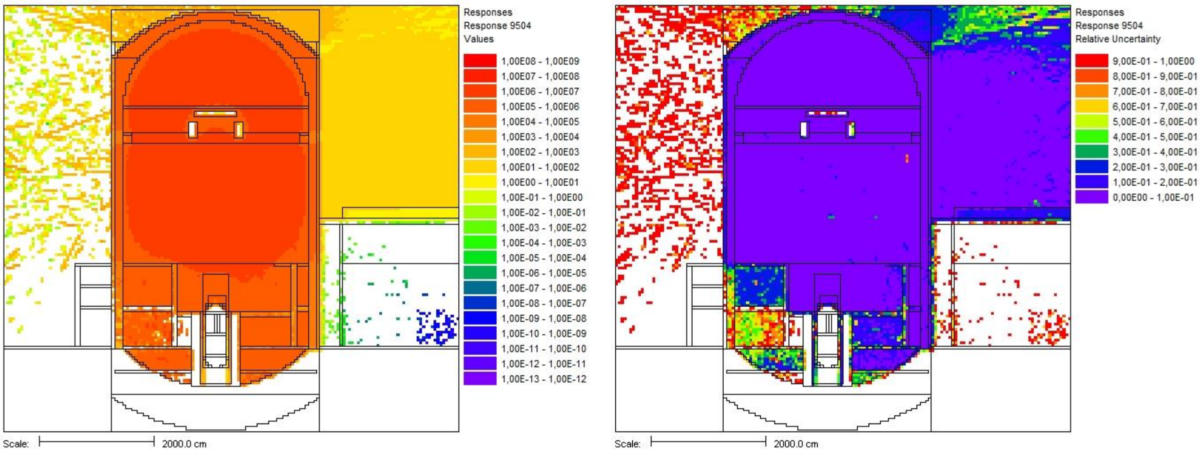

Figure 12: Gamma dose rates with relative errors in plane *y*=0 cm

6 THE CONTRIBUTON STREAMLINES

The reciprocity relations, often used in reactor shielding calculations, were briefly mentioned in Chapter 2 of the paper, where forward and adjoint flux (or importance function) were introduced in operator form of the linear transport equation. The contributon flux, as previously defined, is a concept from radiation shielding, which describes the flow of pseudo particles or contributons that directly contribute to a specific detector response or radiation tally. By mapping these flows, spatial channel theory identifies crucial locations, often high-flux areas, important for placement shielding materials to effectively prevent particle streaming or leakage. The contributons act like a fluid flow, streamlining the optimal path from the source to the detector. The regions with the highest contributon flux are the most efficient places for placing the shielding material, as these areas carry the maximum response toward the detector.

The scalar contributon flux can be constructed manually within hybrid shielding methods like FW-CADIS implemented in SCALE6.2.4 code, by folding space-energy dependent forward flux (source-driven) and adjoint flux (detector-driven). By using contributon-informed approaches, shielding analyses can be optimized in several ways, providing improved efficiency for final MC simulation, resulting in better results for complex, deep-penetration, or streaming scenarios.

The contributon theory was implemented in this work for the case of global adjoint source, to visualize gamma rays streaming paths most likely to contribute to global dose rates in case of accident scenario. The MAVRIC auxiliary routines were used to post-process the forward and adjoint SN flux solutions into a normalized contributon flux. Using the Java-based Mesh File Viewer within the SCALE code, the contributon map was inspected and "clipped" to a range [0-0.01] to keep only a crucial amount of information. The transformative steps on contributon flux were applied as presented in paper on RPV irradiation [22].

The following pictures (Figure 13-15) show normalized contributon flux map on three different model elevations (between floors) in parallel to gamma dose relative error map to easily correlate these variables. It is clear how areas with a high contributon concentration produce the response with a smallest MC error. The default legend label when plotting manually created contributon flux with Mesh File Viewer is misleadingly printed as "Adjoint Photon Flux", since this Java-based program was not foreseen for such applications.

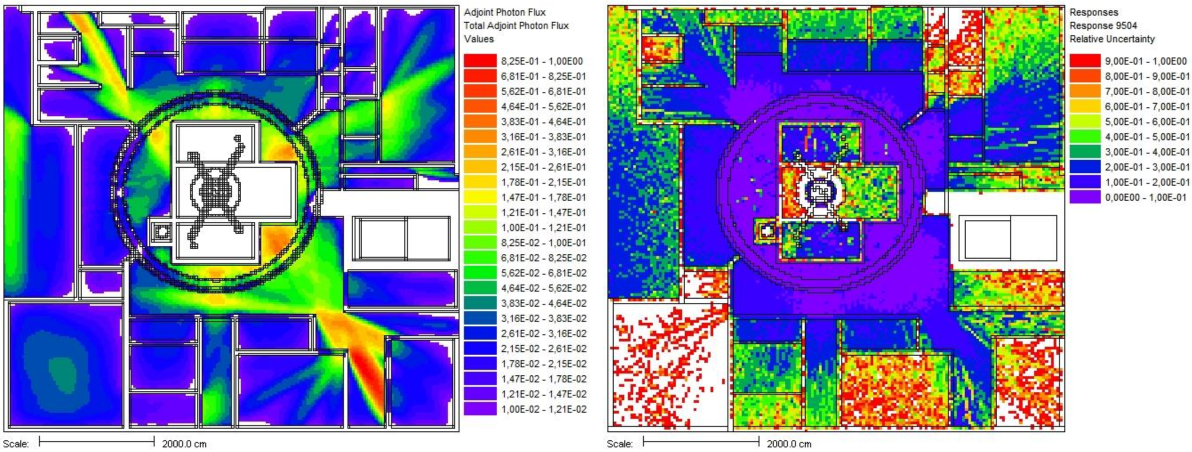

Figure 13: Contributon streamlines vs. gamma dose error (at 342 cm)

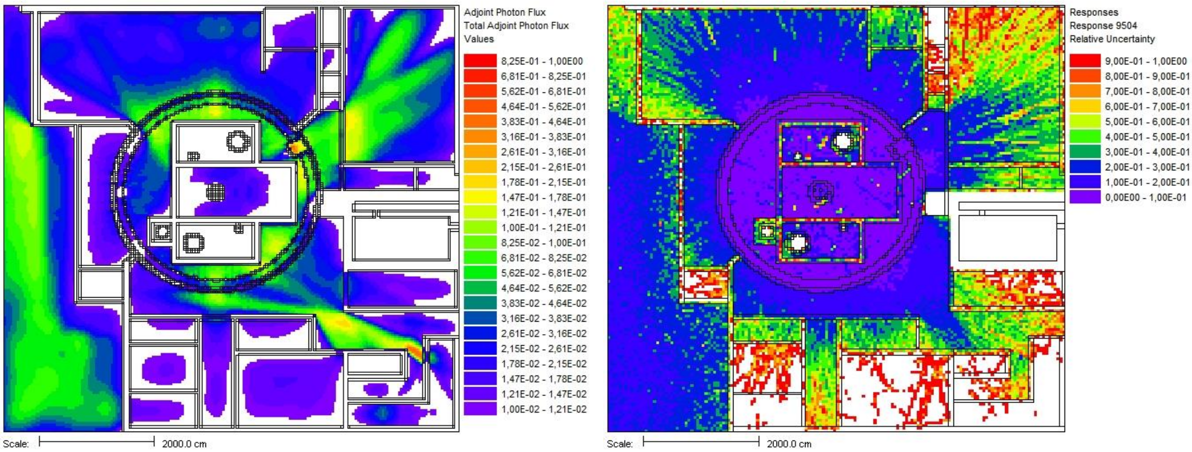

Figure 14: Contributon streamlines vs. gamma dose error (at 832 cm)

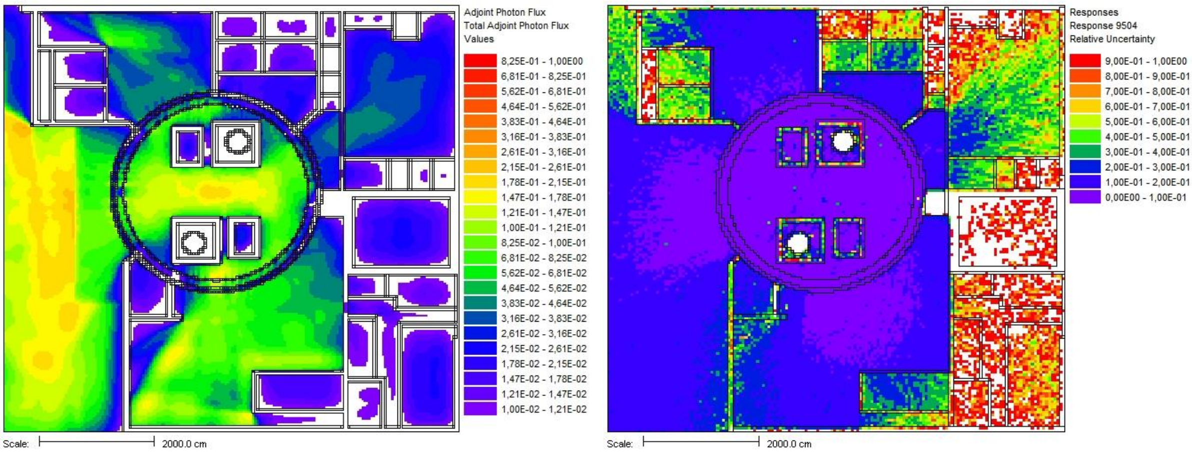

Figure 15: Contributon streamlines vs. gamma dose error (at 1625 cm)

The contributon streamlines in x=0 plane (see Figure 16) through containment building reveals the azimuthal symmetry in gamma ray streaming above the auxiliary buildings, which is also noticeable in relative errors of Figure 8.

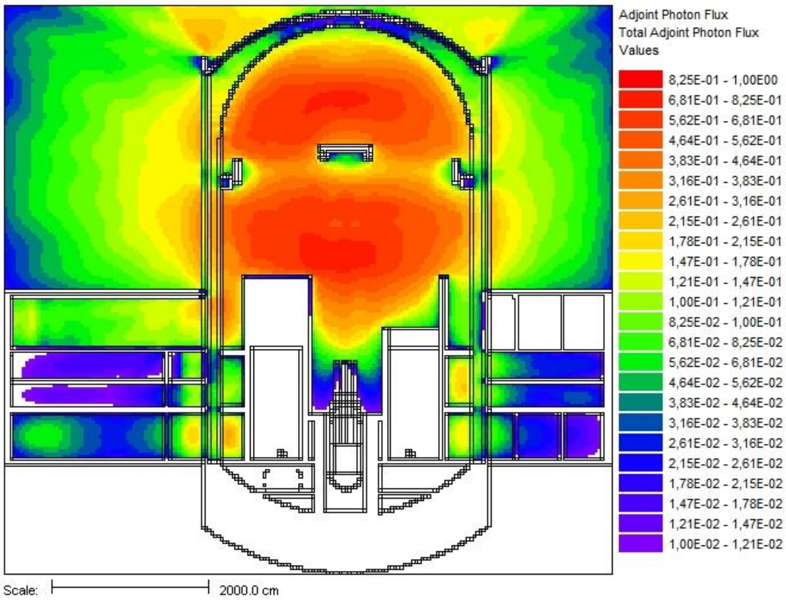

Figure 16: Contributon azimuthal symmetry in x=0 plane

At the moment, the normalized contributon flux was only used for inspection and visualization of the nuclear island model, to pin-point regions which receive a high gamma dose due to intense streaming paths from the containment. However, the step-forward in using the normalized contributon map is the subsequent local SN mesh refinement, aiming at improved deterministic solution by rebalancing the SN mesh. This is still an ongoing work and should be examined more thoroughly by further numerical analysis. The future work will address this possibility of reducing the total MAVRIC computational time using the contributon-informed approach.

7 CONCLUSION

The FW-CADIS hybrid shielding method of SCALE6.2.4 code implemented in MAVRIC sequence was successfully used for the problem of gamma dose mapping over the large NPP model. The driving source of emitted photons was case of hypothetical SBO accident with small LOCA scenario. The accident gamma source of uniform intensity was calculated with RADTRAD code using the 18-group energy structure of ORIGEN code and filling all accessible air regions of the containment interior. The photon flux distribution through different floors, sections and auxiliary buildings was quantified using the MC code Monaco, demonstrating a massive flux attenuation by concrete surroundings. The FW-CADIS proved to be a very versatile method, with flexible adjoint source positioning. The possibility to produce reasonable MC results everywhere in air-filled regions of the NPP island model proved to be a manageable task.

This model represents a challenging deep penetration shielding problem, entirely dependent on advanced VR techniques that will accelerate the MC flux convergence in specific regions of user's interest. For that purpose, MAVRIC will produce an importance map and biased source distribution, based on forward/adjoint solution by Denovo SN solver. The memory restriction dictated the choice of SN mesh, QR quadrature set, Legendre cross section expansion, and Krylov space size. The macromaterial option proved to be a very elegant way to refine the SN solution without calling for an extra computer memory.

Finally, the elements of contributon theory were implemented and presented in form of normalized streamlines indicating high gamma-ray streaming paths contributing significantly to global gamma dose outside the containment building. Future work will address several open questions: (1) possibility to reduce MAVRIC CPU time through FW-CADIS workflow by SN mesh refinement based on the contributon flux solution; (2) optimizing MC simulations for two different time steps during accident propagation i.e. dose maps at 2 h vs. 30 days following the SBO accident; (3) application of MAVRIC utilities for mesh tally objects so to produce gamma dose map ratio of different time steps with visualization of dose areas above the natural background radiation levels.

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