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ESTIMATION OF WHOLE-BODY RADIATION DOSES IN ACCIDENTAL FISSION BURSTS*

By JOSEPH G. HOFFMAN, PH.D.,† *and* LOUIS H. HEMPELMANN, M.D.‡

TWO nuclear accidents occurred at the Los Alamos Scientific Laboratory, on August 21, 1945, and on May 21, 1946. The accidents centered about the occurrence of uncontrolled fission reactions in such a manner that 10 persons were exposed to bursts of penetrating ionizing radiation. Two of these persons died as a result of exposure to the radiation, while some survivors (Cases 2, 9, and 10) showed clinically insignificant reactions. The case histories of 9 of the individuals have been described in detail by Hempelmann, Lisco, and Hoffman.[4] The following account deals with the methods and physical problems of estimating the radiation doses sustained in these 9 cases. The cases are numbered exactly as they were given in the clinical report.[4]

Penetrating ionizing radiations were the sole cause of injury sustained by the personnel. There were no heat or mechanical effects accompanying the release of energy from the critical assemblies of fissile material. A state of criticality was reached inadvertently and then removed as fast as the reaction time of the operators permitted. There were no complications due to the spread of radioactive fission products, these having been retained within the confines of the assembly. Therefore, the radiation doses were due to the fission process itself and only secondarily due to the delayed radiation from the products of fission.

Injury to tissue was brought about by fast neutrons and gamma rays. The former impart their energy to the tissue primarily by collisions with hydrogen atoms to produce recoil protons. After becoming thermalized, the neutrons are captured. The capture in H^1 is followed by the emission of 2.2 mev. gamma quantum. This gamma radiation produces a "selfdosage" of the tissue, or an "autodose." Neutron capture in N^{14} releases a proton, the reaction having a Q value of 0.6 mev. Of particular interest are the induced radioactivities in Na^{24} and P^{32} which follow neutron capture in Na^{23} and P^{31}. These activities occurred in measurable quantities, as is shown in Table 1 (see also Reference 4). The Na^{24} activity provided a physical means by which neutron doses could be estimated.

The gamma rays contributing to the tissue dose were: first, the prompt gamma rays released in the fission process; second, the autodose arising from H^1 captures, as mentioned above; and, third, the delayed gamma rays coming from the fission products remaining after the fission burst. Dosage due to delayed gamma radiation depends, of course, on whether or not the individual remains near the fissionable assembly after the fission burst has occurred. Only in Case 1 below did the delayed gamma radiation assume importance, since that individual remained close to the setup after the critical state had come and gone.

The major components of the complex radiation dose are listed in order of magnitude: (a) fast-neutron collisions producing recoil protons in tissue, (b) hydrogen-capture gamma rays producing an autodose of the whole body, (c) slow-neutron captures in N^{14}, and (d) prompt gamma rays from the fissioning material. Induced activities in Na, Cl, P, and Mn give rise to a negligible tissue dose. However, an important cause of tissue injury, which appeared in two operators close to the fissioning assembly, was the high intensity of soft radiation in the blue glow. This comprised secondary soft x-rays, slow neutrons, and

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$n_{fast} + H \rightarrow \boxed{nH} \rightarrow p + n_{th} + 2.2\,mev\ \gamma$

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TABLE I

PHYSICAL DATA ON PERSONNEL

Case	1 Distance from Assembly, cm.	2 Height, cm.	3 Body Weight, kg.	4 Estimated Torso Thickness,* cm.	5 P^{32} in Urine,† dps	6 Na^{24} in Urine, dps
1	30	179	92.0	30	110.00	22.50
2	300	170	86.3	30	4.70	1.38
3	50	168	59.4	20	357.00	248.00
4	100	175	79.4	25	68.10	15.10
6	140	165	68.0	25	13.60	7.75
7	210	183	78.5	22	2.97	5.35
8	210	178	74.8	22	2.53	3.35
9	400	178	77.1	25	1.40	1.92
10	400	168	59.09	20	1.40	1.27

* Anteroposterior thickness at diaphragm.
† Specific activity in disintegrations/sec./mg. normal element.

secondary electrons, most of which are absorbed in superficial tissue layers.

I. INDUCED RADIOACTIVITY

The detailed protocol on the induced radioactivities in the bodies of the patients has been published (Reference 4, Section VIII), and the results have been discussed in extenso. Here are given the specific activities of P^{32} and Na^{24} in urines (Table I, columns 5 and 6) to show one of the effects of thermalized neutrons in the body. It turned out that the urine activities were not as selfconsistent as were the serum Na^{24} activities. For purposes of dose estimation the serum Na^{24} activities given in Table II, column 1, appeared to give a representative measure of neutrons incident on the body tissues.

It is assumed that the Na^{24}-serum activity measures the average slow-neutron flux throughout the body. Using an average value of serum Na^{23} of 3.25 mg./cc. and a capture cross section of 0.45 barns for Na^{23}, the slow-neutron flux is given by 6.48×10^9 times Na^{24} specific activity and is tabulated in Table II, column 2. For the computation of hydrogen captures of neutrons, the capture cross section is taken as 0.31 barns and the density of H^1 atoms/gm. of tissue as 6.6×10^{22}. The captures in N^{14} are based on a capture cross section of 1.75 barns, and that N^{14} represents 3 per cent by weight of tissue.

The captures in tissue elements shown in Table II are not produced uniformly through the bodies of the personnel. The primary fast neutrons which gave rise to the slow neutrons are assumed to have had an average energy of 0.5 mev. Neutrons of

TABLE II

SLOW-NEUTRON FLUX AND CAPTURES BASED ON SERUM Na^{24} SPECIFIC ACTIVITY

Case	1 Na^{24} in Serum* dps	2 Slow-Neutron Flux, n† $\times 10^9$/cm.	3 Hydrogen Captures/gm. $\times 10^9$	4 N Captures/gm.‡ $\times 10^8$
1	18.00	117.0	2.400	2.660
2	1.10	7.1	0.145	0.161
3	73.60	477.0	9.750	10.820
4	13.30	86.3	1.760	1.960
6	7.10	46.1	0.942	1.040
7	3.80	24.7	0.510	0.561
8	2.03	13.2	0.270	0.300
9	1.54	10.0	0.200	0.230
10	1.22	7.9	0.160	0.180

* Specific activity of Na^{24} in disintegrations/sec./mg. serum sodium.
† Slow-neutron flux $= 6.48 \times 10^9 \times$ specific activity Na^{24}.
‡ N^{14} captures $= 2.27 \times 10^{-3} \times n$. Hydrogen captures/gm. $=$ 0.0204.

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this energy administered over a large area of skin have low penetrating power. The curves of Tait[19] and of Marshak[7] show a reduction to half intensity at about 2.8 cm. depth in aqueous tissue. This is also seen in the calculations of Biram.[1] There is, however, no specific evidence to support the assumption of 0.5 mev. as the average neutron energy. The assumption is based solely on the knowledge that there was sufficient scattering material around the assemblies to ensure at least one collision for most of the fast neutrons.

The neutrons represented in Table II, as measured by serum Na^{24} activity, probably diffused throughout 50 per cent of all the tissues of the body. The diffusion length for thermal neutrons is about 2.9 cm. Diffusion coupled with the maximum penetration of fast neutrons to 8 cm. accounts for half the body tissues. Workers with water baths for thermalizing fast neutrons usually allow 3 to 4 cm. for the diffusion loss of thermal neutrons at the edges of the bath.

By the same token, however, there is the problem of estimating the loss of thermal neutrons from the body. The edge effect arising in 3 cm. is appreciable, since 3 cm. is a significant distance compared to the cross-sectional dimensions of all parts of the body, including the torso. The diffusion loss, along with the loss of scattered fast neutrons and their effect on the estimated tissue dose, can be assessed only by means of judicious guesses until experimental data become available. The captures shown in Table II form the basis for the minimum possible doses. Corrections for diffusion and scattering loss of neutrons are discussed later in this report (Section VII).

II. THE AUTODOSE DUE TO HYDROGEN-CAPTURE GAMMA RADIATION

At the time of the accidents in 1946 the methods for assessing autodosage had not been fully developed in the literature. In order to calculate a minimum possible value for this kind of dose, the reciprocal relationship between a radiation source and absorber was used. The reciprocity theorem is discussed by Mayneord[9] and by Bush.[2] Calculations were made using the approximation formulas for the integral dose in ellipsoidal cylinders as developed by Mayneord[9] with the appropriate corrections for elongation, namely, the ratio of the length to the width. Integral doses were computed for the uniform distribution of hydrogen captures at a density of 10^8/gm. of tissue. The linear absorption coefficient of the gamma rays was 0.028 cm.$^{-1}$, and the source strength was taken as 7.43×10^{-3} r/10^8 H^1 captures.

It turned out, as will be seen in the following, that estimates based on these calculations were low, because the contribution of one part of the body to the other was not accounted for. The calculation for each part, as for example the torso, gave only the dosage arising from the source material within that part. Experiments on a mock-up of a standard man, filled with Na^{24} in water, showed that the first computed minimum values of integral dose were 50 per cent of the experimentally determined values. With the subsequent publication by Bush[2] of the integral autodose calculations for over-all body dosage, taking into account the exposure of all parts by the others, it was found that the first estimates were 57 per cent of his theoretical values.

In the following there will be described the experimental method using a mock-up man to determine the integral dose of hydrogen-capture gamma radiation. This will be followed by the theoretical computation based upon Bush's application of the reciprocity theorem to the problem.

A mock-up man was constructed of 0.030 in. copper sheet (0.762 mm.) to weigh 70.072 kg. when filled with water. The masses of the various parts of the man are shown in Table III. The man described by Mayneord,[10] weighing about 72 kg., served as a prototype for this man. (Compare also the data of the International Commission on Radiological Protection[8] and Lisco's figures, quoted by Schubert,[17] for the properties of the Standard Man.) The purpose was to dissolve $Na^{24}Cl$ in the water of the

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TABLE III

GAMMA-DOSE RATES AT ANTERIOR SURFACE OF 70-KG. WATER MOCK-UP MAN WITH 80,978 DISINTEGRATIONS Na^{24}/MIN./CC.

Part of Man	M, Mass of Parts, kg.	I,* Gamma Intensity, mr/hr.	MI, Integral Dose Rate, gm.r/hr.
Foot (lower)	1.388	29.4	40.7
Knee	8.180	38.7	317.0
Thigh	10.200	59.2	603.0
Diaphragm	36.100	68.3	2470.0
Arms (elbow)	5.620	60.3	339.0
Neck	4.330	46.5	201.3
Head	4.250	46.5	197.5
Total	70.072		4168.5

Height of mock-up man = 168 cm.
Intensity at center of torso (at diaphragm) = 123 mr/hr.
4168.5 gm. r/hr. = 69.5 gm.r/min.

* Gamma intensity multiplied by 0.526 to correct for energy dependence. The average dose rate is 95.7 mr/hr. or 77 per cent of central dose rate.

filled mock-up man and measure the gamma ray dose rates in and about the parts of the body. The two gamma rays from Na^{24}, having energies of 1.38 mev. and 2.76 mev., were assumed to give a good approximation to the 2.2 mev. H^1-capture gamma rays. The gamma ray dose rates for a known number of Na^{24} disintegrations/cc. of mock-up water would serve as a basis for estimating the autodose due to H^1 neutron captures.

Samples of Na^{24} Cl in the Los Alamos "water-boiler" reactor for an hour at the 5 kw. level were measured for their gamma and beta activity. The following table gives the results obtained with three different gamma-detecting meters along with the beta activity:

All meters were calibrated against radium in 0.5 mm. Pt capsule.

The output in gamma r/mc.hr./cm.^{2} at 1 cm. is the constant k of Mayneord[11] and the I_γ of Marinelli, *et al.*[6] This fundamental constant has the value 19.3 r/mc.hr. for Na^{24}. More recently Mayneord[12] quotes measurements as yielding a value of 18.85 r/mc.hr. At the time the above measurements were made, it was assumed that the constant was near 20 r/mc.hr. The table above shows that the counter-type Victoreen survey meter, which had a thin-walled Geiger-Müller tube mounted inside a steel casing, gave over twice the expected gamma intensity. This was attributed to variation in response with gamma energy. This counter meter agreed exactly with the brass-walled, direct current, ionization-chamber-type meter in readings made about the mock-up man.

It was assumed that the air-wall-type chamber gave the correct gamma intensity in roentgens, namely, 23.1 r/mc.hr. This chamber was not suited for practical measurements about the mock-up man. Therefore, the non-air-walled instruments were used and their readings reduced in the ratio of 23.1/44.1 = 0.526, where 44.1 is the average of 41.6 and 46.6.

The autodose rates found in and about the mock-up man are shown in Table III. At the anterior diaphragm surface the gamma intensity on the counter-type survey meter was 130 mr/hr. for 80,978 Na^{24} disintegrations/min./cc. This was corrected to the air-wall chamber equivalent reading by multiplying by 0.526, as were all the intensities in Table III. The integral dose rate measured externally at the diaphragm is seen to be 69.5 gm.r/min., which becomes

DETERMINATION OF GAMMA-ROENTGEN EMISSION OF Na^{24}

Meter	NaCl Weight, gm.	Total Beta Radiation, mc.	Gamma Ray Intensity, mr/mc.hr./cm.^{2} at 1 cm. distance
Victoreen Geiger-Müller counter survey meter	10	2.15	41.6
Brass-walled ionization chamber ("Wattsmeter")	10	2.14	41.6
Victoreen "air-wall" 0.25 r chamber	10	2.14	23.1
Victoreen Geiger-Müller counter survey meter	1	0.264	46.6

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$69.5/80{,}978 = 8.6 \times 10^{-4}$ gm.r/Na^{24} disintegration. Since the dose rate on the central axis of the torso is 123 and the external dose rate is 68.3 mr/hr., the average is 95.7 mr/hr. This is perhaps high in that the difference between the central and external surface-dose rates is not as great in the lower limbs as was found in the torso.

The average body-dose rate of 95.7 mr/hr. for 80,978 Na^{24} disintegrations/min./cc. forms the basis for computing the average gamma ray (2.2 mev.) dose throughout the body. The average body dose becomes 1.97×10^{-5} mr/Na^{24} disintegrations/cc., which is converted to H^1-capture quanta by multiplication by the ratio of the k values, namely, 9.9/19.3, where 9.9 r/mc.hr./cm.^{2} at 1 cm. is the k value for H^1-capture gamma rays. This leads to the average dose rate of 1.05×10^{-5} mr/H^1-capture/cc. Table IV, column 1, shows the gamma ray dose in r obtained by the product of hydrogen captures/gm. and the average dose rate, corrected in the ratio of the body weight to 70 kg.

TABLE IV

INTEGRAL AUTODOSES DUE TO HYDROGEN-CAPTURE GAMMA RAYS

	Mock-up Man Measurements		Theoretical Estimate	
Case	Average Body Dose, r	Integral Auto-Dose,* megagm.r	Autodose Rate for Radium,† megagm.-r/mc.hr.	Theoretical Integral Autodose,† megagm.r
1	33.0	1.91	104	2.220
2	1.9	0.108	99	0.128
3	87.0	5.01	59	5.150
4	21.0	1.20	88	1.380
6	9.5	0.55	73	0.613
7	5.9	0.35	85	0.380
8	3.0	0.18	80	0.190
9	2.3	0.13	84	0.150
10	1.4	0.08	59	0.085

* Computed from the mock-up man constant 6.06×10^{-4} gm.r/H^1-capture.

† Computed from the theoretical tables for radium autodosage of Bush.[2] Column 3 gives integral dose for 1 mc.hr. of Ra/gm. of tissue.

The average integral dose rate for the entire body becomes $(95.7/68.3) \times (8.6 \times 10^{-4}) = 11.8 \times 10^{-4}$ gm.r/Na^{24} disintegrarions/cc. and the integral autodose rate is $11.8 \times 10^{-4} \times 0.513 = 6.06 \times 10^{-4}$ gm.r/H^1-capture.

Integral autodoses based upon this constant are shown in Table IV, column 2. To illustrate the computation, take Case 3 in which the hydrogen captures (Table II) were 9.75×10^9/cc. The body weight is divided by 70 kg. to normalize it against the mock-up man: $59.4/70 = 0.849$. The integral dose is then $0.849 \times 9.75 \times 10^9 \times 6.06 \times 10^{-4} = 5.01 \times 10^6$ gm.r, or 5 megagm.r. The comparison by weight with the mock-up man figures is approximate; it does not take into consideration variations of height and thickness of the individuals.

For a comparison with the theoretical values based upon Bush's[2] computation of integral autodose, Table IV, column 4, shows the integral autodoses, assuming that the doses as computed by Bush for radium can be converted to H^1-capture gamma ray dosage according to the ratio of k values (see, for example, Mayneord,[11] p. 154). The k value for radium in a 0.5 mm. Pt container is 8.3 r/mc.hr. For H^1-capture gamma rays k is 9.9 r/mc.hr., or 9.9 r/1.332×10^{11} r/capture. From Bush's paper the values for integral autodose rates for radium in patients of varying heights and weights are given in Table IV, column 3. As an example of the arithmetic, take Case 3. The radium autodose rate, column 4, is 59 megagm.r/mc.hr., this having been determined from Bush's table by Case 3's weight of 59.4 kg. and 168 cm. height, as given in Table I. The radium autodose rate is corrected for radiation quality by the ratio 9.9/8.3, and then multiplied by the H^1-captures/cc. and divided by 1.331×10^{11}. Thus, $59 \times (9.9/8.3) \times 9.75 \times 10^9 / 1.331 \times 10^{11} = 5.15$ megagm.r.

The autodoses computed thus far are not minimum doses due to capture gamma rays; they are high because the H^1-captures did not occur uniformly throughout the body, but rather were concentrated toward the

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side facing the neutron source. In Section VIII below the distance factor for the source of radiation is discussed.

III. HEAVY-PARTICLE DOSE

Fast-neutron Recoils. The estimation of fast-neutron dose is based on the assumption that each neutron captured in H^1 released 0.5 mev. to the tissue before thermalization and that 1 roentgen-equivalent-physical (rep) corresponds to 93.1 ergs /gm., or 5.8×10^{13} electron volts/gm. Thus, each captured neutron/gm. contributed $0.5\times10^6/5.8\times10^{13}=8.62\times10^{-8}$ rep. This constant, multiplied by the number of neutron captures in H^1/gm. of tissue, gives the dose in rep which is tabulated in column 1, Table V. The number of H^1 captures is taken from column 3, Table II. Although the dose is designated as fast-neutron dose, it comprises energy released in the form of recoil protons and heavier atoms.

N^{14}-Neutron Captures. The dose arising from N^{14} capture of slow neutrons is a heavy-particle dose. The reaction Q value is 0.6 mev. A proton and recoil C^{14} are the heavy particles which cause ionization in tissues; for this reason the N^{14}-capture dose is tabulated with the fast-neutron dose in Table V. The dose in rep is calculated on the assumption that each capture releases 0.6 mev. to the tissue, and that 1 rep equals 5.8×10^7 mev./gm. of tissue. The rep shown in column 2, Table V, are based on the N^{14} captures given in Table II, column 4. (For a discussion of the nature of the N^{14}-capture dose, the reader is referred to Solomon,[16] Chapter 4.)

TABLE V

HEAVY-PARTICLE DOSES: FAST-NEUTRON RECOILS AND NEUTRON CAPTURES IN N^{14}

Case	1 Fast-Neutron Dose rep	2 N^{14} Dose Neutron Capture rep	3 Total of Fast-Neutron and N^{14} Doses rep	4 Total Body Dose* 10^6 rep
1	20.7	2.74	23.44	2.16
2	1.3	0.17	1.47	0.13
3	83.6	11.15	94.75	5.63
4	15.1	2.02	17.12	1.36
6	8.1	1.07	9.17	0.62
7	4.4	0.57	4.97	0.39
8	2.3	0.31	2.61	0.20
9	1.7	0.24	1.94	0.15
10	1.4	0.18	1.58	0.093

* Total body dose is the product of column 3 multiplied by body weight.

Recoil Deuterons. In the 1948 report[5] it was pointed out that the deuteron recoil following H^1-neutron capture has a kinetic energy of 1,300 ev. For 10^9 H^1 captures /gm. of tissue this recoil contributes 0.022 rep. From Table II, column 3, it is seen that the H^2-recoil dose is negligible compared to the H^1-capture gamma ray autodose, Table IV, column 1, even if the relative biological effect (RBE) factor is taken as 10 for the H^2 rep.

IV. DOSE OF PROMPT AND DELAYED GAMMA RADIATION

In order to estimate the dose of the prompt gamma rays from the fissions, measurements were made of the variation of delayed gamma ray intensity from the assembly, to which Cases 3 to 10 were exposed. Over the range of distances (r) from 75 cm. to 2,500 cm. the gamma ray intensity fell off as $1/r^{1.6}$ rather than as $1/r^2$. The deviation from the $1/r^2$ law was also found in the planted film badges which showed a falling-off as $1/r^{1.54}$ for an exposure which included the prompt as well as some of the delayed gamma rays. By way of comparison, the urine-induced activities in P^{32} and and Na^{24} fell off as $1/r^{2.4}$, while the serum Na^{24} went as $1/r^{2.3}$. The distances of personnel are given in Table I and their Na^{24} activities in Tables I and II.

In the above mentioned assembly for Cases 3 to 10, it was estimated that at a 1 meter distance the maximum amount of prompt gamma radiation to emerge would lead to a dose of 7.2 r. On the basis of the observed variation with distance r as $1/r^{1.6}$, the incident gamma ray dose on personnel can be estimated using the distances shown in Table I. In Table VI, column 1,

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are given the prompt gamma ray doses at the skin surface.

Assuming an average energy of 1 mev. for the gamma rays, for which the linear absorption coefficient in water is 0.03 cm.$^{-1}$, the average body dose is calculated from Mayneord's[10] tables and tabulated in column 2. For example, Case 4, at 100 cm. from the source of radiation and having a torso thickness of 25 cm., had an average body dose of 0.732 r/incident r due to plane-wave radiation. (The factors are tabulated in Table IX.) This is corrected for a source at 100 cm. by the factor 0.85. The resultant average body dose is $7.2 \times 0.732 \times 0.85 = 4.5$ r. The prompt gamma ray doses are seen to be small.

Cases 3 to 10 had no significant body dose due to delayed gamma radiation. This group of individuals left the vicinity of the assembly at about 20 seconds after the fission burst. Cases 1 and 2, however, did not leave their positions after the burst. Case 2 was far enough away (300 cm.) so that his dose due to prompt and delayed gamma radiation was negligible. The particular assembly near which he was stationed was heavily shielded. On the other hand, Case 1 was near that assembly (30 cm.) and worked with it during and after the fission burst. On the basis of his account of his protracted manipulations of the assembly, it is estimated that he sustained a minimum average body dose of 220 r of gamma radiation.

Gamma ray measurements on a similar assembly showed a dose rate of 190 r/min., measured in an air-walled chamber, at 30 cm. distance at 10 seconds after the burst. In the earlier reports[4,5] Case 1's minimum was stated as 110 r, which is now regarded as far too low in view of the fact that the patient is known to have worked in and about the setup for at least 10 minutes after the fission burst occurred. The 220 r includes prompt and delayed gamma radiation dose (Table VI).

V. WHOLE-BODY DOSE DUE TO INDUCED RADIOACTIVITIES

Although the activities induced by slow-neutron capture in tissue elements such as Na^{24} were measurable, their contribution to radiation dose was very small. It turns

TABLE VI

PROMPT AND DELAYED GAMMA RAY DOSES AND SOME REPRESENTATIVE AMOUNTS OF INDUCED ACTIVITIES IN PERSONNEL

Case	1 Prompt-Gamma Ray Dose at Skin, r	2 Prompt-Gamma Ray Dose, Body Average, r	3 Body Average, Delayed-Gamma Ray Dose, r	4	5	6	7	8
				Total Amount of Induced Activity in Microcuries				
				Na^{24}	K^{42}	Mn^{56}	Cl^{38}	Mg^{27}
1								
2			220	65.0	15.7	8.6	72	2.15
3	18.1	11.4		170.0	41.0	22.7	191	5.70
4	7.2	4.5		41.0	10.0	5.4	46	1.36
6	3.8	2.4		18.8	4.5	2.5	21	0.60
7	1.8	1.3						
8	1.8	1.3						
9	0.7	0.5						
10	0.7	0.5						

For Case 2 the prompt and delayed-gamma ray doses were negligibly small.
For Case 1 the prompt and delayed doses are lumped together in the delayed gamma ray dose.
Amounts of induced activity can be corrected for possible slow-neutron loss by the factor 1.18.

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out that the dose is small compared to the autodose arising from H^1-capture gamma rays.

For purposes of indicating the magnitude of induced activity and its resultant dose, the following computations for Case 3 are typical. Referring to Table II, column 1, the specific activity, Case 3, is 73.6 dps. /mg. serum Na^{23}. For an Na-content of 3.25 mg/cc. of serum, this activity is $6.47 \times 10^{-3} \mu c$ Na^{24}/cc. The beta rep due to the total disintegration of this amount of Na^{24} is calculated on the basis of Marinelli's[6] evaluation of the constant: 29 beta rep /μc Na^{24} destroyed. The 6.47×10^{-3} μc/cc. of serum then deliver 0.187 rep over a period of several half-lives of Na^{24} (half-life, 14.8 hours). With a hematocrit of 40 per cent this dose becomes $0.187 \times 0.6 = 0.112$ rep/cc. of blood.

The average beta and gamma ray dose throughout the body is best taken on the basis of the total Na in the body and an average amount/cc. of tissue computed. Total amounts of Na are quoted as: 63 gm./70 kg. of man, Shohl;[18] 89.2 gm./66 kg. of man, Moore;[13] and 105 gm. in the Standard Man weighing 70 kg. (International Commission on Radiological Protection[8]). The more recent figure of 105 gm. becomes 1.5 mg. Na/gm. of tissue averaged throughout the body. On the basis of Case 3's specific activity, it turns out that for his 59.4-kg. weight he had 170 μc Na^{24} total. For comparison, the permissible total in a 70 kg. man is 15 μc.[8] The average beta ray dose in Case 3 is 0.083 rep.

The gamma ray dose delivered by the Na^{24} is an autodose like that due to H^1-capture gamma rays. To compute the gamma ray dose rate in Case 3, take an average tissue Na content of 1.5 mg./gm., specific activity of 73.6 Na^{24} dps./mg. Na^{23}, and the average body-dose rate for a 70-kg. man found in Table III, namely, 1.97×10^{-8} r /Na^{24} disintegrations/gm. of man. There are, then, 3×10^{-3} μc Na^{24}/gm. for which the total number of disintegrations is 8.45×10^6, for a mean life of Na^{24} of 21.3 hours. The average body gamma ray dose during the destruction of Na^{24} is 0.14 r. The biologic half-life of Na^{24} of 12 days plays no significant part in this dosage.

The beta and gamma ray doses toegther comprise less than 1 per cent of the H^1-capture gamma ray dose recorded in Table IV. For Case 3 the H^1-capture gamma ray dose is 87 r. The Na^{24} beta dose is 0.083 rep and the gamma ray dose 0.14 r. Since the Na^{24} doses are small, they are not tabulated.

The possible contributions to the induced activity dose due to short-lived isotopes other than Na^{24} were examined. The isotopes K^{42} (12.4 hours), Mn^{56} (2.6 hours), Cl^{38} (0.62 hours), and Mg^{27} (0.16 hours) were the chief ones concerned. The total amounts of isotope along with Na^{24} are tabulated in Table VI for Cases 1, 3, 4, and 6. Taking account of the isotopic abundance, the amount in the body, and the energies of the radiations, the doses from the four isotopes other than Na^{24} are negligibly small. The magnitudes of their contributions decrease in the following order: Cl^{38}, K^{42}, Mn^{56}, and Mg^{27}. The gamma ray doses are in the same order totaling an additional 140 per cent of the Na^{24} average whole-body dose.

VI. ESTIMATE OF GAMMA RAY DOSE

The total induced activities shown in Table VI along with the serum Na^{24} specific activities in Table II provide an indication of the order of gamma ray intensity from the bodies of victims to be expected at various dose levels. The gamma ray intensity has an advantage in that it can be measured at the anterior diaphragm level. The assay of activity in sera or in urines is more elaborate in that it requires a careful preparation of samples and counting. The body elimination of P^{32} has yet to be clarified.[4] Sodium in urine is subject to wide fluctuations. Therefore, the sera Na^{24} are the most reliable measure of neutron flux.

Case 3 in Table VI had a total of 170 μc Na^{24} which was mostly produced in the arms and torso, since he was close to the source of neutrons. His dose was lethal as

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was that of Case 1, although the latter had only 65 μc Na^{24}. The additional dose due to delayed gamma radiation in Case 1 probably was a major factor in his death. For purposes of estimating the amount of Na^{24} which would indicate a lethal dose, it is assumed that the activity of Na^{24} of 18 dps. in Case 1 was less than that corresponding to a lethal dose such as in Case 3 with a serum specific activity of 73.6 dps. This is substantiated to some extent by the fact that Case 4 had a specific activity of 13.3 dps. and survived.

The mock-up man's measurements showed 130 mr/hr. for a concentration of 80,978 Na^{24} disintegrations/min./cc. measured at the diaphram skin surface with the counter-type survey meter (calibrated against Ra), not corrected for the Na^{24} gamma energy. In terms of counts, the same gamma-meter showed 4,500 cpm. /1 mr/hr., or 72 counts/disintegration/cc. of mock-up man. The latter figure shows that 1 gamma ray in every 2,000 emitted in the man was recorded by the counter. If measurements had been made on Case 1 at the time of the accident, an approximate counting rate of about 12,500 cpm., or 2.8 mr/hr., at diaphragm level, would have been recorded due to the Na^{24} alone. The biological half-life in man for Na^{24} of about 12 days makes it necessary to consider only the natural decay for the decrease in intensity with time.

The essential feature of these data is that the Na^{24} gamma rays occur in intensity sufficient for an appraisal to be made of the magnitude of the radiation exposure. There are three aspects of this gamma assessment of dose which need to be pointed out. The first is the correction for the natural decay of Na^{24} according to a 14.8 hour half-life. The second is that the other short half-lived isotopes such as K^{42}, Mn^{56}, Cl^{38}, and Mg^{27} be allowed for. The Mn^{56}, Cl^{38}, and Mg^{27} will have decayed after about 12 hours. After that the K^{42} will continue to contribute about 25 per cent of the gamma reading, since it has a half-life of 12.4 hours. The third and most important qualification on the gamma assay of dose is that it gives a measure only of thermal neutrons in the body. The question as to the spectrum of fast neutrons which gave rise to the thermal neutrons has to be estimated from other information about the exposure.

VII. CORRECTIONS TO THE MINIMUM DOSES

The various components contributing to the total dose are summarized in Table VII under the column entitled "Primary Doses." For illustrating the make-up of the total dose, Case 6 was found to be most suitable. Other cases near the source involved extraneous factors obscuring the fission-burst dose. Case 1 was near a heavily shielded source and, moreover, sustained a large dose of delayed gamma radiation. Case 3 was too near the source to permit accurate evaluation of the distance relative to the source, since his hands were on the assembly and his feet about 90 cm. from its

TABLE VII

SUMMARY OF AVERAGE BODY DOSE COMPONENTS FROM FISSION BURST

Case 6. Average Neutron Energy 0.5 mev.

Component	Primary Doses	Equivalent-Gamma Doses,* r	Equivalent Doses as Percentage of Total
H^1-capture gamma ray (Table IV)	9.5 r	9.5	16.4
Fast neutron (Table V)	8.1 rep	40.5	70.1
N^{14}-neutron capture (Table V)	1.07 rep	5.4	9.3
Prompt gamma rays (Table VI)	2.4 r	2.4	4.2
Total		57.8	100.0

These doses are not corrected for slow-neutron loss or fast-neutron scatter.

* One H^1 rep is biologically equivalent to 5 gamma rep.

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center. Case 4 is known to have been partly shielded from the assembly by Case 3's body. Case 6 was entirely unprotected; his entire body, except possibly his lower legs, was exposed to the source at a reasonably well-ascertained distance of 140 cm.

For a comparison of the relative magnitudes of the components, a relative biological effectiveness (RBE) of 5 is assigned to the H^1 rep. The RBE has been described in the clinical case report[4] (Sections II *C* and IV *A*). Zirkle (Oberlin Conference,[16] p. 53) takes as a rough average RBE=4 for protons. On the other hand, Neary[14] takes RBE=10 in tolerance-level considerations. In Table VII the column called "Equivalent Gamma Dose" has the proton rep multiplied by 5. The last column shows their relative magnitudes. For 0.5 mev. neutrons the recoil rep have already become 70 per cent of the total dose.

The dose components in Table VII are minimum doses. The dose components due to H^2 recoils, slow-neutron-induced activities, and delayed gamma rays have been omitted because they are negligibly small. The dose due to neutron-capture gamma rays from surrounding objects, walls, floors, etc., has not been considered. An important item in considering these as minimum doses is loss of thermal neutrons by diffusion from the body as was mentioned earlier in this report. The first three components in Table VII are directly proportional to the Na^{24}-induced activity in the blood sera.

In considering a possible correction for diffusion loss of slow neutrons, the dimensions of the various parts of the human body are important. The largest part, the torso, is about 20 to 25 cm. thick and 30 to 40 cm. wide, from which diffusion loss is conservatively estimated to be 10 to 15 per cent.

The other body members, such as head (15×20×18 cm.), arms (10 cm. diameter) and thighs (15 cm. diameter), present blocks of aqueous material from which diffusion losses range from 20 to 30 per cent, depending on thickness. As a final estimate of slow-neutron loss due to diffusion, 15 per cent appears reasonable and conservative. Thus, the first three dose components in Table VII should be increased by a factor of 1.18 to account for slow-neutron loss.

The energy of the primary neutrons not only influences the amount of leakage of slow neutrons from the body, but obviously plays an important part in the dosage. In Cases 1 and 2 the assignment of an average energy of 0.5 mev. to the neutrons is justifiable because of the heavy shielding about the critical assembly to which they were exposed. In the remaining 7 cases there is the possibility that a small fraction of the neutrons may have had high energies. As Glasstone and Edlund[3] point out, the fission spectrum of neutrons extends from about 0.1 mev. out to beyond 10 mev., the majority of neutrons having energies in the range 1 to 2 mev.

The pronounced contribution of fast neutrons to the dose is illustrated by the following example which serves also to estimate a maximum possible dose to be added to the computations made thus far. If 5 per cent of the neutrons indicated by Na^{24} activities have an average energy of 5 mev. rather than 0.5 mev., then the total fast-neutron rep in Table VII and Table V, column 1 are increased by 45 per cent. Thus, in Cases 3 to 10 a reasonable maximum dose due to neutron energy in the fast-neutron rep would require that the minimum doses be increased by a factor of 1.45.

There remains yet a correction to be made for fast neutrons scattered from the body before becoming thermalized. This correction applies only to the fast-neutron component, since it implies that a fast neutron imparted a fraction of its energy to the tissue in the form of a recoil atom and then was scattered out of the body. This is a dosage in the form of fast-neutron rep which is tentatively assumed to be 10 per cent of the total.

To summarize the corrections which have been described in the foregoing paragraphs: The first is an 18 per cent increase in the

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TABLE VIII

SUMMARY OF AVERAGE BODY DOSES

Case	1	2	3	4	5	6
	Capture Gamma Ray, r	Fast Neutron, rep	N^{14} Capture, rep	Prompt Gamma Ray, r	Gamma-Equivalents	
					Average Dose, r†	Incident Dose, r‡
1	33.0	27.0	3.23	220.0*	404	587
2	1.9	1.7	0.20		11	16
3	87.0	109.0	13.20	11.4	709	1125
4	21.0	19.6	2.38	4.5	136	219
6	9.5	10.5	1.26	2.4	71	110
7	5.9	5.7	0.67	1.3	39	56
8	3.0	3.0	0.37	1.3	21	30
9	2.3	2.2	0.28	0.5	15	22
10	1.4	1.8	0.21	0.5	12	17

Doses in this table are corrected for slow-neutron diffusion loss and fast-neutron scatter.
* Prompt and delayed doses are combined in this one case.
† In the summation of doses in columns 1, 2, 3, and 4 the heavy-particle doses were multiplied by the RBE= 5.
‡ 1 mev. gamma rays for which μ=0.03 cm.$^{-1}$.

first three components of dose listed in Table VII, since these are proportional to the slow-neutron flux. The second correction is a 10 per cent increase in the fast-neutron component to compensate for fast-neutron scatter out of the body. The average body doses, taking these corrections into account, are summarized in Table VIII, columns 1, 2, 3, and 4. In the same Table, column 5, are the average body doses which are the gamma equivalent of the sum of components listed in the first four columns. It should be emphasized that the average body doses of Table VIII are averages of dose within the tissue and are not to be confused with average incident dose to the body.

By means of the conversion factors in

TABLE IX

CONVERSION FACTORS FOR EXPRESSING AVERAGE BODY DOSES AS INCIDENT 1 MEV. GAMMA AND 80 KEV. ROENTGEN-RAY DOSES*

Case	Source-to-Body Distance Correction		Average Body Dose/r†		Corrected Average Body Dose/r	
	Gamma	Roentgen Ray	Gamma	Roentgen Ray	Gamma	Roentgen Ray
	1	2	3	4	5	6
1	0.75	0.78	0.69	0.23	0.52	0.28
2	0.94	0.96	0.69	0.23	0.65	0.22
3	0.80	0.83	0.78	0.36	0.63	0.30
4	0.85	0.91	0.73	0.30	0.62	0.27
6	0.88	0.94	0.73	0.30	0.64	0.28
7	0.92	0.96	0.76	0.33	0.70	0.32
8	0.92	0.96	0.76	0.33	0.70	0.32
9	0.94	0.97	0.73	0.30	0.69	0.29
10	0.94	0.97	0.78	0.36	0.73	0.35

All entries in this table are in units of r/incident r.
* Assuming the radiating assembly is a point source.
† For incident plane wave.

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Table X

INTEGRAL DOSES IN TERMS OF ENERGY ABSORBED CONVERTED TO EQUIVALENT GAMMA ROENTGENS

Case	1 Heavy-Particle Dose,* megagm.-r	2 Capture-Gamma Dose,† megagm.-r	3 Prompt-Gamma Dose,‡ megagm.-r	4 Delayed-Gamma Dose, megagm.-r	5 Total Integral Dose, megagm.-r
1	13.8	2.25		20	36.0
2	0.8	0.13			0.93
3	36.2	5.90	0.68		42.8
4	8.8	1.30	0.36		10.7
6	4.0	0.65	0.16		4.8
7	2.5	0.41	0.11		3.0
8	1.3	0.21	0.10		1.6
9	1.0	0.15	0.04		1.2
10	0.6	0.09	0.03		0.73

* From Table v, columns 1 and 2, corrected for RBE= 5, and neutron losses.
† From Table iv, corrected for slow-neutron loss (18 per cent).
‡ From Table vi, column 2, multiplied by patient's weight.

Table ix, the average body dose is transformed into incident gamma dose shown in column 6, Table viii. These are the incident doses coming from the assembly (assumed to be a point source) which would produce the body average dose in column 5.

The total integral dose as a sum of the component integral doses is given in Table x, column 5. This is a gamma integral dose in that the heavy-particle dose was converted to the biological equivalent by the RBE factor of 5. The calculation is made by multiplying the average body dose by the body mass to give the integral dose.

VIII. SOFT ROENTGEN RAY EQUIVALENT OF THE HEAVY-PARTICLE DOSE

The low penetrating power of 0.5 mev. neutrons was pointed out in Section ii above. The induced activities ultimately measured in the sera were concentrated at the instant of exposure in the half of the body facing the source of neutrons. The computations of the major dose components listed in Table viii are on the basis of average values throughout the body, because the Na^{24} became uniformly distributed throughout the body. Actually, the fast-particle doses, namely, the fast-neutron and N^{14}-capture doses, were initially concentrated along the surfaces of the body facing the source.

Therefore, the conversion of the dose to gamma-ray equivalents, as shown in columns 5 and 6 of Table viii, and in Table x, column 5, is somewhat misleading as regards the physical picture of how the dose was administered. A closer approximation to the distribution of the heavy-particle dose due to the 0.5 mev. neutrons is obtained by converting it to 80 kev. roentgen ray dosage for which the linear absorption coefficient is $\mu=0.14$ cm.$^{-1}$ and the half-value layer in copper is 0.082 mm. A comparison of the depth-dose data for the 80 kev. roentgen rays with the theoretical wide-beam depth dose for 0.5 mev. neutrons as published by Tait[19] suggests that the dose distribution in whole-body irradiation would be similar for the two radiations.

Table ix shows the factors which enter into the conversion of the heavy-particle rep in Table viii, columns 2 and 3, into an equivalent incident dose of 80 kev. roentgen rays. The heavy-particle average body dose for Case 3 totals 122.2 rep, which comprises the H^1-recoil dose corrected by the factor 1.3 for neutron loss and scatter, and the N^{14}-capture corrected by the factor 1.18 for neutron loss.

The calculation of the incident roentgen

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TABLE XI

FISSION-BURST DOSE EXPRESSED AS INCIDENT GAMMA RAYS AND SOFT ROENTGEN RAYS

Case	Incident 80 Kev. Roentgen Ray Roentgens	Incident Gamma Ray Roentgens*	Hands	
			Right Very Soft Roentgen Ray Roentgens	Left Very Soft Roentgen Ray Roentgens
1	840	487.0	20,000–40,000	5,000–15,000
2	45	3.2		
3	2036	156.0	3,000–10,000	15,000,30,000
4	407	41.0		400–600
6	210	19.0		
7	100	10.0		
8	53	6.2		
9	43	4.0		
10	30	2.6		

* 1 mev. gamma rays having linear absorption coefficient of $\mu = 0.3$ cm.$^{-1}$.

ray dose is based upon Mayneord's[10] tables and correction formulas. The correction for source-to-body distance is given in column 2, Table IX; for Case 3 it is 0.83. The average body dose/incident r is determined by Case 3's torso thickness of 20 cm. and is 0.362 r (column 4, Table IX) for plane-wave radiation. Corrected by 0.83, the average dose becomes 0.30 r/incident r (column 6).

This is the average body dose/r which Case 3 would have received at a distance of 50 cm. from an 80 kev. roentgen ray source. The 122.2 rep multiplied by the RBE factor of 5 make a total of 611 gamma-equivalent r of average body dose which have to be delivered by the roentgen rays. Thus, the incident roentgen-ray dose is 611/0.3, or 2,030 r, which is given in Table XI, column 1. Basically the calculation assumes that the critical assembly approximated a point source resembling the focal spot of a roentgen tube.

IX. BLUE-GLOW DOSE RATES

In the critical-assembly accidents of August 21, 1945, and May 21, 1946, there was reported a blue glow immediately surrounding the assembly. This blue glow had been reported earlier (June 4, 1945) when another assembly had momentarily been out of control. The operators of their respective assemblies, Cases 1 and 3, had their hands and arms in this glow. As the clinical record[4] indicates, these body members sustained extremely high radiation doses. For an estimate of the doses, it is necessary to deduce the order of magnitude of energy flux which will produce the blue glow in air.

It turns out that a glow in air due to ionizing radiations can be seen under varying degrees of background lighting: the lower the background the less intensity required to make a glow visible. The critical assemblies mentioned above produced a glow under widely differing circumstances. The first one was seen against the dark walls of a large steel tank containing the assembly. The incandescent lighting and daylight through remote windows were not bright. The second assembly glow was seen against dark blocks of shielding with incandescent light about 8 feet overhead (at 11:00 P.M.). Case 2 was reading a newspaper with his back toward the assembly. He was aware of a bright flash when this assembly went critical.

The third assembly was seen to glow in a well-lighted laboratory near large windows through which the bright afternoon (3:20 P.M.) sun shone directly. Three of the personnel present were positive in their statements of having seen a blue glow which seemed to have extended 20 cm. beyond

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the critical assembly.* In view of the fact that a blue glow was seen in this brightly lighted laboratory, it is believable that Case 2 should have been aware of a bright flash on his newspaper in the night accident. Yet, it must be remembered that there were considerable differences in material surrounding the two assemblies. The afternoon assembly had relatively little material in the way of heavy metal around it as compared to the night assembly.

Various facts pertaining to blue-glow phenomena due to ionizing radiations are presented in the following discussion. A 20 microampere beam of 5 mev. deuterons can be seen readily in a darkened room. From the range-energy relation and assuming a 1 cm.^{2} beam cross section, a rough estimate is that an absorption of 2.8×10^{19} ev./cc./sec. occurs in the air at the point where the deuterons have 5 mev. energy.

Experiments with high-intensity radioactive sources showed that a blue glow easily seen in a dark room corresponded to the absorption of 4.4×10^{15} ev./cc./sec. in air. Using these data and extrapolating to those of the laboratory in which the afternoon sun gave background illumination (a factor of 10^4 in light intensity is assumed), the figure of 4.4×10^{15} ev./cc./sec. is to be raised to 10^{19}, which is comparable in magnitude to the figure of 2.9×10^{19} ev./cc./sec. for the deuteron beam. The roentgen rate is 6×10^7 r/cc./sec. for the blue glow seen in a well-lighted room.

The dose components in the blue glow comprise soft roentgen rays and electrons as well as the effects of ionization due to the primary fission radiations such as fast and slow neutrons, gamma rays, and recoil particles. In the above computation of dose rate it is assumed that the mechanism of blue-glow formation by deuterons and alpha particles is essentially the same as that for the radiations coming from the critical assembly.

The blue glow in which the hands of Cases 1 and 3 were immersed for fractions of a second produced an exposure at a high rate and of soft radiations. From the accounts given by the individuals, it is estimated that Case 1 sustained about 20,000 to 40,000 r on the right hand and 5,000 to 15,000 r on the left hand. Case 3 received 3,000 to 10,000 r on the right hand and 15,000 to 30,000 r on the left hand. Case 4 had his left hand extended toward the assembly and probably sustained 400 to 600 r on it.

* Five individuals who were near the blue glow in three different assemblies reported a tingling, salty sensation about their tongues while the glow was visible to them.

X. DISCUSSION OF DOSES

There are four different ways in which the whole-body dose can be designated, no one of which has been accepted as the preferred way. This may be due to the meager clinical experience reported in the literature of whole-body irradiation. There may be other ways of specifying whole-body dose; the four which are pertinent to the fission-burst accidents are discussed as follows:

1. The designation of an average value of the rep absorbed throughout the body. The essential figures for this dosage are given in Table VIII, columns 1, 2, 3, and 4. The dose presented in rep or r is simple. If it is desired to account for extreme exposure on one side of the body as occurred in Cases 1 and 3, the average rep provides a convenient reference point from which the dose can be raised or lowered as the case may require. The doses in Table VIII are corrected for estimated slow-neutron-diffusion loss and for fast-neutron scatter from the body.

2. The second specification of whole-body dose is an extension of the average body rep to total whole-body dose as in the concept of integral dose. The total rep is the product of the average body rep times the body mass as in Table V, column 5, where the rep have not yet been corrected for slow-neutron loss and fast-neutron scatter which amounts to an additional 30 per cent for the H^1-recoil dose and 18 per cent for the N^{14}-capture dose. The integral dose in terms of gamma equivalent dose is summarized in Table X. The conversion of heavy-particle rep to gamma rep was made using the RBE factor of 5.

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For practical purposes the gm.r in this report is taken as 93.1 ergs/gm. of tissue. The assumption is that all the various gamma rays give 1 rep/roentgen in any tissue of the body (see Mayneord,[11] p. 144, for units and discussion).

3. The expression of body doses in terms of the incident dose rather than an average dose throughout the tissue. This statement of dose stems from radiotherapeutic experience in which the clinical reaction is measured by incident dose in well-defined radiation applicators. The doses in this form are stated for two different types of radiation. In Table VIII, column 6, the incident gamma radiation from the assembly is given which would produce the average gamma body dose in column 5. This in turn is the sum of the four dose components shown in columns 1, 2, 3, and 4.

It is recognized that the gamma equivalent of all the doses is artificial in that the heavy-particle component was concentrated toward one side of the body while the gamma doses were uniformly distributed. A single figure such as that shown in Table VIII, column 6, is not readily interpreted to show the physical distribution of dose.

The difficulty in the single gamma-equivalent dose is avoided by describing the exposure in terms of two different radiations. The heavy-particle dose is given in terms of incident 80 kev. roentgen rays and the gamma component in terms of an incident gamma dose as in Table XI.

The recourse to a soft roentgen ray dose is somewhat arbitary. Yet it gives a better picture in terms of a known therapeutic radiation. Its use is justified to some extent by the fact that fission bursts will invariably involve scattering materials around the source of neutrons. The degraded neutron-fission spectrum will be the rule rather than the exception. Further data may show the properties of a voltage other than 80 kev. to be more appropriate for the heavy-particle component of dose. The actual roentgen ray voltage is irrelevant except insofar as it provides a working guide for the radiologist in terms of a familiar tool.

4. The fourth index of whole-body dose is peculiar to neutron exposures. It is the specific activity of the Na^{24} in blood serum (Table II, column 1) as has already been pointed out in the clinical report on the 9 cases.[4] The P^{32} activities have yet to be studied in the human being. The complexities apparent in its elimination preclude its being useful at this time. In the earlier report on the accidents[5] it was noted that the appearance of measurable P^{32} in blood serum indicated a lethal dose.

The use of induced activity as an index of radiation injury requires, however, that the presence of fast neutrons be ascertained from other evidence, since readily accessible induced activities give no clue to the energy spectrum of fast neutrons. This problem has been discussed in Section VI in connection with the estimate of dose by the gamma rays coming from Na^{24} in the body.

The earlier doses published in the clinical report[4] (p. 292) are lower than those given here. The integral doses in Table I[4] (p. 292) correspond to those in Table X above except that in Table X the RBE factor of 5 has been applied in the heavy-particle dose. Table II[4] (p. 293), giving the incident doses in terms of soft roentgen rays and gamma rays, corresponds to Table XI above.

In this report the dose of delayed gamma radiation of Case 1 has been increased on the basis of the high intensity of delayed gamma rays known to have existed and the estimated length of time spent near the assembly. This has been discussed in Section IV.

The doses in this paper are higher than those in the clinical report for several reasons, although they are not significantly higher except for the special circumstance of Case 1 discussed above. The capture cross sections for slow neutrons in Na^{23} and in H^1 are taken as 0.45 and 0.31 barns respectively, whereas in the 1948 report these were 0.693 and 0.25 barns. The correction

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for slow-neutron-diffusion loss and fast-neutron scatter from the body was not made in the earlier dose calculations. In this report the source-to-body distance factor has been taken into account, whereas in the earlier report the doses were given in terms of plane-wave incident radiation. While the distance factor entails the undesirable assumption that the critical assembly was a point source, the results seem less artificial than the use of the plane-wave concept. The distance factor raises the incident dose.

The heavy-particle integral dose in column 1, Table x, and its equivalent soft roentgen ray incident dose in Table xi, column 1, reduced to 77.8 per cent of their values, give the doses without the neutron-loss corrections. For example, in Case 3 the soft roentgen ray dose is 2,036 r. Reduced to 77.8 per cent, it becomes 1,585 r.

The absolute magnitude of the doses is determined by the average fast-neutron energy as discussed in Section vii above. In the first appraisals of the exposures an average energy of 0.35 mev. for the neutrons had been assumed. In the accident involving Cases 3 to 10 the material about the assembly was such as to make an estimate of 0.5 mev. seem in order.

There is the possibility that the average energy of 0.35 mev. is appropriate to the accident involving Cases 1 and 2 because of the large amounts of shielding material present. The doses in those cases might thus be considered slightly high. In the other cases it is believed that the doses due to neutron exposure are conservatively estimated and low. Certainly, if the corrections for slow-neutron loss and fast-neutron scatter are removed, the resultant doses must be near the absolute minimums possible.

The possible revision upward has already been indicated in Section vii above and involves the additional dose due to fast neutrons. The increase of 45 per cent in the heavy-particle dose by the presence of 5 per cent of neutrons having a 5 mev. average energy appears to give the order of magnitude of the upward estimates. Although this kind of estimate is consistent with the general knowledge about the fission spectrum, it has not been added to the doses reported here. Such upward revisions will have to await more detailed information about the neutron-fission spectrum.

SUMMARY

In two nuclear accidents involving uncontrolled fission reactions 9 persons were inadvertently exposed to complex ionizing radiations. Whole body doses are computed on the assumption that serum Na^{24} slow-neutron-induced activity provides a measure of fast-neutron intensity.

The selfdosage in the human body due to gamma radiation from slow neutron capture in hydrogen is computed on the basis that the serum Na^{24} activity gives a measure of slow-neutron density. Measurements of gamma ray intensities about a mock-up man filled with Na^{24} in water are described. The assay of induced Na^{24} in the sera of humans by a measurement of gamma ray intensity at the anterior diaphragm is discussed.

Slow-neutron-induced activities although measurable are found to be negligible insofar as radiation dosage is concerned.

In decreasing order of magnitude the dose components are: fast neutrons, hydrogen capture gamma rays, N^{14} captures, and prompt gamma rays.

Doses are expressed in: (a) average rep throughout the body; (b) integral dose; (c) terms of incident r delivered by 1 mev. gamma and soft roentgen rays; and (d) the serum Na^{24} induced activities.

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