First draft

Predicted Genetic and Somatic Effects

of Carbon-14 from Tests of Nuclear Weapons

By 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 5,600 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 paper, lead to the conclusions that the genetic damage, as measured by the predicted number of defective children caused by the mutations induced by the radioactivity, is greater for carbon-14 than for the fission products ordinarily classed as worldwide fallout, and that the somatic effects are of the same order of magnitude.

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 estimated to escape and make carbon-14. The yield of carbon-14 would hence be 1.05 kg. per megaton (maximum 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 AEC.[2] In this address he said that one 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 may conclude that the seven-fold 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 would 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 paper had been made, my attention was called by Dr. 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 USSR journal Atomic Energy.[3] 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-~~megaton~~ 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 ~~the~~ 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[4] 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. Fission products were first released in large amounts on 1 March 1954. 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 ~~during this period~~ 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 has caused the carbon-14 concentration for atmospheric carbon dioxide in New Zealand to increase to 10 percent over its normal value by 1957.[5] The carbon-14 released into the atmosphere becomes mixed in a few years or decades with the biosphere and the top layer (about

300 feet thick) of the ocean.[6,7,8] Mixing occurs more slowly with the deep layers of the ocean. Studies by several authors[6,7,8] have led to closely similar conclusions about the rates of mixing. We shall make use of a simple model discussed by Arnold and Anderson;[8] 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.

In the simple model of Arnold and Anderson two reservoirs of carbon are considered. Reservoir A consists of the atmosphere (0.13 g. C per cm^2), 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_o atoms of carbon-14 released into A by one year of testing (30 megatons, 222 kg. carbon-14 made, 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

$$\underline{N}_A = 0.044 \, \underline{N}_o + 0.956 \, \underline{N}_o \, \underline{e}^{-0.0363\underline{t}}$$

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

$$\underline{N}_A = 0.044 \, \underline{N}_o \, \underline{e}^{-0.000124\underline{t}} + 0.956 \, \underline{N}_o \, \underline{e}^{-0.0364\underline{t}} \qquad (2)$$

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}).

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.

Professor James F. Crow, a member of the NAS-NRC Committee on Genetic Effects of Atomic Radiation, presented an estimate of the genetic effects of 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.[9] He estimated that 0.1 roentgen exposure would produce gene mutations that, with world population as at present, would in the course of several 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. We may for convenience group the first two classes together (as was done also in the NAS-NRC report), and say that 0.1 roentgen gonad exposure of the world population is estimated to give rise to 380,000 seriously defective children, plus 700,000 embryonic and neonatal deaths.

The estimate of the magnitude of the gonad exposure for the current rate of bomb testing reported by the NAS-NRC Committee is 0.1 roentgen in

30 years. Hence one year of testing is estimated to cause about 13,000 seriously defective births plus 23,000 embryonic and neonatal deaths. (This estimate ignores carbon-14.)

The 23rd Semiannual Report of the AEC contains the statement that bomb testing at the present rate can be estimated to cause between 2,500 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 likely that the statement is based upon the estimate made by Crow that a total of 0.1 r during a period of 30 years produces 380,000 seriously defective births (80,000 with gross physical or mental defects plus 300,000 stillbirths and childhood deaths). The value 0.1 r in 30 years is that given by the Committee on Genetic Effects of Atomic Radiation of the National Academy of Sciences-National Research Council in their report of June 1956. From these figures one calculates for one year of testing the number 12,667 seriously defective births; this value may have been rounded off to 13,000 in the AEC Report.

The report of the NAS-NRC 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 <u>one tenth of a roentgen</u>; 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 smallest of the foregoing values, 0.02 r in 30 years, leads to the estimate 2,533 seriously defective births per year of testing. The low value 2,500 given in the AEC Report may be this value rounded off.

The upper limit given in the NAS-NRC report, 0.50 r in 30 years, leads to 63,333 seriously defective births per year of testing at the present rate. This value is, however, not included in the 23rd Semiannual Report of the AEC.

It is my own opinion that the gonad exposure for continued testing at the present rate has a value nearer the upper limit, 0.5 r in 30 years, than the lower limit, 0.02 r in 30 years, and that the probable number of seriously defective births per year of testing is nearer to 63,333 than to 2,533. In the absence of any published detailed discussion of the evidence upon which the estimates of gonad exposures are based, the best that we can do at the present time is to assume that the number of seriously defective births due to ordinary fallout (fission products) per year of testing at the average rate of recent years is between 2,500 and 63,000.

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 of 167 kev.

If we take as the ~~percent~~ present rate of bomb testing the value 30 megatons per year (fission plus fusion), the initial activity of the carbon-14 from one 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} roentgens per year. Of this amount 1.46×10^{-6} is associated with the first term in Equation 2 and 33×10^{-6} 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 non-equilibrium 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 one year of bomb testing, from Crow's numbers, are 50,000 seriously defective children (gross physical or mental defect, still-birth, childhood death) and 90,000 embryonic and neonatal deaths.

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 the rate of about 2,000,000,000 per 100 years. If we assume that no catastrophe intervenes, this rate of increase may continue for hundreds of years, and the population may then remain essentially constant with value corresponding to a number of births per year five times the present value. The number of defective children corresponding to the first term of Equation 2 would then be multiplied by a factor nearly equal to 5, whereas that corresponding to the second term would not change very much. If the world population were to increase in this way, the carbon-14 from one year of testing would cause an estimated total of about 225,000 seriously defective children and 425,000 embryonic and neonatal deaths. On this assumption about world population, the bomb tests carried out so far (estimated total, including 1958, 150 megatons) are predicted to cause about 1,000,000 seriously defective children and 2,000,000 embryonic and neonatal 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 worldwide fallout (taking the maximum value quoted in the 23rd Semiannual Report of the AEC) if the world population stays constant, and about 20 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 the conclusion that one year of testing at the standard rate of 30 megatons a year will ultimately be responsible for the birth of 230,000 seriously defective children and also for 420,000 embryonic and neonatal deaths.

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

We may consider first the predicted number of seriously defective births in the next generation as a result of the ordinary fallout. Crow gives the estimate that 10 percent of the total births with gross physical or mental defect will appear in the first generation, and 6.7 percent of the stillbirths and childhood deaths, weighted average of 7.4 percent. Of the total estimated numbers of seriously defective births from fission products per year of testing, 2,500 to 63,000, between 190 and 4,750 are predicted for the first generation.

In calculating the number of seriously defective births predicted 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 estimated to be liberated into the atmosphere by one year of testing at the standard rate causes an initial increase of 2.3 percent in the carbon-14 concentration, the normal burden of the atmosphere, biosphere, humus, and upper part of the ocean being 3,200 kg. This calculation agrees roughly with the statement by Dr. 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.

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 r, and that for an amount 2.3 percent as much is 0.000035 r per year. With mean life in the small reservoir 27.5 years, the total gonad exposure for the first decades after the testing becomes 0.00096 r. With world population as at present, the number of seriously defective births during the first generation due to carbon-14 from a single year of testing is predicted to be 275. This is near the lowest value estimated for the ordinary radioactive fallout. It is because of the very long life of carbon-14 that the total effect, throughout the lifetimes 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 DNA molecule through the Szilard-Chalmers effect or chemical effect of conversion to a nitrogen atom when a C-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 carbon-14 yield of 74 kg. to 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 number of defective births plus embryonic and neonatal deaths predicted to result from C-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 one year of testing of nuclear weapons produces carbon-14 irradiation, over the entire life of the radiocarbon, equivalent to the ~~whole-body~~ exposure of the present world population to a whole-body dose of 0.061 *r*. This is much larger than the customarily quoted value 0.0033 *r* for whole-body irradiation by fission products of one year of testing, and somewhat larger than the estimated exposure of bone marrow and bone tissue by strontium-90 (given as 0.03 *r* and 0.056 *r*, respectively, per year of testing, as estimated by the AEC Advisory Committee on Biology and Medicine, in the 23rd Semiannual Report of the AEC, 1958). Hence we calculate that the total number of cases of leukemia and bone cancer predicted to be caused by carbon-14 is about equal to the number predicted to be caused by fission products, including strontium-90, and that the number of cases of cancer of other sorts, resulting from radiation damage to tissues other than bone marrow and bone tissue, is predicted to be 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 one year of testing (30 megatons of fission plus fusion) is predicted to cause in the world (estimated future number of births 5 times the present) an estimated total of about 225,000 seriously defective children to be born (stillbirth, childhood death, gross physical or mental defect) plus about 425,000 embryonic and neonatal deaths. These numbers are about 20 times the numbers usually estimated as the probable effects of the fall-out fission products from one year of testing. In addition, the somatic effects of bomb-test carbon-14 are predicted to be about equal to those of fission products, including strontium-90, with respect to causing leukemia and bone cancer, and [redacted] greater than those of fission products with respect to diseases resulting from radiation damage to tissues other than bone tissue and bone marrow.

References

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