chemist's really brilliant contributions? (ii) How can we best tap the reservoir of latent scientific talent that we know exists in our society but which we have heretofore largely ignored? (iii) For those youths who choose science as a career, what is the most practicable method for getting them launched upon their professional work at sufficiently early ages to enable them to realize their potentialities and to make the greatest possible number of important contributions?

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46. An analogous situation exists in the field of sports where, for example, the champion golfer may continue to play at an amateur level for a longer time than he will play at a championship level.
47. Like the word *contribution,* the word *masterwork* refers to the total research output reported during any one year. Often the chemist received his maximum number of credits or tallies for a single discovery, but sometimes, as in the case of Sir Humphry Davy, the chemist made several highly important discoveries during the course of a single year.
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Future Radiation Dosage from Weapon Tests

Extrapolations are offered for three possibilities—testing remains constant, it ceases, it increases.

D. R. Inglis

The world-wide radioactive fallout from H-bomb tests has raised the question whether this change in environment will have serious consequences for the healthy development of man. As has been discussed by W. F. Libby, commissioner of the Atomic Energy Commission, the main constituents which the tests add to man's radioactive environment are strontium-90 and cesium-137 (*1–3*). The former appears to be of greater importance because its chemical similarity to calcium leads to its selective deposition in bone, where in sufficient quantity it may have carcinogenic effects. In spite of the present experimental uncertainties in predicting the biological effectiveness of Sr^{90} from the better-known effects of radium, there seems to be general agreement that the Sr^{90} level now attained as a result of past tests is not a real hazard, when judged on a global scale of normal human misery.

The serious question pertains to future tests and depends, of course, on the rate at which tests may be continued in the future. Many statements, some of them of a sort to placate fears, have been made about the effects to be expected as a result of past tests.

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The purpose of this article (*4*) is to extend the discussion to include the effects of future tests by making various assumptions about the course of future events. For the sake of extrapolating into the future, we shall assume that any one of three possible courses might be followed; and with these three we hope to bracket the likely actual development of future testing.

The three courses, idealized for simplicity of calculation, are (i) that testing continues at its present rate, (ii) that testing now ceases and we consider only the result of the radioactive burden already injected into the stratosphere, and (iii) that the rate of testing continues to increase at the average rate at which it has increased since late 1951. Unless there is a drastic change in the policies of various nations, it seems likely that the actual event will lie between (ii) and (iii), on the average, for many years. The expressions for the accumulated activities corresponding to these different assumptions are derived in the last section of the paper, where the equations referred to in other parts of the paper will be found. These equations are used as the basis for the following qualitative discussions.

Extent of Past Testing

W. F. Libby has given the figure of ½ mc/mi² per megaton for the distributed contamination by Sr^{90} from the explosion of a bomb—that is, an H-bomb of sufficient power to penetrate the stratosphere injects into it enough radioactivity of Sr^{90} that, if the activity should be distributed uniformly above (or on) the earth's surface, it would amount to one-half millicurie per square mile for each megaton (TNT equivalent) of that part of the bomb's power derived from fission. We can use this figure as a unit of bomb radioactivity effective for our purpose.

The most reliable figure available (*2*, p. 952) for the extent of past testing is that about 30 megatons equivalent of fission products had been deposited in the stratosphere by about the end of 1956. Libby also gives the mean life for fallout from the stratosphere as about 10 years, or perhaps a little less, and for radioactive decay of Sr^{90} it is 40 years (corresponding to half-lives of 7 years and 28 years, respectively). These are both longer than the period $T_0 = 5$ years over which tests have been carried out between late 1951 and late 1956, and we may reasonably calculate as though the injection had been at a constant rate equal to the average rate R_0 over this period, although the injection was actually strongly peaked at the middle of the period, in 1954.

Prediction of Effects of Future Tests

1) *Accumulated fallout from a single blast.* The basic problem from which others are compounded is the calculation of the fallout following a single burst of radioactive material into the stratosphere by a single thermonuclear test. Let a single blast introduce an amount A of radioactivity into the stratosphere at time $t = 0$, and assume that the stratospheric circulation distributes this material uniformly in a time that is negligible in comparison to the half-lives for fallout and radioactive decay, so that fallout and decay occur uniformly over the earth's surface (*5*). In this case the radioactive burden in the stratosphere decays both by fallout and by radioactive decay (in close analogy to a nuclide which may decay, for example, by either alpha or beta emission). The accumulated radioactivity y on the surface of the earth then builds up by fallout at a rate which depends on the stratospheric burden at any time t and on the decay constant for fallout, and it is diminished by radioactive decay at a rate depending on the amount y on the ground at this time and the radioactive decay constant. The net effect of these two competing processes at ground level is that, at first, when the fallout from the large stratospheric burden is high and there is still very little to decay on the ground, the amount y on the ground builds up; but as the rate of gain from fallout decreases and the rate of loss from radioactive decay increases, the graph of y versus t levels off at a maximum and thereafter decreases as shown by curve 0 of Fig. 1 (See Eq. 2 in the section "Mathematical considerations"). On the basis of Libby's figures cited above, y reaches a maximum value of $0.535A$ about 16 years after the blast.

2) *Result of continuing tests at a constant rate.* Although tests are actually conducted as a series of isolated events, their effect over a long period may be approximated satisfactorily by assuming an average rate of injection of radioactivity into the stratosphere. Let us therefore consider the effect of continuing H-bomb tests throughout the world at the same average rate R_0 at which they have been conducted over the past 5 years.

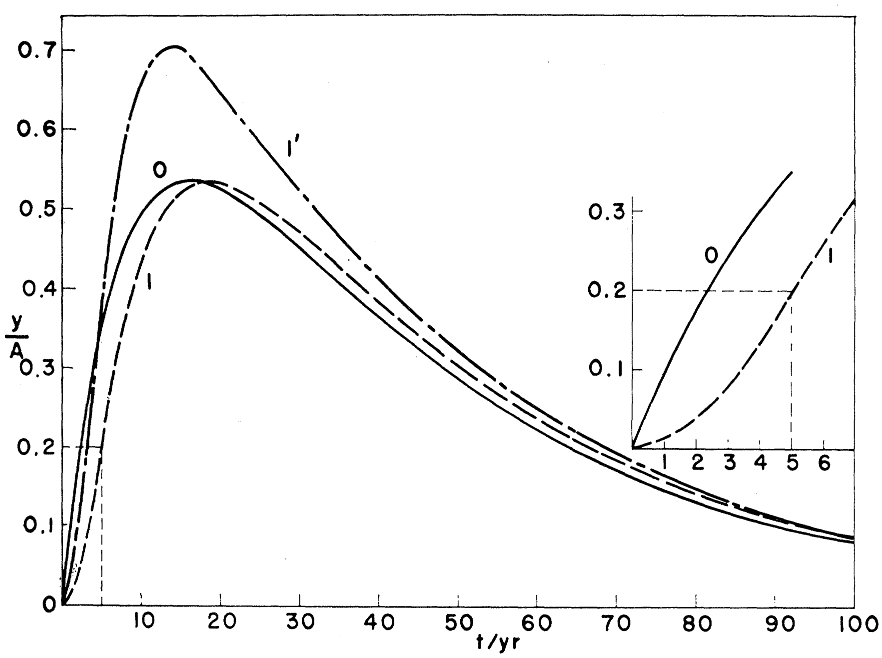

Fig. 1. Curve 0 gives the rise and fall of ground activity (Eq. 2) following a single burst (equal in magnitude to the total testing through 1956). The abscissa is time in years. Curve 1 gives the result (Eq. 12) for testing at a uniform rate, $R_0 = 3$ mc/mi² yr, over the first 5 years, after which testing is discontinued. The ground radioactivity in millicuries per square mile may be found by setting $A = 15$ mc/mi², corresponding to the estimated 30 megatons equivalent of fission products deposited in the stratosphere by the end of 1956. The peak value, $y = 8$ mc/mi², occurs after 16 years—that is, in 1972. This predicted peak is about 2.75 times as large as the calculated value of 2.95 mc/mi² at the end of 1956. Curve 1′ is the same as curve 1 except that it is computed on the assumption that the mean life for fallout is 5 years (instead of 10 years).

The stratospheric burden then builds up to a steady value for which the rate of attrition by fallout and radioactive decay is just balanced by the steady replacement from testing. This course of events, which is described by Eq. 8, is represented by curve 2 of Fig. 2. For the values we have adopted for the constants, y approaches asymptotically to the limiting value of 96 mc/mi^2. This limit is 32.6 times the intensity of radiation from fallout at the end of 5 years. The intensity reaches half of the limiting value in 36 years. For comparison, curve 1 on the same figure shows the result (Eq. 12) if tests had been stopped at the end of 1956. To show the effect of a change in the somewhat doubtful value of the mean life for fallout, curve 2′ shows the result when the mean life is assumed to be 5 years—a value favored by some workers in the field.

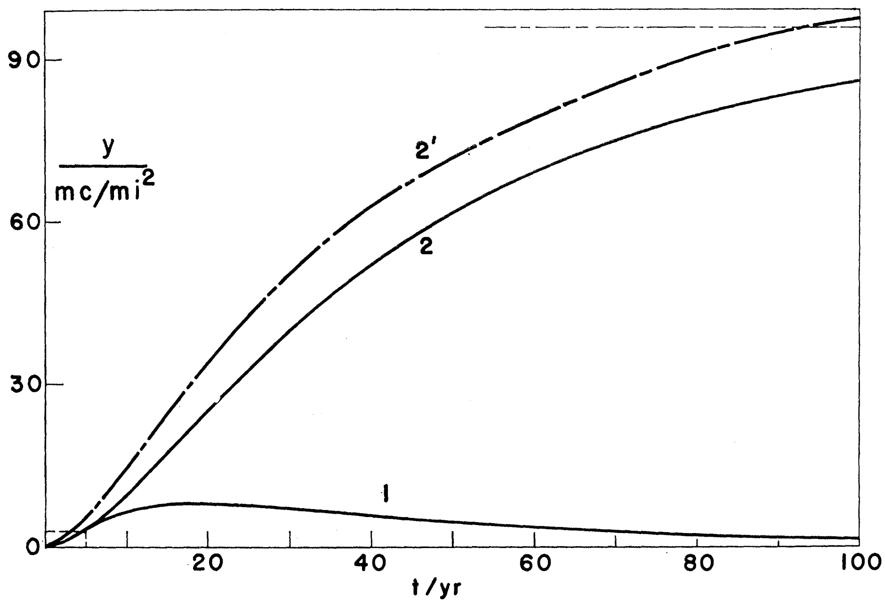

Fig. 2. Curve 2 gives the approach to equilibrium intensity of fallout (Eq. 8) for a steady rate of testing, $R_0 = 3$ mc/mi^2 yr. The horizontal broken line gives the asymptotic value, 96, found from Eq. 10. For comparison, curve 1 is the same as the broken curve 1 of Fig. 1, giving the result if tests should be stopped now (Eq. 12). Curve 2′ is the result if the mean life for fallout is taken to be 5 years (instead of 10 years as assumed for curve 2).

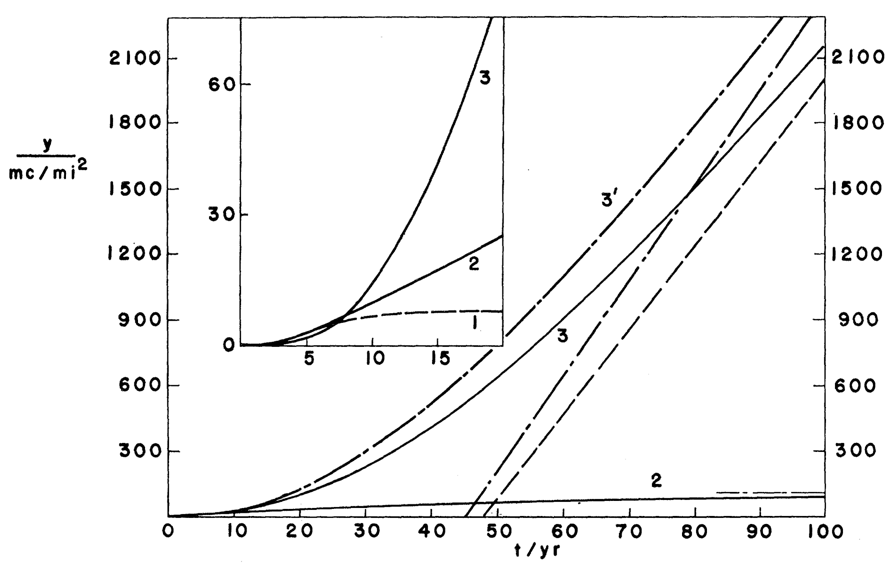

Fig. 3. Curve 3 gives the growth of fallout activity if the rate of testing increases in direct proportion to the time (Eq. 17). The dashed straight line on the right indicates the asymptotic value from Eq. 20. The ordinate gives ground radioactivity in millicuries per square mile. The insert shows detailed comparisons for the first few years. As in Fig. 2, curves 1 and 2 give the respective activities if tests should be discontinued or if they should continue at the present rate. The former is too low to be seen on the scale of the large graph. Curve 3′ and the dash-dotted straight line are the corresponding curve and asymptote if the mean life for fallout is assumed to be 5 years (instead of 10 years).

It should be noted that y is the accumulated amount of one particular radioactive nuclide. The numerical values given above apply to Sr^{90}, the most significant activity for the present discussion. The total amount of radioactivity would be the sum of such terms for all the radioactive materials involved.

3) *Future dosage if tests should be stopped now.* If testing proceeded at a constant rate up to time T_0 and then stopped abruptly, the radioactive material then on the ground would disintegrate according to the simple exponential law of radioactive decay, while the course of events for the material in the stratosphere at time T_0 would be the same as if this material had been injected by a blast at this instant.

This is described mathematically by Eqs. 11 and 12 and is shown graphically by curve 1 of Fig. 1. Except for the initial part, it differs very little from the result of a single large test carried out at time $T_0/2 = 2.5$ years, as is shown by the uniform lateral displacement between curves 0 and 1. [For the ordinate of curve 1, y/A is replaced by $(\lambda_f + \lambda_r)\ y/R_0$ to fit Eq. 12.] Curve 1′ is the same as curve 1, except that it is computed on the assumption that the mean life for fallout is 5 years (instead of 10 years).

4) *Future dosage if the rate of testing should continue to rise at a constant rate.* Unless special international arrangements are consummated, it is to be anticipated that there will be an increasing number of nations testing nuclear weapons in the future, and it is possible that tests by each country will grow in size or number, or both, as a result of the normal expansion of military requirements. As a plausible upper limit to the likely future world-wide testing, barring war, we assume a rate $R(t)$ which increases at a steady rate equal to the average rate of increase from the beginning of H-bomb testing up to the present. Equation 17 which describes this case, is quite complicated, but it predicts that, as is shown by curve 3 of Fig. 3, there is an accelerated increase of the accumulated radioactivity y on the ground, as should be expected. This curve asymptotically approaches the dashed straight line. With the constants adopted for this discussion, the radioactivity y on the ground eventually increases at a steady rate of 38.4 mc/mi^2 per year for this program. The results for the other assumed testing programs are included for comparison in this figure. Curve 3′ and the dash-dotted straight line are the corre-

sponding curve and asymptote if the mean life for fallout is assumed to be 5 years (instead of 10 years).

Discussion and Conclusion

From these calculations we can make several statements comparing future dosages with "present" dosages. If tests had been stopped at the end of 1956, the ground intensity of Sr^{90} would have increased by 1970 to a maximum about two and three-quarters times that at the end of 1956, and thereafter it would gradually decline (Fig. 1). If tests should continue at a steady average rate, the ground intensity would increase to a limiting value about 32.5 times as great as it was at the end of 1956 (Fig. 2). In the extreme case that the rate of testing should go on increasing at the steady rate equal to the average rate of increase during the first 5 years, the ground intensity in 100 years would be about 730 times as great as it was at the end of 1956 (Fig. 3). The last figure, of course, is intended only to supply a plausible upper limit based on an easily formulated assumption and to suggest that in the natural course of events a substantial increase is to be expected. It does not seem likely that peacetime testing will mount to such limits.

If we should attempt to provide a very rough calibration of the scale of dosage we have been using in terms of anticipated human pathology, we would pass beyond the realm of straightforward analysis and into a field of very necessary and vital speculation which is, however, beyond the proper scope of this paper. About it I shall here do no more than make a few very inadequate remarks. Some idea of the extent of the problem may be gained from Libby's papers (*1–3*) and their lists of references, though much work remains to be done on it.

Some perspective on the problem can be gained by comparison of the radioactivity from the tests with the radiation to which large populations are normally exposed. Libby has referred (*3*) to the variation of cosmic rays with altitude, pointing out that the variation of ionization in bone between Denver and New York is much greater than the bone radiation from Sr^{90} due to tests to date. A different approach is to compare Sr^{90} with another radioactive substance, namely radium, which also deposits in bone and which is very widely distributed in small and varying concentrations in drinking water. Radiological studies (*6*) show that the residents of the western suburbs of Chicago, who drink deep-well water containing about ten times as much radium as average drinking water, have an internal dose due to radium greater than the dose they would have from strontium if the surface density of Sr^{90} were 3000 mc/mi². Even with our most pessimistic assumption of a steadily increasing rate of testing, it would take about 125 years for the world-wide average density of Sr^{90} to reach this level.

In any such discussion, allowance must be made for fluctuations. There is considerable variation in the world-wide distribution of Sr^{90}, the north temperate latitudes receiving more than the rest of the world, particularly in the general vicinity of test sites where there is also the additional burden of local fallout of other substances. Moreover, the efficiency with which Sr^{90} is transferred to human beings exhibits large local variations associated with calcium deficiencies in some soils. Thus certain local populations may be jeopardized by Sr^{90} long before the global average seems impressive.

The use of a special population, such as the Chicago suburbanites, as a basis for calibration is very insensitive and can give no more than a rough upper limit, a feeling of assurance that the hazard is not serious compared with other normal hazards of living. It is based on the fact that no recognizably greater incidence of trouble has been found there than elsewhere. To be recognizable, it would have to be much greater—else it would be masked by fluctuations and incomplete diagnoses.

A more sensitive criterion is found in the extrapolation to man of pathology induced experimentally in other animals. Here there is serious uncertainty in the extrapolation, but it is possible to establish a reasonable expectation of the numbers of cases of cancer and genetic abnormality which, while perhaps very small compared with the world population in which they occur, represent nevertheless a lamentable absolute amount of human suffering. The fact that the cause of this particular trouble, in contrast to the other hazards of normal life, is a deliberate act of governments brings it under special scrutiny.

It is nevertheless important that the problem, and the possible solution of the problem, of continued testing be viewed in realistic perspective. Relative quantities are important here as elsewhere, even though deliberate incidence of human misery is involved. Judgment should not be unduly swayed by one prediction of human suffering if the alternative were to increase appreciably the likelihood of a much greater catastrophe. Modern global war would involve such vast tragic consequences to irreplaceable institutions as well as to life and health that its avoidance must be the transcendent consideration. Some (myself among them, as is apparent in other writings) believe that an agreement to stop tests on a world-wide basis would reduce the likelihood of war and should be sought for that reason. In this view, the reduction of the prospective radiation dosage may be viewed as an incidental but relatively minor bonus, a secondary incentive for arranging to stop the tests. It is the primary incentive that must be most seriously considered in weighing the various aspects of the security of the nation and the world. The above analysis, together with an adequate treatment of the problems of pathology here merely mentioned, might give the impression that the secondary incentive is not as urgent as it seems to some. Such an impression should not be permitted to obscure the forcefulness of the primary incentive for stopping tests, that of the prevention of war.

Mathematical Considerations

As stated in the section "Extent of past testing," the data used by Commissioner Libby are (i) the total testing in the 5 years ending with 1956 was about 30 megatons' equivalent of TNT; (ii) about ½ mc/mi² of radioactivity results from 1 megaton equivalent; (iii) the mean life for fallout is about 10 years, or perhaps a little less; and (iv) the mean life for radioactive decay of Sr^{90} is 40 years. Since the decay constants (λ_f and λ_r) are just the reciprocals of the corresponding mean lives, $\lambda_f = 0.10$ per year for fallout and $\lambda_r = 0.025$ per year for radioactive decay of Sr^{90}. If R_0 is taken to be the average rate of production of Sr^{90} from testing during the 5 years ending with 1956,

$$R_0 = (6 \text{ megaton/yr})(\tfrac{1}{2} \text{ mc/mi}^2 \text{ megaton}) = 3 \text{ mc/mi}^2 \text{ yr}.$$

The 5-year period during which these tests have taken place is represented by the time T_0 in the general discussions. For comparison, the curves with primed numbers were computed on the assumption that the mean life for fallout is 5 years, a value favored by some scientists; the corresponding decay constant is $\lambda_f = 0.20$ per year. The values given above have been substituted in the equations below to obtain the numerical results cited in the section "Prediction of effects of future tests."

1) *Accumulated fallout from a single blast.* Assume that at time $t=0$ radioactivity of amount A of some particular nuclide (for example, Sr^{90}) is put into the stratosphere by a single blast. Let λ_r be its radioactive decay constant, the fraction of this nuclide which decays per unit time; and let λ_f be the effective decay constant associated with fallout. (A decay constant is the reciprocal of the corresponding mean life.) It is further assumed that this radioactivity becomes uniformly distributed above the earth before appreciable loss occurs by fallout and decay. If there were no radioactive decay, the activity remaining in the stratosphere after fallout had continued for time t would be

$$x_0(t) = Ae^{-\lambda_f t},$$

and the activity on (or near) the earth's surface would be

$$y_0(t) = A(1 - e^{-\lambda_f t}).$$

But since radioactive disintegration with decay constant λ_r proceeds simultaneously and independently, the actual activities in the stratosphere and on the ground will be less than these by the factor $e^{-\lambda_r t}$. Thus the activity remaining in the stratosphere at time t will be

$$x(t) = Ae^{-(\lambda_f+\lambda_r)t} \quad (1)$$

and the net accumulation on the ground will be

$$y(t) = A(1 - e^{-\lambda_f t})e^{-\lambda_r t}. \quad (2)$$

Curve 0 of Fig. 1 is a plot of Eq. 2.

These results can also be obtained by solving the differential equations obtained by noting that the instantaneous rate of fallout from the stratosphere to the ground is $\lambda_f x$ and the rates of loss by radioactive decay are $\lambda_r y$ in the stratosphere and $\lambda_r x$ on the ground; so

$$dx/dt = -\lambda_f x - \lambda_r x = -(\lambda_f + \lambda_r)x$$

and

$$dy/dt = +\lambda_f x - \lambda_r y$$

The results cited in subsection 1 of "Prediction of effects of future tests" were obtained from Eq. 2.

The resultant effect for a series of blasts is just the sum of terms similar to those in Eqs. 1 and 2, since the rate of decay of the radioactivity from each blast is independent of other events. Thus, if radioactivity of amount A_1 is injected into the stratosphere at time t_1, amount A_2 at time t_2, and so forth, then the radioactive burdens in the stratosphere and on the ground at any later time t are, respectively,

$$x(t) = A_1e^{-(\lambda_f+\lambda_r)(t-t_1)} + A_2e^{-(\lambda_f+\lambda_r)(t-t_2)} + \ldots \quad (3)$$

$$y(t) = A_1[1 - e^{-\lambda_f(t-t_1)}]e^{-\lambda_r(t-t_1)} + A_2[1 - e^{-\lambda_f(t-t_2)}]e^{-\lambda_r(t-t_2)} + \ldots \quad (4)$$

The sums should include only the terms for those blasts that have taken place prior to time t in order to avoid the absurdity of including effects of blasts before the blasts have taken place.

2) *Result of continuing tests at a constant rate.* One easily calculated special case of continued testing is that in which radioactive material is produced at a constant rate R_0. In this case, the A of Eqs. 1 to 4 is replaced by $R_0\, dt_i$, the amount of the material produced between t_i and $(t_i + dt_i)$. This program offers a fairly good approximation to a continued sequence of blasts at a constant average rate, if the time between the blasts is smaller than the half-lives for fallout and radioactive decay. Under these assumptions, the sums in Eqs. 3 and 4 become the integrals

$$x(t) = \int_0^t R_0e^{-(\lambda_f+\lambda_r)(t-t_i)}dt_i. \quad (5)$$

and

$$y(t) = \int_0^t R_0[1 - e^{-\lambda_f(t-t_i)}]e^{-\lambda_r(t-t_i)}dt_i. \quad (6)$$

Straightforward evaluation of these integrals leads to

$$x(t) = \frac{R_0}{(\lambda_f+\lambda_r)}[1 - e^{-(\lambda_f+\lambda_r)t}] \quad (7)$$

and

$$y(t) = \frac{R_0}{(\lambda_f+\lambda_r)} \times \left[\frac{\lambda_f}{\lambda_r} + e^{-(\lambda_f+\lambda_r)t} - \left(\frac{\lambda_f}{\lambda_r}+1\right)e^{-\lambda_r t}\right] \quad (8)$$

These asymptotically approach the limiting values

$$x_\infty = R_0/(\lambda_f + \lambda_r) \quad (9)$$

$$y_\infty = R_0\lambda_f/\lambda_r(\lambda_f + \lambda_r) \quad (10)$$

The numerical results cited in subsection 2 of "Prediction of effects of future tests" were obtained from Eqs. 8 and 10. Curve 2 of Fig. 2 is a plot of Eq. 8, and the broken horizontal line corresponds to Eq. 10.

The value of the mean life for fallout is not well established, and any revision in it would probably be downward. As an illustration of the alteration of the graphs in consequence of such a change, take the mean life to be 7 years (instead of 10 years). The value of y (5 yr) then becomes 3.95 mc/mi² (raised from 2.95), and the asymptotic value $y(\infty)$ is raised proportionately less, from 96 to 102.1 mc/mi². The ratio $y(\infty)/y$ (5 yr) is lowered from 32.6 to 25.9.

3) *Future dosage if tests were to be stopped now.* Assume that testing produces the radioactive material at a constant rate R_0 up to time T_0, when testing is discontinued abruptly. For $0 \leq t \leq T_0$, Eqs. 7 and 8 still apply. Hence the amounts of material in the stratosphere and on the ground at time T_0 are, respectively,

$$x(T_0) = \frac{R_0}{(\lambda_f+\lambda_r)}[1 - e^{-(\lambda_f+\lambda_r)T_0}]$$

and

$$y(T) = \frac{R_0}{(\lambda_f+\lambda_r)} \times \left[\frac{\lambda_f}{\lambda_r} + e^{-(\lambda_f+\lambda_r)T_0} - \left(\frac{\lambda_f}{\lambda_r}+1\right)e^{-\lambda_r T_0}\right].$$

As pointed out in subsection 3 of "Prediction of effects of future tests," the course of events for the material in the stratosphere at time T_0 is the same as if it were injected by a single blast at that instant—that is, $x(t)$ for the present case is obtained by replacing A by $x(T_0)$ and t by $(t - T_0)$ in Eq. 1. Thus the stratospheric burden at any time $t > T_0$ is

$$x(t) = \frac{R_0}{(\lambda_f+\lambda_r)} \times [1 - e^{-(\lambda_f+\lambda_r)T_0}]\, e^{-(\lambda_f+\lambda_r)(t-T_0)};$$

whence

$$x(t) = \frac{R_0}{(\lambda_f+\lambda_r)} \times [e^{(\lambda_f+\lambda_r)T_0} - 1]e^{-(\lambda_f+\lambda_r)t}. \quad (11)$$

The amount of radioactivity on the ground is expressible as the sum of two terms. The first term y_1 represents the residue after the amount $y(T_0)$ which was on the ground at time T_0 has undergone exponential radioactive decay until time t. This term is, therefore,

$$y_1 = y(T_0)e^{-\lambda_r(t-T_0)} = \frac{R_0}{(\lambda_f+\lambda_r)}\left[\frac{\lambda_f}{\lambda_r} + e^{-(\lambda_f+\lambda_r)T_0} - \left(\frac{\lambda_f}{\lambda_r}+1\right)e^{-\lambda_r T_0}\right]e^{-\lambda_r(t-T_0)}$$
$$= \frac{R_0}{(\lambda_f+\lambda_r)}\left[\frac{\lambda_f}{\lambda_r}e^{\lambda_r T_0} + e^{-\lambda_f T_0} - \left(\frac{\lambda_f}{\lambda_r}+1\right)\right]e^{-\lambda_r t}$$

The additional radioactivity on the ground as a result of fallout from the stratosphere is found by the same method as was used to get $x(t)$—that is, A is replaced by $x(T_0)$ and t by $(t - T_0)$ in Eq. 2. Hence, the second portion y_2 of the radioactivity on the ground at any time $t > T_0$ is

$$y_2 = x(T_0)(1 - e^{-\lambda_f(t-T_0)})e^{-\lambda_r(t-T_0)}$$
$$= \frac{R_0}{(\lambda_f+\lambda_r)}[1 - e^{-(\lambda_f+\lambda_r)T_0}] \times (1 - e^{-\lambda_f(t-T_0)})e^{-\lambda_r(t-T_0)}$$
$$= \frac{R_0}{(\lambda_f+\lambda_r)}\left\{[e^{\lambda_r T_0} - e^{-\lambda_f T_0}]e^{-\lambda_r t} + [1 - e^{(\lambda_f+\lambda_r)T_0}]\, e^{-(\lambda_f+\lambda_r)t}\right\}$$

Hence the total amount of radioactivity on the ground at time $t > T_0$ is

$$y(t) = y_1 + y_2$$
$$= \frac{R_0}{(\lambda_f+\lambda_r)}\left\{\left[\frac{\lambda_f}{\lambda_r}e^{\lambda_r T_0} + e^{-\lambda_f T_0} - \left(\frac{\lambda_f}{\lambda_r}+1\right)\right]e^{-\lambda_r t} + [e^{\lambda_r T_0} - e^{-\lambda_f T_0}] \times e^{-\lambda_r t} + [1 - e^{(\lambda_f+\lambda_r)T_0}]\, e^{-(\lambda_f+\lambda_r)t}\right\}$$

$$y(t) = \frac{R_0}{(\lambda_f+\lambda_r)}\left\{\left(\frac{\lambda_f}{\lambda_r}+1\right)[e^{\lambda_r T_0} - 1]e^{-\lambda_r t} - [e^{(\lambda_f+\lambda_r)T_0} - 1]\, e^{-(\lambda_f+\lambda_r)t}\right\} \quad (12)$$

This equation is plotted as curve 1 of Fig. 1.

4) *Future dosage if rate of testing should continue to rise at a constant rate.* The idealized case which is selected as a plausible upper limit to the likely future world-wide testing is taken to be that in which $R(t)$, the rate of production of radioactive materials, increases in direct proportion to the time t. Then if R_0 is the average rate of production during the interval from $t = 0$ to $t = T_0$, the rate at any time t is

$$R(t) = (2R_0/T_0)\,t \quad (13)$$

and the material produced in the interval between t_i and $(t_i + dt_i)$ is

$$(2R_0/T_0)\,t_i \cdot dt_i.$$

When this replaces A in Eqs. 3 and 4 and the sums are replaced by integrals over the time t_i, the result is

$$x(t) = \int_0^t (2R_0/T_0)\,t_i e^{-(\lambda_f+\lambda_r)(t-t_i)}dt_i \quad (14)$$

$$y(t) = \int_0^t (2R_0/T_0)\,t_i \times [1 - e^{-\lambda_f(t-t_i)}]e^{-\lambda_r(t-t_i)}dt_i \quad (15)$$

Hence

$$x(t) = \frac{2R_0}{T_0(\lambda_f+\lambda_r)^2} \times [(\lambda_f+\lambda_r)t - 1 + e^{-(\lambda_f+\lambda_r)t}] \quad (16)$$

$$y(t) = \frac{2R_0}{T_0}\left[\frac{\lambda_r t - 1 + e^{-\lambda_r t}}{\lambda_r^2} - \frac{(\lambda_f+\lambda_r)t - 1 + e^{-(\lambda_f+\lambda_r)t}}{(\lambda_f+\lambda_r)^2}\right]$$
$$= \frac{2R_0\lambda_f}{T_0\lambda_r(\lambda_f+\lambda_r)} \times \left[t - \left(\frac{1}{\lambda_r} + \frac{1}{(\lambda_f+\lambda_r)}\right) + \left(\frac{1}{\lambda_f} + \frac{1}{\lambda_r}\right)e^{-\lambda_r t} + \left(\frac{1}{(\lambda_f+\lambda_r)} - \frac{1}{\lambda_f}\right)e^{-(\lambda_f+\lambda_r)t}\right] \quad (17)$$

The latter result, which is shown as curve 3 of Fig. 3, is expressed somewhat more neatly if the decay constants λ_f, λ_r and $(\lambda_f + \lambda_r)$ are replaced by the corresponding mean lives τ_f, τ_r, and τ_t.

For late times, for which $t \gg 1/\lambda_r$, the exponentials in Eqs. 16 and 17 approach zero, so $x(t)$ and $y(t)$ approach the asymptotic values

$$x = \frac{2R_0}{T_0(\lambda_f+\lambda_r)}\left[t - \frac{1}{(\lambda_f+\lambda_r)}\right] \quad (18)$$

$$y = \frac{2R_0\lambda_f}{T_0\lambda_r(\lambda_f+\lambda_r)}\left\{t - \left[\frac{1}{\lambda_r} + \frac{1}{(\lambda_f+\lambda_r)}\right]\right\} \quad (19)$$

With the assumed numerical values for the constants, Eq. 19 becomes

$$y = (38.4\ \text{mc/mi}^2)(t/\text{yr} - 48). \quad (20)$$

This asymptote is shown as the dashed straight line at the right in Fig. 3.

This assumption of a steadily increasing rate of testing is not, of course, the best possible approximation to the course of events over the past few years. However, refinements in the assumptions for this period have little significance because the effects of these early tests are overshadowed at much later times by the large amounts of activity resulting from the assumed accelerated rate of testing.

References and Notes

1. AEC release, 12 Oct. 1956; W. F. Libby, *Proc. Natl. Acad. Sci. U.S.* 42, 365 (1956).
2. W. F. Libby, *Proc. Natl. Acad. Sci. U.S.* 42, 945 (1956).
3. AEC release, Apr. 1957.

4. This work was performed, under the auspices of the U.S. Atomic Energy Commission, mainly in late 1956, which is the closing date for the data used in the examples. I am grateful to Dr. W. F. Libby, Dr. J. E. Rose, Dr. F. E. Throw, and Dr. L. A. Turner for discussion and suggestions. The order of presentation in the text and the "primed" curves on the graphs were kindly arranged by Dr. Throw.

5. Note that these calculations take no account of the radioactivity introduced directly into the troposphere, especially by fission explosions. Actually, in the Northern Hemisphere, tropospheric fallout constitutes a large fraction of the total, so the stratospheric burdens estimated in this paper are probably too high. Moreover, the biological effectiveness of fallout depends significantly on such factors as its precipitation as an insoluble salt and its redistribution in depth because of soil movements. [See W. F. Libby, *Proc. Natl. Acad. Sci., U.S.* 43, 758 (1957).] Such effects would change the numerical values for the stratospheric component of fallout without altering the general course of events. If certain scientists are correct in believing that horizontal mixing in the stratosphere is not very rapid (for example, L. Machta, "Hearings before the Joint Committee on Atomic Energy on the Nature of Radioactive Fallout and Its Effects on Man," May 27–June 3, 1957), the fallout over the earth's surface will be more or less nonuniform.

6. A. F. Stehney and H. F. Lucas, Jr., *Acta Radiol.* 43, 43 (1955); Geneva Conference, vol. 8, p. 852 (1955). Reference is also made to a forthcoming article by J. E. Rose. I am indebted to Dr. Rose for this and related information which suggested these calculations.

Irving Langmuir, Man of Many Interests

In these days of near hysteria on the world-wide scene, as claims and counterclaims are made of the superiority of this or that method of teaching science, of conducting scientific research, and of supporting basic research studies, it would do everyone involved in this turmoil a lot of good if he would pause a moment to consider Irving Langmuir's life, background and attitude toward science [V. J. Schaefer, "Irving Langmuir, Versatile Scientist," *Bull. Am. Meteorol. Soc.* **38**, 483 (1957); "In Memoriam: Irving Langmuir—Scientist," *J. Colloid Sci.* **13**, 3 (1958)]. With his death, on 16 August 1957, the world lost another of the scientific giants who strode across the scientific scene during the first half of the 20th century, leaving a trail of pioneering achievements which those with pessimistic attitudes attempt to explain away as "due to that period being the golden age of science when scientific breakthroughs were easier to come by, because there was so much virgin field to till."

Langmuir's attitude toward the modern scientific scene of the past few years was in direct conflict with such a philosophy. His enthusiasm for the newer achievements remained undiminished, his impatience being directed only toward those he felt were "dragging their feet" and serving as "wet blankets" in the development of new concepts and ideas.