Atomic waste disposal in the sea: an ecological dilemma?

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The atomic age has now been with us for more than a quarter of a century, but the ecological problems associated with this development are still incompletely realized. Certainly no physicist at Los Alamos in 1945 had a clear idea of the potential effects of adding artificial radionuclides to the environment, and were it not for a few unfortunate Japanese fishermen on the Lucky Dragon, radiation sickness might now be a common disease. Now everyone is sensitized about the potential dangers of radioactive contamination to man, and we are being assured that our standards for the disposal of radioactive wastes, especially in the sea, limit quantities released to concentrations far below any conceivable danger to man. To some it seems that the reassurances that nuclear reactors are safer than television sets and that our children may safely play upon the lawn by the front entrance to an atomic power plant are just a bit too hearty. While one need not feel concerned about the difficult task of well paid Public Relations men, it is possible that as far as our standards of waste disposal for radioactive materials and the potential contamination from power reactors are concerned, we are demonstrating adequate concern. At this time, however, our approach is strictly anthropocentric, and, as far as the marine environment is concerned, we cannot say whether our standards for disposal of atomic wastes are reasonable or not; the "Maximum permissible concentrations" are those we think permissible for ourselves, not the rest of the biosphere (Table 1).

Nevertheless, at the same time we attempt to apply severe standards on peaceful uses of atomic energy, we are exceeding our self-imposed limits in the sea by releasing unspecified amounts of radionuclides at unspecified times and places by an unspecified number of nuclear powered submarines, and by mid Pacific weapons tests. The philosophical implication of this inconsistency is that man still considers it more desirable to survive as a tribe than as a species, but that is a subject for another symposium.

The earth is a ball of radioactive materials in orbit around a second rate thermonuclear reactor, and its inhabitants are constantly subject to bombardment by radioactive materials from the environment, from substances within themselves, and from outer space (Figure 1). Indeed, the bombardment of earth by cosmic rays may have been an important factor in stimulating the beginning of life. Uranium and thorium are among the most common materials making up the surface of the earth, and the average amount of radium in the human body is said to be 1.59×10^{-10} grams (Bugher, 1956). There is so much radioactive potassium (^{40}K) in the soil that there are almost a million disintegrations per minute in every square foot of soil, and each of us may have 27 milligrams of radioactive potassium in his system. (Ibid). Statistics of this sort are often used to reassure us that there is nothing to be afraid of, that the atomic age is not going to turn us all into monsters or induce wholesale cancers. Perhaps the following statement was also meant to be reassuring, but it does not reassure an ecologist: "The significant alterations which man has introduced into the world are a very great acceleration in time in the processes of radioactive decay and in the changing of the

proportions of the resulting radioactive elemental products, with, in some instances, the introduction of forms unrecognizable in nature." (Bugher, 1956, p. 832).

In any event it is realized that we have the problem of disposal of the products of these accelerated processes on our hands. Some of the accelerated products are dangerous radionuclides with long half lives that must be put quietly away somewhere. Either they must be buried in lead tanks in some remote unusable part of the world or sealed up in vessels impervious to pressure or the action of sea water for a considerable period of time and dropped into some deep part of the sea. Others are "low level" wastes either induced from the activity of processing radioactive materials by military or civilian installations or from reprocessing material from power reactors, or the residue of radioactive materials used in hospitals, laboratories and industrial plants. Much of this material is now being released directly into the sea, hopefully to be diluted and dispersed in the "perpetual sink."

The two best known sites for this release of radioactive material are the Windscale Works on the Cumberland coast and the Columbia River. The actual site of release on the Columbia is at Hanford, 250 miles upstream, and while much of the radioactivity (ca 3,000 curies per day) is dissipated by the time the sea is reached, it appears that approximately 1,000 curies per day reaches the sea at the mouth of the Columbia. At the Windscale Works about 90,000 curies a year are released through a pipeline into the Irish Sea. It is pointed out by many if not most authors discussing these situations that the total releases of artificial radionuclides from Windscale and Hanford to the oceans are less than the contribution of ^{90}Sr to the oceans by fallout from atomic weapons tests (e.g. Parker, 1967).

Radionuclides, like any other material added to the ocean, may be diluted or dispersed, or concentrated or transported in various ways (Figure 2). The only essential difference is that their activity dies off at an exponential rate; for some this decay is such a slow process (e.g. ^{14}C with a half life of more than 5,000 years) that the mixing processes of the ocean are more significant. Distribution of many radionuclides is affected by biological processes, by the concentration of particles to which they may have adhered or by selection of substances required for metabolism.

An important aspect of the accumulation of radionuclides in organisms is the so-called biological half life, or retention time with the organisms. An important trace element such as zinc may be retained a few days in oysters, to several months in fish, but we have no precise figures for the residence time in any marine organism (Chipman, Rice and Price, 1958).

It seems logical to assume that there is no preferential selection by organisms in behalf of radionuclides, that the proportion accumulated by organisms will be the same as the proportion occurring in the medium. It is on this assumption that Isaacs and colleagues (1962) developed the Specific Activity approach to waste disposal. In the case of such naturally abundant elements as iodine, calcium and strontium, the radioisotopes are in comparatively low concentration in the sea and hence the possibility of accumulation of dangerous amounts by man is unlikely. According to this approach it would be impossible for an individual to exceed his allowable radiation by consuming sea food as long as the specific activity of radioisotopes is kept below the allowable limit in the regions where the potential food or products to be consumed grows and resides.

This may not always be the case. For one thing it remains to be demonstrated whether or not there may not be preferential uptake of radionuclides as opposed to stable nuclides of some elements. Such a preferential uptake might, of course, be more related to the chemical or physical state in which the radionuclide is available to the organism than to the comparative levels of activity within the environment. It is also possible that the addition of a critical radionculide of a substance not available in stable form in a restricted location would result in a higher level of radioactivity than predicted by the specific activity approach. The availability of a trace element in itself might stimulate biological activity, growth or reproduction and thus prolong the residence time of the radionuclide in the region concerned. However, we have no reliable information on the effect upon organisms of adding low level wastes to our environment, and even less on the significance of adding artificially produced radionuclides not naturally present in the environment. The onset of the atomic age has posed significant questions in ecology and physiology that cannot be answered without critical and intensive investigation, and for many of these aspects research has already been too long delayed.

The Windscale Works

The Windscale Works, or Windscale Chemical Plant, is located on the Cumberland coast of the Irish Sea at Sellafield (Figure 3). The plant was built for the purpose of processing irradiated reactor fuel from the British nuclear power generating stations, and at the outset it was decided that it would be necessary to dispose of large quantities of low-level wastes by releasing them directly into the sea. For this purpose two lines of 10 inch pipe were laid on the bottom of the sea. The discharge point is some 2800 yards or approximately 2.5 kilometers from the shore, and at a depth of about 60 feet or 20 meters. The waste containing water is fresh, and rises to the surface above the discharge point. Preliminary studies were made of the marine ecology of the shore and near-shore hydrography, and experimental releases of radioactive material were first made in 1952. After a two year experimental period, the permissible releases were established and all discharges have been carefully monitored.

In 1957 Windscale achieved notoriety from the "incident" of October 10-11, when potentially dangerous amounts of radioactive iodine and other radionuclides were released from the stack and it was necessary to condemn quantities of milk from areas downwind (Chamberlain and Dunster, 1958). Since this incident involved dispersal by air rather than by sea, it is not discussed in the various recent accounts of the operation at Windscale, and no mention is made of the possibility (or impossibility) of an analogous incident associated with sea disposal. In any event, the average budget of releases into the Irish Sea for the last several years is available (Table 2); the sharp increase in Zirconium-95 and Niobium-95 is due to the addition of a unit for processing uranium fuel in 1964.

samples are analyzed, and regular sea sampling of fish and bottom mud is carried out. All of this adds up to a sustained and expensive monitoring program which might well be emulated in some other parts of the world. It is reported on in some detail by Longley and Templeton (1965).

So far, there appears to have been no accumulation of radioactivity in the waters of the Irish Sea associated with the Windscale releases (Mauchline and Templeton, 1964). Dilution has been so effective that by the time the effluent reaches the Mull of Galloway and Anglesey it is difficult to distinguish the levels of effluent radionuclides from fallout radionuclides, but at times there is indication of pulse of relatively unmixed water moving from Windscale toward the Mull of Galloway. According to Mauchline and Templeton, if the present rate of input of radioactivity to the Irish Sea remains constant, it will be equal to the rate of removal by currents plus the rate of radioactive decay, and the budget is roughly in balance. There are, however, detectable levels of radioactivity in bottom invertebrates in the Irish Sea associated with the Windscale releases (Figure 4).

The Columbia River plume

Unfortunately there is no single comprehensive account of the disposal of radioactive wastes in the Columbia River and of their fate at sea. The radionuclides reaching the sea are mostly ^{51}Cr and ^{65}Zn (Figure 5). Since the half life of ^{51}Cr is only 28 days, it is not a very satisfactory marker for detecting the fate of wastes very far from the mouth of the Columbia. Detectable amounts of ^{65}Zn, (which has a half life of 245 days) have been found in pelagic and in benthic animals off the Oregon coast to depths of 2800 meters. The amounts are stated to be "very much below hazard levels." (Carey et al., 1966). During the summer months, when the plume of the Columbia River drifts to the south, ^{65}Zn is found in mussels (Mytilus californianus) along the coast for perhaps two or three hundred miles, but at localities where upwelling moves the plume water away from the shore, the ^{65}Zn concentration drops quickly (Osterberg, 1965). This suggests that the biological half life of ^{65}Zn is short in mussels. It appears to be much longer in Euphausiids, since the level of activity of ^{65}Zn in Euphausia pacifica does not fall to background in winter when the Columbia plume moves to the north (Osterberg, Pearcy and Pattullo, 1964). Except in the immediate vicinity of the mouth of the Columbia, concentrations of ^{65}Zn are too low to be easily measured in the sea, and accordingly the explanation for the detectable zinc concentrations is to be sought in the biological system itself. As the authors point out:

> The great affinity of marine organisms for zinc and the sensitivity of modern gamma-ray spectrographic techniques make

> ^{65}Zn in euphausiids easy to measure. Unfortunately, however, use of organisms as monitors introduces many uncertainties. The most important is that we do not know how accurately the radioactivity of the euphausiid reflects the radioactivity of the immediate environment. This difficulty is compounded if variations in stable zinc occur; local variations seem likely because of the affinity of marine organisms for zinc. However, no comparable data exist for stable zinc (Osterberg, Pearcy and Pattullo, p. 256).

The possibility suggested here, that there may be situations in which the radionculide may be more abundant than the stable isotope, raises the question whether the Specific Activity approach recommended by Isaacs and his colleagues can be applied without some further modification. If we have a situation where the radionuclide added to the environment represents an element essential to the food chain, as zinc appears to be, and the quantities to be added exceed the quantities of the stable isotope in the environment, we cannot accept the world ocean average concentration of zinc as a standard for the computation of the specific activity. It might even be necessary in such a situation to add suitably large amounts (which might still be in the order of pounds rather than tons) of a salt containing stable zinc to ensure a low specific activity.

Zinc occurs in virtually all marine animals sampled, and perceptible levels of ^{65}Zn have also been found in salmon from Bristol Bay, Alaska, to Eureka, California, suggesting that it may be a useful indicator for studying migration patterns of this fish, since it appears that the salmon from both extremes of this geographical range have at some time in their lives been

within the influence of the effluent of the Columbia River (Osterberg, 1965). Zinc is evidently accumulated rapidly by fish, as albacore (Thunnus alalunga) show an increase of ^{65}Zn of 8 times in the liver between July and September off the Oregon coast (Pearcy and Osterberg, 1968).

So far, the bulk of the work with radionuclides associated with the plume of the Columbia River has been concerned with detecting radioactivity as an indicator of water movement, and to some extent with the fate of the material in the food chains. "We do not know the particular form in which the nuclides occurred in the sea. Their exact state and the paths by which they move through the system are unknown." (Barnes and Gross, 1966, p. 302). The whole experience with the Hanford effluent has been more in the nature of a vast unplanned marking experiment, in strong contrast to the careful advance studies and continuing monitoring program at Windscale. Indeed this unpremeditated marking experiment "homed" at Hanford itself in 1959 when an unexpectedly high ^{65}Zn level was detected in a person who had eaten oysters from Willapa Bay (just north of the Columbia) that had accumulated ^{65}Zn from the river effluent; in this case the concentration factor was 200,000 times that of the sea water (Perkins et al., 1960).

Ecological Questions

Most of our information about the possible effects of radiation on organisms in nature is derived from experiments involving quantities or intensitites that do not occur in nature upon organisms that do well under experimental conditions. It is difficult to interpret information based on experiments with such nearly indestructible organisms as the brine shrimp and fish that may survive in nature in situations not too different from hot urine (e.g. Fundulus). At the present time there are two schools of thought on the question of the effect of low levels of artificial radioactivity on marine orgnisms. Soviet workers have found, for example, that eggs of the anchovy in the Black Sea (the eggs are pelagic, i.e. in the surface layers of the sea) may be damaged by concentrations of ^{90}Sr as low as 10^{-10} curie/liter, and on this basis suggest that the maximum permissible concentration for the surface layers of the sea should be of the same order (10^{-12}) as for man, and that "further radioactive contamination of the seas and oceans is inadmissable." (Polikarpov, 1966, p. 260). The research by Soviet workers in this field is summarized by Polikarpov in his book, and this work is in fact the only attempt so far at a general summary of the problem.

The results of Soviet experiments with pelagic fish eggs and fry do not agree with the results of British and American researchers on eggs and fry of salmonid fish. British studies did not note detectable effects on brown trout until concentrations of 10^{-6} were reached, and, in the words of Parker (1967) "these investigators have suggested that, since this value differs markedly from the Russian value, perhaps different species, experi-

mental conditions, and the short period of experimentation might be possible in part for the difference." Parker then quotes a statement by Bonham and Donaldson (1966) based on experiments with salmon eggs and alevins as summarizing the American point of view: "All of these experiments considered together show that the administration of 0.5 R/day from time of fertilization up to the feeding stage produced no detected damage to the stock sufficient to reduce the reproductive capacity over a period of slightly more than one generation."

According to Parker this means that the British and American data show "no effect" in water concentrations 10^3 greater than those of actual liquid-disposal operations, but that Russian data "indicate that effects are present."

Parker states that since the species, chemicals and "behavior of these variables" are different, the results "may not be too surprising" and concludes with some equanimity: "However, whether or not harmful effects to the environment have occurred has not yet been determined due to diametrically opposed results of the investigations carried out to date on genetic damage to biota from the wastes released." (Parker, p. 380).

This is a disturbing attitude; it seems to say that when there is diametric disagreement between results obtained from incomparable situations, both are wrong. It is quite possible that it may be much more difficult to interpret results based on species that may be more difficult to maintain under laboratory conditions as opposed to those already practically domesticated, and that there may be problems with experimental method in the two cases. Certainly it should be remembered that salmonid fishes of the genus Onchorhynchus have the genetic potential for adjusting to greater changes in the ionic composition of the environment than do oceanic clupeids and this

alone may account for greater tolerance of artificial radioactivity. Fishes such as sardines and anchovies, whose eggs and young depend on conditions in the surface layers of the sea where potential contamination is greatest, are vulnerable to slight environmental changes and it may take considerably less to influence the success of a year class, or of the entire fishery, of such a pelagic stock.

It should be obvious that one cannot add or subtract oranges and apples, that the conclusions of Soviet radioecologists based on pelagic organisms in the Black Sea cannot be offset by conclusions based on hatchery reared fish that may be genetically conditioned by a possibly higher natural background in streambeds. There are obviously too many variables here, and the only logical approach to this "confrontation" is a program of research on related species of similar life history and ecology in several parts of the world. Until proven otherwise by critical work on comparable species, the results of Soviet workers must be accepted as a clear warning that we may indeed be approaching a condition of saturation of the marine environment with potentially dangerous radioactive materials. In any event, results from experimentation with the young stages of salmonid fishes should be viewed, as far as understanding the effects of increased radioactivity in the sea is concerned, in the same light as those with other durable, standard laboratory pets: interesting, but possibly academic as far as the real world is concerned.

In the real world one also cannot consider the effects of radionuclides without reference to other aspects of pollution or natural factors. In the Irish Sea ruthenium-106 is adsorbed on suspended silt which in turn is adsorbed on the Porphyra. What would be the effect of such an installation as

Windscale combined with a massive sewer outfall, or with an industrial plant discharging large quantities of particulate matter into the sea? (Massive disposal of a fine particulate material near the mouth of the Columbia was considered by one industry.) Such "synergistic" combinations of pollutants could alter the pathways of radionuclides in food chains and produce different patterns of circulation and dilution or concentration in the sea.

Windscale and Hanford are two examples of the shape of things to come. There are several smaller scale liquid waste disposal programs in various countries, and others are being planned. So far, all of these controlled releases are being made in regions where there is a certain amount of oceanographic sophistication and the necessary technology for continuous monitoring is available, viz., Norway, Sweden, France, Italy and Japan. Research and surveillance are not good substitutes for pollution, however. It seems obvious, for example, that even in the Pacific Ocean near the mouth of the Columbia, the residence time of such a radionuclide as ^{65}Zn in resident organisms may offset the potential for physical dispersion. What then can be expected from waste disposal in semi-enclosed seas and gulfs? If for example, a large industrial-agricultural unit powered by nuclear reactors were to be placed on the shore of the Red Sea or the Persian Gulf, what might happen? If such a development would also assume increased harvest of the products of the sea, has consideration of the possible effect of radioactive waste disposal in such a closed basin as the Persian Gulf been made? Or is it being assumed that there are no laver bread consumers (or their analogue) and that this aspect of the potential economy need not be considered?

Would it be wise to permit, on a world-wide basis, a development involving a steady discharge of radioactive materials into a region where it might build up and in turn serve as a source of waste disposal to the larger body of water it adjoins? Reassurance that the isotope sewers of Windscale and Hanford are contributing less radioactivity to the environment than nuclear weapons tests is beside the point. As Korringa says, it is "not the accidental calamities but the general trends, the stealthy deterioration of environmental conditions in sections of the sea of vital importance to its living resources, which count most." (Korring, 1968). Even a few more isotope sewers may be "insignificant", but the next order of magnitude may not be far off, and the research and surveillance necessary to keep such waste disposal within limits will be diuluted more rapidly than the wastes may be dispersed. Can we, at the same time we talk of world wide increase of the fisheries resources of the sea, also endanger those resources with radioactive pollution that may not only alter their productivity but render them dangerous for human consumption?

One thing is certain: it is long past the time that we can consider pollution of our environment an unavoidable and economically justifiable price for progress. The inescapable ecological verity is that we must limit this alteration of our environment in the only possible way, by control of our own numbers.

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Tables

1. from Polikarpov, pp. 234-235

2. from Howells, Table 1.

Figures

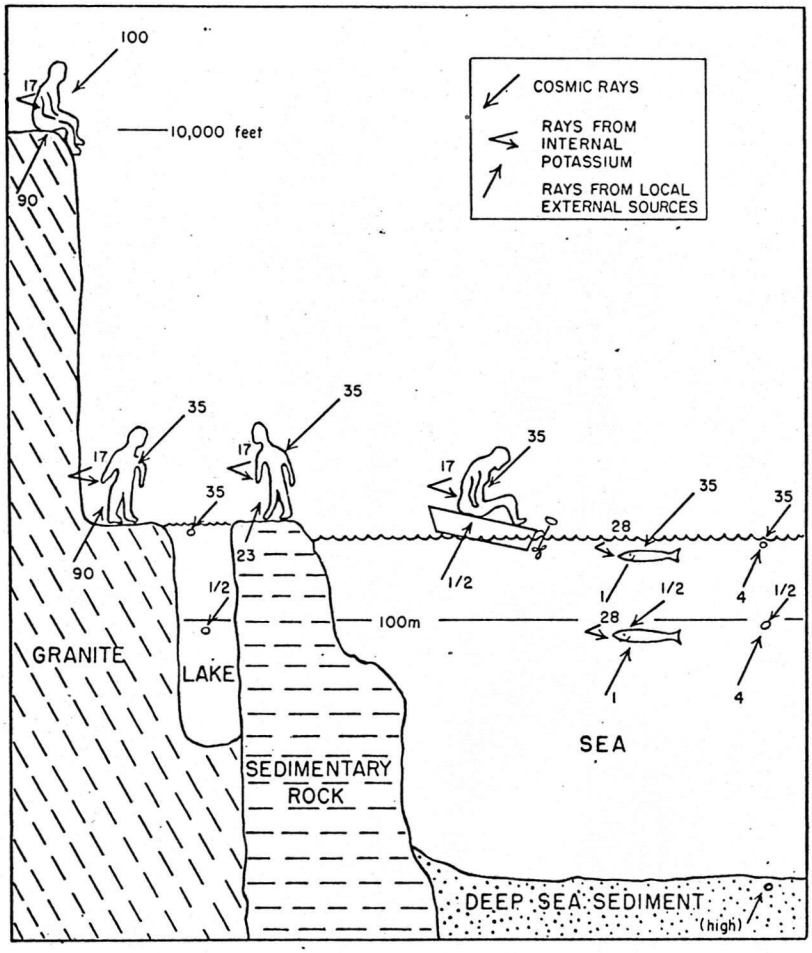
1. Comparative natural radiation doses. Folsom & Harley 1957

2. Schematicndiagram of processes which effect dispersion Waldichuk 1961

3. Sampling stations, Windscale Jowells 1966

4. levels of beta activity in Irish sea. Mauchline & Templeton 1964

5-6 radioactivity, Columbia River plume Osterberg, Cutshall & Cronin 1965



TOTAL NATURAL DOSES (mrad/year)

Man over granite		Man over sedimentary rock	Man over sea	Large fish in sea		Micro-organism in sea	
10.000	m.s.l.			at surf.	100 m.	at surf.	100 m.
207	142	75	52	64	30	39	5

Fig. ~~134~~ 1.
Comparative natural radiation doses. From Folsom and Harley, 1957.

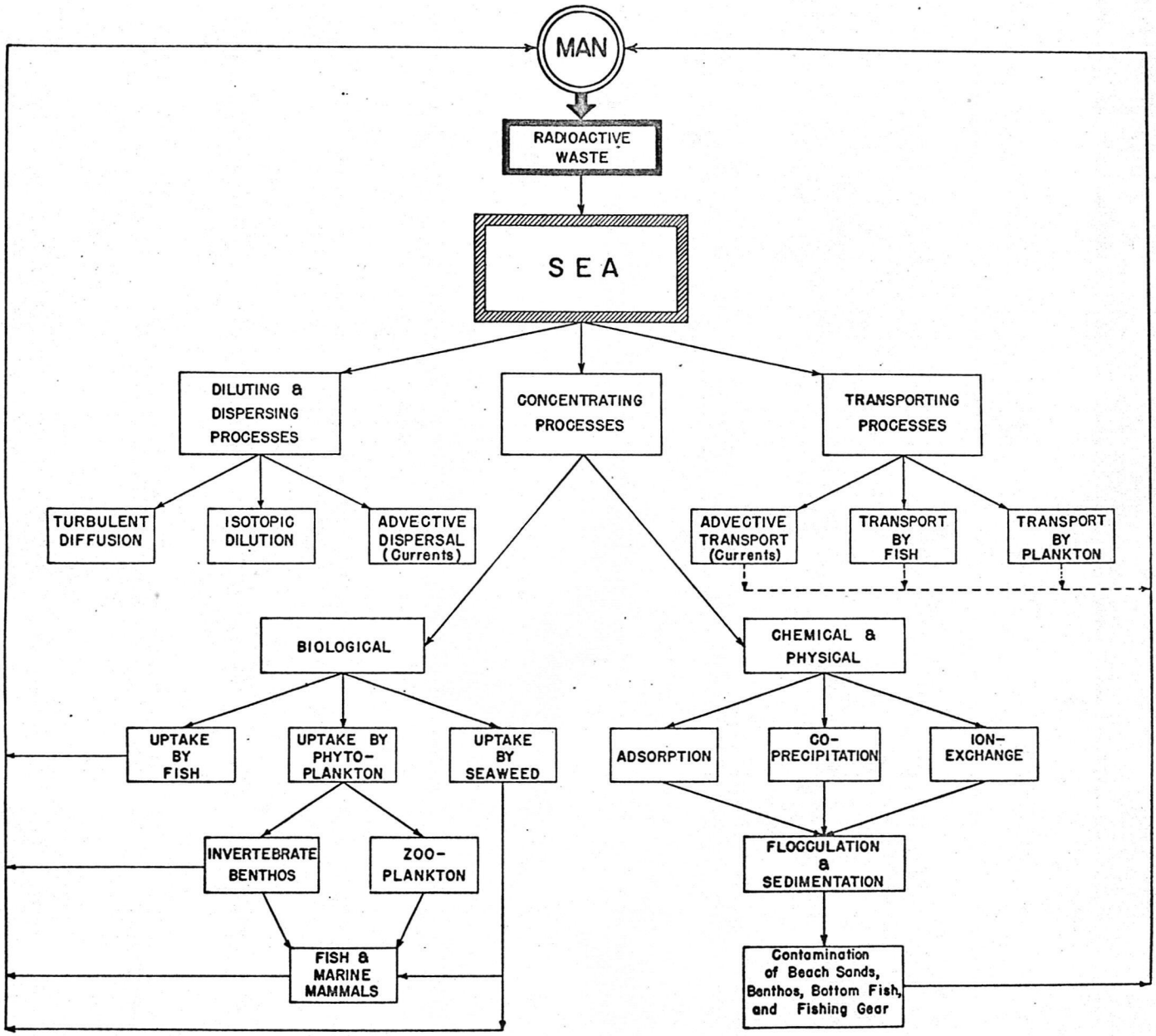


Figure 2. A schematic diagram showing the various marine processes acting on a radioactive waste and the possible routes of its return to man. (Waldichuk, 1961)

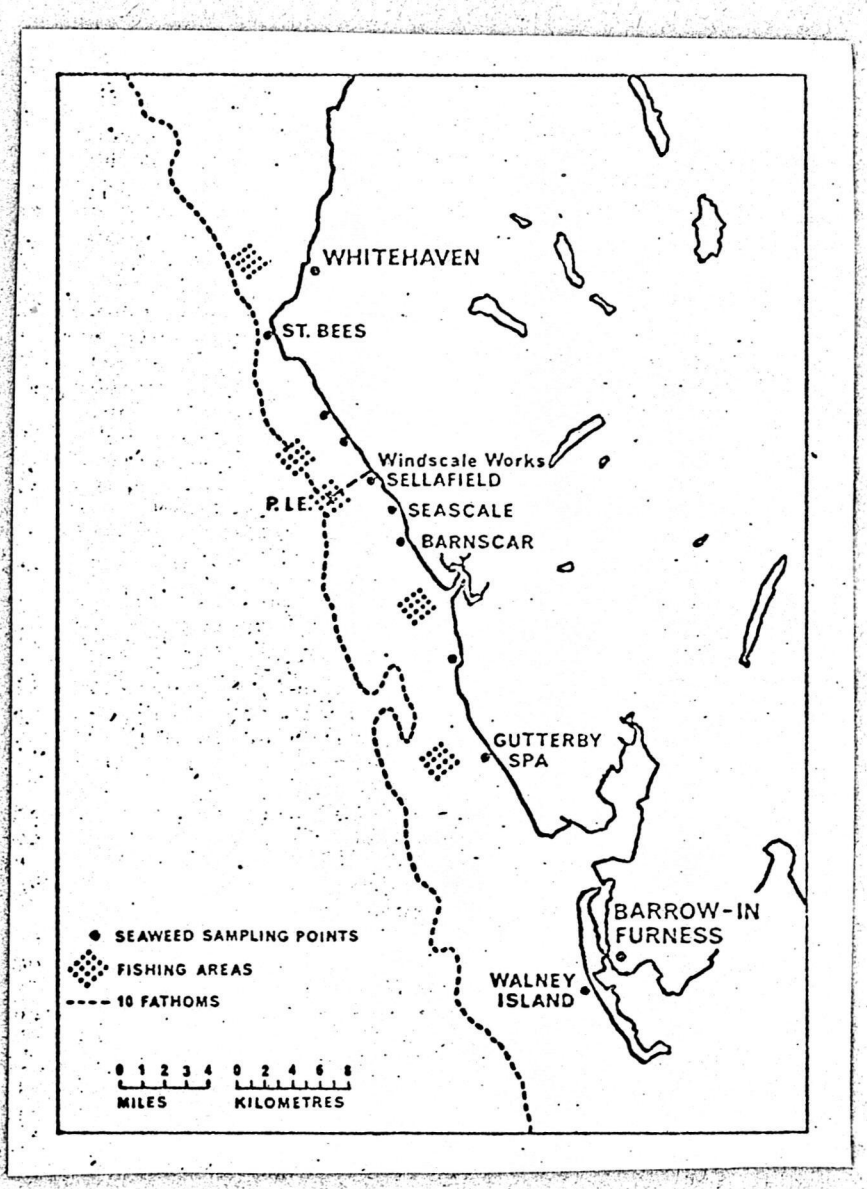


Fig. 3. Marine sampling stations, Windscale Works

(from Howells, 1966)

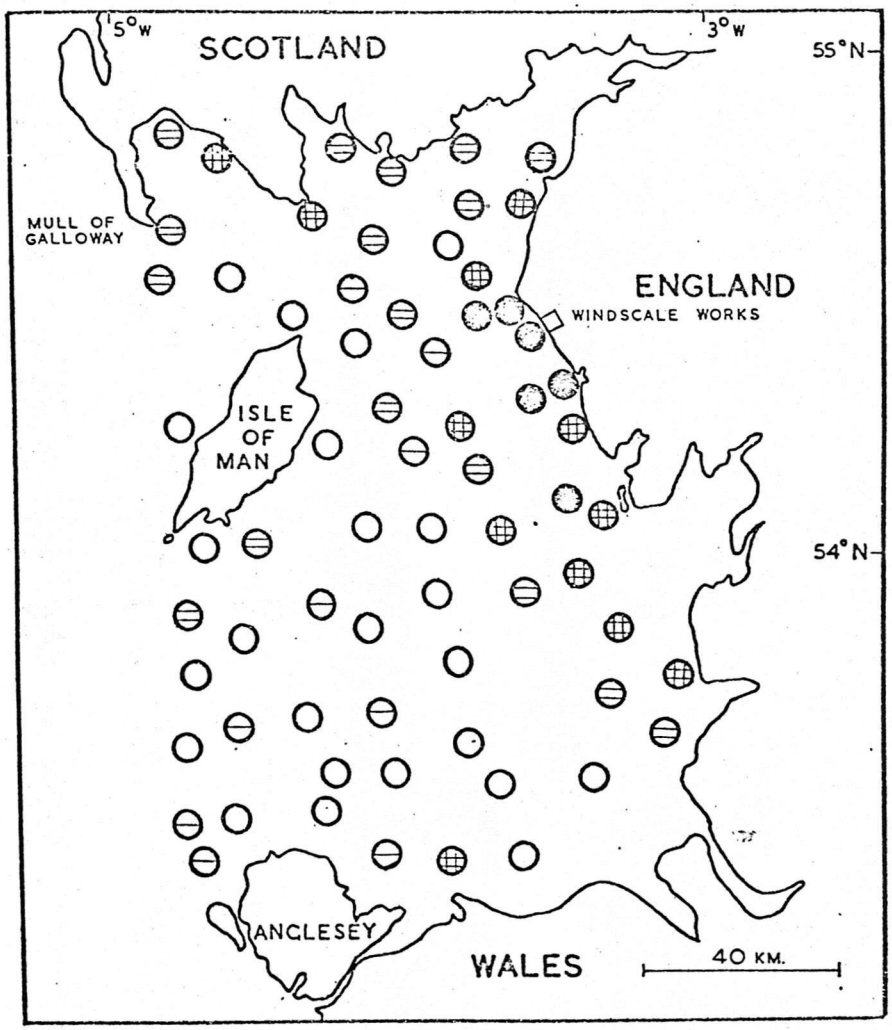


Fig. 4.—The levels of β-activity, originating from the radioactive effluent discharged from Windscale Works, present in bottom invertebrates in the Irish Sea. Corrections have been made for β-activity originating from natural and fallout sources. (After Mauchline, 1963.) ◯ 100–1,000 $\mu\mu$c/g. wet weight. ⊕ 20–99 $\mu\mu$c/g wet weight. ⊖ 10–19 $\mu\mu$c/g wet weight. ⊖ 5–9 $\mu\mu$c/g wet weight. ○ <5 $\mu\mu$c/g wet weight.

(From Mauchline and Templeton, 1964).

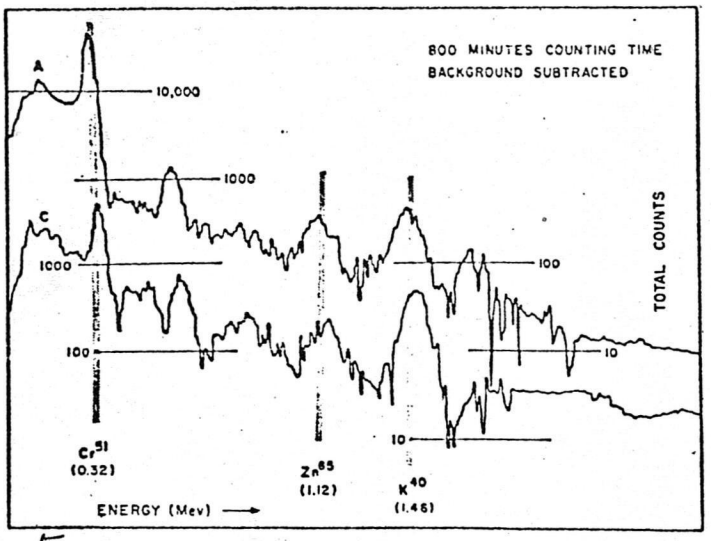


Fig. 5. Spectra of coprecipitates from sea water from the station with most Cr^{51} activity (*A*), and from the station at greatest distance from the mouth of the Columbia River (*C*). Collection sites of the two surface-water samples are points *A* and *C*, respectively, on the map in Fig. 2.

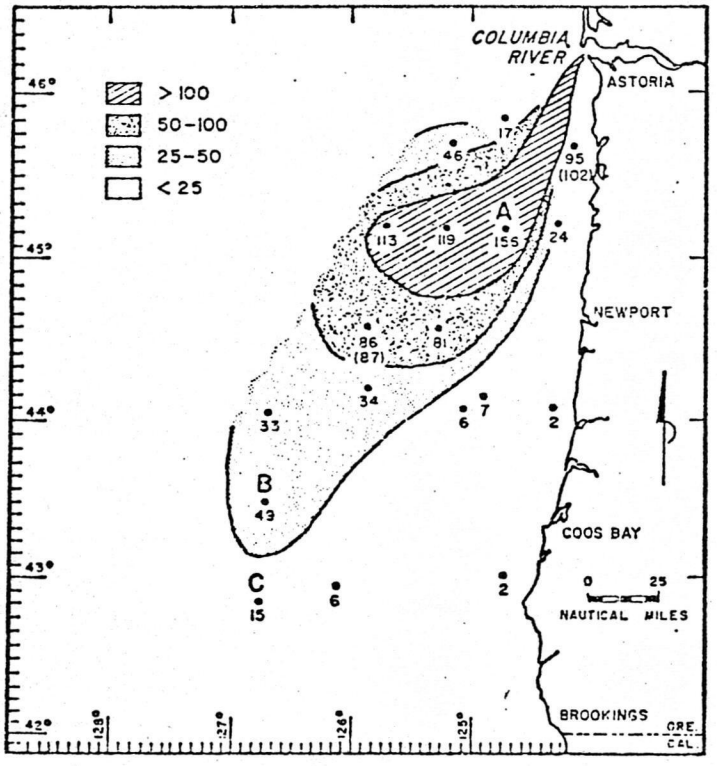


Fig. 6 (left). Chromium-51 (counts per minute per 100 liters of surface sea water), corrected to date of collection, 26 June to 1 July 1965. Parentheses indicate duplicate samples. The number of counts per minute per 100 liters can be converted to picocuries per liter by multiplying by 0.861. The greatest velocity of water movement was between points *A* and *B*.

(From Osterberg, Cutshall and Cronin, 1965).

Table 1

Maximum permissible concentrations (MPC) for man of radionuclides in water and in marine organisms (From Polikarpov, 1967)

Nuclide	MPC in drinking water (Cur/l)		MPC in sea-water (Cur/l)				
	Soviet standard*	US standard**	tentative standards in US (a)		adopted in US (b)	tentative standards in US (a)	(c)
			local situation	general situation			
^{3}H	3×10^{-7}	3×10^{-6}	–	–	–	–	–
^{14}C	2×10^{-7}	8×10^{-7}	–	–	–	–	–
^{24}Na	8×10^{-9}	3×10^{-8}	–	–	–	–	–
^{32}P	5×10^{-9}	2×10^{-8}	–	–	9.6×10^{-11}	4.5×10^{-12}	5×10^{-12}
^{35}S	7×10^{-9}	6×10^{-8}	–	–	1×10^{-5}	1.1×10^{-8}	1.2×10^{-7}
^{42}K	6×10^{-9}	1×10^{-7}	–	–	–	–	–
^{45}Ca	3×10^{-9}	9×10^{-9}	–	–	2×10^{-7}	1.2×10^{-7}	9×10^{-9}
^{51}Cr	5×10^{-7}	2×10^{-6}	2×10^{-8}	7×10^{-10}	5.4×10^{-8}	2×10^{-8}	2×10^{-8}
^{55}Fe	3×10^{-8}	8×10^{-7}	1×10^{-9}	3×10^{-11}	3×10^{-9}	1.4×10^{-9}	8×10^{-10}
^{59}Fe	1×10^{-8}	6×10^{-8}	7×10^{-11}	2×10^{-12}	6×10^{-11}	6×10^{-12}	6×10^{-11}
^{60}Co	1×10^{-8}	5×10^{-8}	3×10^{-11}	1×10^{-12}	8×10^{-10}	5×10^{-11}	5×10^{-11}
^{64}Cu	6×10^{-8}	2×10^{-7}	3×10^{-10}	1×10^{-11}	–	–	–
^{65}Zn	1×10^{-8}	1×10^{-7}	1×10^{-10}	3×10^{-12}	4×10^{-10}	7×10^{-12}	2×10^{-10}
^{90}Sr	3×10^{-11}	1×10^{-10}	2×10^{-11}	1×10^{-12}	2.5×10^{-8}	3.3×10^{-9}	5×10^{-11}
^{95}Zr	2×10^{-8}	6×10^{-7}	4×10^{-10}	1×10^{-11}	–	–	–
^{95}Nb	3×10^{-8}	1×10^{-7}	3×10^{-9}	1×10^{-10}	3×10^{-8}	5×10^{-9}	5×10^{-9}
^{106}Ru	3×10^{-9}	1×10^{-8}	1×10^{-10}	3×10^{-12}	1.6×10^{-10}	1×10^{-10}	1×10^{-10}
^{131}I	6×10^{-10}	2×10^{-9}	3×10^{-10}	1×10^{-11}	1×10^{-7}	1.6×10^{-9}	2×10^{-10}
^{137}Cs	1×10^{-9}	2×10^{-8}	4×10^{-9}	1×10^{-10}	1.6×10^{-7}	1.3×10^{-10}	4×10^{-9}
^{144}Ce	3×10^{-9}	1×10^{-8}	–	–	1.5×10^{-11}	1×10^{-11}	1×10^{-11}
^{182}Ta	1×10^{-8}	4×10^{-8}	3×10^{-10}	1×10^{-11}	–	–	–
^{192}Ir	1×10^{-8}	4×10^{-8}	–	–	–	–	–
Mixture of beta and gamma-emitters	5×10^{-11}	10^{-11}	–	–	–	–	–
Mixture of alpha-emitters	5×10^{-11}	10^{-11}	–	–	–	–	–

* Health regulations for 'Work with radioactive substances and sources of ionizing radiations' (Russian list: Anonymous [1960]).

** 0.1 of the MPC for nuclear energy workers (National Committee on Radiation Protection [1959].

		Concentration factors in marine organisms		MPC in edible marine organisms (Cur/kg of wet weight)				
(d)	in India (e)	(b)	(a)	tentative standards in US (a)		adopted for the Irish Sea (f)	(d)	in India (e)
				local situation	general situation			
–	–	–	–	–	–	–	2×10^{-3}	–
–	2×10^{-9}	–	–	–	–	–	3×10^{-5}	1×10^{-5}
1.6×10^{-4}	–	–	–	–	–	–	8×10^{-5}	–
5×10^{-11}	2×10^{-12}	2×10^{5}	–	–	–	–	2×10^{-6}	3×10^{-7}
1×10^{-5}	9×10^{-8}	5	–	–	–	–	5×10^{-5}	5×10^{-7}
1×10^{-5}	–	–	–	–	–	–	1×10^{-4}	–
5×10^{-7}	4×10^{-8}	20	–	–	–	–	5×10^{-6}	1×10^{-7}
–	4×10^{-8}	10^{3}	3×10^{2}	7×10^{-6}	2×10^{-7}	–	5×10^{-4}	3×10^{-5}
–	7×10^{-10}	10^{4}	3×10^{3}	3×10^{-6}	8×10^{-8}	–	–	1×10^{-5}
4×10^{-9}	5×10^{-11}	10^{4}	3×10^{3}	2×10^{-7}	5×10^{-9}	–	4×10^{-5}	1×10^{-6}
2×10^{-8}	2×10^{-9}	10^{4}	3×10^{3}	1×10^{-7}	3×10^{-9}	–	2×10^{-4}	8×10^{-7}
1.6×10^{-7}	–	5×10^{3}	2×10^{3}	7×10^{-7}	2×10^{-8}	–	8×10^{-4}	–
1.2×10^{-7}	1×10^{-10}	5×10^{3}	3×10^{3}	3×10^{-7}	1×10^{-8}	–	6×10^{-4}	8×10^{-7}
8×10^{-10}	3×10^{-10}	20	13	3×10^{-10}	1×10^{-11}	$(1–5)\times10^{-8}$	8×10^{-9}	2×10^{-9}
–	1×10^{-8}	–	5×10^{2}	2×10^{-7}	6×10^{-9}	–	–	1×10^{-6}
–	2×10^{-8}	2×10^{2}	1.2×10^{2}	3×10^{-7}	1×10^{-8}	–	–	2×10^{-6}
–	2×10^{-10}	10^{3}	3×10^{2}	3×10^{-8}	1×10^{-9}	$(1–3)\times10^{-6}$	–	2×10^{-7}
3×10^{-10}	4×10^{-9}	10^{2}	28	1×10^{-8}	3×10^{-10}	–	3×10^{-7}	2×10^{-7}
3×10^{-7}	6×10^{-9}	50	18	7×10^{-8}	2×10^{-9}	–	1.5×10^{-5}	5×10^{-8}
–	1×10^{-8}	8×10^{3}	–	–	–	–	–	2×10^{-7}
–	–	3×10^{2}	–	1×10^{-7}	4×10^{-9}	–	–	–
–	–	–	–	–	–	–	9×10^{-6}	–
–	–	–	–	–	–	5×10^{-5}–1×10^{-6}	–	–
–	–	–	–	–	–	3×10^{-7}–1×10^{-8}	–	–

(a) PRITCHARD [1960].
(b) Anonymous [1960b].
(c) Committee on the Effects of Atomic Radiation on Oceanography and Fisheries [1959].
(d) Committee on Oceanography [1959b].
(e) PILLAI and GANGULY [1961].
(f) TEMPLETON [1962].

TABLE 2. - MEAN ACTIVITY DISCHARGE RATES TO SEA

(From Howells, 1966)

Radionuclide	Discharge Rate - Curies per Month								
	1957	1958	1959	1960	1961	1962	1963	1964	1965
Ruthenium-106	2218	3522	2956	3302	2095	1916	2781	1924	1752
Ruthenium-103	300	492	746	964	265	153	800	100	150
Strontium-90	137	210	129	43	41	85	46	81	97
Strontium-89	248	72	170	82	114	42	14	16	14
Cerium-144	215	497	583	74	180	200	116	267	288
Yttrium-91 and Rare Earths	300	567	506	83	201	125	90	90	73
Caesium-137	310	516	165	76	91	92	31	111	97
Zirconium-95	59	210	415	196	140	78	47	1797	1479
Niobium-95	535	510	845	523	658	356	272	1735	2803
Total Beta	5366	6846	7659	6461	3981	3742	4020	5055	4560
Total Alpha	4.8	5.2	5.6	6.8	11.1	15.5	19.0	23.5	33.8