# Implementation of Photon Transport in STREAM

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## 1. Introduction

STREAM developed by the Computational Reactor Physics and Experiment Laboratory (CORE) at the Ulsan National Institute of Science and Technology (UNIST) is a deterministic neutron-transport code specialized for the analysis of two-dimensional or three-dimensional reactor cores [1]. Recently, the effort has been taken to implement a photon transport module in STREAM to extend the code's calculation capabilities.

The STREAM photon transport module presented in this paper has been implemented based on the adaptation of the existing MOC solver for the neutron calculation. The verification of this photon module is conducted with the use of VERA 1A problem [2]. STREAM results are in comparison with those obtained from Monte Carlo code MCS – also developed at UNIST [3].

## 2. Method and Results

### *2.1. Photon transport module in STREAM*

The photon transport equation is shown in Eq. (1).

$$\hat{\Omega}\cdot\nabla\psi_{\mathrm{ip}}+\Sigma_{t,ip}\psi_{ip}=\sum_{ip'=1}^{18}\Sigma_{s,ip'\to ip}\phi_{ip'}+Q_{ip} \qquad (1)$$

Where: $\psi_{\mathrm{ip}}$ is the angular photon flux in group *ip*.
$\Sigma_{t,ip}$ is the photon transport cross section of group *ip*
$\Sigma_{s,ip'\to ip}$ is the photon scattering cross section from group *ip'* to *ip*
$Q_{ip}$ is the neutron-induced gamma source

The equation has a similar form to the neutron transport equation, making it possible to adopt several parts of the existed MOC solver implemented for the neutron case.

After solving the eigenvalue problem, the gamma source $Q_{ip}$ is obtained by the convolution of the neutron flux with the gamma production cross section as shown in Eq. (2). The photon calculation was then performed as a fixed source problem.

$$Q_{ip}=\sum_{in\in ip}\phi_{in}^{neutron}\cdot\Sigma_{gp,in\to ip}^{total} \qquad (2)$$

Where $\phi_{in}^{neutron}$ is the neutron flux in group *in*
$\Sigma_{gp,in\to ip}^{total}$ is the gamma production cross section from neutron group *in* to photon group *ip*

Cross section data fed into the photon MOC solver is taken from a photon library generated for STREAM. This photon library is based on the ENDF/B-VII.1 library [4] with the use of NJOY code [5]. Generation of the multi-group photon library for STREAM is detailed in reference [6]. In short, this photon library includes the gamma production cross section and the photo-atomic cross section. Currently, the photon library in STREAM employ 72 neutron energy groups for the gamma production cross section and 18 photon energy groups for the photo-atomic cross section.

The production of gamma from neutron-induced reactions includes: capture, fission, inelastic scattering and other interactions that can also accompanied by gamma emission such as $(n,2n)$, $(n,p\alpha)$.

The photo-atomic cross section contains the total cross section, the scattering cross section, the pair production cross section, the photoelectric absorption cross section and the heat production cross section. The pair production is treated as $(\gamma,2\gamma')$ scattering and is incorporated into the scattering cross section $\Sigma_{s,ip'\to ip}$. Due to the assumption of isotropic scattering, the photon scattering cross section is corrected via out-flow transport correction [7].

The photon heating (photon KERMA) is obtained by the convolution of the photon flux obtained from the MOC fixed source solver with the heat production cross section as shown in Eq. (3).

$$KERMA=\sum_{ip}\phi_{ip}\cdot\Sigma_{ip}^{heat} \qquad (3)$$

### *2.2. Description of the VERA 1A and the comparison method with MCS code*

VERA 1A is a typical pin cell for a PWR. The pin cell has 3.1 wt.% enriched uranium oxide fuel and a pitch of 1.26 cm. The configuration of this pin cell is shown in Fig. 1. Both fuel and moderator temperature are set at 565K.

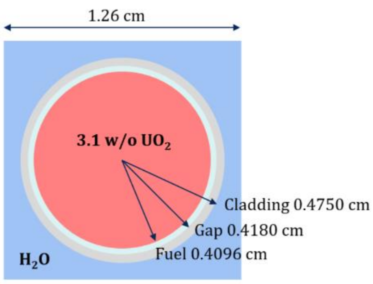


Fig. 1. VERA 1A pin cell.

The photon flux and photon KERMA in each material, namely fuel, gap, cladding and water are calculated and compared to solutions from MCS code. The photon transport capability of MCS and its ability to run the coupled neutron-photon transport mode have been presented in references [8,9]. Additional verification of this VERA 1A pin with MCNP6.1 code has been conducted but the difference between MCS and MCNP6.1 is trivial and therefore, not shown in this paper.

Because the results from Monte Carlo code are normalized by one starting particle while the solutions from STREAM can have an arbitrary magnitude. Thus, a scaling factor $C$ is applied for all STREAM results presented in this paper. The scaling C is defined as the ratio of the total fission source between MCS and STREAM as shown in Eq. (4):

$$C = \frac{MCS\ total\ fission\ source}{STREAM\ total\ fission\ source} \tag{4}$$

With a same system, the power or the number of fissions obtained from different codes should be similar, which is also the meaning for this factor $C$.

In addition, STREAM does not have the cross section for the fluorescence effect. However, NJOY incorporate the heating of fluorescence photon into the heating cross section based on an assumption that these fluorescence photons depositing its energies locally [5]. In other words, STREAM is not able to calculate the fluorescence photon source and dose not transport the fluorescence photons but the heating contribution from these fluorescence photons is partially accounted via NJOY assumption. Therefore, the fluorescence effect in MCS is turned off for photon flux comparison but turned on for KERMA comparison in the following section.

### *2.3. Results for VERA 1A pin cell*

Values of $k_{eff}$ are shown in Table 1.

Table I. $k_{eff}$ of pin cell VERA 1A.

| STREAM | MCS | Difference |
|---|---|---|
| 1.18645 | 1.18661±0.00023 | -16 pcm |

Because the gamma production and the photon flux are obtained based on the neutron flux, a comparison of the neutron flux in the fuel region between STREAM and MCS when applying the scaling factor $C$ is shown in Fig. 3.

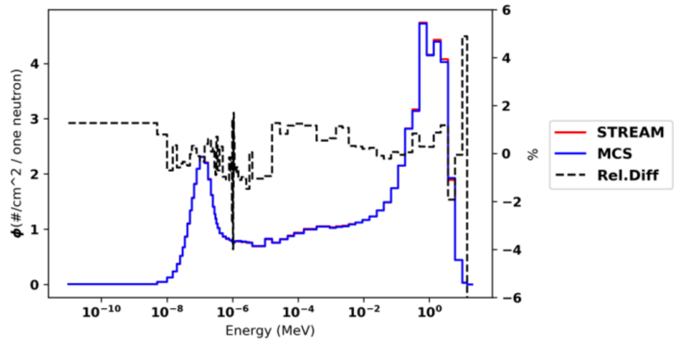


Fig. 3. Comparison of neutron flux in fuel region between STREAM and MCS with the use of scaling factor $C$.

There is a good agreement between the neutron flux of STREAM and MCS with the use of this scaling factor $C$. The photon flux in fuel, gap, cladding and water are presented in Fig. 4, 5, 6, 7, respectively (fluorescence turned off in MCS).

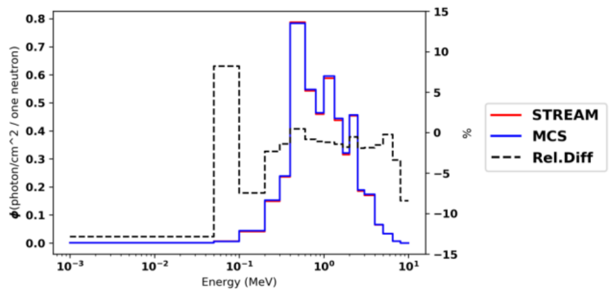


Fig. 4. Photon flux in fuel region.

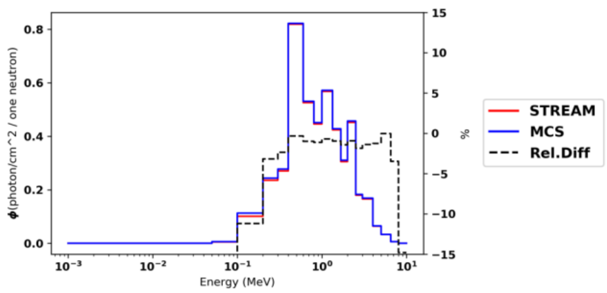


Fig. 5. Photon flux in gap region.

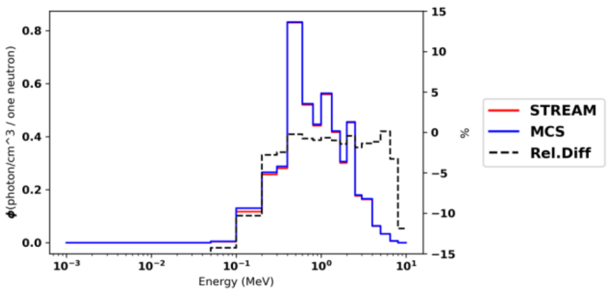

Fig. 6. Photon flux in cladding.

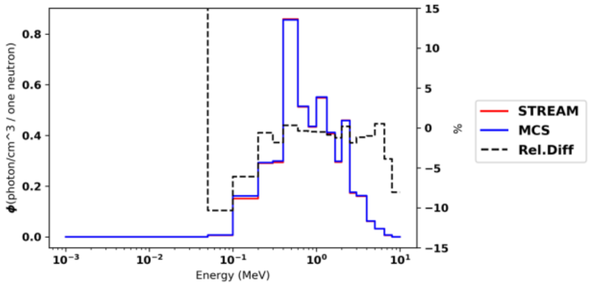

Fig. 7. Photon flux in water.

The photon flux shape and magnitude dose not differ much for different materials of this VERA 1A pin. Thus, the photon distribution in PWR system is relatively flat.

Higher differences are shown at the few first and last energy bins where the flux value is much lower than in other energy bins (around 15% for fuel and 30%-40% for cladding and water). In general, the photon flux between STREAM and MCS has a good agreement. The photon KERMA from STREAM is shown in Table II (fluorescence turned on in MCS).

Table II. STREAM photon KERMA

| Region | KERMA (MeV) | Diff. to MCS (%) |
|---|---|---|
| Fuel | 4.97 | 0.52 |
| Gap | 1.76E-06 | N/A |
| Cladding | 0.50 | -5.72 |
| Water | 0.31 | -1.02 |

No comparison is made for KERMA in gap as the value is rather low and associated with very high uncertainty in MCS. A good agreement is observed for KERMA in the fuel. The KERMA value for cladding and water in STREAM are lower than those obtained from MCS.

Most of the gammas are generated in the fuel as well as fluorescence photons. As mentioned in section 7.2 that fluorescence photons are not transported in STREAM and their energies are deposited locally, fluorescence photons from fuel are not transported to the cladding and water, thus making lower KERMA values in STREAM. Cladding, which is metal, can absorb more fluorescence photon compared to non-metal material such as water. Therefore, the difference for cladding region is higher, nearly 6% while only 1% difference is witnessed for water.

## 3. Conclusion

A photon transport module based on the present MOC neutron solver has been implemented in STREAM code. The photon flux obtained from this photon module for the VERA 1A problem show a good agreement with the solution from the Monte Carlo MCS code. Differences in the photon KERMA between STREAM and MCS can be root in the lack of fluorescence calculation in the deterministic code STREAM. Future work will involve further verification with fuel lattices and three-dimensional calculation with thermal hydraulic feedback.

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