at home in the desert or steppe. Unless the climate itself has changed, and this is not likely to have occurred within historic time (*15*), the proliferation of such plants should be ascribed to the disturbing influence of man.

The most unfortunate consequence of deforestation is that it increases the danger of soil erosion (Fig. 9). The steep slopes prevalent in most of northern Morocco favor rapid runoff and prevent the formation of deep residual soils. Moreover, torrential rains during the winter and spring follow vigorous mechanical weathering during the dry summer months. It would be hard to imagine an area more vulnerable to erosion, and the natural hazard is greatly increased by the destruction of protective vegetation. In northern Morocco, as elsewhere in the Mediterranean region, deforestation and erosion are linked in a chain of causes and effects that begins with the mismanagement of land by man (*16*).

References and Notes

1. See, for example, G. Giordano, "The Mediterranean Region," in S. Haden-Guest, J. K. Wright, E. M. Teclaff, Eds., *A World Geography of Forest Resources* (Ronald, New York, 1956, pp. 317–352.
2. *Atlas du Maroc,* planche 4*a*: "Précipitations annuelles" (Rabat, 1958). The figures cited in this and the following paragraph are taken from the *"notice explicative"* which accompanies the map.
3. *Atlas du Maroc,* planche 19*a*: "Forêts et ressources végétales"; L. Emberger, "Aperçu général sur la végétation du Maroc," in E. Rübel and W. Lüdi, Eds., *Ergebnisse der internationalen Pflanzengeographischen Exkursion durch Marokko und Westalgerien, 1936* (Huber, Bern, Switzerland, 1939).
4. Strabo, *Geography,* book 17, chap. 3.
5. H. C. Darby, "The Clearing of the Woodland in Europe," in W. L. Thomas, Jr., Ed., *Man's Role in Changing the Face of the Earth* (University of Chicago Press, Chicago, 1956), pp. 183–216, especially pp. 184–188.
6. J. Despois, *L'Afrique du Nord* (Presses Universitaires de France, Paris, 1949), p. 84.
7. A. Bernard, *Afrique septentrionale et occidentale* (Colin, Paris, 1937), vol. 1, p. 65.
8. E. Lévi-Provençal, *Arabica* **1**, 40 (1954).
9. *The History and Description of Africa* (Hakluyt Society, London, 1896), vol. 1, pp. 494–539.
10. P. Boudy, *Economie forestière nord-africaine* (Larose, Paris, 1948–1955); for a more concise statement see J. P. Challot, *Rev. Eaux et Forêts* **84**, 233 (1946).
11. G. Kuhnholtz-Lordat, *La Terre incendiée: essai d'agronomie comparée* (Maison Carrée, Nimes, 1939); *J. Agr. trop. et Botan. appl.* **3**, 785 (1956).
12. The statistical handbook of Spanish Morocco for 1952–53 lists 661,000 sheep, 1,104,000 goats, and 1,026,000 human beings. The human population grew by 100,000 in the preceding decade, and the number of goats probably increased correspondingly.
13. R. Furon, "The gentle little goat: Arch despoiler of the earth," *Unesco Courier* **1958**, 30 (Jan. 1958).
14. This trend has been documented in many parts of the world. For a clear illustration see A. Aubréville, *Climats, forêts et désertification de l'Afrique tropicale* (Editions Maritimes et Coloniales, Paris, 1949).
15. For a brief review of the arguments for and against climatic change within historic time see R. Murphey, *Ann. Assoc. Am. Geographers* **41**, 116 (1951).

16. Field studies were made possible by a grant from the Ford Foundation.

Strontium-90 in Man IV

The strontium-90 concentration in human bone increased in 1958 and 1959, will probably reach a maximum in 1960.

J. Laurence Kulp, Arthur R. Schulert, Elizabeth J. Hodges

The moratorium on nuclear detonations has made it possible to define several critical factors in the distribution of fission products over the surface of the earth and their uptake in man. This article (*1*) gives new data on the strontium-90 content of human bone from the world-wide network of sampling stations. Earlier contributions (*2–4*) outlined the geographical variation, the age effect, and the mean concentration of strontium-90 in the human population. This new work permits further refinement of these parameters and indicates the situation in 1959. With the aid of important new data on the stratospheric inventory and residence times (*5*) and the relative importance of the rate of fallout of strontium-90 as against cumulative deposition in the soil (*6*), it is possible to make more reliable predictions of future levels of strontium-90 in man as a result of past weapon tests. It is also possible to indicate the nature of the distribution curve for the bulk of the world population. These new data also have important implications for the situation that would exist in the event of nuclear warfare.

Since the beginning of this study, in 1953, some 9000 samples of human bone have been procured. These have included fetuses, single bone samples from individuals of all ages, and whole skeletons. The bulk of the analyses for strontium-90 have been carried out at several commercial laboratories under contract with the Atomic Energy Commission (*7*). Most of the analyses in 1953–55 were carried out in this laboratory, and a few of the samples collected since then have been analyzed here (*8*).

The absolute calibration at all laboratories is based on NBS standards and is good to 2 to 3 percent. The standard deviation of the radiochemical procedures is ±7 percent, as determined on milk samples and spiked bones with concentrations equivalent to 10 to 1000 disintegrations per minute per sample. For those human bone samples in which the level is at least 5 disintegrations per minute, the over-all reproducibility among the various laboratories is about ±10 percent. This category includes virtually all children's bones, all whole-skeleton ash samples from individuals who died from 1957 to 1960, and large samples consisting of many bones from adults who died in 1958, 1959, and 1960, from the latitude band 30° to 70°N. The other samples, of lower strontium-90 activity, carry larger errors. Laboratory contamination was monitored with analytical reagent grade $Ca_3(PO_4)_2$ and human bone from individuals who died before 1945. Samples of adult bone containing less than 2.0 grams of calcium and children's bones containing less than 0.5 gram of calcium have not been included in this summary because of the larger inherent errors resulting from the low total activity. From 1958 on, most adult bones were composited, equal weights

The authors are on the staff of the Geochemistry Laboratory, Lamont Geological Observatory, Columbia University, Palisades, N.Y.

Table 1. Average strontium-90 concentrations (in micromicrocuries per gram of calcium) in the skeletons of adults of various age groups. Number of samples in parentheses.

Population	Age group (yr)					
	20–29	30–39	40–49	50–59	60–69	70 and over
New York whole skeletons (normalized to 1957)	0.071 ± 0.008 (4)	0.098 ± 0.015 (9)	0.080 ± 0.009 (17)	0.092 ± 0.006 (67)	0.097 ± 0.005 (94)	0.094 ± 0.004 (125)
Western culture area (single bones, 1957)	0.14 ± 0.03 (26)	0.18 ± 0.03 (29)	0.14 ± 0.02 (40)	0.12 ± 0.02 (46)	0.13 ± 0.02 (52)	0.10 ± 0.02 (48)

of bone from each autopsy being used, since the major effort was directed toward esablishment of the best mean for a given station. As will be seen below, the data were adequate for analytical examination of population variations.

In the earlier years (1954–56) the specific activity of strontium-90 in single adult bones was so low that in some of the samples none was detectable. These samples were generally reported as having a specific activity of less than twice the standard-deviation counting error in micromicrocuries of strontium-90 per gram of calcium. In all the averages reported below, this was taken as the maximum value for the concentration of strontium-90 for these samples. The average is not appreciably affected if such samples are assumed to have zero concentration of strontium-90.

In an earlier article (*3*) it was shown that the strontium-90 concentration in adults is essentially independent of age. Therefore, in the discussion and tables these were treated as a homogeneous class regardless of the age at death. Further information is now available in support of this assumption. Table 1 gives comparisons for various groups of adults. The analytical error is considerably smaller in the case of the large, whole-skeleton samples. It may be seen that there is no significant trend with age. The uncertainty indicated for each group in Table 1 is the standard error of the mean.

Since it has not been possible to obtain large numbers of whole skeletons except in New York City, most individuals are represented by single bones. It is essential, therefore, to know the relation of the specific activity of the analyzed piece of bone to the whole skeleton. Earlier work by Schulert *et al.* (*9*) showed that in skeletons of children (ten fetuses, nine young children, and one teen-ager) the specific activity was essentially uniform, whereas in adults the activity in the vertebrae was higher, and that in the long-bone shaft lower, than the body average as a result of the differing exchange rates in the different bones.

Table 2 gives the average ratios for vertebrae, rib, skull, and long-bone shaft to whole skeleton for 19 fetuses. They show uniform strontium-90 distribution within the limits of experimental error—a finding which is not unexpected since the deposition of new bone is the dominant process during this part of the life span.

The accuracy of the earlier determinations in adults was not as high as in 1957-1959, due to the very low concentrations of strontium-90 in the bones. The measurements were, therefore, repeated with individuals who died in 1958 and 1959. Because of the higher activity in the whole skeletons collected in New York City in 1958 and 1959, a more accurate estimate of the distribution of strontium-90 in the human skeleton could be made. Four composite samples of the most important bones were assembled. Each composite contained an equal weight of ash of a given bone type from five individuals. The results are given in Table 3. By weighting the specific activity in accordance with the quantity of a given bone type in the skeleton, the skeletal average is obtained. The ratios of levels in the key bones to levels in the whole skeleton are given in Table 4. These average values were used to compute the skeletal levels of strontium-90 from the individual adult bone samples. The earlier values are given for comparison. Values for all samples have now been corrected in accordance with these new, and more accurate, ratios. The standard deviation of about 10 percent largely reflects analytical error. These data do not provide an estimate of the variation of these ratios among individuals. They do suggest that the standard deviation in these ratios among individuals does not exceed 10 percent.

Table 2. Comparison of strontium-90 concentrations in various bones of 19 fetuses.

	Vertebrae / skel.	Rib / skel.	Skull / skel.	Long-bone shaft / skel.
Average	1.0	1.0	1.0	1.0
S.D.*	0.3	0.3	0.1	0.3
S.E.†	0.1	0.1	0.02	0.1

* Standard deviation. † Standard error.

Strontium-90 Concentration and Age

Since strontium-90 has been present in the diet of human beings for a relatively short time and the rate of turnover of existing bone is slow, the average strontium-90 concentration in the adult skeleton is much lower than that in newly depositing bone. In children the value is strongly dependent on the age of the individual. The average skeletal level for any age at any time can be calculated if the following factors are known: (i) the discrimination factor between strontium and calcium in passing from diet to bone; (ii) the average weight of calcium added to the skeleton at each age; (iii) the average concentration of strontium-90 in the diet of the individual since birth; (iv) the average rate of turnover of mature bone; and (v) the discrimination factor between strontium and calcium from mother's diet to fetus.

The discrimination factor between strontium and calcium from diet to bone is now clearly established for the average Western diet as 4 against strontium (*10–12*). The average weight of calcium deposited each year in the skeletons of children in the United States was derived from the data of Mitchell *et al.* (*13*) and Watson and Lowrey (*14*). The strontium-90 concentration in the average Western diet has been computed from available data (*15–18*). The primary basis is the yearly average from the various milk-distribution networks. Kulp and Slakter (*16*), Bryant *et al.* (*11*), and Bird and Mar (*18*) have shown that for Western culture areas, the average ratio of strontium-90 to calcium in the total diet is about 1.2 times the ratio for milk alone. The following average diet levels,

Table 3. Distribution of strontium-90 in composite bone samples (in micromicrocuries per gram of calcium).

Bone	Composite sample No. A	B	C	D
Vertebrae	0.209 ± 0.007	0.268 ± 0.007	0.424 ± 0.009	0.371 ± 0.009
Rib	0.192 ± 0.008	0.149 ± 0.009	0.254 ± 0.008	0.226 ± 0.008
Tibia	0.049 ± 0.005	0.054 ± 0.007	0.079 ± 0.006	0.078 ± 0.006
Femur	0.061 ± 0.005	0.054 ± 0.007	0.069 ± 0.007	0.097 ± 0.006
Tibia joint	0.121 ± 0.007	0.081 ± 0.008	0.190 ± 0.010	0.168 ± 0.008
Femur joint	0.100 ± 0.007	0.071 ± 0.007	0.240 ± 0.008	
Calculated body av.	0.121	0.109	0.189	0.198

in micromicrocuries of strontium-90 per gram of calcium, for Western culture areas were chosen on the basis of these data: 1954, 2; 1955, 4; 1956, 6; 1957, 8; 1958, 11; and 1959, 15.

When the average strontium-90 concentration in adult bone samples for 1957, 1958, and 1959, the dietary level for 1953–59, and the discrimination factor are known, it is possible to calculate the empirical average rate of exchange (*19*) in whole adult skeletons from this dietary history. The empirical value determined in this way, with fallout strontium-90 as a tracer, is 3.3 percent per year. This value is empirical for the interval in question and reflects the rapid rate of turnover for the most active centers. The long-term average rate is lower because the rate of exchange is lower in the rest of the skeleton (*4*). The long-term exchange rate could be ascertained by this method if the concentration of strontium-90 in the diet remained constant over long periods.

The placental discrimination between the mother's blood and the offspring's bone has been determined experimentally, by Comar *et al.* (*20*), for cows and rats to be about 2 against strontium. This might suggest a discrimination factor of 8 against strontium from the mother's diet to the fetus. Actually, the observed concentration of strontium-90 in fetal skeletons in 1957, 1958, and 1959 averages one-twelfth that in the mother's diet. The explanation for this may be the addition of calcium of very low strontium-90 concentration from the mother's skeleton, plus the prescription of extra mineral calcium for pregnant women. For the purpose of determining the theoretical curve for the strontium-90 concentrations versus age in children, the observed average strontium-90 concentration in fetuses has been used.

Theoretical curves were calculated for 1957, 1958, and 1959 (Fig. 1), based on the assumptions given above. The average obtained from analysis of the bones of individuals who died in 1958 in each age group, with standard error, is also given in this figure. It may be seen that the fit of the data to the theoretical curve is quite good, except that the data do not follow the peak in the 10 to 14 age interval. The maximum occurs at about 1 year of age and is about 10 times the adult level. In 1958 the world average for adults must have been about 0.2 micromicrocurie of strontium-90 per gram of calcium, unless the value for the adult population of China (for which data were not available) greatly exceeds the mean for the rest of the world. This world average increased by about 40 percent in 1959.

Time Effect

If large numbers of samples or restricted types are compared, it is possible to see the regular increase in the specific activity of the human skeleton since the start of the testing of large

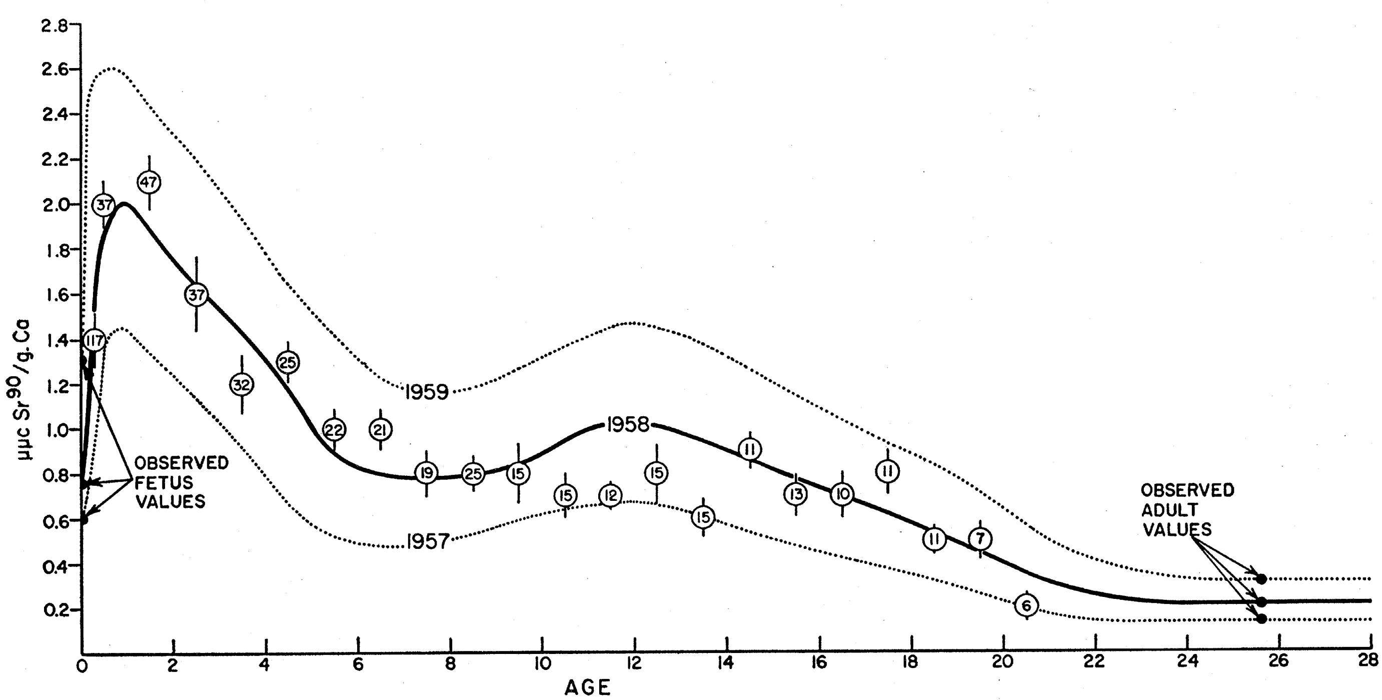

Fig. 1. Calculated curves showing expected strontium-90 concentration in the bones of children and young people in Western culture areas for 1957, 1958, and 1959; the experimental data include the number of samples in each age group for 1958.

Table 4. Ratio of strontium-90 and strontium-85 concentrations in individual bones to concentration in the whole skeleton.

Composite sample No.	Vertebra/skel.	Rib/skel.	Long-bone shaft/skel.
This study (Sr^{90} in 1958–59 N.Y. cadavers)			
A	1.7	1.6	0.45
B	2.4	1.4	0.50
C	2.2	1.3	0.40
D	1.9	1.1	0.47
Average	2.1	1.4	0.45
S.E.*	0.1	0.1	0.02
Sr^{85}, single dose (earlier study) (10)			
	4.8	2.1	0.6
Sr^{90} in 1956 N.Y. cadavers (2)			
	3.4 ± 0.8	1.5 ± 0.4	0.8 ± 0.2
Sr^{90} in 1957 N.Y. cadavers (9)			
	1.8 ± 0.2	1.1 ± 0.2	0.5 ± 0.1

* Standard error.

nuclear weapons. Table 5 shows the data for the whole-skeleton samples from New York City, plus data from whole fetuses and single bones from adults and young children in Western culture areas, in the latitude band 30°–70°N. For the latter compilation the measurements by Bryant *et al.* (*21*) on children's bones from the United Kingdom and those on Chicago fetuses by Libby in 1954 (*22*) are included.

The percentage standard deviation for the New York cadavers shows a consistent decrease from 1954 to 1958, due to the rising level of activity in the samples. The standard error of the mean is small compared with the yearly increment in specific activity. For 1959 the largest percentage increase in activity is seen in the fetus population, a consequence of the fact that fetuses are in equilibrium with the dietary level of the year in which they are born. It was not possible to report standard errors on the adult-bone groups for 1958 and 1959, since most of these samples were composites, but the standard errors would probably have been quite similar to those given for 1957 had the samples been analyzed individually.

The average values for each station for sample categories 0 to 4 years, 5 to 19 years, and adult, for 1958 and 1959, are listed in Table 6. Included in the averages are the data of Bryant (*21*) covering the United Kingdom and Australia and a few measurements by the AEC's Health and Safety Laboratory (*15*). As may be seen from data in Table 5, the standard deviation for large sets of single adult bones from an area in which diet is reasonably uniform is about 80 percent. Thus, since the annual increase in concentration in the diet has been only approximately 50 percent, useful comparisons can be made only between stations with fairly large numbers of samples. If, for example, 70 samples are analyzed, the standard error of the mean should not exceed 10 percent, a value which is similar to the analytical error.

From 1957 through 1959, the strontium-90 level in the milk supply of St. Louis, Missouri, was higher than the average for the United States by a factor of about 2, according to the samples obtained by the U.S. Public Health Service. Therefore, even in the area of Western culture, large populations may have dietary levels that differ by a factor of 2. The standard deviation of the annual average strontium-90 level in milk from stations in the United States does not exceed 45 percent of the mean. Thus, the difference in levels between Houston, Texas, and Bonn, Germany, may merely reflect the different levels in milk from the two milksheds during 1959.

Although Puerto Rico lies at latitude 18°N and receives less fallout per inch of rainfall than the average for Western culture areas in latitude band 30° to 70°N, the difference is compensated for by the higher ratio of nonmilk sources to milk sources in the diet. The same principle probably holds for the Recife, Brazil, station. The fact that the average for adults in Thailand is 50 percent higher than that for Western culture areas between latitudes 30° and 70°N although the fallout in Thailand is lower by a factor of 2 to 4 is also probably related to the difference in the diet.

Distribution Curve

The average value for strontium-90 concentration in adult bone at a given station for a given year may be determined with an accuracy of 5 to 10 percent if at least 100 samples are involved (see Table 5). Since this is comparable to the analytical error, analysis of more than 100 samples for a given station would not appear to be warranted. The average for fetuses at a given station may likewise be determined with an accuracy equivalent to the analytical error if 50 to 100 samples are obtained.

The average for individuals between birth and 20 years can best be determined for any given year from the calculated curves in Fig. 1, after making the empirical correction for the 10–14 age span. The ends of these curves have been anchored to experimental averages for adults and fetuses.

The distribution about the mean for any age in any year and at any station is best determined from large samples in which the analytical error is relatively small, such as the whole-skeleton samples from New York City. All of these samples have been normalized to 1957, and the results are plotted in Fig. 2*B*. A comparable histogram for all 1958 fetuses from Chicago, New York, and England (areas which had similar diets) is given in Fig. 2*A* and shows essentially the same distribution and standard deviation. The high values of about 1.4 micromicrocurie of strontium-90 per gram of calcium for one group of fetus samples may result from special diets associated with pregnancy. This distribution curve (Fig. 2, *A* and *B*) is probably representative of the pop-

Table 5. Strontium-90 concentration (in micromicrocuries per gram of calcium) in human bone from 1953 through 1959. Number of samples in parentheses. S.D., standard deviation; S.E., standard error.

Sample group	Year						
	1953	1954	1955	1956	1957	1958	1959
			New York				
Whole skeleton:							
Average	<0.005 (2)	0.007 (26)	0.027 (58)	0.051 (131)	0.097 (73)	0.134 (28)	
S.D.		0.009	0.020	0.036	0.045	0.044	
S.E.		0.002	0.003	0.003	0.005	0.008	
			Western culture area				
Whole fetuses:							
Average		0.12 (185)			0.59 (54)	0.67 (269)	1.21 (76)
S.D.					0.25	0.27	0.39
S.E.					0.03	0.02	0.06
Single adult bones:							
Average		0.07 (36)	0.11 (184)	0.10 (139)	0.13 (317)	0.21 (184)	0.31 (101)
S.D.		0.08	0.09	0.07	0.10		
S.E.		0.01	0.01	0.01	0.01		
0-4 yr.:							
Average			0.5 (39)	0.7 (53)	1.2 (70)	1.7 (58)	2.3 (59)

ulation of any age group at any station in Western culture areas (standard deviation, approximately 40 percent). The distribution curve for single adult bones from all stations in Western culture areas is considerably wider (Fig. 2C) (standard deviation, approximately 80 percent). This was to have been expected, since (i) the analytical error in individual samples of this type is 20 to 30 percent instead of 10 percent, as in the case of fetuses or whole skeletons; (ii) there is at least an additional 10-percent uncertainty introduced in the estimation of the whole-skeleton value from the single-bone analysis; and (iii) the average strontium-90 concentration in the diet varies from one station to the next. For example, the average adult in New York in 1957 and 1958 carried half the concentration of strontium-90 carried by the average adult in Bonn, Germany. Thus, the distribution curve for all single-bone samples, even for single-bone samples from Western culture areas only, may be biased by the relative contribution from the various stations. For the reasons given above, this distribution is probably broader than the actual distribution in adults in Western culture areas. It may be seen from this curve that at least 90 percent of this population will lie within 2 times the mean and that 97 percent will lie within 3 times the mean. All samples lie within 10 times the mean. The distribution for any specified metropolitan area is given much more accurately by Fig. 2B.

There are not enough samples available from any single station in the rice-diet area to define closely the distribution curve. However, the standard deviation for 33 single-adult-bone samples from Thailand in 1957 was 75 percent of the mean, and for 39 samples from Japan, 55 percent of the mean; these findings suggest that there is no large difference in the character of the distribution curve for these areas as compared to Western localities.

It is possible to estimate the distribution for the adult population of the United States in 1958 from the milk data. This is done by calculating the yearly average for as many stations as possible, grouping these findings into ten large areas by similarity of activity, and weighting for the population of the areas. The data are then plotted, on the assumption that the shape of the curve for whole-skeleton samples from New York City is valid for any single-milkshed area. The curve in Fig. 2D represents a summation of the individual curves calculated in this way. The spread is greater than that for a single area (for example, New York City) and less than the result obtained for single-bone analyses throughout Western culture areas, for reasons discussed above.

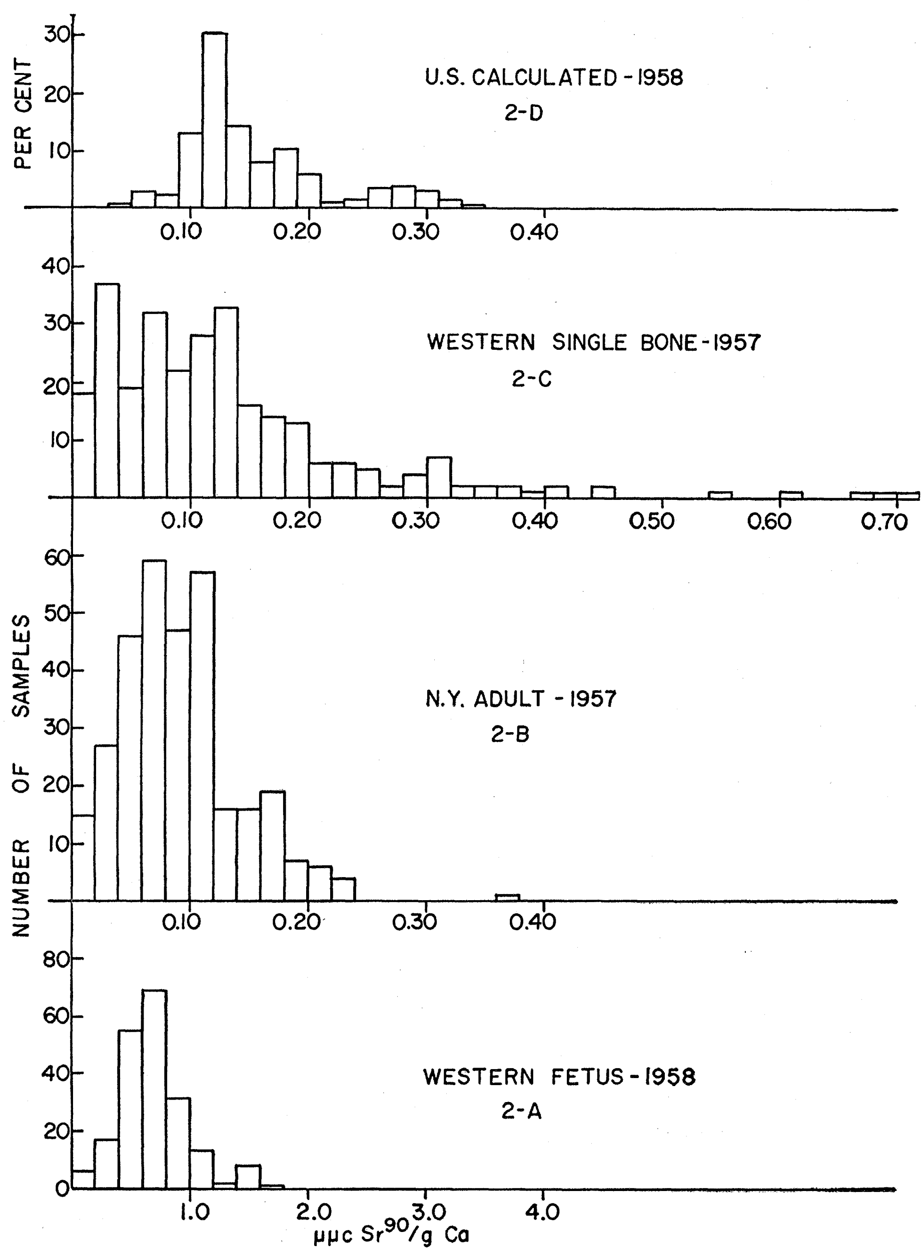

Fig. 2. Distribution curves for strontium-90 concentrations in various population groups.

Future Levels

Various predictions have been made concerning the probable future levels of strontium-90 in bone as a result of nuclear detonations set off before and during 1958 (*2–4*, *23*, *27*). It now appears that all of these estimates were too high and that the peaks for diet, and hence for children's bones, were set too far in the future. These calculations were based on the then available estimates of the size of the stratospheric reservoir (2 to 5 megacuries) and of the half-residence time (5 to 10 years) (*24*) and on the assumption that all of the strontium-90 in the diet passed through the soil. H. Feely, of Isotopes, Incorporated (*5*), has shown from high-altitude air-sampling studies conducted in cooperation with the Department of Defense that the quantity of strontium-90 in the stratosphere is much less than had been previously estimated (0.6 megacurie in the fall of 1959) and that from nuclear events such as those produced by the U.S.S.R. in October 1958, half of the debris had already been deposited in 6 months.

From clouds introduced near the equator, of the sort produced by Operation Hardtack, half of the debris is on the ground in less than 1 year. Walton (*25*) has shown that probably the most accurate estimate of the quantity of strontium-90 on the ground at the end of 1959 was 4.5 megacuries, so it is clear that (i) the strontium-90 yet to be deposited is a small fraction of that already down, and (ii) the total surface deposit will reach a maximum in 1961.

Evidence has been accumulating to show that direct uptake of strontium-90 from rain by plants is the dominant mechanism by which strontium-90 enters the diet of human beings. The most definitive experiment was done by R. S. Russell's group at the Agricultural Research Council Radiobiological Laboratory in the United Kingdom (*6*). In this it was shown, from activity in milk produced in England and Wales in 1958, that no more than 20 percent of the strontium-90 in the 1958 diet could be accounted for by uptake by grass through the soil, and thus that 80 percent must have been taken into the grass directly from rain. Thus, the *rate of fallout* under weather conditions of 1954 through 1959 was much more important than the *cumulative deposit* in determining the dietary level. Since the rate of fallout has already dropped below the 1958 level, it appears that the peak of strontium-90 concentration in the world diet has already occurred, in 1959, and the peak in newly depositing bone will occur this year.

Table 6. Average concentrations of strontium-90 (in micromicrocuries per gram of calcium) in human bone in 1958 and 1959. Number of samples in parentheses.

Station	1958			1959		
	0–4 yr	5–19 yr	Adult	0–4 yr	5–19 yr	Adult
			30°–70°N, Western culture area			
New York	2.1 (16)	0.9 (2)	0.13 (28)	2.8 (5)	1.1 (4)	
Boston	1.5 (3)	0.9 (12)				
Houston	1.6 (8)	1.6 (2)	0.17 (67)			0.23 (46)
Bismarck, N.D.			0.40 (3)			
Vancouver	1.9 (4)	0.8 (21)		2.0 (1)	1.1 (5)	
England	1.4 (50)	0.8 (19)	0.17 (15)	2.7 (27)	1.0 (19)	0.25 (4)
Germany (Bonn)	1.7 (18)	0.6 (11)	0.34 (61)	2.0 (23)	0.8 (7)	0.38 (55)
Israel	0.2 (6)	0.2 (2)	0.16 (27)	1.6 (3)	0.7 (1)	
			30°–70°N, Orient			
Japan (Tokyo)		0.7 (2)	0.17 (30)		0.6 (1)	
			10°–30°N			
Puerto Rico	0.64 (20)	0.65 (10)	0.21 (137)		0.89 (19)	0.28 (51)
Guatemala	0.1 (1)	0.3 (5)	0.08 (28)			
Taiwan		0.8 (4)	0.20 (11)		1.1 (1)	
Thailand (Bangkok)		0.39 (1)	0.30 (10)			
			10°N to 20°S			
Brazil (Recife)	0.72 (3)	0.49 (10)	0.16 (25)	1.96 (8)	0.32 (6)	0.15 (70)
Belgian Congo Leopoldville	1.5 (1)	0.27 (1)	0.07 (4)	1.0 (1)		
Colombia (Barranquilla)		0.2 (2)	0.03 (2)			0.06 (5)
			20°S			
South Africa Durban-Capetown		0.95 (22)	0.22 (2)		0.92 (17)	
Australia	0.60 (52)	0.33 (25)	0.12 (65)		0.46 (2)	0.23 (22)
Chile (Santiago)		0.46 (8)		0.39 (17)	0.27 (16)	

From the inventory values and the residence times indicated above, and the value of 20 percent for the contribution of the cumulative deposit to the level of strontium-90 in the diet, it is possible to calculate the change in the average concentration of strontium-90 in the skeletons of people of any age as a result of nuclear tests to date. Figure 3 shows the probable curve (solid line) for the distribution of strontium-90 in Western man in 1959. It also shows projected curves to 1970 for the skeletal burden in individuals who, in 1959, were 1, 15, and 26 years old, respectively. It may be seen that concentrations in adults will increase slightly and then level off toward the equilibrium level for new bone determined by the diet. Levels in one-year-olds will rise slightly but then will drop sharply toward the equilibrium level. Fifteen-year-olds have much more total strontium-90 (and calcium) built in, and hence their skeletal levels will fall more slowly than those of the one-year-olds, but all will approach the equilibrium level in their lifetimes.

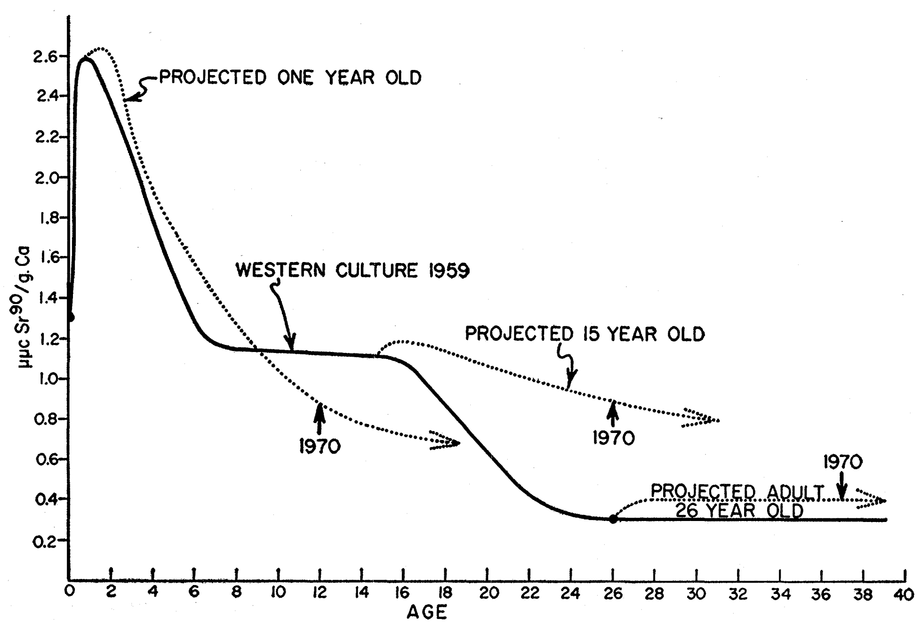

Fig. 3. Concentrations of strontium-90 in Western culture areas for 1959 and projected curves for individuals aged 1, 15, and 26 years, respectively, in 1959.

Russell's estimate of the soil uptake is a maximum; thus, the equilibrium level may be lower than that shown here. The actual ratio of direct uptake to soil uptake for the entire North American continent will be much clearer from the milk-network measurements by the end of 1960, since the rate of fallout will be down by at least a factor of 4 over the 1959 rate and the cumulative deposit will be essentially unchanged.

These new results also have an important bearing on the situation that would arise in the event of nuclear warfare. If 3000 megatons of fission were detonated in the Northern Hemisphere, it is probable that, away from areas of local and intermediate fallout, the long-term strontium-90 level in the diet would reach about 180 micromicrocuries per gram of calcium, or an equilibrium bone level of about 45 micromicrocuries. Thus, under these extreme conditions, the contamination of noncombatant areas would raise the average level of strontium-90 in the population to the point at which the bone dose from natural sources would be approximately doubled (*26*). Food grown in the area of intermediate fallout—a large portion of the United States—would yield an equilibrium concentration of strontium-90 in the diet in the range of 40 to 4000 micromicrocuries per gram of calcium; these concentrations would only produce bone levels up to the maximum permissible concentration for industrial workers even if no special measures were taken. Thus, long-term survival of large populations, even in the countries under attack, would appear to be feasible, provided the serious problem of short-term survival could be solved.

Conclusions

1) The strontium-90 concentration in human bone continued to increase in 1958 and 1959 but the concentration in new bone probably will reach a maximum in 1960.

2) The strontium-90 concentration in adult bone is independent of the age of the individual. The average for Western culture areas in the Northern Hemisphere in 1958 was about 0.20 micromicrocurie per gram of calcium, and in 1959, about 0.30 micromicrocurie.

3) The average strontium-90 concentration for the whole skeleton of an individual may be estimated from the analysis of a single bone to within 10 to 15 percent if sufficient activity is present.

4) The standard deviation for the strontium-90 concentration in fetuses or adults from a single metropolitan area is about 40 percent. The standard deviation for the average strontium-90 level in milk from several dozen stations in North America is also about 40 percent of the mean. These data permit an estimation of the distribution curve for 99 percent of the population of the United States.

5) The maximum strontium-90 concentration is now found in one-year-olds. In 1959 this average value was 2.1 micromicrocuries per gram of calcium for Western culture areas. The concentration varies markedly with age, in a predictable manner.

6) The discrimination factor from mother's diet to fetus appears to be about 12 against strontium as compared with calcium.

7) The strontium-90 level in persons who were one year old in 1959 will drop rapidly if there is no further atmospheric contamination. In 1970 these individuals will carry 0.9 micromicrocurie per gram of calcium.

8) The limited available data do not indicate any large difference in the distribution curves for rice-diet and Western culture areas. In a rice-diet area such as Thailand, however, the diet levels are approximately three times those in the United States per unit of fallout.

9) In general, because of differences in diet, strontium-90 concentrations in some tropical and Southern Hemisphere countries appear to be similar to concentrations in Western culture areas between latitude 30° and 70°N, despite the lower fallout rate in the tropics and the Southern Hemisphere.

10) Previous predictions of strontium-90 levels in diet and bone from tests to date have been high, due to overestimates of the stratospheric reservoir and the stratospheric residence time and an underestimate of the importance of the rate-of-fallout factor. Thus, the peak in the diet passed in 1959; the peak in growing bones will pass this year; and the equilibrium level will be lower than had been predicted by a factor of 5 to 10. This same factor applies to the long-term effect of a nuclear war insofar as the hazard from strontium-90 is concerned.

References and Notes

1. This article is Lamont Geological Observatory contribution No. 430. This research has been supported by the Division of Biology and Medicine of the U.S. Atomic Energy Commission [contract AT(30-1)-1656]. The continued cooperation of the numerous medical doctors throughout the world who have made this investigation possible by supplying the samples is gratefully acknowledged. Rieta Slakter Hirshman is in charge of the Lamont Analytical Laboratory. Many persons have assisted in various aspects of the project, including K. Bartelson, J. Brokaw, J. Clark, M. Mandel, G. Martin, H. McFadden, M. Rippey, M. Solazzi, and J. Sonderburg.
2. J. L. Kulp, W. R. Eckelmann, A. R. Schulert, *Science* **125**, 219 (1957).
3. W. R. Eckelmann, J. L. Kulp, A. R. Schulert, *ibid.* **127**, 266 (1958).
4. J. L. Kulp, A. R. Schulert, E. J. Hodges, *ibid.* **129**, 1249 (1959).
5. H. W. Feely, *ibid.* **131**, 645 (1960).
6. J. D. Burton, G. M. Milbourn, R. S. Russell, *Nature* **185**, 498 (1960).
7. These commercial laboratories are Controls for Radiation, Cambridge, Mass.; Isotopes Inc., Westwood, N. J.; Nuclear Science and Engineering Corp., Pittsburgh, Pa.; Radiochemistry, Inc., Louisville, Ky.; and Tracerlab, Richmond, Calif.
8. A comprehensive report listing all of the individual analyses, calibrations, and analytical methods is in preparation.
9. A. R. Schulert, E. J. Hodges, E. S. Lenhoff, J. L. Kulp, *Health Phys.* **2**, 62 (1959).
10. A. R. Schulert, E. A. Peets, D. Lazslo, H. Spencer, M. Charles, J. Samachson, *Intern. J. Appl. Radiation and Isotopes* **4**, 144 (1959).
11. F. J. Bryant, A. C. Chamberlain, G. S. Spicer, M. S. W. Webb, *Brit. Med. J.* **1**, 1371 (1958).
12. R. H. Wasserman and C. L. Comar, *J. Agr. Food Chem.*, in press.
13. H. H. Mitchell, F. R. Stegerda, H. W. Bean, *J. Biol. Chem.* **158**, 625 (1945).
14. E. H. Watson and G. H. Lowrey, *Growth and Development of Children* (Year Book Publishers, Chicago, ed. 3, 1958), pp. 56–57.
15. *Health and Safety Lab. U.S. Atomic Energy Comm. Publ. Nos. HASL-42* (1958), *HASL-51* (1958), *HASL-65* (1959), *HASL-69* (1959), *HASL-77* (1960).
16. J. L. Kulp and R. Slakter, *Science* **128**, 85 (1958).
17. D. V. Booker, F. J. Bryant, A. C. Chamberlain, A. Morgan, G. S. Spicer, *Atomic Energy Research Establ. (G. Brit.) Publ. No. HP/R 2182* (1957); F. J. Bryant, A. C. Chamberlain, A. Morgan, G. S. Spicer, *Atomic Energy Research Establ. (G. Brit.) Publ. No. HP/R 2056* (1957); R. S. Russell *et al.*, *Agr. Research Council Rept. No. 1* (1959).
18. P. M. Bird and P. G. Mar, *Dept. Natl. Health and Welfare Can. Publ. No. CNHW (RP-2)* (Apr. 1959).
19. *Exchange* is used here in the broadest sense to include ionic exchange, surface exchange, accretion-resorption, diffusion—in short, all processes by which strontium-90 goes into and out of bone.
20. C. L. Comar, I. R. Whitney, F. W. Lengemann, *Proc. Soc. Exptl. Biol. Med.* **88**, 232 (1955).
21. F. J. Bryant *et al.*, *Atomic Energy Research Establ. (G. Brit.) Publ. Nos. AERE C/R 2583* (1958), *AERE C/R 2816* (1959), *AERE R-2988* (1959); J. W. Arden, F. J. Bryant, E. H. Henderson, G. D. Lloyd, A. G. Morton, *U. K. Atomic Energy Authority Ind. Group Publ. No. AERE R-3246* (1960); and personal communication.
22. W. F. Libby, *Environmental Contamination from Weapon Tests, U.S. Atomic Energy Comm. Publ. No. HASL-42* (1958).
23. J. L. Kulp, *Bull. Swiss Acad. Med. Sci.* **14**, 419 (1958).
24. W. F. Libby, *Proc. Natl. Acad. Sci. U.S.* **42**, 365 (1956); *Bull. Swiss Acad. Med. Sci.* **14**, 309 (1958).
25. A. Walton, *J. Geophys. Research*, in press.
26. W. F. Libby, *Proc. Natl. Acad. Sci. U.S.* **45**, 245 (1959).
27. Statement of 1959 Fallout Prediction Panel, read by Dr. William F. Neuman, *Fallout from Nuclear Weapons Tests, Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, 86th Congress, First Session* (1959), p. 1789.