Conf-761037--1

TRANSPORT CALCULATIONS AND SENSITIVITY ANALYSES FOR AIR-OVER-GROUND AND AIR-OVER-SEAWATER WEAPONS ENVIRONMENTS*

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Two-dimensional neutron and secondary gamma-ray transport calculations and cross-section sensitivity analyses have been performed to determine the effects of varying source heights and cross-sections on calculated doses. The air-over-ground calculations demonstrate the existence of an optimal height of burst for a specific ground range and indicate under what conditions they are conservative with respect to infinite air calculations. The air-over-seawater calculations showed the importance of hydrogen and chlorine in gamma production. Additional sensitivity analyses indicated the importance of water in the ground, the amount of reduction in ground thickness for calculational purposes, and the effect of the degree of Legendre angular expansion of the scattering cross-sections (P_ℓ) on the calculated dose.

INTRODUCTION

During the past ten or twelve years – since the advent of fast multigroup transport codes that can handle neutron and gamma-ray interactions simultaneously – a myriad of calculations have been performed to predict the neutron and secondary gamma-ray fields produced by the detonation of nuclear weapons at various heights above the ground [1-5]. The sources have usually included a fission source, a thermonuclear source, and monoenergetic sources up to 14 MeV. Calculations of this type yield sets of data that are too massive for publication and are usually stored on magnetic tape.

In order to better understand the mechanisms involved, a series of air-over-ground and air-over-seawater two-dimensional radiation transport and sensitivity calculations were performed. In an attempt to aid users of the data and the codes, it was hoped that deeper incite into what data was needed and what code input could be reduced might lead to an improvement and optimization of the computations. The first part of this paper deals with the particle transport and findings, while the second part looks at the sensitivity analyses.

The particle transport problem was calculated using the DOT code [6], a two-dimensional neutron and secondary gamma-ray transport system. The forward mode of the code was used in which the forward source was either a tactical weapon fission source or a 14-MeV source [5]. For the sensitivity calculations, the adjoint mode was used in which the adjoint source was the total dose [7].

GENERAL PROBLEM DESCRIPTION

The air-over-ground and air-over-seawater environments for the transport and sensitivity problems were structured in two-dimensional cylindrical geometry. Maximum horizontal range was 1490 meters (m) and vertical height was 1295 m. The ground and seawater was treated as a 50 centimeter thickness at the bottom of the cylinder, and the air was assumed to comprise the remainder of the system. Due to the need for a reflective air mass beyond the points of interest, the results are considered to be accurate only for heights less than 1000 m and for horizontal ranges less than 1200 m [8]. The elemental compositions assumed for the air, ground, and seawater are given in Table 1. Other pertinent cross-section information may be found in Ref. [5].

*Funded by Defense Nuclear Agency, work performed at Oak Ridge National Laboratory, prime contractor for the Energy Research and Development Administration.

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TRANSPORT PROBLEM DESCRIPTION

Figure 1 shows the overall geometry with the five source positions shown. The two sources used in the calculations were a 14-MeV neutron source and a tactical weapon fission source as shown in Table 2 and were represented as point sources. The source heights were 1, 50, 100, 200, and 300 m for the air-over-ground problems and 50 m for the air-over-seawater problems. Unless otherwise stated, detector heights were one m above the air-ground interface.

TRANSPORT RESULTS

Several response functions were applied to the neutron and gamma-ray fluxes calculated for positions on the interfaces. The ones to be presented here were the Henderson neutron and gamma-ray tissue dose, Auxier-Snyder tissue dose, and Claiborne-Trubey tissue dose [5].

Study of the neutron dose plots from the air-over-ground calculations indicates that an optimal relationship exists between the source height and the ground range. That is, a burst height may be specified which will give the maximum dose for a given ground range. This is illustrated in Fig. 2, in which the Henderson neutron tissue dose is plotted as a function of height of the 14-MeV source for several ground ranges. (This figure is designed to show the relative shapes of the curves for the four ground ranges). As the ground range increases, the source height that yields the largest calculated dose also increases. Similar observations may be made concerning the results of the air-over-ground calculations performed with other responses and the tactical weapon fission source.

Earlier investigators [3-4] have reported that the presence of the ground enhances the dose at short slant ranges but depresses the dose at large slant ranges, compared to the dose at the same position obtained from an infinite air calculation. Figure 3 indicates the ground ranges for which ground enhances the neutron and gamma-ray doses (area to the left of the lines) as a function of source height for the 14-MeV source. The regions to the right of the lines therefore represent 14-MeV burst height and ground range combinations for which an infinite-air calculation is conservative or higher. Figure 4 shows similar plots for the neutron and gamma-ray doses produced by the tactical weapon fission source, and Fig. 5 depicts comparable plots for the total tissue doses produced by both sources.

The air-over-seawater calculations (50 m source height) showed that the neutron dose at the interface was depressed while the gamma-ray dose was enhanced relative to the air-over-ground results. Table 3 shows comparable doses at the interface for air-over-ground (A/G) and air-over-seawater (A/SW) calculations at three ground ranges for the 14-MeV and tactical weapon fission sources, respectively. Note that the total dose is dominated by the neutron dose and is therefore depressed for A/SW relative to A/G.

Further analysis showed that in addition to the seawater reducing the neutron flux, it softened the neutron spectrum relative to the ground and increased the gamma-ray dose due to increased capture-gamma-ray production. In a closer examination of the gamma-ray production, one-dimensional spherical ANISN [9] calculations were performed for the fission source in the air-over-seawater configuration with and without chlorine, and also for the air-over-ground configuration. These results are given in Table 4 as a function of gamma-ray energy. The thermal (n,γ) reaction for chlorine produces gamma-rays with energies primarily from 6 to 8 MeV, while hydrogen produces only a 2.2 MeV gamma-ray. As is seen, the chlorine and hydrogen thermal captures contribute substantially to the gamma-ray dose at the interface, but the presence of chlorine has a dominant effect, although it is only a trace element.

SENSITIVITY PROBLEM DESCRIPTION

Cross-section sensitivity analysis has been well documented in the last few years [7,10-14]. The reader is referred to those references for details in theory. It is only sufficient to say that the sensitivity code SWANLAKE [13] was used in this analysis along with the code VIP [14], which transforms two-dimensional data into a form suitable for SWANLAKE.

The fluxes from the forward runs at a source height of 50 m were used with the adjoint fluxes from runs made at adjoint source heights of 0.5 and 415 m and slant ranges at 607 and 1086 m. In the four adjoint calculations, the adjoint source was the total dose, Auxier-Snyder neutron tissue dose plus Claiborne-Trubey gamma-ray tissue dose.

SENSITIVITY RESULTS

Table 5 shows the total doses used for the eight sensitivity calculations. The doses due to the 14 MeV sources range from 2 to 4 times those for the tactical weapon fission source. The neutron to gamma dose ratio is the largest for the tactical weapon fission source at a ground range of 485 m and detector height of 415 m. Moreover, the neutron to gamma-ray dose ratio is always larger for the tactical weapon fission source as compared to the 14-MeV source.

Figure 6 shows a schematic of the air-over-ground geometry broken into 19 zones for sensitivity purposes. The point source is a 14-MeV and the numbers shown are the percent changes of the total neutron and gamma-ray dose due to a one percent increase in the cross sections for each zone. On the right of the figures are shown total and cumulative sensitivities by layer. For example, a one percent increase in the air neutron cross sections in zone 14 would decrease the total dose by .230 percent. A one percent increase in all air cross sections in zone 15 would decrease the total dose by .00426 percent. And a one percent increase in all the air cross sections for zones 14 and 15 would decrease the total dose by .236 percent.

Since air density does not differ much from void, the sensitivity calculations were used to predict the change in dose by replacing a layer of air with void. If zones 18 and 19 of Fig. 6 are dropped, the prediction for dose increase would be .0144 percent. To check this result, a calculation was made with DOT in which the top 300 m of air were voided.

Figure 7 shows a plot of percent change in the total dose 0.5 m above ground due to a decrease in system height versus ground range for 14-MeV source heights. For a source height of 50 m and a ground range of 1085 m, the plot indicates the percent change in the total dose is approximately .04.

Figure 6 shows that increasing the ground cross sections by one percent would decrease the total dose by .0486%. As was done with the top layer of air, one could then say removing 100 percent of the ground would increase the total dose by 4.86 percent. However, voiding the ground should not increase the dose, but decrease it. To check this, a DOT calculation was made with the ground replaced with void. The result was a 68 percent decrease in the total dose. This clearly indicates that decreasing the ground by 100 percent is out of the linear range for linear perturbation theory.

Table 6 shows the predicted percent change in the total dose per percent increase in the cross sections by element. Since the detector and source are in the air, nitrogen dominates the sensitivity. Of the ground constituents, hydrogen is the dominate element in 6 of the 8 cases and is always negative. This not only indicates that the water content is very important but gives some incite into why voiding the ground is far outside the linear range.

Table 7 shows the predicted percent change in total dose per percent increase in the percent by weight of water in ground with constant density of 1.7 g/cc. In all cases, the percent change due to the tactical weapon fission source is roughly twice that due to the 14 MeV source. The ground used in all runs contained 8.6 percent by weight of water. Increasing the percent to 9.6 would decrease the total dose for the first case shown by 2.3 percent.

Table 8 shows the predicted percent change in the total dose in changing from P_3 to P_ℓ calculations. All the tactical weapons fission source calculations could be run with P_1 cross sections and still be within one percent of P_3 calculations. For 14-MeV source runs, P_2 calculations will be within one percent of P_3.

Two further checks were made on the water percent predictions. A run with the percent by weight of water in the ground increased to 30 was made. Table 9 shows the predicted and actual percent change in the total dose. The sensitivity calculations overpredict the changes which means a 30 percent change is outside the linear range. Table 10 shows the results of a calculation made with a hydrogen content less than that in the Nevada type soil. Here all the predictions were below the actual change, indicating again that the linear range had been surpassed. From these tables, it is seen that the linear range can be exceeded very easily due to the high sensitivity to hydrogen, and care must be exercised when using the sensitivity results.

CONCLUSIONS

The air-over-ground calculations demonstrate the existence of an optimal height of burst for a specific ground range and under what conditions they are conservative with respect to infinite air calculations for the sources and ground range span considered here. The air-over-seawater results indicate that compared to air-over-ground results, the neutron dose is lower while the gamma-ray dose is higher. Moreover, the trace element chlorine in seawater has 2 strong effects on gamma-ray doses due to the production of capture gamma-rays.

As far as the sensitivity results are concerned, nitrogen is the dominating element for total dose while hydrogen is the most important in the ground. In some cases, the cross-section Legendre expansion can be reduced, and the results remain within one percent of P_3. The further the detector is from the source, the greater the system height must be in the calculations.

From these studies we have gained a deeper insight into the important mechanisms in air-ground and air-seawater transport. These systems can now not only be proper by designed and analyzed effectively, but a savings in computer cost can be realized.

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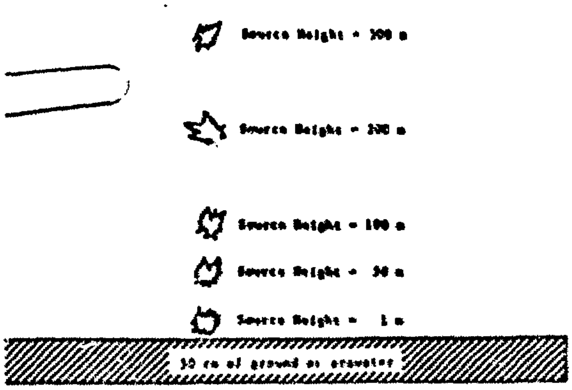

Fig. 1. Schematic of Air-Over-Ground and Air-Over-Seawater Geometries. The system's height and radius were 1295.5 m and 1490 m, respectively. The detectors were 0.5 m above the interface.

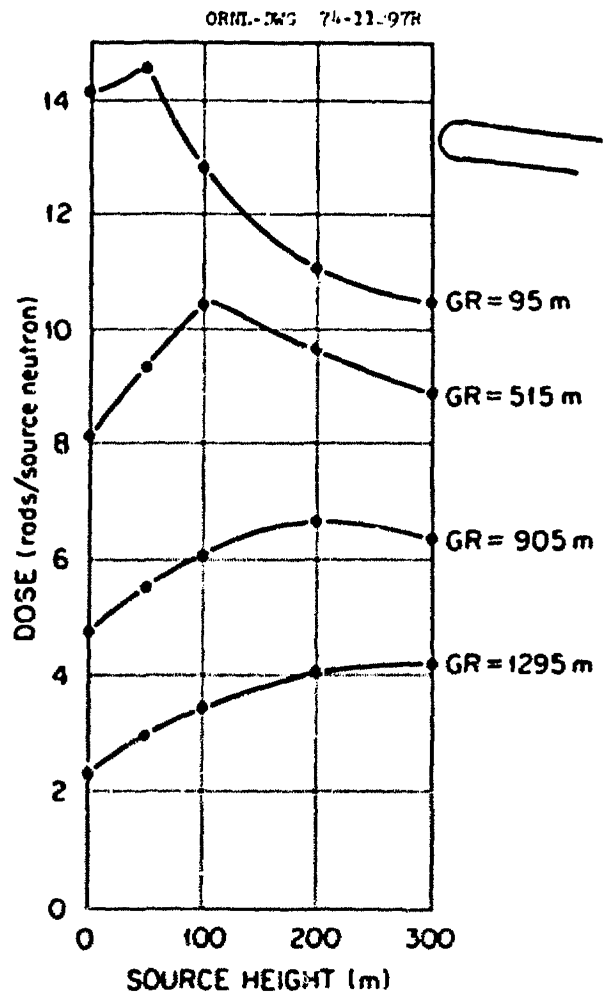

Fig. 2. Plot Showing Relative Shapes of Henderson Neutron Tissue Doses at Various Ground Ranges (GR) from a 14-MeV Source at Various Heights.

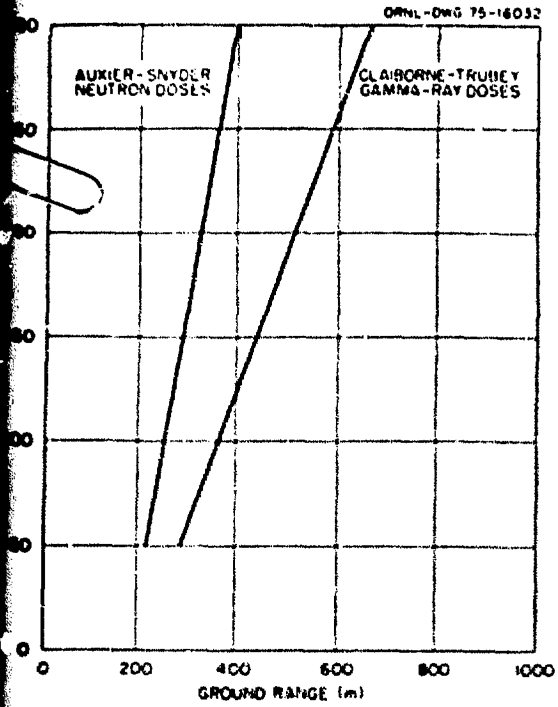

Fig. 3. Plots of 14-MeV Source Height and Approximate Ground Range Combinations for Which the Air-Over-Ground Neutron and Secondary-Gamma-Ray Interface Doses are Equivalent to Infinite-Air Doses. For combinations to the right of the lines the infinite-air calculations yield higher doses, and for combinations to the left of the lines the air-over-ground calculations yield higher doses.

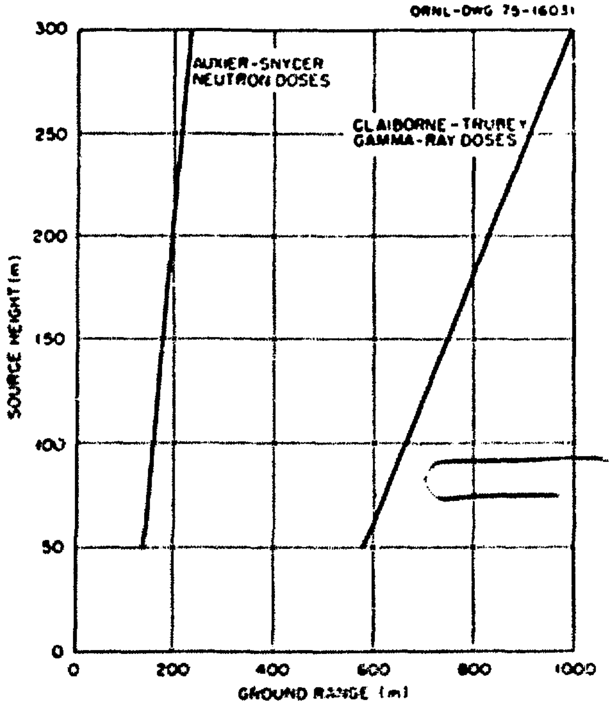

Fig. 4. Plots of Weapon Fission Source Height and Approximate Ground Range Combinations for Which the Air-Over-Ground Neutron and Secondary-Gamma-Ray Interface Doses are Equivalent to Infinite-Air Doses. For combinations to the right of the lines the infinite-air calculations yield higher doses, and for combinations to the left of the lines the air-over-ground calculations yield higher doses.

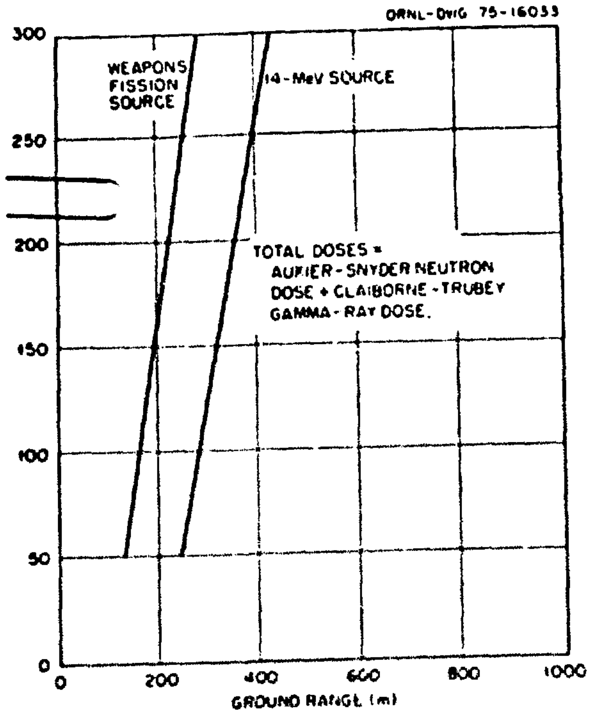

Fig. 5. Plots of Source Height and Approximate Ground Range Combinations for Which the Air-Over-Ground Total Interface Doses Produced by a 14-MeV Source and a Weapons Fission Source are Equivalent to Infinite-Air Doses. For combinations to the right of the lines the infinite-air calculations yield higher doses, and for combinations to the left of the lines the air-over-ground calculations yield higher doses.

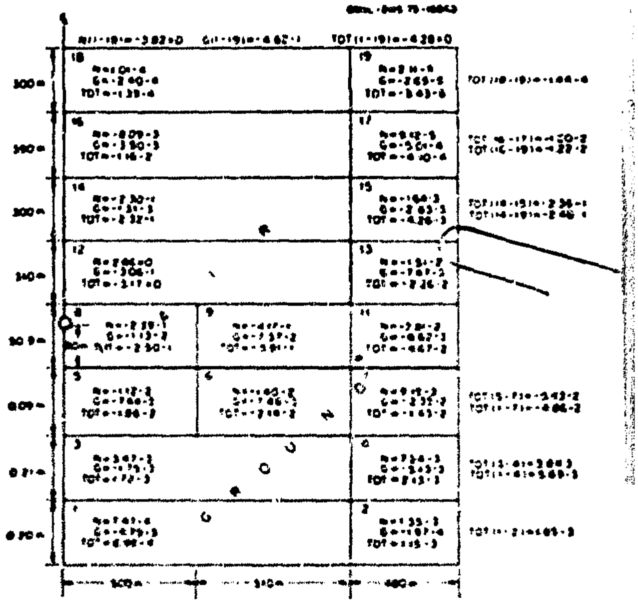

Fig. 6. Percent Change in Auxier-Snyder Neutron Plus Claiborne-Trubey Gamma-Ray Tissue. Dose by zone in air-over-ground geometry per percent increase in the macroscopic cross section of the zone for a 14 MeV source. Detector height = 0.5 m, detector ground range = 1055 m, N = neutron, G = gamma-ray. TOT = N+G. * = detector position

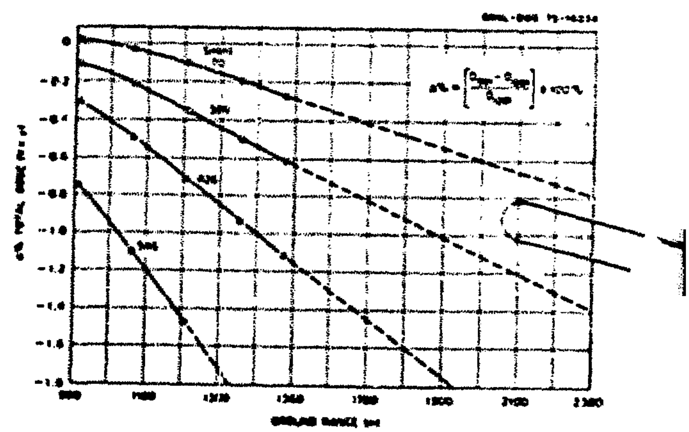

Fig. 7. Percent Change in Total Dose (Auxier-Snyder Neutron Plus Claiborne-Trubey Gamma) from a 14 MeV Source Due to a System Height Decrease from 1281 m to 981 m. Detector height is 0.5 m.

Table 1

Material Compositions and Cross Sections Used in Calculations

Element	Cross Sections*		Composition (atoms/b-cm)		
	Mat No.	Mod. No.	Air (ρ = 1.22 g/ℓ)	Ground (ρ = 1.7 g/cc)	Seawater (ρ = 1.025 g/cc)
H	4148	2		9.7656−3	6.64−2
N	4133	4	4.0242−5ᵃ		
O	4134	2	1.0697−5	3.4790−2	3.32−2
Na	4156	0			2.81−4
Mg	4512	0			3.00−5
Al	4135	3		4.8828−3	
Si	4151	2		1.1597−2	
Cl	1149	--			3.30−4

*Read: 4.0242 × 10^{-5}.

Table 2

Energy Spectrum of Tactical Weapon Fission Neutron Source and 14 MeV Source

Group	Upper Energy (MeV)	Fraction per Energy Group	
		Weapon Fission Source	14 MeV Source
1	17	0.0	1.0
2	12.2	0.0	
3	10	7.342−3*	
4	8.18	1.274−2	
5	6.36	1.832−2	
6	4.96	1.177−2	
7	4.06	5.481−2	
8	3.01	2.871−2	
9	2.46	5.743−3	
10	2.35	1.060−1	
11	1.83	1.468−1	
12	1.11	2.159−1	
13	0.55	1.693−1	
14	0.111	2.227−1	
15−22	0.00335†	0.0	

*Read: 7.342 × 10^{-3}.
† Lower energy limit is 1.1−11.

Table 3

Henderson Neutron and Gamma-Ray Tissue Doses 0.5 m Above Air-Over-Ground (A/G) and Air-Over-Seawater (A/SW) Interface (Burst height = 50 m)

Ground Range (m)	Neutron Dose (rads)		Δ%*	Gamma-Ray Dose (rads)		Δ%	Total Dose (rads)		Δ%
	A/G	A/SW		A/G	A/SW		A/G	A/SW	
Fission Source									
0	1.14−17†	8.47−18	−26	6.41−19	2.00−18	212	1.20−17	1.05−17	−13
515	1.73−20	1.14−20	−34	2.69−21	4.35−21	62	2.00−20	1.58−20	−21
995	3.50−22	2.29−22	−35	1.28−22	1.70−22	33	4.78−22	3.99−22	−16
14-MeV Source									
0	2.51−17	2.14−17	−15	2.67−18	2.90−18	9	2.78−17	2.43−17	−13
515	5.35−20	4.27−20	−20	1.09−20	1.21−20	11	6.44−20	5.48−20	−15
995	1.98−21	1.48−21	−25	6.73−22	7.46−22	11	2.65−21	2.23−21	−16

*$\Delta\% = \frac{A/SW - A/G}{A/G} \times 100\%$.

†Read: 1.14×10^{-17}.

Table 4

Henderson Gamma-Ray Tissue Doses 0.5 m Above Air-Over-Ground and Air-Over-Seawater Interfaces, With and Without Chlorine in Seawater (Fission Source at Height of 50 m)

Energy Range (MeV)	A/G Dose (rads)	A/SW Dose (rads)	Δ%* for A/SW	A/SW Dose (w/o Cl) (rads)	Δ% for A/SW w/o Cl
2.5−12.0	1.45−10†	2.32−10	+60	5.08−11	−65
2.0−2.5	3.61−11	1.64−10	+354	2.02−10	+460
0.02−2.0	6.75−11	1.42−10	+111	1.04−10	+54
0.02−12.0	2.49−10	5.38−10	+116	3.56−10	+43

*$\Delta\% = \frac{A/SW - A/G}{A/G} \times 100\%$.

†Read: 1.45×10^{-10}.

Table 5

Auxier-Snyder Neutron and Claiborne-Trubey Gamma-Ray Tissue Doses in Rads/Source Neutron for Cases Indicated

Case	Ground Range (m)	Detector Height (m)	Neutron Dose	Gamma Dose	Total*	Neutron to Gamma Dose Ratio
Weapon fission source	605	0.5	1.77−20	1.93−21	1.96−20	9.17
14-MeV	605	0.5	4.15−20	6.94−21	4.85−20	5.98
Weapon fission source	485	415	4.01−20	2.54−21	4.26−20	15.79
14-MeV	485	415	7.83−20	1.14−20	8.97−20	6.87
Weapon fission source	1085	0.5	4.23−22	9.80−23	5.21−22	4.32
14-MeV	1085	0.5	1.81−21	4.78−22	2.28−21	3.79
Weapon fission source	1025	415	1.13−21	1.72−22	1.30−21	6.57
14-MeV	1025	415	3.98−21	7.79−22	4.76−21	5.11

*Total may not be sum of neutron and gamma dose due to roundoff.

Table 6

Predicted Percent Change in the Total Dose (Auxier-Snyder Neutron + Claiborne-Trubey Gamma-Ray) per Percent Increase in the Cross Sections by Element

Case	GR[3] (m)	DH[4]	N(Air)[5]	O(Air)[6]	H(Ground)[7]	O(Ground)[8]	Si(Ground)[9]	Al(Ground)[10]	Total
WFS[1]	605	0.5	-2.12+0	-4.89 1	2.09-1	1.39-1	3.72-2	1.70-2	-2.62+0
14 MeV[2]	605	0.5	-1.56+0	3.21-1	-1.12-1	6.31-2	-5.37 4	6.25-3	-1.92+0
WFS	485	415	1.86+9	3.86 1	6.53 2	4.16 2	1.90-2	9.95-3	-2.24+0
14 MeV	485	415	-1.40+0	-2.62 1	-3.37-2	3.89-2	2.39 3	5.48-3	-1.65+0
WFS	1085	0.5	4.33+0	-1.10+0	-2.15 1	1.37-1	3.57-2	1.81 2	-5.45+0
14 MeV	1085	0.5	3.45+0	-7.82 1	1.27-1	7.51-2	1.77-3	5.36-3	-4.28+0
WFS	1025	415	4.00+0	-9.69 1	-7.42-2	4.08 2	2.20 2	1.34-2	-4.96+0
14 MeV	1025	415	3.19+0	6.88-1	-3.73-2	3.80-2	-1.62-3	3.81-3	-3.87+0

1. Weapon fission source
2. 14 MeV source
3. Ground range
4. Detector height
5. Nitrogen in air sensitivity
6. Oxygen in air sensitivity
7. Hydrogen in ground sensitivity
8. Oxygen in ground sensitivity
9. Silicon in ground sensitivity
10. Aluminum in ground sensitivity

Table 7

Predicted Percent Change in Total Dose Per 1% Increase in the Percent by Weight of Water in the Ground with Constant Ground Density of 1.7 g/cc

Case	Ground Range (m)	Detector Height (m)	Percent Change
Weapon fission source	605	0.5	−2.3
14 MeV source	605	0.5	−1.26
Weapon fission source	485	415	−0.76
14 MeV source	485	415	−0.37
Weapon fission source	1085	0.5	−2.45
14 MeV source	1085	0.5	−1.42
Weapon fission source	1025	415	−0.87
14 MeV source	1025	415	−0.41

Table 8

Predicted Percent Change in the Total Tissue Dose (Auxier-Snyder Neutron + Claiborne-Trubey Gamma Ray) in Changing from P_3 to P_ℓ Calculations

Case	Ground Range (m)	Detector Height (m)	P_ℓ	Air	Ground	Total*
Weapon fission source	605	0.5	2	−0.10	+0.14	+0.04
			1	+0.14	+0.23	+0.37
			0	−11.85	+14.42	+2.57
14 MeV source	605	0.5	2	−0.60	+0.87	+0.27
			1	+0.62	+0.62	+1.24
			0	−27.74	+12.95	−14.79
Weapon fission source	485	415	2	−0.01	−0.01	−0.02
			1	+0.29	+0.05	+0.34
			0	−8.68	+4.86	−3.81
14 MeV source	485	415	2	+0.14	+0.03	+0.16
			1	+1.87	+0.32	+2.19
			0	−22.43	+8.66	−13.77
Weapon fission source	1085	0.5	2	−0.12	+0.30	+0.18
			1	−0.81	+0.52	−0.29
			0	−36.19	+16.12	−20.07
14 MeV source	1085	0.5	2	−1.13	+1.00	−0.13
			1	−6.19	+1.23	−4.96
			0	−77.06	+15.16	−61.90
Weapon fission source	1025	415	2	0.00	+0.06	+0.07
			1	−1.00	+0.44	−0.56
			0	−30.30	+5.97	−24.33
14 MeV source	1025	415	2	−0.27	+0.45	+0.18
			1	−4.44	+1.31	−3.13
			0	−65.81	+8.52	−57.29

*Total may not equal sum of air and ground due to roundoff.

Table 9

Comparison of Predicted and Actual Percent Change in the Total Dose Due to a Weapon Fission Source in Changing from 8.6% to 30% by Weight of Water in the Ground[11]

Ground Range (m)	Detector Height (m)	Predicted % Change	Actual % Change
605	0.5	-49.2	-19.9
485	415	-16.3	-6.8
1085	0.5	-52.4	-19.8
1025	415	-18.6	-8.5

Table 10

Comparison of Predicted Percent Change and Actual Percent Change in the Total Dose Due to a Weapon Fission Source in Changing from Nevada Type Soil* to a Soil Lower in Hydrogen Content†,[12]

Ground Range (m)	Detector Height (m)	Predicted % Change	Actual % Change
605	0.5	17.1	33.2
485	415	5.8	9.9
1085	0.5	17.6	31.7
1025	415	6.7	10.0

*See Table 1.

†Hydrogen, Oxygen, Silicon, and Aluminum number densities changed by -82%, -9.9%, +14.1%, and 51.3%, respectively.