can synthesize chalcopyrite by sintering or solid-phase reaction, but quite probably it cannot be grown from the melt since it melts incongruently.

References and Notes

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Oceanography, Fisheries, and Atomic Radiation

In writing this report we have had four groups in mind—research administrators, statesmen, scientists, and the public. For those who have responsibility for the support of research, we have attempted to outline the scientific questions that need to be answered as a basis for intelligent policy, the means by which they can be attacked by classical research methods at the outset, and the broader problems of the oceans that can be hopefully attacked by the use of radioactive tracers. For the statesmen who have responsibility for national and international policy, we have attempted to formulate recommendations, based on our present small body of knowledge and our awareness of our larger area of ignorance, concerning the national and international actions and agreements that are necessary for the happy exploitation of the oceans in the new atomic age. For the scientists, we have attempted to summarize what is known about the actual and potential effects of radioactive materials in the oceanic realm and the interest of marine scientists in these substances. For the public, to which we all belong when we are outside our own specialties, we have summarized the levels of calculated risk that must be balanced against the wonderful promise of atomic energy for the welfare of mankind.

How Does the Atomic Energy Program Affect the Oceans?

We have considered three aspects of the atomic energy program that directly involve the oceans and, therefore, the marine sciences: weapons tests over or in the sea, disposal of radioactive wastes from nuclear power plants, and the use of radioactive substances in increasing our understanding of the oceans and of the creatures that live in the sea. These different aspects cannot easily be separated. Weapons tests and the disposal of radioactive wastes present great opportunities for studying the oceans. On the other hand, increased knowledge of the oceans is essential to avoid or minimize the destruction of marine resources in the development of atomic energy.

The continuing development of atomic energy will produce progressively greater amounts of radioisotopes, and with them greater amounts of radioactive waste material. Since the oceans cover 71 percent of the earth, and ultimately receive the drainage from the land, they are the principal reservoir where radioisotopes will finally accumulate. Relatively small quantities are now being added to the surface waters of the ocean as fallout from weapons-testing programs, and in a few places as waste materials.

When nuclear reactors for the production of power are put into large-scale operation, as they certainly will be in the foreseeable future, the oceans will be seriously considered for the disposal of large quantities of wastes. Even if direct and intentional disposal at sea is not practiced, reactors may be built along sea coasts or on rivers near large population centers, and accidental pollution may occur.

The problem of disposal of radioactive wastes is similar in character to, though potentially far greater in scope than, other problems of pollution. An object lesson can be drawn from our experience with the disposal of human and industrial wastes in inland water bodies and coastal waters and with the smog problem that afflicts many of our large cities. During the early stages of the growth of industries and populations in cities, wastes were added to nearby lakes or bays, and to the air, in what seemed at the time to be innocuous quantities. As a matter of fact, the quantities were small enough to be purified by natural processes. In the course of time, however, the quantities increased insidiously so that today many natural waters cannot purify themselves and without expensive treatment are dangerous to human beings.

In almost every case the problem was ignored until it had become formidable in magnitude. Short-range solutions were employed, based on inadequate knowledge, special interest, and what we now know was an unfounded confidence in the capacity of the atmosphere and the waters to absorb noxious substances. As a result, unnecessary damage was done to human beings and their environment. Much of this could have been avoided if an adequate program of scientific investigation had been started sufficiently far

This article is the text of the summary report of the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries. The report is part of a continuing Study on the Biological Effects of Atomic Radiation conducted by the National Academy of Sciences with the support of the Rockefeller Foundation. The members of the committee are Roger Revelle, Scripps Institution of Oceanography, *chairman*, Howard Boroughs, University of Hawaii; Dayton E. Carritt, Johns Hopkins University; Walter A. Chipman, U.S. Fish and Wildlife Service; Harmond Craig, Scripps Institution of Oceanography; Lauren R. Donaldson and Richard H. Fleming, University of Washington; Richard F. Foster, General Electric Company; Edward D. Goldberg, Scripps Institution of Oceanography; John H. Harley, U.S. Atomic Energy Commission; Bostwick Ketchum, Woods Hole Oceanographic Institution; Louis A. Krumholz, American Museum of Natural History; Charles R. Renn, Johns Hopkins University; M. B. Schaeffer, Scripps Institution of Oceanography; Allyn C. Vine, Woods Hole Oceanographic Institution; Lionel A. Walford, U.S. Fish and Wildlife Service; and Warren S. Wooster, Scripps Institution of Oceanography. Subheads have been inserted in the text. The full report will be published in monograph form by the NAS.

in advance and if scientifically based policies had been followed.

It is imperative that the nature of the wastes associated with the development of atomic energy be evaluated in advance. We know that purification of waters receiving radioisotope waste will proceed only by dilution, by precipitation and settling on the bottoms, and by the decay of radioactivity. Nothing could be done to reverse an undesirable accumulation that might result from ill-considered disposal of this type of waste.

There is no question of trying to keep all of this material out of the sea. It is certain that some of it can be safely added. Tolerability of materials must be determined, and the locations where they should be put must be wisely selected in terms of the quantity and character of the radioactivity. It is not possible today to see clearly the problems of the future; we can only define the studies that must be made to provide a scientific basis for wise evaluation and urge that these studies be begun without delay. The costs of such studies may seem large, but they are actually negligible in terms of the potential benefits. They are also very small when compared with the total present expenditures for the development of atomic energy. We cannot wait to begin these studies until radioisotope pollution becomes serious, for it is irreversible.

Radioactivity in the Sea

Is there naturally occurring radioactivity in the sea? Yes, but one of the remarkable characteristics of the ocean is the extremely low level of the natural radioactivity. Marine animals and plants living more than a few hundred feet beneath the surface are bombarded by much less natural radiation (radioactivity plus cosmic rays) than is received by terrestrial plants and animals.

For example, although radiopotassium accounts for about 90 percent of the activity in the sea, it is present in most igneous rocks at about 100 times the concentration found in the ocean. Uranium, radium, and thorium are 3000 to 1 million times more concentrated in rocks than in the sea. This raises an interesting scientific question concerning the character of genetic change and evolution in many marine creatures. It emphasizes the need for basic biological studies on marine organisms. Because of their experimental difficulty, such studies have been comparatively neglected during the past few decades.

Have weapons tests added measurable amounts of radioactivity to the sea? Yes, though in terms of the total radioactivity of the sea, the amount is negligible. Radioactivity in the waters of the test area is of course very greatly increased at the time of tests, and even after diffusion over thousands of miles, concentrations remain that are readily detectable. Two days after the 1954 tests in the Pacific, the radioactivity of the surface waters near Bikini was observed to be 1 million times greater than the naturally occurring radioactivity. This material was transported and diluted by ocean currents, and 4 months later concentrations 3 times the natural radiation were found 1500 miles from the test area; 13 months later, the contaminated water mass had spread over 1 million square miles. Artificial activity had been reduced to about one-fifth the natural activity, but could be detected 3500 miles from the source.

In what other ways will radioactive materials be added to the oceans? In England radioactive wastes are being piped into the Irish Sea from an atomic installation. In the United States, wastes from laboratories and hospitals are being carried to sea in containers and dumped. At Oak Ridge, some of the fission products are discharged into the Tennessee River system. At Hanford, water from the Columbia River is used for cooling and returned to the river with some induced short-lived radioactivity. Waste products from the uranium fuel processing plants are now being confined, some in containers, others in pits in the ground. When the power reactors and fuel-processing plants reach their expected development, many rivers will have to be used. It will not everywhere be practical to confine the wastes locally. Transporting them to sea in barges or by other means may then be necessary in many cases. Although we may be sure the atomic installations will be carefully engineered and maintained, accidental discharge of waste may occasionally occur. On those occasions, intense radioactivity may reach the sea.

Damage to Marine Life

Has the atomic energy program as yet resulted in serious damage to marine life? Probably no. We know that radioactive radiation is damaging to living things and that marine organisms tend to concentrate many fission-product elements. But there is no evidence that any lasting damage has been done to the animal or plant populations of the sea or of large inland water bodies by the release of radioactive substances.

Certainly in the weapons test area terrestrial forms were killed or injured by the tests. The evidence concerning marine life is not conclusive, but biologists feel certain that deleterious effects occurred in the near vicinity. There is, however, no evidence that populations have been affected after the dilution and transport mentioned above. This is a subject on which intensive studies are essential before a definite answer can be given. We know that "high" levels are lethal, and that "low" levels may have no direct effect, but we cannot give quantitative values for "high" and "low" except in a few cases. Low levels, which produce no measurable effect in the organism itself, may produce genetic effects and thus influence the marine populations in the future, but there is no conclusive evidence that this will be undesirable.

Do living things take up radioactive materials into their bodies? Yes. Radioactive materials added to the sea can remain in solution, precipitate and settle on the bottom, or be taken up by the plants and animals that live in the water. The plants of the sea are mainly microscopic in size, but they can concentrate many thousandfold those elements that are necessary to them. Radioactive substances are also absorbed on the body surfaces of living things. Small plants and animals serve as food for the larger forms, and the radioactive materials are passed on from one to another. The amount of each element accumulated in each form depends upon the rate at which it is taken up, either directly or as food, and the rate it is excreted. Some of the radioactive materials remain in the body for relatively long periods of time and may accumulate to a considerable degree. Others may be lost rapidly and very little will accumulate.

This statement is a great oversimplification. Different plants and animals require and accumulate different elements. Shell fish, for example, concentrate calcium and strontium in their calcareous shells; fish concentrate zinc. It will be necessary to know among other things both the composition of the waste, and the populations in the area, before any particular disposal operation can be evaluated.

Are all the radioactive elements equally harmful? No. Those elements that living organisms naturally accumulate and that have long radioactive half-lives are more harmful than others. Radioactive strontium, and to a lesser extent, cesium and its daughter barium, cerium, praesodymium, and promethium represent particular hazards to human beings from ocean disposal.

Radioactive Waste

How much radioactive waste will be produced by nuclear power reactors in the future? The answer to this depends upon how optimistic one is concerning the development of nuclear power. One estimate assumes that within about 50 years nuclear fission will be producing about half as much power annually as the peoples of the world are using today from all sources.

Accumulations year after year will eventually result in a constant quantity of radioactivity, such that the rate of radioactive decay will balance the rate of production of fission products to give what has been called the steady state. This should be approached within a few decades after full production is reached. The waste radioisotopes at this point would equal between 1 and 2 times the total natural radioactivity in the world oceans. This is roughly 1000 times the amount produced so far in weapons tests.

What means are being considered for disposing of radioactive wastes? The methods being considered fall into two categories, isolation and dispersal. It is probable that a judicious combination of the two methods for different types of wastes or for different countries will be essential. Chemical treatment of the wastes to isolate usable fractions, or those, like strontium and cesium, that decay most slowly, offers promise in simplifying the problem. For isolation, permanent storage in tanks or introduction into geologic structures such as salt domes are being studied by other committees. The only place on earth where dispersal can be considered practical is in the ocean. Because it is large and fluid, the ocean could provide immense dilution. Because of its depth, and the stratification of water masses with differing densities, various degrees of isolation may be possible. It is a prime purpose of this report to emphasize the need for investigation as to whether this possible isolation is adequate.

Will it be safe to introduce very large quantities of radioactive wastes from atomic power indiscriminately into the sea? The answer is certainly no, but the strongest negative must be given for coastal waters and for the upper water layers everywhere that are the home of commercially important fishes. These surface waters interconnect and are in continuous motion. Anything added in one spot will, in the course of a few decades at most, be carried to all parts of the world. There is no place in the sea where very large amounts of radioactive materials can be introduced into the surface waters without the probability of their eventually appearing in another region where human activities might be endangered.

It should not be forgotten that the coastal waters enter the harbors and estuaries and would carry any waste materials there with them; and that many of the major fishery resources of the world are concentrated over banks and near coasts, and would become contaminated.

We must also remember that all plants and animals in the sea, from the smallest bacteria to the largest whale, play a part in concentrating, transporting, and dispersing radioactive and other dissolved and suspended materials.

Does this mean that large quantities of radioactive wastes should never be dumped in the sea? No, not necessarily, but it does mean that the length of life of the radioactive material, its role in biological processes, and the mixing rate of the ocean should be carefully studied before large quantities of wastes are introduced into the sea. Unfortunately, although we know the decay time of most radioactive substances, we know very little about the exchange processes in organisms and in the water. We do know that even the bottom waters of the deep ocean basins slowly exchange with those of the surface, but the rate of this exchange is uncertain.

From what is known, where would be the safest place to dump radioactive wastes in the sea? At the present time it is only possible to give rough engineering estimates, based on order-of-magnitude calculations.

Remembering the importance both of isolation (to allow time for radioactive decay) and dispersal (to reduce the amount of radioactivity per unit volume) the problem is to find places in the ocean where the rate of transfer of radioactive materials to the surface waters would be slow, or where great dilution would occur before radioactive materials came in contact with marine food products or human beings, and preferably where both conditions would prevail.

There are some places where a contaminant could be isolated for long periods. For example, it is estimated that in the deepest parts of the Black Sea the "flushing time" is about 2500 years. This is the time required for most of the deep water to move near to the surface and be replaced with new water mixing downward. In this respect the Black Sea is unique. Elsewhere the "age" of the deep water indicates that exchange with the near surface waters goes on less slowly. Thus in the deeps of the Atlantic and Caribbean the time required for replacement of the water with new water from near the surface is probably only a few hundred years. Some oceanographers believe that the Atlantic deep water sank from the surface in high northern latitudes about 150 years ago.

We are fairly certain that substantial amounts of long-lived radioactive materials, dumped on the bottom in the deep sea, would remain isolated for more than 100 years and that during this period they would become diluted by mixing through an enormous volume of deep water. We do not understand the nature of the physical and biological exchange processes between the deep and surface waters well enough to be able to say whether in the steady state, after decades of nuclear power production, deep-sea disposal would give adequate protection of the commercial fisheries from long-lived fission products such as strontium. Large quantities of short-lived fission products could certainly be disposed of safely in this way.

Use of Radioactive Materials to Study the Ocean and Fisheries

Can radioactive materials be used to learn about the oceans and to increase the harvest from the sea? Yes. For example, an understanding of the flow of material through food chains is essential to the effective use and conservation of the food resources of the sea. The natural elements used by the marine plants and their transfer to the commercially valuable fish and shellfish can be studied on a large scale, using radioactive isotopes. As these readily detectable substances are traced through the various steps of the food chain—plants, animal plankton, small fish, large fish—the efficiencies and interrelationship of the various levels should become much better known. This knowledge is of fundamental importance for the evaluation of the potential of the living resources of the sea as a source of food and other marine products, and as a basis for their full utilization and conservation.

Radioactive materials, both natural and man-made, can also be used in the study of oceanic mixing processes and circulation. These processes serve to supply marine plants with the fertilizers they need from deeper waters, as well as to dilute and disperse radioactive wastes dumped in the sea. At present we cannot measure, but can only estimate, the mixing rates. The ability to trace radioactive materials, even though present in great dilution, will permit us to obtain quantitative information. Improved knowledge of the mixing processes and of currents will help man to locate and evaluate unexploited resources of fish and other food organisms.

For example, 13 months after radioactive materials were introduced into the sea by fallout from weapons tests in the Marshall Islands, a research vessel traced their distribution in the Western Pacific. The extent to which radioactivity was taken up by plankton and fish was measured, as well as the extent to which activity was mixed downward and transported westward in the western limb of the great North Pacific eddy. These measurements showed the average speed at which materials were carried away from the test area, giving convincing proof of the transport and mixing of material over a vast region.

Large amounts of radioactive tracers ranging in magnitude from curies to megacuries can be used at sea in studying oceanographic problems, including the problems of fisheries, and thus laying the groundwork for increasing our harvest from the ocean. Smaller amounts are needed in the laboratory. We are here concerned not with the general problems of physiology and biochemistry but with specific ecological studies, including investigations of the efficiency of transfer of energy along the food chain, rates of filtration, concentration of elements and compounds in various tissues, the rates of accumulation and excretion of elements and compounds, the passage of substances across biological membranes, the concentration and role of biotic and antibiotic substances in the sea, the dynamics of marine populations, including the mass of living material in a given volume of water, the flux of organic substances from one organism to the other and between the organism and the sea water, and the interrelationships between animal and plant communities. In both field and laboratory experiments, fission products are useful, but some problems require the use of artificially radioactive substances produced by other means. An outstanding example is the use of carbon-14 to study the efficiency of various steps in the food chain. Large quantities of this material are needed for field studies in restricted water bodies. Although the cost would be high, the value of the results would more than justify the expenditure.

Conclusions and Recommendations

1) Tests of atomic weapons can be carried out over or in the sea in selected localities without serious loss to fisheries if the planning and execution of the tests is based on adequate knowledge of the biological regime. The same thing is true of experimental introduction of fission products into the sea for scientific and engineering purposes.

2) Within the foreseeable future, the problem of disposal of atomic wastes from nuclear fission power plants will greatly overshadow the present problems posed by the dispersal of radioactive materials from weapons tests. It may be conveninent and perhaps necessary to dispose of some of these industrial wastes in the oceans. Sufficient knowledge is not now available to predict the effects of such disposal on man's use of other resources of the sea.

3) We are confident that the necessary knowledge can be obtained through an adequate and long-range program of research on the physics, chemistry, and geology of the sea and on the biology of marine organisms. Such a program would involve both field and laboratory experiments with radioactive material as well as the use of other techniques for oceanographic research. Although some research is already underway, the level of effort is too low. Far more important, much of the present research is too short-range in character, directed toward *ad hoc* solutions of immediate engineering problems, and as a result produces limited knowledge rather than the broad understanding upon which lasting solutions can be based.

4) We recommend that in future weapons tests there should be a serious effort to obtain the maximum of purely scientific information about the ocean, the atmosphere, and marine organisms. This requires, in our opinion, the following steps: (i) in the planning stage committees of disinterested scientists should be consulted and their recommendations followed, (ii) funds should be made available for scientific studies unrelated to the character of the weapons themselves, and (iii) the recommended scientific program should be supported and carried out independently of the military program rather than on a "not to interfere" basis.

5) Ignorance and emotionalism characterize much of the discussion of the effects of large amounts of radioactivity on the oceans and the fisheries. Our present knowledge should be sufficient to dispel much of the overconfidence on the one hand and the fear on the other that have characterized discussion both within the Government and among the general public. In our opinion, benefits would result from a considerable relaxation of secrecy in a serious attempt to spread knowledge and understanding throughout the population.

6) Sea disposal of radioactive waste materials, if carried out in a limited, experimental, controlled fashion, can provide some of the information required to evaluate the possibilities of, and limitations on, this method of disposal. Very careful regulation and evaluation of such operations will, however, be required. We, therefore, recommend that a national agency, with adequate authority, financial support, and technical staff, regulate and maintain records of such disposal, and that continuing scientific and engineering studies be made of the resulting effects in the sea.

7) We recommend that a National Academy of Sciences–National Research Council committee on atomic radiation in relation to oceanography and fisheries be established on a continuing basis to collect and evaluate information and to plan and coordinate scientific research.

8) Studies of the ocean and the atmosphere are more costly in time than in money and time is already late to begin certain important studies. The problems involved cannot be attacked quickly or even in many cases, directly. The pollution problems of the past and present, though serious, are not irremediable. The atomic waste problem, if allowed to get out of hand, might result in a profound, irrecoverable loss. We, therefore, plead with all urgency for immediate intensification and redirection of scientific effort on a world-wide basis toward building the structure of understanding that will be necessary in the future. This structure cannot be completed in a few years; decades of effort will be necessary and mankind will be fortunate if the required knowledge is available at the time when the practical engineering problems have to be faced.

9) The world-girdling oceans cannot be separated into isolated parts. What happens at any one point in the sea ultimately affects the waters everywhere. Moreover, the oceans are international. No man and no nation can claim the exclusive ownership of the resources of the sea. The problem of the disposal of radioactive wastes, with its potential hazard to human use of marine resources, is thus an international one. In certain countries with small land areas and large populations, marine disposal of fission products may be essential to the economic development of atomic energy. We, therefore, recommend: (i) that cognizant international agencies formulate as soon as possible conventions for the safe disposal of atomic wastes at sea, based on existing scientific knowledge; and (ii) that the nations be urged to collaborate in studies of the oceans and their contained organisms, with the objective of developing comparatively safe means of oceanic disposal of the very large quantities of radioactive wastes that may be expected in the future.

10) Because of the increasing radioactive contamination of the sea and the atmosphere, many of the necessary experiments will not be possible after another 10 or 20 years. The recommended international scientific effort should be developed on an urgent basis.

11) The broader problems concerned with full utilization of the food and other resources of the sea for the benefit of mankind also require intensive international collaboration in the scientific use of radioactive material.