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Environmental Radiation Program

SPECIAL REPORT

RADIOACTIVITY IN COLUMBIA RIVER SEDIMENTS AND THEIR HEALTH EFFECTS

March 1994

Washington State Department of
Health
Environmental Health Programs

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SPECIAL REPORT

RADIOACTIVITY IN COLUMBIA RIVER SEDIMENTS AND THEIR HEALTH EFFECTS

Douglas Wells
March 1994

Washington State Department of Health

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EXECUTIVE SUMMARY

This report addresses the health effects of artificial radioactivity in Columbia River sediments. The existing data regarding radioactivity in Columbia River sediments has been provided by state agencies, federal agencies and academic researchers. These data span the length of the river from the Hanford area to the estuary and coastlines of Oregon and Washington. They include surface sediments and deeper sediments behind the dams of the lower Columbia. All areas of the river were investigated by two or more researchers and the agreement among different studies is quite good. These data are sufficient to establish human health risks.

Radiation doses and attendant risks have been calculated for the maximum concentrations observed in each part of the river. The maximum radiation doses to the maximally exposed individual comes from the deeply buried sediments of McNary Dam. The maximum average annual dose over a 75 year lifetime is 1.6 mrem. This dose requires that the deep sediments be dredged to the surface. The maximum radiation doses from surface sediments come from the Hanford Reach of the river. In general, the calculated doses, like the measured concentrations of artificial radioactivity, decline rapidly with distance from Hanford. In all cases the calculated doses are low and less than 1% of natural background. In fact, the risks from these doses are less than the risks associated with existing federal standards for radionuclides in drinking water and air emissions.

Nevertheless, in the Hanford Reach of the river several risks related to the radiological safety of the river have not been evaluated in this report. These include "sky shine" from nuclear facilities near the river, various "seeps" along the river, and the removal of reactor discharge pipes. The latter two issues may require small-scale sediment remediation. The Department of Health recommends that further radiological risk assessments of the Columbia River focus on these issues and on ecological assessments of the river.

INTRODUCTION

Radioactivity in Columbia River sediments is a topic of intense public interest. This interest is primarily motivated by concern about past releases of radioactivity into the Columbia River by Hanford operations. The goal of this report by the Department of Health is to assess human health risks associated with artificial radioactivity in these sediments. The Department of Health welcomes comments regarding this report, or recommendations regarding other areas in need of investigation.

In pursuit of this goal, this report summarizes the available data regarding concentrations of radioactivity in Columbia River sediments. A large body of data have been accumulated that can be used to evaluate human health and ecological risks from sediments of the river. We have attempted to include as much of these data as possible; however, publishing all of it in this document would require hundreds of pages of data tables alone. The original research and associated data can be found in the cited literature. Nevertheless, some work may have been omitted due, in part, to the abundance of published data.

The Columbia River is the second largest river, in terms of total volume of flow, in the United States. Prior to the construction of numerous dams along this river, it was an exceptionally fast flowing river with a river bottom characterized by coarse gravel and boulders. Despite the river's size and flow, it carries much less sediment per water volume than most other rivers of comparable magnitude. Prior to the dams, areas of significant sedimentation were islands, sandbars and shorelines found along the river and its estuary.

Between 1933 and 1968 the river below the Hanford reservation was altered by the construction of four dams for electric power production and irrigation. A consequence of these alterations is that from the Hanford site down to the river estuary the river is divided into three distinct regions. The Hanford Reach is that part of the river that stretches from below Priest Rapids dam to the head of McNary Reservoir. This stretch of the river remains fast and free-flowing. Sediment deposits are found on islands, peninsulas and beaches. The next region, which we call the Lower Columbia, stretches from the head of the McNary pool to the river estuary. This stretch of the river, due to its many dams and reservoirs, is slow moving and has accumulated significant sediment buildup on the river bottom. The last region is the region where river and ocean meet. This includes the

river estuary as well as the continental shelf from the southern Oregon coast to the northern Washington coast. Each of these regions is treated separately in this report due to their different sedimentation, ecological and other environmental characteristics.

Radioactivity in Columbia River sediments is dominated by natural sources. The principal contributors are radioisotopes of potassium, uranium and its decay products, and thorium and its decay products. In addition, there are many other minor sources of radioactivity from the earth's crust and from cosmic rays.

The history of artificial radioactivity in the Columbia River is dominated by world-wide fallout from atmospheric weapons tests and from Hanford operations. Fallout contributed large amounts of radioactivity to the environment until the 1963 atmospheric nuclear test ban treaty between the USSR and the USA. Nevertheless, Chinese and French tests continued contributing to fallout into the 1980's. Fallout from the Chernobyl accident in 1986 was the most recent significant contribution.

The maximum contribution of Hanford operations to the Columbia River was during peak plutonium production at the height of the cold war. At that time, from the mid 50's to the mid 60's, thousands of curies of radioactivity were discharged daily into the river[Fo64, Ro77]. Most of that radioactivity was very short lived and has since decayed away.

Other artificial sources of radioactivity that enter the Columbia River include nuclear medicines, application of farm and homeowner fertilizers, mining and other industrial activities, burning fossil fuels, and nuclear power production.

In the main body of this report we assume that the reader has only modest familiarity with radiation and radioactivity. However some use of the language of radiation is necessary and it is hoped that appendix A can provide the necessary background for those who need it. The amount of radioactivity found in any substance is commonly quantified in units of curies (Ci), or subunits of curies. This report uses the unit of pico-curies per gram (pCi/g), which is one millionth of one millionth of one curie per gram, to quantify the concentration of radioactivity in sediment samples. However, human health effects depend not only on the concentration of radioactivity, but on the energy of its radiation, the type of radiation emitted, the chemical properties of the source of radioactivity, and how the individual comes in contact with the radiation or its source.

For the purposes of this report, radiation types are limited to alpha, beta and gamma. Generally speaking, alpha and beta emitters are significant health threats when internal to the body but little or no threat when external to the body. In contrast gamma emitters can pose a threat whether they are internal or external to the body. Another useful category we use is based on the half-lives of radioisotopes. We call radioisotopes short-lived if their half-life is less than one year, intermediate-lived if their half-life is between one and thirty years, and long-lived if their half-life is greater than thirty years. Greater detail about radiation and radioactivity, human health effects, and sources of radioactivity in the environment can be found in Appendix A.

Other recent publications relating to the radiological health of the Columbia River, but not necessarily a direct measure of the current state of river sediments, include work on Hanford Reach riverbank springs[Di88], a study of the biological impact of N-springs[Po92], a summary of Hanford-site ecological data[We92a], a review of data regarding surface water pathways to the environment of Hanford-origin radioactivity[Wa92a], and a summary of the impact of Hanford on the Hanford Reach of the Columbia River[CRIEP].

The primary conclusion of this report is that the artificial radioactivity concentrations found in Columbia River sediments do not pose a significant human health risk. The Department of Health recommends that future river risk assessments focus on Hanford-Reach issues such as the removal of reactor discharge pipes, "sky shine" from nuclear facilities near the river, and intermittent seeps along the river's shore.

The remainder of this report is organized as follows. Chapter Two summarizes the available data on radioactivity in Columbia River sediments and compares various results to estimate the reliability and completeness of the data. Greater detail about the published data can be found in Appendix B. Chapter Three analyzes the human and ecological risks associated with the levels found in Chapter Two. Additional information about these risk assessments can be found in Appendix C. Finally, recommendations about public health policy regarding radioactivity in Columbia River sediments are contained in Chapter Four.

Levels of Radioactivity in Columbia River Sediments

Various federal and state agencies have monitored levels of radioactivity in Columbia River sediments since the late 1940's. Early monitoring was irregular and limited in geographic coverage. Since 1960 numerous special investigations, and state and federal monitoring activities have illuminated many aspects of radioactivity in the river sediments. These include the distribution of radioactivity in the river, detailed inventories of the radioisotopes found in river sediments and the primary sources of many of these radioisotopes.

The scope of these efforts has ranged from investigations of particular sites of the river to studies that encompass the length of the river from Priest Rapids Dam to the river estuary. Investigations have sampled surface sediments and deep sediment cores in areas of high sedimentation.

The current radiological state of Columbia River sediments is addressed, in part, by incorporating major studies and monitoring efforts completed in the last thirty years. Results that are reported and compared include data regarding total and regional inventories, concentrations, distributions, sedimentation rates, and estimates of the relative contribution from various natural and artificial sources.

Many of the earlier studies are not directly relevant to current levels of radioactivity. This is due, in large part, to the emphasis on short-lived radioisotopes in most of the older studies. Nevertheless, studies that only report short-lived radioisotopes are useful as confirmation of other studies that include intermediate and longlived radioisotopes. That is, confidence in studies that measured both short and long-lived isotopes is increased when their results are consistent with the results of other investigations that only measured short-lived radioactivity. Older studies are also useful to infer areas in the river where sediment deposition rates are high. Additional useful information found in these studies includes how radioactivity is deposited in the sediments in terms of particle size, dispersion in the sediment depths, and bio-availability.

The results of studies older than five years are adjusted to the expected concentrations in 1993. This corrects for radioactive decay since the completion of those studies and allows one to compare results from different studies. The differences in results can be used to estimate realistic uncertainties in the data. However, we only adjust results for medium and long-lived radioisotopes as it has been more than twenty

years since the last single-pass Hanford reactor shut down in 1971 and therefore more than twenty half-lives have passed for all short-lived radioisotopes. Any remaining short-lived radioactivity is less than one millionth of the levels of radioactivity that existed in 1971.

The sampling locations of individual studies are described in general terms in the text of this report. Specific sampling locations can be found in the cited references.

The remainder of this chapter summarizes the available data from numerous studies of radioactivity in Columbia River sediments. Greater detail of individual studies can be found in appendix B, or in the references cited.

The Hanford Reach: Priest Rapids to McNary

This section of the river, about 60 miles long, is defined by that part of the river from the upper end of the McNary pool to Priest Rapids(cf fig. 2.1). It is the last free-flowing stretch of the Columbia River in the United States, aside from the tidally influenced estuary.

Sediment data from the river bottom of the Hanford Reach are less complete than for other sections of the river. Due to the rocky nature of the river bed there are few areas of significant permanent sedimentation. However, information about exposed sediments is reasonably complete due to recent measurements. These have focused on sampling from surface sediments of the islands, sloughs and shoreline of the Hanford reach.

Surveillance of this part of the river began shortly after plutonium production began during World War II[So62]. However, routine monitoring of river sediments did not begin until 1989[Wo91]. In the interim, numerous special studies were carried out by the Department of Energy (DOE) and its contractors[BAT93, Egg90, Fi76, Fo64, Gl71, Ha73a, Ne61, Ne66, Ne71, Ro77, Wa92, We93, Wo92], by academic researchers[Be81, Be82, Be84, Be86a], or Department of Health investigations[Wa87, Wa94].

The gross distribution and other properties of radioactivity in river sediments was established by aerial[EGG90, Fi76] and surface surveys[Su80]. The aerial surveys measured surface gamma activity from the islands, shores and slough areas of the Hanford reach. The highest observed levels of artificial radioisotopes were of cobalt-60, cesium-137 and europium-152. However, because surface gamma activity does not allow one to accurately infer concentrations of

radionuclides, the principal utility of this technique is to quickly identify "hot" spots for further investigation. The surface survey[Su80] was further able to ascertain that the surface sediments of the Hanford Reach showed slightly elevated radioactivity that was almost uniformly distributed, a number of areas of significantly increased activity, and occasional hot spots consisting of cobalt-60 contaminated metallic "flakes" or "specks".

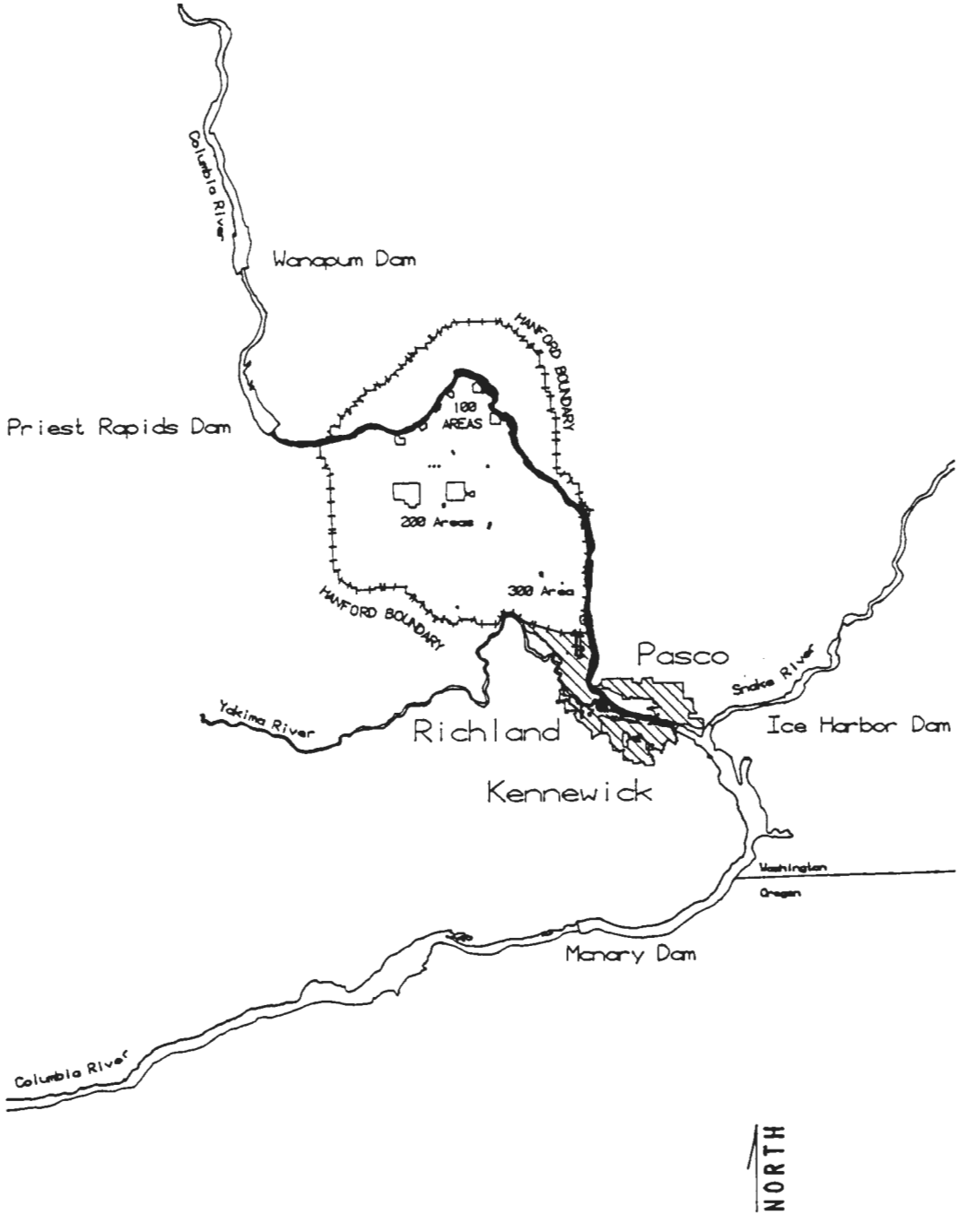
These metallic flakes presumably come from pumps and other metallic components of reactor cooling systems at Hanford.

Recent efforts have focused on surface sediment samples, as well as some deeper sediment samples. These efforts include routine monitoring by the DOE through its contract with Battelle[Wo92, Wo91], special investigations by Westinghouse Hanford Co.[We93] and Battelle[Co93], and special sampling investigations by the Department of Health[Wa94, Wa87]. The emphasis of the two recent studies by Westinghouse and Battelle were on determining if there are any exposed surface sediments in the Hanford Reach with significantly elevated levels of radioactivity. These areas were identified by the aerial surveys. Thus these samples were collected from the areas where the highest concentrations of artificial radionuclides are expected.

An important issue when using aerial surveys to locate surface contamination, which are based on surface gamma activtiy, is whether surface gamma activity is also correlated with the presence of beta and alpha emitters. A number of studies have demonstrated the high correlation of relative concentrations of different radioisotopes[Gl71, Fo72, Ha73a]. These correlations can also be observed in the data of Robertson and Fix[Ro77], Nelson et al.[Ne66], Haushild et al.[Ha73b], Cooper and Woodruff[Co93] and many other studies of Columbia River sediments.

The Westinghouse investigation included participants from the EPA, the Washington Department of Ecology and the Department of Health[We93]. The Department of Health split approximately 20% of the samples for quality assurance purposes. Forty four samples of surface and subsurface sediments were taken from 28 sampling locations. Three locations were near the Vernita Bridge, 22 were in the 100-area sloughs, islands and shorelines, and 3 in the vicinity of

Figure 2.1 - The Hanford Reach of the Columbia River.



the old Hanford townsite. The samples from Vernita Bridge are useful for comparison because Vernita Bridge is upstream of Hanford and therefore unaffected by Hanford activities. Department of Health results[Wa94] from the split samples agreed with the Westinghouse results.

The maximum concentrations measured by the Westinghouse study in the Hanford Reach were generally consistent with concentrations observed near Vernita Bridge. However, several samples, primarily from the vicinity of 100-H and 100-F, showed significantly elevated levels of cobalt-60, cesium-137, europium-152. The uncertainty in their results varied from approximately 3% to 20%. These results are summarized in Tables 2.1 and 2.7

Table 2.1 - Typical and maximum concentrations of selected radionuclides from the 1992 Westinghouse investigation[We93]. Additional Hanford Reach data is tabulated in Table 2.7.

Radioisotope	Typical Conc. (pCi/g)	Maximum Conc. (pCi/g)	Location
Cobalt-60	less than 0.1	0.41 +/- 0.07	100-D
Cesium-137	0.3	4.6 +/- 0.1	100-H
Europium-152	0.3	1.8 +/- 0.2	100-H

The 1992 Battelle study[Co93] was more complete than the Westinghouse study in two respects: they covered more of the Hanford reach and did not censor results that were below the lower limit of detection. They sampled sediments from the Vernita Bridge to the vicinity of the Richland pumphouse. Fifty six samples were collected in all.

While none of the sampling locations were identical with Westinghouse sampling locations, comparison of results from similar locations yields reasonably good agreement. The observed distribution of radioactivity deposition was also similar. For example, both studies measured maximum concentrations of cobalt-60 in the 100-D area and maximum or near-maximum concentrations of cesium-137 and europium-152 in the vicinity of the 100-H area. However, unlike the

Westinghouse study, the Battelle study found relatively high concentrations of cesium-137 and europium-152 in the 100-D area and the Hanford town-site area. In fact the highest concentrations of europium-152 was observed in the Hanford town-site area.

The average concentrations of these radioisotopes follow a similar pattern of higher concentrations in the 100-D, 100-H and Hanford town-site areas. The data uncertainties were typically a few percent. Results are shown in Table 2.2 and Table 2.7.

Table 2.2 - Average and maximum concentrations of radionuclides from the 1992 Battelle investigation[Co93]. Further data is shown in Table 2.7.

Radioisotope	Average Conc. (pCi/g)	Maximum Conc. (pCi/g)	Location
Cobalt-60	0.15	0.91 +/- 0.11	100-D
Cesium-137	0.7	6.0 +/- 0.6	100-H
Europium-152	0.5	2.4 +/- 0.3	Hanf. Twn.

The number of sediment samples taken from the Hanford Reach by the monitoring programs of the Department of Health and Battelle is too small to draw broad inferences about radioactivity in these sediments. However, the consistency of these measurements with Westinghouse and Battelle studies lends additional confidence to the Westinghouse and Battelle results.

The origin of cobalt-60, cesium-137 and europium-152 in the Hanford reach is relatively straightforward. The concentrations of cobalt-60 and europium-152 near the Vernita Bridge is substantially lower than concentrations in the Hanford reach. This implies that Hanford operations is primarily responsible for these radioisotopes. In contrast, the average concentration of cesium-137 near the Vernita Bridge and in the Hanford reach are similar, implying that most of the cesium-137 radioactivity in the Hanford reach comes from fallout. Nevertheless, some of the highest concentrations observed in the Hanford reach for this isotope appear to be too high to reconcile with fallout origins and presumably indicate impact from Hanford operations.

These conclusions are consistent with the conclusions of Beasley *et al.*[Be84]. To identify the origin of radioactivity in the sediments of McNary Reservoir, they took advantage of the fact that the relative abundances of various radioisotopes produced from a nuclear detonation are very different from those produced in a nuclear reactor[Kr76]. They concluded that approximately 75% of the cesium-137 in McNary pool sediments came from fallout, and the remainder from Hanford operations. This conclusion is consistent with the average cesium-137 concentrations in the Hanford reach; however, some of the higher concentrations observed in the Hanford Reach appear to be too high to originate primarily from fallout.

However, concentrations of radioactivity in sediments does not describe all of the observed sediment contamination in the Hanford Reach. The phenomenon of cobalt-60-contaminated "specks" or "flakes" is not addressed by these results. These specks are thought to be small metallic particles from reactor cooling components that passed through the reactor cores and were then deposited in the Columbia River. Most of the information about these specks comes from Sula et al.[Su80]. Sula's survey thoroughly covered the islands, shorelines and sloughs of the Hanford Reach.

Sula found 188 of these specks in his survey of roughly 40 miles of the Hanford Reach. 179 of these were found on the islands and broad shorelines that are easily accessible. Laboratory analysis of 14 of the specks found that they ranged in activity from 1.7 to 24 micro Curies. These results are shown in Figure 2.2. The small number specks that were analyzed limits how well the activities of the "speck population" is known.

Considering only the islands and broad shorelines, Sula found an average concentration of 0.0030 specks per square meter of and a maximum of 0.0056 per square meter in the vicinity of D-island. If the cobalt-60 from these specks were distributed uniformly in the sediments in the vicinity of D-island to a depth of 15 cm, Sula's results imply that the maximum concentration in 1979 was 0.28 pCi/g, or 0.04 pCi/g in 1993. This is a crude estimate that assumes that the concentrations of specks submerged in the river bed are the same as concentrations of specks in exposed sediments. This estimate also assumes that Sula was 100% efficient at finding specks in those areas that he surveyed.

The distribution of specks versus shoreline characteristics, sediment depth and river mile were also investigated. The first observation was that specks were concentrated in areas of coarse sediments and cobble.

This contrasts sharply with other forms of contamination, which tend to concentrate in areas where fine sediments accumulate. It was also observed that all of the specks are in the first 6 inches or less of sediment or cobble. However, it is not clear how meaningful this claim is since specks that were deeper would be more difficult toobserve due to absorption and scattering of gamma rays from the rock and sediment above. The speck concentration appears to decrease by approximately an order of magnitude per forty river miles in the free-flowing part of the river. This trend is shown in figure 2.3. It is unlikely that specks can be found downstream of McNary becausespecks are considerably more dense than sediment and would rapidly sink to the bottom in the slow-moving waters of McNary pool.

The recent study by Battelle [Co93] also investigated the issue of specks. Unlike the survey of Sula et al., D-Island received special scrutiny, and is therefore not directly comparable to Sula's results. However, the rest of Battelle's survey can be reasonably compared. They found only one speck, which results in a (very crude) estimate of 0.000008 specks per square meter, in sharp contrast with Sula's 0.003. What could account for such a large discrepancy? One major factor is radioactive decay. There were 13 years between these studies and in that time approximately 82% of the cobalt-60 had decayed to stable nickel-60. In addition, 13 years of weather and river flow changes could result in substantial scouring and burial of the specks. Finally, the '92 Battelle survey was guided primarily by areas of high radioactivity as seen in an aerial survey[EGG90]. These areas of higher contamination are also areas of high sedimentation. As noted by Sula, these are the areas where specks are rare. In light of these facts, it is not particularly surprising that the '92 Battelle survey failed to find many specks.

The source of these specks was clearly Hanford operations.

Greater detail about Hanford Reach data, particularly earlier sampling efforts, can be found in Appendix B.

Lower Columbia River: McNary to Estuary

This section of the river begins at the head of the McNary reservoir and extends downstream to the vicinity of Longview, Washington(cf fig. 2.4). This section is approximately 270 miles long and slow moving due to four major dams and their reservoirs. The slow movement allows much of the suspended sediment to settle onto the river bed and has led to substantial sediment deposits in each of the

Figure 2.2 - Activities of "specks" in the Hanford Reach in 1979 from Sula et al.[Su80]. These activities have declined by almost an order of magnitude since then.

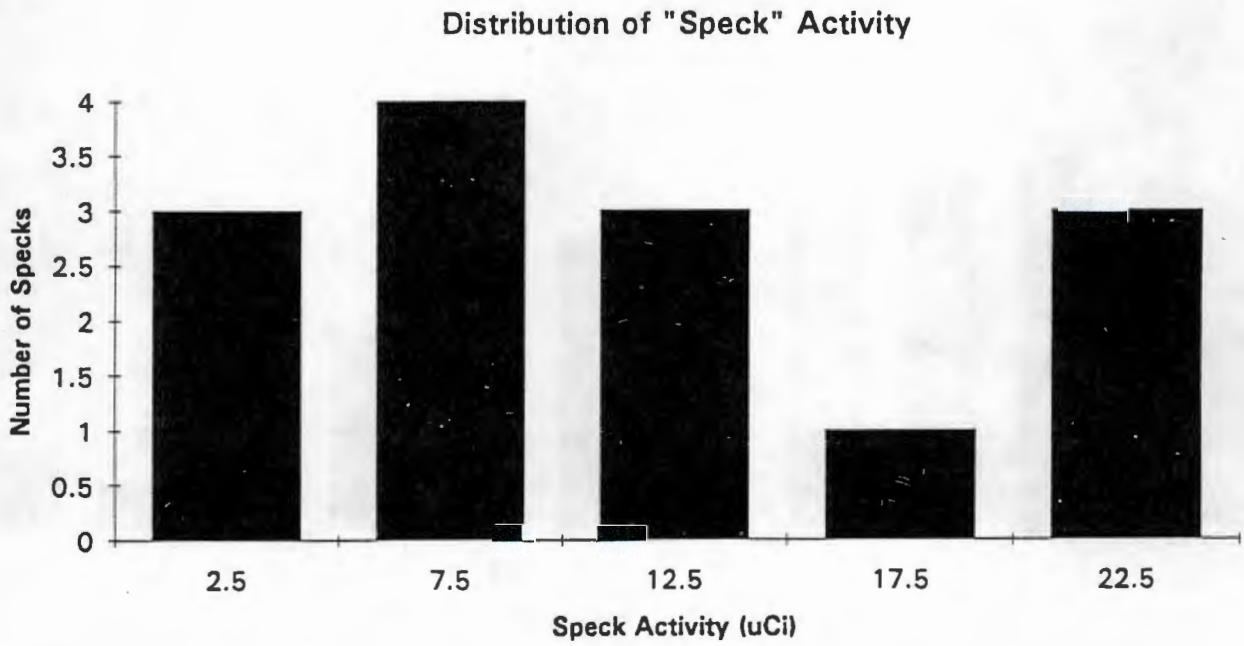
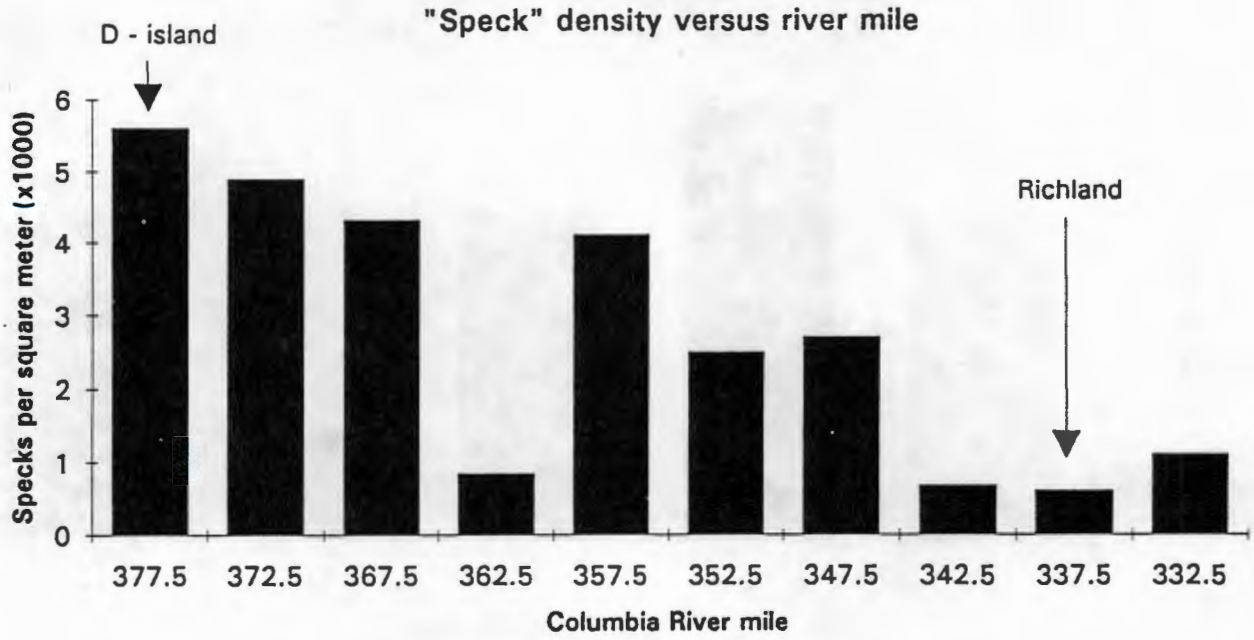


Figure 2.3 - Distribution of "speck" concentrations in the Hanford Reach as measured by Sula et al[Su80] in 1979. The 1992 study by Cooper et al.[Co93] found much lower speck concentrations.



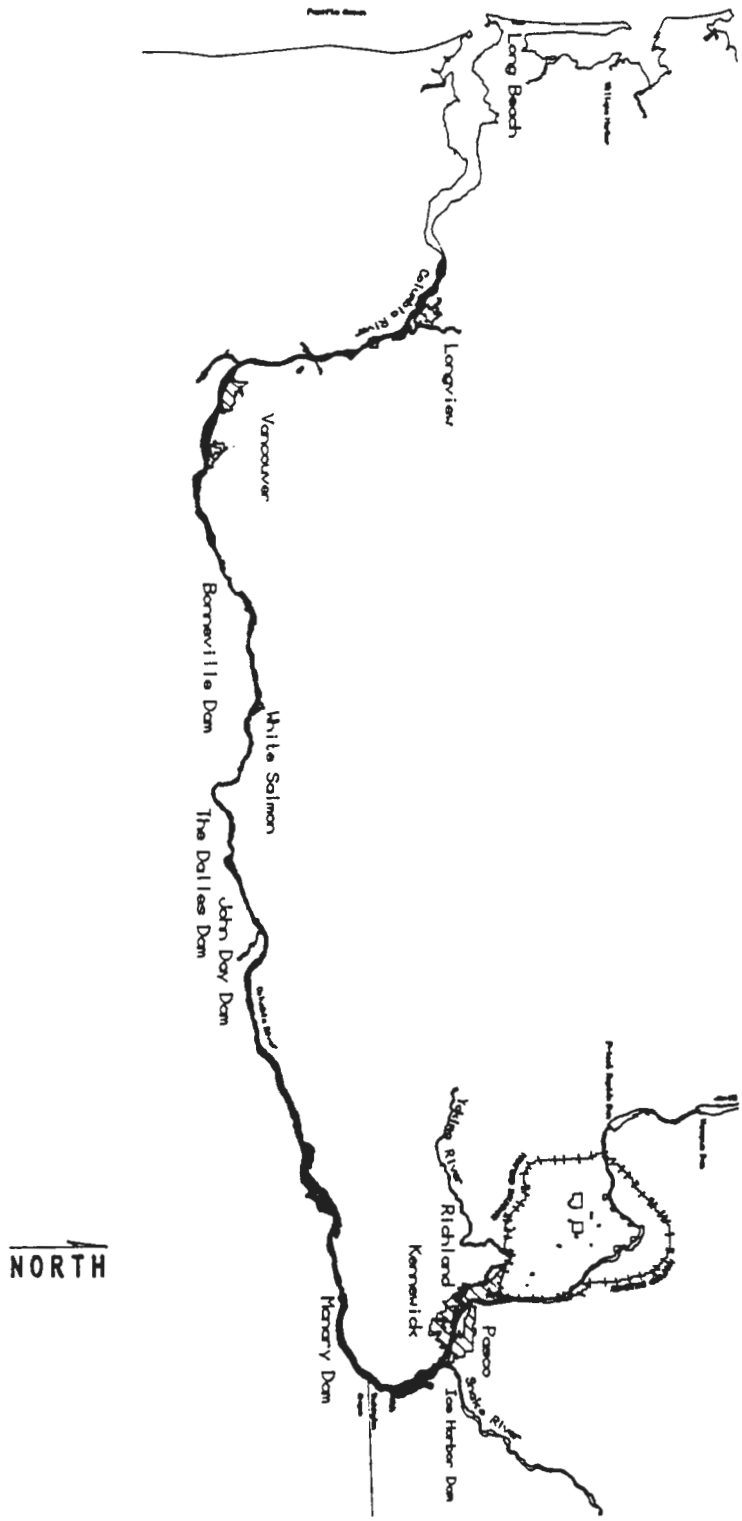
dam reservoirs. The most significant of these deposits are the sediments of McNary Reservoir, where both the Yakima and Snake Rivers enter the Columbia River.In this stretch of the river, both the sampling efforts and the potential human and ecological risks fall into two distinct classes. The first class is surface sediments, both submerged and exposed. These are the top 15 cm (6 inches) of sediments. Potential risks from contaminated surface sediments include direct contact, ingestion and "shine" (external exposure from gamma emitters). The second class is deeply buried sediments, where a possible pathway to humans is dredging the accumulated sediments to the surface.

There have been numerous efforts directed towards measuring concentrations and inventories of radioisotopes in the lower Columbia River. These include academic investigations[Be81, Be84, Be86a, Be86b], monitoring programs by the Health Departments of Washington and Oregon[Or67, Or77, Or87, Or92, Jo92, Wa87, Wa94] and DOE sponsored studies[Ro77, Fi71, Gl71, Ha73a, Ha73b, Ne66, Wo92, Wo93]. This report will emphasize the results of the most recent monitoring activities[Wa94, Wa87, Or92, Or87, Wo92, Wo93, Jo92] and special investigations[Be81, Be84, Be86a, Be86b, Ro77]. However, it should be noted that many of the earlier studies made valuable contributions, one of which is the consistency of their results with more recent studies.

Recent surface sediment sampling downstream of McNary has been done by the Oregon Health Division[Or87,Or92]. The Oregon program has maintained its historical emphasis on sampling from areas of high sedimentation. Many of the sampling sites, which stretched from McNary to Astoria, are behind dams or from sand bars. Natural radionuclides are typically abundant and easily measured. For example40K is typically 10 to 20 pCi/g. In contrast, results for all artificial radioisotopes were typically near or below the lower limit of detection. For example, cesium-137 concentrations have consistently been measured to be less than or equal to 0.1 pCi/g.

Another surface sediment sampling program has recently begun by the Bi-State Lower Columbia River Water Quality Survey, which is a collaborative program by the states of Oregon and Washington[Jo92]. They sampled surface sediments in a number of locations from the Bonneville dam to Astoria. They found, like the Oregon program, that artificial radioisotope concentrations were generally near or below the lower limit of detection.

Figure 2.4 - The Lower Columbia River.



Surface sediments behind McNary have been monitored by Battelle[Wo92, Wo93] and the Washington State Department of Health[Wa87, Wa94]. These samples were compared to samples taken upstream at Priest Rapids Dam. For Department of Health samples, only cobalt-60 and Europium isotopes were found to be elevated when compared to concentrations behind Priest Rapids Dam. The Battelle results were generally in good agreement with Department of Health results. However, they also found elevated levels of strontium-90 in McNary Dam sediments when compared to Priest Rapids Dam. Maximum concentrations of artificial radionuclides in surface sediments are consistently found in McNary pool.

Maximum concentrations of selected radionuclides from all of these surface sediment monitoring programs are shown in Table 2.3. More complete results are tabulated in Table 2.7.

Table 2.3 - Maximum concentrations of selected radionuclides in surface sediments of the lower Columbia from the monitoring programs of the Health Departments of Washington and Oregon, the Bi-State Lower Columbia River Water Quality Survey, and Battelle. A more complete list of results can be found in Table 2.7 at the end of this chapter.

Radioisotope	Maximum Conc. (pCi/g)	Reference	Location
Cobalt-60	0.50 +/- 0.03	[Wa87]	McNary Pool
Cesium-137	1.2 +/- 0.1	[Wo93]	McNary Pool
Europium-152	0.98 +/- 0.07	[Wa87]	McNary Pool
Plutonium-239/240	.022 +/- .002	[Wo93]	McNary Pool

Deep sediment sampling in the lower Columbia river has been done by Robertson and Fix[Ro77] and by Beasley *et al.*[Be81, Be84, Be86a, Be86b]. In 1977 Robertson and Fix[Ro77] published results of their deep-core sediment samples behind Priest Rapids, McNary, John Day, the Dalles and Bonneville Dams. They found that the bulk of the artificial radioactivity was typically a meter or more below the surface sediments. The measurements showed very low concentrations of

artificial radioactivity near the surface and, for long-lived radioisotopes, higher concentrations in deeper sediments deposited in the early 1960's. This distribution is consistent with the history of Hanford operations.

Intermediate and long-lived artificial radioisotopes that were observed in these sediments were cobalt-60, cesium-137, europium-152/154, plutonium-239/240 and americium-241. In all cases the highest concentrations were found in McNary sediments. The maximum concentrations observed in dams downstream of McNary were typically about 50% or less of the McNary maximum concentrations. The McNary maximums (adjusted for radioactive decay to 1993) are tabulated in Table 2.3 and Table 2.8.

The uncertainties in Robertson and Fix's measurements were not completely reported. Uncertainties were provided for approximately half of the plutonium and americium results; however, the uncertainties for gamma emitters, such as cobalt-60, were not published. In this report we estimate these uncertainties by using the reported lower limits of detection.

Table 2.4 - Maximum concentrations of selected radionuclides in deep sediments of the lower Columbia from the study of Robertson and Fix[Ro77]. These results have been adjusted to account for radioactive decay to 1993. The uncertainties are estimated from the reported lower limits of detection. A more complete list of results can be found in Table 2.8 at the end of this chapter.

Radioisotope	Maximum Conc. (pCi/g)	Location
Cobalt-60	1.6 +/- 0.1	McNary Pool
Cesium-137	5.1 +/- 0.3	McNary Pool
Europium-152**	9.6 +/- 0.1	McNary Pool
Plutonium-239/240	0.12 +/- 0.001	McNary Pool

** - this concentration assumes that all of the europium-152/154 that was measured by Robertson and Fix was europium-152. If some of it was europium-154, then the maximum concentration would be less than 9.6 pCi/g.

The deep sediment studies by Beasley *et al.*[Be81, Be84, Be86a, Be86b] also extensively sampled deep-core sediments from the reservoirs of McNary, the Dalles and Bonneville dams as well as the Ice Harbor Dam on the Snake River. They also sampled sediments below the Bonneville dam in areas of heavy sedimentation. While the maximum concentrations were not reported, the reported "typical" concentrations and their distribution in depth were in good agreement with the Robertson and Fix results. The uncertainty in their data was reported to be approximately 10%.

Beasley *et al.* also estimated total inventories for the Columbia River Basin. The sediments of McNary Pool accounted for about 60% of the total. Deep sediment results are tabulated at the end of this chapter in Table 2.8.

The identification of the origins of the observed artificial radioisotopes is relatively straightforward. For surface sediments, comparisons of radioisotope concentrations behind Priest Rapids Dam, which was unaffected by Hanford operations, are compared to radioisotope concentrations in the lower Columbia. The result is that cobalt-60 and europium isotopes originate primarily from Hanford operations. In contrast, the general consistency of cesium-137, plutonium isotopes and americium-241 concentrations in Priest Rapids sediments with lower Columbia River sediments implies that the origin of these radioisotopes is primarily fallout. Both Hanford operations and fallout appear to have contributed significantly to strontium-90 concentrations.

For deeper sediments a similar analysis has been done using sediments from behind both Priest Rapids and Ice Harbor Dams for comparison. Both of these dams were not impacted by Hanford operations and therefore serve to define the contributions from natural background and fallout. In addition, use has been made of the substantially different ratios of radioisotope concentrations generated from nuclear reactors and nuclear fallout[Kr76]. For example, the ratio of concentrations of plutonium-238 to plutonium-239 is significantly different if the source of the plutonium is a nuclear reactor or a nuclear weapon.

These techniques have been used to estimate that 20-25% of the plutonium and americium-241 deposits in McNary sediments came from Hanford operations and the remainder came from fallout. However, this fraction dwindled further down the river to approximately 3-4% at the river estuary. The total Hanford-derived

plutonium percentage was less than 20%. Similarly, the authors attributed approximately 25% of the cesium-137 to Hanford and 75% to fallout, while 90-100% of the cobalt-60 and nickel-63 was traced to Hanford.

Columbia River Estuary and Continental Shelf

This vast area includes the river estuary, starting in the vicinity of Longview, Washington, and extends to the surrounding continental shelf and shores from southern Oregon to northern Washington(cf fig. 2.5). The river portion is about 60 miles long and is slow moving, tidally influenced and part of the mixing zone of river and ocean waters. External to the river mouth, the major ocean current is northerly, although strongly influenced by the plume of the Columbia River.

In 1961 Hanford operations reported that approximately 1000 curies per day were carried by the Columbia River past Vancouver, Washington due to Hanford activities[Ne61]. The vast majority of this radioactivity was from the short-lived isotopes of chromium-51 and zinc-65. This level of radioactivity was typical of the Columbia River in the early and mid 1960's[Fo64].

The geographic extent of radioactive contamination in sediments was answered by early investigations of short and intermediate-lived radioisotopes[Os62, Hu71, Fo72, Gr72, Se80] and by the monitoring program of the Oregon Health Division[Or67, Or77]. These studies were all in good agreement regarding the range of significant contamination. The maximum concentrations for all measured radioisotopes were consistently offshore within 15 miles of the mouth of the river, and the measured concentrations all declined rapidly as the distance from the river mouth increased beyond 15 miles.

More recent investigations into surface sediments have been performed by the Oregon Health Division[Or87, Or92] and the Bi-State Lower Columbia River Water Quality Study[Jo92]. The Oregon program began in 1962 as an effort to identify and quantify any radiological hazards in the lower Columbia River stemming from Hanford Operations. These measurements have continued to the present and thus span the entire period from peak activity at Hanford to more than twenty years after shut-down of the last single-pass reactors. Sampling locations were chosen for their accessibility and ubiquitous sedimentation. These sites included all of the dams downriver of Hanford, the estuary and the Oregon coast from Astoria to Winchester Bay.

Their recent results have consistently found artificial radioisotopes in surface sediments in the estuary and along the Oregon coast to be at or below the lower limit of detection. For cesium-137 and plutonium-239 these lower limits of detection are 0.1 pCi/g and 0.008 pCi/g, respectively. Similar results have been reported by the Bi-State lower Columbia River Water Quality Survey[Jo92]. Maximum concentrations from these two sampling programs are summarized in Table 2.5 and Table 2.7.

Table 2.5 - Maximum concentrations of selected radionuclides in surface sediments of the Columbia Estuary from the monitoring programs of Oregon and the Bi-State Lower Columbia River Water Quality Survey. A more complete list of results can be found in Table 2.7 at the end of this chapter.

Radioisotope	Maximum Conc. (pCi/g)	Reference
Cobalt-60	0.03 +/- 0.02	[Jo92]
Cesium-137	0.19 +/- 0.03	[Jo92]
Plutonium-239/240	0.009 +/- .005	[Jo92]

Investigations into deeper sediments in the estuary and environs were performed by Beasley et al.[Be81a, Be82, Be84, Ca81]. The annual export of plutonium and americium to the Pacific Ocean and concentrations of cobalt-60, cesium-137, plutonium-239/240 and americium-241 in deep sediments of the estuary and coasts were measured.

These data were used to estimate total inventories, average concentrations, and the distribution of radioactivity in the estuary and along the Washington and Oregon coasts. The bulk of these deposits were found in the top 20 cm of sediments. Typical data uncertainties were 20%. These data are summarized in Tables 2.6 and 2.8 below.

Figure 2.5 - The Columbia River Estuary and Adjacent Coasts.

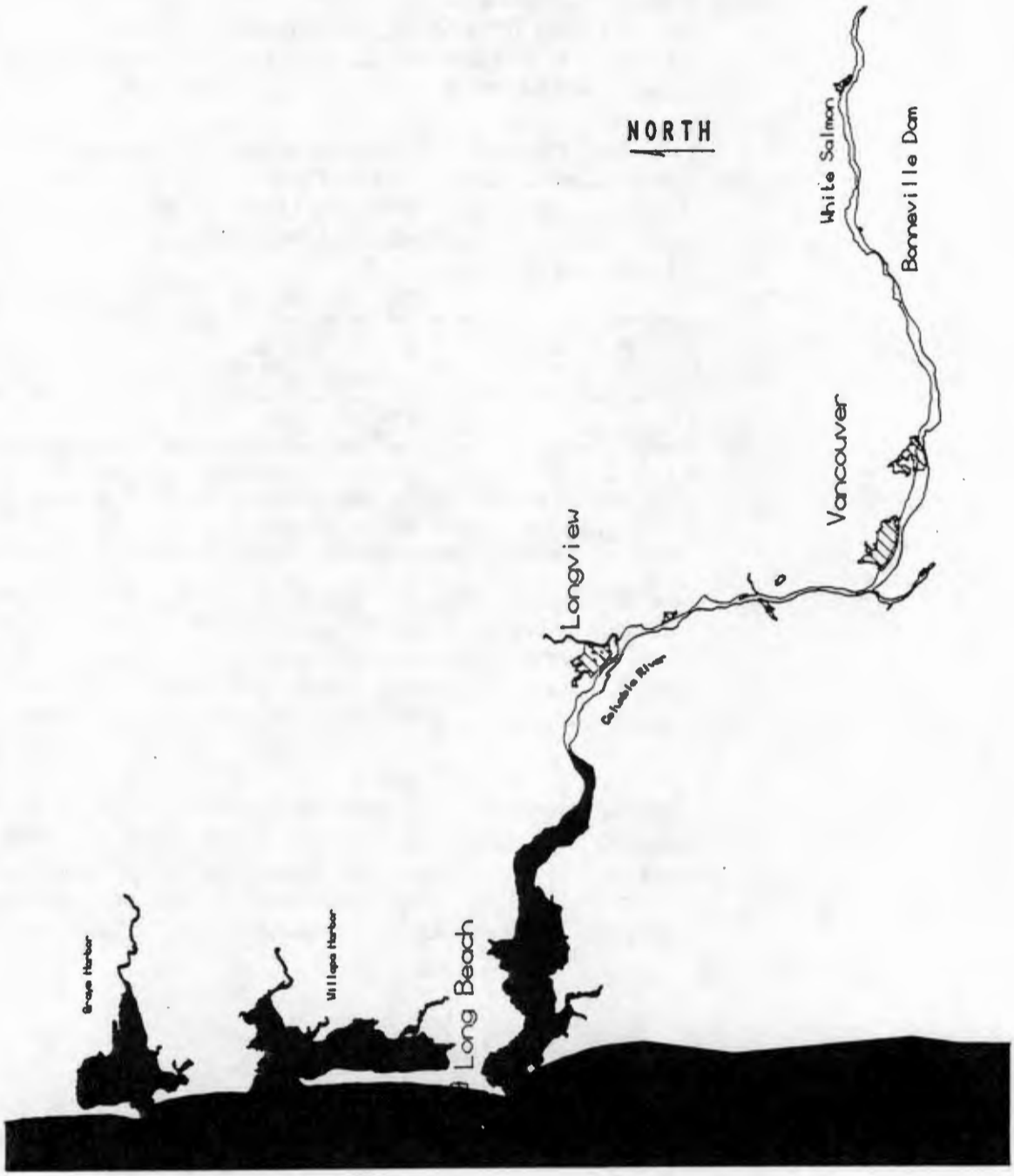


Table 2.6 - Average and maximum concentrations of radionuclides in deep sediments of the Columbia River estuary from the investigations of Beasley *et al.*[Be81a, Be82, Be84, Ca81].

Radioisotope	Average Conc. (pCi/g)	Maximum Conc. (pCi/g)
Cesium-137	0.077 +/- .016	0.36 +/- 0.07
Plutonium-239/240	0.027 +/- .009	0.14 +/- 0.03
Americium-241	0.009 +/- .002	0.039 +/- .008

The relative contributions of various sources of radioactivity were estimated from ratios of concentrations of radioisotopes in both the deep-core samples and the samples of suspended sediments undergoing export to the Pacific Ocean. Beasley *et al.* estimated that 3-4% of the plutonium in deep sediments upstream of the river mouth was of Hanford origin, while 96-97% was from fallout. Greater than 99% of the plutonium off the Washington and Oregon coasts was attributed to fallout. Similarly, all of the americium-241 in the estuary and its environs was attributed to fallout. In contrast, 90-100% of the cobalt-60 and approximately 25% of the cesium-137 was attributed to Hanford operations.

The Distribution of Artificial Radioactivity

The maximum concentrations of artificial radioactivity are higher in the Hanford Reach and decline rapidly with distance downstream of Hanford. This trend is even more apparent for average concentrations. Figures 2.3 and 2.4 shows this trend for maximum concentrations of cobalt-60 and plutonium-239/240 respectively.

Figure 2.3 - The decline of the maximum concentration of cobalt-60 in surface sediments as one travels downstream of Hanford. Note that the "lower Columbia" concentration is at McNary Dam. This trend holds in general for all artificial radioisotopes.

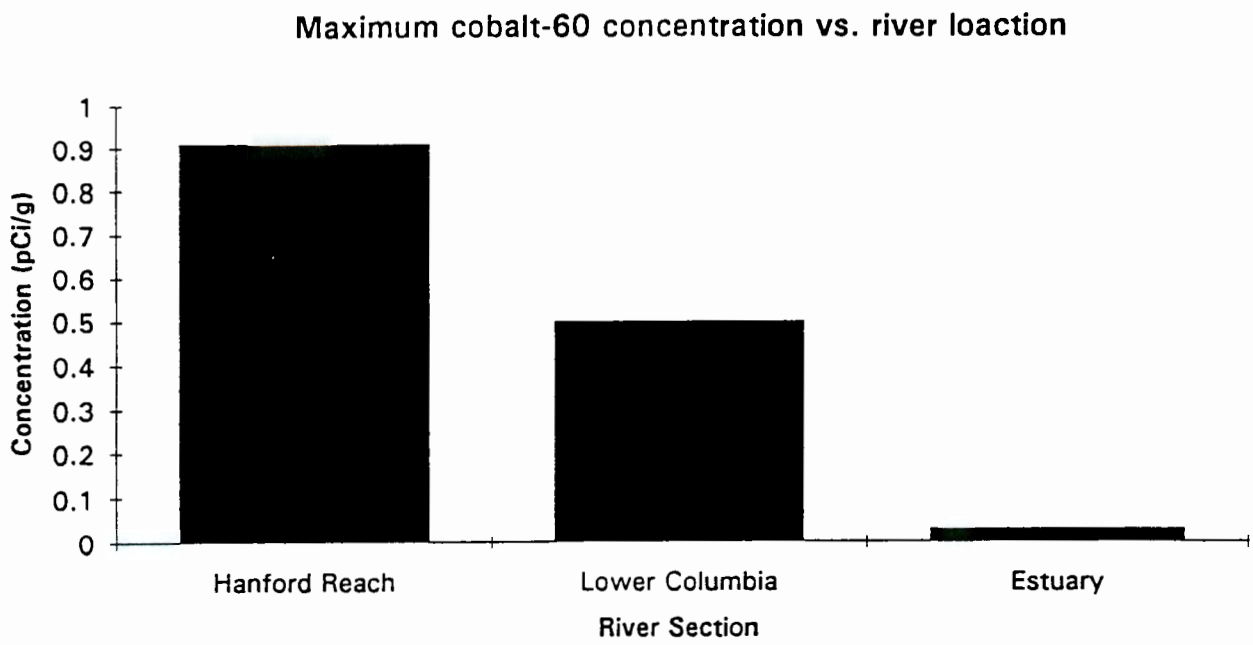


Figure 2.4 - The decline of the maximum concentration of plutonium-239/240 in surface sediments as one travels downstream of Hanford. Note that the "lower Columbia" concentration is at McNary Dam. This trend holds in general for all artificial radioisotopes.

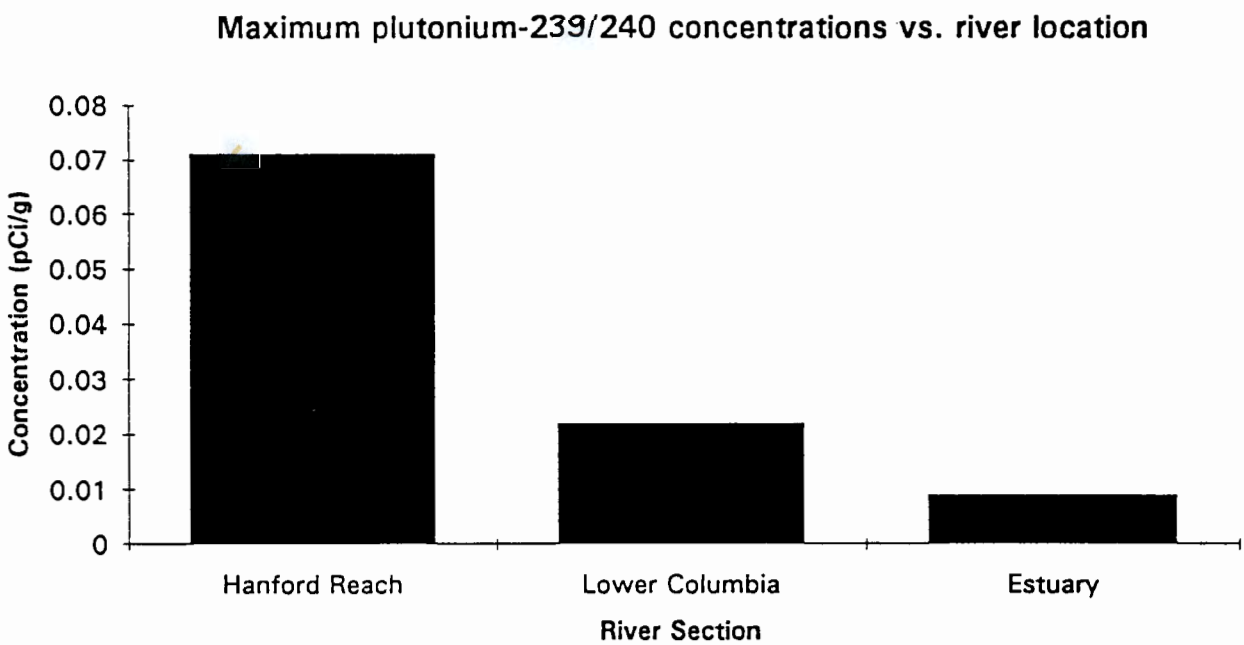


Table 2.7 - Maximum concentrations observed in surface sediments in the Columbia River. NA indicates that this radioisotope was not measured.

Radioisotope	Concentration(pCi/g)		Location/Reference
(Hanford Reach)			
sodium-22	0.13	+/- 0.04	100-D /[Co93]
cobalt-60	0.91	+/- 0.11	100-D /[Co93]
strontium-90	0.089	+/- 0.019	100-F /[Co93]
cesium-137	6.0	+/- 0.6	100-H /[Co93]
europium-152	2.4	+/- 0.3	Hanf. town/[Co93]
europium-154	0.24	+/- 0.16	100-H /[We93]
europium-155	0.19	+/- 0.06	Hanf. town/[Co93]
uranium-238	2.6	+/- 0.4	100-D /[We93]
plutonium-238	0.0012	+/- 0.0006	100-F,300area/[Co93]
plutonium-239/240	0.071	+/- 0.003	100-H /[We93]
americium-241	(less than) 0.1		/[We93]
(Lower River)			
cobalt-60	0.50	+/- 0.03	McNary Pool/[Wa87]
strontium-90	0.064	+/- 0.008	McNary Pool/[Wo93]
cesium-137	1.2	+/- 0.1	McNary Pool/[Wo93]
europium-152	0.98	+/- 0.07	McNary Pool/[Wa87]
plutonium-239/240	0.022	+/- 0.002	McNary Pool/[Wo93]
americium-241	(less than) 0.003		/[Jo92]
(Estuary and Coasts)			
cobalt-60	0.03	+/- 0.02	Lew&Clk Ref./[Jo92]
strontium-90	NA		
cesium-137	0.19	+/- 0.03	Longview /[Jo92]
europium-152	(less than) 0.1		/[Jo92]
plutonium-239/240	0.009	+/- 0.005	Skamokawa /[Jo92]
americium-241	(less than) 0.003		/[Jo92]

Table 2.8 - Maximum concentrations observed in deep sediments in the Columbia River and its estuary (corrected for decay). The uncertainties in the lower river concentrations, all of which are in the McNary pool, are estimated from the reported lower limits of detection[Ro77] or, in the case of 63Ni, from Beasley et al.[Be84]. NA indicates that this radioisotope was not measured. Note that the bed of the Hanford Reach is coarse cobble, due to the swift flow of the river, and therefore has no deeply buried sediments.

Radioisotope	Concentration(pCi/g)		Location/Reference
(Lower River)			
cobalt-60	1.6	+/- 0.1	McNary Pool/[Ro77]
nickel-63	4.4	+/- 0.9	McNary Pool/[Be86a]
strontium-90	NA		
cesium-137	5.1	+/- 0.3	McNary Pool/[Ro77]
europium-152**	9.6	+/- 0.1	McNary Pool/[Ro77]
plutonium-239/240	0.12	+/- 0.01	McNary Pool/[Ro77]
americium-241	0.021	+/- 0.005	McNary Pool/[Ro77]
(Estuary and Coasts)			
cobalt-60	NA		
strontium-90	NA		
cesium-137	0.36	+/- 0.07	Offshore/[Be82]
europium-152	NA		
plutonium-239/240	0.14	+/- 0.03	Offshore/[Be82]
americium-241	0.039	+/- 0.008	Offshore/[Be82]

* -- Estimated from inventory ratios.
** -- This concentration assumes that all of the europium-152/154 measured by Robertson and Fix was europium-152. If, instead, it was 100% europium-154 then the maximum concentration would be 5.8 +/- 0.1 pCi/g.

Human Health Effects

An assessment of health effects from radioactivity includes calculating possible human exposure pathways, the associated radiation doses and their risks. The approach of the Department of Health in assessing health risks from artificial radioactivity in Columbia River sediments is addressed in this chapter. Numerical results are tabulated in Tables 3.1 and 3.2 and displayed in Figures 3.1 through 3.5 at the end of this chapter.

Calculations of radiation doses from concentrations of radionuclides in the environment can involve many complex models of human exposure, uptake, storage and biological elimination. However, the two major components of these calculations are simple. First, one must calculate the dose received per unit contamination for each pathway. In this document these calculations were based on federal and international guidance[NCRP76, NCRP84, ICRP30, NRC77, Ke92, EPA88, EPA89, EPA91, HSBRAM]. The second major component is to estimate the amount and duration of exposure to the maximally exposed individual for each pathway. The Department of Health used the data in Chapter 2, known properties of the shorelines of the Columbia River and federal and state guidance documents for this component[EPA91, HSBRAM, Sc93]. The final dose calculation is simply the product of these two components.

The dosimetry estimates for the cobalt-60 specks is more difficult. Unlike broadly distributed contamination over an area, there are no regulatory guidelines for very small areas of elevated activity. The only potentially relevant guidelines are for worker protection and these have limited application to specks distributed throughout the environment[NCRP46, NCRP106]. To calculate doses from these specks, the Department of Health used the general principles of calculating doses from environmental contamination as outlined above.

The Department of Health calculates doses from radioactive specks, as above, by separating the problem into two components. The first component is to calculate the dose if one were to inhale, ingest or otherwise be exposed to a typical speck. The second component is to calculate the probable number of specks the maximally exposed individual would be exposed to for each pathway. We use the same parameters for the maximally exposed individual as above and the data of Sula[Su80], and Cooper[Co93] to make these estimates. The product of these two components yields the final dose for each pathway. Details of these calculations can be found in Appendix C.

The health effects of radiation are substantially better known than most other carcinogens because, in addition to animal data, there is a wealth

of human data. However, like all carcinogenic "agents", when levels of exposure are less than the level where one can readily observe health effects, scientists must use extrapolations to estimate health effects. For example, it is relatively easy to observe the health effects of smoking two packs of cigarettes per day; but, when an individual only smokes two packs per year, health effects are not evident. In this case the risks are estimated from extrapolating from heavy smokers. In our analysis the relationship between dose and risk is assumed to be linear at environmental levels. That is, the risk associated with a dose is directly proportional to that dose.

The risk estimates of this report consider only carcinogenic risks due to radiation dose and do not account for the toxicological characteristics of the radioisotopes in question. Generally, except for uranium, the toxicological effects of radionuclides are much less than the carcinogenic effects due to radiation. Estimates of risk are taken from the National Academy of Sciences report BEIR V[Be90a]. The data from Japanese victims of atomic weapons are the most important data in their analysis. Thus their estimates are extrapolations from persons exposed to doses of 10,000 mrem or more in a very short period of time. BEIR V estimates cancer fatalities per 100,000 individuals for continuous lifetime doses of 100 mrem/year to be 600 for females and 520 for males. Averaging the results of the two sexes, a continuous lifetime radiation exposure of 100 mrem per year results in a excess cancer death rate of 560 deaths per 100,000 persons.

There is much debate over the validity of extrapolating the effects and risks seen at high radiation doses to doses below background levels. Some researchers claim that the risks are significantly higher than the linear response estimates. Others claim that the risks are significantly lower. However, the only claim that can be made with certainty is that the risk of cancer at radiation doses below about 10,000 mrem is so small that no one has been able to unambiguously measure it.

Most radiation protection organizations view the linear response relationship as a conservative, or protective, estimate of risk from radiation[NCRP39, Be90a]. It should be noted that the uncertainty of the linear extrapolation is sufficiently great that the risk of very low levels of radiation may be zero. As stated in BEIR V: "The possibility that there may be no risks from exposures comparable to external natural background radiation cannot be ruled out. At such low doses and dose rates, it must be acknowledged that the lower limit of the range of uncertainty in the risk estimates extends to zero.".

One of the challenges of any risk assessment is to construct a realistic scenario to describe how a member of the public might come in contact with a hazardous material or situation. The Department of Health uses a recreational scenario in this report to estimate public health risks from radioactivity in Columbia River sediments. The recreational scenario is meant to describe an individual who fishes, swims, hunts and camps in and along the river. Use of this scenario is consistent with other risk assessments of the Columbia River[Co93], with guidelines by the DOE[Sc93], by the EPA[EPA89] and in the Tri-Party Agreement risk assessment document[HSBRAM].

The pathways from sediments to human exposure include ingestion, either directly or through consumption of fish in the river, inhalation and external exposure to gamma rays (often referred to as "shine"). Gamma emitters such as cobalt-60 contribute to dose principly through shine. In contrast, alpha emitters, such as plutonium-239, and beta emitters contribute to dose primarily through the ingestion and inhalation pathways.

Important factors in the assessment of the recreational scenario include the amount of time spent by an individual on or near river sediments and where the individual spent their time. More generally, one must decide who is the relevant hypothetical individual exposed to these sediments. The Department of Health concurs with other regulatory agencies that the relevant individual is the "maximally exposed individual"(MEI). However, a careful comparison of exposure assessment parameters for the maximally exposed individual varies widely[Sc93, HSBRAM, EPA91, NRC77]. In this document, the Department of Health has generally used the more conservative (more protective) parameters of Battelle[Sc93] in assessing risks.

Exposure to radioactive contamination in surface sediments is more easily realized than for deeper sediments. The exposure scenario for deeper sediments must include a path to the surface. Since most of the contamination in deep sediments is found both underwater and buried more than a meter below the surface sediments, we assume that this material has been dredged to the surface without mixing with less contaminated sediments.

Many of the assumptions made in these estimates are intrinsically conservative. For example, the Department of Health "no-mixing" assumption for dredging deep sediments is clearly unrealistic. This is supported by the U.S. Army Corp of Engineers dredging of the Port of Kennewick in 1993. The Department of Health sampled the dredged material on April 2, 1993 after it was deposited on Shot Rock

Island. The maximum results for cobalt-60 indicated 0.23 pCi/g. In comparison, of the many deep core samples from McNary pool taken by Robertson and Fix[Ro77], the minimum concentration of cobalt-60 in the depths associated with peak Hanford activities was 0.56 pCi/g (corrected for decay to 1993).

Other conservative assumptions used for these estimates include the assumption that the maximum observed concentrations in each part of the river all occur in the same place, that the maximally exposed individual spends 500 hours per year at this one spot(62.5 8-hour days) and that the river will never wash, scour or cover the contaminated sediments. More information about dose assessment assumptions and parameters can be found in Appendix C.

The doses, and attendant risks, that are calculated in this document are divided into surface sediments, which are those sediments in the top 15 cm(6 inches), and deep sediments. Results are also divided into the Hanford Reach of the river, the Lower Columbia and the Estuary. Finally, the doses are separated into individual doses for each artificial radioisotope found at significant concentrations. In this case "significant" means that the isotope has been clearly identified in the sediments at levels above that which could be accounted for by natural and fallout origins. It does not mean the risks are significant.

Only intermediate and long lifetime radionuclides are included in these dose estimates. The dose from each pathway is added to calculate a total dose for each radionuclide.

The doses in this report are calculated through the use of Argonne National Laboratory's computer code "RESRAD"[Re93], and have been checked through manual calculations using federal regulatory guidance[EPA88, EPA91, Ke89, NRC77, Sc93]. Details of these calculations can be found in Appendix C.

One of the major results of these dose estimates is that doses from gamma-emitters dominate the total doses. Of these, the most significant contributors are cobalt-60, cesium-137 and europium-152. The contribution of the remaining radioisotopes, which are primarily alpha and beta emitters, are negligible in comparison. Virtually all of the dose contribution for gamma-emitters comes from the external pathway (i.e. - "shine").

The estimated doses from artificial radioactivity in Columbia River sediments for the years 1993 and 2023 are tabulated in tables 3.1 and 3.2. The highest calculated doses correspond to the deeply buried

sediments of McNary Dam. In the scenario where these sediments are dredged to the surface, the maximally exposed individual would receive an average dose of 1.6 mrem per year over a 75 year lifetime, and a maximum annual dose of 7.4 mrem in 1993. The rapid decline of potential annual dose shown in figures 3.1 through 3.5 is due to radioactive decay.

To place these doses in perspective it is useful to compare them to natural background radiation doses. The average natural background doses in the United States (excluding medical exposures and radon) are in the range of 100 mrem/year. Inclusion of radon increases natural background doses to approximately 300 mrem/year.

In Washington State the Department of Health has estimated that natural background radiation doses, including radon, range from approximately 175 mrem in the north-west part of the state to as high as 1635 in the north-eastern part[Er93]. In the vicinity of Hanford natural background is approximately 565 mrem per year. Thus the potential doses to the MEI discussed above range from approximately 1% of Hanford-area background, in the scenario where deeply buried sediments behind McNary are dredged to the surface, to approximately 0.015% of Hanford-area background from dredged sediments in the river estuary.

In the United States approximately 1 out of every 4 individuals contract cancer at some point in their life and approximately 1 out of every 5 die from cancer. The estimates of BEIR V imply that lifetime exposure to average natural background radiation levels in the United States causes approximately 1 out of every 60 individuals(1 in 60) to die of a fatal cancer. Thus natural background radiation causes about 10% of the total fatal cancer cases. If an individual spent their lifetime in the general vicinity of Hanford, the chance of contracting a fatal cancer from natural background radiation is roughly twice the national average. The risk of a fatal cancer due to lifetime exposure to the calculated doses of the MEI in this report range from a maximum of approximately 1 in 11,000 (from deeply buried sediments behind McNary) to 1 in 400,000 (from the deeply buried sediments of the river estuary). These lifetime risk calculations include the reduction of dose associated with the decay of the contamination as the years pass.

Another useful comparison can be made with the U.S. Environmental Protection Agency's (EPA) regulations for air emissions and drinking water. The air emissions standard (40 CFR, Part 61) is 10 mrem per year from all radionuclide sources of a facility. The lifetime-exposure

risk estimates of BEIR V indicates that this (maximum) dose corresponds to approximately a 1 in 2,000 chance of a fatal cancer. The EPA drinking water standards (40 CFR, Part 141) sets a dose limit of 4 mrem per year for radionuclides in public drinking water systems. The lifetime-exposure risk level of this (maximum) dose is approximately a 1 in 4,500 chance of a fatal cancer. All of the lifetime-exposure risk estimates in this document concerning artificial radioactivity in Columbia River sediments are well below these risks.

Table 3.1 - Dose estimates for the "maximally exposed individual" (MEI) from maximum measured concentrations of artificial radioactivity in **surface sediments** of the Columbia River. This assumes that the maximum concentrations all occur in one place and that the MEI spends 500 hours per year at that location. NA indicates that that radioisotope was not measured. See table 2.1 for locations and references to these concentrations.

Radionuclide:	Concentration (pCi/g)	Dose (1993) (mrem/year)	Dose (2023) (mrem/year)
(Hanford Reach)			
sodium-22	0.13	0.095	0.000008
cobalt-60	0.91	0.96	0.017
cobalt-60(specks)	0.04	0.04	0.001
strontium-90	0.089	0.00002	0.000005
cesium-137	6.0	1.5	0.68
europium-152	2.4	1.1	0.20
europium-154	0.24	0.12	0.0095
europium-155	0.19	0.0018	0.00003
uranium-238	2.6	0.047	0.030
plutonium-238	0.0012	0.00006	0.00004
plutonium-239/240	0.071	0.0037	0.0030
americium-241	(less than) 0.1	0.0056	0.0022
TOTAL		3.8	0.93
(Lower Columbia)			
cobalt-60	0.50	0.53	0.0091
strontium-90	0.064	0.00002	0.000004
cesium-137	1.2	0.30	0.14
europium-152	0.98	0.45	0.080
plutonium-239/240	0.022	0.0012	0.0009
americium-241	(less than) 0.003	0.0002	0.00007
TOTAL		1.3	0.23
(River Estuary)			
cobalt-60	0.03	0.032	0.0006
strontium-90	NA	-----	------
cesium-137	0.19	0.047	0.021
europium-152	(less than) 0.1	0.046	0.0082
plutonium-239/240	0.009	0.0005	0.0004
americium-241	(less than) 0.003	0.0002	0.00007
TOTAL		0.13	0.031

Table 3.2 - Dose estimates for the "maximally exposed individual" (MEI) from maximum measured concentrations of artificial radioactivity in **deeply buried sediments** of the Columbia River. These dose estimates assume that the deep sediments were dredged to the surface without mixing with less contaminated sediments. It is also assumed that the maximum concentrations all occur in one location and the MEI spent 500 hours per year at that location. NA indicates that that radioisotope was not measured. See table 2.2 for locations and references to these concentrations.

Radionuclide:	Concentration (pCi/g)	Dose (1993) (mrem/year)	Dose (2023) (mrem/year)
(Lower Columbia)			
cobalt-60	1.6	1.7	0.029
nickel-63	4.4	0.000004	0.000003
strontium-90	NA	------	------
cesium-137	5.1	1.3	0.57
europium-152	9.6	4.4	0.79
plutonium-239/240	0.12	0.0063	0.0050
americium-241	0.021	0.0012	0.0005
TOTAL		7.4	1.4
(River Estuary)			
cobalt-60	NA	------	------
strontium-90	NA	------	------
cesium-137	0.36	0.089	0.041
europium-152	NA	------	------
plutonium-239/240	0.14	0.0074	0.0058
americium-241	0.039	0.0022	0.0009
TOTAL		0.099	0.047

Figure 3.1 - The calculated annual total effective dose equivalent to the MEI from the maximum measured concentrations of artificial radioactivity in the surface sediments of the Hanford Reach. The gradual decline of dose with each passing year is primarily due to radioactive decay. Year 1 represents the year 1994.

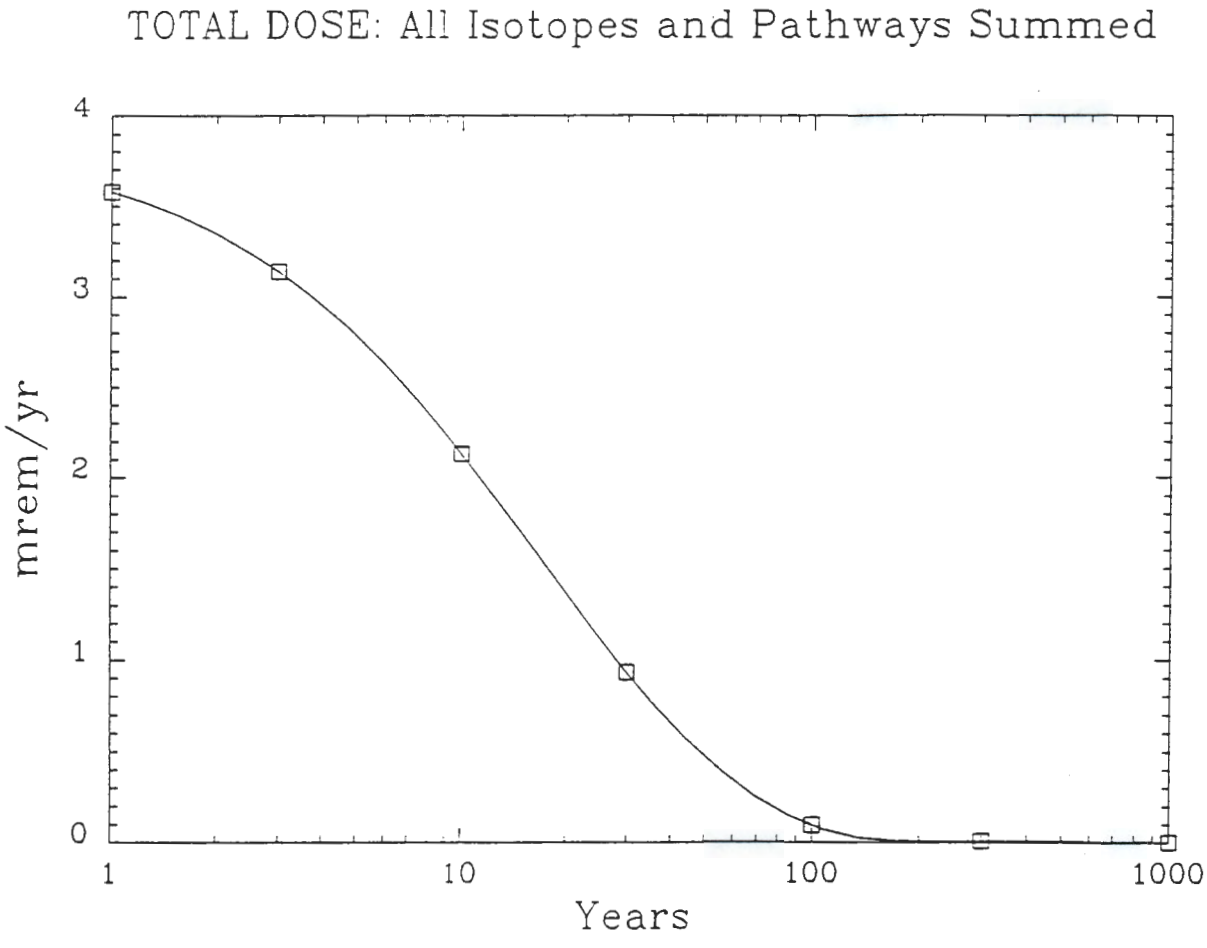


Figure 3.2 - The calculated annual total effective dose equivalent to the MEI from the maximum measured concentrations of artificial radioactivity in surface sediments of the lower Columbia River(McNary Pool). The gradual decline of dose with each passing year is primarily due to radioactive decay. Year 1 represents the year 1994.

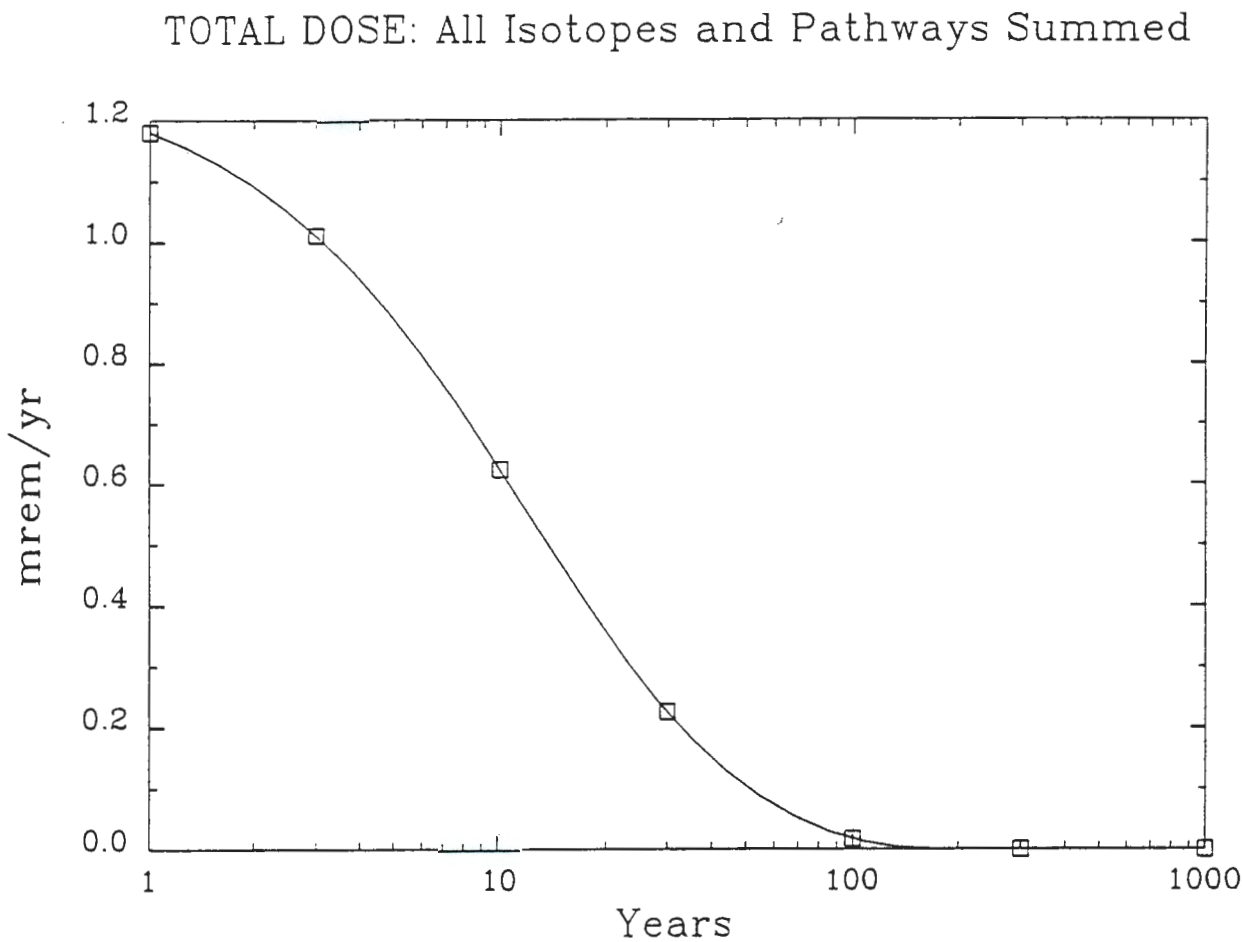


Figure 3.3 - The calculated annual total effective dose equivalent to the MEI from the maximum measured concentrations of artificial radioactivity in surface sediments of the river estuary. The gradual decline of dose with each passing year is primarily due to radioactive decay. Year 1 represents the year 1994.

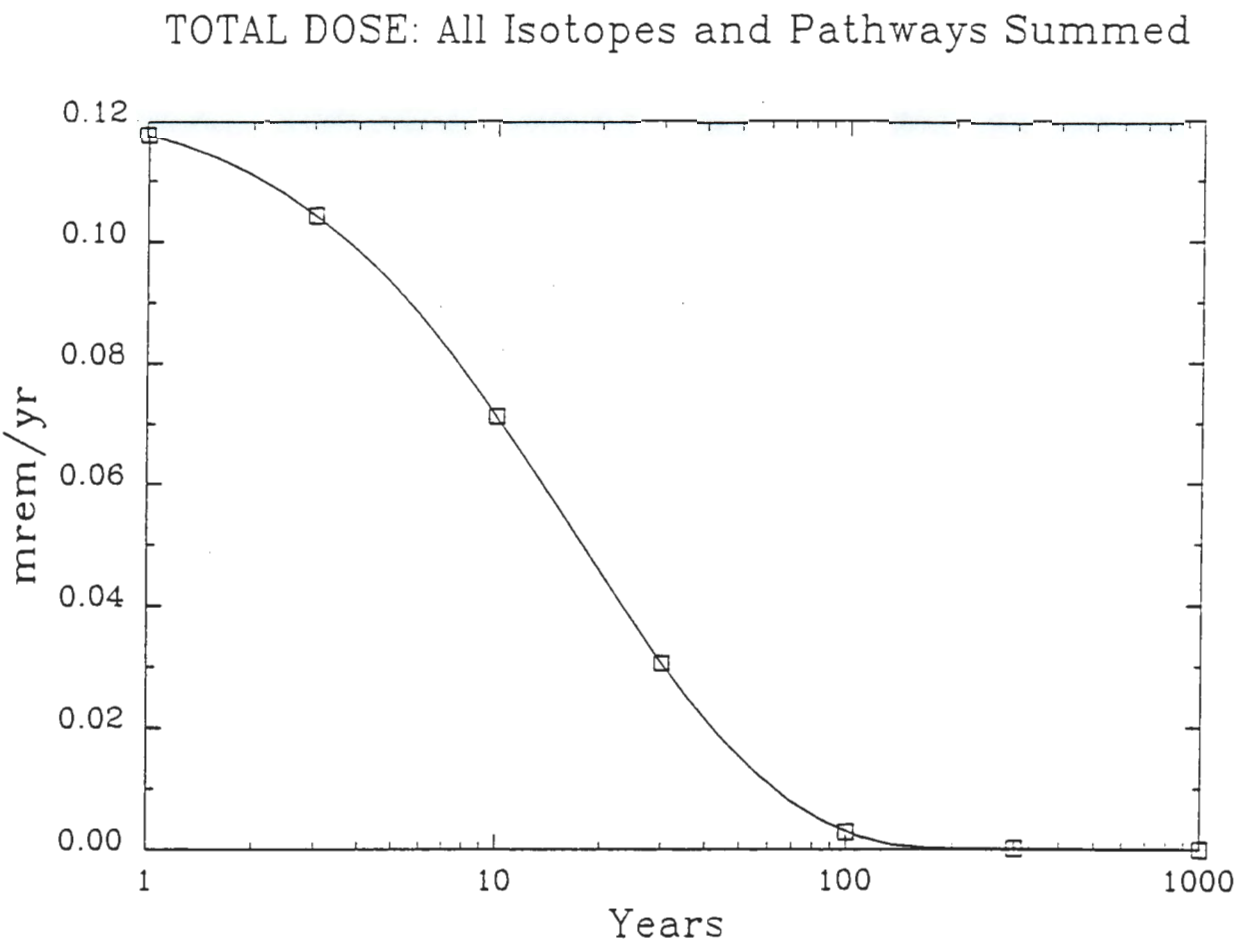


Figure 3.4 - The calculated annual total effective dose equivalent to the MEI from the maximum measured concentrations of artificial radioactivity in deeply buried sediments of the lower Columbia River(McNary Pool). It is assumed that these sediments have been dredged to the surface without mixing with less contaminated sediments. The gradual decline of dose with each passing year is primarily due to radioactive decay. Year 1 represents the year 1994.

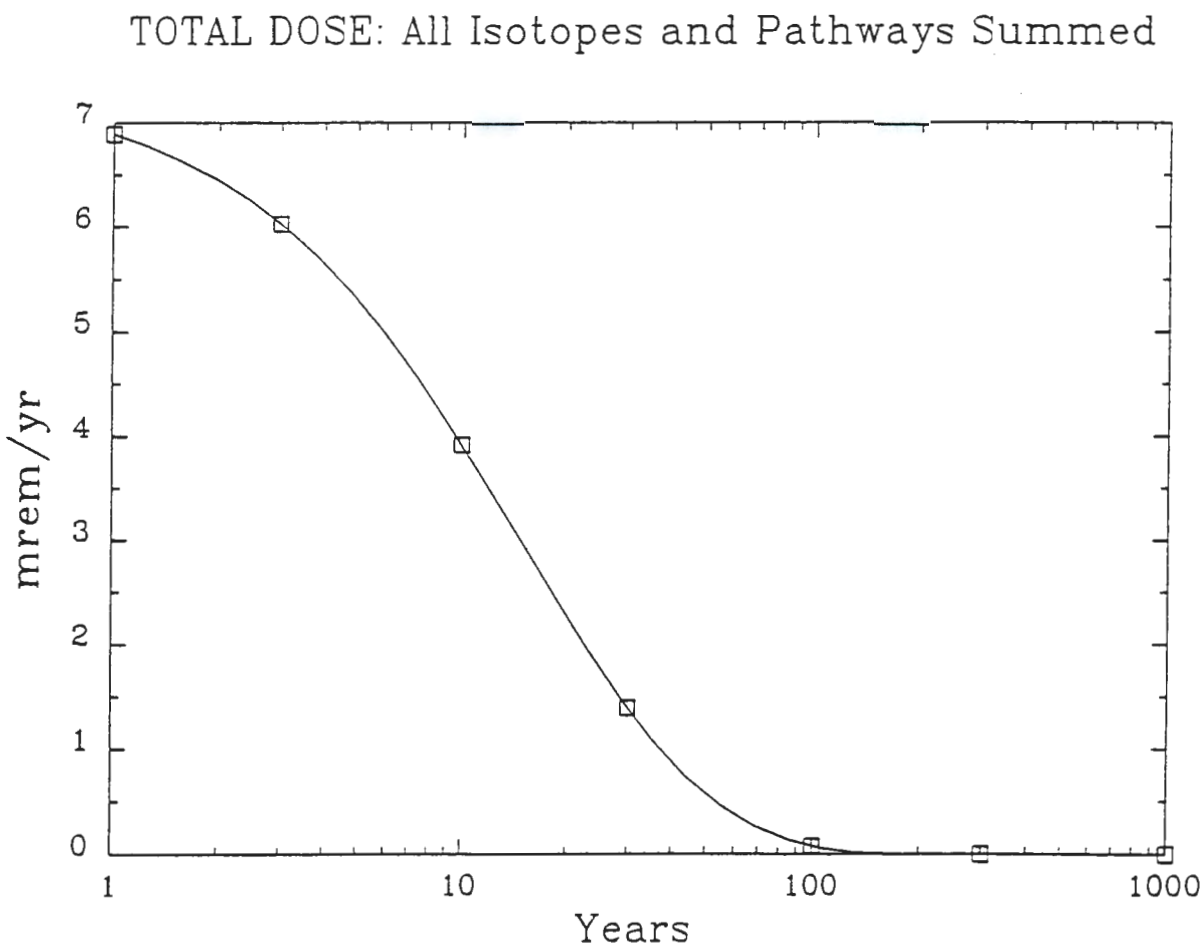
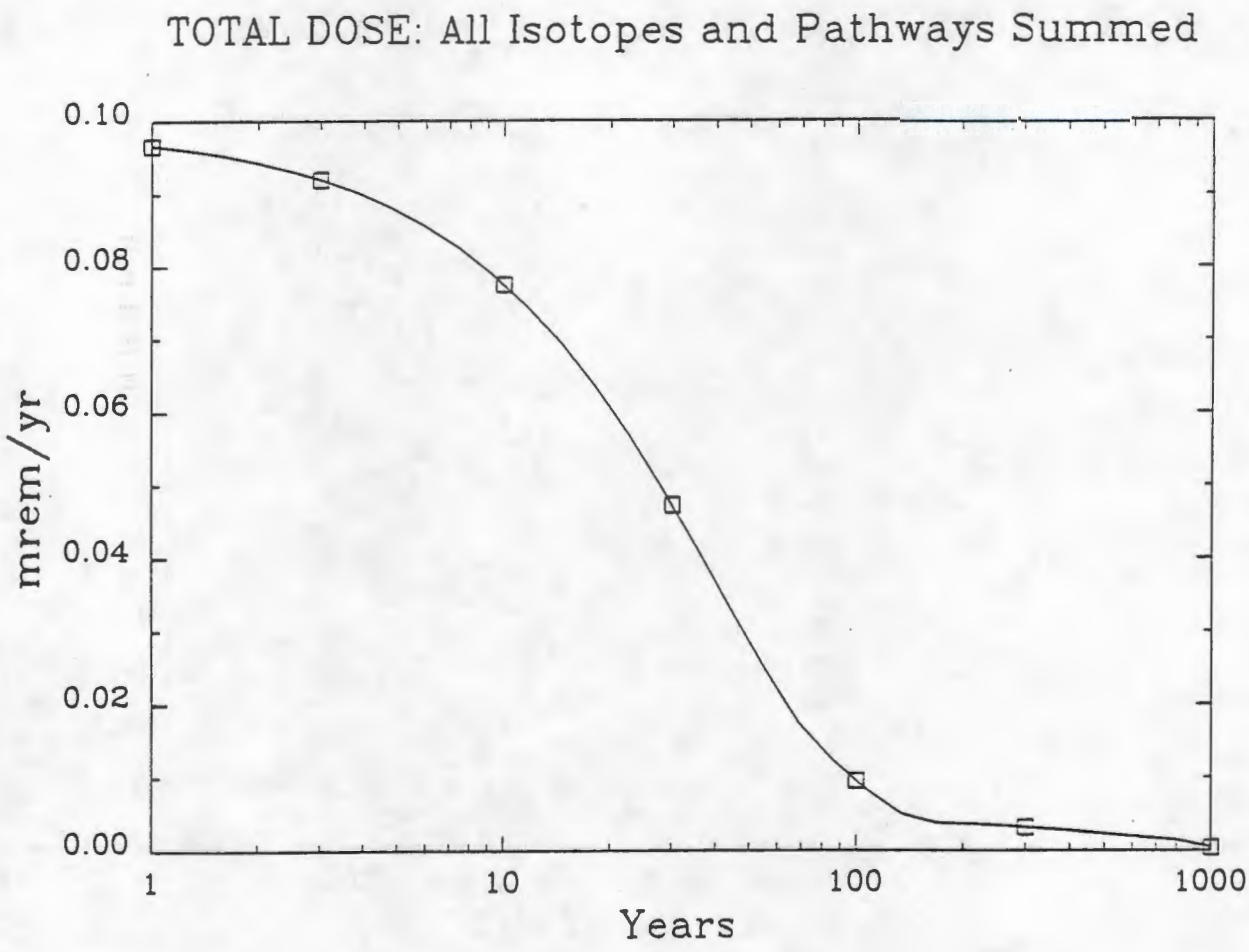


Figure 3.5 - The calculated annual total effective dose equivalent to the MEI from the maximum measured concentrations of artificial radioactivity in deeply buried sediments of the river estuary. It is assumed that these sediments have been dredged to the surface without mixing with less contaminated sediments. The gradual decline of dose with each passing year is primarily due to radioactive decay. Year 1 represents the year 1994.



Summary and Recomendations

The calculated doses and attendant risks from exposure to artificial radioactivity in Columbia River sediments are small for every section of the river. In particular, even the most contaminated sediments of the river, which are the deeply buried sediments in the McNary Pool, yield a risk level that is less than the risks associated with federal and state radionuclide air emission and drinking water standards. In addition, the concentrations of artificial radioactivity in Columbia River sediments, and their associated potential doses, diminish rapidly with distance from Hanford.

Data regarding radioactivity in Columbia River sediments has been provided in abundance by state and federal agencies, and academic researchers from the early 1960's to the present. These data cover every section of the river from the Hanford Reach to the Washington and Oregon coasts. The extensive coverage and overlap of many independent investigations ensure that these data are sufficient to establish human health risks.

In the Hanford Reach of the river several risks related to the radiological safety of the river have not been included in this report. These include "sky shine" from nuclear facilities near the river, various "seeps" along the river, which are intermittent springs from contaminated groundwater, and the potential for releasing cobalt-60 specks in the process of removing or stabilizing reactor discharge pipe "outfalls". Ecological risks have also not been evaluated.

The Department of Health recommends that further risk assessments should concentrate on issues specific to the Hanford Reach. These issues include skyshine from facilities near the river, contaminated seeps and reactor pipe outfall removal.

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Appendix A

Radiation and Human Health

About Radiation and Radioactivity

Radiation is a natural process to redistribute energy. For example, the hot temperature of the sun causes it to emit visible light, which is a form of radiation. This radiation redistributes energy from the surface of the sun to the earth and fuels all of the life upon the earth. The important aspect of this radiation is that it has just the right energy for plants to build organic molecules and hence grow. In contrast, higher energy radiations, often called ionizing radiation, have too much energy for life to utilize. In fact their collisions with organic molecules can destroy them. This destruction may have negative health effects upon the animal or plant that has been exposed to radiation. It is ionizing radiation that is cause for concern and which is discussed throughout the rest of this report.

The common forms of radiation found in the environment are referred to as alpha, beta and gamma. Alpha's are heavy particles that can be characterized by their extremely short range. In fact alpha's are just the nucleus of a helium atom. The range of alpha particles is so short that they can not penetrate human skin, or even a few inches of air. Beta's are much lighter particles that also have short range, but somewhat longer than alphas. Examples of a "beta particles" that are too low in energy to qualify as ionizing radiation are electrons circling an atom, or electrons flowing through home-wiring to supply electricity. Gamma's are massless particles that have a very long range, and therefore great ability to penetrate the human body. Their analogue in the low-energy range, and therefore nonionizing range, is visible light.

Radioactivity is the name given to the phenomena of matter emitting ionizing radiation. Similarly, matter that emits radiation is termed radioactive. All matter is made of atoms; which consist of electrons circling around a central core or nucleus. The nucleus is made of protons, which carry charge, and neutrons, which are uncharged. Atoms are all referred to as belonging to the same element if they all have the same number of protons. For example hydrogen has one proton, carbon has six protons and oxygen has eight protons.

The convention we will use is the name of an atom followed by the sum of its number of protons and neutrons. For example carbon-12, which is the most naturally abundant form of carbon, consists of six protons and six neutrons for a total of twelve protons and neutrons. Carbon-13 and carbon-14, which consist of six protons and seven and eight neutrons respectively, are also found in nature. Each of these different forms of carbon are called isotopes of carbon. All isotopes of

a particular element have the same chemical properties, but different isotopes have different nuclear properties. One such property is radioactivity. If an isotope is radioactive it is called a radioisotope. In the example given carbon-12 and carbon-13 are nonradioactive isotopes of carbon. Carbon-14 is radioactive, and therefore a radioisotope of carbon. In this report we use the terms radioisotope and radionuclide interchangeably

All radioisotopes will eventually decay, by emitting radiation, to nonradioactive isotopes. For example carbon-14 decays to nitrogen-14. An important property of any radioisotope is the half-life. The half-life is the amount of time it takes for half of that radioisotope to decay. In the example above carbon-14 has a half-life of 5,730 years. Thus if one had one pound of pure carbon-14, after 5,730 years there would be 1/2 pound of carbon 14 and 1/2 pound of nitrogen-14. After another 5,730 years, for a total of 11,460 years, there would be 1/4 pound of carbon-14 and 3/4 pound of nitrogen-14. This decay process would continue indefinitely until all of the carbon-14 had decayed to nitrogen-14. The physical process of radioactive decay is illustrated in Figure A.1, where the decay of tritium (hydrogen-3) to helium-3 is shown. Tritium is chosen for this illustration because of its relative simplicity.

In contrast to this simple decay scheme, heavier radioisotopes often decay to another radioisotope, which decays to another radioisotope, and so on until this decay process culminates in a nonradioactive isotope. This sequence of decays is called a decay chain. Each of the isotopes produced by these decays are called decay products. For example, uranium-238 decays to thorium-234, which decays to protactinium-234 and so on until the decay chain ends with nonradioactive lead-206.

From the perspective of human health, exposure to radiation is quantified in terms of radiation dose. Radiation dose measures the amount of energy deposited in biological tissues per weight of tissue. Thus low energy radiation, such as visible light, yields a negligible radiation dose. Conversely, ionizing radiation, because it is high energy radiation, can deposit large amounts of energy, and hence cause a significant radiation dose.

Figure A.1 - A decay-event is shown of a tritium nucleus (hydrogen-3).

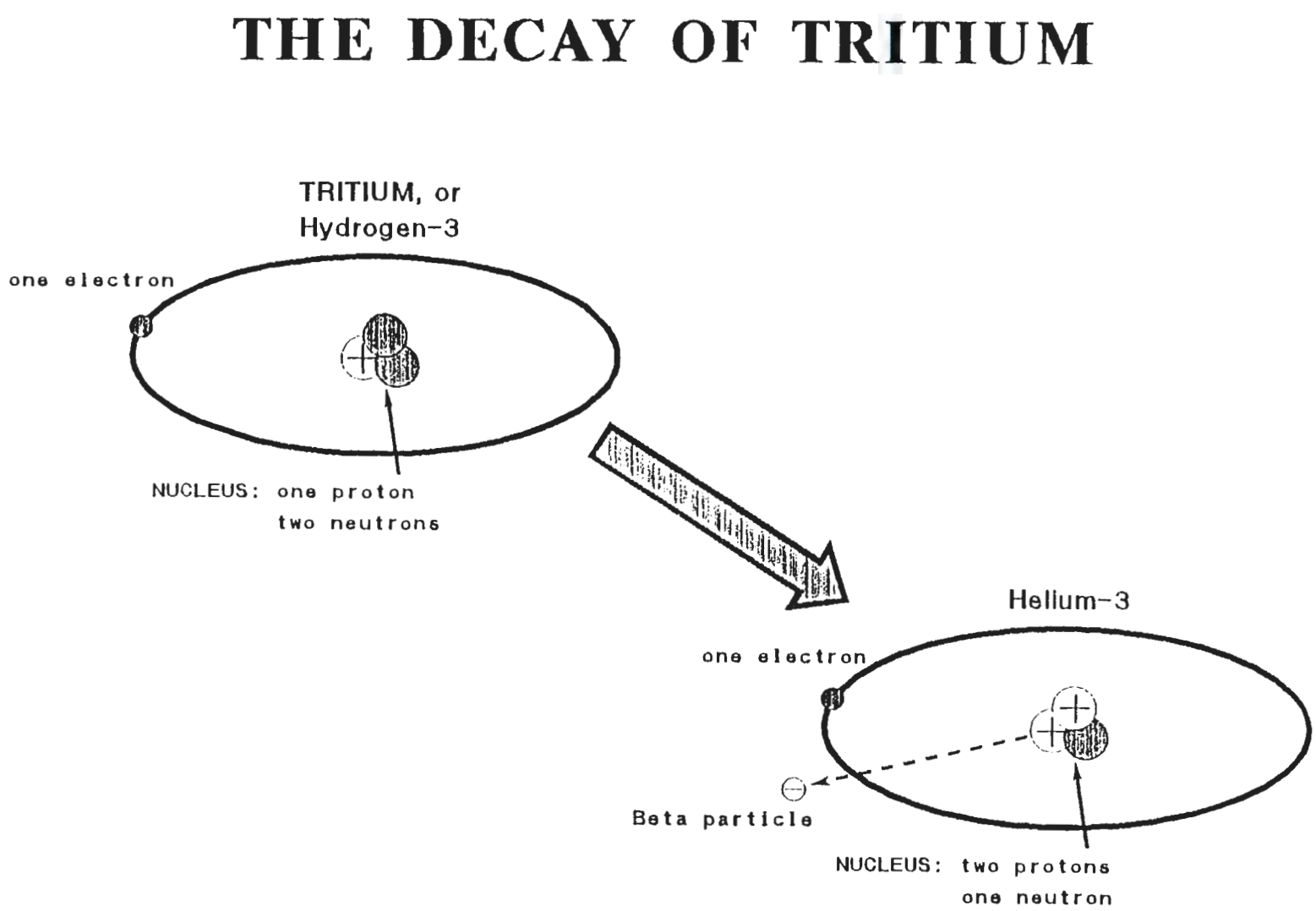
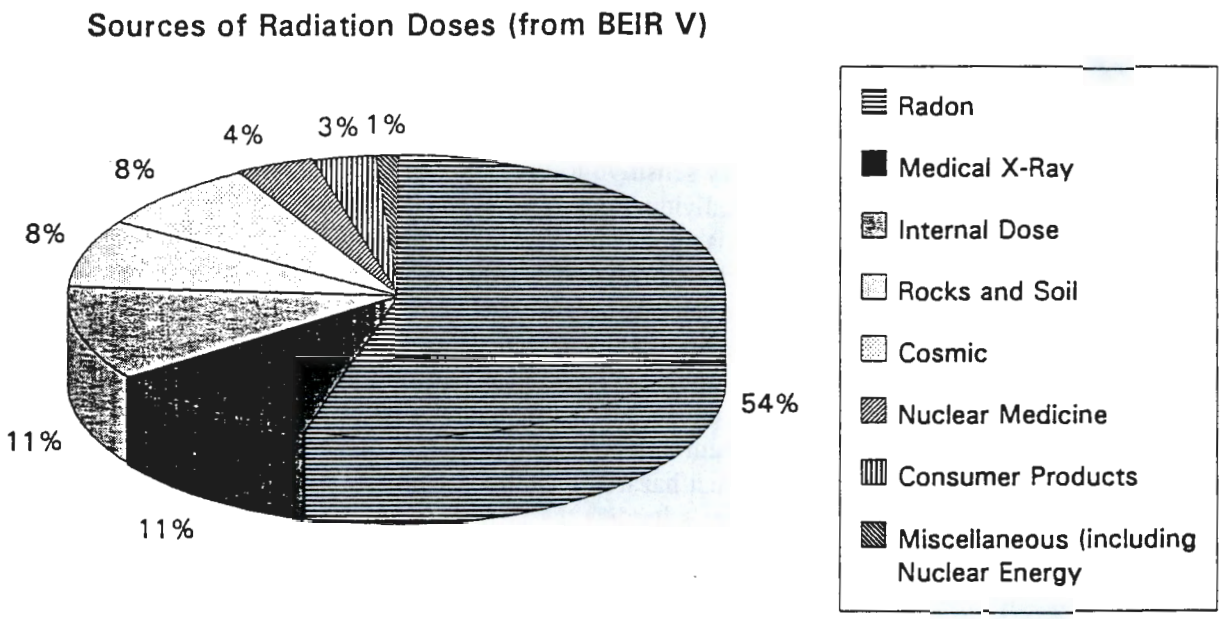


Figure A.2 - The radiation dose to the average American and its breakdown into various sources.



Radiation doses are commonly measured in units of rems or milli-rems (mrem). The most significant radiation dose received by the general public is due to radon-222 exposure (Figure 3). Radon-222 is part of the uranium-238 decay chain and is commonly found in homes by the decay of uranium-238 naturally present in the soil below the home. An average individual in the U.S. receives approximately 200 mrem per year (mrem/year) from radon. Another 158 mrem/year is received from natural sources and medical procedures, of which 40 mrem/year comes from inside the body. The primary pathway into the body is by the consumption of food and water. Thus these 40 mrem/year are primarily from food and water. The average American receives less than 1 mrem/year from nuclear facilities. The total average whole body dose nationwide is approximately 360 mrem/year, or approximately one mrem per day. The components of the average annual radiation dose from various sources is shown in fig. A.2.

The radiation dose that an individual receives from a particular isotope is very sensitive to the type of radiation that the isotope emits and how the individual comes in contact with the radiation. For example, radioisotopes that are alpha emitters will not yield a radiation dose, and therefore are not dangerous, as long as they are external to the body. This is because the short range of alpha's does not allow them to penetrate human skin. Conversely, once inside the body via ingestion, inhalation or absorption through the skin, alpha emitters are very dangerous. Examples of alpha emitters include radon-222, uranium-238 and plutonium-239. Beta emitters are slightly greater external hazards than alpha emitters, but like alpha's, the short range of beta's implies that beta emitters are much greater internal hazards than external hazards. An example of a beta emitter is strontium-90. In contrast to beta and alpha emitters, gamma emitters can yield a significant dose, and hence are significant radiological hazards whether, they are internal to the body or not. This is due to the great penetrating power of gamma's. An example of a gamma emitter is the decay product of cobalt-60, which is nickel-60.

It is conventional, although incorrect, to refer to cobalt-60 as a gamma-emitter because the gamma decay of nickel-60 occurs very soon after the cobalt-60 nucleus beta-decays to nickel-60. This misuse of language is widely applied to all of the well-known gamma emitters because of its convenience. Other examples of "gamma emitters" that do not directly emit a gamma ray are cesium-137 and europium-152. This report follows this convention.

Health Effects

The ways, or paths, that environmental radioactivity, whether natural or artificial, can lead to a radiation dose are called exposure pathways. One such pathway is called "shine", which is the direct emission of gamma rays from gamma-emitters in soils. Other pathways include inhalation of airborne soils that contain radionuclides, ingestion of radioactive soils or water and many other potential paths.

Calculation of radiation dose from a known concentration of radioactivity in the environment is a complex process that is fraught with uncertainty. Nevertheless, there are now a number of computer models and federal and international guidance documents to guide environmental dose assessments. Once these doses have been calculated, the final step in estimating health effects is to convert radiation doses to human health risks.

The health effects of radiation are substantially better known than most other carcinogens because, in addition to animal data, there is a wealth of human data. However, like all carcinogenic "agents", when levels of exposure are less than the level where one can readily observe health effects, scientists must use extrapolations to estimate health effects. For example, it is relatively easy to observe the health effects of smoking two packs of cigarettes per day; but, when an individual only smokes two packs per year it is literally impossible to observe health effects. In this case the risks are estimated from extrapolating from heavy smokers. In radiation protection the relationship between dose and risk is assumed to be linear at environmental levels. That is, the risk associated with a dose is directly proportional to that dose.

The risk estimates of this report consider only carcinogenic risks due to radiation dose and do not account for the toxicological characteristics of the radioisotopes in question. Generally, except for uranium, the toxicological effects of radionuclides are much less than the carcinogenic effects due to radiation. Estimates of risk are taken from the National Academy of Sciences report BEIR V[Be90a]. The data from Japanese victims of atomic weapons are the most important data in their analysis. Thus their estimates are extrapolations from persons exposed to doses of 10,000 mrem or more in a very short period of time. BEIR V estimates cancer fatalities per 100,000 individuals for continuous lifetime doses of 100 mrem/year to be 600 for females and 520 for males. Averaging the results of the two sexes, a continuous lifetime radiation exposure of 100 mrem per year results in a excess cancer death rate of 560 deaths per 100,000 persons.

There is much debate over the validity of extrapolating the effects and risks seen at high radiation doses to doses below background levels. Some researchers claim that the risks are significantly higher than the linear response estimates. Others claim that the risks are significantly lower. However, the only claim that can be made with certainty is that the risk of cancer at radiation doses below about 10,000 mrem is so small that no one has been able to unambiguously measure it.

Most radiation protection organizations view the linear response relationship as a conservative, or protective, estimate of risk from radiation[NCRP39, Be90a]. It should be noted that the uncertainty of the linear extrapolation is sufficiently great that the risk of very low levels of radiation may be zero. As stated in BEIR V: "The possibility that there may be no risks from exposures comparable to external natural background radiation cannot be ruled out. At such low doses and dose rates, it must be acknowledged that the lower limit of the range of uncertainty in the risk estimates extends to zero.".

Radiation Detection and Measurement

Ionizing radiation was first measured almost a century ago. While the technology for detection of radiation has improved enormously, it is still difficult to measure the low levels of radioactivity typically found in the environment. In order to understand the levels of radioactivity discussed in this report it is useful to discuss how radioactivity is quantified and the uncertainties in the results.

The curie, Ci, is the basic unit of radioactivity and is defined as the number of nuclear decays per second found in one gram of radium-226. Environmental data are generally reported in fractions of a curie. Data in this report are reported in picoCuries (pCi), which is one trillionth of a curie. One picoCurie is the amount of material that yields 2.22 nuclear decays per minute. Since many radioisotopes decay rapidly, the measured radioactivity of a sample may be less than at the time of collection. Researchers and laboratories routinely calculate and report the sample activity to be that activity at the time of collection.

Radioactivity measurements are reported in terms of sample concentration. The concentration in each sample reflects the radioactivity per sample weight or volume, as the case may be. Radioactivity concentration in sediments is calculated in picocuries per gram (pCi/g) on a dry weight basis. "Dry weight" essentially means that the radioactivity concentrations apply to these samples after a drying process has been applied to them. We report all sediment

concentrations in terms of "dry weight" when available, or estimated dry weight concentrations when the original research is reported on a wet weight basis. We estimate dry weight concentrations from wet weight concentrations by assuming that the density of dry sediments is 60% of the density of wet sediments. While this may be a crude estimate, we believe it is sufficient for the purposes of this report.

All radioactivity measurements for samples are reported with an uncertainty. The uncertainty arises for a number of reasons including imperfections in the apparatus or procedure, human error and counting uncertainty. The counting uncertainty arises because radioactive decay is a random process. This means that if one counts the radioactive decays of a sample several times, each for a fixed time, one will find that the measured number of decays varies randomly. However these random answers all cluster near an average value. For example, if one were to measure the decays of a sample for one minute and count ten decays, subsequent minute-long measurements might find 9 decays, 7 decays, 12 decays, etc. It is usually assumed that the counting uncertainty is the dominant uncertainty. The uncertainties we report are the counting uncertainties only.

The randomness of radioactive decay, and the resulting counting uncertainty, is difficult to understand; but there is an example of random levels of radiation from everyday life. Radiowaves are very low energy radiation. Their energy is even lower than visible light. Sources of radiowaves include human activities such as radio towers, as well as natural sources such as the sun. If one tunes a radio to "between stations" one hears what is termed "static" or "noise". This noise has an average value, or loudness, which is analogous to the measured level of radioactivity as discussed above. However, the noise also fluctuates randomly about the average noise rather than sounding like a constant tone. These random fluctuations of radiowaves are analogous to the random number of counts observed in a measurement of radioactivity. These fluctuations lead to an uncertainty in a measurement of average noise just as there is a counting uncertainty in a radioactivity measurement.

One consequence of the uncertainties in a measurement of radioactivity is that it is not possible to determine zero concentration of a radioisotope. Rather, when the uncertainty is such that one cannot distinguish between the sample and background counting rates, we report that the sample radioactivity is less than some concentration. This minimum concentration is termed the Lower Limit of Detection

(LLD). Practical sample size, counting time and background radiation all combine to determine the LLD. A sample result near the LLD, where most environmental levels are, is not considered a health risk.

An analogous situation is trying to tune a radio to find a weak radio signal. When the "static noise" is high it is very difficult to determine whether the desired radio signal is present or not.

Uncertainties are usually reported as a "1 sigma" or "2 sigma" uncertainty. A 1 sigma uncertainty is interpreted to mean that one should have 68% confidence that the true concentration in the sample lies somewhere between the measured concentration minus the uncertainty and the measured concentration plus the uncertainty, whereas a 2 sigma uncertainty implies 95% confidence. When available, the reported uncertainty is included with all results. All uncertainties included in this report are "2 sigma" uncertainties.

Measurement of different types of radiation require different laboratory techniques. For example the technique used to measure gamma radiations is called "gamma scan". Unfortunately this technique is insensitive to radionuclides that primarily emit alpha or beta radiation. Similarly, alpha and beta spectroscopy techniques are insensitive to gamma radiation. Some of the results of this report are limited by the breadth of techniques employed. These limitations of individual results are noted in the text.

It is useful to classify the radioisotopes discussed in this report into categories. One category is half-life. By short lifetime we mean the half-life is less than one year, by intermediate lifetime we mean the half-life is one to thirty years, and by long lifetime we mean the half-life is greater than thirty years. We also classify radioisotopes by their source, or origin. Major sources include Hanford, worldwide fallout from nuclear weapons tests, and natural sources. These radioisotopes, their half-lives and principle sources are listed in Tables A.1 through A.3.

The levels of radioactivity in the Department of Health samples for this report were measured at the Department of Health Public Health Laboratories in Seattle. Analytical techniques are based on standard methods. This facility serves as a regional reference laboratory and as such operates under a rigorous quality assurance program. This program contains quality control elements which help ensure the laboratory's high analytical proficiency and accuracy. Laboratory quality control includes analysis of samples distributed by the federal government's quality assurance programs; split samples distributed on

a smaller scale between cooperating federal, state and private laboratories; and internal procedures relating to the counting facilities and analytical techniques. The Department of Health quality assurance programs ensure that the sample collection, transfer, data entry and analysis are performed in accordance with internal procedures. These steps are necessary to ensure no bias is introduced to a sample. Greater detail on the analytical techniques and quality assurance program can be found in Washington State Environmental Radiation Program Annual Reports [Wa90].

Results from other laboratories, programs and researchers are generally reported uncritically if the results are relevant. In most cases the published results appear to have been subjected to rigorous quality-control scrutiny. Much of this data has been published in peer-reviewed journals, and therefore also subjected to the scrutiny of research competitors. Cases where data reliability is questionable are noted.

Table A.1
Table of Short-lived Radioisotopes

Short-lived Radioisotope	Half-Life	Primary Sources in the Columbia River
Beryllium-7	53 days	Natural
Scandium-46	84 days	Hanford
Chromium-51	28 days	Hanford
Manganese-54	312 days	Hanford
Cobalt-57	272 days	Hanford
Cobalt-58	71 days	Hanford
Iron-59	45 days	Hanford
Zinc-65	244 days	Hanford
Strontium-89	51 days	Fallout
Zirconium-95	64 days	Fallout
Ruthenium-103	39 days	Fallout
Ruthenium-106	372 days	Fallout
Antimony-124	60 days	Hanford
Iodine-131	8 days	Fallout
Barium-140	13 days	Fallout
Cerium-141	33 days	Fallout
Cerium-144	284 days	Fallout

Table A.2
Table of Intermediate-lived Radioisotopes

Intermediate-lived Radioisotope	Half Life	Primary Sources in the Columbia River
Hydrogen-3 (Tritium)	12.3 years	Natural, Fallout, Hanford
Iron-55	2.7 years	Hanford
Cobalt-60	5.3 years	Hanford
Strontium-90	29 years	Fallout
Cesium-137	30 years	Fallout
Europium-152	13.5 years	Hanford, Fallout
Europium-154	8.6 years	Hanford, Fallout
Europium-155	4.7 years	Hanford, Fallout
Thorium-228	1.9 years	Natural
Plutonium-241	14.4 years	Fallout, Hanford

Table A.3
Table of Long-lived Radioisotopes

Long-lived Radioisotope	Half Life	Primary Sources in the Columbia River
Potassium-40	1,250,000,000 years	Natural
Nickel-59	76,000 years	Hanford
Nickel-63	100 years	Hanford
Iodine-129	16,000,000 years	Fallout
Radium-226	1,600 years	Natural
Thorium-230	75,400 years	Natural
Thorium-232	14,000,000,000years	Natural
Uranium-234	250,000 years	Natural
Uranium-235	700,000,000 years	Natural
Uranium-238	4,500,000,000 years	Natural
Plutonium-238	88 years	Fallout, Hanford
Plutonium-239	24,110 years	Fallout, Hanford
Plutonium-240	6,560 years	Fallout, Hanford
Americium-241	432 years	Fallout, Hanford
nat-Uranium		Natural
nat-Thorium		Natural

Sources of Radioactivity in the Columbia River

Sources of radiation in the environment in general and the Columbia River in particular are primarily natural but also artificial. Naturally occurring radiation comes from the radioactive decay of sources such as potassium-40, radon, thorium and uranium. These radioisotopes have been present since the formation of the earth. Another natural source of radiation we are continually exposed to is from cosmic rays. Cosmic rays are very high energy radiations that bombard the earth from outer space. In addition, cosmic rays produce radioactive elements through violent collisions with nonradioactive isotopes in the atmosphere and on the surface of the earth. For example, this process is the source of most of the carbon-14 in the environment. Naturally occurring sources produce most of the environmental levels of radiation. This is also true for the Columbia River.

In the past century, environmental radiation levels have also been influenced by human activities such as the use and manufacture of radioactive materials. Such activities include the practice of nuclear medicine, uranium mining operations, nuclear power generation, nuclear weapons activities, and nuclear waste disposal. Other activities that contribute include: the use of fertilizer containing relatively high concentrations of natural radioisotopes by farmers and homeowners, the practice of dumping radioactive materials into landfills, other mining activities, and burning fossil fuels that are relatively rich in natural radioactivity.

It is useful to note that "artificial radioisotope" is somewhat misleading. There are no man-made radioisotopes that do not also occur in nature. Artificial radioisotope simply means that the radioisotope in question is so rare in nature that one can be sure of its human origins if its presence has been measured.

The documented contribution of radioactivity from human activities to the Columbia River is dominated by Fallout and Hanford Operations. Other contributions from nuclear facilities such as WNP-2 and Trojan nuclear power plants are negligible by comparison. The contribution from industrial, farming and homeowner practices is unknown.

Operations at the U.S. Department of Energy Hanford Site contributed significant amounts of radioactive materials to the Columbia River. These activities began with the start of the first of nine plutonium producing reactors in 1944. The progressive closure from 1964 to 1971 of all Hanford reactors except the N-Reactor reduced emissions of radioactive material into the Columbia River to very low levels.

The N-Reactor was put in cold standby February 16, 1988, and has remained in standby since then. Present environmental radiation levels within the state remain nearly at natural environmental levels except for areas on the Hanford Site and near uranium processing facilities.

The sources of releases of radioactivity from a nuclear reactor are the reactor fuel, fission products, neutron-activated reactor fuel and other neutron-activated materials. The first three of these are all contained in metallic fuel cladding and thus require fuel element failure to achieve a release. The last of these include reactor equipment, reactor structures and minerals dissolved in the reactor coolant(usually water). For example, the radioisotopes cobalt-60 and zinc-65 are often found in reactor cooling water. These radionuclides are produced from the presence of nonradioactive cobalt-59 and zinc-64 in cooling water.

Nuclear reactors are typically cooled with water in one of two designs. The first and older design is called "single-pass" or "once-through". In this design the cooling water is drawn from an environmental source, passed through the reactor core and then discharged back into the environment. In this design all of the neutron-activated material in the cooling water is directly discharged into the environment, and the only barrier preventing reactor fuel, fission products and neutron-activated reactor fuel from entering the environment is the fuel element cladding.

Modern designs are all "closed-loop" or "double-pass". In this system the cooling water that passes through the reactor core is contained in a closed circulation system, and the excess heat is transferred to a secondary cooling system which draws and discharges water directly from and to the environment. Thus closed loop systems require at least one failure to allow neutron-activated material in cooling water to reach the environment, and at least two failures for fuel-related material to reach the environment. Thus a closed loop reactor should, in principle, contribute negligibly to environmental radioactivity, whereas a single-pass reactor can contribute large amounts of radioactivity to the environment. All commercial reactors have a closed-loop cooling system. At Hanford the first eight reactors that were built were all single pass reactors, while the last one (N-reactor) was a closed-loop reactor. The discharges from the single-pass reactors dominated the Hanford-origin radioactive emissions to the river.

Despite the contributions from Hanford, environmental radiation levels in the State of Washington and the Columbia River were most altered by residual fallout from nuclear weapons testing. The United States and the U.S.S.R. ceased atmospheric testing following adoption of the

1963 Nuclear Test Ban Treaty. Consequently, only long-lived fallout radionuclides from these tests remain. Other countries, principally China, continued above-ground nuclear weapons tests until 1981. Fallout from the Chernobyl nuclear power accident in 1986 has provided the most recent major contribution of artificial radioactivity to the environment.

Like nuclear reactors, nuclear weapons are sources of nuclear fuel, fission products, neutron-activated fuel and neutron-activated metals. Unlike nuclear reactors however, nuclear weapons explosions, by design, release to the environment all of the unused fuel, all of the neutron activated fuel and all of the fission products. Thus one would expect, barring reactor fuel element failures, that environmental levels of fission products such as strontium-90 and cesium-137, and neutron-activated fuel such as plutonium-239 stem primarily from fallout. This expectation is born out by the studies cited in this report. In contrast, both single-pass reactors and nuclear weapons tests can release significant amounts of neutron-activation metals such as cobalt-60. The experimental evidence, however, is that in the Columbia river radioisotopes such as cobalt-60 are primarily of Hanford-origin.

Appendix B

Levels of Activity in Columbia River Sediments

The body of data that has been accumulated regarding radioactivity in Columbia River sediments is vast. While Chapter 2 of this report summarizes the most recent results, there are many other relevant studies available. This appendix summarizes some of the other most significant results.

The Hanford Reach: Priest Rapids to McNary

One of the earliest investigations of this section of the river was by Nelson et al.[Ne66]. They collected surface and deep core sediment samples. They reported great difficulty, however, finding areas from the river bed that had sufficient sedimentation for deep-core sampling. Similar sampling difficulty was found by Robertson and Fix[Ro77] and Beasley *et al.*[Be84].

An important conclusion of this investigation is that radionuclide concentrations in the silt and clays found behind dams is hundreds of times higher than concentrations in the larger particles which predominate along the Hanford Reach. While this study showed that the concentrations of radioactivity in the river bottom sediments of the Hanford Reach were very low (often below the lower limit of detection), they could not exclude a significant total inventory of radioactivity in this reach since most of the river bed is made of coarse cobble.

An extensive aerial investigation was published by J.J.Fix in 1976[Fi76]. This study included aerial measurements of surface gamma activity and surface and deep core sediment samples. The study covered the Columbia River shoreline, islands and slough areas from Priest Rapids Dam to 13 miles downstream of McNary Dam. The radionuclides measured were short and intermediate lifetime nuclei.

The highest levels of surface gamma activity were found to come from cobalt-60 and europium-152. These areas were chosen for surface sediment sampling. Analysis of these samples confirmed that the highest concentrations of radionuclides in these sediments were cobalt-60 and europium-152; however, while there was a correlation between the aerial survey and sediment sample results, the correlation was not strong enough to infer radioactivity concentrations in sediments from an aerial survey alone. Nevertheless, the correlation between aerial survey results and surface sediment concentrations is strong enough to quickly identify areas for further investigation.

Other surveys have been performed since then, both of the aerial type and manual surveys using handheld instruments[EGG90, Su80]. The aerial survey[EGG90] simply identified gross properties of the distribution of radioactivity along the river. In contrast the manual survey by Sula *et al.*[Su80] was able to identify smaller features of contaminations, such as flakes of radioactive metal.

Sula *et al.* surveyed the river shorelines, islands and sloughs from the uppermost reactor to the confluence of the Columbia River with the Snake River. The distribution of measured activity was approximately uniform and slightly elevated above background, with a number of areas of significantly increased activity, and some very local hot spots. They attributed the hot spots to radioactive metallic flakes from pumps and other metallic components of reactor cooling systems.

Routine sampling of sediments from the Hanford Reach was resumed by the DOE in 1988[Wo92]. These samples were surface samples from the top 6 inches of sediments. Sampling was concentrated on sandy areas of islands, sloughs and shoreline.

In general, these measurements have found concentrations to be low and consistent with background levels. An exception to this is uranium, whose measured concentrations were slightly elevated relative to Priest Rapids Dam, and comparable to concentrations behind McNary Dam. These concentrations were typically approximately 1.1 pCi/g.

In 1992 DOE supported two major surface sediment studies along the Hanford reach. These studies were conducted by Westinghouse[We93] and Battelle[Co93]. Both of these investigations emphasized finding the highest areas of radioactivity. They collected samples from areas of sedimentation where aerial surveys found elevated activity, and therefore, one might expect maximum radioactivity concentrations.

The 1992 Westinghouse study[We93] took sediment samples from the Hanford reach between B-reactor and the Hanford town site. These sites were chosen based on aerial survey results and areas of obvious sediment deposition downriver from reactor discharge areas, areas of low-flow and areas of back-flow. Forty four samples of surface and subsurface sediments were taken from 28 sampling locations. Three locations were taken near Vernita Bridge, which is upstream of Hanford activities, 22 were taken from the 100-area sloughs, islands

and shorelines, and 3 from the vicinity of the old Hanford townsite. The EPA, Washington Department of Ecology and Department of Health all participated in this study. The Department of Health split 20% of these samples.

For most radioisotopes the maximum observed concentrations in the Hanford reach were consistent with the concentrations observed near Vernita Bridge. However, several samples, primarily from the vicinity of the 100-H and 100-F reactors, showed elevated levels of cobalt-60, cesium-137, europium-152 and uranium isotopes. The maximum observed concentrations of these radioisotopes were 0.41 pCi/g, 4.60 pCi/g, 1.80 pCi/g and 4.60 pCi/g respectively. These should be compared, with caution, to the maximum levels observed at Vernita Bridge of 0.14 pCi/g and 1.80 pCi/g for cesium-137 and uranium respectively. The concentrations of cobalt-60 and europium-152 at Vernita Bridge were below the lower limit of detection. The uncertainty in these results varied from approximately 3% to 20%.

We emphasize that caution should be used in the comparison of maximum concentrations because there were many more samples taken from the Hanford reach than from the Vernita Bridge area. Under these circumstances it is a general statistical property that even if the two areas had similar concentrations of radioactivity one would expect maximum concentrations from the Hanford reach to significantly exceed maximum concentrations from the Vernita area.

The measured average concentrations are difficult to calculate because only results above the lower limit of detction were reported. However typical concentrations for cobalt-60, cesium-137, europium-152 and uranium were approximately 0.1 (or less) pCi/g, 0.3 pCi/g, 0.3 pCi/g and 1.7 pCi/g respectively. As with maximum concentrations, the typical concentrations tended to be higher in the 100-H and 100-F areas.

The Battelle study[Co93] chose sampling sites based primarily on areas of elevated activity observed in an aerial survey[EGG90]. These sites were areas of exposed sediments on the river shoreline, on the many islands of the Hanford reach, and along the sloughs. Sampling extended from the Vernita Bridge to the vicinity of the Richland pumphouse. Fifty six samples were taken in all.

Similar patterns of radioactivity deposition were observed in both studies. Both studies measured maximum concentrations of cobalt-60 in the 100-D area and maximum or near-maximum concentrations of cesium-137 and europium-152 in the vicinity of the 100-H area.

However, unlike the Westinghouse study the Battelle study found relatively high concentrations of cesium-137 and europium-152 in the 100-D area and the Hanford town-site area. In fact the highest concentrations of europium-152 was observed in the Hanford town-site area. The average concentrations of these radioisotopes follow a similar pattern of higher concentrations in the 100-D, 100-H and Hanford town-site areas.

The maximum observed concentrations of cobalt-60, cesium-137 and europium-152 were 0.91 pCi/g, 5.97 pCi/g and 2.41 pCi/g respectively. Average concentrations of these three radioisotopes were approximately 0.15, 0.7 and 0.5 pCi/g respectively. The reported data uncertainties are typically a few percent. While none of the sampling locations were identical with the Westinghouse sampling locations, comparison of results from similar locations yields reasonably good agreement.

Since important conclusions of this report hinge on the Battelle and Westinghouse studies, some criticisms of these studies is in order. The Battelle study found that of the 56 samples taken, the zinc-65 concentration was less than zero for 55 samples. Since zinc-65 is a short-lived radioisotope, one expects these concentrations to be effectively zero. This implies that there was a systematic oversubtraction of background in the data analysis. Without access to the original data, it is unclear to the Department of Health how large a problem this is. However, since zinc-65 was measured by the technique called gamma spectroscopy, it could mean that many of the reported radioisotope concentrations that were measured with the same technique are too low.

In contrast to this, the Westinghouse study failed to report any concentrations that were below the lower limit of detection. The Department of Health finds this more disquieting than the zinc-65 problem in the Battelle study because so many results were less than the lower limit of detection, and because this does not allow one to test the quality of the results for an isotope where the answer is known(i.e. - zinc-65).

The Department of Health environmental monitoring program sampled sediments along the Hanford reach of the river in 1987 and 1992[Wa87, Wa92]. These samples were tested for a wide variety of radionuclides. The measured radioactivity was typically consistent with background; however some elevated levels of activity were found. These results are comparable to the 1992 DOE special investigations results, and to Battelle's ongoing environmental monitoring program

results. The number of sediment samples from the Hanford reach that were taken by the monitoring programs of the Department of Health and Battelle is too small to draw broad inferences about radioactivity in these sediments. However, the consistency of these measurements with the Westinghouse and Battelle studies lends additional confidence to the Westinghouse and Battelle results and helps alleviate the Department of Health concerns noted above.

Lower Columbia River: McNary to Estuary

One of the earliest attempts to inventory radionuclides in the lower Columbia river was by Nelson *et al.*[Ne66]. Water samples were collected from the Columbia River at Pasco and Vancouver. The concentrations of radionuclides were used to estimate the Curie content of the river at these two points and the depletion of Curie content at Vancouver relative to Pasco was attributed to radioactive decay and deposition in river sediments. As these data were collected near the peak of power production (1964), the emphasis of this study was primarily on short-lived isotopes. In addition sediments suspended in the water were separately analyzed. Surface and deep core sediment samples were also taken from behind McNary Dam and along the Hanford reach of the river.

Transport rates and total deposition of radionuclides in the Columbia river were inferred from these data. Large fluctuations in concentrations of radionuclides were observed and attributed to seasonal "scouring" of the river valley.

From these data and historical records of river radioactivity they inferred a total inventory of radioactivity in river sediments between Pasco and Vancouver, WA of 11,000 to 38,000 Ci. This estimate was for January 1965. Of this they estimated 90% was composed of chromium-51 and zinc-65. Essentially all of the chromium-51 and zinc-65 has decayed by now (1993). Their estimates of the 1965 inventory from Pasco to Vancouver are given in Table B.1. Other early studies of various aspect of radioactivity in the Columbia River[Fi71, Gl71, Ha73a, Ha73b, Ne71] produced similar results.

Table B.1 - Nelson's estimates of the 1965 inventory of artificial radionuclides for the lower Columbia River.

Radioisotope	Curies	Primary Source
scandium-46	512	Hanford
chromium-51	11,800	Hanford
manganese-54	320	Hanford
cobalt-58	140	Hanford
iron-59	140	Hanford
cobalt-60	450	Hanford
zinc-65	8,060	Hanford
zirconium-95/niobium-95	110	Fallout
antimony-124	5	Fallout
barium-140	30	Fallout

The Oregon State Health Division began routinely measuring radioactivity from the lower Columbia River, estuary and Oregon shore in 1962[Or67, Or77, Or87, Or92]. This program began as an effort to identify and quantify any radiological hazards in the lower Columbia river stemming from Hanford Operations. These measurements have continued to the present, thus spanning the entire period from peak activity at Hanford to more than twenty years after shut-down of the last single-pass reactors.

Sediment samples were collected from surface sediment. Sites were chosen for their accessibility and ubiquitous sedimentation. These sites included the John Day Dam and all of the dams downriver, the estuary and along the Oregon shore to Winchester Bay. While the locations of some of these sites have changed since 1962, many have continued to be used.

The concentrations of radionuclides in river sediments showed great variation. For example, from August, 1962 to July, 1963 the concentration of zinc-65 in the sediments behind the John Day Dam varied from 2.0 pCi/g to 134 pCi/g with an average of 46 pCi/g.

These changes were associated with changes in river flow, Hanford activities and weapons testing.

More recently, their sample collection has focused on long-lived radioisotopes. The results have consistently found that naturally abundant radioisotopes such as potassium-40 and radium-226 are present and easily measured, while artificial intermediate and long-lived radioisotopes such as cesium-137 and plutonium-239 are at or near the lower limit of detection, regardless of sampling location. The reported lower limit of detection for cesium-137 and plutonium-239 was 0.1 and 0.008 pCi/g respectively.

Lower Columbia River surface sediment sample collection has also been conducted recently by Bi-State Lower Columbia River Water Quality Reconnaissance Study[Jo92]. Surface sediment samples were taken from locations along the lower Columbia River and concentrations of long-lived radionuclides were measured. These radioisotopes include americium-241, plutonium-238/239/240, europium-152, europium-154, cesium-137 and cobalt-60. Only cesium-137 was detected consistently, although at very low levels; while all the remaining isotopes were typically below the lower limit of detection. These data were interpreted as an indication that surface sediments along the lower Columbia are at or near background levels.

The Washington State Department of Health began monitoring radioactivity in Columbia River Sediments in 1972. The initial motivation was to establish radiological background levels before Trojan Nuclear Power Plant began operations. These samples were taken from Cottonwood Island in the Columbia River downstream of Trojan. Monitoring of river sediments in the vicinity of Trojan ceased in 1985. In 1978 monitoring of sediments had begun on the Hanford Reach of the Columbia river in the vicinity of Washington Public Power Supply reactor number 2 (WNP-2), which was then under construction.

The early samples from the vicinity of Trojan Nuclear Power Plant found very little radioactivity, although strontium-90 was measurable from fallout and zinc-65 was still measurable from previous Hanford operations. By 1975 the activity of strontium-90 and zinc-65 had decayed to below measurable limits. No radiological impact from Trojan operations was ever observed.

The observed radioactivity in the WNP-2 sediment samples have also been very low and generally consistent with background levels. Results of these routine monitoring efforts can be found in the departments

annual reports from 1972 to the present[Wa94].
Surface sediments behind McNary have been sampled by the Department of Health in 1987 and 1992[Wa87, Wa94]. These samples were compared to samples taken upstream at Priest Rapids Dam. Only cobalt-60 and Europium isotopes were found to be elevated when compared to concentrations behind Priest Rapids Dam. The maximum observed concentrations of cobalt-60, strontium-90 and europium-152 by the Department of Health was 0.50 +/- 0.03 pCi/g, 0.019 +/- 0.008 pCi/g and 0.98 +/- 0.07 pCi/g respectively.

Early monitoring of the Columbia River by the Department of Energy (then the Atomic Energy Commission) or its subcontractors was conducted from 1948 to 1960[So62]. These monitoring activities were motivated by a number of issues. These include understanding the distribution of radioactivity in the river and possible health effects, the determination of radiological conditions for the safety of navigators, and the evaluation of radiological effects on the river from effluent discharge pipes.

These efforts were primarily measurements of water radioactivity; however, some samples of suspended sediments and river bottom sediments were collected and analyzed. These samples were referred to as "mud" in the older literature. The geographic range of these measurements varied from year to year, but ranged from the vicinity of Priest Rapids Dam to Pasco. Sample collection of sediments ceased in 1960. Unfortunately these measurements were limited to a few locations and years, and hence general inferences about the state of Columbia River sediments cannot be made from these data.

The U.S. Department of Energy, through its contractor Battelle Pacific Northwest Laboratories, began routine surface sediment sampling in 1988. Sampling was confined to McNary and Priest Rapids Dams and some sloughs along the Hanford Reach of the river. Of those artificial radionuclides clearly observed, only cobalt-60 concentrations was substantially higher at McNary than Priest Rapids Dam. Strontium-90 concentrations at McNary were also was found to be elevated relative to Priest Rapids. Typical concentrations behind McNary for these two radionuclides were 0.2 pCi/g and 0.03 pCi/g respectively. Other radionuclides behind McNary were found to have similar concentrations to Priest Rapids results. This is expected from their probable natural or fallout origin.

In 1976 D. E. Robertson and J. J. Fix[Ro77] took deep-core sediment samples behind the Bonneville, Dalles, John Day, McNary and Priest Rapids Dams, as well as several locations along the Hanford reach of

the river. Emphasis was placed on a careful sampling of the sediments behind McNary. By the time this study was conducted most of the short-lived radionuclides had decayed away. Thus the radionuclides measured were primarily intermediate and long-lived isotopes.

The major objectives of this study were to characterize the distribution of radionuclides in the river in terms of sediment depth and location along the river, as well as estimate the total inventory of radionuclides in the river. Other objectives were to determine the origin, fate and health effects of these radionuclides.

Of the radioactivity observed, approximately 25% was attributed to potassium-40, which is a naturally abundant long-lived radioisotope. Approximately 52% was iron-55; however, the radiation from iron-55 is so low in energy that the health and environmental effects are small compared to the other radioisotopes found. The remaining radioactivity was primarily intermediate-lived isotopes cobalt-60, europium-152/154 and cesium-137, and long-lived isotopes thorium-228 and radium-226. The latter two isotopes are, like potassium-40, naturally abundant. They also observed plutonium and americium. The authors concluded that most of the cesium, plutonium and americium is from fallout rather than Hanford operations because their concentrations in Priest Rapids sediments were similar to the concentrations in McNary sediments.

Robertson and Fix's results for the average and maximum concentrations, and inventories of radioisotopes in sediments behind McNary Dam are tabulated in Table B.2. These concentrations and inventories, corrected for radioactive decay to the year 1993, are also tabulated in Table B.2. These latter estimates were made with the assumption that there have been no introductions of additional radioactivity in quantities comparable to the existing inventories. In the case of europium-152/154, the average half-life of 11 years was used. Robertson and Fix did not report the uncertainty of their data.

Robertson and Fix also measured the distribution of radioisotopes along the lower Columbia. One important observation was that the dams downstream of McNary had significantly lower sedimentation rates, lower concentrations and smaller inventories than McNary. The average sedimentation rate varied considerably over the McNary reservoir, ranging from 5 to 18 cm per year(2 to 7 inches). The areas

Table B.2 - Robertson and Fix's results for radioactivity in McNary Dam sediments.

Radioisotope	Average Concentration in 1976 (pCi/g)	Peak Concentration in 1976 (pCi/g)	Peak Concentration in 1993 (pCi/g)	Inventory behind McNary Dam in 1976 (Ci)	Inventory behind McNary Dam in 1993 (Ci)	Primary Source
potassium-40	13.5	18.9	---	1900	---	Natural
radium-226	1.4	4.9	---	190	---	Natural
thorium-228	0.5	0.74	---	63	---	Natural
manganese-54	0.05	0.93	0	9.4	0	Hanford
iron-55	31.5	---	---	4000	51	Hanford
cobalt-60	4.3	16.6	1.6	600	65	Hanford
cesium-137	3.4	7.6	5.1	470	317	Fallout
europium-152/154	3.7	23.1	7.9	520	178	Fallout
plutonium-238	0.002	0.004	0.004	0:3	0.3	Fallout
plutonium-239/240	0.045	0.12	0.12	6.3	6.3	Fallout
americium-241	0.01	.021	.021	1.5	1.5	Fallout

of highest radionuclide concentrations were accumulating sediments at rate of 8 to 16 cm per year(3 to 6 inches). If these sedimentation rates are correct, then one would expect that an average additional two meters of new sediments have accumulated since the data of this study were taken. Deep core sediment samples from a 1975 study by J. J. Fix[Fi76] were consistent with these results.

The 1977-78 studies of the Columbia River Basin by T. M. Beasley and C. D. Jennings[Be81,Be84,Be86a,Be86b] is perhaps the most complete investigation of deep lower Columbia River sediments. They collected 50 core sediment samples from sites ranging from Ice Harbor Dam and the Hanford reach of the Columbia river to the river estuary.

It has been shown that the ratios of concentrations of different artificial radioisotopes in the environment depends on their origin. The ratios generated from nuclear reactors and nuclear fallout are very different[Kr76]. Using this fact, Beasley and Jennings inferred that 20-25% of the Plutonium deposits in McNary sediments come from Hanford operations and the remainder comes from fallout. However, this fraction dwindled further down the river to approximately 3-4% at the river estuary. The total Hanford-derived plutonium percentage was less than 20%. Similarly, the authors attributed approximately 25% of the cesium-137 to Hanford, while 90-100% of the cobalt-60 and nickel-63 was traced to Hanford.

Beasley *et al.* also deduced inventories of radionuclides in the Columbia River Basin. These inventories were 270 Ci of cobalt-60 (which by 1993 would have decayed to 39 Ci), 125 Ci of nickel-63 (108 Ci), 254 Ci of cesium-137 (180 Ci), 4.1 Ci of plutonium-239/240, and 1.2 Ci of americium-241 for a total of 529 Ci (224Ci). The McNary sediments account for about 60% of the total. Note that the estimates of McNary inventories by Robertson and Fix were approximately three times higher than these estimates. This discrepancy is perhaps indicative of the uncertainty in the total inventory of Columbia River radioactivity; however, this discrepancy is not in the measured concentrations. Both studies measured similar concentrations of radioactivity. The difference lies in the inferred sedimentation rate and average sediment depth[Be86b].
Beasley *et al.* concluded by noting that concentrations of radioactivity in Columbia River sediments were so low that they were difficult to detect. Even in sediments behind McNary the natural radioactivity was, in 1978, almost 10 times the manmade activity.

Radioisotope	Average Surface Concentration in Upper Estuary (pCi/g)	Total Inventory in Upper Estuary (Ci)	Primary Source
zirconium-95/niobium-95	1	140	Fallout
ruthenium-106	1	270	Fallout
potassium-40	14		Natural

Further information about the distribution, concentration and inventory of radioisotopes in the estuary and its environs was provided by M. G. Gross in 1972[Gr72]. Radioactivity in sediments were measured from the mouth of the Columbia river to approximately 400 miles off the coast, and from northern California to the entrance of Puget Sound. 496 samples were taken from 1961 to 1963. 290 of them were within 60 miles of the Columbia river mouth. The samples were surface samples 1 cm deep, with three additional deep-core samples.

The data was separated into radioisotopes of natural origin: potassium-40 and bismuth-214, principly fallout origin: zirconium-95/niobium-95 and ruthenium-103/rhodium-103, and principly Hanford origin: zinc-65, chromium-51, manganese-54 and cobalt-60. A sharp reduction in concentrations of artificially produced radioisotopes with increasing distance from the river mouth was observed. For example, the maximum concentration of zinc-65 was 180 pCi/g, but the area where concentrations were higher than 50 pCi/g was confined to a small region near the mouth of the river. Similar distributions were observed for chromium-51 and manganese-54, while cobalt-60 was observed to be more uniformly distributed. Like the upper estuary sediment study[Hu71], Gross observed that short-lived radioisotopes were primarily in the surface layer of sediments, while the lone intermediate-lived radioisotope of this study (cobalt-60), was more uniformly distributed in the sediments.

Gross also estimated the surface and total inventory in coastal sediments. These are tabulated in Table B.4. Unfortunately, the uncertainty of these results was not reported. The estimated rate of sediment deposition was 10 trillion grams (22 billion pounds) deposited each year within 10 kilometers (6.3 miles) of the river mouth. If these sediments were uniformly distributed, approximately 10 meters (34

feet) of "clean" sediments have accumulated in this area since the shutdown of the last single-pass Hanford reactors.

Table B.4 - The results of M. G. Gross from samples collected between 1961 and 1963.

Radioisotope	Primary Source	Reservoir in Surface Sediment (Ci)	Total Reservoir in Coastal Sediment (Ci)
chromium-51	Hanford	300	600-900
manganese-54	Hanford	4	
cobalt-60	Hanford	9	17-26
zinc-65	Hanford	1150	2300-3450
zirconium-95/niobium-95	Fallout	130	
ruthenium-103/rhodium-103	Fallout	65	
potassium-40	Natural	800	
bismuth-214	Natural	32	

The Oregon State Health Division monitoring activities extended to the estuary and Oregon coast[Or67, Or77, Or87, Or92]. Samples were restricted to surface sediments and collection sites were chosen for their accessibility and ubiquitous sedimentation.

The emphasis of early measurements was primarily on short-lived radioisotopes. The isotopes studied were potassium-40, which is a naturally abundant long-lived radioisotope, chromium-51, manganese-54, zinc-65, all three of which were produced by Hanford operations, and zirconium-95/niobium-95 and ruthenium-103, which are primarily fallout products from nuclear weapons testing. The short half-life of most of these isotopes implies that the measured concentrations reflected the (then) recent past of the Columbia River. Like the results

of the lower Columbia River, measurements of concentrations showed substantial seasonal variation.

As the single-pass reactors were shut down in the late 60's and early 70's the emphasis on short-lived radioisotopes switched to intermediate and long-lived isotopes. The radioisotopes sampled today are primarily long-lived isotopes. These include: beryllium-7, potassium-40, cesium-137, radium-226, thorium-230, thorium-232, natural uranium and plutonium-239. All of these isotopes, with the exceptions of plutonium-239 and cesium-137 are naturally abundant although many of them can also be indicators of nuclear activities.

The early results of Oregon monitoring were reported on a wet-weight basis. The zinc-65 concentrations at Astoria (converted to estimated dry weight concentrations) varied from 2.5 to 151.0 pCi/g with a typical value of approximately 65 pCi/g; while the chromium-51 concentrations varied from 17 to 922 pCi/g with a typical value of approximately 350 pCi/g. These concentrations reflect the high level of single-pass reactor activity at Hanford in the 60's. They are very high in comparison to current concentrations, which for chromium-51 and zinc-65 are below the Oregon lower limit of detection of approximately 1 pCi/g.

In sharp contrast to estuary results, concentrations along the Oregon coast were relatively low. For example, at Tillamook Bay the maximum observed concentration of zinc-65 was 2.7 pCi/g, with an average concentration of approximately 0.8 pCi/g. These modest concentrations were further confirmation that major environmental effects from Hanford-origin radioactivity in the Columbia River, if they existed, were confined to the river, its estuary and the nearby environment.

Radionuclides derived from fallout, such as zirconium-95/niobium-95, ruthenium-103 and ruthenium-106, also showed large variations in sediment concentrations. For example, at Astoria zirconium-95/niobium-95 concentrations ranged from 0.2 to 62 pCi/g and ruthenium-103/ruthenium-106 concentrations varied from 0.3 to 18 pCi/g. These variations presumably reflect changes in river flow and weapons testing.

After the shutdown of the last single-pass reactor in 1971 the levels of radioactivity from short-lived radionuclides rapidly declined. By 1977 the measured concentrations in surface sediments of most Hanford-origin radionuclides had decreased to levels below the lower limit of detection. By this date the radioactivity of lower Columbia River

sediments was dominated by natural sources such as potassium-40, which contributed more than 50% of the total, and fallout radioisotopes. In the ensuing years only intermediate and long-lived isotopes could still persist; however, generally even these are consistent with natural background levels or below the lower limit of detection. For example, a 1987 survey by the Oregon Health Division of surface sediments behind lower Columbia River dams and at Tillamook Bay all found that plutonium-239 concentrations were below the lower limit of detection, which was 0.008 pCi/g.

Oregon results from sampling in the vicinity of Trojan also showed levels consistent with background and therefore no measurable impact from Trojan operations.

Information about the export of plutonium and americium to the Pacific ocean from the Columbia river was provided by Beasley *et al.* in 1981[Be81a]. Concentrations of plutonium-239/240 and americium-241 in suspended sediments of the Columbia River were measured near the river outlet from the period July 1978 and July 1979. In addition, a deep sediment core was taken near Astoria, Oregon for the purpose of inferring the history of river radioactivity export.

The primary result of Beasley *et al.* was that the Columbia river was exporting 70 +/- 28 mCi of plutonium-239/240 and 17 +/- 6 mCi of americium-241 in suspended sediments to the Pacific Ocean per year. The deep core sediment sample showed higher concentrations of plutonium-239/240 than the surface sediments. These higher concentrations were correlated with the peak of atmospheric nuclear testing in the early 1960's. This suggests that plutonium and americium deposits are immobile in the sediments. Their results were used to estimate the total export, as of 1979, to the Pacific Ocean from the Columbia River of 4-8 Curies of plutonium-239/240 and 1-2 Curies of americium-241.

The relative contributions of sources of plutonium was inferred by examining the ratio of plutonium-240 to plutonium-239 and taking advantage of the fact that worldwide fallout and reactor sources have very different ratios[Kr76]. The authors of this study concluded that approximately 96-97% of the exported plutonium is from fallout, and approximately 3-4% is of Hanford origin.

Further information about plutonium, americium-241 and cesium-137 in off-shore sediments near the mouth of the Columbia river was provided by Beasley *et al.* in 1982[Be82]. Nine deepcore sediment samples were taken in 1974-1976 of continental shelf sediments. These

samples were taken from approximately 20 miles south of the Columbia river mouth to approximately 70 miles north.

The results of these samples, along with earlier data[Ca81], were used to estimate the depth, distribution and inventory of plutonium-239/240, americium-241 and cesium-137. Beasley *et al.* estimate a total inventory of plutonium-239/240 off the Washington and Oregon coasts to be approximately 47 +/- 10 Curies. Of this, the estimated maximum that could have come from Hanford operations was 8 Curies. The observed ratios of plutonium-239/240 to americium-241 and cesium-137 suggested that approximately 15 +/- 3 Curies of americium-241 and 200 +/- 40 Curies of cesium-137 were present in these sediments.

The bulk of these deposits were found in the top 20 cm of sediments. This implies that the measured average concentration per unit area of 8.0 +/- 2.6 mCi per square kilometer for plutonium-239/240 yields an average concentration per unit mass of approximately 0.027 +/- 0.009 pCi/g (dry weight), assuming the sediment density is 1.5 g per cubic centimeter.

Interestingly, the bulk of the Pu contamination was attributed to deposition of plutonium carried to the coast by Pacific Ocean currents. The source for this plutonium is worldwide fallout. In contrast, the cesium-137 inventory was primarily attributed to deposition from the Columbia river. The two principle contributors to the Columbia river were Hanford operations and fallout. No attempt was made to separate the relative contribution of these two sources. The authors noted what appeared to be a modest degree of downward mobility of plutonium in the sediments and attributed this to inorganic processes.

Coastal data were supplemented by 9 deep-core sediment samples within the upper estuary taken by T. M. Beasley and C. D. Jennings[Be84]. These samples were part of a larger study to inventory the Columbia River basin for man-made radionuclides. The areas sampled ranged from the Hanford Reach to the estuary. Samples were taken in the years 1977-1978. Particular emphasis was placed on areas of heavy sedimentation. As in all of the studies performed well after the shutdown of single pass reactors, only medium and long lifetime radionuclides were found. These isotopes are cobalt-60, cesium-137, plutonium-239/240 and americium-241.

The estimated inventory of radioactivity in the estuary from these data was 0.8 Ci plutonium-239/240, 0.23 Ci americium-241, 23 Ci cesium-137, and 15 Ci of cobalt-60. The reported uncertainties in these

estimates was approximately 20%. The relative contribution of various sources of radioactivity were estimated from ratios of concentrations of radioisotopes. For plutonium it was estimated that 3-4% was of Hanford origin, while 96-97% was from fallout. In contrast 90-100% of the cobalt-60 and approximately 25% of the cesium-137 was attributed to Hanford operations.

Appendix C

Dosimetry of River Sediments

Radiation dosimetry from environmental radioactivity requires accounting for all significant human exposure pathways and parameters. The radiation doses in this report, for example, are meant to describe the maximally exposed individual in the recreational scenario. What, specifically, does this mean?

The recreational scenario of this report describes a range of individuals who camp, hunt, fish, boat and otherwise recreate along the shores of the Columbia River. This scenario, to be complete, must describe how much fish and sediments the recreator ingests. It also must answer questions such as how many hours each year recreators spend on the river, how many years the recreator spends on the river, how much river water they drink and many others. The answers to these questions, which are the parameters of the recreational scenario, are the maximum parameter values an individual could reasonably be expected to achieve with while recreating along the river. The individual who meets these parameters is called the maximally exposed individual.

The most important pathways from the environment to humans that were included in the dose calculations of this report were external gamma exposure from gamma emitters in the sediments, inhalation of resuspended sediments, and ingestion of sediments. Other pathways, such as the uptake of radioactivity in sediments by aquatic organisms, native plants and river water and their subsequent consumption by humans were found to contribute a negligible fraction of the total dose.

The human exposure pathways from surface sediments is relatively straight-forward because an individual can readily come in contact with them. Human exposure to deep sediments, which are those sediments deeper than 15 cm (6 inches), requires an additional assumption. We assume that deep sediments have been dredged to the surface and deposited on an exposed shoreline or island.

Only radionuclides whose half-life is greater than one year are included in these dose assessments.

Generally, daughters or decay products are treated separately from the parents. An exception to this are "gamma emitters" because the daughter nucleus is the actual gamma emitter and decays extremely rapidly after the parent decay. In these cases we include the daughter decay in the dose assessment.

Dose assessment parameters used for this report are taken from federal documents[Sc93, HSBRAM, EPA91, NRC77] and are listed in Table C.1. In general, these parameters are very conservative(protective).

Table C.1 - Scenario parameters used by the Department of Health for dose calculations in this report.

Parameter	Value	Reference/Comment
Hours per year recreating on the river.	500 hours (62.5 8-hour days)	[Sc93]/ HSBRAM recommends 48 hours.
Years spent recreating on the river.	75 years	[HSBRAM]
Depth of contaminated sediments.	15 centimeters	[EPA93, KE89]
Depth of contaminated sediment cover material.	0 - no cover	We assume no remedial actions, such as a cover material.
Area of contaminated sediments.	10,000 meters squared	This primarily matters for shine calculations, and differs from an infinite plane by only a few percent.

The doses in this report are calculated through the use of Argonne National Laboratory's computer code "RESRAD"[Re93]. This program performs complex model calculations that include human radionuclide uptake, storage and elimination. This program also models radionuclide transport, dispersion, decay etc. A detailed discussion regarding RESRAD calculations is beyond the scope of this report. Further information about RESRAD can be obtained from Argonne National Laboratory[Re93].

The Department of Health has checked these calculations with manual calculations using federal regulatory guidance[EPA88, EPA91, EPA93, Ke89, NRC77, Sc93].

The pathway that contributes most to the doses from Columbia River sediments is external exposure(shine). Gamma emitters are the most important contributors to this pathway. The manual calculations of this report calculate annual dose from shine by:

$$\text{Dose(shine)} = C * H * P * t,$$

where C is the sediment radioisotope concentration in units of pCi/g, H is the dose per hour per unit concentration in units of (mrem/hour)/(pCi/m^3), p is the soil density(g/m^3) and t is the number of hours spent at the contaminated area(hours). A soil density of 1.5 g/cm^3 was used in these calculations. The factor H is taken from federal guidance document No. 12[EPA93, Ke89] and is a result of detailed computer modeling of a "generic" site. The RESRAD calculations compute a site-specific "H" internally.

Other parameters affecting the absorbed dose due to ground shine from radionuclides in soils(sediments)include the distribution of radionuclides along the surface and in depth, the size and depth of the area affected, the effect of soil density on H, and radiation shielding. The latter factor is a function of nearby structures that may absorb gamma rays, such as boats, ridges, sand dunes and water.

Inhalation of suspended dust is the second most important exposure pathway. Exposure from this pathway is highest for alpha emitting radionuclides. Inhalation of radionuclides at a contaminated site can occur from the resuspension of contaminated soil into the atmosphere. The manual dose calculations of this report are calculated by:

$$\text{Dose(inhale)} = C * H * S * Q * t,$$

where C is the radioisotope concentration in the sediment(pCi/g), H is the dose per unit activity inhaled(mrem/pCi), S is the mass of suspended dust per unit volume(g/m^3)(sometimes called the dust-loading factor), Q is the breathing rate(m^3/hour) and t is the number of hours the individual spent at the contaminated site. A dust-loading factor of 0.0001 g/m^3 and a breathing rate of 1 m^3/hour were used in these calculations[Sc93]. The factor H is taken from federal guidance report No. 11[EPA88, Ke89]. RESRAD calculates a site-specific "H" internally.

Other parameters that may affect these calculations include the particle size distribution of suspended dust, the distribution of contamination, how long suspended dust stays suspended and other weather-dependent factors.

The soil ingestion pathway is the third most significant exposure pathway for the doses of this report. A significant fraction of dose from beta and alpha emitting radionuclides comes from this pathway. The manual calculations of this report calculate these doses by:

$$\text{Dose(ingest)} = C * H * Q * t$$

where C is the sediment radioisotope concentration in units of pCi/g, H is the dose per unit ingested radioisotope activity in units of mrem/pCi, Q is the quantity of sediment ingested per day(g/day), and t is the number of days spent at the contaminated area(days). An ingestion-rate factor of 0.2 g/day was used for these calculations[HSBRAM]. The factor H is taken from federal guidance report No. 11[EPA88, Ke89]. RESRAD calculates a site-specific "H" internally.

Other parameters that affect the dose from ingestion include soil or sediment composition, the chemical forms of radioactive contamination and types of activities that take place on contaminated areas.

Other pathways, such as native plant ingestion, fish ingestion and river water ingestion contributed negligibly to dose.

One of the important results of these dose estimates is that doses from a few gamma-emitters dominate the total doses. The contributions from cobalt-60, cesium-137 and europium-152 in the Hanford Reach, for example, constitutes 93% of the total dose. The shine pathway accounts for 99% of the total dose calculated in this report. The contribution of the alpha and beta emitters are small in comparison.

In general doses calculated from RESRAD compared favorably with manual calculations. Discrepancies between these two methods were typically less than 30%. Comparisons for many of the important contributors to dose are shown in Table C.2.

Table C.2 - A comparison of annual doses in the recreational scenario from contaminated sediments. The two calculations are RESRAD and manually-calculated doses from the formalism of this appendix. Concentrations in each case are 1 pCi/g.

Radioisotope	Dose(RESRAD) (mrem)	Dose(Manual) (mrem)
gamma-emitters		
cobalt-60	1.05	0.72
cesium-137	0.25	0.17
europium-152	0.46	0.32
beta-emitters		
strontium-90	0.00022	0.0019
alpha-emitters		
plutonium-239	0.052	0.065
americium-241	0.056	0.070

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