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RADIOACTIVITY II

Studies of Radioactivity from Nuclear Explosions for Peaceful Purposes

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Summary

Estimates are made of the extent and duration of hazards from radioactivity to the general public due to fallout from a cratering explosion. The nuclear explosive is assumed to be "clean" in the sense that only a small fraction of the yield is derived from fission. Hypothetical examples take an explosive of total yield 100 kT, of which 10 kT, 1 kT and zero - the ultimate in cleanliness - are derived from fission. The maximum permitted level to the public is taken as 0.5 rem in a period of one year.

Sources of activity considered are fission products, residual thermonuclear material (tritium), neutron induced activity in the device materials and neutron induced activity in the surrounding rock. Estimates of the production are made, and are associated with a distribution function derived from the Sedan fallout measurements.

The hazards from radioactivity associated with the creation of a storage reservoir for natural gas have also been considered. In this case the main problem is contamination of the product by tritium left in the chimney. The possibility of flushing out this tritium with water is discussed.

I. INTRODUCTION

Two possible applications of nuclear explosives for peaceful purposes, posing different problems in regard to radioactivity, have been considered in Parts II and III of this paper. They are a cratering shot of yield 100 kT which might be used, for example, to create a water reservoir or part of a harbour, and a deeply buried contained shot of yield 25 kT which could be used to create storage for natural gas or oil.

These studies are entirely theoretical. They depend heavily on published data obtained from US Plowshare Program reports.

II. CRATERING EXPLOSION

1. Model

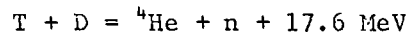
A 100 kT explosion at optimum depth for cratering is considered. Project Sedan {1} of July 1962 is a practical example, in which a 100 kT device was emplaced at 635 ft depth in alluvium and produced a crater of radius 608 ft and maximum depth 323 ft. The crater volume was about 6.6 million cubic yards

corresponding to the removal of about 8.4 million tons of material. The radioactive fallout pattern of Sedan is well documented and it is used here to define a typical distribution function in a way which will be described later on.

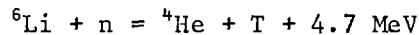
There are important differences between the hazards from dynamic effects and radioactivity. Dynamic effects - air blast and ground shock (or seismic disturbance) - are effectively instantaneous and may cause damage to property. On the other hand, radioactivity can persist for a long time and may put the public health at risk. But, whereas dynamic effects are a direct consequence of the force of the explosion, and cannot be greatly changed for a given yield, radioactivity is really incidental to the purpose of the explosion and can be reduced by technological skill.

The obvious method of reducing the radioactivity produced by a nuclear explosion is to reduce the fission yield. Sedan, for example, produced less than 30% of its yield from fission. To explore this aspect we shall consider three hypothetical examples each of 100 kT total yield but including 10 kT, 1 kT and zero fission yield.

Most of the yield in "clean" devices must be obtained from fusion, a typical reaction being that between tritium and deuterium



The reacting particles must have high energies if the reaction is to proceed with sufficient speed. The neutrons produced (1.45×10^{24} per kT of fusion yield) are ultimately captured by nuclei in the environment, either in the device itself or surrounding rock. They might be used to manufacture the tritium from ${}^6\text{Li}$, viz,



so creating a reaction cycle. The function of the fission trigger is to create the conditions needed to start the cycle.

A basic model explosive could therefore comprise a fission trigger, a mass of ${}^6\text{LiD}$, and a container of heavy material to restrain the expansion of the reacting material. Lead would be a suitable container material as its neutron activation cross section are small and the radioactive products decay quite quickly. A possible alternative is tungsten.

2. Amounts of Activity Produced

Four different sources of activity produced in the explosion are considered. These are fission products, residual materials from the nuclear explosive, neutron induced activity in inert device materials and neutron induced activity in the surrounding rock.

2.1 Fission Products

The activity produced is directly proportional to the fission yield. Beta and gamma energy emission rates from the fission products are well known as a function of time after fission {2} and the data for 1 kT of fission products are shown in Figures 1 and 2. A general measure of the relative fallout level is the energy emission from 1 hour to infinite time, assuming a continuous exposure beginning at 1 hour. Variations in the commencement of exposure will be considered later. The actual fallout source is found by

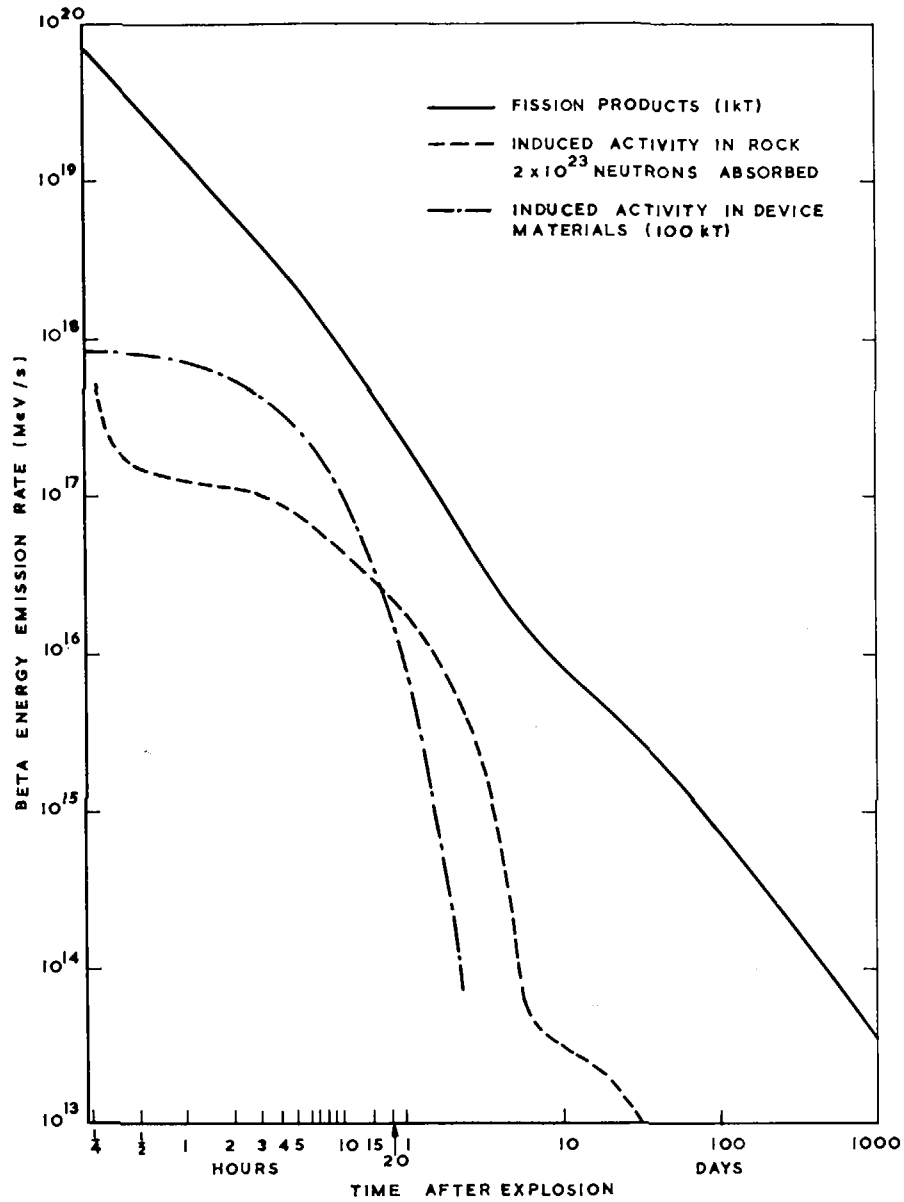


FIGURE 1. BETA ENERGY EMISSION RATES

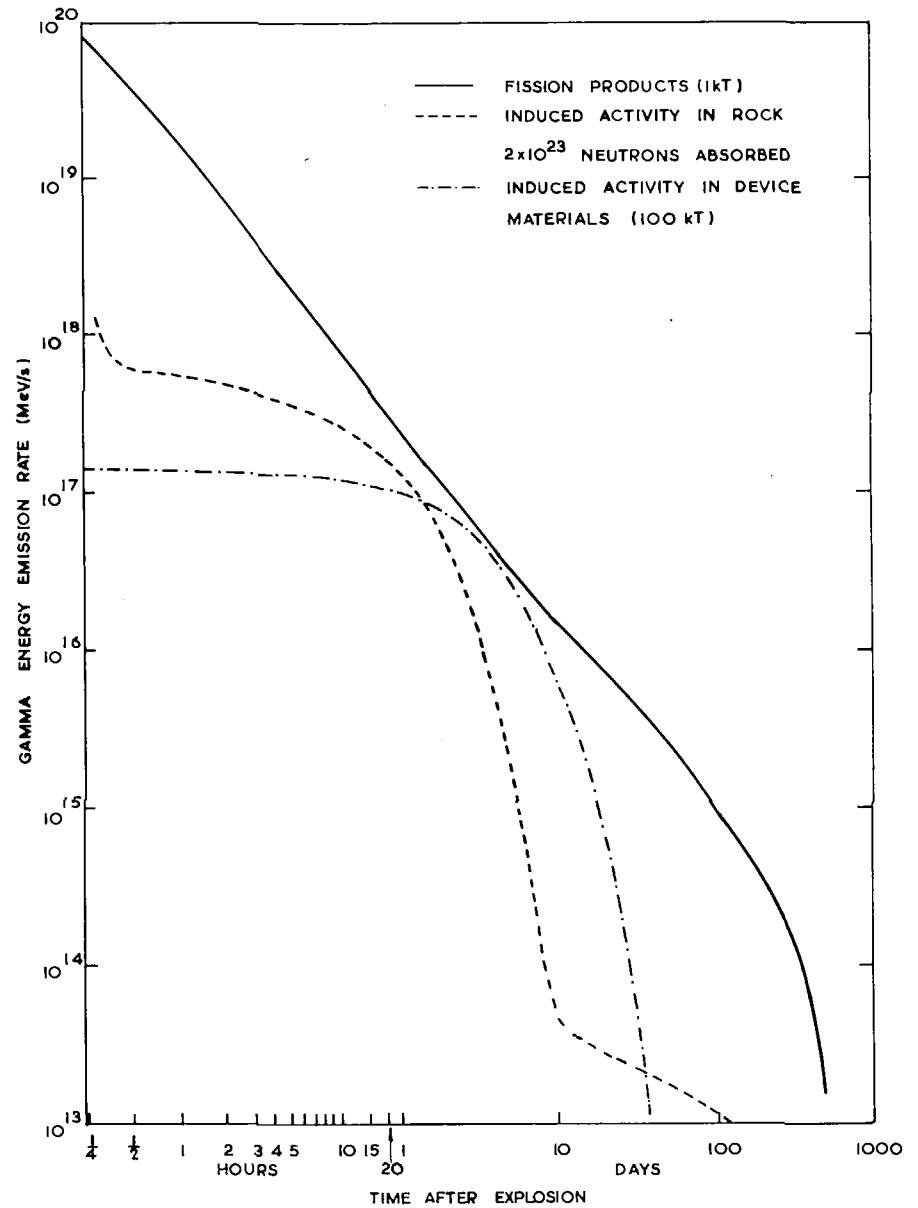


FIGURE 2. GAMMA ENERGY EMISSION RATES

multiplying by the distribution function (see section 3). Integration of the emission rates over time gives

$$\beta\text{-energy emission from 1 hr to infinite time} = 1.8 \times 10^{23} \text{ MeV/kT}$$

$$\gamma\text{-energy emission from 1 hr to infinite time} = 1.8 \times 10^{23} \text{ MeV/kT*}$$

2.2 Residual material from the explosive

The residual activity of concern is tritium. As tritium decays by the emission of weak β particles it is mainly an internal hazard to the body and, as such, its quantity is most usefully expressed in curies. The amount remaining after an explosion producing 100 kT fusion yield may range from 7×10^5 to 5×10^6 Ci {3}. For definiteness, we assume an amount of 2×10^6 Ci, and therefore subsequent estimates of tritium levels will be uncertain by a factor of at least 3. The assumed amount of residual tritium corresponds to 200 g, compared with about 700 g which react in producing 100 kT fusion yield.

2.3 Neutron induced activity in the device

The materials of which the device is made are exposed to a high fast neutron flux and, in general, both stable and active nuclides will be produced. Activity produced by neutron capture in the fissile and thermonuclear materials is insignificant compared with that of fission products and tritium already considered. The container, however, deserves separate consideration. If it is lead the principal products of neutron capture reactions are stable isotopes and the active nuclides ^{203}Pb and ^{209}Pb both of which have short lives. In Sedan tungsten was present, but this gives rise to a substantially greater hazard over an extended period of time than lead.

Our estimates of the radiation from the activity induced in lead in a 100 kT explosive are

$$\beta\text{-energy emission from 1 hr to infinite time} = 1.15 \times 10^{22} \text{ MeV}$$

$$\gamma\text{-energy emission from 1 hr to infinite time} = 3.8 \times 10^{22} \text{ MeV}$$

By comparison with the energy emission from fission products (1.8×10^{23} MeV/kT) these amounts are small if the fission yield is 1 kT or more. But there would be a significant contribution to the gamma emission if the fission yield is less than 1 kT in a total yield of 100 kT, which is likely to become dominant if the total yield were increased without increasing the initiating fission yield. Our calculations indicate that a ten fold increase in total yield would result in about 7 times more induced activity.

The energy emission rates for a 100 kT device encased with pure lead are shown in Figures 1 and 2. Activation calculations show that the small amounts of certain impurities present in commercially pure lead, namely, Sb, Fe, Ni and Zn, make an insignificant contribution over the period shown.

2.4 Neutron induced activity in rock

Neutrons escaping from the device will be captured in the surrounding medium. Typical rock consists mainly of SiO_2 , but also contains appreciable amounts of Na, Al, Mg, K, Ca and Fe, and small amounts of many other elements. Neutron capture in most elements produces some radioactive nuclides. A detailed study of the products with half lives greater than 24 hours has been made for a typical granite by Ng {4}. The compositions of several other types

* The equality of these results is coincidental

of rock are also listed, so that one can estimate the probable variation of any specified product from one type of rock to another. Generally, the most important products are formed in maximum or near-maximum amounts in the granite to which the study applies. We have extended this work to include some products with shorter half lives, which are important in the initial fallout.

The number of neutrons entering the rock can be reduced by encasing the device in a neutron shield which consists, essentially, of a moderator, hydrogen, and an efficient, non-activating, slow neutron absorber, boron. In principle, a shield of sufficient thickness could reduce the neutron induced activity in the rock to any desired level, but in practice the cost of excavating space sets a limit. It can reasonably be assumed that the required thickness will be decided by the magnitude of the activity induced in the rock relative to that from the other sources.

A calculation in which a 100 kT device was shielded with water containing 5% by weight of boron in solution gave about 2×10^{23} neutrons entering the rock. It showed that 95% of these neutrons were captured within the first 100 cm of rock, which was taken to be dry, 35% of the captures occurring at high neutron energy (above $2\frac{1}{2}$ MeV) and 65% after slowing to low energies. Table I shows the percentages of neutrons captured by the principal absorbing elements in granite. Fast captures have been calculated explicitly only for those elements against which a figure is shown in the table.

Table I. Fate of the neutrons in granite

Element	Per cent by weight	Number atoms per g	Per cent of neutrons captured	
			Fast	Slow
Li	0.007	6.1×10^{18}		3.80
B	0.0015	8.4×10^{17}		5.55
O	48.66	1.83×10^{22}	22.0	
Na	2.77	7.26×10^{20}		3.35
Mg	0.56	1.39×10^{20}	0.08	0.08
Al	7.70	1.72×10^{21}	1.3	3.65
Si	32.30	6.93×10^{21}	10.7	9.76
Cl	0.024	4.1×10^{18}		1.21
K	3.34	5.14×10^{20}		9.36
Ca	1.58	2.37×10^{20}	0.05	0.92
Ti	0.23	2.89×10^{19}		1.48
Mn	0.06	6.6×10^{18}		0.77
Fe	2.70	2.91×10^{20}	0.08	6.71
Sm	0.0006	2.4×10^{16}		1.18
Eu	0.00017	6.8×10^{15}		0.26
Gd	0.001	3.8×10^{16}		15.52
Others	0.066		0.8	1.40

It is noteworthy that small fractions of powerful absorbers such as Gd and B account for a significant number of neutrons. Changes in the amounts present may be represented by a change in the total absorption coefficient. The change in production of a radioactive nuclide of interest can therefore be estimated by scaling by the ratio of the amounts of its parent present and the inverse ratio of the total absorption coefficients for the two rocks.

These calculations are for dry rock with zero hydrogen content. Hydrogen is a useful, non-activating, slow neutron absorber, however, accounting for about 10% of the slow captures in rocks containing 5% by weight of water. The presence of hydrogen also increases the moderating properties of the rock, and increases the fraction of slow captures at the expense of fast captures. At 5% water content these factors balance approximately and the activation by slow neutrons is scarcely changed.

Table II shows the principal products which contribute to the beta and gamma energy emission integrated from 1 hour to infinite time. Clearly, ^{24}Na is the dominant nuclide for both radiations. Examining the 11 analyses quoted by Ng {4} the maximum sodium content is 2.84% and, taking account of the effect of fast captures in Mg and Al, the maximum ^{24}Na production could be about 15% greater than Table II shows. Similarly, worst case estimates of ^{31}Si and ^{42}K are 15% and 30% greater respectively than in Table II.

The major activities decay quite rapidly and after a few days become insignificant compared with more slowly decaying nuclides. The results of Ng's work have been used to find the beta and gamma energy emission rates at these later times, scaling the slow neutron captures to 1.3×10^{23} (65% of 2×10^{23} neutrons entering). Results are shown in Figures 1 and 2. Although Ng calculates the fast captures on the assumption that the neutrons entering are all at 14 MeV, we do not think neglect of moderation in the device and shield makes much difference. The production of ^{54}Mn from ^{54}Fe (n,p) was found to be only 17% less with a degraded spectrum than Ng obtains for the same flux of 14 MeV neutrons.

It is clear that, with appropriate shielding, the energy emission from the induced activity in the rock from 1 hour onwards is of the same order of magnitude as that from induced activity in lead in the device. After about 10 days, however, the gamma energy emission rate from the induced activity in rock decays rather slowly indicating a possible long term residual hazard from the fallout, but this is always considerably less than the energy emission rate from even 1 kT of fission products.

3. Distribution of activity in the fallout

In this study a fallout distribution based on data obtained from the Sedan experiment is assumed. In order to apply these data to the model explosions (0, 1 and 10 kT of fission products and set amounts of induced activities) values are needed for the amounts of activity produced by the Sedan device. In particular, we need to estimate its fission yield, the precise value of which has not been disclosed. We know that "less than 30 per cent of the energy came from fission", but for our purpose an upper limit is not good enough because scaling to a different fission yield leads to an underestimate of the levels. Some additional data reported by Nordyke and Williamson {1} can be used to make a better estimate for the present purpose.

First, they give the fallout pattern in terms of the gamma dose-rate at 24 hours after the explosion constructed from a radiation survey between 20 and 28 hours. Radiochemistry results show that about 42 per cent of these dose-rates are due to fission product activity, 55 per cent to ^{187}W and 3 per cent to ^{24}Na and other induced activities. Secondly, they integrate over the area of the fallout pattern and find that the dose from 1 hour to infinite time is equivalent to a total deposition of 2.0 kT of fission product activity, and we assume that this evaluation includes a terrain shielding factor. We also assume that a component due to ^{187}W is included, and by consideration of the decay rates of fission products and ^{187}W , we deduce that the actual amount of fission product activity deposited is equivalent to 1.4 kT of fission. Thirdly, the most probable value of the fraction of activity produced which is deposited in the fallout is 10 per cent, with a possible spread between 6 and 17 per cent {5}. Taking 10 per cent venting gives us an estimate of 14 kT for the fission yield of Sedan. It is assumed that there is no significant fractionation, and this is supported by radiochemical analysis of the local fallout {6} but is not true of long range fallout in which high enrichment of volatile chain products has been observed in activity brought down by rain{7}.

Table II. Induced activities in acid rocks -

β and γ energy emission from 1 hour to infinite time for 2×10^{23} neutrons entering the rock

Radio-nuclide	Half life	Parent element and weight %	Abundance of parent nuclide	Fraction of neutrons captured	Average energy per disintegration (MeV)		Energy emission from 1 hour to infinite time (10^{22} MeV)	
					β	γ	β	γ
^{24}Na	15.0 h	Na 2.77	1	0.0335	0.465	4.122	0.289	2.64
		Al 7.70	1	0.0047			0.042	0.37
		Mg 0.56	0.786	0.0006			0.005	0.05
^{31}Si	2.62 h	Si 32.30	0.0305	0.00205	0.49	~ 0	0.016	0
^{32}P	14.3 d	P 0.07	1	0.00024	0.57	~ 0	0.003	0
		S 0.04	0.95	0.00023			0.003	0
^{42}K	12.52 h	K 3.34	0.069	0.00344	1.09	0.275	0.072	0.02
^{56}Mn	2.58 h	Mn 0.06	1	0.0077	0.62	1.81	0.073	0.21
		Fe 2.70	0.917	0.0007			0.007	0.02
^{152}Eu	13 y	Eu 1.7×10^{-4}	0.478	0.0020	0.10	1.05	0.004	0.04
TOTAL							0.523	3.35

This estimate allows us to set up a reference pattern, Figures 3 and 4, which shows the gamma dose-rate contours at 24 hours due to fission products alone when a 100 kT explosion including 1 kT fission yield occurs under Sedan conditions. The observed dose-rates are multiplied by the factor $0.42/14 = 0.03$. Figure 5 shows the corresponding dose-rate as a function of range along the "hot line" of the pattern.

4. Dose limits

Before conclusions can be drawn about the areas and duration of hazards to members of the public from given amounts and distribution of activity some limiting levels must be specified. It would be inappropriate to discuss this problem at length here, so we shall simply take the figures given by the ICRP{8} for small populations, which we interpret as limits suitable for planning purposes, but which may not necessarily be accepted in the authorization of a specific project.

These dose limits are one tenth of the recommended annual maximum permissible dose for occupational workers, with the single exception that for irradiation of the thyroid of children the limit is one twentieth of the occupational maximum permissible dose. We therefore adopt the dose limits given in Table III.

Table III. Dose limits for members of the public

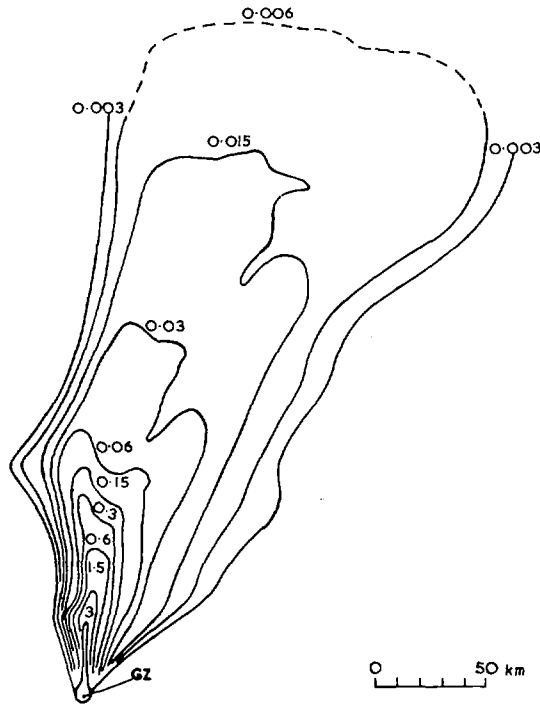
<u>Organ</u>	<u>Annual dose limit (rems)</u>
Gonads, red bone marrow	0.5
Whole body in uniform irradiation	0.5
Skin, bone	3.0
Thyroid (children under 16)	1.5
Hands, forearms, feet, ankles	7.5
All other organs	1.5

These limits are regarded as allowable in addition to the dose received from natural background radiation and by the patient in the course of medical procedures. They do not allow for possible genetic risks because the exposure of large numbers of people is not envisaged and the dose rate to the critical organ is expected to decay within a relatively short time. Genetic hazards require the gonad dose to be less than 5 rems in 30 years.

5. External hazards

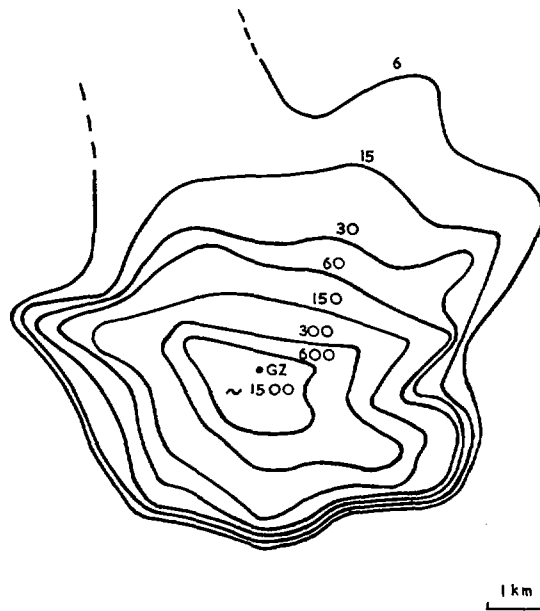
The primary external hazard is from radioactive fallout. To assess the extent of the hazard the gamma dose-rate contours shown in Figures 3 and 4 must be related to the dose limits for whole body irradiation. For the present purpose it is sufficiently accurate to assume that the gamma dose-rate is proportional to the energy emission rate, and then the data of Figure 2 for fission products lead to the result that an integrated dose of D mR from 1 hour to infinite time corresponds to a dose-rate of $4.6 \times 10^{-3} D$ mR/hr at 24 hours. If gamma rays from the fission products were the only hazard we should take $D = 500$ mR. Then, if the fission yield is 1 kT, the approximate boundary of the region within which the dose limit is exceeded would be shown by the 2.3 mR/hr contour of Figure 3. The connection is not quite exact because the integrated dose depends on the time of arrival of the fallout, which is not necessarily 1 hour and is not the same everywhere on the contour.

This simple calculation can readily be extended to take account of beta radiation from the fission products and radiation from induced activities. It is assumed that all types of activity are distributed in the local fallout in



GAMMA DOSE-RATES IN mR/HR AT H+24 HOURS

FIGURE 3. MEDIUM RANGE FALLOUT PATTERN FOR FISSION PRODUCTS FROM 100 KT CRATERING EXPLOSION WITH 1KT FISSION. SCALED FROM SEDAN PATTERN.



GAMMA DOSE RATES IN mR/HR AT H 24+HOURS

FIGURE 4. SHORT RANGE FALLOUT PATTERN FOR FISSION PRODUCTS FROM 100 KT CRATERING EXPLOSION WITH 1KT FISSION. SCALED FROM SEDAN PATTERN.

the same way as the fission product gamma activity. The most susceptible organs, the gonads and red bone marrow, are protected against beta particles from an external source by the body tissue itself. The critical organ is the skin for which the annual dose limit is 3 rems. Introducing additive dose terms for the induced activities there are two criteria, both of which should be satisfied, to determine the region where the dose does not exceed either 500 mR to the whole body from gamma rays or 3000 mrem to the skin from beta and gamma rays, viz.,

$$D_{\gamma F}(t) + D_{\gamma d}(t) + D_{\gamma r}(t) < 500 \text{ mR} \quad \dots (1)$$

$$\text{and } D_{\gamma F}(t) + D_{\gamma d}(t) + D_{\gamma r}(t) + D_{\beta F}(t) + D_{\beta d}(t) + D_{\beta r}(t) < 3000 \text{ mrem} \quad \dots (2)$$

where $D(t)$ represents the dose in mrem from time t to infinite time to a man standing on a uniformly contaminated plane, and the subscripts β , γ , F , d , r identify, respectively, beta and gamma contributions, and the sources fission products, induced activity in the device and induced activity in the rock.

It is convenient to divide both criteria by $D_{\gamma F}(1)$ the gamma dose from $t = 1$ hour to infinite time from fission products. Then, if $\beta(t)$ and $\gamma(t)$ with appropriate subscripts represent the ratios of each partial dose to $D_{\gamma F}(1)$, the criteria (1) and (2) may be rearranged as

$$D_{\gamma F}(1) < \frac{500}{\gamma_F(t) + \gamma_d(t) + \gamma_r(t)} \quad \dots (3)$$

$$\text{and } D_{\gamma F}(1) < \frac{3000}{\gamma_F(t) + \gamma_d(t) + \gamma_r(t) + \beta_F(t) + \beta_d(t) + \beta_r(t)} \quad \dots (4)$$

These expressions define limiting values of $D_{\gamma F}(1)$, and allow the appropriate contour on Figures 3 and 4 to be found by using

$$\text{Dose rate at 24 hours} = 4.6 \times 10^{-3} D_{\gamma F}(1) \text{ mR/hr} \quad \dots (5)$$

These criteria apply to an explosive with 1 kT fission yield. An example with W_F kT fission yield, and no other change, can be handled by introducing a factor W_F multiplying $\gamma_F(t)$ and $\beta_F(t)$ in (3) and (4).

The dose ratios for gamma ray sources may be obtained from the data of Figure 2 by integration over time. The dose ratios for beta particle sources require some further calculation because of the small range of betas compared with gammas. The area of the contaminated plane which can contribute is smaller, but, on the other hand, the energy deposition density at the body surface is larger. We do not feel that the determinations of beta to gamma dose ratios known to us are entirely satisfactory, but we shall use here a value of 12:1 calculated by Dale {9} for the ratio of the doses delivered over the interval 1 hour to 1 year to a lightly clothed man standing on a plane contaminated with fission products. This value appears to agree reasonably well with data obtained by Dunning {10} over the first few days following fallout deposition if one allows for the change in relative energy emission rates over Dunning's period of observation.

Table IV gives values of the dose ratios required to evaluate (3) and (4). It will be apparent that the dose to the skin (beta + gamma) is limiting. However, the conditions which lead to this conclusion are rather artificial as it has been assumed that exposure to both the beta and gamma field is continuous. Any light building or vehicle will give good protection against the beta particles, but possibly not against gamma rays, so that one can reasonably assume that actual beta doses are substantially overestimated by

Table IV. For this reason we shall use the gamma dose criterion (3) subsequently in this paper, but the beta dose should be taken into account if totally unprotected people might be exposed.

The accuracy of the values in Table IV may decrease for exposure beginning a long time after deposition because no account has been taken of weathering or redistribution in wind blown dust.

Table IV. Ratios of doses to fission product gamma dose from 1 hour to infinite time

Exposure begins at time t	Fission Products		Induced activity in device		Induced activity in rock		Total	Total
	$\beta_F(t)$	$\gamma_F(t)$	$\beta_d(t)$	$\gamma_d(t)$	$\beta_r(t)$	$\gamma_r(t)$	$\beta + \gamma$	γ
1/4 hr	16.7	1.47	0.89	0.21	0.39	0.20	19.98	1.88
1/2 hr	14.3	1.22	0.85	0.21	0.38	0.19	17.2	1.62
1 hr	12.0	1.00	0.77	0.21	0.36	0.19	14.5	1.40
2 hr	9.89	0.81	0.62	0.21	0.33	0.18	12.0	1.20
3 hr	8.66	0.72	0.50	0.21	0.31	0.17	10.6	1.10
6 hr	6.98	0.59	0.27	0.20	0.25	0.14	8.43	0.93
1 d	4.38	0.39	0.006	0.16	0.10	0.068	5.10	0.62
10 d	2.24	0.20	-	0.009	0.010	0.006	2.47	0.22
100 d	1.07	0.041	-	-	0.005	0.005	1.12	0.046
1 yr	0.35	0.007	-	-	0.004	0.004	0.37	0.011

Applying the ratios of Table IV and the equations (3) and (5) one can see the contraction of the limiting contour with increasing delay before reentry. For the example with 1 kT fission yield Figure 6 shows typical limiting contours and Table V shows maximum downwind extent. After about 10 days only the area of short range fallout extending to a radius of some 5 km around ground zero needs to be restricted.

Introducing the fission yield factor into (3) similar results can be found for different amounts of fission. Figure 7 compares limiting contours for 10 kt, 1 kT and zero fission yields for exposure beginning at 1 hour.

Table V. Maximum extent of limiting dose contours for exposure beginning at different times - 1 kT fission

Exposure begins at time	Equivalent 24 hr dose rate (mR/hr)	Maximum range (km)
1 hr	1.64	45
3 hr	2.1	40
6 hr	2.5	37
1 d	3.7	28
10 d	10.5	< 10
100 d	50	5

From the results obtained in this section it is clear that a substantial reduction in the area enclosed by the limiting contour for the external gamma dose from the fallout is to be expected if the fission yield is reduced from

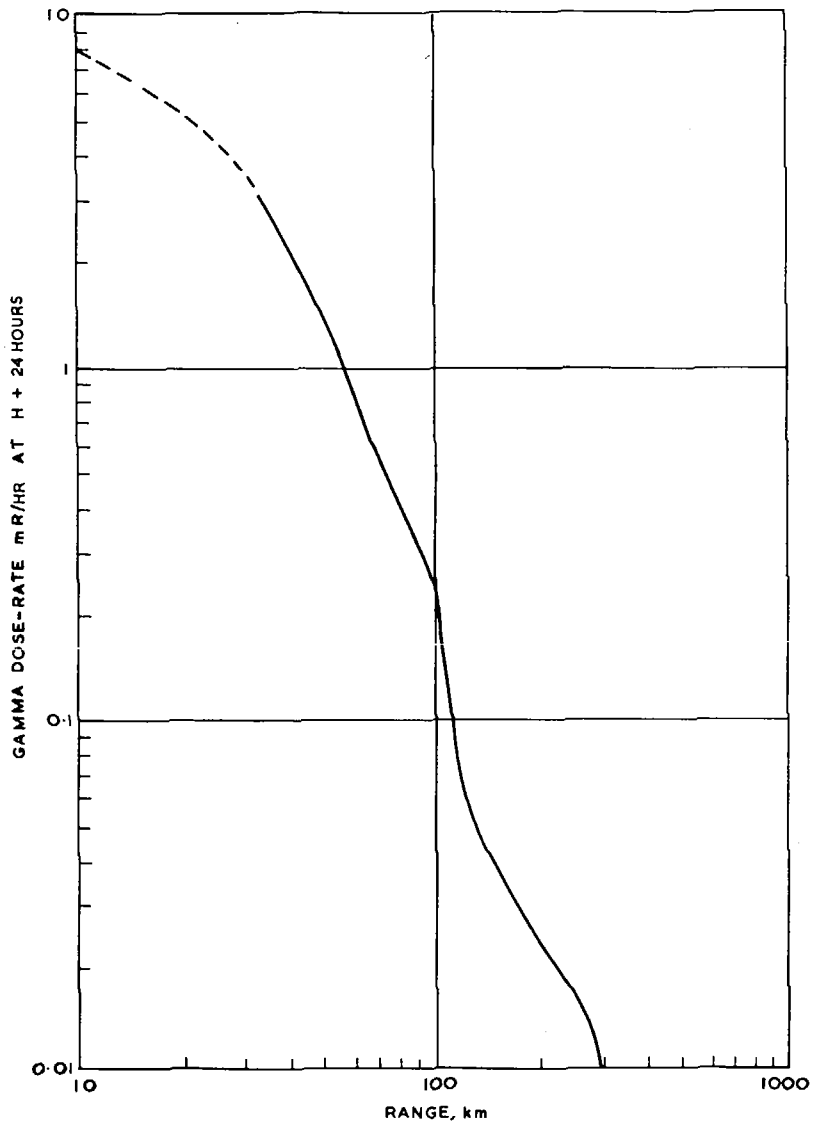


FIGURE 5. GAMMA DOSE RATE FROM FISSION PRODUCTS ALONG
HOT LINE OF ILLUSTRATIVE FALL OUT PATTERN

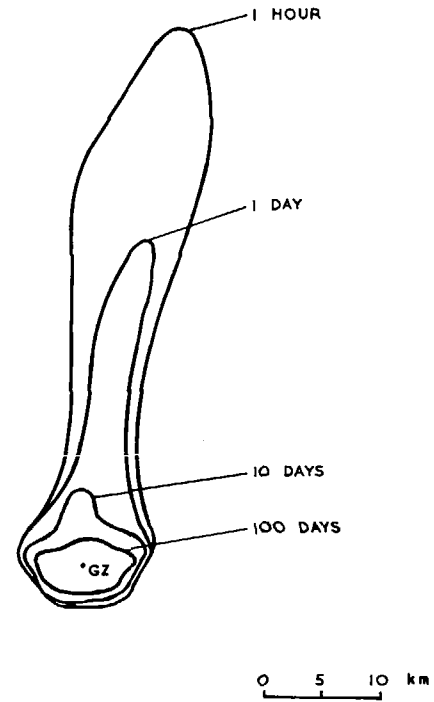


FIGURE 6. 0.5 R DOSE CONTOURS FOR EXPOSURE BEGINNING AT DIFFERENT TIMES
100 KT CRATERING EXPLOSION WITH 1 KT FISSION

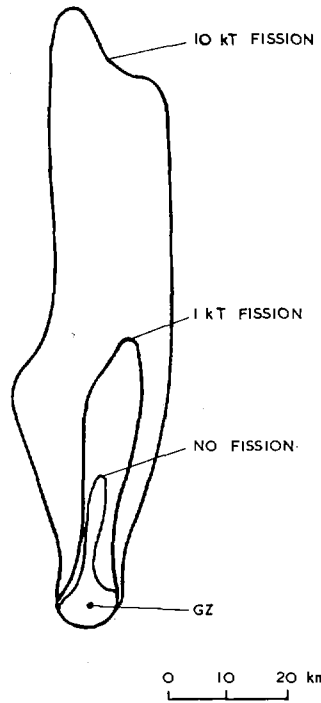


FIGURE 7. 0.5R DOSE CONTOURS FOR 100KT CRATERING SHOTS WITH DIFFERENT FISSION YIELDS

10 kT to 1 kT in a 100 kT explosive. Some further reduction could be achieved by reducing the fission yield below 1 kT, but at about the 0.2 kT level the inevitable induced activities are roughly equal to the fission product contribution. In these examples the neutron shielding has been held constant, the amount being chosen so that the gamma emission from induced activity in the rock is of the same order as that from induced activity in the device. Obviously, if the fission yield is several kT the neutron shielding requirement could be relaxed without undue penalty.

The external dose received from exposure to the drifting cloud has also been considered. Sedan data {11} were scaled to the 1 kT fission example and show that the dose received at a given distance may be of order 15% of the dose to infinite time from the fallout. For example, at 66 km range the cloud dose would be about 20 mR, delivered between 2½ and 4 hours after explosion, whereas the dose from fallout is about 150 mR. The cloud dose is regarded as an insignificant extra hazard, bearing in mind the low accuracy of all these calculations.

6. Internal Hazards

Internal hazards may arise from the entry of radioactivity into the body from the environment. Possible routes are inhalation, consumption of contaminated food or water and injection into the bloodstream through injuries. Because the source is within the body short range radiations, such as α and soft β particles, as well as γ rays are important.

The ICRP {8} recommends limiting doses for the various body organs, and gives the equilibrium fractions of practically all nuclides of interest present in the organs under conditions of steady intake and elimination. These factors are used to establish maximum permissible concentrations (MPC) of each nuclide in air and water for occupational workers. To set concentration limits for members of the general public we reduce the occupational MPC by a factor 10 for all nuclides except iodine, for which the factor is 20. In our problem, however, intake (in terms of curies of activity) is sometimes decreasing with time and to allow for this it is assumed that the annual dose limit may be received within a shorter time interval if this increases the concentration limit. Then the steady intake concentration limit for a given nuclide may be increased by the factor $365 \lambda_r$, where λ_r is the physical decay constant in units (days)⁻¹, provided this factor is greater than unity. No account has been taken of any difference in the distribution within the body between steady and transient cases.

Some problems in which internal hazards might be important have been studied and are briefly discussed below. To assess the relative importance of internal hazards a comparison is made with the local external hazard (where one exists). It is necessary to express the activity distribution in curie units. To convert the data of Figures 3 and 4 the gamma dose-rate 1 metre above a uniform ground distribution of 1 mCi/m² of fission products at 1 hour is taken to be 10 mR/hr {12} assuming a terrain shielding factor 0.7. At 24 hours this dose-rate has fallen to 0.16 mR/hr. Thus the 1 mR/hr level on Figures 3 and 4 corresponds to about 6 mCi/m² of 1 hour fission products.

6.1 Short term hazards

Short term hazards arise from the intake of fairly rapidly decaying nuclides at early times. Inhalation of activity from the initial cloud and of volatile elements, iodine in particular, evaporating from the fallout is considered.

To deal with inhalation of the cloud debris let the concentration of a nuclide X_j in the cloud at the time it reaches the individual be C_j $\mu\text{Ci}/\text{cm}^3$ and q_j μCi be the limiting amount of X_j that may be inhaled during a single exposure. Then the intake may be expressed in terms of the concentration limit by

$$I_j = \frac{B \int C_j dt}{q_j} \quad \dots (6)$$

where B cm^3/s is the breathing rate, and the integral is taken over the time of passage of the cloud in seconds. We take $B = 350$ cm^3/s , the value appropriate to the working part of the day. $\int C_j dt$ can be estimated by making use of the external dose measurement for the passage of the cloud and q_j can be calculated from ICRP formulae and data {8}. For total fission products q is evaluated by assuming a $t^{-1.2}$ decay law instead of a specific decay constant λ , and in this case q depends on the time of inhalation.

Table VI summarises the results for inhalation at 66 km range for the example with 1 kT fission.

Table VI. Inhalation hazards from debris cloud at 66 km range

Nuclide	Total activity at 3 hours μCi	q_j μCi	Critical Organ	I_j (concentration limits)
Fission Products	1.2×10^{14}	300	GI (LLI)	0.21
^{203}Pb	1.2×10^{13}	1000	Kidney	0.006
^{209}Pb	5.0×10^{13}	2200	GI (LLI)	0.012
^{24}Na	2.0×10^{12}	180	GI (LLI)	0.006
^{56}Mn	1.4×10^{12}	540	GI (LLI)	0.0014
^{131}I	1.0×10^{11}	0.6	Thyroid	0.088
^{133}I	1.3×10^{12}	4.2	Thyroid	0.17
^{135}I	5×10^{12}	12	Thyroid	0.22

These results relate to members of the public, and where the thyroid is the critical organ they relate to children below the age of 16. The thyroid receives 0.46 of the dose limit and the gastro-intestinal tract 0.23 of the dose limit, but this is at a range rather greater than the limiting range for the external dose limit from initial fallout. Closer in the intake will be larger, so the problem of inhalation of cloud debris appears quite serious, although it can be avoided by temporary evacuation.

Data from Sedan {4} indicate that 2.8% of the expected ^{131}I deposition in the fallout evaporates daily between days 3 and 10. The continuous source from a place where the level of fission product activity at 1 hour was $\sigma(r)$ mCi/m^2 is therefore at most

$$S(r) = \frac{0.028 \times 1.5 \times 10^5}{8.64 \times 10^4 \times 4 \times 10^8} \sigma(r) \text{ mCi}/\text{m}^2\text{s} \quad \dots (7)$$

where 1.5×10^5 Ci is the maximum quantity of ^{131}I produced and 4×10^8 Ci is the total activity of 1 kT of fission products at 1 hour.

Consider a surface wind blowing along the hot line of the fallout pattern carrying the vapour to a person at 50 km range. Sutton {13} gives the concentration at distance x metres from a cross-wind line source of material (gas, smoke or evaporating liquid) as

$$\text{Concentration} = 0.035 S dx \left(\frac{x}{100}\right)^{-0.9} \text{ mCi/m}^3 \quad \dots (8)$$

Substituting for S, putting $x = 50000 - r$ and integrating along the hot line of the fallout pattern, using the fact that 1 mR/hr observed gamma dose rate at 24 hours corresponds to 6 mCi/m² of 1 hour fission products, leads to a maximum concentration of 3×10^{-4} $\mu\text{Ci/m}^3$. With breathing rate 20 m³/day, and allowing for decay of the ¹³¹I, the intake by a person continuously exposed is at most 0.07 μCi , which is a factor 8 lower than the limiting intake for a child under 16 (Table VI). The intakes of ¹³³I and ¹³⁵I are about 0.1 μCi each, but the limits are also higher. Most ($\sim 80\%$) of the intake comes from activity carried from the ground zero circle. Variable winds will therefore result in an actual intake over several days which is less than the amount calculated, and inhalation of iodine vapour is expected to be a minor hazard.

Another example in which a person at the limit of the ground zero circle, 5 km range, inhales vapour from an air current across the crater zone resulted in an intake 6 times the value calculated above. This is close to the limit for uncontrolled persons, but such persons are not likely to be so near in the relevant time period.

6.3 Long term hazards from inhalation

A hazard will exist if resuspended contaminated dust is inhaled. It is a difficult one to evaluate with reasonable accuracy because of the uncertainties in the concentration in the air of active particles of sizes which will be retained in the lung, and in the level of surface contamination over long periods of time. Particles of interest are those less than 10 microns diameter at unit density, for sand the corresponding diameter is 6 μ . When such small particles become airborne they will be carried some distance by the wind before being deposited again, and so over long period they will become widely dispersed.

Stewart{14} has discussed in detail the estimation of airborne concentrations above contaminated surfaces, describing both experimental and theoretical studies. He expresses the relationship in terms of a resuspension factor K, defined as

$$K(\text{m}^{-1}) = \frac{\text{Airborne concentration (units m}^{-3}\text{)}}{\text{Surface contamination level (units m}^{-2}\text{)}}$$

The value of K depends on a number of parameters, some of which are difficult to quantify. The important ones seem to be violence of disturbance of the surface, roughness, moisture content, particle size, wind speed, height above the surface and effects of weathering. Insufficient data exist for a complete understanding of the variation of K with these parameters, but Stewart recommends values outdoors of 10^{-6} m^{-1} under quiescent conditions and 10^{-5} m^{-1} under conditions of moderate activity. These are certainly upper limits; some of the experiments result in factors a few orders of magnitude lower, particularly when the particles are small. In the experiments in which values of order 10^{-5} m^{-1} were found only about 10% of the activity was carried on small particles in the hazardous size range. Furthermore, Stewart shows by eddy diffusion theory that small particle contamination can persist for times of order one year only if K is less than 10^{-6} m^{-1} (except under a continuous inversion in the atmosphere). Therefore, we believe it is safe to adopt a value of $K = 10^{-6} \text{ m}^{-1}$ as an upper limit, which may, in some circumstances, be a substantial overestimate.

The inhalation hazard from resuspension of deposited fission products and induced activity is estimated, assuming continuous exposure for at least one year. The amount of each nuclide present is expressed in terms of the limiting air concentration using ICRP data {8}, allowing for decay of nuclides with moderately short half lives and reducing the limits by an extra factor 3 because intake of a mixture of radionuclides should be assumed to affect the whole body rather than a specific critical organ. Inhalation of fission products is more important than inhalation of induced activities, the hazard being due principally to ^{90}Sr and ^{144}Ce . In terms of the fission product activity present at 1 hour the limiting air concentration is 10^{-3} mCi/m³ when exposure begins at 10 days after the explosion, rising to 2×10^{-3} mCi/m³ and 3×10^{-3} mCi/m³ for exposures beginning at 100 days and 1 year respectively.

Taking the resuspension factor $K = 10^{-6} \text{ m}^{-1}$, the limiting surface deposition of fission products is therefore at least 10^3 mCi/m² at 1 hour. This level of fallout corresponds to a gamma dose rate of 170 mR/hr at 24 hours, which occurs only within the ground zero circle even for the example with 10 kT fission yield (Figure 4). Similar calculations for the other examples show that the inhalation hazard exceeds its limit only within an area where uncontrolled access must in any case be prevented because of the external gamma dose, for reentry times up to at least one year.

6.4 Long term hazards from ingestion

Ingestion of activity might occur through drinking water or consuming food from a contaminated area. Contamination of the ground water supply is considered. An assessment requires a determination of the probable concentrations of radionuclides in the water at the explosion site. For a few nuclides these concentrations are high by comparison with the limiting concentrations in drinking water, so the transport of activity from the site to the source of the drinking water supply is important. Flow rates can vary enormously, but in general ground water moves slowly, taking years rather than days to move a distance of one mile. In these circumstances, short-lived nuclides decay to insignificance within short distances. The biologically significant long-lived nuclides are tritium, the fission products ^{90}Sr and ^{137}Cs and the neutron activation product ^{60}Co .

Contamination of ground water by underground nuclear explosions has been discussed in detail by Piper and Stead {15}. To calculate the initial concentration of activity for a cratering explosion they consider the volatile nuclides to be dispersed in four equal parts: (a) to the atmosphere, (b) in ejecta surrounding the crater, (c) uniformly through the fall-back material within the crater, and (d) uniformly through the lower hemisphere of the shock zone. The shock zone is the region within which propagation of the pressure pulse is supersonic in the medium. It extends to about twice the initial cavity radius, and within it the rock is deformed beyond its elastic limit and is well broken up. In post-shot drilling to contained explosions activity has been found within this region, but little has been found beyond it even though fractures have occurred.

The activity which gets into ground water is that within regions (c) and (d). The mass of rock in each of these regions is about 7×10^{12} g for a 100 kT explosion and it is assumed here that the mass of contained water is 5% of the rock mass, 3.5×10^{11} g in each region.

Tritium is likely to be chemically combined in the water and move with it. 2×10^6 Ci are assumed to be left after the explosion, so the initial concentration in the water is about $1.5 \mu\text{Ci}/\text{cm}^3$. The concentration limit in drinking water is $3 \times 10^{-3} \mu\text{Ci}/\text{cm}^3$ for the general public {8} so the level is 500 times the limit.

The other nuclides mentioned above will be preferentially held in the solid debris rather than the water, the distribution coefficient depending on the characteristics of the nuclide-rock-water system. Using the same values as Piper and Stead the ^{90}Sr concentration is about 40 times the concentration limit in the 1 kT fission example, but ^{137}Cs and ^{60}Co are not important.

Tritium is therefore the principal hazard in ground water, unless the fission yield is 10 kT or more in a 100 kT shot. The level is likely to be so high that it is vital to determine the motion of water at the explosion site whenever there is any chance of it reaching supplies used for human or agricultural consumption. Reported flow rates are generally a few feet per day or less, so one would expect any hazard to be limited to within about 20 km of the explosion because sufficient radioactive decay would occur by the time the tritiated water had travelled this distance. However, the time involved is of order 100 years. Dilution of the tritium as it moves has been neglected.

7. Conclusions

Calculations on a hypothetical model of a 100 kT explosive with low fission yield indicate the value of a fission yield of 1 kT or less. Reduction below 1 kT fission gives a diminishing return, and at the 0.2 kT level the induced activity in the device structure (lead) contributes as much to the fallout dose as the fission products. Neutron shielding between the device and the surrounding rock is necessary.

Taking the Sedan fallout distribution pattern as an illustrative example, the external gamma dose limit, assumed to be 0.5 R, extends to 45 km when the fission yield is 1 kT. After 10 days resettlement beyond 10 km from ground zero may be possible, but continuous residence close to the crater may not be permissible for at least one year.

In general, the external gamma dose from fallout will be the controlling hazard, but in special cases the beta dose should be taken into account.

Possible internal hazards could arise from inhalation of iodine in the airborne cloud and drinking water contaminated with the tritium. The first is transient and can be avoided by temporary evacuation of people along the cloud track. Evacuation may be necessary beyond the limiting range for the external fallout dose, but in practice a safety factor is likely to be applied to fallout predictions in any case. The level of tritium in water at the explosion site is certain to exceed the limiting level in drinking water. Whether or not this is hazardous depends on the flow of this water towards sources of water supply. If the flow is slow, of order a few feet per day, the risk is likely to be confined to any sources within 20 km of the explosion site. However, it will not immediately be apparent that a source is at risk.

III. CONTAINED EXPLOSIONS FOR STORAGE

1. The Problem

One possible application of contained nuclear explosions is gas storage in the chimney. In this application there will be no uncontrolled release of radioactivity in the environment, provided proper precautions are taken to prevent venting up the emplacement hole and to avoid contamination of aquifers. The principal problem is contamination of the product by tritium and ^{85}Kr .

As an example consider a 25 kT explosive at a depth of 2000 feet. The cavity volume, the available storage volume, is then of order 10^5 m^3 . The explosive yield in this case would come mainly from fission, but if a thermo-nuclear device is used there would be some residual tritium and we shall assume here that 4 g ($4 \times 10^4 \text{ Ci}$) remain as in the Gasbuggy shot. {16}

Apart from tritium, noble gas activities and potentially volatile products such as iodine must be considered. The most important of these in the long term is ^{85}Kr , a fission product with half life 10.6 years. Gasbuggy produced 350 Ci of ^{85}Kr . Other noble gas activities are produced initially in far greater amounts, but decay fairly quickly. For example ^{133}Xe , a fission product with half life 5.3 days, has an initial activity of 10^7 Ci from 25 kT fission, but after 80 days its activity falls below that of ^{85}Kr . There may also be substantial production of ^{37}Ar , half life 35 days, in the surrounding rock by the $^{40}\text{Ca} (n, \alpha) ^{37}\text{Ar}$ reaction. The concentration in early Gasbuggy samples was about 40 times greater than that of ^{85}Kr {17} but the maximum permissible concentration in air is 300 times that of ^{85}Kr {8}. The concentration of 8-day ^{131}I observed in the Gasbuggy samples was very low {17}. These considerations suggest that tritium and ^{85}Kr are the only gaseous nuclides of concern provided a few months elapse before operations begin on the chimney.

The chimney could be filled with gas at a pressure of about 80 atmospheres. Assuming all the tritium is dispersed uniformly in the gas, its concentration when released at atmospheric pressure is 5×10^{-3} Ci/m³. There will be dilution when the gas is used, but the concentration limit for uncontrolled release is only 2×10^{-7} Ci/m³ {8}, so the tritium concentration in the gas appears to be too high to permit domestic consumption.

Some form of purging is therefore necessary. It is considered that gaseous purging may be unsatisfactory, because the passage of many void volumes will be needed to flush out the contaminants to the degree required {18}. Gaseous purging would be more attractive if one could be sure that the tritium was present only in the form of water vapour, for the stored gas would be dried when it is drawn off and 97% of the water vapour removed. But it is thought that significant exchange of tritium between water vapour and stored gas will take place during the residence time in storage, typically of order one year, and this exchange will be promoted by the radiation field existing in the chimney.

For these reasons flushing the chimney with water has been considered. This is particularly attractive if the storage is offshore below the sea bed or near the shore on land. Filling the cavity with sea water will drive out whatever gas is initially contained, including ^{85}Kr and some tritium. The water itself will become contaminated with tritium, ^{90}Sr and ^{137}Cs , but it is not likely to leach out refractory nuclides held in the solidified residue at the chimney base. After the cavity is emptied a large area of wet rock surface and saturated water vapour will be left, and will, of course, be contaminated. If necessary, the cycle could be repeated. The radiological consequences of these operations are briefly discussed below.

2. Venting of cavity gas

Release of cavity gas to the atmosphere should be at a controlled rate such that the concentration at some reasonable distance downwind of the point of release is below the limit for uncontrolled exposure. Suppose the desired concentrations 2×10^{-7} Ci/m³ of tritium and 3×10^{-7} Ci/m³ of ^{85}Kr {8} are to be achieved at 1 km range. Sutton {13} gives the peak concentration at x metres downwind of a continuous point source emitting S units/sec as

$$2 \times 10^{-3} \left(\frac{x}{100} \right)^{-1.76} S \text{ units/m}^3$$

when the wind speed at 2m height is 5 m/s. Hence, we find $S_{\text{max}} = 6 \times 10^{-3}$ Ci/s for tritium, $S_{\text{max}} = 9 \times 10^{-3}$ Ci/s for ^{85}Kr . If we assume, pessimistically, that all the tritium is present in the gas phase, its concentration in the

cavity gas is 0.4 Ci/m^3 , so the venting rate could be $1.5 \times 10^{-2} \text{ m}^3$ of cavity gas per second. At this rate, complete venting would take about 2000 hours. However, it is more likely that most of tritium will be present in the liquid phase. Gasbuggy samples suggest that about 30% of the tritium was present as HT and CH_3T as early times (23 hours), but the HT decreased rapidly so that by 38 days only about 6% of the tritium was present in gaseous species, mostly as CH_3T . The concentration of tritium is still several times that of ^{85}Kr , however. These data suggest that the gas release time could probably be reduced to 600 hours, and possibly to about 120 hours, without exceeding continuous exposure limits at 1 km range. But it should be borne in mind that the rock composition may affect the exchange rate between hydrogen and water, for example, equilibrium may be established more quickly in carbonate than in silicate formations.

3. Discharge of water from chimney

The water filling the chimney will become contaminated by T, ^{90}Sr and ^{137}Cs , the last two fission products having gaseous precursors and therefore being dispersed through the rubble. The tritium concentration is at most 0.4 Ci/m^3 which is 130 times the concentration limit in drinking water. The ^{90}Sr and ^{137}Cs , however, will not all be in solution. In ground water contamination studies [15] it was found that these nuclides are held preferentially in the rock, and the greatest fraction in the water was

$$\frac{1}{10} \times \frac{\text{volume of water}}{\text{mass of rock}}$$

for dolomite. This fraction can be much less for other rock types. Taking the chimney height to be 4 times the cavity radius and the rock density as 2 g cm^{-3} , the fraction is $1/60$. The total amount of each nuclide in the water in our example is then 75 Ci. For ^{90}Sr , the concentration corresponds to 7500 times the concentration limit.

Howells [19] gives guidance on the rate at which this contaminated water could safely be discharged into the sea. He was concerned with discharge from the Windscale reactor site in Cumberland, UK, of beta active effluent at concentrations of $10^{-2} - 10^{-1} \text{ Ci/m}^3$ of which a few per cent is ^{90}Sr , that is, a concentration of ^{90}Sr of the same order of magnitude as ours. Maximum discharge rates for ^{90}Sr when the limiting criteria are uptake by fish and uptake by edible seaweed are 10^5 and $1.2 \times 10^4 \text{ Ci/month}$ respectively. On this basis 75 Ci of ^{90}Sr could be discharged within one day.

4. Residual contamination in the chimney

After pumping out the water, saturated vapour filling the void volume and a film of water on the rock surfaces will remain. Assuming a chimney temperature of 35°C saturated air contains 40 g/m^3 water. Thus the tritium concentration in the vapour is $1.6 \times 10^{-5} \text{ Ci/m}^3$ or 80 times the limit for direct inhalation. This level might be acceptable for gas storage under pressure because the dilution factors mentioned previously would apply. But exchange reactions may increase the tritium concentration above that due to water vapour alone, so an estimate of the total amount of tritium left in the chimney is necessary.

The amount of water left in the chimney depends on the surface areas of the broken rock and the average film thickness both of which are difficult to evaluate. Rodean [20] gives a value for the specific surface (surface : volume ratio) of 5.78 ft^{-1} determined from Hardhat photographs. This leads to a total surface area of about $6 \times 10^6 \text{ m}^2$ in our example. From surface

tension data the maximum droplet thickness is estimated to be 0.05 cm, so assuming a film of this thickness the total liquid volume is of order $3 \times 10^3 \text{ m}^3$, i.e. 0.03 of the void volume. Probably this is an overestimate unless the rock is porous (unlikely in a storage application) or a pool is left at the chimney base.

This rough estimate of the tritium left after one flushing is 3% of the initial amount. Thus two cycles might be expected to reduce the tritium by a factor of 1000, and if it is assumed that the tritium then remaining is transferred by exchange reactions to stored gas at 80 atmospheres, the concentration in the gas at atmospheric pressure is $5 \times 10^{-6} \text{ Ci/m}^3$, or 25 times the limit for uncontrolled release. Further dilution when the gas is used may be expected to reduce this concentration below the limit for uncontrolled release.

5. Conclusions

This preliminary survey has not revealed any serious health hazards underlying the proposal to flush out storage cavities with sea water. Venting of the gaseous activity initially present, ^{85}Kr and tritiated gas, could take 25 days, possibly less, if an area 1 km in radius was controlled. Disposal at sea of the water, with principal contaminant ^{90}Sr , should be permissible within one day.

The major uncertainty is the fraction of tritium remaining after flushing which is estimated to be 3%. Experimental determination of this fraction is desirable, but for the present this study suggests that two or three flushing cycles will be enough to reduce the tritium concentration in burnt gas below the limit for uncontrolled release. Complete exchange of tritium into the stored gas has been assumed.

As tritium is a greater problem than ^{85}Kr in this application the use of an all fission explosive might be considered. Even then tritium will be produced from lithium in the rock, but the production can be reduced by neutron shielding. The shielded Rulison shot is expected to yield an initial concentration of tritium in the cavity gas which is one tenth that of Gasbuggy [21].

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