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LONG RANGE FALLOUT FROM CLEAN WEAPONS (*)

A primary motivation for the development of clean weapons has been the desire to minimize worldwide radioactive fallout. For a conventional two stage weapon, which derives approximately 50% of its energy from fission, the dominant contribution to fallout is produced by the radioactive fission products, of which $Sr^{90}$ is believed to be the most important worldwide hazard. [redacted] This radioactivity will be induced by neutron reactions with bomb materials and with elements in the environment (air, water, ground). The purpose of this memorandum is to note some principle induced long range activities and to indicate their importance relative to fission products.

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It is convenient to divide the radioactive materials which we consider into two classes depending on whether their half lives are greater than or less than about a year. Roughly speaking, only those isotopes with half lives of more than a year can contribute to truly worldwide fallout, because times required for atmosphere deposition of fallout products over the whole world appear to be measured in years. However materials with half lives appreciably shorter than a year may be hazardous at great distances from nuclear detonation sites. In particular tropospheric fallout, discussed by Libby, may be expected to distribute radioactivity from detonations in the USSR, Europe, or U.S. over the north



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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, $Sr^{90}$ is the classic example of a worldwide hazard and $Sr^{89}$ 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:

$Sr^{90}$: [redacted] DoE b(3)

[redacted] At 5% one obtains .16 Megacuries $Sr^{90}$ per Megaton fission (Mc/MT fission). $Sr^{90}$ is discussed in order to compare clean and fission weapons.

$C^{14}$: Formed in 95% of all air captures. This gives:

.02 Mc/MT for air burst

.01 Mc/MT for surface burst.

$Co^{60}$: May be produced in up to ~.1% of neutron captures in ground, leading to $10^{23}$ atoms/MT for surface burst. [redacted] DoE b(3)

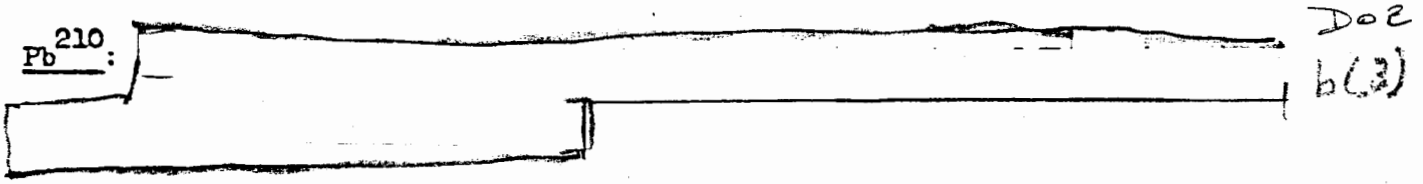
Taking this higher figure we obtain

.12 Mc/MT.

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


.4 Mc/MT.

$Pb^{210}$:




3 curies/MT.

$Cl^{36}$: For surface detonation over sea water will produce about 60c/MT.

$Ca^{41}$: For surface detonation on typical ground will produce about 4c/MT with a maximum of about 240c/MT for a surface burst on limestone.

$Cs^{134}$: 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:

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

$Ca^{45}$: Formed by neutron capture in ground -- in about .05% of captures in average ground, .2% in concrete and 3% in limestone. For detaonations 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.

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

$P^{32}$: May produce from ~.05% of neutron captures in average ground. This leads to about .5 Mc/MT but may vary considerably with phospherous content of soil.

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

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$Po^{210}$: [redacted]

The above figures are summarized in Table I:

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TABLE I

MAXIMUM PROBABLE YIELDS OF LONG LIVED ISOTOPES

| Isotope | Half Life | Decay Mode & Energy | Amount Per MT and Means of Formation | |
|---|---|---|---|---|
| $C^{14}$ | 5600 y | $\beta^-$ .16 Mev | .02 Mc | a |
| $Co^{60}$ | 5.2 y | $\beta^-$ 2.8 $\gamma$ | .12 Mc | b |
| $Fe^{55}$ | 2.9 y | k .22 | .4 Mc | b |
| $Pb^{210}$ | 20 y | $\beta^-$, $\alpha$(6.5) | 3 C | b |
| $Cl^{36}$ | $3.1 \times 10^5$ y | $\beta^-$ .7 | 60 C | w |
| $Ca^{41}$ | $1.1 \times 10^5$ y | k .44 | 16 C | c |
| $Cs^{134}$ | 2.3 y | $\beta^-$ 2.05 $\gamma$ | 3000 C | g |
| $Ca^{45}$ | 160 d | $\beta^-$ .25 | .27 Mc | c |
| $W^{185}$ | 74 d | $\beta^-$ .43 $\gamma$ | 100 Mc | b |
| $P^{32}$ | 14.5 d | $\beta^-$ 1.71 | .5 Mc | g |
| $Fe^{59}$ | 45 d | $\beta^-$ 1.56 $\gamma$ | .2 Mc | b |
| $Po^{210}$ | 138 d | $\alpha$ 5.3 | 300 C | b |

For comparison purposes, the amounts of $Sr^{90}$ and $Sr^{89}$ which would be produced [redacted] DOE b(3)

are given below in Mc per megaton of total yield.

| | | | | |
|---|---|---|---|---|
| $Sr^{90}$ | 28 y | $\beta^-$(2.8) | .008 Mc | [redacted] DOE b(3) |
| $Sr^{89}$ | 54 d | $\beta^-$ 1.5 | 1.5 Mc | |

a = air burst.

b = neutron induced reactions in possible bomb materials.

c = surface burst on concrete.

g = surface burst on typical ground.

w = surface burst on sea water.

[redacted] DOE b(3)

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 earths surface of .45 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 permissable amount of $C^{14}$ in body at 25$\mu$c[1] (for large populations) and body mass as including about 10 kg C; then the maximum permissable ratio of $C^{14}$/to C in biosphere is $2.5 \times 10^{-3}$ $\mu$c $C^{14}$ per gram of C. This corresponds to a total $C^{14}$ production of $5.6 \times 10^3$ Mc or a yield of $3 \times 10^5$ 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 $\mu\mu$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 $3 \times 10^5$ 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

[1]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.

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 $\lesssim 10\%$. 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 μc/kgm Ca or $3 \times 10^3$ Mt to .1 μc/kgm Ca.

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(Which number is most similar to the 25 μc $C^{14}$?) 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).

The chief hazard of $Co^{60}$ 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 $Co^{60}$ is deposited uniformly over the earth surface where it has a mean life against removal by weathering of ~ 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/$mi^2$ or a total yield of about $2 \times 10^5$ Mt. This indicates that $Co^{60}$ could be directly a hazard comparable to the inevitable $C^{14}$, 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 $Co^{60}$. If one takes $10 \mu gm/cm^2$ of available Co on earth surface, $5 \times 10^{-4}$ gm of $Co^{60}$ in a person, a maximum permissable amount of $Co^{60}$ in body of .3 $\mu c$, and assumes equilibrium between $Co^{60}$ 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 $Co^{60}$ lifetime. Nevertheless it would appear wise to devote further study to $Co^{60}$.

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

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, an isotope deserving of considerable attention.

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 $W^{185}$

disintegration is about 1/3 of the $Mo^{99}$ energy. This would lead to a maximum permissable steady amount of $W^{185}$ in body of about 15μc for large populations. If all the $W^{185}$ is fixed in the bones during a short time one might permit ~ 150μc as the maximum initial amount in body or a permissable ingestion of about .4 curies. Now $10^6$ megatons of tungsten weapons would produce ~ $10^8$ Mc of $W^{185}$ or .4 c in about 1 $mi^2$. With a $W^{185}$ half life of 74 days, it is difficult to see how even a few percent of the fallout on 1 $mi^2$ could be ingested by a person. Because of the short half life, it does not seem possible that the $W^{185}/Mo$ ratio in the body could become close to the $W^{185}/Mo$ ratio in the soil -- a calculation assuming such equilibrium would lead to more concern, but is apparently unjustified. It thus appears that $W^{185}$ represents a negligible hazard. However it would seem important to have some experimental confirmation of the above analysis before committing oneself to a large program of constructing tungsten weapons.

Conclusions:

Among the radiological products of clean weapons, $C^{14}$ appears to constitute the most appreciable world wide hazard while for surface bursts there may be expected to be a comparable shorter range contamination due to $Ca^{45}$. $Co^{60}$ appears dangerous enough so that its production in weapons should be minimized (i.e., minimal use of Co, Ni, or Ca) and its dissemination in the biosphere studied. $W^{185}$ does not appear hazardous but should be studied.

It is difficult to compare the relative hazards from $C^{14}$ and $Sr^{90}$ quantitatively. If the $Sr^{90}$ were uniformly distributed, $C^{14}$ might represent a hazard equivalent to $Sr^{90}$ from a few % fission. Uneveness of the $Sr^{90}$

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distribution would appear to render $Sr^{90}$ relatively more hazardous -- at least if one assumes that the harmful effects of radiation are threshold phenomena.

It should, of course, be kept in mind that these conclusions are based on 1/10 of the "maximum permissable amounts" as given in NBS Handbook 52, and that these "maximum permissable amounts" are quite arbitrary and only indirectly and tenuously related to experimental information.

It is interesting to compare our conclusions with those in a recent article by O. I. Leipunsky (USSR). Leipunsky concludes that $C^{14}$ is a hazard comparable to $Sr^{90}$ even for a standard weapon; and that the $C^{14}$ produced in a (D, T) "clean" weapon is more hazardous than $Sr^{90}$ from a standard weapon. His assumptions differ from ours in three important respects: (1) He takes seven times as many neutrons per megaton captured in air. [redacted] DoE b(3) (2) He assumes that the critical organ for $C^{14}$ is gonads and that carbon density in gonads is 1/3 of that in fat. (3) He argues that to compare hazards one must integrate over the entire possible duration of the isotope. This gives $C^{14}$ an added factor of 10 danger as compared to $Sr^{90}$ ($C^{14}$ half life 200 times longer than $Sr^{90}$ but $C^{14}$ diluted by factor 20 in oceans). This last point has much merit for long term considerations and may tempt one to conclude that over the long run $C^{14}$ from a 5% clean weapon may be more hazardous than $Sr^{90}$. Leipunsky also discusses hazard from tritium, which we should include in the above discussion.

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