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THE IMPORTANCE OF TRITIUM IN THE CIVIL DEFENSE CONTEXT

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THE IMPORTANCE OF TRITIUM IN THE CIVIL DEFENSE CONTEXT *

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Abstract

The importance of tritium in the civil defense context is assessed by comparing the dose rate and 50-year dose integral for tritium from fusion with the external dose of gamma-emitting fission products.

The tritium dose is computed by assuming equilibration of fallout tritium with water in the biosphere and with body water of man. The fission product gamma dose for late-time dose significant nuclides are tabulated in terms of $R/hr/kt/mi^2$ as a function of time.

Tritium is shown to be relatively unimportant in the civil defense context when compared with the external gamma dose from an equal yield of fission products.

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INTRODUCTION

The survival of man in an environment contaminated with radioactive fallout after a nuclear attack is the basis upon which the importance of tritium in the civil defense context can be assessed. Although tritium is a weak beta emitter, the radiation hazard to man can be significant because of the high yield of residual tritium from fusion devices. Also, tritium is relatively mobile, and as tritiated water, becomes rapidly dispersed in the environment where it is available for ingestion by man. On the other hand, the hazard is reduced somewhat by the dilution of tritium with the large amount of water in the environment.

The importance of any single isotope can only be compared with respect to other radioisotopes produced in a nuclear explosion. As a first estimate therefore, the radiation hazard to man from residual tritium will be compared with that of fission-product radioactivity.

When certain reasonable assumptions are made, the dose rate as a function of time and the 30-year dose integral can be determined per unit area and unit explosive yield for residual tritium from fusion and for fission-product radioisotopes. For example, in the civil defense context, we assume a two-week shelter period following the detonation of nuclear weapons with equal parts of fission and fusion. The two-week shelter period eliminates blast, heat, shockwave, and prompt radiation effects from consideration. The assumption of equal parts of fission and fusion is necessary to normalize the explosive yield. The results obtained in this study can be scaled directly for any other ratio of fission to fusion.

Finally, we assume that fallout is uniformly deposited over a one-square-mile area per kiloton of yield. The essential consideration of this assumption is that tritium is distributed in the same manner as the fission products. Any deviation from uniform distribution will not affect the results of this study as long as the tritium and fission-product fallout distribution changes in the same way. The results can also be scaled directly for any area of deposition per unit explosive yield.

Fleming (1) provides a convenient summary of external gamma dose as a function of time for uniformly deposited, unfractionated plutonium fission products in terms of $R/\text{hr}/\text{kt}/\text{mi}^2$. To simplify the comparison, only those nuclides which contribute significantly to the external gamma dose at late times will be considered in comparison to the tritium dose. Many short-lived fission products are of course eliminated from consideration by the two-week shelter period.

The tritium dose rate can be expressed in the same terms as the gamma dose rate if we assume that the uniformly distributed residual tritium yield is thoroughly mixed and in equilibrium with water in the fallout environment by the end of the two-week shelter period. The specific activity approach then permits dose calculations based on equilibration of tritiated water with vegetation, livestock, and man.

TRITIUM DOSIMETRY

In order to use the specific activity approach, the water compartment of the biosphere in which tritium fallout will be mixed must be determined. The water compartment can be estimated from studies on the behavior of

tritium in a desert ecosystem by Koranda and Martin (2) and in the tropical rainforest ecosystem by Martin et al. (3) and Jordan et al. (4). These studies show that tritium behavior in the environment is influenced largely by rainfall. The extremes of the range of rainfall are probably represented by these diverse ecosystems from the low of 5 inches/yr in the desert to the high of 100 inches/yr in the rainforest.

Tritium behavior may be considered in terms of a simple mixed tank model. A single deposition of tritium is assumed to mix completely with a finite soil-water volume defined as the water compartment capacity C. The incoming flux of rainwater, F, which represents the flow through the compartment C, is assumed to be immediately and completely mixed with the water compartment. The outgoing flux of water from the compartment must be equal to the incoming flux and contains the instantaneous diluted concentration of tritium. The physical removal of tritium is thus exponential with time. The mean residence time T for tritium is defined as the average time a tritium atom remains in the compartment, and is given by the ratio of the capacity, C, to the flux, F :

$$T = C/F \quad (1)$$

The exponential physical removal of tritium was demonstrated in the desert and rainforest ecosystem studies. The capacity, C, of the water compartment can be determined from a measurement of the flux of rainwater, F, and from the observed mean residence time, T, where :

$$C = F \times T \quad (2)$$

In the rainforest experiment described by Jordan et al. (4), the surface deposition of tritium moved down into the soil profile, giving a peaked distribution with depth. The peak tritium concentration moved deeper into the soil profile and became more diffuse with time. Martin et al. (3) described how the residence time was determined by plotting the integrals of the tritium depth distribution curves with time. The mean residence time for tritium in the rainforest ecosystem following a surface application of tritium was 42 days. The incoming flux of rain was 100 inches/yr or $6.66 \text{ kg/m}^2/\text{day}$, and so the capacity of the water compartment, C, from Eq. (2) is:

$$C = F \times T = 6.66 \times 42 = 280 \text{ kg/m}^2$$

A similar pattern of tritium behavior with time was observed in the soil of the desert ecosystem at Sedan crater. The mean residence time for tritium determined by Martin and Koranda (5) was 18.8 months or 570 days. The incoming flux of rain was only 5 inches/yr or $0.35 \text{ kg/m}^2/\text{day}$, and so the water compartment capacity, C, from Eq. (2) is :

$$C = F \times T = 0.35 \times 570 = 200 \text{ kg/m}^2$$

The agreement in the calculated values for the water compartment capacity of these diverse ecosystems can be explained by the difference in the depth of the zone of interaction of their respective soils. Although the rainforest soil had a relatively high average water content, only a shallow layer of soil water mixed with incoming rain. The water compartment of the wet tropical rainforest soil corresponded to a depth

zone of less than two feet. In the dry desert soils, significant interaction of tritium was observed at depths of six feet. The estimated water compartment capacity for the biosphere was therefore taken to be the average value of 240 kg/m^2 .

This estimate is conservatively low with respect to dose calculations, because desert plants growing at Sedan crater typically had tritium concentrations in their water, indicating a water compartment of 3 to 9 times that of the measured value. There appeared to be greater dilution of the tritium than could be accounted for by the water compartment. This is apparently due to the fact that the tritium is not uniformly distributed in the soil. The plants draw water from selected depths in the soil, whereas the water compartment is determined from the integrated depth profile.

The tritium concentration in the biosphere can be calculated from a tritium yield of 2 g/kt dispersed over a square-mile area and diluted by the water compartment of 240 kg/m^2 . The resulting specific activity of tritium is:

$$A = \frac{(2 \text{ g/kt}) (9800) \text{ Ci/g} (3.86 \times 10^{-7}) \text{ mi}^2/\text{m}^2}{240 \text{ kg/m}^2} = 3.15 \times 10^{-5} \text{ Ci/kg/kt/mi}^2$$

If a man is equilibrated with this specific activity, the resulting dose rate, D_0 , would be :

$$D_0 = (3.15 \times 10^{-5}) \text{ Ci/kg/kt/mi}^2 (7.44) \text{ R/hr/Ci/kg} = 2.34 \times 10^{-4} \text{ R/hr/kt/mi}^2$$

The dose rate, D_t , at any time t is given by :

$$D_t = D_o e^{-(\lambda_p + \lambda_r)t} \quad (3)$$

where λ_r is the radiological decay constant for tritium (0.0565 yr^{-1}) and λ_p is the physical removal decay constant.

The integrated dose, I , from $t = 0$ to $t = t$, is given by :

$$I_t = \frac{D_o (1 - e^{-(\lambda_p + \lambda_r)t})}{(\lambda_p + \lambda_r)} \quad (4)$$

The 30-year dose integral for no physical removal ($\lambda_p = 0$) is :

$$I_{30} = (2.34 \times 10^{-4} / 0.0565)(8760 \text{ hr/yr})(1 - e^{-30(0.0565)}) \text{ R/kt/mi}^2$$

$$I_{30} = 30 \text{ R/kt/mi}^2$$

If allowance is made for the physical residence time of tritium, the thirty-year dose integral is much lower. Even when the most conservative observed value, 18.8 months ($\lambda_p = 0.639 \text{ yr}^{-1}$), in the desert ecosystem is used for the physical residence time, the dose integral becomes:

$$I_{30}' = 3 \text{ R/kt/mi}^2$$

FISSION-PRODUCT DOSIMETRY

A tabulation of the dose rate at various times and the 2-week to 30-year dose integral for the late-time dose significant gamma-emitting fission products is given in Table I. The dose rates were taken directly from Fleming's (1) data, wherein the point of exposure is three feet

above a smooth infinite plane uniformly contaminated with the nuclide in question. The late-time dose significant nuclides are those which contribute 1% or more of the total external gamma dose integral from two weeks to 30 years. The nuclides listed account for more than 95% of the dose rate at any time after two weeks post detonation.

At early times following the two-week shelter period, the dose rate is due mainly to fission products with half-lives in the range of several days to several weeks. The contribution of $^{140}\text{Ba}/^{140}\text{La}$ for example, is half of the total dose rate at $t = 2$ weeks. Due to their relatively short half-lives, the contribution of these nuclides falls off rapidly with time. The long-lived nuclides such as $^{106}\text{Ru}/^{106}\text{Rh}$ and ^{137}Cs contribute only a small fraction of the dose rate at $t = 2$ weeks but become increasingly significant at later times. At $t = 2$ years for example, these nuclides account for 85% of the total external gamma dose rate of the uniformly deposited fission products.

In the period from two weeks to two years, the major fraction of the dose rate is from nuclides with half-lives on the order of months which have relatively high yields, such as $^{95}\text{Zr}/^{95}\text{Nb}$ and ^{103}Ru . These nuclides account for more than 85% of the dose rate at $t = 20$ weeks and more than 60% of the dose rate at $t = 50$ weeks. These nuclides also account for more than 50% of the total 2-week to 30-year dose integral.

Except for ^{95}Nb , the 2-week to 30-year dose integrals are computed for each significant nuclide by means of Eq. (4) with the physical decay constant, $\lambda_p \approx 0$. In computing the ^{95}Nb dose integral, its growth from the decay of ^{95}Zr must be considered. All other nuclides are produced at early times or have short-lived precursors, so that the change in

dose rate with time is due only to radiological decay. The sum of all individual contributors gives a total 2-week to 30-year dose integral of 1124 R/kt/mi^2 .

The dose rate decreases rapidly with time, so that most of the integrated dose is delivered at early times post detonation. For example, during the period from 2 weeks to 20 weeks, 680 R/kt/mi^2 or more than 60% of the total 2-week to 30-year dose integral is delivered. An additional 200 R/kt/mi^2 is delivered in the period from 20 weeks to 50 weeks. Thus, nearly 80% of the 30-year total integrated gamma dose is delivered during the first year post detonation.

COMPARISON OF TRITIUM DOSE TO EXTERNAL GAMMA DOSE

The dose rate and the 2-week to 30-year dose integrals for tritium and for the gamma-emitting fission products are listed in Table II in terms of R/hr/kt/mi^2 and R/kt/mi^2 , respectively. Table III lists the same data, except the tritium is assumed to have an 18.8 month residence time in the biosphere. It can be seen that in both cases the gamma dose rate is very much greater than that of the tritium, particularly at early times. The Dose Ratio is the ratio of the fission-product gamma to tritium dose rate.

At early times, the Dose Ratio is about 10^4 but decreases rapidly to a ratio of about 70 at $t = 50$ weeks. The decline with time then becomes more gradual until a minimum ratio of 7 is reached at about $t = 4$ years. The ratio then increases slowly to a value of about 10 at $t = 30$ years. When the tritium residence time in the biosphere is assumed to be 18.8 months, the Dose Ratio has a minimum value of

50 at $t = 2$ years. In either case, the fission-product external gamma dose rate is always at least 7 times that of the tritium dose rate. When the physical residence time of tritium is considered, the tritium dose rate is never more than 2% of the external gamma dose from fission products.

The comparison of tritium with the external gamma dose from fission products can also be made on the basis of the 2-week to 30-year dose integral. The dose integral for the fission products is 1124 R/kt/mi^2 ; the value for tritium is 30 R/kt/mi^2 or 3 R/kt/mi^2 when the residence time is considered. The fission product dose integral is thus at least 37 times that of the tritium dose integral and is more likely to be 370 times as much.

CONCLUSIONS

This analysis was done on a relative scale. The importance of other internal beta emitters and of activation products can be assessed in a similar manner, relative to the fission-product external gamma scale. The full significance of the fallout radiation hazard to the survival of man in the event of nuclear attack will depend on assessment of the absolute values of dose rate and dose integrals. The extent of preventive or corrective measures to be taken against the fallout radiation hazard can then be determined. Many hypothetical attack situations which go beyond the scope of this paper will have to be considered in making the assessment of the absolute hazard. The task may be simplified somewhat by the approach presented here, which shows that tritium is relatively unimportant in the civil defense context when compared to the external gamma dose from fission products.

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TABLE I
LATE-TIME DOSE SIGNIFICANT γ -EMITTING FISSION PRODUCTS

Nuclide	<u>Dose Rate (R/hr/kt/mi²)</u>					Dose Integral 2 weeks - 30 years
	2 weeks	20 weeks	50 weeks	100 weeks	200 weeks	R/kt/mi ²
⁹⁵ Zr	9.5×10^{-2}	2.6×10^{-2}	2.6×10^{-3}	7.0×10^{-5}	—	214
⁹⁵ Nb	2.5×10^{-2}	4.0×10^{-2}	6.0×10^{-3}	1.4×10^{-4}	—	225
¹⁰³ Ru	1.4×10^{-1}	1.5×10^{-2}	4.0×10^{-4}	—	—	192
¹³⁷ Cs- ^{137m} Ba	8.2×10^{-4}	8.2×10^{-4}	8.2×10^{-4}	7.8×10^{-4}	7.3×10^{-4}	156
¹⁰⁶ Ru- ¹⁰⁶ Rh	8.2×10^{-3}	6.3×10^{-3}	4.2×10^{-3}	2.2×10^{-3}	5.5×10^{-4}	104
¹³¹ I	1.6×10^{-1}	—	—	—	—	45
¹³² I	4.0×10^{-1}	—	—	—	—	45
¹³⁶ Cs	1.0×10^{-1}	1.0×10^{-4}	—	—	—	45
¹⁴⁰ Ba/ ¹⁴⁰ La	1.2×10^0	1.1×10^{-3}	—	—	—	22
¹⁴¹ Ce	2.0×10^{-2}	1.5×10^{-3}	—	—	—	23
¹⁴⁴ Ce- ¹⁴⁴ Pr	1.2×10^{-3}	8.5×10^{-4}	5.0×10^{-4}	2.2×10^{-4}	—	11
¹⁴⁷ Nd	2.8×10^{-2}	1.0×10^{-5}	—	—	—	11
Others	8.0×10^{-2}	7.5×10^{-4}	2.0×10^{-4}	1.0×10^{-4}	—	31
Total	2.26×10^0	9.24×10^{-2}	1.47×10^{-2}	3.51×10^{-3}	1.28×10^{-3}	1124

TABLE II

ESTIMATED TRITIUM INTERNAL RADIATION DOSE COMPARED WITH FISSION PRODUCT DOSE

	<u>Dose Rate (R/hr/kt/mi²)</u>						<u>Dose Integral</u>
	2 weeks	20 weeks	50 weeks	100 weeks	200 weeks	30 years	2 wks - 30 yrs R/kt/mi ²
Total Fission Products (per kt fission)	2.26×10^0	9.24×10^{-2}	1.47×10^{-2}	3.51×10^{-3}	1.28×10^{-3}	4.1×10^{-4}	1124
Tritium (per kt fusion)	2.33×10^{-4}	2.29×10^{-4}	2.22×10^{-4}	2.10×10^{-4}	1.88×10^{-4}	4.29×10^{-5}	30
Dose Ratio <u>Fission Products</u> <u>Tritium</u>	$\sim 10^4$	400	70	17	7	10	37

TABLE III

ESTIMATED TRITIUM INTERNAL RADIATION DOSE COMPARED WITH FISSION-PRODUCT DOSE
USING 18.8 MONTH RESIDENCE TIME FOR TRITIUM

	<u>Dose Rate (R/hr/kt/mi²)</u>						<u>Dose Integral</u> 2 wks - 30 yrs R/kt/mi ²
	2 weeks	20 weeks	50 weeks	100 weeks	200 weeks	30 years	
Total Fission Products (per kt fission)	2.26×10^0	9.24×10^{-2}	1.47×10^{-2}	3.51×10^{-3}	1.28×10^{-3}	4.1×10^{-4}	1124
Tritium (per kt fusion)	2.28×10^{-4}	1.82×10^{-4}	1.26×10^{-4}	6.74×10^{-5}	1.94×10^{-5}	8.0×10^{-10}	3
Dose Ratio <u>Fission Products</u> <u>Tritium</u>	$\sim 10^4$	500	120	50	70	5×10^5	370