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DRAFT COLUMBIA RIVER PATHWAY REPORT

Phase I of the Hanford Environmental
Dose Reconstruction Project

July 20, 1990

Pacific Northwest Laboratory
Richland, Washington 99352

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This report was prepared by Battelle staff at the Pacific Northwest Laboratory, which is operated by Battelle Memorial Institute, under the direction of an independent TSP. The work described here was directed and monitored by the TSP; however, this report has not yet been reviewed and approved by the TSP. At the TSP's direction, the report is being made available to the public at the same time it is provided to the TSP. The information contained herein is considered preliminary until it undergoes review by the TSP.

PREFACE

This is one of three draft reports that summarize the first phase of a four-phase radiation dose assessment titled the Hanford Environmental Dose Reconstruction (HEDR) Project. This, the Draft Columbia River Pathway Report, is directed to technical audiences, as is the Draft Air Pathway Report. The Draft Summary Report, which presents both the air and river exposure pathways, is intended for a general audience. Detailed descriptions of all aspects of the HEDR Project and the dose reconstruction process are available in more than 20 supporting documents (Appendix A).

The river pathway portion of Phase I has several objectives. Foremost among these is to determine whether sufficient information exists or can be reconstructed from incomplete records to enable a dose reconstruction study to proceed and to demonstrate that this is the case. A second objective is to design conceptual and computational models specifically to deal with uncertainties in the variables needed to estimate doses to offsite populations. The final objectives are to determine if the data and models are sufficient to enable credible doses to be calculated and to compare HEDR doses with previously published dose estimates. In summary, Phase I is a pilot or demonstration phase. The dose estimates, which were calculated to demonstrate the feasibility of the process for reconstructing doses, are therefore preliminary. The estimates will definitely change as input and model structures are refined in later phases.

The reader must recognize the preliminary nature of the dose estimates that are presented and discussed in this and the two companion reports. As the HEDR Project continues, the averages, ranges, and distributions of dose estimates will change, for at least three reasons: refinement of input to models; refinement of models; and changes in the extent of the final study area.

It is also important to note that the objectives of the HEDR Project do not include estimating risk or extrapolating to health effects that might have resulted from radiation exposures. A related epidemiological study, the Hanford Thyroid Disease Study, is being conducted for the Centers of Disease

Control (CDC) by the Fred Hutchinson Cancer Research Center. This study will seek to determine whether there is a correlation between thyroid disease and estimated thyroid doses near the Hanford Site from exposures to iodine-131 releases during the early years of operation. The CDC study does not address the Phase I period for the river pathway, 1964-1966, that is the subject of this report.

The HEDR Project is directed by an independent Technical Steering Panel (TSP) of scientists and representatives of the states of Oregon and Washington, of regional Native American Tribes, and of the public. The TSP's charter is to direct, review, evaluate, and approve all HEDR Project work; funding is provided by the U.S. Department of Energy, but the agency is not in the review or approval cycle.

The work described in this report was conducted in accordance with the requirements of ANSI/ASME NQA-1 1986 Edition, Quality Assurance Program Requirements for Nuclear Facilities, as interpreted by the PNL Quality Assurance (QA) program.

ABSTRACT

This report summarizes the water pathway portion of the first phase of the Hanford Environmental Dose Reconstruction (HEDR) Project, conducted by Battelle staff at the Pacific Northwest Laboratory under the direction of an independent Technical Steering Panel. The HEDR Project is estimating radiation doses that could have been received by the public from the Department of Energy's Hanford Site, in southeastern Washington State.

Phase I of the water-pathway dose reconstruction sought to determine whether dose estimates could be calculated for populations in the area from above the Hanford Site at Priest Rapids Dam to below the site at McNary Dam from January 1964 to December 1966. Of the potential sources of radionuclides from the river, fish consumption was the most important. Doses from drinking water were lower at Pasco than at Richland and lower at Kennewick than at Pasco.

The median values of preliminary dose estimates calculated by HEDR are similar to independent, previously published estimates of average doses to Richland residents.

Later phases of the HEDR Project will address dose estimates for periods other than 1964-1966 and for populations downstream of McNary Dam.

EXECUTIVE SUMMARY

This is one of three draft reports that summarizes Phase I of a four-phase radiation dose assessment titled the Hanford Environmental Dose Reconstruction (HEDR) Project. Preliminary dose estimates were calculated to demonstrate the feasibility of reconstructing doses. These estimates will definitely change as input and model structures are refined in later phases. Detailed descriptions of all aspects of the HEDR Project and the dose reconstruction process are available in more than 20 supporting documents.

BACKGROUND

The HEDR Project was prompted by mounting concern about possible health effects to the public from more than 40 years of nuclear operations at the Hanford Site, in southeastern Washington State. The Hanford Site was selected in 1943 (Figure 1) as the location for the facilities used to produce plutonium for atomic bombs used in World War II. The first three nuclear reactors--B, D, and F--began operating in 1944 and 1945. After World War II ended in 1945, the reactors continued to irradiate uranium fuel and to produce plutonium. From 1949 through 1963, six new reactors--H, DR, C, KW, KE, and N--began operating. From 1964-1988, as the government needed less plutonium, it eventually closed its production reactors. The largest releases of radionuclides to the Columbia River resulted from the direct cooling of the reactors (except N Reactor) with river water. Naturally occurring elements in the cooling water and chemicals added in the water-treatment process underwent nuclear transformation while passing through the reactors and while adhering to cooling-system tubing in the reactors. Lesser releases of radioactivity to the river resulted from ruptures in fuel elements and the subsequent loss of fission products.

The release of radioactive materials from Hanford was controlled through several steps, including process controls, effluent and environmental monitoring, and personnel monitoring.

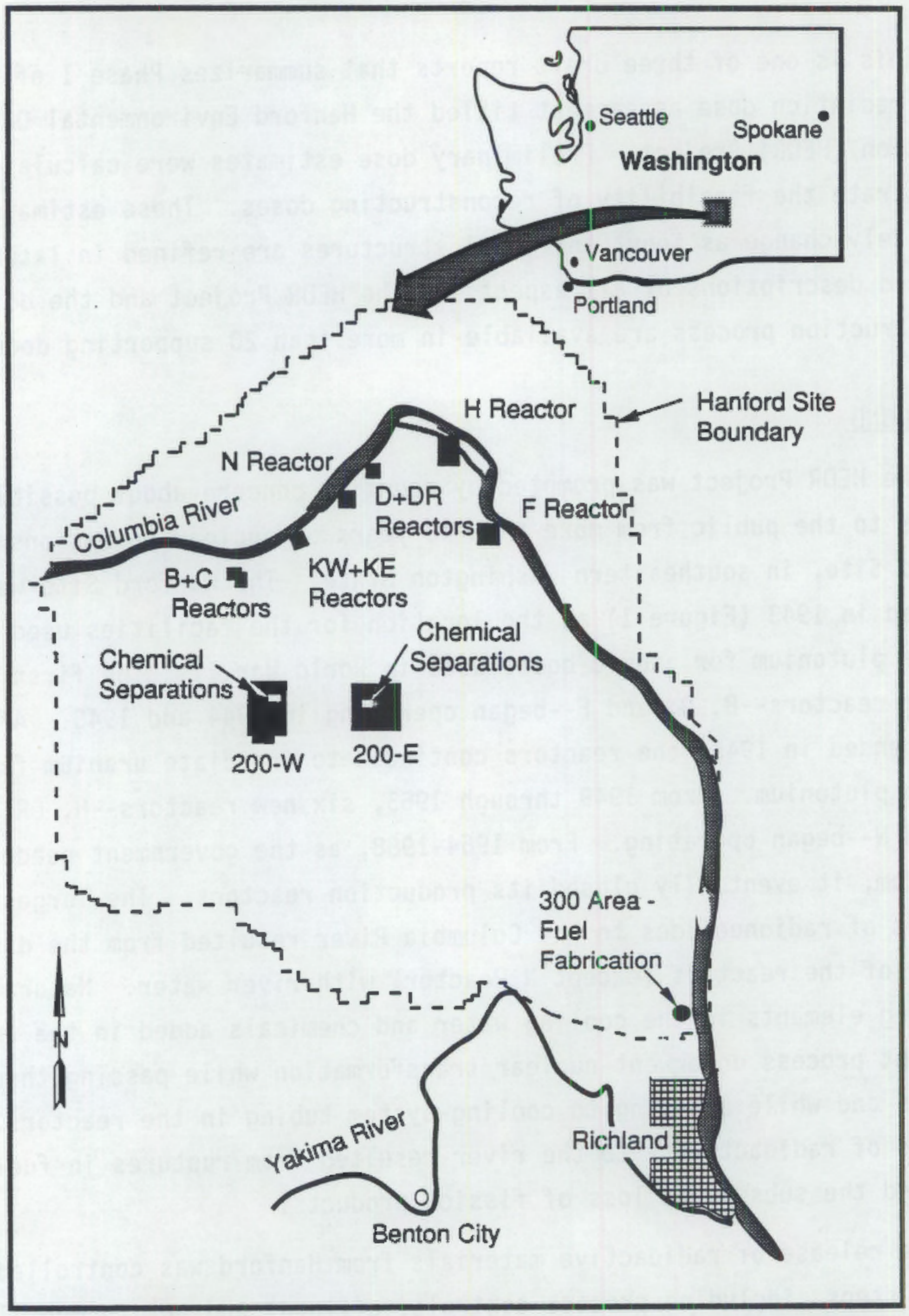

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FIGURE 1. Hanford Site and Key Operating Facilities, 1964-1966

Effluent monitoring, which began with the startup of Hanford facilities in 1944, consisted of measuring or estimating the amounts of radioactive materials vented to the atmosphere and released to soils and to the Columbia River. Daily measurements of materials released to the river continued throughout the operation of the reactors.

Environmental monitoring began before facilities were completed and eventually included measurements of radioactivity in the air, on the ground, on vegetation, in food, and in Columbia River water, drinking water, sediment, fish, and other aquatic and marine life.

Onsite personnel monitoring of radiation exposure began when Hanford employees first began working at the site (Wilson 1987). In addition to measuring external exposure using pencil dosimeters, hand and foot counters, and scans of clothing and extremities with Geiger counters, a bioassay program and whole-body counts were conducted, beginning in 1959. These latter measurements provide useful comparisons to the dose estimates of the HEDR Project.

Offsite monitoring of people began in 1965. Over 5,000 schoolchildren in the Tri-Cities area were monitored with the whole-body counters from 1965 to 1968. These monitoring data provide valuable comparisons with previously published dose estimates for the same period and with the estimates calculated by the HEDR Project.

Potential radiation doses to the general population near the Hanford Site were estimated and reported for the first time in 1957. Estimates of these doses have been included in annual environmental monitoring reports ever since. As technology has improved, dose calculation methods have evolved and improved. Through 1973, dose estimates were based on measurements of radionuclides in the environment and in foods. By 1974 (Fix 1975; Fix and Blumer 1975), concentrations of radionuclides in the environment decreased to the point where dose estimates had to be based on modeling from measured or estimated releases. The decreases in environmental concentrations of radionuclides originating from Hanford resulted from improved control technology, the closing of the original reactors, and the closing of major chemical-processing operations.

The HEDR Project consists of four distinct phases. The first phase of the river pathway portion of the study, a pilot or demonstration phase, was purposely limited to the area from Priest Rapids Dam above the Hanford Site to the first downstream dam, McNary; to January 1964 through December 1966; and to radionuclides that are estimated to have accounted for more than 80% of the doses (Napier 1990). The unit of months was selected as the level of temporal resolution for Phase I. This limited scope influenced the selection of models and parameters and resulted in some conservatism in the designation of the ranges and forms of distributions.

Phase II is designated a review and testing phase, during which sensitivity analyses will be used to identify key parameters and the effects of model structure. Phases III and IV will refine parameters, modify models, expand areas, extend time periods, and ensure that all key emissions of radioactive materials from Hanford will have been addressed.

APPROACH

Figure 2 shows a simplified project conceptual diagram for calculating doses from the river pathway. Pathways considered in Phase I are consumption of contaminated fish, drinking treated or raw river water, and recreational exposure to the river. Input to the HEDR model consists of distributions, rather than point estimates, for each of the parameters and results in distributions of dose estimates. This approach incorporates estimates of uncertainties resulting from spatial and temporal variability, incomplete historical information, and estimates of historical analytical and sampling errors.

The period 1964-1966 was selected because it provides an optimum combination of extensive monitoring information, independent measurements, relatively high river concentrations, and a population newly exposed to drinking water having relatively higher concentrations of radionuclides than other downstream communities, that of Richland. Because of the extensive monitoring data available for Phase I analysis, modeling was conducted only when data for specific radionuclides were insufficient. Phase I used a simple model that uses effluent measurements and river discharge as input and

Generalized Data Flow: Surface Water

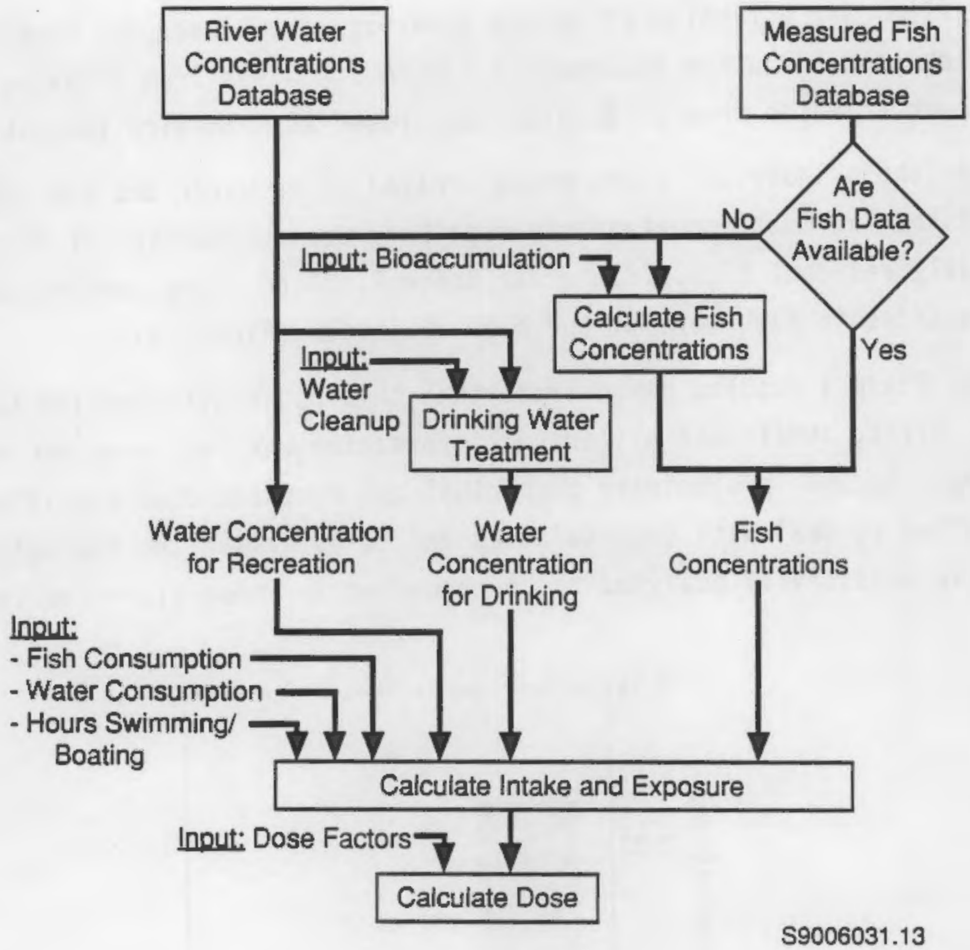

FIGURE 2. Conceptual Diagram of the HEDR Columbia River Pathway Model

uses only radioactive decay and dilution to provide radionuclide concentrations at specific downstream locations.

Monthly concentrations of radionuclides in effluent, Columbia River water, Columbia River fish, and in drinking water for 1964-1966 were taken directly from previously published documents. The radionuclides addressed in Phase I were selected based on analyses of the sources and estimates of their contributions to dose (Napier 1990).

RESULTS

Preliminary estimates of median drinking water doses for Richland, Kennewick, and Pasco are depicted in Figure 3. Doses from drinking water were lower at Pasco than at Richland and lower at Kennewick than at Pasco.

For those individuals who drank treated river water and ate Columbia River fish, the most important river pathway was consumption of fish, especially resident fish, from areas above Richland where concentrations of radionuclides in fish were at the highest levels (Figure 4).

The Phase I results demonstrate that this phase attained its key objectives. First, sufficient historical information was retrieved and reconstructed. Second, preliminary conceptual and computational models were constructed to deal with uncertainties and to establish the foundation for extensive sensitivity analyses to be conducted in Phase II. Finally, the

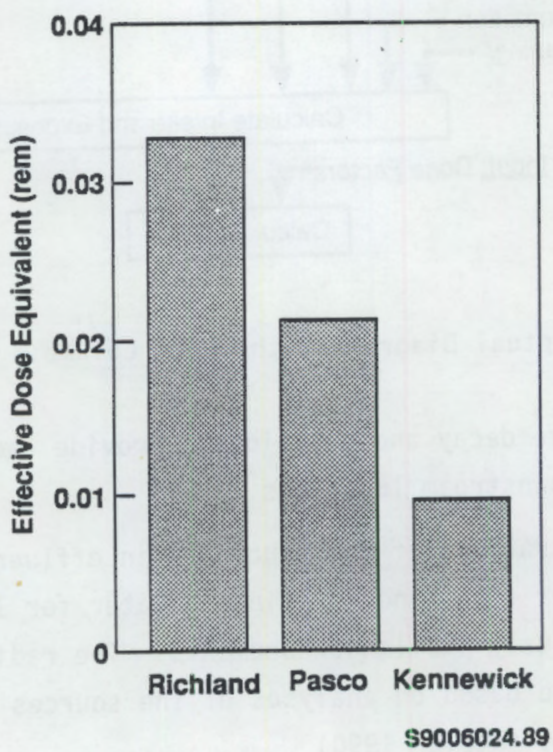

FIGURE 3. Preliminary Dose Estimates from the Drinking-Water Pathway for Tri-Cities Residents, 1964-1966 (median values)

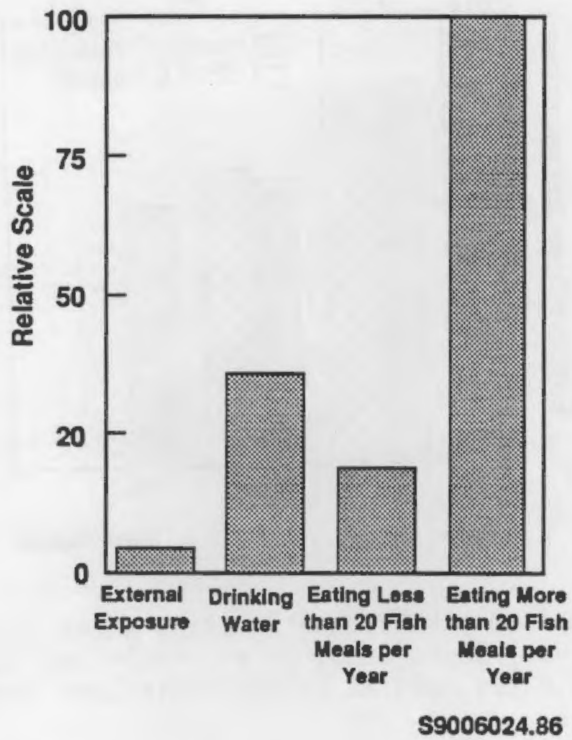

FIGURE 4. Relative Importance of Fish, Drinking-Water, and External Exposure Pathways (Richland residents, 1964-1966)

data and modeling approach were sufficient to produce credible, although clearly preliminary, dose distributions. These objectives were attained by demonstrating that the range of preliminary dose estimates includes independent, previously published estimates of doses to average, typical, and maximally exposed individuals and that the range includes doses estimated on the basis of previously published whole-body counts of workers and schoolchildren.

The previously published estimates for 1964-1966 are compared with HEDR Phase I preliminary dose estimates in Figure 5 [historical dose, converted to current dosimetry, Effective Dose Equivalent (EDE)]. The previously published "average" or "typical" exposure of a Richland resident, summed from

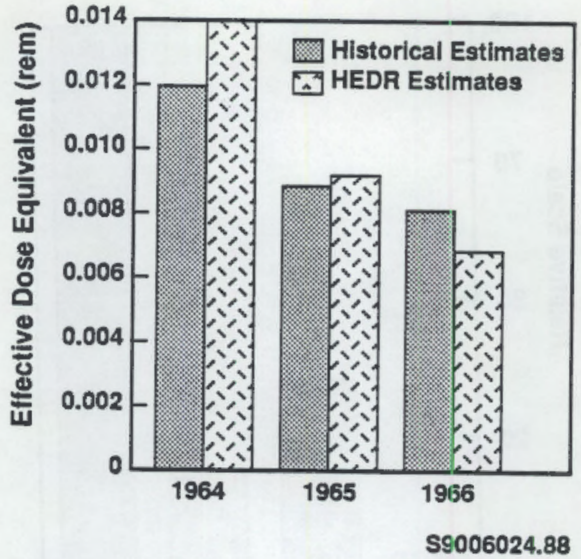

FIGURE 5. Previously Published Drinking-Water Pathway (average values) Doses Compared with HEDR Preliminary Dose Estimates (median values) (Richland adults)

1964-1966 was 0.03 rem[a] (0.0003 Sv). Approximately 50% of the Richland population was likely to have received doses greater than 0.035 rem (0.00035 Sv).

About 4,700 records of whole-body counts of workers are available for 1964-1966. These measurements show the amount of one radionuclide, zinc-65, that had been absorbed by the body from drinking treated Columbia River water, eating Columbia River fish, or eating produce that had been irrigated with Columbia River water downstream of the reactors. This radionuclide could be readily detected with the whole-body counter. Dose estimates based on previously published whole-body measurement of zinc-65 in Hanford workers are slightly lower than the fraction of HEDR-calculated doses attributable to zinc-65. Historical whole-body measurements of schoolchildren are also slightly lower than HEDR calculated body burdens of zinc-65. These comparisons indicate that the HEDR model results are consistent with actual measurements from the 1960s.

(a) All doses in this report are Effective Dose Equivalent.

The preliminary Phase I dose estimates for the river pathway indicate that essentially none of the Richland population might have received cumulative doses (1964-1966) from the drinking-water pathway higher than the national, annual, average background.

Later phases will address dose estimates for periods other than 1964-1966 and for populations downstream of the Phase I study area. Rough dose estimates for the drinking-water pathway can be extrapolated to earlier and later periods and to downstream locations. Estimates of doses for the period 1957-1972, when the last of the original eight production reactors had been shut down, are available in published reports and, as shown in this report for the period 1964-1966, provide a reasonable estimate of doses to average and maximally exposed individuals in Richland. Doses for 1944-1956 can be estimated from power levels and from environmental measurements. Power levels were considerably lower in the early years of operation when fewer reactors were operating, resulting in much lower releases of radionuclides to the Columbia River (Nelson 1960).

Extrapolations of dose estimates for the few downstream locations where communities used treated Columbia River water for drinking can be based on previously published measurements of radionuclide concentrations at Bonneville Dam or Vancouver, Washington. In general, the concentrations of radionuclides in the Columbia River at these downstream locations were about 10% or less of the concentrations at Richland (Foster and Wilson 1965).

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1.0 INTRODUCTION

1.1 PROJECT OBJECTIVES

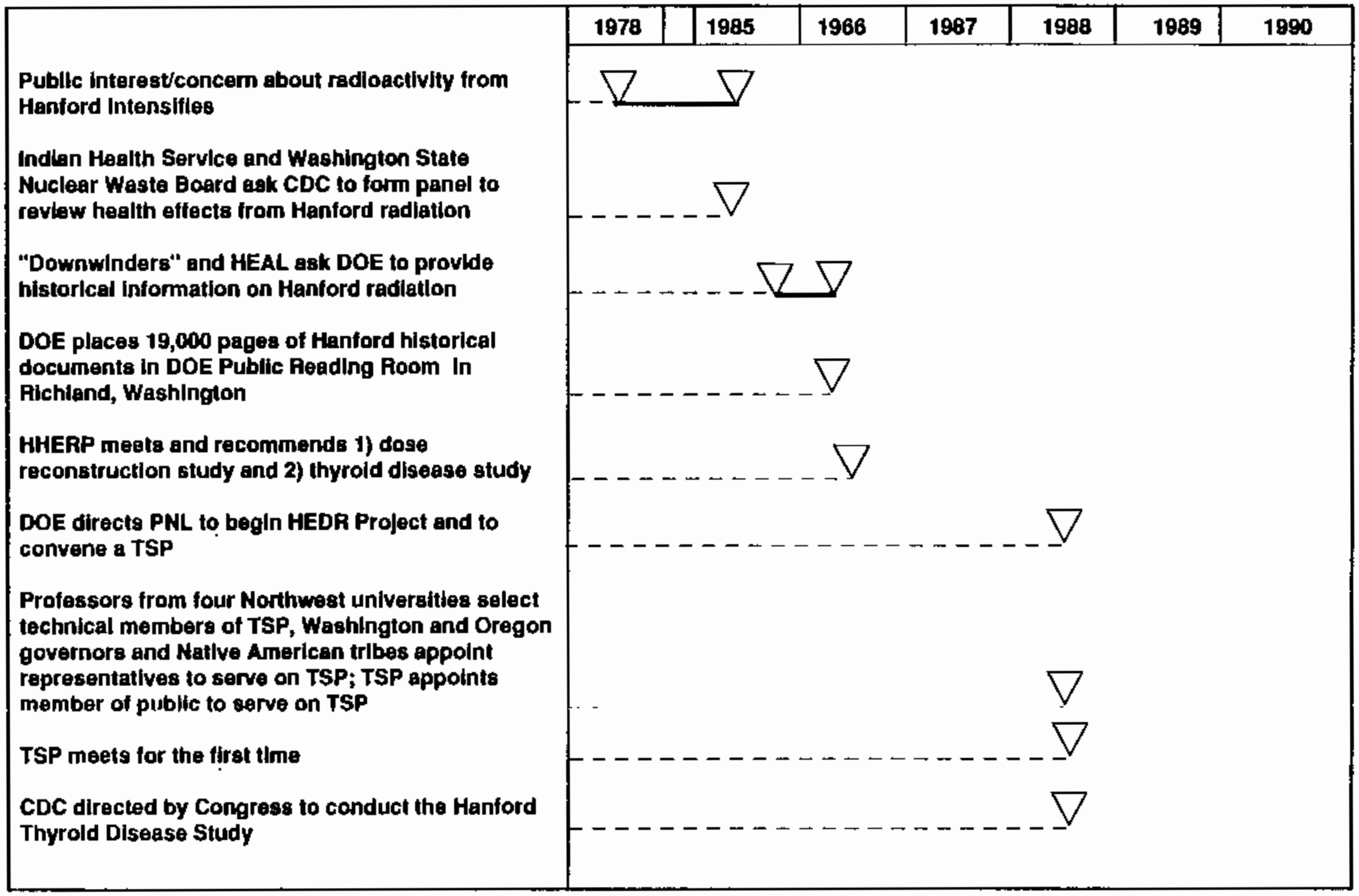
The primary objective of the Hanford Environmental Dose Reconstruction (HEDR) Project is to estimate the radiation doses that people could have received from nuclear operations at the Hanford Site. The secondary objective is to make project records available to the public. Copies of project records are maintained in the Department of Energy-Richland Operations (DOE-RL) Public Reading Room in the Federal Building, Richland, Washington.

1.2 PROJECT HISTORY

The HEDR Project was prompted by mounting concern about possible health effects to the public resulting from more than 40 years of nuclear operations at the Hanford Site (Figure 1.1). In 1986, the Hanford Health Effects Review Panel--convened by the Centers for Disease Control at the request of the Washington State Nuclear Waste Board and the Indian Health Service--recommended as a top priority that potential doses from radioactive releases at the Hanford Site be reconstructed. The Panel also recommended that a thyroid disease study be initiated.

Representatives from the states of Washington and Oregon, from three regional Native American tribes, and from the DOE agreed that a dose reconstruction study should be funded by the DOE, be conducted by Battelle, Pacific Northwest Laboratories, and be directed by an independent panel of scientists and state and Native American representatives. A Technical Steering Panel (TSP) was deemed necessary to provide credible, independent scientific direction and to provide a forum for participation by the states, Native American tribes, and the public.

Representatives from four Northwest universities selected technical members of an independent TSP to direct the dose-reconstruction work. The TSP includes members with technical expertise in environmental pathways, epidemiology, surface-water transport, groundwater transport, statistics, demography, agriculture, meteorology, nuclear engineering, radiation



CDC = Centers for Disease Control
DOE = U.S. Department of Energy, Richland Operations
HEAL = Hanford Education Action League
HHERP = Hanford Health Effects Review Panel
PNL = Pacific Northwest Laboratory
TSP = Technical Steering Panel
HEDR = Hanford Environmental Dose Reconstruction (Project)

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FIGURE 1.1. Timeline of Events Leading to Establishment of the HEDR Project

dosimetry, and cultural anthropology. The TSP also includes individuals appointed to represent the states of Washington and Oregon, cultural and technical experts nominated by the Native American tribes in the region, and an individual representing the public. The TSP reviews, evaluates, and approves all technical decisions and reports.

1.3 HANFORD SITE

The Hanford Site in southeastern Washington State (Figure 1.2) was selected in 1943 as the location for the facilities used to produce plutonium for atomic bombs used in World War II. The Hanford fuel cycle is illustrated in Figure 1.3. The first three nuclear reactors--B, D, and F--began operating in 1944 and 1945. After World War II ended in 1945, the reactors continued to irradiate uranium fuel and to produce plutonium. From 1949 through 1963, six new reactors--H, DR, C, KW, KE, and N--began operating. In addition to producing plutonium, N Reactor produced steam to generate electricity. This reactor also differed from earlier reactors in that cooling-water discharges of radionuclides were much smaller than those from earlier reactors. From 1964-1988, as the government needed less plutonium, it eventually closed all of its production reactors on the Hanford Site.

The use of river water to cool the reactors resulted in the greatest releases of radionuclides to the Columbia River. Releases of radionuclides to the ground from nuclear facilities resulted in the movement of some radionuclides to the groundwater and from the groundwater to the Columbia River.

1.4 MONITORING OF RADIOACTIVE MATERIALS FROM HANFORD

The release of radioactive materials from Hanford was controlled through several steps, including process controls, effluent and environmental monitoring, and personnel monitoring. Effluent monitoring, which began with the startup of Hanford facilities in 1944, consisted of measuring the amounts of radioactive materials vented to the atmosphere and released to soils and to the Columbia River. Measurements of materials released to the river began with startup and continued throughout the operation of the reactors.

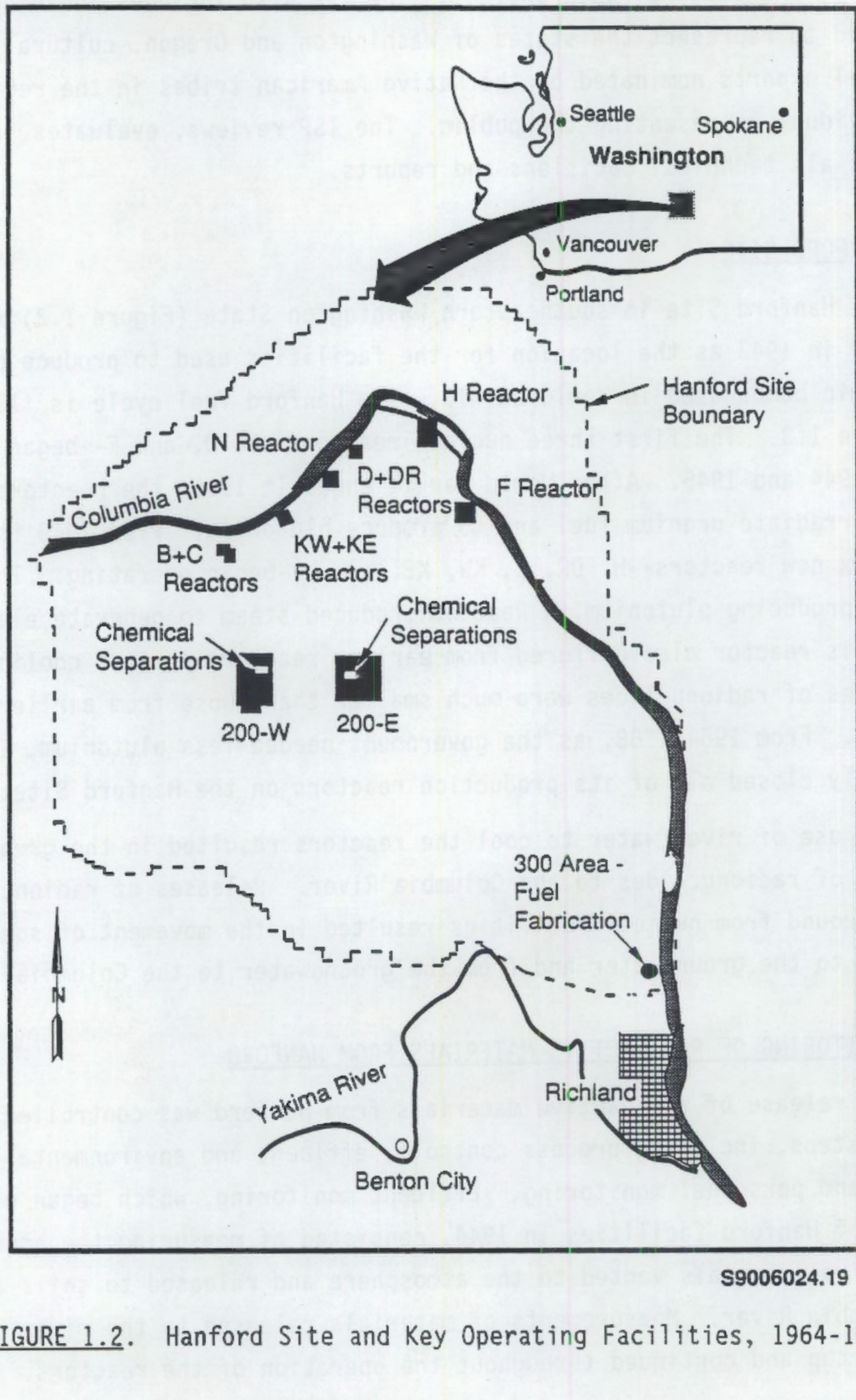


FIGURE 1.2. Hanford Site and Key Operating Facilities, 1964-1966

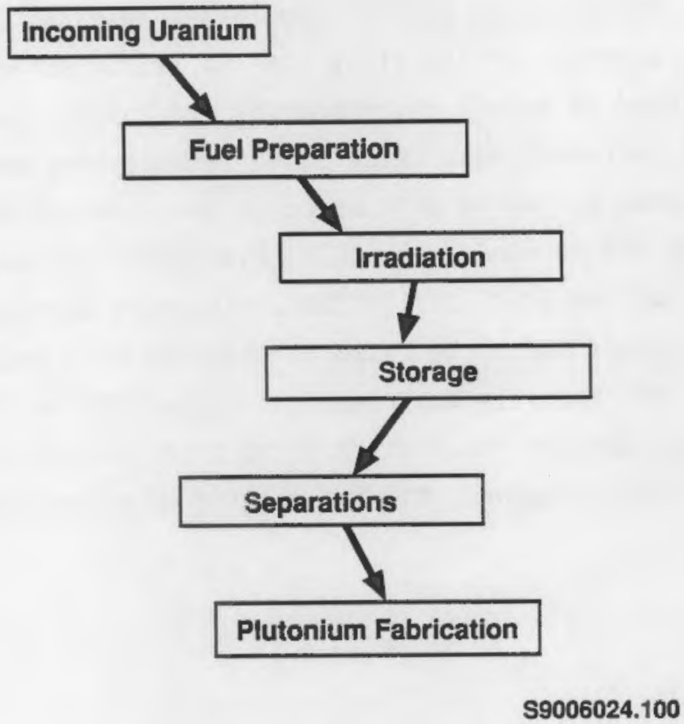


FIGURE 1.3. Nuclear Fuel Cycle

Environmental monitoring started before facilities began operating and eventually included measurements of radioactivity in the air, on the ground, on vegetation, in food, and in Columbia River water, drinking water, sediment, fish, and other aquatic and marine life.

Radiation monitoring of Hanford workers began in 1944 (Wilson 1987). In addition to measuring external exposures using pencil dosimeters, hand and foot counters, and scans of clothing and extremities with Geiger counters, a bioassay program and limited scans of the thyroid glands of specific workers were also begun. Beginning in 1959, whole-body counts were also conducted. These later measurements provide useful comparisons with the dose estimates of the HEDR Project.

Offsite monitoring of people began in 1965. Over 5000 schoolchildren in the Tri-Cities area were monitored with whole-body counters from 1965-1968. These monitoring data provide valuable comparisons with previously published dose estimates for the same period and with the estimates calculated by the HEDR Project.

Radiation doses to the general population near the Hanford Site were estimated and reported for the first time in 1957. Estimates of these doses have been included in annual environmental monitoring reports ever since. As technology has improved, dose calculation methods have evolved and improved. Through 1973, dose estimates were based on measurements of radionuclides in the environment and in foods. By 1974 (Fix 1975; Fix and Blumer 1975), concentrations of radionuclides in the environment decreased to the point where dose estimates had to be based on modeling from measured or estimated releases. The decreases in environmental concentrations of radionuclides originating from Hanford resulted from improved control technology, the closing of the original reactors, and the closing of major chemical-processing operations.

2.0 METHODS

This section describes the conceptual and computational approaches used during Phase I to reconstruct potential radiation doses to offsite populations from releases of radionuclides to the Columbia River and to soils (and groundwater). Detailed descriptions of all aspects of the HEDR Project and the dose reconstruction process are available in the more than 20 supporting documents in Appendix A. Table 2.1 references the HEDR reports that contain information about models and parameters used in Phase I. Appendix B contains the models and information used in the surface-water code.

2.1 PHASE I AREA, TIME PERIODS, AND RADIONUCLIDES

The HEDR Project consists of four distinct phases (Figure 2.1). The first phase, a pilot or demonstration phase, was purposely limited in geographic coverage, time, radionuclides, and pathways. This limited scope influenced the selection of models and parameters and resulted in some conservatism in the designation of the forms and ranges of distributions.

Phase II is designated a review and testing phase, during which sensitivity analyses will be used to identify key parameters and the influences of model structure. Phases III and IV will be used to refine parameters, modify models, expand areas, extend time periods, and ensure that all key emissions of radioactive materials from Hanford will have been addressed.

2.1.1 Area

The Phase I study area for the river pathway was selected to include the communities immediately downstream of the Hanford Site, which are most likely to have received the highest doses from drinking treated Columbia River water or from eating fish caught in this area (Figure 2.2). Any individuals from outside the Phase I study area who fished this section of the Columbia River might have received higher doses from this pathway.

The area between Priest Rapids Dam and McNary Dam was also selected because up to 80% of the people who drank treated Columbia River water between Hanford and the river's mouth lived along this stretch of the river during the Phase I period, 1964-1966. In addition, the most extensive and

TABLE 2.1. Applicable HEDR Reports - Columbia River Exposure Pathway

Topic	Title	Author, Date
Source Terms	Radionuclide Sources and Radioactive Decay Figures Pertinent to the HEDR Project, PNL-7177 HEDR	Heeb, CM, 1989
	Uncertainties in Source Term Calculations Generated by the ORIGEN2 Computer Code for Hanford Production Reactors, PNL-7223 HEDR	Heeb, CM, 1989
	Selection of Dominant Radionuclides for Phase I of the HEDR Project, PNL-7231 HEDR	Napier, BA, 1990
Drinking Water and Fish Concentrations	Preliminary Summaries for Vegetation, River and Drinking Water and Fish Radionuclide Concentration Data (DRAFT), PNL-SA-17641 HEDR	Woodruff, RK, 1989
	Estimates of Columbia River Radionuclide Concentrations: Dose for Phase I Dose Calculations, PNL-7248 HEDR	Richmond, MC, and Walters, WH, 1990
Ground Water	Response to TSP Directive 88-4, Ground-Water Contamination Data, PNL-6847 HEDR	Freshley, MD, 1989
Demography	Demographic, Agricultural, Food Consumption, and Lifestyle Research for the Hanford Environmental Dose Reconstruction Project, PNL-6834 HEDR	Beck, DM, et al., 1989
Facility Operations	A History of Major Hanford Operations Involving Radioactive Material, PNL-6964 HEDR	Ballinger, MY, and Hall, RA, 1989

PHASE I	PHASE II	PHASE III
Model Development & Testing	Sensitivity/Uncertainty Analysis	Expansion and Refining
• Select limited scope: geographical area, time period, radionuclides, populations • Find, evaluate, and summarize historical data • Develop conceptual & mathematical models and incorporate uncertainty • Apply models/data to limited scope to test the model	• Evaluate Phase I model results • Identify key parameters for dose calculation via sensitivity analyses • Determine feasibility/value of reducing uncertainty in parameters • Propose to expand scope (geographic area, time period, populations) in context of established dose threshold • Recommend action to reduce uncertainties and recommend changes in conceptual/math models	• Expand scope as warranted by Phase II work • Reduce uncertainty in key parameters per Phase II recommendations • Modify models per Phase II recommendations **PHASE IV** Dose Calculation • Calculate final estimated doses

FIGURE 2.1. The HEDR Phased Approach

continuous monitoring data and the only direct, continuous monitoring of drinking water are available from this area.

2.1.2 Time Period

The Phase I time period for water exposure, 1964-1966, was selected for several reasons. Richland, the community closest to Hanford and therefore the most likely to have received the highest doses from drinking treated Columbia River water, did not use Columbia River water until 1964. Doses at Pasco and Kennewick, where residents used Columbia River water before 1964, were known to be lower because they are farther downstream, because they are downstream of the confluence of the Yakima River, and, in the case of Kennewick, because residents obtained water from river shore wells, which helped to filter some radioactive materials from the water before it reached the treatment plant.

The Phase I time period of 1964-1966 also was selected for the following reasons:

- Extensive monitoring data were available.
- Continuous monitoring (or cumulative monitoring) began in 1964 to supplement "grab" sampling. This monitoring provided better estimates of average concentrations of longer-lived radionuclides.

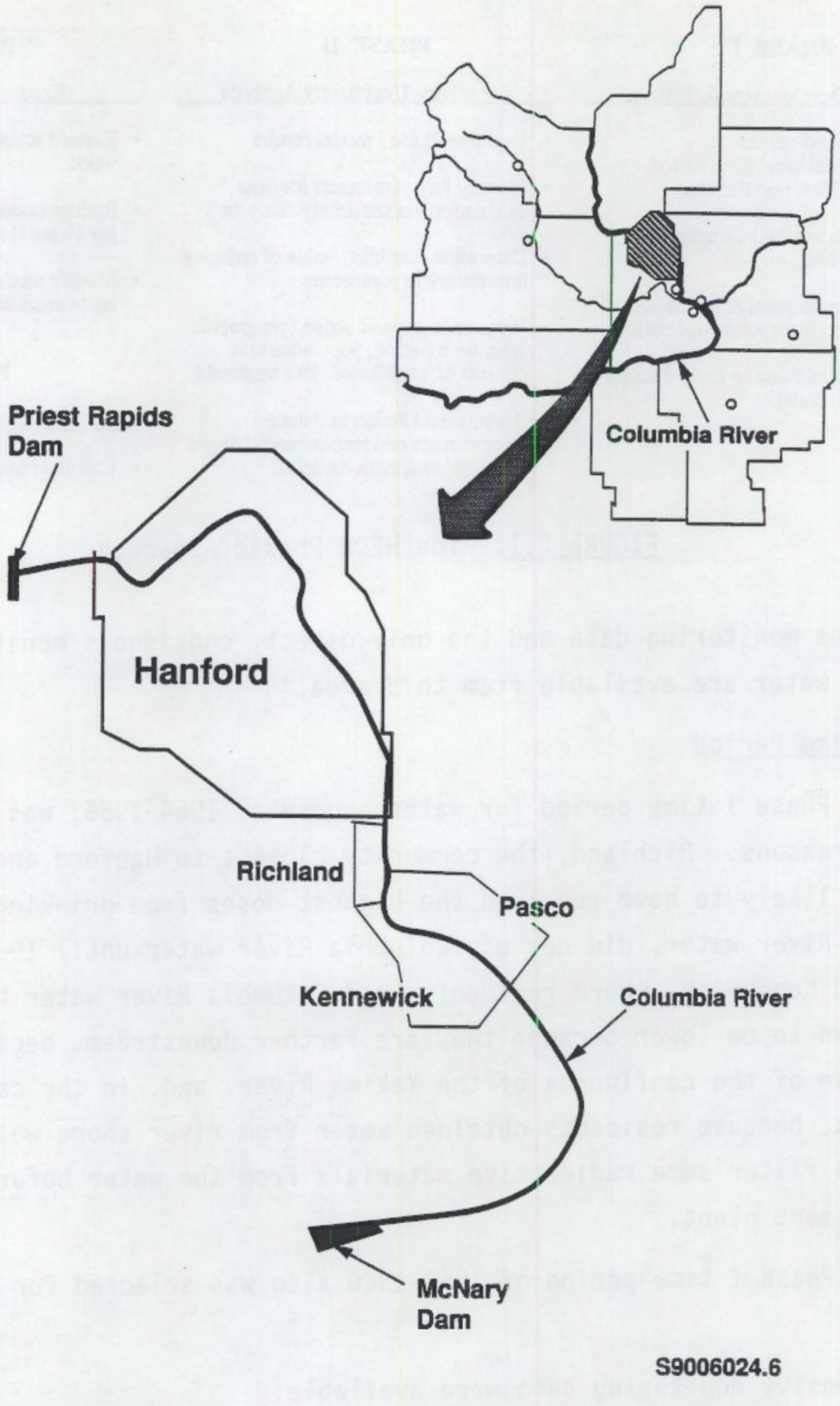


FIGURE 2.2. Phase I Study Area for Estimating Doses from the Columbia River Pathway

- All reactors were still in operation in 1964, and were operating at the highest historical power levels.
- Data from independent sources such as the State of Oregon and the U.S. Geological Survey are available for this period.

Finally, the middle 1960s were selected because during earlier periods, such as 1944 to 1947, which was selected for the air pathway, only two or three reactors were operating and reactor power levels, and consequently radioactive discharges to the river, were much lower.

2.1.3 Radionuclides

Not all radionuclides that were discharged from the reactors in cooling water (or that moved from soils to groundwater and thereby to the Columbia River) contributed significantly to dose. Several radionuclides (phosphorus-32, zinc-65, arsenic-76, neptunium-239, sodium-24, manganese-56, copper-64, chromium-51) were identified as key radionuclides for Phase I because HEDR estimated that they accounted for more than 80% of the dose to maximally exposed individuals (Napier 1990). The relative importance of these radionuclides in contributing to dose depended on the pathway, the stretch of the river from which drinking water was withdrawn or where fish were caught, the species of fish, and fluctuations in radionuclide concentrations with time. Nevertheless, these radionuclides accounted for most of the river pathway doses to populations in the Tri-Cities during 1964-1966.

2.1.4 Pathways

The drinking-water pathway exposed more people in the Phase I study area than did the fish pathway, but people who ate large quantities of certain species of fish could have received the higher doses, because several species of fish eat aquatic life that concentrate radionuclides from the river. Migratory species such as salmon and steelhead trout, on the other hand, eat little or nothing while migrating from the ocean to their spawning grounds, and therefore have lower radionuclide loads. Other pathways, such as swimming or boating or walking along the river shore, resulted in exposures that were, on average, considerably lower than exposures from the drinking-water and fish pathways. (The irrigation pathway will be addressed in later phases.)

From the time Hanford facilities first began operating, highly radioactive liquids were routed to underground storage tanks and less radioactive liquids were discharged directly to ponds, ditches, and engineered structures called cribs. Some of the radioactive liquids moved through the soils into groundwater and some traveled in the groundwater to be discharged into the Columbia River. These radioactive liquids contributed very little to the much larger amounts of radioactive liquids that were routinely discharged into the Columbia River as part of the cooling water from the original reactors. In any case, since Phase I dose calculations for the Columbia River pathway are based on environmental monitoring data, radionuclides that might have entered the Columbia River from groundwater in detectable amounts are included in the Phase I dose calculations.

2.2 EXPLICIT INCORPORATION OF UNCERTAINTY

Previously published doses from the river pathway for 1964-1966 were based on average measured concentrations of radionuclides in food (Columbia River fish, marine organisms, vegetables) and drinking water and on average measurements of external radiation along the river shoreline. These previously published doses were point estimates for average and hypothetical maximum individuals in 1964 and for typical and hypothetical maximum individuals in 1965 and 1966 (Foster and Wilson 1965; Foster et al. 1966a, 1966b; Honstead et al. 1967). There is no information about what proportion of the population in the Phase I area might have received doses within some specified percent of the average. Similarly, the dose estimate for a hypothetical maximum individual cannot be interpreted to be representative of any number of individuals.

To obtain information about the degree to which dose estimates might apply to certain proportions of the population in the Phase I study area and to deal with uncertainties in previously published data, the HEDR model uses distributions, rather than point estimates, as input to all submodels, and it generates distributions as outputs. The distributions are presented as complementary cumulative-distribution functions that provide immediate information concerning median values, the likelihood of exceeding any specified dose value, and the proportion of values between any two selected values, etc. Consequently, average, maximum, or minimum values can be defined by the reader according to his or her own definitions of maximum, minimum, or average.

By incorporating uncertainty in the dose calculation process, sensitivity analyses can readily be used to identify key parameters and their relative influence on uncertainties in dose estimates. This approach enables resources to be allocated to reduce uncertainties in those parameters (and those aspects of model structure) that contribute the most to uncertainties in the dose results.

2.3 SELECTION OF MODELS, PARAMETERS, AND DISTRIBUTIONS

The period 1964-1966 was selected because it provides an optimum combination of extensive monitoring information, independent measurements, relatively high river concentrations, and a population newly exposed to treated drinking water having the highest concentrations of radionuclides, that of Richland (Foster and Wilson 1965). Because of the extensive monitoring data, modeling was conducted only when data for specific radionuclides were insufficient.

The project selected a simple routing model that uses effluent measurements and river discharge as input and uses only radioactive decay and mixing to provide radionuclide concentrations at specific downstream locations (Richmond and Walters 1990). Because factors such as radionuclide interactions with sediment and aquatic biota during transport to downstream locations were ignored, this simple routing model is likely to overestimate concentrations of those radionuclides that are known to be selectively removed by physical and chemical processes between the effluent discharge point and various downstream locations. To what degree exclusion of these parameters from the model structure influenced Phase I preliminary dose estimates will be assessed in Phase II.

Monthly concentrations of radionuclides in effluents, Columbia River water, Columbia River fish, and drinking water for the period 1964-1966 were taken directly from historical documents (Foster and Wilson 1965; Foster et al. 1966a, 1966b; Honstead et al. 1967). The radionuclides of interest were selected based on analyses of the source inventories and estimates of their contribution to dose (Napier 1990). The radionuclides and their half-lives are phosphorus-32 (14.3 days), neptunium-239 (2.36 days), zinc-65 (244 days), arsenic-76 (1.10 days), manganese-56 (0.11 days), copper-64 (0.53 days), sodium-24 (0.62 days), and chromium-51 (27.7 days).

Gaps in monthly data made it necessary to calculate concentrations of some radionuclides. As a first approximation, radionuclide concentrations in the Columbia River water column were calculated assuming that dilution and decay were the primary processes controlling the fate of radionuclides released to the river. Calculations were performed using the following equation:

$$C_j(i) = (r_i/Q_j) \exp(-K_i T_j) \qquad (1)$$

where $C_j(i)$ = concentration of the i-th radionuclide at the j-th downstream river location (Ci/ft^3),

r_i = reactor-effluent mass-flow rate (Ci/month)

Q_j = Columbia River discharge at location j (ft^3/month)

K_i = decay constant (1/day)

T_j = travel time from the reactor areas to location j (day).

In Equation (1), the concentration of a radionuclide in the river is equal to dilution times decay. Equation (1) is used only to calculate radionuclides; concentrations of radionuclides in the river bed sediments were not calculated for Phase I. The assumptions implicit in using Equation (1) and the limitations in calculating radionuclide concentrations in the Columbia River are the following:

- On a monthly time scale, the flow and radionuclide transport in the Columbia River reach between Priest Rapids Dam and McNary Dam and in each subreach can be represented as a succession of steady-state time periods.

- The reactor effluent discharge rates are constant within each month. The effects of longitudinal dispersion (mixing) are neglected, and complete mixing of effluent at the discharge point is assumed.

- Radionuclides are completely mixed, or uniformly distributed in a cross section of the river, at any location in the reach between Priest Rapids Dam and McNary Dam. Under actual conditions, this assumption is not realistic near the reactor-effluent outfalls and for a number of miles downstream, depending on flow conditions in the river. In addition, this assumption does not apply at locations downstream from where tributaries, such as the Yakima, Snake, and Walla Walla rivers, enter the Columbia.

- The effluent spent a relatively short time in retention basins prior to discharge to the river, compared with the half-life of the individual radionuclides. The retention time of the effluent was typically 4 hours (Honstead 1967).

- Radionuclide sources and sinks in the river are neglected. Sorption to sediment and subsequent deposition or resuspension of contaminated bed sediment are assumed to be small compared with the concentrations of radionuclides dissolved in the water column.

Despite these assumptions, Equation (1) is a useful tool for preliminarily estimating radionuclide concentrations for Phase I and for comparing these estimates with measured concentrations to evaluate the consistency of the available data.

Five subreaches of the river between Priest Rapids Dam and McNary Dam were selected for estimating the radionuclide concentrations in the river water for Phase I. These five subreaches, designated Ringold, Richland, Pasco, Finley, and McNary (Figure 2.3), were selected because they correspond to geographic locations of interest, such as population centers and confluences of the tributaries of the Columbia River. Each tributary enters the Columbia River in a different subreach.

The calculations for dilution and decay of radionuclides downstream of the reactors used hydrographs for the Columbia River and its tributaries in the reach between Priest Rapids Dam and McNary Dam. The monthly average discharges or flow rates for the Columbia River and its tributaries are provided in Richmond and Walters (1990). These authors also list the average monthly discharges of the Columbia River in each subreach for 1964 through 1966. The discharges for each subreach were calculated by summing the discharge for the Columbia River and any tributaries entering the subreach.

Travel times for radionuclides suspended in the water column were estimated. Using a set of flow-time curves calculated by the U.S. Army Corps of

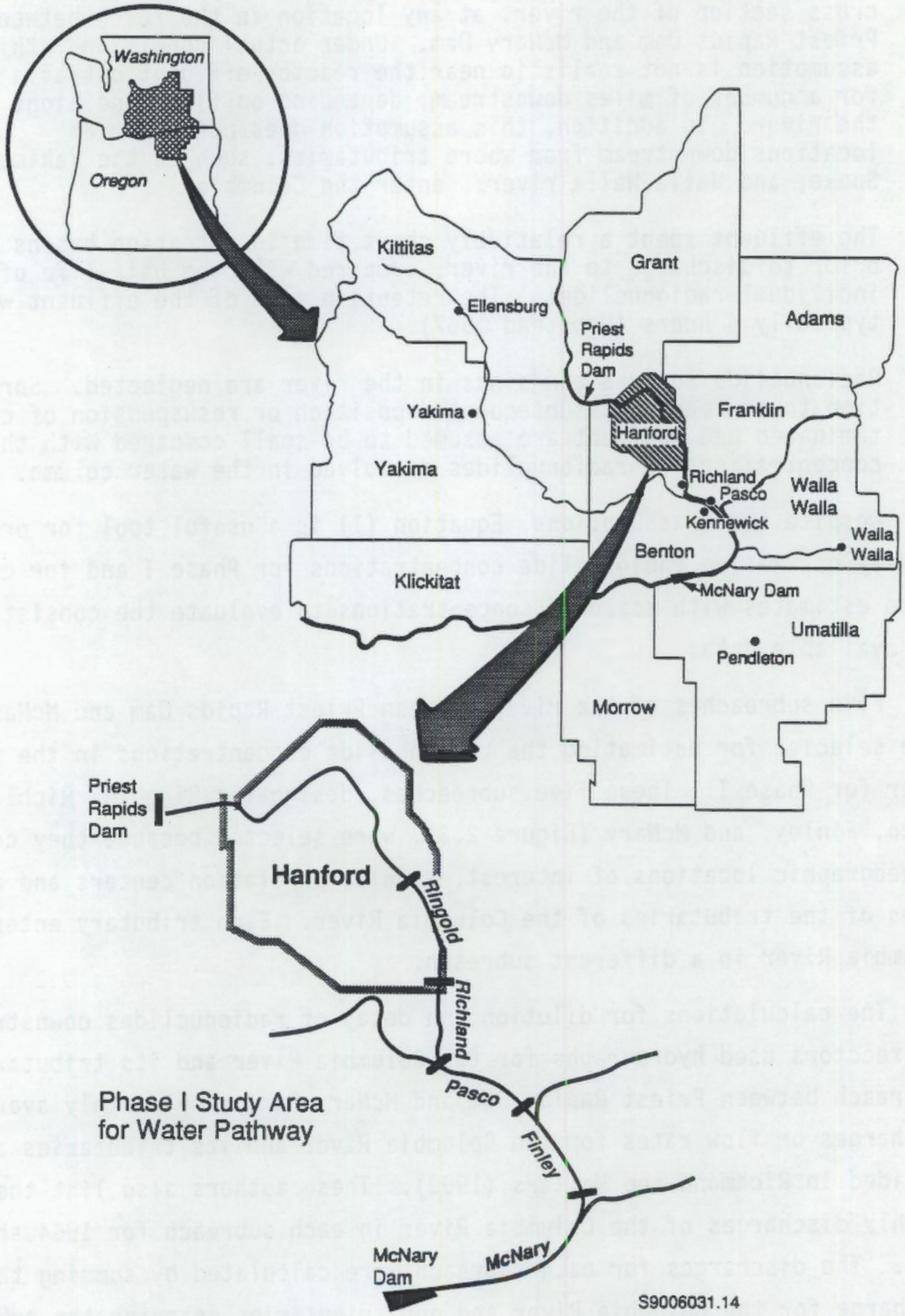


FIGURE 2.3. Columbia River Subreaches for Phase I of the Water Pathway

Engineers, Richmond and Walters (1990) estimated approximate travel times for each subreach. These travel-time estimates are used to account for radioactive decay in the various subreaches of the river, based on the half-lives of key radionuclides. More accurate estimates of travel times for the wide range of flow conditions in the Columbia River could be determined using unsteady river-flow calculations. However, the approach of estimating travel times based on the backwater curves was judged to be adequate for Phase I.

Monthly averaged radionuclide mass-flow rates and daily measurements of radionuclide concentrations in reactor effluent used in the Phase I calculations are from Owen (1967). The samples were collected before the effluent entered the retention basins, but the values recorded were corrected for 4 hours of decay and therefore reflect the concentrations of radionuclides discharged to the river. Richmond and Walters (1990) summed the monthly average mass flow rates for the dominant radionuclides for all of the operating reactors.

Sensitivity analyses will be conducted in Phase II to determine if additional modeling is needed to provide data missing from earlier periods or from specific locations of interest along the river.

The general logic of the HEDR model is shown in Figure 2.4. The model uses two large data bases for input: the output of the river water modeling discussed above, and a collection of available monitored fish concentrations.

The fish concentration data base is derived from the reported individual samples taken from each stretch of the Columbia during the years 1964-1966. Sufficient detail was available to develop seasonal distributions of data for the radionuclides phosphorus-32 and zinc-65 for three types of fish: omnivores (whitefish, carp, catfish, etc.), primary predators (bluegill, perch, etc.), and secondary predators (such as bass and trout). Data from the Columbia River from earlier years were used to develop water-to-fish concentration ratios for the radionuclides arsenic-76 and neptunium-239, for which few samples were taken in the Phase I period. Finally, generic concentration ratios were used for short-lived or low-uptake radionuclides.

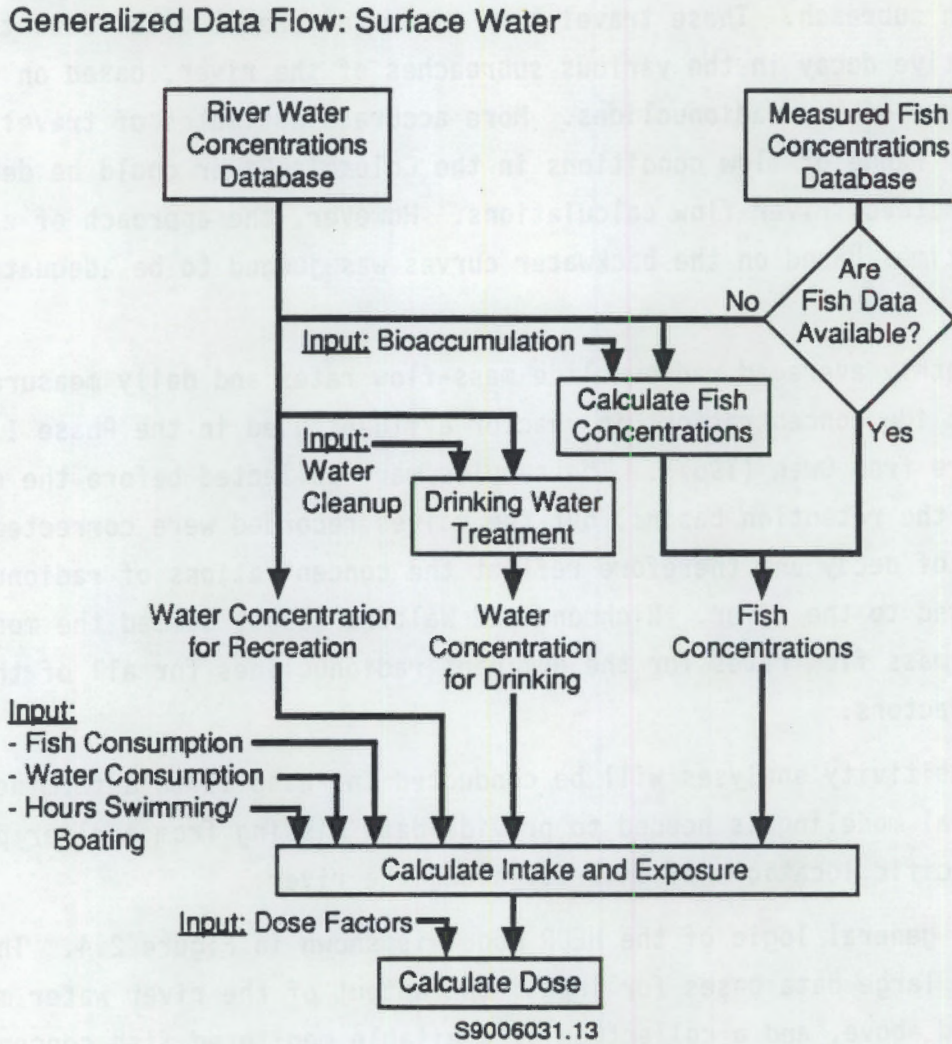


FIGURE 2.4. Conceptual Diagram of the HEDR Columbia River Pathway Model

Drinking-water concentrations are provided for three types of treatment: none, alum-flocculation used in Richland and Pasco, and well-filtration used in Kennewick. Transmission factors for these processes were derived from monitoring data at the various water treatment plants during the Phase I period.

Doses from recreation (swimming and boating) are calculated as a function of the raw river water concentration. Doses from shoreline exposure while fishing were not addressed in Phase I. Drinking doses for each stretch of the river are provided for each of the cleanup systems available on that stretch. Doses from fish consumption are calculated for generic diets--three are provided. The first is simply no fish consumption, which applied to between 75 and 85% of the Tri-Cities population. The second is a "low" consumption diet of between 1 and 20 meals of fish per year (200 grams per meal). The third is a "high" consumption diet ranging from 20 to 200 fish meals per year.

Additional pathways, such as consumption of irrigated crops, have been omitted from the Phase I model, because relatively few people were affected. The need for inclusion of these other pathways will be investigated in Phase II of the Project.

Equations describing the calculations are presented in Appendix B. All calculations are performed in a Monte Carlo fashion, with realizations drawn from the distributions for each parameter for each simulation (Appendix B). The resultant output is a distribution of doses for each type of individual investigated.

2.3.1 Drinking-Water Concentrations

Phase I drinking water doses are based on the estimated river concentrations and estimates of water treatment plant transmission factors. The distributions of transmission factors are based on monitoring of water entering and leaving the treatment plants, as reported in Foster and Wilson (1965), Foster et al. (1966a, 1966b), and Essig (1967).

Previously published measurements of selected radionuclides in the drinking water supplies of Richland, Kennewick, and Pasco show that concentrations were lower than in untreated river water sampled at the water-withdrawal sites. These lower concentrations are due to water treatment, in the case of Richland and Pasco, and in addition to water treatment, to filtering of river water by soil, in the case of Kennewick, which withdrew water with river shore wells.

2.3.2 Fish Concentrations

Previously published estimates of doses to a hypothetical maximally exposed individual were highest for individuals who might have eaten large quantities of freshly caught fish of specific kinds, from specific locations, and at specific times of year. Whitefish had the highest average concentrations among several fish species, and highest concentrations were found in fish at Ringold (see, for example, Foster and Wilson 1965). Fish not eaten fresh would contain reduced concentrations of shorter-lived radionuclides such as phosphorus-32.

In summary, doses from the fish pathway are expected to be highly sensitive to amounts consumed, season caught, storage time, species, and location where caught.

2.3.3 Population Distributions

The communities of Richland, Kennewick, and Pasco accounted for up to 80% of the use of treated Columbia River water for drinking between Hanford and the river mouth. Previously published estimates of the numbers of individuals in the Phase I study area who ate Columbia river fish exist; however, the geographic distributions of these individuals were not available for the Phase I calculations. Historical data will be sought and reviewed during later phases.

3.0 PRELIMINARY DOSE ESTIMATES

The preliminary dose distributions can be understood in the context of the factors that resulted in some individuals having relatively higher and others relatively lower doses. Dose distributions were calculated for "reference individuals," individuals who shared certain characteristics, as illustrated with the following example.

By "walking" through Figure 3.1, individuals who lived in the Phase I area during 1964-1966 can estimate the range of dose values that might apply to them and how likely these doses were. For example, if one ate less than 20 meals of Columbia River fish per year, fished upstream of Richland, and lived in Richland, then one's estimated dose is in the range identified by number 12 in Figure 3.2. The doses for this category range from 0.04 to approximately 0.07 rem (0.0007 Sv). The distribution in Figure 3.3 provides additional information about doses to Richland populations. This figure shows the median, percentage of doses between two values, and the percentage of doses greater than a specific value. The entire range of doses by river reach, organ, year, and exposure pathway are shown in Appendix C.

As is clear from Figures 3.1 and 3.2, the highest doses were received by individuals who consumed large quantities of fish from areas above Richland and who drank untreated, or raw, river water. (Some individuals might have used Columbia River water not treated by municipal treatment plants.) Doses from drinking water are lower at Pasco than at Richland and lower at Kennewick than at Pasco (Figure 3.4); this reflects dilution and travel time. The lower doses in Kennewick reflect the use of a well field along the Columbia. Several radionuclides are filtered by the soils through which they travel from the river to the adjacent wells.

Figure 3.5 depicts the relative importance of the various river pathways for people in the Tri-Cities who consumed fish from the Columbia River, drank treated river water, or boated and swam in the river.

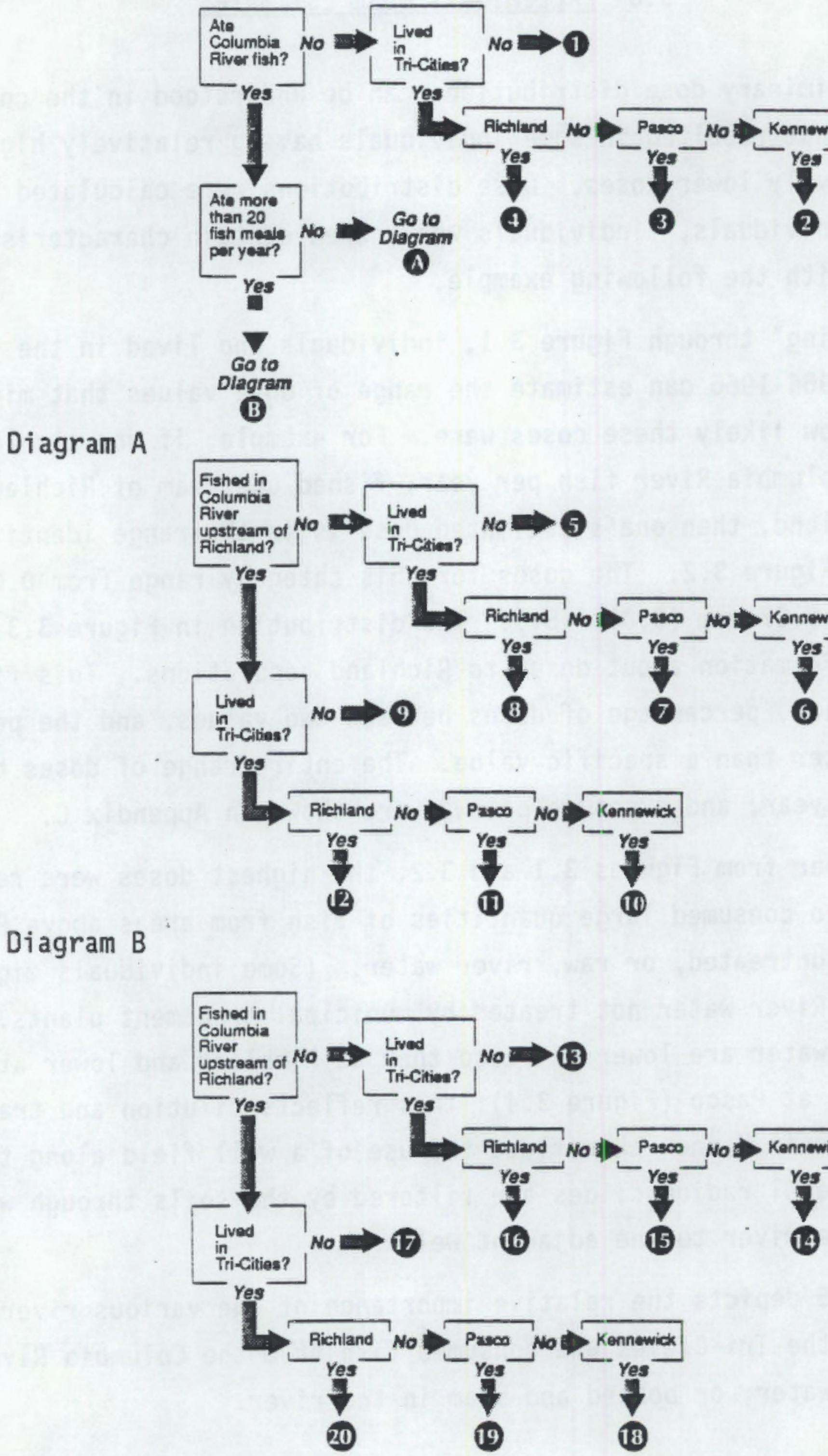
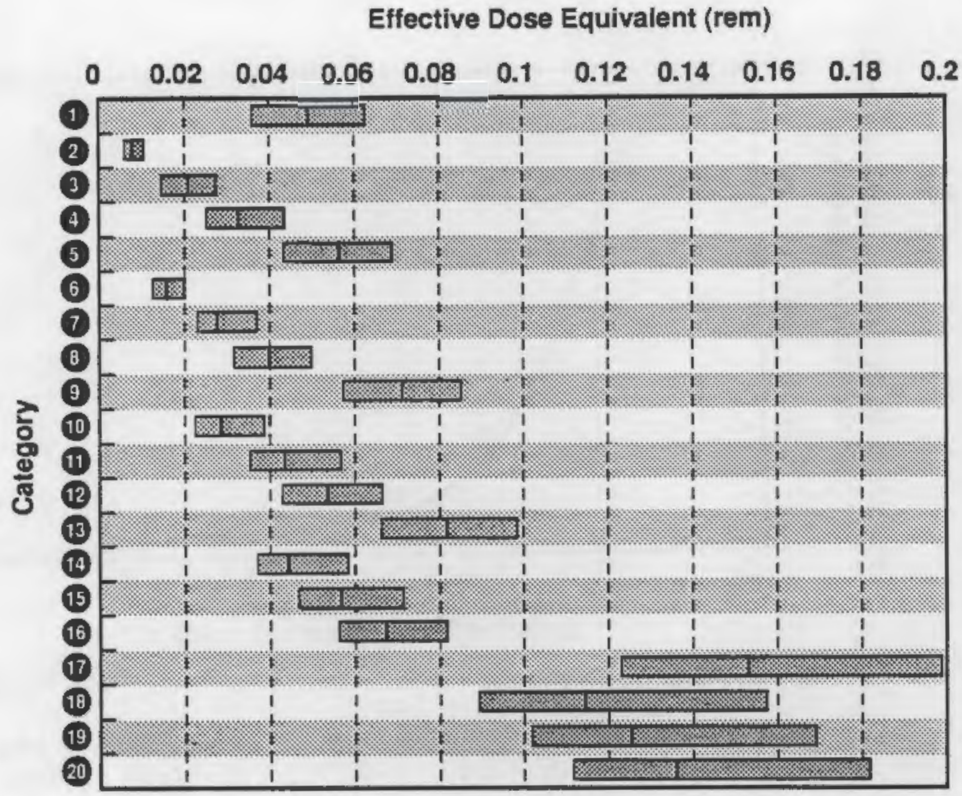


FIGURE 3.1. Guide to Establish Dose Category for 1964-1966 Residents in Phase I Study Area (See Figure 3.2 for ranges of estimated doses)



The vertical lines in the bars are the medians. The median is the dividing point showing where half the people in that category received a larger dose than the median dose and half the people received a smaller dose.

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FIGURE 3.2. Preliminary Dose Estimates for Columbia River Exposure Pathway (Each bar shows the range of doses that people in the category opposite the bar could have received. Each bar covers 90% of the people in that category. Estimated radiation doses for people in both the lowest and highest 5% of each category are not included because the numbers are much less accurate.)

3.1 COMPARISON OF DOSES

The Phase I results demonstrate that this phase attained its key objectives. First, sufficient historical information was retrieved and reconstructed. Second, preliminary conceptual and computational models were constructed to deal with uncertainties and to establish the foundation for extensive sensitivity analyses to be conducted in Phase II. Finally, the data and modeling approach were sufficient to produce credible, although

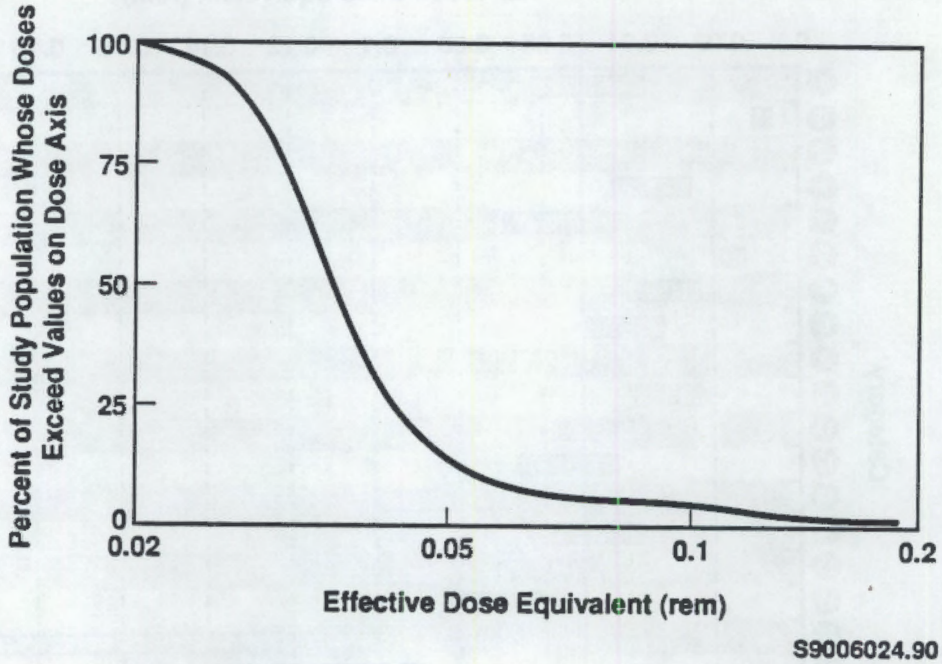

FIGURE 3.3. Preliminary Estimated Doses from Columbia River Exposure Pathway, 1964-1966 (Richland residents)

clearly preliminary, dose distributions. These objectives were attained by demonstrating that the range of preliminary dose estimates includes independent, previously published estimates of doses to average, typical, and maximally exposed individuals and that the range includes doses estimated from previously published whole-body counts of workers and schoolchildren.

3.1.1 Previously Published Dose Estimates

Dose estimates for offsite populations, first published in 1957, have continued to be published annually in monitoring reports. Figure 3.6 compares the previously published estimates for 1964-1966 with HEDR Phase I preliminary dose estimates (median values) (Foster and Wilson 1965; Foster et al. 1966a,b; Honstead and Essig 1967; and Honstead et al. 1967). The historical "average" or "typical" cummulative exposure (1964-1966) of a Richland resident was 0.03 rem (0.0003 Sv). Approximately 50% of the Richland population was likely to have received doses greater than 0.035 rem for the period 1964-1966. Additional detail is attached in Appendix C.

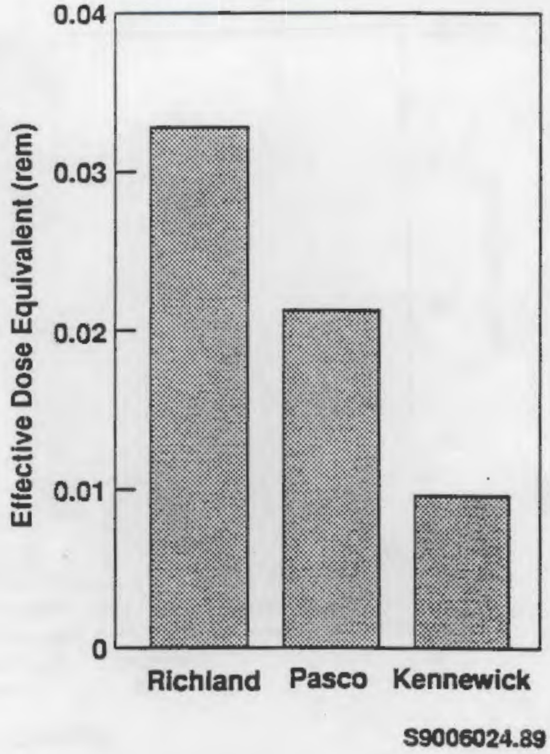

FIGURE 3.4. Phase I Dose Estimates from the Drinking-Water Pathway for Richland, Kennewick, and Pasco Residents, 1964-1966 (median values)

3.1.2 Whole-Body Counts

Approximately 4,700 records of whole-body counts of workers are available for the period 1964-1966. These records show the amount of one radionuclide, zinc-65, that had been absorbed by the body from drinking treated Columbia River water, eating Columbia River fish, or eating produce that had been irrigated with Columbia River water downstream of the reactors. (Irrigation was not considered as a pathway in Phase I.) Many records also show short-lived sodium-24 from the same sources. The radionuclides were among several that could be readily detected with the whole-body counter.

Dose estimates based on previously published whole-body measurements of zinc-65 in Hanford workers are slightly lower than the fraction of HEDR-calculated doses attributable to zinc-65 (Figure 3.7). Previously published whole-body measurements of zinc-65 in schoolchildren are also slightly lower than HEDR-calculated body burdens of zinc-65 (Endres et al.

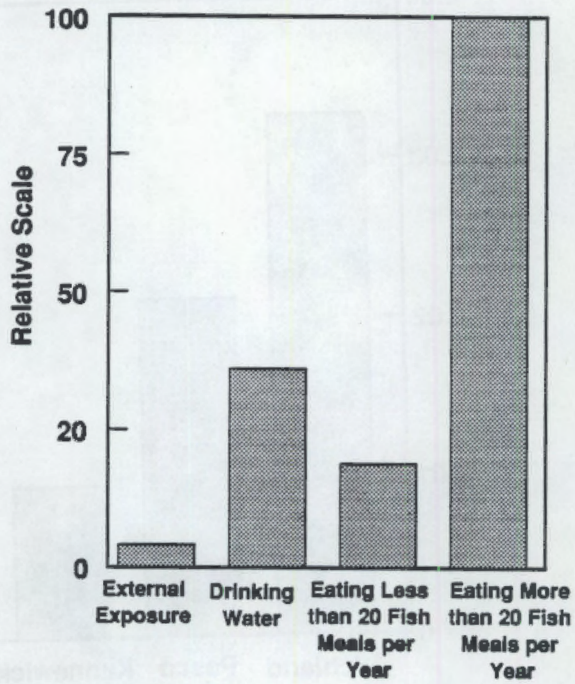

FIGURE 3.5. Relative Importance of Fish, Drinking-Water, and External Exposure Pathways (Richland residents, 1964-1966)

1972). These comparisons indicate that the HEDR model appears to produce dose estimates consistent with actual measurements from the 1960s.

3.2 BACKGROUND RADIATION

One way of placing the preliminary Phase I doses in perspective is to compare them with doses from background radiation.

Annual background doses (including radon) in the Richland area are about 0.36 rem (0.0036 Sv) per year (National Council on Radiation Protection and Measurements 1987; Jaquish and Bryce 1989). The 99th percentile dose (1964-1966) for an individual who drank untreated river water and ate up to 200 meals of fish caught in areas of highest radionuclide concentrations above Richland was 0.23 rem (0.0023 Sv). It is therefore

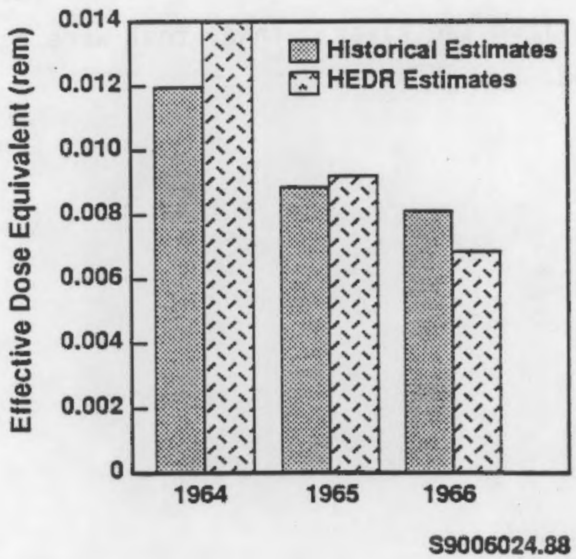

FIGURE 3.6. Previously Published Dose Estimates for 1964-1966 (average values) Compared with HEDR Dose Estimates (Richland adults, drinking-water pathway, median values)

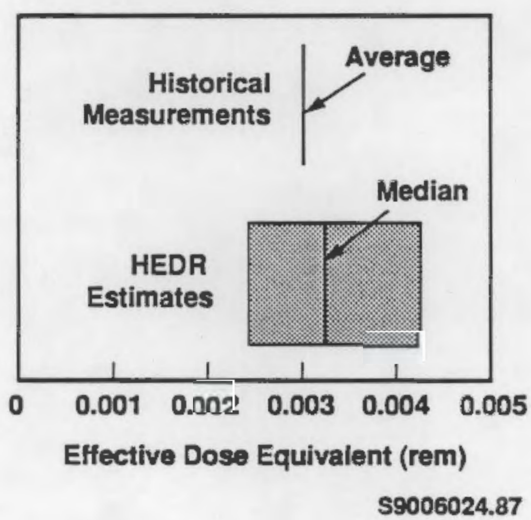

FIGURE 3.7. Comparison of Doses to Hanford Workers from Zinc-65 Measured by the Whole-Body Counter with HEDR Estimates for Richland Residents, 1964-1966

likely that few, if any, people in the Tri-Cities received cumulative (1964-1966) doses from the river pathway that were higher than the annual average background.

4.0 EXTRAPOLATIONS OF DOSE ESTIMATES TO OTHER TIMES AND LOCATIONS

Later phases of the HEDR Project will address dose estimates for periods other than 1964-1966 and for populations downstream of the Phase I study area. Estimates of doses for the period 1957-1972, when the last of the original eight production reactors was shut down, are available in published reports and, as shown in this report for the period 1964-1966, provide a reasonable estimate of doses to average and maximally exposed individuals in Richland. Doses for the period 1944-1956 can be extrapolated from estimates of power levels and from environmental measurements. As shown in Figure 4.1, power levels were considerably lower in the early years of operation when fewer reactors were operating, resulting in much lower releases of radionuclides to the Columbia River.

Extrapolations of dose estimates to the few downstream locations where communities used treated Columbia River water for drinking can be based on previously published measurements of radionuclide concentrations at Bonneville Dam or Vancouver, Washington. In general, concentrations of radionuclides that accounted for most of the drinking-water dose at these downstream locations were about 10% of the concentrations at Richland (Foster and Wilson 1965).

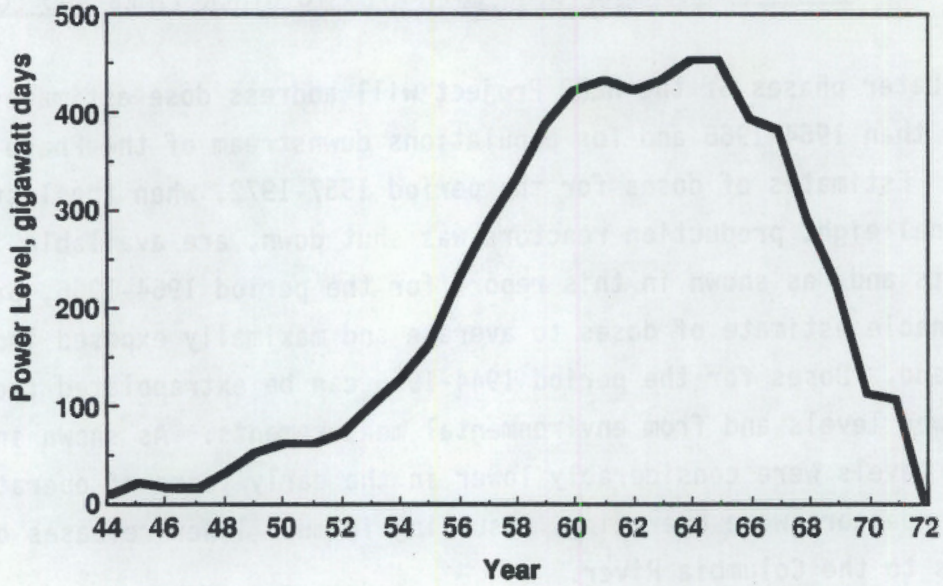

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FIGURE 4.1. Estimated Power Levels at Hanford Reactors (Harty et al. 1978)

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APPENDIX A

HEDR PUBLICATIONS - TO DATE

Title	Author	Publication Date	Publication No.
Hanford Environmental Dose Reconstruction Project Monthly Report	Haerer, HA	Monthly	PNL-6450 HEDR
Work Plan for the Hanford Environmental Dose Reconstruction Project	Haerer, HA	1989	PNL-6696 HEDR REV 1
Proposed Approach for Developing Information on Population Food Consumption and Lifestyles of Native Americans in the HEDR Study Area	Rhoads, RE, and Bruneau, CL	1989	PNL-6803 HEDR
Summary Report of HEDR Workshop on Sensitivity and Uncertainty Analysis	Sagar, B., and Liebetrau, AM	1989	PNL-SA-16804 HEDR
Demographic, Agricultural, Food Consumption, and Lifestyle Research for the Hanford Environmental Dose Reconstruction Project	Beck, DM, et al	1989	PNL-6834 HEDR
Response to TSP Directive 88-4, Ground-Water Contamination Data	Freshley, MD	1989	PNL-6847 HEDR
A History of Major Hanford Operations Involving Radioactive Material	Ballinger, MY, and Hall, RA	1989	PNL-6964 HEDR
Summary of Workshop on Milk Production and Distribution, November 30, 1988 - HEDR Project	Beck, DM, et al.	1989	PNL-6975 HEDR
Feasibility of Using ^{129}I Concentrations in Human Tissue to Estimate Radiation Dose From ^{131}I	McCormack, WD	1989	PNL-6889 HEDR
Hanford Environmental Dose Reconstruction (brochure)	Bruneau, CL	1989	PNWD-1323 HEDR
Radionuclide Sources and Radioactive Decay Figures Pertinent to the HEDR Project	Heeb, CM	1989	PNL-7177 HEDR
Uncertainties in Source Term Calculations Generated by the ORIGEN2 Computer Code for Hanford Production Reactors	Heeb, CM	1989	PNL-7223 HEDR
Atmospheric Transport and Dispersion Modeling for the Hanford Environmental Dose Reconstruction Project	Ramsdell, JV	1989	PNL-7198 HEDR
Preliminary Summaries for Vegetation, River and Drinking Water and Fish Radionuclide Concentration Data (DRAFT)	Woodruff, RK	1989	PNL-SA-17641 HEDR

Title	Author	Publication Date	Publication No.
Atmospheric Transport Modeling and Input Data for Phase I of the Hanford Environmental Dose Reconstruction Project	Ramsdell, JV, and Burk, KW	1989	PNL-7199 HEDR
Fission-Product Iodine During Early Hanford-Site Operations: Its Production and Behavior During Fuel Processing, Off-Gas Treatment, and Release to the Atmosphere	Burger, LL	1989	PNL-7210 HEDR
The Hanford Environmental Dose Reconstruction Project: Background Information (flier)	Byram, SJ	1989	PNL-SA-17658 HEDR
Summary of Literature Review of Risk Communication	Byram, SJ	1989	PNL-7226 HEDR
Milk Cow Feed Intake and Milk Production and Distribution Estimates for Phase I	Beck, DM	1989	PNL-7227 HEDR
Estimations of Traditional Native American Diets in the Columbia Plateau	Hunn, ES and Bruneau, CL	1989	PNL-SA-17296
Estimates of Columbia River Radionuclide Concentrations: Data for Phase I Dose Calculations	Richmond, Walter	1990	PNL-7248 HEDR
Evaluation of Thyroid Radioactivity Measurement Data From Hanford Workers, 1944-1946	Ikenberry, T	1990	PNL-7254 HEDR
I-131 in Irradiated Fuel at Time of Processing From December 1944 Through December 1947	Morgan, LG	1990	PNL-7253 HEDR
Population Estimates for Phase I	Beck, DM	1990	PNL-7263 HEDR
Estimates of Food Consumption	Callaway	1990	PNL-7260 HEDR
Soil Ingestion by Dairy Cattle	Darwin, RF	1990	PNL-SA-17918 HEDR
Computational Model Design Specification for Phase I of the Hanford Environmental Dose Reconstruction Project	Napier, BA	1990	PNL-7274 HEDR
Selection of Dominant Radionuclides for Phase I of the HEDR Project	Napier, BA	1990	PNL-7231 HEDR
A Preliminary Examination of Audience-Related Communications Issues: Hanford Environmental Dose Reconstruction Project	Holmes, CW	1990	PNL-7321 HEDR
MESOILT2, A Lagrangian Trajectory Climatological Dispersion Model	Ramsdell, JV	1990	PNL-7340 HEDR
Draft Summary Report	HEDR Staff	1990	PNL-7410 HEDR
Draft Air Pathway Report	HEDR Staff	1990	PNL-7412 HEDR
Draft Water Pathway Report	HEDR Staff	1990	PNL-7411 HEDR

APPENDIX B

MODELS AND INFORMATION USED IN HEDR SURFACE-WATER CODE

CONTENTS

MODELS USED

1. Fish Concentration (used if monitoring data are unavailable)

$$CF_{m,l,s,n} \cdot B_{m,s,n} = W_{m,l,n}$$

where $CF_{m,l,s,n}$ = concentration in fish during month m, at location l, for species type s, for radionuclide n (Ci/kg)

$B_{m,s,n}$ = bioaccumulation factor for month m and fish species type s for radionuclide n (dimensionless)

$W_{m,l,n}$ = water concentration of radionuclide n during month m at location l (Ci/l).

2. Drinking-Water Concentration

$$CD_{m,l,c,n} = T_{c,n} \cdot W_{m,l,n} \cdot e^{-\lambda_n t_w}$$

where $CD_{m,l,c,n}$ = concentration of radionuclide n in drinking water at location l when adjusted by cleanup process c, during month m (Ci/l)

$T_{c,n}$ = water treatment plant transmission factor for cleanup type c, for radionuclide n (dimensionless)

λ_n = radiological decay constant for radionuclide n (days^{-1})

t_w = time water spends in distribution system (days).

3. Dose From Swimming

$$DS_{a,l,m} = \sum_n W_{m,l,n} \cdot ES_{a,m} \cdot F_{s,n,a}$$

where $DS_{a,l,m}$ = dose from swimming to age group a at location l for month m (rem)

$ES_{a,m}$ = exposure time spent swimming for age group a during month m (hours)

$F_{s,n,a}$ = dose rate factor for swimming for radionuclide n and age group a (rem/hour per Ci/l)

4. Dose from Boating

$$DB_{a,l,m} = \sum_n W_{m,l,n} \cdot EB_{a,m} \cdot F_{s,n}/2$$

where $DB_{a,l,m}$ = dose rate for boating for age group a at location l during month m (rem)

$EB_{a,m}$ = exposure time spent boating for age group a at location m (hours)

$F_{s,n}/2$ = assumption that dose rate boating is 1/2 dose rate swimming.

5. Dose from Drinking Water

$$DW_{a,l,m} = \sum_n CD_{l,m,c,n} \cdot EW_{a,m} \cdot F_{I,n,a}$$

where $DW_{a,l,m}$ = dose from drinking water at location l to age group a during month m (rem)

$EW_{a,m}$ = consumption rate of drinking water for age group a during month n (l/month)

$F_{I,n,a}$ = ingestion dose factor for radionuclide n for age group a (rem/Ci)

6. Dose from Fish Consumption

$$DF_{a,l,m} = \sum_n \sum_s CF_{m,l,s,n} \cdot EF_{a,m,s} \cdot F_{I,n,a}$$

where $DF_{a,l,m}$ = dose to age group a at location l during month m from consumption of fish (rem)

n = number of radionuclides

s = number of fish species types

$EF_{a,m,s}$ = consumption rate of fish of species type s during month m by age group a (kg/month)

Parameter Distribution Type Used in the Surface-Water Model

Parameter	Distribution Type
$CF_{m,l,s,n}$	- calculated distribution for radionuclides phosphorus-32 and zinc-65
	- uniform for zinc-65
	- log uniform for phosphorus-32
$B_{m,s,n}$	- normal for arsenic-76, neptunium-239
	- fixed for sodium-24, manganese-56, copper-64, chromium-51
$W_{m,l,n}$	- triangular
$CD_{m,l,c,n}$	- calculated distribution
$T_{c,n}$	- triangular
$\lambda r,_{n}$	- fixed
t_w	- censored normal
$DS_{a,l,m}$	- calculated distribution
$ES_{a,m}$	- censored normal
$F_{s,n,a}$	- log normal
$DB_{a,l,m}$	- calculated distribution
$EB_{a,m}$	- censored normal
$DW_{a,l,m}$	- calculated distribution
$EW_{a,m}$	- censored normal
$F_{I,n,a}$	- log normal
$DF_{a,l,m}$	- calculated distribution
$EF_{a,n,s}$	- triangular

TECHNIQUES FOR SELECTING REALIZATIONS FROM ARBITRARY DISTRIBUTIONS

ALGORITHMS FOR THE GENERATION OF SAMPLES FROM SELECTED PROBABILITY DISTRIBUTIONS

by

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January 15, 1990

Hanford Environmental Dose Reconstruction Project

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1.0 SUMMARY AND INTRODUCTION

The purpose of this report is to document algorithms for generating samples from the probability distributions that are being, or may be, used in the calculation of dose estimates and uncertainties. Algorithms are presented for generating realizations of random variables with the following distributions:

- $U(a,b)$ -- a uniform distribution over the interval (a,b), $a < b$
- $LU(\alpha,\beta)$ -- a loguniform distribution over the interval (α,β), $\alpha < \beta$
- $T(a,b,c)$ -- a triangular distribution over the interval (a,c) with mode at b, $a \leq b \leq c$
- $N(\mu,\sigma^2)$ -- a normal (Gaussian) distribution with mean μ and variance σ^2
- $LN(\theta,\tau^2)$ -- a lognormal distribution with mean θ and variance τ^2.

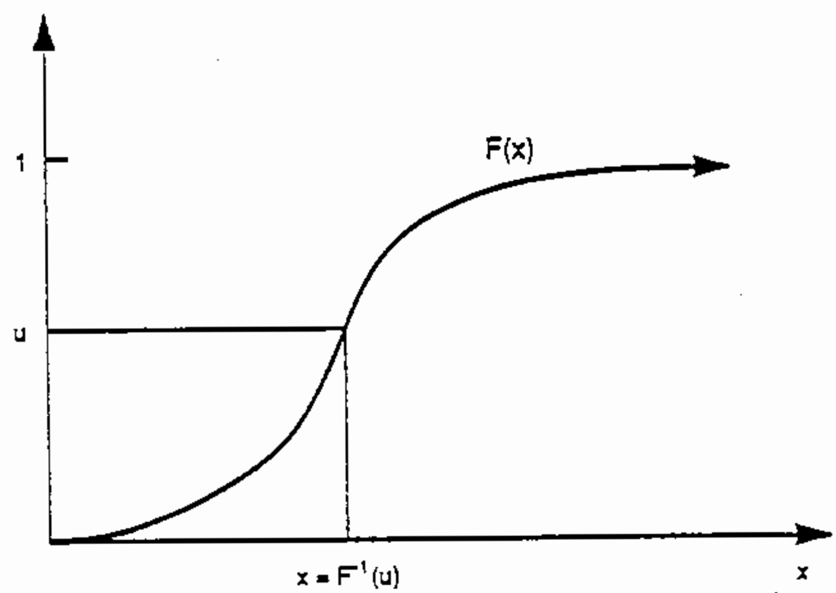
Each algorithm requires the generation of random numbers or values from a $U(0,1)$ distribution. It is anticipated that (pseudo) random numbers will be generated using currently available system routines. Because random numbers are crucial to the generation of realizations from any distribution, an alternative algorithm is presented in Section 4.0 for generating (pseudo) random numbers in case the system random number generator proves unacceptable for some reason.

2.0 GENERAL METHODS FOR UNIVARIATE DISTRIBUTIONS

A fundamental method that theoretically works for any univariate distribution is the Inversion Method. This method, which requires the inversion of the cumulative distribution function (cdf), is based on the following theorem of probability (see Mood, Graybill, and Boes 1974, p. 202):

> If X is a random variable with cumulative distribution function F, then the random variable U, defined by U = F(X), has a uniform distribution over the interval (0,1).

In practice, realizations are obtained by generating a pseudo-random number u (a realization of a U(0.1) random variable), setting this number equal to U in the above theorem, and solving for X. For each realization u, this procedure yields the realization $x = F^{-1}(u)$ of the random variable X. The Inversion Method is shown schematically in Figure 1. The utility of the



R8912159.8

FIGURE 1. The Inversion Method of Generating Realizations from the Cumulative Distribution Function F: x is the realization that corresponds to the random number u.

Inversion Method is limited by the difficulty of obtaining F^{-1}; consequently, alternative methods are preferable for many distributions whose cdfs are difficult to invert. The Inversion Method is used to generate realizations from uniform and triangular distributions.

> Technical Note: If F is not continuous, then there exist values of u for which $F^{-1}(u)$ is not well defined. In this case, x should be taken as the largest value to x_0 such that $F(x) \le u$, i.e., $x_0 = \sup x \; F(x) \le u$.

A second method for generating realizations of specified distributions is by means of transformations. If Y is obtained by transformation from the variable X, say $Y = g(X)$, then realizations of Y can be obtained by applying the transformation g to realizations of X. Transformations are used to generate loguniform variates from uniform variates and lognormal variates from normal variates. Transformations may also be used to generate U(a,b) variates from U(0,1) variates and $N(\mu,\sigma^2)$ variates from N(0,1) variates.

In addition to the two general methods identified above, special methods exist that are efficient for specific distributions. The Box-Muller algorithm given in Section 3.4 is a special method for the generation of standard normal variables [e.g., N(0,1) variables].

The algorithms obtained by applying the methods in this section to the distributions listed in Section 1.0 are given in Section 3.0. A good overview of methods for generation of realizations from univariate distributions is given in Chapter 2 of Johnson (1987); a more extensive discussion is found in Chapter 5 of Bratley, Fox, and Schrage (1983).

3.0 ALGORITHMS FOR SELECTED DISTRIBUTIONS

3.1 The Uniform Distribution

The Inversion Method is used to obtain U(a,b) variates from pseudo-random variates. If X has a U(a,b) distribution, then the cdf of X is

$$F_U(x) = \begin{cases} 0, & x \le a \\ (x - a)/(b - a), & a \le x \le b \\ 1, & x \ge b \end{cases}$$

In the interval $a < x < b$, $F_U(x) = (x - a)/(b - a)$, so F_u^{-1} is given by

$$x = F_U(x)\ (b - a) + a$$

Therefore, we obtain the following algorithm for generating a realization x from a U(a,b) distribution.

Algorithm

Step 1. Generate a pseudo-random number u from the U(0,1) distribution.

Step 2. Compute $x = u\ (b - a) + a$.

References

Iman and Shortencarier (1984, p. 18)
Mood, Graybill, and Boes (1974, p. 105)
Any standard statistics textbook.

3.2 The Loguniform Distribution

Log uniform variates are obtained by transforming uniform variates. By definition, the random variable Y has a loguniform distribution over the interval (α, β), $\alpha < \beta$, $\alpha > 0$, $\beta > 0$, if, and only if, the random variable X = ln Y has a uniform distribution over the interval (a,b), where a = ln α and b = ln β. From this definition, it follows that

$$F_U(x) = (x - \ln \alpha)/(\ln \beta - \ln \alpha)$$

or

$$x = F_U(x)(\ln \beta - \ln \alpha) + \ln \alpha$$

for $\ln \alpha \leq x \leq \ln \beta$. Therefore, we obtain the following algorithm for generating a realization x from a $LU(\alpha, \beta)$ distribution.

Algorithm

Step 1. Generate a pseudo-random number u from a U(0,1) distribution.

Step 2. Compute $y = \exp[u(\ln \beta - \ln \alpha) + \ln \alpha]$.

Reference

Iman and Shortencarier (1984, p. 19)

3.3 The Triangular Distribution

The Inversion Method is used to obtain realizations from a triangular distribution. If X has a triangular distribution over the interval (a,c) with mode b, then the cdf of X is

$$F_T(x) = \begin{cases} 0, & x \leq a \\ (x - a)^2 / [(c - a)(b - a)], & a \leq x \leq b \\ \dfrac{b - a}{c - a} - \dfrac{(x + b - 2c)(x - b)}{(c - a)(c - b)}, & b \leq x \leq c \\ 1, & x \geq c \end{cases}$$

Note that at $x = b$, $F_T(x) = F_T(b) = (b - a)/(c - a)$. Inverting $F_T(x)$ yields the following algorithm for generating a realization x from a triangular distribution with parameters a, b, and c, $a \leq b \leq c$.

Algorithm

Step 1. Generate a pseudo-random number u from a U(0,1) distribution.

Step 2. If $u \leq (b - a)/(c - a)$

Set $u = F_T(x) = (x - a)^2/[(c - a)(b - a)]$

Compute $x = a + [u(c - a)(b - a)]^{1/2}$

Step 3. Otherwise,

$$\text{Set } u = F_T(x) = \frac{b - a}{c - a} - \frac{(x + b - 2c)(x - b)}{(c - a)(c - b)}$$

$$\text{Compute: } x = c - [(b - c)^2 + (b - a)(c - b) - u(c - a)(c - b)]^{1/2}$$

References

Iman and Shortencarier (1984, p. 20)
Johnson and Kotz (1970)

3.4 The Normal Distribution

The inverse of the cdf of a normally distributed random variable X cannot be expressed in closed form, so the inversion method is not the method of choice for generating normal variates. The method used to generate normal variates, which is due to Box and Muller (1958), involves transformation of a pair of pseudo-random numbers to obtain a pair of standard normal variates. These are further transformed to obtain a pair of realizations from a normal distribution with mean μ and variance σ^2.

The Box-Muller algorithm is an efficient method for generating simple random samples of normal variates, but it may not be as efficient for Latin Hypercube Sampling, which involves partitioning the range of the simulated variables. To generate normal variates using Latin Hypercube Sampling, it is desirable to use an algorithm that generates specified percentage points of a normal distribution. The algorithm cited below, due to Beasley and Springer (1977), is used for this purpose.

The Box-Muller Algorithm

Step 1. Generate independent pseudo-random numbers u_1 and u_2 from the U(0,1) distribution.

Step 2. Compute $g_1 = (-2 \ln u_1)^{1/2} \cos(2\pi u_2)$

$g_2 = (-2 \ln u_1)^{1/2} \sin(2\pi u_2)$

Step 3. Compute $x_1 = \sigma g_1 + \mu$

$x_2 = \sigma g_2 + \mu$

The quantities x_1 and x_2 are independent realizations from a normal distribution with mean μ and variance σ^2.

Step 4. (optional) If

$$y_1 = g_1$$

$$y_2 = \rho g_1 + (1-\rho^2)^{1/2} g_2$$

are computed for some ρ, $-1 \le \rho \le 1$, then y_1 and y_2 are realizations from a standard bivariate ($\mu_1 = 0$, $\mu_2 = 0$, $\sigma_1^2 = 1$, $\sigma_2^2 = 1$) normal distribution with correlation coefficient ρ.

References

Box and Muller (1958)
Abramowitz and Stegun (1970, p. 953)
Johnson (1987, p. 29)

Algorithm for Computing Percentage Points of the Normal Distribution

Algorithm AS III, due to Beasley and Springer (1977), is used to calculate percentage points of the normal distribution in connection with Latin Hypercube Sampling methods. The algorithm is fast, numerically accurate, and portable without modification. FORTRAN code for implementing Algorithm AS III is given in the reference cited.

3.5 The Lognormal Distribution

Log normal variates are obtained by transferring normal variates. By definition, the random variable Y has a lognormal distribution with mean θ and variance τ^2 if, and only if, the random variable $X = \ln Y$ has a normal distribution with mean μ and variance σ^2, where

$$\mu = \ln \left[\theta^2 / \sqrt{\theta^2 + \tau^2} \right] \quad \text{and} \quad \sigma^2 = \ln \left[(\theta^2 + \tau^2) / \theta^2 \right] \qquad (1)$$

This definition yields the following algorithm for generating a realization y from a lognormal distribution with mean θ and variance τ^2.

Algorithm

Step 1. Generate a realization x from a normal distribution with mean μ and variance σ^2, where μ and σ^2 are computed using Equation (1) above. (See algorithms in Section 3.4 for generating normal realizations.)

Step 2. Compute $y = \exp(x)$. Then y is a realization from a lognormal distribution with mean θ and variance τ^2.

References

Iman and Shortencarier (1984 p. 17)
Crow and Shimizu (1988)

4.0 THE GENERATION OF PSEUDO-RANDOM NUMBERS

Each algorithm in Section 3.0 requires the generation of values from a U(0,1) distribution. It is anticipated that the pseudo-random number generator available on the PNL VAX network will prove adequate for HEDR Project dose calculations and related uncertainty analyses. In case the system generator proves inadequate for some reason, and for the sake of completeness, a pseudo-random number generator is given here. The selected generator is due to Wichmann and Hill (1982) and produces U(0,1) realizations by combining the results of three multiplicative congruential generators. The algorithm is short, reasonably fast, statistically sound, and machine independent. A FORTRAN implementation is given below. On machines that use only 23 bits for representation of the fractional part of a real number, it is possible for this algorithm to produce exact zeros because of rounding error; see McLeod (1985) for a discussion of this problem and possible modifications. An extensive discussion of uniform random number generators, including the algorithm presented here, is found in Chapter 6 of Bratley, Fox, and Schrage (1983).

Algorithm AS 183 (Wichmann and Hill)

```
      REAL FUNCTION RANDOM(L)
C
C        ALGORITHM AS 183  APPL. STATIST. (1982) VOL.31, P.188
C
C        RETURNS A PSEUDO-RANDOM NUMBER RECTANGULARLY DISTRIBUTED
         BETWEEN 0 AND1.
C
C        IX, IY AND IZ SHOULD BE SET TO INTEGER VALUES BETWEEN
C        1 AND 30000 BEFORE FIRST ENTRY.
C
C        INTEGER ARITHMETIC UP TO 30323 IS REQUIRED.
C
      COMMON /RAND/ IX, IY, IZ
      IX = 171 * MOD(IX, 177) - 2  * (IX / 177)
      IY = 172 * MOD(IY, 176) - 35 * (IY / 176)
      IZ = 170 * MOD(IZ, 178) - 63 * (IZ / 178)
C
      IF (IX .LT. 0) IX = IX + 30269
      IF (IY .LT. 0) IY = IY + 30307
      IF (IZ .LT. 0) IZ = IZ + 30323
C
C        IF INTEGER ARITHMETIC UP TO 5212632 IS AVAILABLE,
C        THE PRECEDING 6 STATEMENTS MAY BE REPLACED BY
C
C        IX = MOD(171 * IX, 30269)
C        IY = MOD(172 * IY, 30307)
C        IZ = MOD(170 * IZ, 30323)
C
C        ON SOME MACHINES, THIS MAY SLIGHTLY INCREASE
C        THE SPEED. THE RESULTS WILL BE IDENTICAL.
C
      RANDOM = AMOD(FLOAT(IX) / 30269.0 + FLOAT(IY) / 30307.0 +
     $              FLOAT(IZ) / 30323.0, 1.0)
      RETURN
      END
```

5.0 REFERENCES

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METHODS OF STORING AND RETRIEVING DATA FROM HISTOGRAMS

Battelle
Pacific Northwest Laboratories

Project Number ____________

Internal Distribution

BS Dennis
RO Gilbert
HA Haerer
BA Napier
B Sagar
File/LB

Date June 26, 1989

To JT Caplinger

From AM Liebetrau

Subject Algorithm for Input of and Generation of Realizations from Cumulative Distribution Functions

The estimation of dose estimate uncertainties will involve simulating realizations of probability distributions. The distributions may be theoretical (i.e., expressed in a functional form) or empirical (estimated from real data or generated by simulation from a hypothetical distribution). The distributions may be used to describe the distribution of input parameters to the dose model or the variability of submodel output variable(s).

The following algorithm can be used to approximate a given distribution function regardless of whether it is theoretical or empirical. The notation used in Eq. (1) below is illustrated in the attached figure.

Step (a): Divide the range of the distribution into k intervals. For Phase I calculations, a maximum of k = 20 intervals will be used.

Step (b): The interval boundaries (denoted by x's) and the cumulative probabilities (denoted by h's) associated with the right-hand endpoints of the k intervals are:

$$(x_0, h_0 = 0), (x_1, h_1), (x_2, h_2), \ldots, (x_{k-1}, h_{k-1}), (x_k, h_k = 1) \quad (1)$$

Where x_0 is the minimum value of the variable and x_h is the maximum value.

The intervals defined by Eq. (1) defined a k-segment piecewise linear approximation to the actual input distribution. A maximum of k = 20 intervals will be used for Phase I calculation. A smaller value of k may be used in cases where an adequate approximation to the actual input distribution does not require 20 intervals. Note that when the distribution is expressed in cumulative form, both the x's and the h's are nondecreasing sequences of numbers. It is convenient to choose the representation in Eq. (1) so that either the x's or the h's are equally spaced. For the Phase I study, we will use equal spacing of the x's.

After a distribution such as that in Step (b) has been assigned to a particular input variable, then realization of the variable may be generated from the assigned distribution as follows:

Step 1: Generate a pseudo-random number, from the uniform distribution over the interval (0,1)). Denote the value of this number by h, where $0 < h < 1$.

Step 2: Determine the index i, i = 1, 2, ..., k, such that $h_{i-1} < h < h_i$.

Step 3: Compute $x = x_{i-1} + \frac{h - h_{i-1}}{h_i - h_{i-1}} (x_i - x_{i-1})$ (2)

The quantity x obtained by (2) is the realization of a random variable x whose cdf is given by (1). Steps 1-3 can be repeated, as necessary, to generate the desired number of realizations from the given distribution.

AML/slc

HANDLING CORRELATIONS IN COMPLEMENTARY FRACTIONS

Battelle
Pacific Northwest Laboratories

Project Number HEDR

Internal Distribution

JW Brothers
RO Gilbert
HA Haerer
AM Liebetrau
B Sagar
DL Strenge
Project Office
File/LB

Date August 18, 1989

To Distribution

From Bruce Napier

Subject Handling Correlations in Complementary Fractions

INTRODUCTION

In several of the calculations to be performed for the HEDR Phase I analyses, a series of fractions must be selected from input distributions. Each of these fractions has its own distribution. The results of the selection process of the fractions must, however, sum to one, which implies a correlation structure. A technique is needed to handle the correlations between the various fractions.

DISCUSSION

Several options are available. We could use a simple rule to adjust the randomly drawn fractions, or we could draw the fractions from a multivariate distribution with an assumed correlation structure.

In general, the fractions are being generated via expert opinion. There is considerable uncertainty about many of them. No information is currently available on correlations between the constituent parts of the sum desired, other than that it is constrained to add to unity. The structure of the proposed computer implementation also does not lend itself to incorporating large correlation matrices.

The question of how to handle these correlations was discussed by Bruce Napier, Al Liebetrau, Dick Gilbert, and Budhi Sagar at a meeting on July 31, 1989.

CONCLUSIONS

It was concluded that for Phase I, at least, a simple adjustment rule would be adequate, given the lack of strong information on correlations. The various fractions should be drawn independently from their distributions, and then the sum of the results should be used to normalize each value so that the total then adds to one.

BAN:cs

CORRESPONDENCE BETWEEN COLUMBIA RIVER LOCATION
AND HEDR CENSUS SUBDIVISION

Battelle
Pacific Northwest Laboratories

Project Number HEDR

Internal Distribution

HA Haerer
TM Poston
MC Richmond
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File/LB

Date August 17, 1989

To CM Beck

From BA Napier

Subject Correspondence Between Columbia River Location and HEDR Census Subdivision Grid Points

INTRODUCTION

Much of the Phase 1 effort has gone into defining parameters to use for the atmospheric dispersion portions of the HEDR calculations. Proportionally less effort has been expended on the surface water pathways. However, definition of the various locations of potential exposure to the river or to river-related products (water, fish, irrigated foods) is also necessary.

DISCUSSION

Ted Poston, who was asked to accumulate and evaluate data on radionuclide concentrations of fish in the Columbia River for 1964-1966, devised a convention for collecting data based on sampling locations. These areas are (memo, T. M. Poston to Distribution, June 12, 1989, "Location of Fish Sampling Sites"):

Site	Approximate River Mile
Priest Rapids	390
Hanford	365
Coyote Rapids	383
Ringold	354
Richland	345
Island View	335
Burbank	322
McNary	294

The first three of these locations are inside of the Hanford Site, and thus of minimal importance for public exposure considerations. The others, however, are stretches of the river for which public access is available.

CONCLUSIONS

I have compared Ted's river stretches to our HEDR census subdivisions on the map. There is a very convenient correspondence for the publicly available locations, as follows:

Site	HEDR Census Subdivision
Ringold	FR4
Richland	BE7, FR5
Island View	BE3, FR3
Burbank	WA3, BE4
McNary	BE3, UM4

Note that each stretch of the river touches two subdivisions, one on either side, if some minor overlaps are ignored. (The Benton County side of the Ringold stretch is still Hanford Site). Given the inexact nature of the selections, this would seem to be reasonable.

These divisions should be used for the transport, demography, and dose calculations required for Phase I.

BAN:cs

APPENDIX C

DOSES BY RIVER STRETCH, ORGAN, YEAR, AND EXPOSURE PATHWAY

DOSES BY RIVER STRETCH, ORGAN, YEAR, AND EXPOSURE PATHWAY

The following five tables present summaries of the radiation doses calculated for Phase I of the HEDR Project. The doses presented in these tables are in units of rad (or rem) for the lower large intestine (labelled GI Tract) and bone marrow and are in rem for the effective whole-body dose equivalent (labelled EDE). Each table presents the results for a single stretch of the Columbia River, as described in the main report. These five stretches are Ringold, Richland, Pasco/Kennewick, Burbank, and McNary, as illustrated in Figure 2.3. For each stretch, the results are presented as annual summaries for 1964, 1965, and 1966 and as the cumulative dose that would have been received had an individual who lived as defined for the entire three years.

Doses are presented by exposure pathway. Those labelled "External" include exposures from swimming in and boating on the Columbia River. The doses presented for drinking water are given in three potential formats:

Drinking 1: Consumption of raw Columbia River water, no drinking-water treatment.

Drinking 2: Consumption of Columbia River water treated with the alum-floc process used in the Richland and Pasco water treatment plants.

Drinking 3: Consumption of Columbia River water obtained through near-river wells before treatment.

Only the types of drinking water applicable to a given stretch of the river are included in the tables (e.g., the Richland stretch has only type 1 and type 2).

Although most residents of the Tri-City area do not fish from the Columbia River, however, two groups of fish consumers were identified. The doses to individuals labelled "Low Fish" are assumed to eat between 1 and 20 meals per year of fish taken from the Columbia River. Those labeled "High Fish" are assumed to eat between 21 and 200 meals per year. The fish are assumed to come from the given river stretch. (The doses presented in the main report are combinations of the doses from drinking water in Richland and eating fish from either the Ringold or Burbank stretches of the river, but the values presented in this appendix are for each pathway independently).

Although doses are presented for only one age group--adults--this appendix presents, for this group, committed doses for two organs and the effective dose equivalent.

The complete calculations performed for Phase I generated distributions of dose for each of the categories described above. The fifth percentile, median (fiftieth percentile), and ninety-fifth percentile doses from each distribution are presented in the tables. Because of the nature of the Monte Carlo calculation process, the uncertainty in doses outside of these ranges is large enough to invalidate their usefulness. The fifth and ninety-fifth percentiles define a range in which ninety percent of the potentially exposed population would fall, and are best used for comparative purposes.

River Stretch 1

	GI Tract			BONE			EDE		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
1964									
External	0.00017	0.00061	0.00118	0.00018	0.00065	0.00159	0.00023	0.00073	0.00142
Drinking 1	0.07016	0.13062	0.22329	0.00607	0.01257	0.02148	0.01042	0.01896	0.02986
Low Fish	0.04017	0.06584	0.10815	0.00049	0.00074	0.00128	0.00473	0.00755	0.01290
High Fish	0.21715	0.34250	0.57596	0.00261	0.00393	0.00661	0.02527	0.03961	0.06741
1965									
External	0.00024	0.00046	0.00076	0.00023	0.00047	0.00081	0.00027	0.00055	0.00092
Drinking 1	0.04060	0.08703	0.16079	0.00428	0.00893	0.01576	0.00682	0.01212	0.01894
Low Fish	0.03532	0.06290	0.12488	0.00039	0.00065	0.00114	0.00390	0.00664	0.01318
High Fish	0.18912	0.31627	0.66767	0.00207	0.00346	0.00624	0.02074	0.03512	0.06608
1966									
External	0.00015	0.00026	0.00043	0.00016	0.00031	0.00050	0.00019	0.00034	0.00054
Drinking 1	0.03191	0.06410	0.10581	0.00349	0.00713	0.01192	0.00515	0.00976	0.01555
Low Fish	0.02317	0.03713	0.06532	0.00029	0.00044	0.00072	0.00271	0.00440	0.00745
High Fish	0.12165	0.19362	0.32008	0.00154	0.00233	0.00362	0.01499	0.02300	0.04059
1964-1966									
External	0.00082	0.00132	0.00198	0.00090	0.00156	0.00252	0.00102	0.00165	0.00246
Drinking 1	0.19894	0.29394	0.41622	0.02056	0.02972	0.04107	0.02994	0.04180	0.05517
Low Fish	0.12464	0.17178	0.24705	0.00143	0.00192	0.00272	0.01449	0.01915	0.02817
High Fish	0.65158	0.90255	1.27554	0.00741	0.01007	0.01427	0.07762	0.10216	0.14858

River Stretch 2

	GI Tract			BONE			EDE		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
1964									
External	0.00068	0.00115	0.00172	0.00076	0.00131	0.00201	0.00089	0.00147	0.00220
Drinking 1	0.06776	0.12450	0.20166	0.00877	0.01636	0.02559	0.01171	0.02106	0.03301
Drinking 2	0.04568	0.08543	0.14202	0.00455	0.00861	0.01410	0.00758	0.01349	0.02086
Low Fish	0.03593	0.05511	0.09359	0.00041	0.00060	0.00100	0.00373	0.00590	0.01003
High Fish	0.18202	0.29005	0.47911	0.00215	0.00311	0.00532	0.01995	0.03106	0.05236
1965									
External	0.00042	0.00073	0.00111	0.00044	0.00081	0.00125	0.00047	0.00088	0.00138
Drinking 1	0.04658	0.08634	0.13821	0.00592	0.01116	0.01781	0.00805	0.01354	0.02006
Drinking 2	0.02960	0.05911	0.10340	0.00312	0.00584	0.00987	0.00498	0.00917	0.01376
Low Fish	0.03101	0.05276	0.09461	0.00035	0.00056	0.00098	0.00346	0.00590	0.01096
High Fish	0.16591	0.28393	0.52173	0.00183	0.00296	0.00529	0.01815	0.03052	0.05777
1966									
External	0.00025	0.00043	0.00068	0.00027	0.00049	0.00077	0.00030	0.00057	0.00092
Drinking 1	0.03283	0.06091	0.10168	0.00527	0.01022	0.01662	0.00618	0.01065	0.01662
Drinking 2	0.02151	0.04269	0.07287	0.00259	0.00495	0.00866	0.00393	0.00704	0.01069
Low Fish	0.01903	0.03173	0.05918	0.00022	0.00034	0.00058	0.00207	0.00347	0.00609
High Fish	0.10246	0.16529	0.30387	0.00116	0.00179	0.00299	0.01110	0.01812	0.03112
1964-1966									
External	0.00169	0.00234	0.00306	0.00193	0.00267	0.00348	0.00214	0.00293	0.00380
Drinking 1	0.19648	0.27396	0.37275	0.02631	0.03807	0.05111	0.03323	0.04621	0.05953
Drinking 2	0.12907	0.19261	0.25769	0.01347	0.01961	0.02663	0.02176	0.02996	0.03994
Low Fish	0.10872	0.14837	0.21075	0.00118	0.00156	0.00215	0.01169	0.01590	0.02262
High Fish	0.56189	0.76333	1.10055	0.00625	0.00822	0.01166	0.06073	0.08372	0.11898

River Stretch 3

	GI Tract 5th	GI Tract 50th	GI Tract 95th	BONE 5th	BONE 50th	BONE 95th	EDE 5th	EDE 50th	EDE 95th
1964									
External	0.00032	0.00061	0.00095	0.00033	0.00066	0.00103	0.00040	0.00073	0.00116
Drinking 1	0.05289	0.10389	0.17163	0.00596	0.01071	0.01685	0.00848	0.01523	0.02381
Drinking 2	0.03797	0.06805	0.10845	0.00286	0.00579	0.00930	0.00527	0.00920	0.01450
Drinking 3	0.00840	0.01814	0.03270	0.00108	0.00231	0.00490	0.00187	0.00365	0.00586
Low Fish	0.02776	0.04292	0.07188	0.00028	0.00043	0.00078	0.00285	0.00448	0.00747
High Fish	0.14409	0.22238	0.36892	0.00146	0.00224	0.00364	0.01550	0.02450	0.04017
1965									
External	0.00002	0.00004	0.00006	0.00003	0.00005	0.00007	0.00003	0.00006	0.00009
Drinking 1	0.03676	0.06529	0.11321	0.00322	0.00623	0.00981	0.00516	0.00925	0.01467
Drinking 2	0.02431	0.04689	0.07248	0.00164	0.00326	0.00575	0.00368	0.00648	0.01028
Drinking 3	0.00653	0.01517	0.02949	0.00070	0.00148	0.00292	0.00126	0.00261	0.00469
Low Fish	0.02569	0.04301	0.07960	0.00026	0.00043	0.00081	0.00268	0.00463	0.00905
High Fish	0.13554	0.22599	0.43703	0.00136	0.00219	0.00413	0.01437	0.02382	0.04410
1966									
External	0.00001	0.00002	0.00004	0.00002	0.00003	0.00004	0.00002	0.00003	0.00005
Drinking 1	0.02403	0.04720	0.07714	0.00291	0.00629	0.01065	0.00405	0.00731	0.01120
Drinking 2	0.01608	0.03234	0.05548	0.00154	0.00321	0.00589	0.00251	0.00481	0.00783
Drinking 3	0.00460	0.01028	0.01934	0.00059	0.00138	0.00288	0.00093	0.00209	0.00354
Low Fish	0.01532	0.02513	0.04386	0.00015	0.00025	0.00044	0.00161	0.00266	0.00473
High Fish	0.07979	0.12824	0.22230	0.00081	0.00128	0.00221	0.00834	0.01377	0.02414
1964-1966									
External	0.00038	0.00067	0.00105	0.00041	0.00073	0.00113	0.00048	0.00081	0.00124
Drinking 1	0.15605	0.22153	0.31119	0.01673	0.02374	0.03210	0.02300	0.03238	0.04465
Drinking 2	0.10273	0.14789	0.20024	0.00854	0.01253	0.01732	0.01501	0.02073	0.02741
Drinking 3	0.02957	0.04500	0.06805	0.00335	0.00550	0.00868	0.00592	0.00845	0.01157
Low Fish	0.08503	0.11616	0.16507	0.00086	0.00116	0.00167	0.00906	0.01226	0.01767
High Fish	0.44782	0.60183	0.87760	0.00445	0.00591	0.00827	0.04776	0.06479	0.09469

-- River Stretch 4 --

	GI Tract			BONE			EDE		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
1964									
External	0.00003	0.00008	0.00013	0.00004	0.00008	0.00013	0.00004	0.00009	0.00015
Drinking 1	0.03118	0.05516	0.08671	0.00335	0.00677	0.01107	0.00444	0.00775	0.01208
Low Fish	0.01418	0.02300	0.04271	0.00014	0.00022	0.00038	0.00147	0.00247	0.00463
High Fish	0.07851	0.12202	0.22143	0.00074	0.00115	0.00223	0.00761	0.01210	0.02183
1965									
External	0.00001	0.00002	0.00004	0.00002	0.00003	0.00004	0.00002	0.00003	0.00005
Drinking 1	0.01898	0.03607	0.05579	0.00247	0.00470	0.00737	0.00306	0.00530	0.00846
Low Fish	0.01182	0.01921	0.03389	0.00012	0.00019	0.00035	0.00119	0.00200	0.00353
High Fish	0.06206	0.09814	0.17476	0.00062	0.00098	0.00164	0.00629	0.00996	0.01750
1966									
External	0.00001	0.00001	0.00002	0.00001	0.00002	0.00003	0.00001	0.00002	0.00003
Drinking 1	0.01492	0.02609	0.04015	0.00200	0.00429	0.00722	0.00242	0.00455	0.00677
Low Fish	0.00716	0.01120	0.01940	0.00007	0.00011	0.00019	0.00073	0.00118	0.00214
High Fish	0.03735	0.05870	0.10071	0.00036	0.00055	0.00096	0.00401	0.00622	0.01035
1964-1966									
External	0.00007	0.00012	0.00018	0.00008	0.00012	0.00018	0.00010	0.00014	0.00020
Drinking 1	0.08544	0.11916	0.15849	0.01099	0.01612	0.02200	0.01316	0.01782	0.02315
Low Fish	0.04227	0.05681	0.08226	0.00039	0.00054	0.00078	0.00444	0.00592	0.00865
High Fish	0.21296	0.29307	0.42534	0.00201	0.00278	0.00415	0.02288	0.03075	0.04382

River Stretch 5

	GI Tract			BONE			EDE		
	5th	50th	95th	5th	50th	95th	5th	50th	95th
1964									
External	0.00001	0.00002	0.00002	0.00001	0.00002	0.00003	0.00001	0.00002	0.00003
Drinking 1	0.01327	0.02614	0.04172	0.00199	0.00432	0.00752	0.00237	0.00406	0.00621
Low Fish	0.00371	0.00553	0.00824	0.00004	0.00006	0.00008	0.00040	0.00058	0.00085
High Fish	0.01965	0.02840	0.04273	0.00021	0.00029	0.00041	0.00202	0.00297	0.00455
1965									
External	0.00001	0.00001	0.00002	0.00001	0.00001	0.00002	0.00001	0.00002	0.00002
Drinking 1	0.00950	0.01698	0.02740	0.00130	0.00264	0.00464	0.00163	0.00278	0.00441
Low Fish	0.00348	0.00528	0.00788	0.00004	0.00005	0.00008	0.00036	0.00055	0.00091
High Fish	0.01828	0.02663	0.03987	0.00019	0.00027	0.00042	0.00185	0.00282	0.00428
1966									
External	0.00000	0.00001	0.00001	0.00000	0.00001	0.00001	0.00001	0.00001	0.00002
Drinking 1	0.00681	0.01292	0.02182	0.00158	0.00374	0.00757	0.00144	0.00267	0.00428
Low Fish	0.00199	0.00302	0.00465	0.00002	0.00003	0.00005	0.00021	0.00032	0.00051
High Fish	0.01046	0.01556	0.02402	0.00011	0.00016	0.00024	0.00110	0.00164	0.00264
1964-1966									
External	0.00003	0.00004	0.00005	0.00003	0.00004	0.00005	0.00004	0.00005	0.00006
Drinking 1	0.04051	0.05695	0.07632	0.00719	0.01101	0.01597	0.00722	0.00969	0.01298
Low Fish	0.01094	0.01401	0.01810	0.00012	0.00015	0.00019	0.00116	0.00148	0.00198
High Fish	0.05717	0.07297	0.09347	0.00061	0.00074	0.00092	0.00598	0.00762	0.00986

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