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**Radiation Transport in Earth for Neutron
and Gamma Ray Point Sources Above
an Air-Ground Interface**

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RADIATION TRANSPORT IN EARTH FOR NEUTRON AND GAMMA RAY
POINT SOURCES ABOVE AN AIR-GROUND INTERFACE*

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ABSTRACT

Two-dimensional discrete ordinates methods have been used to calculate the instantaneous dose rate in silicon and neutron and gamma ray fluences as a function of depth in earth from point sources at various heights (1.0, 61.3, and 731.5 meters) above an air-ground interface. The radiation incident on the earth's surface was transported through an earth-only and an earth-concrete model containing 0.9 meters of borated concrete beginning 0.5 meters below the earth's surface to obtain fluence distributions to a depth of 3.0 meters. The inclusion of borated concrete did not significantly reduce the total instantaneous dose rate in silicon and, in all cases, the secondary gamma ray fluence and corresponding dose are substantially larger than the primary neutron fluence and corresponding dose for depths greater than 0.6 meters.

I. INTRODUCTION

The nuclear radiation environment produced by air-over-ground nuclear weapon detonations is well documented.^{1,2} In these studies, the determination of the neutron and gamma ray radiation levels and the corresponding biological doses in the air was of primary concern. Although earth and seawater¹ were sometimes included in the geometric models used in these investigations, their inclusion was simply for the purpose of obtaining their effect on the radiation levels above these surfaces.

In the present study, the neutron and gamma ray radiation levels and the radiation damage in silicon as a function of depth well below (3.0 m) the earth's surface are calculated. The radiation damage in silicon as a function of depth in earth from nuclear weapons blasts is of interest because of the potential future use of fiber optic cables in defense related communication systems. While fiber optic transmission lines are not affected by the electromagnetic pulse (EMP)³ associated with nuclear detonations, they are sensitive to radiation damage. The radiation damage causes changes in the light absorption characteristics of the cable, resulting in signal loss which, per unit length of cable, is proportional to the total dose received by the cable.⁴

The integrated neutron and gamma ray ionization doses in silicon as a function of depth in earth were calculated using discrete ordinates methods to obtain fluence distributions in earth to a depth of 3.0 m. These calculations were performed for both prompt neutron and prompt gamma ray point sources located at heights of 1.0, 61.3, and 731.5 m above an air-ground interface. Line integrals over approximately 2800 meters of cable were obtained by folding neutron and gamma ray ionization response functions for

silicon with the appropriate fluence distributions. In all cases, the fiber optic cables were assumed to be at a lateral distance of 396.0 m from the source. (This distance was chosen to simulate a possible crater size, i.e., the range of blast damage.)

The prompt neutron and prompt gamma ray sources yielded fluences due to prompt neutrons, prompt gamma rays, and secondary gamma rays caused by inelastic neutron scattering and thermal neutron capture. Neutrons and gamma rays due to fission product decay and gamma rays due to isomeric transitions were not considered.

The calculational models and the parameters, i.e., material compositions, cross sections, etc., used in these models, together with the calculational procedures are discussed in Section II. The neutron and gamma ray doses due to ionization in silicon and a selected number of fluences versus depth in earth are presented and discussed in Section III.

II. CALCULATIONAL MODELS AND PROCEDURES

The radiation transport calculations were performed using the DOT IV discrete ordinates code⁵ in two-dimensional cylindrical geometry with an S_8 (48 angles) angular quadrature. Two geometric models were required to perform the transport calculations due to the large depths in the earth (3.0 m) at which results were desired. An above-ground model consisting of a cylinder with a height of 1050 m and a radius of 1500 m was employed to calculate the radiation transport in air. In this model, the lower 0.5 m of the cylinder was comprised of earth with air comprising the remainder of the cylinder. An earth model also described by a 1500 m radius cylinder but having a height of 3.0 m and comprised entirely of earth was employed

to calculate the radiation transport in earth.

The overall geometry showing the two overlapping calculational models is depicted in Fig. 1. The 0.5 m earth overlap was needed to properly account for multiple scattered particles, i.e., those which are scattered into the air by the earth and then reenter the earth. The change in air density at high altitudes was simulated in the calculations by employing two air densities. The line of demarcation was arbitrarily placed at 200 m above the air-ground interface. The area of coupling between the two models, i.e., the air-ground interface is also noted in Fig. 1 as the coupling boundary.

The material compositions for air, earth and borated concrete together with the ENDF/B-IV cross section material numbers of the elements comprising these compositions are listed in Table I. The two compositions for air represent air at S.T.P. density and air at 90% of S.T.P. density. The composition for earth, which has been used in previous studies¹, represents Nevada dry soil to which 8% water by weight has been added. This type of soil is fairly dry, as most soils contain 4 to 30 percent water by weight, and as such should yield conservative estimates of the radiation levels in earth. The composition of the borated concrete was obtained by adding 1 atom percent natural boron to the Oak Ridge National Laboratory Tower Shielding Facility concrete.⁶

The cross sections used in the radiation transport calculations consisted of a 37 neutron, 21 gamma ray energy group library.⁷ The angular dependence of the scattering cross sections was approximated by a P_3 Legendre expansion for both the neutron and gamma ray groups. The primary neutron and gamma ray source spectra corresponding to this group structure

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Fig. 1. Schematic diagram of geometric model with overlapping calculational models.

Table I. Material Compositions and Cross Sections Used in Calculations

Element	Cross Sections ENDF/B-IV Mat. No.	Compositions (atoms/barn-cm)			
		Air ($\rho=1.22 \times 10^{-3} \text{ g/cm}^3$)	Air ($\rho=1.1 \times 10^{-3} \text{ g/cm}^3$)	Earth ($\rho=1.7 \text{ g/cm}^3$)	Borated Concrete ^b ($\rho=2.3 \text{ g/cm}^3$)
H	1269			9.77-3	8.50-3
N	1275	4.02-5 ^a	3.62-5		
O	1276	1.07-5	9.65-6	3.48-2	3.55-2
C	1274				2.05-2
B-10	1159				1.59-4
B-11	1160				6.43-4
Al	1193			4.88-3	6.00-4
Si	1194			1.16-2	1.70-3
Mg	1280				1.86-3
Ca	1195				1.13-2
Fe	1192				1.90-4

^aRead as 4.02×10^{-5}

^bContains 1 atom percent natural boron

are given in Table II. The neutron spectrum consists of a 14-MeV spectrum (groups 2 through 6) and a fission spectrum (groups 9 through 28).⁷ The relative magnitude of these two spectra were chosen such that the fission neutrons represented only 10% of those in the 14-MeV spectrum. The gamma ray spectrum corresponds to a prompt fission source.⁷ Both the neutron and gamma ray spectra are normalized to one source particle.

The radiation transport calculations were carried out in four steps for each source height for both the prompt neutron and prompt gamma ray sources. These steps consisted of calculating the uncollided fluence and collided fluence incident on the air-ground interface, converting these fluences to a boundary source, and transporting the particles from this source through the earth.

The uncollided fluence and first collision source code GRTUNCL⁸ was utilized first to eliminate fluence distortions, i.e., "ray effects", which occur in discrete ordinates calculations when point or isolated sources exist in a weakly scattering medium such as air. This code employs a semi-analytic approximation to determine the uncollided fluence and first collision scattering source moment distributions throughout the calculational geometry. The spatially-dependent scattered source distribution obtained from GRTUNCL was input to DOT IV which generated an angular dependent internal boundary fluence distribution at the air-ground interface in the above-ground model geometry.

The angular-dependent fluence distribution calculated by DOT IV represents the source strength of collided particles and secondary gamma rays entering the earth's surface. To obtain the total source strength of radiation incident on the earth's surface, the angular direction of the

Table II. Energy Spectra of Neutron and Gamma Ray Sources ^a

Group No.	Neutron		Gamma Ray	
	Upper Energy (eV)	Source (Neutrons)	Upper Energy (eV)	Source (Gamma Rays)
1	1.96+7 ^b	0.0	1.40+7	1.67-5
2	1.69+7	1.72-2	1.00+7	1.35-4
3	1.49+7	2.84-1	8.00+6	3.05-4
4	1.42+7	2.84-1	7.00+6	9.18-4
5	1.38+7	3.22-1	6.00+6	2.76-3
6	1.28+7	3.97-3	5.00+6	8.28-3
7	1.22+7	0.0	4.00+6	2.99-2
8	1.11+7	0.0	3.00+6	2.73-2
9	1.00+7	3.99-4	2.50+6	4.74-2
10	9.05+6	3.18-4	2.00+6	8.21-2
11	8.19+6	4.90-4	1.50+6	1.43-1
12	7.41+6	6.68-4	1.00+6	1.31-1
13	6.38+6	1.67-3	7.00+5	1.49-1
14	4.97+6	2.95-4	4.50+5	1.10-1
15	4.72+6	7.70-4	3.00+5	1.30-1
16	4.07+6	5.00-3	1.50+5	4.84-2
17	3.01+6	2.95-3	1.00+5	3.04-2
18	2.39+6	9.64-4	7.00+4	2.61-2
19	2.31+6	8.84-3	4.50+4	1.60-2
20	1.83+6	1.34-2	3.00+4	1.08-2
21	1.11+6	1.96-2	2.00+4	1.09-2
22	5.50+5	1.36-2	1.00+4	
23	1.58+5	1.75-3		
24	1.11+5	1.10-2		
25	5.24+4	5.21-3		
26	2.48+4	5.95-4		
27	2.19+4	2.18-3		
28	1.03+4	1.31-3		
29-37	3.35+3 ^c	0.0		

^aBoth spectra are normalized to one source particle^bRead as 1.96×10^7 ^cLower energy limit of group 37 is 1.00-5 eV

uncollided fluence generated with GRTUNCL was determined at each space point along the air-ground interface. The total source was then obtained by adding the uncollided fluence to the nearest directional internal boundary angular fluence calculated by DOT IV.

The radiation transport in earth was calculated using the earth model geometry and treating the total angular fluence distribution at the earth's surface as an external boundary source. Coupling the above-ground and earth models in this manner required the use of equivalent radial meshes in both models. Near the cylinder axis, i.e., the source locations, a fine radial mesh size with a $\Delta R \leq 1$ m was chosen to conserve particles in the GRTUNCL calculations. At radial distances far from the source, the radial mesh was chosen such that $R_i \leq 1.3 R_{i-1}$ with a maximum allowable mesh size of 30 m. Although 30 m represents a very large mesh interval size, this distance corresponds to less than one neutron mean free path in air for the range of neutron energies used in this study. In earth, these large interval sizes do represent a considerable number of mean free paths. However, very little radiation transport occurs radially in earth as particles incident on the earth at small grazing angles must travel large radial distances to penetrate even small depths. This is particularly true for radial distances far from the source locations where these large radial mesh sizes were used.

The criteria used in selecting the axial mesh sizes in air was identical to that used in selecting the radial mesh sizes. The axial mesh sizes in earth varied from 0.01 m near the air-ground interface to 0.05 m below a depth of 0.4 m in the above-ground model. In the earth model, a constant ΔZ of 0.05 m was employed at all depths.

The neutron and gamma ray fluence distributions calculated by DOT IV were integrated to obtain the total fluence incident on fiber optic cables buried at various depths in the earth. These integrals were numerically approximated for each axial mesh interval in the earth model using

$$L_{j,g} = \sum_i \phi_{i,j,g} \Delta x_i, \quad (1)$$

where $L_{j,g}$ = the line integrated average fluence in axial mesh interval j and energy group g ,

$$\Delta x_i = x_{i+1} - x_i,$$

$$x_i = (r_i^2 - a^2)^{1/2},$$

r_i = the inner radius of radial mesh interval i ,

a = the lateral distance between source locations and the fiber optic cables, i.e., 396 m

and $\phi_{i,j,g}$ = the average neutron or gamma ray fluence in radial interval i , axial interval j and energy group g .

The line integrals were performed over approximately 2800 m. To obtain the total dose received by a cable, the line integrated fluences were folded with neutron and gamma ray ionization response functions for silicon. These response functions are listed in Table III⁷ for the 37 neutron, 21 gamma ray energy group structure used in the fluence calculations. The folding process was performed by evaluating

$$D_j = \sum_g F_g L_{j,g} \quad (2)$$

where D_j = the total neutron or gamma ray dose received by a fiber optic cable located in axial mesh interval j

and F_g = the neutron or gamma ray ionization response function for silicon in group g .

Table III. Neutron and Gamma Ray Ionization
Response Functions for Silicon

Group No.	Response Function (Rad - m ² /Particle)		Group No.	Response Function (Rad - m ² /Particle)	
	Neutron	Gamma Ray		Neutron	Gamma Ray
1	9.19-14 ^a	3.85-13	16	6.05-15	7.45-15
2	9.19-14	2.94-13	17	4.23-15	8.36-15
3	9.19-14	2.49-13	18	4.78-15	1.45-14
4	9.19-14	2.18-13	19	4.19-15	3.21-14
5	9.19-14	1.86-13	20	2.94-15	7.39-14
6	1.01-13	1.55-13	21	1.94-15	2.26-13
7	1.08-13	1.22-13	22	1.28-15	
8	1.15-13	9.80-14	23	5.52-17	
9	1.16-13	8.28-14	24	8.89-17	
10	1.12-13	6.72-14	25	4.22-17	
11	1.03-13	5.07-14	26	2.80-17	
12	7.69-14	3.68-14	27	1.98-17	
13	3.03-14	2.66-14	28	4.10-19	
14	1.02-14	1.84-14	29-37	0.0	
15	8.52-15	1.12-14			

^aRead as 9.19×10^{-14}

III. DISCUSSION OF RESULTS

The silicon doses over the length of cable versus depth in earth obtained in the present study are displayed in Fig. 2. The doses caused by neutron ionization due to one prompt source neutron are presented in Fig. 2a for each of the three source heights. In Fig. 2b, the secondary gamma ray ionization doses due to one prompt source neutron are presented and the primary gamma ray ionization doses due to one prompt source gamma ray are presented in Fig. 2c.

The ionization doses due to the prompt neutron source, i.e., the prompt neutron and secondary gamma ray doses, are largest at all depths for the 61.3 m source height followed in order by the doses obtained for the 1.0 and 731.5 m sources, respectively. The 1.0 m source is so close to the earth that all source neutrons entering the earth's surface more than a few meters from this source must enter at small grazing angles. Many of these neutrons scatter back into the air particularly those striking the earth at lateral distances greater than 396 m (shortest source-cable distance). Those which do remain in the earth must either travel large lateral distances or lose much of their energy, i.e., undergo a few large angle scatterings or many small angle scatterings, to penetrate even shallow depths. The 731.5 m source yields smaller doses because the $1/r^2$ effect associated with this source height is greater than that associated with either of the lower source heights.

The doses due to prompt gamma rays exhibit a similar behavior for the three source heights to a depth of 0.3 m after which the 731.5 m source height yields larger doses. For prompt gamma rays, the larger grazing angles of the radiation incident on the earth's surface dominates the $1/r^2$

Fig. 2. Integrated dose in S_i versus depth in earth due to prompt neutrons, secondary gammas, and prompt gammas for 1.0, 61.3 and 731.5 m source heights.

effect. This dominance results in a substantially greater contribution to the dose for this source height at large radial distances from the source. The important point to note from these results is the magnitude of the secondary gamma ray ionization doses. These doses are approximately a factor of 10 greater than the doses due to prompt neutrons at all depths for all three source heights.

The total ionization dose in silicon due to prompt neutrons and secondary gamma rays for the three source heights investigated here can be easily determined from Figs. 2a and 2b. For weapons characterized by the neutron spectrum used in this study, i.e., a 14-MeV with a 10% fission tail, summing the dose at corresponding depths in Figs. 2a and 2b, and multiplying by the prompt neutron yield gives the total prompt neutron and secondary gamma ray dose. The prompt gamma ray dose is obtained by multiplying the dose for the equivalent source height and depth in Fig. 2c by the number of prompt fission gammas leaving an equivalent yield weapon blast. The total dose associated with the prompt neutron and prompt gamma ray spectra is the sum of these contributions.

A comparison of the neutron and gamma ray ionization doses in silicon between the earth-only and earth-concrete models is given in Table IV for the 61.3 m source height. The 0.9 m of borated concrete (see Fig. 1) is ineffective in reducing any of the doses (less than a factor of 10 reduction is obtained at all depths). These comparisons are given only for the 61.3 m source height since this source height yielded the largest prompt neutron and secondary gamma ray ionization doses.

The total prompt neutron, secondary and prompt gamma ray fluences for the 61.3 m source height are presented in Fig. 3 for both the earth-only

Fig. 3. Integrated fluence versus depth in earth due to prompt neutrons, secondary gammas and prompt gammas for 61.3 m source height in earth-only and earth-borated concrete.

Table IV. Comparison of Neutron and Gamma Ray Ionization Doses in Silicon
Between Earth-Only and Earth-Concrete Models

Depth (meter)	Prompt Neutron (Rad-meter/source neutron)			Secondary Gamma Ray (Rad-meter/source neutron)			Prompt Gamma Ray (Rad-meter/source gamma ray)		
	E.O. ^a	B.C. ^b	B.C./E.O.	E.O.	B.C.	B.C./E.O.	E.O.	B.C.	B.C./E.O.
0.0	7.35-18 ^c	--	--	2.00-17	--	--	3.68-18	--	--
0.3	2.20-19	2.20-19	1.00	4.69-18	4.46-18	0.95	2.08-20	2.08-20	1.00
0.6	2.44-20	1.84-20	0.75	1.05-18	8.04-19	0.77	4.86-22	1.91-22	0.39
0.9	2.39-21	1.09-21	0.39	1.94-19	5.48-20	0.28	4.18-24	0	0
1.2	3.54-22	6.55-23	0.19	3.93-20	6.23-21	0.16	0	0	--
1.5	4.35-23	5.19-24	0.12	3.65-21	1.08-21	0.12	↓	↓	--
1.8	5.35-24	6.39-25	0.12	2.02-21	2.75-22	0.14	↓	↓	↓
2.1	6.58-25	7.93-26	0.12	4.94-22	7.13-23	0.14	↓	↓	↓
2.4	8.08-26	9.82-27	0.12	1.25-22	1.88-23	0.15	↓	↓	↓
2.7	9.91-27	1.20-27	0.12	3.27-23	5.02-24	0.13	↓	↓	↓
3.0	1.07-27	1.30-28	0.12	8.24-24	1.29-24	0.16	0	0	↓

^aCalculated with Earth Only

^bCalculated with Borated Concrete

^cRead as 7.35×10^{-18}

and earth-borated concrete models. These fluences were obtained by substituting a flat response function in Eq. (2). In the earth-only calculations, the total fluences behave as the ionization doses in silicon except at small depths (< 0.6 m) where the prompt neutron total fluence is greatest. The sharp hump in the secondary gamma curve for the earth-borated concrete case at a depth of 0.5 m is due to backscatter from the concrete. This depth corresponds to the earth immediately above the concrete. Total fluences were also calculated for the 1.0 and 731.5 m source heights using the earth-only model. These fluences are not presented since their magnitudes, relative to the corresponding fluences obtained for the 61.3 m source height, behaved as the ionization doses in silicon.

The total neutron fluence and the neutron fluences above 0.1, 1, 10 and 14-MeV are shown in Fig. 4 for the 61.3 m source height using both the earth-only and earth-borated concrete models. A comparison of corresponding curves in Figs. 4a and 4b reveals some of the reasons for the relatively small decrease in doses associated with the replacement of earth with 0.9 m of borated concrete. The fast fluence, $\phi(E > 10\text{-MeV})$ curve, is only slightly reduced by the presence of the concrete. This small reduction in the fast fluence causes both the production of gamma rays due to inelastic collisions of fast neutrons and the production of capture gamma rays due to slowing down of fast neutrons to be only slightly reduced below the borated concrete. In addition, the production of thermal neutrons, and consequently capture gamma rays, is large at shallow depths, i.e., above the concrete, as illustrated by the changing slope of the $\phi(\text{all } E)$ curve.

The relatively large removal of thermal neutrons by the borated concrete does not significantly reduce the neutron ionization dose in silicon since

Fig. 4. Integrated fluence above 0.1, 1, 10, 14 MeV and total fluence due to prompt neutrons for 61.3 m source height in earth only and earth-borated concrete.

the neutron ionization response function for silicon is zero for neutron energies below 3.35 keV (see Tables II and III). In fact, this removal could possibly increase the secondary gamma ray ionization dose in silicon due to the 0.47-MeV secondary gamma ray produced by thermal neutron capture in boron.

IV. SUMMARY

Neutron and gamma ray ionization doses in silicon have been obtained as a function of depth in earth for three above-ground source heights. These doses were calculated to determine the radiation damage due to nuclear weapon blasts above an air-ground interface in a long fiber optic cable buried at various depths in the earth. The results contained in this study represent the doses due to one prompt source neutron and one prompt source gamma ray. Radiation damage caused by a specific size nuclear detonation can be obtained by multiplying these results by the proper neutron and gamma ray weapon yields.

The magnitudes of the silicon doses demonstrated the secondary gamma ray dominance. This contribution to the radiation damage, which can be quantitatively compared to the prompt neutron damage, was found to be more than a factor of 10 larger than the prompt neutron dose at all depths for all three source heights. Comparative calculations performed by replacing earth with 0.9 m of borated concrete gave similar results. In addition, these comparative results demonstrated, particularly from a shielding cost viewpoint, the ineffectiveness of borated concrete in reducing the ionization doses in silicon.

References

1. J. V. Pace, III, D. E. Bartine and F. R. Mynatt, "Neutron and Secondary Gamma Ray Transport Calculations for 14-MeV and Fission Neutron Sources in Air-Over-Ground and Air-Over-Seawater Geometries," ORNL/TM-4841, Oak Ridge National Laboratory (1975).
2. N. E. Banks, G. J. Klein and H. Lichtenstein, "The Effects of Moisture Content and Soil Composition Upon Air-Ground Tactical Nuclear Environments," ARBRL-TR-02091, Aberdeen Proving Ground, MD (1978).
3. S. Glasstone and P. J. Dolar, Eds., The Effects of Nuclear Weapons, U.S. Department of Defense and U.S. Department of Energy, 1977.
4. S. Kronenberg, H. L. Berkowitz, R. A. Lux, R. L. Pfeffer, H. VanGordon and V. Rosati, "Nuclear Radiation Vulnerability of Proposed Army Fiber Optics Communication Systems," DELET-TR-78-13, Ft. Monmouth, NJ (1978).
5. W. A. Rhoades, D. B. Simpson, R. L. Childs and W. W. Engle, Jr., "The DOT-IV Two-Dimensional Discrete Ordinates Transport Code with Space-Dependent Mesh and Quadrature," ORNL/TM-6529, Oak Ridge National Laboratory (1978).
6. R. W. Roussin and F. A. R. Schmidt, "Adjoint S_n Calculations of Coupled Neutron and Gamma Ray Transport Through Concrete Slabs," Nucl. Eng. & Design 15, 319 (1971).
7. D. E. Bartine, J. R. Knight, J. V. Pace, III and R. Roussin "Production and Testing of the DNA Few-Group Coupled Neutron-Gamma Cross Section Library," ORNL/TM-4840, Oak Ridge National Laboratory (1977).
8. R. L. Childs and J. V. Pace, III, Oak Ridge National Laboratory, private communication.

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