# Human Health Risk Assessment Work Plan Yankee Nuclear Power Station Rowe, Massachusetts

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# 1 Introduction

This document presents a work plan for performing a human health risk assessment to support the environmental site closure underway at the Yankee Nuclear Power Station (YNPS). The YNPS is located in the town of Rowe, situated in northwestern Massachusetts along the Deerfield River adjacent to Sherman Dam (Figure 1). Yankee Atomic Electric Company (YAEC) owns YNPS and surrounding lands, which comprise approximately 1,800 acres, of which approximately 12 acres is occupied by the former nuclear plant itself.

The YNPS began operations in 1961 and ceased operation in 1992. The plant is in the process of being dismantled and YAEC is terminating the YNPS federal license with the Nuclear Regulatory Commission (NRC). In order to terminate its nuclear operating license, YAEC must complete a process of radiological sampling and cleanup as necessary defined by the NRC and set forth in YAEC's License Termination Plan (LTP). In addition, YAEC will comply with the Massachusetts Department of Public Health (MADPH) requirements for meeting radiological guidelines set forth in 105CMR120.291. Both the NRC and MADPH require compliance with radiological "dose-based" requirements for the protection of human health.

In parallel with the license termination and cleanup to meet the NRC and MADPH radiological dose requirements, YAEC is conducting a comprehensive environmental closure that will ensure that the property poses no adverse human or environmental risks once YAEC transfers title of the property.[1] The environmental site closure is being performed as a voluntary action that will adhere to guidelines established by the Massachusetts Department of Environmental Protection (MADEP) as well as guidelines established by the U.S. Environmental Protection Agency (USEPA) -- in addition to the requirements noted above established by NRC and MADPH.

Because the NRC and MADPH standards or guidelines only address radiological constituents, this additional assessment of human health risks associated with non-radiological constituents (for convenience and clarity non-radiological constituents will be referred to here as "chemicals" or "chemical risk assessment") will be conducted following MADEP and USEPA guidelines. In addition, both MADEP and USEPA require the assessment of "cumulative," or additive risks associated with both radionuclides and chemicals. This work plan presents the procedures that will be adopted to evaluate

[1] Future uses are not currently defined. However, a portion of the site constituting the former industrial area will have Activity Use Limitations (AULs) and/or deed restrictions on future uses that will prevent development (including preventing residential uses), installation of wells, *etc.*

cumulative chemical and radiological risks to human health. A separate work plan (Gradient, 2006) describes the companion ecological risk assessments for combined chemical and radiological risks.

## 1.1 Risk Assessment Goals

The NRC/MADPH "dose-based" assessments and the MADEP/USEPA "risk-based" assessment for radionuclides contain similarities and several differences. They are similar in that both share the common purpose of ensuring protection of human health and the environment. In addition, both the dose-based and risk-based approaches evaluate human exposure to radionuclides based on plausible future uses of the site (*e.g.*, resident farmer for NRC/MADPH *versus* hypothetical residential use for the HHRA). Perhaps the clearest difference between the approaches is that the NRC approach limits the maximum human exposure (dose) at a point in time (*e.g.*, compliance with this standard is demonstrated at the time of license termination for NRC or the time of property transfer for MADPH), whereas the risk-based approach evaluates the exposure and risk over the course of an "exposure period," such as a lifetime. In addition, the evaluations differ somewhat in their respective definition of the area over which an individual may be exposed (the "exposure unit" for the evaluation). Yet, as noted above, despite these differences, both approaches are designed to ensure protection of human health.

The overall goal of the cumulative risk assessment approach described herein, is to establish whether post-closure site conditions (*e.g.*, existing structures removed, remediation of radionuclides and chemicals as necessary, and site restoration including a final soil grading plan over the former industrial area) meet environmental conditions that do not pose a significant risk to human health. Should the cumulative risk assessment identify potential risks above background risks and beyond risk guidelines established by MADEP and USEPA, this will serve as the basis for identifying additional remedial measures or environmental controls to reduce these potential risks.

The cumulative risk assessment will evaluate potential human health risks above risks associated with exposure to naturally occurring or ubiquitous constituents in the environment. This is particularly important for naturally occurring radionuclides, inorganic constituents (*e.g.*, metals), and other chemicals associated with ubiquitous anthropogenic sources. Thus, as described below, one element of the HHRA will include an evaluation of background levels of radionuclides and chemicals in the environment in general, as well as within the vicinity of the site, in order to assess incremental risks above background risks.

## 1.2 Risk Assessment Framework

The cumulative human health risk assessment will be conducted primarily according to MCP Risk Characterization guidance (MADEP, 1995). It should be noted that MADEP risk assessment guidelines share the same fundamental procedures established by USEPA for evaluating human health risks to environmental contaminants. Furthermore, even though the MCP indicates that the cumulative risk of cancer-causing constituents must be addressed, MADEP does not have any published radiological risk assessment guidance.[2] Thus, the assessment of radiological risks will rely primarily on USEPA guidance, with the most recent guidance set forth in the USEPA (2000) Soil Screening Guidance for Radionuclides: Technical Background Document, providing the primary source. In addition, the RESRAD multipathway risk assessment modeling system developed by the U.S. Department of Energy (ANL, 2001) for radionuclides will also serve as a source of information as needed.

In addition to this work plan for the cumulative human health risk assessment for the overall site closure, a focused risk assessment in support of the Toxic Substances Control Act (TSCA) Risk-Based Disposal Approval Application (RBDAA) for PCB cleanup in Sherman Reservoir was prepared pursuant to a request by USEPA Region I. That assessment, along with subsequent revisions based on comments received from the USEPA, was completed and approved by the USEPA September 28, 2004. As outlined in this work plan, the cumulative risk assessment for the site includes an evaluation of any residual PCBs in Sherman Reservoir sediments, and other possible COPCs, after sediment remediation, which has been completed under USEPA and MADEP oversight.

Under the Massachusetts Contingency Plan (MCP), a Method 3 Risk Characterization involves four components: risk to human health, risk to safety, risk to public welfare, and risk to the environment. This work plan describes the methodology to perform the human health risk assessment (HHRA) which addresses the first three components. As noted above, a work plan for the assessment of risk to the environment is presented in a companion document (Gradient 2005). This HHRA work plan has been prepared in accordance with the requirements of a Method 3 Risk Characterization pursuant to Section 310 CMR 40.0900 of the MCP.

The MCP Method 3 Human Health Risk Characterization approach involves the following evaluation steps or procedures:

[2] MADEP guidance simply states that cumulative risks of cancer causing constituents must be addressed, without any specific mention of a need to address radiological constituents.

- Hazard Identification determines reasonably foreseeable uses of the site, categorizes soil and groundwater, establishes background, identifies constituents of concern, and identifies applicable or suitably analogous standards.
- Dose-Response Assessment describes the relationship between the level of exposure and the likelihood of an adverse effect.
- Exposure Assessment identifies potential routes of exposure, potential receptors of concern, and the frequency, duration and extent of exposure.
- Risk Characterization combines the information from the previous three steps to describe the type (carcinogenic and noncarcinogenic) and magnitude of risk of the exposed receptors.
- Uncertainty Analysis identifies the nature and the general magnitude of the uncertainty and variability inherent in the characterization of risks.

Established risk assessment and risk characterization procedures set forth in MADEP and USEPA guidance documents for human health risk assessment will be followed in preparing the HHRA, including the following:

- "Guidance for Disposal Site Risk Characterization – In Support of the Massachusetts Contingency Plan", (MADEP, 1995)
- "Implementation of the MADEP VPH/EPH Approach- Final Policy", (MADEP, 2002a)
- "Technical Update: Calculation of Enhanced Soil Ingestion Rate", (MADEP, 2002b)
- "Technical Update: Weighted Skin-Soil Adherence Factors", (MADEP, 2002c)
- "Risk Assessment Guidance for Superfund; Volume 1: Human Health Evaluation Manual. Part A." (USEPA, 1989)
- USEPA's Soil Screening Guidance for Radionuclides: Technical Background Document (USEPA, 2000)

# 2 Hazard Identification

This Hazard Identification component of the HHRA will identify reasonably foreseeable future uses of the site, categorize soil and groundwater, establish background concentrations for constituents detected at the site, evaluate constituents of potential concern, and identify applicable or suitably analogous standards to be used in the risk characterization.

## 2.1 Site Background

Originally designed as a 145-megawatt (MWe) electric generating plant and later increased to 185 MWe, YNPS was built between 1958 and 1960 as a prototype plant intended to operate for six years. The plant ultimately operated for over 30 years, from 1961 until 1992 when the YAEC Board of Directors decided to cease power operations permanently at YNPS and decommission the facility.

Since the initiation of plant decommissioning activities in 1992, YAEC has conducted numerous environmental sampling programs to support the decommissioning efforts. These investigations have included sampling of building surfaces and materials, soil, soil gas, groundwater, stormwater systems, surface water, sediments and fish. Samples have been analyzed for both radiological and non-radiological parameters. These historical sampling efforts provide an initial body of data and information that will be augmented during the continuing Site Closure Investigations.

Plant decommissioning and demolition is currently underway. All radiological systems with the exception of the Spent Fuel Storage Installation (ISFSI) systems have been removed from the plant. The spent nuclear fuel is being stored in the ISFSI, an on-site dry cask storage facility, until the Department of Energy satisfies its obligations to remove the spent fuel to a Federal facility. The ISFSI is fenced and protected by surveillance 24-hours a day. Although the plant decommissioning and environmental restoration is scheduled to be completed by 2006, the YNPS license with the NRC will not be officially "terminated" until such time that the Department of Energy removes the spent fuel to permanent storage at a federally licensed storage facility (no such facility currently exists). Thus, YAEC will retain control of that portion of the site consisting of the ISFSI and former industrial area until the spent fuel is removed. This "YAEC Retained Area," which will continue to be subject to surveillance 24-hours a day, will not allow uncontrolled access to the public.

## 2.2 Reasonably Foreseeable Future Use of the Site

Although the future status of the Site is currently not fully defined, likely future use of the Site may consist of open space with some potential for recreational/limited development activities. In situations where the end use of a property has not been defined, the MCP requires the evaluation of risk under a residential scenario and this scenario will be evaluated in the human health risk assessment. This assumption will provide a conservative assessment, as the most likely future Site use (*e.g.*, recreational/open space) would not involve the kind of frequent exposure that would be the case under a "residential" exposure scenario.

Although a future residential exposure scenario may be hypothetically plausible for the majority of the 1800 acre property, open-space and recreation activities are the more likely future use conditions. Furthermore, an Activity Use Limitation (AUL) may be required over that portion of the site constituting the former industrial area. In addition, as a component of the final site restoration/grading plan, a 3-foot overburden will be in place in the former industrial area. The AUL would preclude excavation without a DEP-approved soil management plan, and would occur only under the oversight of a Licensed Site Professional (LSP).

## 2.3 Classification of Site Soils and Site Groundwater

Soil and groundwater at the site will be categorized in accordance with 310 CMR 40.0930 as required for a Method 3 Risk Characterization. MADEP defines three soil (S-1, S-2, S-3) and three groundwater (GW-1, GW-2, GW-3) classifications based on the nature of exposure. Soil classifications are based on accessibility of site soil, frequency of exposure, and intensity of exposure. Soil classification S-1 is based on the assumption of highest potential for exposure, while classification S-3 assumes the lowest potential for exposure. Groundwater classifications are also based on the type of potential exposure. Classification GW-1 has been established to protect against risks under the assumption that site groundwater may be used directly as a potable water source. Classification GW-2 protects against risks associated with volatilization of compounds from shallow groundwater and infiltration into buildings through cracks and other imperfections in slabs and foundations. Finally, classification GW-3 protects against risks associated with the discharge of groundwater to surface water.

Under an assumed residential exposure scenario, the corresponding soil category would be S-1. However, as noted above, the AUL in the former industrial area will limit possible contact with soils for

the industrial portion of the site. Consequently, soils within the area subject to the AUL will be classified S-3. For the evaluation of recreational activities and potential exposures, contact with soil may occur, however the intensity and frequency of use will be expected to be lower when compared to a residential exposure scenario. Thus, under recreational scenarios the appropriate soil category would likely be S-3 (301 CMR 40.0933).

The MADEP has indicated it considers the groundwater at the site to be GW-1. In addition, all groundwater beneath the Site is characterized as GW-3 because MCP considers all groundwater as a source of discharge to surface water.

## 2.4 Background Constituent Concentrations

Cumulative risks will be calculated and presented in the HHRA as the risks due to the presence of radiological and chemical constituents above the risks associated with background exposures. MADEP (1995) defines background as "those levels of oil and hazardous material that would exist in the absence of the disposal site of concern that are:

(a) ubiquitous and consistently present in the environment at and in the vicinity of the disposal site of concern; and,

(b) attributable to geologic or ecologic conditions, atmospheric deposition of industrial process or engine emissions, fill materials containing wood or coal ash, releases to ground water from a public water supply system, and/or petroleum residues that are incidental to the normal operation of motor vehicles."

Given their ubiquitous presence in the environment, MADEP (2002d) has developed statewide background levels for metals and PAHs in both "natural" soil and soil containing fill material. Site-specific information will be used to characterize local conditions and identify constituents of concern, including other media such as surface water, groundwater, and sediment. The site-specific information may be supplemented with statewide and literature background values for comparative purposes. Median and maximum detected concentrations of constituents in specific media will be compared to the site background levels. In addition, for constituents with sufficiently robust background and site data (*e.g.*, radionuclides), distributional methods and statistical plotting methods will also be used to assess background conditions. Constituents present at levels consistent with local/regional background levels will not be retained as constituents of potential concern (COPCs) for the risk assessment.

Background levels of radionuclides will also be evaluated in the risk assessment. Data collected by YAEC for its Radiological Environmental Monitoring Program (REMP) in addition to site characterization data collected to support the LTP, will be used to evaluate background levels of radionuclides. In addition, published information relating to radionuclide levels in soil, sediment, and water may also be reviewed and summarized in order to establish background concentrations. Radionuclides present at the site that are consistent with local and regional background levels will not be retained as COPCs for risk characterization.

## 2.5 Constituents of Potential Concern

All constituents detected in soil, sediment, surface water, or groundwater will be retained as constituents of potential concern (COPCs) if their frequency of detection is greater than 5% and they exceed background concentrations. Based on the operations and materials used at the plant, samples from environmental media have been (in previous site investigations) and will be analyzed for (but not necessarily limited to) the following COPCs (Gradient, 2005):

- volatile organic compounds (VOCs);
- semivolatile organic compounds (SVOCs);
- petroleum hydrocarbons[3]
- priority pollutant 13 metals, plus boron and lithium;
- hexavalent and trivalent chromium;
- total cyanide and cyanide amenable to chlorination;
- chlorinated herbicides;
- polychlorinated biphenyls (PCBs);
- dioxins and furans;
- hydrazine; and
- radiological constituents.

## 2.6 Applicable or Suitably Analogous Standards

Section 310 CMR 40.0993(2) of the MCP requires that Applicable or Suitably Analogous Standards be identified in a Method 3 risk characterization. In Massachusetts, standards are available for drinking water, surface water, and air quality. As required by the MCP, Massachusetts Drinking Water Quality Standards may be applicable to site groundwater if site groundwater is classified as GW-1

[3] Depending on the levels of total petroleum hydrocarbons found, additional extractable petroleum hydrocarbon/volatile petroleum hydrocarbon (EPH/VPH) analyses may be performed (MADEP, 2002a).

groundwater. Massachusetts Surface Water Quality Standards would be applicable to surface water in Sherman Reservoir. Massachusetts Air Quality Standards (310 CMR 6.00) also known as the National Ambient Air Quality Standards (NAAQS), which are only available for six compounds, are also applicable.

# 3 Dose-Response Assessment

The chemical risk characterization will evaluate both non-cancer and cancer causing potential for COPCs. The USEPA and MADEP have established chemical toxicity factors that will be used in this assessment. For chemical constituents, the toxicity factors that will be used for the risk characterization include:

- Oral cancer slope factors (CSF)
- Inhalation cancer unit risk factors (UR)
- Chronic oral reference doses (RfD)
- Chronic inhalation reference concentrations (RfC)

Appropriate values for these toxicity factors will be obtained from Agency guidance documents, including USEPA's Integrated Risk Information System (IRIS) database (USEPA, 2003a), USEPA's Health Effects Assessment Summary Tables (HEAST; USEPA, 1997a), and MADEP guidance documents (MADEP, 1994).

Because there are no USEPA-derived toxicity criteria for dermal exposures, oral toxicity factors will be used and appropriately modified using relative absorption factors (RAFs) to be applicable to dermal exposures as described in USEPA's dermal guidance (USEPA, 2001c).

For radiological constituents, toxicity factors published in USEPA's Health Affects Summary Tables (HEAST) and updates.[4],. These toxicity factors include:

- Radiological oral cancer slope factors ($rCSF_o$)
- Radiological inhalation cancer slope factor ($rCSF_i$)
- External exposure cancer slope factor ($rCSF_e$)

[4] The most current toxicity factors are published at: http://www.epa.gov/radiation/heast/index.html.

# 4 Exposure Assessment

The purpose of the exposure assessment is to estimate the magnitude of potential human exposure to site-related constituents. For example, human exposure can occur due to direct contact with soil and other environmental media, inhalation of constituents in the air, and ingestion of soil, water, or food containing contaminants. The degree of chemical intake will depend on the frequency of exposure, the duration, the particular pathway of exposure, and the rate of contact or intake with environmental media. The HHRA will describe the plausible exposure scenarios and quantify exposure to site-related COPCs. The sections that follow identify the potential human receptors and exposure pathways that will be considered in the HHRA, the equations to be used to estimate chemical and radiological exposures, and the methods that will be adopted to determine of the exposure point concentrations (EPCs) for chemicals and radionuclides.

## 4.1 Identification of Potential Receptors and Exposure Pathways

Although the ultimate use for the Site has not been determined, it will likely include open space for recreational activities. The MCP requires consideration of future residential uses of a Site in the absence of restrictions precluding such a use. Future uses for the Site could also involve some level of construction activities and utility maintenance, including basic structures associated with either recreational activities (*e.g.*, parking lot, possible restroom facilities, *etc.*), or construction related to hypothetical residential development. Finally, activities associated with maintenance of the dam on Sherman Reservoir will also be included in the assessment. Thus, the following exposure scenarios will be evaluated in the HHRA:

- hypothetical residential use
- recreational use
- on-site construction/utility worker under future redevelopment activities
- dam maintenance workers exposed to sediment maintenance of the Sherman Dam

Table 1 presents the exposure pathways and receptors. The conceptual site model (Figure 2) illustrates the potential source areas, mechanisms of transport, exposure pathways, and receptors for the Site.

Although a hypothetical future residential scenario will be considered, such a scenario would apply only to those areas of the site not covered by the AUL described earlier. The AUL for the former

industrial area of the site will prevent direct contact pathways such as incidental ingestion and dermal contact with subsurface materials. Furthermore, the 3-foot of material that will be part of the final site grading plan would prevent uptake of COPCs into vegetables that might conceivably be grown on this area, thus eliminating this potential indirect pathway. While direct contact pathways and consumption of vegetables are not complete pathways for the area subject to the AUL, possible exposure from external radiation (*e.g.*, ionizing radiation emitted as the result of radioactive decay) associated with any residual radionuclides above background will be evaluated. In order to evaluate the attenuation provided by the 3-feet of overburden in the former industrial area, the U.S. Department of Energy RESRAD multipathway risk assessment model (ANL, 2001) will be used. First, the external radiation dose assuming no overburden will be calculated, then a parallel calculation for a scenario that includes 3-foot of soil overburden will be calculated. For both scenarios, a unit concentration (*e.g.*, 1 pCi/g) will be used (the dose and risks scale directly as a function of the source concentration), and the results of the two calculations will provide a dose-reduction factor for each radionuclide.

For the hypothetical residential scenario in areas not subject to the AUL, possible exposures to soil by potential future residents will be evaluated for shallow soils as well as subsurface soils up to 3 feet below ground surface (bgs) per MCP guidance (MADEP, 1995). Potential routes of exposure to soil will include incidental soil ingestion, dermal contact, and inhalation of resuspended particulates. Potential uptake of COPCs from soil into homegrown food will also be evaluated. Potential future use of groundwater by residents may also be a potential pathway for human exposure *via* ingestion, dermal contact, and potential inhalation of VOCs infiltrating into building structures (if VOCs are found in groundwater). In addition, direct radiation exposure will be evaluated for radionuclides.

Based on historical sampling and ongoing site characterization, PCBs and other COPCs have been detected in sediments of Sherman Reservoir in the vicinity of the East Storm Drain. Direct human contact with sediment or surface water in Sherman Reservoir is considered an unlikely or *de minimis* exposure scenario due to the presence of a steep bank along the shoreline, riprap (*i.e.*, rocky shoreline), and the fact that sediments containing PCBs and other possible COPCs lie well beneath the water surface. In addition, the dam is licensed to remain in operation for the foreseeable future, and prohibits recreational access near the dam for safety reasons. Thus, consumption of fish caught in Sherman Reservoir is the human pathway of plausible concern that will be evaluated in the HHRA (ecological risks for Sherman Reservoir sediments will be evaluated as described in a companion work plan).

In addition to hypothetical future residential exposures, a recreational activity scenario will be considered for the site. Although recreational activities could presumably occur anywhere on the 1,800 acre site, the recreational scenario will focus on the YNPS industrial area as this is the area where possible contact with residual chemicals and radionuclides is considered most likely to the extent that future exposures to site-related COPCs might occur. Potential exposures by child, adolescent, and adult visitors will include incidental ingestion of surficial soil, dermal contact with surface soil, inhalation of airborne particulates, and ingestion of fish caught in the reservoir. Possible future ingestion or dermal contact with groundwater (*i.e.*, from water supplied in restrooms or drinking fountains under a hypothetical scenario) will also be evaluated.

For either the hypothetical residential scenario, or the recreational scenario, some form of redevelopment – even if limited -- would occur at the Site for these scenarios to occur (*e.g.*, possible construction of access roads, parking areas, visitor facilities, residences, *etc.*). To address this possiblity, the HHRA will evaluate chemical and radionuclide exposure for a "construction/utility worker scenario." Although construction workers could come into contact with environmental media less frequently than a "resident" scenario, the construction worker would be more likely to be exposed to subsurface materials. Following MADEP guidance, subsurface soil samples up to 15 feet will be used to characterize potential exposures to subsurface soils. Possible avenues of exposure to be evaluated for construction activities will include incidental soil ingestion, dermal contact, and inhalation of resuspended particulates during construction activities. In addition, future construction workers could potentially be exposed to constituents in shallow groundwater during excavation/trenching activities. Evaluation of potential exposures to groundwater will include ingestion, dermal contact, and possible inhalation of volatile organic compounds (VOCs).

Possible exposure to radionuclides determined to be COPCs at the Site will be evaluated for all potential receptors and pathways described above (resident, recreator, construction worker, and utility worker). In addition, possible direct radiation exposure *via* external radiation, which does not require ingestion or direct contact with an environmental medium, will also be evaluated.

## 4.2 Exposure Quantification

In order to evaluate chemical risks and non-cancer hazards, it is necessary to estimate the chemical intake, or average daily dose (ADD), for the pathways of possible exposure. Chemical intake varies as a function of the chemical concentration in a particular environmental medium, the frequency of

contact with, or intake of, that medium, and the duration of the exposure. Section 4.2.1 presents the methodology that will be used to estimate the chemical intake (*e.g.*, ADD) for the HHRA.

Exposure to radionuclides is calculated in a somewhat analogous manner, although it is calculated in terms of total intake of radioactive material, rather than an average daily dose. The exposure calculation methods for radionuclides are presented in Section 4.2.2.

### 4.2.1 Chemical Exposure Quantification Methods

Chemical intake for either ingestion or direct contact (*e.g.*, dermal exposure) with soil, sediment, water or food, can be expressed as (MADEP, 1995):[5]

$$ADD = \frac{EPC \times IF \times RAF \times ED \times EF \times CF}{BW \times AT} \quad (4\text{-}1)$$

where:

| | | |
|---|---|---|
| ADD | = | Average daily dose (mg/kg-day) |
| EPC | = | Exposure point concentration (mg/kg or mg/L depending on medium) |
| IF | = | Intake factor (mg/d or L/day depending on medium) |
| RAF | = | Relative absorption factor (unitless) |
| EF | = | Exposure frequency (days/year) |
| ED | = | Exposure duration (years) |
| CF | = | Conversion factor – depending on intake factor units |
| BW | = | Body weight (kg) |
| AT | = | Averaging time (days)<br>$AT_{cancer}$ = 70 yrs × 365 days/yr<br>$AT_{non\text{-}cancer}$ = ED × 365 days/yr |

*Dermal Pathway Intake Factor (IF)*

For the dermal exposure pathway, chemicals are not ingested, but rather may permeate the skin and become absorbed into the body. The "intake" depends on how much of the body surface area is potentially exposed, and the "loading" of either soil or water on the skin. Thus, the intake factor for Equation (4-1) is given by:

[5] EPC is referred to as the concentration of oil or hazardous material [OHM] in MADEP terminology. MADEP guidance also separates the exposure frequency term into a term for the number of events per day, multiplied by the number of events per year, yet typically the number of events per day is implicitly given a value of 1.0 (MADEP, 1995). In the equation here, these two exposure factors are combined into a single exposure frequency term for simplicity.

$$IF = SA \times AF \quad (4\text{-}2)$$

where

| | | |
|---|---|---|
| SA | = | Skin surface area in contact with medium ($cm^2$/day) |
| AF | = | Adherence factor -- mass of soil/sediment adhered to skin ($mg/cm^2$) |

*Inhalation Pathway*

For inhalation exposures, the risk characterization is based on comparing the ambient concentration to a concentration-based toxicity benchmark (either a non-cancer "reference concentration," or a cancer "unit risk factor"). Consequently, instead of an average daily dose, it is necessary to calculate an effective average COPC concentration in air. The effective average COPC concentration accounts for the amount of time an individual is exposed to COPCs in a particular exposure setting. The effective average COPC concentration in air will be quantified using the following equation (MADEP, 1995):

$$EPC_{air} = \frac{C_{air} \times ET \times EF \times ED}{AT} \quad (4\text{-}3)$$

where:

| | | |
|---|---|---|
| $EPC_{air}$ | = | Time averaged exposure point concentration ($mg/m^3$) |
| $C_{air}$ | = | COPC concentration in air ($mg/m^3$) |
| RAF | = | Relative absorption factor (unitless) |
| ET | = | Fraction of day exposed (hr/24-hr) |
| EF | = | Exposure frequency (days/year) |
| ED | = | Exposure duration (years) |
| AT | = | Averaging time (days)<br>$AT_{cancer}$ = 70 yrs × 365 days/yr<br>$AT_{non\text{-}cancer}$ = ED × 365 days/yr |

The preceding equations will be used to quantify the average daily COPC dose or concentration for each pathway-receptor combination for non-radiological COPCs. For carcinogenic risks, the average daily dose is calculated by averaging over a lifetime (*e.g.*, 70 year average lifetime), whereas for non-cancer hazards the average daily dose is calculated by averaging over the exposure duration (ED). These differences in the averaging period for the respective assessments are indicated in the definitions of the averaging period (*e.g.*, AT) variable above.

Table 2 presents the exposure factors for each of the receptors and pathways that will be used to characterize potential COPC exposure for each receptor group and pathway to be considered in the HHRA. Because this HHRA is being conducted following the MCP, the MADEP-recommended exposure factors will be adopted, which in many instances are comparable to USEPA exposure factors. For comparison, we have summarized USEPA exposure factors in Table 2.

### 4.2.2 Exposure Quantification for Radionuclides

Potential exposure to radionuclides is calculated in terms of radioactivity (in pico-curies, or "pCi") rather than in chemical mass units. Exposures *via* ingestion and inhalation pathways are calculated using similar approaches to those just described for chemical exposure, simply expressing exposure as the total amount of radioactivity (pCi) received over a particular duration. In the equations below, the radiation exposure is expressed in terms of an "intake factor." The intake factor accounts for either ingestion (*e.g.*, soil, water, food) or inhalation. Radiation intake for these pathways is given by (USEPA, 2000):[6]

$$IF = EPC \times IR \times EF \times ED \quad (4\text{-}4)$$

where:

| | | |
|---|---|---|
| IF | = | Intake factor (pCi) |
| EPC | = | Exposure point concentration (*e.g.*, pCi/g, pCi/$m^3$, pCi/L) |
| IR | = | Media intake rate (*e.g.*, g/day, $m^3$/day, L/day) |
| EF | = | Exposure frequency (days/year) |
| ED | = | Exposure duration (years) |

As can be seen by comparing Equation (4-1) and (4-4), the intake factor for radionuclides is a function of exposure duration and exposure frequency. The media intake rates, exposure frequency and duration for radionuclide intake are identical to those for the chemical exposure estimates, and are provided in Table 2.

The concentration of radionuclides in the environment declines according to radionuclide-specific decay rates. Thus, the EPC is not a constant, but rather declines as a function of time according to the following exponential equation:

$$EPC(t) = EPC_o\, e^{-\lambda t} \quad (4\text{-}5)$$

[6] The equations presented by USEPA (2000) are for a "risk-based" concentration in soil, air, water, *etc.* The intake is given by simply rearranging those equations such that they are expressed as a "risk equation" without substituting a "target risk" value.

where

$EPC(t)$ = concentration as a function of time (pCi/g)

$EPC_o$ = initial concentration at time t=0 (pCi/g)

$\lambda$ = $\frac{\ln(2)}{t_{1/2}}$ is the decay constant (per year)

$t_{1/2}$ = half-life (years)

The average concentration ($\overline{EPC}$) over a particular time period (T) is given by integrating the declining concentration over the time period:

$$\begin{aligned} \overline{EPC} &= \frac{1}{T}\int_0^T EPC_o e^{-\lambda t} dt \\ &= EPC_0 \frac{(1-e^{-\lambda T})}{T\lambda} \end{aligned} \quad (4\text{-}6)$$

In the above equation, the time period "T" is equivalent to the exposure duration (ED) in Equation (4-4). Thus, combining the expression for the average concentration for EPC in Equation (4-6) with the intake factor expression in Equation 4-4), gives the following decay-adjusted intake factor

$$IF = EPC_0 \frac{(1-e^{-\lambda T})}{\lambda} \times IR \times EF \quad (4\text{-}7)$$

where $EPC_o$ is the exposure point concentration at the beginning (time t=0) of the exposure period.

For radionuclides with short half-lives (*e.g.*, shorter than the typical exposure duration of interest), the time-averaged concentration can be appreciably less than the initial concentration. Conversely, for long-lived radionuclides, the adjustment for radioactive decay is insignificant.

In addition to accounting for radioactive decay, intake factors (*e.g.*, ingestion rates, *etc.*) typically differ for children and adults. Attachment A provides the exposure equation accounting for these different child/adult intake rates, also taking into account radioactive decay.

One further consideration is important for assessing exposure to radionuclides, especially those with short half-lives. As noted earlier, a portion of the site will be "retained" by YAEC until the spent

fuel is removed under DOE obligations. As a consequence, possible future public access to the YAEC Retained Area will not begin until the spent fuel is removed. For planning purposes, YAEC is assuming that the fuel removal will occur no sooner than 16 years after the site restoration/grading is complete. In order to account for these considerations, the exposure to radionuclides will be "decay adjusted" such that the "initial" concentrations will be calculated as the concentration measured after the completion of the Final Status Survey (FSS), decayed for 16 years. Thus, the initial concentration of radionuclides in Equations (4-6) and (4-7) will be:

$$EPC_o = EPC_{FSS}\, e^{-\lambda t} \qquad (4\text{-}8)$$

where $EPC_{FSS}$ (pCi/g) is the exposure point concentration determined at the completion of the FSS (in 2005), and the other terms are as previously defined. The decay adjusted initial concentrations will use t=16 years for purposes of the risk assessment. The average concentration calculated over a particular exposure duration (T) will be calculated using Equation (4-6) with the starting point concentration ($EPC_o$) determined by Equation (4-8).

## 4.3 Determination of Exposure Point Concentrations

As indicated in the preceding section, chemical dose and radionuclide intake both are a function of the respective exposure point concentrations (EPCs) in environmental media, coupled with intake factors. The environmental media that will be evaluated in the HHRA include the following:

- soil
- sediment
- surface water
- groundwater
- outdoor and indoor air
- home-grown produce
- fish

Before describing the approach to calculating EPCs for each media, we provide a brief description of the data sources that will be used to support the risk assessments.

Since decommissioning activities commenced in 1992, YAEC has collected environmental data as necessary to support the dismantling/decommissioning of the plant. Data collected in support of

decommissioning since 1997 for soil, groundwater, storm sewer/catch basin sediments, and Sherman Reservoir sediments, have been compiled into an electronic database. In addition, in the Spring of 2000, paint chips associated with lead-based paint were observed flaking from certain plant structures and subsequent investigations determine the paint chips to contain PCBs. The investigation of the paint chip release was reported to MADEP and EPA. Additional sampling has been conducted to support remediation of the PCB paint chip release under the MCP and TSCA. These data collected since 2000 have also been compiled into the electronic database for the site. Finally, on-going environmental sampling in support of the Site Closure Plan (as set forth in the Field Sampling Plans) has been conducted by YAEC. These Site Closure data are also compiled in the electronic site database.

In addition to these chemical data, radiological constituents have also been measured to support the LTP. Radiological data compiled in the Historical Site Assessment (HSA) are maintained in the electronic database for the site. These data include radiological data for soils, sediments, and groundwater. As set forth in the LTP, additional radiological data will be collected for the FSS to support license termination, and these FSS data will be incorporated into the YNPS database.

The chemical and radiological data in the YNPS electronic database will form the foundation for data used in the risk assessments. Chemical data collected from 2000 through 2006, and radiological data collected during the FSS to support the LTP will be used to support the cumulative risk assessment. In addition, historical Radiological Environmental Monitoring Program (REMP) data collected by YAEC will be used as necessary to identify local and regional background levels of radionuclides in environmental media.

The following sub-sections present the approach that will be used to estimate EPCs for the environmental media to be evaluated in the exposure and risk assessment.

### 4.3.1 Soil

Soil sampling efforts have focused on defining the environmental conditions in the vicinity of the former industrial area of the site. Thus, a larger number of samples is available for the industrial area and adjacent locations compared to the non-industrial areas of the site. Soil samples from the outlying undeveloped/wooded areas (*i.e.*, the majority of the 1800 acre YNPS property) have been collected for radionuclide analysis as reported in the HSA; additional soil samples from these outlying areas will be

collected for chemical characterization in support of the Site Closure Plan and will be incorporated into the YNPS database and risk assessment.

As specified in MADEP (1995) guidance, the EPCs for soil will be determined by calculating the average concentrations of COPCs in soil over the exposure unit appropriate to each exposure scenario. In addition, the data within the exposure units will be evaluated to determine whether or not localized "hot spots" may exist, and if so, methods consistent with MADEP guidance will be used to address any hot spots.

The exposure units for possible soil exposures include 1) the area covered by the AUL, 2) areas within the YAEC Retained Area but not covered by the AUL, and 3) all other areas (*e.g.*, these generally fall within the wooded outlying areas).

For the portion of the site within the YAEC Retained Area that will be subject to an AUL, up to 3-foot of graded overburden material will exist, preventing direct contact pathways in this area. Thus, the exposure in this area will be limited to possible direct radiation from radionuclides beneath the overburden – attenuated by the depth of graded overburden. The average radionuclide concentration will be calculated based on the decay adjustments in Equations (4-6) and (4-7) presented earlier. Data used for this assessment will include radiological data collected during the FSS (excluding radionuclide results for any soils removed during remediation).

For the YAEC Retained Area not covered by the AUL, possible residential and recreational exposure scenarios will be evaluated. As noted earlier, future exposures are assumed to begin after the spent fuel in the ISFSI is removed by DOE, which for planning/calculation purposes is assumed to be 16 years from the completion of site restoration/grading in 2005. For the residential exposure scenarios in areas not subject to the AUL, possible exposures are most likely for shallow soils. All soil samples collected up to 3 feet deep will be used to estimate potential exposures for child and adult residents.

As noted earlier, the environmental sampling has focused on areas in the vicinity of the former industrial area, and it is expected that samples in outlying wooded areas will demonstrate the absence of site-related COPCS. Consequently, for the evaluation of future recreational exposures, average soil EPCs will be estimated using the same shallow soil data as will be used for the residential exposure scenario for the non-AUL exposure areas.

For future construction/utility repair workers, who could potentially be exposed to subsurface soils during construction/maintenance of subsurface utilities, soil data up to 15 feet will be used to estimate the average soil EPC for COPCs per MADEP (1995) guidance.

In all cases, the average EPC concentrations will be determined by using the detected values and, in cases where the constituent was not detected, using a proxy value equal to one-half the detection limit, per MADEP (1995) guidance. As noted for PCB sampling in sediment (below), in areas where soil samples were collected in a targeted (non-random) manner, the sample results will be averaged using a surface weighted average concentration.

### 4.3.2 Sediment

Sediment data from the environmental Site investigations will be used to calculate separate average exposure point concentrations of COPCs in sediment for Sherman Reservoir, Wheeler Brook and the West Storm Drain areas (excluding sample results remediated for PCBs pursuant to TSCA). Sediment samples collected up to one-foot depth will be used to estimate potential exposures. For Sherman Reservoir, only near-shore samples (*e.g.*, within 10 to 25 feet) will be used to estimate EPCs. EPCs will be calculated by averaging concentrations for each constituent, using the detected values and, in cases where the constituent was not detected, using a proxy value equal to one-half the detection limit (MADEP, 1995).

The sediment samples for PCBs collected in Sherman Reservoir in the vicinity of the East Storm Drain discharge have been collected using a "targeted," or intentionally biased, sampling strategy. That is, a higher density of samples was collected in areas known to have PCBs (as compared to a completely uniform grid). Given this biased sampling approach, the exposure point concentration for sediments will be calculated using a surface weighted average concentration ("SWAC") approach. An area-weighted averaging approach for targeted sampling results is endorsed by MADEP (1995 -- p. 2-22). A surface weighted averaging approach was adopted in the TSCA RBDAA, which was approved by USEPA.

The SWAC calculation will be performed using standard and established techniques (such as nearest neighbor or inverse distance methods as examples) that are available in computer software programs. The data will be plotted and the SWAC method clearly defined in the risk assessment. In addition, the food web models/equations that will be used to estimate chemical uptake in biological

tissues based on the chemical concentration in sediment will use the SWAC values from sediment samples as their inputs.

### 4.3.3 Surface Water

As noted earlier, contact with surface water in Sherman Reservoir is likely to be limited for safety reasons near Sherman Dam. Furthermore, Sherman Reservoir surface water samples collected in 1999 and 2000 show no detectable levels of PCBs. The 2002 YAEC Annual Radiological Environmental Report (YAEC, 2002) also shows that radionuclides were not detected in surface water samples from Sherman Reservoir, and "gross-beta" activity, an indicator of hard to detect radionuclides, was consistent with levels upstream in Harriman Reservoir. Thus, the surface water pathway is considered a de minimis pathway for the human health risk assessment.

### 4.3.4 Groundwater

The most recent rounds of data available from the YNPS monitoring wells will be used in the EPC calculations (up to 4 quarterly rounds, with emphasis on the most recent quarterly results). EPCs will be calculated by averaging concentrations for each constituent at a given well location, using the detected values and, in cases where the constituent was not detected, using a proxy value equal to one-half the detection limit, per MADEP (1995) guidance.

### 4.3.5 Air -- Resuspended Particulates

There are no current data for COPCs for the air exposure pathway. The COPC concentration in air for resuspended particulates will be estimated based on the COPC concentrations in surface soil using the following equation (MADEP, 1995):

$$C_{air} = EPC_{soil} \times PM_{10} \times CF \qquad (4\text{-}9)$$

where:

| | | |
|---|---|---|
| $C_{air}$ | = | Effective concentration of constituents in air from fugitive dust ($mg/m^3$) |
| $EPC_{soil}$ | = | COPC concentration in surface soil (mg/kg) |
| $PM_{10}$ | = | Concentration of particulate matter in air < 10 microns in diameter ($\mu g/m^3$) |
| CF | = | Conversion factor ($10^{-9}$ kg/μg) |

Fugitive dust concentrations for the construction worker scenario will be calculated by multiplying the soil EPCs discussed above by the MADEP default $PM_{10}$ concentration of 60 $\mu g/m^3$, for "enhanced exposure" (*e.g.*, grading or excavation scenarios). The $PM_{10}$ concentration will be used to estimate the concentration of respirable particulates in the air breathed by the construction workers. These particulates are assumed to be derived from soil and, therefore, to have the same constituent concentrations.

For other non-grading or excavating scenarios, MADEP recommends a value of 32 $\mu g/m^3$ for open field situations in which soil is sparsely vegetated or bare and particulate matter readily becomes airborne. However, as an area becomes more vegetated, it is less likely that soil particulate matter will become airborne. Therefore, on a site-specific basis, MADEP recommends that the percentage of $PM_{10}$ that is soil derived may be reduced to as low as 40% (MADEP, 1995). Depending on site-specific conditions, the fugitive dust concentrations for future residents and park visitors will be calculated by multiplying the soil EPCs discussed above by the MADEP default $PM_{10}$ concentration ranging from 13 to 32 $\mu g/m^3$.

### 4.3.6 Air -- Volatile Constituents Indoors and Outdoors

If VOCs are found in groundwater or soil, possible exposure to COPCs in indoor air will be modeled for potential volatilization from vadose zone soils and shallow groundwater. The average VOC concentrations measured in the most recent groundwater sampling and vadose zone soil data from within a hypothetical building footprint will be used to calculate indoor air EPCs for child and adult residents using USEPA's indoor air model (EPA, 2001b). Half the detection limit will be used for non-detects in these calculations, per MADEP (1995) guidance.

If VOCs are found in soil and/or groundwater, VOC concentrations in outdoor air will be calculated considering two emission sources: 1) vadose zone soil; and 2) shallow groundwater. The overall modeling approach will involve estimating the VOC flux reaching the ground surface from these sources and calculating the degree of dispersion and dilution expected in ambient air (by applying a dispersion factor). The VOC flux from soils will be calculated using the approach presented in Jury *et al.* (1990); the VOC flux from groundwater to ambient air will be calculated using the Farmer model (USEPA, 1992). A Site-specific air dispersion factor will be developed using surface metrological data

from the nearest available meteorological station and the USEPA-recommended air dispersion model the Industrial Source Complex Short Term (ISCST3) model.

### 4.3.7 Home Grown Produce

The COPC concentration in homegrown produce will be estimated using average soil EPCs and recommended chemical and radionuclide uptake factors (MADEP, 1995; USEPA, 2000):

$$EPC_{HGProd} = EPC_{soil} \times UF \quad (4\text{-}10)$$

where:

| | | |
|---|---|---|
| $EPC_{HGProd}$ | = | Exposure point concentration of constituents in home grown produce (mg/kg dry weight) |
| $EPC_{soil}$ | = | COPC concentration in surface soil (mg/kg) |
| UF | = | Plant-specific uptake factor ($mg/kg_{plant}$ per $mg/kg_{soil}$ dry weight) |

### 4.3.8 Fish

EPCs for fish will be estimated using available data from the Sherman Reservoir fish samples for PCBs, supplemented with modeled concentrations for other COPCs in sediment for which monitoring data in fish are unavailable. Average COPC concentrations in the edible portion of the fish (*e.g.*, filet) will provide the basis for human exposure calculations.

For PCBs, the estimation of EPCs for fish will be adjusted to account for the removal of PCBs from sediment, which is expected to result in a decline in the PCB concentration in fish. The methods approved by USEPA for the TSCA RBDAA will be adopted in this assessment. The post-remediation PCB concentration in fish tissue will be estimated based on the PCB concentration in fish filets measured prior to sediment remediation, multiplied by the ratio of the post/pre-remediation PCB concentrations in sediment as follows.

$$C_{fish-post} = C_{fish-pre} \times \frac{C_{sed-post}}{C_{sed-pre}} \quad (4\text{-}11)$$

where

| | | |
|---|---|---|
| $C_{fish}$ | = | concentration of COPC in fish (mg/kg) |
| $C_{sed}$ | = | concentration of COPC in sediment (mg/kg) |

The notation "pre" and "post" indicate values for pre- and post-remediation conditions, respectively. This approach is equivalent to applying a site-specific biota-sediment accumulation factor (BSAF) as is shown below.

$$BSAF = \frac{C_{fish-pre}}{C_{sed-pre}} \quad (4\text{-}12)$$

In order to estimate the post-remediation PCB concentration in fish, the BSAF is multiplied by the post-remediation PCB concentration in sediment:

$$C_{fish\text{-}post} = C_{sed\text{-}post} \times BSAF \quad (4\text{-}13)$$

Combining terms from the equations above gives:

$$C_{fish-post} = C_{sed-post} \times \frac{C_{fish-pre}}{C_{sed-pre}}$$

or,

$$C_{fish-post} = C_{fish-pre} \times \frac{C_{sed-post}}{C_{sed-pre}}$$

For radionuclides, the Phase II fish data, supplemented by YAEC's REMP monitoring data for fish samples from Sherman Reservoir collected from the most recently available data, will provide the basis for the EPC estimation. For all other COPCs in sediment (for which there are no fish monitoring data), concentrations of these COPCs in fish will be estimated using the equations in Attachment B (these are the methods used for the focused risk assessment supporting the TSCA RBDAA).

# 5 Risk Characterization

This section summarizes the approach that will be used to calculate total potential risks from exposures to non-radiological as well as radiological COPCs. EPCs will also be compared to Applicable or Suitably Analogous Standards as required by the MCP.

## 5.1 Chemical Health Risks

### 5.1.1 Cancer Risks

Carcinogenic risks are characterized as the incremental probability that an individual will develop cancer during their lifetime due to chemical exposure. The term "incremental" implies that this risk corresponds to the added probability of cancer above the background cancer risk typically experienced by all individuals in the course of daily life. Cancer risks are expressed as a unitless probability (*e.g.*, one in a million, or $10^{-6}$) of an individual developing cancer over a lifetime, above the background risk, as a result of the exposure.

For ingestion and dermal exposures, cancer risks for non-radiological constituents will be calculated by multiplying the average daily dose or ADD by the cancer slope factor (CSF) as follows[7]:

$$CancerRisk = ADD \times CSF \qquad (5\text{-}1)$$

where:

ADD = Average Daily Dose averaged over lifetime (mg/kg-day)
CSF = Cancer Slope Factor (risk per mg/kg-day)

For inhalation exposures, cancer risk will be calculated by multiplying the exposure point concentration in air by the inhalation unit risk factor (UR) as follows:

$$CancerRisk = EPC_{air} \times UR \qquad (5\text{-}2)$$

[7] Note that cancer risk is calculated over a lifetime, thus the ADD is the average daily dose averaged over a lifetime of exposure as described in Section 4.

where:

$EPC_{air}$ = Exposure Point Concentration in air ($\mu g/m^3$)
UR = Inhalation Unit Risk Factor (risk per $\mu g/m^3$).

Cancer risks estimated from chemical exposures will be added to the cancers risks estimated from radiological exposures (described below) to derive total cancer risks for each of the receptor groups.

### 5.1.2 Non-Cancer Health Hazards

In contrast with carcinogenic health risks, which represent the increased probability of incurring cancer over a lifetime, non-carcinogenic health hazards do not yield a probability of an adverse health affect occurring. USEPA and other agencies have developed acceptable daily intakes and reference concentrations, referred to as Reference Dose (RfD) and Reference Concentration (RfC), respectively.[8] The RfD or RfC represent estimates of the daily exposure level that can be experienced by an individual, including sensitive individuals such as children, for a lifetime with negligible risk of adverse health effects. Therefore, if the estimated exposure from the site is equal to or less than the RfD or RfC then adverse non-cancer health impacts are not expected. However, if the estimated exposures from the Site are greater than the RfD or RfC, this would indicate only that further evaluation is necessary, not that adverse effects will occur.

To evaluate non-cancer risks, the ratio of the chemical exposures to the acceptable daily intake or concentrations will be calculated. This ratio is referred to as a Hazard Quotient, or HQ. For ingestion and dermal exposures, HQs will be calculated using the following equation:

$$HQ = \frac{ADD}{RfD} \qquad (5\text{-}3)$$

where:

HQ = Hazard Quotient (dimensionless).
ADD = Average Daily Dose of the constituent (mg/kg-day)
RfD = Oral Reference Dose (mg/kg-day)

[8] These RfDs and RfCs have been adopted by other state agencies, including MADEP.

For inhalation exposures, HQs will be calculated using the following equation:

$$HQ = \frac{EPC_{air}}{RfC} \quad (5\text{-}4)$$

where:

HQ = Hazard Quotient (dimensionless).
$EPC_{air}$ = EPC of the constituent in air ($mg/m^3$)
RfC = Inhalation Reference Concentration ($mg/m^3$)

The hazard quotients for individual COPCs will be summed across all exposure routes and media to derive a total hazard index (HI) for each receptor.[9] Note however that childhood and adult non-cancer hazard indices are not additive.

### 5.1.3 Lead Risk Characterization

If lead is found to be a COPC, the assessment of the possible non-cancer impacts of lead exposure will be conducted following established USEPA approaches for assessing lead health impacts. According to scientific literature published by U.S. and Canadian scientists, blood lead levels are considered the most reliable indicator of potential adverse health effects of lead (USEPA, 1994; USEPA, 2001a; ATSDR, 1999; CDC, 1991; Hilts *et al.*, 1998; Feldman and Randel, 1994). Thus, in the assessment of potential health impacts from lead contaminated soils, significant weight must be given to the blood lead data. USEPA notes that "Blood lead concentrations are not only indicators of recent exposure, but also are the most widely used index of internal body lead burdens associated with potential health effects" (USEPA, 1994).

Children's exposure to lead will be assessed using the Integrated Exposure and Uptake Biokinetic (IEUBK) Model (USEPA, 1994; USEPA, 2002b). The IEUBK Model is a computer-based deterministic simulation that estimates the blood lead concentration in children resulting from their exposure to lead in soil, dust, drinking water, diet, and air. Specifically, the model estimates the intake and uptake of lead into the body and then uses biokinetic modeling to predict blood lead levels. Because of variations in behavior and physiology among individual children, different children will have different blood lead

[9] The summing of HI values for the different pathway represents a conservative approach because the reference dose for a given COPC for a given pathway is calculated for a certain toxicological end-point (*e.g.*, liver, kidneys, *etc.*). To calculate an accurate estimate of potential non-carcinogenic health risks, HI values with the same toxicological endpoints should only be summed. However, as a conservative screening step HI values for all COPCs and pathways were summed to determine if non-carcinogenic health risks posed by the Site were likely to be of concern.

levels, even if they are exposed to the same environment. The IEUBK Model addresses this by treating its central estimate of blood lead concentration (averaged over childhood from age 0 to 7 yrs) as a geometric mean (GM) of a lognormal distribution among similarly exposed children. A default GSD of 1.6 is used to calculate the proportion of children in the variable population falling above 10 μg/dL.

The USEPA adult lead model (USEPA, 2003b) will be used to evaluate risk from exposure to lead for adults and adolescents. The model considers women of childbearing age as the most sensitive receptor to determine the potential health effects from exposure to lead at the site. The adult lead model was developed by the USEPA Technical Review Workgroup for Lead, specifically for adult exposure scenarios. The USEPA adult lead model will be used to generate an estimate of the geometric mean blood lead levels (μg/dL) in women of child-bearing age, and the geometric standard deviation (GSD) will be used to calculate the 95$^{th}$ percentile blood lead level. Exposure point concentrations (EPCs) will be the arithmetic mean concentration of lead in soil for each property or exposure area. The most recent NHANES data for the Northeast will be used to specify the baseline blood lead level and GSD for both adolescents and adults for use in the Adult Lead Model. Predicted 95$^{th}$ percentile blood lead levels will be compared against the benchmark value of 11 μg/dL[10] for adults and 10 μg/dL for adolescents in order to assess whether lead exposures exceed health-based guidelines.

## 5.2 Radiological Risk Characterization

USEPA classifies all radionuclides as carcinogens, based on their property of emitting ionizing radiation and on the extensive weight of evidence provided by epidemiological studies of radiologically induced cancers in humans. At radionuclide-contaminated sites, USEPA generally evaluates potential human health risks based on radiation toxicity (*i.e.*, adverse effects caused by ionizing radiation rather than on the chemical toxicity of each nuclide present). Intakes by ingestion, inhalation, and absorption are potentially important exposure pathways for radionuclides. As summarized in Section 4.2.2, radionuclide intake is expressed in units of activity (*i.e.*, picocurie or pCi) rather than mass. Radionuclides that enter the body through these internal exposure pathways may become incorporated into tissues and emit alpha, beta, or gamma radiation.

Cancer risk associated with exposures to radionuclides in soil (*e.g.*, soil ingestion, inhalation of particulates) and groundwater will be evaluated using the equations given below.

[10] A comparison value of 11 μg/dL is derived from the USEPA/Centers for Disease Control and Prevention (CDC) level of concern (10 μg/dL), divided by the maternal/fetal blood ratio of 0.9 (USEPA, 1996).

$$Risk_{oral} = IF_o \times rCSF_o \quad (5\text{-}5)$$

$$Risk_{inhalation} = IF_i \times rCSF_i \quad (5\text{-}6)$$

where

$IF_o$, $IF_i$ = Radionuclide Intake factors for oral and inhalation exposures (pCi)
$rCSF_o$ = Radionuclide oral ingestion cancer slope factor (Risk/pCi)
$rCSF_i$ = Radionuclide inhalation cancer slope factor (Risk/pCi)

The intake factors ($IF_o$ and $IF_i$) were defined previously in Section 4.2.2.

When radioactive decay products also contribute to cancer risk, the cancer slope factor used to characterize the risk of the parent radionuclide plus daughter products (*e.g.*, rCSF+D) will be used to characterize incremental cancer risks above background.

External Radiation Exposure Risks:

In addition, radionuclides can also have a deleterious effect on humans without being taken into or brought in contact with the body. This is because high-energy beta particles and photons from radionuclides from contaminated air, soil, or water can travel long distances with only minimum attenuation in these media before exerting their energy in human tissue. Such "external radiation" exposures can result from exposure to residual radionuclides at the site. Gamma and x-rays are the most penetrating of the emitted radiation and comprise the primary contribution to the radiation dose from external exposures.

Cancer risk associated with external radiation exposures will be evaluated using the following equation (USEPA, 2000):[11]

$$Risk = \overline{EPC} \times \left(\frac{EF}{365\ days/yr}\right) \times ED \times ACF \times [ET_o + (ET_i \times GSF)] \times CSF_{ext} \quad (5\text{-}7)$$

where:

$\overline{EPC}$ = Average concentration in soil (pCi/g), defined by Equation (4-6)

[11] This is the same equation used by the Soil Screening Guidance for Radionuclides electronic calculator at: http://risk.lsd.ornl.gov/rad_start.shtml,

| | | |
|---|---|---|
| EF | = | Exposure frequency (days/yr) |
| ED | = | Exposure duration (years) |
| ACF | = | Area correction factor (default = 0.9; USEPA, 2000) |
| $ET_o$ | = | Exposure time fraction outdoors (default = 0.073; USEPA, 2000) |
| $ET_i$ | = | Exposure time fraction indoors (default = 0.683; USEPA, 2000) |
| GSF | = | Gamma shielding factor (default = 0.4; USEPA, 2000) |
| $CSF_{ext}$ | = | Cancer slope factor for external radiation (risk/yr per pCi/g) |

## 5.3 Combined Chemical and Radiological Risks

The cancer risks for chemical and radiological pathways are additive. Thus, the estimate of combined radiological and chemical components of risk is simply the summation of the two components. These combined risks will be evaluated to determine whether chemical and radiological COPCs require additional remedial actions after the decommissioning efforts in order to protect human health and ensure compliance with the MCP.

## 5.4 Comparison of Radionuclide Risk *versus* Dose

As noted earlier, the NRC and MADPH have established radioactive dose-based criteria for radionuclides. These dose-based criteria can be related to the cancer risk calculations using a so-called "dose conversion factor," or DCF. The DCF represents the radiation dose per unit of radiation activity for a particular exposure pathway (radionuclide-specific). The relationships between cancer risk and radiation dose are summarized below by exposure pathway.

*Ingestion Pathway*

Combing Equation (4-4) and Equation (5-5), the cancer risk for the oral (ingestion) pathway is given by:

$$Risk_{oral} = \overline{EPC} \times IR \times EF \times ED \times rCSF_o \qquad (5\text{-}8)$$

where:

| | | |
|---|---|---|
| $\overline{EPC}$ | = | Average exposure point concentration over duration of exposure (*e.g.*, pCi/g, pCi/L) |
| IR | = | Media intake rate (*e.g.*, g/day, L/day) |
| EF | = | Exposure frequency (days/year) |
| ED | = | Exposure duration (years) |

$rCSF_o$ = Radionuclide oral ingestion cancer slope factor (Risk/pCi)

The radiation dose for ingestion exposures is given by an analogous equation:

$$Dose_{oral} = EPC_o \times IR \times EF \times DCF_o \quad (5\text{-}9)$$

where

$EPC_o$ = Concentration of radionuclide at time of license termination (*e.g.*, concentration at time t=0; pCi/g)
$Dose_{oral}$ = Oral radiation dose (mrem/yr)
$DCF_o$ = Oral dose conversion factor (mrem/pCi)

An inspection of Equation (5-8) and Equation (5-9) reveals similarities and an important difference. Because risks are calculated over a "lifetime," the concentration term in Equation (5-8) is an average over the exposure duration. In contrast, the NRC 25 mrem/year maximum dose in a single year must be demonstrated at the time of license termination (*e.g.*, not an average over a lifetime) – the DPH dose-based requirement for 10 mrem/yr would be met at the time of property transfer. Therefore, the concentration value used in Equation (5-9) is not an average over the exposure duration, but rather the "initial" concentration ($EPC_o$) at the time of license termination or property transfer. For long-lived radionuclides, this distinction is not important because the average concentration over the time period to be considered for cancer risk (30 years) will be essentially equivalent to the initial concentration. However, for those radionuclides with relatively short half-lives, such as Cobalt-60 with an approximate half-life of 5.3 years, the average concentration over a 30-year period is 4-fold lower than the initial concentration in year "0".

If Equations (5-8) and (5-9) are combined, substituting the relationship for the average concentration given by Equation (4-6), the relationship between the radiation dose and cancer risk is given by:[12]

$$Risk_o = Dose_o \times ED \times \frac{(1 - e^{-\lambda T})}{T\lambda} \times \left(\frac{rCSF_o}{DCF_o}\right) \quad (5\text{-}10a)$$

For long-lived radionuclides, this relationship is simply:

[12] Note, that because T=ED, Equation (5-10a) can be simplified to: $Risk_o = Dose_o \times \frac{(1 - e^{-\lambda T})}{\lambda} \times \left(\frac{rCSF_o}{DCF_o}\right)$

$$Risk_o = Dose_o \times ED \times (\frac{rCSF_o}{DCF_o}) \quad (5\text{-}10b)$$

In other words, the cancer risk associated with a given radiation dose for an individual radionuclides is proportional to the ratio of the cancer slope factor and the dose conversion factor. This relationship is radionuclide- and pathway-specific.

In a similar manner, the corresponding equations for the inhalation and external radiation pathways are given below.

*Inhalation:*

$$\text{Risk}_i = \text{Dose}_i \times \text{ED} \times \frac{(1-e^{-\lambda T})}{T\lambda} \times (\frac{\text{rCSF}_i}{\text{DCF}_i}) \quad (5\text{-}11)$$

where

$\text{Dose}_i$ = Inhalation radiation dose (mrem/yr)
$\text{DCF}_i$ = Inhalation dose conversion factor (mrem/pCi)

*External Radiation:*

$$\text{Risk}_{ext} = \text{Dose}_{ext} \times \text{ED} \times \frac{(1-e^{-\lambda T})}{T\lambda} \times (\frac{\text{rCSF}_{ext}}{\text{DCF}_{ext}}) \quad (5\text{-}12)$$

where

$\text{Dose}_{ext}$ = External radiation dose (mrem/yr)
CSFext = External radiation cancer slope factor (risk per pCi/g)
$\text{DCF}_{ext}$ = External radiation dose conversion factor (mrem/yr per pCi/g)

Values for the radionuclide cancer slope factors are compiled by USEPA based on updates to the HEAST tables.[13] Values for pathway-specific DCF factors are found in RESRAD (ANL, 2001); the DCF values in RESRAD are obtained from Federal Guidance Reports 11 and 12.[14]

[13] Current values of cancer slope factors for radionuclides are given at: http://www.epa.gov/radiation/heast/index.html.
[14] Available at: http://www.epa.gov/radiation/federal/techdocs.htm.

## 5.5 Comparison of EPCs to Applicable or Suitably Analogous Standards

Section 310 CMR 40.0993(6) of the MCP requires that EPCs be compared to Applicable or Suitably Analogous Standards, which include Massachusetts Drinking Water Quality Standards, NAAQS, and Massachusetts' surface water quality standards (*i.e.*, USEPA's ambient water quality criteria (AWQC), 2002a). A comparison to these Applicable or Suitably Analogous Standards will be performed in the HHRA.

## 5.6 Risk to Safety and Public Welfare

The purpose of evaluating the risk of harm to safety is to identify if any post-closure conditions will exist at the Site that may result in a release of hazardous material in the foreseeable future that will pose a threat of physical harm or bodily injury to people. Such conditions include the presence of rusted or corroded drums, weakened berms, threat of fire or explosion, reactive chemicals, unsecured pits, lagoons, ponds, or other dangerous structures, any uncontained materials which may exhibit the characteristics of corrosivity, reactivity, flammability, or are considered infectious materials. The MCP also specifies that the risk to public welfare should be evaluated by considering whether nuisance conditions that might be affecting public welfare exist at the Site. Because YNPS is being completely dismantled and the Site restored, the above mentioned conditions or nuisances will not exist.

The risk assessment will evaluate the possible human health concerns relating to any residual constituents and radionuclides in environmental media. In addition, the MCP requires a determination of whether constituent concentrations exceed Upper Concentration Limits (UCLs) prescribed in 310 CMR 40.0996, and this determination will be presented in the HHRA.

## 5.7 Uncertainty Analysis

There are many uncertainties inherent in current risk assessment methodology that may serve to under- or over-estimate potential health risks. The predominant uncertainties in the risk characterization will be discussed when characterizing the potential health risks. Some typical areas of uncertainty encountered in the risk assessment may include:

- adequacy of site characterization;
- quality of analytical data;

- accuracy of modeling;
- accuracy of the assumption concerning frequency, duration and magnitude of exposures; and,
- availability and accuracy of toxicity data.

Although the magnitude of the uncertainties may not be possible to quantify, the nature of the risk assessment process under the MCP is to err on the side of public health safety. The HHRA will present a discussion of the uncertainties inherent to the risk assessment process and provide a perspective for stakeholders on the interpretation of the risk assessment results.

Finally, the risk assessment report will conclude whether or not a condition of no significant risk of harm to human health, safety, and public welfare exists for the YNPS. Should the cumulative risk assessment identify potential risks above background risks and beyond risk guidelines established by MADEP and USEPA, this will serve as the basis for identifying additional remedial measures or environmental controls to reduce these potential risks.

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# *Tables*

**Table 1**
**Exposure Pathways and Receptors**
**YNPS Human Health Risk Assessment**

| Receptors | Media | Exposure Pathways |
|---|---|---|
| Child/Adult Resident | Soil | Ingestion<br>Dermal contact<br>External Radiation |
| | Air | Inhalation of Particulates<br>Inhalation of VOCs |
| | Groundwater | Ingestion<br>Dermal contact |
| | Home-grown food<br>Fish (diet) | Ingestion<br>Ingestion |
| | Sediment | de minimis (see text)<br>de minimis (see text) |
| | Surface Water | de minimis (see text)<br>de minimis (see text) |
| Utility Workers on Sherman Reservoir Dam Maintenance | Sediment | Ingestion<br>Dermal contact<br>External Radiation |
| | Surface water | de minimis (see text)<br>de minimis (see text) |
| Construction/Utility Workers | Soil | Ingestion<br>Dermal contact<br>External Radiation |
| | Air | Inhalation of Particulates<br>Inhalation of VOCs |
| | Groundwater | Ingestion<br>Dermal contact |
| Child/Adolescent/Adult Park Visitor | Soil | Ingestion<br>Dermal contact<br>External Radiation |
| | Air | Inhalation of Particulates<br>Inhalation of VOCs |
| | Sediment | de minimis (see text)<br>de minimis (see text) |
| | Surface Water | de minimis (see text)<br>de minimis (see text) |
| | Fish (diet) | Ingestion |

**Table 2**
**Exposure Factors For YNPS Human Health Risk Assessment**

| Exposure Pathway/Exposure Factor | MADEP Value | MADEP Comment/ Reference | USEPA Value | USEPA Comment/ Reference |
|---|---|---|---|---|
| **Resident -- Adult** | | | | |
| *Body Weight (kg)* | 70 | MADEP (1995) | 71.8 | USEPA (1997) |
| *Exposure duration (yrs)* | 24 | MADEP (1995) | 24 | USEPA (1997) |
| *Air:* Exposure Time Fraction (hr/24hr) | 1 | High end assumption -- implicit | 1 | Implicit |
| *Soil:* Exposure Frequency (d/yr) | 130 | 5 days/week April-October (MADEP, 1995) | 350 | USEPA (1997) |
| *Soil:* Ingestion Rate (mg/day) | 50 | MADEP (2002b) | 50 | USEPA (1997) |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.13 | MADEP (2002a) | 0.07 | RME residential scenario (USEPA, 2001) |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 5,657 | includes face, hands, forearms, lower legs, feet, MADEP 2002a. | 5700 | RME residential scenario (USEPA, 2001) |
| Home Grown Produce Ingestion (g/day-dry wt.) | 0.73 | sum of lettuce, peas, carrots, and tomatoes 26 to 30 yr (MADEP, 1995) | 0.76 | Consumer-only values for same vegetables, adjusted by % consuming, 90% moisture, and assigning 60 kg BW (USEPA, 1997) |
| *Groundwater:* Ingestion Rate (L/day) | 2 | MADEP (1995) | 2.3 | 90th percentile adult water ingestion; USEPA, 1997. |
| *Fish:* Ingestion Rate (g/day) | 26 | sport-caught freshwater fish (MADEP, 1995) | 25 | recreational freshwater angler -- 95th percentile (USEPA, 1997) |
| **Resident -- Child** | | | | |
| *Body Weight (kg)* | 16.1 | MADEP (1995) | 16.6 | average body weight for age group 1-6, USEPA, 1997. |
| *Exposure duration (yrs)* | 6 | MADEP (1995) | 6 | USEPA (1997) |
| *Air:* Exposure Time Fraction (hr/24hr) | 1 | High end assumption -- implicit | | |
| *Soil:* Exposure Frequency (d/yr) | 130 | 5 days/week April-October (MADEP, 1995) | 350 | USEPA (1997) |
| *Soil:* Ingestion Rate (mg/day) | 100 | MADEP (2002b) | 100 | USEPA (1997) |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.35 | MADEP (2002a) | 0.2 | RME residential scenario (USEPA, 2001) |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 2434 | includes face, hands, forearms, lower legs, feet, MADEP 2002a. | 2800 | RME residential scenario (USEPA, 2001) |
| Home Grown Produce Ingestion (g/day-dry wt.) | 0.25 | sum of lettuce, peas, carrots, and tomatoes 2 yr old (MADEP, 1995) | 0.18 | Adjusted from adult rate in proportion to body weight |
| *Groundwater:* Ingestion Rate (L/day) | 1 | MADEP (1995) | 0.9 | Ages 1-10 (USEPA, 2002) |
| *Fish:* Ingestion Rate (g/day) | 6 | Adjusted from adult rate in proportion to body weight | 6 | Adjusted from adult rate in proportion to body weight |
| **Recreational Activities -- Adult** | | | | |
| *Body Weight (kg)* | 70 | MADEP (1995) | 70 | USEPA, 1997. |
| *Exposure duration (yrs)* | 12 | MADEP (1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure Frequency (d/yr)* | 24 | 2-days/week for 3 months | - | no "defaults" -- based on site-specific exposures |
| *Air:* Exposure Time Fraction (hr/24hr) | 0.167 | 4 hrs/day | - | no "defaults" -- based on site-specific exposures |
| *Soil:* Ingestion Rate (mg/day) | 50 | MADEP (1995) | 50 | USEPA, 1997. |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.13 | MADEP, 2002a, based on USEPA 2001 Soccer Player (adults). | 0.01 | Soccer Player (adult), USEPA, 2001. |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 5657 | includes face, hands, forearms, lower legs, feet (MADEP 2002a) | 5700 | assume same as resident |
| *Fish:* Ingestion Rate (g/day) | 26 | sport-caught freshwater fish (MADEP, 1995) | 25 | recreational freshwater angler -- 95th percentile (USEPA, 1997) |
| **Recreational Activities -- Adolescent** | | | | |
| *Body Weight (kg)* | 41.6 | MADEP (1995) | 43.2 | USEPA (1997) |
| *Exposure duration (yrs)* | 12 | MADEP (1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure Frequency (d/yr)* | 24 | 2-days/week for 3 months | - | no "defaults" -- based on site-specific exposures |
| *Air:* Exposure Time Fraction (hr/24hr) | 0.167 | 4 hrs/day | - | no "defaults" -- based on site-specific exposures |
| *Soil:* Ingestion Rate (mg/day) | 50 | MADEP (1995) | 50 | USEPA, 1997. |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.13 | MADEP, 2002a, based on USEPA 2001 Soccer Player (teen) | 0.04 | Soccer Player (teen), USEPA, 2001. |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 5657 | includes face, hands, forearms, lower legs, feet (MADEP 2002a) | 5322 | assumes head,forearms, hands, lower legs, feet, USEPA, 2001. |
| *Fish:* Ingestion Rate (g/day) | 26 | sport-caught freshwater fish (MADEP, 1995) | 25 | recreational freshwater angler (USEPA, 1997) |

**Table 2**
**Exposure Factors For YNPS Human Health Risk Assessment**

| Exposure Pathway/Exposure Factor | MADEP Value | MADEP Comment/ Reference | USEPA Value | USEPA Comment/ Reference |
|---|---|---|---|---|
| **Recreational Activities -- Child** | | | | |
| *Body Weight (kg)* | 16.1 | average body weight for age group 1-6, MADEP, 1995. | 16.6 | average body weight for age group 1-6, USEPA, 1997. |
| *Exposure duration (yrs)* | 6 | MADEP (1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure Frequency (d/yr)* | 24 | 2-days/week for 3 months | - | no "defaults" -- based on site-specific exposures |
| *Air:* Exposure Time Fraction (hr/24hr) | 0.167 | 4 hrs/day | - | no "defaults" -- based on site-specific exposures |
| *Soil:* Ingestion Rate (mg/day) | 100 | MADEP (2002b) | 100 | USEPA (1997) |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.35 | MADEP (2002a) -- based on USEPA 2001 child playing, wet soil | 0.2 | Child playing, wet soil (USEPA, 2001) |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 2434 | includes face, hands, forearms, lower legs, feet (MADEP 2002a) | 2829 | assumes head, forearms, hands, lower legs, feet (USEPA, 2001) |
| *Fish:* Ingestion Rate (g/day) | 26 | sport-caught freshwater fish (MADEP, 1995) | 25 | recreational freshwater angler (USEPA, 1997) |
| **Construction/Utility Worker** | | | | |
| *Body Weight (kg)* | 70 | MADEP (1995) | 71.8 | USEPA (1997) |
| *Exposure duration (yrs)* | 0.5 | MADEP (1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure Frequency (d/yr)* | 250 | e.g., 5 days/week (MADEP, 1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure Time Fraction (hr/24-hr)* | 0.33 | 8-hour day | - | no "defaults" -- based on site-specific exposures |
| *Soil:* Ingestion Rate (mg/day) | 100 | upper bound soil and dust ingestion, MADEP, 2002b. | 50 | USEPA (1997) |
| *Soil:* Skin Adherence Factor (mg/cm$^2$) | 0.29 | MADEP (2002a) | 0.1 | USEPA (2001) |
| *Soil:* Surface Area Exposed (cm$^2$/day) | 3477 | includes hands, forearms, face and feet (MADEP, 2002a) | 3,300 | "Industrial" Worker (USEPA, 2001) |
| *Groundwater:* Ingestion Rate (L/day) | 0.05 | incidental ingestion rate (MADEP, 1995) | 0.05 | USEPA (1989) |
| **Dam Maintenance Utility Worker** | | | | |
| *Body Weight (kg)* | 70 | MADEP (1995) | - | no "defaults" -- based on site-specific exposures |
| *Exposure duration (yrs)* | 1 | Combined exposure duration and exposure frequency | - | no "defaults" -- based on site-specific exposures |
| *Exposure Frequency (d/yr)* | 20 | equate to total number of "maintenance events" | - | no "defaults" -- based on site-specific exposures |
| *Sediment:* Skin Adherence Factor (mg/cm$^2$) | 1 | default for "sediment adherence" (MADEP, 2002a) | - | no "defaults" -- based on site-specific exposures |
| *Sediment:* Surface Area Exposed (cm$^2$/day) | 3477 | includes hands, forearms, face and feet (MADEP, 2002a) | - | no "defaults" -- based on site-specific exposures |
| *Surface Water:* Ingestion Rate (L/hr) | 0.05 | incidental ingestion rate (MADEP, 1995) | - | no "defaults" -- based on site-specific exposures |
| *Surface Water:* Area Exposed (cm$^2$) | 3477 | includes hands, forearms, face and feet (MADEP, 2002a) | - | no "defaults" -- based on site-specific exposures |

Sources:


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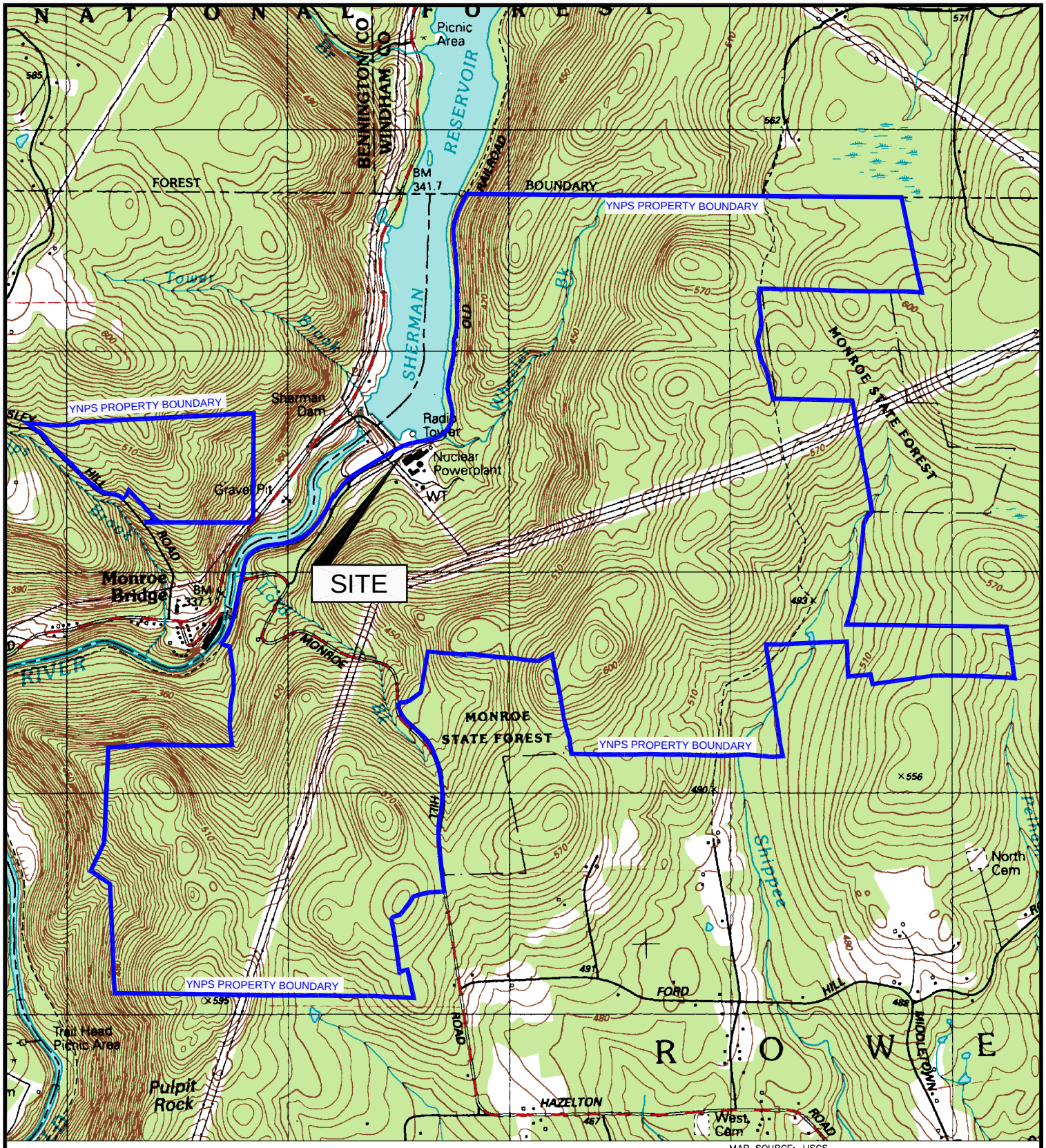
# *Figures*

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# FIGURE 1

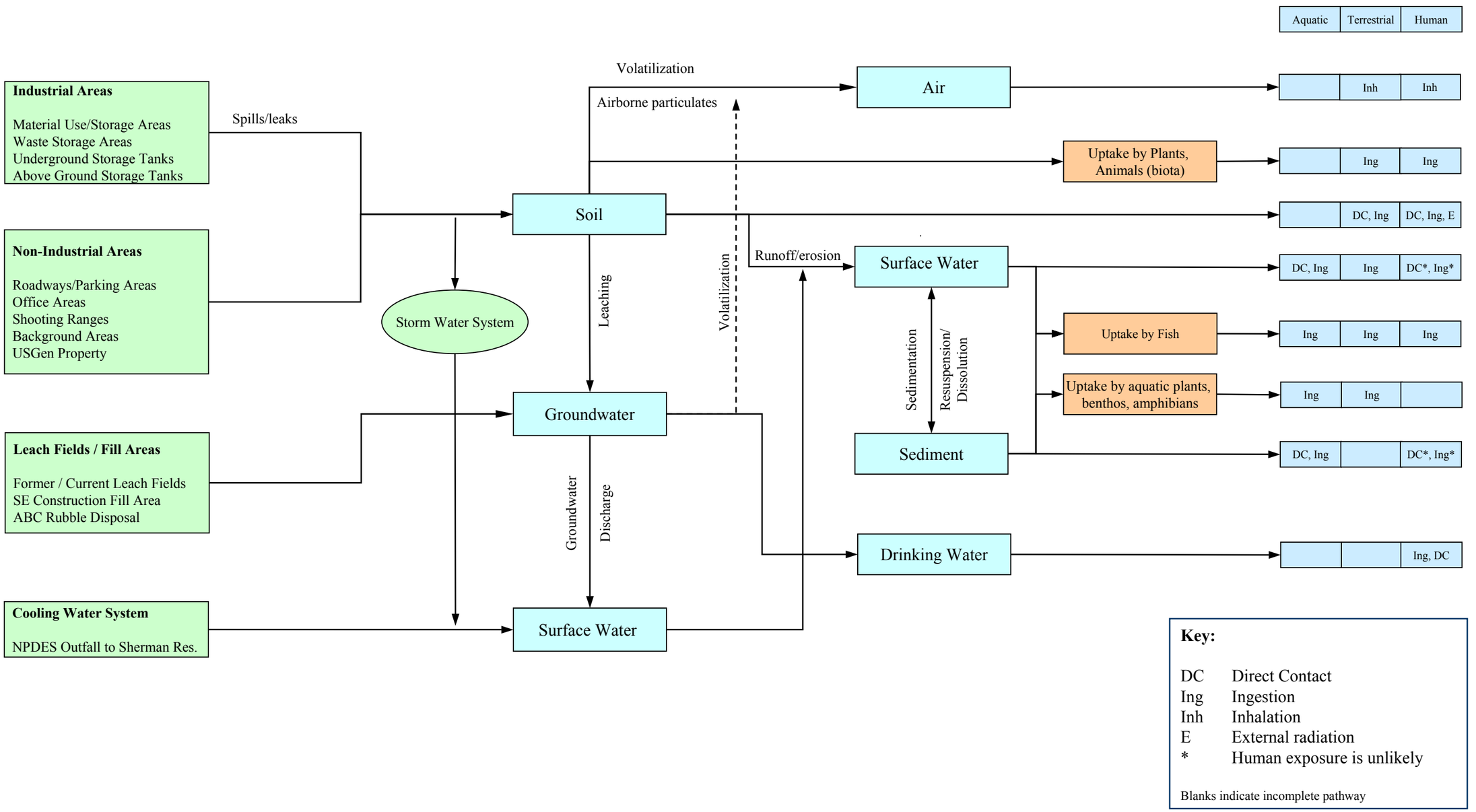
## YNPS SITE LOCATION

YANKEE NUCLEAR – ROWE, MA

| | | | | | |
|---|---|---|---|---|---|
| MODIFIED BY: | JJC | CHECKED BY: | DEM | PROJ. NO.: | 202073 |
| DATE: | 05/04/04 | DATE: | 05/12/04 | FILE: | locus |

**Figure 2**
**YNPS Human and Environmental Risk Assessment Conceptual Site Model**

Chemical Release Sources, Pathways of Exposure, and Potentially Exposed Receptors



# *Attachments*

# Attachment A

# Radiation Exposure Equations Accounting for Decay and Variable Child/Adult Intake Rates

**Intake Factor For Radionuclides**

In Section 4.2.2, the equation defining intake for radionuclides was defined, and it is repeated below for ease of reference:[1]

$$IF = C(t) \times IR \times EF \times ED \quad \text{(A-1)}$$

where

IF = Intake factor (pCi)

C(t) = Concentration (*e.g.*, pCi/g, pCi/$m^3$, pCi/L)

IR = media intake rate consistent with concentration units (*e.g.*, g/day, $m^3$/day, L/day)

EF = exposure frequency (d/yr)

ED = exposure duration (yrs)

$CSF_{ing}$ = cancer slope factor for ingestion (risk/pCi)

As described in Section 4.2.2, radionuclides undergo radioactive decay over time, according to the following exponential equation:

$$C(t) = C_0 e^{-\lambda T} \quad \text{(A-2)}$$

The average concentration over a time interval from time t=0 to time t=T is given by:

$$\overline{C} = C_0 \frac{(1 - e^{-\lambda T})}{T\lambda} \quad \text{(A-3)}$$

where

$C_0$ = Concentration at time t=0 (*e.g.*, initial concentration)

C(t) = Concentration at time t=T (time in years)

$\overline{C}$ = Average concentration from time t=0 to time t=T

$\lambda$ = $\frac{\ln 2}{t_{1/2}}$ where $t_{1/2}$ is the decay half-life in years

[1] For brevity, the exposure point concentration term (EPC) is shortened to "C" here.

**Intake Factor Variable Child/Adult Ingestion Rates**

In order to account for different ingestion rates of children and adults, Equation (A-1) can be re-written as:

$$\begin{aligned} IF_{adj} &= IF_{child} + IF_{adult} \\ &= \overline{C}_1 \times IR_1 \times ED_1 \times EF \quad + \quad \overline{C}_2 \times IR_2 \times ED_2 \times EF \end{aligned} \tag{A-4}$$

where

| | | |
|---|---|---|
| $\overline{C}_i$ | = | average concentration during time period 1 and 2 (pCi/g) |
| $IR_i$ | = | ingestion rate during time period 1 and 2 (g/d) |
| IF | = | child and adult intake factors over exposure period (pCi) |
| $ED_i$ | = | exposure duration for time period 1 and 2 (yrs) |

The average concentration during the childhood exposure, from time t=0 to time t=$T_1$, is given by Equation (A-3) as:

$$\overline{C}_1 = C_0 \frac{(1-e^{-\lambda T_1})}{T_1 \lambda} \tag{A-5}$$

For the post-childhood (*e.g.*, "adult") exposure period, the average concentration is given by a similar expression, except that the "initial concentration" for the post-childhood exposure starts at an initial concentration, $C_o$(t=6), corresponding to the concentration at the end of year 6 (*e.g.*, the end of the childhood exposure):

$$\overline{C}_2 = C_o(t=6) \frac{(1-e^{-\lambda T_2})}{T_2 \lambda} \tag{A-6}$$

or

$$\overline{C}_2 = C_o e^{-\lambda T_1} \frac{(1-e^{-\lambda T_2})}{T_2 \lambda} \tag{A-7}$$

Substituting Equations (A-6) and (A-7) into Equation (A-4) then gives an adjusted overall intake factor ($IF_{adj}$) for combined childhood and adult intake:

$$IF_{adj} = \left[ \frac{C_0}{T_1 \lambda}(1 - e^{-\lambda T_1}) \times IR_1 \times ED_1 \quad + \quad \frac{C_o e^{-\lambda T_1}}{T_2 \lambda}(1 - e^{-\lambda T_2}) \times IR_2 \times ED_2 \right] \times EF \qquad \text{(A-8)}$$

Combining terms (such as $T_1 = ED_1$ and $T_2 = ED_2$), Equation (A-8) can be simplified to:

$$IF_{adj} = \frac{C_0}{\lambda}\left[ (1 - e^{-\lambda T_1}) \times IR_1 \quad + \quad e^{-\lambda T_1}(1 - e^{-\lambda T_2}) \times IR_2 \right] \times EF \qquad \text{(A-9)}$$

Equation (A-9) gives the combined childhood plus adult intake factor when intake rates vary for children and adults.

# Attachment B

# Exposure Estimation Methods For Fish/Biota

**Determination of Exposure Point Concentrations in Biota**

Other than data for radionuclides and PCBs in fish, concentrations of other COPCs have not been measured in fish or biota at the site . Therefore, biota exposure point concentrations are estimated in this assessment based on three types of uptake factors, depending on published values for particular chemicals: linear uptake, log-linear regression uptake, and biota sediment accumulation factors (BSAF).

Linear uptake factors consist of ratios of the concentration of a given chemical in biota to that of sediment (*i.e.*, the model assumes that exposure to the food item is primarily from chemicals in sediment) (Sample *et al.*, 1997). These models assume that accumulation is linear and constant across all sediment concentrations. Linear uptake factors are useful in the absence of site-specific data.

Log-linear regression uptake models are appropriate when data indicate that bioaccumulation by invertebrates is non-linear, decreasing as contaminants in sediment concentrations increase. Various sediment properties, such as pH, clay content, calcium, and organic matter, can strongly affect both the concentrations of contaminants in sediment and the bioavailability of those contaminants for uptake by receptors, thus producing the observed non-linear relationships. Because contaminant uptake is influenced by characteristics of the organism and by the properties of the chemical, separate uptake factors are recommended for each chemical and taxonomic group considered (Sample *et al.*, 1997).

Finally, the BSAF approach is used to estimate the uptake of organic COPCs in fish. The primary exposure pathway for fish is the consumption of contaminated food. Deposited sediments often act as a local sink for contaminants, which may increase the contaminant exposure for sediment-associated biota that indiscriminately ingest sediment particles while foraging. BSAFs are transfer coefficients that relate concentrations in biota to concentrations in sediment. They are calculated as the ratio of the concentration of organic chemical in fish tissue (normalized by lipid content) to the concentration of organic chemical in sediment (normalized by organic carbon content).

## B.1 Invertebrates

To estimate metal constituents in invertebrates, linear uptake or regression model uptake equations will be used as appropriate depending upon available published information.

*Linear Bio-Uptake Model:*

$$C_{invert} = UF_{invert} * C_{sed}$$

where:

| | | |
|---|---|---|
| $C_{invert}$ | = | concentration of chemical in invertebrate (mg/kg) wet weight |
| $UF_{invert}$ | = | linear uptake factor ([mg-chem/kg invert]/[mg-chem/kg sediment]) |
| $C_{sed}$ | = | concentration of chemical in sediment (mg/kg) dry weight |

For organic chemicals:

$$UF_{invert} = K_{bw}/K_d$$

where:

| | | |
|---|---|---|
| $K_{bw}$ | = | $10^{(Kow - 0.6)}$ |
| $K_d$ | = | foc * Koc |
| $f_{oc}$ | = | fraction of organic carbon (0.06 Sherman Reservoir; 0.04 for WSD). |

For inorganic chemicals, uptake factors (UF) are available from Sample et al, (1998), Bechtel/Jacobs, (1998); Sample *et al*. (1997).

*Log-Linear Regression Models (Bechtel/Jacobs, 1998)*

Power models have been used to develop regression equations relating chemical uptake in invertebrates for metals and PCBs. The power model is of the form:

$$C_v = m(C_s)^b$$

The log-transformed linear regression model is then:

$$\log(C_v) = m' + b \log(C_s)$$

or

$$C_v = 10^{(m' + b \log(C_s))}$$

The Bechtel/Jacobs (1998) log-regression model was based on dry-weight sediment chemical concentration data for metals and organic-carbon normalized data for PCBs. The regression equations also were derived based on the dry-weight metal concentration in invertebrates, whereas for PCBs the regressions were based on lipid-normalized data. Thus, the general form of the equations above translate into the following specific log-regression models for metals and PCBs, resepctively:

*Regression Model for Metals*

$$C_{v-DW} = 10^{(m' + b \log(C_s))}$$

$$C_{v\text{-}WW} = C_{v\text{-}DW} \times (1\text{-}WC)$$

*Regression Model for PCBs:*

$$C_{v-LP} = 10^{(m' + b \log(C_{s-OC}))}$$

$$C_{s-OC} = C_s / OC$$

$$C_{v\text{-}WW} = C_{v\text{-}LP} \times LP_v$$

where:

| | | |
|---|---|---|
| $C_v$ | = | Chemical concentration in invertebrates (mg/kg) |
| $C_{v\text{-}WW}$ | = | Chemical concentration in invertebrates (mg/kg – wet weight) |
| $C_{v\text{-}DW}$ | = | Chemical concentration in invertebrates (mg/kg – dry weight) |
| $C_{v\text{-}LP}$ | = | Lipid-normalized PCB concentration in invertebrates (mg/kg-lipid) |
| m' | = | y-Intercept of the log-transformed regression model ($mg/kg_{biota}$) |
| b | = | Slope of the log-transformed regression model ($mg/kg_{biota}$ per $mg/kg_{sed}$) |
| $C_s$ | = | Chemical concentration in sediment (mg/kg – dry weight) |
| $C_{s\text{-}OC}$ | = | Organic carbon normalized chemical concentration in sediment (mg/kg-OC – dry weight) |
| $LP_v$ | = | Lipid content in invertebrates (kg-lipid/kg-tissue) |
| OC | = | Organic carbon content in sediment (kg-OC/kg-sediment) |
| log[] | = | Base 10 logarithm |

The lipid content of invertebrates (0.02 kg-lipid/kg-tissue) reported by Sample *et al.* (1997), will be used for $LP_v$.

## B.2 Fish

Chemical concentrations for organic COPCs in fish will be estimated using one of two methods: 1) a two-step process that combines estimates of chemical concentrations in invertebrates (as discussed in previous Section), coupled with the use of an assimilation of the invertebrate diet into fish tissue; or 2) biota sediment accumulation factors (BSAF) relating the chemical concentration in fish, to the chemical concentration in sediment. The selection of the particular approach will be based on the availability of published

### B.2.1 Assimilation Approach

The concentration in fish tissue as a function of the COPC concentration in food (invertebrates) can be estimated by the following equation:

$$C_{fish} = C_v \times 0.8$$

where

$C_{fish}$ = chemical concentration in fish (mg/kg-wet weight)
$C_v$ = chemical concentration in invertebrate food source (mg/kg-wet weight)
0.8 = assimilation efficiency (Thomann and Connolly, 1984)

The assimilation efficiency of food (invertebrates) is the fraction of food ingested that does not appear in the feces, *i.e.*, conservatively assumed to be incorporated into fish tissue.

### B.2.2 BSAF Approach

For the uptake of organic COPCs into fish for which measured data are unavailable, a biota–sediment accumulation factor (BSAF) was used to estimate fish tissue concentrations as recommended by USEPA (1997c):

$$EPC_{fish} = BSAF \times EPC_{sed} \times \frac{LP}{OC}$$

where:

$EPC_{fish}$ = concentration of organic constituent in fish tissue (mg/kg)
BSAF = Biota sediment accumulation factor (mg-chem/kg-lipid per mg-chem/kg-OC)

$EPC_{sed}$ = Chemical concentration in sediment (mg/kg)

LP = lipid content in fish whole body or filet (kg-lipid/kg-tissue)

OC = organic carbon fraction in sediment (kg-OC/kg-sed)