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Radioactive Carbon from Nuclear Explosions and Nonthreshold Biological Effects[a]

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In this article, which appeared in the June 1958 issue of the Soviet journal, Atomic Energy, *Sakharov estimated that about 10,000 people would ultimately suffer cancers, genetic disorders, and other ill effects from the radioactivity produced by a 1-megaton nuclear explosion in the atmosphere. According to this estimate, the 1961 Soviet test of a 58-megaton nuclear explosive—an explosion that by itself accounts for about 10 percent to the total yield of all atmospheric nuclear explosions in history—will, in the long term, injure or kill about half a million people.*

Sakharov took his arguments against testing all the way to Khrushchev, but, according to his account, Khrushchev brusquely informed him that the responsibility of scientists was limited to designing the weapons. It was the responsibility of the governmental leaders to decide what to do with them. Thus ended Sakharov's faith in going through channels.*

Even though the Soviet journal in which this article appeared was being translated and published in English and independent US scientists—notably Linus Pauling—were making similar estimates, the Sakharov paper received almost no public notice in the West.

How has Sakharov's estimate stood the test of time? In a brief appendix, I compare the assumptions that he made for population radiation doses and biological dose-effect coefficients with the most recent estimates for the same numbers. Sakharov's population-dose estimate appears somewhat high and his dose-effect coefficient somewhat low. However, his resulting estimate of 10,000 deaths and other health injuries from the low-dose radiation effects from each megaton of nuclear explosion in the atmosphere over the thousands of years that the explosion-produced carbon-14 would cycle through the biosphere is in good agreement with the estimate that would be made today.

FRANK VON HIPPEL
US Chairman of the Board of Editors

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a. *This first appeared in the Soviet journal* Atomic Energy, *4, 6, June 1958. Translated from the Russian by Consultants Bureau, Inc.*

* Harrison E. Salisbury, ed., *Sakharov Speaks* (New York: Alfred A. Knopf, 1974), pp.32–34.

INTRODUCTION

When any nuclear weapons are exploded, including the so-called "clean" (fissionless) hydrogen bomb, a very large number of neutrons enter the atmosphere (see section 2) and they are then captured by atmospheric nitrogen according to the reaction

$$n + N^{14} \rightarrow p + C^{14}$$

which gives rise to long-lived radioactive carbon-14. This radioactive carbon enters human tissue, where it decays, causing radiation damage, with a dose of $7.5\ 10^{-4}$ r per megaton burst (see section 3).

I shall make the following assumptions to evaluate the harm to humanity due to the production of radioactive carbon:

- The human population in the next few thousand years will be thirty billion persons
- A dose of 1 r to the reproductive organs leads to hereditary diseases in 10^{-4} cases (see section 4)
- Other nonthreshold biological effects triple the number of cases (see section 4).

The total number of radiocarbon victims from a megaton burst is found, on the above assumptions, to be 6,600 persons. This number is spread over a period of the order of 8,000 years. According to Leipunsky's data,[1] nonthreshold biological effects due to radiostrontium and external radiation due to radiocesium increase the number of cases by a factor of 1.5, the cases occurring in our generation and the one following. The total number of cases due to nuclear tests which have already been performed (50 megaton energy) is estimated at 500,000 persons. This would seem to be a conservative estimate. One cannot eliminate the possibility that the total number of cases is already one million persons and is yearly increased by 200,000–300,000 persons.

Continued testing and all attempts to legalize nuclear weapons and testing cannot be reconciled with humanity or international law. Because the so-called "clean" (fissionless) bomb is radioactively harmful, there is absolutely no ground for the propagandistic assertions concerning the particular qualities of this instrument of mass destruction.

NEUTRON FORMATION IN NUCLEAR BURSTS

In an atomic (fission) explosion each act of fission is accompanied by an increase in the number of neutrons by a factor of $\nu - 1$ (where ν is the number of neutrons produced per neutron captured in fission). An insignificant number of neutrons produced are captured by the surrounding material (with formation of plutonium). We assume that in each act of fission (at 180 MeV) the number of neutrons produced is $\nu - 1 = 1.5$. In military terminology one usually describes the energy of a burst in terms of the equivalent mass of TNT. A burst of 1 megaton TNT equivalent corresponds to the fission of 60 kilograms of uranium or plutonium, with the emission of 2.25×10^{26} neutrons.

There are two different types of pure thermonuclear bomb, namely those which use liquid deuterium and those which use the chemical compound of deuterium with the light isotope lithium-6. The first of these bombs produces many more neutrons per unit energy. We shall, however, restrict our considerations to the second, since it would seem that it is just this type of bomb which is at present receiving most attention. The fundamental reactions taking place in this bomb are:

$$D + D \rightarrow He^3 + n \qquad (1)$$

$$D + D \rightarrow H^3 + p \qquad (2)$$

$$n + Li^6 \rightarrow He^4 + H^3 \qquad (3)$$

$$H^3 + D \rightarrow He^4 + n \qquad (4)$$

The effective probability (that is, the product of the cross section by the rate of reaction) for reactions 3 and 4 is about one hundred times as great as that for reactions 1 and 2.

Most of the energy of the burst comes from the "fast" reactions 2 and 4. These reactions aid each other, and together they leave the total number of neutrons and tritium nuclei invariant. The "slow" reactions 1 and 2 serve as the initial neutron and tritium sources.

A detailed investigation of the kinetics of reactions 1–4 shows that when the lithium-6 is sufficiently burned out, one cycle of reactions 3 and 4 leaves about 0.2 neutrons and 0.2 tritium nuclei which arise as a result of 1 and 2. In this cycle 22 MeV of energy is liberated, which means that one neutron is liberated per 110 MeV of burst. This number is very close to the figure 180 MeV/1.5 = 120 MeV for an atomic burst.

In a hydrogen bomb surrounded by a uranium shell, a large amount of the energy results from fission of uranium-238 by fast neutrons from reactions 4 and 1. Since, however, the number of neutrons per unit energy is almost the same for a pure atomic and a pure thermonuclear burst, we may say that in this case also we get 2.25×10^{26} neutrons per megaton.

CALCULATION OF THE RADIATION DOSE

We shall use experimental data referring to natural carbon-14.[2] Cosmic rays cause many kinds of nuclear reactions in the upper layers of the atmosphere, and one of the products of these reactions is neutrons at the rate of 2.6–2.4 neutrons $cm^{-2}\ s^{-1}$. After being slowed down, about 95 percent of these neutrons are captured by atmospheric nitrogen, forming carbon-14 according to the reaction

$$n + N^{14} \rightarrow p + C^{14}$$

The half-life of carbon-14 is 5,570 years. Even in biochemical processes, carbon-14 is chemically very similar to stable carbon. During this lifetime the carbon-14 concentration reaches equilibrium with the stable carbon of the so-called exchange reservoir, that is, atmospheric carbon in the form of carbon dioxide, carbon in rivers and ocean waters in the form of soluble compounds, and finally carbon in living organisms. For natural carbon-14 this concentration has been measured experimentally. In 1 gram of natural carbon of the exchange reservoir there take place 0.25 decays per second, which corresponds to 6×10^{10} atoms of carbon-14 per 5×10^{22} atoms of carbon-12. The surface area of the earth is 5×10^{18} square centimeters. We find that the probability for decay of a single carbon-14 nucleus formed in the atmosphere per gram of carbon of the exchange reservoir is $0.25/(2.6 \times 5 \times 10^{18}) = 2 \times 10^{-20}$ per gram.

We shall assume that the geochemical environment of the earth will not change significantly over the next several thousand years. Then the decay probability per gram of carbon which we have obtained for natural carbon-14 is good also for carbon nuclei formed at present in nuclear bursts.

This same statement can be phrased in terms of linear equations. Every solution of a set of linear equations (with independent variables x and t) whose right side is $q(t)$ at the point $x = 0$ can be expressed by a superposition of singular solutions of the following type:

$$\text{Singular solution} \begin{cases} \text{source} & \delta(x)\,\delta(t - t_0) \\ \text{solution} & \mathrm{n}(x, \tau) \end{cases}$$

$$\text{Superposition} \begin{cases} \text{source} & \delta(x)\,q(t) \\ \text{solution} & N(x,t) = \int_0^\infty q(t - \tau)\,\mathrm{n}(x,t)\,\mathrm{d}x \end{cases}$$

where $\tau = t - t_0$ and n is a Green's function.

In the special case of a steady source q_0 at the point $x = 0$, the solution at $x = x_0$ is

$$N_0(x_0) = q_0 \int_0^\infty \mathrm{n}(x_0, \tau)\,\mathrm{d}\tau \quad \Rightarrow \quad \int \mathrm{n}\,\mathrm{d}\tau = \frac{N_0}{q_0}$$

In our case x denotes the coordinates of points in the exchange reservoir, and $x = 0$ denotes the upper layer of the atmosphere; $q_0 = 2.6/4\pi R^2$ neutrons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$; $N_0 = 0.25$ decays $\mathrm{s}^{-1}\ \mathrm{g}^{-1}$; $R = 6.3 \times 10^8$ is the radius of the earth in centimeters; $\mathrm{n}(x_0, t - t_0)$ is the number of decays per gram of natural carbon per second at the point x_0 at time t divided by the number of carbon-14 nuclei produced in the atmosphere at time t_0.

We then obtain $\int \mathrm{n}\ \mathrm{d}t = 2 \times 10^{-20}$ per gram.

For a 1-megaton burst we obtain $(2.25 \times 10^{26}) \times (2 \times 10^{-20}) = 4.5 \times 10^6$ decays per megaton per gram.

We shall express the radiation dose in roentgens, setting a roentgen approximately equal to a rad, which we take as the dose that will produce 100 ergs of ionization energy per gram of tissue.

The maximum energy of carbon-14 beta decay is 0.154 MeV, about two-thirds of which is carried away by a neutrino. Thus about 0.05 MeV is liberated in the tissues, or 8×10^{-8} ergs per decay.

Assuming further that carbon makes up about 18 percent of the weight of the body, we find the total energy liberated per gram of tissue from a 1-megaton bomb to be $0.18 \times (4.5 \times 10^6) \times (8 \times 10^{-8}) = 7.0 \times 10^{-2}$ ergs per gram $= 7.5 \times 10^{-4}$ r.

The data are not as good when we come to the time distribution of the decay, that is, on the form of the function $n(x_0, t)$. Using Anderson's[3] estimate of 8.5 g/cm^2 for the mass in the exchange reservoir, we can assume that within this reservoir equilibrium is attained in a time short compared with the lifetime of carbon-14, and that the carbon-14 leaves the reservoir at an insignificant rate. On these assumptions the time dependence of the decay will be an exponential of the form $\exp(-t/8{,}000 \text{ years})$

NONTHRESHOLD BIOLOGICAL EFFECTS OF RADIATION

A thermonuclear war involves the potential danger to all of humanity of being subjected to a lethal radiation dose (about 600 r). This danger would not seem to exist in testing nuclear arms, since at the present rate of testing the dose per person is never greater than 1 roentgen. However, billions of persons are subjected to this dose in addition to the natural background, and will be so subjected (in the case of carbon-14) for several hundreds of generations. The amount of sickness caused by this additional radiation from testing under these conditions is found from the so-called nonthreshold biological effects. The number of cases is proportional to the total dose for all of humanity (that is to the dose in roentgens per person multiplied by the number of persons) independent of the distribution of the radiation over the population or of its time dependence.

The simplest nonthreshold effect of radiation is hereditary.[4] The substance which transmits heredity is the gene, a special structure in the chromosomes of cell nuclei. For an irreversible change of a gene (a so-called gene mutation) a single act of ionization is sufficient, so that genetic changes can occur as a result of the weakest radiation doses with a probability which is exactly proportional to the dose.

Each gene is in a certain sense a letter in the biochemical program of the development of an embryo. Therefore a change in one gene may in certain cases (for dominant mutations or accumulation of mutations) lead to very significant hereditary changes.

At the present time human births involve about 2 percent hereditary diseases (schizophrenia, hemophilia, diabetes, and many others) caused by mutations. The number of actual mutations is less than this, since some people with hereditary diseases reproduce, and a single mutation may give rise to effects over several generations. This does not, however, destroy the proportionality between the number of mutations and the number of hereditary sicknesses. According to presently accepted ideas based on Meller's experiments with mice, 5 percent of mutations, and therefore also of hereditary sicknesses, results from natural radioactivity (10 r over a human life of 60 years*). Collecting all these figures, we obtain the coefficient which gives the increase of hereditary sickness due to radiation, namely

$$\frac{0.02 \times 0.05}{10} = 10^{-4} \text{ per roentgen.}^{\dagger}$$

The mean human population during the time it takes the carbon-14 to decay will probably be about 30 billion persons (about 10 or 11 times greater than at present). This estimate is not incompatible with increases in the earth's productivity as science progresses.

Using this figure, we obtain (for radioactive carbon alone) $(3 \times 10^{10}) \times 10^{-4}$

* *Editor's note: 30 years would appear to be be a more genetically significant lifetime.*

† As in the case of section 3, the use of the expressions for the steady-state natural process gives a proper integral over time, but no information on the decay law for an instantaneous source. Recessive genes may require dozens and even hundreds of generations before they make their presence felt.

$\times (7.5 \times 10^{-4}) = 2{,}200$ cases of hereditary sickness from a megaton bomb, or 110,000 cases from all the tests already carried out. We are assuming that the tests already performed add up to 50 megatons.

In animal and plant life mutations sometimes give rise to more advanced biological forms. It is conceivable that human mutations (and hereditary sickness) should also be welcomed, since they may be considered a necessary evil in the biological progress of the human race. Actually, however, human nature now changes primarily because of social factors. We are inclined to consider uncontrollable mutations merely as an evil, and experiments with nuclear weapons as being merely an additional cause for the death of tens and hundreds of thousands of persons.

Another example of nonthreshold biological effects of radiation is the possible increase in the amount of cancer[5] and leukemia.

It has been shown experimentally that the carcinogenic effects of various nonradiational carcinogenic substances are additive. There is no reason to believe that the active radicals which arise as a result of ionization will behave in a qualitatively different way. Therefore, the increase in the amount of cancer, or equivalently, the drop in the age at which cancer occurs, will be a linear function of the dose to which humanity is subjected. The total coefficient for all types of cancer and leukemia is taken to be of the same order of magnitude as that for genetic damage, namely $1\text{–}2 \times 10^{-4}$ cases/r. Partially verifying this coefficient are data on the frequency of leukemia, a professional disease of radiologists and in some sense related to cancer. The effect of radiation on this disease is easy to study, since it occurs infrequently in nature. A dose of a single roentgen in a year gives rise to additional leukemia fatalities at the rate of 2×10^{-6}, and over a 30-year [occupational] lifetime this becomes 6×10^{-5}. This coefficient is of the same order of magnitude as that suggested for other forms of cancer.

A possible (though not experimentally proven) nonthreshold effect of radiation is a drop in the immunological reactions of the organism. In all probability premature aging and death is also a nonthreshold effect. The mean life expectancy of medical radiologists (who are subjected to an average dose no greater probably than 1,000 r) is five years less than that for the general population. This means that premature death may occur at the rate of 10^{-4} per roentgen.

Further, we should perhaps note that although mutations are not desirable in the human race, for viruses and bacteria they may greatly increase the chance of survival. Examples are the mutation which occurred in diphtheria in the middle of the 19th century and the periodic flu epidemics that affect a large part of the world's population. It is difficult to evaluate this effect, although it is plausible that it is just as harmful to human health as is the genetic effect.

On the whole, according to our approximate and probably conservative estimate, the loss of human life from all nonthreshold biological effects is at least three times that for the genetic effects alone, which means a rate of about 3×10^{-4} per roentgen. Summing of all the above effects (without deductions for "vagueness") would give 6×10^{-4} per roentgen.*

Thus the radiocarbon from the tests which have already taken place will affect about 330,000 persons. As is well known, an important factor is the fallout of radioactive strontium and cesium. Using Leipunsky's data[6] we may estimate that the bone damage due to strontium and the external effects of cesium are about 0.5 of the carbon-14 effect. For the sake of completeness, we shall give a brief description of the corresponding calculations. If tests are to continue at the present level (that is 10–15 megatons per year) the radioactive strontium concentration in the bones will be about 65 strontium units (pCi/g of calcium) which means that the radiation dose will be 160×10^{-3} r per year or $1–1.5 \times 10^{-2}$ r per megaton. This dose causes sickness at about half the rate of the 7.5×10^{-4} r per megaton for the radiocarbon, since it involves a population of about 2.5 billion people (giving the factor 1/12) and involves only the skeleton, which gives the factor 1/3. The effect of external gamma radiation due to cesium is of the order of 10^{-3} r per megaton, and taking into account the smaller population, this leads to an effect which is about 10 percent of carbon-14 effect. Thus, the total losses from a 1-megaton burst are about 10,000 persons, and the total losses from all nuclear bursts to date are about 500,000. This is a conservative estimate, and if we were to include other radioactive isotopes, other kinds of radioactive damage, and a more complete calculation of all threshold and nonthreshold biological effects we would obtain

* *Editor's note: the remainder of the calculation, nevertheless, uses 3×10^{-4} per roentgen.*

a larger figure. We cannot exclude the possibility that the total number of victims is already approaching 1 million persons, and that each year continued testing increases this number by 200,000–300,000 persons.

What moral and political conclusions can be drawn on the basis of the above figures?

One of the arguments presented by those who maintain the theory that tests are "harmless" is that cosmic rays lead to doses which are greater than those from the tests. This argument forgets that we are adding to the world's toll of human suffering and death, the suffering and death of hundreds of thousands additional victims, including some in neutral countries and in future generations. Two world wars have also added less than 10 percent to the death rate of the 20th century, but this does not make war a normal phenomenon.

Another argument which is found in the literature of several countries is, in effect, that the progress of civilization and new technological advances have in many other cases led to human suffering. As an example, comparison is often made with automobile accidents. But this analogy is not valid. The automobile raises human living standards and leads to accidents only in individual cases as a result of carelessness on the part of persons who are then legally responsible. The suffering caused by the tests, however, follows immutably from each burst. To the present author it seems that all of the moral implications of this problem lie in the fact that the crime cannot be punished (since it is impossible to prove that any specific human death was caused by radiation) and in the defenselessness of future generations against our acts.

The cessation of tests will lead directly to the saving of the lives of hundreds of thousands of people and will have the more important indirect result of aiding in reducing international tensions and the danger of nuclear war, the fundamental danger of our age.

ACKNOWLEDGEMENTS

The author takes this opportunity to express his gratitude to O.I. Leipunsky for valuable discussion.

NOTES AND REFERENCES

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3. Ibid.

4. H.J. Muller, *Acta Radiologica* **41**, 5 (1954); N.P. Dubinin, "Radiation and Human Heredity" [in Russian] (manuscript); S.N. Ardashnikov and N. Shapiro, "On the Possible Effect on Man's Heredity of the Increased Radiation Level Due to the Tests of Atomic Armaments" [in Russian] (manuscript).

5. Glucksmann, ed., *Biological Hazards of Atomic Energy* (Oxford: Clarendon Press, 1953).

6. O.I. Leipunsky, op. cit.

APPENDIX: REVISITING SAKHAROV'S ASSUMPTIONS

Frank von Hippel

Sakharov's estimate is a product of two factors:

- The population radiation dose—the sum of all the estimated radiation doses to individuals exposed to the radioactivity produced by a nuclear explosion until that radioactivity finally decays away
- The sum of a set of dose-effect coefficients translating each individual dose into the probability of a health effect.

I will review what we know on each of these questions below.

Population Radiation Doses

The 1982 UN report, *Sources and Effects of Ionizing Radiation* (p.243), contains an estimate of the "dose commitments" to the world population from past atmospheric testing of 0.26 rads from carbon-14 and about 0.12 rads from fission products (one rad = 10^{-2} sieverts). The doses are calculated in essentially the same way Sakharov did. The dose commitments are then defined by taking the average individual dose rate and integrating over time:

$$\text{Dose commitment} = \int_0^{\infty} d(t)\, dt$$

Almost all of the dose commitment from carbon-14, which has a radioactive half-life of

5,600 years and diffuses only very slowly over thousands of years from the atmosphere-surface water-biosphere system into the deep ocean, is still in the future. Most of the dose commitment from the shorter-lived fission products has already occurred.

According the same UN report (p.227), the estimated cumulative yield of atmospheric tests was 545 megatons. Therefore, the above estimate leads to an estimated dose commitment of $0.26/545 = 5 \times 10^{-4}$ person-rads per megaton from carbon-14. Sakharov's estimate is about 1.5 times larger.

The population dose is obtained by multiplying the dose commitment by a world population of a size appropriate to the period during which most of the dose would be incurred. An appropriate world population by which to multiply for the dose commitments from the fission products is about 4 billion. (The population in 1960 was about 3 billion and it is over 5 billion today.) In the case of the dominant isotope, carbon-14, however, 90 percent of the dose will be incurred after 2050. The appropriate size of the world population in this distant future is unknown.

Sakharov assumed a future world equilibrium population of 30 billion—six times that of the late 1980s. This number seems implausibly large today. The UN projection for 2050 is about 10 billion. If we assume that number, then the population-dose from the carbon-14 produced by a 1-megaton nuclear explosion would be $5 \times 10^{-4} \times 10^{10} = 5 \times 10^{6}$ person-rads—about one quarter of Sakharov's estimate. The radiation doses from other nuclear-explosion–produced isotopes would increase this number only by about 20 percent, because of the smaller size of the world population when they were delivered.

Dose-effect Coefficients

According to the 1990 US National Academy of Sciences' (NAS) report, *Health Effects of Exposure to Low Levels of Ionizing Radiation* (table 4-2), a central estimate of the risk of cancer death from whole-body exposure to gamma and beta radiation at low rates in the US today is about 0.9×10^{-3} per rad, with an uncertainty factor of about 30 percent. This estimate would be approximately doubled to 1.8×10^{-3} if nonlethal cancers were included. The NAS report (table 2-1) also estimates a risk of 0.06×10^{-3} cases of serious genetic disorders in subsequent generations per rad—with a very large uncertainty.

These coefficients therefore yield an estimate of about 2×10^{-3} cancers and genetic disorders per rad. By comparison, Sakharov used an estimate of 3×10^{-4}, including effects (damage to the body's immune system and mutations of influenza and other bacteria) for which I can find no recent official estimates. Even so, Sakharov's dose-exposure coefficient is only one sixth the official mid-range estimate today for cancer and genetic defects alone.

In summary, Sakharov's population-dose estimate currently appears to be a factor of four too high and the sum of his dose-effect coefficients a factor of six too low but the product of these factors has not changed significantly in view of the still very great uncertainties of both.