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Genetic and Somatic Effects of Carbon-14

This by-product of nuclear-weapon testing may do more genetic and somatic damage than has been supposed.

Linus Pauling

In his 1956 paper on radioactive fallout (*1*) Libby pointed out that neutrons released in the explosions of nuclear weapons react with nitrogen nuclei in the air to make carbon-14, which has a half-life of about 5600 years. In his discussion of bomb-test carbon-14 he said that "Fortunately, this radioactivity is essentially safe because of its long lifetime and the enormous amount of diluting carbon dioxide in the atmosphere." He pointed out that 5.2 tons of neutrons would be needed to "double the feeble natural radioactivity of living matter due to radiocarbon. Such an increase would have no significance from the standpoint of health." He mentioned that, for a given energy release, thermonuclear weapons produce more neutrons than fission weapons, and concluded that "the essential point is that the atmosphere is difficult to activate and the activities produced are safe."

Perhaps because of a feeling of reassurance engendered by these statements, I did not make any calculations of the genetic and somatic effects of the carbon-14 produced in the testing of nuclear weapons until April 1958. I was then surprised to find that these calculations, which form the subject of this article (*2*), lead to the conclusions that the genetic damage, as measured by the predicted number of children born with defects caused by the mutations induced by the radioactivity, may be greater for carbon-14 than for the fission products ordinarily classed as world-wide fallout, and that the somatic effects may be of the same order of magnitude.

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In his 1956 paper Libby stated that a 20-kiloton weapon, involving fission of 1 kg of plutonium or uranium, would produce 10 g of neutrons, of which 15 percent might reasonably be expected to escape and make carbon-14. The yield of carbon-14 would hence be 1.05 kg per megaton (the maximum would be 7 kg per megaton, if all neutrons were effective).

More information was given in his 27 March 1958 address on radioactive fallout, delivered at the symposium of the Swiss Academy of Medical Sciences in Lausanne and released on that day by the Atomic Energy Commission (*3*). In this address he said that 1 megaton with fusion and fission weighed as they have actually occurred would generate 3.2×10^{26} atoms of carbon-14, which is 7.4 kg. He pointed out that this estimate is higher than the earlier estimate based on an assumed 15-percent escape efficiency, and said that the new value is based on firmer information.

The old value was for fission alone. If we assume it to be valid, we might conclude that the sevenfold increase to the new value is to be attributed to a high yield for fusion. For example, if the energy yields for fusion and fission have been equal for past explosions the carbon-14 yield for fusion might be calculated to be 13.8 kg per megaton, about 13 times that given for fission.

(On 29 May 1958, after the calculations described in this article had been made, my attention was called by Ben Tucker to the paper "Radioactivity danger from the explosion of clean hydrogen bombs and ordinary atomic bombs," by O. I. Leipunskii, published in the December 1957 issue of the U.S.S.R. journal *Atomic Energy* (*4*). The values given there agree only very roughly with my values. Leipunskii gives 5.2 kg per megaton as the amount of carbon-14 produced by fission and 33 kg per megaton as the amount produced by fusion. The latter value represents a 96-percent effectiveness of the neutrons calculated to be released in the $H^2 + H^3$ reaction giving 1 megaton of energy, or a somewhat smaller effectiveness if some of the 12.5-Mev neutrons produce additional neutrons by $n,2n$ reactions. The Libby value 7.4 kg per megaton for fission and fusion in the ratio of past explosions is 39 percent of 19.1, the Leipunskii value for fission and fusion in 50:50 ratio.)

Libby gives 10^{28} as the best estimate of the number of carbon-14 atoms introduced into the atmosphere (mostly into the stratosphere) by the bomb tests so far, keeping in mind that a substantial amount falls back as calcium carbonate, especially in the case of ground shots over coral. The number 10^{28} atoms (232 kg) corresponds to 31 megatons of bombs. I assume that one-third of the generated carbon-14 is released to the atmosphere, two-thirds falling back as calcium carbonate. This estimate is based upon the statement by Libby (*5*) in December 1956 that total bomb tests up to the time his paper was written (it was submitted for publication on 17 October 1956) had liberated 30 megatons of fission products. It is my understanding, from the table of nuclear explosions given in *The Nature of Radioactive Fallout and Its Effects on Man* (*6*, pp. 2063–

2065), that fission products were first released in large amounts on 1 March 1954, the earlier explosions having been those of small bombs or of fission-fusion bombs with no large third stage. If the testing has continued at the same rate from October 1956 to January 1958 (reference date for the 1958 statement by Libby) as from 1954 to 1956, the value 232 kg of carbon-14 introduced into the atmosphere corresponds to 45 megatons of fission and, with the surmise that the fission-fusion ratio has been 1, to 90 megatons of total tests, and hence to the above estimate that one-third of the carbon-14 becomes atmospheric CO_2.

The 232 kg of carbon-14 (Libby's estimate) introduced into the atmosphere by the bomb tests had caused the carbon-14 concentration for atmospheric carbon dioxide in New Zealand to increase to 10 percent over its normal value by 1957 (*7*). The carbon-14 released into the atmosphere becomes mixed in a few years with the biosphere and the top layer (about 300 feet thick) of the ocean (*8, 9*). Mixing occurs more slowly with the deep layers of the ocean. Studies by several authors (*8, 9*) have led to closely similar conclusions about the rates of mixing. We shall make use of a simple model discussed by Arnold and Anderson (*9*); essentially the same conclusions would be reached with use of any model compatible with the value 600 years for the age of the dissolved carbon in the ocean.

Two Reservoirs of Carbon

In the simple model of Arnold and Anderson two reservoirs of carbon are considered. Reservoir A consists of the atmosphere (0.13 g of carbon per square centimeter), the land biosphere (0.05 g cm^{-2}), and humus (0.2 g cm^{-2}), totaling 2.0×10^{18} g of carbon, of which 3200 kg is carbon-14. Within this reservoir there is rapid equilibration of carbon-14. Reservoir C is the entire ocean, including the ocean biosphere; it contains 8.5 g cm^{-2} (44×10^{18} g) of carbon, 22 times as much as A.

The equilibrium between A and C can be expressed by a forward rate constant k and reverse rate constant k', with values $k = 0.035$ yr^{-1} and $k' = 0.0016$ yr^{-1}, respectively.

Let us consider N_0 atoms of carbon-14 released into A by 1 year's testing at a standard rate, which we assume to be 30 megatons per year, with 222 kg of carbon-14 made and 74 kg released into A. The later number (N_A) of these atoms in A is given by the equation

$$\frac{dN_A}{dt} = -kN_A + k'(N_o - N_A) \qquad (1)$$

The solution of this equation is

$$N_A = \frac{k'}{k+k'}N_o + \frac{k}{k+k'}N_o e^{-(k+k')t}$$

which with insertion of the values of k and k' becomes

$$N_A = 0.044N_o + 0.956N_o e^{-0.0363t}$$

So far N_0 has been considered a constant. We replace it by $N_0 e^{-0.000124t}$, corresponding to the radioactive decay of carbon-14 with mean life 8070 years (half-life 5586 years), to obtain

$$N_A = 0.044N_o e^{-0.000124t} + 0.956N_o e^{-0.0364t} \qquad (2)$$

Hence, the freshly made carbon-14 in reservoir A, which gives it access to the bodies of human beings, can be considered as consisting of a 4.4-percent fraction with mean life 8070 years and a 95.6-percent fraction with mean life 27.5 years (the reciprocal of 0.0364 yr^{-1}).

Genetic Effects at Present Population Levels

Let us first evaluate the genetic effect of the carbon-14 from bomb tests on the assumption that the population of the world will remain constant.

James F. Crow, a member of the National Academy of Sciences–National Research Council Committee on Genetic Effects of Atomic Radiation, presented an estimate of the genetic effects of a 0.1-roentgen exposure of the gonads in his testimony before the Special Subcommittee on Radiation of the Joint Congressional Committee on Atomic Energy on 4 June 1957 (*6*, p. 1021). He estimated that a 0.1-roentgen exposure of the gonads of the present world population would produce gene mutations that would in the course of many generations give rise to the birth of 80,000 children with gross physical or mental defect, 300,000 stillbirths and childhood deaths, and 700,000 embryonic and neonatal deaths. Of these, 8000, 20,000, and 40,000, respectively, were expected to occur in the first generation. In addition, he estimated that there would be produced a larger but unknown number of minor or intangible defects, which might represent the major part of the damage, because by virtue of their being milder they are less likely to cause the sterility or death of the person who possesses them and therefore are more likely to persist in the population and thus to affect a larger number of persons.

The estimates for the three categories were made in different ways, and the categories are not mutually exclusive. In particular, deaths at about the time of birth are included in both the second and the third category. Crow has told me that in his opinion there is little overlap between the first and the second category.

These estimates must be recognized as highly uncertain. Crow said that they might be 5 times too high or 5 times too low, or more, but that we are better off estimating even very crudely what the numbers involved are than not making any numerical estimates at all. I agree with this statement.

Uncertainty in these estimates does not affect the discussion of relative effects of carbon-14 and fission products given below.

It must be emphasized that, although large numbers are given below as the estimated effects of the testing of nuclear weapons at the recent rate, these numbers are very small in comparison with numbers representing the effects of natural radiation and other mutagenic agents. For example, it is stated in the National Academy of Sciences–National Research Council report that about 2 percent of total live births have tangible defects of simple genetic origin (this is roughly the first category of the three given above). With 75 million births per year, this corresponds to 1.5 million per year with gross physical and mental defect. The estimated effect of continued testing of nuclear weapons at the recent rate is an additional 15,000 per year (including the effect of carbon-14). Hence the bomb tests are expected to produce not more than a 1-percent increase in defective births (or between 0.2 percent and 5 percent, if we use Crow's suggestion about uncertainty in the estimates).

The estimate of the magnitude of the gonad exposure for the average rate of bomb testing for the 5 years preceding 1956, reported by the National Academy of Sciences–National Research Council committee, is 0.1 roentgen in 30 years. Hence 1 year of testing at that rate, it is estimated, will cause about 2700 children with gross physical or mental defect, 10,000 stillbirths and childhood deaths, and 23,000 embryonic and neonatal deaths. (This estimate ignores the effects of carbon-14.)

The *Twenty-third Semiannual Report of the Atomic Energy Commission* contains the statment that bomb testing at the present rate, it can be estimated, will cause between 2500 and 13,000 defective children to be born per year of testing. This statement is in the report of the Advisory Committee on Biology and Medicine. It seems to correspond to the above calculation, with recognition of the uncertainy of the amount of overlap between the first two categories.

The report of the National Academy of Sciences–National Research Council committee contains the sentence "With these understandings, it may be stated that U.S. residents have, on the average, been receiving from fallout over the past five years a dose which, if weapons testing were continued at the same rate, is estimated to produce a total 30-year dose of about *one tenth of a roentgen*; and since the accuracy involved is probably not better than a factor of 5, one could better say that the 30-year dose from weapons testing if maintained at the past level would probably be larger than 0.02 r and smaller than 0.50 r. The rate of fall-out over the past five years has not been uniform. If weapons testing were, in the future, continued at the largest rate which has so far occurred (in 1953 and 1955) then the 30-year fall-out dose would be about twice that stated above."

It is accordingly possible that a somewhat larger estimate than 0.1 roentgen in 30 years should be made for the average gonad exposure corresponding to the recent rate of testing of nuclear weapons. Little can be done to make the estimates of the effects of fission products more reliable in the absence of any published detailed discussion of the evidence upon which the estimates of gonad exposure are based.

Now let us consider the genetic effects of carbon-14. The gonad exposure due to natural carbon-14 has been given by Libby (*10*) as 0.0015 roentgen per year. This dosage was calculated on the basis of the assumptions that the body is 18 percent carbon, the specific activity of carbon is 15 disintegrations per minute per gram, and the mean energy of the beta radiation is 40 percent of the maximum energy, 167 kev.

If we take as the present rate of bomb testing the value 30 megatons per year (fission plus fusion), the initial activity of the carbon-14 from 1 year of bomb tests is 0.0015 roentgen per year multiplied by 74/3200, the ratio of the amount of carbon-14 released to reservoir A by the tests to the amount of natural (cosmic-ray produced) carbon-14. This initial activity is 35×10^{-6} roentgen per year. Of this amount, 1.46×10^{-6} roentgen is associated with the first term in Eq. 2 and 33×10^{-6} roentgen with the second term. The total gonad exposure is obtained by multiplying these quantities by the corresponding mean lives, 8070 and 27.5 years, respectively, to obtain 0.0118 and 0.0009, respectively, with sum 0.0127 roentgen.

We see that the second term (the nonequilibrium term with respect to mixing with the large ocean reservoir) contributes only about 8 percent as much as the first term to the total effect. On the other hand, it is the more important of the two with respect to the present generation and the next one.

The total gonad exposure due to carbon-14 over the entire life of the isotope (per person now living, world population assumed constant), 0.0127 roentgen, is 4 times that usually assumed for worldwide fallout (0.0033) roentgen, corresponding to 0.1 roentgen in 30 years). The estimated effects of carbon-14 from 1 year of bomb testing, from Crow's numbers, are 12,000 children with gross physical or mental defect, 38,000 stillbirths and childhood deaths, and 90,000 embryonic and neonatal deaths.

Genetic Effects at Predicted Population Levels

Now let us consider the effect of the increase in world population that can be reasonably anticipated. At the present time the world population is growing at a rate such as to double in about 50 years. If we assume that no catastrophe intervenes, this rate may continue for hundreds of years, and the population may then remain essentially constant, with a value for number of births per year 5 times the present value. The number of defective children corresponding to the first term of Eq. 2 would then be multiplied by a factor nearly equal to 5. If the world population were to increase in this way, the carbon-14 from 1 year of testing would cause an estimated total of about 55,000 children with gross physical and mental defect, 170,000 stillbirths and childhood deaths, and 425,000 embryonic and neonatal deaths. On this assumption about world population it is estimated that the bomb tests carried out so far (estimated total, including 1958, 150 megatons) will cause about 5 times these numbers of defective children and deaths.

Thus we see that the genetic effects of carbon-14 from bomb tests are estimated to be about 4 times as great as those of ordinary world-wide fallout (calculated for the customarily quoted value of gonad exposure) if the world population stays constant, and about 17 times as great if the world population increases as assumed.

There is a simpler way of making the calculation (*11*). Let us assume that there is very rapid mixing of the carbon-14 released in the bomb tests throughout the entire reservoir, including the depths of the ocean. With this assumption and the other assumptions given above, a straightforward calculation can be carried out, leading to nearly the some numbers.

These predicted effects of carbon-14, which over the period of thousands of years are greater than those of the fission products in the world-wide fallout, may be thought to have little significance because of uncertainty about the nature of the world of the rather distant future. It is accordingly of interest to calculate what the effects of 1 year of testing will be on the next generation.

Effects of One Year's Tests on the Next Generation

We may consider first the predicted numbers of seriously defective births in the next generation as a result of the ordinary fallout. From Crow's estimates and the gonad exposure 0.1 roentgen in 30 years, there are 270 children with gross physical or mental defect, 670 stillbirths and childhood deaths, and 1304 embryonic and neonatal deaths.

In calculating the number of seriously defective births expected to occur in the first generation as a result of the presence of added amounts of carbon-14 in the atmosphere we cannot neglect the rate of diffusion of carbon-14 into the depths of the ocean. The 74 kg of carbon-14 liberated into the atmosphere by 1 year of testing at the standard rate causes an initial increase of 2.3 percent of the carbon-14 concentration, the normal burden of the atmosphere, biosphere, humus, and upper part of the ocean being 3200 kg. This calculation agrees roughly with the statement by Libby that "the observed carbon-14 rise might be as high as 3 percent per year as appears to have been observed." The rate of increase, reported from experiment, for carbon dioxide in the atmosphere is about 2.1 percent per year.

It may be pointed out that the observed rate of increase of carbon-14 in the atmosphere provides some justification of the assumed standard recent rate of testing, 30 megatons of fission plus fusion per year (together with the assumption that one-third of the carbon-14 that is produced is liberated to the atmosphere), as shown by the agreement of the calculated 2.3-percent increase per year and the observed 2.1-percent increase. The same rate of increase in the atmosphere and the same genetic and somatic effects would result from, say, 20 megatons per year with one-half escaping. The calculation of genetic and somatic effects could be based directly on the observed rate of increase of carbon-14 in the atmosphere.

The rate of diffusion of the carbon-14 into the depths of the ocean corresponds to a mean life of 27.5 years in the smaller reservoir. The gonad exposure for natural carbon-14 is 0.0015 roentgen per year and that for an amount 2.3 percent as much is 0.000035 roentgen per year. With a mean life for carbon-14 in the small reservoir of 27.5 years, the total gonad exposure for the first decades after the testing becomes 0.00096 roentgen. With world population at the present level, the estimated numbers in the three categories during the first generation due to carbon-14 from a single year of testing are 80, 200, and 400, respectively. These are smaller than estimates for the ordinary radioactive fallout. It is because of the very long life of carbon-14 that the total effect, throughout the life-times of the isotopes, becomes greater for carbon-14 than for the fission products.

The possibility must be considered of a special mutagenic action of carbon-14: the damage of a deoxyribonucleic acid molecule through the Szilard-Chalmers effect or the chemical effect of conversion to a nitrogen atom when a carbon-14 atom in the molecule undergoes radioactive decomposition. We assume 50,000 genes per individual, 200,000 carbon atoms per gene, 5×10^9 future world population up to 30 years of age, and a carbon-14 yield of 74 kg to the atmosphere per year of testing, and calculate 70,000 as the number of mutations by this mechanism per year of testing. This number, presumably an upper limit, is only about 10 percent of the numbers in the three categories expected to result from carbon-14 irradiation, and we conclude that the special mechanism involving carbon-14 atoms in the genes themselves is less important than irradiation in causing genetic damage.

The calculation of predicted somatic effects of bomb-test carbon-14 in comparison with those of fission products can be easily made. With the same assumptions as for the foregoing calculation of the genetic effects, including the assumption of a fivefold increase in world population, it is found that 1 year of testing of nuclear weapons produces carbon-14 irradiation, over the entire life of the radiocarbon, equivalent to the exposure of the present world population to a whole-body dose of 0.061 roentgen. This is much larger than the customarily quoted value of 0.0033 roentgen for whole-body irradiation by fission products from 1 year of testing, and somewhat larger than the estimated exposure of bone marrow and bone tissue by strontium-90 (given as 0.03 and 0.056 roentgen, respectively, per year of testing, as estimated by the Atomic Energy Commission's Advisory Committee on Biology and Medicine, in the *Twenty-third Semiannual Report of the Atomic Energy Commission,* 1958). Hence we calculate that the total number of cases of leukemia and bone cancer expected to be caused by carbon-14 is about equal to the number expected to be caused by fission products, including strontium-90, and that the number of cases of cancer of other sorts expected to result from radiation damage to tissues other than bone marrow and bone tissue is greater for bomb-test carbon-14 than for fission products.

Summary

On the basis of information about carbon-14 given by Libby, calculations are made of the predicted genetic and somatic effects of the carbon-14 produced by the testing of nuclear weapons. It is concluded that 1 year of testing (30 megatons of fission plus fusion) is expected to cause in the world (estimated future number of births per year 5 times the present number) an estimated total of about 55,000 children with gross physical or mental defects, 170,000 stillbirths and childhood deaths, and 425,000 embryonic and neonatal deaths. (There is an unknown amount of overlap of these three categories.) These numbers are about 17 times the numbers usually estimated as the probable effects of the fallout fission products from 1 year of testing. In addition, the somatic effects of bomb-test carbon-14 are expected to be about equal to those of fission products, including strontium-90, with respect to leukemia and bone cancer and greater than those of fission products with respect to diseases resulting from radiation damage to tissues other than bone tissue and bone marrow. All of the estimated numbers are subject to great uncertainty; they may be as much as 5 times too high or 5 times too low. The uncertainty in the estimation of the relative effects of carbon-14 and fission products in world-wide fallout is not so great.

References and Notes

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