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U.S. DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE

memorandum

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REPLY TO ATTN OF: CTID:DSH (U-0590)

SUBJECT: Request for Declassified Report LA-687

TO: R. D. Krohn, Classification Officer, LANL

We concur that the report "Radiation Doses in the Pajarito Accident of May 21, 1946" - LA-687, is unclassified and we concur in its public release.

John Barcroft

R. R. Fredlund, Jr.
Director, Classification and Technical Information Division

LOS ALAMOS SCIENTIFIC LABORATORY

of the

UNIVERSITY OF CALIFORNIA

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RADIATION DOSES IN THE PAJARITO ACCIDENT OF MAY 21, 1946

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RADIOLOGICAL SAFETY

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Abstract

In the Pajarito accident of May 21, 1946, eight people were exposed to complex radiations. The contributions to the total dose from a fission burst by the various radiations are as follows, in order of importance and magnitude: 1. Fast neutrons; 2. Hydrogen capture gammas; 3. Prompt gammas; 4. Delayed gammas. The data on personnel in the August 21, 1945, accident have been included for comparison.

The most important information about the neutron dosage is derived from the Na^{24} of the blood serum. The greatest uncertainty in dosage lies in lack of experimental data on the number of fast neutrons from the fission burst and on their biological effectiveness. The capture gamma dose from hydrogen has been computed and also verified experimentally. The prompt and delayed gamma doses have been computed on the basis of reasonable assumptions.

The data show that the appearance of P^{32} in blood serum indicates a lethal tissue dose of plutonium fission neutrons. Estimates on blue glow energy transfer rates indicate that any tissue in the glow must sustain a lethal dose.

The induced activities in persons involved with Pajarito accident indicate that it is possible to assess sub-lethal neutron doses on the basis of gamma-roentgen measurements on the bodies of exposed individuals. The induced activities also indicate that the metabolism of P^{32} formed in vivo warrants further study.

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SECTION I

Neutron Induced Activities In The Human Body

Tables I, II, and III summarize the data on serum and urine samples taken from personnel at various times after the accident at Pajarito. The Cl^{38} (37 min) activities could not be measured due to hurried circumstances. Potassium determinations were not made; hence, it is possible that in the urine samples K^{41} (14.1 hrs) contributes to the apparent activity of Na^{24} (14.3 hrs). The K^{41} activity is regarded as negligible in the serum activity (compared to the Na^{24}). In view of the very high P^{32} activities found in serum and urine, it was later realized that the P^{32} in the red cells should have been measured.

The tables at the end of the text show that the specific activities of Na^{24} in serum and urine agree fairly well. The one exception is the high Na^{24} in Slotin's urine sample I. This high value may be accounted for by the geometry of the accident: Slotin's bladder being close to the assembly (the equatorial plane of the active sphere was 84 cm from the floor surface). The fairly constant specific activities in the serum over the interval of 88.6 hrs in Slotin, and 65.8 hrs in Graves, are noteworthy because those individuals received at least one liter of physiological saline solution per 24 hours (intravenously) after the accident. The constancy of the specific activity suggests that there is no selective elimination of the active Na^{24}.

The anomalously high specific activity of P^{32} in the urine is a subject which requires further investigation. According to Table IV the specific activities of Na^{24} and P^{32} should be as $1 : 1.08 \times 10^{-2} = 93$, whereas Tables II and III show them to be nearly equal. The reactions listed in Table IV were examined to see if P^{32} could arise from the $Cl^{35}(n,\alpha)P^{32}$ and $S^{32}(n,p)P^{32}$ reactions in significant amounts. The following table summarizes estimates of the activities expected from the known abundances of the elements.

	Abundance of element (mg/cc)	Relative specific activity from Table IV	Resultant relative activity of P^{32}
Blood Cl^{35}	3.38	2.3×10^{-3}	7.8×10^{-3}
P^{31}	0.38	1.08×10^{-2}	4.1×10^{-3}
S^{32}	0.		0.
Urine Cl^{35}	0.18	2.3×10^{-3}	0.41×10^{-3}
P^{31}	0.44	1.08×10^{-2}	4.7×10^{-3}
S^{32}	0.31	1.08×10^{-2}	3.3×10^{-3}

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The abundance of elements is taken from Shohl (Table XV). It is realized that the urine components may vary by as much as a factor of 5. The concentrations of Cl may be 20 to 30 times higher than the figure shown. This, however, could not account for the very large discrepancies shown in Tables II and III. It should be noted that in blood the Cl reaction with fast neutrons may contribute an additional 200% to the expected activity of P^{32}. In urine the presence of S may contribute nearly another 100%, depending, of course, on the energy spectrum of the neutrons involved.

In Slotin's case (Table I) the P^{32} in serum is 16 times higher than it should be, and is 1/28 of that of the urine P^{32}. This suggests that a process of selective elimination occurs with P^{32} in the manner of a Szilard-Chalmers reaction. This point is under investigation. Preliminary measurements of activated solutions showed that the Cl^{38}:Na^{24} activity ratio was 2.6 (expected, 3) and the Na^{24}:P^{32} ratio was 80 (expected, 93) in aqueous solutions. Thus, the activities in mock-up solutions were nearly as expected from the known cross sections. The movement of P^{32} in the body is important because if the P^{32} is selectively eliminated, it may possibly make a convenient means of monitoring for neutron dosage immediately after exposure, say, for times up to 72 hours.

The following computations constitute an attempt to estimate the total radiation doses suffered by personnel involved in two accidents with critical assemblies primarily on the basis of the Na^{24} serum induced activities. Since there are no data relating the slow neutron induced activities to the magnitude of incident fast neutron flux in the case of human tissue, the computations must be regarded as tentative. In a first approximation it is simpler to use the induced activities given in Table I for Na^{24} as a measure of radiation dose. The computations of dosage given in the following sections were made firstly to indicate the kind of experimental data needed to assess dose from serum induced activities and, secondly, to show where possible the relative orders of magnitude of the various kinds of dose. The first accident occurred 11:00 p.m., August 21, 1945, involving two persons; the second accident occurred May 21, 1946, involving eight persons. In both cases the radiation dosage was due to several different forms of nuclear radiation, including fast neutrons, gamma rays, slow neutrons, electrons, and X rays. Of these, the neutrons contributed the major fraction of the energy delivered into the bodies of the workers. Unfortunately, in both accidents safety badges (which had photographic film and elements for detecting neutrons) were not only not worn by personnel but left at points far removed from the critical assembly. For example, in the Pajarito Laboratory accident all personnel badges were in a lead box in a room about one hundred (100) feet from the assembly. Immediately after the accident Dr. Slotin asked to have the badges taken from the lead box and placed on the critical assembly. This was done by Dr. Schreiber at what is now recognized to have been a great personal risk. This risk existed for two reasons: (a) the delayed gamma radiation intensity near the assembly added to his total dose and (b) the presence of volatilized plutonium was undetermined. Upon questioning afterwards, Dr. Slotin said he thought that placing the films on the assembly would give information about the dosages to personnel. Actually, such film dosages were of little value and, since the neutrons had gone in the first flash, no neutron data was recorded. This incident is presented here to remind scientific personnel that after an accident the safest mode of conduct is to get as far as possible away from the source of radiation. In cases of heavy radiation doses it is known that human beings may suffer from vertigo immediately after dosage and are in no condition for rational behavior. A response similar to that of Dr. Slotin occurred in the other fatal radiation accident -- that of Harry Daghlian. After the appearance of the blue glow, Daghlian sensed that an accident had occurred and proceeded to disassemble the critical material and its tamper. In so doing he added heavily to the beta and gamma dosage to his hands and arms. In his particular case there is a possibility that he might have survived if he had not insisted on remaining so close to the active materials.

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SECTION II

Computation of Number of Fissions: Pajarito Accident

The number of fissions is estimated from the measured gamma-roentgen intensities.

At 10:10 p.m., 6.83 hr after 3:20, measured 1.3 R/hr at 20 cm from center of active sphere.

Assume 2×10^9 quanta/cm^2/R for quanta of 1 Mev.

Assume inverse square law, $20^2 = 400$.

Assume that 1/5 of gammas get out of sphere. $(1.3 \times 2 \times 10^9 \times 400 \times 5)/3600 = 1.44 \times 10^9$ quanta/cm^2/sec at 1 cm at 6.83 hr.)

Assume that the gamma decay law is $t^{-1.2}$, then 6.9 hr = 2.46×10^4 sec. According to this decay law the intensity at 10 sec is

$(2.48 \times 10^4/10)^{1.2} = 1.18 \times 10^4$ times the intensity at 6.9 hr. The quantum intensity is given by

$1.44 \times 10^9 \times 1.18 \times 10^4 = 1.7 \times 10^{13}$ quanta/cm^2/sec at 1 cm at time 10 sec.

Multiply by $4\pi = 12.5$ to get total quanta:

$1.7 \times 12.5 \times 10^{13} = 2.13 \times 10^{14}$ quanta/sec at 10 sec.

Use the decay law $N/sec = (0.72f)/t^{1.2}$ to get the number of fissions, f:

$f = 16 \times 2.13 \times 10^{14}/0.72 = 4.7 \times 10^{15}$ fissions.

Other estimates of the number of fissions are computed from roentgen readings at different times and places as listed in the following table:

Estimates of Number of Fissions

Time	Hours	Distance (cm)	R/hr	Fission Estimated
10:00 p.m.	6.7	100	0.075	1.38×10^{15}
10:00 p.m.	6.7	40	0.15	4.4×10^{14}
10:20 p.m.	7	40	0.35	1.0×10^{15}
5:15 p.m.	2	300	0.051	1.89×10^{15}
10:10 p.m.	6.9	20	1.3	4.7×10^{15} (Case outlined above)

Average number of fissions: 1.9×10^{15}

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SECTION III

Fast And Slow Neutron Doses

In estimating the total dose due to neutrons based on the slow neutron induced activities, we will analyze the various sources of energy released in tissue as follows:

a. Slow neutron capture in N^{14} to give a proton and a recoil C^{14} in the reaction N^{14} (n,p) C^{14}, Q = 0.62 Mev.

b. H^2 recoils produced on slow n capture in H^1.

c. Self dosage of body by neutron capture gamma radiation in H^1 according to H^1 (n,γ) H^2, = 2.2 Mev.

d. Elastic scatter of fast neutrons in aqueous tissue. It turns out that items (c) and (d) contribute most heavily to the total doses and that these two items are the least understood in the accident cases under consideration.

e. Summary of slow and fast neutron dosage components.

f. Mock-up measurements with Na^{24}.

<u>Analyses:</u>

a. <u>N^{14} slow neutron capture</u>

The biological effect of the reaction N^{14} (n,p) C^{14} in tissue appears to have been ascertained.[1] The analysis is made on the following basic data: assume the presence of N^{14} atoms to be 3% by weight in tissue; the slow neutron capture cross section in N^{14} is 1.75 barns; and the Q of the reaction is 0.60 Mev. It turns out that for the release of 83 ergs per gram of tissue, or 1 rep, the neutron flux is 3.8×10^{10} n/cc which we shall round out to 4×10^{10} n/cc per N^{14} rep (see first paragraph of Section VI for definition of rep).

b. <u>H^2 recoils</u>

The recoil energy released in tissue due to the reaction H^1 (n,γ) H^2, $\sigma = 0.25$ barns, is a negligible fraction of the total neutron dose. The 2.2-Mev gamma imparts a recoil kinetic energy to the H^2 of about 1300 ev. Assuming that H_2O is 76% by weight of aqueous tissue, we get 6.02×10^{22} atoms H/g. For a slow neutron density of 4×10^{10} n/cc, the H^2 recoils release 0.015 rep which is only 1.5% of the energy released in the N^{14} reaction.

1 Zirkle, R, CH-2808.

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c. Dosage due to capture gammas

1. The capture gammas arising from the reaction $H^1 (n,\gamma) H^2$, where γ = 2.2 Mev., in aqueous tissue are reabsorbed in the tissue. This causes a gamma dosage which is dependent upon the geometry of the tissue and upon the distribution of neutrons throughout the tissue mass. The estimates of dosage given below deal only with the H^1 capture process gammas, for which the capture cross section (slow neutron) is σ = 0.25 barns. For aqueous tissue the number of H^1 atoms per gm is taken as $N = 6.06 \times 10^{22}$. The number of neutron captures in H^1/gm tissue for a neutron density of n/gm is then:

$$\rho = N\sigma n = 6.06 \times 10^{22} \times 0.25 \times 10^{-24} n = 0.015 n.$$

For the neutron flux of 4×10^{10} n/gm which gives rise to 1 rep due to the N^{14} reaction (see a, p. 13), the density of H^1 captures per gm of tissue is:

$$\rho = 0.015 \times 4 \times 10^{10} = 6 \times 10^8 \text{ captures/gm.}$$

For the purpose of computing dose, consider the 6×10^8 captures as occurring at a point. The dosage rate from such a source given in "R/cm^2@ 1 cm distance" is:

$$(6 \times 10^8 \times 2.2 \times 0.05)/(4\pi \times 6.24 \times 10^5 \times 83) = 0.101 \text{ rep/cm}^2 \text{ in } H_2O.$$

Here the linear absorption coefficient for 2.2-Mev gammas is taken as 0.05 cm^{-1}. [1] We assume 6.24×10^{11} ev/erg and 1 rep = 83 ergs/gm tissue.

2. The self-dosage due to capture gammas in the body is best estimated by means of the reciprocal relationships which exist between radiation source and absorber. [2] For the purpose at hand we shall consider integral doses in simple geometries such as spheres and cylinders. The application is illustrated by the computation of the integral dose in a sphere. If a point source of radiation having linear absorption coefficient μ is placed at the center of a sphere of radius, a, the integral dose is:

$$\Sigma = \int \frac{A\, e^{-\mu r}}{r^2} 4\pi r^2 \, dr \text{ gram-roentgens}$$

[1] Philip Morrison, Metallurgical Laboratory Handbook, Chapter V. See also H. A. Wilson, "Body Tissue Ionization Due to Neutrons," CH-821.

[2] For a summary of these relationships see W. V. Mayneord, "Mathematical Theory of Integral Dose in Radium Therapy," Brit. J. Radiol. 28, 12-19 (1945).

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where A is the dose in R/cm^2 1 cm distance from the point source. Conversely, if the sphere is filled uniformly with the radiating material to a density p/gm the dose at the center is given by:

$$D = p\int \frac{A\ e^{-\mu r}}{r^2}\ 4\pi\ r^2\ dr \text{ roentgens so that } D = p\ \Sigma \text{ or } D = \Sigma \text{ if } p = 1.$$

The reciprocal relationship has been generalized for sources outside absorbers and sources of any geometrical shape.[1] Here we are concerned with the dose at the center of the mass of absorbing tissue because the gamma dosage there is a maximum for a uniform neutron density.

3. The integral dose, Σ, in a sphere of tissue due to the integrated neutron flux of 4×10^{10} n/cc is given by:

$$\Sigma = \frac{4\pi \times 0.101}{\mu}\ (1 - e^{-\mu r}) \text{ (where } \mu = 0.05 \text{ cm}^{-1} = 25.4\ (1 - e^{-\mu r}).$$

For a radius, r, equal to the mean free path equal to $1/\mu$ = 20 cm the integral dose is:

Σ = 25.4 x 0.63 = 16.0 gm-R.

The integral dose in an infinite medium is, of course, 25.4 gm-R. Below is the table of integral doses in spheres of various sizes:

<u>Integral Doses in Spheres of H_2O Due to a Point Source</u>

<u>of Radiation Comprising 6×8^{10} Neutron Captures</u>

μ = 0.05 cm^{-1} $4\pi/\mu$ = 251 A = 0.101 r/cm^2@1 cm

r (cm)	μr	$e^{-\mu r}$	$(1 - e^{-\mu r})$	$\frac{4\pi}{\mu}(1 - e^{-\mu r})$ A (gm-R)
2	0.1	0.905	0.095	2.41
3	0.15	0.861	0.139	3.53
5	0.25	0.779	0.221	5.6
10	0.5	0.607	0.393	10
15	0.75	0.472	0.528	13.4
20	1.0	0.368	0.632	16.0
25	1.25	0.287	0.713	18.1
30	1.5	0.223	0.777	19.7
				25.4

[1] Mayneord, loc. cit.

[redacted]

A source of uncertainty lies in the selection of the absorption coefficient for tissue and possible correction for degeneration of gammas in large masses of H_2O. An estimate might be made on the basis of Speiers[1] experimental measurements of electron density in tissue and an application of Klein-Nishina formula for $h\gamma = 2.2$ Mev. The effect of μ lies chiefly in the exponential term. Note that μ is cancelled out by the fact that it occurs in the numerator and denominator of the factor preceding the exponential term.

It should be pointed out that the limiting value of 25.4 gm-R produced by 6×10^8 neutron captures also sets the maximum dose which can be measured in an infinite mass of tissue when 6×10^8 neutron captures per unit volume occur uniformly throughout it. This basic fact provides a criterion for the use of any approximation formula that might be used for the estimation of dose in the complex geometries of the human body. Thus, when 6×10^8 captures occur per unit volume of tissue throughout the body, the maximum dose of 2.2 Mev gammas that might be measured at any point is 25.4 R. This result could also have been arrived at by a consideration of the fact that in an infinite medium the energy absorbed per unit volume equals the energy emitted per unit volume. This line of reasoning, however, gives no specific method for approximating the dose in the various parts of the human body. The figures used to arrive at the amount of energy emitted per gm of tissue are: 6×10^8 neutron captures/gm, each gamma = 2.2 Mev or $2.2 \times 10^6 \times 1.6 \times 10^{-12}$ ergs; and, taking 83 ergs per gm-R in tissue:

$$(6 \times 10^8 \times 2.2 \times 10^6 \times 1.6 \times 10^{-12})\ /83 = 25.4 \text{ R.}$$

<u>Applications to the human body:</u>

In order to arrive at reasonable estimates of the dosage in the parts of the human body we shall use an approximation formula given by Mayneord[2] for a mass of cylindrical shape. The integral dose for a point source at the geometrical center of the mass is given by:

$$\Sigma = E \quad A \quad 2\pi a\ e^{-\mu a/2}, \text{ where } a = \left(\frac{3\ V}{4\pi}\right)^{1/3} \qquad (1)$$

Here A is the intensity of source in R/cm^2 @ 1 cm and 0.101 R/cm^2 as above, and E is the elongation correction factor given by Fig. 2b. The elongation is the ratio of the long to short axis of the cylindrical mass. This approximation was arrived at by considering a mass of volume, V, (volume equals mass in case of aqueous tissue) in a spherical shape of radius, a. The elongation correction factor was computed for cylinders of the same mass as the sphere of volume V. The validity of the method depends on the

[1] Brit. J. Radiol., 19, 52 (1946).

[2] Brit. J. Radiol., 18, 12 (1945).

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fact that the total integral dose in a mass varies slowly with geometry as long as the mass is kept constant.

Fig. 2a shows the integral dose for masses up to 5000 gm. This covers the cases of small parts of the human body for sizes up to 5 kg. As an example, consider the lower leg in Fig. 1 where the cross sectional diameter is 10 cm., length, 45.5 cm., and mass 4.09 kg. The elongation is 45.5/10 = 4.55. The integral dose for 4.09 kg is 10.25 gm-R (Fig. 2a) and the value of E is 0.76, making the resultant integral dose 0.76 x 10.25 = 7.8 gm-R. Going to large masses, such as the trunk, we have computed integral doses as follows: assuming an elliptical cross section for the trunk such that the ratio of semi-axes is 1.8 and the length is 60 cm, we compute the volume, V, to get $a = (3V/4\pi)^{1/3}$. With this value of a we use equation (1) to get the integral dose from a point source at the center, assuming that the mass is a cylinder of circular cross section. This approximation slightly over-estimates the dose in that it effectively places the mass closer to the point source than it would be in a cylinder of elliptical cross section. For comparison, in Fig. 3 we have plotted the integral dose in a sphere having a diameter equal to the antero-posterior cross section of the trunk under consideration, namely, the abscissa gives the shorter semi-axis of the elliptical cross section of the trunk.

The integral doses in Figs. 2 and 3 are also the doses in R units at the centers of the masses when the masses are uniformly filled with radiation emitting material, in this specific case neutron captures at a density of 6×10^8 per gm. In order to get an average dose over the entire mass we refer to Mayneord's study [1] of the dose as a function of position in a radioactive sphere in which he shows that on the surface the dose is 1/2 that at the center of the sphere. This approximation holds fairly well for cylindrical geometries. The average dose, then, over the entire mass is the average of the dose at the center and the dose at the surface. The latter we shall take to be 1/2 the former, making an average of 0.75. Therefore, the integral dose for the parts of the body computed using the doses given by Figs. 2 and 3, and then multiplied by 0.75, will give an average integral dose. This is shown in Table V where we have taken the dimensions of the model man, wt 70 kg (Fig. 1) and computed the integral dose for the various parts of the body for a neutron capture density 6×10^8/cc. Table V shows the mass of parts of the body. The average dose is 0.555 or 0.6 megagram-roentgens (megm-R). To compare this with the total energy available, assume the body volume to be 7×10^4 cc to give $6 \times 10^8 \times 7 \times 10^4 = 4.2 \times 10^{13}$ total neutron captures. If these are placed at a

[1] Mayneord, Brit. J. Radiol. 18, 12 (1945).

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point in an infinite tissue medium, the total integral dose is $25.4(4.2 \times 10^{13})/(6 \times 10^{8}) = 1.77 \times 10^{6}$ gm-R. The body dose from Table V is then 0.6/1.77, or 37% of the total available.

Self-dosages in the accident:

The self-dose due to capture gammas for each of the personnel in the accidents will be estimated on the assumption that they can be compared with the model man on the basis of weight. In Table VI we have computed the integral dose by dividing the weights in kg by 70 kg and assuming that for each unit the integral dose is 0.6 megm-R. See Table XI for physical data on personnel.

For a comparison of these integral doses with those administered in routine radium therapy, we note that 3 megm-R is a clinically' significant dose in that it causes a drop in lymphocyte count, and may lead to radiation sickness. More severe modes of radium and X-ray therapy lead to integral doses of the order of 6 to 10 megm-R. An important difference in the administration of therapeutic doses is that they are administered over a period of several days, whereas the doses under consideration here were given in a time of the order of one second (except the case of Daghlian where the total time was probably 100 sec). A further comparison is afforded by the integral dose tables given by Mayneord [1] where the average dose throughout the body per roentgen on the skin surface is 0.7 gm-R for radium gamma rays from a source at infinity. For a 60-kg man this leads to 42,000 gm-R per R on the skin surface and 100 R lead to 4.2 megm-R total integral dose. Thus, in Slotin's case, the 3.59 megm-R would be equivalent to about 85 R on the skin, the radiation coming from a source at infinity. The comparison is only approximate because the distribution of dose in the case of capture gammas in tissue is concentrated along the geometrical center of the parts of the body.

d. Fast neutron dose in tissue [2]

The estimation of the fast neutron dose from the measured slow neutron induced activities in the blood serum sodium is outlined as follows:

1. The neutron flux, n, is determined from the specific activity of sodium by the relationship:

$$N^* = N\sigma n$$

where N^* is the specific activity in cps/mg Na, N is the number of atoms of Na per mg, and σ is the capture cross section of Na^{23} for slow neutrons (0.69×10^{-24} cm^2). Thus, $n = N^*/N\sigma$ is called the neutron flux because it is a measure of the number of slow

[1] Mayneord, Brit. J. Radiol., 12, 359 (1944).

[2] We wish to acknowledge our indebtedness to Dr. Carson Mark for his valuable discussions of this dose.

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neutrons per unit volume in the tissue, in the time, t, over which neutrons appeared in the tissue. The time, t, is of the order of a second at most.

2. The neutron flux is u pt, where u is the neutron velocity, p is the density of neutrons per cc maintained over a time, t, and

$$N^* = N\sigma u \, pt$$

We shall assume a slow neutron energy of 0.04 ev, this being the value given for the average energy of neutrons slowed in paraffin (Met. Lab. Hdbk, Chapt. IV). The value of $u = 2.8 \times 10^5$ cm/sec for an energy 0.04 ev. In water, the lifetime, τ, of 0.04 ev neutrons is 2.4×10^{-4} sec, Neglecting losses of slow neutrons from a slab of aqueous tissue 15 cm on edge, the total number of neutrons/cc which must have reached the energy 0.04 ev is

$$pt/\tau = (upt/u)\ (1/\tau).$$

Taking the value of $n = 4 \times 10^{10}$ n/cc one gets

$$pt/\tau = (4 \times 10^{10}/2.8 \times 10^5)\ (1/2.4 \times 10^{-4}) = 6 \times 10^8/\text{cc}.$$

The actual number of neutrons reaching thermal energies will be higher than this figure by virtue of leakage from the surface. In a 15-cm slab of water the estimate of leakage loss is about 25% so that the average life of a neutron in the system (tissue) is less than τ. We shall assume the average life to be 0.75τ, and the number of neutrons reaching thermal energies is 8×10^8/cc.

3. In order to correct this figure for the number of fast neutrons which escaped from the body before coming thermal, we refer to the measurements on the distribution of nascent thermal neutrons in water originating from a fission source. The figure, 8×10^8/cc, has then to be raised to 1.1×10^9/cc as a final estimate of the numbers of fast neutrons per cc which gave rise to a slow neutron flux of 4×10^{10} n/cc.

4. Given the total number of fast neutrons per cc, one has to guess at their average energy in order to estimate the amount of energy they lost in elastic collisions. The average energy is estimated as 0.35 Mev. Very few of these will have escaped from the body without several collisions. On the average the neutrons will lose about half their energy in the first collision. The best estimate is that each neutron lost 0.35 Mev in tissue. Taking 1 rep = 5×10^{13} ev/cc one has the total dose of

$$(1.1 \times 10^9 \times 0.35 \times 10^6/5 \times 10^{13}) = 7.7 \text{ rep}.$$

There is no specific data from the accidents to give any measure of the neutron energies incident on personnel. We shall take the dose to be 8 rep due to fast neutrons for which $n = 4 \times 10^{10}$/cc. This is also the value of n for which 1 rep is released by the N^{14} capture reaction (see p. 13).

5. On this basis the total rep-grams have been calculated from the induced activities as shown in Table VII. The integral dose in rep-grams shown as UWS

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is dosage in the form of recoil atoms due to elastic scattering of neutrons. The next column gives the integral dose (U W 24) where we have multiplied the U W 8 by 3 in order to convert the heavy particle dosage to an equivalent gamma ray dose for comparison with the gamma ray dose in Table VI. The conversion by the factor 3 is based on the assumption that 1 "n" unit of fast neutrons gives 2.5 rep and 1 "n" is 7.5 as effective as 1 R of gamma rays, (7.5/2.5 = 3). It is evident that fast neutrons are the most effective means of conveying energy to tissue.

e. Summary of fast and slow neutron dosage components

We summarize the neutron doses arrived at in the preceding computations. The fast neutron energies are unknown. We assume that each fast neutron lost 0.35 Mev in the body. For a fast neutron flux of 1.1×10^9 n/cc, there arose an integrated slow neutron flux of 4×10^{10} n/cc, of which 6×10^8 were captured by H^1 in each cc tissue. For the flux of 4×10^{10} slow n/cc the doses were as follows:

Process	Energy Released	Biological Equivalent * Gamma Energy	% Total Energy	% Biol. Equiv. Gamma Energy
N^{14} (n,p) C^{14}	1 rep	3 rep	5.7	8.7
H^1 (n,γ) H^2	8.6**	8.6	50	24.8
H^1 recoils	7.7	23	44.3	66.5

* 1 rep of H^1 recoils is assumed biologically equivalent to 3 gamma rep.

** Average energy per cc tissue estimated as follows: for an integrated flux 4×10^{10} n/cc the total body (70 kg) integral dose is 0.6 megm-R. For a plane wave of gamma radiation ($\mu = 0.05$ cm^{-1}) incident on the 70-kg body having torso thickness 23 cm, the average integral dose is 0.63 gm-R per incident R

$$\therefore 70 \times 10^3 \times 0.63 \times R = 6 \times 10^5 \text{ gm-R}$$

incident dose = 13.6 gamma-R

hence average dose in tissue is 13.6 x 0.63 = 8.6 rep.

f. Mock-up measurements with Na^{24} (measurements of 14 March 1947)

To simulate the process of neutron capture in H^1 in living humans a mock-up of the human body was made and filled with water. In the water was dissolved NaCl which contained Na^{24} (14.8 hr). The description and results of the experiment are written in a separate report. To get the measured body dose due to the H^2 capture gammas the essential results are as follows:

At diaphragm level, Fig. 6, anterior skin surface, a reading of 130 milliroentgens per hour was recorded when the activity of Na^{24} was 80,978 disintegrations/cc/min

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of body solution. Mass of mock-up was 59 kg H_2O.

$0.13/(60 \times 80{,}978) = 2.7 \times 10^{-8}$ R/dis/cc of solution. To convert this to the case of H^2 capture gammas one notes that there are for Na^{24}

3.3×10^{-10} R/dis/cm^2 @ 1 cm.

For H^2 one has 1.5×10^{-10} R/dis/cm^2 @ 1 cm. The ratio of roentgen output per disintegration is $1.5/3.3 = 0.455$. Hence for H^2 in the mock-up one has

$2.5 \times 10^{-8} \times 0.455 = 1.14 \times 10^{-8}$ R/capture/cc of solution.

The intensity at the geometrical center of the torso should be twice that at the skin surface. Or the average intensity should be 1.5 times that at the skin surface. The average intensities in the torso mass are then

$1.5 \times 2.5 \times 10^{-8} = 3.75 \times 10^{-8}$ R/dis/cc sol/, Na^{24}

$1.5 \times 1.14 \times 10^{-8} = 1.7 \times 10^{-8}$ R/capt/cc tissue/, H^2.

We can now compute the integral doses due to H^1 capture gammas in the bodies of personnel in critical assembly accidents. The basic data are the Na^{24} activities observed in the sera and urines. The data in Table VIII start with the "integrated slow neutron flux" as determined from the Na^{24} slow neutron induced activities. It was shown above that for an integrated slow neutron flux of 4×10^{10}/cc there occur 6×10^8 captures in H^1 per cc. The number of captures per cc of tissue is multiplied by 1.7×10^{-8} to give the gamma roentgens dose in the torso.

The gm-R doses in Table VIII are somewhat higher than those computed in Table VI. They are high because they are computed on the basis that all of the limbs have the same average dose as the torso. Obviously this is not the case. However, detailed measurements in the limbs were not done, and the proper experimentally determined correction cannot yet be applied. As an example, the case of Slotin shows from Table VIII a dose of 4.14 megm-R, whereas the computed value was 3.6 megm-R. This constitutes sufficient agreement, particularly since the 4.14 megm-R are known to be too high. We refer to Table VI for the theoretically estimated values of integral dose computed for comparison with the values in Table VIII.

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SECTION IV

Gamma Dosages: Prompt and Delayed Gammas

The body doses due to prompt and delayed gammas from the fission burst can be estimated only very crudely. If the "planted" disaster badges containing high range film Co slabs and $Ca(PO_4)_3$ had been left about the room it is possible that somewhat more data would have been available to fill in the gaps in our knowledge which exist in the first three meters about the active sphere. For instance, at Pajarito a badge had been planted under the table top on which the assembly rested, but at the time of the accident it was not there. The only badges left at their planted spots were those on the walls of the laboratory (see Fig. 5).

It is perhaps fortunate that the gamma dosages, prompt and delayed, turn out to be a minor fraction (20% or less) of the total dose sustained because the gamma dosages are the most difficult to estimate under the circumstances. In the case of neutron doses one has the induced activities within the body as an index of dosage. This is not true for the gammas.

Figure 4 shows the standard health-physics chart of the Pajarito laboratory with the approximate locations of the personnel at the time of the accident. These locations are based on interviews held after the accident and are probably only approximate. On the basis of these distances the specific activities of P^{32} and Na^{24} in urine, and Na^{24} in serum, are plotted in Fig. 5. For comparison are given the $1/r^2$ line, the film badge data, and the delayed gammas as a function of distance. The delayed gammas are corrected to 6.7 hr after the fissions occurred. They were measured by means of a brass-walled d-c ion chamber known as the "Wattsmeter" (calibrated against radium). The induced activities give slopes which are greater than 2, whereas the delayed gamma measurements give slopes which are less than 2. The data are such that considerable freedom is allowed in drawing a line through the points, except in the case of the delayed gammas. For the film badges, Morrison and Wright recommended an exponent 1.2.

a. Prompt gamma doses

In order to make an estimate of the prompt gamma dosage, we assume a 1.0-Mev gamma escapes from the Pu sphere per fission. For this energy of gammas the quantum flux is $2 \times 10^9/1.0$ quanta/cm^2/R. For 2.4×10^{15} fissions at 100 cm the dosage is

$$(2.4 \times 10^{15} \times 1.0)/(4\pi \times 10^4 \times 2 \times 10^9) = 9.4 \text{ R}.$$

If the number of prompt gammas escaping per fission is greater than one and of energy

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other than 1.0 Mev, the calculation is to be corrected directly proportional to the total gamma energy. The 9.4 R above is probably the minimum possible. The estimates of the prompt gamma dosages for the personnel can be made, assuming the distance of each person from the source as indicated in Fig. 4 and assuming that the intensity falls off as the 1.6 power of the distance as indicated by the measurements on delayed gammas in Fig. 5. The prompt gamma doses are indicated in Table X.

The integral doses shown in the last column are obtained by multiplying the weight in grams (Table XI) by the corrected intensity (Table X) and by the constant 0.63 gm-R per incident roentgen. This assumes the source to be at infinity. The proper correction factor for divergence of the beam for a source near the body is given by Mayneord.[1]

The prompt gamma doses for Daghlian cannot be estimated here because no data were available on the absorption of gammas in the tungsten-carbide blocs used in the assembly. Compared with the Be tamper case given in Table X, it can be said that the prompt gamma dose in Daghlian was less than that in Slotin, due to higher absorption in tungsten-carbide.

To correct for the absorption of gammas in the 9-inch O.D. Be tamper shell, we refer to the measurements of Mr. C. Wright on the delayed gammas from the source. Wright found that with no Be tamper over the sphere the intensity was 0.062 R/hr. This was reduced to 0.048 R/hr by the Be tamper shell, which is 77% of the original intensity and corresponding to a reduction of 23%. Thus, the gamma intensities in Col. 4, Table X, are to be multiplied by 0.77 to give the actual dosage intensities.

b. <u>Delayed gamma doses</u>

At 5:20 p.m., two hours after the accident, the delayed gamma intensity at 300 cm distance was measured as 0.066 R/hr. Assuming that the delayed gammas decayed as $t^{-1.2}$, we compute the intensity at 10 sec time. The time factor is then (2 hr = 72,000 sec) : $(7200/10)^{1.2}$ = 2584. At 300 cm the intensity at 10 sec was then 2584 x 0.066 = 171 R/hr. At 100 cm this becomes $(300/100)^{1.6}$ x 171 = 1000 R/hr @ 10 sec, or 0.32 R/sec @ 10 sec. In the first 10 sec the delayed gamma intensity is assumed to be constant. If we assume that the personnel were in this region for 20 sec, then a dose of 6.4 R was sustained (at 100 cm). At 50 cm distance in Slotin's case this dose is 2.5 x 6.4 = 16 R. The time spent by the personnel in the vicinity of the source is not known. Interviews with the personnel indicated that they all ran away quickly when Slotin threw the Be tamper from the Pu sphere to the floor. The estimate of 20 sec is probably amply long except in the case of Dr. Schreiber, who returned to the assembly twice -- first to place film badges on the assembly and second to fetch the coats of his colleagues.

[1] <u>Brit. J. Radiol.</u>, <u>12</u>, 359 (1944).

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SECTION V

Dosage Due To Induced Activities In The Body

The major fraction of induced activity in the body is considered as being due to that produced by slow neutrons. The activities due to n, 2n reactions are believed to be negligible because of the relatively small numbers of high energy (greater than 1 Mev) neutrons. Since slow neutron cross sections are usually greater than those of n, 2n, or γ, n processes, the calculations below are indicative of the order of magnitude of dosage to be expected from induced activities.

For Na^{24} the average beta energy is 540 kev (Table XII). We shall compute the entire activity in the body of Slotin, assuming that the specific activity of Na^{24} was uniform throughout the body and was 75 cps/mg Na^{23} (Table I). According to Moore[1], there are 89.2 gm Na in a body of 66 kg weight. This is to be compared with Shohl's value of 63 gm (Table XV). For purposes of estimation we shall take 75 gm Na in a body of weight 70 kg, of which 15 kg is bone. The total energy emitted is

$$0.54 \times 75 \times 10^{3} \times 75 \times (1/1.3 \times 10^{-5}) = 2.32 \times 10^{11} \text{ Mev}$$

where 1.3×10^{-5} sec^{-1} is the decay constant for Na^{24}. To convert this to rep we take 6.24×10^{11} ev/erg and 1 rep = 83 ergs/gm tissue. Then 1 rep = 5.17×10^{7} Mev/gm tissue. The energy above can be assumed in a rough approximation to have been expended in 70 kg of aqueous tissue. The energy concentration is then in terms of rep units:

$$2.32 \times 10^{8}/(7 \times 10^{4} \times 5.17 \times 10^{7}) = 6.4 \times 10^{-2} \text{ rep } (Na^{24} \text{ betas}).$$

This is a low dosage given over a period of time of the order of several half-lives of Na^{24} (14.5 hr). If the concentration of Na^{24} is not uniform but concentrated a wide range of concentrations is allowable before the dosage becomes significant. Also, the specific activity may vary over wide limits which, in turn, means that the slow neutron density may vary by large factors before a significant beta dosage occurs.

[1] Moore, Science, 104, 157 (1946).

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SECTION VI

Summary Of Doses Due To Fission Burst

In Table XIII are summarized the dosages computed in foregoing sections. The various components are given in "megm-R" which denotes the gram-roentgen-equivalent-physical (rep) units in units of 10^6. The fast neutron doses have been converted to the gamma dose (Table XIV) and soft X-ray dose (Table XIV A) which would produce the same biological effect. The prompt gamma doses constitute a small fraction of the total and are shown only to indicate their relative magnitude. The delayed gamma doses are of the same low order of magnitude and since there was great uncertainty about how long the Pajarito personnel were in the vicinity of the source, the doses are omitted. Daghlian's case is an exception because he proceeded to take down the assembly with his hands after the fission burst occurred and thereby acquired a significant portion of his total dose.

It is believed that the figures in Table XIII represent the lowest possible doses. This is based on the fact that the fast neutrons contribute the largest portion of the biological dosage. The fast neutron doses in Table XIII are based on the assumption of an average neutron energy of 0.35 Mev. It would not be unreasonable to assume an average energy three times this and thus arrive at a fast neutron dosage for Slotin of 3 x 10.8 = 32.4 megm-R (approx), which leads to an equivalent gamma dosage finally of 880 R as is indicated in the second column of Table XIV. By assuming a mean energy of 1 Mev for the fast neutrons, we guess that we are accounting for the probable effects of high energy neutrons. No definite information is available on the relative biological effectiveness of neutrons having energies greater than 5 Mev. In order to make a specific estimate of the maximum possible biological dose sustained by the personnel, we make the following guesses.

Assume that there are 5% of all neutrons spread in the energy spectrum beyond 2 Mev. Assume an average biological effectiveness of these neutrons of three times that at 1-Mev energy. And assume an average energy of 6 Mev. Then the dose equivalence for the 5% of neutrons in this energy range is 6 x 3 x (1/20) = 0.9. This means that relative to the 1-Mev neutrons the higher energy neutrons will contribute an additional 90% of the biologically effective dosage. In order to compute this additional effect, one should add 90% to the fast neutron dose computed for the "unmodified" dose in Table XIV. However, in the "unmodified" dose the gamma ray contribution due to capture and prompt gammas is already down to 10% of the total and for simplicity we have added 90% to the "unmodified" dose to arrive at what seems to be the maximum possible, shown in the last column of Table XIV.

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The equivalent dosage given in the last column of Tables XIII and XIV is presented only because therapeutic usage in well-defined applicators has led to the designation of dosage in R as measured on the body surface. The conversion of dosage from integral dose in gm-R to the equivalent plane wave radiation dose in R, which would deliver the same total energy, must be accepted with the fundamental qualification that although the total energy is the same, the distribution in the body is not the same in both cases. While the designation of total energy in gm-R does not specify the variations in density over the body, it is at least one step closer to reality than the artificial designation of equivalent plane wave R units. With this in mind, Table XIV has been compiled to show the actual total energies, in megm-R, of the doses corresponding to the figures in Table XIII. It should be remembered that the megagram-roentgens are the gamma ray equivalents into which all the dose components were converted.

Since the doses in Tables XIII and XIV show total doses which have been converted to gamma equivalents, it seems advisable to compute them in another form to illustrate the trend when the doses are converted to low energy radiation equivalents. If the neutrons are assumed to have an average energy of 0.5 Mev, they will have low penetration in aqueous tissue -- certainly not more than 3 cm. This means that the fast neutron dose will be concentrated in the outer layers of tissue facing the source. The slow neutron dose will also be concentrated in that limited portion of the body; the N^{14} disintegration dose will be delivered to only that side of the body. The Na^{24} appearing in the serum will be a dilution of the actual concentration produced in the region in which the slow neutrons are absorbed.

To take account of the low penetration of neutrons of 0.5-Mev energy, we compute the dose in terms of the distribution produced by 80-kev X rays. Mayneord's factor for the integral dose for 80-kev X rays at 250 cm target distance is 0.20 gm-R per incident roentgen. For the relative biological effectiveness per unit energy (rbe) delivered, assume the value of 5. This means that the ratio of effectiveness per unit energy in the form of atomic recoils to that in the form of 80-kev X rays is 5. The total dose will now comprise two components -- one due to low penetration neutrons, the other of very penetrating gamma rays from hydrogen captures and prompt fission gammas. The neutron dose is concentrated in the tissue region facing the source, whereas the gamma dose is fairly uniformly spread throughout the body. Table XIV A shows the relative magnitudes for these two components: the last two columns differing by about one order of magnitude, the neutron dose being the larger. We believe that the breakdown of the total dose into a low penetration neutron component and a high penetration gamma ray component gives a more realistic picture of the dose distribution than does the conversion of the entire dose into gamma equivalents.

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SECTION VII

Methods Of Estimating Dosage In Neutron Accidents

The most important fact in assessing the magnitude of radiation dosage in accidents involving neutrons is the specific activity of Na^{24} in body fluids. For large doses of neutrons from fission assemblies, the data presented in Table I, showing the activities in the blood serum, provide the best guide by means of a direct comparison. Table I provides a kind of calibration of biological response versus Na^{24} induced serum activity. It is probable that any measurable P^{32} activity found in the serum indicates a lethal neutron dose if the neutrons come from a source whose average neutron energy is near 1 Mev. This statement must be qualified by the possibility that P^{32} may be selectively eliminated from the blood system. The measurement of serum P^{32} activity must be made on blood samples obtained as soon as possible after the dose is received.

A means for assessing the neutron dose from the Na^{24} activity is that of measuring the gamma radiation given off by the person. This provides a rapid method of estimation of dose. The measurements on the mock-up man (see Section III, f.) given in Fig. 6 form the basis for such a measurement. Unfortunately, such measurements were not made on the personnel in the Pajarito accident. The measurements of Fig. 6 were made with a Victoreen Model 263 gamma survey meter having a Geiger-Muller Tube detector. The data of Fig. 6 show that a 130 mR/hr reading was obtained when the meter was placed against the chest (diaphragm) of the mock-up having 80,978 Na^{24} dis/cc water. This corresponds to 2.5×10^{-8} gamma R/dis Na^{24}/gm H_2O in mock-up. In Table I the Na^{24} activity of serum sample II is about 10,240/(5 x 0.15) = 13,660 cpm. If the serum activity is uniformly distributed in the body, one might expect a reading in Slotin of (13,660/80,978) 130 = 20 mR/hr at t = 0. In actual fact, however, there are two factors: the human body is not uniformly filled with serum Na^{23}, and at the chest level the meter is near the sternum cartilage which has a high concentration of Na. The exact relation between such a gamma reading and measured serum activities can only be determined from additional data on humans or from cadaver measurements.

Assuming for the purpose of illustration of the method that the inhomogeneities even out to a uniform distribution of Na (as would be the case where the gamma R meter is 100 cm from the chest), we can estimate the lowest neutron doses measurable by this method. A Geiger-Muller type of survey meter can easily detect 10^{-5} R/min. An intensity of 10^{-6} R/min usually gives a reading 3 to 5 times general background. Such a meter can detect 385 cpm Na^{24} per cc of tissue according to the mock-up measurements (Fig. 6). With a uniform specific activity this would correspond to about 230 cpm/mg Na^{23} in the blood (3.1 mg Na/cc serum and assuming all Na is in the serum). The relationship of the detectable Na^{24} activity to the tolerance amount of slow neutrons is estimated by assuming a slow neutron capture cross section in Na^{23} of 0.69×10^{-24} cm^2. As shown in Section III, an integrated slow neutron flux of 4×10^{10}/cc leads to a serum activity of 96 cpm/mg Na and gives rise to an integral dose of 0.6 megm-R due to H^1 captures and 0.35 megm-R due to N^{14} capture process (assuming a biological effectiveness factor of 3 per unit energy for heavy particles -- Section III, e.). Thus, the total integral dose is 0.95 megm-R, which corresponds to a specific activity of 96 cpm/mg Na. In pure energy units, without conversion to biologically equivalent gamma radiation, the integral dose is 0.67 megm-R.

This dose is to be compared with the tolerance dose of gamma radiation. For gamma radiation, the tolerance rate of 0.1 R/day leads to an integral dose of 4500 gm-R where $\mu = 0.05$ cm^{-1}.[1] The detectable gamma activity of 230 cpm/mg Na^{23} in the serum is then due to a neutron density which causes a dose 527 times daily tolerance. Therefore, the method is not applicable to tolerance dose measurements but rather to the assaying of subacute neutron doses. It may be possible to assess doses smaller than the factor of 527 would indicate. This would involve going to readings of the order of 2×10^{-6} R/min, i.e., nearer the background levels. Also, use could be made of the capture formation of Cl^{38} (37 min), the specific activity of which is 3 times that of Na^{24}. The capture cross section in Cl^{37} is 0.137×10^{-24} cm^2. These two items might give an added factor of 15 in sensitivity so that a neutron density 35 times background could be detected. However, the measurement must be made before and after the Cl^{38} has decayed.

[1] Mayneord, Brit. J. Radiol., 12, 359 (1944).

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SECTION VIII

Blue Glow Phenomena In Critical Assembly Accidents

The appearance of blue glow in the air immediately about critical assemblies was reported in the accidents which occurred June 4, 1945, August 21, 1945, and May 21, 1946. From the standpoint of assessing the radiation dosages accompanying the appearance of the blue glow it is desirable to know the magnitude of energy flux which can produce the glow phenomenon. The numbers of fissions which were computed in the accidents are as follows:

Accident Date	Number of Fissions	Tamper
June 4, 1945	3×10^{16}	Tuballoy blocs with H_2O of variable height in a steel tank. 25 core. Water flows in through valve system at bottom of tank.
August 21, 1945	10^{16}	Tungsten-carbide blocs around 49 core. One tungsten-carbide bloc determines criticality controlled by hand.
May 21, 1946	3×10^{15}	Beryllium hemispheric shells around 49 core. Upper hemisphere controlled by hand.

The numbers of fissions are remarkably close to one another considering the widely differing conditions of tamper control. In the June 4, 1945, accident the only control was in the rate of flow of water into the tank around the tuballoy blocs. In this case the blue glow was seen around the tuballoy which was above the water surface. It was seen against a dark background formed by the walls of the tank and the black tuballoy blocs. The only lighting was that given by incandescent lamps suspended from the ceiling and by daylight from distant windows. In the August 21, 1945, accident no adequate description of the blue glow was available. It was seen against the dark background of tungsten-carbide blocs in the presence of electric incandescent lamps (the accident occurred at night around 11:00 p.m.). Hemmerly, the security guard with Daghlian, was sitting with his back toward the assembly and reading a paper near a light. He was aware of a bright flash on his newspaper when the accident occurred. The Pajarito accident occurred in a well-lighted laboratory near large windows through which the bright afternoon sun (3:20 p.m.) shone. Three of the people present were positive in their statements of having seen a blue glow which seemed to have extended up to 20 cm beyond the beryllium tamper. In view of the fact that the glow was seen in the brightly lighted Pajarito laboratory, it is believable that the security guard should have seen

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a flash in the earlier accident at night. It must be remembered, however, that the August 21, 1945, assembly had around the core large tungsten-carbide blocs which are heavy absorbers when compared with the low absorbing beryllium shell tamper which was used in the Pajarito assembly.

In order to estimate the rate of absorption of energy in air to produce the blue glow, the following facts were found. Under controlled conditions the blue glow is seen in cyclotron beams. After the August 21, 1945, accident Dr. Marshall Holloway pointed out that in a darkened room at Cornell a 20-microamp beam of 5-Mev deuterons could be seen easily. From the range-energy relation and assuming a 1 cm^2 beam cross section, one computes that 2.8×10^{19} ev/cc/sec are being absorbed in the air where the beam has 5-Mev deuterons.

In another instance of controlled source of radiation, Dr. Don Martin pointed out that 10 curies/cm^2 of polonium gives an easily discernible aura of blue about the source in the dark. This glow is about 5 cm deep -- the range of the 5.3-Mev alphas. This was investigated further.

On June 6, 1946, 4:00 p.m., Dr. Don Martin demonstrated the aura of blue glow which is produced about concentrated alpha particle sources of polonium as follows:

<u>5 Curies Po/cm^2</u> on a sphere totaling 18 curies gave an easily discernible glow of deep violet in air. The aura makes a sphere which is about 2 x 5 cm in diameter (the range of the alphas at Los Alamos being about 5 cm in air). The room lights had to be out. Yet as soon as they were out one could see the glow, especially by indirect vision. As one's eyes became dark-adapted the aura took on a definite shape and could be studied by direct vision.

<u>1.5-2 Curies Po/cm^2</u> on a sphere totaling 3 curies had a glow which required some dark adaptation (about 2 min) before it could be seen.

<u>1 Curie/cm^2</u> on a rectangular Pt foil (1 curie total Po) was used to show fluorescence in glass. In the dark the outlines of a glass bottle surrounding the source could be seen. Diameter of bottle about 4 cm. The bombardment of the glass produced a blue light. At present it is not known how this light is produced.

<u>Estimates of energy absorption rate in air</u>

For the production of blue glow in a dark room by an 18-curie Po source we take the following estimates:

Alpha energy 5 Mev
range in air at Los Alamos 5 cm
source on a sphere 1 cm in diameter
1 curie = 3.7×10^{10} sec^{-1}
1 R = 6.66×10^{10} ev/cc air

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The total energy emitted by the Po source will be dissipated in a volume of air = $4\pi\,(5.25)^3/3$ = 4.18 x 145 = 606 cc air. The energy in the form of alphas is given off at a rate, if we assume 20% loss in the source holder, of

$$18 \times 3.7 \times 10^{10} \times 5 \times 10^{6} \times 4/5 = 2.66 \times 10^{18} \text{ ev/sec.}$$

Assuming uniform dissipation in the sphere of radius 5.5 cm, one has a rate of energy absorption per cc of air as

$$2.66 \times 10^{18}/606 = 4.4 \times 10^{15} \text{ ev/cc/sec.}$$

In terms of R/sec this becomes

$$4.4 \times 10^{15}/6.66 \times 10^{10} = 6.6 \times 10^{4} \text{ R/cc/sec.}$$

To consider the same ionization produced by gamma rays, one has to correct for altitude by the factor of 760/550, or 1.38.

A case in which the number of fissions was about 6×10^{15} occurred in the rerun of the Daghlian accident. The rerun was carried out by Slotin, Frisch, and Aebersold on October 2, 1945. Aebersold reported that the intensity of prompt gammas built up in "several seconds." No blue glow was seen in the darkened laboratory. The data here are crude and one can only estimate that the energy absorption in the air was about 10^{14} ev/cc/sec if the fissions occurred over an interval of 5 sec.

In order to estimate the energy absorption rate, say, in the Pajarito accident which caused the blue glow, one has to extrapolate from the known case on Po in a dark room to the case of electron bombardment and possibly neutron recoils in a lighted room. We shall assume that a factor of 10^4 existed in the light intensity in the Pajarito laboratory over the dark-room case in which the polonium sources were studied. Roughly, then, the energy absorption at Pajarito was 10^{19} ev/cc/sec if one can assume that the blue glow is excited by electrons, neutrons, etc. in the same manner as Po alphas. This would lead to a roentgen rate of 6×10^7 R/cc/sec. While a major portion of this energy may be in a form which cannot penetrate deeply into tissue, it is nevertheless of such a magnitude as to provide extremely high dosages to hands as was found in the cases of Slotin and Daghlian. If only 0.1% of this energy is penetrating radiation, it will give a lethal dose in 1 sec to any limb in the blue glow. The soft component itself will easily destroy the superficial layers of tissue.

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TABLE I

Na^{24} and P^{32} Activities in Serum

Name	Sample	Time taken (hours after exposure)	mg Na per cc	cc plated	mg Na plated	Na^{24} cpm @ t = 0	Na^{24} Corr.* dps	Na^{24} Corr.* dps per mg Na	P^{32} cpm per mg P @ t = 0	P^{32} Corr.* dps per mg P
Slotin	Serum I	1.2	3.22	3	9.66	6400	711	73.6	103**	12.8
	II	46.9	3.09	5	15.45	10240	1137	73.6		
	III	66.1	3.03	5	15.15	10700	1177	77.8		
Graves	Serum I	1.1	3.20	3	9.60	1150	128	13.3		
	II	46.8	3.27	5	16.35	2100	222	13.6		
	III	65.8	3.13	5	15.65	1800	200	12.8		
Young	Serum I	1.9	3.25	3	9.75	620	69	7.1		
	II	46.7	3.16	5	15.80	540	60	3.8***		
Kline	Serum I	1.4	3.36	3	10.08	900	100	10		
	II	46.6	3.22	5	16.10	700	77.8	4.83***		
Cieslicki	Serum I	1.5	3.28	3	9.84	180	20	2.03		
Cleary	Serum I	1.8	3.22	3	9.66	260	29	3.0		
Schrieber	Serum I	2.0	3.24	3	9.72	135	15	1.54		
Perlman	Serum I	1.4	3.18	3	9.54	110	12.2	1.22		

*Counter Efficiency: 0.15.

**Based on 3-cc sample of serum which had 0.39 mg phosphorous and had a count of 40 cpm.

***Counting rate less than 100% of background--activity estimated only.

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TABLE II

P^{32} Activities in Urine

Name	Sample	Time taken--hours after exposure	mg P per cc	cc plated	mg P plated	P^{32} cpm @ t = 0	P^{32} Corr.* dps @ t = 0	P^{32} Corr.* dps per mg P
Slotin	Urine I	1.2				11600	1290	
	II)	3.8				3200	356	
(Pooled)**	III)	5.3	0.256	5	1.28	4120	457	357
Graves	Urine I	1.2	1.22	5	6.10	2630	290	47.5
	II	3.1	0.101	5	0.505	310	34.4	68.1
Young	Urine I	2.2	0.735	5	3.67	450	50	13.6
Kline	Urine I	1.9	1.37	5	6.85	360	40	5.84
Cieslicki	Urine I	2.2	1.32	5	6.60	150	16.7	2.53
Cleary	Urine I	1.2	1.27	5	6.35	170	18.9	2.97
Schreiber	Urine I	1.2	1.12	5	5.60	70	7.8	1.4
Perlman	Urine I	2.2	1.12	5	5.60	70	7.8	1.4

*Corrected for Counter Efficiency of 0.15.

**Specimens passed at 1.2 and 3.8 hours pooled.

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TABLE III

Na^{24} Activities in Urine

Name	Sample	Time taken--hours after exposure	mg Na per cc	cc plated	mg Na plated	Na^{24} cpm @ t = 0	Na^{24} Corr.* dps @ t = 0	Na^{24} Corr.* dps per mg Na
Slotin	Urine II	3.8 hrs.	1.635	5	8.18	18300	2033	248
Graves	Urine I	1.2	2.94	5	14.7	2000	222	15.1
Young	Urine I	2.2	6.01	5	30.1	2100	233	7.75
Kline	Urine I	1.9	4.87	5	24.3	3000	333	13.7
Cieslicki	Urine I	2.2	3.32	5	16.6	500	55.6	3.35
Cleary	Urine I	1.2	1.62	5	8.1	490	54.4	5.35
Schreiber	Urine I	1.2	2.79	5	13.9	240	26.7	1.92
Perlman	Urine I	2.2	2.98	5	14.9	170	18.9	1.27

*Corrected for Counter Efficiency of 0.15.

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TABLE IV

Slow Neutron Activation Reactions in Tissue

Reaction	Isotopic abundance (%)	σ Absorption cross section for normal atom (barns)	Half-life	λ Decay constant	Specific activity factor (1) (cm^2/sec)	Relative specific activity
$Na^{23}(n,\gamma)Na^{24}$	100	0.693	14.8 hr	1.3×10^{-5} sec^{-1}	3.75×10^{-31}	1.00
$P^{31}(n,\gamma)P^{32}$	100	0.23	14.3 d	5.63×10^{-7}	4.05×10^{-33}	1.08×10^{-2}
$Cl^{37}(n,\gamma)Cl^{38}$	24.6	0.137	(2) 37 min	3.11×10^{-4}	1.12×10^{-30}	3
$Cl^{35}(n,\gamma)Cl^{36}$	74.5	29	(3) 1500 yr*	1.46×10^{-11}	1.18×10^{-35}	3.15×10^{-5}
$Cl^{35}(n,\alpha)P^{32}$	74.5	0.025	(4) 14.3 d	5.63×10^{-7}	4.4×10^{-34}	1.17×10^{-3}
$Cl^{35}(n,\alpha)P^{32}$	74.5	0.054	(5) 14.3 d	5.63×10^{-7}	9×10^{-34}	2.3×10^{-3}
$Cl^{35}(n,p)S^{35}$	74.5	0.14	(5) 87 d	9.22×10^{-7}	3.7×10^{-34}	10^{-3}
$Cl^{35}(n,p)S^{35}$	74.5	$0.35 \pm .05$	(6) 87 d	9.22×10^{-7}	9.25×10^{-34}	2.47×10^{-3}
$S^{32}(n,p)P^{32}$	95	0.22	(5) 14.3 d	5.63×10^{-7}	4.05×10^{-33}	1.08×10^{-2}

* Currently quoted as $>10^3$ yr, Met. Lab. Hdb., Chapter III.

1) For normal element. This factor is σNA.

2) From Met. Lab. Hdb., Chapter IV; Seren CP2301, quotes 0.15b for thermal neutrons.

3) Goldhaber, M., Phys. Rev., Feb. 1946.

4) Average value over entire neutron fission spectrum, quoted by P. Morrison.

5) L. Seren (CP-2301). Fast neutrons in $Cl^{35}(n,\alpha)P^{32}$. Thermal neutrons in $Cl^{35}(n,p)S^{35}$.

6) D. J. Hughes (CP-2984), Thermal Neutrons.

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TABLE V

Total Body Integral Dose Due to Capture Gamma Self-Irradiation: $H^1(n,\gamma)H^2$ reaction

Body Part	Mass M (kg)	E Elongation	D, Dose at center (R)	E Elongation correction	ED, Corrected dose at center	Integral dose, MDE (gm R)
Trunk	38100	3	13.1			5.0×10^5
Head	4330	1.1	9.9	0.99	9.8	4.15×10^4
Neck	1290	1.71	7.3	0.94	6.9	0.89×10^4
Upper arm	1815	1.75	8.0	0.93	7.5	1.4×10^4
Forearm	0312	3.7	4.5	0.81	3.6	0.11×10^4
Thigh	5550	4.3 [1]	10.6	0.77	8.2	4.56×10^4
Lower leg	4090	4.1	9.8	0.78	7.6	3.1×10^4
Foot	0694	3.0 [1]	6.1	0.85	5.2	0.36×10^4

Total legs	1.6×10^5	
Total arms	3.0×10^4	2.4×10^5
Head and neck	5.0×10^4	

Total dose: 7.40×10^5 gm-R. Multiplied by 0.75 to give average dose over body: $7.4 \times 10^5 \times 0.75 = 0.555 \times 10^6$ or 0.6 megm-R per 6×10^8 neutron captures per gm tissue in the body. The trunk has 5/7.4 = 67.6% of total dose.

[1] Assuming thigh receives radiation from torso, and that foot receives from lower leg and floor.

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TABLE VI

Average Integral Doses Due to Capture Gammas

Name	Integrated neutron density* (per cc)	U, Integrated neutron flux divided by 4 x 10^{10}	W Body weight (kg)	W/70	UW/70	Capture gamma (megm-R)
Slotin	30.4 x 10^{10}	7.6	59.4	0.85	6.46	3.59
Graves	6.08	1.52	79.4	1.13	1.72	0.96
Kline	4.2	1.02	62.6	0.894	0.91	0.51
Young	2.9	0.73	68	0.97	0.70	0.39
Cleary	1.22	0.55	78.5	1.12	0.62	0.34
Cieslicki	0.84	0.21	74.8	1.07	0.23	0.125
Schreiber	0.64	0.16	77.1	1.1	0.176	0.098
Perlman	0.51	0.127	59	0.842	0.11	0.0595
Daghlian	7.5	1.87	92	1.31	2.45	1.41
Hemmerly	0.46	0.115	86.2	1.23	0.141	0.00783

Integral dose computed on the basis that a 70-kg man sustains an average over-all body dose of 0.6 megm-R for a neutron density of 4 x 10^{10}/cc.

*Integrated neutron density is more commonly known as neutron flux in the literature of neutron physics.

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TABLE VII

Average Fast Neutron Integral Doses
Computed from the Na^{24} Serum Activities

Name	n, Integrated neutron flux (per cc)	U n/4 x 10^{10}	W Body weight (kg)	Integral dose[(1)] U W 8 (rep-gm)	Gamma equivalent (U W 24) rep-gm (megm-R) [(2)]
Slotin	30.4 x 10^{10}	7.6	59.4	3.61 x 10^{6}	10.8
Graves	6.08	1.52	79.4	0.96	2.9
Kline	4.2	1.02	62.6	0.51	1.5
Young	2.9	0.73	68	0.4	1.2
Cleary	1.22	0.55	78.5	0.346	1.04
Cieslicki	0.84	0.21	74.8	0.125	0.37
Schreiber	0.64	0.16	77.1	0.10	0.3
Perlman	0.51	0.127	59	0.06	0.18
Daghlian	7.5	1.87	92	1.38	4.1
Hemmerly	0.46	0.115	86.2	0.079	0.24

(1) Assuming 8 rep of fast neutron recoils for each unit of integrated neutron flux = 4 x 10^{10} neutrons/cc.

(2) U W 8 multiplied by 3 on assumption that 1 "n" unit is 7.5 times as effective biologically as 1 gamma roentgen, and 1 "n" gives 2.5 rep.

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TABLE VIII

Hydrogen Capture Gamma Doses in Human Bodies on the Basis of Mock-up Measurements with Na^{24}

Name	Integrated slow n flux (per cc tissue)	$\frac{I \times 6 \times 10^8}{4 \times 10^{10}}$ captures/cc	Captures/cc x 1.7×10^{-8} = D = gamma R*	W Body weight (kg)	D Integral dose (gm-R)**
Daghlian	7.5×10^{10}	11.2×10^8	19	92	1.52×10^6
Hemmerly	0.46	0.69	1.17	86.3	0.009×10^6
Slotin	30.4	45.6	77.5	59.4	4.14
Graves	6.08	9.1	15.5	79.4	1.11
Kline	4.2	6.3	10.7	62.6	0.60
Young	2.9	4.35	7.4	68	0.45
Cleary	1.22	1.83	3.12	78.5	0.22
Cieslicki	0.84	1.26	2.14	74.8	0.14
Schreiber	0.64	0.96	1.63	77.1	0.12
Perlman	0.51	0.765	1.3	59	0.069

* Gamma R average dose in torso.

** Corrected for the 90% reduction indicated by Table IX.

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TABLE IX

Distribution of Gamma Dosages Over Mock-up with Na^{24} Radiator

Body Part	I, Relative Gamma Intensity (mR/hr)	M Mass (kg)	M x I
Feet	24.4	1.388	34
Knees	32.1	8.180	263
Thighs	49.1	11.10	545
Diaphragm	52.5	38.100	2000
Neck	38.6	5.620	217
Head	38.6	4.33	167
Arms	50	4.254	212
		72.972	3438

3438/72.97 = 47.2 mR/hr average gamma intensity

47.2/52.5 = .897 = 90%, i.e., average intensity over the entire body is 90% of that at the diaphragm.

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TABLE X

Estimated Prompt Gamma Doses in Pajarito Accident

Name	Distance, r, from source (cm)	Relative intensity*	Gamma roentgen intensity** (R)	Intensity corrected for Be shell*** (R)	Integral dose (megm-R)
Slotin	50	1	23.6	18.1	0.677
Graves	100	0.4	9.4	7.2	0.360
Young	140	0.21	5.5	3.8	0.163
Kline	210	0.11	2.5	1.8	0.071
Cieslicki	210	0.11	2.5	1.8	0.083
Cleary	210	0.11	2.5	1.8	0.088
Schreiber	400	0.037	0.89	0.7	0.034
Perlman	400	0.037	0.89	0.7	0.031

* Assuming intensity falls off as $1/r^{1.6}$.

** Assuming a single 1.0-Mev gamma per fission escapes from source.

*** Assuming 77% transmission through the Be shell tamper.

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TABLE XI

Physical Data on Personnel

Name	Distance from source (cm)	Height (inches)	Total Body Weight		Body surface area* (sq. m.)	Blood volume** (liters)	Estimated torso (1) thickness (cm)
			lb	kg			
Daghlian	30	68.5	203	92	2.06	4.8	30
Hemmerly	300	67	190	86.3	1.98	4.8	30
Slotin	50	66	131	59.4	1.67	3.62	20
Graves	100	69	175	79.4	1.95	4.80	25
Kline	210	68.5	138	62.6	1.75	3.81	20
Young	140	65	150	68	1.75	4.14	25
Cleary	210	72	173	78.5	2.00	4.78	22
Cieslicki	210	70	165	74.8	1.92	4.56	22
Schreiber	400	70	170	77.1	1.95	4.7	25
Perlman	400	66	130	59	1.67	3.6	20

* By formula of DuBois.

** 6.4% of total body weight, but not to exceed 4.8 liters whole blood density = 1.05 gm/cc.

(1) Antero-posterior thickness.

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TABLE XII

Beta Energies and Ranges in Water from Biologically Important Radioisotopes*

Element	Z	A	Radiation	T(days)	E_0(Mev)	E_β(kev)	Maximum range in water (cm)
C	6	11	$\beta^+, 0$	0.01415	0.97	380 ± 40	0.41
N	7	13	$\beta^+, 0$	0.00703	1.24	475 ± 45	0.55
Na	11	22	β^+, K, γ	1170	0.57	225 ± 20	< 0.25
	-	24	β^-, γ	0.61	1.39	540 ± 20	0.64
P	15	32	$\beta^-, 0$	14.5	1.712	695 ± 20	0.82
Cl	17	38	β^-, γ	0.0259	4.94(53%)	2230 ± 90	2.70
					2.79(11%)	1190 ± 40 } 1390 ± 70	
					1.19(36%)	400 ± 35	
Mn	25	56	β^-, γ	0.108	2.81(50%)	1240 ± 50	1.48
					1.04(30%)	410 ± 35 } 890 ± 40	
					0.65(20%)	280 ± 25	

* See: Marinelli, L. D., Brinckerhof, R. F., and Hine, G. J., "Average energy of beta-rays emitted by radioactive isotopes," Rev. Mod. Phys., 19, 25-28 (1947);

also, Marinelli, L. D., Quimby, Edith H., and Hine, G. J., "Dosage determination with radioactive isotope," Am. J. Roentg., 59, 260-281 (1948).

[redacted]

TABLE XIII

Whole Body Doses Due to Fission Burst. [5] Summary.

(Average Neutron Energy 0.35 Mev and rbe Equal to 3)

Name	Fast [1] neutrons (megm-R)	Capture [2] gammas (megm-R)	Delayed gammas (megm-R)	Prompt [3] gammas (megm-R)	Total Integral dose (megm-R)	Equivalent [6] external irradiation gamma R on skin
Slotin	10.8	3.59		0.68	15.07	360
Graves	2.9	0.96		0.36	4.22	80
Kline	1.5	0.51		0.16	2.17	49
Young	1.2	0.39		0.07	1.66	35
Cleary	1.04	0.34		0.08	1.46	27
Cieslicki	0.37	0.125		0.09	0.59	11
Schreiber	0.3	0.098		0.03	0.43	8
Perlman	0.18	0.06		0.03	0.27	6.5
Daghlian	4.1	1.41	5.00 [4]		10.51	163
Hemmerly	0.24	0.078			0.32	5.3

(1) From Table VII; (2) From Table VI; (3) From Table X.

(4) Data on delayed gammas are not available for estimating this dose. The 5 megm-R is probably low.

(5) Minimum possible doses. Also, these doses are exclusive of the high doses sustained by the hands of Slotin and Daghlian which were known to have been in the blue glow. Data on blue glow indicate that at least 15,000 R must have been delivered to the hands.

(6) The dose due to a plane wave of gamma radiation which would deliver the same total energy to the body as given under "Total Integral Dose."

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TABLE XIV

Estimates of Dosage Limits in Fission Burst Whole Body Doses Expressed in Gamma Equivalent Radiation Dose

	Dosage in Equivalent Plane Wave External Gamma Radiation			Dosage in megm-R		
Name	Minimum from Table XIII (R)	Unmodified neutron spectrum** (R)	Absolute* maximum (R)	Minimum from Table XIII	Unmodified neutron spectrum**	Absolute* maximum
Slotin	360	880	1670	15.07	36.7	70.0
Graves	80	180	340	3.22	10.0	19
Kline	49	108	200	2.17	5.2	10
Young	35	86	160	1.66	4.1	7.8
Cleary	27	65	120	1.46	3.5	6.6
Cieslicki	11	22	42	0.59	1.3	2.5
Schreiber	8	18	34	0.43	1.0	1.9
Perlman	6.5	14	26	0.27	0.6	1.1
Daghlian	163	290	550	10.51	18.7	36.0
Hemmerly	5.3	18	34	0.32	1.1	2.1

* "Absolute Maximum" is 1.9 times the "probable" dose.

** "Unmodified" has 3 times the fast neutron dose as has the "Minimum from Table XIII."

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TABLE XIV A

Name	0.5-Mev fast neutron recoil dose (megm-R)	Capture gamma dose (megm-R)	Prompt gamma dose (megm-R)	Low penetration component--80-kev dose equivalent (R)	Penetrating component--gamma ray dose** (R)
Slotin	26.2	3.59	0.68	1930	114
Graves	7.0	0.96	0.36	390	26
Kline	3.7	0.51	0.16	260	17
Young	2.9	0.39	0.07	186	11
Cleary	2.5	0.34	0.09	140	8.7
Cieslicki	0.9	0.125	0.08	55	4.4
Schreiber	0.75	0.098	0.034	42	2.7
Perlman	0.45	0.06	0.03	33	2.4
Daghlian	10.00	1.41	*	480	110
Hemmerly	0.6	0.008	—	31	0.14

* Received 5.0 megm-R delayed gamma dose.

** Plane wave radiation to the whole body.

Low penetration component is computed with rbe factor of 5. The average body dose is 0.2 gm-R per incident roentgen of 80-kev X-rays for target-skin distance of 250 cm.

TABLE XV

Mineral Composition of Human Body

from A. T. Shohl, A.C.S. Monograph 82, 19-20, Reinhold, 1939.

Whole Body	Total weight (gm)	Fat (gm)	Water (gm)	Dry weight (gm)	Ash (gm)	N (gm)	Na (gm)	K (gm)	Ca (gm)	Mg (gm)	Cl (gm)	P (gm)	S (gm)
Fetus, 3-4 mo	126	0.6	116	10	1.5	1.0			0.42	0.022	0.34	0.27	
Fetus, 5 mo	500	5	455	45	8.5	6.0	1.29	1.0	2.9	0.10	1.25	1.8	0.74
Fetus, 6 mo	880	19	755	125	19.0	12	1.85	1.4	5.3	0.17	1.60	3.25	1.55
Fetus, 7 mo	1155	32	975	180	30	20	2.4	2.1	6.9	0.23	2.95	4.3	1.7
Premature, 7 mo	1190	36	970	220	32	20	2.8	2.1	8.6	0.25	3.05	4.4	
	(kg)	(kg)	(kg)	(kg)	(kg)								
New-born	2.9	0.35	2.08	0.8	0.1	55	4.7	5.1	23.6	0.7	5.0	13.8	6.3
Adult	70.0	12.6	41.4	29.0	3.0	2100	63.0	150.0	1160.0	21.0	85.0	670.0	112.0
Adult/5-mo fetus	140	252	90	650	430	420	49	150	400	210	67	410	150
Adult/new-born	23	36	20	36	33	38	13	29	50	30	17	48	18

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TABLE XVI

Mineral Composition of Organs of Human Body (Shohl)

	New-born		Adult										
Organ	Weight (kg)	(%)	Weight (kg)	(%)	Fat (kg)	H_2O (kg)	Na (gm)	K (gm)	Ca (gm)	Mg (gm)	Cl (gm)	P (gm)	S (gm)
Whole body	3.1		66.2										
Muscles	.78	25.1	28.7	43.0	2.1	21.0	19.1	109.0	1.85	6.10	13.5	58.5	60
Skeleton	.43	13.7	11.6	17.5	1.1	5.1	18.7	6.4	1150.00	11.0	20.	530.	16
Blood serum	.13	6.5	2.7	7.0	0.03	2.5	9.1	0.5	0.27	0.09	10.	0.4	
Blood cells	.06		1.8			1.2	?	7.6	?	0.11	5.2	1.8	
Skin			4.8	7.3	0.7	3.1	6.5	4.4	0.8	0.5	12.2	2.4	18
Subcutaneous tissue	.61	19.7	12.6	19.0	8.2	4.2					16.		
Brain	.38	12.3	1.4	2.2	0.17	1.1	2.1	4.1	0.15	0.2	1.8	4.6	2.9
Liver	.14	4.6	1.8	2.7	0.38	1.1	2.7	3.1	0.17	0.31	2.3	3.2	0.5
Intestines	.07	2.1	1.4	2.2	0.13	1.1	3.0	4.5	0.21	0.12	1.0	1.5	
Lungs	.05	1.8	1.0	1.5	0.02	0.8	2.4	1.5	0.17	0.07	2.6	1.2	
Kidney	.02	0.8	0.3	0.5	0.015	0.2	0.5	0.5	0.07	0.07	0.7	0.4	
Heart	.02	0.8	0.3	0.5	0.025	0.2	0.4	0.3	0.03	0.05	0.4		
Spleen	.01	0.3	0.16	0.2	0.005	0.1			0.02	0.02	0.3	0.6	
Pancreas	.004	0.1	0.1	0.1	0.010	0.1	0.8	0.2	0.02	0.02	0.2	0.3	

TABLE XVII

Mineral Composition of Human Body (Shohl)

Whole Body	Fat (%)	Water (%)	Na (gm)	Na (meq)	K (gm)	K (meq)	Ca (gm)	Ca (meq)	Mg (gm)	Mg (meq)	Cl (gm)	Cl (meq)	P (gm)	P (mM)	S (gm)	S (meq)
Fetus, 3-4 mo	0.5	93					3.4	170	.18	15	2.7	76	2.14	69		
Fetus, 5 mo.	1.2	91	2.58	112	2.00	51	5.9	295	.21	17	2.5	70	3.58	115	1.48	92
Fetus, 6 mo.	2.5	87	2.16	94	1.62	41	6.2	310	.21	17	2.5	70	3.82	123	1.80	113
Fetus, 7 mo.	2.5	86	2.14	93	1.88	48	6.2	310	.22	18	2.6	73	3.82	123	1.53	96
Premature, 7 mo	3.0	85	2.42	105	1.71	44	7.5	375	.22	18	2.7	75	3.82	123		
New-born	12.0	80	1.78	78	1.90	49	9.2	460	.27	23	2.0	56	5.40	174	2.46	154
Adult	18.0	72	1.09	48	2.65	68	20.1	1000	.36	30	1.56	42	11.6	374	1.96	123
Adult Organs																
Muscles	7.5	79	0.72	31	3.60	93	.07	4	.23	19	0.66	18	2.20	71	2.5	
Skeleton	10.0	44	1.8	79	0.61	16	110	5250	1.05	88	1.9	54	50.5	1630		
Blood Serum	0.6	92	3.35	145	0.20	5	.11	5	.03	3	3.70	104	0.15	5	0.001	
Blood cells	0.6	65	?	?	4.20	108			.06	5	1.93	54	1.00	32	0.001	
Skin	15.0	73	1.6	70	1.07	27	.20	10	.14	11	3.0	85	0.65	21		
Brain	12.6	90	1.7	75	3.3	85	.12	6	.16	13	1.5	42	3.8	122	1.3	
Liver	21.3	79	1.9	82	2.15	55	.12	6	.22	18	1.6	45	2.1	69	1.9	
Intestine	6.5	85			2.9	70	.14	7	.08	6	0.65	18	1.00	32	1.20	
Lungs	1.7	78	2.5	109	1.5	39	.17	8	.07	6	2.6	73	1.2	39	1.27	
Kidney	5.2	80	1.75	72	1.75	45	.20	10	.21	17	2.2	62	1.4	45		
Heart	8.3	77	1.85	80	2.50	64	.10	5	.17	14	1.35	38	2.70	87		
Spleen	3.0	77					.10	5	.15	12	1.6	45	3.8	122	1.70	
Pancreas	10.5	80	0.87	38	2.26	58	.17	8	.19	16	1.8	51	3.4	110		
Thyroid	4.4								.10	8	1.8	51	3.4	110		
Testicle	4.5						.09	4	.10	8	2.4	67				
Uterus			1.45	63	1.45	37	.22	11	.16	13	2.6	74	0.57	18		
Adrenal					1.03	26	.16	8	.10	8	2.4	67				

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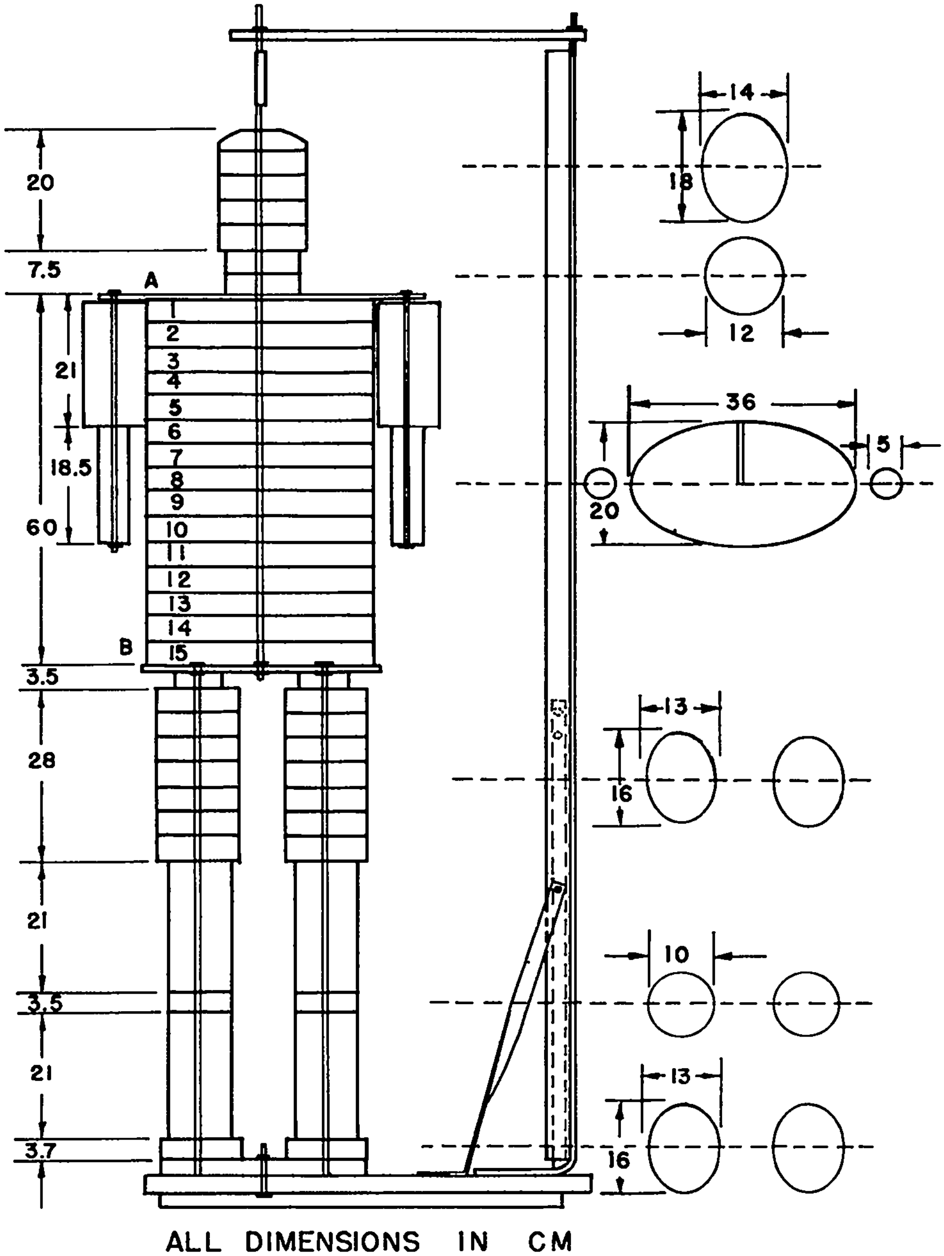

Fig. 1

Dimensions of a model human body. From W. V. Mayneord, "Integral Dose When the Whole Body is Irradiated. Part I," Brit. J. Radiol. 27, 151 (1944).

[redacted]

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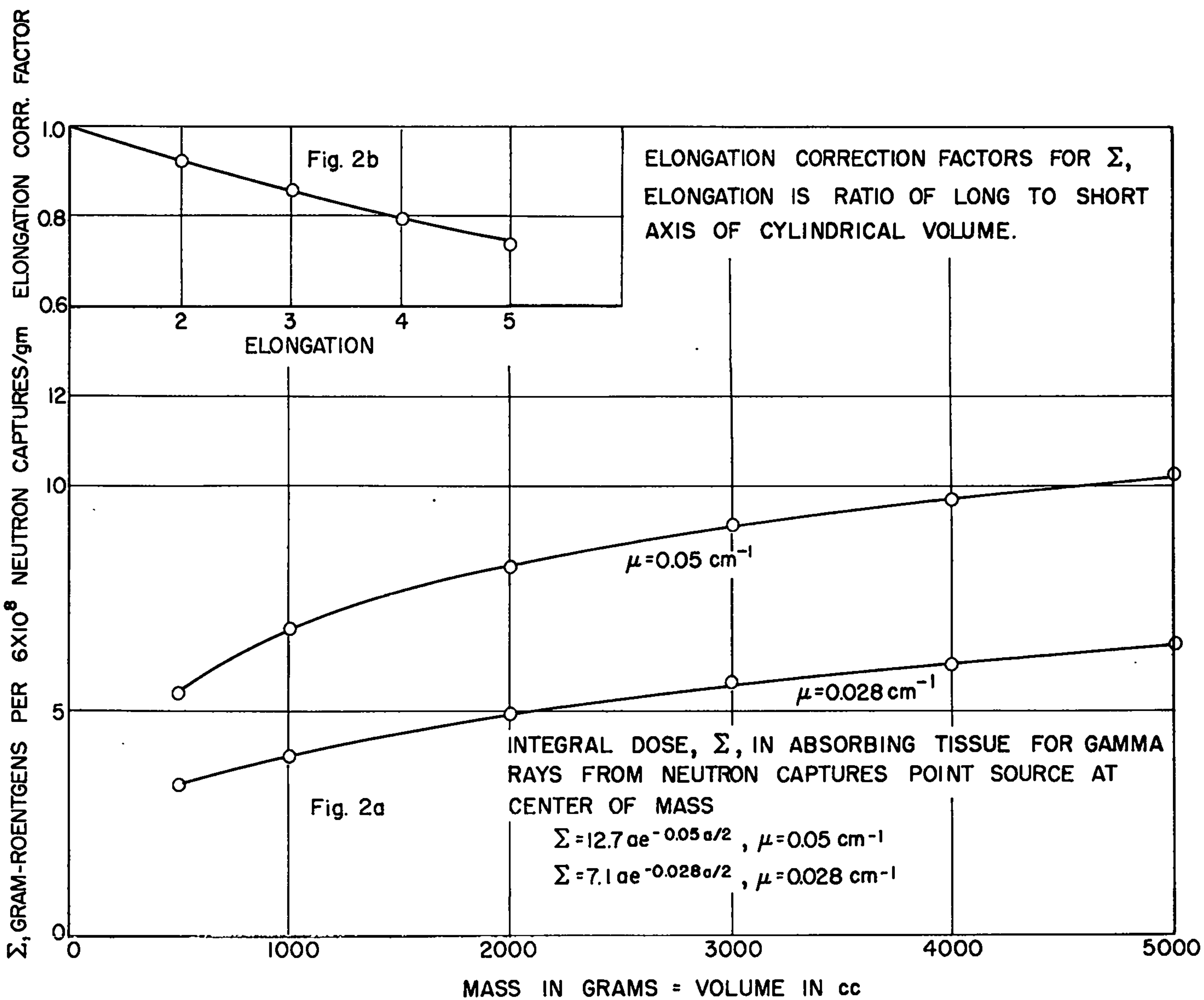

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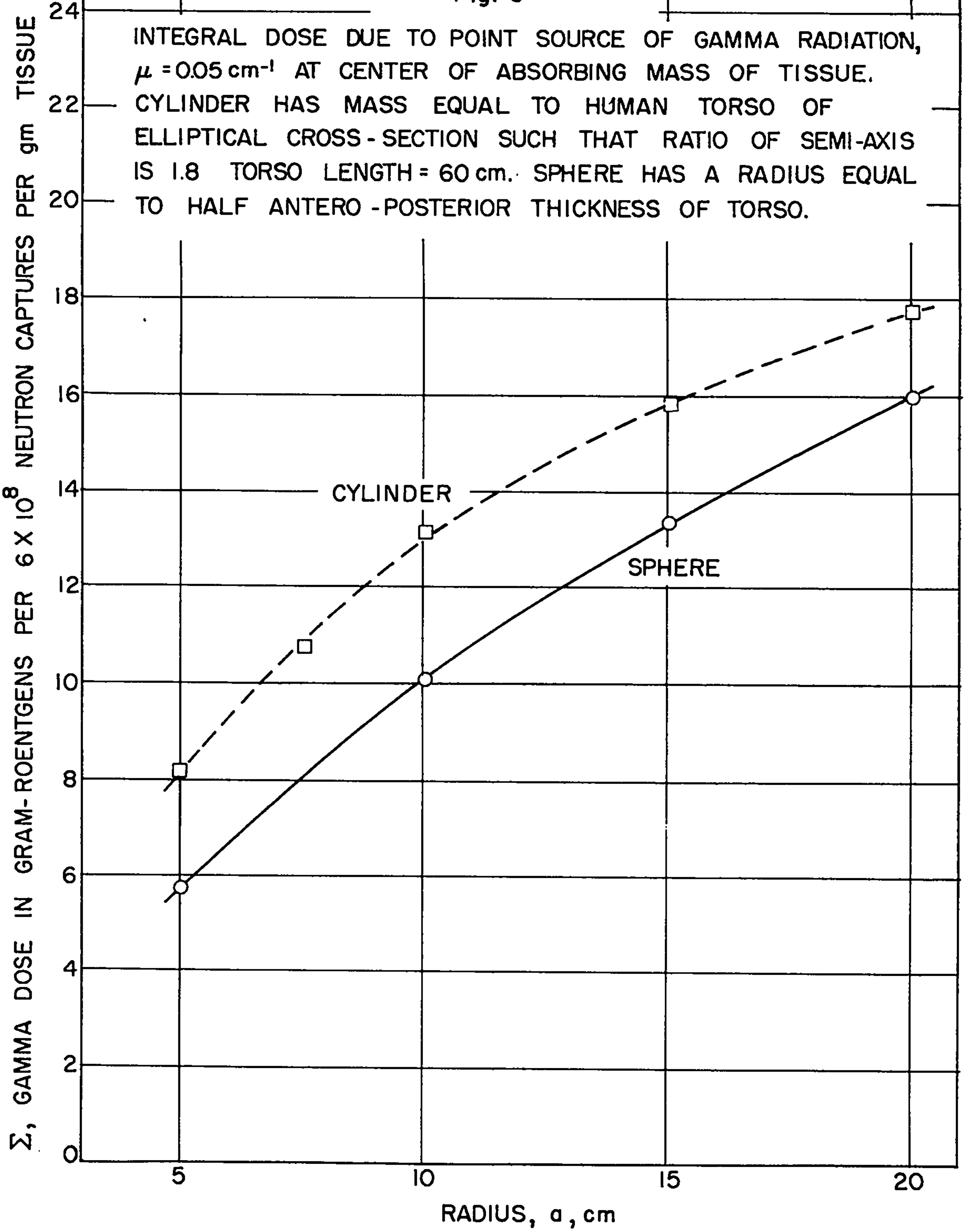
Fig. 3



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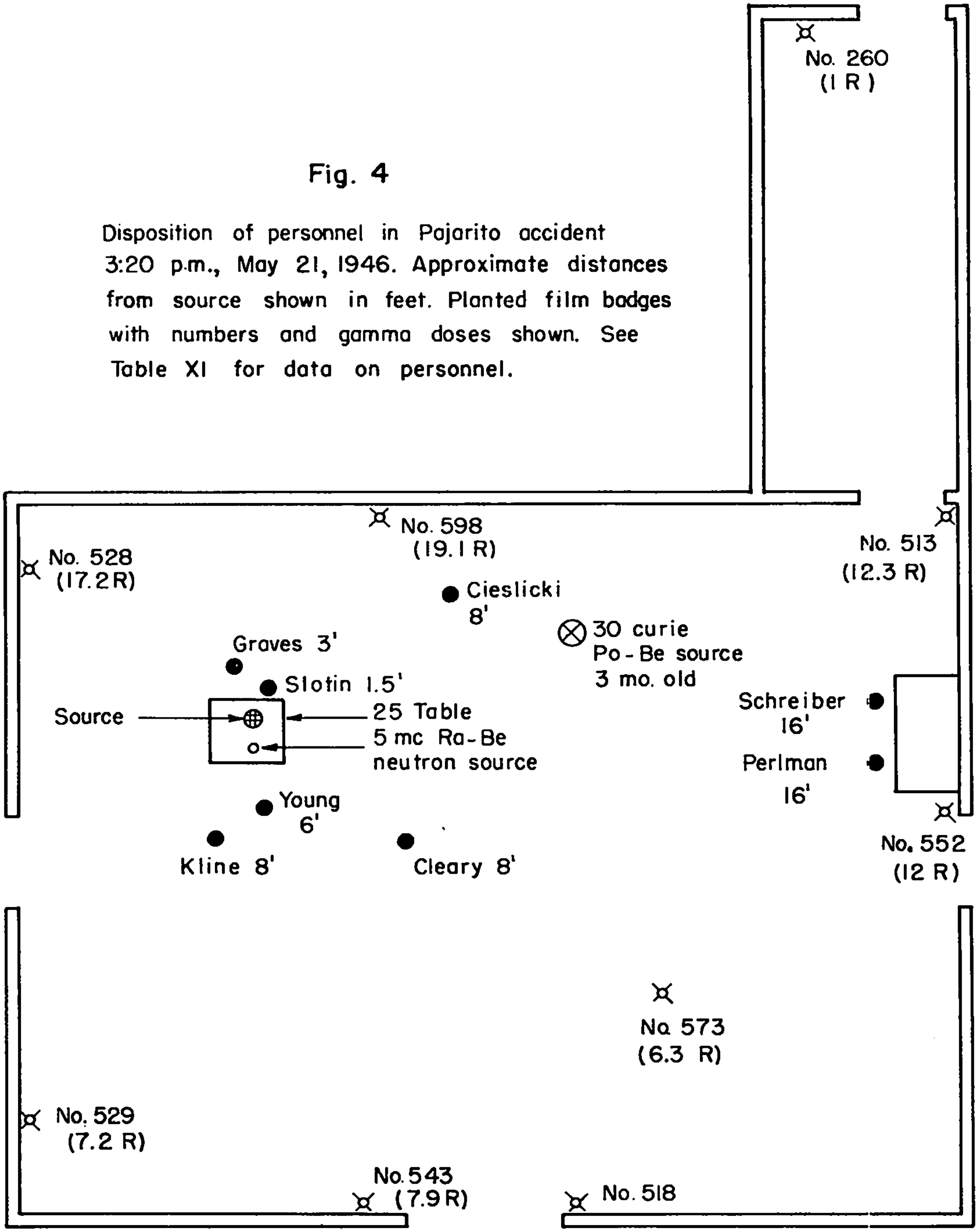

Fig. 4

Disposition of personnel in Pajarito accident 3:20 p.m., May 21, 1946. Approximate distances from source shown in feet. Planted film badges with numbers and gamma doses shown. See Table XI for data on personnel.

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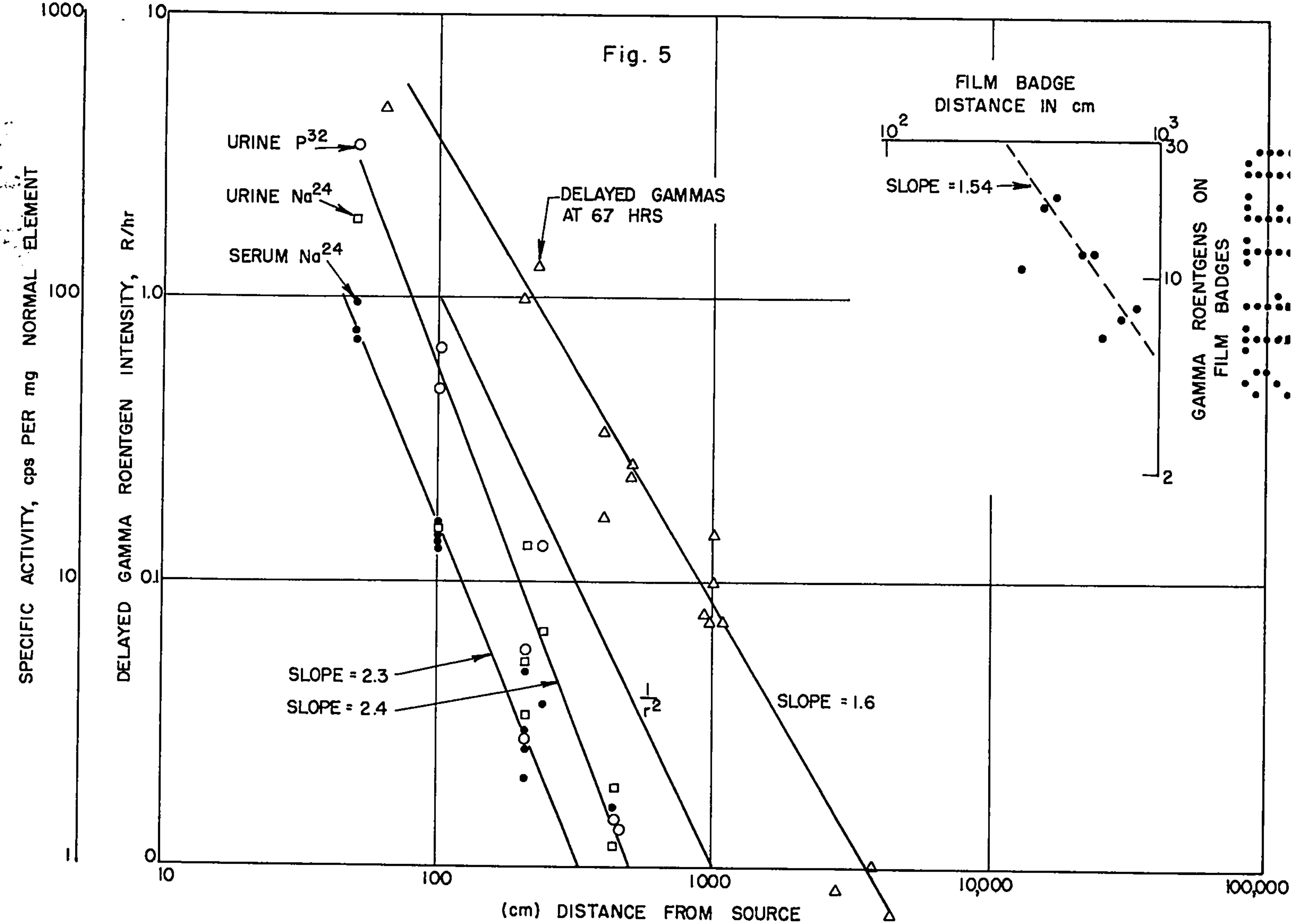

Fig. 5

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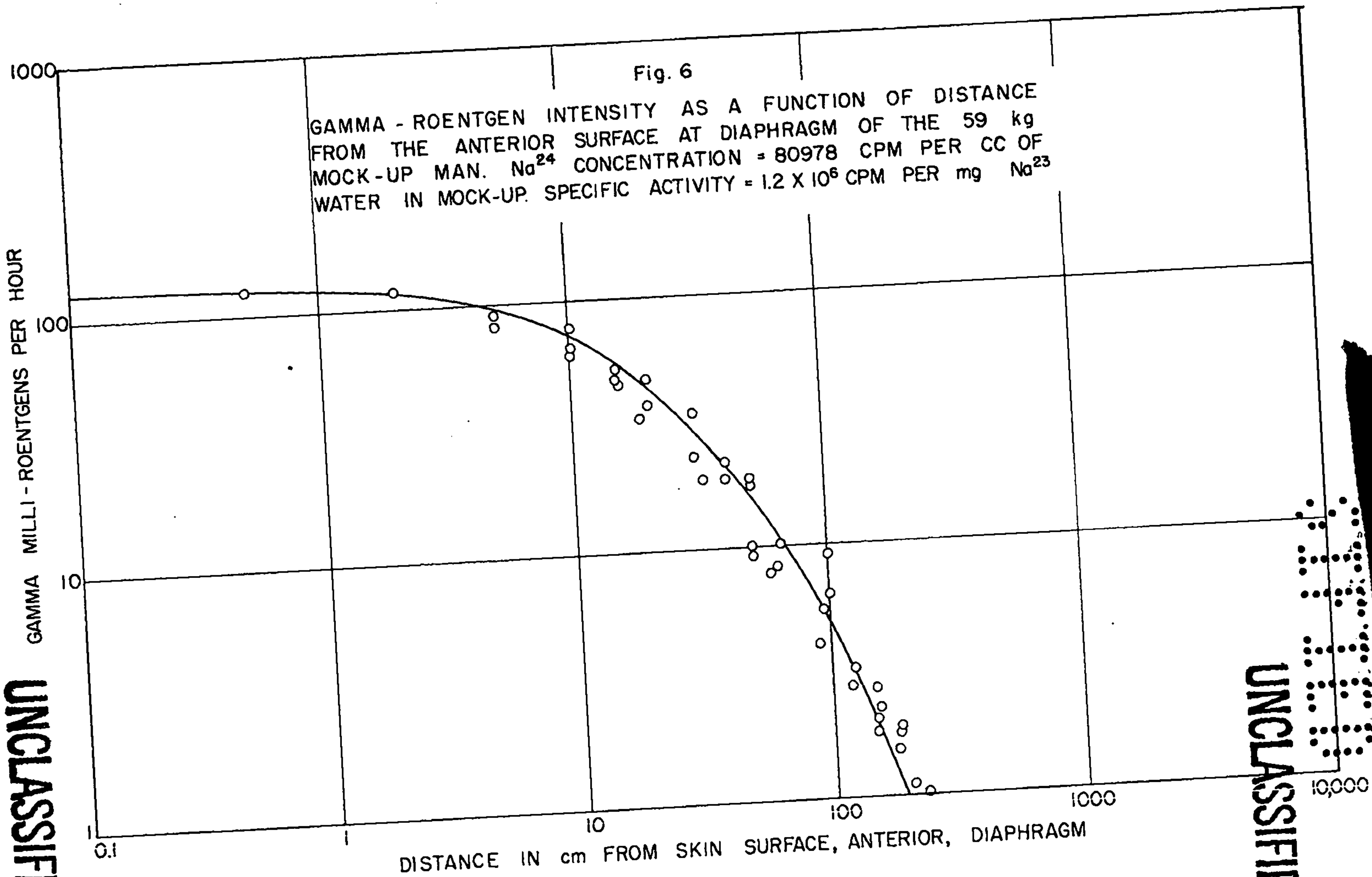

Fig. 6

GAMMA - ROENTGEN INTENSITY AS A FUNCTION OF DISTANCE FROM THE ANTERIOR SURFACE AT DIAPHRAGM OF THE 59 kg MOCK-UP MAN. Na^{24} CONCENTRATION = 80978 CPM PER CC OF WATER IN MOCK-UP. SPECIFIC ACTIVITY = 1.2×10^6 CPM PER mg Na^{23}

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