UNCLASSIFIED

407821

Reprints of Papers Presented at the

First National Symposium on Radioecology by the Staff of the Laboratory of Radiation Biology

University of Washington

Radionuclides in Plankton and Tuna from the Central Pacific.

Radioactivity of Marine Organisms from Guam, Palau and the Gulf of Siam.

Qualitative Distribution of Radionuclides at Rongelap Atoll.

Increase in Radioresistance of Fish to Lethal Doses with Advancing Embryonic Development.

Factors Controlling the Distribution of the Rare Earths in the Environment and in Living Organisms.

Iron and Cobalt in Ecology.

Some Aspects of the Biology of Zirconium.

BEST COPY AVAILABLE

HISTORIAN'S OFFICE
INVENTORY CONTROL
Job 1320
Box 9
Folder 45

U.S. DOE ARCHIVES
RG
Collection 1320
Box 9
Folder 45

Reprinted from *Radioecology*, edited by Schultz and Klement, Reinhold Publishing Corporation and the American Institute of Biological Sciences, New York, 1963.

isms do not discriminate between different isotopes of a given element; thus, if the introduced radionuclide has the same chemical and physical form as the corresponding stable element, the two are taken up according to their ratio of abundance. However, radioisotopes do differ from their stable counterparts in that they are subject to radioactive decay. If the biological half-lives of a given element, in several organisms comprising a food chain, are not taken into account, erroneous interpretations may be made, especially if the radioisotope has a relatively short physical half-life. These errors may be corrected if the average ratio of radioactive to stable isotope of an element is determined for each level within the food chain.

The principal factors which control the uptake and retention of radionuclides by marine organisms are: (1) the amount of radionuclide introduced into the sea, (2) the site of introduction into the sea in relation to position and depth, (3) the degree of physical dispersion by currents and gravity, (4) the chemical and physical characteristics of the radioelement, (5) the chemical and physical forms of non-radioactive materials associated with the radionuclide, (6) the degree of isotope dilution of the radioelement by the corresponding stable element (or chemically similar elements) in sea water, (7) the degree to which the radionuclide is adsorbed to the organisms, (8) the degree of selective uptake, and (9) the biological half-life of the element in the organisms.

Fallout areas near the sites of nuclear weapons tests are of value for investigations of the fate of radionuclides in the marine environment in that large amounts of radiomaterials may be introduced into a given area in a short time and at adequate levels to be detected for a relatively long time following contamination. Because the fallout is usually deposited over large areas, most of the animals collected over a period of time in the area may be considered to have been exposed to a chronic rather than to an acute exposure of radioactive materials.

[1]Present address, Puerto Rico Nuclear Center, Mayaguez, Puerto Rico.

were counted for total beta radioactivity and selected samples were subjected to radiochemical separation and analysis. These techniques and methods have been described elsewhere (Donaldson et al., 1956; Kawabata and Held, 1959; Lowman, 1958; Lowman et al., 1957; Palumbo and Lowman, 1958).

RESULTS

In the present paper the ratios of total radioactivity and the percentage of total radioactivity contributed by individual radionuclides are considered with respect to sea water and in the food chain composed of plankton, omnivorous fish, and carnivorous fish. In most cases the averages of several samples collected within a contaminated area are used in order to reduce the effect of individual variability, a factor which has been considered elsewhere (Bonham, 1958; Donaldson et al., 1956; Lowman 1958, 1960; Welander, 1958).

In studies on the uptake of radioactivity from sea water by plankton the fractionation of the radioactivity between the water and plankton is usually compared on an equal volume or equal weight basis and a concentration factor for the radioactivity by the plankton may thus be derived. However, uptake of radioactivity by plankton from sea water may also be compared on the basis of the fraction of the total radioactivity in the water that is accumulated by the contained organisms.

The importance of marine organisms in affecting the movement and distribution of radioactive contamination in the sea has been emphasized by several authors (Ketchum, 1957; Lowman, 1958; Revelle and Shaefer, 1957). In areas of the sea where relatively large populations of organisms exist in relation to the total water volume the organisms may exert an effect of this type (Ketchum, 1957).

[2]Scientific names from: List of common and scientific names of fishes from the United States and Canada, 2nd edition. Am. Fish. Soc. Spec. Publ. 2. 102 pp. (1960).

DOE ARCHIVES

water are based on the theoretical radionuclide composition of fallout[3] at the given times and are subject to error because they are not corrected for fractionation and precipitation in the sea water.

[3] Ratio of cobalt-60 to strontium-90 (Strom et al., 1958), ratios of cobalt-60 to manganese-54, iron-59, cobalt-58, uranium-237, and neptunium-239 (Knapp, 1960), ratio of iron-55 to iron-59 (Lowman, 1960).

weeks was evident. At approximately one week the three radioelements, cobalt, zinc, and iron contributed only .15 per cent of the total radioactivity in the water but accounted for 62 per cent of the radioactivity in the plankton. At approximately six weeks the values were 2.44 per cent and 73 per cent respectively. The accumulation of fission products by the plankton at one and six weeks was variable and no marked pattern of active concen-

DOE ARCHIVES

taken in a mass of water that had been contaminated for about six weeks. During this time the contaminated body of water had been dispersed over an area with a diameter of several hundred miles although a central area of higher radioactivity still persisted. If one assumes a more or less random movement of the tunas and if a similar distribution of radionuclides is found in the same organs of different fish, it is probable that the tunas had remained in some part of the contaminated area sufficiently long for the individual radionuclides within the tissue and organs to have reached a state of equilibrium with the radionuclides in the food items. The average level of radioactivity in the food items would not necessarily be the same, however, as those of the food items taken at the above described sampling station.

In Table 2 is shown the percentage of total radioactivity contributed by individual radionuclides in plankton and flying fish at one week and in tunas and water at six weeks after contamination. and Lehninger (1951) indicate that marine organisms tend to concentrate positive polyvalent ions but not positive monovalent ions although the latter may be present in the environment in high amounts.

The ability of the transition elements to form complexes with biological materials is usually not affected by the chemical composition of the biological sustrate, and the stability of the metal-biological complex is usually in the following biological order.

$$Mn^{++} < Fe^{++} < Co^{++} < Ni^{++} < Cu^{++} > Zn^{++}$$

Uptake of the radioisotopes of these elements from sea water by the plankton probably reflects the stability of the metal-biological substrate described above. In plankton samples taken at approximately one and six weeks (Table 1) the order of uptake in relation to the levels of radioisotopes in

Table 2. Percentage of total radioactivity contributed by fission products and by the neutron-induced isotopes uranium-237, cobalt-57, 58, 60; iron-55, 59; zinc-65, and manganese-54 determined in plankton and fish samples collected at the Eniwetok Proving Ground in 1958. The total radioactivity per gram dry weight is also shown.

	Water[1]	Plankton	Flying Fish		Tuna					
			White muscle	Liver	White muscle A	B	Liver C	D	Dark muscle A	B[2]
Ruthenium, zirconium and uranium	52.0	13.0	trace	trace	0.0	0.0	0.0	0.0	0.0	0.0
Barium-140; lanthanum-140	18.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cesium-137; barium-137m	0.08	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0
Cobalt-57, 58, 60	0.67	43.0	10.0	8.7	0.9	2.5	0.0	2.3	1.1	2.1
Iron-55, 59	0.93	16.0	31.3	81.3	5.8	8.1	25.5	15.0	12.4	9.7
Zinc-65	0.84	3.0	58.8	9.9	91.9	89.0	74.5	82.6	86.3	88.0
Manganese-54	0.12	0.0	0.0	0.0	0.2	0.4	0.0	0.1	0.2	0.2
Total radioactivity (disintegrations per minute per gram dry weight)	-	2.3	2.2	1.1	3.3	1.2	3.6	2.0	5.3	2.9
	-	X_{10^6}	X_{10^4}	X_{10^6}	X_{10^3}	X_{10^4}	X_{10^4}	X_{10^5}	X_{10^3}	X_{10^4}

[1] At six weeks.

[2] Samples from four different fish: A - big eye tuna (Thunnus obeus); B - yellow fin tuna (Thunnus albacares); C - yellow fin tuna; D - big eye tuna.

DOE ARCHIVES

biologically important in enzyme systems and in oxygen and electron transfer. Iron is a component of hemoglobin, myoglobin, cytochromes, and cytochrome oxidases and other enzymes associated with oxidation. Zinc is found in the respiratory protein of the blood in some snails and in the enzyme carbonic anhydrase. Manganese is associated with peptidases, transphorases, dehydrogenases, decarboxylases, and oxygen disposal system in plants (Eyster et al., 1958; Steward and Pollard, 1957).

Of the three elements, the radioisotopes of iron and zinc were concentrated in the liver of the omnivorous fish to a level in which the disintegration rate per unit weight of tissue was approximately double that in the plankton. On a percentage basis radioactive iron contributed 16 per cent of the total activity in the plankton and approximately 31 per cent and 81 per cent respectively in the white muscle and liver of the omnivorous flying fish. In the carnivorous tunas iron-55,59 accounted only for an average of 7 per cent and 20 per cent respectively in the same organs. Thus the percentage of total radioactivity contributed by iron-55,59 in plankton was about ½ and 1/5 respectively of the percentage accounted for in the white muscle and liver of the omnivore and radioactive iron contributed only 1/4 as much of the total percentage or radioactivity in the muscle and liver of the carnivorous tunas as it did in the corresponding tissues of the omnivore.

The reduction in percentage composition of radioactive iron in the tissues of the tunas compared with those in the flying fish is compensated by the increased percentages of zinc-65. On the plankton, almost completely excluded the fission products and, on a comparative basis, concentrated zinc-65 and iron 55,59, but discriminated against cobalt-57,58,60. Carnivorous tunas, which feed primarily on omnivorous fishes, discriminated in favor of zinc and manganese and against iron and cobalt in comparison to the relative percentages of these radionuclides in their food supply.

ACKNOWLEDGMENTS

This work was performed under contract number AT(45-1)540 between the U. S. Atomic Energy Commission and the University of Washington.

REFERENCES

Anonymous. 1958. The results of a physical and biological oceanographic survey at Eniwetok. Staff, Pacific Oceanic Fishery Investigations, U. S. Fish and Wildlife Service, Honolulu, T.H. 55 pp.

Bonham, K. 1958. Radioactivity of invertebrates and other organisms at Eniwetok Atoll during 1954-55. Univ. of Washington, U. S. AEC report UWFL-53. 52 pp.

Donaldson, L.R., A.H. Seymour, E.E. Held, N.O. Hines, F.G. Lowman, P.R. Olson, and A.D. Welander. 1956. Survey of the radioactivity in the sea near Bikini and Eniwetok Atolls, Univ. of Washington, U. S. AEC report UWFL-46. 38 pp.

Eyster, C., T.E. Brown, H.A. Tanner, and S.L. Hood. 1958. Manganese requirement with respect to growth, Hill reaction, and photosynthesis. Plant Physiol. 33: 235-241.

products in plants and animals of the Pacific Proving ground, Univ. of Washington, U. S. AEC report UWFL-51. 61 pp.

Welander, A.D. 1958. Radiobiological studies of the fish collected at Rongelap and Ailinginae Atolls. Univ. of Washington, U. S. AEC report UWFL-55. 33 pp.

DOE ARCHIVES

and the United Kingdom for 1957 and 1958 (Dunham, 1959) was produced by these detonations. Thirty to eighty per cent of the radioactivity produced by the barge and surface detonations could be expected to occur as local fallout (Libby, 1959) and to enter the ocean within a day or two after detonation and within a few hundred miles of the test site. Practically all of the radioactivity from the underwater detonations would remain in the ocean.

One objective of the study was to determine if local fallout from Hardtack could be detected in ocean waters at distances of 1,000 miles or more from the test site (Guam and Palau are 1,200 and 1,950 miles, respectively, west of Eniwetok). If so, then an estimate could be made of the rate of movement of local fallout by ocean currents, in this instance the North Equatorial Current, since month intervals beginning in June 1958 and continuing until November 1959, except in the Gulf of Siam. There were four collections in the Gulf of Siam and six each at Palau and Guam. Samples included fish, crabs, lobsters, snails, clams, algae, and plankton. In addition, 72 weekly plankton samples were collected at Palau, site of field headquarters for the George Vanderbilt Foundation.

Plankton samples were preserved in ten per cent formalin, but all other samples were sent fresh-frozen from the field stations to the laboratory. The samples were held in a freezer until they were processed, at which time they were thawed, dissected, weighed, dried at 95° centigrade, reweighed, ashed at temperatures up to 540° centigrade, and again reweighed prior to counting.

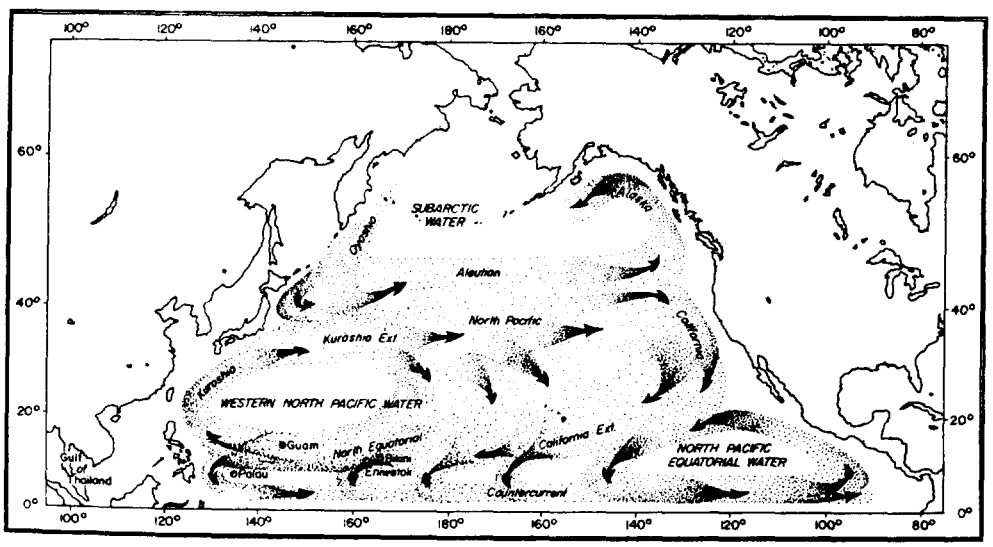

Figure 1. The major surface current systems in the north Pacific Ocean (after Seckel and Waldron, 1960).

DOE ARCHIVES

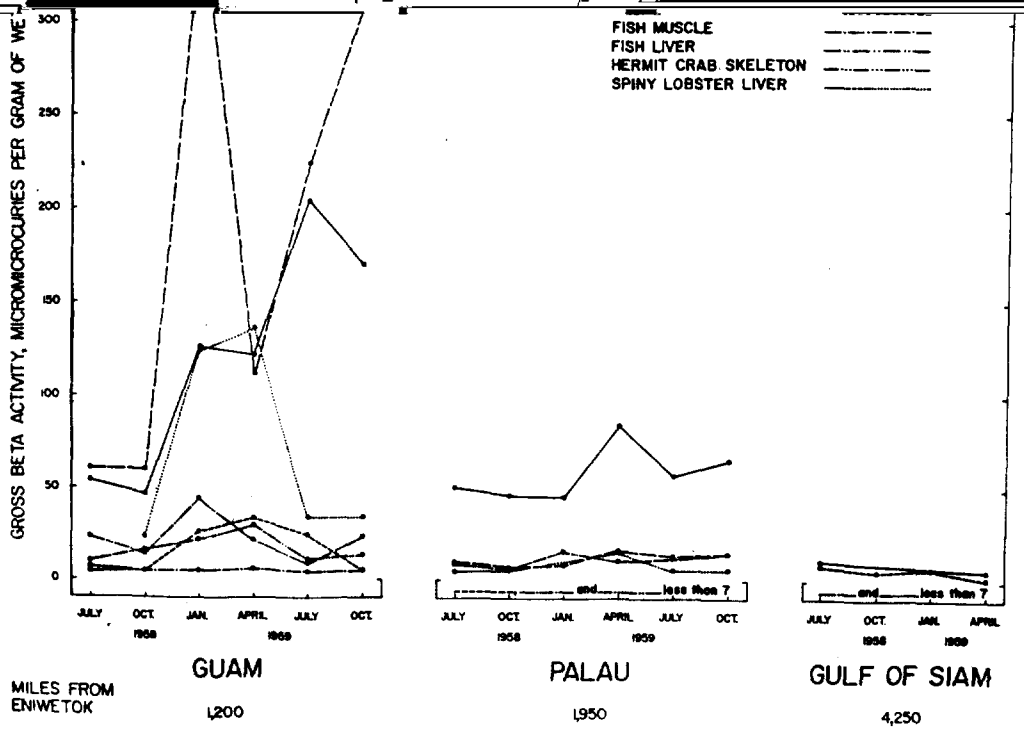

Figure 2. Average gross beta activity of marine organisms from Guam, Palau, and the Gulf of Siam, 1958-1959. Average based on two to thirteen observations.

DOE ARCHIVES

[illegible] (Epinephelus), fish liver (Katsuwonus), clam kidney (Tridacna), clam soft parts (Arca), algae (Dictyota), and plankton.

---

[1] 95 per cent error in net count; $E_{95} = 1.96\ (Ns/t_s + Nb/t_b)^{1/2}$; from U. S. Public Health Service Radiological Health Handbook, 1960.

[2] Approximate value based upon decay scheme for silver-110m and efficiency factor for cesium-137. Without a standard for silver-110m Compton correction factors not calculated and therefore estimates of other radionuclides in sample also are approximate.

DOE ARCHIVES

(1) It appears reasonable to assume that significant increases in gross beta counts of some marine biological samples were a valid criterion of the arrival of water-transported, local fallout from Hardtack.

(2) One type of sample in which the presence of Hardtack fallout was not evident was fish muscle, for which the counts remained at essentially background level for all collections regardless of date or area of collection. For Guam the values ranged fro 3.9 to 6.1 micromicrocuries per gram of wet weight; for Palau, from 3.5 to 5.6; and for the Gulf of Siam, from 3.5 to 6.6.

(3) The counts of gross beta activity differed greatly for the three collecting areas. The counts of Guam samples were considerably higher than those from Palau, which in turn were very much higher than the counts of the Gulf of Siam samples. The levels of radioactivity in the Gulf of Siam samples were approximately background and did not change significantly with date of collection.

(4) The arrival at Guam of Hardtack fallout transported by the North Equatorial Current occurred between October, 1958, and January, 1959. The arrival at Palau was approximately three months later, between January and April, 1959, but was not as sharply indicated because the levels of radio-

zinc-65, zirconium-95, and silver-110m. The greatest value was 2,300 micromicrocuries of cobalt-57 per gram of wet weight of clam kidney (Tridacna).

It is to be noted that silver-110m was reported as cesium-137 and manganese-54 at the time this paper was presented at the Symposium. The nuclides had been identified by gamma spectrometry and the two principal gamma peaks for silver-110m, 0.67 Mev (million electron volts) and 0.89 Mev, were mistaken for the 0.66 Mev gamma peak of cesium-137 and the 0.84 Mev gamma peak of manganese-54. Further investigations by Palumbo and other co-workers in our Laboratory suggested the presence of silver-110m, which was verified by chemical separation of silver from the sample and by gamma spectrometry of the separated component. The identification of silver-110m is of special interest because it is a fallout nuclide which has not been reported previously, and so far it has been detected only in the "liver" of the spiny lobster. At the time that silver-110m was identified in the sample of spiny lobster, collected at Guam in November 1959, Palumbo also identified as silver-110m an "unknown" nuclide in spiny lobster liver collected at Eniwetok in March 1961.

Gamma-emitting nuclides other than those listed in Table 1 may have been present in the samples but were not identified because their radioactivity was below the level of detectability, or their photopeak

DOE ARCHIVES

samples with the highest gross beta counts were clam kidney and spider snail liver, with maximums of 204 and 356 micromicrocuries per gram, respectively. Gross beta counts of some Guam and Palau samples prior to the arrival of the Hardtack fallout indicate the presence of radionuclides from prior test series. Gamma-emitting nuclides other than naturally occurring potassium-40 included, in order of abundance, cobalt-57, cobalt-60, manganese-54, cerium-144, zinc-65, and silver-110m. The greatest value was 2,300 micromicrocuries per gram of wet weight for clam kidney (Tridacna). The occurrence of silver-110m in the liver of the spiny lobster was of special interest because it is a previously unreported fallout nuclide and so far

and Geophysics (Tokyo) 5(3-4): 253-262.

Seckel, H., and K.D. Waldron. 1960. Oceanography and the Hawaiian skipjack fishery. Pacific Fisherman 58(3): 11.

Seymour, A.H., E.E. Held, F.G. Lowman, J.R. Donaldson, and D.J. South. 1957. Survey of radioactivity in the sea and in pelagic marine life west of the Marshall Islands, September 1-20, 1956. Univ. of Washington, U. S. AEC report UWFL-47. 57 pp.

Thomas, C.W., D.L. Reid, and L.F. Lust. 1958. Radiochemical analysis of marine biological samples following the "Redwing" shot series - 1956. Hanford Atomic Products Operation, General Electric Co., U. S. AEC report HW-58674. 81 pp.

DOE ARCHIVES

APPENDIX TABLE A. Average gross beta values, micromicrocuries per gram of wet tissue, of marine organisms collected at Guam, Palau, and Gulf of Siam, 1958 and 1959. Average based on three observations unless noted.

			Guam						Palau						Gulf of Siam			
			1958		1959				1958		1959				1958		1959	
Group	Name	Tissue	June	October	January	April	June	October	June	October	January	April	June	October	June	October	January	April
Fish	Grouper	muscle	4±.46	4±.44	4±.22	5±.23	4±.51	5±.26	4±.21	4±.32	4±.21	4±.65	4±.22	4±.20	5±.43	4±.40	5±.15	3±.33
		liver	10±.65	17±4.8	16±3.8	43±13.	5±1.8	14±7.3	7±1.7	7±2.6	3±.52	5±1.4	3±.44	4±.23	6±.75	2±1.1	2±.25	3±.33
	Surgeonfish	muscle	4±.04	6±.79	5±.24	6±.34	4±.03	5±.21	5±.28	5±.11	5±.62	4±.45	4±.20	5±.41				
		liver	8±.67	20±1.6	26±1.7	31±3.3	19±1.4	16±1.1	5±.73	6±1.2	8±1.6	6±.89	5±.58	8±.59				
	Goatfish	muscle	5±.13	6±.58	5±.33	6±.52	4±.41	4±.22	5±.51	6±.32	4±.34	4±.07	5±.66	5±.37				
		liver	11±2.5	11±.45	24±3.1	15±2.2	9±2.8	10±3.3	5±.77	4±1.4	5±.94	6±1.1	7±.80	5±.82				
	Tuna	muscle, dark													4±.05	4±.41	3±.39	3±.05
		muscle, light													5±.25	5±.73	4±.39	4±.30
		liver													5±.23	4±.07	4±.20	4±.03
	Anchovy	muscle													3±.35	7±1.6	4±.29	
		liver														5±3.0	3±.29	
		viscera													4±.44			
		midsection																3±.11
	Leiognathus	muscle													4±.34	6±.24	4±.48	2±.08
		liver														14±.14	2±1.1	2±.41
		viscera													4±.62			
Molluscs	Spider snail	muscle	5±.90	5±.45	14±2.4	28±1.4	21±6.0	23±11.	4±.56	7±2.0	4±.21	4±.61	5±.21	4±.08				
		liver	61±13.	60±14.	356±54.	112±12.	224±27.	312±50.	9±1.5	7±.28	8±1.1	16±6.7	13±2.3	14±1.1				
	Tridacna clam	muscle	4±.36	3±.24	6±.86	5±.64	4±.28	4±.46	2±.21	2±.42	3±.16	3±.21	3±.21	3±.10	3±.48			3±.31
		kidney	54±8.9	47±4.2	126±22.	122±3.7	204±29	170±56.	50±13.	46±10.	45±7.0	84±13.	57±3.3	65±5.5	11±1.41			6±.55
	Arca clam	foot															1±.66	2±.40
		soft parts													3±.43	2±.32	2±.29	3±.31
	Pinna pen shell	muscle															2±.20	
		viscera															4±.41	
	Pteria oyster	muscle															2[2]	
		viscera															3[2]	
Crustacean	Land hermit crab	muscle	4±.05	4±.38	3±.16	5±.37	2±.43	3±.19	3±.02	3±.23	2±.36	2±.16	3±.05	3±.36				
		skeleton	23±2.4	14±2.1	44±29.	22±5.8	9±2.2	23±1.3	8±.52	6±1.2	16±3.6	10±1.7	12±3.1	14±3.7				
		skeleton and muscle	12[2]															
		viscera	8[2]															
	Swimming crab	muscle													3±.11	2±.17	2±.26	2±.37
		liver													4±.85	1±.21	3±.61	1±.18
	Coconut crab	muscle							2[2]									
		skeleton							10[2]									
	spiny lobster	muscle		6±.88	8±.65	15±2.4	7±.93	10±1.7	3±.44	4±.66		6±.30	4±.45	4±.30				
		liver		23±7.4	124±21.	136±67.	34±2.4	34±7.5	4±.27	5±1.3		15±3.3	6±.38	6±.38				
Algae	Caulerpa	whole	10±.22	7±.03	36±7.9	61±4.2	44±3.8	6±50	1±.16	2±.20	2±.08	3±.18	1±.13	1±.12				
	Halimeda	whole	4±.46	2±.10	16±.53	5±.87	5±.24	5±.78	0.7±.68	1±.27	2±.08	3±.37	2±.45	4±.37				
	Sargassum	whole		5±.15													7±.10	2±1.0
	Dictyota	whole													11±.30			
	Gracilaria	whole																2±.05
	Laurencia	whole													5±.60			

[1]Average ± one standard error of the mean.

[2]One sample only.

DOE ARCHIVES

Appendix Table B. Common and scientific names and collecting areas of samples as recorded in "Field Data Record" of the George Vanderbilt Foundation.

Group	Common name	Scientific name	Guam	Palau	Gulf of Thailand[1]
Fish	surgeonfish	Acanthurus lineatus	x	x	
	goatfish	Mulloidichthys samoensis	x	x	
	grouper, sea bass	Cephalopholis argus	x	x	
	grouper, sea bass	Epinephelus merra	x	x	
	grouper, sea bass	Epinephelus hexagonatus	x	x	x
	tuna, bonito	Katsuwonus pelamys			x
	anchovy	Engraulis spp.			x
	anchovy	Stolephorus spp.			x
	leiognathid	Gerres argyreus			x
Crabs	hermit crab	*	x	x	
	coconut crab	*		x	
	swimming crab	*			x
Spiny lobster	lobsters,		x	x	
	"langoustre," langusta	*		x	
Snails	sea snails	Lambis lambis	x	x	
Clams	clam	Tridacna		x	x
	clam	Tridacna elongata	x	x	
	clam	Arca sp.			x
Oyster	oyster	Pinna			x
Plankton	plankton		x	x	x
Algae	alga	Caulerpa	x	x	
	alga	Halimeda			x

[1] Referred to as Gulf of Siam in text.
*Not given.

Appendix Table C. Gross beta activity of plankton from Guam, Palau, and the Gulf of Siam, 1958–1959. Single determinations (micromicrocuries per gram of wet weight).

Guam		Palau						Gulf of Siam	
Sample date	Activity	Sample date	Activity	Sample date	Activity	Sample date	Activity	Sample date	Activity
1958		1958		1959		1959		1958	
July		June		January		July		July	
13	34±3.7	22	11±2.0	4	3±1.0	5	4±1.1	4	27±3.1
October		29	12±3.6	11	2±0.7	12	1±0.7	October	
5	42±3.4	July		18	6±1.0	19	2±1.0	3	0.5±.35
1959		6	10±1.5	25	8±0.6	26	3±0.8	1959	
January		13	1±0.8	February		August		January	
9	130±4.3	20	6±0.9	1	1±0.8	2	0.5±0.8	5	3±0.8
April		27	31±3.0	8	2±1.5	9	2±0.7	April	
6	50±4.0	August		15	1±0.9	16	1±0.6	2	11±2.3
August		3	0.6±0.4	22	4±0.9	23	0.6±0.9		
18	6±0.8	10	8±1.5	March		30	0.9±0.7		
October		17	6±1.5	1	5±1.2	September			
8	4±0.8	24	1±0.6	8	11±1.6	6	1±0.6		
		31	2±0.6	15	14±2.2	13	1±0.7		
		September		22	3±0.9	20	6±1.0		
		7	1±0.5	29	3±1.0	28	4±1.2		
		14	0.5±0.6	April		October			
		21	3±0.9	5	7±1.2	4	2±0.7		
		28	3±1.0	13	4±1.0	11	2±0.8		
		October		19	6±1.4	18	2±1.0		
		5	2±1.0	20	14±1.7	25	0.5±0.4		
		12	0.8±1.0	26	5±2.0	November			
		19	1±1.3	May		1	1±0.7		
		28	2±2.5	3	4±1.5				
		November		10	3±1.3				
		2	1±1.0	17	2±1.3				
		9	2±2.1	24	3±1.4				
		16	3±1.8	31	8±2.1				
		23	1±0.6	June					
		30	0.9±0.4	7	6±2.2				
		December		14	2±1.5				
		7	2±0.7	21	4±1.2				
		14	0.8±1.0	28	9±2.7				
		21	0.6±0.8						
		28	0.8±0.6						

[1] Values are the 95 per cent errors in the net count; $E_{95} = 1.96\ (Ns/t_s + Nb/t_b)^{1/2}$; from U.S. Public Health Service Radiological Health Handbook, 1960.

DOE ARCHIVES

QUALITATIVE DISTRIBUTION OF RADIONUCLIDES AT RONGELAP ATOLL

E. E. HELD

Laboratories of Radiation Biology, University of Washington, Seattle, Washington

In March, 1958, a radioecological study of Rongelap Atoll was instituted at the request of the Division of Biology and Medicine, U. S. Atomic Energy Commission (AEC). This report will be concerned with generalizations regarding the distribution of radionuclides at the atoll in the fall of 1959, some five years after contamination with radioactive fallout.

Rongelap Atoll was accidentally contaminated on March 1, 1954, with radioactive fallout from a thermonuclear device detonated at Bikini Atoll some 80 miles to the west. Gamma radiation dose rates at Rongelap on D + 1 (detonation + one day) ranged from 3.5 roentgens per hour at the southern islets of the atoll to 35 roentgens per hour at the northern islets (Dunning, 1957). Eighty-two natives residing on Rongelap Island, in the south, were evacuated and did not return until June, 1957. At that time the returning population approached 300 in number but since appears to have stabilized at 230.

Several radiological and biological surveys, primarily of a monitoring nature, were conducted from the time of the first contamination until 1958 (Dunning, 1957). During this time the gamma radiation dose rates over land areas declined at approximately the rate predicted for mixed fission products by Miller and Loeb (1958). Slight rises in gamma dose rate were observed in 1956 and 1958, resulting from tests conducted during these years. However, the total contribution of radionuclides from these subsequent fallouts amounted to a fraction of one per cent of the amount from the 1954 fallout.

Rongelap Atoll is located in the Marshall Islands, in the Central Pacific Ocean, at about 11° North. It is a typical atoll with a lagoon area of 388 square miles and about 180-foot average depth. The emergent land area is about three square miles and is made up of 61 small islets ranging in size from a fraction of an acre to the largest island, Rongelap, which is about four miles long and one-half mile across at its widest point.

There is one small islet on the western reef and the remainder are strung along the northern, eastern, and southern reefs. The islets on the northern reef are not as well developed as those to the east and south. The waters of the lagoon are essentially isothermal (Robinson, 1954). The circulation, generated by the northeast trade winds, is from east to west at the surface with a returning bottom current (Von Arx, 1954). The estimated time for renewal of water in the lagoon is about 30 days.

The parent material of both soils and the lagoon bottom is primarily calcium carbonate originating mainly from coralline algae, corals and foraminifera. There is also some accumulation of pumice dust in the soils.

The natives of the area are Micronesians. Their agriculture is limited in variety of products and the only significant export is copra. About half of the food consumed at the present time is imported. Fish and other marine organisms are eaten but these sources are not exploited as much as they could be. The Rongelapese are almost entirely dependent on cisterns as a source of water. Rainfall in this area is comparatively low and the islets small, so that there is not a well-developed fresh water lens. There is, however, some potable water in wells at Rongelap and Eniwetok Islets.

The native style wattle and palm frond buildings have been replaced by plywood and aluminum structures built to Rongelapese specifications by the AEC. Sanitation habits have been altered by the advent of pit toilets.

The terrestrial fauna is limited in variety. The only mammal present is the small field rat, Rattus exulans. The most common birds are the fairy tern, Gygis alba, and the noddy terns, Anous stolidus and A. tenuirostris, which nest in large numbers on some of the uninhabited islets. The reptiles are represented by skinks, geckos, and a blind snake. Land crabs are common, the most spectacular being Birgus latro, the coconut or robber crab. Insects are few, both in number of species and individuals. The most severe pest appears to be the beetle, Brontispa sp., which attacks the coconut palm.

In contrast to the land areas there is a tremendous proliferation of both numbers and variety of organisms on the reefs and in the lagoon. For example, there are over 700 species of fish. Plankton, however, is extremely sparse and as a consequence the water is so clear that green algae are found growing at depths of 180 feet.

Since the question of the effects of radiation on the organisms inevitably arises, it might be well to consider it briefly before going on to the main subject. There is no doubt that the levels of radiation were of sufficient intensity to affect living organisms, However, under actual field conditions and without benefit of study before the addition of radiation as an ecological factor, it is difficult to do more than speculate concerning the cause of the specific anomalies observed. Fosberg (1959) has accurately described the poor condition of the plants at the northern islets of Rongelap Atoll and has suggested that the primary cause of this condition is radiation. In our opinion, however, other factors, particularly edaphic factors, have probably been more important than radiation. The fact that the nitrogen content of the soils of the northern islets is lower than that of the rest of the atoll is at least circumstantial evidence that for some time there have been differences between these areas with respect to plant growth. Stone et al. (1957) have concluded from studies of Drosophila populations at Bikini, Eniwetok, Rongelap, and uncontaminated atolls that while there is evidence of genetic changes caused by radiation other factors mask the radiation effects. In short, it is not likely that such questions will be resolved without controlled experimentation with the species involved, under varying conditions, and with an eye toward the possibility of synergistic effects.

Approximately five years after fallout the long-lived fission products cesium-137 and strontium-90 are the principal radionuclides found in the land organisms, while the neutron-induced radionuclides zinc-65, cobalt-60 and manganese-54 are found primarily in the marine organisms.

Still detectable in the soil are manganese-54, iron-55, cobalt-57, cobalt-60, zinc-65, strontium-90, zirconium-95, ruthenium-106, antimony-125, cesium-137, cerium-144, and europium-155, which remain concentrated in the upper one to two inches. Where higher levels of radionuclides have been present these nuclides have been reported in a wide variety or organisms. It is likely that most of these radionuclides are actually present in most if

DOE ARCHIVES

clides since their movement has been detected in leachates to depths of 30 inches, but the levels are so low in ground water that special techniques would have to be developed to detect them.

The land plants contain principally cesium-137 and strontium-90. Manganese-54 and zinc-65 have been found in plants from the more heavily contaminated islets but are present in relatively insignificant amounts. In general, cesium-137 accounts for 90 per cent or more of the radioactivity in the land plants and strontium-90 for the remainder. This is unlike the situation usually found on continental soils and is a consequence of the low potassium content of Rongelap soil. Amendments of potassium to Rongelap soil reduce the uptake of cesium-137 by plants (Walker et al., 1961), and affect the distribution of cesium-137 within the plant. There are, of course, differences between plant species and plant parts with respect to the relative amounts of cesium-137 and strontium. For example, copra contains very little strontium-90 as compared with Pandanus fruit, and the basal leaves of various plants contain more strontium-90 relative to cesium-137 than do the terminal leaves. This variation is related to differences in mobility between cesium and potassium, and strontium and calcium.

The rats contain cesium-137 and strontium-90, reflecting the radionuclides present in the plants on which they feed. The coconut crab and the land hermit crab (Coenobita perlatus) contain the same nuclides but concentrate strontium-90, as has been reported for Coenobita from Eniwetok Atoll (Held, 1960).

The occurrence of radionuclides in man at Rongelap has been summarized by Cohn et al. (1960). In 1958 these nuclides were cesium-137 and strontium-90 coming form the food plants, and zinc-65 coming to man from marine products.

The birds, which feed almost exclusively on marine organisms, contain primarily zinc-65 and occasionally small amounts of manganese-54 and cobalt-60. Strontium-90 is also found in small amounts in bird bone and may reflect direct uptake from the ingestion of soil, although there is no direct evidence that this occurs.

Radionuclides in fish are limited to manganese-54, cobalt-60, and zinc-65, the latter being predominant. On a dry-weight basis for a sample of goatfish (Mulloidichthys samoensis) testes have the highest levels, the liver, gastrointestinal tract, and eyes are lower by about an order of magnitude, and the muscle and bone lower by still another order of magnitude. If the total amount of radioactivity by tissue is considered, then bone is the principal depository of zinc-65 (Joyner, 1961, personal communication). The sources of zinc-65 for fish are open to question. In some instances in- [illegible] out and have remained localized in portions of the coral colony actively growing at that time. The clams contain mostly zinc-65, cobalt-57 and cobalt-60. Weiss and Shipman (1957) originally reported the concentration of cobalt-60 in the kidney of Tridacnid clams collected at Rongelap in 1956. Animals such as the sea cucumber (Holothuria, Stichopus) and spider snail (Lambis, Strombus), which ingest large amounts of bottom sediments, contain ruthenium-106, cerium-144, and probably europium-155.

Of several species of algae sampled in 1959 the only radionuclides detected were ruthenium-106, cerium-144 and europium-155. In general, the levels of radioactivity in the algae are lower than in the fish or invertebrates.

The plankton contain manganese-54, cobalt-57,60, zinc-65, zirconium-95, ruthenium-106, and cerium-144, but all in minute amounts. In 1959 plankton samples collected by pumping a total of two and a half million gallons of water were pooled for gamma-ray spectrum analysis and were found to contain only enough of these nuclides for qualitative analysis without resorting to chemical separations. Further analysis has been deferred until other studies with the individual samples can be completed.

The lagoon sediments contain strontium-90, ruthenium-106, cerium-144, and europium-155. The radioactivity is associated mainly with the fines and is concentrated in the top two to four inches, dropping off rapidly with depth.

Radionuclides other than naturally occurring potassium-40 were not detected in sea water although larger samples and more sensitive techniques undoubtedly would have revealed their presence.

In sum, on land the present distribution of long-lived fission products, strontium-90 and cesium-137, can be expected to remain very much as it is now. The levels of radioactivity will be reduced primarily by physical decay of the radionuclides so long as other factors such as changed agricultural practices or a catastrophic storm do not occur. In the lagoon, the levels of radioactivity will decline more rapidly than on land because of the presence of shorter-lived radionuclides, with the exception of strontium-90. The latter does not enter the marine food web to any significant extent and may remain as a label useful in evaluating the long-term effects of physical forces in the lagoon.

SUMMARY

The qualitative distribution of radionuclides at Rongelap Atoll as determined approximately five

DOE ARCHIVES

ears after contamination by fallout from a thermonuclear device indicates distinct differences between the terrestrial and marine environments. The levels of radioactivity are low, the concentrations being less than the maximum permissible concentration for radionuclides in food or drinking water of man. Of the wide spectrum of radionuclides concentrated in the surface layers of the soil, strontium-90, antimony-125, and cesium-137 are the principal nuclides entering into the soil solution. The principal nuclides in the land plants and plant-eating animals such as coconut crabs and the indigenous rats are cesium-137 and, to a lesser degree, strontium-90. Bottom sediments contain mainly strontium-90 and europium-155. The radionuclides in the lagoon water have not been detected but are probably present in minute amounts. Planktonic organisms contain traces of manganese-54, cobalt-57,60, zinc-65, zirconium-95, ruthenium-106 and cerium-144. The principal nuclide found in the marine algae is cerium-144. In the marine invertebrates cobalt-60 and zinc-65 occur most commonly. Corals and coralline algae contain some strontium-90, while the fish and sea birds are found to contain mostly zinc-65. The presence of zinc-65, cesium-137, and strontium-90 in the body of the natives reflects a diet of both marine and terrestrial origin.

ACKNOWLEDGMENTS

This work was performed under contract number AT(45-1)540 between the U. S. Atomic Energy Commission and the University of Washington.

REFERENCES

Cohn, S.H., J.S. Robertson, and R.A. Conard. 1960. Radioisotopes and environmental circumstances: The internal radioactive contamination of a Pacific island community exposed to local fallout. In R.S. Caldecott and L.A. Snyder (eds.), Radioisotopes in the Biosphere, Univ. of Minnesota Printing Dept., Minneapolis. pp. 306-330.

Cole, D.W., S.P. Gessel, and E.E. Held. 1961. Use of the tension lysimeter in coral atoll and glacial till soils. Soil Sci. 25: 321-325.

Dunning, G.M. (ed.). 1957. Radioactive contamination of certain areas in the Pacific Ocean from nuclear tests. U. S. Atomic Energy Commission, U. S. Government Printing Office, Washington, D.C. 60 pp.

Fosberg, F.R. 1959. Long-term effects of radioactive fallout on plants. Atoll Research Bulletin No. 61. National Academy of Sciences-National Research Council, Washington, D.C. 11 pp.

---. 1959. Plants and fallout. Nature 183(4673): 1448.

Held, E.E. 1960. Land crabs and fission products at Eniwetok Atoll. Pacific Sci. 14(1): 18-27.

Miller, C.F., and P. Loeb. 1958. Ionization rate and photon pulse rate of fission products from slow neutron fission of U^{235}. U. S. Naval Radiological Defense Laboratory, San Francisco, report USNRDL-TR-247. 91 pp.

Robinson, M.K. 1954. Sea temperature in the Marshall islands area. U. S. Geological Survey professional paper 260-D. pp. 281-291

Stone, W.S., M.R. Wheeler, W.P. Spencer, F.D. Wilson, J.T. Neuenschwander, T.G. Gregg, R.L. Seecof, and C.L. Ward, 1957. Genetic studies of irradiated natural populations of Drosophila. In Studies in the genetics of Drosophila. Univ. of Texas, Publ. 5721. pp. 260-316.

Von Arx, W.S. 1954. Circulation systems of Bikini and Rongelap lagoons. U. S. Geological Survey professional paper 260-B. pp. 265-273.

Walker, R.B., E.E. Held, and S. P. Gessel. 1961. Radiocesium in plants grown on Rongelap Atoll soils. In Recent Advances in Botany, Proc. of the 9th Intern. Bot. Congr., Univ. of Toronto Press, Toronto, Canada. pp. 1363-1367.

Weiss, H.V., and W.L. Shipman. 1957. Biological concentration by killer clams of cobalt-60 from radioactive fallout. Science 125(3250): 695.

DOE ARCHIVES

stage of development was expressed as percentage of developmental period from ferti-

broken lines, estimated lethal dose-50's from graphs.

DOE ARCHIVES

lization to hatching for fish, or to metamorphosis for amphibia. Regressions were calculated (Snedecor, 1956) using logarithmic transformation. The number of observations, the regression coefficients, and the probabilities determined from the value of "t" appear in a summarizing table (Table 6).

ANALYSIS OF PUBLISHED RESULTS

Welander (1954) irradiated the eggs of rainbow trout (Salmo gairdnerii) in various stages from one-cell to late-eyed stage. From his Table 1 and 2 it is possible to relate lethal dose-50 as determined both at hatching and about two months later at the completion of yolk absorption to percentage of incubation reached at the time of irradiation. Lethal dose-50's were also estimated from Welander's (1954, page 235) graphs, and both calculated and estimated lethal dose-50's are used in Table 2 and Figure 3.

Table 2. Lethal dose-50 of rainbow trout at six stages of incubation.

Per cent of incubation when irradiated	Lethal dose-50 in roentgens			
	At hatching		At end of yolk stage	
	calculated[1]	estimated	calculated[1]	estimated
.28	78	80	58	70
2.54	468	600	313	400
17.3	524	700	461	600
25.	735	1,000	454	500
67.	-	3,000	415	600
89.	-	4,000	904	1,000

[1]Lethal dose-50's calculated by Welander (1954, page 233).

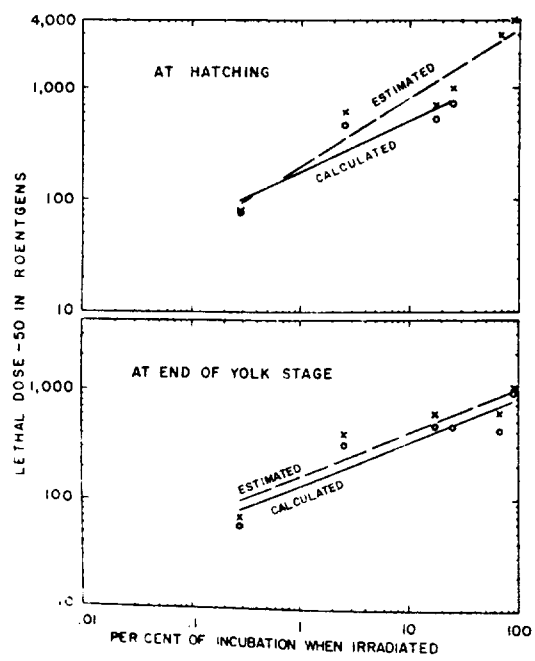

Figure 3. Relationship of lethal dose-50 to per cent of incubation of rainbow trout eggs when irradiated (Welander, 1954). Lethal dose-50's determined at hatching (upper), and at end of yolk stage (lower). Circles and solid lines, based on calculated lethal dose-50's, crosses and broken lines, based on estimated lethal dose-50's.

Rugh and Clugston (1955) described the effects of x-radiation upon various stages in the embryonic development of Fundulus heteroclitus. Although the lethal dose-50 is not stated, their descriptions of results permitted our estimating the lethal dose-50 (Table 3) at four stages which can be converted to percentage of the total incubation period (11 days) using the time-table of embryonic development contributed by Solberg (1938). Table 3 and Figure 4 give the trend of embryonic radioresistance of Fundulus which closely resembles the preceding trends.

Table 3. Responses of embryos of Fundulus heteroclitus to x-irradiation, from Rugh and Clugston, (1955), with subjective estimates of lethal dose-50 based upon their descriptions.

Stage irradiated			
Name or number	Per cent of incubation	Effect	Estimated lethal dose-50 at hatching (roentgens)
1- to 2-cell	1.14	-300 to 400 roentgens resulted in stunted, but otherwise normal development;600 roentgens,25 per cent hatched, stunted; reached stage 15 when controls at stage 22....	400
2- to 8-cell	1.90	-Only slightly less sensitive than 1- to 2-cell; 500 roentgens permitted quite normal development.....	600
11;expanding blastula	5.30	-1,000 roentgens permitted only a few to hatch.....	800
8-day embryo	72.8	-Tolerated up to 3,000 roentgens without a marked decrease in the number developing normally.....	3,000

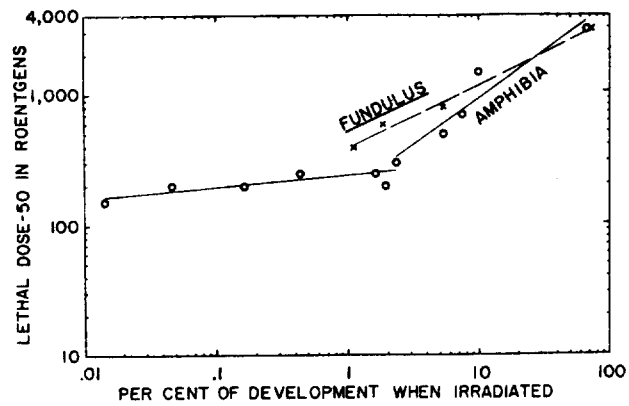

Figure 4. Relationships of lethal dose-50 to per cent of incubation of the eggs of Fundulus (Rugh and Clugston, 1955), crosses and broken line; and of lethal dose-50 to per cent of time from fertilization to metamorphosis of amphibia (Rugh, 1954), circles and solid lines.

Belyaeva and Pokrouskaya (1957, 1958) reported for the loach, Misgurnus fossilis, that anaphase-telophase was the most sensitve mitotic phase, 20 times as sensitive as interphase, and that radioresistance rose with advancing embryological development. From their description of results, lethal dose 50's may be roughly estimated for four stages (Table 4), but, because of the high resistance at last blastula, variability is too great for statistically significant regression (Table 6).

Rugh (1954) described the results of irradiating amphibia at various stages from the uterine egg

trout	Welander	hatching	4	179	.457	.547	3.59	<.08	6	198	.612	.245	6.92	<.005
Fundulus	Rugh and Clugston	end of yolk	6	131	.390	.231	4.68	<.01	6	163	.390	.214	5.04	<.01
Misgurnus	Belyaeva and Pokrovskaya	hatching							4	394	.469	.149	13.7	<.01
Amphibia	Rugh	metamorphosis			(preneurulation)				4	214	.925	1.62	2.33	<.2
					(postneurulation)				7	241	.0896	.0794	2.90	<.05
									5	185	.698	.415	5.35	<.02

[1] Values in the fitted logarithmic equation, $y = ax^b$.

[2] Addition and subtraction of $t_{.05}s_b$ from b give the .05 confidence interval.

DOE ARCHIVES

DOE ARCHIVES

Snedecor, G.W. 1956. Statistical Methods Applied to Experiments in Agriculture and Biology. Iowa State Coll. Pres. Ames. xiii, 534 pp.

Solberg, A.N. 1938. The susceptibility of Fundulus heteroclitus embryos to x-radiation. J. Exptl. Zool. 78(4): 441-469.

Welander, A.D. 1954. Some effects of x-irradiation of different embryonic stages of the trout (Salmo gairdnerii). Growth 18(4): 227-255.

bundance in radioactive fallout, these nuclides deserve detailed consideration from the standpoint of their distribution in the environment and their uptake by living organisms.

There is little information regarding the presence of the rare earth elements in nature. In Vinogradov's (1953) compilation of the chemical composition of marine organisms only a few data are given for the rare earths. Trace amounts of praseodymium, neodymium, samarium, cerium, lanthanum, and yttrium have been found in the coralline alga, Lithothamnion. Yttrium has been found in radiolarians, globigerina silts and gorgonaceans and samarium has been found in two species of corals. In the land environment small amounts of rare earths have been found in soils and in crops and native plants (Robinson, 1943).

The rare earths occur usually in insoluble form and thus are not readily available for uptake by living systems. The factors which control the rare earth nuclides in the environment and in the biota can be divided for the sake of convenience into two groups, the physico-chemical and the biological. The biological factors relate to the ability or inability of the organisms to absorb nuclides in the particulate state, and these factors depend in turn on the types of organisms and the methods by which nutrients enter them.

The physico-chemical factors govern the distribution and availability of the nuclides and include the radioactive half-life, the physical state and the chemical behavior of the element and certain other forces in nature which will be discussed.

Although many radioactive lanthanides are formed in the production of nuclear energy, only a few of these have been studied in relation to their distribution in the environment and their fate in

Yttrium-90			1.8	21.8	64.2 hours
Yttrium-91	3.4	7.6	3.9		57.5 days
Neodymium-147	4.8	4.1			11.1 days
Praseodymium-143	10.0	11.2			13.8 days
Samarium-151				2.5	approx. 93 years

[1]From Hunter, H.F., and N.E. Ballou (1951).

[2]From Strominger, D., J.M. Hollander, and G.T. Seaborg, (1958).

The physical state of the rare earth nuclides is a most important factor in determining their uptake and distribution in the environment. When the rare earth nuclides are formed in the high temperatures associated with nuclear detonations, they exist probably as oxides; and upon contact with other matter and with the sea or with fresh water, they retain their particulate nature, primarily as the hydroxides of the type $R(OH)_3$. Greendale and Ballou (1954) determined the physical states of various fission products following their vaporization in sea water and distilled water and found that the major portion of the cerium and yttrium was in the particulate state (Table 2).

Table 2. Physical state of cerium and yttrium following an underwater vaporization.[1]

Element	Solution	Physical state (per cent) ionic	colloidal	particulate
Cerium	sea water	1	4	95
		2.7	4	94
	distilled water	0	0.5	99.5
		0	2	98
Yttrium	sea water	0.4	2.2	98
		0.2	6.6	93
	distilled water	1.6	13	86
		1.3	19	80

[1]From: Greendale, A.E., and N.E. Ballou (1954).

tions conducted by Nishita and Larson (1957) showed

the physiological pH of the digestive tract makes their absorption difficult.

The principal source of rare earth nuclides for fish and terrestrial animals, also, is the food they ingest. The physical state of the nuclide in the food governs its fate in the organism. In fish there appears to be some absorption of cerium-144 after ingestion, indicating that at least a portion of this nuclide is in the soluble form. Chipman (1958), for example, found that cerium-144 was accumulated in small amounts by the bone and liver of crabs. In addition, Rudakov (1958) reported that high amounts of Ce^{144}-Pr^{144} were absorbed by carp fingerlings after a one-hour immersion in a radioactive solution, and that with the passage of time there was a redistribution of the nuclides in the tissues. At one day they were found mainly in the liver. At one month the radioactivity in the bone was twice as high as that in the liver. Other results, including those obtained from samples collected at the Eniwetok Proving Ground show that Ce^{144}-Pr^{144} is incorporated in small amounts in muscle, liver, kidney, lung, gills, and skeletal tissues of fish (Thomas et al., 1958; Broughs et al., 1956; Seymour et al., 1957; University of Washington, 1955; Rinehart et al., 1955).

In terrestrial animals there appears to be very little absorption of the rare earth nuclides from the digestive tract. The results of Durbin et al. (1956) showed that cerium-144, europium-152 and europium-154, terbium-160, and thulium-170 administered orally to rats were not absorbed significantly. However, parenteral injection of several radiolanthanides, complexed with an organic acid to increase their solubility, showed that absorption from the site of injection was almost complete within four days. The primary sites of deposition initially were the liver and skeleton. After ten months, however, the site of greatest concentration was the bone; other tissues contained only very small amounts of the rare earth nuclides (see also Kyker and Anderson, 1956). Similarly, in samples of rats collected at Eniwetok Atoll shortly after a nuclear detonation, the rare earth activity was highest in the skeleton and liver (Thomas et al., 1958). Samples of rat tissues collected approximately two and one-half years after the last test series in 1958 (Operation HARDTACK I) contained no detectable rare earth radioactivity although there was some in the soil and plants (Lowman and Palumbo, unpublished data). These data indicate that very little of the rare earth nuclides ingested under natural conditions is retained in the tissues of terrestrial animals.

The inhalation of particulate matter is also a factor to be considered. This process could be important, especially during periods of heavy fallout from nuclear tests and accidental discharge of radioactive materials from reactor stacks. Experiments have shown that rats subjected to aerosols containing lanthanum-140 (Cohn et al., 1957) and cerium-144 (Hennacy, 1961) had a relatively high initial concentration of these nuclides in their gastrointestinal tracts and low concentrations in other tissues. Cerium-144 was eliminated rapidly from the gastrointestinal tract but increased in the liver. The relatively rapid uptake by the liver suggested that some of the cerium was in the soluble form.

As in other animals, the rare earth elements enter man during the ingestion of food and the inhalation of air and dust. Based on the data of J. G. Hamilton and co-workers, Morgan (1960) estimated that less than 0.01 per cent of the rare earth elements pass from the gastrointestinal tract to the blood. It was found also that only a small fraction of the longer-lived rare earth nuclides taken in by inhalation reaches the critical organs for these nuclides.

These and similar data have been considered in establishing for man the maximum permissible concentrations in air, water, and food. The values for some of the rare earth nuclides are presented in Table 4.

The last biological factor to be considered here is the selectivity and concentration of the rare earths by different species. Organisms in the lower trophic levels concentrate them to a greater degree than do organisms in the higher trophic levels. For example, Krumholz and Foster (1957) estimated that the concentration factor was 1,000 for phytoplankton, 500 for filamentous algae, and 100 for fish. Also, it has been shown by Spooner (1949), Rice (1956), and Rice and Willis (1959)

Table 4. Maximum permissible concentrations of some rare earth radionuclides in air and in water for occupational exposure (From: K.Z. Morgan, 1960).

Nuclide	Half-life (days) Physical	Bio-logical	Effec-tive	Critical organ[1]	Maximum burden in total body (microcuries)	Maximum permissible concentration for 40-hour week (microcuries per cubic centimeter) Water[2]	Air	Fraction reaching organ By ingestion	By inhalation
Lanthanum-140	1.68			GI -(s)		7×10^{-4}	2×10^{-7}		
				GI-(i)		7×10^{-4}	10^{-7}		
Cerium-144	290	1500	243	Bone-(s)	5	0.2	10^{-8}	3×10^{-5}	0.075
				GI-(s)		3×10^{-4}	10^{-8}		
	290	293	146	Liver-(s)	6	0.3	8×10^{-8}		
				Lung-(i)			10^{-8}		
Promethium-147				GI-(i)		3×10^{-4}	6×10^{-9}		
				GI-(s)		6×10^{-3}	6×10^{-8}		
	920	1500	570	Bone-(s)	60	1.0	10^{-6}	3×10^{-5}	0.09
				Lung-(i)			6×10^{-8}		
Samarium-151				GI-(i)		6×10^{-3}	10^{-7}		
				GI-(s)		0.01	10^{-6}		
	4.7×10^{4}	1500	1442	Bone-(s)	100	2.0	2×10^{-6}	3.5×10^{-5}	0.09
				Lung-(i)			6×10^{-8}		
Europium-152				GI-(i)		0.01	10^{-7}		
				GI-(s)		2×10^{-3}	10^{-6}		
	4.7×10^{3}	1480	1125	Kidney-(s)	20	0.3	2×10^{-7}	3×10^{-6}	7.5×10^{-3}
				Lung-(i)			5×10^{-8}		
				GI-(i)		2×10^{-3}	10^{-8}		
							2×10^{-8}		
							4×10^{-7}		

[1] GI - gastrointestinal tract, lower large intestine; s = Soluble; i = insoluble.
[2] Air includes the water in food.

DOE ARCHIVES

tions, however, showed that this apparent selectivity was in reality a surface adsorption phenomenon (Bowen, personal communication). Since a biological requirement for the rare earth elements has not been demonstrated positively, the selectivity described in the examples above is probably due to differences in the external surfaces of the organisms. Chipman (1958) and Davis et al. (1958) suggested that the extent of accumulation of the rare earth nuclides by aquatic organisms is at least partly related to the surface area of the organism.

SUMMARY

Many radioactive lanthanides are made available in the production of nuclear energy; however, studies of their distribution in the environment and their uptake by living organisms have been confined primarily to Ce^{144}-Pr^{144}, lanthanum-140, promethium-147, and yttrium-90, 91.

Ecological factors governing the distribution of the rare earths are physico-chemical and biological. The first are concerned with the properties of the nuclide and the nature of the environment, and the second with the selectivity and retention of the nuclide by the organism.

Because the rare earth nuclides usually exist in the particulate state, they are not readily available to and are poorly absorbed by terrestrial or aquatic organisms. They are accumulated principally by surface adsorption, and the degree of accumulation can be related to surface area and to species differences.

Laboratory studies indicate that animals, including man, are unable to absorb the rare earths to any extent from the gastrointestinal tract and that elimination of them is rapid. The principal sites of deposition are the bone and the liver.

ACKNOWLEDGMENTS

This work was conducted under contract number AT(45-1)1385 between the U. S. Atomic Energy Commission and the University of Washington.

REFERENCES

Broughm, H., S.J. Townsley, and R.W. Hiatt. 1956. The metabolism of radionuclides by marine organisms. II. The uptake, accumulation, and loss of yttrium-91 by marine fish, and the importance of short-lived radionuclides in the sea. Biol. Bull. 111(3): 352-357.

---, W.A. Chipman, and T.R. Rice. 1957. Laboratory experiments on the uptake, accumulation, and loss of radionuclides by marine organisms. In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences, National Research Council, Washington. Publ. 551. pp. 80-87.

Bowen, V.T., and A.C. Rubinson. 1951. Uptake of lanthanum by a yeast. Nature 167(4260): 1032.

---, and T.T. Sugihara. 1958. Marine geochemical studies with fallout radioisotopes. In Proc. 2nd

Chipman, W.A. 1958. Accumulation of radioactive materials by fishery organisms. Proc. Gulf and Caribbean Fish. Inst. 11th Ann. Session. pp. 97-110.

Cohn, S.H., W.B. Lane, J.K. Gong, L. Weisbecker, and W.L. Milne. 1957. Studies on the metabolism of inhaled aerosols of strontium and lanthanum. U.S. Naval Radiological Defense Lab., San Francisco, report USNRDL-Tr-175. 26 pp.

Davis, J.J., R.W. Perkins, R.F. Palmer, W.C. Hanson, and J.F. Cline. 1958. Radioactive materials in aquatic and terrestrial organisms exposed to reactor effluent water. In Proc. 2nd Intern. Conf. Peaceful Uses Atomic Energy, United Nations, Geneva, 1 September-13 September, 1958, 18: 423-428.

Durbin, P.W., M.H. Williams, M. Gee, R.H. Newman, and J.G. Hamilton. 1956. Metabolism of the lanthanons in the rat. Proc. Soc. Exptl. Biol. Med. 91(1): 78-85.

Greendale, A.E., and N.E. Ballou. 1954. Physical state of fission product elements following their vaporization in distilled water and sea water. U.S. Naval Radiological Defense Lab., San Francisco, report USNRDL-436. 24 pp.

Harley, J.H. [ed.]. 1956. Operation Troll. Health and Safety Laboratory, New York, U.S. AEC report NYO-4656. 37 pp.

Hennacy, R.A. 1961. Translocation and inhalation of $Ce^{144}O_2$. In Hanford Atomic Products Operation, General Electric Co., Hanford Biology Research Annual Report for 1960. U.S. AEC report HW-69500. pp. 77-80.

Hunter, H.F., and N.E. Ballou. 1951. Fission product decay rates. Nucleonics 9(5): C-2-7.

Jacobson, L., and R. Overstreet. 1948. The uptake by plants of plutonium and some products of nuclear fission absorbed on soil colloids. Soil Sci. 65(2): 129-134.

Krumholz, L.A., and R.F. Foster. 1957. Accumulation and retention of radioactivity from fission products and other radiomaterials by fresh-water organisms. In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences-National Research Council, Washington. Publ. 551. pp. 88-95.

Kyker, G.C., and E.B. Anderson, [eds.]. 1956. Rare earths in biochemical and medical research: A Conference sponsored by the Medical Division, Oak Ridge Institute of Nuclear Studies, October 1955. Oak Ridge Institute of Nuclear Studies, U.S. AEC report ORINS-12. 447 pp.

Lowman, F.G. 1960. Marine biological investigations at the Eniwetok Test Site. In Disposal of Radioactive Wastes. Intern. Atomic Energy Agency, Vienna. pp. 105-138.

Martin, De C., Jr. 1958. The uptake of radioactive wastes by benthic organisms. Proc. Ninth Pacific Sci. Congr. 16: 167-169.

Moeller, T. 1956. The rare elements - an introduction to their chemistry. In Rare earths in biochemical and medical research: A Conference sponsored by the Medical Division, Oak Ridge Institute of Nuclear Studies, October 1955. Oak Ridge Institute of Nuclear Studies, U.S. AEC report ORINS-12. pp. 1-11.

---, and H.E. Kremers. 1945. The basicity characteristics of scandium, yttrium and the rare earth elements. Chem. Rev. 37(1): 97-159.

[illegible] 1960. Report of ICRP Committee [illegible] permissible dose for internal radiation (1959) with bibliography for biological, mathematical and physical data. Health Physics [illegible] 1-380

[illegible], M., and K.H. Larson. 1957. Summary of certain trends in soil-plant relationship studies of the biological availability of fallout debris. Univ. of California at Los Angeles, U.S. AEC report UCLA-401. 68 pp.

—, E.M. Romney, and K.H. Larson. 1961. Uptake of radioactive fission products by crop plants. Agr. Food Chem. 9(2): 101-106.

Sahama, K., and T.G. Sahama. 1950. Geochemistry. University of Chicago Press, Chicago, Illinois. xvi, 838 pp.

Rice, T.R. 1956. The accumulation and exchange of strontium by marine planktonic algae. Limnol. Oceanogr. 1(2): 123-138.

—, and V.M. Willis. 1959. Uptake, accumulation, and loss of radioactive cerium-144 by marine planktonic algae. Limnol. Oceanogr. 4(3): 277-290.

Rediske, J.H., J.F. Cline, and A.A. Selders. 1955. The absorption of fission products by plants. Hanford Atomic Products Operation, General Electric Co., U.S. AEC report HW-36734. 17 pp.

Rinehart, R.W., S.H. Cohn, J.A. Seiler, W.H. Shipman, and J.K. Gong. 1955. Residual contamination of plants, animals, soil, and water of the Marshall Islands one year following Operation Castle fallout. U.S. Naval Radiological Defense Lab., San Francisco, report USNRDL-454. viii, 29 pp.

Robinson, W.O. 1943. The occurrence of rare earths in plants and soils. Soil Sci. 56(1): 1-6.

Rudakov, N.P. 1958. Marking of fish by radioactive cerium (Ce^{144}-Pr^{144}). Rybnoe Khoziaistvo 34: 29-31.

Selders, A.A., J.H. Rediske, and R.F. Palmer. 1953. The absorption and translocation by plants of radioactive elements from "Jangle" soil. Hanford Atomic Products Operation, General Electric Co., U.S. AEC report HW-27620. 12 pp.

Seymour, A.H., E.E. Held, F.G. Lowman, J.R. Donaldson, and D.J. South. 1957. Survey of radioactivity in the sea and in pelagic marine life west of the Marshall Islands, September 1-20, 1956. Univ. of Washington, U.S. AEC report UWFL-47. 57 pp.

Spooner, G.M. 1949. Observations on the absorption of radioactive strontium and yttrium by marine algae. J. Mar. Biol. Assoc. U.K. 28(3): 587-625.

Stevenson, P.C., and W.E. Nervik. 1961. The radiochemistry of the rare earths, scandium, yttrium, and actinium. National Academy of Sciences, National Research Council, Washington. Nuclear Science Series NAS-NS 3020. x, 282 pp.

Strominger, D., J.M. Hollander, and G.T. Seaborg. 1958. Table of isotopes. Rev. Mod. Phys. 30(2): 585-904.

Thomas, C.W., D.L. Reid, and L.F. Lust. 1958. Radiochemical analysis of marine biological samples following the "Redwing" shot series - 1956. Hanford Atomic Products Operation, General Electric Co., U.S. AEC report HW-58674. 81 pp.

University of Washington. 1955. Radiobiological resurvey of Rongelap and Ailinginae Atolls, Marshall Islands, October - November, 1955. Univ. of Washington, U.S. AEC report UWFL-43. 91 pp.

Vinogradov, A.P. 1953. The elementary chemical composition of marine organisms. Sears Foundation for Marine Research. Yale University, New Haven, Connecticut. xiv, 647 pp.

Nickel	.00054	0.20	0.002	0.00000005	0.0014	0.004
Copper	.0029	2.7	0.01	0.0000002	0.005	0.004
Zinc	.000058	+	0.01	0.0000003	0.004	0.007
Molybdenum	.00021	+	0.01	0.000001	0.008	0.01
Iodine	+	+	0.0015	0.000001	0.0009	0.11
	+	+	0.00003	0.000006	0.000018	33.0

[1] Adapted from Mason, 1958

[2] Isaacs, J.D. personal communication, after Goldberg, 1961

[3] Adapted from Goldschmidt, in Rankama and Sahama, 1950.

[4] Present address: Puerto Rico Nuclear Center, Mayaguez, Puerto Rico.

DOE ARCHIVES

the seas where a major part of the iron and a lesser part of the cobalt was precipitated and deposited at the bottom. In many instances the bottoms of the seas were raised to altitudes higher than the surface of sea and the cycle was repeated.

Thus, leaching of the earth's crust was an important factor in the distribution and deposition of iron and cobalt in both the lithosphere and hydrosphere.

In natural water, iron is present as Fe^{3+}, Fe^{2+}, and $Fe(OH)^{2+}$. Iron, in the ferrous form, remains in solution with precipitation occuring after its oxidation to the ferric state. The transport of ferric hydroxide is dependent upon its solubility which, in turn, is dependent upon the pH of the medium. At pH six, ferric hydroxide is about 100 times as soluble as at pH seven and is 100,000 times as soluble as at pH 8.5 (Cooper, 1937). Iron in weakly acid streams flowing into the seas therefore is precipitated in the slightly alkaline sea water. This fact is illustrated by the observations that the average iron content of fresh waters is about 100 times the level found in marine waters (Mason, 1958).

The high levels of iron available to terrestrial, fresh water, and bottom dwelling marine organisms, in contrast to the reduced amounts available to free living marine organisms, probably influenced the incidence of utilization of iron by the inhabitants of the different environments.

Iron, when precipitated in sea water, forms a positively charged colloid and the precipitate carries scavenged ions with it as it settles to the bottom. Many ions, including arsenic, molybdenum, nickel, vanadium, phosphorus, antimony, copper, selenium, and lead, are removed from solution by this mechanism. In addition, the manganous ion may be catalytically oxidized by a gel of ferric hydroxide hydrate and this reaction probably accounts in part, at least, for the low transfer percentage of manganese in comparison to vanadium, cobalt, nickel, and copper. The co-precipitate of manganese and iron is capable of removing additional ions from the sea water, including cobalt, zinc, thorium, tin, and silver (Arrhenius, 1959).

The removal of heavy ions by ferric hydroxide is of great importance in the survival of past

DOE ARCHIVES

the geochemical characteristics of these elements have been determined. However, these types of observations do not necessarily provide the information required to determine the mechanisms which control the uptake of these elements by organisms from their environments. Even if the amounts of iron and cobalt were measured in representative samples of the organisms and their environments, only the static condition at the time of sampling would be determined.

iron-55, iron-59, cobalt-57, cobalt 58 and cobalt-60, have been reported (Kawabata, 1954; South and Lowman, 1955; Rinehart et al., 1955; Yamada et al., 1955; Saiki et al., 1955; Mori and Saiki, 1956; Yoshii, 1956; Nagasawa et al., 1956; Seymour et al., 1957; Lowman, et al., 1957; Lowman, 1958; Palumbo and Lowman, 1958; Welander, 1958; Lowman, 1960).

Only a limited number of observations have

DOE ARCHIVES

been compared with the radioactivity in plankton, sessile invertebrates, filter feeding and carnivorous fishes, and birds whose source of food is marine organisms. On land the amount of radioactivity have been measured in soils, plants, and herbivorous animals. In addition, analyses of soils under the nesting areas of birds have been made in which the radionuclide content has been altered by the excrement of the birds which feed upon marine organisms.

Iron and cobalt are microconstituents of living material and, although present in small amounts, are important in the normal metabolism of most organisms (Table 2). All of the microconstituents except boron and silicon have high specific gravities and atomic numbers in comparison with the primary and secondary constituents.

In sea water, iron and cobalt are also microconstituents, contributing only 0.000001 and 0.00000005 percent respectively of the total mass. The radioactive forms of these elements introduced in fallout are therefore subject to limited isotope dilution by the corresponding stable element in the water. A comparison of the isotope dilution in sea water than are the primary and secondary constituents. Thus, for equal amounts of radionuclides added to sea water an organism would have to concentrate 2.2×10^8 times as much stable hydrogen and 8.0×10^5 times as much stable calcium as it would stable cobalt to contain an equal amount of each of the three radionuclides.

Marine organisms do exhibit the ability to concentrate many elements from sea water (Donaldson et al., 1956; Boroughs et al., 1957; Krumholz et al., 1957; Lowman et al., 1957, 1959; Seymour et al., 1957; Lowman 1958; Palumbo et al., 1959), and it is usually assumed that the organisms rapidly acquire a major fraction of the radioisotopes of these elements introduced in fallout. At the Eniwetok Proving Ground this does not occur, probably as a result of the plankton contributing only one part per million of the total volume of sea water plus organisms. Although plankton exhibit high concentration factors for some elements the relatively small amount of these organisms in the tropical waters resulted in their containing only 1/10,000 of the total radioactivity at one week and 1/30,000 at six weeks after the water in

Table 3. Percent of total radioactivity in sea water and plankton contributed by fission products and neutron-induced radionuclides at approximate times of 48 hours, one week and six weeks (Knapp, 1960; Lowman, 1960). The percents of total are underlined.

	Less than 48 hours		Greater than One week		Six weeks	
	Water	Plankton	Water	Plankton	Water	Plankton
Molybdenum - 99, Technetium - 99m	5.9	12.0	5.0	0	0.02	0
Cerium - 141,144, Praesodymium - 141,144	0.83	3.0	2.1	0	20.0	5.0
Ruthenium - 103,105,106, Rhodium - 103,105,106	2.1	3.0	2.2	5.0	16.0	1.4
Barium - 140, Lanthanum - 140	2.6	2.0	6.8	23.0	18.0	0
Tellurium - 132, Iodine - 132	6.2	8.0	5.6	0	0.05	0
Zirconium - 95, Niobium - 95	0.38	1.0	1.0	6.0	18.0	20.0
Strontium - 89,90	0.30	0	0.76	0	8.2	0
Cesium - 137	<0.01	0	0.05	0	0.08	0
Neptunium - 239	54.0	69.0	33.0	2.0	0.02	0
Uranium - 237	24.0	3.0	43.0	2.0	18.0	0
Cobalt - 57,58,60	0.02	0	0.05	43.0	0.67	24.0
Zinc - 65	0.02	0	0.05	3.0	0.84	25.0
Iron - 55,59	0.02	0	0.05	16.0	0.93	24.0
Manganese - 54	trace	0	0.01	0	0.12	0.6

DOE ARCHIVES

for freshwater phytoplankton which have a much larger surface to volume ratio than do the zooplankton.

The plankton considered above comprise primarily two trophic levels in the food chain, the phytoplankton or primary producers and the zooplankton. The zooplankton are eaten by omnivorous fishes (flying fishes) which are in turn eaten by the carnivorous fishes (tunas). The radionuclide composition of the two types of fishes have been discussed in another paper of this series (Lowman, 1962), and will not be considered in detail, however, the distribution pattern of cobalt-57,58,60, and iron-55,59, in the three trophic levels are as follows:

	Time after contamination (weeks)	Per cent of total Radioactivity: Cobalt-57,58,60	Iron-55,59	Total radioactivity (disintregrations per minute per gram of dry weight)
Plankton	1	43	16	2.3×10^6
Omnivorous fish				
Muscle	1	10	31	2.2×10^4
Liver	1	9	81	1.1×10^6
Carnivorous fish				
Muscle	6	0.9 to 2.5	6 to 8	3.3×10^3 to 1.2×10^4
Liver	6	0.0 to 2.3	15 to 25	3.6×10^4 to 2.0×10^5

On a dry weight basis the total radioactivity in the plankton was approximately two and 100 times that in the liver and muscle respectively of the omnivorous fish. The levels of radioactivity in the plankton and omnivorous fish cannot be compared directly with those in the carnivorous fish (tuna) because the latter fishes are capable of migrating great distance in short periods of time and the length of time they had been in the area of contamination before they were taken cannot be determined.

upon small fish and to a lesser degree upon squid. Analyses for iron-55,59 have not been made on the tissues of these animals, and in gamma spectra of the liver, gut, kidney, muscle, and lung tissues of the terns, only the gamma peak of zinc-65 was detected (Lowman, et al., 1957). Iron-55 is probably present in the tissues of the terns in large amounts, however. Indirect evidence has been found that this is the case in analyses of soil samples from areas in which these birds nest (Palumbo and Lowman, 1958). A comparison is shown below of soil samples taken in bird nesting areas and from an island where nests were not present.

	Per cent of Total Radioactivity in Soil: Non-nesting area (Lowman, et al., 1957)	Nesting area (Palumbo and Lowman, 1958)
Ce^{144}-Pr^{144}	43.6	41.7
Iron - 55,59	0	40.6
Cobalt - 57,58,60	1 to 2	0.4
Manganese - 54	0	0.8
Zinc - 65	0	0

In the non-nesting area the soil did not contain the radioisotopes of iron, manganese, or zinc, but did contain one to two per cent of radiocobalt. In the nesting area, zinc-65 was not found in the soil, which contained excretory products from birds although it was present in high amount in the tissues of the birds. However, approximately 41 per cent of the total radioactivity in the soil was contributed by iron-55,59 with only trace amounts of radiocobalt and manganese. On the basis of the soils data and the gamma spectrum data on the birds, these animals excreted high amounts of iron-55,59, almost all of the cobalt-57,58,60, and manganese-54, and retained the zinc-65. The fact that the gamma peaks of cobalt-57,58,60, and manganese-54 were not found in the bird tissues and that these radionuclides were present in low amounts in the soil, indicates that the birds ingested relatively low amounts of radioactive cobalt and manganese and large amounts of iron-55,59 and zinc-65 and retained the radiozinc to a

DOE ARCHIVES

Plankton, collected from an area of sea water which had been contaminated with radioactivity for a period of six weeks, exhibited average concentration factors for radioactive iron and cobalt of 90,000 and 100,000, respectively, and contained the stable counterparts of these elements in about the same ratio as they were present in the water.

The roles of iron and cobalt in two food chains have been investigated in the marine environment in the Central Pacific. These include:

Water ⟶ plankton ⟶ omnivorous fish ⟶ carnivorous fish

and

Water ⟶ plankton ⟶ omnivorous fish ⟶ birds

In the first food chain, discrimination against cobalt-57,58,60,was progressive throughout the trophic levels. Iron-55,59 was actively concentrated in the omnivorous fish, and it accounted for a reduced percentage of the total radioactivity in the carnivorous fish due to the presence of large amounts of zinc-65.

In the second food chain the birds, which feed primarily upon omnivorous fish and secondarily upon squid, did not retain significant amounts of the radioisotopes of cobalt or iron but retained a major part of the ingested zinc-65.

ACKNOWLEDGMENTS

This work was performed under contract number AT(45-1) S40 between the U.S. Atomic Energy Commission and the University of Washington.

REFERENCES

Arrhenius, G. 1959. Sedimentation on the ocean floor. In Ph. H. Abelson, (ed.), Researches in Geochemistry. John Wiley and Sons, New York. pp. 1-24.

Biddulph, O. 1951. The translocation of minerals in plants. In E. Truog, (ed.), Mineral Nutrition of Plants. Univ. of Wisconsin Press, Madison, Wisconsin. pp. 261-275.

Boroughs, H., W.A. Chipman, and T.R. Rice. 1957. Laboratory experiments on the uptake, accumulation, and loss of radionuclides by marine organisms. In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences, National Research Council, Washington. Publ. 551. pp. 80-87.

Conley, W.R. 1954. Hanford atomic-energy plant - joint discussion. Water supply. J. Am. Water Works Assoc. 46: 629-633.

Ketchum, B.H., and W.L. Ford. 1952. Rate of dispersion in the wake of a barge at sea. Trans. Am. Geophys. Union 33: 680-684.

Knapp, H.A. 1960. External gamma doses and dose rates from fallout from nuclear explosions. Fallout Studies Branch, Div. Biol. Med., U.S. AEC report. (in manuscript).

Krumholz, L.A., and R.F. Foster. 1957. Accumulation and retention of radioactivity from fission products and other radiomaterials by freshwater organisms. In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences-National Research Council, Washington. Publ. 551, pp. 88-95.

---, E.D. Goldberg, and H.A. Boroughs. 1957. Ecological factors involved in the uptake, accumulation, and loss of radionuclides by aquatic organisms. In The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences, National Research Council, Washington. Publ. 551. pp. 69-79.

Lowman, F.G. 1958. Radionuclides in plankton near the Marshall Islands. Univ. of Washington, U.S. AEC report UWFL-54. 31 pp.

---. 1960. Marine biological investigations at the Eniwetok Test Site. In Disposal of Radioactive Wastes, Vol. II. Intern. Atomic Energy Agency, Vienna. pp. 105-138.

Lowman, F.G. 1962. Radionuclides in plankton and tuna from the Central Pacific. In this volume, pages 145-149.

---, R.F. Palumbo, and D.J. South, 1957. The occurrence and distribution of radioactive non-fission products in plants and animals of the Pacific Proving Ground. Univ. of Washington, U.S. AEC report UWFL-51. 61 pp.

---, R.F. Palumbo, D.J. South and D.R. Weeks. 1959. The biological and geographical distribution of W185 in the vicinity of the Eniwetok Test Site, April-September, 1958. Univ. of Washington, U.S. AEC report UWFL-57 (Secret). 61 pp.

Mason, B. 1958. Principles of Geochemistry. Second ed., John Wiley and Sons, New York. vii, 310 pp.

Meyer, B.S. and D.B. Anderson. 1947. Plant Physiology. D. Van Nostrand Co., Inc. New York. x, 696 pp.

---, D.B. Anderson, and R.H. Bonning. 1960. Introduction to Plant Physiology. D. Van Nostrand Co., Princeton, N.J. 541 pp.

Miller, E.V. 1957. The Chemistry of Plants. Reinhold Pub. Corp., New York. 174 pp.

Moeller, D.W. 1957. Radionuclides in reactor cooling water-identification, source, and control. Oak Ridge Natl. Lab. U.S. AEC report ORNL-2311. 161 pp.

DOE ARCHIVES

Mori, T., and M. Saiki. 1956. Studies on the radioactive material in the radiologically contaminated fishes. In Researches in the Effects and Influences of the Nuclear Bomb Test Explosions Vol., II, Japan Society for the Promotion of Science. Ueno, Tokyo. pp. 889-894.

Nagasawa, K., I. Kawashiro, G. Nakayama, T. Kashima, J. Serizawa, S. Ohkuma, S. Kawamura, and S. Nishizaki. Results of investigations and examinations on the influences upon sea foods in Japan caused by the hydrogen bomb experiments at Bikini Atoll, 1954. In Researches in the Effects and Influences of the Nuclear Bomb Test Explosions, Vol. II, Japan Society for the Promotion of Science. Ueno, Tokyo. pp. 895-916.

Palumbo, R.F., and F.G. Lowman. 1958. The occurrence of antimony-125, europium-155, iron-55, and other radionuclides in Rongelap Atoll soil. Univ. of Washington, U.S. AEC report UWFL-56. 27 pp.

---, ---, A.D. Welander, and D.R. Weeks, 1959. Distribution of radioactivity in sea water and marine organisms following an underwater detonation at the Eniwetok Test Site. Univ. of Washington, U.S. AEC report UWFL-58 (Secret).

Rankama, K., and Th. G. Sahama. 1950. Geochemistry. Univ. of Chicago Press, Chicago. 912 pp.

Rediske, J.H., and O. Biddulph. 1953. The absorption and translocation of iron. Plant Physiol. 28: 576-593.

Rinehart, R.W., S.H. Cohn, J.A. Seiler, W.H. Shipman, and J.K. Gong. 1955. Residual contamination of plants, animals, soil, and water of the Marshall Islands one year following Operation Castle fallout. U.S. Naval Radiological Defense Lab., San Francisco, report USNRDL-454. viii, 29 pp.

Robeck, G.G., C. Henderson, and R.C. Palange. 1954. Water quality studies of the Columbia River. U.S. P.H.S. Robert A. Taft Sanitary Engineering Center, Cincinnati. 99 pp. plus appendices A,B,C, and D.

Saiki, M., S. Okano, and K. Mori. 1955. Studies on the radioactive material in the radiologically contaminated fishes caught at the Pacific Ocean in 1954. Bull. Japan Soc. Sci. Fisheries 20: 902-906.

Seymour, A.H., E.E. Held, F.G. Lowman, J.R. Donaldson, and D.J. South. 1957. Survey of radioactivity in the sea and in pelagic marine life west of the Marshall Islands. Univ. of Washington, U.S. AEC report UWFL-47. 49 pp.

Sherman, H.C. 1957. Essentials of Nutrition. Macmillan Co. New York, 505 pp.

Solovera, E.A., and N.A. Makarova. 1961. The effect of trace elements on the process of greening and on the stability of the chlorophyll-protein-lipoid complex. Fiziol. Rastenii (Transl.) 7: 347-350. Translated from Fizid. Rastenii 7:419-422 (1960).

South, D.J., and F.G. Lowman. 1955. In radiobiological survey of Rongelap and Ailinginae Atolls, Marshall Islands, October-November, 1955. Univ. of Washington, U.S. AEC report UWFL-43. 85 pp.

Underwood, E.J. 1956. Elements in Human and Animal Nutrition. Academic Press, New York. 430 pp.

Vinogradov, A.P. 1953. The elementary chemical composition of marine organisms. Sears Foundation for Marine Research, New Haven, Connecticut. xiv, 647 pp.

Webb, D.A., and W.R. Fearon. 1937. Studies on the ultimate composition of biological material. Part 1. Aims, scope and methods. Sci. Proc. Roy. Dublin Soc. 21: 487-504.

Welander, A.D. 1958. Radiobiological studies of the fish collected at Rongelap and Ailinginae Atolls. Univ. of Washington, U.S. AEC report UWFL-55. 30 pp.

Yamada, K., H. Tozawa, K. Amano, and A. Takase. 1955. Studies on the radioactivity in certain pelagic fish. III. Separation and confirmation of Zn65 in the muscle tissue of a skipjack. Bull. Japan Soc. Sci. Fisheries 20: 921-926.

Yoshii, G. 1956. Studies on the radioactive samples (especially "Katsuwonus vagans") collected by the "Shunkotsu Maru" in the Pacific Ocean in 1954. In Researches in the Effects and Influences of the Nuclear Bomb Test Explosions, Vol. II, Japan Society for the Promotion of Science, Ueno, Tokyo. pp. 917-936.

DOE ARCHIVES

DOE ARC

Lowman, F.G. 1958. Radionuclides in plankton near the Marshall Islands, 1956. Univ. of Washington, U.S. AEC report UWFL-54. 31 pp.

Islands. Univ. of Washington, U. S. AEC report UWFL-47. 57 pp.

Steinberg, E.P. 1960. The radiochemistry of zirconium and hafnium. National Academy of Sciences, National Research Council, Washington, D.C. Nuclear Science Series, NAS-NS3011. vi, 52 pp.

DOE ARCHIVES

Thomas, C.W., D.L. Reid, and L.F. Lust. 1958. Radiochemical analysis of marine biological samples following the "Redwing" shot series-1956. Hanford Atomic Products Operation, General Electric Co., U.S. AEC report HW-58674. 85 pp.

Timofeeva-Resovskaya, E.A., and N.V. Timofeev-Resovskii. 1959. Accumulation of chemical elements from water solutions by fresh-water organisms. II. Coefficient of accumulation of different radioisotopes by Limnea stagnalis. Byull. Moskov. Obshchestva Ispytatel. Prirody, Otdel. Biol. 63(5): 123-131. (Chem. Abstr. 53(8): abstr. 7444g).

Tomiyama, T., and K. Kobayashi. 1958. Direct uptake of radioisotopes by fish. Proceedings of the 9th Pacific Sci. Congr. Oceanography, Dept. of Science, Bangkok, Thailand. 16: 159-166.

Vinogradov, A.P. 1959. The Geochemistry of Rare and Dispersed Chemical Elements in Soils. 2nd edition. Translated from Russian by Consultants Bureau, Inc., New York. 209 pp.

DOE ARCHIVES