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RADIOBIOLOGICAL STUDIES AT THE ENIWETOK TEST SITE AND ADJACENT AREAS OF THE WESTERN PACIFIC

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The nuclear experiments conducted at Bikini and Eniwetok Atolls in the Marshall Islands are more than experiments to measure physical forces; they are unparalleled scientific experiments involving a great number of scientific disciplines. Among the disciplines represented, biology is taking a leading role.

Biologists have been a part of this scientific team activity since the inception of the atomic tests at Bikini in 1946. Studies with the radioactive materials resulting from the weapons tests and deposited in the sea and on the islands have made it possible to follow the biological cycling of these materials even where they have become diluted to infinitesimal quantities, by standards of ordinary chemical analysis. Hines (1951) has described the general problem of evaluation of this research.

Much attention has been given to the more immediate effects of the weapons tested upon the fauna and flora of the atolls but such studies, important as they are, have not occupied the total planning, thinking and execution of the program of biological studies. Extensive investigations using the facilities, personnel, and equipment available at the test organizations and test sites have answered many questions relating to the economy of the sea, have opened up new knowledge of the life zones of coral atolls, and have reshaped in important ways some of the basic concepts of biological science. By using the radioactive or "tagged" minerals available and the methods of microchemist and physicist, biology has advanced to a more exact science.

Since the pre-test preparations for Operation Crossroads in 1946, representatives of marine biology, oceanography, and geology have made intensive studies at some of the atolls in the northern Marshall Islands, with the result that few oceanic areas have been studied as intensively by such a variety of specialists as have Bikini and Eniwetok Atolls.

Notable contributions have been made to the knowledge of the geology of atolls by Tracey et al. (1948) and Ladd (1952). Von Arx (1954) has reported on the water circulation in Bikini lagoon, and the action of ocean waves on Bikini reefs has been described by Munk and Sargent (1954). Robinson (1954) made studies of the sea temperature in the Marshall Islands. Barnes et al. (1948) reported on the ocean circulation in the Marshall Islands area, and Mao and Yoshida (1954) described the physical oceanography of the same region. Schultz et al. (1953) have described the fishes of the Marshall and Mariana Islands. The plants of Bikini, etc. were studied and reported on by Taylor (1950), Fosberg (1953), St. John (1949), and Biddulph (1952). Dawson (1957) has reported on the algae of Eniwetok Atoll.

Studies on the distribution of radioactive materials produced by the atomic tests conducted in the Marshall Islands have been published by the Laboratory of Radiation Biology,* University of Washington, as research and development reports for the U. S. Atomic Energy Commission.

An atoll may be described as a roughly oval, coralline reef rising 15,000 feet above the ocean floor. Within the surrounding reef there is enclosed a shallow lagoon generally with a maximum depth of about 180 feet. The lagoon is open to the ocean by one or more passes cutting through the reef, most of which is awash except at low tides. Emergent land consists of low sandy islands with an elevation seven to ten feet above sea level; elevations as high as twenty feet are rare. The islands occupy only a small fraction of the total area of an atoll. Bikini lagoon covers 229 square miles (Handbook on the Trust Territory of the Pacific Islands) and has a dry-land area of two and a third square miles divided among some thirty-six islands and islets; Eniwetok lagoon covers 388 square miles, has a dry-land area of two and one-fourth square miles, and forty islands.

These atolls lie in a zone of the northeast trade winds. Because of the constancy of direction of the winds, there are distinct differences in reef form between the windward and leeward sides of the atoll. The windward side is generally considered the region of most rapid growth and is

*Formerly the Applied Fisheries Laboratory characterized by a narrow, slightly elevated ridge near the reef edge, the Lithothamnion ridge, which is lacking on the leeward side. The latter drops off vertically to depths of 100 to 200 feet on the seaward side, while the seaward slope of the windward reef falls away at an angle of about forty-five degrees.

On the reef and in the lagoon,there is an abundance of colorful plant and animal life in which the keen competition between different species for space and food is very evident. On every hand there is evidence of rapid growth and simultaneous destruction. Masses of reef-building coral are competing with each other and with the coralline marine algae for space, one often overgrowing the other. Schools of green parrot-fish gnaw wide scratches on the coral. Fleshy patches of algae are pressed tightly against the surface of the coral to hold against the surges of the water pushed across the reef by the crashing breakers. Sea urchins and clams grind niches into the hard coral, some of them constantly feeding on the cover of bacterial and algal film which is as constantly being replaced. The clams, the corals, some small fish and other forms are ceaselessly removing from suspension in the water the small, often microscopic, plants, animals, and bits of debris which make up the plankton. In regions of quieter water, where sand has been deposited, sea cucumbers and spider snails, among the larger forms, turn the sand again and again in their gleaning for food.

Large schools of goatfish, mullet, surgeon fish, and other plant and plankton feeders are a common sight. Preying on unwary or disabled members of these schools are the carnivorous fish -- the groupers, tuna, jacks and sharks. Ultimately the waste products and carcasses of these and other carnivores are returned to the lagoon and reef to complete the cycle.

Little or no time is lost between steps in the biological cycling of materials for there is not only an abundance of organisms but also a wide variety of species -- some 700 among the fishes alone (Schultz *et al.*, 1953) -- so that whatever is not utilized by one is quickly taken by another. There is here a perfect economy of use of substances essential to life.

Available substances are rapidly taken up by the biota, never remaining long in the water to be diluted and washed away. This is dramatically demonstrated following an atomic test in which radioactive materials are deposited in the water. Within hours, the great bulk of these materials is to be found in the living organisms. Plankton and some of the algae, which are the key organisms in the food chain, may concentrate within themselves more than a thousand times the amount of radioactive substances found in the sea water. The herbivorous fish and invertebrates have lower concentrations of radionuclides at any given time than do the plants on which they feed, and progressing along the food chain to the carnivores the concentrations become lower and lower. Within each organism there is a differential concentration from tissue to tissue, the digestive organs having a higher concentration than the other tissues, where a more selective deposition as to specific isotopes has taken place.

More specifically, plankton, the oceanic plants and animals that drift about passively with little or no resistance to water movements, may influence greatly the distribution of radioactive materials in the sea. These forms include many groups of organisms from the simple one-celled plants to the larval forms of vertebrates.

Plankton acquire radioisotopes by absorption, adsorption, or both. Plankton, especially phytoplankton, present a greater absorptive surface to the environment than any other group of marine organisms. Thus, the major initial concentration of radioactive isotopes probably occurs in the phytoplankton -- the same organisms which comprise the foundation of the food chain in the sea. The isotopes especially concentrated by these forms are, for the most part, representatives of those elements which tend to form strong complexes with organic material. They include nearly all of the anionic radioisotopes, with the exception of iodine, and the cationic radioisotopes produced by neutron induction, including radioactive zinc, cobalt, iron and manganese. All of the cationic radioisotopes concentrated in the plankton are biologically important elements comprising the essential parts of enzyme systems and, on one case at least, an essential vitamin.

The levels of radioisotopes present in the plankton vary with time after release of the radioactive materials, mainly because of the variation in availability due to physical decay of the individual radioisotopes (Bonham, 1958). In general, however, plankton contain the three radioactive isotopes of cobalt, Co^{57}, Co^{58} and Co^{60}, at a level of 11 to 50 percent of the total radioactivity. Zn^{65} is present at a level of 12 to 47 percent; Fe^{55-59} at a level of 1 to 40 percent; Mn^{54} in trace amounts, and the fission products Zr^{95}-Nb^{95} at levels of 3 to 44 percent; Ru^{106}-Rh^{106} is present from 0 to 7 percent; Ce^{144}-Pr^{144}, 0 to 13 percent; and Cs^{137} in trace amounts, if present at all (Lowman 1958). Sr^{90}-Y^{90} has not been found in plankton.

Once the radioactive materials have been absorbed or adsorbed by the plankton, their distribution is likely to be greater both vertically and horizontally than if distribution were solely dependent upon the surface currents. One reason for a greater distribution would be that absorption by plankton makes the radionuclides available to larger organisms which can move beyond the current's boundaries. Similarly these materials also become available to the local resident populations and, as they are recycled through the food chain, the effect is a delay in their distribution away from the original area of contamination. Another factor influencing the distribution of radioactive materials by plankton is their diurnal vertical migration. If this migration were great enough to take the plankton below the current stream, it would extend the vertical distribution and also slow down the horizontal distribution, because the plankton would be moving horizontally more slowly than the water.

Plankton may carry radioactive materials from the deeper waters of the lagoons to the surface or even up onto the reefs and eventually to the islands by vertical migration. At Bikini it has been observed, for example, that these materials were picked up by the plankton in the deeper waters of the lagoon during the daytime. The concentrated radionuclides in the plankton were then transported to the surface by the diurnal vertical migration of these minute forms. At the surface, their presence at night caused the surface radiation content to increase measurably over the daylight readings. The fouling organisms on the bottoms of the ships and the plankton feeders on the reef became increasingly radioactive at night as the transport of the radioactive products continued.

It can be said then that plankton may cause the distribution of radionuclides in the sea to be different from that which would be expected from the distribution by currents alone in the following respects: (1) a delay in the movement from the area of original contamination, (2) a slower down-current movement, (3) a limited dispersion up-current or beyond the currents' boundaries, (4) a greater vertical distribution, and (5) an over-all greater dispersion of relatively lower concentrations.

Aquatic plants or algae may be free-floating (as are the phytoplankton), attached to the reefs, or growing in the shallow water. Just as do land plants, the algae contribute to the food supply of animal populations. Minerals as well as organic materials, concentrated and incorporated into the algae, are passed on in the food chain to the animals that feed upon them. Thus the radioactive materials pass through the algae to the animals in the normal course of food gathering.

The affinity of algae for some of the radioisotopes is well known. For example, Asparagopsis, a marine alga found on the reefs at Bikini and Eniwetok, has a great affinity for iodine (Palumbo, 1955). In the presence of I^{131} Asparagopsis becomes radioactive. This alga is a succulent morsel sought by fishes; thus the I^{131} passes to the fish and along the food chain.

The land plants of the tropical islands of the Pacific atolls become contaminated with radioactive materials in two ways: (1) by fallout of material from the air or from the rain water with direct absorption through the leaves, and (2) by absorption from the soil.

The soils of the atolls are generally deficient in potassium. This deficiency speeds the uptake of Cs^{137} by the plants. Although Ce^{144} is present in the soils it is so firmly bound there that little is available to the plants.

The radioisotopes remain concentrated in the top two inches or less of soil. The rooting habits of the plants, therefore, are associated with uptake of the radioisotopes. The plants with feeder roots close to the surface thus take up more of the radionuclides than do those with deeper root systems.

While all of the tissues of the plants may contain radioisotopes, the major concentrations are to be found in the leaves, bark, seeds, corms or nuts. Since these are the most used portions of the plant for animal foods, the plants pass the radioactive materials on to the animals where they are incorporated into the animal tissue, only to be released in the normal biological cycle and passed back to the land for reabsorption.

The invertebrates, or animals without backbones, make up the great bulk of the animal life of an atoll. The role of these animals in the cycling of radioactive materials in an atoll is as varied as the invertebrate forms. Sea cucumbers have been compared with earth worms in their ceaseless turning of the gravel and sand as they obtain their nutriment from bacteria and algae. Corals and clams remove microorganisms and particulate matter from the water and also are host to the unicellular algae, Zooxanthellae, which are found in their tissues. The Zooxanthellae may be thought of as a vast reservoir of trapped plankton. Their relationship to their host is not completely understood but it is probable that they play an important part in the removal of phosphate wastes. Corals and clams are eroded by algae and sponges, which bore holes in the skeleton or shell, thus contributing to a return of carbonates to the water. Crabs, sipunculid worms and others also attack the skeleton of the corals. Some of the land crabs contribute to the deposition of radioisotopes from the sea onto the islands by dragging fish and algae ashore when feeding.

In short, within the invertebrates and their symbionts alone complete biological cycles occur from land to sea and back again, from inorganic substances to organic and back again.

The fishes of the waters in and about the Marshall Islands have received a major share of the attention in the study of the biological cycling of radioactive materials(Applied Fisheries Laboratory, 1950 ; Donaldson et al, 1956 ; Seymour et al. 1957 ; Welander, 1957 ; Lowman, Palumbo and South, 1957 ; Welander, 1958). Despite detailed study, the great variety of fishes with a correspondingly great variation in feeding habit make this a very difficult area in which to summarize results.

In general, the fishes may be divided by feeding habit into three groups: the herbivores, omnivores and carnivores. Since the herbivores feed directly on the algae, the radioisotopes concentrated from the water by the algae are passed on directly to the fish, and from the fish to the animal eating the fish. The herbivores, represented by such fishes as the surgeonfish and parrotfish, have the greatest amount of radioactivity of the three major groups.

Omnivorous fish such as the damselfish have less contamination than have the herbivorous fish, for they feed on more complex organisms.

The herbivorous and omnivorous fish tend to concentrate the same isotopes found in the plankton except for the radioisotopes which are taken up only in trace amounts by these animals. Zn^{65} usually accounts for 50 per cent or more of the total radioactivity in the organs of these fish and Fe^{55-59} comprises a major part of the remaining activity. The radioactive isotopes of cobalt account for 7 to 20 percent of the radioactivity and Mn^{54} 2 to 6 percent.

The minimum concentrations of radioactive materials are found in the carnivores, for these fishes, like the reef-dwelling groupers, or the roaming carnivores, like the tuna and barracuda, obtain their "tag" of radioactive material only after it has been passed through a number of living forms which select, retain, or reject various radioisotopes. With the passage of time longer-term studies indicate that several years after a single contamination of an area the carnivorous fish contain the greatest amount of radioactivity.

The carnivorous fish such as tuna and bonito, caught in the open ocean, contain Zn^{65} at the highest levels of any of the three groups of fish. In these animals Zn^{65} accounts for 75 to 92 percent of the total radioactivity; Fe^{55-59}, 6 to 25 percent; the cobalt radioisotopes, 1 to 3 percent; and Mn^{54}, less than 1 percent.

In all species of fish, the greatest amount of radioactivity is found in the alimentary tract, with liver, skin, bone and muscle having lesser amounts in descending order. Skin and bone are quite similar in the amounts present, and usually the radioactivity averages about twice that found in the muscle. The liver may have two to nine times as much radioactivity as the bone or skin, and the alimentary tract contains two to four times as much as the liver.

Unlike the fishes -- the aquatic vertebrates -- the land vertebrates are limited in both kinds and numbers on the islands of the atolls used for the experiments. Two kinds of birds, the fairy or white tern and the common noddy tern and the insular field rat are sufficiently abundant and have adequate distribution to be useful as study material.

The terns gather their food from the sea, where they feed mostly upon small pelagic fish, which in turn feed upon plankton. Radioisotopes not absorbed and retained by the birds may be dropped upon the islands in the resting and nesting areas. This transfer of radioactive materials from the sea to the land by the fish-eating birds is a useful way to measure the reverse flow or "uphill" transfer of minerals from sea to land. An indirect effect is the change of availability of radioactive materials following fertilization of the soil by the birds.

Studies of the rats on the islands near the detonation sites have proven to be extremely useful in evaluating the over-all effects of atomic weapons. Since they are confined to the small islands and must both live and eat on the contaminated areas, they may receive both external as well as internal exposure to radiation.

The highest concentration of radioactive materials in the rats is in the bone, with liver and kidney somewhat lower. The skin, muscle, lung and intestinal tract are, in general, lowest in radioactive content. The relative levels in the various tissues vary with time, although the general pattern is that noted above.

This species of rats is essentially herbivorous; they obtain their food from the land plants, seeking out and eating the seeds of grasses, sedges, sand burrs, and leaves of some of the succulent plants.

The plants upon which the rats feed concentrate Sr^{90} and Cs^{137}. These radioisotopes account for approximately 100 percent of the radioactivity within the organs of these animals except immediately after shot, when additional short lived radioisotopes are also present. During this time, I^{133}, I^{131} may be present in very high levels in the thyroids.

By following the pattern of gross radioactivity it has been possible to delineate the broad trends in the distribution of radioactive materials in an atoll and its surrounding area. There remains much that can profitably be done to amplify this study, but enough is now known to point the need for increased attention to the task of following the distribution of specific isotopes. Thus, more can be learned about selective absorption of elements by different organisms, and an unparalleled opportunity is presented to study the role of trace elements in the marine environment.

In the remote atolls of the Marshall Islands important contributions to biology have been made; the need now is to apply the knowledge, techniques and skills to increasing the productive capacity of our fresh-water areas. There is every evidence that the rewards in increased food production from aquatic resources will rival or exceed the spectacular results that have been obtained from applying these new concepts to agriculture.

In short, the Pacific testing areas comprise a laboratory in which the biologists have worked with the secondary but long-range problems incident to the peaceful employment of atomic energy. Conditions there are especially suitable for the study of the disposition and distribution in nature of the radioactive by-products of such employment.

Biologists have been participants in this scientific team activity since the inception of the atomic tests at Bikini in 1946. This participation has been of almost revolutionary importance to the biologists, for it has given them unprecedented opportunity to observe the biological cycling of radioactive materials deposited on sea and land from the detonation of atomic weapons. But twelve years of field and laboratory work also have demonstrated that the problems of the biologists are those that have fundamental significance too in the larger matter of proper planning for the future use of atomic energy. Experience in the Pacific has permitted the biologists to develop new techniques of investigation and has suggested other areas in which the techniques may be tested and applied. The program in the Pacific, permitting the biologists to use the facilities of the test organizations at the test sites, has answered many questions relating to the economy of the sea, has opened up new knowledge of the life zones of coral atolls, and has reshaped in important ways the basic concepts of biological science.

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