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SOME FURTHER CONSIDERATIONS ON RADIATION DOSAGE TO SHEEP FROM FALL-OUT DURING THE SPRING 1953 NUCLEAR WEAPONS TESTS

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A. Introduction

Calculations of radiation dosage to the thyroids of sheep ingesting fall-out have been made elsewhere (1). It was there concluded that these doses were not large enough to account for deaths among the animals. It is contended here that although the activity found in the thyroid serves as an index of total radiation exposure, the thyroid dose is but one of several possible types of internal irradiation which will occur when ingestion of mixed fission products has taken place. The most important of these appears to be the dose to the bone marrow from long lived isotopes with slow biological turnover. This effect has generally been considered to be chronic in character, but it appears possible that "short term" effects may also occur if the concentrations are sufficiently high and the emitters are of moderately long half life. Strong evidence of bone marrow damage has been found in samples taken from the skeletons of several of these animals and subjected to histopathological examination (2). This accompanies the evidence of thyroid and other damage also observed, and is undoubtedly of greater importance than the latter to the survival and well being of the animal. These observations and the calculations presented here constitute rather strong arguments for the conclusion that radiation effects played an important role in the increased mortality observed among the animals.

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The calculations are based on the only available experimental data: a) the concentrations of activity measured in the thyroids some weeks after the fall-outs, and b) the dose rates in air as measured in the fall-out areas at the time the fall-outs occurred. The only additional assumptions are: a) that the fission product mixture contained the same relative proportions of several radioactive nuclides as are calculated by Hunter and Ballou (3), and b) that the animals ate 2000 gm dry vegetation per day and remained in a fall-out area for about 30 days. (The latter assumption can be relaxed somewhat and shorter exposure times be assumed; it can still be shown that the given thyroid activities imply high concentrations of activity in the bone over a considerable period). In addition to the bone marrow activity calculations, rough estimates are made of a) the total dose to the intestinal wall from the fission products as a whole which pass through, and b) local external beta doses from fission products clinging to the body surface.

In computing the doses, the figures for thyroid activity and dose rates on the ground given in reference (1) are used. Comparable figures are later given for the samples measured in this laboratory, which had lower activities throughout. Since these latter animals showed definite pathology, the higher activities given in reference (1) should almost certainly indicate similar effects in those animals.

The dose to the thyroid for the Shot 9 case, where the final thyroid activity was measured on 3 July, will first be recalculated, using the Hunter - Ballou expression for the activity of I^{131}.

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This also yields a figure for initial uptake of fission products as a whole, which permits the calculations of uptake to the bone of several isotopes of Sr, Y, Ba and La. These elements probably contribute the major portion of activity within the bone. The relation between initial uptake and concentration of fission products per unit area (estimated from the dose rates measured in air) then may be used to extrapolate to Shot 2 case as was done in reference (1). For the animals exposed to both Shot 2 and Shot 9 fall-out, this procedure will yield total doses and concentrations.

B/ Assumptions

1. Highest measured activity on July 8 was 4.6×10^{-2} $\mu c/gm$ of I^{131} in thyroid.

2. Time of both fall-outs was 2 hours after detonations. Initial gamma dose rates:

20 mr/hr for Shot 9 at 3.5 hr.

500 mr/hr for Shot 2 at 2 hr.

3. The animals ate 2000 gm of vegetation per day. Retentions of the elements are as given by Hamilton (4) and are stated in what follows:

4. Activities of nuclides with time, in disintegrations per minute per 10,000 fissions, are as given by Hunter and Ballou (3) and are stated in the following discussions.

8. Calculations of Thyroid Dose from I^{131} for Shot 9.

I^{131} in thyroid - Shot 9. 11 gm Thyroid.

$$a_o = ae^{+\lambda t} \qquad \lambda = 0.0855$$
$$(T_{\frac{1}{2}} = 8.1d)$$
$$t = 24d$$
$$a = (0.046)(11)$$
$$a_o = 0.506\ (7.8) = 3.9 \text{ mc on 15 June.}$$

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Let $A_I(t)$ = Activity I^{131}, d/m per 10,000 fissions.

$A(t)$ = Total activity of fission products, d/m per 10,000 fissions.

$u(t)$ = Total activity of fission products in the area, $\mu c/ft^2$

$u_I(t)$ = Activity I^{131} in the area, $\mu c/ft^2$

q = Area, in ft^2/day, grazed by sheep

p = Fraction I^{131} eaten which goes to thyroid.

If the fission products in the area are not disproportionated,

$$\frac{u(t)}{A(t)} = \frac{u_I(t)}{A_I(t)}$$

and thus the amount of I^{131} per day going to the thyroid of the sheep is

$$Q(t) = pqu_I(t) \quad \ldots\ldots\ldots\ldots \quad (1)$$

Then the change in the thyroid activity per day is given by

$$\dot{a} = pqu(t)\frac{A_I(t)}{A(t)} - \lambda_{r+b}a \quad \ldots\ldots\ldots \quad (2)$$

Where λ_{r+b} = total biological and radioactive decay constant for I^{131}

a = amount of I^{131} (μc) in thyroid at any time t (days)

Also, from H. M Parker, ref (5)

$$\dot{D} = 55\frac{\bar{E}}{m}a \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where $\dot{D}$ = dose rate, rep/day, to organ; the dot denoting the time derivative of D.

Let:

m = mass of organ, gm

$\bar{E}$ = average energy of beta radiation, Mev

(all radiation assumed absorbed in the tissue).

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Thus from (2) and (3),

$$\ddot{D} + \lambda_{r+b}\dot{D} = \frac{55\bar{E}}{m}\, pqu(t)\frac{A_I(t)}{A(t)} \quad \ldots\ldots\ldots\ldots \quad (4)$$

Equations (2) and (4), when solved, give the activity of the tissue at any time and the total dose received.

From ref (3), $A_I(t)$ is of the form

$$A_I(t) = k_1 e^{-\lambda_1 t} - k_2 e^{-\lambda_2 t} \quad \ldots\ldots\ldots\ldots \quad (5)$$

with

$k_1 = 0.0205$ $k_2 = 0.00359$ t = time after fission, days

$\lambda_1 = 0.0855$ $\lambda_2 = 0.554$

The first term in the above is due to the radioactive decay of I^{131}, while the second term - and a third term which was neglected since it is small after 3 hours - allow for the contributions from other decay chains to the I^{131} activity. (The second term also falls to a negligible amount by 4 days, but is included).

A(t) is of the form $A(t) = kt^{-n}$

Where k = 6170, n = 1,12 for $t < 4$ hrs (N. E. Ballou).

Since an initial uptake is to be determined, a time $t_o = 3.5$ hr. is taken, at which both u(t) and A(t) are known. Then, letting $\bar{E} = 0.20$ Mev. m = 11 gm,

One may define a quantity $$R_o = \frac{pqu(t)}{A(t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

And the rate of intake of I^{131} at time t is: $$R_I(t) = R_o A_I(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Also, $$k_3 = \frac{55\bar{E}}{m} = 1$$

and letting $\lambda r + b = 2\lambda_1$ as in ref (1), there results for equation (2)

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$$\dot{a} + 2\lambda_1 a = R_o(k_1 e^{-\lambda_1 2} - k_2 e^{-\lambda_2 t})$$

with a solution

$$a = \frac{R_o k_1}{\lambda_1}\left[e^{-\lambda_1 t} - e^{-\lambda_1(2t-t_1)}\right] + \frac{R_o k_2}{2\lambda_1 - \lambda_2}\left[e^{(2\lambda_1-\lambda_2)\,t_1 - 2\lambda_1 t} - e^{-\lambda_2 t}\right]. \quad (8)$$

having taken $a = 0$ at $t = t_1$; and for equation (4)

$$\ddot{D} + 2\lambda_1 \dot{D} = k_3 R_o(K_1 e^{-\lambda_1 t} - K_2 e^{-\lambda_2 t})$$

with a solution

$$D = \frac{k_1 k_3 R_o}{2\lambda_1{}^2}\left[e^{-\lambda_1 t_1} + e^{-\lambda_1(2t-t_1)} - 2e^{-\lambda_1 t}\right] \quad (9)$$

$$+ \frac{k_2 k_3 R_o}{2\lambda_1\lambda_2(2\lambda_1-\lambda_2)}\left[2\lambda_1 e^{-\lambda_2 t} - (2\lambda_1-\lambda_2)e^{-\lambda_2 t_1} - \lambda_2 e^{-2\lambda_1(t-t_1)-\lambda_2 t_1}\right]$$

having chosen $D = D$, $\dot{D} = 0$ at $t = t_1$.

(For long t and small λ the constant t_1 may be set $= 0$.)

Substituting the values chosen into equation (8), there results with $t = 27$ days as in reference (1) and $t_1 = 0.15$ day,

$$3.9 = R_o\left[\frac{0.0205}{0.0855}\ (0.0874) - 9.37 \times 10^{-3}\ (9.0 \times 10^{-3})\right]$$

$R_o = 186$ μc/day per d/mI^{131} per 10^4 fissions,

or $R_I(t) = 186(0.0169) =$ __3.1 μc__ I^{131}/day initially.

While

$$D = \frac{1.91}{8.31 \times 10^{-3}}\ (0.801) + \frac{0.668}{0.0363}\ (0.347) = 209 + 6 \cong \underline{\underline{220\ \text{rep.}}}\ \text{in 27 days}$$

If t_1 0 and $t_2 = \infty$, there results

$$\bar{a} = 261(1 + 0-0) - 18.4(0 - 0 + 0.383) = 261 + 7 \cong \underline{\underline{270\ \text{rep.}}}\ \text{to}\ \infty.$$

Formulas (7) and (8) may thus be simplified by neglecting the smaller exponential terms, but letting $t = \infty$ results in about 20 per cent too

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high a dose estimate. It is seen that a somewhat lower initial uptake figure results from these calculations, but the total dose is about the same as ref (1) concludes.

D. Extrapolation to the Shot 2 Case.

If one calculates from the initial uptake a value for initial concentration of activity in the area, a discrepancy appears in comparing it with the initial dose rate measured in air. This leads to differences in the estimate of uptake and damage for the Shot 2 case.

From equation (6),

$$u(t) = \frac{R_0}{pq} A(t)$$

$$\text{For } t_1 = 3.5 \text{ hr}, \; u(t_1) = \frac{186}{0.2(20)} \; (0.70)t^{-1.12} = 700 \; \mu c/ft^2$$

which is the total activity of the fission products at time t_1, assuming that the area grazed, $q = 20 \; ft^2/day$.

Or arrived at in another way,

$$u_I(t_1) = \frac{R_I(t_1)}{pq} = 0.77 \; \mu c/ft^2 \text{ of } I^{131}.$$

Since at 3.5 hr, $\frac{A_I(t_1)}{A(t_1)} = 0.0011$ of the total fission product activity,

$$u(t_1) \sim 0.77/0.0011 = 700 \; \mu c/ft^2.$$

Thus, if the final concentration in the thyroid was as measured, this concentration of total fission products on the ground is implied.

Using the relation given in ref (1),

$$10^6 \text{ curie fission products per mi}^2 = \phi(4.1 r/hr).$$

Whence $\phi = 8.7$ in the relation $(\mu c/ft^2) = \phi \; (mr/hr)$.

Thus a dose rate in air is implied of $\frac{700}{8.7} = 80$ mr/hr, or a factor of 4 greater than that measured. If one accepts the only

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other measured quantity, that of the dose rate, as about 20 mr/hr, a better value for either p or q must be chosen. Since p, the fraction retained, seems a conservative estimate at 0.20 and is a fairly well known quantity, one can accept it and see what value of q would lead to the value of $u(t_1)$ implied by the measured air dose rate, which is

$$u(t_1) = 20(8.7) = 170\mu c/ft^2$$

Then

$$q = \frac{B_I(t_1)}{pA_I(t_1)} = \frac{3.1}{0.2(170)(0.0011)} = 82\ ft^2/day$$

or a factor of about 4 as noted.

It is evident that when this is applied to the Shot 2 case, where only the dose rate in air at 3.5 hr is known, this increase in area covered will increase the dose estimate by the same factor. The figure of 82 ft^2/day seems more reasonable than that of 20 ft^2/day. If one keeps the assumption of 2000 gm total vegetation eaten per day by the sheep, this implies that the area contained about 25 gm/ft^2 of edible dry vegetation. Alternatively, the animal could well have eaten more than 2000 gm per day. It might of course be suggested that only a fraction of the fission products present on each square foot of soil was actually ingested, in which case the total ground covered would be necessarily greater. In any case, it is the product of such a fraction and such an area which is important; it is only necessary to assume this "effective" area to be constant from day to day in both localities. This is probably not bad, since whether the same amount of

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vegetation is eaten in a small area or over a large one, the quantity of fission products ingested is proportional to the area of plant surface eaten rather than the ground covered, as long as the deposition was similar and the animals ate in the same manner. One might assume this for a sheep.

For humans, an effective (biological + radioactive) half life of 6 days is observed; thus the biological half life is somewhat more than simply equal to the radioactive halflife as is here assumed. Thus

$$6 = \frac{8 \times T_b}{8 + T_b} \; ; \; T_b = 24d$$

If this applies here, both a lower initial uptake and lower total dose are implied by a given activity measured in the thyroid. The thyroid dose calculated here may thus be a generous estimate. On the other hand, a lower uptake figure would put the figure of grazing and retention rate assumed still further in disagreement with the figure for ground concentration based on the dose rates measured in the area.

Using the values of air dose rate and q which have been discussed, one may estimate the dose to the sheep from Shot 2 as was done in ref (1).

Here the dose rate at 2 hrs was 500 mr/hr. At 3.5 hours, this is then

$$500\left(\frac{3.5}{2.0}\right)^{-n}$$

With n = 1.2, this equals 260 mr/hr, and $u(t_1) = 8.7(260) = 2300\ \mu c/ft^2$ as in ref (1). Then

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$$R_o = \frac{2300\ (0.2)(82)}{6170\ (0.0024)} = 2.5 \times 10^3 \text{ at } 3.5,^{hr} \text{ and}$$

$$R(t) = 2.5 \times 10^3 (0.0169) = 42 \mu c I^{131}/\text{day initial uptake}$$

Then from equation 9

$$D = \frac{25.8}{7.31 \times 10^{-3}}(0.987) - \frac{9.01}{0.0363}(0.352) = 3.48 \times 10^3 + 87 \cong \underline{3600 \text{ rep}}$$

in approximately 100 days.

As a check, let us see how much of this rather high concentration of activity would remain by t = 106d (March 24 - June 15).

$$a = 2.5 \times 10^3 \quad \frac{0.0205}{0.0855}(1 \times 10^{-4}) - 0 \quad = 0.06\ \mu c \text{ in total}$$

thyroid.

For a 11 gm thyroid, this is approximately 5.5×10^{-3} μc/gm, or about 5.5×10^{-3} $(2.22 \times 10^7) = 1.2 \times 10^5$ counts per minute. For an average 40% efficient scintillation counter with well, about 5000 cpm would be present due to this first dose, at the time of counting. Since this is 0.06 μc out of a total of 0.506, about 11% of the activity counted would be due to the Shot 2 exposure. This would reduce by 11% the estimates of R_o for Shot 9, hence also the value of q and thus those of R_o and D for Shot 2. A dose of about 3200 rep might then be more accurate. However, it should be noted that on the "high spot" hypothesis the total dose from shot 2 might be much less as pointed out in ref(1), also that irregular distribution of activity in the thyroid might alter the dose estimates based on it. In the other direction, p may be closer to 0.30 than 0.20, and hence more retention and higher dosages would have occurred.

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E. Thyroid doses from other isotopes of iodine. The dosages due to the other short lived isotopes of I may now be estimated. I^{131} and I^{135} are of interest as pointed out in ref (1); in addition, it is evident that I^{132} is very important and cannot be neglected. One term of the ref (3) expressions is here used, except in the case of I^{132}.

I^{133}: Shot 9: $\bar{E} = 0.45$ Mev $K_1 = 0.269$ $K_3 = 2.25$ $\lambda_1 = 0.792$ per day

$$D = \frac{2.25(186)(0.269)}{2(0.792)2} \left(\underbrace{e^{-0.792(0.15)}}_{(0.89)} + \underbrace{e^{-0.792(54)}}_{(0)} - \underbrace{2e^{-0.792(27)}}_{(0)} \right)$$

$D = \underline{80 \text{ rep}}$

Shot 2:

$$D = \frac{2.5 \times 10^3}{186}(80) = 12.4(80) = \underline{1200 \text{ rep}}$$

I^{135}: Shot 9: $k_1 = 0.981$; $\lambda_1 = 2.49$

$K_3 = 1.5$; $\bar{E}\,(av) = 0.3$ Mev

$$D = \frac{1.5(186)(0.981)}{2(2.49)^2} \left(\underbrace{e^{-0.374}}_{0.688} + 0-0 \right) = \underline{15 \text{ rep}}$$

Shot 2:

$D = 13.4(15) = \underline{200 \text{ rep}}$

I^{132}: Here the half life of I^{132} itself is short, 2.4 hr, but it is the daughter product of Te^{132} which has a 77 hr half life. Hence I^{132} is present in the fission products for several days and contributes a considerable dose. It will be assumed that the I^{132} has decayed through one half life by the time it reaches the thyroid, i.e., that the time of transport

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of an I^{132} atom from intestinal tract to thyroid is 2.4 hrs. To allow for both the above circumstances, one must use two exponentials in the expression for $A_I(t)$ given in ref. (3) and multiply $A_I(t)$ by $\frac{1}{2}$ in equation 2. Again using equation 8 with these modifications, (with $\lambda(r + b) = \lambda_1 + \lambda_b$ here and not $2\lambda_1$):

$\bar{E} = 0.7$ Mev $\quad K_1 = 0.0581 \quad \lambda_1 = 0.216 \quad \lambda_b = 0.0855$ as before

$K_3 = 3.5 \quad K_2 = 0.0416 \quad \lambda_2 = 6.93$

$t_1 = 0.15d \quad t_2 = 27d$

For Shot 9:

$$D = \frac{3.5(186)0.0581}{2(0.216)(0.302)}\left(e^{-0.216(0.15)} + 0 - 0\right)$$

$$+ \frac{3.5(186)(0.0416)}{2(6.93)(0.302)}\left(e^{-6.93(0.15)} - 0 + 0\right)$$

$= 280 - 24 =$ <u>280 rep</u>

For Shot 2:

$D = 13.4(280) =$ <u>3700 rep</u>

These latter dosages all occur within short times, of the order of a week or less, and leave no evidence in the form of lingering activity. We can only estimate them on the basis of the relative amounts of the various isotopes in the fission products present at any time. Again, an error of 11% may also be present due to lingering Shot 2 I^{131} activity in the samples,

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and a factor of perhaps one half might be necessary to allow for high spots.

The dose estimates in parts C & D are based on continuous ingestion of I^{131} over the entire period. If ingestion ceased after about 30 days, but the I^{131} remained in the thyroid, the dose would be smaller; an estimate only will be made here of another factor of about 8/9. However, it must be emphasized that the dose from the I^{132}, which is as large as the total I^{131}, dose, is received within the space of several half lives of Te^{132}, or about 9 days, while that due to I^{133} is received during about 3 days and from I^{135} in approximately 1 day. These exposures have been calculated assuming they commenced at 3.5 hr; it is of importance in calculating the uptakes of short lived nuclides to fix this time. It is evident that the totals could have been as high as 9,000 rep, and probably exceeded 4,500. This is still conservative, considering the thyroid damage observed in the samples.

F. Activity in the Bone

The irradiation of the bone marrow may be estimated utilizing the uptakes of total fission products calculated in C and D. The isotopes Sr89, Sr90, Sr91, Y90, Y91, Ba140 and La140 will be considered here. Rather than total doses or dose rates, concentrations in μc for the whole animal will be estimated, as it is felt that these figures are more easily interpreted. The data on uptake and retentiongiven by Hamilton (4) will be used as a basis for evaluating their relative importance. Data on radioactive decay and chain relationships are from ref (3).

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1. Sr^{89}.

$$A_{Sr}(t) = 0.00418e^{-0.0131} \quad (t \text{ in days})$$

P_{Sr} = 0.03 to 0.40; 0.1 will be used here.

This is felt to be a conservative estimate.

Here p is the product of Hamilton's "oral absorption" and "accumulation in principal organ."

Biological half life > 200 days. Thus the value $\lambda_b = \frac{0.693}{200} = 3.47 \times 10^{-3}$ will be used here.

Shot 9:

The concentration in the bone is given by equation (8) modified for the case $\lambda_b = \lambda_1$ and with $k_2 = 0$. In this case, $R_o = 186 \frac{P_{Sr}}{P_I} = 186 \frac{0.1}{0.2} = 93$.

Let $t_1 = 0$ and $t = 27d$.

Then

$$a = \frac{93(4.18x10^{-3})}{3.47x10^{-3}} \left(e^{-0.0131(27)} - e^{-(0.0131+0.00347)(27)}\right)$$

$= 112 (0.701 - 0.639) = \underline{\underline{6.9\mu c}}$ on 19 June

This is still building up on this date.

Shot 2:

$t = 27$ days

$$a = 6.9 \times \frac{2.5 \times 10^3}{186} = 13.4(6.9) = \underline{\underline{92\ \mu c}}$$

The uptake of Sr^{89} for theShot 2 case has been estimated from the Shot 9 case assuming the values of p q and the λ's to be the same as for Shot 9. Since the ingestion of the fission products probably did not last longer tahn 30 days, the times have been kept at 27 days as well. Thus the Shot 9 results need only be multiplied by $\frac{Ro(\text{Shot 2})}{Ro(\text{Shot 9})}$.

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2. Sr^{90}. $\lambda_1 = 7.49 \times 10^{-5}\ day^{-1}$ $\lambda_2 = 3.47 \times 10^{-3}\ day^{-1}$

$K = 2.69 \times 10^{-5}$ $p = 0.10$ $Ro = 186$

Shot 9:

$$a = \frac{93(2.69 \times 10^{-5})}{(3.47 \times 10^{-3})} (0.0913) = \underline{\underline{0.066\ \mu c}}$$

Shot 2:

$$a = 13.4\ (0.066) = \underline{\underline{0.88 \mu c}} \text{ at 27 days.}$$

The uptake of Sr^{90} is negligible in comparison with that of Sr^{89}.

3. Sr^{91}. $\lambda_1 = 1.713$ $\lambda_2 = 3.47 \times 10^{-3}$ $k = 0.651$

Here $t_1 = 0.146$ day, since this is a short lived nuclide.

$$a = \frac{93(0.651)}{3.47 \times 10^{-3}} \left(e^{-1.713t} - e^{-1.713t - 0.00347(t-t_1)}\right)$$

The buildup of Sr^{91} reaches a peak and then falls off within several days:

Shot 9:

t:	0.5d	1d	2d
a:	8.0μc	9.4μc	3.1μc

For the Shot 2 case:

t:	0.5d	1d	2d
a:	110μc	130μc	42μc

It is seen that a considerable concentration of Sr^{91} exists for 2 or 3 days, which shortly disappears. In its place, however, the daughter product Y91 remains, as will be seen in the next calculation.

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4. Y^{90}. $\lambda_1 = 7.59 \times 10^{-5}$ day^{-1} $\lambda_2 = 0.255$ day^{-1}

$$\lambda_b = \frac{0.693}{500} = 1.39 \times 10^{-3} \quad k_1 = 2.67 \times 10^{-5}$$

Since excretion is greater than 500 days half life, it may be neglected for the times here involved. Then

$$\dot{a} = E_o K_1 (e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

and for the same times as before, for Shot 9,

$$a = \frac{0.0003}{0.20}\ 186\ (2.67 \times 10^{-5})\ (-3.8 + 27.1)$$

$$= \underline{\underline{1.7 \times 10^{-4}\ \mu c}} \text{ in 27 days. Negligible for both shots.}$$

This is the uptake of Y^{90} from outside. But in addition the Sr^{91}, which is about 65 times as strongly concentrated in the bone, liberates Y^{91} there as mentioned. The deposition occurs within the first few days. Neglecting excretion, the concentration of Y^{91} due to this process is given by:

5. Y^{91}.

$$\dot{a} = \lambda_1 a' - \lambda_3 a$$

Where

$$a' = \frac{E_o K_1}{\lambda_2} \left(e^{-\lambda_1 t} - e^{(\lambda_1 + \lambda_2)t + \lambda_2 t_1}\right)$$

Which results in

$$a = \frac{\lambda_1}{\lambda_2} E_o K_1 \left[\left(\frac{1}{\lambda_1 - \lambda_3} - \frac{1}{\lambda_1 + \lambda_2 - \lambda_3} \right) e^{-(\lambda_1 - \lambda_3)t_1 - \lambda_3 t} \frac{- e^{-\lambda_1 t}}{\lambda_1 - \lambda_3} + \frac{e^{-(\lambda_1 + \lambda_2)t + \lambda_2 t_1}}{\lambda_1 + \lambda_2 - \lambda_3} \right] \quad \ldots\ldots\ldots\ldots\ldots (10)$$

For $\lambda_1 = 1.713$ $\quad k_1 = 0.651$

$\lambda_2 = 3.47 \times 10^{-3}$ $\quad E_o = 93$

$\lambda_3 = 0.0122$ $\quad$ times as before

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Shot 9:

$$a = \frac{1.713}{3.47 \times 10^3} \quad 93(0.651) \frac{(3.47 \times 10^{-3})}{(1.701)(1.704)} \; e^{-0.577} - 0 + 0$$

$$= \underline{20 \ \mu c}$$

Shot 2:

$$a = 20(;3/4) = \underline{270 \mu c} \text{ by 4 days}$$

(This might be reduced by a factor of 2 if one Sr^{91} half life (9.7 hr) has passed before deposition within the bone has occurred. However, deposition is probably more rapid than this.

6. Ba^{140}. Using equation 8, with

$$\lambda_1 = 5.41 \times 10^{-2} \qquad R_o = 93$$

$$\lambda_2 = \frac{0.693}{50} = 1.39 \times 10^{-2} \qquad k_1 = 0.0229$$

Shot 9:

$$a = \frac{93(0.0229)}{1.39 \times 10^{-2}} \quad (0.232 - 0.159)$$

$$= \underline{11 \ \mu c}$$

Shot 2:

$$a = 11(13.4) = \underline{150 \ \mu c} \text{ in 27 d.}$$

7. La^{140}. A situation analogous to that of Y^{91} occurs here. Only a small amount of La^{140} might be expected to enter fromthe gut, but there also exists the buildup from the decay of Ba^{140} once within the bone. It may be calculated in the same way as was the concentration of Y^{91}, using equation (10) with

$$\lambda_1 = 5.41 \times 10^{-2} \qquad k_1 = 0.0229$$

$$\lambda_2 = 1.39 \times 10^{-2} \qquad R_o = 93$$

$$\lambda_3 = 0.416 \qquad \text{Times as before}$$

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Then

$$a = \frac{5.41}{1.39} (93) (0.0229) \left(\frac{e^{-1.46}}{0.362} - \frac{e^{-1.84}}{0.348}\right)$$

$$= \underline{1.5\ \mu c} \text{ at 27 days (Shot 9)}$$

And for Shot 2:

$$a = 1.5\ (13.4) = \underline{\underline{20 \mu c}} \text{ at 27 days.}$$

G. Dose to the Intestinal Walls.

The total dose to the intestinal wall from the beta radiation of the fission products as a whole may also be estimated. As a rough approximation the intestine may be regarded as a cylinder of one centimeter radius and 10 meter length, filled with a homogeneous mixture of fission products and water. Using the estimated value of E_m for fission products during various time intervals after burst, the value of μ may be estimated for water during these times as follows:

$$\frac{\mu}{P} = \frac{0.693}{d_{\frac{1}{2}}}$$

Where μ = linear absorption coefficient, cm^{-1}

P = density, gm/cm^3 (for water $P = 1$)

$d_{\frac{1}{2}}$ = half-intensity thickness of material, gm/cm^2.

The quantity $d_{\frac{1}{2}}$ is usually about one eighth of the range of a beta spectrum. As a first approximation, then, one may calculate μ/P from the Feather range - energy relation:

$$R = 0.543E_m - 0.160 \qquad (gm/cm^2)$$

and $$\mu = \frac{8(0.693)}{0.543E_m - 0.160} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

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As a check, one may estimate a half thickness value for a given energy spectrum from the absorption curve in Al. (See Table). Using the Feather Value, it is seen that for d = 1 cm, the value of μd for these intervals exceeds 6 and the cylinder behaves like an infinite slab with respect to self absorption, for which (ref. 6):

$$I = A_o/4\mu \quad \ldots\ldots\ldots\ldots \quad (12)$$

If one takes all the betas to be absorbed within a 3mm shell of intestinal mucosa whose density is about 1 gm/cm^3, the total mass of irradiated wall will be 690π gm. The total area will be $a \simeq 2\pi r l = 2000$ cm^2, and the total flux will be Ia, or

$$Q \simeq Ia = \frac{2000\pi\, 82 A_T(t)}{4\mu \;\; 2000} \approx 21 \frac{\pi}{\mu} A_T(t) \text{ betas/sec} \times 3.7 \times 10^4 .$$

all of which is absorbed in the tissue. Hence equation (3) will apply. Thus

$$\dot{D} \simeq 55 \frac{\bar{E}}{690\pi}\, 21 \frac{\pi}{\mu} A_T(t) \;\simeq\; 1.7 \frac{\bar{E}}{\mu} A_T(t) \text{ rep/day} \quad \ldots\ldots\ldots\ldots \quad (13)$$

Where $\bar{E}$ is in Mev, μ in cm^{-1}, $A_T(t)$ in μc/ft^2 .

Since it has been assumed that the sheep turns over 2000 gm/day, this amount is always in the intestine, with its activity falling off as $A_T(t) = A_{T_o}(\frac{t}{t_o})^{-n}$.

Then the total dose is

$$D = \frac{1.7}{\mu} A_{T_o}\, t_o^{\,n_1} \int_{t_o}^{t} \bar{E}\, t^{-n} dt \quad \ldots\ldots\ldots\ldots \quad (14)$$

The integral will be divided into three periods over which n, E_m, and thus μ, are taken as constant to a first approximation. Then for the shot 2 case, where t_o = 0.15 day and A_{T_o} = 2300 μc/ft^2,

$$D = 1.7\,(2300) \sum_{i=1}^{3} t_o^{\,n_i} \frac{\bar{E}_i}{\mu_i} \frac{(t_o^{1-n_i} - t^{1-n_i})}{(n_i - 1)} \quad \ldots\ldots\ldots \quad (15)$$

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For the periods under consideration, (ref.7)

i	t_o	t	n_i	E_m	$\bar{E}_i$	$d_{\frac{1}{2}}$(abs)	$d_{\frac{1}{2}}$(Feather)	μ_i
1	0.15d	1d	1.12	1.9 Mev	0.75 Mev	0.10 gm/cm^2	0.11 gm/cm^2	6.4 cm^{-1}
2	1	4	1.25	1.2	0.44	0.05	0.06	11
3	4	30	0.98	0.85	0.29	0.03	0.04	18

Thus the total dose in 30 days, D, is

$$D = 1.7\ (2300)\ (0.030 + 0.047 + 0.133)$$

$$= \underline{\underline{820 \text{ rep}}} \quad \text{for shot 2, and } 820/13.4 = \underline{\underline{60 \text{ rep}}} \text{ for shot 9.}$$

It is of interest to note that 120 rep of the shot 2 dose occurs in the first day, 180 rep between first and fourth day, and the remaining 520 rep in the following 26 days out of 30, and similarly for shot 9. This of course cannot be considered as more than an order of magnitude calculation in view of the assumptions, but it does illustrate that a rather significant degree of damage could occur in this radiosensitive area.

H. External beta doses. Several cases were reported (8) of animals with activity deposited on head, abdomen, etc. If one assumes that this deposit results from contact with the ground, particularly around the mouth and head, one can calculate an extreme case for external beta exposure from this material by assuming that the material was deposited at the beginning of the exposure and remained throughout it. In addition, an external beta exposure to the head from the ground itself can be estimated.

For the first case an 8 July dose rate reading of 50 mr beta on the head of an animal is taken from ref. 7. This is the highest of the group of readings given.

$$\dot{D}_{t_2} = \dot{D}_{t_1} \times \left(\frac{t_2}{t_1}\right)^{-1.2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

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Let $\dot{D}_{t_2} = 0.05$ rep/hr $\quad t_2 = 26d \quad t_1 = 0.15d$

then $\dot{D}_{t_1} = 0.05 \left(\frac{26}{0.15}\right)^{1.2} = 25$ rep/hr (beta)

and
$$D = 5\dot{D}_{t_1} t_1^{1.2} (t_1^{-0.2} - t_2^{-0.2})$$
$$= 5(25)(0.098)(24)(0.96)$$
$$= \underline{\underline{280 \text{ rep.}}}$$

If a comparable deposit had occurred on shot 2 where the level of contamination was higher, one might estimate a dose of 280 (13.4) = 3800 rep for a similar body area.

From the ground itself one can make a similar guess; here one uses the shot 9 figure of 20 mr gamma at 3.5 hr after burst as a beginning. Estimates of the ratio of ionization from beta radiation to that of gamma in fall-out fields range from about 20 to 140:1, at the contaminated surface (ref.9). Using the same time interval and a dose rate initially of $\dot{D}_{t_1} = (0.020)\ 20 = 0.40$ rep/hr beta, then $D = 280\ (0.40)/25 = \underline{\underline{4.5 \text{ rep beta}}}$

While if the ratio was 140:1, $\dot{D}_{t_1} = 85\ (0.020)\ 140 = 2.8$ rep/hr beta

and $D = 280 \times (2.8)/25 = \underline{32 \text{ rep beta}}$

for shot 9, with a comparable exposure after shot 2 of

$$D = \underline{\underline{60 - 430 \text{ rep}}} \text{ beta.}$$

Such doses probably would be only to areas around the mouth, and would of course be in the superficial tissues of the skin.

I. Dose estimates for sheep exposed elsewhere. Some figures for the I^{131} activities in sheep thyroid samples counted in this Laboratory (10) and the corresponding dose estimates made on the basis of parts A to H will be finally listed. They are lower in all cases than the doses calculated in parts A to H.

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Bullock #1

0.550 gm sample. 29,100 cpm on 19 June 40% eff. counter

Activity in thyroid on 19 June, 0.06 μc/gm

Activity in 11 gm thyroid at death, 1.0 μc.

If exposure occurred at shot 9, the rate of intake of I^{131} at 3.5 hrs was:

$$R(t) = 186 \times \frac{1.0}{3.9} (0.017) = 0.81 \text{ μc per day.}$$

Dose to the thyroid from shot 9 I^{131}: $D = \frac{1.0}{3.9} (203) = 52$ rep

Similarly,

Corry #5. Shot 9 I^{131}: $D = 52 \times \frac{38300}{29100} = 69$ rep

Bullock #3. Shot 9 I^{131}: $D = 52 \times \frac{192}{291} = 34$ rep

Webster #3. Shot 9 I^{131}: $D = 52 \times \frac{119}{291} = 21$ rep

Three other animals with lower activities were listed.

If one assumes that these animals ingested and retained the other isotopes in the same proportions as calculated for the Hiko - Cedar City animals, one may estimate total thyroid doses, bone concentration of other isotopes, fission product beta dose to the gut wall and external exposure. This would apply to Shot 9 which is assumed to have produced all the activity detected in the thyroids. These results together with the total for the Hiko - Cedar City animals are summed up below. If the animals whose samples were counted here also received another exposure from an earlier shot or if these I^{131} activities themselves resulted from an earlier shot it would materially increase the dose estimates. It is not known whether this occurred, but the condition of the tissues observed here seems to imply higher doses and concentrations than would have resulted from Shot 9 alone. If a Shot 2 - Shot 9 exposure occurred with a ratio of fall-out intensity similar to that for the

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Hiko - Cedar City case, then the doses would all be increased by about a factor of 10, as is seen in the first sections of this discussion. If such was the case, bone samples of the animals would so indicate by the activity of Sr^{89} and Y^{91}, which would still be present and would yield values higher than below indicated when extrapolated back to time of exposure. However, such a determination appears impossible at this time.

	Bullock #1	Corry #5	Bullock #3	Webster #3
Total I; Thyroid	150 rep	200 rep	100 rep	60 rep
Sr^{89}; Bone	1.8 μc	2.4 μc	1.2 μc	0.7 μc
Sr^{90}	0.02	0.03	0.01	0.01
Sr^{91}	2.4	3.2	1.6	1.0
Y^{91}	5.1	6.7	3.4	2.1
Ba^{140}	2.8	3.7	1.8	1.1
La^{140}	0.4	0.5	0.3	0.2
Gut Wall	15 rep	20 rep	10 rep	6 rep
Mouth, External	1 - 8 rep	1 - 11	0.7 - 5	0.4 - 3

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I. Summary

1. Using the data from ref. 1, an estimation of several additional doses to the Hiko - Cedar City sheep exposed to fall-out from both Shot 2 and Shot 9 is made. It is contended here that the thyroid dose was higher than ref. 1 indicated, and that total loads of other isotopes in the bone were of even greater importance than the thyroid dose. Some irradiation of the gut appears possible as well as local, moderately strong external doses to mouth and head.

a. Total thyroid beta dose from both exposures was estimated at 4500 to 9000 rep (4 isotopes of iodine).

b. Maximum concentrations in the bone were estimated, at times indicated, of:

Sr^{89}	(53d half life)	99 μc	27 day levels, both shots	
Sr^{90}	25 yr	1 μc	27 day levels, both shots	
Sr^{91}	9.7 hr half life	140 μc	1 day level	"
Y^{91}	61 day	290 μc	4 day level	"
Ba^{140}	13 day	160 μc	27 day level	"
La^{140}	40 hr	22 μc	27 day level	"

c. Total beta dose to mucosa of small intestine from fission products as a whole on the order of 10^3 rep.

d. Local dose around mouth and head as high as 10^3 rep from clinging material: as high as 10^2 - 10^3 rep from the ground.

e. Total external gamma dose negligible.

2. On the basis of data from thyroid sample counting done in this Laboratory, similar doses to several animals exposed in other areas are calculated. This is done assuming the activity in the thyroid on the date of

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counting was all due to Shot 9. All results are of the order of one-sixtieth of the above. No reasonable estimate of exposure due to any other shot can be made unless further information is available on these animals.

Alternatively, the activity in the thyroid could have been due to an exposure from an earlier shot. This appears more likely than a Shot 9 exposure, given the observed pathology in the thyroid and bone marrow of these animals. For example, a continual ingestion from Shot 2 until death of the animals on 14 June (with no exposure from other shots), would imply an initial ingestion rate of about 400 μc/day. This would be consistent with all the above assumptions if the sheep had been in a fall-out area where the gamma dose rate at 3.5 hrs had been about 2 r/hr. Under these conditions:

a. Total thyroid dose would have been about 32000 rep from I^{131} alone and as high as 90000 rep from all I isotopes.

b. Concentrations in the bone might have reached 2.5 mc of Y^{91}, 880 μc of Sr^{89} etc. for the total animal -- a factor of 9 higher than those calculated for the Hiko - Cedar City case, and a factor of about 540 higher than the assumption of a Shot 9 exposure to these other animals indicates.

c. Gut doses of about 10^4 rep beta might have occurred as well.

These two extremes provide a measure of the range of possible doses. It appears likely that an exposure did occur earlier than Shot 9, but probably not as early as Shot 2.

3. It can be concluded that radiation damage occurred with the above doses, although perhaps not in sufficient degree to be a prime cause of death. However, the animals were probably weakened enough to succumb to other causes which would not have been lethal in themselves, and newborn

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animals were almost certainly harmed by both their own and their mother's exposures, which would account for the increased mortality of young lambs observed. The data is scanty and the estimates admittedly rough, but this conclusion seems reasonable. It is felt that these exposures constitute a clear example of the internal hazard from fission product fall-outs in which protracted ingestion of the material may take place. Although this hazard is of course maximized for a grazing animal, the relevance of these exposures to such human problems as water supply and crop contamination should not be overlooked.

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REFERENCES

1. Dunning, Compilations of Radiation Dose to the Thyroid of Sheep Resulting from the Ingestion of Iodine from Fallout during the Spring 1953 Nuclear Tests. Enclosure, letter from P. B. Pearson, Biology Branch USAEC, 19 October 1953.
2. Pathology Report on Nevada Sheep, USNRDL (July 1953)
3. Hunter, H. F., and Ballou, N. E. Simultaneous Slow Newtron Fission of U^{235} Atoms. Individual and Total Rates of Decay of the Fission Products. ADC-65 (1949).
4. Hamilton, et al. Radiology 49, 269 (1947).
5. Advances in Biological and Medical Physics, Vol. I (1948).
6. Field, E. L., Estimation of Self-Absorption Within a Homogeneous Cylindrical Source. Nucleonics 11, 66 (1953).
7. Sondhaus, C. A., USNRDL-394 (CONFIDENTIAL) (1952).
8. Letter from Seth R. Woodruff, Las Vegas Field Office, USAEC, 15 June 1953.
9. Tochilin, E., et al. WT-345 (SECRET) (1952).
10. Reed, J. S., USNRDL, Memo to R. J. Veenstra, 8 July 1953.

[redacted]