

GPU-Accelerated Point-Kernel Dose Mapping from CFD Lagrangian Particle Data

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1. Study Background

Radiation conditions around plant buildings can change markedly over short distances because aerosol transport is affected by wakes and recirculation. This spatial variation is important when emergency workers enter the plant site. CFD particle tracking can describe the local dispersion, but the subsequent dose calculation becomes large when thousands of positions must be evaluated throughout a long transient.

In this study, an APR1400 station blackout (SBO) case with a CsI aerosol release was post-processed on a GPU. A distance-based lookup table (LUT) and parallel summation were used to retain all tracked parcels while producing dose maps over the full outdoor evaluation plane. The paper focuses on the calculation outline, computational scale, and worker-dose results.

2. Computational Method

2.1 CFD Data and Receptor Definition

Large-eddy simulation and Lagrangian tracking provided the transient flow and CsI parcel data. The dataset consisted of 2,228 HDF5 records covering 22,260 s. Dose was sampled every 10 m on a horizontal plane at $z = 1$ m. The CFD domain contained 20,915 candidate receptors; intersection with the Fluent building geometry identified 462 indoor points, leaving 20,453 outdoor receptors for worker assessment.

Figure 1 shows the time-dependent release rates used to define the accident source term. The present dispersion and dose calculation focused on the CsI aerosol component represented by the CFD particle records.

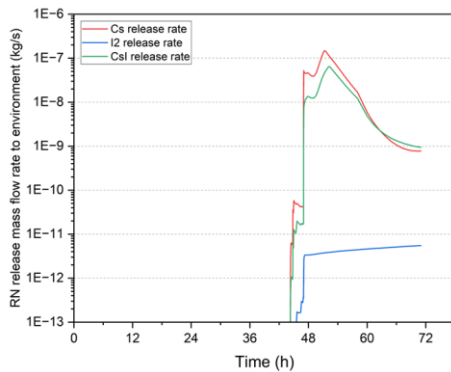


Fig. 1. Time-dependent radionuclide release rates used to define the accident source term.

2.2 Particle-Resolved Dose Formulation

At each output time, the external dose rate at receptor j was calculated by adding the mass-weighted terms from the tracked parcels,

$$\dot{D}_{(ext,j)}(t) = \sum_{p=1}^{N_{p(t)}} m_{p(t)} \cdot K_{(tot)}(r_{jp}) \quad (1)$$

where m_p is the CsI mass represented by parcel p and r_{jp} is its distance from the receptor. The integrated point kernel is

$$K_{(tot)}(r) = \sum_n f_n a_n \Gamma_n \cdot B_n(\mu_n r) \cdot \frac{e^{-\mu_n r}}{r^2} \quad (2)$$

where f_n , a_n , Γ_n , μ_n , and B_n represent radionuclide fraction, specific activity, gamma dose constant, air attenuation, and buildup, respectively [3,4]. Particle contributions were included across the entire CFD domain without an upper-distance truncation.

Inhalation dose was obtained from the CsI concentration assigned to each receptor using ICRP Publications 72 and 89 [5,6]. Air intake was set to 0.54 m³/h in the resting case and increased to 3.0 m³/h for heavy activity. Unprotected and self-contained breathing apparatus (SCBA) cases were represented by APF values of 1 and 10,000. External and inhalation terms were combined and integrated over the CFD time sequence.

2.3 GPU Implementation

Because the integrated kernel $K_{tot}(r)$ depends only on distance, its values were prepared once as a LUT. For each CFD record, parcel coordinates and masses were transferred as single-precision arrays, and the receptor-parcel distances, LUT interpolation, and dose summation were evaluated on the GPU.

The sequence is shown in Fig. 2. GPU-side parallelization avoided repeatedly calculating the full radionuclide kernel and reduced the need for large intermediate arrays. This was a computational optimization only: every parcel remained an individual contributor to the receptor dose. The calculation was performed with CuPy on an NVIDIA RTX 6000 Ada GPU.

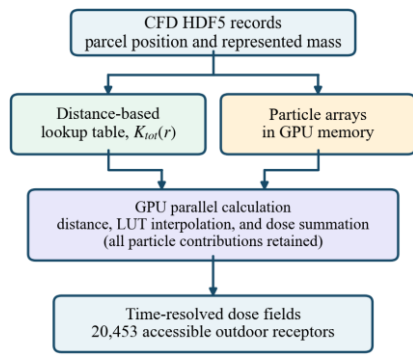


Fig. 2. Data flow of the GPU implementation for full-domain point-kernel summation.

3. Computational Results

3.1 Computational Performance

Parcels were present in 2,203 records, and the largest record contained 3.59 million parcels. A non-empty record required 0.891 s on average, corresponding to 7.49×10^{10} receptor-parcel pairs/s. The complete sequence, including aggregation and time-series extraction, was finished in about 34 min. A separate CPU comparison was not conducted.

3.2 Spatial and Cumulative Worker Dose

Figure 3 presents external and inhalation dose-rate maps at the same physical time of 5.66 h. The external field is distributed broadly around the release area, whereas the inhalation field follows the narrower aerosol plume. The highest accessible external rate in the time series was 5.90×10^{-4} $\mu\text{Sv/s}$, and the largest unprotected resting inhalation rate was 9.64 $\mu\text{Sv/s}$.

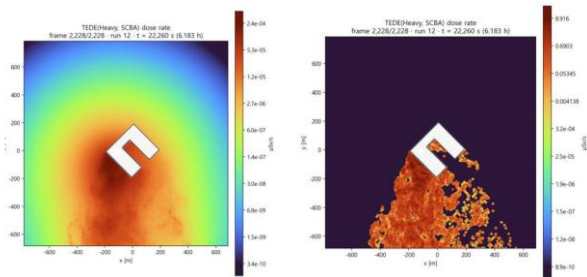


Fig. 3. External and inhalation dose-rate distributions at a common time of 5.66 h on the $z = 1$ m plane; gray areas denote excluded building interiors.

For the 6.18 h calculation, cumulative external dose reached 0.00534 mSv. Without respiratory protection, the most exposed receptors accumulated 6.68 mSv during resting and 37.1 mSv during heavy activity. With SCBA protection, these values decreased to 0.00596 and 0.00900 mSv. The results therefore

indicate that inhalation is important without respiratory protection, while the external pathway becomes relatively more important when SCBA is applied.

Figure 4 compares the maximum cumulative doses for the four worker conditions and shows the unprotected heavy-work dose history at the highest-dose receptor. In this case, 50% and 90% of the final dose were accumulated by 4.73 and 5.92 h, respectively.

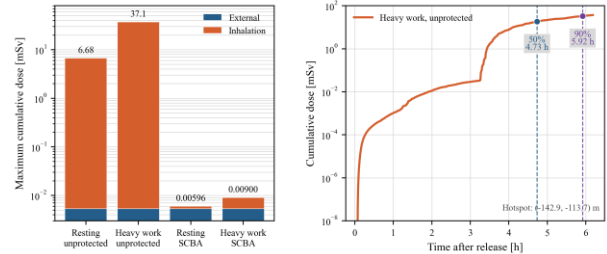


Fig. 4. Maximum cumulative dose by worker condition and the unprotected heavy-work dose history at the highest-dose receptor.

4. Conclusions

A GPU-assisted procedure was applied to convert CFD particle records into site-wide worker dose maps. LUT evaluation and parallel summation made the 2,228-record calculation practical without replacing the tracked particles with a simplified plume. Dose histories were obtained at 20,453 outdoor positions, and the comparison showed the strong effect of workload and respiratory protection on the worker dose. The resulting maps can be used to compare candidate work locations and protective-equipment conditions during emergency planning.

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