In equation (25) the second integral can also be written as $d\sigma/dx_1$, the conversion of the measure into a function, and x_1 can be any point in space. Using equation (25) with relation (10), we control the portion of the weight of the total measure in the boundary part $d\rho$ in terms of the size of $\sqrt{t_2 - t_1}$ compared with the distance $d(x_2)$ from x_2 to B. Then we use equation (25) again to establish the approximation of $d\sigma$ to $S(x_2t_2x_1t_1)\,dx_1$. This reduces the problem of estimating the continuity of T at time t_2 to the free-space problem where relation (2) applies. The elliptic boundary-value problem corresponds to the parabolic one where everything is independent of time and a steady state obtains. The best continuity control is obtained by selecting $t_2 - t_1$ in proper relation to $|x_2 - x_2'|$, $d(x_2)$ and $d(x_2')$, x_2 and x_2' being two points in R. Proceeding crudely, we obtain relation (3).

Previously, relation (3) was known only up to two dimensions and was obtained by somewhat special methods. This limited the study of nonlinear elliptic problems to one and two dimensions. Relation (2) was, at most, known only in one space dimension. The key inequality (10) contains more strength than we have used here to derive relations (2) and (3).

In all our discussion we have ignored smoothness questions, because, in obtaining the results we obtain, the essential thing is that no *quantitative* smoothness assumptions are used, while any *qualitative* smoothness, such as C^∞, assumed for the coefficients of equation (1) is quite harmless.

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RADIOACTIVE FALLOUT

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1. INTRODUCTION

The radioactivity produced by the fission reaction changes its characteristics continuously and rapidly following the explosion of an atomic weapon, and the conditions of firing are of extreme importance in determining the rate at which the radioactivity descends to earth. As a result, there are in general three different kinds of radioactive fallout, the relative importance of which is determined by the nature of the weapon, principally its yield, and the conditions of firing. The first of these three types is the *local fallout*, which is insignificant unless the fireball touches or comes close to the ground but which, in case the fireball does touch the ground, can amount to a major fraction, in some instances as much as 80 per cent of the total debris. This type of fallout consists of radioactivity which is carried down by the larger particles. It consists largely of matter drawn up into the fireball from the surface, which is either totally or partially vaporized. Under these conditions so much matter is vaporized by virtue of the fireball's touching the ground that the particle sizes formed in the freshly cooled vapor are large.

The second and third types of radioactive fallout are world-wide in nature and consist of finer material; they are divided according to whether the material happens to lie in the lower part of the atmosphere, the troposphere, where rain and weather phenomena occur, or in the higher part of the atmosphere, the stratosphere, which is free of such precipitating mechanisms. The *tropospheric fallout* occurs in a matter of two or three weeks or a month or so. It occurs largely as a result of rain and snow, and water precipitation in general, and falls in the general latitude of the test site. The *stratospheric fallout*, in contrast, takes years. We are not completely certain, but it appears that an average time of something like ten years, or perhaps somewhat less, is a reasonable figure, and during this time the distribution becomes nearly world-wide. When the stratospheric fallout manages finally to pass into the troposphere, it is quickly removed by the same type of mechanism that brings down the world-wide tropospheric fallout, namely, rain and moisture.

The precipitating mechanisms consist in general of the collision of the tiny particles with moisture droplets in clouds, together with the interception of particles by falling raindrops. The first mechanism was recently suggested by Dr. Greenfield in connection with "Sunshine" problems. In addition to the scavenging action of rains and fogs, there is definite evidence for a considerable probability of pickup on direct contact of air with surfaces such as the leaves of grass and trees. Frequently, grasses are found to have higher strontium 90 content than would correspond to the soils in which they grow, and this is due undoubtedly to direct pick-up.

The dissemination of strontium 90 and all fallout is greatly dependent upon the firing conditions. There is every evidence that important factors include not only contact of the fireball with the surface but the nature of the surface—whether it is land or water, the type of soil or the composition of the water, whether fresh or sea water. Also, the height to which the fireball rises is important—in particular, the height relative to the tropopause, the dividing layer between the troposphere and the stratosphere. Yield is the main consideration here. A rough rule is that megaton weapons push through the tropopause into the stratosphere, and kiloton weapons stay below the tropopause in the troposphere.

Thus we see immediately that kiloton weapons deposit their fission products much more quickly than do megaton weapons. Of course, this is of less importance in so far as the long-lived fission products, such as strontium 90 and cesium 137, are concerned, but it is of more importance for the shorter-lived fission products. As a general rule, an air-fired kiloton weapon will deposit its radioactive fallout in a period of between two weeks and one month, on the average, after the detonation, whereas an air-fired megaton weapon will deposit its radioactive fallout over many years—on the average, about ten years. Thus the effects which are due to the short-lived fission products are larger for a given amount of fission energy release in kiloton weapons than they are for air-fired megaton weapons. Considering the average age of the kiloton fission products to be one month, the external gamma-ray exposure from a megaton of fission fired as, say, 50 bombs of 20 kilotons each would be 30 times that for a single bomb giving one megaton of fission energy—if both were fired well up in the air. The fission products from the small bombs fired in Nevada would fall in the latitudes 10° N. to 60° N. in about one month, while the larger bomb would give fallout over essentially the whole earth in about ten years. For strontium 90 effects there is relatively little difference per unit of fission yield, since even the residence time in the stratosphere is small compared with the 28-year half-life of radioactive strontium and the 27-year half-life of radioactive cesium, which is produced at slightly higher yield than strontium 90 and which appears to be disseminated in about the same way.

The contents of radiostrontium and radiocesium in the stratosphere are shown by direct measurement to be roughly the same, although the radiocesium is somewhat higher, possibly because of the slightly higher fission yield. The content of radiocesium in rain water is comparable to that of strontium 90. Also, the content of radiocesium in the human body as measured by Marinelli at Argonne and by Anderson and Langham at Los Alamos agrees well with the fact that it has an average residence time in the human body of about five months, as compared with many years for strontium 90. The radiocesium data are very interesting because of their bearing on the fallout dissemination mechanism and the confidence with which we can establish the probable future behavior of radioactive strontium. The data confirm previous suggestions as to the dissemination mechanism, that is, we find that radiocesium fallout, except of the local variety, is carried down very largely in the form of moisture droplets and that there is some direct pickup by leaves and grass on surfaces. It is captured and held tightly by the top two inches of most soils, so that the water which falls and runs off in the form of rivers is clean by the time it has drained a short distance through soil. All this is very similar to the radiostrontium behavior.

The plants pick the strontium 90, and radiocesium to a lesser extent, out of the soil and also off their leaves and take it into their systems. There appears to be a discrimination mechanism which operates in most plants, so that the strontium 90 content of the plant is considerably less, relative to its calcium content, than in the case of the soil. On the average, the discrimination factor between the topsoil and plants against strontium relative to calcium seems to be about 1.4. When the cows eat grass, they further discriminate by about a factor of 7 in making milk; hence there is an over-all protection factor for strontium 90 from the topsoil to milk of about 1.4 × 7 or 10. Also, there is a further discrimination factor against strontium relative to calcium in the human body. This factor is not known accurately but is known definitely to be at least as large as 2 and is thought possibly to be as high as 8. Research is now in progress to settle this. Therefore, there is a series of protective factors which makes the concentration of radiostrontium derived from milk relative to calcium in human bone not over one-twentieth and possibly as little as one-eightieth of that in the topsoil. Of course, it should be pointed out that a considerable part of the fallout is picked up directly on the leaves, and to this the factor of 1.4 does not apply; thus, for this fraction of the fallout, the protective factor may be reduced to 14. Since milk is the source of most of our calcium, this means that the actual ratio of radiostrontium concentration in new human bones relative to that in the topsoil should approach these numbers.

It must be realized that, although only a small part of the calcium is derived from vegetables and meat, a similar calculation must be made for this portion and the total average ratio obtained. It seems that the meat-vegetable over-all discrimination factor is about 10; if 20 per cent of the calcium is derived from such sources on the average, the average over-all factor will be between $^1/_{13}$ and $^1/_{30}$.

The experimental data on new human bone in children appear to give a smaller figure, $^1/_{60}$, as mentioned later.

A matter of importance in connection with the amount of strontium 90 which one would expect to be deposited in human bone as a result of atomic weapon detonations is the calcium concentration in the topsoil. Since calcium is so similar to strontium, it seems very likely, and the evidence confirms this, that high available calcium content of the soil will reduce the probability of strontium 90 being taken up into the plants. Of course, this probably does not have nearly as great an effect on the uptake of the material which is picked up directly on the leaves. We might expect, therefore, that soils which are particularly low in calcium might show higher strontium 90 contents for the grasses grown on them. This is, in fact, so, and sheep and goats and cattle feeding on such pasture displays a higher strontium 90 bone content.

How such calcium deficiencies in the soil should affect the strontium 90 uptake by the human population is a most important question. One sees immediately that food distribution systems are such that the food supply is derived from large areas, and that there is consequently a sharp reduction in the sensitivity of the human population to calcium deficiencies in local soils. This is brought out particularly well by the data on the radium contents of human bones and their obvious lack of strong dependence on the radium contents of local waters. But for people who consistently drink milk from cows grazing on such ground there should be definite effect on the amount of radiostrontium uptake, and the effect should be proportional to the radiostrontium content of the milk. So the question resolves itself largely into this: What are the strontium 90 contents of the foods that people in such regions actually consume? We find, on inspection of the food-eating habits and calculation of the strontium 90 intake relative to calcium, that the increase in average strontium 90 concentration of the food due to the low calcium content of the particular soils can hardly be more than fivefold for a soil calcium deficiency of fifty fold. That is, whereas normal soil carried about 20 gm. of available calcium in the top 2.5 inches, a region with soil of only 0.4 gm. per square foot would produce a human-body burden equilibrium of about five times that which the normal soil would produce.

In order to understand the hazard of radiostrontium, which is generally agreed to be the most hazardous of the long-lived fission products, we try to establish the maximum permissible concentration both for occupational workers and for the population in general. These numbers have been set at 1 microcurie and 0.1 microcurie for the standard man, respectively. That is, an occupational worker may carry 1 microcurie of strontium 90 in his body, whereas the average standard adult in the general public should not have over 0.1 microcurie of strontium 90. This last figure corresponds to a concentration of 100 micromicrocuries per gram of body calcium, or what we call 100 "Sunshine Units"; that is, 1 micromicrocurie of strontium 90 per gram of body calcium is defined as 1 Sunshine Unit.

Now we must try to see in some other way how our normal experiences can be brought to bear on the question, "How dangerous is atomic weapons testing from the point of view of radioactive fallout?" At the present time, we have in our bodies about 0.1 or 0.2 Sunshine Unit, and children have about one-half of a Sunshine Unit. A little later I will speak about the question of the variation from these average values; but, assuming at the moment that these are the values, what is the threat or the hazard from these quantities? Obviously, they are much smaller than the 100-Sunshine-Unit tolerance figure mentioned above. To obtain a comparison with normal experience, let us consider the fact that we know in a general way the magnitude of the radiation levels to which we are normally subjected by the cosmic rays, the potassium in our own bodies, and the uranium, thorium, and potassium in the ground and in our surroundings. We know that these quantities amount to something like 150 milliroentgens per year for an average person in this latitude. But we also know that there are considerable variations with conditions.

For example, a person living in a brick house may very well get 25–50 milliroentgens per year more than one living in a wooden house, because of the natural radioactivity of the bricks. It is also very well known that, whereas at sea level in this latitude the cosmic-ray dosage is 37 milliroentgens per year, at 5,000 feet altitude, as in Denver, Colorado, the dosage from cosmic rays is 60 milliroentgens per year—a difference of 23 milliroentgens per year. What is this in terms of strontium 90 body burden?

First, we must consider what part of the natural radiation, if any, is similar to the radiation of strontium 90 in biological effect, so that we can say without doubt and hesitancy that the physiological effects, whatever they are, will be the same for the same energy absorbed. Fortunately, the cosmic rays seem to fit this bill. In other words, we are at liberty to compare the cosmic-ray radiation dosages with the dosages from radiostrontium in our bone structure. The reason this is permissible is that the ionization density along the tracks of the mu-mesons which are the principal cosmic-ray components at sea level and at altitudes of 5,000 feet are nearly the same as those of the yttrium 90 beta rays, the principal radiation which radiostrontium emits; that is, radiostrontium has a radioactive daughter, yttrium 90, which emits a very energetic beta ray, and the ionization density along the track of this radiation is very similar to that of the mu-mesons of the cosmic rays and their disintegration electrons; it is generally accepted by health physicists and radiobiologists that radiations of the same ionization density have very similar, if not identical, biological effects for the same energy absorbed. The high energy of yttrium 90 gives it an average distance of penetration in tissue of 2 millimeters; hence any effect of local nonuniformity of deposition of strontium 90 in the bone is removed. The cosmic-ray exposure is, of course, uniform throughout the bone structure. Therefore, we can equate cosmic-ray dosage with strontium 90 dosage, and it is thus possible for us to say that the difference between one altitude and another is equal in effect, other effects being equal, to a certain number of Sunshine Units in bone. Now, to follow this thought through, 1 Sunshine Unit is equal to 3 milliroentgens per year. Therefore, the difference in annual cosmic-ray radiation dosage between Washington, D.C., or any place at sea level in this latitude, and Denver, Colorado, is equal to 8 Sunshine Units, that is, 16 times the present body burden of equilibrium bone or bone near equilibrium as we see it in young children who are growing now.

Therefore, we must see whether anything in our experience indicates that these differences are significant in terms of the occurrence of the principal effects expected of radiostrontium, namely, leukemia and bone cancer. Now, of course, when one looks for such vital statistics, one finds that they are very hard to acquire. However, the National Institutes of Health of the Department of Health, Education, and Welfare have given us statistics for the occurrence of leukemia and bone cancer for the year 1947 for the three cities New Orleans, San Francisco, and Denver. They are shown in Table 1. It is clear from this table that there is no obvious effect of altitude, and it is also clear that there are other factors which are noticeably more important than cosmic-ray dosage. Of course, there may still be a considerable effect of altitude hidden in large fluctuations caused by other factors which presumably are largely unknown, and we cannot say that this *proves* anything. It does, however, give us some assurance from normal experience that the effect of 8 Sunshine Units will not cause a detectable increase in bone cancer or leukemia.

TABLE 1

Occurrence of Bone Cancer and Leukemia

(New Cases per Year per 100,000 Population)

	Bone Cancer	Leukemia
Denver	2.4	6.4
New Orleans	2.8	6.9
San Francisco	2.9	10.3

This fits well with the laboratory data on animals and the limited experience on humans with radium. That is, 1 microcurie, being 1,000 Sunshine Units, is still considered to be pretty safe on the basis of the laboratory data. It is set as a tolerance for occupational workers, and it is therefore reasonable that 8 Sunshine Units should give an effect so small as to be very, very difficult to detect. It is, I think, helpful for us, however, to realize that the present body burden of strontium 90 in new bone from the weapons tests that have occurred in the past is equal to the increase in cosmic-ray intensity that goes with an increase of some 400 feet in altitude, a very small fraction of the difference in cosmic radiation intensity between Denver and sea level. Therefore, at the same time that we consider the possible effects of strontium 90 from such concentrations, we may deduce from our everyday ordinary experience limits on the effects to be expected. None of the evidence on the occurrence of bone cancer or leukemia as a function of altitude has given us any reason to believe that the present tolerance limits are in any way in error. The present body burdens in new bones are small compared to these limits.

Separate from the strontium 90 effects are the effects of general gamma radiation, the radiation that is received mainly from outside the human body and which comes mainly from the very young fission products in the local fallout area, but which can come in smallest part from radiocesium accumulating on the ground in the case of the stratospheric fallout or, more importantly, from the shorter-lived fission products deposited by the tropospheric fallout. Of course, weapons tests are so conducted as to avoid exposures to local fallout; hence our present discussion of the effects of weapons will be restricted to the much smaller gamma-ray doses from the off-site tropospheric and stratospheric types of fallout. In time of war, of course, it would be the local fallout which would be of more direct concern, next to blast and thermal effects, and it is to this aspect of fallout that Federal Civil Defense Administration addresses itself in the main. In regard to nuclear tests, we have to study the effects on human genetics and the possible effects of such doses of radiation on health. Let us again apply the criterion of normal human experience to this. Measurements have shown that the general average intensity of fallout gamma rays from tests is from 1 to 5 milliroentgens per year. Now the general magnitude of the effects to be expected from this can be compared with the natural radiation intensity. We find, as mentioned earlier, that such things as living in a brick house instead of a wooden house can produce as much as 25–50 milliroentgens extra dosage per year, that there are certain areas in the world where the average dose in this country of 150 milliroentgens per year is exceeded by tenfold, that people living on granitic rock as compared with those living on sedimentary rock receive about 70 milliroentgens per year more dosage due to the higher content of uranium and thorium in these rocks, and that people living at higher altitudes have a higher natural cosmic-ray dosage. Also, of course, we know that medical uses of X-rays can be considerably larger than any of these fallout dosages.

We do have experience and valid evidence that the somatic effects other than cancer and leukemia, that is, the effects of radiation on ordinary human health, require dosages which are very much larger—of the order of 25–50 roentgen units—in order to be observed as changes in the blood, and 100–200 roentgens for injury symptoms, whereas the dosages we are speaking of, from test fallout, are about one hundred thousand fold smaller.

As for genetic effects, these are extremely difficult to evaluate, since so little is known about human genetics. But, judging from experience with plants, insects, animals, and lower organisms, there is every reason to expect some genetic effects of radiation. The question is how much radiation is required for a given level of effect. There are a certain number of mutations in every new human generation. Are these largely induced by natural radiation, or are they mainly of chemical, or rather biochemical, origin, or both? From a chemical point of view, it seems likely that not all the spontaneous mutations in the human or any other species are caused by radiation effects, because it seems likely that radiation acts in inducing mutations mainly via molecules which it generates in the human cell, and that the mutations are caused by these chemicals and therefore in a sense are chemical in nature. Now, if this is so, and the radiation-induced mutations are nearly always caused by chemicals which are produced in the first instance by radiation, then chemicals which are not themselves produced by radiation, but have other origins, can cause mutations; thus it seems likely that a major part of the natural or spontaneous mutations in any species is not radiation-induced. This point is an important one to settle, for the reason that we have to compare the effects of fallout radiation with the fraction of the natural spontaneous mutations due to the radiation to which we are normally subjected. In other words, if the normal mutations are all due to radiation, then the effects of the additional radiation from general test fallout, or from other sources of radiation such as atomic power or the medical uses of isotopes and X-rays, will be larger. It seems likely, and many genetic authorities agree on genetic grounds with this conclusion, that a major portion of the spontaneous mutations of the human species is due not to radiation but to other causes. Therefore, a fraction of the spontaneous mutations in the human species is taken as being due to irradiation. Now, what this fraction is, it is difficult to say; but Professor H. J. Muller has estimated that this might be 10 per cent. Therefore, one estimates that the 150 milliroentgens per year from natural radiation now causes about 10 per cent of the spontaneous mutations and, therefore, that the test fallout, if continued indefinitely, will, at the present level of about 1–5 milliroentgens per year, cause an increase in the natural spontaneous mutation rate of something like one-fiftieth of 10 per cent, or 0.2 per cent of the spontaneous mutations. In the extreme, if it should prove that all the spontaneous mutation rate is radiation-induced despite the chemical arguments, the effect would be ten times as great, or 2 per cent. Dr. Gordon Dunning, of the Division of Biology and Medicine of the Atomic Energy Commission, estimated 1.4 per cent in 1955, based on the assumption that the annual fallout was equal to the highest amount experienced heretofore in any one year, and that 10 per cent of spontaneous mutations were due to natural radiation (*Scientific Monthly*, **81,** 265, December, 1955). This effect is one which is comparable to moving to a slightly different locality and is much less serious than changing from one house to another or doing any of a dozen things. The only important point is that genetic effects appear only if large numbers of people are subjected to them. Therefore, we would expect that the effects of large populations changing their environment—for example, living at a higher altitude or living in a region of naturally higher radioactivity—should cause genetic effects if test fallout does so. An examination of vital records should be made to test for such effects, and the Atomic Energy Commission is doing so as best it can. The United Nations Scientific Committee on the Effects of Atomic Radiation has been comparing the data on natural background dosages, and it is hoped that this study will be continued and that the search will be made for observable effects of variations in the natural background dosage, for it is certain that any effects due to gamma rays from fallout must be already present in much larger measure due to the natural dosage.

II. VARIATION IN INDIVIDUAL STRONTIUM 90 BURDENS

What is the likelihood that even if the average strontium 90 content is well within tolerance limits, a few individuals should exceed tolerance limits? Let us consider first the case which will ultimately hold, the situation of complete equilibrium with the environment in so far as the strontium 90 burden is concerned. The only way we can make judgments about the expected individual variations from the mean concentration is by direct experiment on human-body composition, not only for strontium 90 but for other analogous constituents. Most of the recent data on the strontium 90 body burden are from odd bits of bone removed during surgical operations, but fortunately we have actual data for the strontium 90 content of the entire bodies of some several dozen stillborn children[1] in the city of Chicago in the year 1953. A strenuous effort is now being made in Project Sunshine to continue this series and also to check the human-bone data by analyses of complete skeletons. We present the distribution of the strontium 90 data for the stillborn children in Figure 1. Data for the occurrence of ordinary nonradioactive strontium in human bones also have been published.[2] These obviously refer to the full steady-state condition and are obviously at least as nearly in equilibrium with the environment as the fallout radioactive strontium ever will be. These data are presented in Figure 2. The occurrence of radium in the human body also has been used, since it is chemically similar to both calcium and strontium and therefore is a bone-seeker, and because it is obviously also in steady-state equilibrium. The data used were those of Palmer and Queen[3] (Fig. 3) And, finally, we use the recent data on occurrence of normal potassium in human bodies as determined by Anderson and Langham[4] at the Los Alamos Scientific Laboratory, presented in Figure 4. All these data show a normal frequency distribution as indicated by the theoretical curves. The respective widths of the curves (standard deviations) are 36 per cent for radiostrontium, 40 per cent for normal strontium, 40 per cent for radium, and 18 per cent for natural radiopotassium. It is completely clear from these data that the distributions agree with one another in general shape and that the magnitude of the distribution of the strontium 90 contents of the Chicago stillborn babies was not in any way anomalous. Therefore, we shall take the distribution curve for radiostrontium to be the same as for the normal strontium data. The occurrence of nonradioactive normal ordinary strontium in the bones should certainly tell us what the equilibrium distribution will be for radioactive strontium, and from it we should be able to learn the points about distribution which we cannot yet learn in any detail from the radioactive strontium itself. Turekian and Kulp noted in their study of normal strontium in human bone that in a given region the deviation from the average was about 34 per cent of the average, that is, for human bone from the regions Colorado, Texas, Cologne, Bonn, Venezuela, Chile, Vancouver, China, and India. In each instance the ratio of the standard deviation from the mean itself was taken and the average calculated, to obtain 34 per cent. Therefore, we take 34 per cent as the expected standard deviation from the mean *for a given locality* for the eventual strontium 90 equilibrium burden in human bones.

With this result we can, assuming a normal error-curve shape of the distribution of probabilities, answer the immediate question: What is the probability of an individual exceeding the tolerance even though the mean does not? On the basis of this analysis, we find that at steady state and in equilibrium the variation from the mean will constitute an error curve with a shape corresponding to the standard deviation, being one-third of the mean. Therefore, at steady state among people living in a given locality, only one person in about 700 will have more than twice the average strontium 90 burden, and the chances of anyone having as much as three times the normal burden will be about one in twenty million.

Now, what about the nonequilibrium distribution, when the strontium 90 is finding its way into the biological system? Obviously, the burden will be much lower here, but the deviation from the mean will probably be much higher percentagewise, particularly in adults, where most of the bone has been deposited before strontium 90 was produced. The present strontium 90 content of adults depends very much on the growth rate and the metabolic activity of the various bones in the given individual's body which happens to be sampled. However, the specific concentration of the strontium 90 deposited will not exceed that in new bone developed entirely in the present biological environment, i.e., the local concentration in adult bone will not exceed that for the whole bone in young children, whose total bodies are composed of the mixture of strontium 90 and calcium which now is present in food. Since the present child-adult ratio is about 4 to 1 for average total strontium 90 content, the factor of concentration in adults' active bone regions may be as much as fourfold greater than the whole-body average. Thus the apparent spread for random bone samples taken from adults should be very

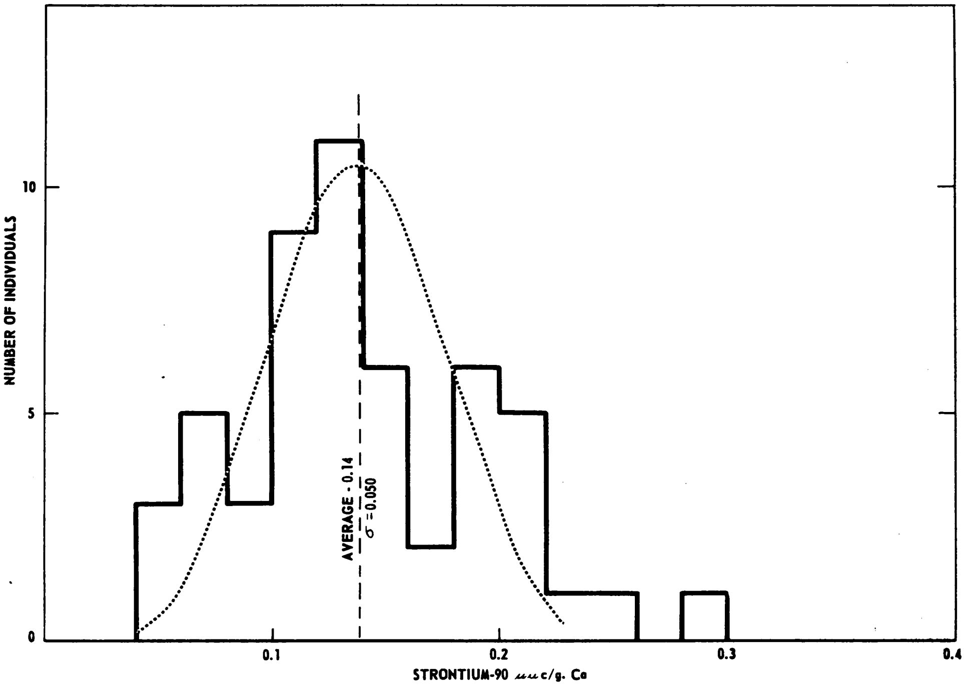
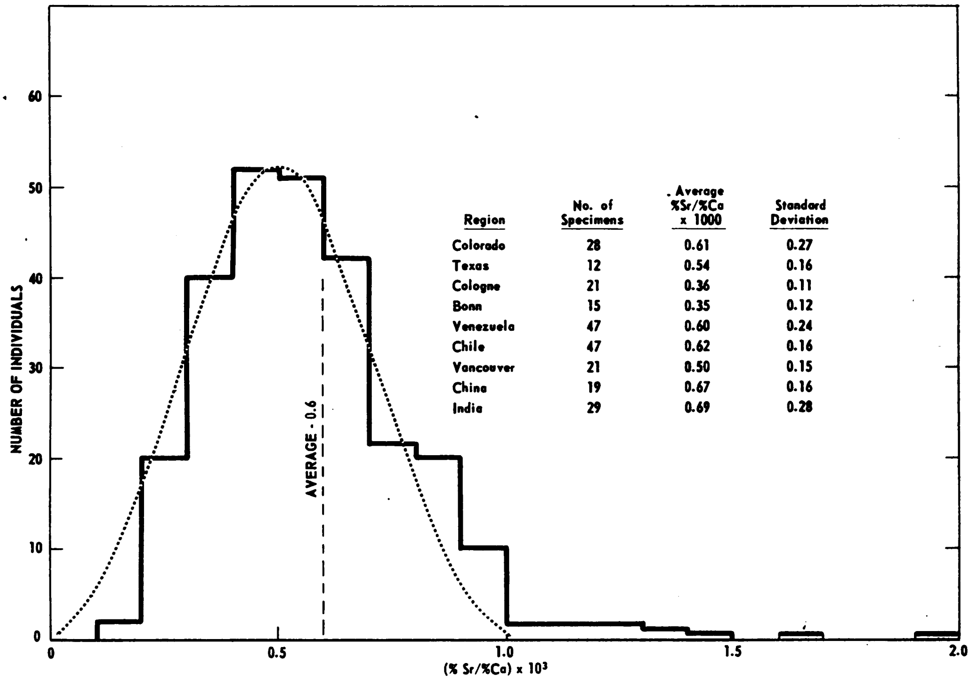


FIG. 1.—Radio strontium (Chicago, 1953; Stillborns)



Region	No. of Specimens	Average %Sr/%Ca x 1000	Standard Deviation
Colorado	28	0.61	0.27
Texas	12	0.54	0.16
Cologne	21	0.36	0.11
Bonn	15	0.35	0.12
Venezuela	47	0.60	0.24
Chile	47	0.62	0.16
Vancouver	21	0.50	0.15
China	19	0.67	0.16
India	29	0.69	0.28

FIG. 2.—Normal strontium (Turekian and Kulp)

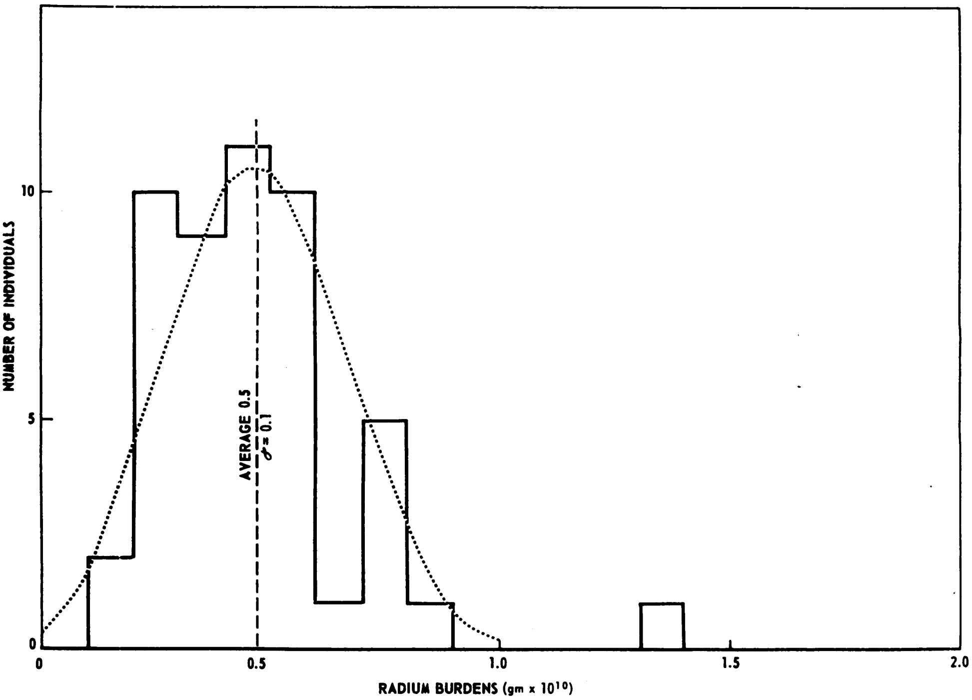
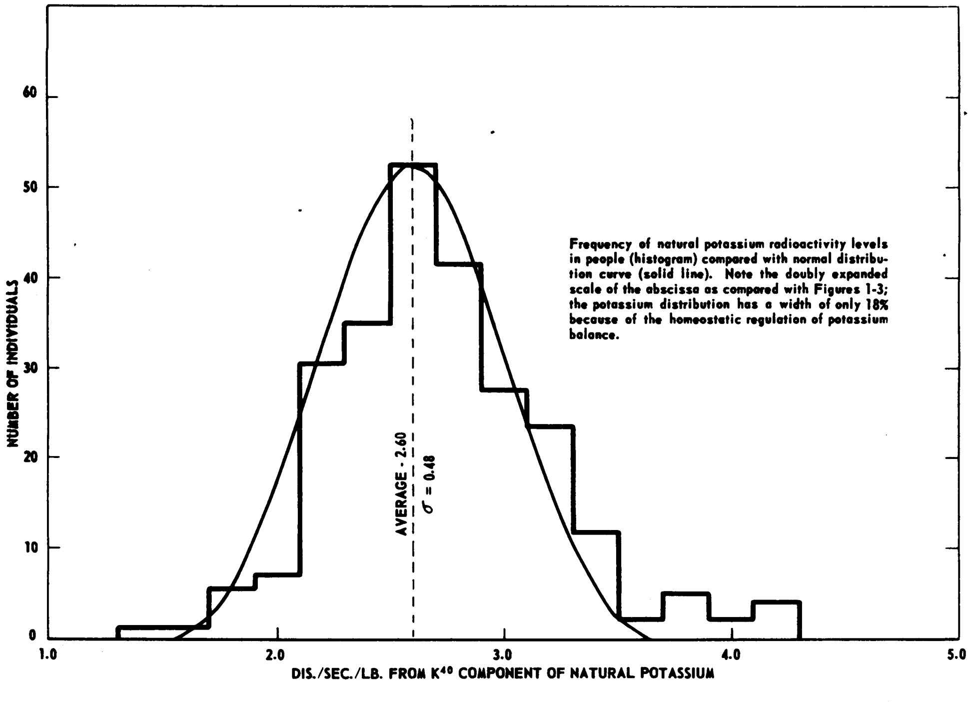


FIG. 3.—Radium (Palmer and Queen, MW-31242) (no correlation with drinking water)



Frequency of natural potassium radioactivity levels in people (histogram) compared with normal distribution curve (solid line). Note the doubly expanded scale of the abscissa as compared with Figures 1-3; the potassium distribution has a width of only 18% because of the homeostatic regulation of potassium balance.

FIG. 4.—Potassium (Anderson and Langham, unpublished) (age group, 20–39 years)

large compared with the true equilibrium spread for these reasons. As equilibrium is approached, however, the spread must decrease very, very markedly.

The data on human bones indicate a very wide scatter, but it seems extremely clear that the variation is a reflection of the fact that the main skeleton of adult individuals is not in equilibrium with the present food supply and that the variations reflect the different rates at which the various bones in the bodies of individuals are coming into equilibrium with the food supply in the general biological environment. A study of whole skeletons taken from one given locality, now under way as a part of Project Sunshine, will clarify the point about the variations among individuals in their rate of coming into equilibrium with the general biological environment. This study is being carried on in Dr. Kulp's laboratory.

It should appear from these studies that the variation from the mean of adults will be larger than the factor of one-third which apparently is normal for the types of equilibrium distribution considered above. It is, of course, very important to establish the truth of this prediction clearly. However, the general agreement in shape of the distribution curves for such widely different materials as normal potassium in whole bodies, radium, and normal elementary strontium in fragmentary human bone, and actual fallout radioactive strontium in the whole bodies of stillborn children give us good reason to believe that there is nothing extraordinary in the distribution of radiostrontium in human bone.

III. VARIATION OF THE STRONTIUM 90 BODY BURDEN WITH LOCALITY

Most important of the causes of variation of the strontium 90 content of individuals with locality is, of course, the amount of fallout in a given region. The general rules about the intensity of fallout have been described above. For air-fired megaton weapons our present indication is that the fallout is almost world-wide, and for reasons of simplicity and in the absence of better information at the present time, we work on the model that this is a uniform distribution, over the entire world, of material that falls from the stratosphere. Further evidence and data on this point are rapidly being collected which will undoubtedly settle the stratospheric horizontal mixing question.

At the present time, the general latitudes in the Northern Hemisphere between 10° and 60° N. have the highest strontium 90 content. In the United States, which, because of proximity to the Nevada test site, has unusually high fallout, there are at the present time about 25 millicuries per square mile of strontium 90. For average soil this means a concentration in the topsoil of about 50 Sunshine Units. With the factors of discrimination mentioned above, this means that an equilibrium body burden between 1.7 and 3.9 Sunshine Units is to be expected. Actually, the present body burden in young children indicates that the lower value is probably more realistic. The present body burden in children—about 0.5 Sunshine Units—probably was derived from an average strontium 90 content in the topsoil of something like 15 millicuries per square mile, or about 25–30 Sunshine Units during the time the strontium 90 was being acquired. Thus we find that the experimental value for the ratio between the body burden of young children and the average concentration in the topsoil is about 50 to 1—rather closer to the higher range of the laboratory results than to the lowest range. Table 2 contains the latest data for the total strontium 90 fallout as measured in United States soils, and Figure 5 displays these data graphically. The northern part of the United States has about 20–30 millicuries of strontium 90 per square mile, the southern states somewhat less. The low figure of 7 millicuries per square mile for Grand Junction, Colorado, is probably due to local climatic and sample-site conditions.

TABLE 2*

HEALTH AND SAFETY LABORATORY 1956 SURVEY OF U.S. SOILS FOR STRONTIUM 90 SAMPLES TAKEN BETWEEN OCTOBER 8 AND 13, 1956

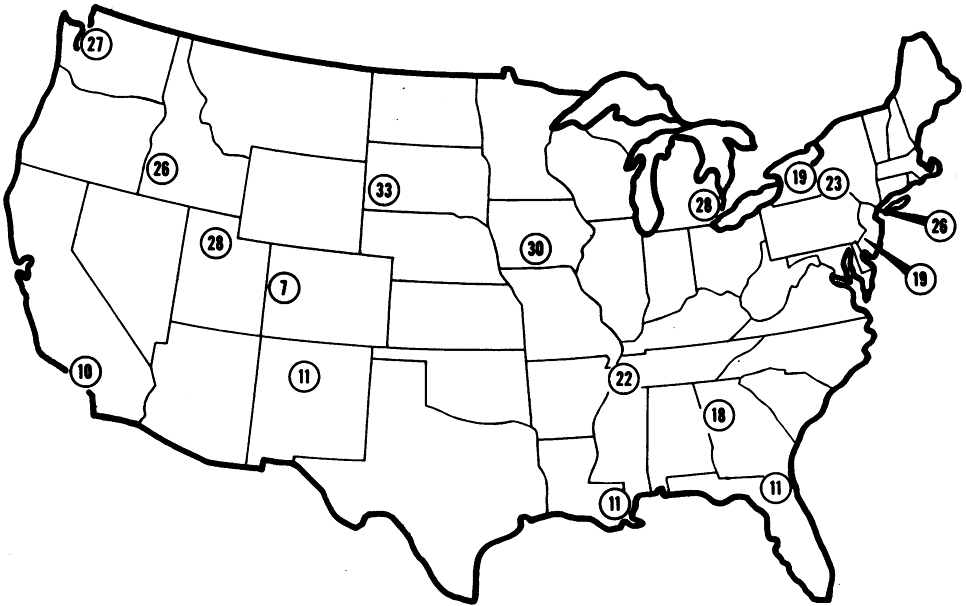
SAMPLING SITE	DEPTH (INCHES)	DISINTEGRATIONS/ MIN/GM SOIL	MC/MI^2	MC/MI^2	
				AV.	TOTAL
Albuquerque, N.M.	0–2	0.078 ± 0.001	7.5 ± 0.1	7.3	
		0.075 ± 0.001	7.2 ± 0.1		
	2–10$^1/_2$	0.008 ± 0.002	4.4 ± 0.9	3.4	11
		0.005 ± 0.002	2.4 ± 0.8		
Atlanta, Ga.	0–2	0.35 ± 0.007	14 ± 0.3	15	
		0.42 ± 0.009	16 ± 0.4		
	2–6	0.018 ± 0.004	2.8 ± 0.6	3.0	18
		0.021 ± 0.003	3.3 ± 0.5		
Binghamton, N.Y.	0–2	0.32 ± 0.007	17 ± 0.4	18	
		0.35 ± 0.007	18 ± 0.4		
	2–6	0.019 ± 0.003	4.4 ± 0.8	5.0	23
		0.024 ± 0.005	5.6 ± 1.1		
Boise, Idaho	0–2	0.23 ± 0.006	20 ± 0.6	22	
		0.26 ± 0.006	23 ± 0.6		
	2–6	0.012 ± 0.002	3.1 ± 0.6	3.5	26
		0.015 ± 0.002	4.0 ± 0.6		
Des Moines, Iowa	0–2	0.31 ± 0.007	23 ± 0.5	23	
		0.31 ± 0.007	23 ± 0.5		
	2–6	0.028 ± 0.002	7.6 ± 0.7	7.1	30
		0.024 ± 0.003	6.6 ± 0.7		
Detroit, Mich.	0–2	0.26 ± 0.006	20 ± 0.5	20	
		0.27 ± 0.006	20 ± 0.5		
	2–6	0.038 ± 0.003	7.3 ± 0.5	7.8	28
		0.044 ± 0.003	8.4 ± 0.6		
Grand Junction, Colo.	0–2	0.10 ± 0.001	7.8 ± 0.1	7.0	
		0.091 ± 0.001	7.1 ± 0.1		
		0.11 ± 0.019	8.2 ± 1.4		
		0.070 ± 0.013	5.1 ± 1.0		
	2–10$^1/_2$	≤0.002	≤0.45	≤0.48	7
		≤0.002	≤0.51		
Jacksonville, Fla.	0–2	0.11 ± 0.009	7.3 ± 0.6	7.3	
	2–6	0.013 ± 0.004	2.7 ± 0.9	3.4	11
		0.020 ± 0.005	4.0 ± 1.0		
Los Angeles, Calif.	0–2	0.12 ± 0.008	6.9 ± 0.5	7.5	
		0.14 ± 0.009	8.0 ± 0.5		
	2–7	0.009 ± 0.002	3.3 ± 0.9	2.8	10
		0.006 ± 0.002	2.2 ± 0.7		
Memphis, Tenn.	0–2	0.27 ± 0.006	15 ± 0.4	15	
		0.26 ± 0.006	15 ± 0.4		
	2–6	0.028 ± 0.003	6.5 ± 0.7	6.6	22
		0.029 ± 0.003	6.6 ± 0.7		
New Orleans, La.	0–2	0.24 ± 0.006	8.8 ± 0.2	8.6	
		0.22 ± 0.006	8.3 ± 0.2		
	2–6	0.009 ± 0.002	3.3 ± 0.9	2.8	11
		0.006 ± 0.002	2.2 ± 0.7		
New York, N.Y.	0–2	0.21 ± 0.006	10 ± 0.3	12	
		0.29 ± 0.007	14 ± 0.3		
	2–6	0.072 ± 0.004	14 ± 0.8	14	26
		0.068 ± 0.004	14 ± 0.8		
Philadelphia, Pa.	0–2	0.17 ± 0.005	12 ± 0.4	12	
		0.16 ± 0.005	11 ± 0.4		
	2–6	0.029 ± 0.003	7.3 ± 0.8	6.8	19
		0.026 ± 0.003	6.4 ± 0.7		
Rapid City S.D.	0–2	0.29 ± 0.006	20 ± 0.4	22	
		0.34 ± 0.006	23 ± 0.4		
	2–6	0.053 ± 0.004	12 ± 1.0	11	33
		0.045 ± 0.003	10 ± 0.7		

TABLE 2*—(*continued*)

SAMPLING SITE	DEPTH (INCHES)	DISINTEGRATIONS/ MIN/GM SOIL	MC/MI^2	MC/MI^2 AV.	MC/MI^2 TOTAL
Rochester, N.Y.	0–2	0.22 ± 0.006	16 ± 0.4	16	
	2–6	0.013 ± 0.002	2.5 ± 0.4	2.5	19
		0.013 ± 0.002	2.5 ± 0.4		
Salt Lake City, Utah	0–2	0.32 ± 0.007	22 ± 0.5	22	
		0.33 ± 0.007	23 ± 0.5		
		0.31 ± 0.007	22 ± 0.5		
	2–8	0.016 ± 0.002	5.7 ± 0.7	5.8	28
		0.016 ± 0.002	5.9 ± 0.8		
Seattle, Wash.	0–2	0.46 ± 0.011	17 ± 0.4	17	
		0.44 ± 0.010	16 ± 0.4		
	2–6	0.051 ± 0.007	9.4 ± 1.2	9.5	27
		0.052 ± 0.004	9.6 ± 0.7		

* Strontium extracted with 6 *N* HCl at room temperature. Replicates represent individual soil aliquots taken after sampling and air drying. Each error term represents one standard deviation due to counting error.

The differential rates at which the fallout has been occurring probably are best measured by the so-called "pot collection" method. A bucket with vertical walls of appreciable height is placed out in the open and allowed to collect the total fallout for a given period, including the rain, snow, dust, etc. The bucket is left out whether it has rained or not and covers the total fallout for a given period. Figures 6 and 7 give the curves so obtained for the New York and Pittsburgh areas, together with the estimated errors of measurement. It is interesting to note the changes in slope and to correlate them with the occurrence of test activities and the relatively short-lived tropospheric fallout. The minimum slopes which appear during quiet periods when no one is testing are the stratospheric fallout of which we have spoken, and these slopes, when we have enough pots operating all over the world, will, when taken together with the results of the measurements



Numbers are in mc/mi^2 at individual site.

FIG. 5.—Strontium 90 in United States soil (HASL, October 8, 1956) (HCl extraction method).

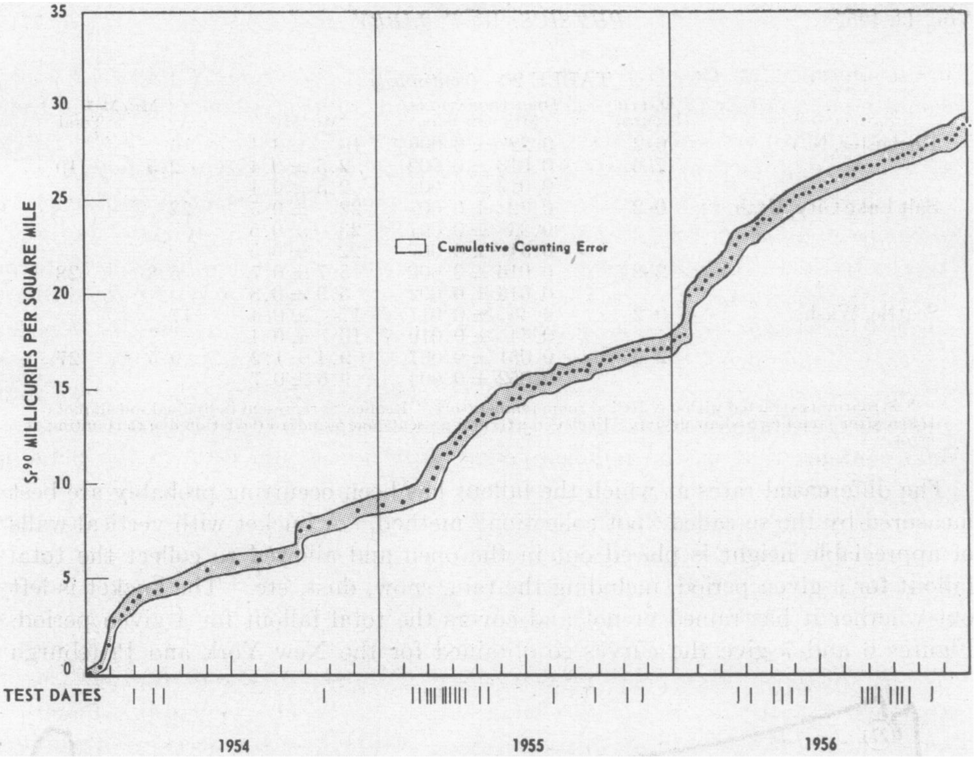


Fig. 6.—Rain data, New York collection pot

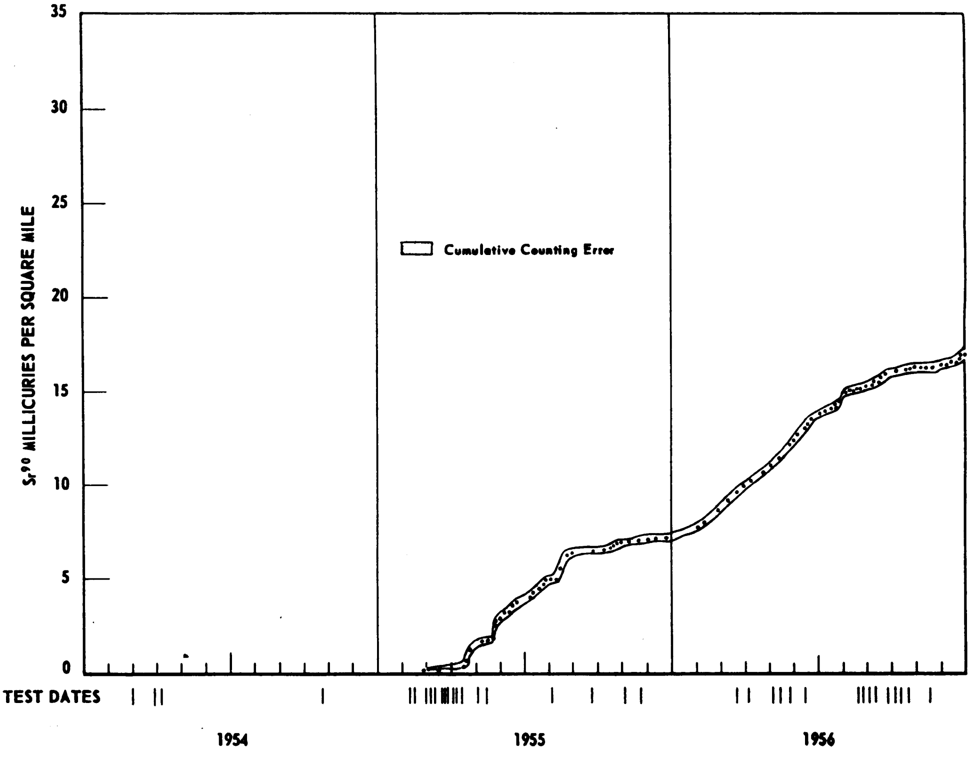


Fig. 7.—Rain data, Pittsburgh collection pot

of the amounts of radiostrontium and radiocesium in the stratosphere, give an accurate value for the stratospheric residence time and settle the mixing question.

In addition to the intensity of fallout, the question of the fraction of the radiostrontium, and, for tropospheric fallout, the radioiodine of 8-day half-life, that is in assimilable form is an important one. So far, most fallout strontium appears to be completely water-soluble and therefore most assimilable, though continued tests on this point should be made. Direct leaf pickup of course promotes assimilation of the strontium, because the plant differentiation against strontium when it assimilates it from soil thus is avoided. Another factor is, of course, the concentration of available calcium in the soil. By "available" calcium we mean calcium which is available to plants and not the total calcium in the soil. It is known that soils which are high in available calcium produce plants of lower radioactive strontium content; that is, the radioactive-strontium-to-calcium ratio in the plant is lower as a direct consequence of the lower concentration of radiostrontium in the available soil calcium. In addition, as mentioned previously, plants tend to prefer calcium to strontium with a discrimination factor of about 1.4. Sheep which grow in certain areas of Wales have shown concentrations in their bones approaching 150 Sunshine Units, while sheep and cattle growing in the United States have hardly ever exceeded one-fifth of this. The Welsh soil in certain areas is very low in calcium and, as a result, grows grasses of high radiostrontium content. Of course, it is clear that fertilization with calcium will immediately relieve this difficulty; but in the absence of such fertilization, the question is: How serious is the effect of calcium deficiency in promoting strontium 90 pickup through the food chain?

As was remarked earlier, there is an averaging which occurs in food distribution systems, and calcium-deficient soils are naturally rather poor producers; as a consequence, the weight of the food so produced is less than for a good, well-fertilized, well-balanced soil. This factor reduces the flow into the general food system of material of exceptionally high strontium 90 content. It will therefore probably be sufficient to consider the radiostrontium of milk, since milk is the main source of calcium, in order to test for the radiostrontium content of the food in given areas. Direct measurements have shown that a factor of 5 encompasses the total variation due to all factors, including calcium deficiencies in acid soils.

The general intake must depend on the food distribution pattern, and the relatively small fluctuation in milk contents must reflect this. The number of individuals who rely totally on the food output of soil of very low calcium content is very small indeed, but it must be true that these individuals, if they grew up on such a provincial, isolated farm, would have as much as 10–50 times the normal average strontium 90 content. The normal calcium concentration in soils in the United States is about 20 gm. per square foot for the top 2.5 inches, and about the poorest soil known has about 0.4 gm. available calcium per square foot for the top 2.5 inches—a deficiency factor of 50.

It is clear from a detailed examination made by the author for people living in calcium-deficient areas with normal food distribution patterns that a factor of 5 is about as large an effect as can be expected from a fifty-fold deficiency of calcium in the soil. The food from outside the calcium-deficient area reduces by a factor of about 10 the increase in strontium 90 pickup rate which would be expected from the calcium deficiency in the soil if people lived entirely off the soil for their whole growing period of 20 years or so.

The food of lowest strontium 90 content is fish flesh, because of the great dilution the fallout receives by the hundred meters of sea water above the thermocline, which rapidly mix with the fallout within a few hours or days. This means that the specific concentration of radioactive strontium, or any other fallout constituent in sea water, is relatively very much lower than it would be in soil. For example, 100 meters of sea water has 370 gm. of dissolved calcium per square foot, as compared with the average of 20 gm. per square foot for the top 2.5 inches of soil which absorbs and holds the fallout radiostrontium. Therefore, in principle, sea food and fish are lowest among foods in content of radiostrontium fallout.

IV. EFFECTS OF CONTINUED TESTING AND GENERAL CONCLUSIONS

In summary, then, we see that the present body burden of strontium 90 from atomic weapons tests in the United States corresponds to the radiation dosage to the bones which would result from a few hundred feet increase in altitude, and the present vital statistics show no observable effect on the occurrence of bone cancer or leukemia of much larger changes in altitude. The tolerance figure of 100 Sunshine Units, or 0.1 microcurie for an average individual, or 100 micromicrocuries per gram of body calcium, that is recommended now is about two hundred times the present level for new bone in the United States, and it will not be exceeded by fallout from weapons tests in any foreseeable circumstances.

The distribution of strontium 90 burdens among individuals *for a given locality* will be a normal error curve with a standard deviation of about one-third of the average concentration. This means that about one individual in 300 will have more than twice the normal average value for a given locality, and that about one in several million will have three times the average value.

The effect of locality is more important, however, particularly in the effect of calcium deficiency in the soils. Careful consideration of this question indicates that there will be a very few individuals who show a strontium 90 content which is strictly inversely proportional to the available calcium concentration of the soil in their region. This is due to the fact that food distribution systems automatically average over a wide area, and people assimilate their calcium slowly. Most people drink milk and eat cheese and other calcium-bearing foods from a rather wide area, and this effect reduces by an estimated factor of 10 the potential effect of calcium deficiency in the local soils.

On the basis of laboratory experiments, the human-body concentration of strontium 90 at equilibrium will be between 13 and 30 times less than that in the topsoil. The present data indicate that the higher figure is closer to the truth, and so we will be conservative in taking the figure of 20 for this ratio. Therefore, the present burden of 50 Sunshine Units in the topsoil of the United States may eventually lead to as much as 2.5 Sunshine Units in human bones but more likely will lead to about 1.7.

Of course, as testing continues and more fallout occurs, the levels will rise. The strontium 90 that still resides in the stratosphere at the present will fall out, according to our expectations, at a rate which just about compensates for the decay of the material already deposited, so that no great additional increase from this source is to be expected from weapons fired in the past. If the testing should continue at about the same rate it has averaged over the last five years, then we should, at equilibrium, after an infinite time, approach a level of 8 times the present rate, since the average life of strontium 90 is 40 years. This assumes that future testing will be conducted so as to give in each future five-year period the same as the last five have. And so we would expect in the United States at that time an average human strontium 90 concentration of 20 Sunshine Units, with the conservative factor of 20 between the topsoil concentration and the concentration in human bone, or 5 Sunshine Units if the factor of 80 is used. In other words, in the United States something between 5 and 20 Sunshine Units would be the equilibrium concentration of human bones if testing continued indefinitely at the average rate of the past five years. This level would be approached after only a few decades. After 28 years the level would be half this equilibrium value, and after another 28 years—56 years total—from an arbitrary beginning which we have set as 1952, we would expect in the year 2008 three-fourths of the equilibrium figures. So somewhere between 4 and 15 Sunshine Units of strontium 90 in human bones in the United States might result from the present type of testing being continued for the next 50 years.

In those particular areas in the world where the soil is low in calcium, this level might go fivefold higher. At the present rate of testing, we might indeed approach the figure of 100 Sunshine Units, the tolerance limit for large populations, at the beginning of the twenty-first century for these certain limited regions in the world. The observed conditions in these regions could be relieved, however, by fertilization of the soil with calcium, using either calcium nitrate or lime, as appropriate from other considerations.

Project Sunshine continues to study the problems of world-wide fallout—the stratospheric inventory of radiostrontium and radiocesium, the occurrence of these isotopes in the soils and water and the biosphere all over the earth, the biological effects at certain levels of contamination with strontium 90, and to a lesser degree with cesium 137, and the possible genetic effects of the low gamma-ray dosages associated with world-wide fallout from atomic tests. All these are studied not only with the object in mind of devising methods of protection against atomic warfare, but also with the thought of possible application in the remote event of industrial accidents which may happen in connection with certain of the peaceful uses of atomic energy, particularly atomic power. Certainly an understanding of the basic principles of world-wide fallout is applicable to the control and safe handling of isotopes. All of this is done in collaboration with the United Nations Scientific Committee on the Effects of Atomic Radiation, and it is to be hoped that, as the data appear, all the countries in the world will join together in this international effort to understand better the effects of the great new fact in life, the nuclear atom.

[1] W. F. Libby, "Radioactive Strontium Fallout," these PROCEEDINGS, **42**, No. 6, 365–390, 1956; University of Chicago, Project Sunshine Bulletin No. 12, August 1, 1956.

[2] K. K. Turekian and J. L. Kulp, *Science*, **124**, 405, 1956.

[3] Hanford Report, HW-31242.

[4] E. C. Anderson, R. L. Schuch, W. R. Fisher, and W. Langham, "Potassium and Cesium Radioactivity in People and Foodstuffs" (in press).