Biological Availability of Strontium-90 from Atomic Tests

From 50 to 100 percent is available to the biosphere, depending on the immediate environment of the bomb.

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Strontium-90, produced by nuclear explosions, has received considerable attention as a potential hazard to human life. The suggestion has been made by W. F. Libby that this hazard might be reduced if nuclear explosions were conducted in a manner such that strontium-90 is incorporated in insoluble particles and is thus made unavailable to living organisms. Such incorporation would have to take place in the bomb cloud during the time required for condensation and solidification of the volatilized material. Since krypton-90, a gaseous predecessor of strontium-90, decays with a half-life of 33 seconds, the relevant time scale for condensation includes the first several minutes following detonation. Very little is known about physical conditions in a bomb cloud during this period. However, visual observations indicate that condensation of the main body of the debris occurs during the first minute, even for megaton explosions.

The experiments described here provide data concerning the solubility and biological availability of strontium-90 in samples collected from the airborne debris from devices which were exploded in a number of different environments. The experiments were designed not only to provide information on the incorporation of strontium-90 in relation to device yield and matrix material but also to establish a simple test for strontium-90 availability, as a parallel to the classical ammonium acetate method for determination of the exchangeable calcium content of soil (*1*).

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The methods employed for collection and preparation of the debris samples were such that alteration of the particles was kept to a minimum. Samples were collected by airplanes from atomic-test clouds on dibutylphthalate-impregnated cellulose filter panels. The portion of the panel selected as a sample was treated with ether to remove the dibutylphthalate, and the cellulose was then destroyed with atomic oxygen at a low temperature (100° to 150°C). The residual material was suspended in water, 1*F* HCl, or isopropyl alcohol, as desired.

Aliquots were removed from the water suspensions at approximately 7 days and again at 400 days after preparation. These aliquots were filtered with type VF Millipore filters (*2*), and the retained material was treated with 1*F* HCl for a period of 48 hours. The acid suspension was then filtered with a type VF filter, and the three fractions—water, 1*F* HCl, and insoluble residue—were analyzed for strontium-90 (*3*). Samples which were originally suspended in 1*F* HCl were treated similarly; however, only two fractions (1*F* HCl and insoluble residue) were obtained.

Barley plants were grown in soil samples in which were incorporated the water-insoluble fractions from portions of the various water suspensions of bomb debris. The portion of the suspension selected for each growth experiment was centrifuged, and the supernatant liquid was filtered with a type VF filter. The insoluble residue from the centrifugation and filtration was washed and incorporated in a 317-gram portion of soil. After removal of about 10 grams of soil for strontium-90 analysis, one crop was grown in each of three 100-gram portions of each soil sample. The method for growth of the plants was essentially that of McGeorge (*4*), with 0.05 gram of $NH_4H_2PO_4$ and 0.05 gram of KNO_3 added as fertilizer for each crop. The seedlings were cut off 0.25 inch above the soil at the end of 17 days. Only the tops were analyzed for strontium-90 because of the difficulty of removing the soil from the roots. The calcium contents of the plants, roots, seeds, and soil and the strontium-90 contents of the plants and soil samples were determined (*5*).

Data from the experiments on assimilation of strontium-90 from the soil samples are presented in Table 1. Included are a sample of carrier-free strontium-90 and a sample consisting of the water-soluble fraction from a debris sample. The values of exchangeable and total calcium in the soil are 0.816 milligram and 2.0 milligrams of calcium per gram of soil, respectively. The 100 seeds from which each crop was grown contained, on the average, 1.6 milligram of calcium. The roots, which were not included in the crop, contained about 30 percent of the total calcium in the plants. We estimate that an average of 1.0 milligram of the calcium in each crop originated in the seed.

Data from the experiments on solubility of strontium-90 in debris samples are presented in Table 2. For samples 1 through 10 the data are given as the fraction of the total strontium-90 in each sample which is soluble in water, insoluble in water but soluble in 1*F* HCl, or insoluble in 1*F* HCl. For samples 11 through 13 the data are given as the fraction of the total strontium-90 which is soluble in 1*F* HCl or insoluble in 1*F* HCl.

The "biological availability" of the strontium-90 in a sample is obtained from assimilation data. The method of calculation is indicated in the two following definitions.

Relative uptake of strontium-90 from a sample equals

$$\left(\frac{\mathrm{Sr}^{90}\text{ in crop}}{\mathrm{Sr}^{90}\text{ in soil}}\right) \div \left(\frac{\text{Ca in crop} - \text{Ca from seed}}{\text{exchangeable Ca in soil}}\right)$$

Biological availability of strontium-90 in a sample equals the ratio: relative uptake of strontium-90 from a sample

Table 1. Assimilation of strontium-90 by barley plants from soil containing debris from atomic tests. Samples 1 through 10 contain the water-insoluble fractions of debris from atomic tests Nos. 1 through 10, respectively; sample 60 contains the water-soluable fraction of debris from test 6; and sample 0 contains carrier-free strontium-90.

Soil sample No.	Duration of water leach (days)	Crop No.	Sr^{90} In crop (count/min)	Sr^{90} In soil (count/min gm)	Ca in crop
0		1	5788	2950	3.08
		2	4868		2.18
		3	7735		3.37
1	170	1	319	256	2.98
		2	298		2.87
		3	298		3.11
2	170	1	500	420	3.45
		2	649		3.75
		3	361		3.75
3	200	1	183	591	4.48
		2	119		3.40
		3	129		3.40
4	140	1	286	167	3.28
		2	278		3.41
		3	379		4.77
5	180	1	35	11.2	3.85
		2	33		3.82
		3	20		2.92
6	130	1	20.4	15.1	2.32
		2	23.7		3.80
		3	22.7		3.04
7	200	1	143	262	2.03
		2	288		3.75
		3	311		3.95
8	120	1	242	624	3.93
		2	142		2.98
		3	137		3.11
9	200	1	1063	259	4.41
		2	1085		5.25
		3	936		3.85
10	160	1	91	31.7	3.89
		2	90		4.50
		3	68		3.58
60	130	1	2451	649	4.46
		2	2376		4.26
		3	1667		3.08

Table 2. Solubility of strontium-90 in bomb debris from atomic tests.

Atomic test and sample No.	Time elapsed from shot to collection (hr)	Sr^{90} distribution*			Duration of exposure	
		Water	$1F$ HCl	Residue	Water (days)	Acid (days)
1	1.3	0.45	0.26	0.29	7	2
		0.64	0.25	0.11	420	2
2	1.5	0.58	0.24	0.18	7	2
		0.63	0.19	0.18	420	2
3	4.3	0.49	0.069	0.44	7	2
		0.64	0.014	0.35	450	2
4	2.1	0.91	0.072	0.018	8	2
		0.91	0.070	0.024	390	2
5	1.7	0.95	0.020	0.030	7	2
		0.98	0.009	0.010	420	2
6	1.8	0.49	0.47	0.036	7	2.5
		0.98	0.016	0.007	390	2
7	2.1	0.65	0.17	0.18	7	2
		0.76	0.053	0.19	445	2
8	3.1	0.30	0.11	0.59	8	2
		0.44	0.077	0.48	390	2
9	2.8	0.36	0.64	0.005	7	2
		0.44	0.55	0.012	450	2
10	3.9	0.92	0.071	0.006	11	2
		0.97	0.024	0.009	410	2
11–1	6		0.98_2	0.018	0	6
11–2	9		0.99_5	0.005	0	7
11–3	12		0.98_0	0.020	0	23
11–4	28		0.98_4	0.016	0	6
12–1	6		0.98_2	0.018	0	4
12–2	9		0.99_4	0.006	0	4
12–3	26		0.98_8	0.012	0	5
13–1	6.5		0.99_5	0.005	0	8
13–2	8		0.99_3	0.007	0	8
13–3	11		0.99_6	0.004	0	7
13–4	28		0.98_8	0.012	0	10
13–5	28		0.97_9	0.021	0	10

* See text.

to relative uptake of strontium-90 from carrier-free strontium-90.

The "acid solubility of strontium-90 in a sample is equal to the fraction of the strontium-90 which is soluble in $1F$ HCl. It is assumed that strontium-90 that is soluble in water is also soluble in $1F$ HCl.

The values of biological availability and acid solubility for a number of debris samples as calculated from the data in Tables 1 and 2 are presented in Table 3. It is important to note that the first ten of these samples are the water-insoluble residues from the debris samples and that the 11th is the water-soluble fraction of a debris sample. The values given for acid solubility were obtained by linear interpolation of the 7-day and 400-day data in Table 4 to obtain the value at the time the soil samples were prepared. The correlation factor between acid solubility and biological availability is 0.87.

A résumé of matrix, yield, and acid solubility information for gross debris samples from the 13 atomic tests is presented in Table 4.

The correlation factor of 0.87 shows that measurement of acid solubility is a suitable substitute for measurement of biological availability. Such a test can serve as a measure of the immediate availability of strontium-90 but not necessarily as a measure of the long-term availability. The need for this precautionary note is indicated by the solubility data for atomic tests number 1, 3, and 8, which demonstrate that a long-term dissolving process can occur in addition to a rapid dissolving process.

Availability of Strontium-90 in Bomb Debris

Any completely successful attempt to reduce the biological availability of strontium-90 by incorporation of the strontium-90 in particles must meet certain requirements. These requirements are: (i) incorporation only in particles which are able to resist prolonged exposure to the weathering of soil and water; (ii) incorporation in particles which are large enough so that strontium-90 does not diffuse appreciably from the particles in 28 years; (iii) a temperature-time history for the condensation of the matrix which would allow incorporation of strontium-90 formed by decay of the noncondensable krypton-90 of 33-second half-life. The extent to which these requirements are met determines the extent to which the availability of

Table 3. Comparison of acid solubility with biological availability.

Sample No.	Water-insoluble fraction	
	Acid solubility	Biological availability
1	0.55	0.52
2	0.55	0.40
3	0.093	0.076
4	0.78	0.59
5	0.42	0.88
6	0.83	0.67
7	0.37	0.39
8	0.15	0.10
9	0.99	1.00
10	0.85	0.76
60*	(1.00)*	(1.00)*

* In order to demonstrate that water-soluble strontium-90 leached from bomb debris is completely available, the water-soluble fraction of debris from atomic test No. 6 was fed to plants. The sample is labeled 60.

strontium-90 is reduced. Complete failure for any one requirement presumably results in complete failure in the solubility reduction.

The debris from atomic test shots fired on iron towers in Nevada is apparently mostly magnetite. This is indicated by a typical red-brown color and by magnetic properties of the debris. Magnetic probes collected 85 and 50 percent of the fission-product activity from isopropyl alcohol suspensions of debris from tests 1 and 3. Less than 10 percent of the activity could be collected from debris from shots which were not fired on iron towers, with the exception of test 8, where 40 percent of the activity was collectible on a magnetic probe. Typical debris from shots fired in Nevada on balloons is composed of a mixture of black and light-yellow particles. Shots fired at the Pacific Proving Ground produce fluffy conglomerates of calcium carbonate or crystalline particles of sodium chloride from coral or sea water, respectively. It is interesting to note, for the Nevada shots, that the water solubility of fission products as a whole is generally considerably smaller than the water solubility of strontium-90. Typical values of solubility of fission-product activities are 13, 16, and 10 percent for tests 1, 3, and 7, respectively.

The existence of a substance such as magnetite or glass in widespread mineral deposits would seem to be evidence of its ability to resist prolonged exposure to the weathering of soil and water. The rate of dissolution of magnetite in water is not known, and the only evidence for the slowness of this rate is obtained from the 400-day water-leach experiments reported in Table 2. On the other hand, the etching of glass takes place in water in periods that are short by comparison with 28 years (*6*). In any consideration of weathering the particle size or surface-to-volume ratio is important. Thus, in concluding that etching in water is important for glass, we consider particles with a diameter of the order of 10^{-4} centimeter.

A second mechanism for loss of strontium-90 from particles consists of diffusion of the strontium-90 atoms to the particle surface followed by exchange of the strontium-90 with ions in the surrounding medium. In the absence of some extremely stable form for the incorporated strontium-90, the surface strontium-90 atoms will exchange rapidly by comparison with the 28-year half-life of strontium-90. On the other hand, diffusion of strontium-90 atoms from sites in the interior to sites on the surface will require a much longer time. The diffusion coefficient for strontium in magnetite is estimated to be 10^{-23} to 10^{-31} square centimeter per second. The corresponding diffusion rate is insignificant for a diffusion period of 28 years and a particle size of 10^{-5} centimeter. About 6 percent of the volume of a particle of 10^{-5}-centimeter diameter lies within 10^{-7} centimeter of the surface, and strontium atoms contained therein may be exchangeable.

The major fraction of the strontium-90 in fission products is formed by decay of krypton-90 to rubidium-90, followed by decay of rubidium-90 to strontium-90. Krypton is not incorporable in condensing material. The fraction of the mass-90 chain (Kr^{90}-Rb^{90}-Sr^{90}) present as krypton-90 in uranium-235 fission products is 0.6 at 9 seconds, 0.5 at 20 seconds, 0.2 at 1 minute, and 0.05 at 2 minutes (*7*). If the rubidium-90 can be incorporated in condensing material and if the fireball stays hot for about 2 minutes, then about 95 percent of the mass-90 chain —and, therefore, of the strontium-90— can be incorporated.

The solubilities of strontium-90 in debris samples from iron-tower shots

Table 4. Location, matrix, yield, and acid solubility of strontium-90 for atomic tests.

Atomic test No.	Location*	Matrix material	Energy released (kilotons)	Acid solubility of Sr^{90} in gross debris samples	
				7 days	400 days
1	Tower, NTS	Lead Iron Concrete Paraffin	~10	0.71	0.89
2	Tower, NTS	Iron Silica Concrete	~10	0.82	0.82
3	Tower, NTS	Iron Magnetite concrete Concrete	~50	0.56	0.65
4	Balloon, NTS	Aluminum and miscellaneous Lead Feldspar	~5	0.98	0.98
5	Balloon, NTS	Aluminum and miscellaneous Lead Feldspar	~10	0.97	0.99
6	Balloon, NTS	Aluminum and miscellaneous Lead Glass	~10	0.96	0.99
7	Balloon, NTS	Aluminum and miscellaneous Lead Glass	~50	0.82	0.81
8	Air burst, NTS	Iron Aluminum	~50	0.41	0.52
9	PPG	Steel Concrete Coral island	>1000	1.00	0.99
10	PPG	Steel Coral Sea water	>1000	0.99	0.99
11	PPG	Steel Silica Sea water	>1000	0.99	
12	PPG	Steel Sea water	>1000	0.99	
13	PPG	Steel Concrete Water Coral island	>1000	0.99	

* NTS, Nevada Test Site; PPG, Pacific Proving Ground. A typical tower contained about 100 tons of material. A typical balloon contained a few tons of material. The air burst involved less material than the balloon.

in Nevada range from 0.56 to 0.89; the shot of highest yield produced the debris with the lowest solubility. The solubilities of strontium-90 in debris from balloon and air shots in Nevada range from 0.41 to 0.99; the shot of highest yield produced the debris with the lowest solubility. The strontium-90 in debris from Pacific shots is uniformly acid-soluble.

These observations indicate that all three requirements have been partially fulfilled for Nevada shots but that at least one of the requirements has not been met at all for Pacific Proving Ground shots. The temperature-time requirement should be most nearly fulfilled for tests in which the energy release is very large and the heat capacity of the debris is relatively small. The heat capacity of the debris is not relatively small for most Pacific shots. The uniform solubility of debris from these shots can be attributed to dilution of the fireball by large quantities of coral or sea water. This dilution has two effects. It cools the fireball rapidly and provides soluble particulate matter as a matrix (calcium carbonate, calcium oxide, sodium chloride—all soluble in 1*F* HCl). Unfortunately, no debris samples were available from megaton air bursts, in which both of these effects would be absent.

The most encouraging data come from test number 8, an air burst with a matrix of aluminum and iron. The solubility of the strontium-90 in debris from this test was only 0.52 after exposure to water for more than a year. Although temperature-time histories of fireballs formed by atomic explosions of this magnitude are not known, a condensation time of 20 to 30 seconds is a reasonable assumption. The 0.52 solubility of the strontium-90 observed for test number 8 is consistent with complete incorporation of the rubidium-90 and strontium-90 present in the fireball 20 seconds after the explosion. The data from test number 8 indicate that a small amount of material can incorporate strontium-90 in an insoluble form, provided that the fireball stays hot long enough for the krypton-90 to decay. The data from the Nevada tower shots indicate that the use of much larger quantities of material does not reduce the solubility.

It is reasonable to assume that the important requirements for incorporation of strontium-90 are that the greater part of the condensable material in the fireball be capable of forming insoluble particles and that the condensation of this material take place as long as possible after the explosion, to allow for decay of krypton-90. On this basis it is conceivable that a megaton burst at an altitude of several miles, involving several tons of aluminum or iron, would produce debris in which 80 percent or more of the strontium-90 would be insoluble. However, the likelihood of such an outcome should be regarded as a hypothetical possibility rather than as a distinct probability.

A megaton burst at ground level on a thick layer of magnetite should produce debris with a solubility equal to or less than the 0.65 solubility observed for test number 3. Such a ground-level environment would involve the disadvantage of a short condensation time, due to the heat capacity of the material engulfed by the fireball, and the possible advantage of increased local fallout as opposed to world-wide fallout. The choice of air versus surface environment would presumably be influenced by the amount of soluble strontium-90 which each would supply to the biosphere.

References and Notes

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Personality Attributes of Gifted College Students

Gifted students are less authoritarian and show more esthetic and intellectual interest than other students.

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Education at all levels has been permeated in recent years with a tremendous concern for the adequate development of superior and gifted students. Most of the attention and effort has been directed toward identifying such students and devising educational processes suited specifically to their needs. Relatively few attempts have been made to re-examine personality attributes of such individuals with the improved assessment devices of the post-World War II period. This study (*1*) represents an appraisal of some major behavioral characteristics, as measured by objective personality inventories, of a large number of post-adolescent youth of exceptional mental ability.

Early studies of intellectually gifted children were undertaken, at least in part, to examine the notion then commonly held that extraordinary mental proficiency is usually accompanied by physical frailty, early and drastic decline of abilities, insanity, or other compensating deficiencies. These misconceptions were readily refuted by the work of Terman (*2*) and Hollingworth (*3*). But early success in establishing that certain traits are not characteristic of the gifted has not been followed by much success in determining what is consistently characteristic of the gifted, other than exceptional intellectual ability.

The term *gifted* is often used to

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