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ACCUMULATION AND LOSS OF COBALT AND CESIUM
BY THE MARINE CLAM, MYA ARENARIA,
UNDER LABORATORY AND FIELD CONDITIONS

F. L. Harrison

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Accumulation and Loss of Cobalt and Cesium

by the Marine Clam, Mya Arenaria, Under Laboratory and Field Conditions

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ABSTRACT

The accumulation of ^{60}Co and ^{137}Cs by clams was followed in the laboratory in aquarium systems in which the levels of radioactive and stable cesium and cobalt were held constant. At 3- to 21-day intervals during the 6-month accumulation period, groups of 8 animals were removed from the water and their soft tissues were dissected into 7 different organs and tissues. The concentrations of both ^{60}Co and ^{137}Cs in the edible tissues increased rapidly and then levelled off at concentrations of ^{60}Co that were about 200 times that of the water and of ^{137}Cs that were about 5 times that of the water. Variations in concentration among the body parts were larger for ^{60}Co than for ^{137}Cs .

The effect of stable element concentration in water on the accumulation rates were assessed in groups of animals maintained in seawater containing 0.5, 2.5, and 12.5 $\mu\text{g/litre}$ each of stable cobalt and cesium. Little regulation of cesium accumulation was observed at these concentrations; the rates of accumulation increased with the concentration in water. Some regulation of cobalt occurred at the higher concentrations.

The accumulation of ^{60}Co and ^{137}Cs was followed also in clams introduced into a discharge canal receiving radioactive waste from a boiling-water reactor. Groups of 6 animals were sampled at 3-week intervals and concentrations were measured in the pooled, total soft tissues. Results obtained in the field will be compared to those obtained in the laboratory.

Loss of ^{60}Co and ^{137}Cs was followed in animals that had accumulated a radioactive burden in the laboratory and then were transferred to unfiltered

oceanic water at a marine station. Loss of ^{60}Co by the whole clam was monophasic, that of ^{137}Cs was biphasic.

The kinetics of accumulation and loss were described by exponential equations. The rate constants of accumulation and loss and the steady-state concentration factors are being used in models to predict the dose to man from the consumption of animals exposed to radioactive releases.

INTRODUCTION

An important route of entry of radionuclides of cesium and cobalt from the ocean into man is via consumption of molluscs. Bivalve molluscs because of their source of food and method of feeding accumulate these radionuclides to concentrations that are higher than those of the water [1, 2, 3, 4, 5, 6, 7, 8].

Radiocesium and radiocobalt from nuclear device operations and from nuclear reactors and fuel reprocessing plants have been detected in bivalves, but their rates of accumulation and loss of the nuclides have been little studied. Information on the turnover of these elements in food products is of special importance because of the potential hazard of the long-lived radionuclides. Information on the turnover of the two elements obtained simultaneously is of special interest because they differ in physiological role, geochemistry, and chemical and physical properties.

The marine clam *Mya arenaria* was used in laboratory and field studies to assess the turnover rates of ^{60}Co and ^{137}Cs . This species has a wide distribution and is commonly harvested for food. The objectives of the studies were (1) to obtain turnover-rate constants that could be used in a mathematical model of an estuary to predict the changes in ^{60}Co and ^{137}Cs concentrations in the animals after appearance of the radionuclides in their ecosystem; (2) to evaluate the effects of food and concentrations of stable element on these rate constants, and (3) to obtain better understanding of the metabolism of cobalt and cesium in clams.

MATERIAL AND METHODS

Accumulation

Laboratory Experiments

Mya arenaria were collected from mud flats on the eastern shore of San Francisco Bay and maintained in our marine biology laboratory until they were entered into experiments. The aquaria were supplied with refrigerated, recirculated water obtained from the Steinhart Aquarium pipeline that extends 3-1/2 miles out into the ocean [9]. Water from the pipeline was filtered at the Steinhart Aquarium and then was transported to LLL in a fiberglass tank used exclusively for seawater.

Their accumulation of ^{60}Co and ^{137}Cs was followed in groups of 50 to 100 clams of uniform size (60 to 100 g). The number of animals was determined by the size of the aquarium; the density of clams did not exceed one per 4 litres of water. The levels of radionuclides and stable cobalt and cesium were held constant [10]. The water used in the aquarium systems was from the same source as that used in our circulating seawater system described above; the temperature was held at 10 to 12°C. During the experiment stable and radioactive nuclides of cobalt and cesium were added

in ionic form. The specific activities were held constant for the duration of the experiment. Because of the long half-lives of the radionuclides, no decay corrections were made.

In those experiments dealing with accumulation of radionuclides from water alone, the aquaria were devoid of sand and gravel. They were emptied and wiped clean, and the water was totally exchanged once a week to minimize the growth of microorganisms. For those experiments dealing with accumulation from food and water, the aquaria had a substratum of sand and gravel, only one-third to one-half of the water was exchanged weekly, and suspensions of radioactive diatoms were added to the water once weekly. The water was circulated and aerated continuously to minimize fluctuations in concentration and to insure adequate oxygenation. The concentrations of the radionuclides and the temperature of the water were checked daily. Any clams that died were removed as soon as they were detected.

The diatoms (Phaeodactylum tricornutum) were made radioactive by growing them in 1-litre batches of culture medium to which ionic ^{60}Co and ^{137}Cs were added to the same specific activity as the aquaria water; the concentration of the stable Cs and Co was five times that of the aquarium water. The original pure culture of the diatom was obtained from Scripps Oceanographic Institute. Suspensions of diatoms were given to the clams at least one week after the initial inoculation of the culture medium. By this time, more than 90% of the activity was removed from the solution and the exponential growth phase of the diatoms was completed; the cultures at this time contained about 1 cm^3 cells per litre, measured as packed cells.

Groups of 8 animals were removed from the water at 3- to 21-day intervals. The soft tissues were removed from the shells and dissected into the following parts: mantle; gills and labial palps; digestive gland and stomach; intestine and gonad; siphon muscle and muscular margin of mantle; adductor and foot muscle; "peel" (the nonliving material on the exterior of the siphon and mantle edge); body fluid (pallial fluid and circulating fluid). Each dissected tissue was weighed and then counted in a gamma well counter. The data were processed by a computer program that corrected for background, efficiency, and overlap in the energy levels of emissions of the two radionuclides.

Field Experiments

Two hundred clams from the same source as those used in the laboratory experiments were transported to Humboldt Bay, California. There they were placed in plastic baskets suspended from a raft in the center of the discharge canal of the Pacific Gas and Electric reactor [11]. Thereafter the clams were taken from the water at 7- to 21-day intervals, removed from their shells, and dissected into peel and remaining soft tissues. The tissues were lyophilized to obtain dry weights, ashed in a muffle furnace for

48 hours at 450°C, and then counted on a Ge(Li) detector for quantitation of the radionuclides [12].

The concentrations of ^{60}Co and ^{137}Cs in the aquarium water were determined in 30-gallon-integrated samples collected over 1-week intervals. Immediately after collection the water was acidified with HCl to a final pH between 1 and 2. Sample analysis was initiated in the field where carrier was added the day previous to the precipitation of the nuclides by methods described previously [11]. The methods were tested under the conditions of collection and precipitation used in the field. The recovery of radionuclides was 87% or greater for ^{54}Mn , ^{60}Co , ^{65}Zn , ^{133}Ba and ^{137}Cs .

Sediment was collected by allowing it to settle onto a container in the raft during the period of water-sampling. It was weighed and analyzed for ^{60}Co and ^{137}Cs . The results were used to calculate the amount of siltation to which the animals were exposed.

Loss

A group of clams was maintained without food in an aquarium system in the laboratory for 48 days under the same conditions as those described for accumulation, that is, both radioactive and stable nuclides were held constant. The concentrations of stable cobalt and cesium were 0.5 µg/litre. The animals were then transported to the Humboldt State University Marine Laboratory at Trinidad Head, California. There they were placed in aquaria receiving once-through, untreated, unfiltered seawater containing the food organisms and other particulate material to which the clams are exposed normally. At suitable intervals, four animals were removed from the water, dissected and processed exactly as in the accumulation experiments.

Twelve animals were selected also for whole-body counting during this loss period. The animals were removed from the water, drained, placed in plastic bags, and positioned on a template on a 3-inch NaI crystal for the determination of ^{60}Co and ^{137}Cs activities. At first they were counted at two-day intervals; this was increased to weekly and biweekly intervals as the rates of loss decreased.

RESULTS

Accumulation Under Laboratory Conditions

Cesium

Accumulation from water and food. The accumulation of ^{137}Cs from the water and food was followed in the laboratory for 179 days. The concentration of stable cesium in the water was 0.5 µg/litre (0.0035 µM) and that of ^{137}Cs was 0.6 µCi/litre. The concentration of ^{137}Cs in the clams

increased rapidly at first and then more slowly (Figure 1). In this graph and in subsequent considerations of concentration, the data are expressed as concentration factors; the concentration factor (CF) is defined as the concentration per gram of animal wet tissue divided by the concentration per milliliter of water. The steady-state CF was about 4.6 for the whole body and about 3 in the body with the peel removed; data are presented for both because 30 to 40 percent of the activity was in the nonliving peel, which sometimes is removed in preparation for consumption.

The accumulation of an element can involve a number of different processes. If the rate-determining process can be described mathematically, a model can be developed to predict changes in concentration with time for the stable and/or radioactive element. The accumulation of cesium in these experiments appeared to be described mathematically by

$$Cs(t) = Cs_s \left(1 - e^{-k_o t} \right) \quad (1)$$

where $Cs(t)$ is the concentration of tagged cesium in the animal at time t , Cs_s is the concentration of tagged cesium in the animal at steady-state conditions of uptake and loss, and k_o is the biological loss-rate constant. Since the cesium concentration in the aquarium water was held constant, the CF values for cesium can be substituted for the cesium concentration terms to give

$$CF(t) = CF_s \left(1 - e^{-k_o t} \right) \quad (2)$$

where $CF(t)$ is the CF of cesium in the animal at the time t , and CF_s is the steady-state CF. By rearranging and taking the logarithm of equation (2), an equation of a straight line is obtained, the slope of which is the loss-rate constant, k_o :

$$\ln \left[\frac{CF_s - CF(t)}{CF_s} \right] = -k_o t. \quad (3)$$

The loss-rate constant for cesium accumulation for the whole body and for the body with the peel removed was 0.16. A CF_s value of 4.6 was approximated for the whole body and a value of 3 was approximated for the body with the peel removed. Equation (2), with these values and rate constants, was used to calculate the curves for changes in CF with time shown in Figure 1.

Changes in concentration of ^{137}Cs were followed also in various parts of the clam body. In the peel, the CF value was about 20 at 14 days;

this tissue had the highest CF values. The CF values in the peel and shell (Table I) were more variable than those of the other tissues. Since both these structures are external and nonliving, the variability may be due to changes in the accumulation of cesium by microorganisms living on their surfaces rather than to changes in the rate of incorporation of cesium into their matrices. The CF values determined for the mantle, gills, muscles, and digestive gland and stomach were very similar, approximately 10. However, this level was reached more slowly in the muscle than in the other tissues (Figure 2).

The steady-state CF value for the remaining visceral mass was lower than that for the digestive gland and stomach, as was also the rate of accumulation. These differences may indicate that the digestive gland and stomach are sites of absorption of cesium and/or that they are metabolically more active. Frequently, the gonad, which makes up most of the visceral mass, contains large amounts of lipid; since lipid-rich cells are typically low in potassium, the cesium levels would be expected to be low also.

Blood had the lowest CF values; the concentration was about the same as in the water. Low extracellular cesium is characteristic of animals in general; thus, extracellular cesium would be expected to be low in clams, whose body fluid contains very few circulating cells.

Steady-state conditions of uptake and loss appeared to have been reached in all the body parts examined (Table I). From these data, CF_s values were estimated, and biological loss-rate constants, biological half-times, and cesium fluxes were calculated (Table II). The CF_s and rate-constant values were used in Equation (2) to calculate the changes in concentration with time for representative tissues (Figure 2).

Biological half-times determined from the data on accumulation were similar for some tissues. Values of about 2 days were obtained for the gills and labial palps, for the digestive gland and stomach, for the body fluid, and for the peel. Except for the body fluid, large quantities of water circulate over or through these parts and more rapid turnover could be expected. Mantle and remaining visceral mass had half-times of approximately 4 days whereas the muscle had the longest half-time, 15 days.

The cesium flux in the tissue is the product of the steady-state concentration factor, the biological loss-rate constant, and the concentration in water. When the flux is expressed in micrograms per day per gram tissue, the average movement of cesium across cells can be compared from one body part to another. When the flux is expressed in micrograms per day per body part, the participation of the part in the body metabolism of cesium can be assessed. The largest flux of cesium both on a gram and on a tissue basis is in the peel. The smallest flux on a gram basis is in the body fluid and on a tissue basis in the mantle.

Effect of concentration of stable cesium. To predict the amount of radiocesium accumulated by an organism, it is necessary to know if the concentration of the stable nuclide is under metabolic control. To test for a homeostatic mechanism for cesium, clams were exposed to increased concentrations of cesium in the water in an attempt to saturate any existing regulatory mechanism.

Accumulation by clams of ^{137}Cs from water only (excluding diet) was followed at several concentrations of stable cesium in the water: 0.5 $\mu\text{g/litre}$ (the same as in the above experiment), 2.5 and 12.5. The concentration factors determined for the whole body and the body with the peel removed were approximately the same (data for the latter are shown in Figure 3). The clam appears to have no regulation of cesium concentration in the range of concentrations tested. However, the cesium fluxes in the tissues would be 5-fold larger in the animals living in water containing 2.5 μg cesium per litre, and 25-fold larger in those living in water containing 12.5 μg cesium per litre. Also included in Figure 3 are data from the experiment in which the clams were exposed to radionuclides both in their aquarium water and in their food. No significant differences were detected between these CF values and those from the experiment in which the radionuclide was supplied only in the water.

Cobalt

Accumulation from water and food. The accumulation of ^{60}Co was followed in clams in water maintained at a concentration of 0.5 $\mu\text{g/litre}$ (0.008 μM). The CF values for ^{60}Co were considerably higher than those for ^{137}Cs determined in the same clams (Figure 4). The CF value was much lower in the body with the peel removed, since 65 to 80 percent of the ^{60}Co activity in the clam body resided in the peel.

Variations in concentration among the body parts were greater for ^{60}Co than ^{137}Cs . In the peel, CF values higher than 2000 were determined (Table III). The next highest, about 300 were in the digestive gland and stomach. In the mantle, the gills and labial palps, the remaining viscera, and the muscle, they approached 100. However, the rates of accumulation of the ^{60}Co differed among these tissues. The lowest CF values were found in the body fluid. Representative data are shown graphically in Figure 5.

From the experimental data for ^{60}Co , like that for ^{137}Cs , CF_s values were approximated, and biological loss-rate constants, biological half-times, and radionuclide fluxes were calculated (Table IV). In all the tissues, the CF_s values as well as the biological half-times for ^{60}Co exceeded those for ^{137}Cs . The turnover of ^{60}Co was fastest in the digestive gland and stomach and slowest in the body fluid. Large fluxes of ^{60}Co were observed in the digestive gland and stomach and in the peel (on a gram basis).

Effect of concentration of stable cobalt. When the cobalt concentration in the aquarium water was increased from 0.5 to 2.5 and to 12.5 $\mu\text{g/litre}$, the CF values in clams exposed to the water for the same time interval decreased (Figure 6). The reduction was not linear, however; i.e., a five-fold increase in the water concentration did not result in a five-fold decrease in the CF. In Figure 6 are included data from the experiment in which the clams were exposed to ^{60}Co both in their water and in their food; usually the CF values were higher in these animals than in those exposed to the radionuclide via water alone.

Accumulation under Field Conditions

The accumulation of ^{60}Co and ^{137}Cs was followed for 174 days in clams introduced into a discharge canal receiving radioactive waste from a boiling water reactor. Radionuclides are introduced into the water flowing through the discharge canal on an intermittent basis, usually weekly [13]. Since the water contains considerable amounts of suspended material, radionuclides could have been accumulated by the clams from the water, food and/or sediment. The concentration of ^{60}Co in the unfiltered water ranged between 1 and 3 $\mu\text{Ci/litre}$, that of ^{137}Cs between 0.3 and 1.5 $\mu\text{Ci/litre}$, and that of stable cobalt between 0.1 and 0.4 $\mu\text{g/litre}$ [14]. The concentration of stable cesium is assumed to be about 0.4 $\mu\text{g/litre}$, the concentration in most seawater [15].

Cesium

In all the samples of clam tissues, the levels of ^{137}Cs were too low for accurate determination of the concentration.

Cobalt

The concentration of ^{60}Co reached 10,000 to 20,000 $\mu\text{Ci/kg}$ in the peel and about 1000 $\mu\text{Ci/kg}$ in the body with the peel removed (Figure 7). The very high concentrations in the peel were possibly due to surface contamination with settled silt, which had high concentrations of ^{60}Co (20,000–30,000 $\mu\text{Ci/kg}$).

Concentration factors calculated from the ^{60}Co data are of questionable value because the concentrations in water were changing continuously. If an average water concentration of 2 $\mu\text{Ci/litre}$ is assumed for the period during which intermittent releases were relatively constant in ^{60}Co (Day 75 to 120), the CF value is approximately 500 for the body with the peel removed.

Loss of ^{60}Co and ^{137}Cs under Field Conditions

Clams that had accumulated ^{60}Co and ^{137}Cs for 48 days in the laboratory were transferred to unfiltered oceanic water, and changes in concentration of the radionuclides were followed in a group of living clams via whole-body counting as well as in the body parts of groups that were

dissected and counted. During the 177-day loss period, stable cobalt and cesium were available to the animals from ions and molecules in solution in the water and from living and nonliving material in suspension.

Cesium

The loss-rate constants determined individually in 12 intact clams were quite similar; the loss followed a biphasic curve (Figure 8). The short-lived component contained about 65% of the activity and had a half-time of about 2 days; the long-lived component had a half-time of 75 days.

In the dissected clams, concentrations of ^{137}Cs in the whole body with the peel removed decreased rapidly at first and then more slowly (Table V). The value for concentration of stable cesium in water used in the calculation of CF values was $0.5 \mu\text{g/litre}$, that in the water in which the animals had accumulated the ^{137}Cs .

The changes in CF of ^{137}Cs during the loss period in the whole body and in the body with the peel removed indicated the presence of two components. About 75 percent of the activity was in the short-lived component, which had a $T_{1/2}$ of 4 days. The long-lived component, containing 25 percent of the activity, had a $T_{1/2}$ of 60 days in the whole body and 41 days in the body with the peel removed (Table II). The data were analyzed by the method described by Baptist and Price [16] and by Jefferies and Hewett [17]. In the least square analyses of this and subsequent data, individual rather than mean CF values were used because of the small size of the samples.

In all the body parts, the ^{137}Cs appeared to be in two pools. The short-lived pool varied in percentage of total activity from one body part to another, but was always the larger of the two. Turnover was rapid in the short-lived pools; the $T_{1/2}$ values ranged from 1 to about 5 days (Table II).

Steady-state CF values calculated from the loss-experiment data were quite similar to those from the data obtained from the accumulation experiment in the laboratory, except for the digestive gland and stomach and the remaining visceral organs. Greater differences in those organs suggest that accumulation and loss of cesium may follow different pathways.

The calculated fluxes of cesium in all the body parts were greater during the loss period than during the accumulation period. The differences can be attributed in part to resolution of only short-lived pools from the analyses of accumulation data, because of variability within the samples.

Cobalt

The decrease in concentration of ^{60}Co determined by whole-body counting of clams was exponential and monophasic (Figure 9). The rate of loss was slower for ^{137}Cs and was more variable from clam to clam. The $T_{1/2}$ values ranged from 100 to 300 days.

In the dissected clams, the loss of ^{60}Co in the whole body and in the body with the peel removed also followed a monophasic curve. CF_s , k_o , $T_{1/2}$, and fluxes were calculated from the loss data (Table VI) and are presented in Table IV.

Among the body parts, two pools of ^{60}Co appeared to be present; except in the visceral organs. However, the major fraction of the activity was in pools with long biological half-times.

The biological loss-rate constants were obtained from data from the accumulation as well as from loss experiments. Agreement between values obtained by the two kinds of calculations was poorer for ^{60}Co than for ^{137}Cs .

Generally, for the pools containing most of the activity, the lower rate constants were obtained from loss experiments than from accumulation experiments; exceptions were the body fluid and the digestive gland and stomach. Since the rate constants are used in the calculations of the other parameters, these too differ in value. However, although the absolute values do not agree, the trends are similar; i.e., the same body parts had high and low fluxes and high and low CF_s values.

DISCUSSION

Cesium

The metabolism of cesium in bivalve molluscs, like that in other animals, is probably related to that of potassium. The high intracellular concentration of potassium in cells is generally the result of the coupling of the inward movement of potassium to the active outward transport of sodium [18]. It is not known whether the movement of cesium in bivalve molluscs is coupled to a sodium pump, but cesium, like potassium, is considerably more concentrated intracellularly than extracellularly.

Concentration factors for cesium in the same range as those for Mya arenaria have been determined previously for other clams [7, 19, 20, 21] but, generally, rate constants have not been reported. Bryan [3] reported a half-time of accumulation of 65 hours for the whole body of Mytilis galloprovincialis.

No concentration effect on the steady-state concentration factor for cesium was detected in the range of concentration tested here. Bryan [3]

described the effect of the addition of carrier on CF values for ^{137}Cs in the isopod crustacean Sphaeroma hookeri. When the concentration of stable cesium was increased by a factor of 3.3×10^4 , the CF value was reduced from 6.3 to 5.6. In the freshwater clam, Anodonta nuttalliana, the CF for ^{137}Cs determined in water containing cesium in the normal environmental range increased only when the potassium concentration was reduced to a low level [22]. Wolfe and Coburn [7] reported increased CF values with decreased salinity. At 10°C , the predicted CF value for ^{137}Cs was increased from 4.47 to 11.6 when the salinity was reduced from 20 ‰ to 1 ‰.

The concentration of potassium in seawater is about 10 mM, about 3×10^6 higher than that of cesium ($0.0035 \mu\text{M}$). Even if cesium is transported by the same mechanism as potassium, competition for the same sites would have little effect at the normal range of cesium concentrations in seawater. Consequently, in mathematical models of most estuaries the effect of stable cesium concentration on the accumulation of ^{137}Cs can be readily predicted.

The relatively good agreement in the calculated values of CF_s , k_0 , $T_{1/2}$, and fluxes between values from laboratory accumulation data, and those from field loss data suggests that the chemical form of the radionuclide was similar and that the major source of the ^{137}Cs for the clams is from the water since no significant differences were detected among them in the two situations.

Cobalt

The general characteristics of radionuclides of cobalt in seawater and their CF values in marine molluscs have been reviewed by Polikarpov [21]. Our values determined in the body of Mya arenaria are within the range of those reported by Polikarpov [21] and subsequently by others [6, 8].

Variations in CF_s among the body parts was much greater for ^{60}Co than for ^{137}Cs . High CF values for the peel are probably due to adsorption of the radionuclide since the material is nonliving and would not be metabolically active. Radionuclides of zinc and manganese were found to accumulate in the peel also [23].

The component of the peel that binds radionuclides has not been identified. The peel appears to be an extension of the organic matrix of the shell. This matrix is formed by the mantle and chemical analysis has shown the presence of three fractions: a protein, a scleroprotein, and a polypeptide [24]. Mucopolysaccharides are associated with the matrix also.

The lower biological loss rate constants from loss experiments compared to those from accumulation experiments may indicate that cobalt follows a different metabolic pathway during accumulation and loss. Some

metabolic regulation of cobalt was suggested by the experiments in which the concentration of stable cobalt in the water was increased. Thus, cobalt may be deposited more rapidly in a compartment than it can be mobilized from it.

The CF_s for the body with the peel removed estimated from the ^{60}Co data obtained in the accumulation experiment conducted in the discharge canal were approximately 5-fold greater than those obtained in laboratory accumulation and field loss experiments. The higher CF values may have been related to the heavy siltation that occurred in the discharge canal during the interval the CF_s was approximated. The concentration of ^{60}Co was high in the sediment and its presence on the labial palps and gills and on or in the digestive organs would result in elevated CF values. In addition, ^{60}Co associated with particles may have been removed from the particles during their passage through the gut. The gut contents undergo a decrease in pH during transit and the residence time (several days) is sufficient for desorption and/or dissolution to have occurred.

Siltation also may have affected the availability of the ^{60}Co . The layer of silt in the baskets in which the clams were maintained probably contained anaerobic bacteria synthesizing cobaltamine. Thus, ^{60}Co in the water may have been present in both organic and inorganic forms.

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TABLE I

Cesium-137 concentration factors in Mya arenaria during the accumulation period

Body part		Duration of accumulation (days)										
		3	7	14	35	53	74	95	116	137	158	179
Mantle	mean	5.6	7.1	8.4	9.2	8.9	11.1	10.7	10.2	11.8	9.0	8.4
	s. d.	0.8	1.3	1.2	1.0	0.8	1.3	1.1	1.3	4.2	1.0	1.3
Gills & labial palps	mean	5.2	7.4	8.2	9.1	8.8	10.7	9.6	10.1	10.8	9.2	8.1
	s. d.	0.4	0.8	0.9	0.4	0.8	1.1	0.8	1.2	2.3	0.9	0.8
Muscles	mean	2.1	3.6	5.2	8.2	8.1	10.4	10.9	11.1	11.0	10.5	9.3
	s. d.	0.2	0.5	0.6	0.4	0.5	0.4	1.0	0.9	1.1	0.6	1.2
Digestive gland & stomach	mean	5.4	9.0	9.8	9.6	9.4	10.6	10.0	11.3	10.8	10.1	8.9
	s. d.	1.2	1.0	0.9	0.5	0.6	0.8	0.7	1.8	2.3	0.8	0.6
Visceral remains	mean	2.1	2.5	3.4	3.3	2.8	4.5	5.5	5.4	5.6	4.3	3.7
	s. d.	0.3	0.5	0.4	1.0	0.8	1.1	1.3	1.3	1.7	0.7	0.8
Body fluid	mean	0.9	0.9	0.9	1.2	0.7	1.0	0.9	1.1	1.2	1.2	1.1
	s. d.	0.1	0.1	0.2	0.1	0.1	0.4	0.2	0.1	0.1	0.2	0.1
Peel	mean	16.1	19.0	19.9	23.2	15.2	26.3	19.9	19.9	24.3	14.4	12.2
	s. d.	1.8	1.6	4.2	6.5	2.3	5.1	3.6	4.6	6.1	3.8	1.8
Total body	mean	2.6	3.3	3.7	4.2	3.5	5.5	5.0	5.0	6.0	3.9	3.5
	s. d.	0.3	0.3	0.4	0.6	0.7	0.8	0.5	0.7	1.5	0.4	0.5
Shell	mean	1.7	1.6	1.6	2.2	1.4	3.3	4.1	3.1	4.4	3.3	2.6
	s. d.	0.4	0.4	0.8	1.0	0.3	0.7	1.5	1.0	1.2	1.2	0.9

TABLE II

Cesium-137 steady-state concentration factors, biological loss-rate constants, biological half-times, and fluxes in Mya arenaria determined during accumulation and loss experiments

Body part	CF _s	k _o (day ⁻¹)		Fraction SL ^a	T _{1/2} (days)		Flux in body part	
		SL	LL ^c		SL	LL	µg/day/g (1 × 10 ⁴)	µg/day/part ^b (1 × 10 ⁴)
		(a) Accumulation						
Whole body	4.6	0.16	-----	1.0	5.0	----	3.7	180.
Body (peel removed)	3.0	0.16	-----	1.0	5.0	----	2.4	110.
Mantle	9.5	0.17	-----	1.0	4.1	----	8.1	2.9
Gills & labial palps	9.5	0.29	-----	1.0	2.4	----	14.	22.
Muscles	10.	0.047	-----	1.0	15.	----	3.0	21.
Digestive gland & stomach	10.	0.32	-----	1.0	2.2	----	16.	11.
Visceral remains	4.0	0.17	-----	1.0	4.1	----	3.4	26.
Body fluid	1.1	0.33	-----	1.0	2.1	----	1.6	52.
Peel	20.	0.32	-----	1.0	2.2	----	32.	120.

^aShort-lived pool.

^bWeight of part i.e. that determined in a hypothetical clam with body weight of 50 g.

^cLong-lived pool.

TABLE II (Cont.)

Cesium-137 steady-state concentration factors, biological loss-rate constants, biological half-times, and fluxes in Mya arenaria determined during accumulation and loss experiments

Body part	s	k_o (day ⁻¹)		Fraction	$T_{1/2}$ (days)		Flux in body part	
		SL	LL	SL ^a	SL	LL	μg/day/g	μg/day/part ^b
				(1 × 10 ⁻¹)			(1 × 10 ⁻⁴)	
(b) Loss								
Whole body	4.6	0.19	0.011	0.75	3.6	60.	5.7	260.
Body (peel removed)	3.1	0.19	0.017	0.77	3.6	41.	4.0	180.
Mantle	12.	0.15	0.0094	0.95	4.6	74.	8.8	3.2
Gills & labial palps	10.	0.54	0.045	0.85	1.3	15.	14.	22.
Muscle	7.0	0.21	0.021	0.65	3.3	33.	5.1	36.
Digestive gland & stomach	16.	0.15	0.050	0.66	4.6	14.	9.3	6.0
Visceral remains	7.9	0.20	0.023	0.77	3.5	30.	7.1	53.
Body fluid	1.0	0.68	0.022	0.80	1.0	32.	1.6	46.
Peel	18.	0.45	0.0084	0.72	1.5	82.	42.	150.

^a Short-lived pool.

^b Weight of part is that determined in a hypothetical clam with body weight of 50 g.

^c Long-lived pool.

TABLE III
Cobalt-60 concentration factors in *Mya arenaria* during the accumulation period

Tissue		Duration of accumulation (days)										
		3	7	14	35	53	74	95	116	137	158	179
Mantle	mean	7.4	10.4	15.3	41.0	41.6	58.9	63.4	57.2	86.7	86.6	84.0
	s. d.	3.6	3.8	3.4	13.6	11.6	18.7	20.5	15.2	46.6	45.6	40.0
Gills & labial palps	mean	4.3	7.1	10.8	26.6	28.3	41.8	46.8	49.8	59.1	83.8	95.0
	s. d.	1.0	1.3	2.2	8.9	4.5	11.9	20.6	10.5	13.8	25.4	33.0
Muscles	mean	2.6	4.0	8.4	20.1	21.6	40.6	62.2	27.9	49.5	66.4	80.8
	s. d.	0.5	1.2	3.9	8.6	7.2	26.2	25.2	6.5	23.0	20.8	27.0
Digestive gland & stomach	mean	39.8	64.0	103.1	278.0	168.0	248.1	234.9	289.2	296.7	361.6	307.3
	s. d.	24.2	30.5	45.1	78.9	85.8	112.2	172.4	162.5	86.2	92.1	116.0
Visceral remains	mean	7.4	8.0	16.6	25.9	26.4	50.0	54.9	54.9	55.4	78.8	83.7
	s. d.	5.0	1.4	5.2	9.7	6.9	17.6	18.9	18.2	19.8	18.6	27.7
Body fluid	mean	3.2	5.8	7.8	15.3	18.8	26.8	35.5	29.2	34.2	53.8	55.8
	s. d.	0.8	1.4	2.0	6.8	6.1	9.7	13.3	11.7	9.9	11.1	14.1
Pect	mean	116.	227.	441.	1136.	1356.	1426.	1793.	1621.	1731.	2122.	2128.
	s. d.	23.	57.	93.	350.	367.	251.	668.	306.	473.	583.	573.
Total body	mean	11.5	21.7	40.0	89.8	121.6	155.1	194.0	168.8	194.0	236.0	221.4
	s. d.	2.3	4.2	8.0	20.3	60.8	15.0	65.0	33.6	54.0	59.0	7.3
Shell	mean	10.3	14.6	23.0	62.3	120.2	74.2	91.8	100.0	95.4	214.0	183.0
	s. d.	3.4	5.8	9.2	31.0	48.0	18.8	10.8	18.0	16.3	53.0	48.0

TABLE IV

Cobalt-60 steady-state concentration factors, biological loss-rate constants, biological half-times, and fluxes in Mya arenaria determined in accumulation and loss experiments

Body part	CF _s	k _o (day ⁻¹)		Fraction SL ^a	T _{1/2} (days)		Flux in body part	
		SL	LL ^c		SL	LL	µg/day/g (1 × 10 ⁴)	µg/day/part ^b (1 × 10 ⁴)
(a) Accumulation								
Whole body	220.	0.015	-----	1.0	47.	----	16.	800.
Body (peel removed)	82.	0.0080	-----	1.0	87.	----	3.3	150.
Mantle	100.	0.011	-----	1.0	65.	----	5.5	2.0
Gills & labial palps	100.	0.0070	-----	1.0	99.	----	3.5	5.6
Muscles	100.	0.0074	-----	1.0	95.	----	3.7	26.
Digestive gland & stomach	350.	0.027	-----	1.0	26.	----	47.	31.
Visceral remains	100.	0.0088	-----	1.0	79.	----	4.4	33.
Body fluid	100.	0.0059	-----	1.0	120.	----	2.9	84.
Peel	2400.	0.012	-----	1.0	60.	----	130.	490.

^a Short-lived pool.

^b Weight of part is that determined in a hypothetical clam with body weight of 50 g.

^c Long-lived pool.

TABLE IV (Cont.)

Cobalt-60 steady-state concentration factors, biological loss-rate constants, biological half-times, and fluxes in Mya arenaria determined in accumulation and loss experiments

Body part	CF _s	k _o (day ⁻¹)		Fraction SL ^a	T _{1/2} (days)		Flux in body part	
		SL	LL ^c		SL	LL	μg/day/g (1 × 10 ⁴)	μg/day/part ^b (1 × 10 ⁴)
(b) Loss								
Whole body	790.	0.0055	-----	1.0	120.	----	22.	1100.
Body (peel removed)	120.	0.0030	-----	1.0	240.	----	1.8	83.
Mantle	87.	0.046	0.0024	0.33	15.	290.	1.2	0.4
Gill & labial palps	120.	0.23	0.0019	0.40	3.0	370.	14.	22.
Muscle	20.	0.0038	-----	1.0	180.	----	0.4	2.8
Digestive gland & stomach	100.	0.12	0.0082	0.78	5.7	84.	100.	66.
Visceral remains	150.	0.079	0.0041	0.72	8.8	170.	21.	160.
Body fluid	16.	0.010	-----	1.0	69.	----	0.8	23.
Peel	4800.	0.021	0.0038	0.31	33.	180.	49.	180.

^a Short-lived pool.

^b Weight of part is that determined in a hypothetical clam with body weight of 50 g.

^c Long-lived pool.

TABLE V

Cesium-137 concentration factors in Mya arenaria during the loss period.

Body Part		Duration of loss (days)								
		0	4	10	21	42	74	126	144	177
Total body	mean	7.5	3.7	2.54	1.63	1.08	0.62	0.74	.41	.10
	s.d.	1.2	0.35	0.10	0.47	0.78	0.31	0.32	.13	----
Body (peel removed)	mean	5.7	2.7	1.6	1.1	0.63	0.22	0.10	0.13	.05
	s.d.	0.68	0.56	0.11	0.39	0.22	0.08	0.05	0.08	----
Shell	mean	3.9	3.2	2.9	2.2	1.8	0.67	0.56	0.37	0.51
	s.d.	0.89	0.79	0.56	0.67	0.25	0.64	0.28	0.12	----
Mantle	mean	14.	7.0	2.7	1.3	0.58	0.36	0.11	0.09	0.08
	s.d.	1.3	3.9	1.2	0.31	0.07	0.19	0.12	0.09	----
Gills & labial palps	mean	13.	2.9	1.3	0.81	0.31	0.09	0.03	0.03	0.03
	s.d.	.76	1.5	0.17	0.15	0.05	0.06	0.03	0.03	----
Muscles	mean	12.2	6.7	4.3	3.0	1.6	0.84	0.36	0.21	0.01
	s.d.	4.1	0.71	0.2	0.42	0.26	0.31	0.21	0.14	----
Digestive gland & stomach	mean	15.	9.9	5.0	1.4	0.78	0.16	0.18	0.17	0.16
	s.d.	0.68	1.1	2.7	1.1	0.45	0.10	0.08	0.11	----
Visceral remains	mean	13.	6.3	3.6	1.4	1.6	0.55	0.15	0.11	0.05
	s.d.	0.8	2.3	0.61	0.55	1.1	0.37	0.11	0.03	----
Body fluid	mean	1.7	0.35	0.22	0.18	0.15	0.05	0.04	0.01	0.02
	s.d.	0.96	0.05	0.02	0.05	0.05	0.03	0.01	0.01	----
Peel	mean	28.	10.	8.2	5.7	5.2	3.4	4.5	4.0	0.82
	s.d.	10.5	3.2	1.6	2.0	4.0	2.7	2.5	4.6	----

TABLE VI

Cobalt-60 concentration factors in Mya arenaria during the loss period.

Body part		Duration of loss (days)								
		0	4	10	21	42	74	126	144	177
Total body	mean	180.	180.	190.	170.	90.	110.	110.	110.	110.
	s.d.	78.	79.	25.	53.	26.	55.	43.	16.	-----
Body (Peel removed)	mean	7.7	12.4	8.6	7.3	5.9	4.8	5.1	7.1	2.9
	s.d.	3.3	3.2	0.7	1.7	1.4	1.8	1.4	2.2	-----
Shell	mean	110.	74.	120.	75.	64.	71.	56.	48.	16.
	s.d.	71.	16.	18.	32	9.5	50.	16.	26.	-----
Mantle	mean	80.	45.	42.	31.	26.	19.	22.	-----	15.
	s.d.	50.	30.	29.	7.0	4.5	4.4	4.3	-----	-----
Gills & labial palps	mean	26.	23.	23.	16.	16.	14.	15.	16.	14.
	s.d.	3.3	8.1	13.	3.0	0.9	4.7	5.6	8.8	-----
Muscles	mean	28.	18.	22.	14.	13.	17.	18.	15.	7.2
	s.d.	21.	1.6	2.6	6.7	1.0	16.	12.	11.	-----
Digestive gland & stomach	mean	140.	81.	55.	34.	18.	12.	7.6	8.3	6.1
	s.d.	48.	33.	41.	16.	6.4	2.2	4.0	1.3	-----
Visceral remains	mean	76.	78.	38.	25.	14.	15.	14.	15.	9.2
	s.d.	40.	40.	15.	21.	5.3	9.6	4.4	10.	-----
Body fluid	mean	19.	18.	10.	14.	11.	7.8	7.0	3.3	2.5
	s.d.	6.2	4.9	1.4	6.3	4.4	3.1	0.9	0.9	-----
Peel	mean	2000.	1200.	1300.	1100.	600.	840.	740.	900.	350.
	s.d.	750.	610.	100.	300.	200.	470.	230.	400.	-----

FIGURE LEGENDS

- Figure 1. Cesium concentration factors for the whole body and the body with the peel removed determined during the accumulation period in the laboratory. Water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms were fed at weekly intervals. The symbols represent data points; the lines are calculated curves.
- Figure 2. Cesium concentration factors for representative clam body parts determined during the accumulation period in the laboratory. The water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms were fed at weekly intervals. The symbols represent data points; the lines are calculated curves.
- Figure 3. Cesium concentration factors in the body with the peel removed determined during accumulation periods in the laboratory. Δ , water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms were fed at weekly intervals. ∇ , water concentration was 0.5 $\mu\text{g/litre}$; no food was fed. $\bigcirc$, water concentration was 2.5 $\mu\text{g/litre}$; no food was fed. $\square$, water concentration was 12.5 $\mu\text{g/litre}$; no food was fed. The symbols represent data points; the line is a calculated curve.
- Figure 4. Cobalt concentration factors for the whole body and the body with the peel removed determined during the accumulation period in the laboratory. Water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms were fed at weekly intervals. The symbols represent data points; the lines are calculated curves.
- Figure 5. Cobalt concentration factors for representative clam tissues determined during the accumulation period in the laboratory. The water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms were fed at weekly intervals. The symbols represent data points; the lines are calculated curves.
- Figure 6. Cobalt concentration factors in the body with the peel removed determined during accumulation periods in the laboratory. Δ , water concentration was 0.5 $\mu\text{g/litre}$ and labeled diatoms fed at weekly intervals. $\bigcirc$, water concentration was 0.5 $\mu\text{g/litre}$; no food was fed. ∇ , water concentration was 0.5 $\mu\text{g/litre}$; no food was fed. $\square$, water concentration was 12.5 $\mu\text{g/litre}$; no food was fed. The symbols represent data points; the line is a calculated curve.

- Figure 7. Concentrations of ^{60}Co in the clam body with the peel removed, in the clam peel, in the settled silt, and in the water determined during the accumulation period in the discharge canal of the Pacific Gas & Electric Humboldt reactor.
- Figure 8. Percentages of the initial activity remaining in whole clams determined by whole-body counting during the loss period at the marine station. The symbols represent data points; the lines are calculated values.
- Figure 9. Cesium concentration factors for the whole body and the body with the peel removed determined during the loss period at the marine station. The symbols represent data points; the lines are calculated values.
- Figure 10. Cobalt concentration factors for the whole body and the body with the peel removed determined during the loss period at the marine station. The symbols represent data points; the lines are calculated values.

Fig. 2
F. Harrison

Fig. 3
J. Harrison

COBALT CONCENTRATION FACTOR

Fig. 4
F. Harfiro

FIG. 5
F. Harrison

Fig. 6
F. Harrison

^{60}Co pCi/kg

Fig. 7
F. Harrison

Fig. 8
F. Harrison

CESIUM CONCENTRATION FACTOR

Fig. 9
F. Harrison

Fig. 10
F. Harrison