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A PREDICTION SYSTEM FOR THE NEUTRON-INDUCED ACTIVITY CONTRIBUTION TO FALLOUT EXPOSURE RATES

by

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ABSTRACT

A system has been devised to predict the neutron-induced activity contribution to fallout exposure rates. The system uses the simplifying assumptions of 1) a semi-empirical formula to determine the soil capture fraction and 2) thermal neutron cross sections to represent weapon-neutron cross sections. Results, using these assumptions, agree with those of another complete system for predicting the neutron-induced activity contribution to fallout exposure rates. In addition, results from various portions of the system agree with results obtained by more complicated methods.

SUMMARY

In the general problem of predicting fallout exposure rates from nuclear detonations is embedded the problem of predicting exposure rates from neutron-induced activity in the fallout. Certain restrictions, engendered by computer limitations, were necessary in order that the neutron-induced activity predictions be suitable for inclusion in the solution to the general fallout problem. A system based on weapon neutron spectra would require a computer program too extensive for incorporation in the general program. Brevity, without undue sacrifice of accuracy, was a requisite. This requisite was satisfied by assuming that weapon neutrons could be treated as thermal neutrons and that a semi-empirical formula for thermal neutrons could be used for the purpose of making soil-capture fraction and isotropic-capture fraction predictions.

The following comparisons each showed excellent agreement in the region of interest: a) a comparison of the thermal soil-capture fraction predictions of this system and a Monte Carlo system using weapon-neutron spectra; b) a comparison of the predictions of the semi-empirical formula used in this system with the so-called "exact" solution; and c) a comparison of the exposure rates predicted by this system with those predicted by an extensive classified system using weapon neutron spectra.

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I. INTRODUCTION

A particle activity module[1] has been developed at USNRDL to predict exposure rates due to all fallout particles. The prediction system discussed in this report was devised to predict only the neutron-induced activity contribution to these fallout exposure rates. A computer program has been written for the system by D. Hoffman of this laboratory. An adapted version of it has been included in the general program.

Residual nuclear radiation emitted subsequent to an airburst nuclear explosion is almost entirely due to radioactive fission products present in the weapon residues. However, if a nuclear weapon is detonated near a land surface, some of the neutrons released in the fission process which escape the weapon will induce radioactivity in the soil. If the point of detonation is sufficiently near the surface, the soil will be vaporized with the weapon residues. Thus, fallout particles formed as the fire ball condenses will contain neutron-induced activity as well as fission-product activity.

Although the neutron-induced activity portion of fallout activity is in general quite small, there are circumstances under which it may be significant. It is for this reason, as well as for completeness, that the neutron-induced activity prediction system was incorporated in the fallout program. However, in order to insure that the neutron program would not occupy a larger portion of the generalized program than its importance warranted, two major simplifying assumptions were made: 1) all neutrons are emitted at thermal energies; and 2) soil albedo for thermal neutrons can be determined semi-empirically. The effects of these simplifications will be amplified in the text; however, it is appropriate to state here that soil albedo (ratio of number of neutrons leaving soil to number entering soil) has been found to be nearly independent of incident neutron energy; and also that, since the soil is volatilized and mixed in the fireball, the depth of neutron penetration before capture is of no consequence (as it is for prediction systems wherein the soil remains undistrubed*).

This report is arranged in such a manner that the reader is first introduced to the rationale of the system. The resulting equations and specifications of the required input quantities follow. An estimation

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* See, for instance, Lessler and Guy[2] and Holland and Gold[3].

of the value of each input quantity, based on available unclassified information, is then made. The associated computer program and tabular inputs are relegated to the appendices.

II. METHOD

As has been noted, the neutron-induced activity program was designed to be a part of the generalized land fallout model program. As such, the form of the output of the neutron program was restricted. At the point in the general program where the neutron program was to be introduced, it was required that the neutron program output be in the form:

> $(D_I)_{total} = (D_I)_{casing} + (D_I)_{soil}$ in units of of roentgens/hr per fission/cm^2, where the exposure rates are those found at three feet above an infinite plane uniformly contaminated with induced activity. The contamination density of the induced activity is expressed in terms of fissions per square centimeter.

$(D_I)_{total}$ is the final output of the neutron program. The general program adds this quantity to the fission exposure rates and operates on the sum to determine fallout exposure rates.

The history of weapon neutrons from release to capture, and the conversion of the capture products to induced-activity exposure rates in the required form is traced in the following section.

A. Rationale

Each neutron per fission released in the nuclear process is accounted for on the basis of its probable fate. The only possible fates are assumed to be:

1. A neutron released by the fissioning of a weapon nucleus is either captured by another weapon nucleus, or it is emitted by the weapon.

2. If it is emitted by the weapon, it is either captured by the weapon casing, in which event it is a potential contributor to fallout activity, or it escapes the weapon.

3. If it escapes the weapon, it is either captured in air and lost*, or it is captured in soil.

4. If it is captured in soil, the soil is either not volatilized and the neutron is lost, or the soil is volatilized and the neutron is a potential contributor to fallout activity.

* The word "lost" here means that the neutron is no longer a possible contributor to fallout activity.

5. Those neutrons captured in the weapon casing or in volatilized soil are contributors to fallout activity if the daughter of the capturing nucleus is radioactive (i.e., a gamma-ray emitter. Beta-ray activity is not a part of this prediction system).

After finding the neutrons per fission captured in the soil and in the weapon casing, the fraction captured by each isotope of the soil and casing must be determined. Following this determination, the neutron captures per fission by a given isotope must be converted to roentgens per hour per fission per square centimeter for that isotope. Finally, the total exposure rate $(D_I)_{total}$ is found by summing over these isotopic exposure rates.

B. Basic Equations

The basic equation for the induced-activity exposure rates due to activity induced in soil isotopes will first be stated and then its factors will be examined.

$$(D_I)_i \text{ (for soil isotopes)} = N_o e^{-\Sigma X} \Omega_f \alpha (f_c)_i K_i$$

where N_o = neutrons per fission emitted by the weapon

$e^{-\Sigma X}$ = fraction of neutrons emitted which escape

Ω_f = fraction of those entering soil which enter volatilized soil (solid angle fraction)

α = fraction of those emitted (escaping)* which are captured in soil (soil capture fraction)

$(f_c)_i$ = fraction of those captured in volatilized soil which are captured by the i^{th} isotope of the soil (isotopic capture fraction)

K_i = roentgens per hour due to i^{th} isotope per i^{th} isotope atom deposited per cm^2. The exposure rate being for a point at 3 ft above an infinite plane on which one nucleus of the i^{th} type is deposited per cm^2. Note: K_i is time dependent.

The first five factors simply determine how many neutrons per fission are captured by the i^{th} isotope. The final factor, K_i, then converts this to exposure rate in the appropriate form. The equivalent equation for casing isotopes is

$$(D_I)_i \text{ (for casing isotopes)} = N_o(1-e^{-\Sigma X}) (f_c)_i K_i$$

where $(1-e^{-\Sigma X})$ = casing capture fraction

* When the casing is assumed to be of zero thickness, the number emitted is equal to the number escaping. See Section C-2.

The basic equation for the total neutron-induced activity contribution to fallout exposure rates is then

$$(D_I)\text{total} = \sum_i (D_I)_i \text{ (summed over soil isotopes)} +$$

$$+ \sum_i (D_I)_i \text{ (summed over casing isotopes)}$$

C. Estimation of Input Values

1. Neutrons Emitted per Fission, N_o.
(see ENW[4], Sections 1.41 - 1.66)*

a) From 1.43, "...when a nucleus captures a neutron and suffers fission f neutrons are released; let t be the average number of neutrons lost...."**

b) From 1.44, "For uranium-235, f is about 2.5, t may be taken to be roughly 0.5...."

Since it takes one neutron to cause a nucleus to fission, there is an overall excess of 2.5 - 1 = 1.5 neutrons per fission emitted by the fission process. Therefore, for a pure fission weapon,
$N_o = 1.5 \frac{\text{fission neutrons}}{\text{fission}}$. Note that this is an overall excess and includes all of those neutrons released in the last generation of fission as well as the t = 0.5 neutrons per fission lost during the chain reaction.

For a fission-fusion weapon, we use the following to estimate the number of fusion neutrons emitted per fission:

c) from 1.66, "$H^2 + H^2 = He^3 + n + 3.2$ Mev

$H^2 + H^2 = H^3 + H^1 + 4.0$ Mev

$H^3 + H^2 = He^4 + n + 17.6$ Mev...."

or $5H^2 \rightarrow H^1 + He^3 + He^4 + 2n + 24.8$ Mev.

This shows that two neutrons are released per 24.8 Mev (fusion).

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* The practice of using ENW, or any other source of reliable unclassified information, is maintained throughout this report to deduce reasonable input values. Naturally, the classified weapon data for a specific weapon are the correct input values to be used.

** Note that "lost" here means lost to the fission or fusion process.

d) Since 2.625×10^{25} Mev is equivalent to 1 kiloton,

$$\frac{2 \text{ neutrons}}{24.8 \text{ Mev}} \times \frac{2.625 \times 10^{25} \text{ Mev}}{\text{KT (kiloton)}} = 2.12 \times 10^{24} \frac{\text{fusion neutrons}}{\text{KT (fusion)}}$$

e) From 1.41, 1.45×10^{23} fissions is equivalent to 1 KT (fission); and

f) $\ell/\ell = \frac{0.5}{2.5} = \frac{1}{5} \frac{\text{neutrons lost}}{\text{neutrons released}}$.*

On combining c), d), e), and f), we find

$$N_o\left(\frac{\text{fusion neutrons}}{\text{fission}}\right) = \frac{1}{5} \frac{\text{neutrons lost}}{\text{neutrons released}} \times \frac{2.12 \times 10^{24} \frac{\text{(fusion neutrons released)}}{\text{KT (fusion)}}}{1.45 \times 10^{23} \frac{\text{fissions}}{\text{KT (fission)}}} \times \frac{W_F\,[\text{KT(fusion)}]}{W_f\,[\text{KT(fission)}]} = 3 \frac{W_F}{W_f} \frac{\text{fusion neutrons}}{\text{fission}}$$

The total number of neutrons emitted per fission by the weapon is then

$$N_o = 1.5 \frac{\text{fission neutrons}}{\text{fission}} + 3 \frac{W_F}{W_f} \frac{\text{fusion neutrons}}{\text{fission}}$$

No provision has been made to calculate N_o from this formula in the computer program. N_o itself is the input quantity.

2. Casing Capture Fraction, $(1-e^{-\Sigma X})$.

In the version of this prediction system incorporated in the generalized land fallout model computer program, the casing capture fraction has been omitted. The quantity usually reported in the classified literature is the number of neutrons escaping the casing. If this quantity is used for S_2, the casing capture fraction is automatically zero. Thus, since computer space is at a premium in the general program, the retention of the ability to account for the casing effects may be unjustified. However, a method for calculating casing captures has been retained in the program reported here, since computer space is not at a premium and some estimation of the casing effects may prove desirable.

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* That is, we assume the ratio of neutrons "lost" to neutrons released for the fission-fusion case to be essentially that given by Section 1.44 of EMW. Higher or lower fractions could be inserted at this point as desired by a user.

In the expression $(1-e^{-\Sigma X})$, Σ is the integral macroscopic cross section and X is the effective casing thickness, i.e.,

$$\Sigma = \rho \frac{N_A}{A} \sigma \text{ (integral) } cm^{-1}$$

where ρ = casing density

N_A = Avogadro's number

A = effective atomic weight of casing elements

and σ = integral capture cross section

Effective casing thickness means the path length the neutrons must travel in casing materials. The determination of this length requires a thorough knowledge of all casing parameters and of the angular and energy distribution of neutrons incident on the internal face of the casing. The determination of X must be made independently of this prediction system. The same is true of σ (integral), for, as noted in the introduction, all neutrons are emitted at thermal energies in this prediction system. Thus, the computer calculates

$$\Sigma' = \rho \frac{N_A}{A} \sigma \text{ (thermal)}, \text{ not } \Sigma = \rho \frac{N_A}{A} \sigma \text{ (integral)}$$

To correct for this, an adjusted effective casing thickness,

$$X' = X \frac{\sigma \text{ (integral)}}{\sigma \text{ (thermal)}}$$

is entered as input so that

$$\Sigma' X' = \Sigma X$$

and the desired numerical value is achieved. The computer requires as input the casing density and fraction by weight of casing elements to calculate Σ'. The neutrons per fission captured by the casing are then treated in the same manner as those captured in soil, as will be discussed, to arrive at the exposure rates from casing-induced nuclides.

To simplify the discussion in the balance of this report, no further distinction will be made between the terms "neutrons emitted" and "neutrons escaping".

3. Solid Angle Fraction, Ω_f

In Figure 1, h << one capture mean free path for neutrons. From the figure, it is seen that all neutrons emitted from the weapon in a downward direction enter the soil. This is equivalent to stating that the earth subtends a solid angle of 2π steradians and that air attenuation is zero. For the heights of burst of significance both statements are nearly exact.

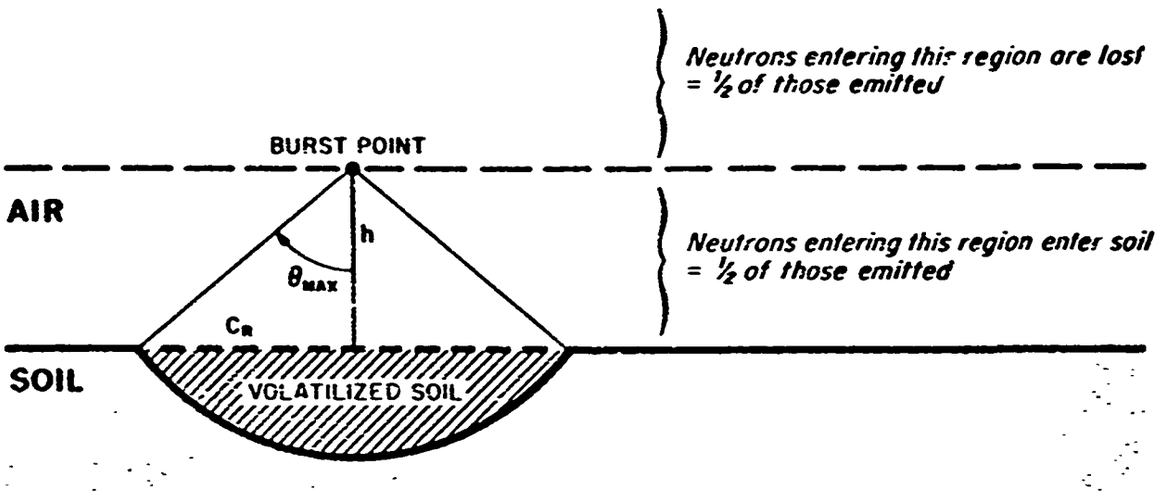

Fig. 1 BURST GEOMETRY

If we denote the solid angle subtended by the volatilization crater as Ω, and the ratio of the solid angle subtended by the crater to that subtended by the earth as Ω_f, then this ratio (solid angle fraction) is

$$\Omega_f = \frac{\Omega}{2\pi}$$

Since, in polar coordinates, the crater solid angle can be expressed as

$$\Omega = 2\pi \int_0^{\theta_{max}} \sin\theta d\theta = 2\pi (1-\cos\theta_{max})$$

and, as seen from the figure,

$$\cos \theta_{max} = \frac{h}{\sqrt{h^2 + C_R^2}},$$

we find,

$$\Omega_f = 1 - \frac{h}{\sqrt{h^2 + C_R^2}}$$

In order to determine Ω_f for a given height of burst, h (ft.), and weapon yield, W (KT), we must determine the crater radius, C_R (ft.), as a function of h and W. In order to find this function we again turn to Ellw[4]) as a convenient source of unclassified information:

a) from 6.08, "It has been estimated that for a 1-kiloton nuclear burst near the surface, the diameter of the crater, i.e., of the hole, will be about 130 feet in dry soil...."

b) From 6.09, "... for an explosion of W kilotons yield, on the surface, the diameter ... of the crater will be $W^{\frac{1}{3}}$ times the values quoted above for a 1 kiloton burst."

c) From 2.117, ("...R is the fireball radius in feet and W is the explosion yield in kilotons....")

"R (at breakaway) for air burst $\approx 110\ W^{0.4}$."

"The size of the fireball is not well defined in its later stages, but as a rough approximation the maximum radius may be taken to be about twice that at the time of breakaway...."

d) From 6.11, "As the height of burst increases, the dimensions of the center vary in a rather complicated manner.... In fact, for an appreciable crater to be formed, the height of burst should be not more than about one-tenth of the maximum fireball radius."

e) From 2.05, "...the fireball from a 1-megaton weapon ... increases to a maximum value of 7200 feet (across)."

Using a and b, we find

$$C_R \approx 65\ W^{\frac{1}{3}} \text{ at } h = 0.$$

Now, if we use (from c above) R (at breakaway) for air burst $\approx 110W^{0.4}$ and R (maximum) $\approx 2R$ (at breakaway) and combine these with $C_R = 0$ for $h \geq \frac{1}{3}$ maximum fireball radius (from d above), we find $C_R = 0$ at

$$h \approx \tfrac{1}{3} \times 2R \quad \text{(at breakaway)}$$

$$\approx \tfrac{1}{3} \times 2 \times 110W^{0.4}$$

$$\approx 22W^{0.4}$$

Solving $h \approx 22W^{0.4}$ for a 1-megaton burst, we find $C_R = 0$ for $h \approx 349$ ft. and W = 1 MT. Alternatively, if we use (from e above)

$$R \text{ (maximum)} = \frac{7200}{2} = 3600 \text{ ft for } W = 1 \text{ MT},$$

then $C_R = 0$ at $h \approx \frac{1}{3} \times 3600 = 360$ ft. We wish now to test the effect of assuming cube root scaling for height of burst. For a 1-megaton burst,

$$C_R = 0 \text{ at } h = 36W^{\frac{1}{3}} = 360 \text{ ft.}$$

Thus, $h = 36W^{\frac{1}{3}}$ is within a few percent of $h = 22W^{0.4}$ at 1-MT. It agrees exactly at about 1.6 MT and remains within 40% from 1 KT to 100 MT. Since all of the above information from ENW is approximate, it seems reasonable to use cube root scaling for height of burst, since its use simplifies the calculations.

Since the crater radius decreases in a rather complicated (and unknown) manner as the height of burst increases, the simplest expression, i.e., linear, was used to relate crater radius to height of burst. Thus,

$$C_R = 65W^{\frac{1}{3}} - \frac{65W^{\frac{1}{3}}}{22W^{\frac{1}{3}}} h$$

or, letting $\tilde{C}_R = C_R/W^{\frac{1}{3}}$ and $\tilde{h} = h/W^{\frac{1}{3}}$,

$$\tilde{C}_R = 65 - 1.6\,\tilde{h}$$

Inserting this result into the expression for Ω_f we have

$$\Omega_f = 1 - \frac{h}{\sqrt{h^2 + C_R^2}}$$

$$= 1 - \frac{\tilde{h}}{\sqrt{4.24\,\tilde{h}^2 - 234\,\tilde{h} + 4225}} \qquad (0 \leq \tilde{h} \leq 36)$$

$$= 0 \qquad (\tilde{h} > 36)$$

The computer input quantities are h (ft) and W (KT). The general program tests for $h > 36$; however, this program does not. The program should not be used for $h > 36$.

4. Soil Capture Fraction, α

The neutron number albedo or reflection coefficient of soil may be defined as

A = neutrons exiting soil/neutrons entering soil.

For an infinite medium, the neutrons are either captured or reflected; therefore,

1 - A = neutrons captured in soil/neutrons entering soil.

The soil capture fraction, α, is defined as,

α = neutrons captured in soil/neutrons emitted by the weapon

Using the geometry assumed in Fig. 1, it is seen that

$\frac{1}{2}$ = neutrons entering soil/neutron emitted by the weapon; therefore,

$$\alpha = \tfrac{1}{2}(1-A)$$

Halpern[5] has derived a theoretical formula for the neutron number albedo of the plane surface of an infinitely thick medium, given an incident isotropic distribution of thermal neutrons. The formula may be written

$$A = 1 - 2.31\left(\frac{\sigma_s}{\sigma_{ssc} + \sigma_s}\right)^{\frac{1}{2}}$$

where σ_{ssc}* and σ_s* are the respective thermal neutron scattering and capture cross sections of a given soil. Using Halpern's formula,

$$\alpha \text{ (thermal)} = \tfrac{1}{2}(1-A)$$
$$= 1.155\left(\frac{\sigma_s}{\sigma_{ssc} + \sigma_s}\right)^{\frac{1}{2}}$$

In order to determine the effect of the simplifying assumptions on the soil capture fraction predictions, the Monte Carlo values of Biggers[6] were used to calculate soil capture fractions for each of 48 energy-range groups. The results are shown in Table 1.

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* The methods of calculating σ_{ssc} and σ_s are given in Section C.5.

TABLE 1

SOIL CAPTUR FRACTIONS

(Biggers' Soil)

Energy (Mev) \ Range (meters)	0-250	250-500	500-1000	>1000	$\alpha(E)$
.0005	.118 (.90)	.139 (.094)	.159 (.002)	— (.000)	.120 (.010)
.001	.121 (.90)	.132 (.098)	.155 (.002)	— (.000)	.122 (.107)
.01	.116 (.82)	.126 (.170)	.107 (.010)	— (.000)	.117 (.107)
0.1	.111 (.73)	.116 (.240)	.122 (.030)	— (.000)	.112 (.107)
1	.100 (.58)	.111 (.300)	.107 (.070)	.077 (.040)	.103 (.280)
3	.151 (.53)	.118 (.310)	.102 (.160)	.106 (.017)	.126 (.1263)
4	.138 (.51)	.115 (.310)	.116 (.160)	.108 (.020)	.127 (.1263)
6	.172 (.51)	.129 (.310)	.130 (.150)	.123 (.020)	.151 (.1264)
8	.193 (.53)	.140 (.280)	.128 (.160)	.123 (.030)	.166 (.0025)
10	.191 (.54)	.148 (.270)	.131 (.160)	.117 (.030)	.168 (.0025)
12	.188 (.54)	.141 (.270)	.124 (.170)	.104 (.030)	.163 (.0025)
14	.188 (.53)	.130 (.270)	.125 (.150)	.126 (.030)	.160 (.0025)

The entry without parentheses in each bin is the soil capture fraction $\alpha(R,E)$ for Biggers' soil for neutrons emittted at energy E and entering the soil in the range R. The entry in parentheses is the ratio of the number of neutrons entering the soil in the given energy-range bin to the total number emitted at the given energy. These parenthetical entries are used as range weighting factors, w_R, to determine each $\alpha(E)$ shown in the final column of the table. The entry with parentheses in the $\alpha(E)$ column is the ratio of the number of neutrons of the given energy to the total number of neutrons emitted by a fission weapon (a Watt fission spectrum was used)[2]. These parenthetical entries are used as energy weighting factors, w_E, to determine α (fission spectrum). Thus,

$$\alpha(E) = \sum_R w_R \, \alpha(R,E)$$

and

$$\alpha \text{ (fission spectrum)} = \sum_E w_E \, \alpha(E).$$

The result is

$$\alpha \text{ (fission spectrum)} = .120 \text{ neutrons captured/neutron emitted.}$$

When α (thermal) is calculated using the formula based on Halpern, with the σ_s and σ_{ssc} being calculated for the soil used by Biggers, the result is

$$\alpha \text{ (thermal)} = .119$$

Thus the α (thermal) formula agrees with the calculations based on Biggers' data. Further, an inspection of the $\alpha(E)$ column shows the capture fraction to be highly insensitive to the energy of the emitted neutron so that spectral differences should not affect the results.

Another investigator, Rafalski[7], reports the solution of the so called "exact" equation for the reflection of a parallel beam of neutrons normally incident on an infinitely thick wall.

The equation is

$$A = 1 - \frac{2\Sigma_t}{\Sigma_s} (1 - k) \sqrt{1 - \frac{\Sigma_s}{\Sigma_t}} \; \varphi(\mu)\Big|_{\mu=1}$$

where Σ_t and Σ_s are the macroscopic total and scattering cross sections, the function $\varphi(\mu)$ is found from the integral equation

$$\int_0^1 \frac{y\,\varphi(y)}{y+\mu}\,dy = \frac{\frac{\Sigma_s}{\Sigma_t}}{2\,\varphi(\mu)\,(1-k^2\mu^2)}$$

and the coefficient k is found from the transcendental equation

$$\tanh k\,\frac{\Sigma_t}{\Sigma_s} = k$$

In Appendix A, the sample output shows a soil for which $\sigma_s = .203$, $\sigma_{ssc} = 9.16$ and the resulting $\alpha = .170$. When these cross sections are used in conjunction with the "exact" solution, $\alpha = .170$ (graphical interpolation was used and the last figure is uncertain). In still another comparison (using the cross sections Biggers reported for his soil) $\alpha = .144$ ("exact"-interpolated) while, using the same cross sections with the prediction system formula, $\alpha = .140$.

All intercomparisons in this section indicate that the simplifying assumptions are quite justified for soil, and that the simple soil capture fraction formula used in this prediction system is acceptable.

The computer has been programmed to compute α, σ_{ssc} and σ_s for a given soil given the fraction by weight of each element in the soil, the abundance of each isotope of the element, and the scattering and capture cross sections of each isotope. The details are given in the following section.

5. Isotopic Capture Fraction, $(f_c)_i$

Given that a neutron is captured in the soil, we wish to know the probability that it is captured by a given isotope of a given element of that soil.

Let f_i = number of atoms of i^{th} isotope per atom of soil

σ_i = thermal neutron capture cross section of i^{th} isotope

Then, since σ_s = thermal neutron capture cross section of soil (as previously defined

$$\sigma_s = \sum_i f_i\,\sigma_i$$

and, since $(f_c)_i$ = neutrons captured by i^{th} isotope per neutron captured in soil (as previously defined),

$$(f_c)_i = \frac{f_i \sigma_i}{\sigma_s}$$

[Neutron resonances in light nuclei ($Z < 30$) are almost completely scattering[8], and, since soil elements are nearly all in this category, they are presumed to follow closely the 1/v law; therefore, the relative captures are proportional to thermal cross sections and no integral cross section adjustment for weapon-spectrum energies need be used to refine the isotopic capture fraction estimate.]

The values of f_i are not generally available in the literature. The fraction by weight of the $k^{\underline{th}}$ element in a given soil $(f_w)_k$, is the quantity usually reported. As a consequence, provision has been made in the computer program to convert this quantity to f_i by the relationship

$$f_i = \frac{(f_w)_k/A_k}{\sum_k (f_w)_k/A_k} (f_{ik})$$

where A_k = atomic weight of $k^{\underline{th}}$ element
and f_{ik} = atoms of $i^{\underline{th}}$ isotope per atom of k.

The program also obtains A_k, given f_{ik} and A_{ik} = atomic weight of $i^{\underline{th}}$ isotope of $k^{\underline{th}}$ element by

$$A_k = \sum_i f_{ik} A_{ik}$$

The computer inputs are $(f_w)_k$, f_{ik} and σ_i. A tabulation of the $(f_w)_k$ values of 18 elements in three soils is contained in Appendix B, Table 1. The f_{ik} and σ_i values of the 53 isotopes of these elements are contained in Appendix B, Table 2. Also contained in Table 2 are the scattering cross sections of the isotopes, $(\sigma_{sc})_i$, used as input to calculate

$$\sigma_{ssc} = \sum_i f_i (\sigma_{sc})_i$$

This is the soil scattering cross section used in the program to calculate the soil capture fraction, α. The cross sections and isotopic fractions are taken from BNL 325[8] and from the G. E. Chart of the Nuclides[9].

6. Conversion to Exposure Rate, K_i

Referring back to the basic equation

$$(D_I)_i = N_o e^{-\Sigma X} \Omega_f \alpha \, (f_c)_i \, K_i \, ,$$

the remaining quantity to be discussed is

$$K_i \left[\text{R/hr} \,/\, \text{neutron captured by } i^{\underline{th}} \text{ isotope/cm}^2\right].$$

For each neutron captured by a nucleus of the $i^{\underline{th}}$ isotope, a daughter nucleus is produced. We are concerned here with radioactive daughters, each of which has a characteristic decay scheme with its own decay constant,

$$\lambda_i \left[\frac{\text{disintegrations}}{\text{sec.}}\right],$$

and its own set of characteristic gamma-rays and their emission ratios, $(f_\gamma)_{ij}$ [photons of $j^{\underline{th}}$ energy/disintegration of atom of $i^{\underline{th}}$ isotope].

Let R_j [R/hr / photon of $j^{\underline{th}}$ energy per cm^2 per sec] =

the conversion factor relating the gamma-ray exposure rate at 3' above an infinite plane to the emission of one photon of the $j^{\underline{th}}$ energy per second from each square centimeter of that plane. Then

$$K_i = \lambda_i e^{-\lambda_i t} \sum_j (f_\gamma)_{ij} R_j$$

where t is the time after capture (Time after capture is taken to be time after detonation).

Appendix B, Table 2 contains one additional quantity, $(T_{\frac{1}{2}})_i$, the half-life of the daughter of the $i^{\underline{th}}$ isotope. This is the quantity usually reported in the literature. Provision has been made in the computer program to convert it to λ_i by

$$\lambda_i = \frac{.693}{(T_{\frac{1}{2}})_i}$$

and to convert each $T_{\frac{1}{2}}$, in whatever standard time units it has been reported (seconds, minutes, hours, days, years), to λ in seconds. Therefore t is entered in seconds.

The decay schemes of the isotopes, also taken from Reviews of Modern Physics,[10] yielded the $(f_\gamma)_{ij}$ for each isotope. They are listed in Appendix B, Table 3. The only non-standard quantity used in the conversion was R_j. The calculations were made by S. C. Rainey* of this laboratory using the Gates and Eisenhauer[11] build-up factors. They are also tabulated in Appendix B, Table 3.

The inputs to the computer for the conversion are $(T_{\frac{1}{2}})_i$, t, and R_j.

*Private communication

III. DISCUSSION AND CONCLUSIONS

We wish to distinguish between the internal accuracy of the prediction system and the overall accuracy. Internal accuracy means the accuracy of the assumptions used in calculating α, $(f_c)_i$, and Ω_f. N_o, ΣX, and K_i are external calculations, i.e., the data base is input to the system and would be required for any other system.

The only internal part of $(f_c)_i$ is the use of σ_i (thermal) rather than the unknown σ_i (integral), which is variable, not only with weapon neutron spectra, but with depth in the soil. The evidence advanced to verify the formula for α seems to indicate that the use of thermal cross sections is justified for the soil capture fraction; therefore, any biasing in the soil capture fractions due to the use of thermal cross sections would appear to be considerably less than any biasing due to erroneous $(f_w)_k$ values.

It may be noted that the high-cross section, trace elements Gd, Sm, and B have been included in the $(f_w)_k$ tabulations of Appendix B, Table 2. To show the effect of their presence, we let

$$\beta = \frac{\text{neutrons producing radioactive nuclides}}{\text{fission}}$$

then

$$\beta = N_o \, \Omega_f \, \alpha \sum_{\text{active}} (f_c)_i$$

where

$\sum_{\text{active}} (f_c)_i$ = the isotopic capture fractions summed over radioactive daughters only

but remembering that

$$\alpha = 1.155 \left(\frac{\sigma_s}{\sigma_{ssc} + \sigma_s} \right)^{\frac{1}{2}}$$

and

$$(f_c)_i = \frac{\sigma_i f_i}{\sigma_s}$$

we can write

$$\beta = \frac{1.155\ \Omega_1 H_o \sum_{\text{active}} f_i\ \sigma_i}{(\sigma_{ssc} + \sigma_s)^{\frac{1}{2}}\ (\sigma_s)^{\frac{1}{2}}}$$

The neutron-induced daughters of Gd, Sm, and B isotopes are stable; therefore, the summation over the active isotopes is affected by the presence of these trace elements only to the extent that the isotopic fraction of each active-daughter isotope is decreased by the inclusion of Gd, Sm, and B in the soil. Since the elements appear in soil in minute concentrations, the numerator is insensitive to their presence. The same argument holds true for the σ_{ssc} in the denominator since these trace elements have negligible scattering cross sections. However, the capture cross section σ_s does increase somewhat by their inclusion, and β will go down roughly as $(\sigma_s)^{\frac{1}{2}}$ increases (in general $\sigma_{ssc} \gg \sigma_s$).

To give a quantitative example we use $\sigma_s = .203$ from the sample output in Appendix A. This σ_s was calculated using the NTS (Polan) soil listed in Appendix B, Table 1. For this soil the $(f_w)_k$ of Gd = 0. Let us assume the true Gd content should have been that listed for the Earth's Crust, Appendix B, Table 1, $(f_w)_{Gd} = 6.4 \times 10^{-6}$. To simplify the calculation we use the atomic weight and cross section of the element, as taken from the Chart of the Nuclides[9], rather than make the calculations based upon the individual isotopes of the element. From the chart then,

Atomic Weight of Gd, $A_{Gd} = 157.25$

and

$\sigma_{Gd} = 4.6 \times 10^4$ barns/atoms (thermal cross sections)

A hand calculation shows $\sum_k (f_w)_k/A_k = 7.2 \times 10^{-2}$ for NTS (Polan).

Therefore, using A_{Gd} to get the atomic fraction, f_{Gd},

$$f_{Gd} = \frac{(f_w)_{Gd}/A_{Gd}}{\sum_k (f_w)_k/A_k}$$

$$= \frac{6.4 \times 10^{-6}/157.25}{7.2 \times 10^{-2}}$$

$$= 5.65 \times 10^{-7}\ \frac{\text{atoms of Gd}}{\text{atom of NTS (Polan) soil}}$$

Now, remembering that

$$\sigma_s = \sum_i f_i \sigma_i$$

$$= .203 \text{ (without Gd)}$$

When Gd is added, we have

$$\sigma_s = .203 + f_{Gd}\sigma_{Gd}$$

$$= .203 + 5.65 \times 10^{-7} \times 4.6 \times 10^{4}$$

$$= .203 + .026$$

$$= .229 \quad \text{barns (with Gd)},$$

so that the addition of 6.4 parts per million (by weight) of Gd increases σ_s by more than 10%. The ratio of the β's then is

$$\frac{\beta(\text{with Gd})}{\beta(\text{without Gd})} \approx \left(\frac{.203}{.229}\right)^{1/2}$$

$$= .942$$

and the change is minor.

If, however, a soil analysis is only made for elements having an abundance of at least 10^{-4} parts by weight, then as much as 10^{-4} parts of Gd could be present without being reported, then $f_{Gd} = 8.83 \times 10^{-6}$ and

$$\sigma_s = .203 + 8.83 \times 10^{-6} \times 4.6 \times 10^{4}$$

$$= .203 + .406$$

$$= .609 \text{ (with Gd)}$$

and the ratio of the β's becomes

$$\frac{\beta(\text{with Gd})}{\beta(\text{without Gd}} \approx \left(\frac{.203}{.609}\right)^{1/2}$$

$$= .58$$

Thus, neglecting 10^{-4} parts of Gd would result in a significant over-protection of exposure rates.

If, now, we investigate changes in β as a function of changes in the $(f_v)_k$ values of the significant contributors to exposure rates of the sample output in Appendix A, we see that Na(Z=11) and Mn(Z=25) contribute better than 95% of the exposure rate; therefore, the change in β is nearly directly proportional to any change in the weight fractions of these elements.

The weight fractions of the significant contributors, like those of the trace elements, are of course external to the system, and like N_o, ΣX, and K_i would be required by any other system, regardless of its sophistication.

With respect to the solid angle fraction, Ω_f should be correct for a surface burst since no calculations using h, C_R, and W are involved. The greatest error in Ω_f will be for low yield weapons detonated near the maximum height of burst. But, in this region, the per-cent error becomes academic because the neutron-induced activity contribution to fallout approaches zero as height of burst increases while the fission contribution remains constant.

To check the internal accuracy of our system, its output for given conditions was checked against a similar, but more elaborate, system reported in the classified literature by Polan et al.[12] Polan's input was the spectral distribution of neutron energies for each of six weapons with varying fission-fusion ratios. The total number of neutrons reported as being emitted by each weapon was converted to N_o for use in our prediction system. All weapons were caseless and detonated at surface zero, thus $e^{-\Sigma X}$ and Ω_f were not involved. The average of the ratios of the predictions for the six weapons showed Polan's to be 0.8% higher, with the maximum disagreement showing Polan to be 2.7% higher.

Some of the elements included in our system were not included in Polan's and vice versa; therefore, to insure that the agreement was not wholly fortuitous, a hand calculation was made of σ_{ssc} and σ_s using Polan's soil composition. From these, the soil capture fraction, α, was calculated and compared with Polan's only reported capture fraction for one soil and one weapon. The ratio of the capture fractions showed Polan's to be 4.4% higher.

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APPENDIX A

Computer Program

1. Equivalent Symbols and Glossary
2. Program
3. Sample Output

Equivalent Symbols of Text and Program

Text	Program
$(\sigma_{sc})_i$	SIGISC
$(f_w)_k$	FW(L)
f_{ik}	FAI(I,L)
σ_i	SIGI(I,L)
$T_{\frac{1}{2}}$	HL
$(f_\gamma)_{ij}$	FOG(N,I,L)
R_j	RNY(N,I,L)
σ_s	SIGS
D_I	SDRL
W	WYK
h	HOB
x	THICK
ρ	RHOC
N_o	EMITN
$\tilde{h}$	SCHOB
Ω_f	FOM
σ_c	SIGC
Σ	SIGM
α	ALB
σ_{ssc}	SIGSSC

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C   GLOSSARY -
C  ALR = NEUTRONS CAPTURED BY SOIL PER NEUTRON EMITTED
C  EMITN = NEUTRONS EMITTED PER FISSION OF THE WEAPON
C  FAI(I,L) = ATOMS OF ISOTOPE I OF L PER ATOM OF L
C  FAT(L) = ATOMS OF L PER ATOM OF SOIL
C  FOG(N,I,L) = PHOTONS OF A PARTICULAR ENERGY PER DISINTEGRATION
C  FOM = SOLID ANGLE FRACTION SUBTENDED BY VOLALITIZATION CRATER OF
C      WEAPON
C  FW(L) = THE FRACTION BY WEIGHT OF THE ELEMENT OCCURING IN THE
C      SOIL OF INTFREST
C  HL(I,L) = THE HALF-LIFE OF DAUGHTER ISOTOPE OF I OF L IN SECONDS,
C      MINUTES, HOURS, DAYS, OR YEARS
C  HOB = HEIGHT OF BURST (FFET)
C  ISO = ARRAY, THE NUMBER OF ISOTOPES PER ELEMENT OCCURING IN NATURE
C  KEV(I,L) = THE NUMBER OF DIFFERENT PHOTON ENFRGIES EMITTED BY THE
C      DAUGHTER PRODUCED BY THE ABSORPTION OF A NEUTRON BY THE ISOTOPE I
C      OF THE ELEMENT L
C  LH(I,L) = AN INDEX DENOTING THE UNITS OF THE HALF-LIFE OF THE
C      DAUGHTER OF I (1= sec, 2 = m, 3 = hr., 4 = d, 5 = yr.)
C  LMAC = NUMBER OF ELEMENTS (UP TO 20) IN CASING
C  LMAX = NUMBER OF ELEMENTS (UP TO 20) IN SOIL.
C  NA = ARRAY, THE ATOMIC MASS NUMBER OF THE ISOTOPE I OF THE ELEMENT L
C  NZ = ARRAY, ATOMIC NUMBER OF THE ELEMENT
C  RHOC = DENSITY OF CASING IN GM/CM**3
C  RNY(N,I,L) = THE EXPOSURE RATE WHICH WOULD BE MEASURED AT 3 FT ABOVE
C      AN INFINITE PLANE UNIFORMLY CONTAMINATED WITH A SOURCE EMITTING
C      ONE PHOTON OF A PARTICULAR ENERGY PER CM**2 PER SEC.
C      ((R/HR) / PHOTON / (CM**2-SEC))
C  SCHOB = SCALED HEIGHT OF BURST
C  SDRL(J) = R / HR / FISSION / CM**2 AT TIME J
C  SIGC = THERMAL ABSORPTION CROSS SECTION OF WEAPON CASING (BARNS)
C  SIGI(I,L) = THE THERMAL NEUTRON ABSORPTION CROSS SECTION OF
C      ISOTOPE I OF L (BARNS)
C  SIGISC(I,L) = THE THERMAL NEUTRON SCATTERING CROSS SECTION OF ISOTOPE
C  I OF L (BARNS)
C  SIGM = MACROSCOPIC ABSORPTION CROSS SECTION OF WEAPON CASING (CM**-1)
C  SIGS = THERMAL ABSORPTION CROSS SECTION OF SOIL (BARNS)
C  SIGSSC = SCATTERING CROSS SECTION OF SOIL FOR THERMAL NEUTRONS
C           (BARNS)
C  THICK = THICKNESS OF WEAPON CASING IN CM.
C  WYK = WEAPON YIELD IN KT
```

FORTRAN INPUT CARD LIST - Program Title - Induced Activity (p. 1 of 8)
LIST TITLE

CARD	WORD	COLS.	FORMAT	MNEMONIC	UNITS	
1	1	1-2	I2	NTIMES	no.of times	Number of times after burst
2	1	1-10	F10.0	T(1)	sec	Time after burst
	2	11-20	F10.0	T(2)	sec	
	3	21-30	F10.0	T(3)	sec	
	4	31-40	F10.0	T(4)	sec	
	5	41-50	F10.0	T(5)	sec	
	6	51-60	F10.0	T(6)	sec	
	7	61-70	F10.0	T(7)	sec	
3	1	1-2	I2	LMAC	no.of L	Number of casing elements (≤ 20)

NOTES:

FORTRAN INPUT CARD ARRAY WORKSHEET

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title-Induced Activity (p. 2 of 8)
ARRAY TITLE - Induced Activity Casing Element Table

MNEMONIC	NZ		ISO		FW				
WORD	1		2		3				
COLS	1-2		3-7		8-20				
FORMAT	I2		I5		E13.3				
UNITS	Element At.No.		No. of Isotopes		weight fraction in casing				

	Card No.	
	(4)	LMAC
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

FORTRAN INPUT CARD ARRAY WORKSHEET

Note: These cards follow and correspond in number to those of the Induced Activity Casing Element Table

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title- Induced Activity (p. 3 of 8)
ARRAY TITLE - Induced Activity Casing Isotope Table

MNEMONIC	NA	KEV	FAI	SIGI	HL	LH	SIGISC	
WORD	1	2	3	4	5	6	7	
COLS	1-3	4-5	6-14	15-29	30-39	40-42	43-57	
FORMAT	I3	I2	F9.5	F15.5	F10.3	I3	F15.5	
UNITS	Isotope Atomic Mass No.	No. of Photon Energies	Isotope Atoms per Element Atom	barns (absorp.)	$T_{\frac{1}{2}}$	$T_{\frac{1}{2}}$ (Unit Index)	barns (scatter)	

	Card No.	
	( )	LMAC
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

FORTRAN INPUT CARD ARRAY WORKSHEET

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title- Induced Activity (p.4 of 8)
ARRAY TITLE - Induced Activity Casing Isotope Photon Energy Table

MNEMONIC	FOG		RNY					
WORD	1		2					
COLS	1-10		11-20					
FORMAT	F10.0		E10.0					
UNITS	Photons per Disintegration		Exposure Rate per Photon					

	Card No.	
	( )	LMAC
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

FORTRAN INPUT CARD ARRAY WORKSHEET

*Header Card	Word	Cols.	Format	Mnemonic	Units
	1	1-2	I2	LMAX	No. of soil elements (LMAX ≤ 20)

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title- Induced Activity (P.5 of 8)
ARRAY TITLE - Induced Activity Soil Element Table

MNEMONIC	NZ		ISO		FW			
WORD	1		2		3			
COLS	1-2		3-7		8-20			
FORMAT	I2		I5		E13.3			
UNITS	Element At. No.		No. of Isotopes		Weight Fraction in Soil			

	Card No.	
	( )	LMAX
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

*Follows Induced Activity Casing Isotope Photon Energy Table and Precedes Induced Activity Soil Element Table.

FORTRAN INPUT CARD ARRAY WORKSHEET
Note: These cards follow and correspond in number to those of the Induced Activity Soil Element Table

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title-Induced Activity (p.6 of 8)
ARRAY TITLE -Induced Activity Soil Isotope Table

MNEMONIC	NA	KEV	FAI	SIGI	HL	LH	SIGISC	
WORD	1	2	3	4	5	6	7	
COLS	1-3	4-5	6-14	15-29	30-39	40-42	43-57	
FORMAT	I3	I2	F9.5	F15.5	E10.3	I3	F15.5	
UNITS	Isotope Atomic Mass No.	No. of Photon Energies	Isotope Atoms per Element Atom	barns (absorp.)	$T_{\frac{1}{2}}$	$T_{\frac{1}{2}}$ (unit index)	barns (scatter)	

	Card No.	
	( )	LMAX
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

FORTRAN INPUT CARD ARRAY WORKSHEET
Note: These cards follow and correspond in number to those of the Induced Activity Soil Isotope Table

FORTRAN INPUT CARD ARRAY WORKSHEET - Program Title- Induced Activity (p.7 of 8)
ARRAY TITLE - Induced Activity Soil Isotope Photon Energy Table

MNEMONIC	FOG		RNY					
WORD	1		2					
COLS	1-10		11-20					
FORMAT	F10.0		E10.0					
UNITS	Photons per Disintegration		Exposure Rate per Photon					

Card No.

	( )	} LMAX
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	
	( )	

FORTRAN INPUT CARD LIST - Program Title - Induced Activity (p.8 of 8)
LIST TITLE BOMPAR (Final Card)

CARD	WORD	COLS.	FORMAT	MNEMONIC	UNITS	
	1	1-10	F10.0	WYK	KT	
	2	11-20	F10.0	HOB	ft.	
	3	21-30	F10.0	THICK	cm	
	4	31-40	F10.0	RHOC	gm/cm^3	
	5	41-50	F10.0	ENTN	neutrons/fission	

NOTES:

```
      DIMENSION T(10), NZ(20), NZC(20), ISO(20), FW(20), NA(10,20),
     2  A(10,20), KEV(10,20), FAI(10,20), SIGI(10,20), HL(10,20),
     3  LH(10,20), SA(20), FAT(20), SFAI(20), FAC(10,20), XLAM(10,20),
     4  DRL(10,20), FOG(5,10,20), RNY(5,10,20), FOGRNY(10,20),
     5  DRI(10,20), DRC(10,20), SDRL(10), SDRC(10), SDRTOT(10),
     6  DRK(10,20), DRE(10,20), SDRK(10), SDRE(10),
     7  SIGISC(10,20), SFAISC(20)

      KRD = 5
      KTR = 6
      READ INPUT TAPE KRD, 10,
     1  NTIMES
      READ INPUT TAPE KRD, 12,
     1  (T(J), J=1, NTIMES)

      KK = 1
      AC = 0.

C     STATEMENTS 100 TO 260 ARE PERFORMED TWICE.  THE FIRST TIME, EXPOSURE
C     RATE FROM ACTIVATED ELEMENTS OF THE BOMB CASING IS CALCULATED.
C     THE SECOND TIME, EXPOSURE RATE DUE TO INDUCED ACTIVITY OF THE SOIL
C     ELEMENTS IS CALCULATED.

  100 READ INPUT TAPE KRD, 10,
     1  LMAX
      IF (KK-1) 101, 101, 102
  101 LMAC = LMAX

  102 READ INPUT TAPE KRD, 14,
     1  (NZ(L), ISO(L), FW(L), L=1, LMAX)

      DO 103 L = 1, LMAX
      IS = ISO(L)
  103 READ INPUT TAPE KRD, 16,
     1  (NA(I,L), KEV(I,L), FAI(I,L), SIGI(I,L), HL(I,L), LH(I,L),
     2  SIGISC(I,L), I=1, IS)

      DO 104 L = 1, LMAX
      IS = ISO(L)
      DO 104 I = 1, IS
      KE = KEV(I,L)
  104 READ INPUT TAPE KRD, 18,
     1  (FOG(N,I,L), RNY(N,I,L), N=1, KE)

      SIGS = 0.
      SIGSSC = 0.
      SFWMAX = 0.
      DO 120 L = 1, LMAX
      SA(L) = 0.
      IS = ISO(L)
      DO 110 I=1, IS
      A(I,L) = NA(I,L)
  110 SA(L) = SA(L) +A(I,L)*FAI(I,L)
  120 SFWMAX = SFWMAX + FW(L)/SA(L)
      DO 150 L = 1, LMAX
      FAT(L) = FW(L)/(SA(L)*SFWMAX)
```

```
      SFAI(L) = 0.
      SFAISC(L) = 0
      IS = ISO(L)
      DO 140 I = 1, IS
      SFAISC(L) =SFAISC(L)+ FAI(I,L)*SIGISC(I,L)
  140 SFAI(L) = SFAI(L) + FAI(I,L)*SIGI(I,L)
      IF (KK-1) 141, 141, 149
  141 AC = AC + FAT(L)*SA(L)
  149 SIGSSC = SIGSSC + FAT(L)*SFAISC(L)
  150 SIGS = SIGS + FAT(L)*SFAI(L)
      IF (KK-1) 151, 151, 152
  151 SIGC = SIGS
  152 DO 200 L = 1, LMAX
      IS = ISO(L)
      DO 200 I = 1, IS
      FAC(I,L) = FAT(L)*FAI(I,L)*SIGI(I,L)/SIGS
      LG = LH(I,L)
      GO TO (200,160,170,180,190), LG
  160 HL(I,L) = HL(I,L)*60.
      GO TO 200
  170 HL(I,L) = HL(I,L)*3600.
      GO TO 200
  180 HL(I,L) = HL(I,L)*86400.
      GO TO 200
  190 HL(I,L) = HL(I,L)*31536000.
  200 XLAM(I,L) = .693/HL(I,L)
      DO 201 J = 1, NTIMES
  201 SDRL(J) = 0.0
      DO 260 J = 1, NTIMES
      DO 240 L = 1, LMAX
      DRL(J,L) = 0.
      IS = ISO(L)
      DO 220 I = 1, IS
      FOGRNY(I,L) = 0.
      KE = KEV(I,L)
      DO 210 N = 1, KE
  210 FOGRNY(I,L) = FOGRNY(I,L) + FOG(N,I,L)*RNY(N,I,L)
      DRI(I,L) = FAC(I,L)*XLAM(I,L)*FOGRNY(I,L)*EXPF(-XLAM(I,L)*T(J))
  220 DRL(J,L) = DRL(J,L) + DRI(I,L)
      IF (KK-1) 230, 230, 240
  230 DRC(J,L) = DRL(J,L)
      NZC(L) = NZ(L)
  240 SDRL(J) = SDRL(J) + DRL(J,L)
      IF (KK-1) 250, 250, 260
  250 SDRC(J) = SDRL(J)
  260 CONTINUE
      GO TO (270,280), KK

  270 KK = 2
      GO TO 100

C     REDUCTION OF SOIL EXPOSURE RATE IS NOW MADE ACCORDING TO THE
C     FRACTION OF NEUTRONS ESCAPING ABSORPTION BY THE BOMB CASING,
C     THE SOLID ANGLE FRACTION OF THE FIREBALL TOUCHING THE GROUND AT
C     THE TIME OF HYDRODYNAMIC SEPARATION, AND THE FRACTION OF
C     NEUTRONS THAT REMAIN IN THE SOIL
```

```
280 ALB = 1.155*SQRTF(SIGS/(SIGSSC + SIGS))

    READ INPUT TAPE KRD, 10,
   1  NWEP

    DO 330 M = 1, NWEP
    READ INPUT TAPE KRD, 12,
   1  WYK, HOB, THICK, RHOC, EMITN


    SCHOB = HOB/WYK**0.33333333
    FOM =       1.-SCHOB/SQRTF(4.24*SCHOB**2-234.*SCHOB+4225.)
    SIGM = RHOC*0.6023*SIGC/AC
    EMITC = EMITN*EXPF(-SIGM*THICK)
    DO 300 J = 1, NTIMES
    DO 290 L = 1, LMAX
    DRK(J,L) = DRC(J,L)*(EMITN-EMITC)
290 DRE(J,L) = DRL(J,L)*EMITC*FOM*ALB
    SDRK(J) = SDRC(J)*(EMITN-EMITC)
    SDRE(J) = SDRL(J)*EMITC*FOM*ALB
300 SDRTOT(J) = SDRK(J) + SDRF(J)

    WRITE OUTPUT TAPE KTR, 30,
   1  WYK, HOB, SCHOB, THICK, AC, RHOC, EMITN, EMITC, SIGC, SIGS,
   2  SIGSSC, FOM, ALB

    WRITE OUTPUT TAPE KTR, 32,
   1  (T(J), J=1, NTIMES)

    DO 310 L = 1, LMAC
310 WRITE OUTPUT TAPE KTR, 34,
   1  NZC(L), (DRK(J,L), J=1, NTIMES)

    WRITE OUTPUT TAPE KTR, 36,
   1  (SDRK(J), J=1, NTIMES)

    WRITE OUTPUT TAPE KTR, 38,
   1  (T(J), J=1, NTIMES)

    DO 320 L = 1, LMAX
320 WRITE OUTPUT TAPE KTR, 34,
   1  NZ(L), (DRE(J,L), J=1, NTIMES)

    WRITE OUTPUT TAPE KTR, 40,
   1  (SDRE(J),J=1, NTIMES)

330 WRITE OUTPUT TAPE KTR, 42,
   1  (SDRTOT(J), J=1, NTIMES)


 10 FORMAT (I2,8X,F10.0)
 12 FORMAT (7F10.0)
 14 FORMAT (I2,I5,E13.3)
 16 FORMAT (I3,I2,F9.5,F15.5,F10.3,I3,F15.5)
 18 FORMAT (F10.0,E10.0)
```

```
30 FORMAT (15H1 3179  INDUCED  //  12H YIELD (KT) , F10.1, /
  1      12H HOB (FEET) , F11.0,10X,11HSCALED HOB , F11.3  /
  2      7H CASING, / 6X, 15HTHICKNESS (CM) ,F6.2,5X,12HAV. AT. WT. ,
  3      F7.3, 5X, 20HAV. DENSITY (GM/CC) , F6.3, /
  4      39H NUMBER OF NEUTRONS EMITTED PER FISSION, F5.2,  /
  5      47H NUMBER OF NEUTRONS ESCAPING CASING PER FISSION, F5.2,  /
  6      31H AVERAGE CAPTURE CROSS SECTIONS, / 6X, 9HOF CASING,E10.3,
  7      / 6X,7HOF SOIL,E12.3/30H SOIL SCATTERING CROSS SECTION,E10.3,
  8      /22H SOLID ANGLE FRACTION ,F6.4, / 23H SOIL CAPTURE FRACTION
  9      F6.4,   ///)
32 FORMAT (10X,39HR/HR PER FISSION/SQCM DUE TO THE CASING  //
  2      25X, 12H TIME (SEC)  /
  3      12H ELEMENT (Z) , 5X, 10F10.0   /)
34 FORMAT (I7, 10X, 1P10E10.3)
36 FORMAT (12HOCASING SUM , 5X, 1P10E10.3  //)
38 FORMAT (///5X,37HR/HR PER FISSION/SQCM DUE TO THE SOIL //
  2      25X, 12H TIME (SEC)  /
  3      12H ELEMENT (Z) , 5X, 10F10.0   /)
40 FORMAT (12HO  SOIL SUM , 5X, 1P10E10.3  )
42 FORMAT (11HOCASING AND, /
  2      12H SOIL SUMMED, 5X, 1P10E10.3  )

   CALL EXIT
   END (0, 0, 0, 0, 0)
```

3179 INDUCED

YIELD (KT) 2.0
HOB (FEET) -0. SCALED HOB -0.
CASING
THICKNESS (CM) -0. AV. AT. WT. 36.415 AV. DENSITY (GM/CC) 3.000
NUMBER OF NEUTRONS EMITTED PER FISSION 1.00
NUMBER OF NEUTRONS ESCAPING CASING PER FISSION 1.00
AVERAGE CAPTURE CROSS SECTIONS
OF CASING 0.103E+01
OF SOIL 0.203E-00
SOIL SCATTERING CROSS SECTION 0.916E+01
SOLID ANGLE FRACTION 1.0000
SOIL CAPTURE FRACTION 0.1700

R/HR PER FISSION/SQCM DUE TO THE CASING

	TIME (SEC)	
ELEMENT (Z)	3600.	4032.
26	0.	0.
13	0.	0.
CASING SUM	0.	0.

R/HR PER FISSION/SQCM DUE TO THE SOIL

	TIME (SEC)	
ELEMENT (Z)	3600.	4032.
26	3.742E-17	3.742E-17
64	0.	0.
14	9.019E-16	8.738E-16
19	1.038E-14	1.031E-14
13	2.529E-19	2.889E-20
11	2.679E-13	2.655E-13
22	2.247E-17	9.508E-18
1	0.	0.
20	2.196E-15	1.221E-15
17	8.986E-15	7.867E-15
62	0.	0.
25	6.713E-13	6.500E-13
12	2.256E-15	1.334E-15
5	0.	0.
23	0.	0.
24	1.442E-18	1.442E-18
15	0.	0.
8	0.	0.
SOIL SUM	9.631E-13	9.372E-13
CASING AND SOIL SUMMED	9.631E-13	9.372E-13

APPENDIX P

TABLE 1

Elemental Soil Composition

Element	Z	Earth's Crust Weight Fraction $(f_w)_k$	NTS* (Jones) Weight Fraction $(f_w)_k$	NTS (Polan[11]) Weight Fraction $(f_w)_k$
H	1	1.4×10^{-3}	0	2.639×10^{-2}
B	5	3.0×10^{-6}	1.0×10^{-4}	0
O	8	4.66×10^{-1}	5.001×10^{-1}	5.47×10^{-1}
Na	11	2.83×10^{-2}	1.34×10^{-2}	4.9×10^{-3}
Mg	12	2.09×10^{-2}	4.4×10^{-3}	2.09×10^{-2}
Al	13	8.13×10^{-2}	7.63×10^{-2}	4.8×10^{-3}
Si	14	2.772×10^{-1}	2.756×10^{-1}	2.772×10^{-1}
P	15	1.18×10^{-3}	0	1.18×10^{-3}
Cl	17	3.14×10^{-4}	0	3.14×10^{-4}
K	19	2.59×10^{-2}	2.96×10^{-2}	2.59×10^{-2}
Ca	20	3.63×10^{-2}	8.66×10^{-2}	3.63×10^{-2}
Ti	22	4.4×10^{-3}	2.4×10^{-3}	4.4×10^{-3}
V	23	1.5×10^{-4}	0	0
Cr	24	2.0×10^{-4}	0	2.0×10^{-4}
Mn	25	1.0×10^{-3}	3.0×10^{-4}	5.0×10^{-4}
Fe	26	5.0×10^{-2}	1.12×10^{-2}	5.0×10^{-2}
Sm	62	6.5×10^{-6}	6.5×10^{-6}	0
Gd	64	6.4×10^{-6}	6.4×10^{-6}	0

* Modified by the author from reference 2.

TABLE 2

Isotope Capture Parameters[7,8,9]

Isotope	f_{ik} Elemental Fraction	σ_i Absorption Cross Section (barns)	$(T_{\frac{1}{2}})_i$ Daughter Half-Life	$(\sigma_{sc})_i$ Scat. Cross Sect. (barns)
H 1	.99985	.33	10^{30}s*	19
H 2	.00015	.00057	12.26y	19
B 10	.1978	3840	10^{30}s	4
B 11	.8022	.05	.03s	4
O 16	1.0000	.0002	10^{30}s	4.2
Na 23	1.0000	.53	15h	4
Mg 24	.7870	.03	10^{30}s	3.6
Mg 25	.1013	.27	10^{30}s	3.6
Mg 26	.1117	.03	9.5m	3.6
Al 27	1.0000	.23	2.3m	1.4
Si 28	.9221	.08	10^{30}s	1.7
Si 29	.0470	.28	10^{30}s	1.7
Si 30	.0309	.11	2.62h	1.7
P 31	1.0000	.19	14.3d	5
Cl 35	.7553	44.4	3.08×10^{5}y	16
Cl 37	.2447	.565	37.5m	16

* 10^{30}s means the daughter is stable.

TABLE 2 (Cont.)

Isotope	f_{ik} Elemental Fraction	σ_i Absorption Cross Section (barns)	$(T_{\frac{1}{2}})_i$ Daughter Half-Life	$(\sigma_{sc})_i$ Scat. Cross Sect. (barns)
K 39	.9310	2.2	1.3×10^9 y	1.5
K 40	.0002	70	10^{30} s	1.5
K 41	.0688	1.1	12.4h	1.5
Ca 40	.9697	.2	10^{30} s	3.2
Ca 42	.0064	40	10^{30} s	3.2
Ca 44	.0206	.7	15cd	3.2
Ca 48	.0018	1.1	8.5m	3.2
Ti 46	.0793	.6	10^{30} s	4
Ti 47	.0728	1.7	10^{30} s	4
Ti 48	.7394	8.0	10^{30} s	4
Ti 49	.0551	1.9	10^{30} s	4
Ti 50	.0534	.14	5.8m	4
V 50	.0024	130	10^{30} s	5
V 51	.9976	4.9	3.76m	5
Cr 50	.0431	17.0	27.8d	3
Cr 52	.8376	.8	10^{30} s	3
Cr 53	.0955	18	10^{30} s	3
Cr 54	.0238	.38	3.6m	3
Mn 55	1.0000	13.3	2.58h	2.3

TABLE 2 (Cont.)

I Isotope	f_{ik} Elemental Fraction	σ_i Absorption Cross Section (barns)	$(T_{\frac{1}{2}})_i$ Daughter Half-Life	$(\sigma_{sc})_i$ Scat. Cross Sect. (barns)
Fe 54	.0582	2.9	2.96y	11
Fe 56	.9166	2.7	10^{30}s	11
Fe 57	.0219	2.5	10^{30}s	11
Fe 58	.0033	1.1	46d	11
Sm 144	.0316	2	400d	0
Sm 147	.1507	87	10^{30}s	0
Sm 148	.1127	0	10^{30}s	0
Sm 149	.1384	40800	10^{30}s	0
Sm 150	.0747	0	10^{30}s	0
Sm 152	.2663	224	47h	0
Sm 154	.2253	5.5	24m	0
Gd 152	.0020	125	230d	0
Gd 154	.0215	0	10^{30}s	0
Gd 155	.1473	61000	10^{30}s	0
Gd 156	.2047	0	10^{30}s	0
Gd 157	.1568	240000	10^{30}s	0
Gd 158	.2487	4	18.0h	0
Gd 160	.2190	.8	3.6m	0

TABLE 3

Exposure Rate Parameters

Parent Isotope	Photon Energy (Mev)	$(f_\gamma)_{ij}$ Photons per Disintegration	R_j R/hr / photon/cm^2-sec ($\times 10^{-6}$)
H 1	0	0	0
H 2	0	0	0
B 10	0	0	0
B 11	4.43	.026	15.13
B 11	3.22	.013	12.00
O 16	0	0	0
Na 23	2.75	1.000	10.70
Na 23	1.37	1.000	6.40
Mg 24	0	0	0
Mg 25	0	0	0
Mg 26	1.015	.300	5.05
Mg 26	.843	.700	4.33
Al 27	1.78	1.000	7.75
Si 28	0	0	0
Si 29	0	0	0
Si 30	1.264	.007	6.04
P 31	0	0	0

TABLE 3 (Cont.)

Parent Isotope	Photon Energy (Mev	$(f_\gamma)_{ij}$ Photons per Disintegration	R_j $\frac{R/hr}{photon/cm^2\text{-}sec}$ $(x10^{-6})$
Cl 35	0	0	0
Cl 37	2.16	.470	8.92
Cl 37	1.59	.310	7.14
K 39	1.46	.110	6.70
K 40	0	0	0
K 41	1.53	.180	6.95
Ca 40	0	0	0
Ca 42	0	0	0
Ca 44	0	0	0
Ca 48	4.68	.006	15.76
Ca 48	4.05	.010	14.10
Ca 48	3.10	.890	11.68
Ti 46	0	0	0
Ti 47	0	0	0
Ti 48	0	0	0
Ti 49	0	0	0
Ti 50	.928	.042	4.68
Ti 50	.605	.013	3.23
Ti 50	.323	.945	1.75
V 50	0	0	0
V 51	1.433	1.000	6.62

TABLE 3 (Cont.)

Parent Isotope	Photon Energy (Mev)	$(f_\gamma)_{ij}$ Photons per Disintegration	R_j $\frac{R/hr}{photon/cm^2\text{-}sec}$ $(x10^{-6})$
Cr 50	.323	.090	1.75
Cr 52	0	0	0
Cr 53	0	0	0
Cr 54	0	0	0
Mn 55	2.98	.005	11.34
Mn 55	2.65	.018	10.40
Mn 55	2.13	.195	8.84
Mn 55	1.81	.282	7.85
Mn 55	.845	.977	4.55
Fe 54	0	0	0
Fe 56	0	0	0
Fe 57	0	0	0
Fe 58	1.289	.430	6.10
Fe 58	1.191	.030	5.77
Fe 58	1.098	.570	5.38
Sm 144	0	0	0
Sm 147	0	0	0
Sm 148	0	0	0
Sm 149	0	0	0
Sm 150	0	0	0
Sm 152	0	0	0
Sm 154	0	0	0

TABLE 3 (Cont.)

Parent Isotope	Photon Energy (Mev)	$(f_\gamma)_{ij}$ Photons per Disintegration	R_j $\frac{R/hr}{photon/cm^2\text{-}sec}$ $(x10^{-6})$
Gd 152	0	0	0
Gd 154	0	0	0
Gd 155	0	0	0
Gd 156	0	0	0
Gd 157	0	0	0
Gd 158	0	0	0
Gd 160	0	0	0

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A system has been devised to predict the neutron-induced activity contribution to fallout exposure rates. The system uses the simplifying assumptions of 1) a semi-empirical formula to determine the soil capture fraction and 2) thermal neutron cross sections to represent weapon-neutron cross sections. Results, using these assumptions, agree with those of another complete system for predicting the neutron-induced activity contribution to fallout exposure rates. In addition, results from various portions of the system agree with results obtained by more complicated methods.

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