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Strontium-90 in Man V

The concentration in the bones of children had been dropping, but recent tests will reverse the trend.

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The nuclear detonations of the fall of 1961 may nearly double the surface burden of fission products in the Northern Hemisphere. This large input underscores the need to know the mechanism of dispersion of this radioactive debris and its eventual effect on man. A significant increase in knowledge of the fallout problem was made possible by the moratorium on nuclear tests from November 1958 to August 1961. This permitted the first useful measurement of the separate contribution of the rate of fallout and the cumulative deposit to the strontium-90 concentration in the diet for the North American continent. It also made it possible to test predictions concerning the distribution of strontium-90 in the world population. This article (*1*) is the final report of a series (*2–4*) which has described the experimental work on strontium-90 in human bone which began in 1953.

The ultimate objective of this program has been to ascertain the principles that govern the concentration of strontium-90 in the world population with sufficient accuracy to predict the average concentration for any age group, at any location on the earth, at any time in the future after any given pattern of nuclear detonations. To achieve such an objective, information must be obtained concerning the primary input of nuclear debris into the atmosphere, the nature and rate of dispersion in the air and the rate of removal to the surface of the earth, the uptake in foodstuffs, and finally the actual concentration in human bone. The primary input can be determined from theory and various experimental programs conducted at the national test sites. The inventory and mechanism of movement of strontium-90 in the stratosphere have been studied in Project HASP (*5*). The New York Operations Office of the Atomic Energy Commission has maintained rain and soil collection programs (*6, 7*) which measure the rate of fallout as well as the cumulative deposit over the world. Food analyses have been conducted by many laboratories, but the most widespread consistent sampling in North America has been done with milk by the Los Alamos Scientific Laboratory (*8*) and more recently by the U.S. Public Health Service (*9*). The effort at the Geochemistry laboratory of the Lamont Geological Observatory has been primarily concerned with human bone.

During the course of this investigation over 10,000 samples of human bone were received from a world-wide network of 39 stations, from 1953 to 1960. These samples were largely single bones from individuals of all ages, but they also included whole fetuses and adult skeletons. In many cases adult samples were composited in groups of ten or more. Most of the analyses for strontium-90 were carried out at commercial laboratories under contract with the Atomic Energy Commission (*10*). The absolute calibration at all laboratories is based on NBS standards and is accurate to within 3 percent. The standard deviation for the radiochemical procedures is ± 7 percent, as determined on samples of powdered milk and on bones spiked with strontium-90 in the range of 10 to 1000 disintegrations per minute per sample. For human bone samples that carry strontium-90 at a level of at least five disintegrations per minute, the overall 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 between 1957 and 1960, and pooled samples of bones of adults who died in the period 1958–60 and who lived in the latitude band between 30° and 70°N. The other samples, of lower strontium-90 activity, carry larger errors. Laboratory contamination was monitored by analyzing $Ca_3(PO_4)_2$ of reagent grade and bone from individuals who died before 1945. Samples of adult bone containing less than 1.0 gram of calcium and children's bones containing less than 0.5 gram of calcium have not been included in the final summaries because of the larger inherent errors resulting from the low total strontium-90 content in these small samples.

The individual measurements and details of the methods of analysis, calibration, quality control, and calculations, as well as the history of the study, have been given in the final project report (*11*). Some of these data and the related interpretation, as well as discussions of problems of more limited scope, have been published in reports which deal with analytical techniques (*12*); the vertical penetration of stron-

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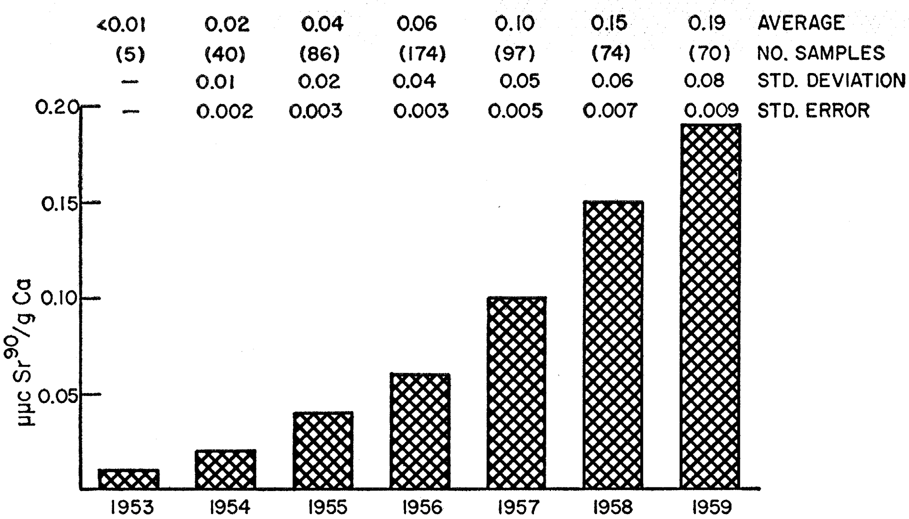

Fig. 1. Average strontium-90 concentrations in whole-skeleton samples of New York adults for the period 1953–59.

tium-90 in soil (*13*); the distribution of radium (*14*), common strontium (*15*), and strontium-90 (*16*) in the human skeleton; the metabolism of strontium and calcium in man (*17*); strontium-90 in frozen foods, wheat, and special diets (*18*); and carbon-14 in man from nuclear tests (*19*).

Concentrations in Fetuses

The fetus reflects the strontium-90 concentration in the human being more rapidly than any other age group, since most of the skeletal structure is produced within the last 3 months of pregnancy. Table 1 gives the average concentrations for fetus samples from New York and Chicago for each quarter, half year, and year from 1957 through the first quarter of 1961. The Chicago and New York averages are nearly identical for 1959. The trend is upward to 1959 and then downward in 1960, closely following the trend in the diet. The ratio of the strontium-90 concentration in the average adult diet over that in the fetus is about 12, with an uncertainty of about 10 percent. It has been established that the discrimination factor between strontium and calcium from diet to bone for the average Western diet is 4 against strontium (*17, 20, 21*). Comar *et al.* (*22*) have found the placental discrimination between the mother's blood and the offspring's bones for cows and rats to be about 2 against strontium. If these values strictly apply, an overall discrimination of 8 would be expected. The experimental ratio of the strontium-90 concentration in the adult diet to that in the fetus is 12 but this involves more factors than discrimination. Lough *et al.* (*23*) have found that human mother's milk carries about one-tenth the concentration of the mother's diet. Bryant and Loutit (*24*) show that the ratio of stable strontium to calcium in fetal bone is 0.6 that in the mother's bone, and from this finding they conclude that the placental discrimination in man may be less than that in animals, but the analytical errors of this experiment and that of Comar *et al.* (*22*) overlap. It appears most likely, as suggested earlier (*4*), that the addition of mineral calcium to the diet of the pregnant woman reduces the concentration of strontium-90 in her diet to a level significantly below that of the average population.

The measurements on fetuses from New York and Chicago are compared with data from other parts of the world in Table 2. Levels of strontium-90 are higher in fetuses from Bonn and Copenhagen than in those from New York, whereas levels in the United Kingdom are slightly lower. Since the standard deviation for these populations is probably about 40 percent (*4*), the standard error on the mean calculated from the number of samples in these sets is sufficiently small so that the observed differences between stations, and between the calendar years, are significant. For example, the standard error of the mean for New York for 1959 is ± 0.04, whereas for Bonn it is ± 0.18 micromicrocuries of strontium-90 per gram of calcium.

In central North Dakota, levels in milk were two or three times the national average for the U.S. in 1958 and 1959, but in the low-rainfall areas of the West, from Arizona to Idaho, the strontium-90 concentration is half the national average. The values for fetuses from these areas correlate with the levels in milk.

The samples from Australia appear to carry about half the concentration of strontium-90 found in those from New York.

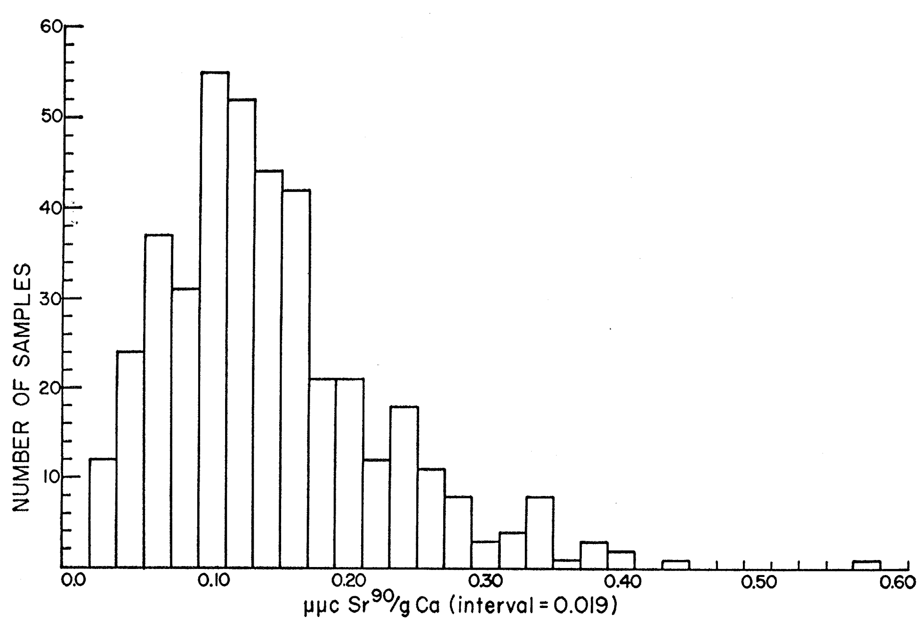

Fig. 2. Histogram showing frequency of occurrence of strontium-90 concentrations in whole-skeleton samples from New York City.

Concentrations in Adults

It has been shown (*4*) that there is no significant difference in the strontium-90 concentration in adults as a function of age, at least for ages from 30 to 70 years. New data for 1959 and 1960 show that adults who were teen-agers at the beginning of the fall-out era have higher skeletal concentrations than the average adults. Thus, since the contamination began about 7 years ago, people who were 19 years old or younger in 1953 have average skeletal values above those for older adults.

Since the concentration of strontium-90 in adults is independent of age, the average turnover of the strontium and calcium in the bone must be constant during adult life. Indeed, this basic physiological process may not vary significantly at any age.

By using the strontium-90 in the diet for each year, the discrimination factor of 4, and a series of overall exchange rates for bone, the corresponding concentrations in adult bones were calculated. These values may then be compared with the observed values.

Table 3 gives the predicted values of strontium-90 in adult bone for people who have been on a diet similar to that of New York City or eastern North America (40 to 60 inches of rainfall), assuming either 2.0 percent or 3.0 percent annual turnover in the strontium in their bone. These predicted values are compared with the measured bones from two sets of samples: New York City and U.S.–Canada. The data (Table 4) (*9*) are taken for the calendar year so that they represent the average individual on 1 July of the year. The computation requires the average strontium-90 level in the diet for the 12 months preceding death which is approximately 1 January of the same year. It appears that the overall rate of exchange lies between 2 and 3 percent.

Thus, although it has been demonstrated (*16*) that the exchange rate is higher in certain bones than in others, the overall rate has remained constant during a period of varying concentration of strontium-90. Bryant and Loutit (*24*) have shown that the apparent turnover rates ranged from about 1 percent for long-bone shaft to 8 percent for vertebrae. The mean of their values for 11 subjects, weighted for the proportion of the total skeleton, would be

Table 1. Concentrations of strontium-90 in U.S. diet in the 40- to 60-inch rainfall belt and in New York and Chicago fetuses, by quarter, 1954–61.

Quarter	U.S. diet ($\mu\mu c$ Sr^{90}/g Ca)	New York: Samples (No.)	New York: $\mu\mu c$ Sr^{99}/g Ca: Quarter	New York: $\mu\mu c$ Sr^{99}/g Ca: Half year	New York: $\mu\mu c$ Sr^{99}/g Ca: Year	Chicago: Samples (No.)	Chicago: $\mu\mu c$ Sr^{90}/g Ca: Half year	Chicago: $\mu\mu c$ Sr^{90}/g Ca: Year
				1954				
1, 2	1.8					64	0.10*	
3, 4	2.9					10	0.16*	0.15
				1957				
1, 2	7	4		0.5				
3, 4	8	16		0.6	0.55			
				1958				
1	11	43	0.63					
2	15	13	1.10	0.9		34	0.67	
3	13	8	1.14					
4	13	4	1.84	1.3	1.0	24	0.81	0.7
				1959				
1	17	10	1.45					
2	23	9	0.83	1.1		36	1.02	
3	15	16	1.53					
4	14	24	1.07	1.3	1.2	46	1.36	1.2
				1960				
1	15	9	1.04					
2	13	50	1.39	1.2		5	1.16	
3	10							
4	9	21	0.74	0.9	1.1			
				1961				
1	8	31	0.97					

* Data of W. F. Libby, Institute for Nuclear Studies, University of Chicago.

Table 2. Concentrations of strontium-90 in fetuses from world stations. The figure in parentheses after each value is the number of samples.

Station	$\mu\mu c$ Sr^{90}/g Ca: 1957	1958	1959	1960	Reference
		North America			
New York	0.6 (30)	1.0 (115)	1.2 (141)	1.1 (80)	(*11*)
Chicago		0.7 (58)	1.2 (82)		(*11*)
St. Louis			1.2 (11)		(*37*)
Rocky Mt. Area			0.5 (7)		(*37*)
North Dakota		1.3 (6)			(*11*)
Houston			1.0 (8)		(*11*)
		Europe			
Bonn				0.9 (47)	(*11*)
		1.2 (10)	1.6 (13)	1.3 (21)	(*38*)
Copenhagen		1.4 (11)	2.2 (66)	1.7 (24)	(*39*)
Glasgow and London	0.6 (50)	0.7 (129)	1.1 (152)	1.0 (111)	(*40*)
		Asia			
Taipeh, Taiwan	1.0 (9)	0.5 (17)			(*11*)
		Australia			
		0.4 (10)	0.6 (35)	0.5 (43)	(*41*)

Table 3. Estimated and observed rates of exchange of strontium-90 in adult bone.

Year	Activity in diet* ($\mu\mu c$ Sr^{90}/g Ca)	Calculated specific activity ($\mu\mu c$ Sr^{99}/g Ca): 2.0% exchange	3.0% exchange	Observed activity† ($\mu\mu c$ Sr^{90}/g Ca)
		New York City		
1953	0.8	.00	.01	<.01
1954	1.2	.01	.02	.02
1955	2.0	.02	.03	.04
1956	3.4	.04	.06	.06
1957	4.9	.06	.10	.10
1958	5.8	.09	.14	.15
1959	12.9	.16	.24	.19
		U.S. and Canada		
1955	3.2	.03	.05	.06
1956	4.2	.05	.08	.07
1957	6.3	.09	.13	.14
1958	10.2	.14	.21	.19
1959	16.2	.21	.34	.27
1960	14.1	.29	.45	.33

* Diet taken at 1 Jan. of the year. For U.S. and Canada the diet is that for 40- to 60-inch rainfall belt. For New York, diet estimated from milk stations within 10 miles of city. † Observed values taken from Table 4.

in the range of 2 to 3 percent of overall exchange per year for the whole skeleton. There is no evidence here that a rapidly exchangeable pool is first brought to saturation and that the rate of exchange for the skeleton as a whole then drops to a much lower value. If the process were rapid exchange with a fixed fraction of the skeleton, the observed values would directly follow the diet, but this does not appear to be the case.

Since the individual bones or parts of bones in the adult skeleton carry different concentrations of strontium-90, and since most of the available samples consist of single bones from autopsy, it is necessary to obtain a fairly accurate relation between the concentrations of strontium-90 in a given bone type and in the total skeleton. This work was reported earlier (*4*) and the following ratios were given: vertebrae to skeleton, 2.1 ± 0.1; rib shaft to skeleton, 1.4 ± 0.1; and long-bone shaft to skeleton, 0.45 ± 0.02. All adult bone samples reported in this article have been corrected by these factors, to represent whole-skeleton concentrations.

Analyses of the bones of fetuses and young children showed no significant differences from one bone type to another, presumably because deposition of new bone which occurs more or less uniformly over the skeleton far outweighs exchange (*4*). Thus, no differences in concentration could be found between femur and vertebrae in such groups. Bryant and Loutit (*24*) have confirmed this observation on children and teen-agers. They have also analyzed the individual bones of 11 adults and have obtained the following ratios: vertebrae to skeleton, 2.4; rib to skeleton, 1.1. These ratios are in good agreement with the earlier data (*4*).

The best adult samples have been the whole skeletons from New York City. They constitute large enough samples so that even at the very low concentrations of strontium-90 which exist in adult bones the analytical error is reasonably small. The direct analysis of an aliquot of ash from the whole skeleton also eliminates the need to estimate the whole-skeleton average from analysis of a single bone.

In Fig. 1 all of the data on the New York cadaver samples are summarized. The average value increased steadily from 1953 to 1959, from a low of <0.01 to 0.19 micromicrocurie of strontium-90 per gram of calcium. The standard deviation for the population is about 40 percent of the mean for 1958 and 1959—years in which the activity levels were high enough to keep the analytical errors to 10 percent. Figure 2 shows the distribution of strontium-90 in this population; it includes all samples from 1956 to 1959, normalized to 1958. It is noteworthy that the two highest values were derived from 1956 samples, which have in general the largest analytical uncertainty, since the average activity was lowest in 1956. These data are plotted with the assumption of log-normal distribution on probability paper in Fig. 3. It may be seen that this function fits the data fairly well over the interval from 0.2 to 70 percent of the population. There is no theoretical justification for this distribution, and other more complex functions could also fit the data over such an interval. Large extrapolations are therefore unwarranted. To use such a curve to predict the distribution beyond 0.001 percent would appear to be unjustifiable.

The curve of Fig. 3 indicates that levels for 5 percent of the population will exceed twice the average, levels for 0.1 percent will exceed four times the average, and levels for 0.001 percent may exceed 7 times the average. Since most factors in an urban environment tend to equalize the diet over a long period of time, it seems probable that the foregoing figures represent a conservative estimate of the situation. The distribution curve (Fig. 3) derived experimentally for adults should apply to persons of all other ages, since the only significant difference in diet with age would lie in the milk component which shows least variation in its annual average strontium-90 concentration.

Distribution curves derived from the single-bone analyses are not as meaningful in estimating the actual distribution, since these data have much larger analytical uncertainties and correction must be made to obtain the whole-

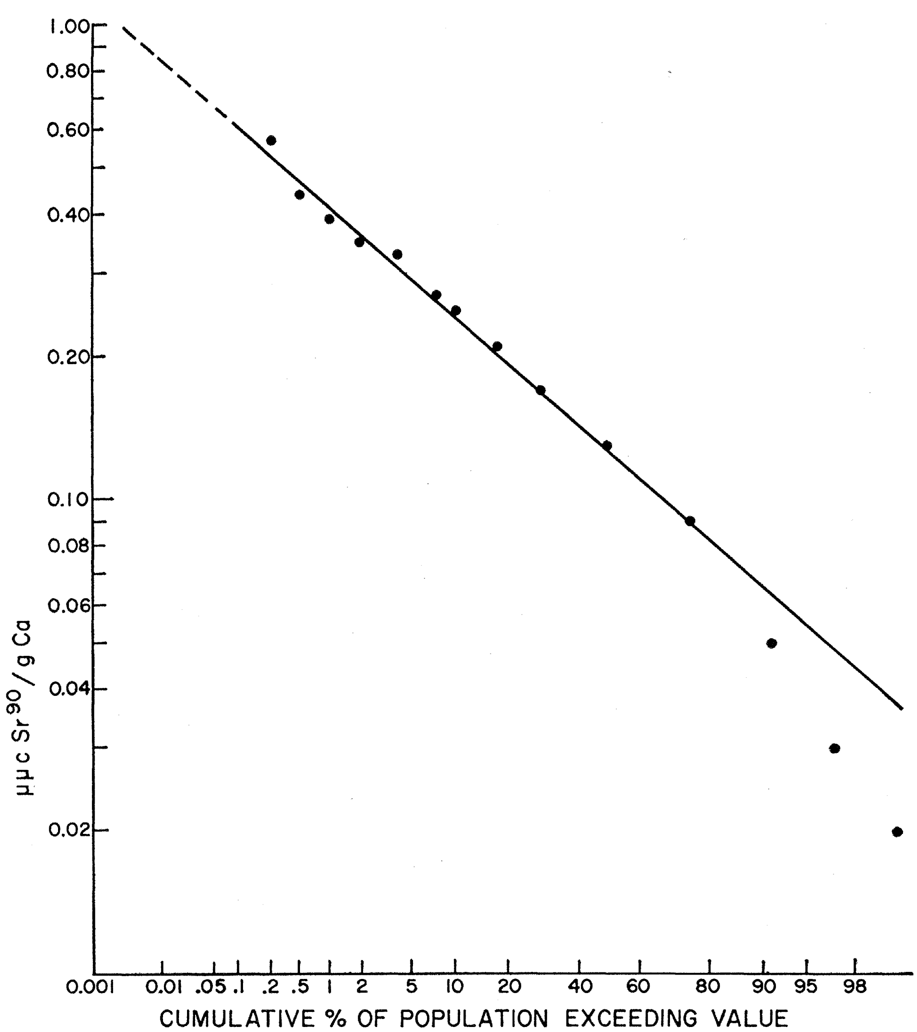

Fig. 3. Distribution curve of New York whole-skeleton samples plotted on probabilty-log-normal scales. Average of this population is 0.15 $\mu\mu c$ Sr^{90}/g Ca.

skeleton burden. The distribution curve for single-bone samples from various population groups that have similar average levels of activity may be useful, however, for purposes of comparison. Such comparisons have been made on the data for single bones from all stations. It is concluded that within the uncertainties of the data there is no major difference between the distribution curves for urban areas, whether these are areas of Western or of Eastern culture, or in the Northern or Southern Hemisphere. It is thought, however, that in rural populations that derive their food from local sources, there may be a wider dispersion of the strontium-90 concentration. On the other hand, attempts to find greater dispersion have been unsuccessful (*11*). Isolated instances of high concentrations have been found in the diets of the isolated Indian tribes of the upper Amazon and of inland Eskimos who live largely on caribou (*11, 18*). There are undoubtedly other groups with a high strontium-90 concentration in their food—groups such as vegetarians with a high whole-wheat component in their diet and inland rice farmers in the 30° to 60° north latitude zone—but these have not as yet been identified experimentally.

Over the last 7 years relatively high concentrations in milk were found in various parts of the United States. Thus, from 1952 to 1954 the effect of proximity to the Nevada Test Site could be detected. This was soon masked by larger world-wide fallout, but uneven deposition or soil type caused local highs in such areas as central North Dakota and eastern Missouri. By 1961 most of these highs had disappeared or had been significantly reduced. Thus, continuous fallout over many years can be expected to yield relatively homogeneous deposition (per inch of mean annual rainfall) throughout the United States. Ultimately, the highest levels in milk should be found in the high-rainfall areas of the southern Appalachians, and the lowest, in the irrigation farms of the Southwest desert.

The data on adult bone samples for the world-wide network are summarized in Table 4. In many cases the samples that were averaged contained some individual samples reported by the analytical laboratory to contain "less than" a certain concentration. In this case

Table 4. Concentrations of strontium-90 in samples of bone from adults throughout the world for the period 1955–1960. The figures in parentheses are number of samples. "Minimum" averages are averages based on the assumption that the concentration for samples reported to contain "less than" a given concentration is zero.

Station	Concentration ($\mu\mu c$ Sr^{90}/g Ca)											
	1955		1956		1957		1958		1959		1960	
	Av.	Min. av.	Av.	Min. av.	Av.	Min. av.	Av.	Min. av.	Av.	Min. av.	Av.	Min. av.
					North America							
Anchorage											< 0.40 (26)	0.33
Vancouver	< 0.10 (68)	0.06	< 0.16 (24)	0.11	< 0.19 (15)	0.18						
Grand Forks							< 0.40 (6)	0.33				
Boston					< 0.13 (158)	0.09						
New York			< 0.12 (3)	0.00	< 0.12 (35)	0.08						
New York*	0.04 (86)		0.06 (174)		0.10 (97)		0.15 (74)		0.19 (70)			
Denver	< 0.13 (34)	0.09	< 0.14 (10)	0.07	< 0.16 (5)	0.15			0.27 (2)			
Galveston					< 0.14 (17)	0.09						
Houston	< 0.18 (5)	0.11			< 0.14 (23)	0.12	0.20 (147)		0.30 (199)		0.23 (31)	
San Juan, P.R.	< 0.18 (4)	0.14	< 0.18 (47)	0.17	< 0.15 (34)	0.12	< 0.21 (151)	0.20	0.24 (134)		0.34 (14)	
Guatemala City, Guatemala					< 0.13 (49)	0.10	< 0.14 (56)	0.12			0.15 (34)	
					Europe							
Copenhagen, Denmark	< 0.08 (11)	0.04	< 0.13 (9)	0.11	< 0.17 (17)							
Bonn, Germany	< 0.12 (60)	0.09	< 0.22 (26)	0.21	< 0.14 (29)	0.11	< 0.37 (85)	0.32	< 0.47 (116)	0.44	0.52 (40)	
London, England	< 0.07 (8)	0.02	< 0.08 (16)	0.04	< 0.16 (13)	0.14	0.22 (6)					
Paris, France			< 0.1 (7)	0.00								
Zurich, Switzerland	0.16 (9)		0.16 (29)		0.12 (4)							
Torino, Italy	< 0.19 (7)	0.06	< 0.16 (8)	0.10	< 0.22 (3)	0.16						
					Asia							
Jerusalem, Israel					< 0.18 (33)	0.14	< 0.12 (65)	0.12	0.13 (28)			
Tabriz, Iran			< 0.06 (1)									
Bombay State, India	< 0.14 (33)	0.04	< 0.11 (31)	0.04	0.18 (22)				0.13 (1)			
Bangkok, Thailand					< 0.28 (33)	0.25	< 0.18 (36)	0.17	< 0.23 (36)	0.04	< 0.22 (46)	0.13
Saigon, Vietnam									< 0.5 (7)	0.2	< 0.4 (9)	0.2
Taipeh, Taiwan	< 0.15 (10)	0.00	< 0.17 (7)	0.02	< 0.14 (6)	0.06	< 0.18 (25)	0.17				
Tokyo, Japan	< 0.2 (2)	0.00	< 0.16 (19)	0.08	< 0.14 (38)	0.09	< 0.12 (58)	0.08	0.16 (20)			
Chiba, Japan					0.18 (48)							
					South Pacific							
Melbourne, Australia									< 0.15 (438)	0.14	< 0.22 (247)	0.22
Sydney, Australia			< 0.10 (13)	0.00	< 0.19 (37)	0.16			0.22 (22)			
					North Pacific							
Honolulu, Hawaii	< 0.2 (2)	0.00	< 0.09 (24)	0.04	< 0.12 (18)	0.00						
Manila, Philippines					< 0.2 (8)	0.18						
					Africa							
Monrovia, Liberia					0.43 (12)							
Nyankunde, Bunia, Congo					0.3 (3)		< 0.14 (2)	0.04				
Leopoldville, Congo					0.13 (9)		< 0.14 (2)	0.04				
Capetown, South Africa			< 0.1 (7)	0.00	< 0.16 (27)	0.07						
Durban, South Africa					< 0.23 (12)	0.19					< 0.24 (125)	0.23
					South America							
Caracas, Venezuela	< 0.16 (35)	0.04	< 0.2 (3)	0.00								
Barranquilla, Colombia	< 0.10 (7)	0.03	< 0.1 (1)	0.00	0.07 (3)		< 0.17 (11)	0.17	< 0.12 (8)	0.08	< 0.4 (3)	0.4
Guayaquil, Ecuador					< 0.08 (2)	0.05						
Recife, Brazil	< 0.13 (13)	0.03	< 0.08 (40)	0.03	< 0.08 (4)	0.6	< 0.15 (23)	0.10	< 0.15 (130)	0.15	< 0.24 (70)	0.18
Santiago, Chile	< 0.20 (40)	0.05	< 0.10 (59)	0.03	< 0.06 (24)	0.03						
Cordoba, Argentina					< 0.11 (19)	0.11						

* Average based on total-skeleton ash samples.

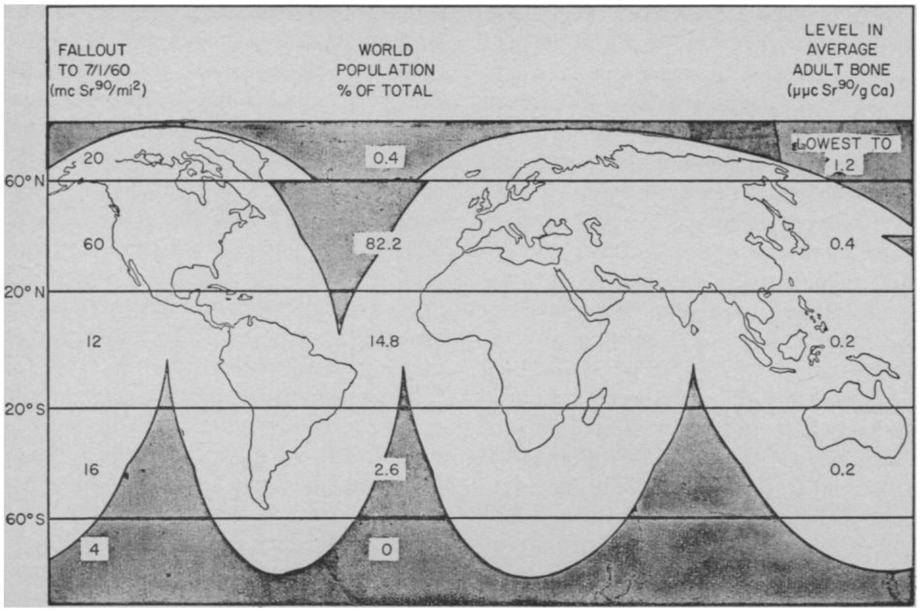

Fig. 4. Levels of strontium-90 in adult bone throughout the world as compared with average fallout levels in 1960.

the "less than" value was assumed to be the correct value, but the final average carries a "less than" sign. Values in the columns headed "Average" in Table 4 therefore represent true maxima. In each such case a minimum value for the average was also calculated, by assuming that all of the "less than" values were actually zero. If the maximum and minimum values are similar, the average can be estimated with small uncertainty.

In almost all cases where there is a significant number of samples, the results indicate a gradual increase in the strontium-90 level with time for a given station. It may be seen in Table 4 that the values for New York are somewhat below the average for North America above 30°N. The values for the North Dakota region are above the average, as are those for Anchorage. Even though the fallout is less in San Juan and Guatemala City than in New York, the levels in bone are similar to those in New York, owing to the lower milk content of the Puerto Rican and Guatemalan diets. In Europe, the values for Bonn for concentrations of strontium-90 in the adult skeleton were significantly higher than the average and were nearly double the values for New York for the period 1958–60. The limited data from Israel suggest a lower level than the average for Europe or North America—a finding which probably is related to the lower rainfall and to food production by irrigation. Most of the other Asian stations appear to fall within the range for the North American and European samples.

The Australian samples are striking in that they appear to have about one half the strontium-90 concentration of samples from the Northern Hemisphere countries, whereas the milk levels are one third. The reason for this is not understood at the present time. A similar situation exists in South Africa; the excellent series from Durban in 1960 gave a value of at least 0.23 micromicrocurie of strontium-90 per gram of calcium—more than half the average for North America and Europe, considered together.

Most of the bone samples from South American countries show lower concentrations than from North American countries, but the ratio of the bone level in North America over that in South America is much smaller than the ratio in total fallout. In Recife, Brazil, for example, the cumulative fallout by the end of 1958 was about 7 millicuries per square mile, whereas in the eastern United States at the same time it was about 40 millicuries. The similarity in the bone levels in 1959 must be explained primarily on the basis of differences in diet.

In 1959 the average strontium-90 concentration in adults from Lodz, Poland, was estimated to be 0.3 micromicrocurie of strontium-90 per gram of calcium (*25*). The average for the U.S.S.R. in 1959 is reported (*26*) to be about 0.4 strontium units, but it is not clear whether corrections from single bone to whole skeletons were made.

In Fig. 4 the distributions of fallout, of population, and of levels in adult bone are summarized for the world. It may be seen that the levels in bone are surprisingly uniform throughout the world. This is a result of the nature and location of the injections of strontium-90 into the atmosphere and the difference in the dietary regimes of the peoples of Western culture in the Northern Hemisphere and peoples of the less developed countries elsewhere.

Thus, for example, the average adult bone values in New York and Tokyo are similar, as is the fallout. Yet the diets are very different. The much lower milk content of the Japanese diet appears to be compensated for by fish, particularly those of soft bones which are consumed, so that the average strontium-90 level is similar to that in the eastern U.S. In Bangkok the bone levels are similar to those in eastern North America but for a different reason. The fallout in Thailand is significantly lower than that in the eastern United States, as Thailand lies in the 10° to 20° north latitude zone, but the diet contains relatively little fish or milk, so that the Sr^{90}/Ca ratio in the food consumed appears similar to that in eastern North America.

It may be that there are great extremes in levels of strontium-90 in the north polar latitudes, where a primitive group such as the Eskimos may subsist largely on fish (in which the level is very low) or largely on caribou (in which it is very high) (*18*). The compilation in Fig. 4 contains no data from the large population of continental China, which, if included, might raise the average for the 20° to 60° north zone.

Concentrations in Young People

It has been shown in earlier work (*3, 4*) that a relatively simple model for the uptake of strontium-90 by the bones of young people can account for the observed distribution with age. This treatment was suggested originally by Langham and Anderson (*27*).

The present model is based on two assumptions, (i) that the rate of exchange of existing bone is independent of age and (ii) that the discrimination factor between strontium and calcium in passing from diet to bone is independent of age. In order to calculate the strontium-90 concentration in the bones of any age group that subsist on the same average diet, the following experimental data are required: (i) the concentration of strontium-90 in the fetus and the adult, (ii) the strontium-90 concentration in the diet for each year, (iii) the amount of calcium added to the skeleton per year at each age, and (iv) the discrimination factor between strontium and calcium, that is, $(Sr/Ca)_{diet} \div (Sr/Ca)_{bone}$. The equation for the concentration of strontium-90 in individuals of each age then is:

$$Q_B = \left[\sum_{i=1}^{p} Ca_{n_i} A_{n_i} + Ca_{ex_i} (A_{n_i} - A_{s_{i-1}}) - 0.025\, Ca_{s_{i-1}} A_{s_{i-1}} \right] / Ca_{s_p}$$

where Ca_n is the number of grams of calcium added in a given 12-month period in the formation of new bone (a value which depends on the age of the individual); Ca_{ex} is the number of grams of calcium exchanged per year; Ca_s is the number of grams of calcium in the skeleton; Ca_{s_p} is the total number of grams of calcium in the present skeleton; A_{n_i} is the specific activity of newly depositing bone, in micromicrocuries of strontium-90 per gram of calcium; $A_{s_{i-1}}$ is the specific activity of the total skeleton in the preceding year; and Q_B is the specific activity of the total skeleton at the midpoint of the given calendar year. The summation is over all years for which there was measurable strontium-90 in the diet. The factor 0.025 accounts for the radioactive decay of the strontium-90 that had been fixed in the skeleton the previous year.

Figure 5 gives the curves calculated for the years 1958 and 1960. The values for fetal samples represent the experimental averages for all samples from North America, but these were predominantly from New York and Chicago. The adult samples were predominantly from New York, Boston, and Houston, with additions from Anchorage in 1960. The rate of exchange was taken as 2.5 percent, as discussed above. The discrimination factor was taken as 4. The amount of calcium added at each age is that obtained by Mitchell *et al.* (*28*). The concentration of strontium-90 in the total diet from 1 July to 1 July were (in micromicrocuries of strontium-90 per gram of calcium): 1953–54, 1.5; 1954–55, 3.2; 1955–56, 4.2; 1956–57, 6.3; 1957–58, 10.2; 1958–59, 16.2; 1959–60, 14.1; and 1960–61, 9.6. Some of these factors require further discussion.

The absolute value of the rate of exchange is probably known to within ±20 percent in adults. In young people the direct addition of strontium-90 in new bone is much greater than the addition from exchange, assuming that the rate of exchange is independent of age. Bryant and Loutit (*24*) have questioned the constancy of the rate of exchange with age and suggest that the exchange may be 100 percent during the first year and may drop to nearly zero during puberty. Their argument in support of these two suggestions is inconclusive, owing to the relatively large uncertainties in their data. Further, the uniformity of strontium-90 levels in the different bones of the skeletons of young people (*4*, *24*) suggests that the contribution to the total specific activity from exchange must be small. If the rates of exchange in vertebrae and in the femur shaft differ by a factor of 4 in young people, as they do in adults, and if the average rate of exchange significantly exceeds a few percent, differences among the bones of one body would be easily observable. Finally, since the discrimination factor from diet to bone is so much greater between the mother's diet and the bone of the fetus than between the diet and the bone of the 1-year-old, complete replacement in the first year would yield a much higher specific activity than is actually observed. Therefore, on the basis of present knowledge there seems no reason to adopt a more complex hypothesis concerning the basic physiological process of calcium replacement in the bone.

The value for the strontium-90 level in diet that was used in these calculations was derived by taking the average level in milk for the eastern United States (Table 5) (that is, the zone of 40 to 60 inches of mean annual rainfall) weighted for population, and then multiplying by 1.2. These averages for milk should be representative of the milk consumed by the people of Chicago, New York, and Boston. The data for the period 1953–56 are taken from earlier work (*4*) which is based on

Table 5. Concentrations of strontium-90 in milk from North American stations in areas of different average annual precipitation. Figures in parentheses are number of stations.

Quarter	Concentration ($\mu\mu c\ Sr^{90}/g\ Ca$)				
	40 to 60 in.	30 to 40 in.	20 to 30 in.	10 to 20 in.	0 to 10 in.
		1957			
1	4.4 (5)	5.4 (11)	3.9 (5)	4.0 (8)	1.6 (4)
2	7.1 (12)	6.0 (23)	7.2 (10)	5.9 (13)	2.1 (5)
3	6.7 (13)	7.7 (24)	6.8 (10)	7.8 (13)	1.7 (3)
4	8.0 (8)	7.3 (17)	9.5 (12)	8.1 (13)	1.6 (5)
Calendar year av.	6.8	6.7	7.4	6.6	1.7
Av. for 1 Apr. 1957 to 31 Mar. 1958	7.4	7.0	7.8	7.3	1.9
		1958			
1	8.3 (8)	7.3 (17)	7.3 (14)	7.5 (13)	2.0 (5)
2	11.6 (11)	9.7 (19)	9.3 (17)	9.8 (13)	2.7 (5)
3	10.9 (23)	9.6 (26)	9.3 (22)	8.2 (16)	4.1 (8)
4	11.6 (13)	10.3 (22)	9.8 (20)	7.7 (12)	2.0 (3)
Calendar year av.	10.8	9.3	9.0	7.7	3.0
Av. for 1 Apr. 1958 to 31 Mar. 1959	11.7	10.0	9.6	8.4	3.0
		1959			
1	13.4 (12)	10.9 (15)	10.1 (15)	8.0 (12)	3.5 (4)
2	18.9 (12)	14.6 (18)	14.3 (16)	13.0 (12)	8.0 (3)
3	12.8 (20)	10.4 (22)	9.8 (16)	10.0 (16)	2.9 (4)
4	12.0 (11)	10.1 (15)	9.6 (13)	10.1 (14)	2.6 (5)
Calendar year av.	14.0	11.5	11.0	10.2	3.9
Av. for 1 Apr. 1959 to 31 Mar. 1960	13.9	11.5	11.0	10.6	3.4
		1960			
1	12.7 (9)	10.8 (14)	10.3 (19)	9.9 (17)	2.3 (7)
2	10.8 (15)	9.8 (24)	10.0 (13)	8.6 (16)	3.8 (4)
3	8.9 (24)	7.4 (28)	7.2 (15)	6.2 (14)	3.1 (7)
4	8.2 (22)	6.6 (23)	7.3 (12)	6.5 (12)	3.2 (4)
Calendar year av.	9.6	8.2	8.8	8.0	3.0
Av. for 1 Apr. 1960 to 31 Mar. 1961	8.5	7.6	7.8	6.8	3.1
		1961			
1	6.8 (21)	6.5 (24)	6.8 (12)	5.1 (11)	2.5 (4)
2	9.4 (22)	8.0 (23)	7.6 (12)	5.9 (10)	4.3 (2)
3	8.8 (20)	6.8 (21)	6.5 (5)	5.7 (7)	3.0 (2)
4	8.7 (21)	8.3 (21)	8.0 (5)	6.1 (7)	7.1 (2)
Calendar year av.	8.4	7.4	7.2	5.7	3.9

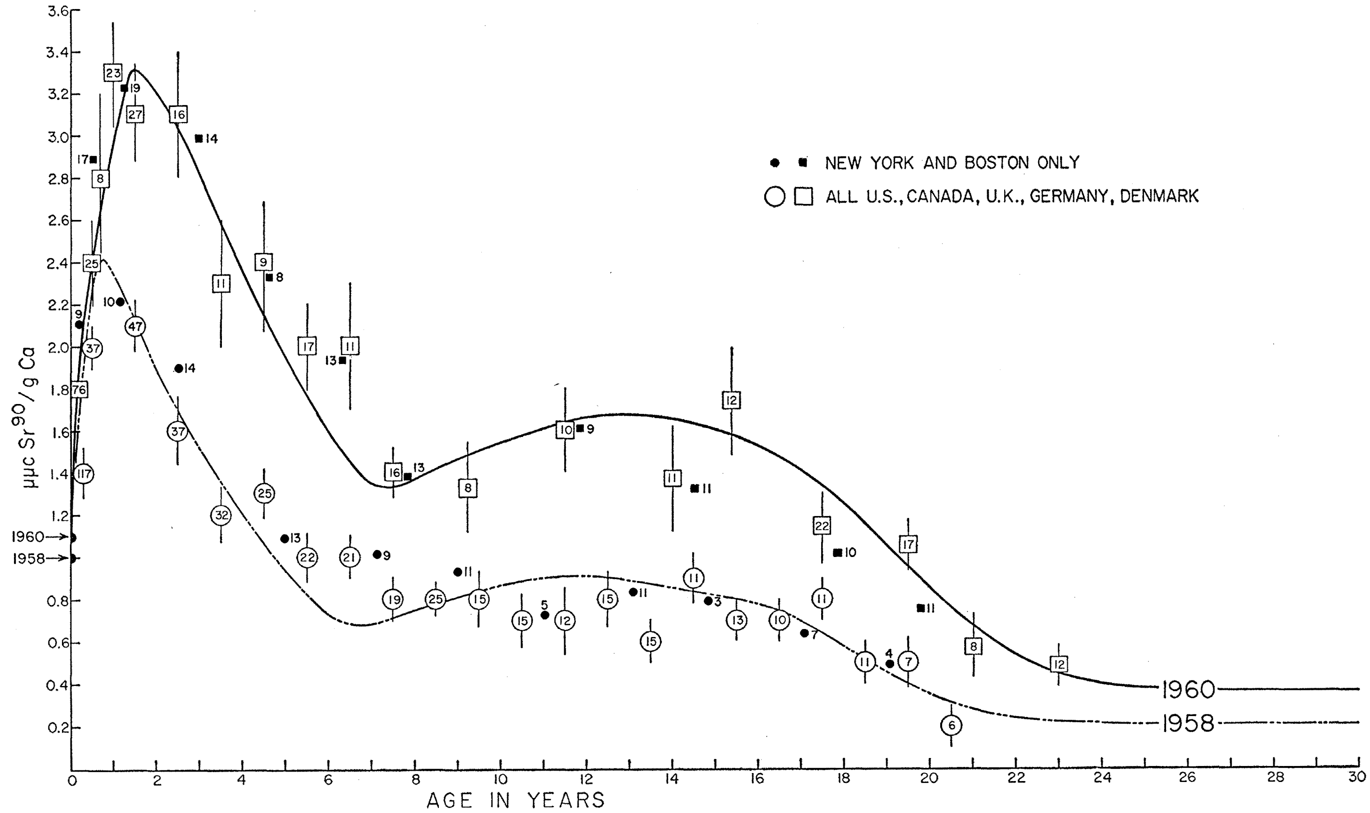

Fig. 5. Curves for calculated values for strontium-90 concentrations in bone in eastern North America, 40 to 60 inches mean annual rainfall, for 1958 and 1960. The average values of two sets of bone samples (New York and Boston; North America and western Europe) are plotted for comparison with the curves. The numbers associated with the points indicate the number of samples, and the length of the vertical line represents the standard error of the mean.

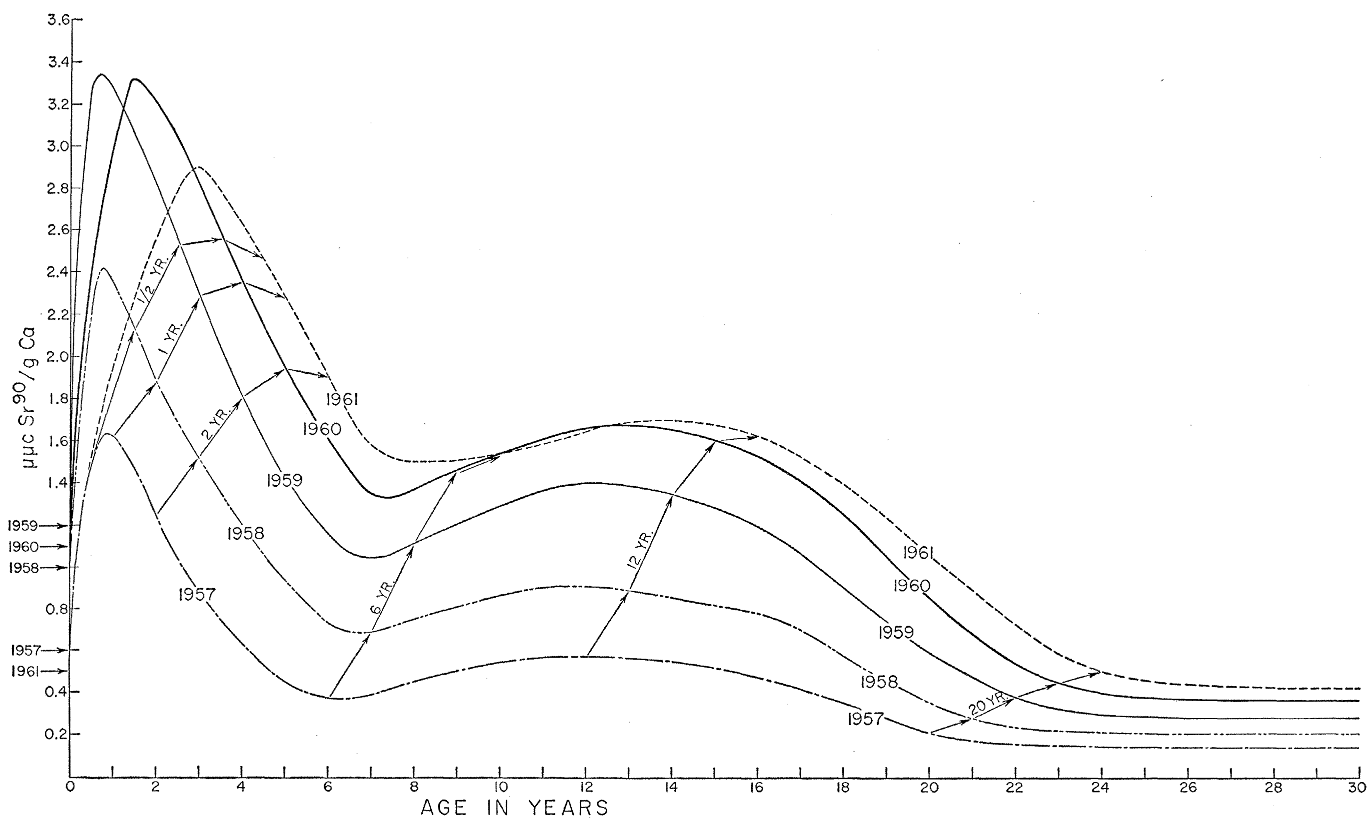

Fig. 6. Curves for calculated values for strontium-90 concentrations in bone for eastern North America for the period 1957–61. (The level part of the curves at the extreme right are based on observed concentrations in adult bones.)

less comprehensive sampling than that represented by the data in Table 5, but larger uncertainties in the diet levels in the early years of lower specific activity do not significantly affect the computations for the period 1958–61.

The ratio of $Sr^{90}{}_{diet}/Ca_{diet}$ to $Sr^{90}{}_{diet}/Ca_{milk}$ (here designated R) had been studied initially by Kulp and Slakter (*18*) for the United States, by Bryant *et al.* (*20*) for the United Kingdom, and by Bird and Mar (*29*) for Canada; these workers found a value in 1957–58 of about 1.2. Subsequent studies by the Health and Safety Laboratory, Consumers Union, and the U.S. Public Health Service (*7*) gave values ranging from 1.21 to 1.32 for various American cities. The most comprehensive study, by Consumers Union on eight cities, gave 1.21. In the United Kingdom the ratio R appears to be closer to 1.0 as a result of the addition of mineral calcium to the national diet (*30*). It is possible that R will vary as the relative contributions of direct absorption and soil uptake change, but by the summer of 1961 when these contributions had been greatly altered there was no evidence in New York or Chicago of any major change (*31*).

The discrimination factor against strontium in favor of calcium is about 4 for adults on average Western diets (*17, 20, 21*). This factor is probably independent of age except possibly in the case of children under 1 year. Bryant and Loutit (*24*) suggest that in the first year of life the discrimination factor may be as low as 2.5 to 2.0. Their suggestion is based on two arguments: (i) that determinations of common strontium in diet and bone show a discrimination factor of about 2.5, and (ii) that the best fit of their 1959 bone data requires a discrimination factor of less than 4 for the first 2 years. On examination neither argument appears conclusive. The determinations of common strontium in the diet were made in 1939. The sources of the foodstuffs in the diet in 1939 may have been very different from the sources of foodstuffs which produced the bones which were analyzed. Moreover, the bone samples used by Bryant and Loutit were largely from Wales, where the diet levels are much higher than in the eastern United States on which the comparative curve was calculated. If the average Welsh diet were used, the discrimination factor of 4 would appear more appropriate.

In Fig. 5 all of the measurements on samples from North America and western Europe north of latitude 30°N have been plotted for 1958 and 1960. The teen-age samples are corrected for bone type, since it is assumed that in the exchange process the relative rate of turnover of the different bones is the same in teen-agers as in adults. The major stations in North America are New York and Boston. The major stations in the rest of the world are London, Glasgow, and Bonn. In Fig. 5 the solid circles and squares represent the New York and Boston data only. These should give the best fit if the model is correct, since the model was based on the diet in eastern North America. The combined data from Europe and North America appear to fit equally well. The average diets of these sets of individuals must be similar, since the fetus levels agree, falling within about 20 percent of the mean, the level for Bonn being higher and that for the United Kingdom lower. The same relation appears to hold for the adults. The model appears to fit the data closely for the age period 0 to 4 years.

If the true discrimination factor, $(Sr/Ca)_{diet} \div Sr/Ca)_{bone}$, for the period 0 to 1 year were 2 instead of 4, the observed values for 1-year-olds would be close to 6 micromicrocuries of strontium-90 per gram of calcium, rather than 3.4 (Fig. 5). Furthermore, the peak would not shift to the right on decrease in the levels in diet, as it is observed to do from 1959–60 (see also Fig. 6), if the discrimination factor changed rapidly from 2 to 4 during the first 2 years of life. It is concluded that, on present evidence, the simple assumption of a constant discrimination factor from birth to adulthood adequately describes the data. If the discrimination factor is actually less than 4, then another factor, such as systematic variation in the diet, must be operative to compensate.

The data in Fig. 5 fall slightly above the curve in the range 5 to 7 years and slightly below in the range 10 to 15 years. Whether this may merely be due to errors in the assumed additions of calcium to the skeleton at each of these ages or whether it is due to some physiological phenomenon cannot be stated at this time. In view of the available number of samples, the standard error on the mean (shown by the vertical lines in Fig. 5), and the purpose of the analysis, the correlation is adequate. To study this model in greater detail it would be necessary to obtain about 100 samples in each age from a population whose diet had been adequately sampled over a number of years.

Rate Factor versus Cumulative Factor

In order to predict levels of strontium-90 in the world population for various intrusions of fission debris into the atmosphere, it is essential to know what proportion of the strontium-90 in the diet results, through direct absorption, from a given rate of fallout and what proportion results from a given cumulative deposit on the ground. The importance of the rate factor was first cogently set forth by Russell (*32*).

A number of lines of evidence supported the observation that direct absorption played an important role, but at the time of our last report (*4*), the only quantitative data were those of Burton, Milbourn, and Russell (*33*) on certain experimental fields in the United Kingdom. These data indicated that in 1958 the rate factor accounted for about 80 percent of the strontium-90 in the milk produced in England and Wales. In more recent studies, these workers (*30*) revised their estimate of the contribution of the rate factor in 1958–59 to 60 to 70 percent, and estimated that in 1960 it was only about 30 percent.

It was pointed out in the last report (*4*) that, in order to obtain a reasonably accurate definition of the relative importance of the rate and cumulative-fallout factors for the North American population, it would be necessary to observe the milk levels throughout North America for 1959 through 1960, when the rate of fallout was expected to drop by about a factor of 5 while the cumulative deposit was expected to remain nearly constant. The data for such a comparison are now available (Table 6).

For a given field, the relationship between the cumulative deposit of strontium-90, the rate of fallout during the growing period of the grass, and the ratio of strontium-90 to calcium in the milk that is produced is a very complex one. The ultimate concentration in the milk depends on the physical and chemical characteristics of the soil, the type of grass, the stage of growth, the precipitation pattern during the period of growth, the specific activity of strontium-90 in each rain, and the

Table 6. Data for calculating the contribution of the rate of fallout and the cumulative deposit to strontium-90 levels in milk in the United States and Canada.

Period	Sr^{90} concentrations		
	Milk* ($\mu\mu c$ Sr^{90}/g Ca)	Rain† (mc/mi²)	Earth's surface‡ (mc/mi²)
Mean annual rainfall, 40 to 60 inches			
Apr. to Oct. 1957	6.9	6.4	23
Apr. to Oct. 1958	11.3	8.1	38
Apr. to Oct. 1959	15.9	11.3	61
Apr. to Oct. 1960	9.9	2.5	65
Apr. to Oct. 1961	9.1	2.4	69
Mean annual rainfall, 30 to 40 inches			
Apr. to Oct. 1957	6.8	4.3	22
Apr. to Oct. 1958	9.7	10.3	37
Apr. to Oct. 1959	12.5	10.3	59
Apr. to Oct. 1960	8.6	2.3	62
Apr. to Oct. 1961	7.4	2.1	65

* Averages for the 6-month growing season 1 April to 1 October (see Table 5). † Totals for the 6-month growing season 1 April to 1 October. ‡ Averages for cumulative deposit on 1 July, the midpoint of the growing season.

cumulative deposit of strontium-90. The average for each of these factors, however, should be reasonably constant over large areas, such as the eastern United States and for sufficiently long periods of time. For such a situation the following relationship should hold:

$$Q_M = AX + BY$$

where Q_M is the average number of micromicrocuries of strontium-90 per gram of calcium in milk for a given large area of fairly uniform mean annual rainfall and average specific activity in rain during the growing season; X is the average rate of deposition of strontium-90 (in millicuries per square mile) per 6 months for a particular growing season; Y is the cumulative deposit of strontium-90 (in millicuries per square mile) measured at midpoint of the growing season; A is the number of micromicrocuries of strontium-90 per gram of calcium in milk, due to direct absorption, divided by the number of millicuries of strontium-90 deposited per square mile during the growing season; and B is the number of micromicrocuries of strontium-90 per gram of calcium in milk, due to the cumulative deposit, divided by the total millicuries of strontium-90 per square mile deposited to the midpoint of the growing season since the start of nuclear testing.

In order to compute the constants A and B, data from two rainfall zones in North America which contain the largest number of milk, soil, and rainfall stations were used. The zone of 40 to 60 inches of mean annual rainfall includes most of the eastern and southeastern United States and is roughly bounded on the west and north by the Mississippi, Ohio, and St. Lawrence rivers. It also includes a smaller area along the coast in the Pacific Northwest. The zone of 30 to 40 inches of mean annual rainfall is roughly bounded on the west and north by a line passing through Houston, Tulsa, Kansas City, Duluth, and Goose Bay, Labrador. Throughout these large areas, it is assumed, the effective growing season is the 6-month period from 1 April to 1 October. The data are assembled in Table 6. The levels in milk are taken from Table 5 which compiles all available analyses (*11*). The cumulative deposition for 1 July of each year is taken from Alexander's collection (*7*) for 1957, 1958, and 1959, with extrapolation to 1960 on the basis of known rainout. The average deposition each year from 1 April to 1 October was obtained by multiplying the average specific activity of rain for the latitude band 30° to 70°N (*5, 6*) by the average rainfall for the 6-month period.

The most accurate estimates of A and B can be made by solving the foregoing equation for 1959 and 1960, since the most drastic change in X and Y occurred in these two years. The results for the 40- to 60-inch zone are $A = .73 \pm .10$ and $B = 0.12 \pm 0.01$, results for the 30- to 40-inch zone are $A = .58 \pm .08$, $B = 0.12 \pm 0.01$. The constants $A = 0.65$ and $B = 0.12$ were then adopted, and the levels in milk for each year from 1957 through 1961 were calculated. The results are given in Table 7 and compared with the observed levels in milk. The error with respect to the observed levels is 5 to 10 percent. The error with respect to the predicted levels is 10 to 20 percent. It may be seen that calculations on the basis of these constants predict the levels in milk for 1957, 1958, and 1961 within the experimental uncertainties. The accuracy is limited largely by the error in the deposition rate. The number of rain stations is much smaller than the number of milk or soil stations in 1958–60. The data for 1957 is scarce.

The percentage of the strontium-90 in milk of these areas that is due to the rate of fallout (direct absorption) is also shown in Table 7. Thus, during the period 1957–59, with successive increases in the rate of deposition as well as in the cumulative deposit, the contributions from the rate and cumulative-deposit factors were roughly equal. Our earlier suggestion (*4*) that the rate factor was dominant during 1954–59 is therefore incorrect. Direct absorption may have been the dominant mechanism of the entry of strontium-90 into the food chain only in 1954–55. In 1960 the contribution of the rate factor (direct absorption) dropped to about 15 percent of the total. In 1961 the cumulative deposit increased about 5 percent and the rate of fallout was similar to that in 1960; hence the level of strontium-90 in milk should have increased by less than 5 percent. This would lie within present experimental and sampling errors.

If the average levels in milk and the average rates of deposition for the entire year instead of the 6-month growing period are used in the calculation, the results are not qualitatively different. By limiting the comparison to the growing period, the factors may be more closely controlled. During the fourth quarter of one year and the first quarter of the next year, the cows largely consume fodder produced in the preceding growing season. Thus, the levels in milk remain fairly constant for these quarters, whereas the fallout rate may change. The effect of undiminished or increased rates of fallout during the winter would primarily serve to increase the cumulative deposit for the next growing season.

Knapp (*34*) has also calculated the rate and cumulative coefficients. His method appears less reliable than that used above for three reasons: (i) Only a fraction of the available milk data were used, namely, those collected by the U.S. Public Health network (*9*); (ii) the milk, rainfall, and soil levels were not compared for regions of similar mean annual rainfall; and (iii) the coefficients were computed by comparing two arbitrarily chosen months, one in 1959 and one in 1960. If other months had been used, the results could have differed by a factor of two. The

Table 7. Contribution of the rate of fallout and the cumulative deposit to strontium-90 concentrations in milk in the United States and Canada (see text).

Year	Sr^{90} concentration in milk ($\mu\mu c$/g Ca)				
	AX	BY	Total	Observed	% Rate
Mean annual rainfall, 40 to 60 inches					
1957	4.0	2.8	7	7	59
1958	5.1	4.6	10	11	53
1959	7.4	7.3	15	16	50
1960	1.6	7.8	9	10	17
1961	1.5	8.3	10	9	15
Mean annual rainfall, 30 to 40 inches					
1957	2.7	2.6	5	7	52
1958	6.5	4.4	11	10	59
1959	6.5	7.1	14	13	48
1960	1.5	7.4	9	9	17
1961	1.4	7.8	9	7	15

Table 8. Concentrations of strontium-90 in the bones of young people of three age groups for the period 1955–60. The figures in parentheses are number of samples.

Locality	1955 6–24 mo	1955 0–4 years	1955 5–19 years	1956 6–24 mo	1956 0–4 years	1956 5–19 years	1957 6–24 mo	1957 0–4 years	1957 5–19 years	1958 6–24 mo	1958 0–4 years	1958 5–19 years	1959 6–24 mo	1959 0–4 years	1959 5–19 years	1960 6–24 mo	1960 0–4 years	1960 5–19 years	References
	Concentrations ($\mu\mu c$ Sr^{90}/g Ca)																		
North America																			
Anchorage														2.4 (1)	3.4 (1)			2.4 (1)	
Vancouver		0.4 (2)	<0.2 (7)		<0.5 (2)	<0.6 (6)		1.6 (2)	<0.7 (16)		1.8 (6)	<0.9 (22)			1.0 (6)				
Grand Forks											2.6 (1)								
Denver	0.6 (1)	0.4 (7)	<0.3 (7)		1.0 (1)	0.3 (2)	1.2 (2)	<0.7 (5)	<0.6 (16)			0.9 (1)		2.3 (5)	1.0 (8)		1.8 (2)	1.2 (3)	
Boston		<0.9 (2)			<0.7 (15)	<0.7 (11)	1.2 (2)	<1.0 (49)	<0.6 (42)	1.8 (1)	1.7 (9)	1.0 (32)							
New York/Boston																3.0 (19)	2.4 (64)	1.5 (74)	
New York		0.2 (1)	<0.9 (1)				1.7 (2)	<1.4 (16)	<0.6 (5)	2.3 (4)	2.1 (24)	0.9 (5)	3.7 (2)	2.7 (5)	1.1 (4)				
Galveston							2.4 (3)	2.0 (4)	0.4 (4)										
Houston	1.3 (2)	0.8 (7)	<0.6 (8)			<0.2 (1)				2.2 (2)	1.8 (4)	<1.0 (4)	3.2 (3)	2.2 (14)	<1.3 (5)			2.5 (2)	
Guatemala City								<0.3 (5)	<0.4 (9)		<0.6 (1)	<0.4 (3)		<0.6 (2)		<0.5 (2)	<0.6 (28)	<0.5 (10)	
San Juan, P.R.		<0.04 (1)	0.2 (1)		0.5 (1)			0.8 (7)	0.5 (10)	<1.2 (3)	<0.7 (34)	<0.9 (11)		2.1 (5)	<1.0 (24)	3.5 (5)	2.7 (10)	1.2 (17)	
Europe																			
Copenhagen		<0.3 (1)	0.4 (3)		0.8 (5)	<0.3 (7)		2.1 (5)	<0.5 (4)										
London	<0.1 (2)	0.9 (3)	<0.2 (7)	0.8 (3)	0.8 (5)	<0.2 (6)			0.8 (1)										
Bonn, Germany	<0.2 (3)	<0.4 (13)	<0.2 (19)	0.6 (4)	<0.4 (13)	<0.2 (14)	1.4 (13)	1.3 (16)	0.3 (4)	2.5 (10)	2.1 (18)	<0.6 (6)	2.2 (13)	2.0 (23)	<1.0 (15)	2.3 (5)	2.0 (15)	1.4 (20)	
Turin, Italy			<0.3 (6)			0.4 (2)			<0.4 (3)										
Zurich	0.8 (2)	0.6 (4)	0.4 (8)	1.1 (3)	<0.9 (9)	<0.6 (22)			0.3 (1)										
AERE, England							1.0 (8)	0.9 (90)	0.5 (21)	2.2 (6)	0.9 (154)	0.7 (25)	4.3 (25)	1.8 (162)	0.8 (44)				*(23, 35)*
Cambridge									0.8 (1)		1.0 (2)			1.1 (5)	0.2 (1)				*(23, 35)*
Glasgow													2.9 (19)	2.4 (101)	0.9 (8)				*(23, 35)*
Bonn, Germany										1.0 (7)	1.2 (18)	0.9 (5)	1.6 (19)	1.6 (38)	0.8 (18)				*(33)*
Asia																			
Tokyo					<0.8 (2)	<0.4 (4)			<0.6 (6)			0.7 (2)			0.6 (1)				
Chiba, Japan							<0.4 (2)	<0.4 (2)	0.6 (3)										
Jerusalem							1.4 (3)	1.4 (3)	0.5 (7)	1.3 (4)	<0.5 (10)	<0.2 (3)		0.4 (1)	0.5 (1)				
Taipeh, Taiwan		<0.8 (1)	<0.5 (3)					1.6 (13)	1.1 (2)		<0.7 (4)	<0.7 (4)			1.1 (1)				
Bombay State	<0.5 (1)	<0.5 (1)	<0.2 (5)			<0.1 (4)			<0.2 (54)			0.3 (2)							
Bangkok									0.3 (1)			0.4 (1)			0.4 (3)				
Saigon															1.0 (1)			0.3 (1)	
North Pacific																			
Manila									0.4 (2)										
South Pacific																			
Melbourne													1.5 (58)	0.9 (226)	0.6 (141)	1.1 (13)	0.6 (114)	0.5 (52)	
Sydney				0.8 (3)	0.8 (3)	0.6 (3)		0.5 (1)	0.5 (2)						<0.7 (1)				
Africa																			
Bunia, Congo												<0.4 (1)							
Leopoldville							<0.5 (1)	<0.6 (4)	1.2 (4)		1.2 (2)								
Capetown, S.A.						<0.1 (1)	0.8 (2)	<0.5 (6)	<0.3 (10)										
Durban, S.A.							0.8 (2)	0.7 (5)	<0.5 (14)			<0.9 (32)			<0.8 (78)	<0.9 (55)		<1.0 (73)	
South America																			
Caracas, Venez.	<0.4 (2)	<0.5 (10)	<0.3 (21)			<0.2 (3)	1.1 (18)	0.9 (18)	<0.4 (6)										
Recife, Brazil		<0.7 (1)	<0.3 (4)			0.1 (9)		<0.3 (1)	0.2 (4)	<0.8 (2)	<0.8 (3)	<0.4 (12)	<1.1 (12)	<1.0 (34)	<0.5 (17)	1.3 (10)	<1.1 (20)	<0.7 (6)	
Barranquilla, Col.			<0.1 (1)			<0.4 (1)			0.1 (2)			0.2 (2)						0.2 (2)	
Santiago, Chile		<0.8 (1)	<0.2 (18)	<0.1 (1)	<0.4 (5)	<0.2 (13)	<0.5 (9)	<0.6 (10)	<0.3 (37)	1.1 (2)	<0.6 (8)	<0.4 (10)	<0.8 (3)	<0.4 (21)	<0.4 (22)	<0.7 (5)	<0.4 (33)	<0.4 (25)	

concentration of strontium-90 in milk is highly variable over short time intervals or small geographical areas. To obtain the most meaningful average values for the coefficients it appears necessary to compare whole growing seasons over large sectors of a continent that have similar rainfall and, therefore, similar cumulative deposits and rates of fallout.

Time Effect

If the model is accepted, on the basis of the observed correlation in Fig. 5, it is readily possible to compute the age curves for all years. In Fig. 6 the curves for 1957 through 1961 are presented. From the known rates of fallout and the cumulative deposit in soil, it is possible to estimate the levels in diet, and hence in bone, for 1961 fairly closely. The large addition of debris from the September–November 1961 tests of the U.S.S.R. will not significantly affect the 1961 levels in diet, since the tests occurred after the growing season and most of the debris will fall in 1962. Note in Fig. 6 that with successive decreases in levels in diet from 1959 to 1961, the peak in the age curve moves to the right, and that after 1960 the curve begins to drop rapidly toward an equilibrium level determined by the cumulative deposit of strontium-90 in the soil. The arrow patterns show the loci for the skeletons of individuals ½ year, 1 year, 2 years, 6 years, 12 years, or 20 years of age in 1957. Had no further tests occurred after 1958, the concentration of strontium-90 in the diet of the population of the eastern United States would have leveled off at 6 to 8 micromicrocouries of strontium-90 per gram of calcium; hence, levels for all these individuals would tend to approach 1.5 to 2.0 micromicrocuries in time. Thus, the great gap between levels in adults and in 1-year-olds which was maintained during the period of increasing levels in diet will rapidly close if the levels in diet are stabilized.

All of the bone data for young people are summarized by year in Table 8, in three age groups, 6 to 24 months, 0 to 4 years, and 5 to 19 years. The first group showed the highest concentrations until 1959. The 0- to 4-year group is a useful reference, as samples have been grouped in this way by other workers. The model age curves show that the concentration of strontium-90 in bone is reasonably uniform in the age group 5 to 19 years (namely, $\pm$ 20 percent). By taking a fairly large age range it is possible to obtain enough samples for useful comparison. In Table 8 the symbol $<$ means that at least one sample was reported to have "less than" a stipulated value. Thus, these averages represent maximum values. From 1958 on, these maximum values will be close to the true values.

If data from the stations with a significant number of samples are compared, a number of useful observations may be made. Data from all stations show an increase for the youngest age group through 1959, with a decline in 1960. In the older group (5 to 19 years) the specific activity increased in 1960 over the 1959 level, as had been expected from the model. By comparing data for different years it may be seen that in North America the following stations appear to have similar levels: New York, Boston, Houston, Denver, Vancouver, and San Juan. The level for the latter is higher than would be expected from the total fallout, but again this is due to a lower proportion of milk in the total diet which raises the concentration of strontium-90 in the average diet. Similar levels are observed in Bonn, London, Glasgow, and Zurich and in Jerusalem, Tokyo, and Taipeh. Stations nearer the equator, or in the Southern Hemisphere, which have enough samples to permit comparison include Durban, Capetown, Bombay, Bangkok, Guatemala City, Recife, Santiago, Caracas, and Melbourne. Levels for these stations range from one-third to two-thirds of those for the eastern United States and Western Europe. In each of these cases the ratio of the concentration of strontium-90 in the average skeleton from the city in question to the concentration in skeletons from the eastern United States is higher than the ratio of cumulative fallout in the two areas.

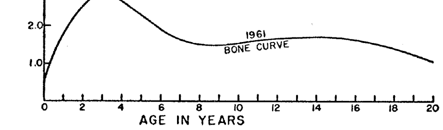

Fig. 7. Loci for predicted strontium-90 concentrations in the bones of a child who was 3 years old in 1961, based on (i) the probable input from the Soviet tests in the autumn of 1961 (2.5 Mc of Sr^{90}), and (ii) the assumption of continued testing of magnitude such that 1.0 megacuries of strontium-90 fall on the Northern Hemisphere each year after 1961.

Future Levels

Determination of the constants for the contribution of the rate (direct absorption) and cumulative (soil uptake) factors to the strontium-90 in milk makes it possible to predict the specific activity in future diets, and thus in newly forming bone, provided the rate of fallout and the cumulative deposit can be specified. The average level in milk for the growing period is first calculated from the equation given earlier. It is then assumed that this level holds from 1 April of the year in question to 1 March of the following year. This concentration is multiplied by 1.2 to obtain the estimated strontium-90 concentration, in micromicrocuries of strontium-90 per gram of calcium, in the average total diet. Dividing this value by 4 gives the specific activity of strontium-90 in newly forming bone.

Two extreme cases may be readily visualized:

1) After an injection into the lower stratosphere of the polar regions that will ultimately deposit N millicuries of strontium-90 per square mile over the area of interest, the rate of fallout will decrease by a factor of 4 or 5 over the first 2 years, and then by about a factor of 2 each year thereafter (*5*). Thus, after about 5 years the total fallout during the growing season would be less than 1 percent of the cumulative deposit (in millicuries per square mile), and hence would contribute no more than 5 percent to the levels in milk. In this case the equilibrium level in milk (in micromicrocouries of strontium-90 per gram of calcium) is readily estimated to be 0.12 N; in total diet, 0.14 N; and in newly forming bone, 0.035 N.

2) For the first growing season after an injection of N millicuries per square mile (ultimate deposition) into the lower polar stratosphere in the preceding fall, the level in milk (Q_M) would be approximately 0.65 $(0.5N) + 0.12\ (0.6N) \cong 0.4N$.

In the fall of 1958 the Soviet testing introduced about 1.3 megacuries of strontium-90 into the Northern Hemisphere. In the 40- to 60-inch rainfall zone of the eastern United States this produced fallout of 14 mc/mi² from 1 April to 1 October 1959 and a total deposition to 1 July of about 16 mc/mi.² In the recent Soviet series of September–October 1961, it is estimated, 2.5 megacuries of strontium-90 were introduced. Under this assumption, the level of strontium-90 in milk in mid-1962 will be about 25 micromicrocuries per gram of calcium if the rate of transfer of the debris from the 1961 tests is as rapid as the transfer of debris from the 1958 Soviet tests. After a few years the level in milk would drop to about 13 micromicrocuries.

In Fig. 7 the locus of the concentration of strontium-90 in the bones of a child who was 3 years old in 1961 is shown, under two assumptions: (i) that no further atmospheric intrusions occur after 1961, and (ii) that events occur that will add 1.0 megacuries to the stratosphere in the northern polar or temperate zone each year. The curves are projected to 1970. It should be noted that although in 1961 bone levels were maximal in 3-year-olds, the large input in 1961 will cause the peak in 1962–63 to occur in 1-year-olds, at a concentration of about 4.3 micromicrocuries of strontium-90 per gram of calcium. Subsequently, the peak will decrease and will occur in children of the next higher age each year until it approaches the equilibrium level of about 3.5 micromicrocuries per gram after 4 to 5 years.

Since it appears probable that less than 10 percent of this debris will be deposited in the Southern Hemisphere (*5*), the bone levels there probably will increase by less than 20 percent of that which existed in 1960–61.

Table 9. Strontium-90 concentrations and radiation doses in the 40- to 60-inch rainfall belt in latitudes 30° to 70°N for a nuclear war of 3000 megatons (fission) in areas distant from the sites of detonation (see text).

Period (yr)	Sr^{90} concentrations ($\mu\mu c$/g Ca)			Radiation dose in bone (mr/yr)			
	Average diet	Skeleton		Sr^{90}		Natural background	External γ fission products
		1-yr-old	Adult	1-yr-old	Adult		
			Case 1				
½ to 1½	3000	600	20	1800	60	100	6000
4 to 5	900	180	43	540	129	100	300
35	450	90	~100	270	300	100	75
			Case 2				
½ to 1½	600	120	5	360	15	100	1200
4 to 5	180	36	7.5	108	22	100	60
35	90	18	~20	54	60	100	15

A 3000-Megaton War

In order to illustrate the use of the above relationships in predicting the situation that would develop in the event of a nuclear disaster, a war involving the production of 3000 megatons of fission is assumed. This amount of fission could be produced by 1000 bombs centered on 300 target points, each bomb averaging 6 megatons of total energy and 3 megatons of fission. If all these bombs were exploded in the 30° to 70° north latitude zone at sufficiently high altitudes so that no significant local fallout occurred, the total amount of strontium-90 introduced into the northern stratosphere would be about 300 megacuries (case 1). If all of the bombs were detonated at the surface, the immediate stratospheric burden would probably be about 60 megacuries (case 2).

With the rate and cumulative-deposit factors calculated above, the average strontium-90 concentration in the diet can be calculated for the first year after the event; for the fifth year, when the concentration in diet would be determined almost entirely by the cumulative deposit; and for the 35th year, after the short-lived activities had become negligible. From these dietary levels, the approximate strontium-90 concentration in the skeletons of 1-year-olds and adults can be calculated. These results are given in Table 9. In addition, the doses in bone from strontium-90 are compared with the natural background radiation at sea level and the dose from external gamma-emitting fission products, on the basis of work of Gustafson (*35*). It may be observed that during the first year after the event, the gamma flux from the shorter-lived isotopes dominates the total dose to the bone but that strontium-90 is the primary source of activity thereafter.

This calculation gives the result if no preventive measures are taken. With proper measures it should be possible to reduce the specific activity of strontium-90 in the diet and the external gamma dose by one or two orders of magnitude. Monitoring foodstuffs for strontium-90 would be best accomplished by measuring the cesium-137 content (*8*).

The conditions described in Table 9 would apply throughout the Northern Hemisphere at latitudes from 30° to 70°N, in areas away from the sites of detonation for areas of 40–60 inches mean annual rainfall. The fallout would probably drop by about a factor of 2 with each 10° band of latitude to the 10° to 20°S zone, for areas of equivalent rainfall. Fallout might then remain nearly constant from 20° to 50°S as a result of some drip from the stratosphere into the troposphere of the Southern Hemisphere. The levels in bone in the 20° to 50°S zone would probably be less than 1/10 those in the Northern Hemisphere.

In an actual 3000-megaton war the world-wide situation would lie between case 1 and case 2 (Table 9). Kahn (*36*) has imagined a war that involves 40,000 megatons of fission. This would increase all of the long-term values in Table 9 by a factor of 13.

Nuclear war at the 40,000-megaton level would clearly have the most serious consequences for all mankind. It appears, however, that even under these extreme conditions survival from lethal radiation damage would be entirely possible away from areas of local fallout if sufficient technological planning and effort were applied to the problem. The social and economic dislocations would in all probability overshadow fallout as man's most pressing problem at that time.

Summary and Conclusions

1) It is now possible to predict the strontium-90 concentration in the world population for specified modes of atmospheric contamination with moderate reliability. For example, the average adult bone level in the eastern United States 5 years after the detonation of a specified quantity of fission products into the lower polar stratosphere can probably be estimated to better than ± 50 percent.

2) The concentration of strontium-90 in fetuses reached a maximum of 1.2 micromicrocuries of strontium-90 per gram of calcium in eastern North America and began to decrease significantly in 1960 and 1961. The ratio of the strontium-90 level in the fetus to the level in the average diet of the adult is about 0.08.

3) The average rate of turnover of strontium and calcium in the adult

skeleton appears to be about 2.5 percent per year, although there is considerable difference among the various bones of the body.

4) The standard deviation for strontium-90 concentration in a population of urban adults appears to be about 40 percent of the mean. The distribution curve for an interval of from 60 to 0.1 percent of the population may be approximated by the log-normal function. In urban populations of Western culture the concentration for 5 percent of the population will exceed twice the mean, that for 0.1 percent will exceed four times the mean.

5) Cities in the Southern Hemisphere showed levels in bone about half those for cities of Western culture in the Northern Hemisphere in 1960, yet the fallout in the Southern Hemisphere is only one-fourth that in the Northern Hemisphere. This is attributed to differences in diet, with a higher milk component in the Northern Hemisphere.

6) A simple model for the strontium-90 concentration in the bones of young people as a function of their age appears to fit the experimental data.

7) The coefficients of the equation describing the relative contributions of the rate of fallout (direct absorption) and the cumulative deposit (soil uptake) to the strontium-90 concentration in milk have been calculated from the observed data for 1959 and 1960. They are as follows: rate factor $A = 0.65$ micromicrocurie of strontium-90 per gram of calcium in milk per millicurie of strontium-90 per square mile during the growing season; cumulative-deposit factor $B = 0.12$ micromicrocurie of strontium-90 per gram of calcium in milk per millicurie of strontium-90 per square mile at the midpoint of the growing season. The predicted levels in milk for 1958 obtained with these coefficients are in excellent agreement with the observed levels. In 1958 and 1959 about half the strontium-90 in milk was attributable to the rate factor, whereas in 1960 the contribution of the rate factor dropped to about 15 percent.

8) Future levels of strontium-90 in man are given (i) for the next decade as a result of the nuclear tests through 1961 and (ii) under the assumption that 1.0 megacurie of strontium-90 is added to the stratosphere of the Northern Hemisphere each year.

9) The radiation doses to the skeleton to be expected from world-wide fallout on the basis of a 3000-megaton (fission yield) war are also given.

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