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ROLE OF SOLUBLES AND PARTICULATES IN RADIONUCLIDE ACCUMULATION IN THE OYSTER CRASSOSTREA GIGAS IN THE DISCHARGE CANAL OF A NUCLEAR POWER PLANT

Florence L. Harrison, Kai M. Wong, Robert E. Heft

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ROLE OF SOLUBLES AND PARTICULATES IN RADIONUCLIDE ACCUMULATION IN THE OYSTER CRASSOSTREA GIGAS IN THE DISCHARGE CANAL OF A NUCLEAR POWER PLANT*

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RUNNING TITLE: Solubles and Particulates in Accumulation

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ABSTRACT

Changes in ^{54}Mn, ^{60}Co, ^{65}Zn and ^{137}Cs concentrations were followed in oysters introduced into a discharge canal receiving low-level radioactive waste from a boiling water reactor. Groups of animals were maintained either in filtered or nonfiltered discharge-canal water. They were sampled immediately before and after single radioactive releases and at one-day intervals thereafter. Radionuclide concentrations were determined also in the water and in suspended and settled particulates.

In the canal water, concentrations changed rapidly during a release, reaching peak values within 30 minutes. The partition between soluble and particulate (filterable) phases in the water differed with the radionuclide. Continuous sampling of suspended particulates after single releases showed considerable variation in concentrations per liter of water for each radionuclide.

Comparisons of animals held in filtered water to those in nonfiltered water showed similar concentrations only for ^{137}Cs. Results indicate that suspended particulates play an important role in the accumulation of some radionuclides and that resuspension of particulates is an important source between periods of releases.

Key Words: Oysters, Particulate, Solubles, Sediment Pollutants, Manganese, Zinc, Cobalt, Cesium, Accumulation, Radionuclides.

INTRODUCTION

Oysters are known to be effective concentrators of many of the trace metals in seawater (Vinogradov 1953, Galtsoff 1964, Brooks and Rumsby 1965, Poilikarpov 1966, Shuster and Pringle 1969). With increased industrialization and urbanization, increased quantities of radioactive and trace metal pollutants may be released into estuarine environments. To maintain healthy populations of oysters, more information is needed on the critical factors in the entry of pollutants into these organisms.

Oysters are filter-feeding animals and as such maintain a steady flow of water through their gills for feeding, respiration, and removal of metabolic byproducts. The rate of water transport through the gills of an adult oyster may vary from several liters per hour to a maximum of 34 liters per hour (Galtsoff 1964). Pollutants can enter these animals by ingestion of living and nonliving particulate matter in suspension in seawater and/or by the sorption of substances dissolved in the water. The latter can occur directly by the accumulation of ions or small molecules by exposed tissues or indirectly by the adsorption of soluble material onto the mucous sheets on the surface of the gills with the subsequent ingestion of these sheets (Galtsoff 1964).

This study was initiated to assess the accumulation of radionuclides by oysters from soluble and particulate materials in seawater of the discharge canal of the Pacific Gas and Electric Company power plant at Humboldt Bay, California. Here the radionuclides in water are highest in the environment receiving the waste and facilities are available and convenient for the installation of experimental equipment.

Oysters were introduced into the discharge canal before a scheduled release and then the concentrations of radionuclides were followed in animals maintained at the discharge canal either in filtered seawater or in nonfiltered seawater. Data on oysters, water, and particulates were obtained during a period of high and a period of low biological productivity, and were obtained simultaneously on four elements that differ in their physicochemical properties. Such information is important for evaluation of the effects on man of consumption of filter-feeding animals exposed to environmental pollutants.

MATERIAL AND METHODS

Site Description

Adjacent to Humboldt Bay (near Eureka, California) is the Humboldt Bay Power Plant, which produces electricity with two 54-MW(e) fossil fuel units and a single 65-ME(e) boiling water reactor (Fig. 1). Cooling water from the south part of Humboldt Bay is pumped from an inlet canal through the condensers of all three generating units and then discharged into a short canal leading back to the central part of the Bay.

Liquid radioactive wastes from the stack, the power building, the refueling area, and the laundry operations are accumulated and processed at the plant. Batches of low-level waste are released into the discharge canal waters at irregular intervals. The radiation levels at release are in accordance with limits prescribed by the U.S. Energy Research and Development Administration and the state of California North Coastal Water Control Board.

The discharge canal is 140 m long and from 12 to 21 m wide depending on the tides. Its bottom and sides consist of mud with a high content of organic material. The volume of the discharge depends on the number of units operating; the flow rate varies from 200,000 to 400,000 liter/min. The temperature of the water is generally about 22°C, but it may be lower or higher depending on the number of fuel units in operation. Temperatures can reach about 28°C at the experimental station when the effluent is heated as part of the operation to remove mussels that may have settled in the condensers lines. More detailed descriptions of the physical paramaters of the discharge canal and adjacent area are given in previous reports (Heft et al. 1971, 1973).

Expetimental Station

The experimental station installed at the discharge canal consisted of a raft and an instrument shed. The redwood raft was based on styrofoam pontoons; it was provided with openings for the suspension of containers to hold the oysters in the water stream and to collect samples of settled particulates. All construction below the water line was nonmetallic to minimize contamination with trace metals. The raft was held in place in the center of the canal by a system of lines and pulleys by which the raft could be pulled into shore at will.

Experimental Animals

Several hundred 3-year old oysters (Crassostrea gigas) obtained from commercial beds in the north part of the bay were introduced into the discharge canal. Half were placed in the water stream in plastic cages suspended from the raft and the other half in aquaria on the raft. The

aquaria were supplied with water pumped through 1.0 μm filter cartridges at a rate of about 30 liter/min during the release; the pump intake was in the same area as the plastic cages. Rapid turnover of the water in the aquaria was obtained by supplying the water to the bottom of the aquaria and by keeping the total volume of contained water small to minimize dilution of the inflowing water.

Oysters were placed in the discharge canal 12 to 14 hr previous to the scheduled release to allow sufficient time for the animals to acclimate to the new environment. The animals were sampled immediately before and after the release and at 1-day intervals after the event. For each sampling, the soft tissues from 50 to 75 animals were removed from their shells, rinsed in filtered seawater, and pooled to give a composite sample; the dissection was performed immediately at the site. For most oysters the wet weight of the soft tissues was about 50 g and the shell length about 12 cm.

Particulates

Throughout the experimental period suspended particulates were collected either on 1 μm Nucleopore or cartridge filters. Analysis of the particulates collected on cartridge filters required removal of the filter material. The cording that made up the filter bed was cut from the central core, weighed wet, dried to constant weight, and then ashed to remove the organic material.

Settled particulates were taken from collection trays suspended from the raft at the same level as the animals in the cages and from trays placed on the bottom of the canal. The trays were sampled by removal of all the material that had deposited from the previous collection.

Water

Water samples from the discharge canal were collected before, during and after the release of the radioactive waste. For each collection about 200 liters of seawater were filtered through 1 μm cartridges. The radionuclides in the particulates and filtrate were analyzed separately by appropriate radiochemical methods. Chemical yields for isotopes of cobalt, cesium, manganese, and zinc were determined from analyses performed by atomic absorption spectrometry.

Sample Processing

Further processing of the oyster and particulate samples were conducted at Lawrence Livermore Laboratory. Dry weights were determined after drying at 103°C in an oven. Ash weights were determined after ashing to constant weight at 450°C in a muffle furnace. All samples were counted on Ge(Li) detectors and the counting data were recorded on tape for computer processing.

RESULTS

Radionuclide Source

The radioactive wastes released into the discharge canal differed widely in radionuclide composition from release to release and the frequency of releases was irregular (Heft et al. 1973). The duration of a single release was usually 6 hours, but was as short as 2 hours.

Radionuclide concentrations in the water in the discharge canal during a release were dependent on the amount of each radionuclide in the liquid waste and on the rate of water flow through the discharge canal. For each release a dilution factor was calculated based on the known conditions of

the release. This dilution factor was used to calculate the expected radionuclide concentrations (soluble plus particulate fraction) at the point of entrance to the discharge canal. Hereafter the term "expected" concentration will refer to that calculated from the dilution factor. For the three releases of concern, the quantities of each radionuclide released and the expected water concentrations are given in Table 1. Since the behavior of ^{134}Cs and ^{137}Cs was the same in both the biotic and abiotic compartment, data will be given for ^{137}Cs only.

The validity of predicting radionuclide concentrations in the water from the known dilution of the source was evaluated by comparing the measured (soluble plus particulate) to the expected concentration values. The measured values expressed as percentages of the expected varied with the radionuclide and, for a given radionuclide, during the release (Table 2).

Agreement between measured and expected values was better for radiocesium than for ^{54}Mn, ^{60}Co, and ^{65}Zn; the poorer agreement for the latter nuclides was probably related to their interaction with particulates. During the July 31 release, lower-than-expected values were obtained for radiocesium at 0900 and 1100. This was probably the result of their collection during startup and stoppage of the release. Results from continuous monitoring of the water with a probe containing a Ge(Li) detector showed that maximum concentrations of $^{134,137}Cs$ were not reached until approximately 30 min after the release had started (Huckabay 1975). The inflowing water appears to mix with that already present in the discharge canal rather than to replace it immediately. However, homogeneity was probably achieved by the

time the water mass reached the sampling station (which was in the lower half of the discharge canal), since water samples collected at the surface and 0.3 m from the bottom had essentially the same concentrations.

The good agreement between the measured and expected values for radiocesium indicates that for conservative radionuclides the concentrations observed during releases will probably correspond well with the expected values (concentrations of "conservative" elements are directly proportional to the salinity). The high flow rate of the water coupled with the small size of the discharge canal results in a relatively rapid turnover of nuclides in solution in the canal water. For nonconservative radionuclides, the concentrations during discharge will be different from that than predicted and the amount of difference can be expected to be radionuclide-dependent.

Partitioning Between Soluble and Particulate Fractions

Suspended particulates appeared to play an important role in the quantities of radionuclides accumulated by oysters maintained in the discharge canal for an 18-month period (Harrison et al. 1975). To establish the relative importance of the soluble and particulate (filterable) fractions in the transport and availability of radionuclides, partitioning between the two fractions in the water was determined in samples collected before, during, and after the April 4 and July 13, 1973 releases. During these releases the partitioning of the total activity was found to be radionuclide-dependent and to vary during the release (Tables 3 and 4). The largest percentages in the particulate fraction were for ^{54}Mn, the smallest for ^{137}Cs. For the December 4, 1973 release radionuclide concentrations were measured only in the particulate fraction (Table 5).

Comparisons of the normalized concentrations in the particulate fraction for the three different releases indicate that the concentrations in the particulates differed from release to release (compare Tables 3, 4, and 5). The concentrations in particulates (pCi/meter^3) were highest in the April 4 release and lowest in the December 4 release.

Radionuclide concentrations in the particulates can be expressed also on a weight basis, since the particulate load of the water was measured. Normalized concentrations in the particulates in pCi/mg were highest in April and lowest in December.

The particulate load (mg/liter) in the discharge-canal water at the sampling site differed in amount from release to release and with time for a single release (cf. Tables 3, 4, and 5). However, the differences in the radionuclide concentrations in the particulate fractions among releases were greater than can be accounted for by differences in particle load. For ^{54}Mn, the highest normalized concentration observed during July was 580 and and during December was 35 pCi/meter^3, whereas the largest particle load in July was 28 mg/liter and in December was 15 mg/liter. These data suggest that the July particles and the December particles differed in composition.

Continuous monitoring of the radionuclide concentration in the particulate fraction in the water after the December release showed that the levels of activity increased and decreased periodically (Table 5). The variations in concentrations in the particulate fraction during the interrelease period could be due to changes in the amounts of the bottom sediments resuspended. For the experiment conducted in April, settled particulates were sampled serially over the same time intervals from collection trays placed on the bottom of the canal near the raft and from

trays suspended from the raft at the level of the oysters. In addition, suspended particulates were sampled once daily by filtration through cartridge filters. Comparisons of concentrations in bottom and raft particulates indicate that they are similar during the release period but lower and more variable in the raft than bottom particulates in subsequent samples (Fig. 2). When the ^{60}Co, ^{65}Zn, and ^{137}Cs concentrations in bottom and raft particulates are plotted against the ^{54}Mn concentrations, the values distribute around a straight line (Fig. 3). These data suggest that bottom and raft particulates are from the same source.

Oysters

Oysters were introduced into the discharge canal during a period of normally high biological productivity (July) and during a period of normally low productivity (December). Half of the animals were maintained in filtered water.

July vs December: Prerelease and immediate postrelease samples. On July 31, 1973, the prerelease oysters were removed from the water at 0850 after having been placed there at 1700 on July 30. Only ^{65}Zn was detected in the prerelease animals maintained in nonfiltered seawater, whereas ^{54}Mn and ^{65}Zn were detected in the prerelease animals maintained in filtered seawater (Table 6). The relatively higher concentrations in the oysters maintained in filtered compared to those in nonfiltered water may be due to increased radionuclide availability as a result of the leaching of the particles deposited on the filter; the particulate collection was made over an approximate 8-hour interval.

In the postrelease animals sampled at 1100, concentrations were elevated for all radionuclides. Concentrations in postrelease oysters in nonfiltered seawater were higher than in those in filtered seawater for all radionuclides. The amounts accumulated per hour in animals in filtered compared to those in nonfiltered seawater were lower by 65% for ^{54}Mn, by 90% for ^{60}Co, by 40% for ^{65}Zn, and by 30% for ^{137}Cs.

On December 4, 1973, the prerelease oysters were removed at 0900 and the postrelease at 1230; animals were placed in the discharge canal water at 1530 on December 3. In the prerelease animals in nonfiltered water ^{54}Mn, ^{60}Co, and ^{65}Zn were detected whereas in filtered water only ^{54}Mn and ^{65}Zn were detected (Table 6). In the postrelease animals ^{54}Mn, ^{65}Zn, and ^{137}Cs were present in animals maintained in nonfiltered and filtered water whereas ^{60}Co was found only in those in nonfiltered water (Table 6).

The amounts accumulated per hour during the release were higher in July than December for all radionuclides except ^{137}Cs; for ^{137}Cs the amounts were very similar. The similarity of the ^{137}Cs results obtained under both regimes and in July and December suggests that the differences observed with regime and time for the other radionuclides were the result of differences in availability of the nuclides and not in conditions in the aquaria and cages.

The greatest differences between the July and December rates were observed for the animals in the nonfiltered water. The decrease in rate was about 100% for ^{54}Mn and ^{60}Co, about 70% for ^{65}Zn, and essentially 0% for ^{137}Cs.

December: Postrelease serial samples. In the serial samples of the oysters taken after the release, the changes in concentration were different

for each radionuclide. For ^{137}Cs the concentrations decreased greatly during the first 24 hours after the release and then decreased by small amounts during subsequent days (Fig. 4). The ^{137}Cs concentrations in the particulate fractions were elevated during the release but low for the remainder of the experimental period (Fig. 4). Small increases in ^{137}Cs were detected in those particulate samples collected between the high-high and the succeeding low tide.

The pattern of change in ^{65}Zn concentration with time after the release differed between the group held in nonfiltered water and that in filtered water (Fig. 4). The slower decrease in concentration with time in the animals in nonfiltered water appears to be due to a continued input of ^{65}Zn from the suspended particulates; during the interrelease interval, periodic increases were detected in the ^{65}Zn concentrations in the particulate fraction of the water (Fig. 4).

Changes in ^{60}Co concentrations in the oysters were very irregular and reflected changes in the concentrations in the particulate fraction (Fig. 5); ^{60}Co was detected only in animals in nonfiltered water. The concentrations of ^{60}Co in this fraction were elevated for a number of the sampling intervals subsequent to the release; the highest concentrations were detected in those samples collected in the time intervals between high-high tide and succeeding low tide. The periodicity of the changes suggest that variations in concentrations are related to changes in the tidal cycle.

Concentrations of ^{60}Co in the particulate fraction were significant even in the prerelease samplings, probably due to the two preceding releases; 16,000 μCi on November 27, and 4,100 μCi on November 30. Since these

quantities were higher than the 780 μCi released on December 4, the discharge-canal sediments probably contained a considerable amount of residual ^{60}Co. Consequently, the ^{60}Co accumulated by the oysters during the December 4 experimental period appear to reflect not only the December 4 release but also the two preceding releases.

The changes in ^{54}Mn concentration with time in oysters maintained in nonfiltered and filtered seawater reflected the changes occurring in the particulate fraction in the water (Fig. 5). As with ^{60}Co, the concentrations of ^{54}Mn in the particulate fractions were relatively high in the prerelease samples, probably because of the large quantities of ^{54}Mn in the two preceding releases, 11,500 μCi on November 27 and 2,800 μCi on November 30; only 520 μCi were released on December 4.

DISCUSSION

The availability of radionuclides to filter-feeding aquatic organisms is determined in part by the amount of particulates in the water - living microorganisms, organic detritus, inorganic material, or any combination of the three. The quantities of suspended particulates in the water column can vary both in time and space.

Two sources of suspended material were available to oysters in the discharge canal: particulates were resuspended from the material deposited onto the bottom and were carried in with the inflowing water. Resuspension of bottom sediments appears to be related to changing hydrological conditions in the bay and discharge canal. Particulate load in the inflowing water is probably dependent on biological and physical processing occurring in

South Humboldt Bay. Evidence for recirculation of water from the discharge canal into the intake canal was obtained by PG&E personnel (Wong et al. 1975, Serpa 1975). This recirculation appears to take place under certain tidal conditions and is not a general occurrence; however, when it occurs, the inflowing water may contain some radioactive particles from the discharge canal as well as unlabeled particulates.

In the suspended particulate fraction obtained from the water, comparisons of observed radionuclide concentrations with expected concentrations in the discharge canal water indicate that the radionuclides differed in their affinity to the particulates. These differences in affinity are related to the chemical properties of the radionuclides and of the particulates. The differences in the observed percentages among radionuclides were similar to the differences in distribution coefficients determined for the radionuclides (Duursma and Gross 1971, Harrison 1971).

The bottom sediments in the discharge canal represent a pool of particulate-bound radionuclides that appears to control the concentrations of radionuclides in the water during interrelease periods. The availability of nuclides in this sediment to filter-feeding organisms is affected by physical and chemical factors (Lee 1970). In the discharge canal, important physical factors are the flow rate of water into the canal, the tidal level of the water in the bay, and the reworking of the sediments by the larger indigenous benthic organisms. Important chemical factors are the specific chemical properties of the radionuclides and the metabolic activities of microorganisms in the sediment layer.

The changes in concentration with time observed in the bottom sediments are probably due in part to dilution with nonradioactive particles present in

the water flowing into the discharge canal. Over the same time interval, the particulate loads in the intake and in the discharge canal water were measured; the quantities of particulates in the intake were about the same as those in the discharge canal. These data indicate that the intake canal water contained sufficient unlabeled particulates to reduce the concentration of radioactive particulates in the discharge canal upon the mixing of the two.

Variations in concentration with time in the particulates in suspension and in those settled onto the raft collection trays were probably due to differing rates of resuspension of bottom sediments and to differing amounts of bound radionuclides in the sediments. Sediments were considered to consist of a historical (unmixed) layer and a mixed layer (Lee 1970). In the discharge canal the homogeneity of the mixed layer depends not only on physical and chemical processes, but also on the frequencies of the radioactive releases and the magnitude of the differences in quantities discharged from release to release. If the bottom sediments in the mixed layer are heterogeneous and the depth of scouring of the bottom sediments varies with tidal cycle, variations in concentrations like those observed would not be expected for the particulates deposited on our raft collection trays and on our filter cartridges.

The differences between July and December in the amounts of radionuclides accumulated by the oysters were probably due to differences in both the quantity and composition of the particulates in the water. Both these parameters are related to events occurring in South Humboldt Bay. Since South Bay is shallow, light can easily penetrate to the bottom; the mud flats support extensive beds of eelgrass. Measurements of phytoplankton

productivity and eelgrass standing stock during the previous year indicate that biological activity was higher in July and August than in December (Harding et al. 1975). Increases in phytoplankton productivity would result in direct increases in suspended particulates; increases in eelgrass productivity would result in indirect increases (suspended detritus from the decomposition of decaying plant material).

Differences between the quantities accumulated in July and December may be related also to the level of stable element in the water. This factor would be important for any element whose concentration in the oysters was under metabolic regulation. For such elements, the rate of radionuclide accumulation would be expected to change with changes in the amount of its stable nuclide in the water; per unit quantity of radionuclide released the amount accumulated would decrease with increased concentrations of the stable nuclide in the water. For elements whose concentration in the oyster is dependent on the amount present in the water and is not under homeostatic control (no regulation), the amount of radionuclide accumulated would be independent of the concentration of the stable element in the water.

Little information is available on the regulation of Mn, Co, Zn, and Cs in oysters. It has been calculated that Zn is accumulated in oysters to levels that are much in excess of that required for metabolic functions (Pequegnat, 1969). Schuster and Pringle (1969) report that, in general, for each doubling of the environmental level of a trace metal, the tissue level of the metal approximately doubled in Crassostrea virginica. Their results obtained from a series of experiments (Pringle, et al., 1968, Shuster and Pringle, 1968, 1969) suggest that in this oyster little or no regulation takes place of the tissue concentrations of Cd, Cu, Cr, Pb, and Zn.

It has been established for many bivalve molluscs that the presence of food material in the water results in circulation of water for feeding as well as respiratory purposes (Galtsoff 1964, Rice and Smith 1958, Davids 1964). Because primary productivity in Humboldt Bay is considerably greater in July than December, it is very probable that in July more of the oysters in the discharge canal would be circulating seawater for feeding purposes. Consequently, the differences in accumulation between the July and December animals are probably related to the presence of the food material in the water.

The role of particulates in radionuclide accumulation differed with radionuclide. In oysters ^{60}Co appears to be accumulated primarily from the suspended particulate fraction whereas ^{137}Cs appears to be accumulated primarily from the soluble fraction; ^{54}Mn and ^{65}Zn accumulation was coupled with the particulate concentrations. Since the particulates vary in amount and composition both temporally and spatially in an environment, the quantities accumulated by organisms will vary correspondingly for those radionuclides with high affinities for particulates.

Evidence that particulates are important in the accumulation of ^{65}Zn by oysters was reported also by Preston (1968). He found that in the River Blackwater estuary the relative concentrations of ^{65}Zn in oysters followed closely the expected pattern of ^{65}Zn actively associated with silt and was poorly related to the expected distribution of ionic zinc in the seawater.

The turnover rates of radionuclides have been measured recently in bivalve molluscs both in the field (Salo 1969, Wolfe 1970, Seymour and Nelson 1972, 1973) and in the laboratory (Romeril 1971, Pentreath 1973A, 1973B, Van Weers 1973, Harrison 1973, Cranmore and Harrison 1975). In the

field ecological halflives of ^{65}Zn have been measured (Salo 1969, Wolfe 1970) as well as effective and biological halflives (Seymour and Nelson 1972). Our results indicate that the turnover rates obtained in the field should vary with the season. Such variation is suggested from the turnover rates observed for ^{65}Zn in oysters (Seymour and Nelson 1972).

Turnover rates determined in the laboratory would be expected to vary with the kinds and amounts of particulates available for food. Recently some reports have become available that consider the effects of food and water on turnover rates. Romeril (1971) attributes the differences in turnover rates and concentration factors he reported and those obtained in the field under natural conditions to be due to the virtual absence of the ingestion pathway under the experimental conditions. Renfro et al. (1974) state that for certain animals such as shrimp, the food pathway does not appear to play as important a role in zinc accumulation as had been generally accepted. In Artemia the rate of incorporation of ^{65}Zn was much slower from the water than from food (Rice and Baptist 1974). However, more information is needed on turnover rates under varying environmental conditions in the field and different controlled feeding regimes in the laboratory before the proper rates can be selected for biological modelling.

Most models of effects of pollutant released into ecosystems have considered the transport and movement of materials in the water mass. It is apparent from this study that for radioactive and trace-element pollutants that have a high affinity for particulates, modelling of both the water mass and the sediments may be more appropriate.

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Table 1. Time and Radionuclide Composition of Releases

	^{54}Mn	^{60}Co	^{65}Zn	^{134}Cs	^{137}Cs	^{144}Ce
April 4, 1973 (0700 to 1300)						
Liquid waste						
Total release (μCi)	130	320	510	12,200	22,100	110
Concentration (pCi/liter)	4,260	8,870	16,900	403,000	732,000	3,640
Discharge canal water:						
Expected concentration (pCi/liter)	1.11	2.32	4.42	105.	191.	0.91
July 31, 1973 (0900 to 1100)						
Liquid waste						
Total release (μCi)	200	530	375	10,700	17,500	87
Concentration (pCi/liter)	18,600	49,800	35,100	1,000,000	1,640,000	8,100
Discharge canal water:						
Expected concentration (pCi/liter)	4.85	12.8	9.05	258.	423.	2.11
December 4, 1973 (0930-1230)						
Liquid waste						
Total release (μCi)	520	780	247	29,100	38,300	171
Concentration (pCi/liter)	32,100	47,600	15,200	1,790,000	2,390,000	10,700
Discharge canal water:						
Expected concentration (pCi/liter)	6.28	9.31	2.97	349.	467.	2.51

Table 2. Measured (Soluble plus Particulate) Radionuclide Concentrations as Percentage of the Expected Concentrations in the Discharge Canal During Two Releases.

	^{54}Mn	^{60}Co	^{65}Zn	^{137}Cs
April 4, 1973				
0800	74	44	87	92
0900	120	67	160	98
1000	63	22	132	104
1200	68	38	87	108
July 31, 1973				
0900	40	52	36	56
1000	42	80	73	103
1100	71	69	50	57

Table 3. Normalized Radionuclide Concentrations[a] in Particulate and Soluble Fractions in Discharge Canal Water

Collection time	Particulates dry weight (mg/liter)	Fraction[b]	Concentration (pCi/m^3) ^{54}Mn	^{60}Co	^{65}Zn	^{137}Cs
April 3, 1973						
1630[c]	8.3	P	≤45	≤20	50[d]	≤0.2
		S	153	47[d]	≤45	1.2
April 4, 1973						
0630	7.4	P	≤45	≤20	≤45	≤0.2
		S	NA[e]	NA	NA	2.4
0800	7.9	P	540	290	250	8.1
		S	110[d]	140[d]	400	910
0815	7.0	P	370	260	220	8.4
		S	NA	NA	NA	NA
0900	9.3	P	740	280	430	9.3
		S	450	380	1130	970
1000	12.8	P	220	220	150	10.0
		S	410[d]	0	1180	1030
1100	8.5	P	220	230	210	9.5
		S	NA	NA	NA	1020
1200	8.1	P	330	220	250	19.0
		S	340	160	620	1060
1400	3.6	P	140[d]	120	110[d]	3.1
		S	NA	NA	NA	550
1600	4.5	P	90[d]	50[d]	≤ 45	≤0.2
		S	≤200	≤130	≤100	5.5
1800	4.1	P	≤45	30[d]	≤45	0.6[d]
		S	NA	NA	NA	1.0

Table 3. (Cont.) Normalized Radionuclide Concentrations[a] in Particulate and Soluble Fractions in Discharge Canal Water

Collection time	Particulates dry weight (mg/liter)	Concentration (pCi/m^3)				
		Fraction[b]	^{54}Mn	^{60}Co	^{65}Zn	^{137}Cs

[a]The normalized concentration is the measured concentration divided by the expected concentration.

[b]P, particulate (> 1 μm); S, soluble (< 1 μm).

[c]Time of initiation of collection; sample collected for 15 min.

[d]Fractional standard deviation > 0.25.

[e]NA, not analyzed.

Table 4. Normalized Radionuclide Concentrations[a] in Particulate and Soluble Fractions in Discharge Canal Water

Collection time	Particulate dry weight (mg/liter)	Fraction[b]	Concentration (pCi/m³) ^{54}Mn	^{60}Co	^{65}Zn	^{137}Cs
July 31, 1973						
0810[c]	22	P	≤10	≤3	≤20	≤0.02
		S	≤6	≤2	≤10	0.9
0900	25	P	290	220	150	9.6
		S	110	300	210	550
1000	28	P	200	140	200	9.0
		S	210	660	530	1010
1105	19	P	580	310	160	1.2
		S	130	380	340	570
1200	18	T	NA[d]	NA	NA	29
1430	16	T	NA	NA	NA	20
2000	13	T	NA	NA	NA	1.5
August 1, 1973						
0230	9	T	NA	NA	NA	3.0
0830	18	T	NA	NA	NA	1.9

[a]The normalized concentration is the measured concentration divided by the expected concentration.

[b]P, particulate (> 1 μm); S, soluble (< 1 μm); T, S plus P.

[c]Time of initiation of collection; sample collected for 15 min.

[d]NA, not analyzed.

Table 5. Normalized Radionuclide Concentrations[a] in Particulates in Discharge Canal Water

Collection time	Particulates dry weight (mg/liter)	Concentration (pCi/l)			
		^{54}Mn	^{58}Co	^{65}Zn	^{137}Cs
December 3, 1973					
1535-1740		2.5	1.1	20	0.009[b]
1740-2200		5.3	6.2	6.7	0.20
December 4, 1973					
2200-0800		22	19	18	0.14
0830-0930		1.9	1.5	6.4[b]	0.05
0930-1030		28	40	41	3.5
1030-1130	14.8	35	45	84	6.0
1130-1230		30	44	68	6.2
1230-1330		2.5[b]	2.4	11[b]	0.31
1330-1545	15.6	6.4	8.0	19	0.24
1545-2000		1.4	1.0	7.4[b]	0.03
December 5, 1973					
2000-0830		0.6[b]	1.0	$\leq$0.3	0.06
0830-1345		24	30	13	0.49
1345-1610		1.8[b]	4.0	$\leq$0.3	0.18
1610-1930		4.0	5.0	$\leq$0.3	0.16
December 6, 1973					
1930-0830		2.7	5.0	6.7[b]	0.14
0830-1230		0.2[b]	0.10[b]	$\leq$0.6	0.01[b]
1230-1730		11	12	15[b]	0.27
1730-2300		0.5[b]	0.8[b]	3.4[b]	0.03
December 7, 1974					
2300-0830		6.5	9.0	14[b]	0.63

[a]The normalized concentration is the measured concentration divided by the expected concentration.

[b]Fractional standard deviation > 0.25

Table 6. Normalized radionuclide concentrations[a] in oysters maintained in the discharge canal of the Humboldt Bay Power Plant.

	^{54}Mn	^{60}Co	^{65}Zn	^{137}Cs
July 31, 1973				
Nonfiltered seawater				
Prerelease (pCi/kg)	ND[b]	ND	17	ND
Postrelease (pCi/kg)	28	20	83	0.76
Rate (pCi/hr)[c]	14	10	33	0.38
Filtered seawater				
Prelease (pCi/kg)	9.5	ND	22	ND
Postrelease (pCi/kg)	19.4	2.6	61	0.52
Rate (pCi/hr)	5.0	1.3	20	0.26
December 4, 1973				
Nonfiltered				
Prerelease (pCi/kg)	11	3.3[d]	40[d]	ND
Postrelease (pCi/kg)	9[d]	4.3[d]	67	1.1
Rate (pCi/hr)	-	0.3	9	0.37
Filtered seawater				
P Prerelease (pCi/kg)	13	ND	22[d]	ND
Postrelease (pCi/kg)	25	ND	67	1.1
Rate (pCi/hr)	4	-	15	0.37

[a]Measured concentration (pCi/kg) divided by expected water concentration in discharge canal (pCi/liter).

[b]Not detected.

[c]Amount accumulated per hour during the release.

[d]Fractional standard deviation > 0.2.

FIGURE LEGENDS

Fig. 1. Map of Humboldt Bay area showing location of the Pacific Gas and Electric Humboldt Bay Power Plant.

Fig. 2. Radionuclide concentrations in serial samples of particulates from the discharge canal during the April 1973 experiment. Bottom particulates (▲—) were collected from trays placed on the floor of the canal in the vicinity of the raft and concentrations are expressed on a dry-weight basis. Raft particulates (△---) were collected from trays placed at the same level as the oysters and are expressed on a dry-weight basis. Suspended particulates (|) were collected by pumping water through a cartridge filter and are expressed on an ash-weight bases. Horizontal lines on the points indicate the duration of the collection for the raft and bottom sediments. The height of the bars represents the average concentration for raft particulates over the time interval represented by the bar width.

Fig. 3. Relationships between radionuclide concentrations of ^{60}Co, ^{65}Zn and ^{137}Cs to those of ^{54}Mn in samples collected during the April 1973 experiment. All concentrations are expressed on a dry weight basis. The samples were those for which data are shown in Fig. 2. The solid line indicates the sample regression of ^{60}Co, ^{65}Zn, or ^{137}Cs concentration on ^{54}Mn concentration. Dashed lines indicate ± sample standard deviation from regression.

Fig. 4. Radionuclide concentrations in serial samples of oysters and suspended particulates collected during the December 1973 experiment.

Fig. 5. Radionuclide concentrations in serial samples of oysters and suspended particulates collected during the December 1973 experiment.

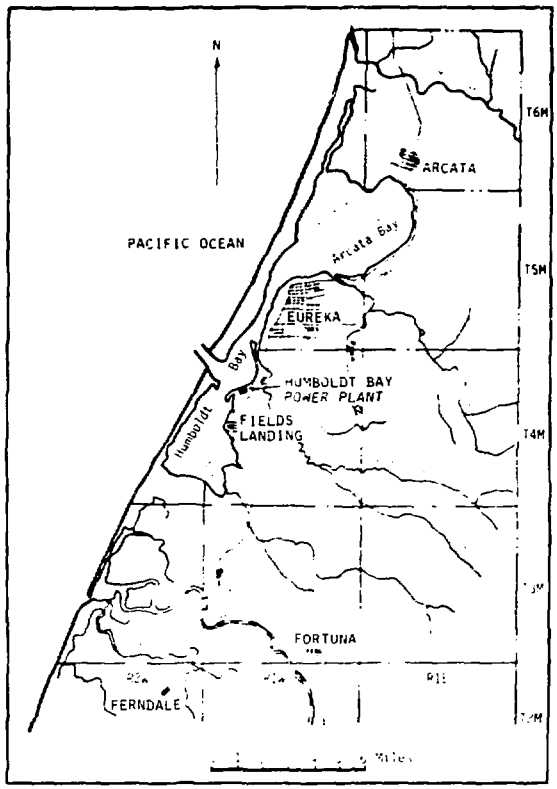

Fig. 1

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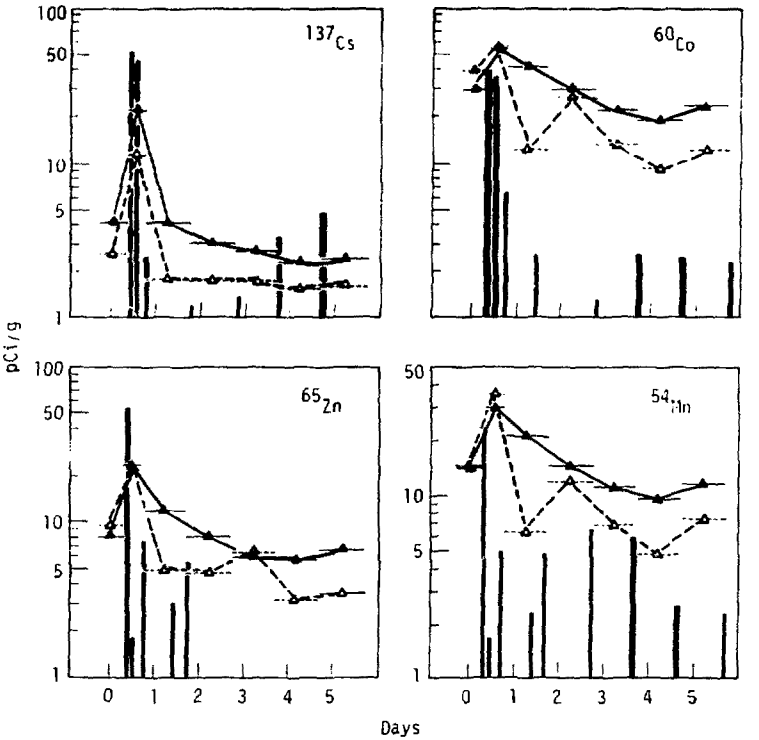

Fig. 2

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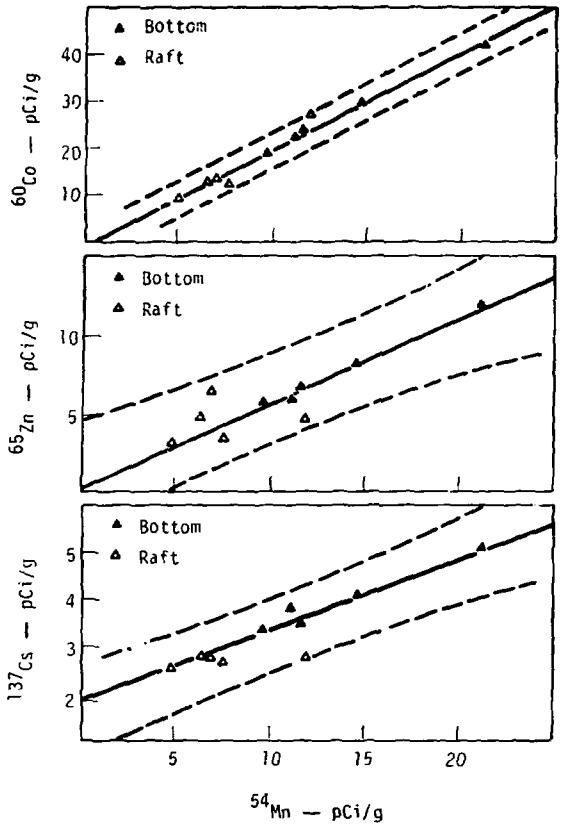

Fig. 3

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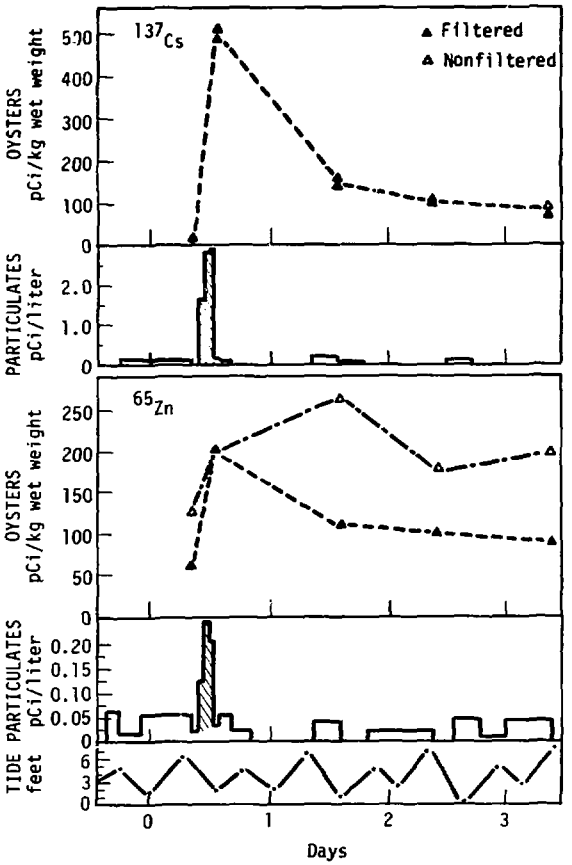

Fig. 4

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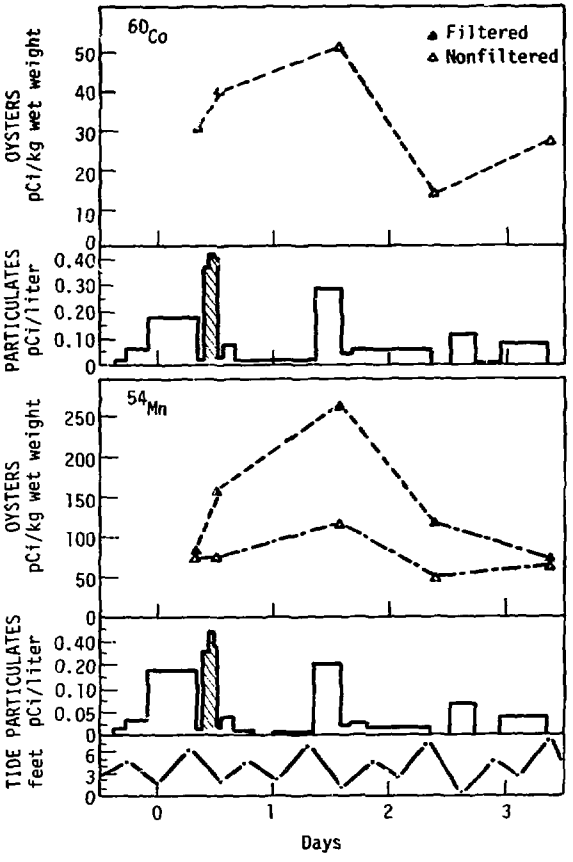

Fig. 5

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