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NEUTRON AND SECONDARY GAMMA-RAY INDUCED HEAT
IN THE GROUND DUE TO POINT 12.2-15 MeV AND
FISSION SOURCES AT AN ALTITUDE OF 50 FEET

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NEUTRON PHYSICS DIVISION

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E. A. Straker, M. B. Emmett,* and M. L. Gritzner*

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NEUTRON AND SECONDARY GAMMA-RAY INDUCED HEAT IN THE GROUND DUE TO POINT 12.2-15-MeV AND FISSION SOURCES AT AN ALTITUDE OF 50 FEET

E. A. Straker, M. B. Emmett, and M. L. Gritzner

Abstract

The energy deposited in ground due to neutrons and the secondary gamma rays has been determined as a function of range, ground depth, and time from an instantaneous point neutron source with either a fission spectrum or a 12.2- to 15-MeV energy band. In all cases, the source was at a height of 50 feet above the air/ground interface. Discrete ordinates and Monte Carlo calculations illustrated that there is a significant effect on the energy deposited due to source energy distribution, but little effect due to small differences in ground composition. The importance of gamma rays produced by low-energy neutrons was found to be small for the 12.2- to 15-MeV source, but large for the fission source.

The energy deposited in concrete structures due to neutrons and their secondary gamma rays can be of importance in silo shielding studies. Previous calculations¹ illustrated the order of magnitude of heating effects from a 12.2- to 15-MeV source of neutrons and the resulting secondary gamma rays, but the effect of the source energy spectrum and the contribution from thermal-neutron capture was only estimated, and the effect of the ground composition (soil or concrete) was not investigated. In this paper the effects of these previously neglected parameters are determined.

Standard radiation transport techniques were used to determine the neutron and secondary gamma-ray fluence in the air-ground geometry. Steady-state neutron and gamma-ray fluences throughout the air and ground were obtained by a re-edit of the scalar fluence tape produced in previous calculations² with the discrete ordinates code DOT.^{3,4} The time dependence of the energy deposition was determined with the multigroup Monte Carlo code MORSE,⁵ which utilized the same cross sections as the DOT code.

The Monte Carlo calculation employed a collision density estimator for the flux in annular volume elements in the ground. Thus, the energy deposited is averaged over each of a number of volume elements having a particular inner and outer radius. To reduce the error in averaging over a volume covering a large radial variation in which the fluence might decrease rapidly, the average of $4\pi R^2$ fluence was obtained where R is the slant range from the source to the collision point at which the estimate was made. That is, the results are for $4\pi \times \text{avg}(R^2 \phi)$ instead of $4\pi \times (\text{avg } R)^2 \text{avg } \phi$. Thus, for the energy deposited at any given slant range X within an interval the results for the radial bin in which X lies should be divided by $4\pi X^2$.

By utilizing multigroup cross sections, the coupled neutron secondary gamma-ray transport was solved as one problem. Importance sampling included Russian roulette and splitting, the exponential transform, and gamma-ray source angle biasing. The cross sections for soil were the same as those used previously,⁴ and the cross sections for concrete were those generated by Fritz.⁶ Compositions of both the soil and concrete are given in Table 1.

EFFECT OF GROUND COMPOSITION

In determining the effect of the ground composition, radiation transport calculations were made for two media which had the specific components of either the soil or concrete. The resulting fluence obtained in each case was weighted by a concrete kerma factor to determine the energy deposited. Thus, any difference in the heating results is due only to the different fluence of neutrons and/or gamma rays. The kerma factors used here (see Table 2) include the combinations from charged-particle reactions in silicon and, for energies greater than 4 MeV, are different from those used previously.¹

Table 1. Ground Compositions

Soil		Concrete	
Element	Atomic %	Element	Atomic %
Hydrogen	16	Hydrogen	10.67
Oxygen	57	Oxygen	44.50
Silicon	19	Carbon	25.3
Aluminum	8	Magnesium	2.3
		Aluminum	0.75
		Silicon	2.12
		Calcium	14.10
		Iron	0.24
Density	1.7 g/cc	Density	2.3 g/cc

Table 2. Concrete Kerma Factors

Neutrons			Gamma Rays		
Group	Upper Energy (eV)	Concrete Kerma (ergs/gm)/(n/cm ²)	Group	Upper Energy (MeV)	Concrete Kerma (ergs/gm)/(γ/cm ²)
1	15.0(+6)*	1.78(-7)	1	10.0	2.65(-7)
2	12.2(+6)	1.41(-7)	2	8.0	2.18(-7)
3	10.0(+6)	1.05(-7)	3	6.5	1.8(-7)
4	8.18(+6)	8.40(-8)	4	5.0	1.46(-7)
5	6.36(+6)	5.9(-8)	5	4.0	1.18(-7)
6	4.96(+6)	5.43(-8)	6	3.0	9.8(-8)
7	4.06(+6)	5.8(-8)	7	2.5	8.4(-8)
8	3.01(+6)	4.1(-8)	8	2.0	7.15(-8)
9	2.46(+6)	3.2(-8)	9	1.66	6.15(-8)
10	2.35(+6)	3.5(-8)	10	1.33	5.05(-8)
11	1.83(+6)	3.12(-8)	11	1.0	4.1(-8)
12	1.11(+6)	2.61(-8)	12	0.8	3.3(-8)
13	5.50(+5)	1.48(-8)	13	0.6	2.42(-8)
14	1.11(+5)	3.55(-9)	14	0.4	1.68(-8)
15	3.35(+3)	1.58(-10)	15	0.3	1.20(-8)
16	5.83(+2)	2.85(-11)	16	0.2	8.0(-9)
17	1.01(+2)	7.1(-12)	17	0.1	1.20(-8)
18	1.90(+1)	5.0(-12)	18	0.05	5.0(-8)
19	1.07(+1)	6.35(-12)			
20	3.06(+1)	1.02(-11)			
21	1.12(+1)	1.63(-11)			
22	0.41(+0)	3.62(-11)			

*Read as 15.0×10^6 .

The effect of the ground composition on the total energy deposited was found to be less than 50%. In general, the difference in the heating between soil and concrete was largest at the maximum ground depth and indicates the effect of the density of the soil on the fluence deep in the ground. The energy deposited by neutrons, which is nearly always less than the energy deposited by secondary gamma rays, was affected the most. Since the variations were not large, most of the results shown here are the average of the results in each time and spatial bin obtained for the soil and concrete.

SPATIAL DISTRIBUTION (12.2- TO 15-MeV SOURCE)

The spatial distribution of the energy deposited is two dimensional; it is a function of both range and depth into the ground. Therefore, the results are presented both in terms of heating at specific depths as a function of range and for heating as a function of depth at specific ranges for both static and time-dependent calculations.

The variation with range in the energy deposited in the 0-2 cm, 4-7 cm, and 10-15 cm intervals of the ground is shown in Figs. 1-3 for the 12.2- to 15-MeV source. The solid curves are from the discrete ordinates calculations and the histograms from the Monte Carlo results. The vertical bars represent fractional standard deviations of the Monte Carlo results. Note that the relative importance of the neutron component decreases as the depth into the ground increases. There is reasonably good agreement between DOT and MORSE results. Note that for larger depths there is a sharp increase in the neutron component of the heat deposited as the range goes to zero. This is due to the high-energy neutrons penetrating deep into the ground because of the near-normal angle of incidence at small slant ranges.

The depth profiles in the range intervals of 50-100, 275-325, and 875-925 are shown in Figs. 4-6 for the 12.2- to 15-MeV source. Again, there is reasonably good agreement between the discrete ordinates results (solid curves) and the Monte Carlo results (histograms). The discrete ordinates results, which were obtained from the scalar fluences of previous calculations, stop at a depth of 50 cm since for the air-ground calculations,² a ground depth of 50 cm was used with an albedo at the vacuum boundary. Comparison with calculations for a 2-meter thickness of ground indicated that the 50-cm thickness with an albedo was satisfactory. These comparisons also indicate that there is no major effect caused by the albedo boundary. (The Monte Carlo calculations include a ground thickness of 10^6 cm.) From Figs. 4-6 it can be seen that the neutron component decreases relative to the gamma-ray component as both the depth and range are increased.

TIME DISTRIBUTION (12.2- TO 15-MeV SOURCES)

Some typical heating rates from Monte Carlo calculations are shown (Figs. 7-12) for range intervals of 50-100 and 275-325 meters in the 0-2, 4-7, and 10-15 cm depth intervals for the 12.2- to 15-MeV source. For the 50-100-meter interval, the time dependence of the energy deposited from gamma rays appears to consist of two components — one at short times ($\sim 10^{-5}$ sec) due to the fast neutron-induced gamma rays and one at later times due to low-energy capture gamma rays. This is very similar to time-dependent results obtained for infinite air.⁷

SPATIAL DISTRIBUTION (FISSION SOURCE)

For a fission source, essentially the same comments hold. Figures 13-15 illustrate the variation with range for the 0-2, 4-7, and 10-15 cm depth intervals. Note that the sharp upturn for small ranges is not as prominent as that for the 12.2- to 15-MeV source (see Figs. 1-3). This is due to the smaller penetrability of the lower-energy neutrons in the fission spectrum.

The variation of the induced heat with depth in the range intervals 50-100, 275-325, and 825-925 meters is shown in Figs. 16-18. Comparison of these results with those of Figs. 4-6 illustrates that for depths less than approximately 20 cm there is a significant difference in the heat deposited from a fission and a 12.2- to 15-MeV source, but for greater depths the total heat deposited is not much different (< 2 factor of 2) for the two sources. The magnitude of the gamma-ray component is essentially the same for the two sources for the 50-100 and 275-325 meter ranges, but the neutron component is significantly less (≈ 5 factor of 5) for the fission source. Thus, the factor of 2-5 greater energy deposited by the 12.2- to 15-MeV source is primarily in the top 15-20 cm of the ground.

TIME DEPENDENCE (FISSION SOURCE)

The heating rate in the range intervals of 50-100 and 275-325 meters for depths of 0-2, 4-7, and 10-15 cm is shown in Figs. 19-24. These curves are quite different from those of Figs. 7-12 for short times ($< 10^{-4}$ sec), but for later times the curves are very similar. Differences of approximately a factor of 30 in the maximum heating rates occur for the 12.2- to 15-MeV source compared to the fission source. Most of this difference is deposited in the top 15 cm of ground, and as the depth increases the heating rate curves become similar.

As postulated in reference 1, the energy deposited by a fission source never exceeds the energy deposited by a 12.2- to 15-MeV source. At large depths in the ground (1 meter) the energy deposited by each is comparable.

EFFECT OF GAMMA RAYS FROM LOW-ENERGY NEUTRONS

There are two components (neutron and gamma-ray) of the energy deposition in the ground. The neutron contribution becomes very small for low-energy (< 0.1 MeV) neutrons, and it is sometimes advantageous to divide the gamma-ray component into that part due to gamma rays from fast neutrons and that part due to gamma rays from low-energy neutrons. Because the computer time for Monte Carlo codes is approximately a factor of 3 longer for determining the complete neutron energy spectrum in air, frequently only the fast neutrons and their secondary gamma rays are considered. Therefore, the importance of ignoring the "low-energy neutron-induced gamma-ray" (LENIGR) component must be determined.

Data have been generated for a 12.2- to 15-MeV neutron source to evaluate the importance of the LENIGR component. The spatial distribution of the energy deposited for depths of 0-2 and 10-15 cm is shown in Figs. 25 and 26. The solid curve is the heating rate for all energy neutrons and their secondary gamma rays, and the dashed curve includes contributions from only the fast neutrons ($E > 0.11$ MeV) and their secondary gamma-ray component. For depths less than 15 cm, there is less than a factor of 2 difference in the energy deposited. However, the difference becomes more pronounced for greater depths as shown for ground range intervals of 50-100 and 275-325 meters in Figs. 27 and 28. At the larger range and for depths approaching 50 cm, there is a factor of 5 increase over the fast-neutron-induced heat if the total secondary gamma rays are considered. The time-dependent heating rate is shown in Fig. 29 for the range interval of 50-100 meters and for the top 2 cm. For times less than 10^{-4} sec, there is no effect (within statistics) on the time-dependent heating rate if the LENIGR component is ignored. Of course, at later times the total contribution is due to this component, but the peak heating rates are not affected.

The LENIGR component for the 12.2- to 15-MeV source was reasonably small except at large depths, large ranges, and long times. For a fission source, the spatial distribution for depths of 0-2 and 10-15 cm is given in Figs. 30 and 31. The effect of the LENIGR component is a factor of 2 for the top 2 cm and a

factor of 5 or larger for the 10-15-cm depth. The depth profiles for ground range intervals of 50-100 and 275-300 meters (see Figs. 32 and 33) further illustrate this effect with a difference of a factor of 100 for large depths and large ranges. However, as expected, the peak heating rate (see Fig. 34) is not affected by the LENIGR component, although it does affect the heating rates at times greater than approximately 10^{-3} sec.

SUMMARY

The spatial distribution of energy deposited is not separable in range and depth, and the effect of the source energy is small for large depths (> 20 cm) and large ranges (> 100 meters), but can be large (a factor of 5) for shallow depths or for short ranges. The maximum heating rate is approximately a factor of 30 greater for the 12.2- to 15-MeV source than for the fission source. The importance of the low-energy neutron-induced gamma-ray component is largest for a fission neutron source and increases with range, depth, and time, but is insignificant insofar as the peak heating rates are concerned.

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Fig. 1. Variation of $4\pi R^2$ Heating Per Source Neutron With Range For the 0- to 2-cm Depth Interval; 12.2- to 15-MeV Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 2. Variation of $4\pi R^2$ Heating Per Source Neutron With Range for the 4 to 7-cm Depth Intervals; 12.2- to 15-MeV Source.

Fig. 3. Variation of $4\pi R^2$ Heating Per Source Neutron With Range for the 10- to 15-cm Depth Interval; 12.2- to 15-MeV Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 4. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth For a Ground Range Interval of 50-100 Meters for a 12.2- to 15-MeV Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 5. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth for a Ground Range Interval of 275-325 Meters for a 12.2- to 15-MeV Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 6. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth for a Ground Range Interval of 875-925 Meters for a 12.2- to 15-MeV Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 7. Heating Rates Per Source Neutron Versus Time in the 0- to 2-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a 12.2- to 15-MeV Source.

Fig. 8. Heating Rates Per Source Neutron Versus Time in the 4- to 7-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a 12.2- to 15-MeV Source.

Fig. 9. Heating Rates Per Source Neutron Versus Time in the 10- to 15-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a 12.2- to 15-MeV Source.

Fig. 10. Heating Rates Per Source Neutron Versus Time in the 0- to 2-cm Depth Interval for a Ground Range Interval of 275-325 Meters for a 12.2- to 15-MeV Source.

Fig. 11. Heating Rates Per Source Neutron Versus Time in the 4- to 7-cm Depth interval for a Ground Range Interval of 275-325 Meters for a 12.2- to 15-MeV Source.

Fig. 12. Heating Rates Per Source Neutron Versus Time in the 10- to 15-cm Depth Interval for a Ground Range Interval of 275-325 Meters for a 12.2- to 15-MeV Source.

Fig. 13. Variation of $4\pi R^2$ Heating Per Source Neutron With Range for the 0- to 2-cm Depth Interval; Fission Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 14. Variation of $4\pi R^2$ Heating Per Source Neutron With Range for the 4- to 7-cm Depth Interval; Fission Source.

Fig. 15. Variation of $4\pi R^2$ Heating Per Source Neutron With Range for the 10- to 15-cm Depth Interval; Fission Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 16. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth for a Ground Range Interval of 50-100 Meters for a Fission Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 17. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth for a Ground Range Interval of 275-325 Meters for a Fission Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 18. Variation of $4\pi R^2$ Heating Per Source Neutron With Depth for a Ground Range Interval of 875-925 Meters for a Fission Source. Histograms are Monte Carlo results and the curves are discrete ordinates results.

Fig. 19. Heating Rates Per Source Neutron Versus Time in the 0- to 2-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a Fission Source.

Fig. 20. Heating Rates Per Source Neutron Versus Time in the 4- to 7-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a Fission Source.

Fig. 21. Heating Rates Per Source Neutron Versus Time in the 10- to 15-cm Depth Interval for a Ground Range Interval of 50-100 Meters for a Fission Source.

Fig. 22. Heating Rates Per Source Neutron Versus Time in the 0- to 2-cm Depth Interval for a Ground Range Interval of 275-325 Meters for a Fission Source.

Fig. 23. Heating Rates Per Source Neutron Versus Time in the 4- to 7-cm Depth Interval for a Ground Range Interval of 275-325 Meters for a Fission Source.

Fig. 24. Heating Rates Per Source Neutron Versus Time in the 10- to 15-cm Depth Interval for a Ground Range Interval of 275-325 Meters for a Fission Source.

Fig. 25. Spatial Distribution Per Source Neutron of the Energy Deposited in the 0- to 2-cm Depth Interval for a 12.2- to 15-MeV Source. —all neutrons and their secondary gamma rays; --fast neutrons and their secondary gamma rays.

Fig. 26. Spatial Distribution Per Source Neutron of the Energy Deposited in the 10- to 15-cm Depth Interval for a 12.2- to 15-MeV Source. —all neutrons and their secondary gamma rays; ---fast neutrons and their secondary gamma rays.

Fig. 27. Depth Distribution Per Source Neutron of Energy Deposited for the Ground Interval of 50-100 Meters for a 12.2- to 15-MeV Source. —all neutrons and their secondary gamma rays; --fast neutrons and their secondary gamma rays.

Fig. 28. Depth Distribution Per Source Neutron of Energy Deposited for the Ground Interval of 275-325 Meters for a 12.2- to 15-MeV Source. —all neutrons and their secondary gamma rays; ---fast neutrons and their secondary gamma rays.

Fig. 29. Time-Dependent Heating Rate Per Source Neutron for the 50-100 Meter Spatial Interval and the 0- to 2-cm Depth Interval Due to a 12.2- to 15-MeV Source. —all neutrons and their secondary gamma rays; ---fast neutrons and their secondary gamma rays.

Fig. 30. Spatial Distribution: Per Source Neutron of the Energy Deposited in the 0- to 2-cm Depth Interval for a Fission Source. —all neutrons and their secondary gamma rays; -fast neutrons and their secondary gamma rays.

Fig. 31. Spatial Distribution Per Source Neutron of the Energy Deposited in the 10- to 15-cm Depth Interval for a Fission Source. —all neutrons and their secondary gamma rays; -fast neutrons and their secondary gamma rays.

Fig. 32. Depth Distribution For Source Neutron of Energy Deposited for the Ground Interval of 50-100 Meters for a Fission Source. —all neutrons and their secondary gamma rays; -fast neutrons and their secondary gamma rays.

Fig. 33. Depth Distribution Per Source Neutron of Energy Deposited for the Ground Interval of 275-325 Meters for a Fission Source. —all neutrons and their secondary gamma rays; -fast neutrons and their secondary gamma rays.

Fig. 34. Time-Dependent Heating Rate Per Source Neutron For the 50-100 Meter Spatial Interval and the 0- to 2-cm Depth Interval Due to a Fission Source. —all neutrons and their secondary gamma rays; - -fast neutrons and their secondary gamma rays.