Land Crabs and Fission Products at Eniwetok Atoll[1]

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PERIODIC STUDIES of the effects of the atomic testing program on the biota of the Marshall Islands have been made since 1946 by the staff of the Applied Fisheries Laboratory, University of Washington (Biddulph and Cory, 1953; Donaldson *et al.,* 1948, 1949, 1956; Palumbo, 1955; Seymour *et al.,* 1957; AEC reports UWFL-7, -16, -19, -23, -33, -42, -43). During the testing program at Eniwetok in 1954 a continuous biological survey was initiated. In this report the portion of the survey concerned with the uptake of radionuclides by the land hermit crab, *Coenobita perlatus* Edw. T.,[3] is presented. Results of possible ecological and physiological significance in the movement of strontium and cesium through the food cycle have been obtained. Strontium-90 concentration in the land crab skeleton may be a sensitive index of biologically available radiostrontium in the environment.

Coenobita is an omnivorous scavenger which feeds primarily on land plants and on detritus washed up on the beaches. It is primarily nocturnal and spends the daylight hours hidden in shrubs or under debris.

The crabs were taken from Belle Island (Bogombogo) which lies 2.3 nautical miles southwest of the site of the Mike test of 1952 and the Nectar test of 1954. This island is downwind from the site of these tests.

Prior to the Mike test Belle Island had a covering of shrubs, coconut palms, and trees (Palumbo, MS). The island was denuded by the blast in November 1952, but by April 1954 it had regained a heavy growth of shrubs, principally *Scaevola frutescens* and *Messerschmidia argentea.* The regrowth was from seedlings and stumps of old plants. A rookery of fairy and noddy terns had also become established. Belle Island was again denuded by the Nectar test of May 1954 save for stumps and some stripped branches. Dead birds and fish were found in the center of the island as well as along the shores. One dead *Coenobita* was found, but almost all of a population of about 50 in one pile of debris survived, probably because of the protection of the debris and their habit of quickly withdrawing into their shell when disturbed. It is probable that they withdrew at the first flash of light before the blast reached them.

Belle Island regained a lush cover of shrubs by August of 1954, less than three months after the Nectar test, and a fairy tern egg found three months later, in late November, marked the beginning of a new rookery on the island.

ACKNOWLEDGMENTS

The wholehearted cooperation of all members of the staff of the Applied Fisheries Laboratory, who at various times participated in the collection and preparation of samples, made this report possible. Miss Dorothy J. South supplied the results of the radiocesium, radiocerium, and some radiostrontium determinations. The cooperation of the U. S. Atomic Energy Commission Division of Biology and Medicine and the Eniwetok Field Office, Task Group 7.1, and Holmes and Narver greatly facilitated the field collecting.

METHODS

Collections were made at approximately daily intervals commencing with the third day following Nectar until the ninth day. Thereafter, the interval between collections was progressively lengthened to approximately monthly intervals. Three crabs were taken at each collection except that in three instances five, and in one instance, only two were taken.

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Samples of carapace (exoskeleton), muscle, hepatopancreas ("liver"), gut with its content, and gill were removed, either from the fresh or frozen specimens, at the Eniwetok Marine Biological Laboratory. The tissues were weighed at the time of dissection and then dried. The packaged dried samples, together with data cards, were sent by air mail to the Applied Fisheries Laboratory, University of Washington, for further processing.

The dried samples were ashed at temperatures up to 550° C. on stainless steel counting plates and were counted in an internal gas-flow counting chamber. The beta counts per plate were converted to total disintegrations per minute per gram (d/m/g) of wet tissue, as of the date of collection, by correcting for sample weight, geometry, backscatter, self-absorption, coincidence, and decay. (See WT–616 (UWFL-33) for a more complete discussion of these procedures.)

The decay corrections for all tissues except carapace were based on the decay rate of a soil sample collected at Belle Island the day after the Nectar shot. (This decay rate was determined by beta counting.) Decay corrections for the carapace were based on the decay rate of $Sr^{90} + Y^{90}$ and Sr^{89}, which constituted virtually 100 per cent of its activity at the time the chemical determinations were made. The decay correction factors ranged from 1.09 to 12.7.

The variation in amount of radioactivity for each tissue at each collection date, although great, was not great enough to obscure general trends in changes of radioactivity with time or differences in levels of radioactivity between tissues.

The term "activity" as used here means radioactivity per unit weight.

"Rate of decline" refers to the rate at which radioactivity is decreasing in a given tissue, organ, or organism in its native environment.

Levels of activity in the crab tissues three days after the Nectar test ranged from 5×10^6 d/m/g in the gut to 7×10^4 d/m/g in the muscle (Figs. 1, 2). The rate of decline of activity decreased with time and was different for each tissue, but in general followed the same trend as the decay of mixed fission products during the first 200 days. Thereafter the rate of decline for each of the crab tissues approached a constant value with a half life in excess of 20 years.

This half life is dependent on factors which include relative abundance and availability of radionuclides in the food and/or environment, rate of decay of radionuclides absorbed, biological half life, and selective uptake of radionuclides. Each of these, except the rate of physical decay, is in turn dependent on varying environmental and physiological conditions. The terms "ecological half life of radioactivity," or more briefly, "ecological half life" and "rate of decline" will be used to include these factors. Ecological half life will be used as the time required for an organism, or its tissues or organs, in its native environment to lose 50 per cent of its radioactivity. When the ecological half life and physical half life are equivalent (rate of decline = rate of decay), the tissue in question must be at equilibrium with respect to the radioisotopes it contains. For single isotopes an ecological half life greater than the physical half life (rate of decline $<$ rate of decay) indicates accumulation of the isotope. In the converse situation where the ecological half life is less than the physical half life, a net loss of the isotope is indicated. This condition could result from loss of the isotope by the environment, or eco-system, or from a physiological change in the organism or its primary food source. Such physiological changes may be transitory or seasonal.

The increase in radioactivity over preshot levels during the first few days after the Nectar test was less in muscle and carapace than in the three other tissues by a factor of 5 to 10. Maximum post-Nectar levels of activity were 100 to 250 times greater than pre-Nectar levels in gut, liver, and gill, but only 22 and 26 times greater in muscle and carapace respectively. The lower rate of accumulation in muscle and carapace would be expected since the material must be absorbed from the gut and hepatopancreas where some selection takes place. The specific patterns of changing radioactive content of the tissues with time, the rate of decline, will be presented individually for each tissue.

The amounts of radioisotopes involved are so

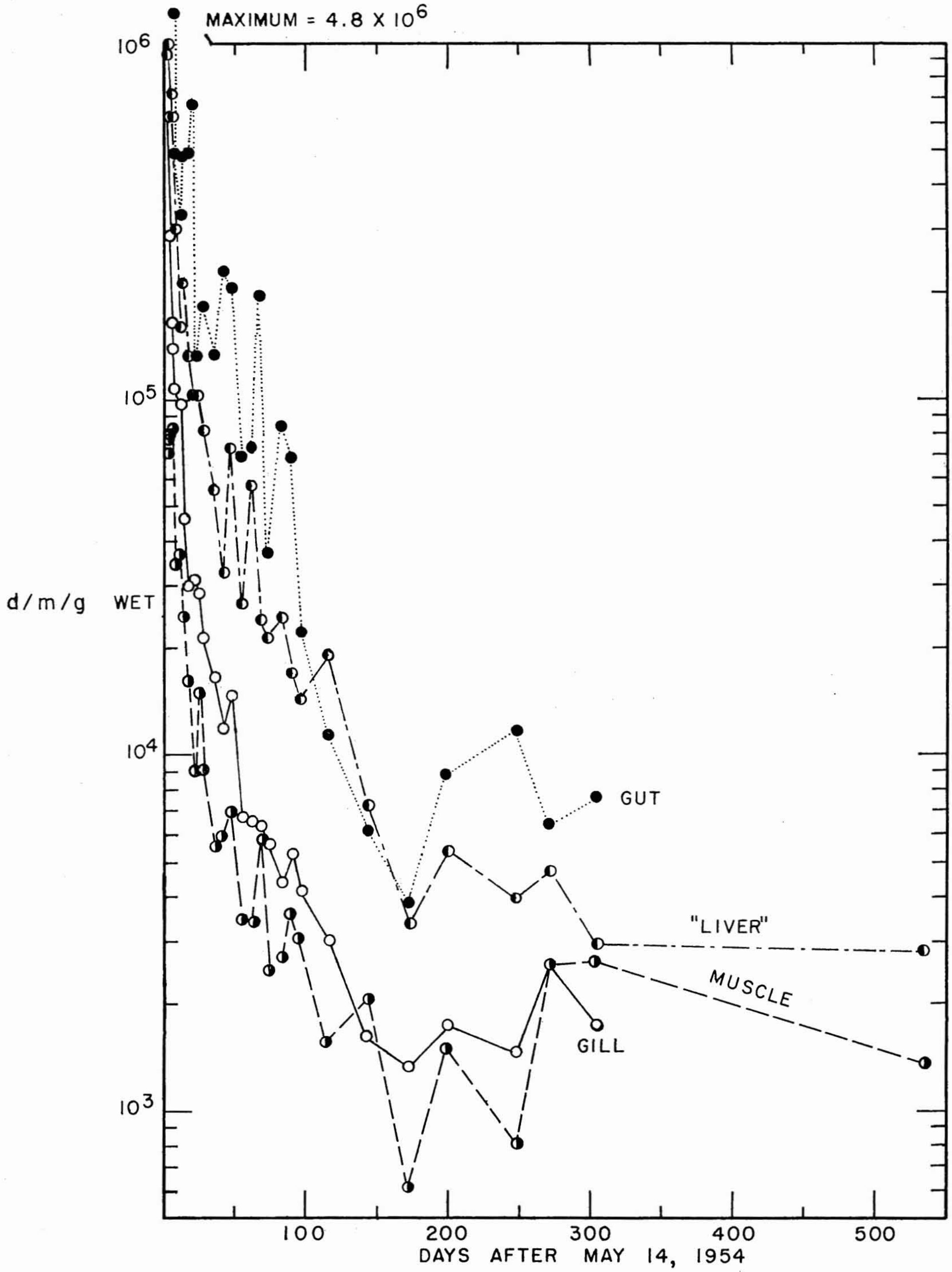

FIG. 1. Beta-activity in *Coenobita* gill, muscle, hepatopancreas ("liver"), and gut on successive collection dates. Values in disintegrations per minute per gram wet weight.

small that they probably do not constitute a significant proportion of the naturally occurring isotopes. If, for example, a tissue contained 10^7 d/m/g wet of Sr^{90}, or 5,000 times the maximum level found in the hermit crab, this would represent only 0.02 mg. of strontium, or about 10^{-5} per cent of the ash weight. The presence of strontium has been reported qualitatively in crustacea and a quantitative estimate of about 1 per cent strontium has been given for the ash of *Eupagurus bernhardus* (Vinogradov, 1953).

RESULTS

Exoskeleton

The carapace was taken as the sample of exoskeleton. It is easily removed, separated from other tissues, and washed free of possible external contamination.

The radioactivity in the carapace due to long-lived isotopes remained approximately constant throughout the period of 537 days during which collections were made. This was determined by recounting all of the samples approximately 600 days after the Nectar test (Figs. 2, 3).

Radiochemical analysis of 18 samples taken at various times during the collecting period (Table 1), and three samples taken 35 days before Nectar, demonstrated that virtually all of the long-lived activity was 28-year Sr^{90} and its Y^{90} daughter.[4]

The nearly constant level in the carapace (ecological half life ≅ physical decay) indicates that this tissue quickly reaches and maintains equilibrium with the available strontium. Gross, Taylor, and Watson (1954) report a plateau of retention of Sr^{90} in rats during continuous feeding at the same rate, and apparent shifting of the plateau with change in daily dose.

It would be expected that this relationship also applies to available calcium, which is metabolically similar to strontium, and to 54-day Sr^{89}, and possibly to Ba^{140}, which at the time the radiochemical analyses were made was present in amounts too small ($<$ 0.2 per cent of total activity, according to Hunter and Ballou, 1951) to be determined by the method used.

[4] Results of calcium analyses of 74 samples of carapace made since submission of the MS give a mean of 158±30 mg. Ca/g wet, and 15,000±4900 strontium units.

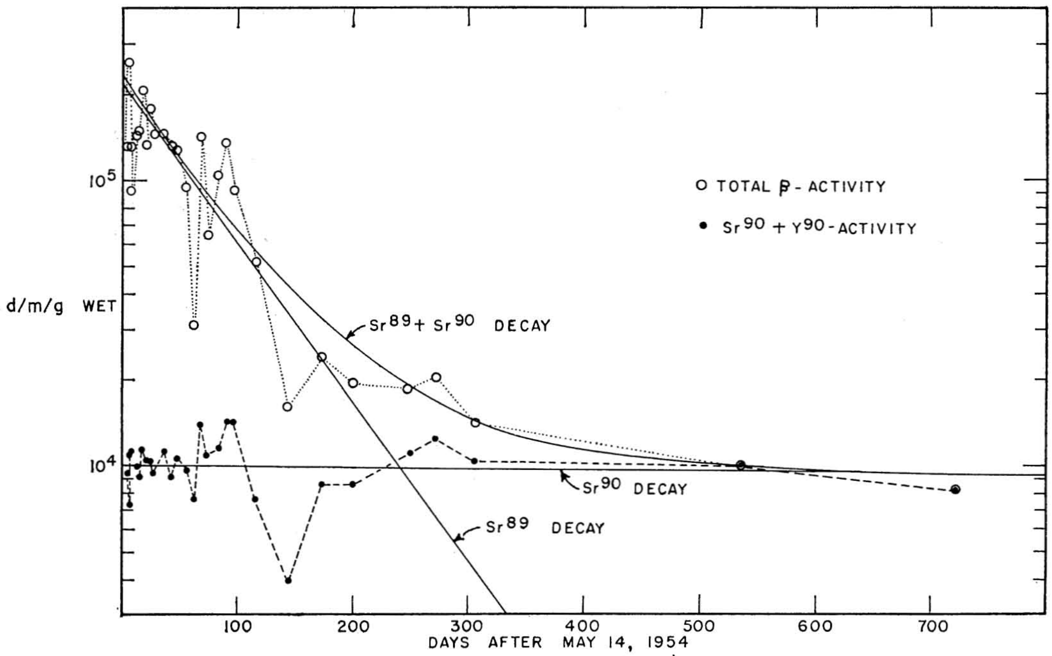

FIG. 2. Radioactivity in *Coenobita* carapace on successive collection dates compared with the decay of radiostrontium. Values in disintegrations per minute per gram wet weight.

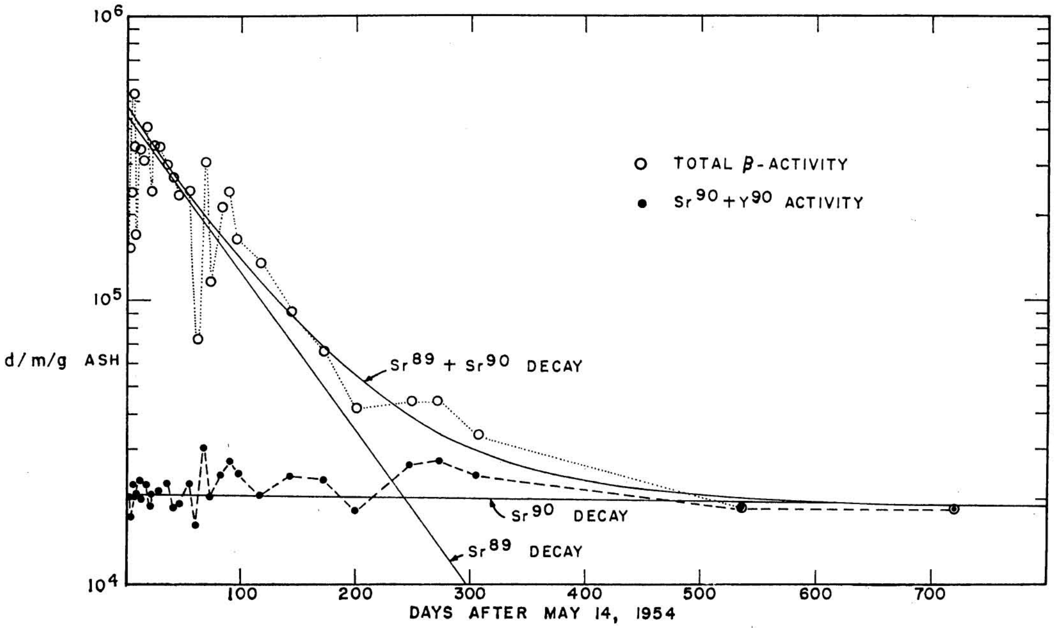

FIG. 3. Radioactivity in *Coenobita* carapace on successive collection dates compared with the decay of radiostrontium. Values in disintegrations per minute per gram of ash.

The amount of Sr^{89} present in the carapace immediately after Nectar was calculated from the yields given by Sullivan (1949) on the basis of the average amount of Sr^{90} in the 44 specimens collected during the first 50 days following Nectar, less the amount present before Nectar. The relative radioactivity of the two isotopes was calculated from their specific activities. A theoretical decay curve was then calculated for the combined Sr^{89}, Sr^{90} + Y^{90} contributed by the Nectar test and the Sr^{90} + Y^{90} residual from prior tests. Figures 4 and 5 show the actual values superimposed on this theoretical curve. Although there were no specific radiochemical determinations early in the period following Nectar, it is reasonable to assume that the exoskeleton has a high degree of selectivity for strontium and that equilibrium must be reached within a few days at most. The assumptions are further supported by decay curves which approach the theoretical curve (Fig. 4).

The relatively low levels of activity at 145 days post-Nectar are a reflection of a change in ratio of ash weight to wet weight; Figure 4 represents the data on an ash weight basis. The change in ratio may be associated with molting, but observations were not made at frequent enough intervals to confirm or deny such an association.

Contributions of radiostrontium to the crab skeleton at Belle Island from past tests at Eniwetok and Bikini are represented in Figure 5. The pre-Mike level is an approximation since it is based on a single specimen and there was, unfortunately, no biological survey during the 1950 tests. The pre-Nectar curves were derived by the method outlined above. The Mike test contributed about twice as much activity as the Nectar test; fallout from the pre-Mike tests and the Bikini tests of 1954 together contributed about 5 per cent of the total Sr^{90} activity.

Sr^{90} on the island is being maintained at an essentially constant level (decreasing only with physical decay), if the omnivorous hermit crab can be considered an accurate index of biologically available strontium. However, the ratio of the strontium in the crab skeleton to that in food items is not known. Judging from the meager data presently available, the radiostrontium content of the crab skeleton is more than

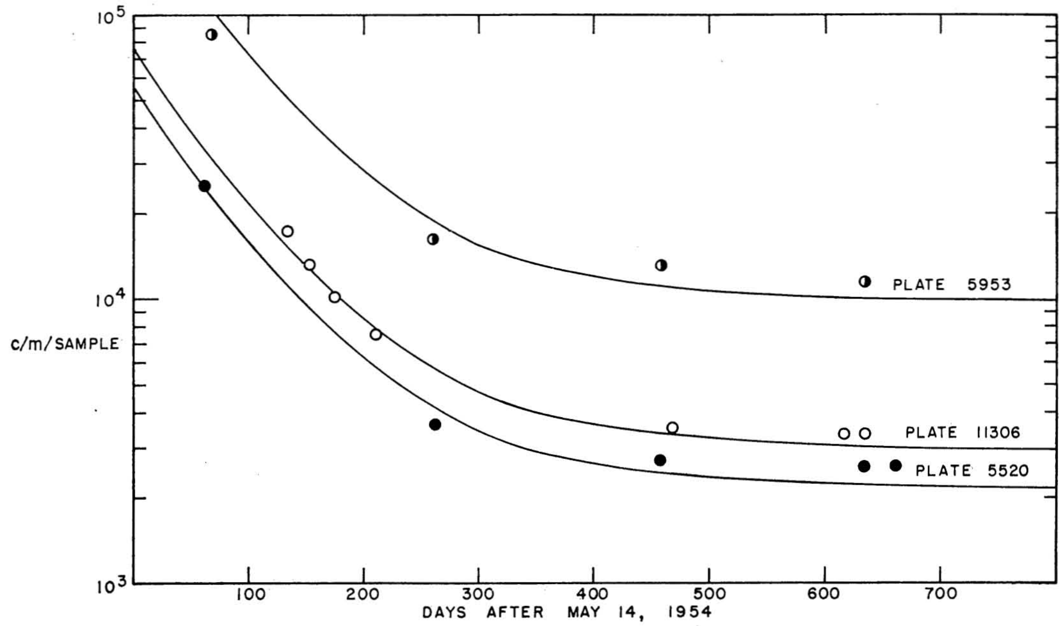

FIG. 4. Decay of beta-activity in three *Coenobita* carapace samples, each compared with the theoretical decay curve (solid lines) for $Sr^{89} + Sr^{90}$ from Figures 2 and 3.

ten times that in land plants on a wet weight basis and is more than three times that in soil on a dry weight basis.

Muscle

Isotopes with half lives greater than 20 years contributed nearly all of the activity in muscle tissue 35 days before the Nectar test. Cs^{137}, $Sr^{90} + Y^{90}$, and $Ce^{144} + Pr^{144}$ accounted for 84, 10, and 1 per cent respectively, of the total activity in muscle tissue collected in February and November, 1955, and analyzed in January and March, 1956. Similar levels, 67, 10, and 1 per cent, were found in coconut crab muscle from Rongelap Atoll (UWFL-43, table 14). In contrast to the exoskeleton, muscle tissue had a variable, though generally decreasing, level of long-lived isotopes throughout the post-Nectar collecting period (Fig. 6). Between 150 and 200 days post-Nectar, the total activity in muscle was due primarily to the long-lived isotopes, as evidenced by the increased ecological half life. The level of total activity in muscle at 172 days (after Nectar) is one-sixth the pretest level, while the level of long-lived isotopes at that time is one-eighth that of the pretest level; subsequently there is an increase in activity. Since both the total activity and the long-lived activity increased by approximately equivalent amounts, the increase must be due to an increased net rate of uptake, reflecting a change in the physiology of the crab or a change in the

TABLE 1

TOTAL β-ACTIVITY AND $SR^{90} + Y^{90}$ IN *Coenobita* CARAPACE

(Determinations made in January and February, 1956. Averages of three samples and their standard errors are given.)

DATE COLLECTED	TOTAL β-ACTIVITY JAN.–FEB., 1956 D/M/G WET	$Sr^{00} + Y^{90}$ ACTIVITY FEB., 1956 D/M/G WET
4/15/54	6900 ± 672	7454 ± 952
5/26/54	10243 ± 968	9763 ± 975
8/12/54 or 8/19/54	14851 ± 1413	15568 ± 1237
10/5/54	4362 ± 431	4043 ± 385
3/15/55	10368 ± 581	11281 ± 479
2/9/55	12516 ± 1594	12532 ± 1484*

* Average of duplicate aliquots of three pooled samples as determined by Dorothy J. South, Applied Fisheries Laboratory.

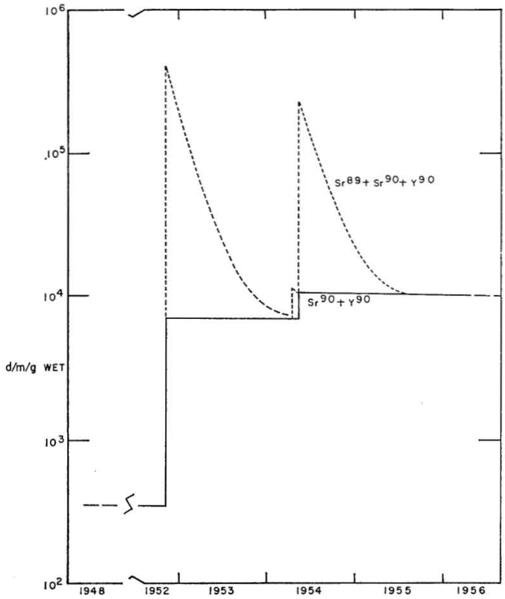

FIG. 5. Radiostrontium in *Coenobita* skeletons at Belle Island.

conditions in the environment, leading in this case to a greater availability of Cs^{137} to the crab. The latter possibility is the more easily explained by the observations.

The same pattern of decrease in activity followed by a rise is evident in the gut and liver of the crab, the leaves of the shrubs, *Scaevola* and *Messerschmidia,* and the muscle of the field rat, *Rattus exulans,* from Janet Island (Engebi) which is also in the northern part of Eniwetok Atoll (Lowman, MS). During the first 200 days (May–November, 1954) rainfall at Eniwetok averaged about 4 inches per month, while for the following 150 days (December–April) the average monthly rainfall was about 0.3 inches (Fig. 7). Since individual variation in the level of activity is great there would be little reason to accept the validity of the correlation were it not repeated in the plants and in rat muscle, which are also high in Cs^{137} content (56 per cent of the total activity in the latter). It appears likely, therefore, that the changes in activity in the crab and rat muscle reflect some underlying mechanism associated with rainfall which is responsible for changes in the levels of activity in the plants.

There could be one or several factors involved in the association with rainfall including, for example, such things as exchangeability of cesium, total amount of root surface available during the wet as compared with the dry season, and increasing acidity of the soil on drying (Stone, 1951). More complete series of radiochemical determinations of the radioisotopes in both plants and soils are needed to understand the mechanisms involved. Contrary to results reported on relative availability of cesium and strontium to plants in other soils, cesium appears to be more readily available than strontium in the atoll island soil (Selders *et al.,* 1955; Neel *et al.,* 1953; Larson *et al.,* 1953; Nishita *et al.,* 1954; Ophel, 1955).

The short half-life isotopes that contributed to the activity in the muscle during the first 150 days are not known. The rate of decline during this period was approximately the same as the rate of decay for mixed fission products.

Radiocesium content of hermit crab muscle is about 1.5 times that in plants (1,000 d/m/g : 700 d/m/g) on a wet weight basis. The radiocerium levels in the soil were too low ($<$ 1 per cent of the total activity) to be detected by the radiochemical methods used.

Hepatopancreas ("Liver")

The rate of decline of activity of the hepatopancreas or "liver" of the crab during the first 175 days post-Nectar is not significantly different from the rate of decay of mixed fission products. This is true despite the fact that there was a pre-existing level of long-lived activity approximately equal to the level existing 537 days post-Nectar. Sr^{90}, Cs^{137}, and Ce^{144} were found.

Equilibrium must be quickly reached and maintained at a constant level proportional to the availability of the long-lived isotopes. Levels of activity were 8,500 d/m/g pre-Nectar, reached a maximum of 10^6 d/m/g four days post-Nectar, and declined to a level of 3,000 d/m/g at 305 days and 537 days (Fig. 1).

Gut with Content

The hermit crab gut with its content was generally more variable than the liver in levels of activity, especially during the first month post-Nectar. This difference is to be expected, since ingested food would have variable amounts of

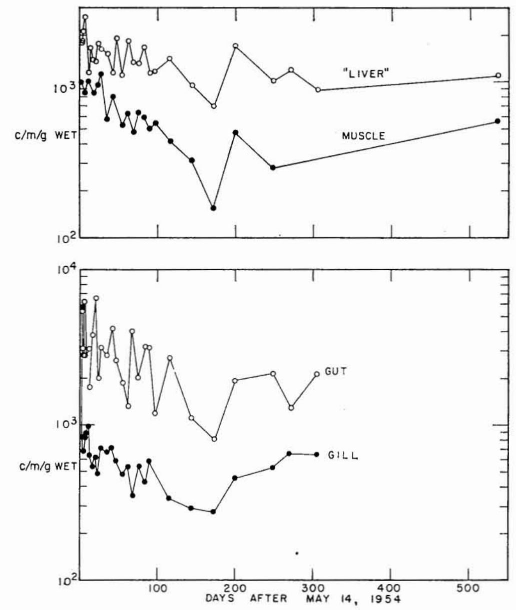

FIG. 6. Counts per minute per gram in *Coenobita* tissues as of 600 days after May 14, 1954, plotted for each collection date.

surface contamination and not all crabs would feed on the same thing at any one time.

Initially, following the Nectar test, the gut had the highest level of activity of all tissues (5×10^6 d/m/g). The activity in the gut also had the shortest ecological half life of all tissues during the first 100 days post-Nectar. By 100 days, the levels of activity in gut and liver approached each other and their ecological half lives were about the same, although the gut remains so variable from collection to collection that only an approximation can be made. The activity in the carapace by 100 days was higher than that in the gut even though the latter had the highest initial activity. This variation is, of course, due to the different rates of decline, which reflect selection of the long-lived isotope Sr^{90} by the carapace.

No chemical analyses of gut samples were made.

Gill

The rate of decline of activity of the gill of the crab is more rapid than the rate of decay of mixed fission products during the first 10 to 20 days post-Nectar, but thereafter approximates the same rate until the 200th day. The early high levels may be due to contamination of the surface of the gills and possibly to excretion of salts through the gills. From the tenth day on, the pattern of decline of the gill is the same as that of muscle. The activity level was generally higher in the gill than in the muscle by less than a factor of two on a wet weight basis.

No chemical analyses of gill tissue were made.

DISCUSSION

During the first 150 days following a nuclear detonation the rate of decline of radioactivity in organisms on atoll islands may be considered to approximate the rate of decay of mixed fission products. This conclusion is supported by data from collections at Rongelap Atoll in 1954 (AEC reports UWFL-42, -43). Errors in the estimate of future levels based on this approximation would tend toward the prediction of higher levels than would actually be attained in the first 150 days. The wide spectrum of available radionuclides present in the early period following a detonation may be available to individual organisms in extremely minute amounts; consequently, differences in the rate of decline reflecting selectivity by an organism are masked, since various combinations of the short-lived nuclides could result in an approximation of mixed fission products decay. The availability of a wide spectrum of radionuclides during the first few days might be due not only to the presence of these nuclides, but also to the fact that they could potentially be absorbed directly by the leaves of plants and thus circumvent fixa-

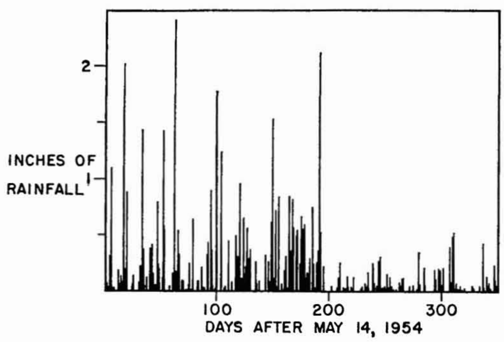

FIG. 7. Rainfall at Eniwetok Island (from records of Detachment 2, 57th Strategic Reconnaissance Squadron, Medium, Weather, USAF).

tion on the soil. Residual contamination from fallout a year or more old would have an insignificant effect on rate of decline during the first 150 days if the total contamination from each detonation were of the same order of magnitude or the first less than the second. This was the case following the Nectar test at Belle Island, which had residual contamination from the Mike test (1.5 years previous to Nectar).

After approximately 150 days following fallout, the rate of decline becomes less than the rate of decay of mixed fission products, reflecting the relative concentration by the island organisms of the long-lived isotopes Cs^{137} and Sr^{90}. Other isotopes, both fission products and neutron induced products, are involved, but Cs^{137} and Sr^{90} with their daughters account for 80 per cent or more of the total activity in land organisms two years following the Nectar test. This is true even though these isotopes together contribute only 18 per cent of the total activity from mixed fission products at that time. On a basis of fission yields, Cs^{137} and Sr^{90} would contribute no more than 35 per cent of the total activity even if all of the activity at Belle Island were from the Mike test. Ce^{144} activity is low (1 per cent in crabs) in the island organisms because of its low rate of uptake by land plants from soil (Neel, 1953). On the other hand, in marine organisms radiocerium does enter into the food chain in significant amounts, 26–71 per cent of the total β-activity, according to AEC report UWFL-43, Bonham, MS.

It appears, therefore, that in so far as the long-lived radioactive fission products strontium, cesium, and cerium are concerned there is what might be called a strontium–cesium food cycle on land and a cerium food cycle in the lagoon.

SUMMARY

1. Periodic determinations of radioactivity in land crabs from Belle Island, Eniwetok Atoll, were made over a period of nearly two years following the 1954 atomic testing program.

2. Radioactivity in the exoskeleton was found to be due almost entirely to radiostrontium and the Y^{90} daughter of Sr^{90} and remained at a nearly constant level, excepting physical decay.

3. An estimate of contributions of radiostrontium from previous tests to a crab skeleton at Belle Island is given.

4. Long-lived fission products in muscle tissue consisted of 84 per cent Cs^{137}, 10 per cent $Sr^{90} + Y^{90}$, and 1 per cent $Ce^{144} + Pr^{144}$.

5. A possible association between the availability of cesium and rainfall is suggested.

6. During the first 150 days following a nuclear detonation the rate of decline of radioactivity in organisms on an atoll island may be considered to approximate the rate of decay of mixed fission products.

7. In so far as the long-lived fission products strontium, cesium, and cerium are concerned there appears to be a strontium–cesium food cycle on land and a cerium food cycle in the lagoon.

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