Study on the Delayed Gamma Dose Field of Fission Products Under Shock Wave Influence

Authors: Hu Jiaqi, Shang Peng, Jinhui Zhu, Zuo Yinghong, Liu Li, Niu Shengli, Wang Xuedong

Date: 2025-07-29T20:20:56+00:00

Abstract

Major nuclear accidents (such as severe reactor accidents, radioactive material terrorist attacks, etc.) are typically accompanied by violent explosions, and the ambient air surrounding the released fission products is inevitably disturbed by shock waves. To reasonably assess the delayed nuclear radiation environment formed by fission products, research on delayed gamma transport of typical fission nuclides under shock wave influence must be conducted. The Low Altitude Multiple Burst Revised (LAMBR) model, based on the image method, is employed to simulate the air density distribution around a delayed gamma source from fission under shock wave disturbance, analyzing the impact of shock waves on fission delayed gamma transport. Based on the mass-thickness equivalent attenuation law and combined with the LAMBR model, a rapid simulation method for fission delayed gamma transport under shock wave influence is established. The delayed gamma doses from fission of 235U, 239Pu, and 238U at ground measurement points are calculated and presented, and empirical formulas for the dose field are established, thereby obtaining the conversion relationships among the delayed gamma dose fields of the three fission nuclides. The calculated fission delayed gamma dose rates and doses are compared and analyzed with results from Monte Carlo methods and the equivalent cavity method. The gamma dose rates calculated by this method are generally consistent with Monte Carlo simulation results, but the computational time is significantly less than that required for Monte Carlo simulations. The study demonstrates that within 1000 m of the ground, as the distance between the source and the ground increases, the enhancement effect of shock waves on fission delayed gamma transport becomes progressively more significant. Furthermore, proportional relationships exist among the delayed gamma dose fields of 235U, 239Pu, and 238U fission.

Full Text

Study on Tissue Dose Field of Delayed Gamma Emitted from Fission Products Under Effects of Blast Wave

HU Jiaqi[1], SHANG Peng[1], ZHU Jinhui[1], ZUO Yinghong[1], LIU Li[1], NIU Shengli[1], WANG Xuedong[1]
[1](State Key Laboratory of Intense Pulsed Radiation Simulation and Effect, Northwest Institute of Nuclear Technology, Xi'an 710024, China)

Abstract

[**Background**] Major nuclear accidents (severe reactor accidents, radioactive material terrorist attacks, etc.) are typically accompanied by violent explosions, and the surrounding air of leaked fission products is inevitably disturbed by blast waves. To reasonably evaluate the delayed nuclear radiation environment formed by fission products, it is essential to investigate the transport of delayed gamma from typical fission nuclides under the influence of blast waves.

[**Purpose**] This study aims to analyze the effects of blast waves on the transport of delayed gamma and to calculate the tissue dose field of delayed gamma emitted from fission products of ^{235}U, ^{239}Pu, and ^{238}U under blast wave effects.

[**Methods**] First, the Low Altitude Multiple Burst Revised (LAMBR) model based on the method of images was employed to simulate the air density distribution around the delayed gamma source under blast wave disturbance. The mass thicknesses of air were calculated using the LAMBR model. Subsequently, the attenuation law based on mass thickness was applied to study the effects of blast waves on delayed gamma transport. By combining the attenuation law based on mass thickness with the LAMBR model, a fast simulation method for delayed gamma transport under blast wave effects was proposed to calculate tissue doses of delayed gamma. Then, the Monte Carlo method and the cavity method were also used to simulate the transport of delayed gamma under blast wave effects and to provide the tissue dose rates of delayed gamma. Finally, empirical formulas for ground-level tissue doses of delayed gamma under blast wave effects were proposed to illustrate the relationships between ground-level tissue doses of delayed gamma emitted from fission products of ^{235}U, ^{239}Pu, and ^{238}U.

[**Results**] The ground-level tissue doses of delayed gamma emitted from fission products of ^{235}U, ^{239}Pu, and ^{238}U were calculated using the fast simulation method, Monte Carlo method, and cavity method, respectively. Considering the effects of blast waves, the maximum relative deviation of tissue doses of delayed gamma reaches up to 45% at an altitude of 1000 m for 500 t TNT equivalents. The maximum relative deviation increased from 4% to 45% as the altitude increased from 100 m to 1000 m. The calculated results are broadly consistent with Monte Carlo simulations, but the computational time remains under 1 minute, which is orders of magnitude shorter than Monte Carlo simulations. The calculated tissue dose rates of delayed gamma are, on average, two times higher than the results of the cavity method. Furthermore, the average relative deviations between ground-level tissue doses calculated using the empirical formulas and the simulations remain within 13%.

[**Conclusions**] The results indicate that compared to calculations without blast wave effects, the transport of delayed gamma is significantly enhanced as the altitude of the delayed gamma source increases within the range below 1000 m. The calculated tissue dose rates based on the fast simulation method basically agree with Monte Carlo simulations and are higher than the results of the cavity method. Moreover, proportional relationships between ground-level tissue doses of delayed gamma emitted from fission products of ^{235}U, ^{239}Pu, and ^{238}U are found.

Keywords: Delayed gamma, LAMBR model, Tissue dose rates, Mass thickness, Monte Carlo method

Introduction

Nuclear energy is an important means to achieve a low-carbon economy and has been widely applied in power systems worldwide. Although nuclear power generation based on fission reactors offers advantages of low carbon emissions, sustainability, and high economic benefits, potential safety risks must be carefully evaluated. Studies show that fission products released in severe reactor accidents pose enormous threats to organisms and the environment. The gamma rays, neutrons, and beta rays spontaneously emitted from fission products are collectively called delayed nuclear radiation. Delayed neutrons have low yield and emission probability, and delayed beta rays have weak penetrability; therefore, delayed gamma dominates the delayed nuclear radiation environment. Since most fission products have long half-lives, delayed gamma can continue to harm the environment for considerable time.

Meanwhile, major nuclear accidents are typically accompanied by violent explosions, and the air around fission products exhibits complex distribution under blast wave disturbance. A vacuum region forms near the source center, with air density gradually increasing outward until reaching a peak, which affects the transport process of delayed gamma. In summary, studying delayed gamma transport under blast wave effects helps deepen understanding of radiation transport processes, and establishing typical delayed gamma dose fields for fission nuclides can provide fundamental support for radiation environment assessment in major nuclear accidents.

The Monte Carlo method is typically used to simulate transport of prompt nuclear radiation from fission reactions, obtaining statistical results through extensive sampling. Since prompt nuclear radiation is generated early and has short duration, its transport process does not require consideration of blast wave effects. However, delayed nuclear radiation has long duration, and air density exhibits complex distribution under blast wave disturbance, which affects particle transport and increases research difficulty. Using the Monte Carlo method to simulate delayed gamma transport requires establishing complex geometric models of air layout evolving over time and simulating multiple moments and scenarios, inevitably consuming substantial computational resources. Therefore, prompt nuclear radiation simulation techniques cannot be directly applied to rapid calculation of delayed gamma dose fields. To analyze blast wave effects on delayed nuclear radiation, the equivalent cavity method was proposed early on, assuming that blast wave compression forms a spherical vacuum cavity around the source, with unchanged air density outside the cavity. This assumption reduces modeling difficulty and improves computational efficiency, but the simplification of complex air density distribution under blast wave effects to a vacuum cavity distribution is somewhat crude.

Published experimental measurements show that the delayed gamma energy spectrum shape from ^{235}U fission at different times is similar, suggesting the source energy spectrum shape does not change over time. The delayed gamma energy spectrum shapes from ^{239}Pu and ^{238}U fission at each moment are also basically the same as that of ^{235}U, and the ^{235}U source energy spectrum can be used as a reasonable approximation. Therefore, the delayed gamma energy spectrum for the three fission nuclides at different moments can use the same shape in calculations. The delayed gamma time spectra from the three fission nuclides differ slightly, especially after 0.001 s, with intensity relationships of $^{238}\text{U} > {}^{235}\text{U} > {}^{239}\text{Pu}$. With identical energy spectrum shapes at different moments, the intensity proportion of each energy group emitted by the source does not change over time, but the total intensity is determined by the time spectrum. If the intensity proportion of each energy group emitted by the source does not change over time and only the transport medium geometry changes over time, the delayed gamma transport process can be analyzed based on the mass thickness equivalent attenuation law.

This paper employs the Low Altitude Multiple Burst Revised (LAMBR) model based on the method of images to simulate air density distribution under blast wave disturbance and analyze blast wave effects on delayed gamma transport. Based on the mass thickness equivalent attenuation law and combined with the LAMBR model, a fast simulation method for delayed gamma transport under blast wave effects is established. The transport processes of delayed gamma from ^{235}U, ^{239}Pu, and ^{238}U fission are studied, and the delayed gamma dose field at ground-level tally points is calculated and presented. Empirical formulas for the dose field are established, and conversion relationships between the three fission nuclide delayed gamma dose fields are obtained. Furthermore, calculated delayed gamma dose rates and doses are compared and analyzed with results from Monte Carlo methods and the equivalent cavity method.

1.1 Blast Wave Reflection Flow Field Calculation Method

When shock waves from explosions encounter solid walls, regular and irregular reflections occur sequentially. The flow field distribution is typically calculated quickly using the method of images. Taking the solid wall as a symmetry plane, real and corresponding virtual explosions are established on both sides. The flow fields of real and virtual explosions are determined based on one-dimensional spherical explosion free-field parameters, and the real reflected flow field distribution is obtained through linear or nonlinear superposition of the two. Previous studies show that the LAMBR model based on the method of images has obvious advantages in calculating physical quantities such as density and velocity in shock wave flow fields. Therefore, this paper adopts the LAMBR model to analyze air density distribution near the delayed gamma source.

Let the pressure, density, and velocity of the real explosion free-field at point P be p_r, ρ_r, and u_r, respectively, and those of the virtual explosion free-field at point P be p_i, ρ_i, and u_i, respectively. According to the LAMBR model, the flow field pressure at point P is expressed as:

$$p = p_0 \left[\frac{p_r}{p_0} + \frac{p_i}{p_0} \right]$$

where p_0 and ρ_0 represent the pressure and density of the undisturbed flow field before wave incidence, respectively. The flow field density at point P is expressed as:

$$\rho = \rho_0 \left[\frac{\rho_r}{\rho_0} + \frac{\rho_i}{\rho_0} \right]$$

where g represents the specific heat ratio. The flow field parameters of real and virtual explosions at any moment in the above formulas can be obtained based on free-field propagation laws using geometric approximation methods.

Calculations show that shock waves generated by isotropic explosion point sources cause layered air density distribution around the source, with air of the same density approximately distributed in spherical shells centered on the source. The air density is low near the explosion center and gradually increases outward to a peak.

1.2 Mass Thickness Equivalent Attenuation Law

Blast waves cause dramatic and complex changes in air density near the delayed gamma source, increasing the difficulty and computational time of Monte Carlo modeling. If two calculation regions have the same medium composition and satisfy geometric similarity conditions, it can be inferred that at positions with the same mass thickness, particle transport fluence and dose are only related to the square of the distance. This allows prediction of particle transport in regions with different densities from benchmark density regions, greatly improving calculation speed.

Assume two different calculation regions F_1 and F_2 with identical spatial material composition. If the material densities satisfy a proportional relationship $\rho_1(r) = k\rho_2(kr)$, then for any position r in F_1, there exists a corresponding position r' in F_2 such that $r' = kr$. Therefore, we have:

$$\int_0^r \rho_1(s)ds = \int_0^{r'} \rho_2(s)ds$$

Since the material composition of F_1 and F_2 is consistent, the scattering cross-section and attenuation coefficient in the transport equation are equal. Therefore, if the source term S is a point source at the same coordinate position in region F_1, then the total radiation field intensity and total dose at corresponding positions in F_2 satisfy:

$$\frac{D_1(r)}{D_2(r')} = \frac{1}{k^2}$$

This shows that for geometrically similar calculation spaces, under the same source conditions, the radiation field parameters at corresponding positions are inversely proportional to the square of the geometric scale.

Research on ionizing radiation protection shows that gamma ray transport laws in media are consistent with the above conclusions under specific conditions. The intensity of gamma rays transported to distance d from the source in the medium is expressed as:

$$N(d) = N_0 B e^{-\mu d}$$

where B represents the buildup factor, N_0 represents the initial gamma intensity, μ represents the mass attenuation coefficient, and md represents mass thickness, which is the integral of medium density over transport distance. The buildup factor for uniform media can be expressed as a function of mass thickness. When the source and medium composition remain unchanged, gamma ray intensity transported in media with the same mass thickness is identical. For non-uniform media with N layers, where layer 1 is closest to the source and layer N is the outermost layer, if the source is isotropic, the buildup factor is expressed as:

$$B = B_N + \sum_{n=1}^{N-1}(B_n - B_{n+1})$$

where B_n is the buildup factor for the n-th uniform medium layer and corresponding shielding thickness. The second term on the right side of equation (6) represents the buildup factor boundary difference. Therefore, the total buildup factor equals the buildup factor of the N-th uniform medium plus the sum of buildup factor boundary differences from layer 1 to layer $N-1$. For media with identical material composition and nuclide microscopic cross-sections, the buildup factor is only related to the sum of mass thicknesses of each layer.

In summary, shock waves generated by isotropic explosion point sources cause layered air density distribution around the source, with air of the same density approximately distributed in spherical shells centered on the explosion source. If the air density of each spherical shell is known, the mass thickness from source to tally point can be calculated. Using a sphere with uniform air density distribution as the benchmark scenario, the relationship between mass thickness and delayed gamma ray intensity from fission can be established through Monte Carlo particle transport simulation. Based on the mass thickness equivalent attenuation law in equation (4), rapid calculation of delayed gamma transport in air with complex density distribution can be achieved.

2.1 Shock Wave Enhancement Effects

An open scenario composed of ground and air was established, with all tally points located 1 m above ground level. The radiation source was set in the air, emitting isotropically, with the blast wave source coinciding with the radiation source. Explosions caused by hydrogen or nuclear fuel energy release in reactor nuclear power plant accidents generally have energy release less than 100 t TNT equivalent. In radioactive material terrorist attacks, terrorists may place radiation sources in conventional explosives to rapidly disperse radioactive materials through explosion. In conventional explosion accidents, the explosion power involved in the Tianjin Port incident was about 500 t TNT equivalent. Therefore, this study sets the upper limit of explosion power at 500 t TNT equivalent, the upper limit of source height above ground at 1000 m, and the upper limit of distance between the source's ground projection point and tally points at 4000 m. ^{235}U, ^{239}Pu, and ^{238}U are typical fission nuclides involved in nuclear reactors, and their delayed gamma source energy spectra and time spectra were taken from literature.

The mass thickness equivalent attenuation law was used to achieve rapid calculation of delayed gamma dose fields from ^{235}U, ^{239}Pu, and ^{238}U fission. First, Monte Carlo methods were used to simulate delayed gamma transport in the benchmark scenario to establish the correspondence between gamma intensity and mass thickness. Then, the LAMBR model was used to calculate the air density distribution around the source under blast wave disturbance. Finally, the mass thickness between source and tally points was calculated, and the gamma dose rates and doses at each tally point were rapidly predicted based on the mass thickness equivalent attenuation law.

For fission nuclide ^{235}U at a source height of 100 m, the calculated delayed gamma doses at ground tally points for blast wave source strengths of 100 t, 300 t, and 500 t are shown in Figure 1Figure 1: see original paper, where solid lines represent calculations considering blast wave effects and dashed lines represent calculations without blast wave effects. The relative deviations are shown in Figure 1(b), where relative deviation is defined as |Gamma dose (without blast wave) − Gamma dose (with blast wave)|/Gamma dose (with blast wave). The results show that blast waves have minimal effect on delayed gamma from fission, with a maximum relative deviation of only 4%.

For fission nuclide ^{235}U at a source height of 500 m, the calculated delayed gamma doses at ground tally points for blast wave source strengths of 100 t, 300 t, and 500 t are shown in Figure 2(a), with relative deviations shown in Figure 2(b). Compared to a source height of 100 m, the blast wave effect is significantly enhanced, with a maximum relative deviation of about 23%.

For fission nuclide ^{235}U at a source height of 1000 m, the calculated delayed gamma doses at ground tally points for blast wave source strengths of 100 t, 300 t, and 500 t are shown in Figure 3Figure 3: see original paper, with relative deviations shown in Figure 3(b). The results show that blast waves have a substantial effect on delayed gamma transport, and the enhancement effect becomes more significant with increasing blast wave source strength, with maximum relative deviations approaching 45%.

The calculated results for ^{235}U delayed gamma dose field show that blast wave effects become increasingly significant with increasing source height, particularly within 1000 m of the ground projection distance. Blast waves alter air density near the source, affecting delayed gamma transport. Taking 300 t blast wave source strength as an example, the air density distribution near the source at a height of 100 m is shown in Figure 4. The figure shows that blast waves cause approximately spherical air density distribution around the source that expands over time. A low-density region exists near the source center, with density gradually increasing outward to a peak. At 0.1 s, the shock wave propagates near the ground; at 0.2 s, the ground-reflected wave propagates to a position near the source; at 0.6 s, the ground-reflected wave propagates to about 200 m in the air, with the wave front still maintaining relatively high density.

The air density distribution near the source at a height of 500 m for 300 t blast wave source strength is shown in Figure 5[Figure 5: see original paper]. At 1 s, the shock wave propagates near the ground, but due to intensity attenuation during propagation, the ground-reflected wave is relatively weak at 2 s. Similarly, if the source height is 1000 m, the shock wave attenuates sufficiently before reaching the ground, with almost no ground-reflected wave remaining. Blast waves create low-density regions near the source that enhance gamma transport, while the high-density region at the wave front reduces gamma transport. At a source height of 100 m, the low-density region formed by the shock wave enhances gamma transport before 0.1 s, but after 0.1 s, the ground-reflected wave propagates upward, and the high-density region at the reflected wave front reduces gamma transport. The cumulative enhancement and reduction effects over time result in gamma doses at ground tally points similar to those without blast wave effects. As source height increases, ground-reflected shock wave intensity significantly weakens, no longer hindering gamma transport. Therefore, as source height increases, the enhancement effect of blast waves becomes more pronounced over the total time interval. The effects of blast waves on delayed gamma transport from ^{239}Pu and ^{238}U fission are similar to those for ^{235}U, with enhancement effects becoming more significant as source height increases.

The evolution of air mass thickness between source and ground tally points over time at a source height of 500 m for 300 t blast wave source strength is shown in Figure 6[Figure 6: see original paper]. The air mass thickness between source and different ground tally points gradually increases over time until reaching a constant value. The mass thickness increases significantly before 3 s, corresponding to the formation of a low-density air region near the source by the shock wave and subsequent rapid air backfill. After 3 s, the mass thickness slowly approaches a constant value, corresponding to the gradual recovery of air density near the source to the initial density. Based on the mass thickness equivalent attenuation law, assuming the source emits unit-intensity delayed gamma at any moment, the calculated gamma dose rates at tally points are shown in Figure 7[Figure 7: see original paper], where source intensity variation over time and geometric corrections are not yet considered. The results show that delayed gamma dose rates decrease as mass thickness increases because greater medium mass thickness leads to faster gamma intensity attenuation.

The time spectrum of delayed gamma from ^{235}U fission is shown in Figure 8[Figure 8: see original paper], obtained from the energy release rate of delayed gamma from ^{235}U fission. Combining the delayed gamma time spectrum with geometric corrections in equation (4), the delayed gamma dose rates at tally points are shown in Figure 9[Figure 9: see original paper]. The dose rate peaks at about 0.5 s and then decreases steadily over time, corresponding to the gradual recovery of air density to the initial density. The time integral of gamma dose rate yields the delayed gamma doses shown in Figure 2(a). The time variation trends of delayed gamma dose rates at tally points from ^{239}Pu and ^{238}U fission are similar to those for ^{235}U.

2.2 Monte Carlo Simulation Results

The Monte Carlo method is widely used in particle transport problems, obtaining approximate values of calculated quantities through extensive sampling. The air density distribution differs at each moment under blast wave effects, requiring geometric models to be established for different times. For ground projection distances greater than 3000 m, the distance from source to tally point far exceeds the mean free path of gamma ray transport in air, involving deep penetration problems. Since gamma rays undergo multiple scattering in air, direct simulation results in only a few particles reaching the detector position, causing large statistical fluctuations. This study employs the cell weight window combined with density approximation iterative variance reduction method, using weight window importance functions to guide particle splitting and roulette, combined with density approximation iteration, to achieve effective simulation of long-distance gamma ray transport in air. Specific details of Monte Carlo modeling and variance reduction methods will be discussed in future articles. The Monte Carlo method establishes models close to physical reality but requires substantial computational time.

For fission nuclide ^{235}U at a source height of 100 m and blast wave source strength of 300 t, the delayed gamma dose rates at ground tally points from 0.01 s to 15 s are shown in Figure 10[Figure 10: see original paper], where solid lines represent Monte Carlo simulation results and dashed lines represent mass thickness equivalent attenuation law calculation results. In Figure 10(a), the 0.01 s curve is multiplied by 0.01, the 0.05 s curve by 0.1, the 0.2 s curve by 10, the 0.3 s curve by 100, the 0.4 s curve by 1000, and the 0.5 s curve by 10000. The same operations are applied to curves in Figures 10(b) and 10(c). Monte Carlo simulated gamma dose rates are basically consistent with mass thickness equivalent attenuation law calculation results at each moment. Monte Carlo simulation values are slightly higher than mass thickness equivalent attenuation law calculation results in near ground projection distance regions, while slightly lower in far ground projection distance regions. This shows that air density distribution near the source under blast wave effects is not completely symmetric, but the mass thickness equivalent attenuation law remains well applicable to this scenario.

2.3 Equivalent Cavity Method Calculation Results

Blast waves cause air mass to concentrate mainly in narrow regions near the wave front, while forming spherical regions with very low air density behind the wave front. Therefore, the equivalent cavity method was early adopted to calculate delayed gamma dose rates and doses. The key point of the equivalent cavity method is using equivalent cavity radius to measure blast wave disturbance, with specific details available in literature. For fission nuclide ^{238}U at a source height of 100 m and blast wave source strength of 500 t, the delayed gamma dose rates at ground tally points calculated using the mass thickness equivalent attenuation law and equivalent cavity method are shown in Figure 11[Figure 11: see original paper]. The gamma dose rates calculated using the mass thickness equivalent attenuation law are generally higher than those from the equivalent cavity method, and the difference between the two decreases as ground projection distance increases.

The gamma dose rates calculated using the equivalent cavity method peak near 0.5 s and then decrease 平缓 ly, corresponding to the process where the equivalent cavity radius reaches its maximum and then gradually approaches zero. Compared with the equivalent cavity method, the mass thickness equivalent attenuation law considers the complex air distribution under blast wave disturbance, providing more realistic simulation of blast wave effects. Therefore, the dose rate calculation results indicate that the equivalent cavity method underestimates the enhancement effect of blast waves on delayed gamma transport.

The delayed gamma doses at ground tally points calculated using the mass thickness equivalent attenuation law and equivalent cavity method are shown in Figure 12[Figure 12: see original paper], where the 100 t curve is multiplied by 0.1 and the 500 t curve by 10. The delayed gamma doses calculated using the mass thickness equivalent attenuation law are generally greater than those from the equivalent cavity method, with similar trends. The two methods converge for ground projection distances above 3000 m.

The equivalent cavity radii corresponding to blast wave source strengths of 100 t, 300 t, and 500 t are shown in Figure 13[Figure 13: see original paper]. The equivalent cavity radius peaks before 0.5 s and then gradually decreases. The maximum equivalent cavity radius for 300 t is about 60 m, and at 2 s, the equivalent cavity radius is about 46 m. Figure 5 shows that the low-density cavity region formed by blast waves has a radius of about 100 m and lasts for a relatively long time, with the low-density cavity radius still approaching 100 m at 2 s. Therefore, the equivalent cavity method fails to accurately represent the enhancement effect of blast waves on delayed gamma transport, resulting in calculated gamma dose rates and doses lower than those from the mass thickness equivalent attenuation law. Figures 2 and 3 show that as ground projection distance increases, the effect of blast waves on gamma transport decreases. For ground projection distances above 3500 m, gamma doses calculated by the two methods are basically consistent, indicating that the equivalent cavity method is a good approximation for handling gamma transport under blast wave effects in far regions.

2.4 Empirical Formula for Fission Delayed Gamma Dose Field

Gamma intensity approximately satisfies an exponential relationship with transport distance in media, and buildup factors are generally used to represent deviations from exponential attenuation. Considering geometric attenuation, an empirical formula for the delayed gamma dose field is established:

$$D = A \cdot Q \cdot \frac{e^{-r/\lambda}}{r^2}$$

where Q represents blast wave intensity measured in TNT equivalent (t), r represents the distance between source and tally point (slant range) in meters, and A and λ are adjustable parameters.

By fitting the calculated results of the ^{235}U delayed gamma dose field, $A = 11.02 \times 10^5$ and $\lambda = 300.41$ were obtained. The comparison between the ^{235}U delayed gamma dose field empirical formula and numerical calculations based on the mass thickness equivalent attenuation law is shown in Figure 14[Figure 14: see original paper]. The empirical formula well reproduces numerical calculations within a slant range of 4000 m, with an average relative deviation of 12.67%. The parameters for ^{239}Pu and ^{238}U delayed gamma dose field empirical formulas obtained through fitting are $A = 9.82 \times 10^5, \lambda = 300.41$ and

$A = 22.05 \times 10^5$, $\lambda = 300.41$, respectively. The empirical formulas for ^{239}Pu and ^{238}U delayed gamma dose fields are basically consistent with numerical calculation results, with average relative deviations of 12.47% and 12.61%, respectively.

The parameters in the empirical formulas for ^{235}U, ^{239}Pu, and ^{238}U delayed gamma dose fields are summarized in Table 1. The three empirical formulas have the same exponential attenuation coefficient λ because the delayed gamma energy spectra emitted by the three nuclides at different times differ very little, and the energy spectra at each moment can be considered identical in use. λ represents the mean free path of gamma transport in air. When air density is the same, λ is only related to microscopic cross-sections. The microscopic cross-section is a function of incident gamma energy. Since the delayed gamma energy spectra from the three fission nuclides are identical, the mean free path of gamma transport in air is also the same. The mass attenuation coefficient of 1 MeV gamma in dry air is 6.359×10^{-3} m$^2 \cdot$ kg^{-1}, giving a mean free path of about 128 m in air under standard atmospheric conditions. The average energy of delayed gamma released from ^{235}U fission is 0.936 MeV, and the fitted λ is 300.41 m, indicating that the mean free path of delayed gamma significantly increases under blast wave effects, and gamma transport is enhanced. A is closely related to the delayed gamma time spectrum of the fission source. After 0.001 s, the gamma intensity released by ^{235}U is slightly higher than that of ^{239}Pu, while the gamma intensity released by ^{238}U is significantly higher than the other two. Therefore, parameter A reflects the relationship of gamma intensity.

In summary, based on the empirical formulas, the conversion relationships between ^{235}U, ^{239}Pu, and ^{238}U delayed gamma dose fields were obtained. Simple multiple relationships were found between the delayed gamma doses from the three nuclides at ground tally points, with the ratio of ^{238}U to ^{239}Pu delayed gamma doses being 2.25, and the ratio of ^{235}U to ^{239}Pu delayed gamma doses being 1.12.

3 Results and Discussion

Based on the mass thickness equivalent attenuation law and combined with the LAMBR model, a fast simulation method for delayed gamma transport under blast wave effects was established and applied to study delayed gamma transport from ^{235}U, ^{239}Pu, and ^{238}U fission under blast wave effects. The LAMBR model was used to calculate the complex air density distribution caused by blast waves and analyze the enhancement effect of blast waves on delayed gamma transport. The delayed gamma dose fields at ground tally points from ^{235}U, ^{239}Pu, and ^{238}U fission were calculated and presented, and empirical formulas were further established to obtain conversion relationships between the three fission nuclide delayed gamma dose fields. The calculated delayed gamma dose rates and doses were compared and analyzed with results from Monte Carlo methods and the equivalent cavity method.

The study found that as the distance between source and ground increases, the enhancement effect of blast waves on delayed gamma transport gradually increases. For a blast wave source strength of 300 t and source height of 1000 m, considering blast wave effects can increase gamma doses at ground tally points by up to 45%. This demonstrates that major nuclear accidents accompanied by violent explosions require consideration of blast wave effects to reasonably evaluate the radiation environment formed by delayed gamma from fission. Monte Carlo simulations of delayed gamma dose rates at ground tally points are close to calculations from the mass thickness equivalent attenuation law, indicating that this law is applicable to this scenario. Furthermore, the equivalent cavity method underestimates the enhancement effect of blast waves on delayed gamma transport in near regions, but its calculation results are close to those from the mass thickness equivalent attenuation law in far regions, indicating that the equivalent cavity method is a good approximation for handling delayed gamma transport under blast wave effects in far regions. The empirical formulas for ^{235}U, ^{239}Pu, and ^{238}U delayed gamma dose fields established in this work well reproduce numerical calculation results and further obtain conversion relationships between the three fission nuclide delayed gamma dose fields. The mean free path in the empirical formulas is significantly larger than that for gamma transport in uniform air, reflecting the enhancement effect of blast waves on gamma transport. The method established in this study can provide references for radioactive environment assessment in major nuclear accidents accompanied by explosions.

Author Contributions

HU Jiaqi was responsible for research design, paper writing, and revision; SHANG Peng provided guidance on calculation models and methods; ZHU Jinhui provided guidance on calculation methods; ZUO Yinghong provided overall guidance and review; LIU Li provided guidance on Monte Carlo simulations; NIU Shengli provided overall guidance and review; WANG Xuedong was responsible for model checking and testing.

References

1. Mourogov V M. Role of nuclear energy for sustainable development[J]. Progress in Nuclear Energy, 2000, 37(1–4): 19–24. DOI: 10.1016/S0149-1970(00)00018-4.
2. Liu L M, Guo H, Dai L H, et al. The role of nuclear energy in the carbon neutrality goal[J]. Progress in Nuclear Energy, 2023, 162: 104772. DOI: 10.1016/j.pnucene.2023.104772.
3. Grishanin E I. The role of chemical reactions in the Chernobyl accident[J]. Physics of Atomic Nuclei, 2010, 73(14): 2296–2300. DOI: 10.1134/S1063778810140073.
4. Fujisawa N, Liu S, Yamagata T. Numerical study on ignition and

failure mechanisms of hydrogen explosion accident in Fukushima Daiichi Unit 1[J]. Engineering Failure Analysis, 2021, 124: 105388. DOI: 10.1016/j.engfailanal.2021.105388.

5. Pakhomov S A, Dubasov Y V. Estimation of explosion energy yield at Chernobyl NPP accident[J]. Pure and Applied Geophysics, 2010, 167(4): 575–580. DOI: 10.1007/s00024-009-0029-9.
6. FU Yanjun, SHANG Peng, ZUO Yinghong, et al. Monte Carlo simulation of the effect of rainfall on neutron atmospheric transport[J]. Modern Applied Physics, 2022, 13(2): 49–54, 60. DOI: 10.12061/j.issn.2095-6223.2022.020207.
7. LIU Li, ZUO Yinghong, NIU Shengli, et al. A variance reduction method for simulating the long-distance transport of neutrons and secondary γ in high-altitude atmosphere by Monte Carlo method[J]. Modern Applied Physics, 2022, 13(1): 30–37, 59. DOI: 10.12061/j.issn.2095-6223.2022.010202.
8. LI Xiazhi, NIU Shengli, ZHU Jinhui. Calculation of space distribution of X-ray energy fluence from nuclear detonation in near space[J]. Modern Applied Physics, 2020, 11(1): 13–17. DOI: 10.12061/j.issn.2095-6223.2020.010201.
9. LIU Li, NIU Shengli, ZUO Yinghong, et al. Monte Carlo simulation of delayed γ-rays ionizing the atmosphere based on debris motion model[J]. Nuclear Techniques, 2024, 47(11): 110501. DOI: 10.11889/j.0253-3219.2024.hjs.47.110501.
10. LIU Li, ZUO Yinghong, NIU Shengli, et al. Application of global variance reduction methods for the calculation of γ radiation field in large space[J]. Nuclear Techniques, 2024, 47(2): 020602. DOI: 10.11889/j.0253-3219.2021.hjs.47.020602.
11. Editorial Committee of Military Training Textbooks of the General Armament Department of PLA. Introduction to the physics of nuclear explosion[M]. Beijing: National Defense Industry Press, 2003.
12. Fisher P C, Engle L B. Delayed gammas from fast-neutron fission of Th232, U233, U235, U238, and Pu239[J]. Physical Review, 1964, 134(4B): B796–B816. DOI: 10.1103/physrev.134.b796.
13. Walton R B, Sund R E. Delayed γRays between 2 and 80 sec after U235(n, f) andPu239(n, f)[J]. Physical Review, 1969, 178(4): 1894–1903. DOI: 10.1103/physrev.178.1894.
14. Popeko L A, Val'skii G V, Kaminker D M, et al. Delayed gamma rays from U235 fission[J]. Soviet Atomic Energy, 1965, 19(2): 1082–1085. DOI: 10.1007/BF01126435.

15. JIA Leiming, WANG Shufei, TIAN Zhou. A theoretical method for the calculation of flow field behind blast reflected waves[J]. Explosion and Shock Waves, 2019, 39(6): 94–102. DOI: 10.11883/bzycj-2018-0167.
16. ZHU Jinhui, LI Xiazhi, ZUO Yinghong, et al. Similarity theory of near-ground gamma-ray transport under different atmospheric density[J]. Modern Applied Physics, 2024, 15(6): 37–43. DOI: 10.12061/j.issn.2095-6223.202403003.
17. Gusev H F. Protection against ionizing radiation (Vol. 1)[M]. Beijing: Atomic Energy Press, 1998.
18. Chan P C, Klein H H. A study of blast effects inside an enclosure[J]. Journal of Fluids Engineering, 1994, 116(3): 450–455. DOI: 10.1115/1.2910297.
19. Kong B, Lee K, Lee S, et al. Indoor propagation and assessment of blast waves from weapons using the alternative image theory[J]. Shock Waves, 2016, 26(2): 75–85. DOI: 10.1007/s00193-015-0581-4.
20. Wu Z, Guo J, Yao X, et al. Analysis of explosion in enclosure based on improved method of images[J]. Shock Waves, 2017, 27(2): 237–245. DOI: 10.1007/s00193-016-0655-y.
21. XIE Zhongsheng, DENG Li. Numerical calculation method of neutron transport theory[M]. 2nd ed. Xi'an: Xi'an Jiaotong University Press, 2022.
22. International Nuclear Safety Advisory Group. INSAG-7 the Chernobyl accident: updating of INSAG-1[R]. INSAG-7, 1992.
23. U. S. Atomic Energy Commission Idaho Operations Office. IDO report on the nuclear incident at the SL-1 reactor[R]. IDO-19302, 1962.
24. FANG Qin, YANG Shigang, Chen Li, et al. Analysis on the building damage, personnel casualties and blast energy of the "8.12" explosion in Tianjin port[J]. China Civil Engineering Journal, 2017, 50(3): 12-18. DOI: 10.15951/j.tmgcxb.2017.03.002.
25. ZUO Yinghong, NIU Shengli, SHANG Peng, et al. Weight window variance reduction method for simulating long distance γ-ray transport[J]. Modern Applied Physics, 2020, 11(1): 37–42. DOI: 10.12061/j.issn.2095-6223.2020.010205.
26. XIA Yihua. Advanced course of ionizing radiation protection[M]. Harbin: Harbin Engineering University Press, 2010.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.