0076040

THE COLUMBIA RIVER ESTUARY AND ADJACENT OCEAN WATERS

Bioenvironmental Studies

RECEIVED
FEB 06 2008
EDMC

Edited by
A. T. Pruter
D. L. Alverson

Prepared under the auspices of the
Division of Technical Information, United States Atomic Energy Commission

UNIVERSITY OF WASHINGTON PRESS
SEATTLE AND LONDON

©1972 by U. of WA Press. Copyright assigned to the General Mgr. of the U.S. AEC. All Royalties from the sales of this book accrue to the U.S. gov't.

Taken from Bob Peterson's copy of book.

Chapter 1

The History of Hanford and Its Contribution of Radionuclides to the Columbia River

R. F. Foster*

ABSTRACT

Establishment of the plutonium-producing reactors in eastern Washington during the period 1943-1945 resulted in the discharge of cooling water that contained radionuclides to the Columbia River. Because these radionuclides appeared in the river and its estuary and in the adjacent North Pacific Ocean, studies of their significance to aquatic and marine life and to man were undertaken. These radionuclides have also served as unique and valuable tags for studies not only of the dispersion of the river water but also of the mechanisms and rates through which complex physical, chemical, and biological processes proceed.

The earliest studies concerned with the possible impact of the Hanford plant on fish were begun in 1943 at the Applied Fisheries Laboratory, University of Washington. Very soon after the first reactors began operating, laboratory and field studies were begun at the Hanford site and have continued ever since. Public and scientific interest in radioactive waste and the presence of radionuclides in the environment increased substantially in the late 1950s, and this interest helped to stimulate a much broader based research effort, especially of the Columbia River estuary and of the adjacent North Pacific Ocean.

The bioenvironmental studies described in this volume are a classic example of how the advent of the Atomic Age has aided the advancement of the environmental sciences. In the studies reported in this volume, this has occurred in three quite different ways:

1. The presence of radioactive materials in the Columbia River, its estuary, and the adjacent North Pacific Ocean prompted studies to define the distribution and fate of the radionuclides so that significant pathways leading to human exposure could be identified and any populations of marine organisms that were especially vulnerable to the accumulation of nuclides could be located.

2. The presence of radioactive materials in the water, biota, and sediments provided a tag not only for identifying substances of Columbia River origin but also for measuring the rates at which the complex physical, chemical, and biological processes proceed.

---

*Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington.

3. The flux of the radionuclides through all compartments of the river, estuarine, and marine environments has emphasized the interrelation of these compartments, and this has stimulated coordinated efforts between biologists and physical and chemical oceanographers.

The radioactive materials that have so heavily influenced these studies originate, for the most part, at the U. S. Atomic Energy Commission Hanford plutonium-production plant, which is located on the Columbia River some 375 miles above its mouth. It would be pretentious to imply that the studies reported here would never have been carried out if the Hanford plant had not been built, inasmuch as the bioenvironmental knowledge that has been developed is vitally needed by, and has broad applications in, many different fields. Nevertheless, the opportunity provided by the radioactive tracers and a keen interest on the part of many state and federal agencies and the general public all combined to stimulate an intensity and scope of research that would not have occurred otherwise.

THE HANFORD SITE

The Hanford site on the Columbia River (Fig. 1.1) was selected as the location of the plutonium-production plant after an intense nationwide search in 1943 by the Manhattan District of the Corps of Engineers. (The Atomic Energy Commission was not created until 1946 and did not take over the operation of the Hanford plant until Jan. 1, 1947.) In a very real sense, the bioenvironmental factors were dominant in the choice of the site, and probably at no prior time in history was so much attention given to the potential impact of an industrial plant on the environment. This attention was in part a compensation for the complete absence of experience with any kind of installation that even remotely resembled what was to be built at Hanford. It also reflected the thoroughness with which the statesmen of science associated with the project delved into all the technical facets.

The mission of the Hanford plant was to produce an artificial element (plutonium) that was nonexistent prior to 1941. Without a Hanford plant, plutonium would exist only in milligram quantities and as a laboratory curiosity. Hanford was needed because scientists believed that large amounts of plutonium could be fashioned into an atomic bomb that would swiftly bring an end to World War II. However, at the time that Hanford was chosen as the plutonium-production site, no one knew positively that the reactors that had been conceived as the means of creating plutonium from uranium would actually operate. Nor did anyone know positively whether the plutonium created in the reactors would actually work in an atomic bomb.

The basic processes to be carried out at Hanford were the changing of uranium atoms into plutonium atoms and the recovery of the plutonium in highly purified form by chemical engineering and metallurgical techniques. The Hanford complex had to include (1) fuel-fabrication plants where pure uranium could be fashioned and jacketed into elements suitable for irradiation, (2) reactors where the uranium fuel elements could be irradiated and the plutonium produced, (3) chemical-separation plants where the irradiated fuel could be processed and the plutonium recovered, and (4) waste-storage and -retention areas where highly

Fig. 1.1—Map showing the location of the Hanford Works.

radioactive chemical solutions could be kept isolated from the environment for very long periods of time.

According to theory, a chain reaction of fissioning uranium atoms could supply the flux of neutrons required to create plutonium atoms from some of the nonfissioning uranium atoms in the fuel elements. The chain reaction, however, would release very large quantities of heat and would also leave as debris highly radioactive fragments of the uranium atoms (fission products). The heat could be removed most efficiently by circulating coolant water; the radioactive debris would eventually have to be stored as waste. Any material in the near vicinity of the chain reaction would be bombarded by stray neutrons, and neutron-activated radioisotopes would be formed. The plant was designed to prevent the fission products from getting into the cooling water or the atmosphere, but the structural materials used in the reactor could not be guaranteed to stand up for long periods of time in a radiation environment never before experienced. At the outset there were also unexplored facets of the reactor-control system, of the plutonium-recovery process, and of radioactive-waste management.

The Hanford site (Fig. 1.2), however, met both the known and the unexplored aspects of the plutonium-production process. The Columbia River, with a flow second only to the Mississippi River in the conterminous United States, was available for cooling water, and it could be relied upon to dilute to safe levels the kinds and quantities of radionuclides anticipated in the reactor coolant. The site was sparsely populated and agricultural development was minimal. Thus the government could acquire and maintain tight security on a relatively large control zone without disrupting many home and farm sites. The waste-storage areas could be located well inland from the river where there was a deep (200 to 300 ft) layer of dry soil above the water table. The atmosphere was relatively unstable most of the time and thus favorable for the rapid dispersal of airborne wastes. The semiarid climate favored year-round construction activities and plant operation, even though the summers were uncomfortably hot. Finally, an adequate block of electric power was available from the hydroelectric dams on the river to supply the heavy demands of the pumps and other process equipment.

Consideration of the potential effects of the effluents from the Hanford plants on the environment included:

1. The impact of releases to the atmosphere on vegetation, native and domestic animals, and people—with special attention to the transfer of radioactive contaminants through vegetation to grazing animals.
2. The impact of releases to the Columbia River on the valuable fishery resources of the river—especially salmon—and on people who used the river as a source of drinking water and recreation.
3. The impact of releases to the ground on the quality of the ground water.

Only those aspects that relate to the Columbia River will be considered further in this review of bioenvironmental studies undertaken in the estuary and in the adjacent Pacific.

EARLY RESEARCH

The earliest studies that were undertaken to determine the possible impact of the plant effluent on Columbia River fish were begun in laboratories remote from the

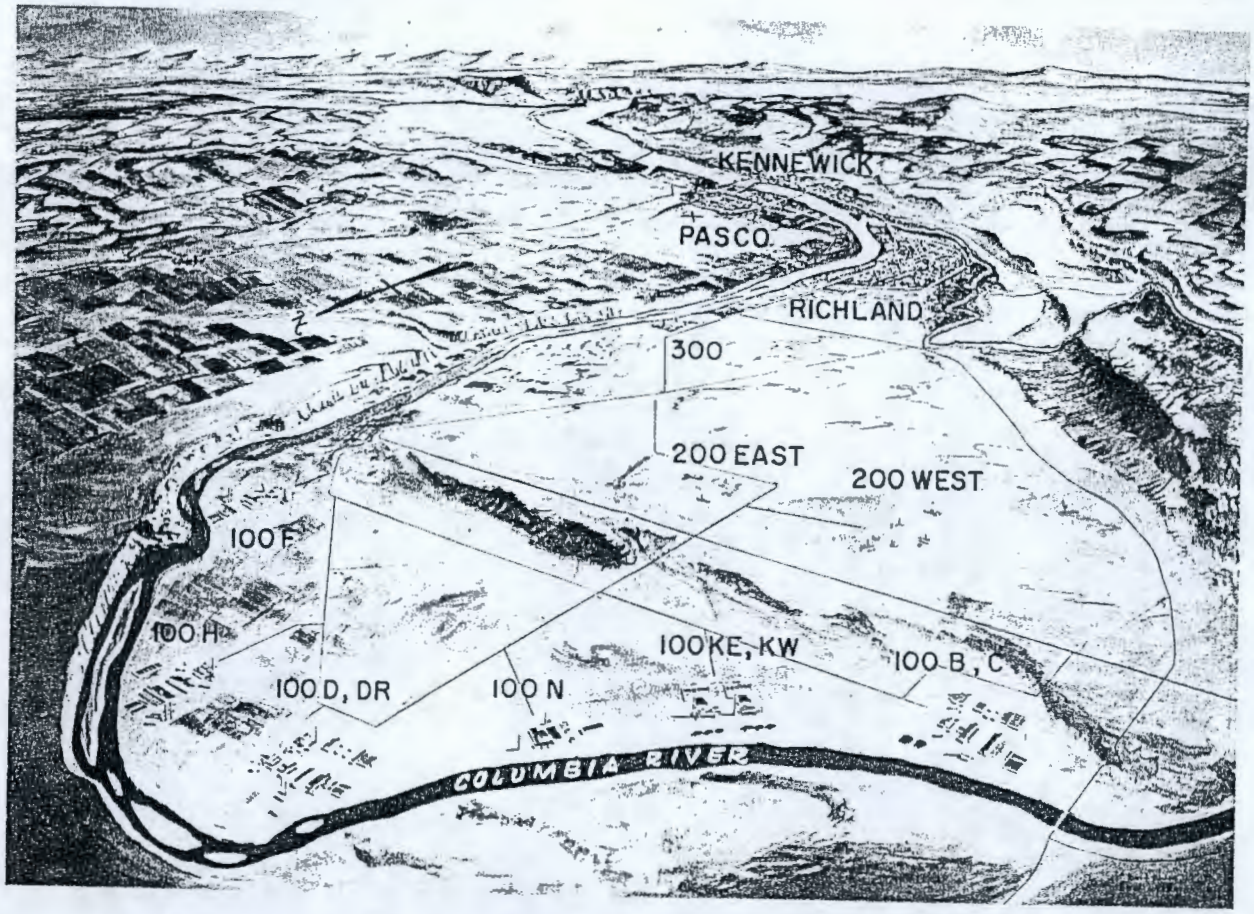

Fig. 1.2—Locations of reactors, chemical separation plants, and other areas along the Columbia River. The reactors are designated by the prefix 100; the chemical separation plants, by the prefix 200. The fuel-fabrication facilities and many of the research laboratories are in the 300 area.

plant site. One reason for this was timing—the studies were begun in 1943, well over a year before the first reactor started operation. Another reason was security—intense secrecy was applied to the Hanford plant prior to the detonation of the first atomic bomb, and scientists using radiation or radioisotopes were purposely kept dissociated from the production site. The events leading to the establishment of the Applied Fisheries Laboratory at the University of Washington in 1943 (Fig. 1.3) and the early work of this laboratory on the effects of X rays on fish are described in detail by Hines (1962). Concurrently, studies on the uptake of some radioisotopes from water by fish were begun at the University of Chicago by Prosser et al. (1945).

The first of the three original reactors built at Hanford began operation in September 1944, the second was started up later in 1944, and the third came on the line early in 1945. By midyear, studies on the toxicity of the reactor effluent to fish had begun in a special laboratory built for the purpose at the 100-F reactor site (Fig. 1.4). This bioassay-type test showed that the concentrations of effluent that existed in the Columbia River downstream from the reactors were not harmful to trout and salmon. The results of these early bioassay tests were reported by Foster (1946) and Olson (1948).

Field work on the river specifically concerned with fish and other biota was begun in 1946. At the outset these studies were designed to explore the possibility that radionuclides released to the river with the reactor effluent were picked up by fish and other aquatic forms. The early work was reported by Herde (1947). When it was recognized that the river biota were concentrating certain radionuclides, more comprehensive bioenvironmental studies were undertaken (Coopey, 1948; Davis and Cooper, 1951) which included benthic invertebrates as well as fish.

By 1949 the laboratory and river studies at Hanford had shown that the fisheries resources of the Columbia River were not threatened by the plutonium plant and that there was no health hazard to people who used the river and its fish. On the other hand, it was also recognized that the reconcentration of some radionuclides by aquatic forms was a very important mechanism by which radioactive material could be transferred to man. It was also recognized that the heat and process chemicals (sodium dichromate) added to the river with the reactor effluent could adversely affect aquatic life if the quantities were increased by perhaps an order of magnitude. Consequently, long-range plans for bioassay and bioenvironmental studies were formulated, and a permanent aquatic biology laboratory was constructed in the 100-F area in 1952 (Fig. 1.5).

Prior to 1950 the only studies of radioactive materials in the Columbia River were those carried out by the Hanford laboratory (operated for the AEC by the General Electric Company) and the Applied Fisheries Laboratory of the University of Washington. In 1950 the U. S. Public Health Service sent a team to Hanford to carry out a comprehensive study over a two-year period. Although the radioactive aspects of the study were novel to some of the investigators, their job was accomplished in a thorough manner, and their report (Robeck, Henderson, and Palange, 1954) is still an excellent reference.

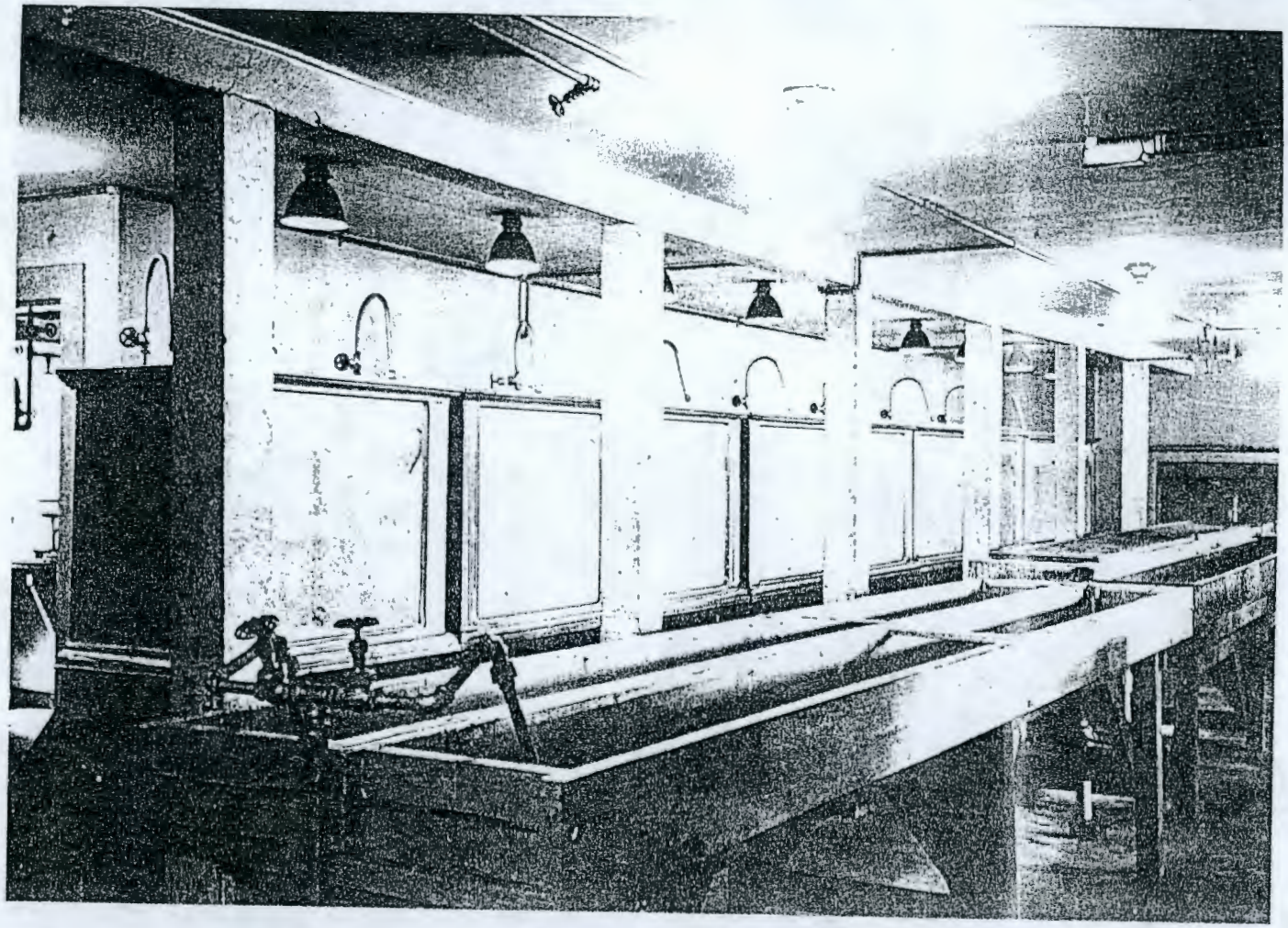

Fig. 1.3—The Applied Fisheries Laboratory at the University of Washington.

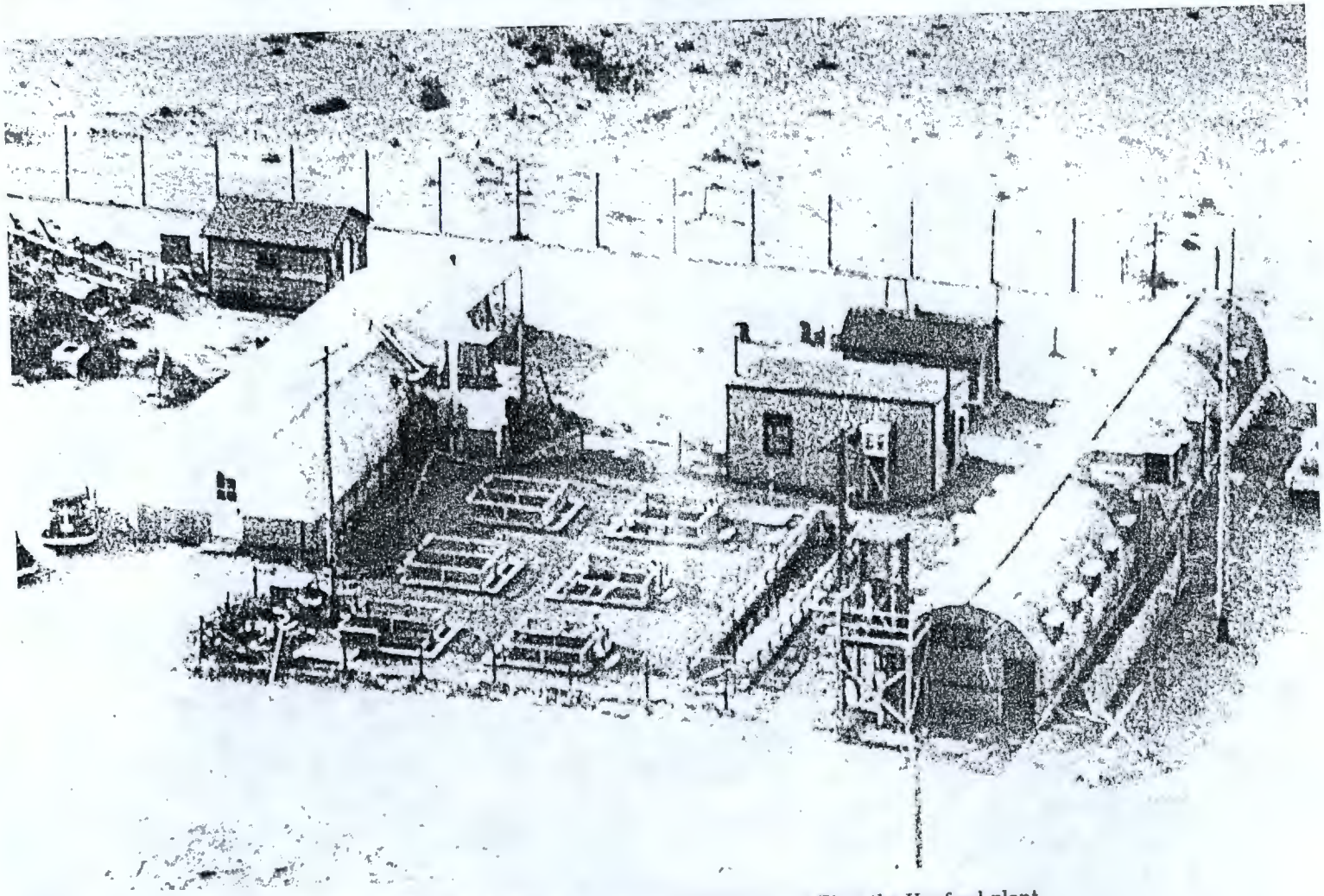

Fig. 1.4—The Fisheries Laboratory (Building 146-F) at the Hanford plant.

Fig. 1.5—The tank room of the Aquatic Biology Laboratory (Building 146-FR) for bioassay and bioenvironmental studies.

EVENTS LEADING TO ESTUARINE AND MARINE STUDIES

The secrecy surrounding the Hanford site from its inception through the first months of operation was lifted abruptly in August 1945 with the detonation of the atomic bombs over Hiroshima and Nagasaki. From this time on, officials made a concerted effort to inform other government agencies, interested scientists, and the public of the operations carried out at Hanford and of the studies underway to ascertain the impact of the plant effluents on the environment. Security restrictions were no longer applied to the bioenvironmental studies except for data that might disclose the capacity of the plant or certain technical details of the plutonium-production process. Late in 1945 and during 1946, representatives of the U. S. Fish and Wildlife Service and the Oregon and Washington Departments of Fisheries and Game were invited to Hanford to observe the site and review the Columbia River studies underway.

In 1949 the AEC set up the Columbia River Advisory Group (CRAG) to review the Columbia River program and its results and to provide advice on program direction and waste-disposal practices. The members of CRAG were senior officers in the Washington Pollution Control Commission, the Washington State Department of Health, the Oregon State Sanitary Authority, and the Portland Office of the U. S. Public Health Service. These men were provided with security clearance so that no pertinent information had to be withheld. The CRAG met at irregular intervals over a span of about 15 years.

During the early 1950s the tremendous potential for electric power production from controlled chain reactions received much attention. In 1955 the first International Conference on the Peaceful Uses of Atomic Energy was held in Geneva, Switzerland, under the auspices of the United Nations. This conference provided the first opportunity to describe the bioenvironmental studies of the Columbia River to an international audience, and this was done in papers by Foster and Davis (1956), Hanson and Kornberg (1956), and Parker (1956). Second and third Geneva conferences were held in 1958 and 1964, and new data were reported at each of these meetings (Davis et al., 1958; Parker et al., 1965).

The late 1950s was a period in which the general public became much more aware of and more concerned about the presence of radioactive materials in the environment. The awareness and especially the concern resulted partly from the extensive testing of new nuclear devices in the atmosphere by both the United States and the USSR and partly from projections of the future use of nuclear power in the civilian economy. In 1956 the National Academy of Sciences began publication of a series of reports from committees formed to consider the biological effects of atomic radiation. One of these committees, headed by Roger Ravelle, dealt with the effects of radiation on oceanography and fisheries (National Academy of Sciences—National Research Council, 1957). Special task groups formed by the NAS—NRC Committee on Oceanography also considered the disposal of radioactive waste into particular marine environments, including the Pacific Coast of the United States (National Academy of Sciences—National Research Council, 1962). In February and March of 1959, the Congress of the United States held hearings on radioactive-waste disposal from industry. Also in 1959 the International Atomic Energy Agency held a conference in Monaco on the disposal of radioactive wastes.

As the scientific community and the general public became more informed, broad interest in extending the scope of the bioenvironmental studies was generated. A part of this interest was in the use of radioactively tagged Columbia River water as a tool for studying the dynamics of the physical, chemical, and biological systems of the estuary and adjacent Pacific Ocean, and a part of the interest was focused on the fate of the nuclides as a practical demonstration of the behavior of radioactive wastes in estuarine and marine environments. To carry out the extended program, the AEC placed several new research contracts with groups which were uniquely equipped to undertake the work and which had a special interest in the work. These included the U. S. Bureau of Commercial Fisheries (now the National Marine Fisheries Service), the Department of Oceanography of the University of Washington, the Department of Oceanography of Oregon State University, and the U. S. Geological Survey. Some of the efforts of the University of Washington Laboratory of Radiation Ecology (Applied Fisheries) and of the Hanford laboratory were also redirected so as to contribute even more fully to the overall program. A program coordinating organization, called the Working Committee for Columbia River Studies, was formed in 1962.

HANFORD AS A SOURCE OF RADIONUCLIDES

Although no water-cooled reactor had ever operated before the start-up of the 100-B unit at Hanford in September 1944, the presence of a complex mixture of radionuclides in the effluent water was predicted on the basis of the design. This prediction prompted the studies on the effects of radiation on fish that were initiated at the University of Washington in 1943; it also prompted the inclusion of special structures and precautions to assure that excessive amounts of the radioactive contaminants were not released to the Columbia River. The structures included large concrete retention basins where the effluent could be held for a few hours before release. Even such brief retention allowed significant radioactive decay of many of the very short-lived nuclides.

The major source of the radionuclides in the effluent was correctly predicted to be from the neutron activation of elements dissolved in the cooling water or present on the surfaces of the reactor piping and fuel elements. The Hanford reactors were designed so that the cylindrical fuel pieces of uranium lay as long horizontal columns inside large aluminum tubes. When the reactors are operating, the heat created by atomic fission within the fuel pieces must be carried away. Cooling water pumped through the aluminum tubes and passed through a space between the fuel elements and the tube wall keeps the temperature at desired levels. An aluminum jacket surrounds the fuel elements and prevents the uranium metal from contacting the cooling water.

Virtually any material inside the reactor is bombarded by neutrons and becomes, to some degree, radioactive. This includes all the structural materials and the materials present in the cooling water. Minimizing the radioactive content of the spent cooling water is a delicate feat of water chemistry. Because the primary job of the cooling water is to remove heat, the chemistry of the water must be adjusted to prevent the buildup of scale or film on the hot aluminum surfaces of the fuel and the tubes. However, the cooling water must also be

noncorrosive so that the tubes and the aluminum jackets of the fuel are not eaten away. The addition of sodium dichromate aids in this feature. Finally, the cooling water should not contain impurities (or process chemicals) that will be activated by the neutrons into especially troublesome radioisotopes. The optimization of all these factors through special water-treatment practices has received continuous investigation since the plants were first designed.

The quantity of fission products released to the Columbia with the reactor cooling water was expected to be small in relation to the neutron activation products, and this has proved to be the case. The fission products that do appear come from two separate sources. The dominant and continuing source is the fissioning of "tramp" uranium carried as a natural constituent of the river water. In passing through the reactor core with the cooling water, this tramp uranium is affected by the neutrons in much the same way as the uranium that is contained in the fuel elements. Thus, some of the ^{235}U atoms are split, and fission products result. The second source is intermittent and exists only at times when fission products that have built up within the fuel pieces are able to escape through the cladding. Such events are called fuel-element ruptures, and the reactors are equipped with special instruments to detect them. Whenever a rupture is known to exist, the reactor is shut down, and the offending fuel element is replaced. Thus, the introduction of fission products from ruptures into the Columbia River is not continuous but occurs briefly at irregular and infrequent intervals.

The quantity of radionuclides entering the Columbia River from the Hanford complex as a whole has varied substantially since the first reactors began operating in 1944. The variations resulted from the construction and start-up of additional reactors, the operation of individual reactors at different power levels, changes in the chemical characteristics of the river water, modifications in the water-treatment process, and, more recently, the deactivation of most of the reactors. The operating history of the plutonium-producing reactors at Hanford is shown in Fig. 1.6.

Although the kinds and relative abundance of radionuclides released to the river have been grossly similar for the several reactors (except for N, which produces steam for electrical power production), the absolute quantities have varied substantially between different units. Further, the abundance of any particular radionuclide released from a specific reactor changes from month to month. Apart from the basic design and power level of the reactors, the important factors that influence the amounts of individual radionuclides created and released include (1) the concentration of parent (target) elements present naturally in the Columbia River water, (2) the efficiency of the water-treatment process in removing parent elements from the raw river water, (3) the addition of new parent elements by the water-treatment process, (4) the characteristics of deposits (film) that build up on the surfaces of the fuel channels and the fuel elements, (5) the frequency and severity of fuel-element ruptures, and (6) the length of time the effluent is retained in storage basins before release to the river. The N-reactor should be considered separately because, unlike the other production reactors, it is cooled by demineralized water that is recirculated, and only very small amounts of radionuclides are released to the river.

The last year in which all the production reactors operated was 1964. Data for 1964 can therefore be used to illustrate the kinds and quantities of radioactive

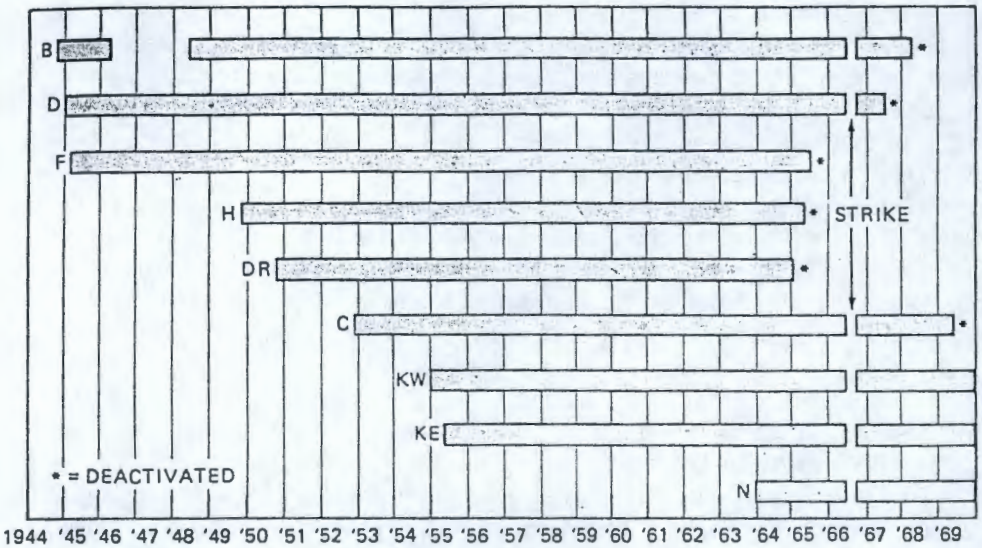

Fig. 1.6—Operating history of plutonium-producing reactors. The letter symbols refer to the reactors designated by the prefix 100 in Fig. 1.2.

materials present in the Columbia River when they were most abundant. The data available from samples taken at Richland are especially useful because at this station the effluent from the several reactors located 25 to 40 miles upstream is very nearly thoroughly mixed throughout the river. However, the quantities of the short-lived nuclides in the river are somewhat reduced at Richland because of the transit time (12 to 36 hr) between the reactors and this sampling point. Further, small fractions of most of the nuclides become associated with bottom sediments and periphyton.

The concentrations (during 1964) of the radionuclides that are most abundant in the Columbia River at Richland are shown in Fig. 1.7. These nuclides are ^{24}Na, ^{32}P, ^{51}Cr, ^{64}Cu, ^{65}Zn, ^{76}As, and ^{239}Np. Because of their potential importance to radiation exposure of people, routine measurements are also made on ^{131}I (ordinarily in the range of 4 to 50 pCi/liter),* ^{54}Mn (5 to 40 pCi/liter), ^{46}Sc (routine analyses not begun until 1968; its concentration is similar to that of ^{65}Zn), and ^{90}Sr (1 to 2 pCi/liter from worldwide fallout). Several other nuclides, though present in relatively low concentrations, can be measured accurately by sophisticated analytical techniques. These include ^{58}Co, ^{60}Co, ^{59}Fe, ^{95}Zr—Nb, ^{106}Ru—Rh, ^{124}Sb, ^{137}Cs, and ^{140}Ba—La.

As the radionuclides introduced into the Columbia River by the Hanford plant are transported downstream, their concentration in the river water diminishes substantially. For the very short-lived nuclides, such as ^{24}Na, ^{76}As, ^{64}Cu, and ^{239}Np, radioactive decay is responsible for most of the depletion. Dilution with water added by tributary streams is of some significance in all cases.

---

*Although ^{133}I is also present at Richland at a concentration about six-fold greater than ^{131}I, it is more difficult to measure owing to its very short half-life.

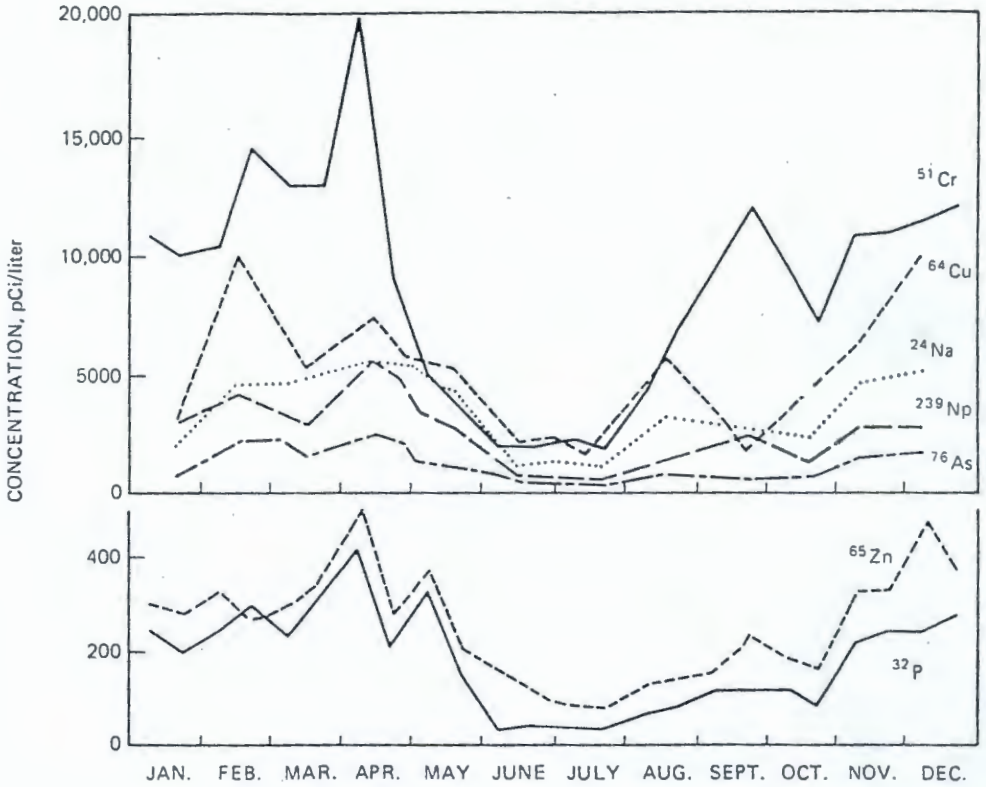

Fig. 1.7—Concentrations of radionuclides in Columbia River water at Richland in 1964.

The dominant depleting mechanism for virtually all the intermediate and long-lived nuclides is, however, deposition on the bottom of the river (Nelson, Perkins, and Nielsen, 1966).

Very soon after the radionuclides enter the river with the reactor effluent, major portions of most of them become adsorbed on suspended sediments or taken up by the phytoplankton. The radioisotopes of biologically important elements enter the food web and are ultimately deposited in fish and other organisms that may be used as food by man. However, the fraction of the total inventory of radionuclides that is retained in aquatic animals is quite small.

Deposition of the suspended sediments is of paramount importance in the depletion of the nuclides from the river water, and McNary Reservoir, the first impoundment downstream from Hanford, is an effective trap. Based on the quantities of radionuclides transported by the river at Pasco and at Vancouver, the depletion in this 220-mile stretch of the Columbia varies from a minimum of about 10% for ^{124}Sb and ^{51}Cr to as much as 80% for several nuclides during most of the year (Nelson, Perkins, and Nielsen, 1966). A part of the radioactive materials deposited with the sediments is resuspended by the spring freshet and again transported by the river.

Some of the data on the flux of radioactive material in the Columbia has been generated by research programs concerned with aquatic biology and with the

sediments. A major portion of it has also been generated by the Environmental Surveillance Program, however. This surveillance program is directed primarily toward the evaluation of the radiation dose to man that results from the release of radionuclides into the environment. The program has shown that, although the nuclides of Hanford origin are readily measured in the Columbia River and in the North Pacific Ocean and in many species of fish and shellfish, the quantities that reach people are small and the radiation exposure that results is well within acceptable limits. For 1964 (the example year used above), the dose that might have been received by some few people who consumed extraordinary quantities of resident fish caught in the near vicinity of the reactors is estimated at not more than 25% of the limit recommended by the International Commission on Radiological Protection for members of the public. The estimates for more recent years are lower because smaller amounts of the nuclides are entering the river since some of the reactors have been deactivated.

REFERENCES

Coopey, R. W., 1948, The Accumulation of Radioactivity as Shown by a Limnological Study of the Columbia River in the Vicinity of Hanford Works, USAEC Report HW-11662, Hanford Atomic Products Operation.

Davis, J. J., and C. L. Cooper, 1951, Effect of Hanford Pile Effluent upon Aquatic Invertebrates in the Columbia River, USAEC Report HW-20055, Hanford Works.

—, R. W. Perkins, R. F. Palmer, W. C. Hanson, and J. F. Cline, 1958, Radioactive Materials in Aquatic and Terrestrial Organisms Exposed to Reactor Effluent Water, in *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958*, Vol. 18, pp. 423-428, United Nations, New York.

Foster, R. F., 1946, Some Effects of Pile Area Effluent Water on Young Chinook Salmon and Steelhead Trout, USAEC Report HW-7-4759, Hanford Engineer Works.

—, and J. J. Davis, 1956, The Accumulation of Radioactive Substances in Aquatic Forms, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955*, Vol. 13, pp. 364-367, United Nations, New York.

Hanson, W. C., and H. A. Kornberg, 1956, Radioactivity in Terrestrial Animals near an Atomic Energy Site, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955*, Vol. 13, pp. 385-388, United Nations, New York.

Herde, K. E., 1947, Radioactivity in Various Species of Fish from the Columbia and Yakima Rivers, USAEC Report HW-3-5501, Hanford Engineer Works.

Hines, N., 1962, *Proving Ground*, p. 366, University of Washington Press, Seattle, Wash.

National Academy of Sciences—National Research Council, 1957, The Effects of Atomic Radiation on Oceanography and Fisheries, Publication No. 551.

National Academy of Sciences—National Research Council, 1962, Disposal of Low-level Radioactive Waste into Pacific Coastal Waters, Publication No. 985.

Nelson, J. L., R. W. Perkins, and J. M. Nielsen, 1966, Reactions of Radionuclides from the Hanford Reactors with Columbia River Sediments, in *Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters*, Symposium Proceedings, Vienna, May 1966, pp. 139—161, International Atomic Energy Agency, Vienna (STI/PUB/126).

Olson, P. A., 1948, Some Effects of Pile Area Effluent Water on Young Silver Salmon, USAEC Report HW-8944, Hanford Works.

Parker, H. M., 1956, Radiation Exposure from Environmental Hazards, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955*, Vol. 13, pp 305-310, United Nations, New York.

—, R. F. Foster, I. L. Ophel, F. L. Parker, and W. C. Reinig, 1965, North American Experience in the Release of Low-level Waste into Rivers and Lakes, in *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1964*, Vol. 14, pp. 62-71, United Nations, New York.

Prosser, C. L., W. Pervinsek, Jane Arnold, G. Svihla, and P. C. Tompkins, 1945, Accumulation and Distribution of Radioactive Strontium, Barium—Lanthanum, Fission Mixture, and Sodium in Goldfish. USAEC Report MDDC-496, pp. 1-39.

Robeck, G. C., C. Henderson, and R. C. Palange, 1954, Water Quality Studies on the Columbia River, Special Report, pp. 1-99, Appendixes A-D, Public Health Service, U. S. Department of Health, Education, and Welfare.

Physic
and Its

ABSTRACT

The Columbi
Dam) on its
combined dra
Flow of the C
winter, but fl
high headwate
dams on the
ft/sec from S
stream of the
flows within
Columbia Riv
intrusion, nam
of about 23
included geon
flow, and tida
and probable c

THE RIVEF

The Columl
originates sc
miles of its
the northeas
it receives t
River is gen
again with
becomes the

*Departm
†Original c

ability to maintain economically viable domestic fisheries for certain species. How well we meet the challenge of foreign fishing fleets and that posed by the growth of our own land-based industries of the Columbia River basin will determine the future success or failure of many of our presently important regional fisheries.

In this chapter commercial fisheries are categorized as (1) freshwater species, i.e., species resident in the Columbia River and available for harvesting there throughout their lives; (2) anadromous species, such as salmon, which migrate as adults from the ocean into the Columbia and may be harvested in either river or ocean waters; and (3) marine species, such as halibut, shark, and shrimp, which are only harvested in the ocean.

Latest landings shown in the tables are for the year 1966, the most recent year for which final catch statistics were available when this chapter was written. For certain fisheries, particularly those where substantial changes have occurred in relation to long-term trends, preliminary statistics for 1967 and 1968 have been cited in the text to provide a more up-to-date summary.

FRESHWATER SPECIES

Many species of freshwater fish resident in the Columbia River and its tributaries are the object of regular or occasional commercial fisheries. Freshwater crawfish and carp have been harvested since before or shortly after the turn of this century.

Freshwater Crawfish

In the Columbia River basin, crawfish (*Pacifastacus*) are harvested mainly in the Cowlitz and Columbia rivers near Vancouver and Longview, Wash., and in the Willamette and Sandy rivers in Oregon. Metal pots or traps, commonly baited with fresh or frozen heads of carp, shad, or salmon, are the primary fishing gear. Large crawfish are marketed for human consumption, and smaller ones are used mainly by sport fishermen as bait for trout.

The largest catches of crawfish were made during the late 1800s and early 1900s, when annual landings ranged from 116,000 to 187,000 lb (Table 4.1). Production was somewhat lower after World War I and until World War II, but still averaged around 100,000 lb annually. Landings have progressively declined since World War II and in 1961—1965 averaged only 13,000 lb annually. Most of the limited catches of recent years have been from Oregon rivers.

Carp

Carp (*Cyprinus* sp.), which probably originated in the temperate parts of Asia, were introduced in Europe and North America, where they are now widely distributed and abundant. They prefer quiet weed-grown waters but may inhabit rather swiftly flowing streams. Carp are able to withstand brackish waters and large variations in temperature. Construction of dams on the Columbia River and its tributaries has probably increased the habitats favorable to carp; this species has considerable commercial potential.

In the Columbia River basin, carp have been harvested commercially in Moses, Sprague, Long, Roosevelt, and Banks lakes and in McNary Pool upstream from

Table 4.1—COMMERCIAL LANDINGS OF CRAWFISH IN COLUMBIA RIVER DISTRICTS OF OREGON AND WASHINGTON, 1888–1966*

Years	Average yearly landings, † lb	Years	Average yearly landings,† lb
1888	14,000	1931–1935	105,000
1892	20,000	1936–1940	93,000
1895	59,000	1941–1945	29,000
1899	116,000	1946–1950	36,000
1904	187,000	1951–1955	34,000
1908	178,000	1956–1960	31,000
1915	184,000	1961–1965	13,000
1922–1925	88,000	1966	2,000
1926–1930	145,000		

*Sources: Sette and Fiedler (1929) for years 1888–1927; United States Fish and Wildlife Service, Fishery Industries of the United States, for 1928–1941, and Fishery Statistics of the United States for 1942–1966.

†Landings prior to 1922 were available only for the years shown.

McNary Dam. Carp have also been taken commercially in sloughs of the lower Columbia. Small amounts of carp have been harvested with gill nets, but the bulk of the commercial catch has been taken with beach seines. The fish have been used for human consumption, for mink feed, and for reduction to fish meal. Washington landings of carp have far exceeded those in Oregon. During the period 1961–1965, an average of 941,000 lb was landed annually, and in 1966 some 425,000 lb was harvested (Table 4.2).

Table 4.2—COMMERCIAL LANDINGS OF CARP IN COLUMBIA RIVER DISTRICTS OF OREGON AND WASHINGTON, 1888–1966*

Years	Average yearly landings,† lb	Years	Average yearly landings,† lb
1888	0	1926–1930	522,000
1892	0	1931–1935	93,000
1895	0	1936–1940	140,000
1899	0	1941–1945	110,000
1904	20,000	1946–1950	9,000
1908	30,000	1951–1955	16,000
1915	250,000	1956–1960	178,000
1922–1925	372,000	1961–1965	941,000
		1966	425,000

*Sources: Sette and Fiedler (1929) for years 1888–1927; United States Fish and Wildlife Service, Fishery Industries of the United States, for 1928–1941, and Fishery Statistics of the United States for 1942–1966.

†Landings prior to 1922 were available only for the years shown.

ANADROMOUS SPECIES

Anadromous species, which ascend rivers and streams from the ocean to spawn, include such well-known fishes as Pacific salmon (*Oncorhynchus*) and steelhead trout (*Salmo gairdneri*). They also include less-known fishes, such as American shad (*Alosa sapidissima*), eulachon (*Thaleichthys pacificus*), sturgeon (*Acipenser*), and Pacific lamprey (*Lampetra tridentata*).

Salmon and Steelhead Trout Fisheries

All five species of salmon found in waters along the Pacific Coast of North America occur in the Columbia River, as does the steelhead trout. Pink salmon (*O. gorbuscha*), however, are found there only occasionally. Chum salmon (*O. keta*) catches have been small since the late 1940s, partly because of closed fishing seasons that prevent the catching of this species. Only two species—the chinook (*O. tshawytscha*) and the coho (*O. kisutch*) or silver—are now harvested in substantial numbers. The Columbia River is also one of the principal steelhead trout (*S. gairdneri*) streams of the Pacific Northwest. Collectively, salmon and steelhead trout support one of the most valuable fisheries in the Pacific Northwest.

Salmon fisheries of the Columbia River can be conveniently classed as aboriginal and modern. Aboriginal was the period before the white man arrived when Indians were the sole users of the resource. Modern includes an intermediate period of short duration when white settlers and traders bartered with the Indians for salmon or caught the fish for local use or limited export. The contemporary fishery can be viewed as beginning in 1866 when the introduction of canning resulted in a vast expansion of markets for salmon.

Aboriginal Fishery As noted by early explorers, the economy and mode of life of Columbia River Indians were almost entirely dependent upon salmon. Salmon was not only the main source of food but also served as the principal medium of exchange. Upwards of 18,000,000 lb of salmon reportedly was harvested each year by Columbia River basin Indian tribes when white men first arrived (Craig and Hacker, 1940). Salmon harvest by Indians probably declined in the mid-1800s as a result of a marked reduction in the Indian population brought about by epidemic diseases introduced by the white man. Commercial catches of Columbia River salmon did not again equal the amount harvested by the original Indian population until the late 1870s; since the late 1940s the river catches have been considerably less.

The Indians used a variety of fishing gear for harvesting salmon and steelhead trout on all major tributary streams and the main-stem Columbia. Harvesting gear included spears, dip nets, fish traps or weirs, seines, lines with baited hooks, and perhaps even gill nets. Except for substitution of modern materials for the natural construction materials used by the Indians, much of the fishing gear in use today closely resembles that used by the Indians.

Present Indian fisheries are largely confined to tributary streams and to pools of the Bonneville Dam and The Dalles Dam. The fishery in the Bonneville pool has developed largely since the Indians' ancestral fishing grounds at Celilo Falls (Fig. 4.2) were flooded in 1956 by the reservoir of The Dalles Dam. Present-day Indian harvests are but a fraction of those taken prior to arrival of the white man.

Fig. 4.2—Indians fishing at Celilo Falls (1952). (*Courtesy R. Matheny, U. S. Fish and Wildlife Service.*)

Modern Fishery The modern fishery involves both the river and ocean fisheries because both harvest large numbers of Columbia River salmonids.

The modern fishery can be said to have begun in 1866 when the first salmon were canned. Growth was rapid after 1866, and by 1883 some 39 canneries were operating and packed 629,000 cases, or approximately 30,000,000 lb of fish. By 1890 the number of canneries had declined to 21, and their combined pack had fallen to 436,000 cases. During the period 1967—1968, an annual average of 78,000 cases was packed by the 6 canneries still operating along the Columbia.

During the late 1890s a transition occurred from heavy salting to mild curing (light salting) of salmon. Mild-cured salmon is kept under refrigeration and is usually processed into a kippered product. Generally, only large, fat, red chinook salmon and, to a lesser extent, extra large coho salmon are used for mild curing. Prior to 1923 almost the entire mild-cured pack consisted of chinook salmon. Since 1923 mild-cured packs have been predominantly chinook, but they have included variable proportions of cohos. The largest mild-cured pack, over 8,000,000 lb net weight, was put up in 1905; the annual pack gradually fell thereafter, and in recent years it has been less than 50,000 lb annually.

The decline in canned and mild-cured salmon packs reflects not only the reduction that has occurred in the abundance of Columbia River salmon but also the basic change that has occurred in marketing procedures. Growth of transportation facilities, including the completion of a transcontinental railroad to

Portland, Ore., in 1883, made possible the shipment of fresh fish to metropolitan markets on the Pacific Coast and in the Midwest. The development of mechanical refrigeration has enabled shipment of frozen salmon to markets throughout the United States and abroad.

As in the aboriginal fishery, a variety of fishing gear and methods have been used in the modern fishery. Gill nets were the primary gear used in the early fishery. Fish wheels, seines, and traps also found early use (Figs. 4.3, 4.4, and 4.5). For a while purse seines were used at or near the mouth of the Columbia River. Commercial trolling for salmon began in adjacent ocean waters in the early 1900s. Many types of gear, such as fish wheels, beach seines, and traps, have been eliminated by legislation. Gill nets in the river and trolling in the ocean account for almost the entire commercial catch now. Commercial landings of Columbia River salmon and steelhead trout are shown in Table 4.3 for the years 1866—1966. Not included in the table are substantial ocean troll catches of Columbia River salmon which are taken from California to Alaska and partially compensate for the severe decline in commercial landings of river-caught salmon and steelhead trout. Increased catches of coho salmon in recent years reflect the phenomenal success in the art of salmon husbandry in hatcheries (Fig. 4.6).

Chinook, sockeye, coho, and chum salmon and steelhead trout are all harvested by gill nets in the river, with chinook accounting for most of the catches. Both set (stationary) and drift gill nets have been used in the river, but only drift gill nets are now permitted by law (Wendler, 1966). An exception is the set gill nets that are the primary gear used by Indians. Commercial gill-net fishing by non-Indians is now done from the mouth of the Columbia to within 5 miles of Bonneville Dam, a distance of about 140 miles.

About 1912 fishermen discovered they could catch chinook and coho salmon by trolling off the mouth of the Columbia (Van Hyning, 1951). About 500 boats were trolling there in 1915. By 1919 the number had increased to between 1000 and 2000 (Van Hyning, 1951). Since then the number of vessels and men have declined, but the efficiency has greatly increased (Fig. 4.7).

Fall chinook migrate northward from the Columbia and contribute large catches to the British Columbia troll fishery (Wright, 1968). Ocean sport and troll fisheries off Washington and Oregon also take considerable numbers of Columbia River fall chinook as do sport fisheries in the Strait of Juan de Fuca and in the northern portion of Puget Sound. Migration of winter, spring, summer, and upper river fall-run chinooks in the ocean is more to the northward than that of lower river fall chinooks. About three-fourths of the troll harvest of these stocks is taken off British Columbia and Alaska and one-fourth off Washington (Wright, 1968).

Ocean captures of coho reared in Columbia River hatcheries show a markedly different distribution from Columbia River chinooks. Coho occur both north and south of the Columbia River mouth, with a southward movement predominating (Wright, 1968). Because of the extensive southward migration, the Columbia River coho stocks are very important to troll fisheries off Oregon and California.

American Shad

American shad (*Alosa sapidissima*) were first introduced from the Atlantic Coast to the Pacific Coast in 1871, when fry were planted in the Sacramento

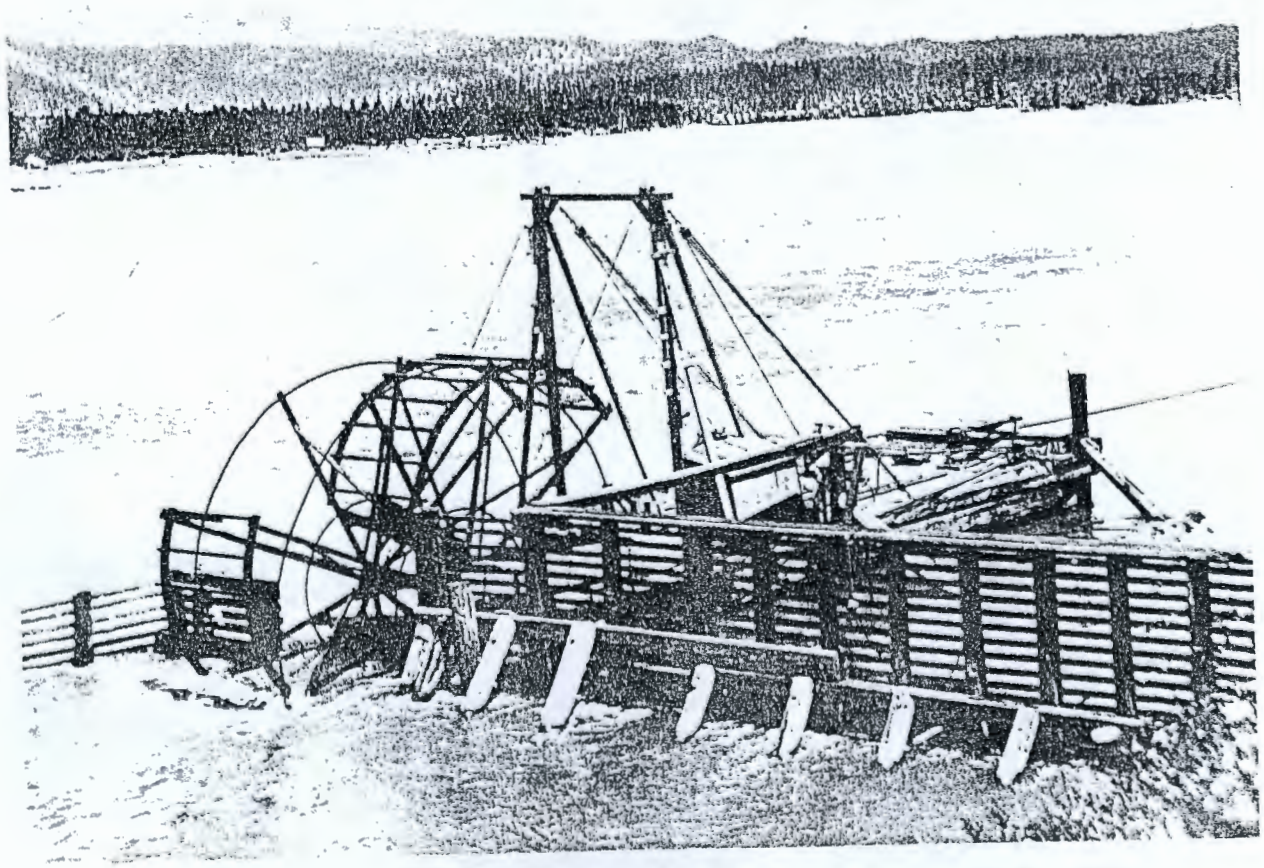

Fig. 4.3—Fish wheel used for harvesting salmon in early years of Columbia River fishing. *(Courtesy P. D. Zimmer and Oregon Historical Society.)*

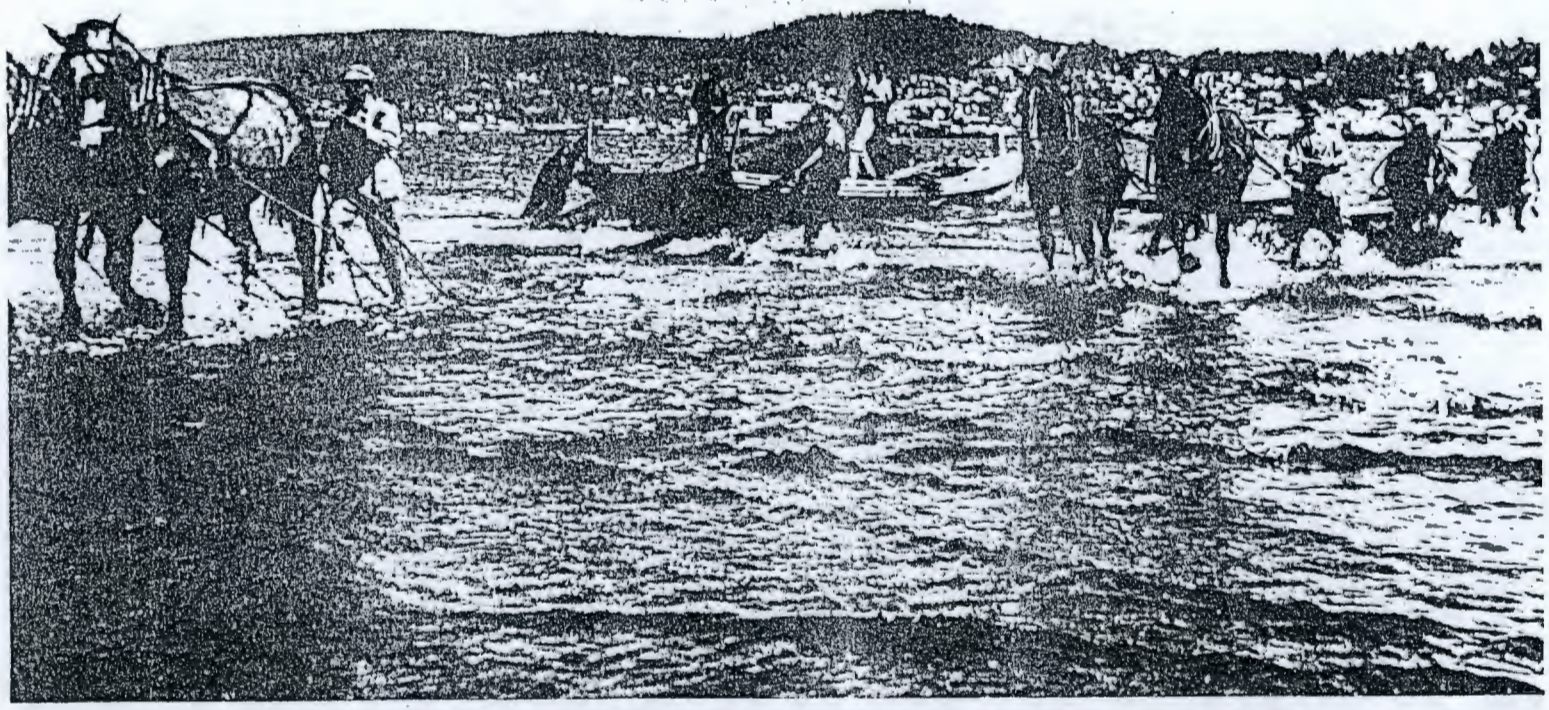

Fig. 4.4—Seines were pulled by horses and laid out from skiffs towed by launches. Between 1927 and 1934, seines took about 15% of the total catch of salmon and steelhead trout from the Columbia River (Craig and Hacker, 1940).

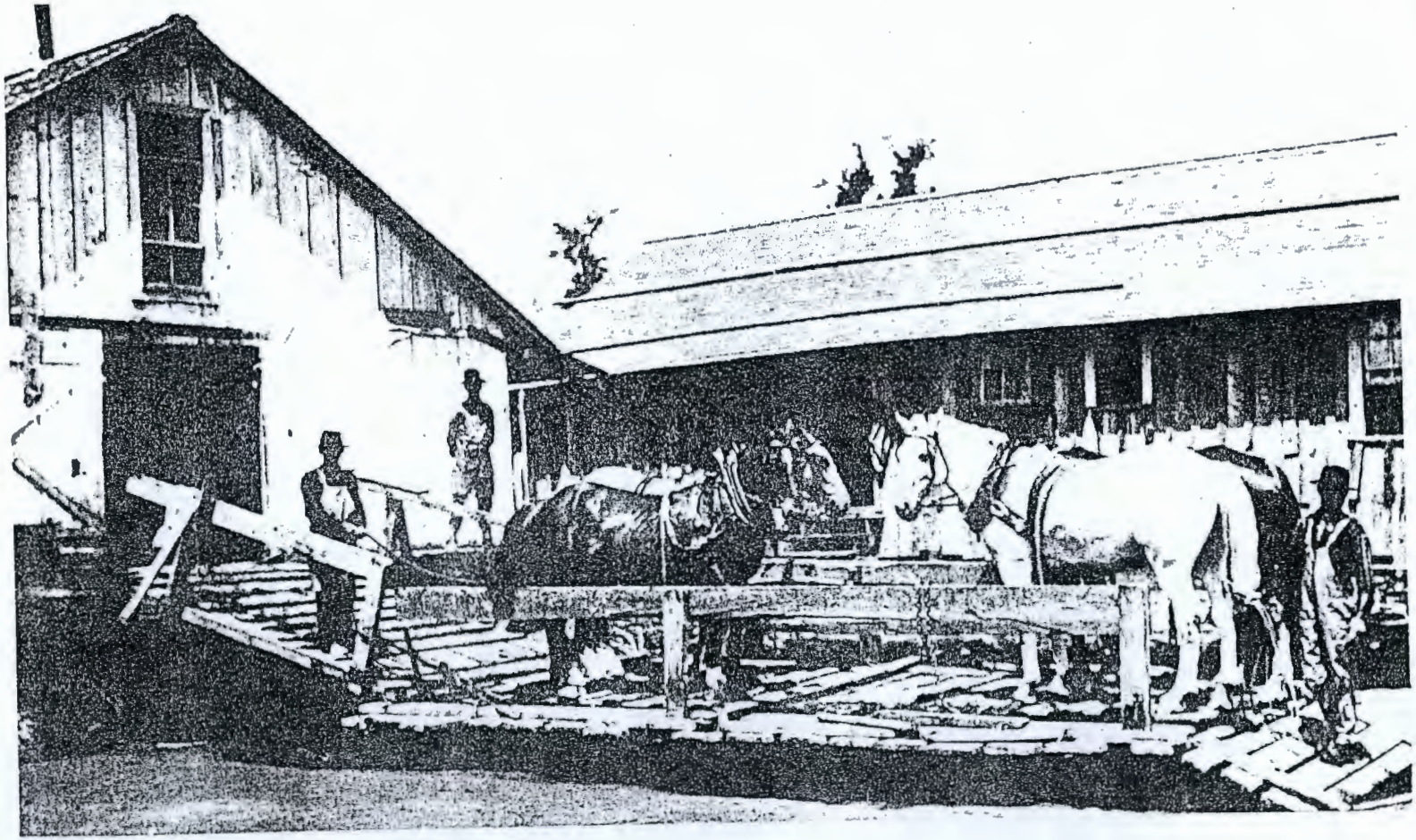

Fig. 4.5—Floating bunkhouse and stable for beach-seine crew and horses used in early years of Columbia River salmon fishery. (*Courtesy P. D. Zimmer and Oregon Historical Society.*)

Table 4.3—AVERAGE ANNUAL COLUMBIA RIVER COMMERCIAL SALMON AND STEELHEAD TROUT LANDINGS, EXCLUDING TROLL CATCHES, BY SPECIES, 1866–1966*†

Years	Average annual landings, 10^6 lb					
	Chinook	Sockeye	Coho	Chum	Steelhead	Total
1866–1870	4.1					4.1
1871–1875	19.4					19.4
1876–1880	31.3					31.3
1881–1885	39.4					39.4
1886–1890	24.2	1.0			0.9	26.1
1891–1895	24.2	2.4	2.4	0.3	3.7	33.0
1896–1900	23.3	1.8	3.3	0.4	2.1	30.9
1901–1905‡	28.9	0.8	1.4	1.1	0.6	32.8
1906–1910	23.3	0.7	2.9	2.2	0.6	29.7
1911–1915	27.0	0.9	3.5	3.0	1.9	36.3
1916–1920	30.4	0.8	4.5	3.5	2.0	41.2
1921–1925	22.0	1.2	6.2	2.1	2.4	33.9
1926–1930	20.3	0.7	6.0	4.0	2.9	33.9
1931–1935	18.2	0.3	3.4	1.1	1.8	24.8
1936–1940	14.8	0.3	1.8	1.5	2.1	20.5
1941–1945	16.1	0.2	1.2	2.2	1.9	21.6
1946–1950	14.0	0.2	1.1	0.7	1.3	17.3
1951–1955	7.7	0.3	0.7	0.3	1.5	10.5
1956–1960	5.9	0.5	0.3	0.0	0.7	7.4
1961–1965	5.0	0.1	1.1	0.0	0.7	6.8
1966	3.7	0.0	4.4	0.0	0.4	8.5

*Sources: Cleaver (1951) for years 1866–1949; Smith (1956) for 1950–1953; United States Fish and Wildlife Service, Fishery Statistics of the United States, for 1954–1966.

†Note: Troll catches are excluded because they contain an unknown proportion of salmon from the Columbia River; i.e., not all troll-caught salmon landed in Columbia River district ports are of Columbia River origin.

‡Average for 1902–1905 because no breakdown of species was available in 1901.

River, Calif. Fish from this initial plant appeared in the Columbia by 1876 or 1877 and were supplemented in 1885 and 1886 by stocking Atlantic Coast fry in the Columbia, Willamette, and Snake rivers. First commercial landings of shad were reported from the Columbia in 1889, and less than 10 years later annual landings averaged over 500,000 lb (Table 4.4).

Traps, seines, and fish wheels have all been used to catch shad; however, only gill nets are now used commercially. Most of the catch is during the spawning migrations in May, June, and July. Shad are abundant in the lower reaches of the Columbia, and some have been taken as far upstream as the Snake River. During the period 1926–1966, annual landings averaged 563,000 lb. Shad are also being increasingly sought by sport fishermen.

Fig. 4.6—Spring Creek hatchery operated by the U. S. Fish and Wildlife Service on the Columbia River. (*Courtesy E. L. Perry, National Marine Fisheries Service.*)

Fig. 4.7—Trolling vessels at Westport, Wash. (*Courtesy H. Heyamoto, National Marine Fisheries Service.*)

Table 4.4—AVERAGE ANNUAL COMMERCIAL LANDINGS OF SHAD IN THE COLUMBIA RIVER DISTRICTS OF OREGON AND WASHINGTON, 1889—1966*

Years	Average annual landings,† lb	Years	Average annual landings,† lb
1889—1890	68,000	1926—1930	1,245,000
1891—1892	170,000	1931—1935	483,000
1896—1900	572,000	1936—1940	295,000
1902—1905	189,000	1941—1945	545,000
1906—1910	357,000	1946—1950	841,000
1915	581,000	1951—1955	311,000
1923	334,000	1956—1960	178,000
1925	665,000	1961—1965	563,000
		1966	796,000

*Sources: Cleaver (1951) for years 1889—1949; Smith (1956) for 1950—1953; United States Fish and Wildlife Service, Fishery Statistics of the United States, for 1954—1966.

†Landings prior to 1925 are known only for the indicated years.

Eulachon

The eulachon, or Columbia River smelt (*Thaleichthys pacificus*), occur from northern California to the Bering Sea and are especially abundant in the Columbia River. Prior to the manufacture of candles, these fish were dried, fitted with wicks, and used as a source of light. This application explains why eulachon are still sometimes referred to as candlefish. Indians formerly used substantial quantities of them for food and also rendered them into oil for cooking. During the winter eulachon enter the Columbia in dense schools and ascend various tributaries, mainly the Cowlitz, Lewis, Grays, and Sandy rivers.

Records do not show when eulachon first became commercially important, but in 1895 over 250,000 lb was landed. Commercial landings were largest from the late 1930s through the 1940s and reached an all-time high of 5,750,000 lb in 1945. Recent commercial landings of eulachon have ranged between 1,000,000 and 2,000,000 lb annually (Table 4.5), and have exceeded landings for all other species taken in the Columbia except chinook salmon and, in recent years, coho salmon.

Table 4.5—AVERAGE ANNUAL COMMERCIAL LANDINGS OF EULACHON IN THE COLUMBIA RIVER DISTRICTS OF OREGON AND WASHINGTON, 1895—1966*

Years	Average annual landings,† lb	Years	Average annual landings,† lb
1895	282,000	1931—1935	1,612,000
1896—1900	832,000	1936—1940	2,548,000
1902—1905	474,000	1941—1945	3,437,000
1906—1910	524,000	1946—1950	2,731,000
1911—1912	435,000	1951—1955	1,728,000
1923	1,188,000	1956—1960	1,787,000
1925	1,578,000	1961—1965	1,075,000
1926—1930	1,277,000	1966	740,000

*Sources: Cleaver (1951) for years 1896—1949; Smith (1956) for 1950—1953; United States Fish and Wildlife Service, Fishery Statistics of the United States, for 1954—1966.

†Landings prior to 1925 are known only for the indicated years.

As the eulachon ascend the Columbia, they are harvested with gill nets. After they enter the tributaries, dip nets are used. The Cowlitz River has usually accounted for about one-half the total landings. Commercial landings have been governed more by market demands than by abundance. Eulachon are used almost entirely for human consumption.

Sturgeon

Two species of sturgeon, the white sturgeon (*Acipenser transmontanus*) and the green sturgeon (*A. medirostris*), occur in the Columbia River. As a food fish, the white sturgeon is considered superior to the green sturgeon.

Sturgeon were so numerous at some places on the Columbia that they caused considerable damage to the gill nets used by early salmon fishermen. For years the

smaller sturgeon (generally those under 50 lb) caught by salmon fishermen were deliberately killed; and, in a few places on the river, special efforts were made to eradicate them. Sturgeon were caught in all the major types of salmon gear, including gill nets, seines, fish wheels (Fig. 4.8), and traps, as well as on hook-and-line gear.

Sturgeon were not used much as food by the original Indians and early white settlers of the Columbia basin. About 1880 a commercial fishery commenced. In

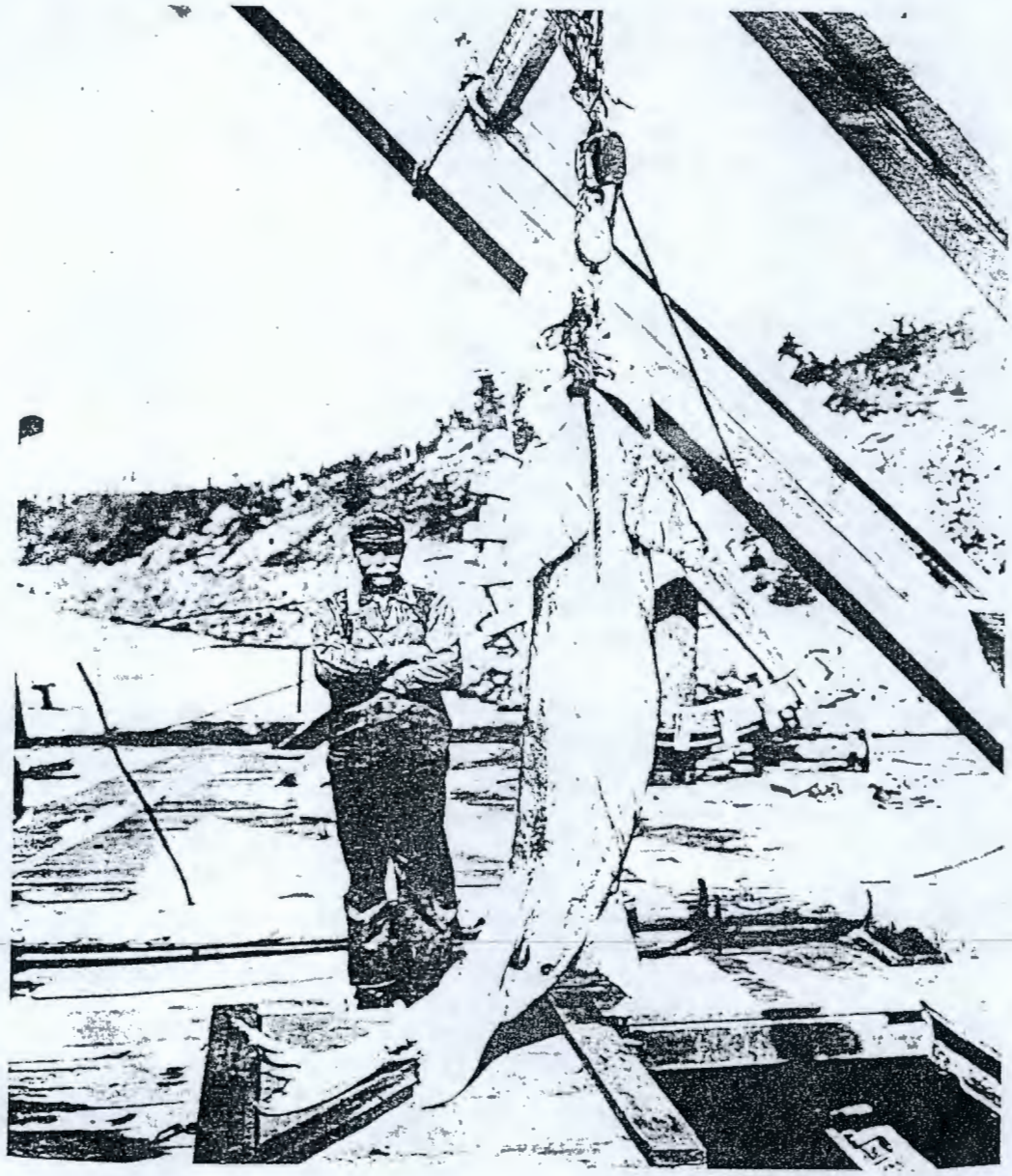

Fig. 4.8—A 637-lb white sturgeon caught in McGowan's fish wheel near Cascade Locks in 1912. (*A. Pierce, Courtesy Ivan Donaldson.*)

1888 a rail shipment of frozen sturgeon to the East marked the beginning of an important industry. Quick acceptance of smoked Columbia River sturgeon and of caviar made from sturgeon eggs stimulated rapid development of the fishery; by 1892 a peak production of 5,500,000 lb was reached. Despite the relatively large fishing effort in subsequent years, landings fell rapidly (Table 4.6), and the fishery soon became incidental to other fisheries. Since World War II commercial landings of sturgeon have generally ranged between 250,000 and 500,000 lb annually. Although sturgeon is highly esteemed as a fresh fish, the bulk of the catch is smoked and canned.

Table 4.6—AVERAGE ANNUAL COMMERCIAL LANDINGS OF STURGEON CAUGHT IN THE COLUMBIA RIVER AND TRIBUTARY STREAMS, 1889—1966*

Years	Average annual landings,† lb	Years	Average annual landings,† lb
1889—1890	2,416,000	1931—1935	93,000
1891—1892	4,514,000	1936—1940	109,000
1895	4,704,000	1941—1945	170,000
1899	73,000	1946—1950	414,000
1904	138,000	1951—1955	320,000
1915	135,000	1956—1960	341,000
1923	183,000	1961—1965	242,000
1925	231,000	1966	268,000
1926—1930	181,000		

*Sources: Cleaver (1951) for years 1889—1949; Smith (1956) for 1950—1953; United States Fish and Wildlife Service, Fishery Statistics of the United States, for 1954—1956.

†Landings prior to 1925 are known only for the indicated years.

Commercial regulations, which include closed seasons and prohibitions against retention of immature (under 4 ft long) and large (over 6 ft long) sturgeon, together with a changed attitude by commercial fishermen, probably account for the increasing abundance of sturgeon in recent years. Most commercially caught sturgeon are now taken in gill nets during salmon and steelhead fishing, but a few are taken with handlines. The average weight of sturgeon caught in gill nets in recent years has been about 40 lb (Wendler, 1959).

Pacific Lamprey

The Pacific lamprey (*Lampetra tridentata*), which occurs from southern California to Alaska, is an eellike vertebrate with a long slender body and a jawless mouth surrounded by a horny sucking disk containing platelike teeth. The earliest known use of lamprey was as food by Indians. The Pacific lamprey is not used now to any extent as food. Present-day anglers use it as bait for sturgeon and other fishes.

The fishery commenced at Oregon City on a limited scale in 1941. Statistics on landings are available starting with 1943. The fishery peaked in 1946, when 397,000 lb was landed (Table 4.7). Last reported landings were for 1952.

Table 4.7—ANNUAL COMMERCIAL LANDINGS OF PACIFIC LAMPREY AT WILLAMETTE FALLS, OREGON, 1943—1952*

Year	Landings, lb	Year	Landings, lb
1943	207,000	1948	231,000
1944	73,000	1949	115,000
1945	249,000	1950	0
1946	397,000	1951	184,000
1947	360,000	1952	262,000

*Sources: Cleaver (1951) for years 1943—1949; Smith (1956) for 1950—1952.

Formerly, Pacific lamprey were harvested commercially as they ascended the fish ladder at Willamette Falls in Oregon City. Lamprey entered one of a series of traps placed along the sides and the upper ends of the pools in the ladder. A trough led from each trap into a flume and then into a central live box. The lamprey were dipped from the live box with scoop nets, placed in drums, barged downstream, transferred to a truck, and hauled to a reduction plant. Oil containing vitamin A was extracted, and the residual material was manufactured into fish meal for poultry and livestock (Mattson, 1949).

MARINE SPECIES

As food resources the many marine species occurring in waters contiguous to the Columbia River greatly exceed the Columbia's freshwater and anadromous species. Not all the marine species are the object of a commercial fishery: such species as Pacific saury (*Cololabis saira*), northern anchovy, some flounders (Pleuronectidae), and several rockfishes (Scorpaenidae) are underused or unused resources for the future.

Both resident and migratory species occur in ocean waters adjacent to the Columbia. An example of a resident species is the sedentary razor clam, which is abundant on exposed beaches of northern Oregon and southern Washington. In contrast to razor clams, the albacore tuna is a highly migratory species that appears in varying quantities and localities in Pacific Northwest waters from year to year. Rather arbitrary decisions had to be made concerning geographical reporting areas to show the magnitude of catches of various species within the influence of Columbia River waters. For migratory species statewide landings have been used, supplemented in some cases by reference to percentage of state totals made in Columbia River ports. For relatively nonmigratory species, it was generally possible to show landings by coastal districts where the harvests were known to have been made.

U. S. Fisheries

United States marine fisheries are for fish, shellfish, and mammals. Descriptions of each fishery follow.

Chapter 28

Sediment-Associated Radionuclides from the Columbia River

M. Grant Gross*

ABSTRACT

Gamma-ray spectrometry was used to determine abundances of naturally occurring radionuclides (^{40}K and ^{214}Bi), fission products (^{95}Zr—^{95}Nb, ^{103}Ru—^{103}Rh, and ^{141}Ce), and radionuclides from the Hanford reactors (^{60}Co, ^{65}Zn, ^{51}Cr, and ^{54}Mn) in sediment from the northeast Pacific Ocean near the Columbia River mouth. Naturally occurring radionuclides were ubiquitous in the sediments; on the continental shelf their activity levels were nearly constant and generally exceeded the levels of other radionuclides except near the Columbia River mouth. Fission products were widely dispersed in 1963 and showed highest activities near the river mouth, as did the radionuclides from Hanford. Both the Hanford radionuclides and the fission products were slightly more abundant and more widespread north of the river mouth than south. Northward-setting near-bottom currents on the continental shelf off Washington and Oregon apparently cause the northward skewing of the distributions of Hanford and fission-product radionuclides.

The surface layer (1 cm thick) of the sediment contains about 11% of the ^{51}Cr and about 14% of the ^{65}Zn reservoir supported by the average 1963 discharge of sediment-associated radionuclides from the Columbia River. The total reservoir of radionuclides in the continental-shelf sediment in the area studied may be as much as three times as large as the activity of the 1-cm-thick surface layer.

Radionuclide discharges from the Hanford Atomic Products Operation (Haushild et al., 1966; Perkins, Nelson, and Haushild, 1966) into the Columbia River provided unique opportunities to study interactions between a major river and the coastal ocean (Gross, Barnes, and Riel, 1965). The introduced radionuclides were especially valuable for studies of sedimentary processes and the routes of sediment movement inasmuch as sediment-associated radionuclides (Nelson et al., 1966) with short half-lives uniquely identified sediment recently discharged by the river (Gross, 1966). Furthermore, the radionuclide discharge was large enough to "tag" the river's sediment load without otherwise changing the system's physical characteristics.

---

*Department of Oceanography, University of Washington, Seattle; present address: Marine Sciences Research Center, State University of New York, Stony Brook, New York.

Table 28.1—LOCATION AND TIME OF CRUISES TO SAMPLE SEDIMENT-ASSOCIATED RADIONUCLIDES

Area sampled	Date (cruise number)	Number of samples analyzed
Grays Harbor	July 1961	20
Willapa Bay	May 1962	29
Washington—Oregon beaches	Sept. 1961	18
Continental margin	July—Aug. 1961 (*B.B.* 291)	41
Eastern Cascadia Basin	June 1962 (*B.B.* 308)	12
	(*B.B.* 312)	43
Western Cascadia Basin—ridge system Tufts Plain	Aug. 1962 (*B.B.* 311)	43
Washington—Oregon continental shelf	Sept. 1963 (*B.B.* 333)	290
	Total	496

This study of the sediment-associated radionuclides from the Columbia River began in the summer of 1961 when cruises were made to sample sediment from the continental shelf, from beaches near the river mouth, and from deeper areas under the river plume. In 1962, additional samples were collected from the deeper areas to determine if radioactive sediment was present on the deep-ocean bottom and in Grays Harbor and Willapa Bay (Table 28.1, Fig. 28.1). Analysis of samples taken during these surveys showed a substantial level of radioactivity in sediment collected from the continental shelf and in Willapa Bay (Gross, McManus, and Creager, 1963). A detailed study of continental shelf sediment near the river mouth (Fig. 28.1) was conducted in August and September 1963 (*Brown Bear* cruise 333) to investigate this phenomenon further. From this study it is possible to delineate deposition areas for sediment-associated Columbia River radionuclides, to identify some of the processes controlling their distribution, and to calculate the amount of sediment-associated radionuclides on the continental shelf at that time. This chapter presents the results of studies undertaken to investigate the fate of radionuclides associated with river-borne sediments.

SAMPLING AND ANALYTICAL PROCEDURES

In surveys made during 1961 and 1962 (Fig. 28.1), sediment samples were collected with Van Veen samplers (Van Veen, 1936) in waters less than 200 m deep. In 1961 when deeper locations were sampled, various coring devices were used, and in 1962 the deep stations were sampled with open gravity corers (Emery and Dietz, 1941) or grab samplers (Shipek, 1965). Regardless of the type of sampler used during 1961 and 1962, the uppermost layer (usually 1- to 3-cm thick) was removed for analysis.

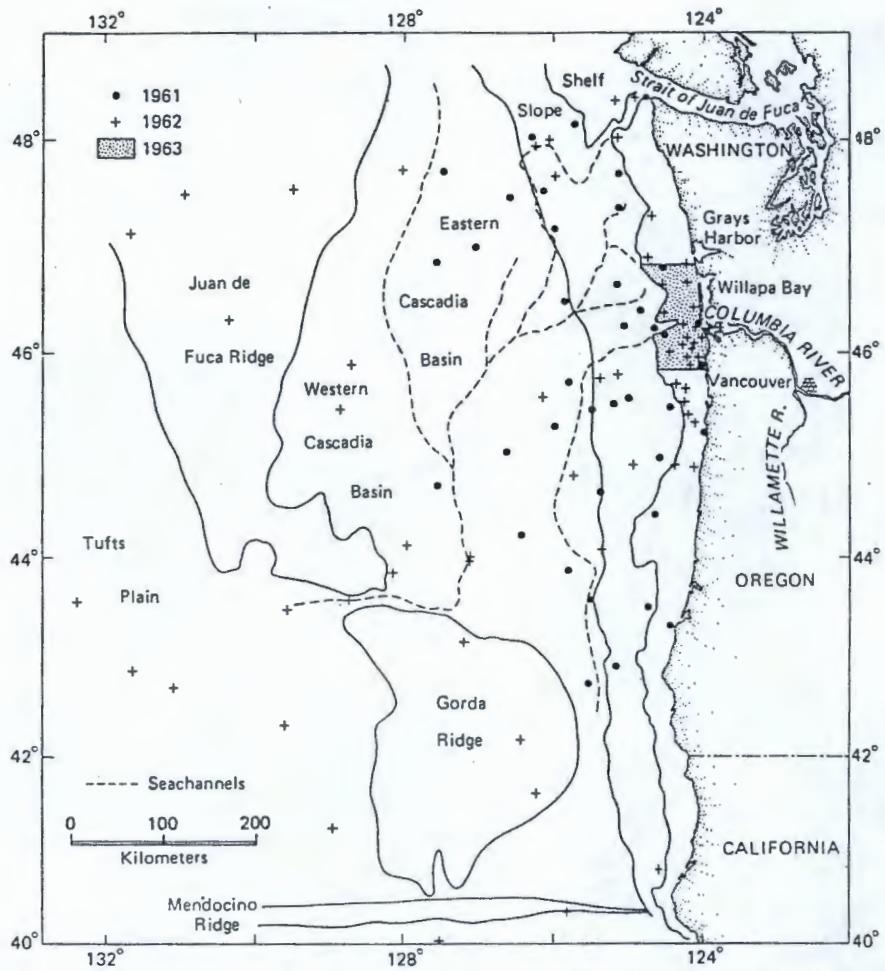

Fig. 28.1—Location of sediment samples collected during 1961 and 1962 in the various physiographic provinces. Figure 28.2 shows the area of the 1963 survey and station locations.

In 1963, 290 sediment samples were collected from the continental shelf 40 km south of the river mouth to 70 km north (Fig. 28.2). The surface layer, approximately 1 cm thick, taken from two grab samples obtained at each location, was placed in a plastic container and dried without desalting under infrared heaters at temperatures below 50°C. Layers (1 cm thick) were subsampled at various depths from 10 cores obtained from the continental shelf.

The plastic sample containers, sealed by plastic screw lids, were wrapped in plastic sheeting to prevent surface contamination by fallout; the plastic wrapping was changed immediately before the counting operation. A period of at least two weeks was allowed to elapse between the sealing and the analyzing of the samples to permit the samples to attain equilibrium in the ^{226}Ra series.

The gamma-ray activity of each sample was counted for 100 min or more using a 7.6- by 7.6-cm NaI(Tl) crystal connected to a multichannel pulse-height analyzer. The spectra obtained were analyzed by a computer program (Seymour

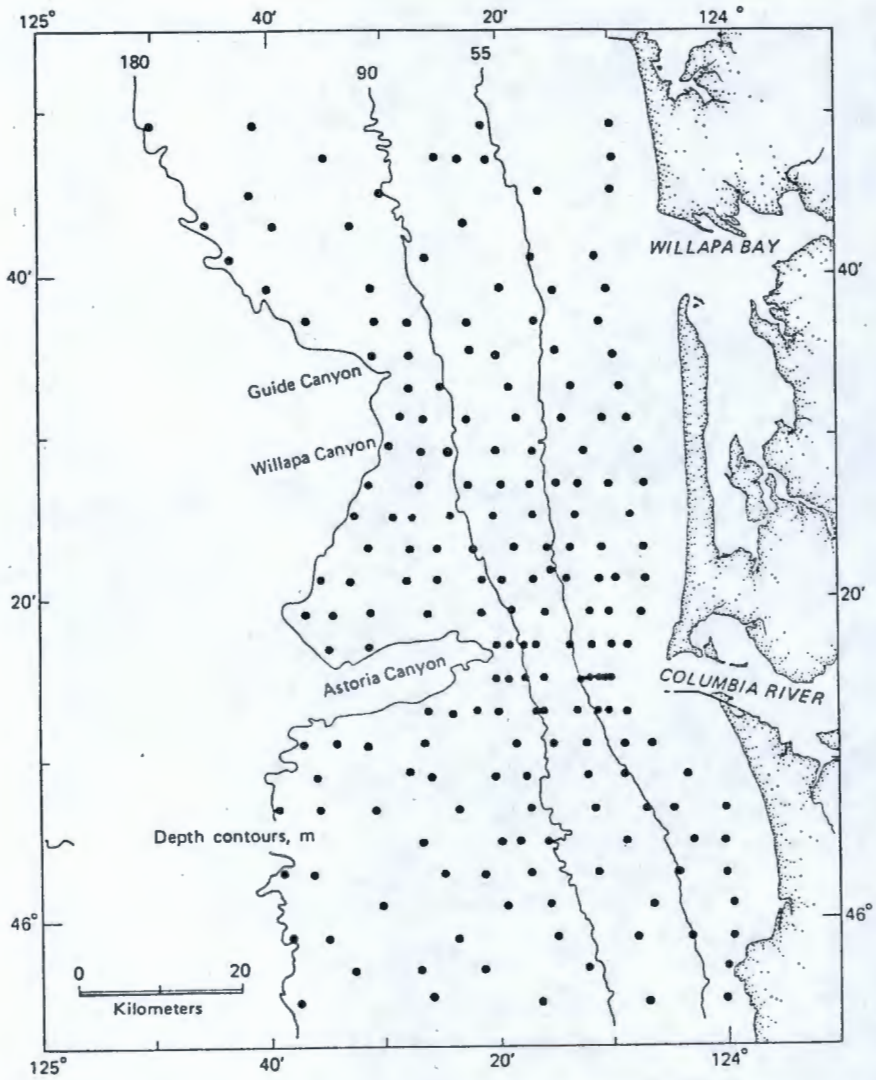

Fig. 28.2—Location of surface samples and cores taken in the summer of 1963.

and Lewis, 1964) that calculated the activity in picocuries (10^{-12} curie) per gram of dry sediment for each of nine radionuclides and their radioactive daughters (^{40}K, ^{60}Co, ^{65}Zn, ^{54}Mn, ^{95}Zr—^{95}Nb, ^{214}Bi, ^{103}Ru—^{103}Rh, ^{51}Cr, and ^{141}Ce) after correction for variations in sample geometry, radioactive decay after sampling, and mutual interferences of the individual gamma-ray spectra (Fig. 28.3, Table 28.2). The resultant data were considered significant if the calculated activity was greater than the 99% confidence interval for the background.

Results for ^{40}K and ^{214}Bi were checked by determining gamma-ray activities of several National Bureau of Standards (NBS) standard samples for which the ^{226}Ra activities and approximate potassium contents were known. The results (Table 28.3) indicate good agreement between the NBS values and those obtained by the procedures used in this study. This test also indicated that no part of the

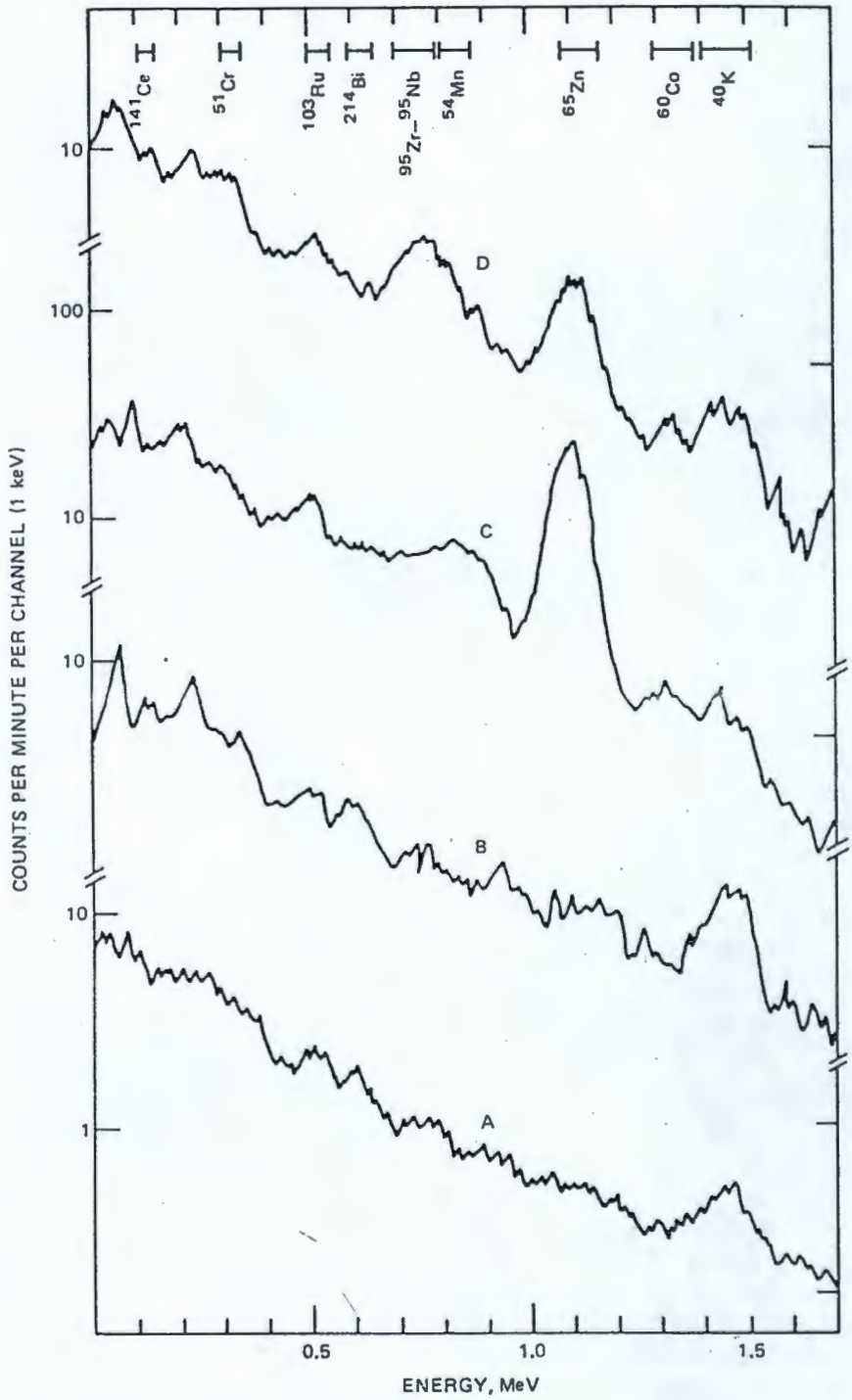

Fig. 28.3—Typical gamma-ray spectra of sediment samples and approximate channel limits used to calculate specific activities of radionuclides. (A) Detector background, November 1961. (B) Nearshore sand, 6-m depth off Washington coast, August 1961. (C) Silty sand, Columbia River mouth, August 1961. (D) Silty sand, Columbia River mouth, June 1963.

Table 28.2—RADIONUCLIDES, HALF-LIVES, AND GAMMA-RAY PHOTOPEAKS

Radionuclide	Half-life	Photopeak, MeV	Programmed photopeak limits, MeV
^{40}K	1.3×10^9 years	1.46	1.40—1.51
^{60}Co	5.3 years	1.17, 1.33	1.28—1.38
^{65}Zn	245 days	1.12	1.07—1.16
^{54}Mn	290 days	0.84	0.80—0.87
^{95}Zr	65 days	0.72	0.70—0.79
^{95}Nb	35 days	0.77	
^{214}Bi	1620 years (^{226}Ra)*	0.61	0.58—0.64
^{103}Ru—^{103}Rh	41 days	0.51	0.49—0.54
^{51}Cr	28 days	0.32	0.30—0.34
^{141}Ce	32 days	0.13	0.12—0.15

*Parent radionuclide.

Table 28.3—COMPARISON OF SUGGESTED VALUES FOR NATIONAL BUREAU OF STANDARDS STANDARD ROCK SAMPLES AND ANALYTICAL RESULTS OBTAINED BY THE UNIVERSITY OF WASHINGTON

Samples (NBS sample number)	^{214}Bi, pCi/g		K, %	
	NBS*	UW*	NBS	UW*
Columbia River basalt (4978)	0.33 ± 0.04	0.38 ± 0.03	0.81	0.87 ± 0.08
Gabbro-diorite (4982)	0.18 ± 0.02	0.18 ± 0.02	1.3	1.2 ± 0.1
Triassic diabase (4984)	0.18 ± 0.03	0.19 ± 0.03	0.48	0.35 ± 0.07
Deccan trap (4985)	0.21 ± 0.06	0.26 ± 0.03	0.65	0.60 ± 0.08

*Standard deviation based on counting statistics for individual samples.

naturally occurring gamma-ray spectrum (at these activity levels) was causing spurious results for other radionuclides in the data-reduction process, except for ^{214}Bi.

Another test of the counting procedures involved recounting samples from cores about 15 months (December 1964) after their collection. During the 15-month period, the activity of radionuclides with relatively short half-lives was greatly reduced by radioactive decay except for ^{60}Co ($T_{1/2} = 5.3$ years). If subsequent analysis of the data indicated the presence of short-half-life radionuclides, original misidentification of a part of the natural radioactive spectrum would have been indicated. The results of this test, however, showed no significant activity for any short-half-life radionuclide except ^{141}Ce; consequently, all ^{141}Ce data were discarded. The data were not recomputed, however, because errors associated with the ^{141}Ce photopeak (Fig. 28.3) would not greatly

affect calculated activities for other radionuclides whose gamma rays had higher energies.

NATURALLY OCCURRING RADIONUCLIDES

Radioactivity due to long-lived nuclides (^{40}K, ^{238}U series) was detected in samples from all areas. For most samples statistically significant information was obtained about the level of naturally occurring background radiation in the sediment.

Potassium-40 dominated the gamma-ray spectra (see Fig. 28.3) in most of the sediments analyzed. An indistinct zonation of ^{40}K activity roughly parallels the coastline (Fig. 28.4). Lowest ^{40}K activities occur in nearshore sands (water depths less than about 50 m) and tend to be highest on the continental shelf southwest of the river mouth. Cause of this zonation is not immediately obvious. For example, there is no apparent correlation of ^{40}K activity and mean grain size. Perhaps the high ^{40}K activities are due to local abundance of a potassium-rich mineral phase, such as glauconite, in the sediment. The average ^{40}K activity (13 pCi/g) in shelf sediment (Table 28.4) corresponds to a potassium concentration of 1.6%, which is normal for marine sediments (Poldervaart, 1955, p. 132) and for Columbia River sediment (Whetten, 1966; White, 1967). There was no systematic variation of ^{40}K with depth below the water—sediment interface in cores analyzed, nor was there any obvious correlation between ^{40}K activity and type of sediment on a regional basis (Table 28.5).

In contrast to the simple gamma-ray spectrum of ^{40}K, the ^{214}Bi spectrum is far more complex and more troublesome for the data-reduction process. For example, some early reports of widespread occurrences of radioactive Columbia River sediment on the deep-ocean floor (Gross, McManus, and Creager, 1963; Gross, 1963) were the result of misidentification of peaks in the ^{214}Bi spectrum. Computer programs used for the studies reported here did not produce reliable data on the ^{214}Bi activity in sediment containing much ^{65}Zn; thus, samples with detectable amounts of ^{65}Zn were not used to calculate the average abundance of ^{214}Bi in sediment (Table 28.4).

The ^{214}Bi data obtained in this study agree well with results obtained by Utterback and Sanderman (1948), who used radon-counting techniques; they found that sediment from Puget Sound and the San Juan Islands had an average ^{226}Ra activity of 0.6 pCi/g. If secular equilibrium (Breger, 1955) between the ^{226}Ra and ^{214}Bi (its daughter product) is assumed, the sediment analyzed in this study had an average ^{226}Ra activity of 0.5 pCi/g.

Bismuth-214 was detected in most samples analyzed, but, because of the problems of spectral mismatch in sediment containing ^{65}Zn, it was impossible to delineate distribution patterns of ^{214}Bi in the continental-shelf sediment, although a distinct pattern is apparent for the region as a whole. On the continental shelf and slope, the average ^{214}Bi activity is 0.5 pCi/g, but it is substantially greater in sediment from Cascadia Basin and the ridge provinces (Table 28.4, Fig. 28.1). Sediment from Tufts Plain has ^{214}Bi activities that are higher than the values for continental-shelf sediment but distinctly lower than the values obtained for sediment from the ridge provinces or from parts of Cascadia

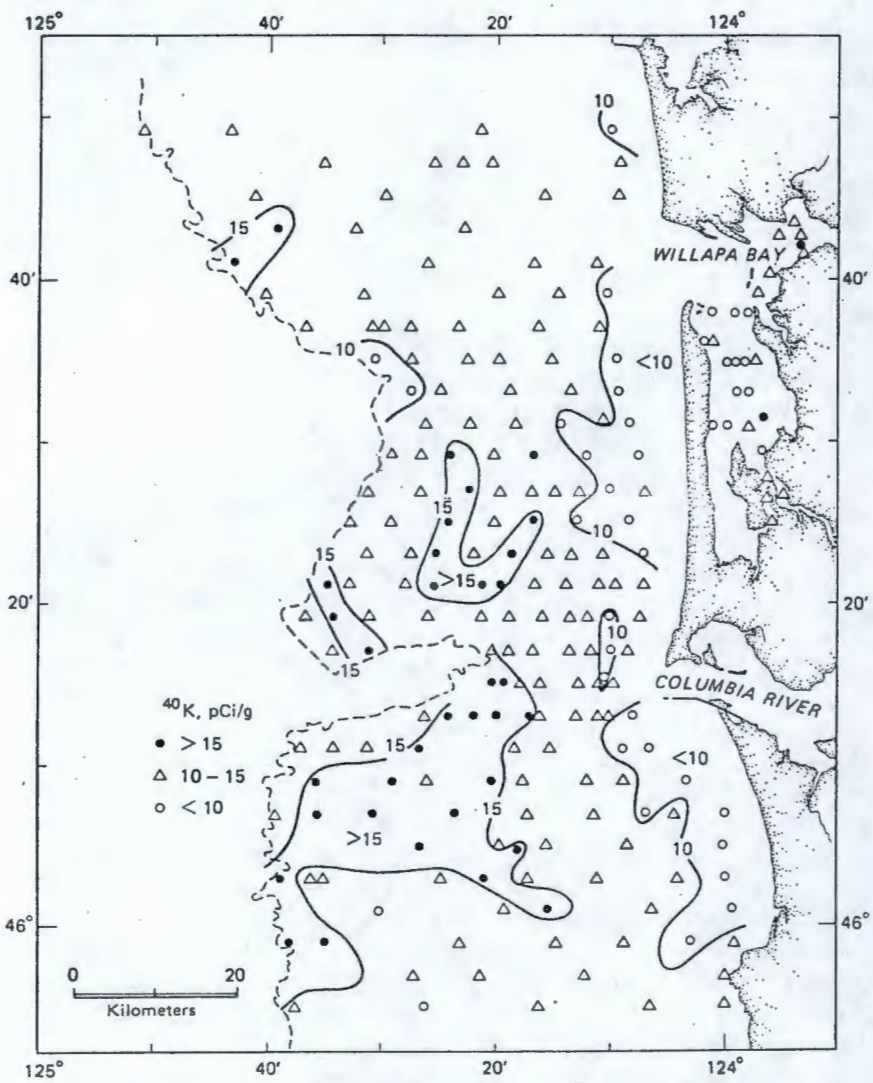

Fig. 28.4—Potassium-40 in continental-shelf sediment.

Basin. There was apparently no significant variation of ^{214}Bi activity with depth below the water—sediment interface in continental-shelf cores.

RADIONUCLIDES IN SURFACE SEDIMENT ON THE CONTINENTAL SHELF

Data for artificial radionuclides are plotted to show distributions of ^{65}Zn (Fig. 28.5), ^{51}Cr (Fig. 28.6), ^{60}Co (Fig. 28.7), ^{95}Zr—^{95}Nb (Fig. 28.8), and ^{54}Mn (Fig. 28.9) in the surface layer of continental-shelf sediment. From these data two typical distribution patterns can be distinguished:

1. Radionuclides derived from atmospheric fallout (^{95}Zr—^{95}Nb and ^{103}Ru—^{103}Rh) were widely distributed on the continental shelf but were most abundant in the sediment deposited within about 10 km of the river mouth. Activities of

Table 28.4—ACTIVITY (MEDIAN AND RANGE) OF NATURALLY OCCURRING RADIONUCLIDES IN SURFACE SEDIMENTS IN VARIOUS PHYSIOGRAPHIC PROVINCES, NORTHEAST PACIFIC OCEAN

	^{40}K, pCi/g	^{214}Bi, pCi/g
Columbia River estuary	14*(13–15)† (5)‡	ND§
Continental shelf		
Washington and Oregon	14(8–26) (31)	0.5(0.2–1.8) (14)
Near Columbia River	13(6–23) (196)	0.5(0.2–2.1) (53)
Continental slope	13(10–23) (8)	0.6(0.2–0.8) (8)
Eastern Cascadia Basin	13(9–17) (4)	1.8(0.5–3.2) (5)
Western Cascadia Basin	14(11–15) (3)	2.2(1.8–3.6) (3)
Juan de Fuca and Gorda Ridges	13(12–15) (2)	3.0(0.3–12) (4)
Tufts Plain	12(12–16) (4)	1.2(0.3–13) (3)

*Median value.
†Range.
‡Number of samples with statistically significant activities.
§ ND = no data, interference from ^{65}Zn spectrum.

Table 28.5—POTASSIUM-40 ACTIVITY IN DIFFERENT SEDIMENT TYPES*

	^{40}K median (range), pCi/g	Number of samples
Sand	14 (9–20)	26
Silty sand	14 (8–23)	11
Sandy silt	18	1
Clayey silt	13 (10–26)	9
Silty clay	13 (10–18)	12

*Nomenclature after Shepard, 1954.

these radionuclides in the sediment diminished with distance from the river mouth, and the distribution was generally skewed northward.

2. Radionuclides (^{51}Cr, ^{65}Zn, ^{60}Co, and ^{54}Mn) known to come primarily from the Columbia River (Perkins, Nelson, and Haushild, 1966; Haushild et al., 1966) are most abundant near the river mouth and show a general northward skewing of their distributions. The major exception is ^{60}Co (Fig. 28.7), which is distributed in a band nearly parallel to the coastline at depths between 60 and 90 m throughout this part of the continental shelf.

For each sediment-associated radionuclide, the highest activity levels occur within about 10 km of the river mouth and correspond closely with the area

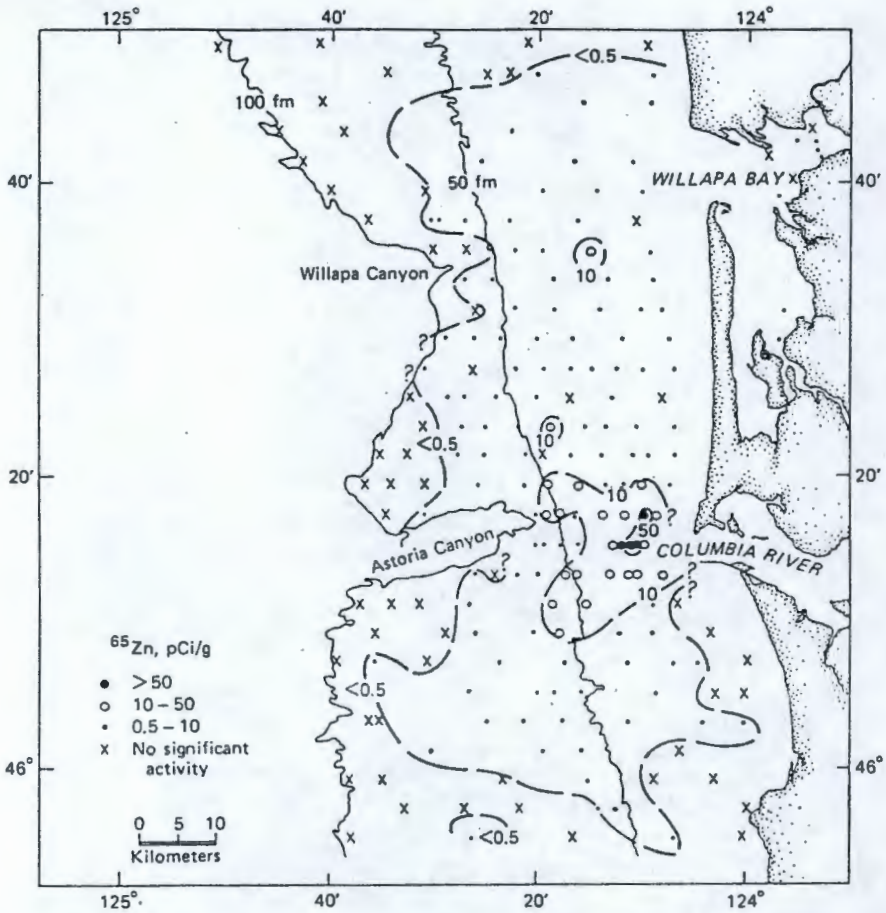

Fig. 28.5—Zinc-65 in continental-shelf sediment. [From M. G. Gross, Distribution of Radioactive Marine Sediment Derived from the Columbia River, *J. Geophys. Res.*, 71: 2019 (1966).]

where maximum shoaling due to sediment accumulation has occurred since 1926 (Lockett, 1962). High activities of the sediment in this area are thought to be a result of recently deposited sediment that has been little diluted by older, less-radioactive materials. Northward skewing of the distributions is apparently due in part to the northward-setting near-bottom currents, which apparently persist throughout the year in this area (Morse, Gross, and Barnes, 1968; Gross, Morse, and Barnes, 1968) and to the northward-setting surface currents, which are well developed during the winter (Barnes and Gross, 1966).

RESERVOIRS OF SEDIMENT-ASSOCIATED RADIONUCLIDES—CONTINENTAL SHELF

With the observed distributions and concentrations of radionuclides, it is possible to estimate the reservoir of sediment-associated radionuclides in surface sediment (layer 1 cm thick) on the continental shelf. This is only part of the total

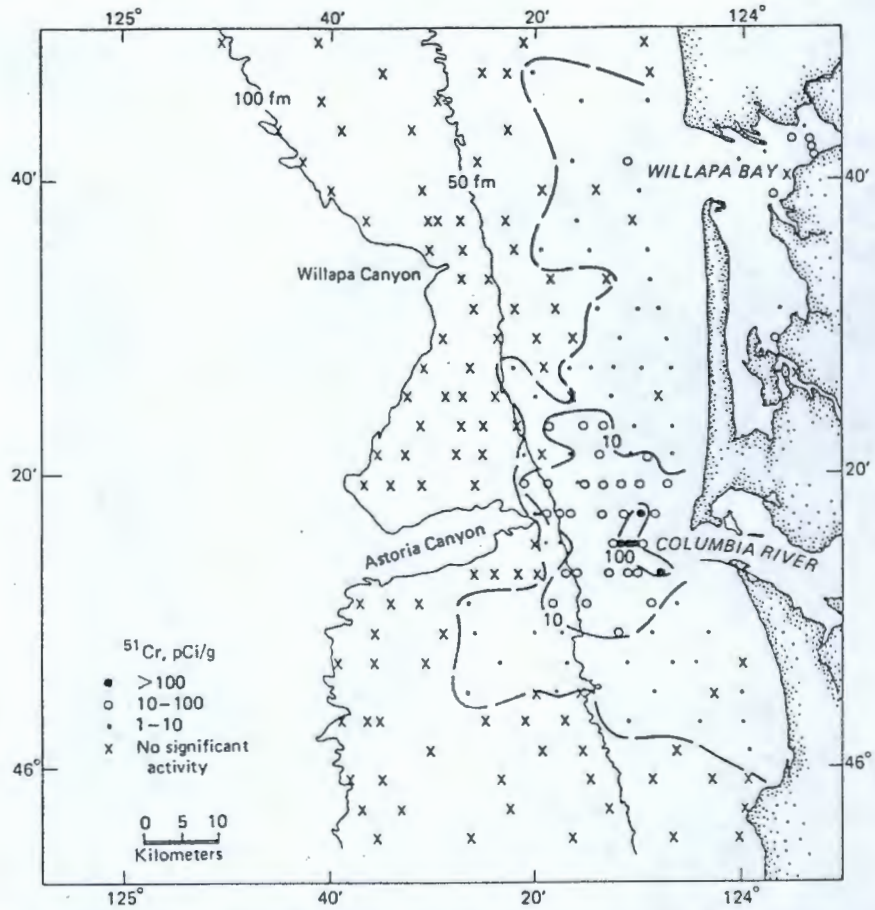

Fig. 28.6—Chromium-51 in continental-shelf sediment. [From M. G. Gross, Distribution of Radioactive Marine Sediment Derived from the Columbia River, *J. Geophys. Res.*, 71: 2020 (1966).]

radionuclide reservoir supported by the discharge of the Columbia River; for instance, some radioactive sediment probably occurs at greater depths below the water—sediment interface. A complete inventory of sediment-associated radionuclides cannot be made until an adequate budget for river-borne sediment has been established.

In 10 cores of continental-shelf sediment, porosity ranged from 25 to 59% and averaged 47%; I assumed 50% for my calculations. Sediment grain density varies from 2.45 to 2.71 g/cm^3 and averages about 2.6 g/cm^3.

The reservoir for each radionuclide was calculated by multiplying the area enclosed by each contour (in Figs. 28.4 through 28.9) by the median and the mass per unit area of the 1-cm-thick surface layer (1.3×10^{10} g/km^2). Results of these calculations are given in Table 28.6.

Discharge of sediment-associated radionuclides by the Columbia River was measured at Vancouver, Wash. (Fig. 28.1), during 1962 (Haushild et al., 1966). Although these data were collected about 180 km upstream from the river mouth, they provide the basis for an estimate of the total reservoir of sediment-associated

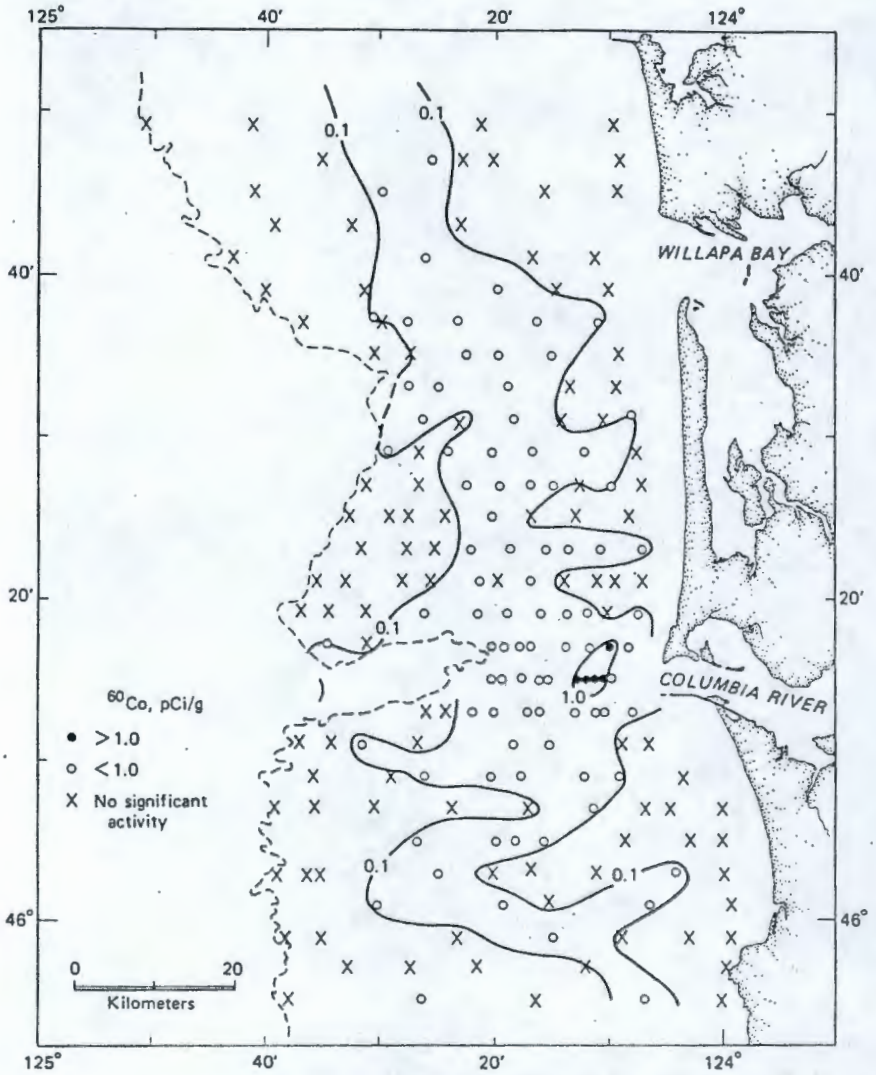

Fig. 28.7—Cobalt-60 in continental-shelf sediment.

radionuclides supported by the Columbia River discharge and the activity of newly discharged sediment just prior to the 1963 survey reported here. Comparable data collected during 1964 confirmed the 1963 results (Nelson et al., 1966).

The total reservoir of sediment-associated radionuclides can be estimated from the data of Haushild et al. (1966) by assuming that no radionuclides are removed from particles entering the ocean and that a steady state exists so that radioactive decay per unit time in the total reservoir is balanced by supply from the river. Average discharge of sediment-associated radionuclides between January and September 1963 at Vancouver, Wash., is given in Table 28.6, together with an estimate of the total reservoir of radioactivity supported by this discharge. Note that the inventory of radionuclides in the surface sediment layer on the

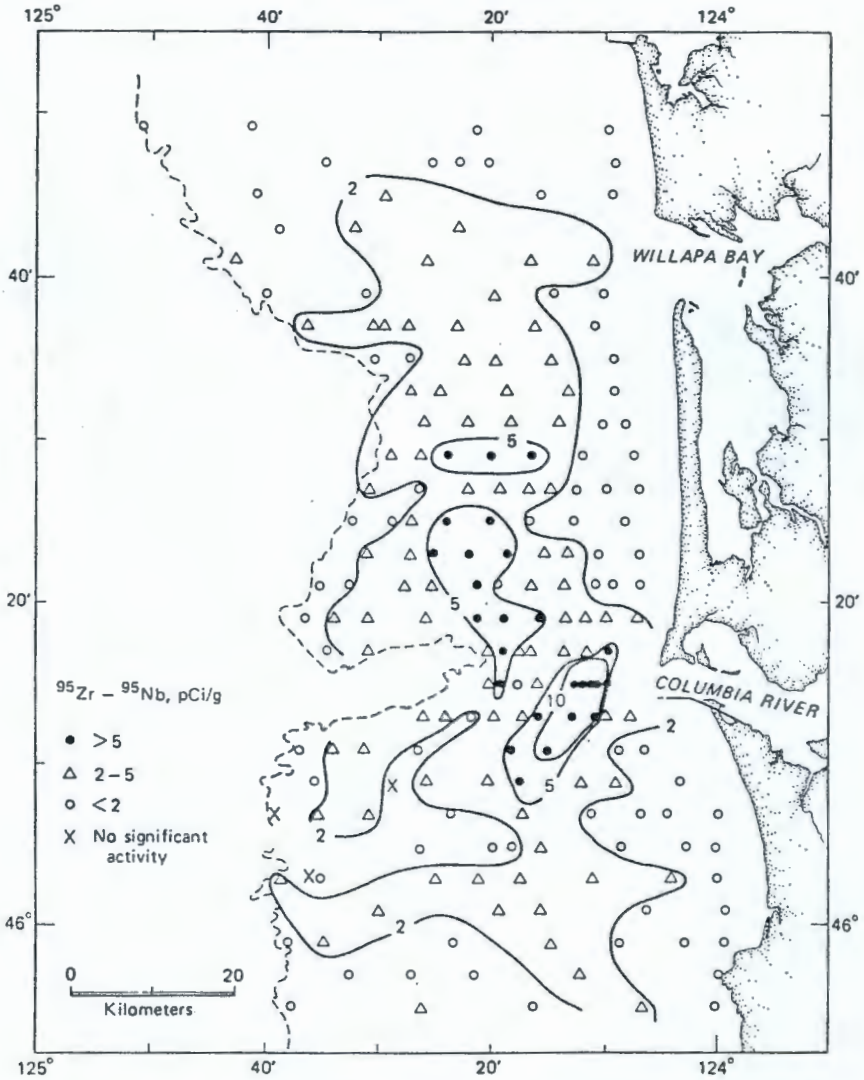

Fig. 28.8—Zirconium-95—niobium-95 in continental-shelf sediment.

continental shelf accounts for only about 11% of the ^{51}Cr and 14% of the ^{65}Zn discharged with river-borne sediment during this period.

Although it is possible to estimate the reservoir of fission products in the continental-shelf sediment, the complexities of their introduction into the ocean prevent quantitative evaluation. Some activity doubtlessly was contributed directly to the ocean surface by atmospheric fallout (Holland, 1963) from the weapons test series that began in September 1961 (Glasstone, 1964). The nuclides considered here are known to occur primarily in particulate form (Freiling and Ballou, 1962), to sink rather quickly through the water (Osterberg, Carey, and Curl, 1963a; Gross, 1967), and to become incorporated in the sediments.

Relatively high activity levels of fallout nuclides in sediment near the river mouth indicate that the river also contributes these radionuclides to the sediment.

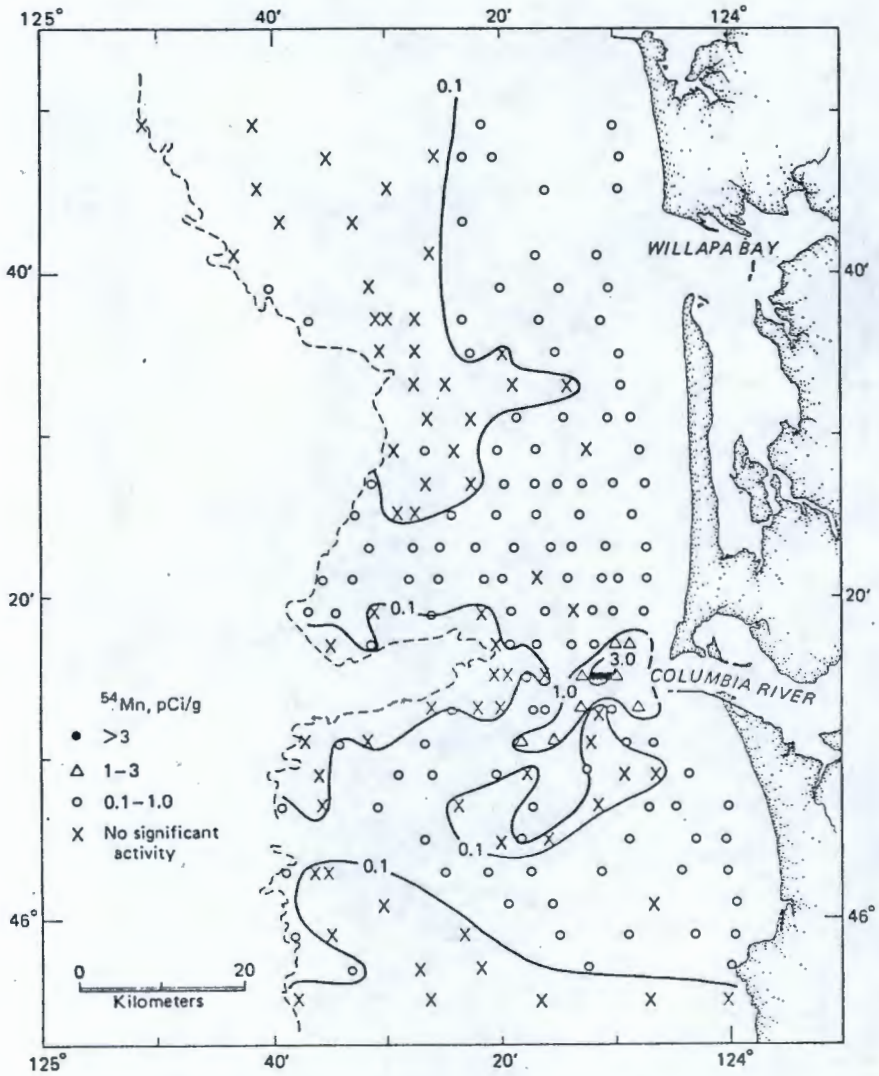

Fig. 28.9—Manganese-54 in continental-shelf sediment.

Hanford reactors released little fission material (Perkins, Nelson, and Haushild, 1966) into the river. Thus most fission radionuclides in the river came from atmospheric fallout in the drainage basin and were then carried into the ocean with the water or associated with particles (Haushild et al., 1966; Perkins, Nelson, and Haushild, 1966). These radionuclides were later incorporated in sediment deposits.

It would be desirable to know the total amount of each sediment-associated radionuclide on the continental shelf. Unfortunately, this cannot be determined without a more detailed knowledge of the vertical distribution of radionuclides in the sediment than was obtained from this study. We can, however, estimate the approximate size of this reservoir by comparing the activity per unit area of the

Table 28.6—ESTIMATED COLUMBIA RIVER DISCHARGE OF SEDIMENT-ASSOCIATED RADIONUCLIDES AND THE RESERVOIR IN SURFACE SEDIMENT ON THE CONTINENTAL SHELF, 1963

	Average discharge, Ci/day	Estimated reservoir in equilibium with average discharge,* Ci	Reservoir in surface sediment,† Ci	Fraction of river-supported reservoir, %
^{51}Cr	67	2700	300	11
^{65}Zn	23	8100	1150	14
^{95}Zr—^{95}Nb	4.4	410	130	32
^{103}Ru—^{103}Rh	1.7	100	65	65
^{60}Co			8.5	
^{54}Mn			3.9	
^{214}Bi			32	
^{40}K			800	

*January through September 1963, recalculated after Haushild et al. (1966).
†Surface layer 1 cm thick, grain density 2.6 g/cm^3, porosity 50%.

Table 28.7—ESTIMATED RESERVOIR OF CERTAIN SEDIMENT-ASSOCIATED RADIONUCLIDES PER UNIT AREA IN SURFACE LAYER AND IN SEDIMENT CORES FROM CONTINENTAL SHELF, SEPTEMBER 1963 (*BROWN BEAR* CRUISE 333)

Core			Reservoir per unit surface area, pCi/cm^2					
			^{60}Co		^{65}Zn		^{51}Cr	
No.	Position	Distance from river mouth, km	Surface*	Total†	Surface*	Total†	Surface*	Total†
186	46°15′N 124°12′W	11	2.6	6.4	90	180	220	370
213	46°19′N 124°16′W	17	1.0	1.0	18	34	52	52
253	46°23′N 124°19′W	24	1.0	1.0	13	40	1.4	1.4

*Surface layer, 1 cm thick.
†Estimated total reservoir based on activity detected in subsurface samples.

surface layer (1 cm thick) and the total activity in three cores of continental-shelf sediment (Table 28.7). These data suggest that the total reservoir per unit area is not more than three times the reservoir contained in a 1-cm-thick surface layer. Thus the total reservoir of sediment-associated radionuclides on the surveyed portion of the continental shelf appears to be at most three times the calculated reservoir (Table 28.7) in the surface layer and, at most, could account for about 42% of the ^{65}Zn and 33% of the ^{51}Cr supported by the average 1963 discharge of sediment-associated radionuclides at Vancouver, Wash. On the other hand, this reservoir of sediment-associated ^{95}Zr—^{95}Nb and ^{103}Ru—^{103}Rh exceeded the reservoir supported by the river discharge (Table 28.6), which is further evidence that the Columbia River was only one of several sources of fallout nuclides.

Table 28.8—RADIONUCLIDE ACTIVITIES IN COLUMBIA RIVER SUSPENDED SEDIMENT (MAY THROUGH JULY 1963) AND MAXIMUM VALUES OBSERVED IN SURFACE LAYER OF CONTINENTAL-SHELF SEDIMENT (SEPTEMBER 1963) NEAR THE RIVER MOUTH

	Activity of suspended sediment,* pCi/g	Activity of continental shelf sediment,† pCi/g
^{51}Cr	3500	520
^{65}Zn	1000	180
^{95}Zr—^{95}Nb	180	27

*Median values, calculated from Haushild et al. (1966).
†*Brown Bear* cruise 133, sample 183, 46°15.2'N, 124°10.5'W, taken Sept. 4, 1963.

It is also interesting to compare the average radioactivity per unit mass of suspended sediment in the river at Vancouver and the activity of the surface-sediment layer at a station close to the river mouth in 1963 (Table 28.8). The activity of ^{51}Cr, ^{65}Zn, and ^{95}Zr—^{95}Nb per unit mass of sediment at the river mouth was reduced to about one-sixth of the average value at Vancouver; data taken during 1962 showed a comparable decrease between the two points. Without data for the lower river and estuary, it is impossible to determine whether the reduction in specific activity of the sediment was a result of selective removal of the most radioactive constituents before or during deposition or of mixing with large quantities of nonradioactive sediment. Perhaps both processes were operative to some degree.

Radioactive decay during transit from Vancouver to the ocean apparently was relatively unimportant because the relative abundance of the nuclides did not change between the two locations shown in Table 28.8, although the half-life of ^{65}Zn is almost 245 days, or nine times that of ^{51}Cr (27.8 days). If radioactive decay had been significant, the activity ratios would change substantially between Vancouver and the river-mouth deposits.

Because of the multiple sources for the fallout radionuclides (^{95}Zr—^{95}Nb and ^{103}Ru—^{103}Rh), it is impossible to assess the significance of the changes in the specific activities between Vancouver and the ocean.

DEPOSITION OF COLUMBIA RIVER SEDIMENT

Identification and evaluation of the major reservoirs of sediment-associated radionuclides from the Columbia River require an understanding of depositional sites for Columbia River sediment. Although the data on sediment-associated radionuclides provide some valuable clues, they do not provide a complete answer. Therefore we must use other data to identify the probable areas of recent sediment deposition and the locations of the major reservoirs of sediment-associated radionuclides.

Table 28.9—ESTIMATED MASS OF SEDIMENT DEPOSITED IN THE COLUMBIA RIVER MOUTH AND ON THE ADJACENT CONTINENTAL SHELF*

Deposition area (period of observations)	Mass of sediment, 10^{12} g/year
Lower estuary, <10 km from the river mouth (1868 through 1958)	1.2†
Entrance channel (1956 through 1960)	2.5
Continental shelf near river mouth, <10 km from river mouth (1926 through 1962)	4.5

*Recalculated from Lockett (1962).
†Excludes Clatsop Spit area on the south side of the Columbia River estuary.

First, consider the amount of sediment carried by the Columbia River. From October 1962 through September 1963, the Columbia River transported about 8.4×10^{12} g (8.4 million tons) of sediment past Vancouver, Wash. Another 1.1×10^{12} g was contributed by the Willamette River, in addition to an unknown amount derived from the small tributaries near the Columbia River mouth (Haushild et al., 1966). I will assume that the total sediment discharge of the river system during this time was 10^{13} g (10 million tons) and that 55% of it occurred during May, June, and July 1963. These observations agree well with those from 1910 to 1912 reported by Van Winkle (1914).

Useful information about long-term trends in sediment accumulation is available from data presented by Lockett (1962) obtained from repeated surveys of the estuary and river mouth areas. If a sediment grain density of 2.6 g/cm^3 and a porosity of 50% are assumed, it is possible to calculate from Lockett's data the average mass of sediment deposited near the river mouth (Table 28.9). These data indicate that about 35% of the sediment discharged by the river is deposited in the lower estuary and about 45% within 10 km of the river mouth. Both these areas probably contain substantial quantities of sediment-associated radionuclides. Because of the difficulties of operating a ship in this area or of collecting samples, the area near the river mouth, where shoaling is most rapid, was not adequately sampled during the 1963 survey (Fig. 28.2).

The amount of Columbia River sediment transported off the continental shelf to be deposited on the adjacent deep-ocean floor cannot be estimated. However, failure to detect Columbia River radionuclides in sediment on the continental slope or at its base near the river suggests that little radioactive sediment was deposited on the nearby deep-ocean bottom, although radionuclides from the Columbia River were reported in sediments in Astoria Canyon off the Columbia River (Osterberg, Kulm, and Byrne, 1963b). Also, the distribution patterns (Gross, 1966) and the relative scarcity of short-lived radionuclides in sediment near the continental-shelf edge (Gross and Nelson, 1966) suggest that most radioactive sediment moved primarily parallel to the coast. This is consistent with other data on sediment properties (Gross, McManus and Ling, 1967).

Finally, various characteristics of the surface sediment (Duncan, 1968; Nelson, 1968) on the deep-ocean floor near the Columbia River indicate that little

bottom-transported sediment from the river is presently accumulating in this area. Instead, sediment on the deep-ocean floor appears to be derived primarily from the low-salinity surface water from the Columbia River plume, which moves southwestward from the river mouth and lies above the deep ocean during late summer. If appreciable amounts of Columbia River sediment were deposited in offshore basins from 1961 to 1963, our failure to detect Hanford radionuclides in the sediment could be explained by substantial mixing with nonradioactive sediment or by long transit times in the water relative to the half-life of the nuclides involved.

ACKNOWLEDGMENTS

This is contribution 532 from the Department of Oceanography, University of Washington. The research was supported by the U. S. Atomic Energy Commission under Contract AT(45-1)-1725.

REFERENCES

Barnes, C. A., and M. G. Gross, 1966, Distribution at Sea of Columbia River Water and Its Load of Radionuclides, in *Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters*, Symposium Proceedings, Vienna, May 16—20, 1966, pp. 291—302, International Atomic Energy Agency, Vienna (STI/PUB/126).

Breger, I. A., 1955, Radioactive Equilibrium in Ancient Marine Sediments, *Geochim. Cosmochim. Acta*, 8: 63—73.

Duncan, J. R., Jr., 1968, Late Pleistocene and Postglacial Sedimentation and Stratigraphy of Deep-Sea Environments off Oregon, Ph. D. Thesis, Oregon State University, Corvallis.

Emery, K. O., and R. S. Dietz, 1941, Gravity Coring Instrument and Mechanics of Sediment Coring, *Geol. Soc. Amer., Bull.*, 52: 1658—1714.

Freiling, E. C., and N. E. Ballou, 1962, Nature of Nuclear Debris in Sea-Water, *Nature*, 195: 1283—1287.

Glasstone, S., 1964, *The Effects of Nuclear Weapons*, rev. ed., Superintendent of Documents, U. S. Government Printing Office, Washington, D. C.

Gross, M. G., 1963, Radioactivity of Marine Sediments near the Columbia River, *Trans. Amer. Geophys. Union*, 44: 210.

——, 1966, Distribution of Radioactive Marine Sediment Derived from the Columbia River, *J. Geophys. Res.*, 71: 2017—2021.

——, 1967, Sinking Rates of Radioactive Fallout Particles in the Northeast Pacific Ocean, 1961—1962, *Nature*, 216: 670—672.

——, C. A. Barnes, and G. K. Riel, 1965, Radioactivity of the Columbia River Effluent, *Science*, 149: 1088—1090.

——, D. A. McManus, and J. S. Creager, 1963, Preliminary Report on the Sediments and Radioactivity in the Vicinity of the Columbia River Effluent, University of Washington, Department of Oceanography Technical Report 84.

——, D. A. McManus, and H.-Y. Ling, 1967, Continental Shelf Sediment, Northwestern United States, *J. Sediment. Petrol.*, 37: 790—795.

——, B.-A. Morse, and C. A. Barnes, 1968, Near-Bottom Residual Drift on the Continental Shelf, Northwestern United States, *Trans. Amer. Geophys. Union*, 49: 191.

——, and J. L. Nelson, 1966, Sediment Movement on the Continental Shelf near Washington and Oregon, *Science*, 154: 879—885.

Haushild, W. L., R. W. Perkins, H. H. Stevens, Jr., G. R. Dempster, Jr., and J. L. Glenn, 1966, Radionuclide Transport in the Pasco to Vancouver Washington Reach of the Columbia River, July 1962 to September 1963, U. S. Geological Survey Open-File Report, Portland, Ore.

Holland, J. Z., 1963, Distribution and Physical-Chemical Nature of Fallout, *Fed. Proc.*, 22: 1390—1397.

Lockett, J. B., 1962, Phenomena Affecting Improvement of the Lower Columbia River and Entrance, in *Proceedings of the 8th Conference on Coastal Engineering*, pp. 695—755, University of California, Council on Wave Research, Mexico City.

Morse, B.-A., M. G. Gross, and C. A. Barnes, 1968, Movement of Seabed Drifters near the Columbia River, *J. Waterways Harbors Div., Amer. Soc. Civil Eng.*, 94(WW1): 93—103.

Nelson, H. N., 1968, Marine Geology of Astoria Deep-Sea Fan, Ph. D. Thesis, Oregon State University, Corvallis.

Nelson, J. L., R. W. Perkins, J. M. Nielsen, and W. L. Haushild, 1966, Reactions of Radionuclides from the Hanford Reactors with Columbia River Sediments, in *Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters*, Symposium Proceedings, Vienna, May 16—20, 1966, pp. 139—161, International Atomic Energy Agency, Vienna (STI/PUB/126).

Osterberg, C. L., A. G. Carey, Jr., and H. Curl, Jr., 1963a, Acceleration of Sinking Rates of Radionuclides in the Ocean, *Nature*, 200: 1276—1277.

——, L. D. Kulm, and J. V. Byrne, 1963b, Gamma Emitters in Marine Sediments near the Columbia River, *Science*, 139: 916—917.

Perkins, R. W., J. L. Nelson, and W. L. Haushild, 1966, Behaviour and Transport of Radionuclides in the Columbia River Between Hanford and Vancouver, Washington, *Limnol. Oceanogr.*, 11: 235—248.

Poldervaart, Arie, 1955, Chemistry of the Earth's Crust, in *Crust of the Earth* (A Symposium), pp. 119—144, A. Poldervaart (Ed.), Geological Society of America Special Paper 62.

Seymour, A. H., and G. B. Lewis, 1964, The Distribution of Radionuclides in Marine Organisms and Water near the Mouth of the Columbia River, 1961—1963 (mimeographed), Laboratory of Radiation Biology, University of Washington, Seattle.

Shepard, F. P., 1954, Nomenclature Based on Sand-Silt-Clay Ratios, *J. Sediment. Petrol.*, 24: 151—158.

Shipek, C. J., 1965, A New Deep-Sea Oceanographic System, *Ocean Science and Ocean Engineering, 1965*, 2: 999—1008.

Utterback, C. L., and L. A. Sanderman, 1948, Radium Analyses of Marine Sediments in Northern Pacific and Adjacent Waters, *J. Mar. Res.*, 7: 635—643.

Van Veen, Johann, 1936, *Onderzoekingen in de Hoofden*, Landsdrukkerij, The Hague.

Van Winkle, Walton, 1914, Quality of the Surface Waters of Washington, U. S. Geological Survey Water-Supply Paper 339.

Whetten, J. T., 1966, Sediments from the Lower Columbia River and Origin of Graywacke, *Science*, 152: 1057—1058.

White, S. M., 1967, The Mineralogy and Geochemistry of the Sediments on the Continental Shelf off the Washington—Oregon Coast, Ph. D. Thesis, University of Washington, Seattle.

OCEAN WATERS

en, and Norman
: Health Service
itute of General
ıtract AT(45-1)-

iladelphia.
n-51 in Sea Water:

ugh Aquatic Food

:inity of Hanford,
aboratory.
Concentration of
roblems in Water
:ation 999-WP-25,

; and Fishes in the

ver Estuary, M. S.

ɔll, *Pac. Sci.*, 16:

alifornia Shrimps,
ɔrnia Department

logy, Appleton—

Columbia Estuary
ing, Mexico City,

arine Organisms,

ımbia River Flow
ntroduced by the

ıd Transport of
ver, Washington,

ɔf ^{32}P and ^{65}Zn
Seas, Oceans and
87, International

f Generations in
Bot. (London),

Flounders After
gs of the Second
s Evans (Eds.),

'fect of Hanford
gs of the Second
s Evans (Eds.),

Chapter 30

Seasonal and Areal Distributions of Radionuclides in the Biota of the Columbia River Estuary

William C. Renfro*
William O. Forster†
Charles L. Osterberg‡

ABSTRACT

This chapter describes the distribution of some radionuclides in organisms of the Columbia River estuary. Because zinc is of importance in the biological system and can be readily measured, ^{65}Zn was studied most intensively. Other radionuclides measured at least once in the biota were ^{60}Co, ^{54}Mn, ^{51}Cr, ^{46}Sc, ^{32}P, and some fallout fission products. Phytoplankton and zooplankton had relatively high but variable amounts of ^{65}Zn and ^{51}Cr with no apparent seasonal or areal trends. The specific activity of ^{65}Zn varied seasonally in fish and shrimp and generally reached a maximum in spring or summer. Starry flounders (*Platichthys stellatus*) and staghorn sculpins (*Leptocottus armatus*) from upstream locations exhibited higher radioactivity levels than those from stations farther downstream. During the period of this study (1964—1968), there was an obvious decline in ^{65}Zn specific activities of organisms. At the same time the number of reactors in operation at Hanford was reduced from eight to three.

Plutonium-production reactors at Hanford, Wash., release many radionuclides to the Columbia River. Most of these radioactive materials quickly decay after their release to the environment. Longer lived radionuclides, however, do persist to become associated with particulate matter in the water and be precipitated to the river bottom, or to remain in solution and be carried to the sea. Radioisotopes of elements essential to the biochemical reactions of plants and animals may be removed by various means and utilized by organisms. In this manner the biologically important radionuclides are transferred from the strictly abiotic, physical realm and begin a continuous cycling through various food webs.

This chapter describes quantitatively the distributions of radionuclides in organisms from the Columbia River estuary. Particular emphasis is placed on the manner in which the more common radionuclides vary with season and location within the estuary.

Measurements of radionuclide concentrations in organisms in and near the estuary were first reported by Watson, Davis, and Hanson (1963). In April 1959

*Department of Oceanography, Oregon State University, Corvallis, Oregon.
†Puerto Rico Nuclear Center, Mayagüez, P. R.
‡Division of Biology and Medicine, U. S. Atomic Energy Commission, Washington, D. C.

Table 30.1—RADIONUCLIDE CONCENTRATIONS IN PLANKTON NET CATCHES

A. Unsorted Catches

Date	Sta.	Concentration,* pCi/g dry weight				
		^{65}Zn	^{51}Cr	^{46}Sc	^{54}Mn	Other
4/27/64	H	656 ± 6	4,337 ± 34	56 ± 3	41 ± 2	
	A	797 ± 10	6,242 ± 62	59 ± 6	66 ± 3	
	C	554 ± 1	1,455 ± 4		13 ± 1	
6/1/64	H	364 ± 3	1,116 ± 20	46 ± 2		^{60}Co: 8 ± 2
	C	653 ± 3	1,282 ± 19	8 ± 1	8 ± 1	
6/10/64	H	133 ± 2	427 ± 13	10 ± 1	7 ± 1	
	A	716 ± 4	1,653 ± 25	46 ± 2	36 ± 1	
9/8/64	H	568 ± 10	9,255 ± 47	102 ± 6	75 ± 3	
	A	521 ± 6	6,171 ± 26	32 ± 3	49 ± 2	
	C	148 ± 3	863 ± 9	8 ± 1	4 ± 1	
9/25/64	H	606 ± 16	897 ± 66	51 ± 8	47 ± 4	
	A	422 ± 7	2,782 ± 29	14 ± 4	31 ± 2	
10/22/64	H	654 ± 10	5,533 ± 40	64 ± 5	23 ± 2	^{60}Co: 11 ± 2
	A	736 ± 9	6,194 ± 41	26 ± 4	56 ± 2	
	C	4 ± 1	54 ± 4			
4/19/65	A	1,223 ± 6	5,668 ± 29	140 ± 3	61 ± 2	^{60}Co: 20 ± 2
	C	407 ± 5	2,971 ± 26	86 ± 3	21 ± 1	

B. Zooplankton

Date	Sta.	Concentration,* pCi/g dry weight			
		^{65}Zn	^{51}Cr	^{32}P	Other
1/12/67	A	1,180 ± 80	900 ± 226		
4/26/67	A	623 ± 30			
	E	267 ± 12			^{60}Co: 20 ± 4
	D	620 ± 35			
	C	545 ± 28			
5/25/67	E	585 ± 70	1,198 ± 21	24,314 ± 4,384	^{144}Ce: 391 ± 54
	D	547 ± 26		17,083 ± 3,779	
6/26/67	A	123 ± 11	856 ± 77	6,935 ± 703	
7/24/67	H	327 ± 31	940 ± 146	6,161 ± 1,338	
	A	621 ± 66	815 ± 230	13,089 ± 1,686	
	E	328 ± 17	261 ± 63	5,316 ± 696	
	D	494 ± 32	1,178 ± 156	14,721 ± 1,670	
	C	455 ± 28	895 ± 140	12,903 ± 1,663	
12/12/67	A	997 ± 31	684 ± 77	8,231 ± 468	
	D	793 ± 27	497 ± 66	6,787 ± 416	
1/27/68	A	824 ± 20	455 ± 60	4,416 ± 480	
2/23/68	D	177 ± 8	211 ± 21	3,173 ± 120	
4/8/68	A	359 ± 10	102 ± 17	6,743 ± 317	
5/10/68	A	192 ± 24		13,553 ± 1,408	
6/7/68	D	654 ± 42	561 ± 133	42,025 ± 2,781	^{46}Sc 73 ± 17
7/2/68	E	124	440 ± 60		

Table 30.1—(Continued)

C. Phytoplankton

Date	Sta.	Concentration,* pCi/g dry weight			
		^{65}Zn	^{51}Cr	^{46}Sc	Other
7/24/67	B	132 ± 11	463 ± 36	31 ± 5	
8/19/67	A	137 ± 12	1,118 ± 65	28 ± 5	
9/19/67	A	269 ± 45	4,124 ± 348		
12/12/67	H		2,123 ± 611	352 ± 80	
5/10/68	D	4 ± 1	13 ± 1		
	B	12 ± 2			^{60}Co: 7 ± 1
6/7/68	A	533 ± 21	561 ± 49	241 ± 11	^{32}P: 4,583 ± 701
7/2/68	A	202 ± 24	273 ± 66	103 ± 14	
	E	269 ± 22	395 ± 64	184 ± 14	^{32}P: 5,103 ± 1,141
	C	178 ± 20		66 ± 11	
8/26/68	H	220 ± 25		132 ± 14	
	A	182 ± 16	413 ± 43	112 ± 9	
	E		197 ± 42	49 ± 9	
	C	56 ± 8	116 ± 22	53 ± 6	

D. Wood fibers

Date	Sta.	Concentration,* pCi/g dry weight				
		^{65}Zn	^{51}Cr	^{46}Sc	^{32}P	Other
1/12/67	H	623 ± 88	5,006 ± 565			
3/8/67	H	1,000 ± 119	4,219 ± 521			
	A	1,105 ± 153	5,594 ± 740			
4/26/67	A	669 ± 46	2,042 ± 191			
5/25/67	H	820 ± 69	1,617 ± 205			
5/25/67	A	623 ± 50	1,505 ± 326			
	E	459 ± 38	2,164 ± 177			
	D	525 ± 51	3,316 ± 273			
	C	631 ± 58	2,578 ± 260			
	B	617 ± 56	2,517 ± 247			
6/26/67	H	564 ± 57	1,124 ± 160			^{144}Ce: 150 ± 30
	A	698 ± 42	1,096 ± 129			
	E	517 ± 46	1,254 ± 146			^{144}Ce: 115 ± 24
7/24/67	H	1,598 ± 125	3,875 ± 391		9,797 ± 1,535	
	A	594 ± 44	1,283 ± 132		2,554 ± 502	
	E	598 ± 43	1,516 ± 146		3,535 ± 540	
8/19/67	H	446 ± 36	2,167 ± 156	106 ± 15	3,276 ± 695	
9/19/67	E	392 ± 35	1,606 ± 159			
1/27/68	C	131 ± 6	580 ± 31	26 ± 3	604 ± 142	
2/23/68	H	125 ± 7	302 ± 21	42 ± 3	297 ± 62	
	A	312 ± 22	746 ± 62	111 ± 11		
5/10/68	H	311 ± 19	400 ± 45	106 ± 10	5,169 ± 521	
6/7/68	A	518 ± 40	725 ± 100	197 ± 18		
7/2/68	A	494 ± 22	496 ± 148	208 ± 15		
	E	326 ± 22	635 ± 157	215 ± 17		

*±1 standard deviation based on counting statistics.

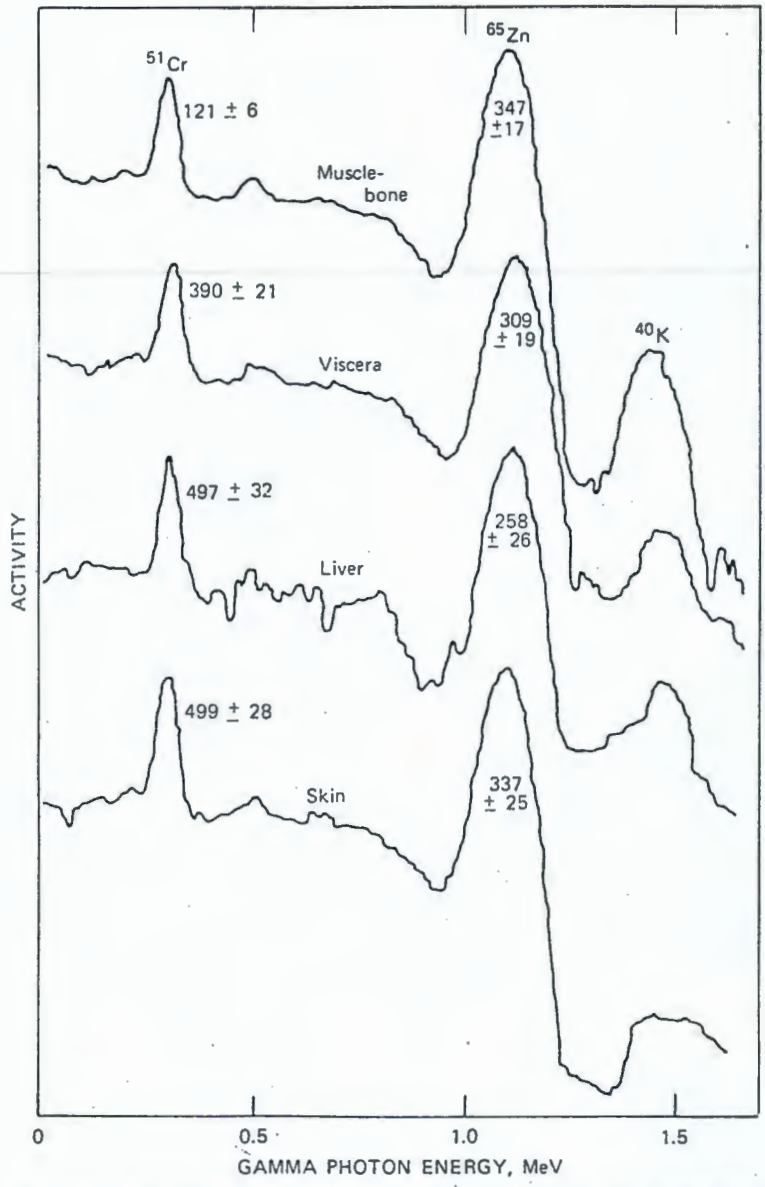

Fig. 30.2—Gamma-ray spectra of juvenile starry flounder from station H (Harrington Point) collected Jan. 5, 1965. Activities of ^{51}Cr and ^{65}Zn and their single standard deviations are in pCi/g dry weight.

Chromium is not generally considered to play an essential role in the physiology of organisms (Foster, 1963). Therefore, the presence of ^{51}Cr in all tissues of these small flounders is of interest. Watson, Davis, and Hanson (1963) and Seymour and Lewis (1964) found that ^{51}Cr was only sporadically present in marine organisms along the Washington and Oregon coasts, although it was often the most abundant radionuclide in the water. The levels of chromium in Mediterranean plants and animals measured by Fukai and Broquet (1965) generally were around 1 ppm dry weight. Davis et al. (1958) reported chromium concentrations from 2 to 20 ppm dry weight in Columbia River plants and animals. Regardless of its minor biological role, chromium appears to be present in (or on) some aquatic and marine organisms and may be found in the internal tissues of some organisms. Apparently, the starry flounder can incorporate ^{51}Cr in all its tissues on occasion. In general, however, appreciable ^{51}Cr levels were found only in small starry flounder from the upriver station. Nearer the ocean, muscle—bone samples of all organisms showed little or no ^{51}Cr activity. The prominence of ^{51}Cr in the starry flounder spectra is not the result of great concentration of this radionuclide by the fish; rather, it reflects the large abundance of ^{51}Cr atoms relative to ^{65}Zn atoms in the environment. For example, Frederick (1967) calculated the concentration of ^{51}Cr to be as high as 1.4 pCi/ml, whereas ^{65}Zn levels in the water were probably less than 0.04 pCi/ml (as estimated from Perkins, Nelson, and Haushild, 1966). On a wet basis the muscle—bone sample had 27 pCi of ^{51}Cr per gram and 76 pCi of ^{65}Zn per gram. Hence, the concentration factor for starry flounder muscle—bone was 19 (27 pCi/g ÷ 1.4 pCi/ml) for ^{51}Cr and 1900 (76 pCi/g ÷ 0.04 pCi/ml) for ^{65}Zn.

To compare the levels of ^{65}Zn in fish and invertebrates collected by otter trawl in various seasons and areas, we used specific activities. The use of ^{65}Zn specific activity (pCi ^{65}Zn/g total zinc) allows the direct comparison of organisms having widely varying total zinc concentrations as a result of season, age, size, sex, and location as well as species differences. Furthermore, ^{65}Zn specific-activity measurements provide insight into the rate at which the organisms turn over zinc.

The ^{65}Zn specific activities of juvenile starry flounder less than 100 mm long from stations H and A are shown in the upper curve of Fig. 30.3. Single standard deviations are indicated by vertical lines and are calculated on the basis of estimated errors due to (1) weighing, (2) counting, (3) uncertainty in activity of the ^{65}Zn standard used to calibrate the system, and (4) atomic absorption spectrophotometric determination of stable zinc. The data from which this figure was derived are summarized in Tables 30.2 and 30.3. Each point represents a composite sample of from 1 to 10 small fish, mostly ranging from 30 to 70 mm in length. Although the smooth curve is fitted to the datum points by eye and is subject to considerable interpretation (particularly in the dashed portions), the seasonality in ^{65}Zn specific activities is clear. From the low levels attained toward the end of the winter period of reduced metabolism and negligible food intake, the levels rise steadily and reach a maximum in middle or late summer of each year. A 45-day shutdown of the Hanford reactors, beginning in July 1966, caused the decline of ^{65}Zn specific activity to begin earlier, be more precipitous, and end at lower levels than in previous years.

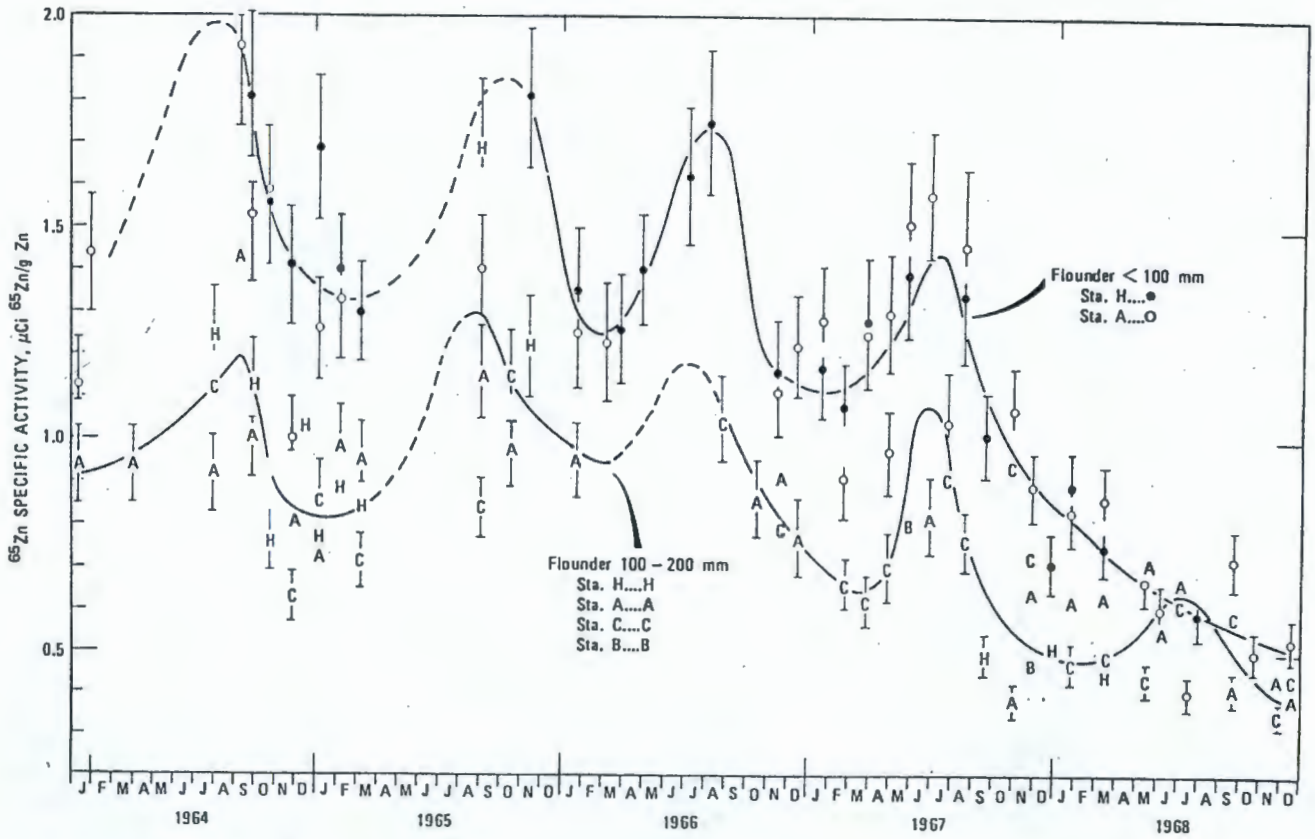

Fig. 30.3—Specific activities of ^{65}Zn of muscle—bone samples from starry flounders from the Columbia River estuary. Circles are used to indicate specific activities of flounder less than 100 mm long, and letters are used for flounders 100 to 200 mm long. Vertical lines indicate one standard deviation.

The lower portion of Fig. 30.3 is a scatter of points showing ^{65}Zn specific activities of larger flounders measuring 100 to 200 mm long. Each point represents a composite sample of from one to five individual fish. These larger fish, roughly one to two years old, although highly mobile (Beardsley, 1969), apparently remain in one part of the estuary for extended periods because they show definite areal differences in ^{65}Zn specific activities. Flounders from upstream stations generally have higher ^{65}Zn specific activities than contemporary fish from seaward stations; the order by station is H > A > C > B.

Almost without exception the smaller, more rapidly growing animals have higher ^{65}Zn specific activities than the larger fish captured at the same time and place (Fig. 30.3). Presumably, the smaller fish turn zinc and ^{65}Zn over at more rapid rates than the larger fish do; thus their ^{65}Zn atoms have a shorter residence time and thus less probability for decay. The larger fish, with their slower turnover rates, experience a greater decay of ^{65}Zn with resultant lower ^{65}Zn specific activities. Additional explanations for differences in ^{65}Zn specific activities between the two age classes of flounder should also take into account differences in the ^{65}Zn specific activities of their food and in their movements within the estuary.

Sand Shrimp

The sand shrimp, *Crangon franciscorum* Stimpson, was most consistently taken in the otter-trawl collections at stations A and C in the middle of the estuary. In Fig. 30.4 the ^{65}Zn specific activities of shrimp taken at these stations are shown for the five-year period 1963—1968. Each point represents a composite sample of from 5 to 30 whole shrimp ranging from small juveniles to adults. The single standard deviation for each value is based on estimated errors due to (1) weighing, (2) counting, (3) uncertainty in the activity of the ^{65}Zn standard used to calibrate the gamma-ray spectrophotometer, and (4) errors in the total zinc analysis by the atomic absorption spectrophotometer. Data from which the figure was derived are given in Table 30.4.

Seasonal trends are fairly similar at both stations. In general, lowest levels occur during the colder months followed by peaks in early spring and summer. In late summer of each year, there is a marked decline. This late-summer drop was particularly sharp following the shutdown of the Hanford reactors in the summer of 1966. The significantly lower levels during 1968 can be at least partially attributed to the reduced number of operating reactors at Hanford.

Staghorn Sculpin

The Pacific staghorn sculpin, *Leptocottus armatus* Girard, is a ubiquitous fish of the shallow bays from southern California to Alaska. Its diet is varied but dominated by shrimp, other crustaceans (Jones, 1962), and fish (Haertel and Osterberg, 1967). Spawning occurs during fall and winter in the ocean and in bays, and young of that year move into the fresh waters of the upper portions of estuaries (Jones, 1962). The staghorn can be found throughout the area in shallow tributaries and deep channels, fresh water and waters of full oceanic salinity, and densely vegetated areas and open, unprotected areas of the estuary.

Table 30.2—CONCENTRATIONS* OF ^{65}Zn AND TOTAL ZINC IN STARRY FLOUNDER LESS THAN 100 mm IN STANDARD LENGTH

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Jan. 8, 64	A	533 ± 3	472 ± 37	1.13 ± 0.11	29.50	5.47
Jan. 29, 64	A	981 ± 10	681 ± 54	1.44 ± 0.14	34.45	8.78
Sept. 8, 64	H	1380 ± 33	717 ± 57	1.93 ± 0.19	47.00	10.32
Sept. 8, 64	A	356 ± 18	660 ± 53	2.06 ± 0.19	30.98	9.00
Sept. 25, 64	H	1481 ± 80	819 ± 7	1.81 ± 0.20		13.61
Sept. 25, 64	A	1025 ± 39	671 ± 53	1.53 ± 0.16	36.17	9.72
Oct. 22, 64	H	1023 ± 8	660 ± 52	1.55 ± 0.15	36.42	8.55
Oct. 22, 64	A	1565 ± 31	984 ± 78	1.59 ± 0.15	28.85	8.60
Nov. 25, 64	H	864 ± 17	614 ± 49	1.41 ± 0.14	39.07	9.42
Nov. 25, 64	A	724 ± 21	727 ± 58	1.00 ± 0.10	38.13	9.79
Jan. 5, 65	H	912 ± 27	541 ± 43	1.69 ± 0.17	33.93	7.47
Jan. 5, 65	A	646 ± 19	512 ± 41	1.26 ± 0.12	30.15	7.93
Feb. 6, 65	H	895 ± 5	640 ± 51	1.40 ± 0.13	36.64	7.39
Feb. 6, 65	A	918 ± 27	688 ± 55	1.33 ± 0.14	38.21	8.02
Mar. 4, 65	H	759 ± 8	582 ±47	1.30 ± 0.12	35.73	8.84
Apr. 7, 65	H	1491 ± 34	627 ± 50	2.38 ± 0.23	29.66	6.75
Aug. 30, 65	A	703 ± 4	504 ± 40	1.40 ± 0.13	40.35	7.56
Nov. 11, 65	H	975 ± 27	538 ± 43	1.81 ± 0.17	38.80	8.62
Jan. 22, 66	A	976 ± 28	780 ± 62	1.25 ± 0.13	37.82	7.83
Jan. 22, 66	H	767 ± 35	568 ± 45	1.35 ± 0.15	36.68	7.28
Mar. 2, 66	A	748 ± 35	607 ± 49	1.23 ± 0.14	39.06	7.98
Mar. 25, 66	H	796 ± 29	627 ± 50	1.26 ± 0.13	37.02	7.14
Apr. 28, 66	H	945 ± 55	674 ± 55	1.40 ± 0.13	44.56	9.26
July 7, 66	H	1770 ± 74	1093 ± 87	1.62 ± 0.16	48.78	10.34
Aug. 4, 66	H	1300 ± 30	743 ± 59	1.75 ± 0.17	45.45	9.92
Nov. 15, 66	A	705 ± 14	634 ± 51	1.11 ± 0.10	32.95	9.51
Nov. 15, 66	H	727 ± 17	629 ± 50	1.16 ± 0.12	40.00	7.38
Dec. 13, 66	A	651 ± 11	531 ± 43	1.22 ± 0.12	37.97	7.77
Jan. 11, 67	H	633 ± 18	541 ± 43	1.17 ± 0.12	48.82	7.31
Jan. 11, 67	A	750 ± 30	584 ± 47	1.28 ± 0.13	36.30	7.09
Feb. 23, 67	H	636 ± 14	592 ± 47	1.08 ± 0.10	31.48	6.32
Feb. 23, 67	A	520 ± 10	571 ± 46	0.91 ± 0.09	32.87	7.00
Mar. 24, 67	A	383 ± 16	307 ± 25	1.25 ± 0.13	39.59	7.43
Mar. 24, 67	H	786 ± 63	613 ± 49	1.28 ± 0.15	36.79	7.34
Apr. 27, 67	A	814 ± 36	624 ± 50	1.30 ± 0.14	45.98	8.44
Apr. 27, 67	H	589 ± 23	605 ± 48	0.97 ± 0.10	44.59	13.32
May 24, 67	A	1674 ± 52	762 ± 61	1.51 ± 0.15	54.58	15.25
May 24, 67	H	867 ± 47	624 ± 50	1.39 ± 0.15	48.77	9.04
July 24, 67	A	506 ± 33	485 ± 39	1.04 ± 0.12	45.46	9.16
Aug. 18, 67	A	860 ± 67	589 ± 47	1.46 ± 0.18	37.46	7.99
Aug. 18, 67	H	882 ± 60	658 ± 53	1.34 ± 0.16	44.36	8.24
Sept. 20, 67	H	758 ± 10	751 ± 60	1.01 ± 0.10	49.49	8.15
Nov. 1, 67	A	637 ± 6	598 ± 48	1.07 ± 0.10	36.09	7.03
Nov. 28, 67	A	500 ± 5	583 ± 47	0.86 ± 0.08	33.10	5.83
Dec. 27, 67	H	444 ± 6	625 ± 50	0.71 ± 0.07	31.99	6.18

Table 30.2—(Continued)

Date	Sta.	^{65}Zn pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act. μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Jan. 26, 68	H	523 ± 6	584 ± 47	0.89 ± 0.08	30.74	5.62
Jan. 26, 68	A	520 ± 3	625 ± 50	0.83 ± 0.08		5.58
Mar. 12, 68	H	511 ± 8	686 ± 55	0.75 ± 0.07	31.44	6.31
Mar. 12, 68	A	417 ± 6	486 ± 39	0.86 ± 0.08	28.29	5.02
May 16, 68	A	410 ± 4	614 ± 49	0.67 ± 0.06	41.47	8.63
June 7, 68	A	479 ± 9	797 ± 64	0.60 ± 0.06	41.26	4.19
July 17, 68	H	273 ± 9	685 ± 55	0.40 ± 0.04		9.80
July 31, 68	H	418 ± 15	707 ± 57	0.59 ± 0.06		8.54
Sept. 23, 68	A	304 ± 6	422 ± 34	0.72 ± 0.07		6.78
Oct. 22, 68	A	333 ± 6	667 ± 53	0.50 ± 0.05		6.66
Dec. 16, 68	A	284 ± 5	538 ± 43	0.53 ± 0.05		5.90
Jan. 17, 69	A	1039 ± 17	693 ± 55	1.50 ± 0.14		6.65

*± standard deviation based on counting.

Figure 30.5 shows the ^{65}Zn specific activities of muscle—bone samples taken in trawl collections over a five-year period in the estuary (see also Table 30.5). Each point represents a composite sample of from one to several individual fish caught at the designated station. To avoid confusion, we enclosed only a few points by single standard deviations computed from consideration of errors due to (1) counting, (2) weighing, (3) uncertainty in the ^{65}Zn calibration standard, and (4) errors in stable-zinc analysis. The vertical lines connecting samples taken on the same day are included simply to aid in interpretation of the data. In two instances (station C, August 1964, and Station C, July 1965), there was a five-fold range between the lowest and highest ^{65}Zn specific activities. However, muscle—bone samples taken at the same time and place generally had similar values.

Seasonal trends in ^{65}Zn specific activities are not so pronounced in the staghorn sculpins as in the flounders or sand shrimp, although the levels for sculpins at each station are generally somewhat higher in summer and fall than during winter and spring. Despite the fact that the sculpin tolerates a broad range of environmental conditions and might be expected to move freely over the entire estuary, there were obvious differences in the ^{65}Zn specific activities of fish from the different stations. In almost all collections made on the same day, the specific activities varied directly with the distance of the station from the isotope diluting effects of the ocean water at the mouth of the estuary. Hence, the ^{65}Zn specific-activity order with station usually is H > A > C > B. Long-term trends (Fig. 30.5), although not pronounced, suggest a decline over the five-year period. The levels of ^{65}Zn specific activities in muscle—bone samples from each station were, on the average, higher in 1964 than in 1968.

One point to be made with regard to ^{65}Zn specific activities in fish and shrimp taken in otter trawls from several locations in the estuary is that ^{65}Zn specific activity varies seasonally. At least some of this seasonal change can be

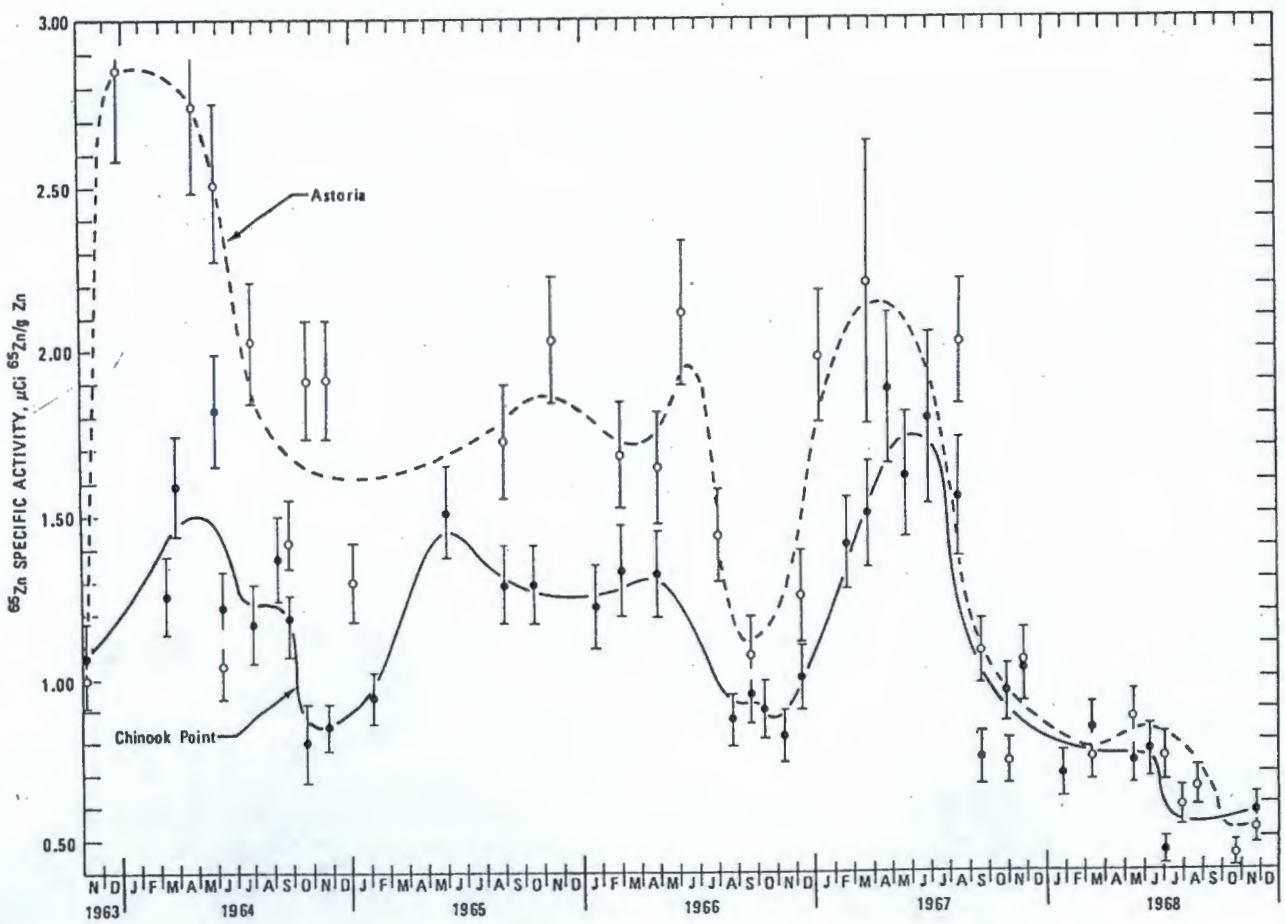

Fig. 30.4—Specific activities of ^{65}Zn in whole sand shrimp from stations A and C. Vertical lines indicate single standard deviations.

Table 30.3—CONCENTRATIONS* OF ^{65}Zn AND TOTAL ZINC IN STARRY FLOUNDER 100-200 mm IN STANDARD LENGTH

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Jan. 8, 64	A	568 ± 3	603 ± 48	0.94 ± 0.09	34.45	6.55
Mar. 31, 64	A	1113 ± 24	1184 ± 95	0.94 ± 0.09	39.21	9.57
July 27, 64	H	857 ± 3	694 ± 56	1.24 ± 0.12	34.68	7.80
July 27, 64	A	800 ± 7	865 ± 69	0.92 ± 0.09	41.70	9.72
July 27, 64	C	586 ± 3	521 ± 42	1.12 ± 0.10	41.22	7.04
July 30, 64	C	721 ± 13	644 ± 52	1.12 ± 0.11	33.52	7.42
Sept. 8, 64	H	636 ± 10	578 ± 46	1.10 ± 0.15	42.12	7.27
Sept. 8, 64	A	730 ± 6	516 ± 41	1.42 ± 0.11	27.96	8.19
Sept. 25, 64	H	720 ± 11	637 ± 51	1.13 ± 0.11	42.43	8.12
Sept. 25, 64	A	599 ± 4	593 ± 47	1.01 ± 0.10	36.20	7.23
Oct. 22, 64	H	511 ± 10	672 ± 54	0.76 ± 0.07	34.82	7.34
Oct. 22, 64	A	647 ± 10	696 ± 56	0.93 ± 0.09	36.24	7.32
Nov. 25, 64	H	567 ± 5	559 ± 45	1.01 ± 0.10	34.02	7.56
Nov. 25, 64	A	504 ± 11	614 ± 49	0.82 ± 0.08	43.77	8.28
Nov. 25, 64	C	351 ± 15	558 ± 45	0.63 ± 0.06	18.17	5.83
Jan. 5, 65	H	466 ± 14	597 ± 48	0.78 ± 0.08	37.62	6.72
Jan. 5, 65	A	410 ± 3	547 ± 44	0.75 ± 0.07	30.49	7.89
Jan. 5, 65	C	418 ± 14	488 ± 39	0.86 ± 0.09	24.28	6.22
Feb. 6, 65	H	565 ± 4	631 ± 51	0.88 ± 0.08	36.64	7.35
Feb. 6, 65	A	820 ± 13	827 ± 66	0.99 ± 0.09	37.71	8.62
Mar. 4, 65	A	608 ± 15	642 ± 51	0.95 ± 0.09	39.80	8.23
Mar. 4, 65	C	322 ± 5	454 ± 36	0.71 ± 0.07	25.04	5.12
Mar. 4, 65	H	488 ± 4	591 ± 47	0.83 ± 0.08	48.09	9.24
Aug. 30, 65	H	1281 ± 17	758 ± 61	1.69 ± 0.16	41.26	11.08
Aug. 30, 65	C	324 ± 2	384 ± 30	0.84 ± 0.07	29.05	6.19
Aug. 30, 65	A	566 ± 1	493 ± 39	1.15 ± 0.11	34.36	6.85
Oct. 14, 65	C	640 ± 2	558 ± 44	1.15 ± 0.11	31.65	7.44
Oct. 14, 65	A	501 ± 20	505 ± 40	0.99 ± 0.10	31.16	6.08
Nov. 11, 65	H	736 ± 19	605 ± 48	1.22 ± 0.12	50.51	7.08
Jan. 22, 66	A	675 ± 16	712 ± 57	0.95 ± 0.09	35.60	7.05
Aug. 24, 66	C	5634 ± 116	5418 ± 433	1.04 ± 0.10	37.34	7.74
Oct. 13, 66	A	675 ± 26	786 ± 63	0.86 ± 0.09	55.41	11.23
Nov. 15, 66	C	398 ± 8	501 ± 40	0.79 ± 0.08	37.14	7.95
Nov. 15, 66	A	564 ± 13	617 ± 49	0.91 ± 0.09	37.09	8.45
Dec. 13, 66	A	417 ± 8	541 ± 43	0.77 ± 0.09	39.13	7.57
Feb. 23, 67	C	271 ± 7	411 ± 33	0.66 ± 0.06	23.97	4.69
Mar. 24, 67	C	268 ± 8	433 ± 35	0.62 ± 0.06	32.08	5.70
Apr. 27, 67	C	360 ± 19	514 ± 41	0.70 ± 0.08	38.55	6.96
May 24, 67	B	330 ± 22	413 ± 33	0.80 ± 0.09	29.26	6.35
May 24, 67	C	350 ± 24	354 ± 28	0.99 ± 0.12	41.20	6.65
June 27, 67	C	578 ± 23	365 ± 29	1.58 ± 0.15	41.21	7.93
June 27, 67	A	517 ± 25	629 ± 50	0.82 ± 0.09	51.57	10.10
July 24, 67	C	345 ± 9	383 ± 31	0.90 ± 0.09	30.87	5.32
Aug. 18, 67	C	302 ± 7	399 ± 32	0.76 ± 0.07	28.75	5.24
Sept. 20, 67	H	209 ± 4	423 ± 33	0.49 ± 0.05	24.33	3.39

Table 30.3—(Continued)

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Nov. 1, 67	C	350 ± 3	369 ± 30	0.95 ± 0.09	36.39	7.69
Nov. 1, 67	A	22 ± 1	57 ± 5	0.38 ± 0.04	39.53	7.38
Nov. 28, 67	B	177 ± 4	378 ± 30	0.47 ± 0.04	22.90	3.74
Nov. 28, 67	C	46 ± 2	64 ± 5	0.72 ± 0.07	27.80	5.52
Nov. 28, 67	A	266 ± 5	416 ± 33	0.64 ± 0.06	37.53	6.50
Dec. 27, 67	H	261 ± 5	520 ± 41	0.50 ± 0.05	28.05	5.55
Jan. 26, 68	C	210 ± 5	447 ± 36	0.47 ± 0.05	34.01	5.59
Jan. 26, 68	A	289 ± 6	469 ± 38	0.62 ± 0.06	30.10	5.16
Mar. 12, 68	C	252 ± 4	515 ± 41	0.49 ± 0.05	31.24	5.47
Mar. 12, 68	H	218 ± 4	499 ± 40	0.44 ± 0.04	33.33	6.57
Mar. 12, 68	A	329 ± 7	520 ± 42	0.63 ± 0.06	31.94	5.82
May 16, 68	C	261 ± 4	602 ± 48	0.43 ± 0.04	40.92	8.65
May 16, 68	A	463 ± 9	329 ± 26	0.71 ± 0.07	43.52	9.21
June 7, 68	A	375 ± 8	672 ± 54	0.56 ± 0.05	39.31	14.47
July 2, 68	C	276 ± 5	441 ± 35	0.62 ± 0.05	35.12	7.21
July 2, 68	A	302 ± 6	454 ± 36	0.66 ± 0.06		10.57
Sept. 23, 68	A	236 ± 5	576 ± 46	0.41 ± 0.04		5.13
Sept. 23, 68	C	349 ± 4	600 ± 48	0.58 ± 0.06		6.41
Nov. 25, 68	C	176 ± 4	500 ± 40	0.35 ± 0.03		4.06
Nov. 25, 68	A	221 ± 5	532 ± 43	0.42 ± 0.04		5.12
Dec. 16, 68	C	202 ± 7	491 ± 39	0.41 ± 0.04		3.75

attributed to changes in Columbia River flow rates. The ^{65}Zn specific activity downstream from Hanford is influenced by the relative volume of the river diverted through the reactors. During high river flow a smaller fraction of the total volume (and, thus, a smaller fraction of the total amount of zinc in the river) is exposed to the neutron flux of the reactors (Cushing, 1967). The result is a lower ^{65}Zn specific activity in the river water and estuary during seasons of high runoff.

Seasonal changes in ^{65}Zn specific activity in fishes and shrimp also result from changes in environmental temperatures. Davis and Foster (1958) state: "For those aquatic forms that accumulate radioactive substances principally via ingestion, the concentration of radioisotopes fluctuates with metabolic rate." Therefore, in those seasons when water temperatures are highest, metabolic rates and food intakes are most rapid, as is the turnover of zinc (and ^{65}Zn) by poikilothermic animals. Under these circumstances the residence time for ^{65}Zn atoms is short, and the chance for an individual radioactive atom to decay while it is in the organism's body is reduced. Thus, in warm seasons all organisms from primary producers to herbivores to carnivores have relatively high ^{65}Zn specific activities. During colder months, when metabolic rates and food intakes are slowed, relatively low ^{65}Zn specific activities prevail in all organisms.

A second point observed in the data is that ^{65}Zn specific activities in organisms vary according to where the organisms are captured in the estuary. Organisms from the farthest upstream station consistently had higher ^{65}Zn

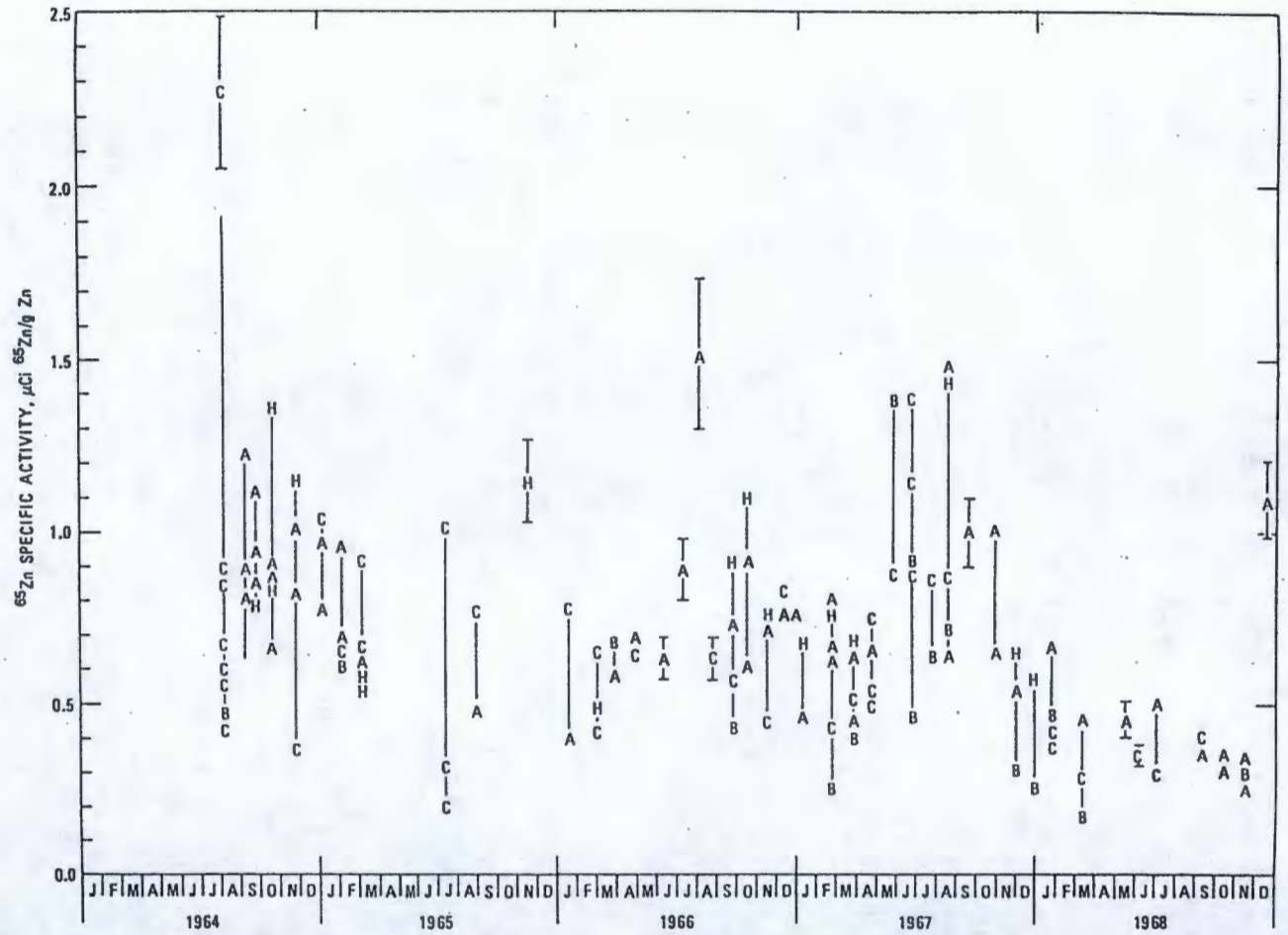

Fig. 30.5—Specific activities of ^{65}Zn in muscle—bone samples of staghorn sculpins from four stations in the Columbia River estuary. Vertical lines connect specific activities of samples taken on the same date. A few representative single standard deviations are also indicated by vertical lines.

Table 30.4—CONCENTRATIONS OF ^{65}Zn AND TOTAL ZINC IN WHOLE SAND SHRIMP

Date	Sta.	^{65}Zn, pCi/g ash	Zinc, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Nov. 5, 63	A	441 ± 4	440 ± 35	1.00 ± 0.09	29.33	5.44
Nov. 5, 63	C	435 ± 4	408 ± 33	1.07 ± 0.10	28.10	5.60
Jan. 8, 64	A	939 ± 8	329 ± 26	2.85 ± 0.27	38.73	6.86
Mar. 17, 64	C	748 ± 2	591 ± 47	1.26 ± 0.12	31.99	8.32
Mar. 31, 64	C	1023 ± 3	643 ± 51	1.59 ± 0.15	31.92	8.69
Apr. 29, 64	A	1723 ± 19	629 ± 50	2.74 ± 0.26	33.59	7.31
June 1, 64	A	1403 ± 5	558 ± 45	2.51 ± 0.24	54.47	9.00
June 1, 64	C	1871 ± 42	1028 ± 82	1.82 ± 0.17	44.25	8.50
June 10, 64	A	1299 ± 44	1249 ± 100	1.04 ± 0.10	52.61	8.44
June 10, 64	C	1057 ± 5	866 ± 69	1.22 ± 0.11	25.05	7.87
July 27, 64	A	928 ± 3	457 ± 37	2.03 ± 0.19	33.76	7.14
July 30, 64	C	605 ± 30	517 ± 41	1.17 ± 0.12	43.41	7.17
Sept. 8, 64	C	604 ± 8	441 ± 35	1.37 ± 0.13	23.45	6.13
Sept. 25, 64	A	927 ± 13	654 ± 52	1.42 ± 0.13	35.51	7.60
Sept. 25, 64	C	717 ± 18	600 ± 48	1.19 ± 0.12	28.94	7.27
Oct. 22, 64	A	1019 ± 10	534 ± 43	1.91 ± 0.18	35.78	7.02
Oct. 22, 64	C	313 ± 38	391 ± 31	0.80 ± 0.12		5.86
Nov. 25, 64	A	988 ± 10	518 ± 41	1.91 ± 0.18	21.19	6.17
Nov. 25, 64	C	449 ± 9	529 ± 42	0.85 ± 0.07		5.82
Jan. 5, 65	A	726 ± 10	558 ± 45	1.30 ± 0.12	29.09	7.34
Feb. 6, 65	C	420 ± 2	445 ± 36	0.94 ± 0.08	23.89	6.95
June 2, 65	C	730 ± 3	483 ± 39	1.51 ± 0.14	68.63	14.2
Aug. 30, 65	A	1165 ± 12	677 ± 54	1.72 ± 0.17	34.05	6.01
Aug. 30, 65	C	602 ± 5	466 ± 37	1.29 ± 0.12	26.45	5.61
Oct. 14, 65	C	597 ± 3	463 ± 37	1.29 ± 0.12	31.50	5.72
Nov. 15, 65	A	1052 ± 3	519 ± 42	2.03 ± 0.19	44.54	6.33
Jan. 18, 66	C	564 ± 29	462 ± 37	1.22 ± 0.13	39.74	7.83
Mar. 2, 66	A	1249 ± 38	745 ± 60	1.68 ± 0.16	32.54	8.56
Mar. 2, 66	C	695 ± 25	523 ± 42	1.33 ± 0.14	30.68	6.70
Apr. 28, 66	A	963 ± 59	586 ± 47	1.64 ± 0.17	32.40	7.23
Apr. 28, 66	C	674 ± 14	491 ± 39	1.32 ± 0.13		6.38
June 7, 66	A	1138 ± 74	566 ± 45	2.01 ± 0.22	38.97	6.53
Aug. 4, 66	A	964 ± 22	667 ± 53	1.44 ± 0.14	37.92	6.74
Aug. 24, 66	C	421 ± 12	486 ± 39	0.87 ± 0.08	37.04	6.44
Sept. 23, 66	C	426 ± 9	447 ± 36	0.95 ± 0.09	35.36	6.58
Sept. 23, 66	A	509 ± 34	477 ± 38	1.07 ± 0.12	34.25	5.82
Oct. 13, 66	C	393 ± 13	434 ± 35	0.90 ± 0.09	36.25	5.56
Nov. 15, 66	C	455 ± 13	554 ± 44	0.82 ± 0.08	36.93	6.84
Dec. 13, 66	C	623 ± 21	625 ± 50	1.00 ± 0.10	35.86	8.12
Dec. 13, 66	A	702 ± 33	563 ± 45	1.25 ± 0.14		6.33
Jan. 11, 67	A	774 ± 35	391 ± 31	1.98 ± 0.20	31.29	5.67
Feb. 23, 67	C	818 ± 19	581 ± 46	1.41 ± 0.14	34.29	6.32
Mar. 24, 67	C	651 ± 24	433 ± 35	1.50 ± 0.16	27.00	5.55
Mar. 24, 67	A	941 ± 33	428 ± 34	2.20 ± 0.43	20.00	4.29
Apr. 27, 67	C	958 ± 74	511 ± 41	1.88 ± 0.23	35.20	7.30

Table 30.4—(Continued)

Date	Sta.	^{65}Zn, pCi/g ash	Zinc, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
May 24, 67	C	1204 ± 83	741 ± 59	1.62 ± 0.19	37.85	6.80
June 27, 67	C	1026 ± 11	573 ± 46	1.79 ± 0.26	48.11	7.74
Aug. 18, 67	C	764 ± 29	439 ± 35	1.55 ± 0.18	21.91	5.79
Aug. 18, 67	A	1225 ± 8	607 ± 48	2.02 ± 0.19	33.12	6.21
Sept. 20, 67	C	521 ± 12	697 ± 56	0.75 ± 0.08	24.45	5.94
Sept. 20, 67	A	701 ± 8	660 ± 53	1.08 ± 0.10	33.19	6.49
Nov. 1, 67	A	343 ± 5	465 ± 37	0.74 ± 0.07	27.34	4.94
Nov. 1, 67	C	462 ± 9	488 ± 39	0.95 ± 0.09	33.86	6.69
Nov. 28, 67	C	534 ± 11	525 ± 42	1.02 ± 0.10	29.47	6.09
Nov. 28, 67	A	652 ± 11	623 ± 50	1.05 ± 0.10	34.61	6.17
Jan. 26, 68	C	348 ± 4	493 ± 39	0.70 ± 0.07	29.28	6.41
Mar. 12, 68	A	437 ± 7	585 ± 47	0.75 ± 0.07	31.35	6.56
Mar. 12, 68	C	554 ± 11	662 ± 53	0.84 ± 0.08	28.20	6.48
May 16, 68	A	388 ± 14	440 ± 35	0.87 ± 0.09	30.67	6.41
May 16, 68	C	386 ± 6	520 ± 42	0.74 ± 0.07	30.82	7.04
June 7, 68	C	476 ± 13	619 ± 50	0.77 ± 0.08	28.35	6.81
July 2, 68	C	296 ± 2	644 ± 52	0.46 ± 0.04	29.28	6.19
July 2, 68	A	378 ± 15	505 ± 40	0.75 ± 0.07	28.84	6.60
July 31, 68	A	427 ± 12	714 ± 57	0.60 ± 0.06		6.51
Aug. 23, 68	A	325 ± 3	491 ± 39	0.66 ± 0.06		6.31
Oct. 22, 68	A	222 ± 4	491 ± 39	0.45 ± 0.04		5.80
Nov. 25, 68	C	309 ± 5	532 ± 42	0.58 ± 0.06		5.90
Nov. 25, 68	A	326 ± 13	604 ± 48	0.53 ± 0.05		5.72

Fig. 30.6—Number of plutonium-production reactors operating at Hanford, Wash., by year.

Table 30.5—CONCENTRATIONS OF ^{65}Zn AND TOTAL ZINC IN STAGHORN SCULPIN MUSCLE—BONE SAMPLES

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
July 30, 64	B	100 ± 6	217 ± 17	0.46 ± 0.05	21.69	4.58
July 30, 64	C	426 ± 21	724 ± 58	0.59 ± 0.06	48.89	10.94
July 30, 64	C	369 ± 18	818 ± 65	0.45 ± 0.04	39.05	10.03
July 30, 64	C	554 ± 28	654 ± 52	0.85 ± 0.08	51.05	12.02
July 30, 64	C	516 ± 30	774 ± 62	0.67 ± 0.07	65.17	15.34
July 30, 64	C	323 ± 16	142 ± 11	2.27 ± 0.22	14.85	3.67
July 30, 64	C	392 ± 20	689 ± 55	0.57 ± 0.05	9.99	2.69
July 30, 64	C	102 ± 5	114 ± 9	0.90 ± 0.09	13.79	3.71
Sept. 8, 64	H	664 ± 36			57.16	11.86
Sept. 8, 64	A	271 ± 14	447 ± 36	0.61 ± 0.06		
Sept. 8, 64	A	686 ± 35	558 ± 45	1.23 ± 0.12	30.20	6.40
Sept. 8, 64	A	364 ± 18	403 ± 32	0.90 ± 0.09	34.72	7.65
Sept. 8, 64	A	462 ± 24	562 ± 42	0.82 ± 0.08	53.03	15.05
Sept. 25, 64	H	418 ± 21	609 ± 49	0.79 ± 0.08	45.76	10.09
Sept. 25, 64	A	537 ± 27	479 ± 38	1.12 ± 0.11	52.03	14.52
Sept. 25, 64	A	570 ± 29	599 ± 48	0.95 ± 0.09	82.29	20.25
Sept. 25, 64	A	567 ± 29	669 ± 54	0.85 ± 0.08	65.26	14.48
Oct. 22, 64	H		615 ± 49			
Oct. 22, 64	H	665 ± 36	490 ± 39	1.36 ± 0.13	48.97	11.66
Oct. 22, 64	H	912 ± 46			25.46	6.56
Oct. 22, 64	H	554 ± 28	649 ± 52	0.85 ± 0.08	47.03	11.16
Oct. 22, 64	A	434 ± 22	482 ± 39	0.90 ± 0.09	33.59	7.77
Oct. 22, 64	A	323 ± 16	489 ± 39	0.66 ± 0.06	56.86	13.76
Oct. 22, 64	A	613 ± 31	706 ± 56	0.87 ± 0.08	96.40	43.86
Nov. 25, 64	H	739 ±	649 ± 52	1.14 ±		
Nov. 25, 64	A	577 ± 29	691 ± 55	0.84 ± 0.08	59.99	17.46
Nov. 25, 64	A	590 ± 30	579 ± 46	1.02 ± 0.10	56.98	13.42
Nov. 25, 64	A		557 ± 45			
Nov. 25, 64	C	289 ± 17	787 ± 63	0.37 ± 0.04	50.99	12.90
Jan. 5, 65	A	466 ± 24	473 ± 38	0.98 ± 0.09	44.62	10.80
Jan. 5, 65	A	395 ± 20	508 ± 41	0.78 ± 0.07	47.82	11.68
Jan. 5, 65	C	420 ± 21	407 ± 33	1.03 ± 0.10	51.18	13.00
Jan. 5, 65	C		460 ± 37		46.76	12.50
Feb. 6, 65	A	693 ± 12	719 ± 58	0.96 ± 0.09	59.71	12.16
Feb. 6, 65	A	438 ± 22	632 ± 51	0.69 ± 0.07	57.26	12.69
Feb. 6, 65	C	241 ± 12	367 ± 29	0.66 ± 0.06	38.32	8.56
Feb. 6, 65	C	348 ± 17	530 ± 42	0.66 ± 0.06	51.94	11.93
Mar. 4, 65	A	402 ± 21	631 ± 50	0.64 ± 0.06	66.00	13.12
Mar. 4, 65	C	353 ± 7	389 ± 31	0.91 ± 0.09	45.58	10.43
Mar. 4, 65	C	290 ± 15	466 ± 37	0.64 ± 0.06	40.30	8.77
Mar. 4, 65	H	362 ± 15	605 ± 48	0.60 ± 0.06	66.31	15.07
Apr. 7, 65	H	358 ± 10	590 ± 47	0.61 ± 0.06	52.12	12.65
Apr. 7, 65	A	362 ± 18			46.99	11.25
Apr. 19, 65	A	515 ± 26				
June 2, 65	C	446 ± 23				
June 2, 65	C	302 ± 15				
July 14, 65	C	433 ± 22	428 ± 34	1.01 ± 0.10		
July 14, 65	C	187 ± 10	943 ± 75	0.20 ± 0.02		
July 14, 65	C	295 ± 15	955 ± 76	0.31 ± 0.03		
July 14, 65	C	180 ± 14	972 ± 74	0.19 ± 0.02		

Table 30.5—(Continued)

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Aug. 30, 65	A	218 ± 12	446 ± 36	0.49 ± 0.05	51.54	11.72
Aug. 30, 65	C	281 ± 14	369 ± 30	0.76 ± 0.07	51.27	12.56
Oct. 14, 65	C	282 ± 14			53.75	12.11
Nov. 11, 65	H	566 ± 36	491 ± 39	1.15 ± 0.12	53.22	10.76
Jan. 18, 66	C	288 ± 17	381 ± 30	0.76 ± 0.08	53.67	10.72
Jan. 22, 66	A	166 ± 9	400 ± 32	0.42 ± 0.04	40.89	8.39
Mar. 2, 66	C	378 ± 22	591 ± 47	0.64 ± 0.06	55.04	11.69
Mar. 2, 66	C	173 ± 10	426 ± 34	0.41 ± 0.04	49.29	10.90
Mar. 2, 66	H	323 ± 19	676 ± 54	0.48 ± 0.05	46.80	11.36
Mar. 25, 66	B	248 ± 19	371 ± 30	0.67 ± 0.08	41.21	8.26
Mar. 25, 66	A	434 ± 25	731 ± 58	0.59 ± 0.06	64.13	13.55
Apr. 28, 66	A	251 ± 15	364 ± 29	0.69 ± 0.07	51.04	10.18
Apr. 28, 66	C	354 ± 19	539 ± 43	0.66 ± 0.06		12.77
June 7, 66	A	494 ± 29	783 ± 63	0.63 ± 0.06		9.41
July 7, 66	A	562 ± 36	632 ± 51	0.89 ± 0.09	76.62	15.36
Aug. 4, 66	A	866 ± 105	571 ± 46	1.52 ± 0.22	54.53	12.33
Aug. 24, 66	C	332 ± 19	528 ± 42	0.63 ± 0.06	55.10	13.68
Sept. 23, 66	B	221 ± 13	501 ± 40	0.44 ± 0.04	50.38	12.79
Sept. 23, 66	C	184 ± 11	331 ± 26	0.56 ± 0.06	51.84	12.27
Sept. 23, 66	A	360 ± 21	488 ± 39	0.74 ± 0.07	55.08	16.88
Sept. 23, 66	H	624 ± 32	687 ± 55	0.91 ± 0.09	59.88	11.84
Oct. 13, 66	A	324 ± 17	526 ± 42	0.62 ± 0.06	60.27	16.03
Oct. 13, 66	A	547 ± 30	589 ± 47	0.93 ± 0.09	58.69	12.67
Oct. 13, 66	H	615 ± 36	561 ± 45	1.10 ± 0.11	67.80	14.05
Nov. 15, 66	C	337 ± 20	748 ± 60	0.45 ± 0.04	38.46	11.06
Nov. 15, 66	A	444 ± 24	623 ± 50	0.71 ± 0.07	70.59	13.69
Nov. 15, 66	H	450 ± 24	600 ± 48	0.75 ± 0.07	74.30	14.37
Dec. 13, 66	C	627 ± 32	785 ± 63	0.80 ± 0.08	60.24	12.32
Dec. 13, 66	A	527 ± 28	689 ± 56	0.76 ± 0.07	70.00	48.38
Dec. 19, 66	H	546 ± 32	720 ± 58	0.76 ± 0.08	80.25	15.72
Jan. 11, 67	H	421 ± 24	623 ± 50	0.68 ± 0.07	70.00	13.11
Jan. 11, 67	A	318 ± 20	677 ± 54	0.47 ± 0.05	58.29	3.41
Feb. 23, 67	B	97 ± 7	390 ± 31	0.25 ± 0.03	39.35	8.70
Feb. 23, 67	H	306 ± 17	410 ± 33	0.75 ± 0.07	62.04	12.44
Feb. 23, 67	C	155 ± 9	360 ± 29	0.43 ± 0.04	70.81	9.27
Feb. 23, 67	A	304 ± 18	474 ± 38	0.64 ± 0.06	65.42	12.51
Feb. 23, 67	A	400 ± 22	502 ± 40	0.80 ± 0.08	70.89	14.35
Feb. 23, 67	A	338 ± 20	517 ± 41	0.65 ± 0.07	80.86	17.62
Mar. 24, 67	B	135 ± 9	322 ± 26	0.42 ± 0.04	53.82	10.00
Mar. 24, 67	C	192 ± 25	384 ± 31	0.50 ± 0.08	58.35	11.80
Mar. 24, 67	A	288 ± 18	447 ± 36	0.64 ± 0.07	61.08	10.86
Mar. 24, 67	A	186 ± 11	402 ± 32	0.46 ± 0.05	60.00	12.03
Mar. 24, 67	H	302 ± 16	453 ± 36	0.67 ± 0.06	60.00	11.26
Apr. 27, 67	C	340 ± 22	462 ± 37	0.74 ± 0.08	69.81	12.22
Apr. 27, 67	C	271 ± 15	511 ± 41	0.53 ± 0.05	63.85	11.78

Table 30.5—(Continued)

Date	Sta.	^{65}Zn, pCi/g ash	Zn, μg/g ash	^{65}Zn sp. act., μCi ^{65}Zn/g Zn	Wet wt. / Ash wt.	Dry wt. / Ash wt.
Apr. 27, 67	C	232 ± 13	434 ± 35	0.53 ± 0.05	66.10	13.26
Apr. 27, 67	A	433 ± 31	643 ± 51	0.67 ± 0.07	75.48	12.74
May 24, 67	B	665 ± 52	482 ± 39	1.38 ± 0.15	29.05	8.41
May 24, 67	C	418 ± 36	477 ± 38	0.88 ± 0.10	59.61	13.09
June 27, 67	B	532 ± 38	594 ± 48	0.90 ± 0.10	79.18	14.65
June 27, 67	B	275 ± 18	584 ± 47	0.47 ± 0.05	74.49	15.71
June 27, 67	C	793 ± 62	576 ± 46	1.38 ± 0.15	64.62	12.33
June 27, 67	C	532 ± 41	468 ± 37	1.14 ± 0.13	74.74	14.63
June 27, 67	C	463 ± 30	522 ± 42	0.89 ± 0.09	137.93	14.29
July 24, 67	B	219 ± 17	339 ± 27	0.65 ± 0.07	43.14	3.03
July 24, 67	C	399 ± 31	473 ± 38	0.85 ± 0.11	60.68	12.21
July 24, 67	A		533 ± 43		56.75	13.02
Aug. 19, 67	B	266 ± 14	368 ± 29	0.72 ± 0.07	44.82	13.14
Aug. 18, 67	C	417 ± 33	480 ± 38	0.87 ± 0.10	52.48	11.46
Aug. 18, 67	A	608 ± 31	422 ± 34	1.44 ± 0.14	53.98	10.79
Aug. 18, 67	A	499 ± 27	781 ± 57	0.64 ± 0.06	61.90	11.68
Aug. 18, 67	H	786 ± 50	551 ± 44	1.43 ± 0.15	66.11	12.97
Sept. 20, 67	H		645 ± 52		24.47	5.94
Sept. 20, 67	A	497 ± 25	498 ± 37	1.00 ± 0.10	65.11	14.01
Nov. 1, 67	A	278 ± 15	421 ± 34	0.66 ± 0.06	58.18	11.32
Nov. 1, 67	A	474 ± 30	468 ± 37	1.01 ± 0.10	56.88	11.00
Nov. 28, 67	B	114 ± 10	364 ± 29	0.31 ± 0.04	51.42	9.37
Nov. 28, 67	A	252 ± 15	455 ± 36	0.55 ± 0.05	62.46	11.87
Nov. 28, 67	H	290 ± 16	444 ± 36	0.65 ± 0.06	59.03	11.88
Dec. 27, 67	B	107 ± 6	396 ± 32	0.27 ± 0.03	45.47	9.10
Dec. 27, 67	H	260 ± 14	468 ± 37	0.56 ± 0.05	49.96	9.38
Jan. 26, 68	B	224 ± 11	462 ± 37	0.48 ± 0.05	41.18	8.48
Jan. 26, 68	C	233 ± 15	544 ± 44	0.43 ± 0.04	56.92	10.13
Jan. 26, 68	C	194 ± 10	489 ± 39	0.40 ± 0.04	53.70	10.15
Jan. 26, 68	A	353 ± 18	520 ± 42	0.68 ± 0.06	52.29	8.99
Mar. 12, 68	A	185 ± 10	410 ± 33	0.45 ± 0.04	54.93	10.98
Mar. 12, 68	C	107 ± 6	382 ± 31	0.28 ± 0.03	49.61	9.93
Mar. 12, 68	B	65 ± 6	360 ± 29	0.18 ± 0.02	49.36	10.03
May 16, 68	A	218 ± 13	472 ± 38	0.46 ± 0.05	57.30	12.17
June 7, 68	C	190 ± 10	335 ± 43	0.35 ± 0.03	51.09	16.79
July 2, 68	C	140 ± 8	451 ± 36	0.31 ± 0.03		
July 2, 68	A	246 ± 13	489 ± 39	0.50 ± 0.05	52.98	12.52
Aug. 26, 68	A		614 ± 49		53.68	11.24
Sept. 23, 68	A	180 ± 10	478 ± 38	0.38 ± 0.04	52.25	10.15
Sept. 23, 68	C	231 ± 20	568 ± 45	0.41 ± 0.05	58.57	13.11
Oct. 12, 68	A	244 ± 13	651 ± 52	0.37 ± 0.04	59.42	12.89
Oct. 22, 68	A	175 ± 11	497 ± 40	0.35 ± 0.04	51.39	9.81
Nov. 25, 68	C	101 ± 7	304 ± 24	0.33 ± 0.04	51.47	10.38
Nov. 25, 68	A	220 ± 16	622 ± 50	0.35 ± 0.04	49.74	10.25
Nov. 25, 68	A	158 ± 9	535 ± 43	0.30 ± 0.03	55.32	12.74
Dec. 16, 68	A	554 ± 30	504 ± 40	1.10 ± 0.11	52.29	11.41

specific activities than those from more saline locations. At the stations nearest the ocean, increasingly more ocean water with its content of stable zinc is available for isotopic dilution of the ^{65}Zn atoms in the river water. Thus, fish and shrimp at stations nearest the ocean live in and take their food from an environment having lower ^{65}Zn specific activities than those from locations less influenced by tidal mixing.

A third point is the obvious decline in the ^{65}Zn specific activities of organisms in the estuary during this five-year study. If the power level of each reactor remained fairly constant during this time, the diminishing number of reactors in operation (Fig. 30.6) readily accounts for this phenomenon.

ACKNOWLEDGMENTS

The work reported in this chapter began late in 1963 and continues to date. Field work was begun by Lois Haertel, and Norman Kujala carried on the sampling program from 1966 to 1967. Radioanalysis of all the samples was done by Lauren Larsen. Roger Phelps, Jerry Wagner, and Norman Farrow did most of the atomic absorption analyses. James McCauley and Norman Cutshall reviewed the manuscript and offered numerous suggestions. We are indebted to all these colleagues and to others who assisted in the work. Support for the research came from U. S. Atomic Energy Commission Contract AT(45-1)-1750.

REFERENCES

Beardsley, Alan J., 1969, Movement and Angler Use of Four Food-Fishes in Yaquina Bay, Oregon, Ph. D. Thesis, Oregon State University, Corvallis.

Cushing, C. E., 1967, Concentration and Transport of ^{32}P and ^{65}Zn by Columbia River Plankton, *Limnol. Oceanogr.*, 12(2): 330-332.

Davis, J. J., and R. F. Foster, 1958, Bioaccumulation of Radioisotopes Through Aquatic Food Chains, *Ecology*, 39(3): 530-535.

——, R. W. Perkins, R. F. Palmer, W. C. Hanson, and J. F. Cline, 1958, Radioactive Materials in Aquatic and Terrestrial Organisms Exposed to Reactor Effluent Water, in *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955*, Vol. 13, pp. 423-428, United Nations, New York.

Foster, Richard F., 1963, Environmental Behavior of Chromium and Neptunium, in *Radioecology*, Vincent Schultz and Alfred W. Klement (Eds.), pp. 569-576, Reinhold Publishing Corporation, New York.

Frederick, Lawrence Churchill, 1967, Dispersion of the Columbia River Plume Based On Radioactivity Measurements, Ph. D. Thesis, Oregon State University, Corvallis.

Fukai, Rinnosuke, and Daniele Broquet, 1965, Distribution of Chromium in Marine Organisms, *Bull. Inst. Oceanogr.*, 65(1336): 1-19.

Haertel, Lois Steben, 1969, Plankton and Nutrient Ecology of the Columbia River Estuary, Ph. D. Thesis, Oregon State University, Corvallis.

——and Charles Osterberg, 1967, Ecology of Zooplankton, Benthos and Fishes in the Columbia River Estuary, *Ecology*, 48: 459-472.

Jones, Albert C., 1962, The Biology of the Euryhaline Fish *Leptocottus armatus armatus* Girard (Cottidae), University of California Publications in Zoology, University of California Press, pp. 321-367.

Orcutt, Harold George, 1950, The Life History of the Starry Flounder, *Platichthys stellatus* (Pallas), Fish Bulletin 78, pp. 5-64, California Department of Natural Resources.

Perkins, R. W., J. L. Nelson, and W. L. Haushild, 1966, Behavior and Transport of Radionuclides in the Columbia River Between Hanford and Vancouver, Washington, *Limnol. Oceanogr.*, 11: 235-248.

Seymour, Allyn H., and Gary B. Lewis, 1964, Radionuclides of Columbia River Origin in Marine Organisms, Sediments, and Water Collected from the Coastal and Offshore Waters of Washington and Oregon, 1961—1963, University of Washington Report UWFL-86.

Watson, D. G., J. J. Davis, and W. C. Hanson, 1963, Interspecies Differences in Accumulation of Gamma Emitters by Marine Organisms near the Columbia River Mouth, *Limnol. Oceanogr.*, 8(2): 305-309.