



temperature latitudes with a few months. Thus we will consider materials with half lives of a few months as potential long range hazards. Among the fission products, Sr<sup>90</sup> is the classic example of a worldwide hazard and Sr<sup>89</sup> is an example of a long-range but not worldwide hazard.

In the following estimates of amounts of radioactive materials formed, experimental numbers were used where available. For neutron capture in ground and air it was assumed that one neutron per 150 Mev total yield was emitted by the weapon, (taken equivalent to  $2 \times 10^{26}$  neutrons/MT). For an air burst all neutrons were assumed to be absorbed by nitrogen, while for a surface burst half are taken to be captured in ground and half in air. Activities produced in ground are assumed to be mixed in the fireball and fall out like fission products.

The following potentially hazardous radioactive materials have been considered.

A. Half lives longer than 1 year:

Sr<sup>90</sup>:

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At 5% one obtains .16 Megacuries Sr<sup>90</sup> per Megaton fission (Mc/MT fission). Sr<sup>90</sup> is discussed in order to compare clean and fission weapons.

C<sup>14</sup>:

Formed in 95% of all air captures. This gives:

.02 Mc/MT for air burst

.01 Mc/MT for surface burst.

Co<sup>60</sup>:

May be produced in up to ~.1% of neutron captures in ground, leading to 10<sup>23</sup> atoms/MT for surface burst.]

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Taking this higher figure we obtain

.12 Mc/MT.

Fe<sup>55</sup>: Produced in ~.5% of ground captures or  $5 \times 10^{23}$ /MT for surface burst.



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.4 Mc/MT.



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3 curies/MT.

Cl<sup>36</sup>: For surface detonation over sea water will produce about 60c/MT.

Ca<sup>41</sup>: For surface detonation over typical ground will produce about 4c/MT with a maximum of about 240c/MT for a surface burst on limestone.

Cs<sup>134</sup>: For surface detonation on typical ground may be formed in ~.01% of ground captures of  $3 \times 10^3$ c/MT.

B. Half lives less than one year:

Sr<sup>89</sup>: Formed in about 5% of U<sup>235</sup> fissions or 30Mc/MT fission, but only in about 3% of fissions for standard two stage weapons.

Ca<sup>45</sup>: Formed by neutron capture in ground -- in about .05% of captures in average ground, .2% in concrete and 3% in limestone. For detonations on concrete we have

.27 Mc/MT.

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Note that the production of  $Ca^{45}$  will vary markedly with the Ca content of the surface on which the weapon is detonated.

W<sup>185</sup>:

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In addition about 25Mc of  $W^{181}$  may be expected but this is probably appreciably less hazardous than the  $W^{185}$ .

P<sup>32</sup>: May produce from ~.05% of neutron captures in average ground. This leads to about .5 Mc/MT but may vary considerably with phosphorous content of soil.

Fe<sup>59</sup>: From iron in weapons have produced  $4 \times 10^{22}$  atoms per MT or .2 Mc/MT.

Po<sup>210</sup>:

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The above figures are summarized in Table I:

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It will be seen that all the clean radioactive products are unlikely to be a worldwide hazard for energy releases,  $\lesssim 10^5$  megatons. Thus they are probably of no great concern in the present rate of testing weapons and we shall consider only the hazard associated with their use in wartime, i.e., we assume that the radioactivity is injected over a short period of time.

Of the long lived isotopes produced by clean bombs it is likely that  $C^{14}$  is the most hazardous. Estimates may be made from the radiocarbon studies. Libby takes a carbon inventory averaged over the earth's surface of  $.45 \text{ gm/cm}^2$  of carbon in the biosphere and atmosphere (a similar number would obtain for atmosphere plus part of biosphere plus top of ocean). This gives  $2.25 \times 10^{18}$  gm of available carbon on the earth's surface. If from NBS Handbook 52, we take maximum permissible amount of  $C^{14}$  in body at  $25 \mu\text{c}^1$  (for large populations) and body mass as including about 10 kg C; then the maximum permissible ratio of  $C^{14}$ /to C in biosphere is  $2.5 \times 10^{-3} \mu\text{c } C^{14}$  per gram of C. This corresponds to a total  $C^{14}$  production of  $5.6 \times 10^3 \text{ Mc}$  or a yield of  $3 \times 10^5 \text{ Mt}$ .

Measurements exist on the increase in  $C^{14}$  activity due to weapons tests. On the above scale, about 50 Mt of neutrons have been released to the air. We would predict from this a production of 1 Mc of  $C^{14}$  and an increase of  $C^{14}$  in atmosphere and biosphere of about  $.5 \mu\text{c/gm}$ . This corresponds to .02 disintegrations per sec per gm of C, which is about 7% of the natural rate. An increase of about 10% in the  $C^{14}$  concentration in the atmosphere has been observed -- thus indicating that our estimates are reasonable.

It may be noted that detonation of  $3 \times 10^5 \text{ Mt}$  could increase the  $C^{14}$  content of the atmosphere by a factor  $10^3$  above natural levels. Conceivably an increase of this magnitude could produce non-physiological hazards such as perturbation of weather by increasing conductivity of the air. However it appears

<sup>1</sup>Note that this and most subsequently quoted levels would increase the radiation level in a critical organ by a factor 10 above the natural background.

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unlikely that this particular effect could be important. The natural  $C^{14}$  in the air contributes at the most (at sea level over water) only  $10^{-4}$  of the ion pairs which produce the air conductivity. Thus increase of the  $C^{14}$  levels by  $10^3$  would increase air conductivity by only  $\approx 10\%$ . Much larger variations occur naturally, with altitude, and air over earth vs. air over water.

For  $Sr^{90}$ , Anderson and Langham have summarized fission megatons required to produce hazardous levels of  $Sr^{90}$ . For a world average,  $3 \times 10^4$  Mt fission would lead to about  $1 \mu\text{c}/\text{kgm Ca}$  or  $3 \times 10^3$  Mt to  $.1 \mu\text{c}/\text{kgm Ca}$ .

(Which number is most similar to the  $25 \mu\text{c } C^{14}$ ?) Variability of  $Sr^{90}$  distribution and capture has led some to recommend that these yields should be divided by about a factor 10 to have a safe level of  $Sr^{90}$  everywhere (outside the locality of detonation).

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The chief hazard of  $\text{Co}^{60}$  may lie in its use as a trace element of importance to some organisms or simply as a general source of  $\gamma$  radiation from the ground. One may estimate the latter danger as follows: Suppose the  $\text{Co}^{60}$  is deposited uniformly over the earth surface where it has a mean life against removal by weathering of  $\sim 1$  year. If a dose, to exposed flesh, of 1.5 r in one year is considered roughly comparable to the large population figures, we estimate (from figure 9.120 of Effects of Nuclear Weapon) that this corresponds to about 10 curies/ $\text{mi}^2$  or a total yield of about  $2 \times 10^5$  Mt. This indicates that  $\text{Co}^{60}$  could be directly a hazard comparable to the inevitable  $\text{C}^{14}$ , and its production should be kept low in clean weapons. It may be argued that a mean life of 1 year against weathering is much too large, but on the other hand there will no doubt be concentrations in the fallout.

An estimate may also be made on the hazard of ingested  $\text{Co}^{60}$ . If one takes  $10 \mu\text{g}/\text{cm}^2$  of available Co on earth surface,  $5 \times 10^{-4}$  gm of  $\text{Co}^{60}$  in a person, a maximum permissible amount of  $\text{Co}^{60}$  in body of .3  $\mu\text{c}$ , and assumes equilibrium between  $\text{Co}^{60}$  and ordinary Co in biosphere he finds  $2.5 \times 10^5$  Mt required to produce a hazardous level. However, in view of the apparently poor absorption of Co and its short effective half life (as reported in Handbook 52) it would appear unlikely that equilibrium can be established in the  $\text{Co}^{60}$  lifetime. Nevertheless it would appear wise to devote further study to  $\text{Co}^{60}$ .

The remaining long lived isotopes of table I appear less hazardous than  $\text{C}^{14}$ , by an order of magnitude or more.  $\text{Fe}^{55}$  appears harmless unless there are efficient mechanisms for direct consumption of Fe. This conclusion can be reached by considering  $\text{Fe}^{55}$  in equilibrium with available Fe in the same manner that  $\text{Sr}^{90}$  (relative to Ca) was treated by Libby.  $\text{Pb}^{210}$ ,  $\text{Cl}^{36}$ ,  $\text{Ca}^{41}$ ,  $\text{Cs}^{134}$  are created in too small quantities to be hazardous.

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Of the short lived isotopes,  $Ca^{45}$  and  $W^{185}$  appear most worthy of attention.  $P^{32}$  does not appear as hazardous as  $Ca^{45}$  -- because of its shorter half life.

The hazard of  $Ca^{45}$  may be compared with that of  $Sr^{89}$  since these have similar half lives. It may be expected that 1 curie of  $Ca^{45}$  produced by a bomb is about as hazardous as 10 curies of  $Sr^{89}$ . This factor 10 is arrived at through the following factors. Sr is discriminated against relative to Ca in entry into human bones by a factor (10). The energy of the  $Ca^{45} \beta^-$  is (1/6) the energy of the  $Sr^{89} \beta^-$ . The half life of  $Ca^{45}$  is (3) times that of  $Sr^{89}$ . This longer half life will give the  $Ca^{45}$  a longer time to reach bones so that perhaps an added factor (2) advantage is obtained.  $10 = (10)(1/6)(3)(2)$ .

Thus the hazard due to  $Ca^{45}$  production as in Table I is about twice that due to  $Sr^{89}$  from a 5% fission weapon. For a similar detonation over Limestone these figures give  $Ca^{45}$  predominating over  $Sr^{89}$  by a factor of about 30.

A quantitative comparison between damage due to  $Sr^{89}$  and  $Sr^{90}$  is difficult to make. Probably energy deposited by  $Sr^{89}$  in bones is  $\approx 10\%$  of the  $Sr^{90}$  energy.. However it is delivered 100 times as fast. It appears that under adverse conditions the  $Ca^{45}$  formed in a 5% fission weapon could be more damaging than the  $Sr^{90}$ .

$W^{185}$  is,

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an isotope deserving of considerable attention.

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If one assumes that W behaves like Mo in the body, then the saving feature appears to be that only  $2 \times 10^{-4}$  of the ingested  $W^{185}$  (Mo) will reach bone, the critical organ, (NBS Handbook 52). The energy per  $W^{185}$

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