Centers for Disease Control and Prevention
National Center for Environmental Health

Fernald Risk Assessment Project

PHASE II

Screening Level Estimates of the Lifetime Risk of Developing:

Kidney Cancer

Female Breast Cancer

Bone Cancer

Leukemia

Resulting from the Maximum Estimated Exposure to Radioactive Materials Released from the Former Feed Materials Production Center (FMPC)

Final Report

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Foreword

This report incorporates public comments received by CDC on the draft version of the report. CDC released the draft report to the public during the June 23, 1999 meeting of the Fernald Health Effects Subcommittee in Harrison, Ohio. The risk information originally released in the June 1999 draft report entitled "Screening level Estimates of the Lifetime Risk of Developing Kidney Cancer, Female Breast Cancer, Bone Cancer, and Leukemia as a Result of the Maximum Estimated Exposure to Radioactive Materials Released from the Fernald Feed Materials Production Center (FMPC)" remains unchanged. No new information has been added.

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Summary

The Fernald Dosimetry Reconstruction Project

The Fernald Dosimetry Reconstruction Project, sponsored by Centers for Disease Control and Prevention (CDC), was undertaken to provide a means of estimating the radiation dose to specific organs among people who resided in the community surrounding the former Feed Materials Production Center (FMPC) near Cincinnati, Ohio. The FMPC was a government-owned, contractor-operated, uranium-processing facility that was part of the United States' weapons production complex. A computer algorithm was developed in the Fernald Dosimetry Reconstruction Project to allow estimation of organ-specific doses for the population residing within 10 kilometers (6.2 miles) from the center of the FMPC production area during the plant's operating years. This geographic area is referred to in this report as the assessment domain.

The final results of the Fernald Dosimetry Reconstruction Project, released to the public in December 1998, revealed that the primary radiation exposure to nearby residents resulted from breathing radon decay products released from storage silos on the site, and that community residents who were exposed may be at increased risk for lung cancer. The results also indicated that community residents received radiation doses from other radionuclides, primarily uranium and to a lesser extent thorium released from the site as a result of processing activities. These exposures to radionuclides other than radon also have the potential to cause detrimental health effects.

The Fernald Risk Assessment Project

The Fernald Risk Assessment Project was initiated in response to residents' concerns about possible health risks resulting from exposure to radioactive materials released from the FMPC site. The purpose of this multiphase project was to estimate the radiation-related health risks to people who lived near the FMPC during the years of plant operations. The results of the risk assessment project were also used to evaluate the feasibility of conducting an epidemiologic study within the

community. The population for which we estimated the FMPC-related risk, called the assessment population, consists of everyone who resided within 10 kilometers (6.2 miles) of the site for any length of time from 1951 through 1988. The assessment domain was divided into 12 areas to evaluate the potential effect of location of residence relative to the site on health effects. These areas were constructed to correspond to four directions from the site (northeast, southeast, southwest, and northwest) and three distance groups (1 to 4 kilometers, 4 to 7 kilometers and 7 to 10 kilometers from the center of the FMPC production facility). We addressed only those radiation exposures occurring during the years of plant operations, 1951 through 1988. We did not address exposures incurred as a result of working at the FMPC in our analysis because the Fernald Dosimetry Reconstruction Project was not designed to estimate occupational dose.

Phase I - Lung Cancer

Because members of the assessment population may have incurred significant exposures to radon and radon progeny and because radon exposure has been associated with an increased risk of lung cancer, the first phase of our risk assessment project focused on evaluating the effect of FMPC-related radiation exposures on the risk of lung cancer death among the assessment population. The final results of the lung cancer mortality risk assessment were summarized in the report, *"Estimation of the Impact of the Former Feed Material Production Center (FMPC) on Lung Cancer Mortality in the Surrounding Community,"* which was released in December 1998. The primary result given in this report was our estimate that the number of lung cancer deaths among the assessment population may increase by from 1% to 12% as a result of exposure to radioactive materials released from the FMPC site from 1951 through 1988. The first phase of the Fernald Risk Assessment Project dealt only with lung cancer mortality risk and did not address the potential for an increase in risk of other types of cancers that may be related to exposure to radioactive material released from the site.

Phase II – Screening Level Estimates of the Lifetime Risk of Developing Kidney Cancer, Female Breast Cancer, Bone Cancer, and Leukemia

This report contains the results of the second phase of the Fernald Risk Assessment Project. The goal of Phase II was to develop "screening level" estimates of the lifetime risk of developing kidney cancer, female breast cancer, bone cancer, and leukemia. These estimates are called screening level estimates to reflect the fact that we are estimating the increase in the lifetime risk of developing these cancers for a collection of hypothetical individuals assumed to have received the maximum FMPC-related radiation dose during the years the plant was operating, 1951 through 1988. We translated these estimated risks for hypothetical individuals into "upper bound" estimates of the number of each type of cancer that may result among the entire assessment population as a result of their exposure to radioactive material released from the FMPC site. The term "upper bound" signifies that we developed these estimates by assuming that everyone who resided within any of the areas of the assessment domain for any length of time from 1951 through 1988 received the maximum FMPC-related organ dose for that area. As a result of this assumption, the upper bound estimates for the number of FMPC-related cancer cases presented in this report are likely to be larger than the true number of cancer cases in the assessment population that may result from exposures to radioactive material released from the site.

The results of the Fernald Dosimetry Reconstruction Project indicated that although exposure to radon and radon decay products were very important in estimating radiation dose to the lungs and thus lung cancer mortality risk, such exposure did not contribute significantly to the radiation dose to other organs among residents of the assessment domain. As a result, this second phase of the Fernald Risk Assessment Project focuses on the potential health effects that may result from exposure to radionuclides other than radon, primarily uranium, released from the FMPC site during its operating years. The health outcomes addressed in this report include kidney cancer, female breast cancer, bone cancer, and leukemia. These cancers were selected for evaluation on the basis of the following factors: a review of the scientific literature to determine what organs within the human body are likely to receive a radiation dose as a result of exposure to the radionuclides, other that radon, released from the site; the concerns of area residents regarding these exposures as

prioritized by the Fernald Health Effects Subcommittee; and the biologic plausibility of the exposure leading to the development of cancer.

Our goal in developing these screening level risk estimates and upper bound estimates for the number of FMPC-related cancer cases in the assessment population is to provide the affected community with a reference they can use to evaluate their own potential risks associated with FMPC radiation exposure. In addition, the results will be used to guide future risk estimation and public health activities related to radiation exposure among those who resided near the FMPC site during its operating years.

Methods

To develop the screening level estimates of the lifetime risk, we first estimated the maximum FMPC-related organ dose for a collection of 13 hypothetical individuals, one from each of the 12 areas of the assessment domain and another assumed to have drunk and irrigated with well water contaminated with radioactive material released from the site. For each of these hypothetical individuals, we estimated the maximum FMPC-related radiation dose for the kidneys, the female breast, the bone surface, and the bone marrow. Estimates of dose for each organ were derived by making assumptions about the lifestyle characteristics of the hypothetical individual that purposefully increased their estimated radiation exposure. These assumptions are summarized in Figure 1 and Table 2 (on page 39). We estimated the maximum bone marrow dose in order to evaluate the lifetime risk of developing leukemia. Maximum dose estimates for each organ are reported as dose equivalents in units called sieverts.

The estimates of maximum dose were developed using a series of complex mathematical models that mimic the processes by which radioactive material was released from the site, the transport of this material through the air and water, and the radiation absorbed by human organs as a result of this exposure. Because we did not have exact measurements of the components needed to determine the maximum dose, we had to estimate these uncertain values using available information. As a result, we are uncertain about the true maximum FMPC-related radiation dose among the assessment population and this uncertainty is reflected in the estimates of maximum dose presented in this report.

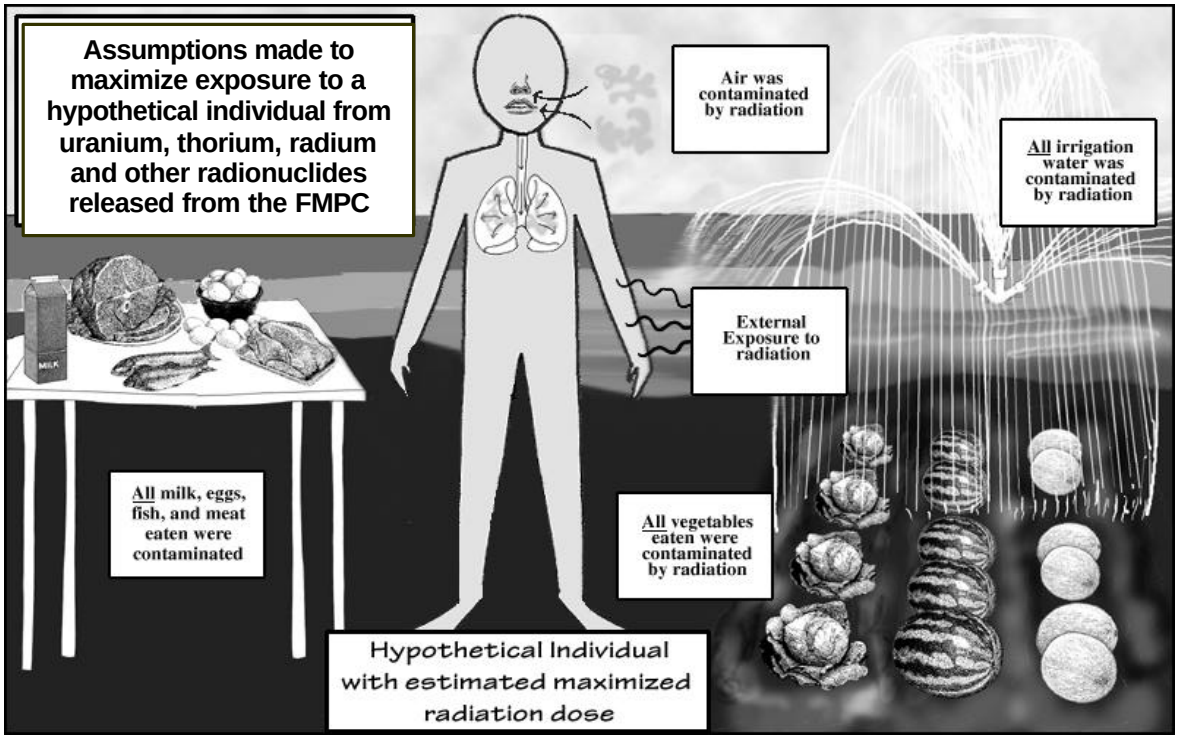

Figure 1. Assumptions made to maximize exposure to a hypothetical individual

We estimated the lifetime risk of developing the cancers of interest by multiplying the estimated maximum organ-specific doses to our hypothetical individuals by assumed values for the increase in the lifetime risk of developing the cancers per sievert of radiation dose received. The estimates of the increase in the lifetime risk per sievert dose of developing bone cancer and leukemia used in this report are based on the recommended values for these parameters given by the International Council on Radiation Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). Estimates of the increase in lifetime risk per sievert dose for kidney cancer and female breast cancer used in the report are based on the recommendations of the Environmental Protection Agency (EPA).

These estimates of the increase in the risk of developing cancer per sievert of radiation dose received are based on the cancer experience of human populations exposed to ionizing radiation, primarily atomic bomb survivors and those people exposed to radiation for medical reasons. Because of differences both in the type of exposure and in the characteristics of the populations on which the risk per unit dose estimates are based, and those of the population in which we wish to estimate risk, we are uncertain about the appropriate values to use for these parameters in our estimation of the FMPC-related lifetime risks. To reflect this uncertainty, we used a range of

possible values for the increase in cancer risk per sievert dose received in our estimation of the FMPC-related lifetime risk.

In addition to estimating the lifetime risk of selected cancers for a set of hypothetical maximally exposed individuals, we also estimated the percentage increase in their lifetime risk over the background lifetime cancer risk. Background cancer risk is defined as the expected cancer risk in the assessment population if there had been no releases of radioactive material from the site. Estimates of the background lifetime cancer risks for kidney cancer, female breast cancer, bone cancer, and leukemia were based on cancer occurrence data from the Surveillance, Epidemiology and End Results (SEER) cancer registry program and were derived using life table methodology developed by the National Cancer Institute.

To aid in interpreting the screening level risk estimates, we also estimated upper bounds for the number of cancer cases that may occur in the assessment population as a result of exposure to radioactive material released from the FMPC site from 1951 through 1988. We developed these upper bound estimates by assuming that everyone who resided in a particular area of the assessment domain for any length of time from 1951 through 1988 received the estimated maximum FMPC-related radiation dose for that area. We developed similar upper bound estimates for the number of cancer cases that may occur among those exposed to contaminated well water by assuming that everyone who lived for any length of time from 1951 through 1988 in the areas 1 to 4 kilometers southeast and southwest of the site received this additional type of radiation exposure.

Because we are uncertain about both the true value of the maximum FMPC-related radiation dose and the increase in the lifetime risk of developing cancer per unit dose, the estimated lifetime risks are also uncertain. In addition, the upper bound estimates of the number of cancer cases related to FMPC radiation exposure are uncertain because they rely on the uncertain estimates of lifetime risk and the size of the assessment population. We attempted to quantify the uncertainty associated with these estimates using a technique called Monte Carlo simulation. By applying the Monte Carlo procedure, we obtained a collection of possible values for the maximum FMPC-related organ doses, the associated estimates of the lifetime risk, the percentage increase in lifetime risk, and the upper bound estimates for the number of FMPC-related cancer cases. The range of possible values represented in these collections represents the uncertainty about the true values of these quantities. We summarized these collections using the median value and the 90% credibility interval. The median is that value greater than half of the estimates produced in the Monte Carlo simulation and

less than the other half. The 90% credibility interval is defined by an upper and lower limit so that 90% of the estimates produced in the Monte Carlo simulation fall between these values.

Results

Kidney Cancer

The median values for the estimated maximum dose to the kidney among the 12 areas of the assessment domain ranged from 0.06 sieverts in the area 1 to 4 kilometers to the northeast of the site to 0.008 sieverts in the area 7 to 10 kilometers to the northwest. The median estimate for the associated lifetime risk for kidney cancer for the hypothetical individual in the area with the highest estimated maximum kidney dose was 0.00005. This implies that if 100,000 people received the estimated maximum kidney dose of 0.06 sieverts, we would expect 5 additional cases of kidney cancer among this group as a result of this exposure. The estimates of maximum dose to the kidneys resulting from FMPC-radiation exposure tended to be higher for areas close to and east of the site.

For all areas within the assessment domain, we estimated that the median value for the lifetime risk of developing kidney cancer as a result of receiving the maximum FMPC-related radiation dose to the kidney increased by 1% or less over the lifetime risk we would expect if there had been no exposure to site-related radioactive material.

The median estimate for the maximum kidney dose for the hypothetical individual who was assumed to have been exposed to well water contaminated with radioactive material released from the site was 0.07 sieverts (90% credibility interval: 0.02 sieverts to 0.20 sieverts). The corresponding estimated percentage increase in the lifetime for this hypothetical maximally exposed individual was 0.7 %, with a 90% credibility interval of 0.2 % to 4 %.

Female Breast Cancer

The estimated maximum radiation dose to hypothetical females resulting from exposure to radioactive material released from the FMPC site tended to be quite low. Median values for the estimated maximum breast dose range from 0.001 to 0.006 sieverts across the areas of the assessment domain. The upper limits of the 90% credibility intervals for the estimated maximum

breast dose were 0.02 sieverts or less for all areas in the assessment domain. The associated median estimates of the percentage increase in the lifetime risk of developing breast cancer as a result of this maximum FMPC-related dose ranged from a 0.01 % to a 0.1 % increase above the lifetime risk of breast cancer we would expect if there had been no exposure to radioactive material released from the site.

The hypothetical female assumed to have been exposed to well water contaminated with radioactive material released from the site received a median estimated maximum dose of 0.002 sieverts which corresponds to a median estimated 0.03 % increase in her lifetime risk of developing breast cancer.

Bone Cancer

Estimates of the maximum radiation dose to the bone surface resulting from exposure to radioactive material released from the FMPC site were higher than the maximum doses estimated for the kidney, female breast, or bone marrow. Median estimates for the maximum dose to the bone surface ranged from 0.07 sieverts (90% credibility interval: 0.02 sieverts to 0.21 sieverts) in the area 7 to 10 kilometers northwest of the site to 0.49 sieverts (90% credibility interval: 0.16 sieverts to 1.43 sieverts) in the area 1 to 4 kilometers to the northeast. The estimated maximum bone surface doses tended to be higher in areas close to and east of the facility. The highest estimated percentage increase in the lifetime risk of developing bone cancer was a median value of 7% (90% credibility interval: of 1 % to 32 %) for the hypothetical individual in the area 1 to 4 kilometers northeast of the site.

The median estimated maximum dose to the bone surface for a hypothetical person whose exposure to FMPC-related radioactive material included drinking and irrigating with contaminated well water was 0.44 sieverts (90% credibility interval: 0.15 sieverts to 1.35 sieverts). The median estimated percentage increase in the lifetime risk of developing bone cancer for this hypothetical individual was 6% with a 90% credibility interval of 1% to 31%.

Leukemia

The estimated values for the maximum FMPC-related radiation dose to the bone marrow follows a pattern similar to that of the maximum doses to the kidney and bone surface, with higher estimated values for areas closer to the site and to the east. The median estimates for the maximum dose

ranged from 0.01 sieverts to 0.04 sieverts in the areas closest to the site in the northeast and southeast directions. The highest estimated median values for the percentage increase in the lifetime risk of developing leukemia were approximately 3% (90% credibility interval: 1% to 13%). These highest estimates for the percentage increase in the lifetime risk occurred in the areas closest to the site to the northeast and southeast.

The estimated maximum dose to the bone marrow for a hypothetical person exposed to radiation contaminated well water was 0.10 sieverts (90% credibility interval: 0.03 sieverts to 0.30 sieverts). This estimated maximum dose corresponds to an estimated median percentage increase of 6% (90% credibility interval: 1% to 32%) in the lifetime risk of developing leukemia over the lifetime risk.

Upper Bound Estimates of the Total Number of Cancer Cases that may Occur due to Exposure to Radioactive Material Released from the FMPC Site.

We estimated that approximately 46,000 people resided within the assessment domain, that is within 10 kilometers of the FMPC site, for some length of time from 1951 through 1988. By combining our upper bound estimates of the number of cancer cases among those assumed to have been exposed to contaminated well water and among those not assumed to have received this additional source of radiation dose, we developed upper bound estimates for the total number of cancer cases that may occur in the assessment population as a result of exposure to radioactive material released from the site. It is important to remember when evaluating these estimates that they are based on the unrealistic assumption that everyone who ever resided within an area of the assessment domain received the estimated maximum dose associated with that area. Because of this assumption, it is likely that the true number of cases of the cancers addressed in this report that may occur in the assessment population as a result of FMPC-related radiation exposure, will be lower than the presented upper bound estimates. With this limitation in mind, we estimated that 4 or fewer "additional" cases of kidney cancer, 3 or fewer additional cases of female breast cancer, and 4 or fewer additional cases of bone cancer may occur within the assessment population as a result of exposure to radioactive material released from the site during its operating years. We use the term additional when describing these upper bound estimates of the number of potential FMPC-related cancer cases to emphasize that they are in addition to the background number of cases of these types of cancer that we would expect in this population if the FMPC had never existed. In addition, we

estimated that, among these roughly 46,000 people, 23 or fewer additional cases of leukemia may occur as a result of FMPC-related radiation exposure including exposure to contaminated well water. These estimates reflect only the effect of exposure due to living near the site and do not include any additional risk that may be incurred as a result of being employed at the facility.

Recommendations

Based on the results presented in this report, CDC does not recommend a more detailed analysis of the potential risk for kidney cancer, female breast cancer, bone cancer or leukemia in the population as a result of radiation released from the site. However, uranium, and other substances released from the site, have chemical as well as radiological properties. Scientists at the Agency for Toxic Substances and Disease Registry (ATSDR) are currently assessing the risk of cancer and non-cancerous kidney disease resulting from the chemical toxicity of uranium and other contaminants released from the FMPC. CDC has shared data developed as part of our assessment of radiation risk with ATSDR for inclusion in their analysis.

In addition, CDC has used the results of the screening level risk estimation presented here, in combination with the estimates of FMPC-related lung cancer mortality risk developed in the first phase of the Fernald Risk Assessment Project, to evaluate the feasibility of conducting an epidemiologic study in the Fernald community.

Chapter
1

Introduction

History of the Feed Materials Production Center (FMPC)

The former Fernald Feed Materials Production Center (FMPC; now known as the Fernald Environmental Management Project, FEMP) was a Department of Energy (DOE) facility that was part of the United States' nuclear weapons production complex from 1951 through 1988. The FMPC's primary purpose was to produce uranium metal for the United States defense program. A 1000-acre site located about 15 miles northwest of Cincinnati, Ohio (see Figure 2), the FMPC processed uranium ore concentrates and compounds recycled from other stages of nuclear production into either uranium oxides or ingots of uranium metal.

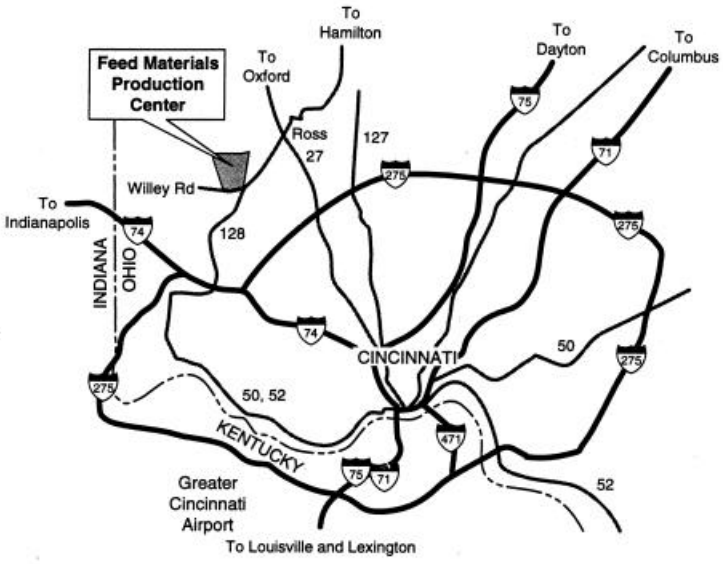

Figure 2. Location of the Former Feed Materials Production Center *(from the Fernald Dosimetry Report (RAC, 1998a))*

These materials were machined into tubular form for reactor fuel cores and target-fuel element fabrication. Production activities at the FMPC ended in 1988. During the FMPC's production years, radioactive material was released from the site into the air during processing, from waste material stored in two large silos (the K-65 silos), and from waste burned in incinerators or buried in waste storage pits. Particulate releases from the FMPC consisted primarily of uranium (natural, depleted, and slightly enriched) and thorium. In addition, the two K-65 silos held waste material that contained very high concentrations of radium. As a result, these silos were a source

for the release of radon and radon decay products. Radioactive liquid waste, primarily water used in the production processes, was also released through run off into sewers and storm drains. Another source of off-site radiation exposure was a contaminated groundwater plume that migrated off the site beginning in the mid 1960s. The radioactive material contained in this plume reached at least three wells to the south of the site after 1967 (Radiological Assessment Corporation, 1998a).

Centers for Disease Control and Prevention (CDC) Involvement

In 1988, the United States Congress requested that the Centers for Disease Control and Prevention's (CDC's) National Center for Environmental Health consider conducting an epidemiologic study of potential associations between the level of radiation exposure and the level of illness in the community surrounding the FMPC. CDC replied that such a study would have little chance of success without adequate estimation of radiation doses in the community and concluded that assessment of the feasibility of such a study was necessary before its initiation. CDC determined that the appropriate first step in assessing potential FMPC-related health effects was to estimate off-site radiation exposure through a dose reconstruction project. In addition, we proposed that a community-based risk assessment was needed in order to evaluate the effect of exposure to radioactive material released from the site on the health of people who lived in the surrounding area. This estimation of the radiation dose and the associated health risks in the affected community is a key step in making a scientifically sound decision concerning the feasibility of conducting an epidemiologic study in the Fernald area.

The Fernald Dosimetry Reconstruction Project

CDC began the Fernald Dosimetry Reconstruction Project in 1990. CDC and its contractor, Radiological Assessments Corporation (RAC), performed a thorough review of historical records and conducted extensive interviews with former and current employees and residents to reconstruct routine plant operations, document unintentional releases, and evaluate unmonitored emission sources. RAC then estimated the amount of radioactive materials released into the air, surface water, and groundwater; developed the methodology and mathematical approaches for modeling how this material moved through the environment; and produced methods for estimating the

radiation dose to specific organs in the body resulting from this exposure. In addition, RAC developed computer software that uses these methods to estimate the FMPC-related radiation dose to a variety of organs for individuals who resided within 10 kilometers (6.2 miles) of the site for any length of time during the plant's production years, 1951-1988 (RAC, 1998b).

The findings of the Fernald Dosimetry Reconstruction Project indicate that radiation exposure to residents of the area surrounding the FMPC was primarily due to the release of radon and radon decay products from the K-65 silos. Radon releases to the air were higher in the 1950s, 1960s, and 1970s. In 1979, structural changes to the silos significantly reduced the amount of radon and radon decay products released. By examining past operations, it was also determined that uranium and, to a lesser extent, thorium and other radionuclides, were also released into the surrounding area during the operating years. The largest releases of uranium occurred in the 1950s and 1960s.

The final report on the dose reconstruction project illustrates that the parts of the body receiving the largest estimated FMPC-related radiation dose were the lung, the bone, the bone marrow, and the kidney (RAC, 1998a). For all exposure situations considered in the report, the estimated dose to the lung resulting from exposure to radon and radon decay products released from the site was significantly higher than the dose from uranium, or any other radionuclide, to the lung or any other body organ.

The Fernald Risk Assessment Project

While the results of the Fernald Dosimetry Reconstruction Project addressed questions concerning the amount of radioactive material released from the FMPC site during its operational years, the project did not provide comprehensive estimates of the potential health effects that may have occurred as a result of these exposures. CDC has addressed these concerns in the Fernald Risk Assessment Project.

The goal of the Fernald Risk Assessment Project was to estimate health risks to people who lived in the area surrounding the former FMPC as a result of exposures to radioactive material released from the site during its years of operation. CDC began the Fernald Risk Assessment Project in response to residents' concerns about these exposures. In addition to providing estimates of the potential health risks associated with past exposure to radioactive material released from the site, project results have been utilized in assessing the feasibility of conducting an epidemiologic study at Fernald. The result may also be used to focus future risk estimation efforts and to aid in the development of other public health activities such as education programs for the public and health care providers.

The Assessment Domain

Figure 3 shows the geographic area, called the assessment domain, used in the Fernald Dosimetry Reconstruction Project and the Fernald Risk Assessment Project. The assessment domain is the area contained in a circle with a radius of 10 kilometers (6.2 miles) the center of which is located in the middle of the FMPC production area. Our goal in the risk assessment project is to estimate the potential health risks associated with exposure to radioactive material released from the FMPC site for people who resided within the assessment domain for any length of time from 1951 through 1988. This group of residents is referred to as the *assessment population*.

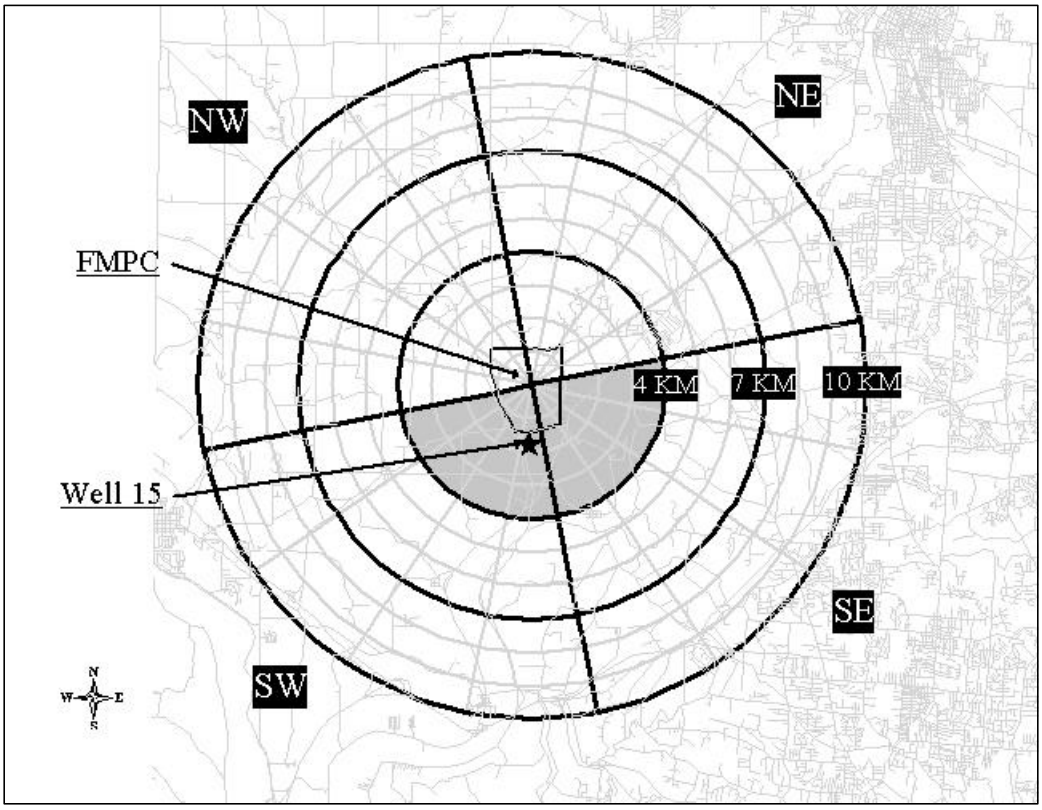

Figure 3. Assessment Domain for the Fernald Risk Assessment Project

To estimate radiation dose and risk to this population, we subdivided the assessment domain into 16 compass directions and within these directions, into 10 distance groups at 1-kilometer increments. Because of this subdivision, the assessment domain consists of 160 small sections, which we refer to as cells. Notice that the group of cells closest to the center of the production areas falls within the boundary of the site. Because the purpose of the Fernald Risk Assessment Project is to address the potential FMPC-related radiation health risks among residents of the surrounding communities and because we can not reliably estimate radiation doses for those exposed within the site's production area using currently available methods, cells that are inside the site boundary were excluded from the risk estimation presented in this report.

To provide a summary of the results of the risk estimation, we combined the 144 off-site cells in the assessment domain into 12 larger geographic areas delineated by the boldface boundaries in Figure 3. These areas were constructed to correspond to four directions from the site (northeast [NE], southeast [SE], southwest [SW] and northwest [NW]) and distance groups of 1 to 4 kilometers, 4 to 7 kilometers, and 7 to 10 kilometers.

Phase I – Lung Cancer

Because the estimated radiation dose to the lung resulting from exposures to radon, uranium, and their decay products released from the site far outweighed the estimated dose to any other organ, the first phase of the our risk assessment project focused on estimating the risk of lung cancer mortality. In December 1998, CDC released a report on the first phase of the Fernald Risk Assessment Project entitled, *Estimation of the Impact of the Former Feed Materials Production Center (FMPC) on Lung Cancer Mortality in the Surrounding Community*. This work provided citizens with a comprehensive assessment of the potential risk of lung cancer mortality associated with the past releases of radioactive materials from the site.

The primary results of Phase I were estimates of the number of lung cancer deaths that may occur among people who were exposed to radioactive material released from the site from 1951 through 1988. Our assessment indicated that the number of lung cancer deaths among the assessment population because of their exposure to radioactive material released from the site during the operating years may be from 1% to 12% higher than it would be if these exposures had not occurred. The estimates of the percentage increase in the number of lung cancer deaths resulting from FMPC-related radiation exposure were intended only to reflect exposure to site-related radioactive material among residents of the surrounding community. As a result, these estimates do not reflect the effects on additional radiation exposures that may have been received by citizens who worked at as well as lived near the site.

The Phase I report showed that the primary cause of the potentially increased lung cancer risk was radon released from the K-65 silos between 1951 and 1988. Because the installation of containment measures to the K-65 silos in 1979 greatly reduced the amount of radon and radon decay products released from the site, the Phase I results indicated that virtually all the estimated increase in lung cancer deaths occurred among those first exposed before 1980.

The final report on the estimated effect of the FMPC on lung cancer mortality in the community is available on CDC's Web site at: www.cdc.gov/nceh/programs/radiation under the Fernald project profile.

Phase II – Screening Level Estimates for the Lifetime Risk of Developing Kidney Cancer, Female Breast Cancer, Bone Cancer, and Leukemia

In consultation with the Fernald Health Effects Subcommittee, an advisory group composed of community residents, health care providers, and local and state officials, we focused Phase II of the Fernald Risk Assessment Project on an evaluation of the risks for selected cancers, other than lung cancer, that may be associated with exposure to radioactive material released from the site. Specifically, this report focuses on the lifetime risk of developing kidney cancer, female breast cancer, bone cancer, and leukemia. These four health outcomes are perceived by the community to be related to past releases of radioactive materials from the FMPC. In addition, biologic and other scientific evidence suggest that these cancers may be associated with the types of radioactive material released from the site from 1951 through 1988.

Differences Between the Phase II Screening Level Cancer Risk Estimates and the Phase I Community Level Estimates of Lung Cancer Mortality Risk

There are several differences between the methods used to produce the organ-specific cancer risk estimates given in this report and the methods used to estimate the lung cancer mortality risks provided in the Phase I report. The main difference is that the estimates given in this report are what we call screening level estimates of the lifetime risk of developing cancer as a result of exposure to radioactive material released from the FMPC site. These values are called screening level to signify that they reflect our estimates of the risk of developing one of the cancers considered in this report sometime during the lifetime of hypothetical individuals who received the ***maximum*** FMPC-related radiation dose. We derived plausible values for these maximum organ-specific doses by making assumptions about the lifestyle characteristics of the hypothetical individuals that increase their exposure to radioactive material released from the site. While these assumptions may, in some cases, be somewhat improbable, for example that all meat consumed by these hypothetical individuals was contaminated with radioactive material, they are not completely unrealistic. As a result, we consider the maximum dose estimates given in this report to be

plausible in that they are likely to be at, or close to, the upper end of the range of organ doses actually incurred by the assessment population as a result of FMPC-radiation exposure.

We estimated the maximum FMPC-related dose in order to estimate the lifetime risk of developing cancer for a person receiving the maximum exposure to radiation released from the site. Therefore, just as with the maximum dose estimates, the estimated lifetime screening level risks are likely to be at, or near, the upper end of the range of FMPC-related cancer risks actually experienced by the assessment population. To aid in interpreting the screening level risk estimates, we also present upper bound estimates for the number of cancers that may occur in the assessment population as a result of exposure to radioactive material released from the site during the operational years. We developed these upper bound case estimates by making the unrealistic assumption that everyone who resided for any length of time in the assessment domain received the estimated maximum dose for their areas within the assessment domain. As a result, the upper bound estimates for the number of FMPC-related cancers presented in this report are likely to be larger than the actual number of these cancers that may occur in the assessment population as a result of their exposure to radioactive material released from the site. In contrast, our goal in the Phase I report was to estimate the range of possible FMPC-related lung cancer mortality risks that *actually* may occur among people who were exposed to radioactive material released from the site from 1951 through 1988. The Phase I risk estimates did not focus on hypothetical individuals but instead tried to reflect the lifestyle characteristics of the exposed population as realistically as possible.

Another difference between the screening-level risk estimates presented in this report and those provided for lung cancer in the Phase I report is that the estimates given in this report reflect the risk of *developing* cancer as opposed to the risk of *cancer induced death*. The risk of dying from lung cancer as a result of FMPC-radiation exposure was given in the Phase I report because the risk of developing and the risk of dying from lung cancer are virtually identical. However, the lifetime risk of developing the cancers we address in this report may be quite different from the associated risk of dying from that cancer. Therefore, in this report, we focus on estimating the lifetime risk of developing cancer among hypothetical individuals who received the estimated maximum FMPC-related radiation dose.

Chapter
2

Selection of the Types of Cancers Addressed in this Report

As noted previously, Phase I of our risk assessment project focused on the relationship between exposure to radioactive material released from the FMPC site and the risk of lung cancer mortality in the surrounding community. The estimated increase in lung cancer risk was primarily due to inhalation of radon and radon decay products emitted from the K-65 silos. Radon and radon decay products are the primary source of the estimated radiation dose to the lung for the assessment population, but contribute very little to the estimated dose to other organs of the body. Therefore, in this report we address the potential effects of exposure to other radionuclides, particularly uranium and to a lesser extent thorium and radium, released from the site during the years of plant operations (RAC, 1998a). The cancer risks addressed in this report are kidney cancer, female breast cancer, bone cancer, and leukemia. Our selection of these health outcomes for inclusion in this screening level risk assessment was based on the following factors:

- A review of the literature to determine what happens to uranium, thorium, and other radionuclides once they enter the body and to identify the organs within the body that are most likely to receive high radiation doses from these exposures.
- A list of community concerns as prioritized by the Fernald Health Effects Subcommittee.
- The biological plausibility of a health outcome and the availability of supporting epidemiological evidence.

Review of Dosimetric and Metabolic Data

As our first step in identifying health outcomes for inclusion in this screening analysis, we reexamined the types of radioactive materials emitted from the FMPC site and the potential routes of exposure (inhalation, ingestion, direct external exposure) to individuals. We then identified the organs and tissue sites in the body ***(other than the lung)*** that most likely received significant radiation doses from these exposures. For example, in considering the uranium isotopes released into the environment from the FMPC, we initially identified a broad list of potential "target" sites that may receive a radiation dose from this exposure. These included the bones, kidneys, gonads (ovaries and testes), liver, and bone marrow. We came up with this initial list using data on the distribution and radioactivity of uranium in the body that results from the intake of naturally occurring uranium in food and water. Uptake of uranium from food and water is the principal source of natural uranium in the general population (NAS, 1988) and represents one route of chronic exposure similar to what has been experienced in the Fernald community. Estimates of annual organ-specific doses from uranium and its decay products have been shown to be higher in these organs or tissues than in others. Moreover, the radiation dose resulting from internal exposure to uranium is highest in the bone, where this radionuclide tends to accumulate (UNSCEAR, 1988). Data from autopsy studies of workers who inhaled uranium dust over a period of at least 10 years also indicate high concentrations of this radionuclide in the bone (NAS, 1988).

We narrowed our initial list of target sites by examining other information on what happens to uranium in the body and how uranium affects organs and tissues. For example, we know that some of the uranium taken into the body is deposited and retained in the kidneys and can cause kidney damage (NAS, 1988). We also know that of the uranium retained in the body, a small percentage is distributed throughout organs and tissues other than the bone and kidney (NCRP, 1998). On the basis of this evidence, we identified bone, bone marrow, and kidney as the most likely sites for further evaluation due to the importance of uranium exposures in the community surrounding the FMPC.

When we reviewed the available information on other radionuclides released from the FMPC site, we found that the radionuclides are also *bone-seekers* and that generally, the dose absorbed by the kidneys and red bone marrow as a result of exposure to these radionuclides tended to be higher than for other organs (UNSCEAR, 1988). As an additional step in our evaluation, we examined the organ-specific doses reported in the Fernald Dose Reconstruction Project Report for a collection of hypothetical exposure scenarios considered in that assessment (RAC, 1998a). In each scenario, the highest doses (other than to the lung) from exposure to uranium, thorium, radium and other radionuclides were estimated to occur in the bone, kidney, and bone marrow. These results support our decision to include screening level estimates of cancer risks that could result from radiation exposure to the organs listed in this report.

Community Concerns

Another component in selecting the outcomes for inclusion in this risk analysis was to review with the Fernald Health Effects Subcommittee the health outcomes that were of concern to the community. In its August 1997 meeting, the Subcommittee recommended to CDC that it "hold in abeyance its evaluation of the feasibility of an epidemiologic study and proceed with evaluation of the risk of diseases of community concerns, such as but not limited to *cancers of the lung, kidney, breast and colon and birth defects* (CDC, August 1997)." After the release of the draft version of CDC's lung cancer risk report in March 1998, we reexamined the list of health outcomes with the Subcommittee to rank them by level of concern and to evaluate the feasibility of conducting a risk analysis of each. On the basis of this discussion, the Subcommittee asked CDC to estimate possible risks for the following health outcomes potentially related to radiation exposure: kidney cancer, leukemia, and female breast cancer (CDC, May 1998).

Biologic Plausibility and Supporting Epidemiological Evidence

Our final step in selecting health outcomes for further analysis involved examining whether an association between the risk of developing a particular type of cancer and exposure to radioactive materials from Fernald was possible based on what is known about human biology, radiation, and cancer induction. In other words, "Was it biologically plausible?" Additionally, we looked at whether existing epidemiologic data from other populations on the relationship between radiation exposure and the occurrence of kidney cancer, breast cancer, bone cancer, and leukemia provided evidence of an increased risk. We also looked at whether sufficient information existed on how lifetime risk of cancers increases with radiation. As we will discuss in Chapter 4, this information on the increase in risk per unit of dose received is an essential component in estimating the lifetime risk of cancer among Fernald area residents.

Biological Plausibility

Given what is (and is not) known about radiation-induced cancer and the radioactive materials released by the FMPC, we believe that the leukemia and cancers of the kidney, breast, and bone are biologically plausible health outcomes. The radionuclides of interest have residence time in both the bone and the kidney, thus providing an opportunity for radiation-induced cellular effects in the bone tissue (including bone marrow) and the filtration and collecting components of kidney tissue. While the breast was not initially identified as a "target" site, breast tissue is quite radio-sensitive, especially in young women (Boice et al., 1996), and a dose to the breast from FMPC-related exposures can be estimated for community residents (RAC, 1998b).

Epidemiologic Evidence

In general, a strong link between radiation exposure and breast cancer, bone cancer, and leukemia has been established from studies in other populations, such at the atomic bomb survivors. Evidence for an association between radiation exposure and kidney cancer has also been reported (Inskip et al, 1990; Cardis et al, 1995; Kleinerman, RA et al, 1995). We reviewed the findings of several epidemiological studies of the effects of exposures to specific radionuclides that appeared

applicable to the Fernald experience. These included studies of occupational exposures to uranium (processing workers/millers) and radium (dial painters) and exposures resulting from medical uses (i.e. Thorium as a contrast agent for medical radiography (Thorotrast), ^{224}Ra injections as a treatment for bone tuberculosis and ankylosing spondylitis and intrauterine, and ^{226}Ra capsules to treat benign gynecologic bleeding disorders). While most studies of male uranium workers have found no evidence of increases in deaths from the cancers of interest, (Archer et al, 1973; Polednak and Frome, 1981; Waxweiler et al, 1983; Dupree et al, 1987; Checkoway et al, 1988; NAS, 1988), scientific review panels caution against over interpretation of these results because these epidemiologic studies were limited in their ability to detect small to moderate increases in risk (NAS, 1988). A recently completed analysis of external radiation exposure and mortality among workers at a uranium processing plant found an excess in kidney cancer deaths and is being further evaluated (Dupree et al, 1998). Studies of radium dial painters, Thorotrast patients, German patients treated with ^{224}Ra injections for bone tuberculosis and ankylosing spondylitis, and women treated for gynecologic bleeding disorders (many of whom were treated with intrauterine ^{226}Ra capsules) provide strong evidence of a relationship between radionuclides similar to those at Fernald (alpha-emitters) and increases in bone cancer and/or leukemia (Boice et al, 1996; NAS, 1988; Inskip et al, 1993). Currently, weaker evidence exists of a link between the radiation effect of these particular types of radionuclides and breast and kidney cancer (Inskip et al, 1990; Boice et al, 1996; NAS, 1988).

To date, information on the relationship between radiation exposure and kidney cancer, breast cancer, bone cancer, and leukemia comes from a compilation of evidence from a variety of populations including atomic bomb survivors, populations exposed to radiation for medical reasons, and occupational groups (Boice et al, 1991; Curtis et al, 1984; Davis et al, 1989; Hoffman et al, 1989; Howe et al., 1996; Inskip et al, 1990; Inskip et al, 1993; Kleinerman et al, 1995; Pierce et al, 1996; Preston et al, 1994; Thompson et al, 1994; Tokunaga et al, 1994; Weiss et al, 1994; Weiss et al, 1995; NAS, 1988; NAS, 1990). These various sources of data, especially data from atomic bomb survivors, have been used by a number of standards-setting organizations and scientific review committees to estimate the lifetime chance of developing or dying from cancer of various types for a unit of radiation exposure (e.g., 1 sievert) (NAS, 1990; UNSCEAR, 1988; ICRP, 1991; Evans et al, 1993; EPA, 1994). These estimates can be used to develop screening level lifetime risk estimates for the Fernald population.

Chapter
3

Definition of Screening Level Estimates of the Lifetime Risk of Developing Cancer

Use of the term ***screening*** in reference to this risk analysis may be confusing. Often, we first hear this term in relation to our health when our health care provider recommends that we get a medical procedure such as a mammogram or another test to find out if we have cancer *before* we experience any symptoms. Or we may see something on television or in print advocating one of these early detection or ***screening*** tests. However, the term ***screening*** has a different meaning when used in terms of radiation dose reconstruction studies and radiation risk estimation. Here, screening refers to procedures designed to allow researchers and the public to understand and rank the importance of specific radionuclides, exposure pathways, and in the case of this risk analysis, develop upper bound, or worst-case estimates for the risk in the population to better target future research efforts.

Screening Level Estimates of the Radiation Dose and Resulting Lifetime Cancer Risk

We define the screening level risk estimates provided in this report as the risk of developing one of the cancers under consideration sometime during the lifetime of a hypothetical individual who received the maximum dose resulting from exposure to radioactive material released from the FMPC site during the years of plant operations. For each of the organs addressed in this report, we estimated the area-specific maximum dose for a hypothetical individual residing in each of the 12 geographic areas illustrated in Figure 3. As will be discussed in the next section, we then used these maximum dose estimates to estimate the lifetime risk of developing cancer for each of these 12 hypothetical individuals.

Because we provide estimates of the lifetime cancer risks for hypothetical individuals receiving the estimated maximum dose, it is likely that the dose and risk estimates presented in this report will be as large or larger than the range of doses and risks actually occurring in the assessment population as a result of FMPC-related radiation exposure. Therefore, when interpreting the results given in this report, one should remember that the purpose of Phase II of the Fernald Risk Assessment Project is to estimate an upper bound for the lifetime FMPC-related cancer risks to community residents, not to provide an assessment of the level of risk that may actually be incurred by all exposed citizens.

Screening Level Risk Estimates are Presented Separately for Individuals Exposed to Well Water Contaminated with FMPC-Related Radioactive Material

The final results of the Fernald Dosimetry Reconstruction Project highlighted the fact that at least three off-site wells to the south of the facility were likely to have been contaminated with radioactive material by the mid 1960s (RAC, 1998a). To account for this additional source of FMPC-related radiation exposure, we developed separate screening level cancer risk estimates for a hypothetical individual who used water from contaminated wells. As with the area-specific risk estimates discussed above, the screening level estimates addressing well water contamination reflect the lifetime risk of developing cancer for a hypothetical individual who received an estimated maximum radiation dose that includes the additional dose resulting from exposure to contaminated well water.

The number of people exposed to contaminated well water is likely to be very small relative to the entire population of the assessment domain. As a result, the risk estimates for a hypothetical person whose maximum dose includes exposure to contaminated well water are unlikely to represent the level of risk in the rest of the assessment population. However, this exposure pathway is of particular interest because the radiation dose to the organs considered in this report may be substantially greater among people who drank and irrigated their gardens with water from contaminated wells.

What Can the Community Learn From the Screening Level Estimates of Lifetime Risk?

The screening level estimates of FMPC-related lifetime cancer risks developed in this report provide the affected community with upper bound estimates of the risks for some cancers that may result from exposure to radioactive material released from the FMPC site during the years of plant operations. By this, we mean that because we have estimated lifetime cancer risks for hypothetical individuals with the *maximum plausible dose*, the actual lifetime risks incurred by people in the assessment population are not likely to be larger than those presented in this report. Therefore, the affected community can evaluate the estimates with the understanding that their own lifetime risk resulting from exposure to radioactive material released from the FMPC is *not* likely to be larger than the screening level estimates presented in this report.

Chapter
4

Methods

This Chapter contains a description of the methods we used to develop the screening level estimates of the lifetime cancer risks and the upper bound estimates of the number of cancer cases that may result from exposure to radiation released from the FMPC site. Because some of this description requires an extensive use of mathematical terms and formulas, we have attempted to explain our approach in two ways. In the text portion of this Chapter, we outline the methods used to make the lifetime risk estimates without relying on mathematical arguments. Throughout the Chapter, however, we have inserted text in boxes that provides a more mathematical explanation of the approach. Readers not wishing to evaluate these mathematical explanations can skip the text contained in these boxes and still obtain a broad understanding of the approach used to develop the screening estimates of lifetime cancer risks and the upper bound estimates of the number of FMPC-related cancers.

For the purposes of this report, we define risk as the probability, or chance, that a person will develop cancer in a specified organ sometime during his or her lifetime as a result of exposure to radioactive material released from the FMPC. Because risk is a probability, it is expressed as a number between zero and one. We present a collection of screening-level estimates of the lifetime risk of developing kidney cancer, female breast cancer, bone cancer, and leukemia as a result of exposure to radioactive material released from the FMPC site from 1951 through 1988. We defined screening level lifetime risk as the risk that a hypothetical individual who received the maximum FMPC-related radiation dose to the organs being considered has of developing cancer in those organs during his or her lifetime. To produce these maximum dose estimates, we considered a collection of hypothetical individuals assumed to have lived in certain locations within the assessment domain for some period of time from 1951 through 1988. We assumed that for this collection of hypothetical individuals had lifestyle characteristics that would increase their estimated FMPC-related radiation dose. (See Figure 1) For example, we assumed that 100% of the vegetables

consumed by these individuals were contaminated with radioactive materials released from the site. We used such worst-case assumptions because the dose and risk estimates presented in this report represent the upper bounds of dose and risk for the assessment rather than the possible range of radiation doses actually received by the exposed population. Therefore, the estimated lifetime risk at the maximum dose, while possible, is likely to be as large or larger than the true risk experienced by persons who actually resided within 10 kilometers (6.2 miles) of the site during the years of plant operations.

Two components are needed to estimate the screening level lifetime cancer risks. First, we need an estimate of the maximum lifetime radiation dose for a collection of hypothetical individuals, one from each of the 12 areas within the assessment domain (see Figure 3) and one for a hypothetical individual assumed to have been exposed to contaminated well water. We report these organ-specific radiation dose estimates in units called sieverts. Once we have an estimate of the maximum dose to each of the hypothetical individuals, we need an estimate of how an average person's risk of developing cancer would increase with the radiation dose he or she received. This value is called the increase in the lifetime risk of developing cancer per unit dose or, in our case, the increase in the lifetime risk of developing cancer per sievert of radiation dose received. The value for this increase in risk per sievert dose comes from studies of other populations that were exposed to radiation. To estimate the hypothetical individuals lifetime risk of developing cancer as a result of radiation exposure received from the FMPC, we multiply the number of sieverts of radiation dose he or she received from the FMPC by the increase in the lifetime risk of developing cancer per sievert dose.

In this section of the report, we describe (1) how we developed estimates of maximum organ-specific doses received by hypothetical individuals as a result of their exposure to radioactive material released from the FMPC site, (2) the estimates we used to describe how a person's lifetime risk of developing cancer increases with each unit of radiation dose received; (3) how we combined these values to estimate a range of possible lifetime risks of developing cancer for the collection of hypothetical individuals, and (4) how we estimated the upper bounds of the number of cancer cases that may occur in the assessment population as a result of their to exposure to radioactive material released from the FMPC site from 1951 through 1988.

Estimating of the Maximum Organ Doses for Hypothetical Individuals in the 12 Areas in the Assessment Domain

The primary product of the Fernald Dosimetry Reconstruction Project was computer software that allows users to estimate organ-specific radiation doses resulting from exposure to radioactive material released from the FMPC from 1951 through 1988 (RAC, 1998b). These dose estimates can be developed for individuals who resided, for any length of time, within 10 kilometers (6.2 miles) of the FMPC site. For the purposes of this report, we used this software to estimate the maximum FMPC-related radiation dose to the kidneys, female breast, bone surface, and bone marrow for a collection of hypothetical individuals. Bone marrow dose estimates were needed to assess the screening-level lifetime risk of developing leukemia. To illustrate how these dose estimates can vary depending on location of residence relative to the site, we estimated the maximum organ-specific doses for 12 hypothetical individuals, one assumed to have resided in each of the areas subdividing the assessment domain shown in Figure 3.

To obtain the area-specific estimates of the maximum dose for each of the organs, we first estimated the maximum plausible organ dose for each of the 144 cells that comprise the off-site portion of the assessment domain. The first step in estimating the maximum cell dose was to produce two tables of dose estimates for each cell, one for female residents and one for males. An example of one of these dose estimate tables is given in Table 1 which contains estimated doses to the kidneys for females who resided in the cell centered 1.5 kilometers northeast of the FMPC site. Each value given in Table 1 is the estimated maximum plausible kidney dose incurred by a hypothetical female who was in the age class given by the column heading during the 5-year time periods given by the row labels. For example, the table shows that the maximum kidney dose received by a female who resided in this cell during 1960-64 and who was five years old at the beginning of that period received a maximum plausible kidney dose of 0.011 sieverts. To estimate the maximum dose incurred by this female during the time period 1960 – 1969 (when she would be between the ages of 5 and 14 years), we would simply add 0.011 sieverts (age class 5-9 years, time period 1960 – 1964)

Table 1. Estimated Maximum 5-Year Cumulative Kidney Dose Equivalent (in Sieverts) for Females who Resided 1.5 Kilometers Northeast of the FMPC Site During Its Years of Operation (1951 through 1988) by Time Period and Age Class of the Female Exposed to Radioactive Material Released from the Site

Time Period	AGE CLASS AT FIRST EXPOSURE (for females)							
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39*
1950 – 1954	0.0016	0.0014	0.0013	0.00067	0.00057	0.00057	0.00055	0.00055
1955 – 1959	0.035**	0.0081	0.0072	0.0051	0.0027	0.0026	0.0025	0.0025
1960 – 1964	0.012	0.011	0.0053	0.0040	0.0025	0.0019	0.0019	0.0018
1965 – 1969	0.0040	0.0041	0.0053	0.0027	0.0020	0.0016	0.0013	0.0013
1970 – 1974	0.0024	0.0021	0.0025	0.0028	0.0016	0.0013	0.0011	0.0010
1975 – 1979	0.0038	0.0016	0.0016	0.0016	0.0016	0.0011	0.00095	0.00086
1980 – 1984	0.00065	0.00096	0.00059	0.00055	0.00054	0.00058	0.00035	0.00030
1985 – 1988	00039	0.00024	0.00042	0.00026	0.00022	0.00023	0.00024	0.00016

* Maximum five-year cumulative kidney doses for those over 40 years of age are equal to the estimates in the 35-39 year old age class.
** Estimated releases of uranium from the FMPC were highest during this time period. In addition, the percentage of this material estimated to be absorbed by the kidneys of persons in this age group is higher than that for other ages.

and 0.0053 sieverts (age class 10-14, time period 1965-1969) for a total of 0.0163 sieverts. If we continued to add additional age- and time period-specific dose estimates from the table to this sum, we would derive an estimate of the maximum lifetime kidney dose for a hypothetical female first exposed to FMPC-related radiation at the age of 5 in the year 1960. Therefore, by specifying the age-class and time period of first exposure, we can add up the age- and time period-specific dose estimates contained in the table to estimate the maximum lifetime kidney dose for any female who lived in this cell for any length of time between 1951 and 1988. To estimate a plausible value for the maximum lifetime kidney dose for any woman who resided in the cell, we calculated a collection of lifetime dose estimates defined by all the various combinations of age and year of first exposure groups that are possible from the dose estimate table. The maximum dose estimate for a female for the cell was then defined as the largest value obtained for this collection of possible

maximum lifetime doses. This value represents our estimate for the maximum dose among all females who resided in the cell for any length of time from 1951 and 1988.

We used a similar approach to calculate the estimated maximum dose among all males who resided within each cell for any length of time from 1951 through 1988. The estimated maximum lifetime dose for each organ for each cell was then defined as the greater of the maximum dose estimates for females and males. When estimating the maximum plausible dose to the female breast for each cell, we based the maximum dose estimate on the collection of possible values for the maximum lifetime dose among females only.

Once we estimated the maximum lifetime dose to each organ for each of the 144 cells, we next estimated the maximum dose for each of the 12 areas of the assessment domain illustrated in Figure 3. For each organ, we defined the maximum dose estimate for a hypothetical individual who resided in one of the 12 areas for any length of time from 1951 through 1988 as the largest of the maximum dose estimates among all the cells contained in that area. For ease of reference, we refer to this collection of 12 maximum dose estimates for each of the organs as the nominal maximum dose estimates. Therefore, a set of 12 nominal maximum dose estimates, one for each of the areas subdividing the assessment domain, was calculated for each of the organs considered in this report

The value of the nominal maximum dose estimates for a hypothetical individual residing in each of the areas depends on the distance and direction of the area relative to the site and on assumed characteristics of the individual, such as age at first exposure, source of vegetables consumed, and the origin of his or her water supply. To produce the maximum dose estimates, we had to make similar assumptions for each of the geographic areas. A list of the assumptions used to derive the dose estimates for the 12 hypothetical individuals in this risk estimation is given in Table 2 and a summary of the assumptions is provided in Figure 1. As previously stated, we geared the assumptions to make the organ-specific dose estimates as large as possible. For example, we assumed that all vegetables consumed came from gardens irrigated with water contaminated with radioactive material released from the site. We also assumed that the source of contaminated water used for irrigation purposes, among those who did not obtained their water from a contaminated well, was Paddy's Run Creek. While this assumption about the source of the water supply is probably unrealistic for the entire assessment domain, because of the relatively high concentration of radioactive material in the creek (RAC, 1998a), it is consistent with our attempt to produce plausible estimates for the maximum lifetime organ-specific doses.

Table 2. Assumed Lifestyle Characteristics Used to Estimate the Maximum FMPC-Related Radiation Dose for Hypothetical Individuals Residing in 12 Geographic Areas of the Assessment Domain Who Did Not Use Contaminated Well Water and for a Hypothetical Individual Who Did Use Contaminated Well Water

Lifestyle Characteristics	ASSUMED VALUES FOR:	
	Twelve Hypothetical Individuals Who Did Not Use Contaminated Well Water	A Hypothetical Individual Who Did Use Contaminated Well Water
Duration of exposure	1951 through 1988	1951 through 1988 *
Location of residence	Center of cell	Center of cell
Location of school	Center of cell	Center of cell
Location of workplace	Center of cell	Center of cell
Percentage of time spent indoors	33 %	33 %
Percentage of time spent outdoors	67 %	67 %
Contaminated drinking water source	None	Well 15 *
Contaminated irrigation water source	Paddy's Run Creek	Well 15 **
Percentage of vegetables consumed that are contaminated	100 %	100 %
Percentage of milk consumed that is contaminated	100 %	100 %

Table 2, Cont'd

Assumed Lifestyle Characteristics Used to Estimate the Maximum FMPC-Related Radiation Dose for Hypothetical Individuals Residing in 12 Geographic Areas of the Assessment Domain Who Did Not Use Contaminated Well Water and for a Hypothetical Individual Who Did Use Contaminated Well Water

Lifestyle Characteristics	ASSUMED VALUES FOR:	
	Twelve Hypothetical Individuals Who Did Not Use Contaminated Well Water	A Hypothetical Individual Who Did Use Contaminated Well Water
Percentage of beef, poultry, eggs, and fish consumed that is contaminated	100 %	100 %
Contaminated water source for fish	Great Miami River	Great Miami River
Percentage of time spent swimming	2 %	2 %
Location of swimming	Great Miami River	Great Miami River
Amount of soil ingested per day	0.5 grams	0.5 grams

* Well 15 was assumed to be contaminated with radioactive material released from the FMPC site from 1965 through 1988.

** Prior to 1965, the source of contaminated irrigation water for this hypothetical individual was assumed to be Paddy's Run Creek.

Estimating the Uncertainty Associated with the Maximum Dose

We produced the nominal maximum dose estimates discussed above using a variety of mathematical models developed in the Fernald Dosimetry Reconstruction Project (RAC, 1998a). These mathematical models were designed to mimic the ways by which radioactive materials were released from the site, transported through the air and water to various parts of the assessment domain, and absorbed into the specified human organs. Because actual measurements of these components of the dose estimation process are not feasible, we do not have precise information on which to base the estimates of the maximum dose. Therefore, we cannot estimate the maximum dose (or for that matter the actual dose) to any person, or group of persons, with absolute certainty. To reflect this lack of precise knowledge, the estimates of the maximum dose given in this report are uncertain and this uncertainty concerning the true value of the maximum dose must be addressed (NCRP, 1997).

We describe the uncertainty associated with the maximum dose estimates using a technique called Monte Carlo simulation (Vose, 1996). In the Monte Carlo approach, we repeatedly estimate possible values for the maximum dose for each area. Within each repetition of the estimation process, a new possible value for the maximum dose is produced. The range of the resulting collection of possible values for the maximum dose reflects our uncertainty about the components of the dose estimation process. This process of repeatedly estimating possible values of the maximum dose for a hypothetical individual was carried out until we obtained 5,000 possible values for the maximum dose for each organ and for each of the 12 areas. We summarized the collection of possible values for the uncertain true maximum dose within each area using the median value and a range called the 90% credibility interval. The median is that value greater than half of the estimates produced in the Monte Carlo simulations and less than the other half. The 90% credibility interval provides a measure of the range of possible values for the true maximum dose. The interval is defined so that 90% of the estimates for maximum dose produced in the Monte Carlo simulation fall between the upper and lower values. This means that 5% of the possible values fall below this range and 5% of the possible values fall above the range.

Estimating the Uncertainty Associated with the Maximum Radiation Dose for Hypothetical Individuals within the Assessment Domain

A great deal of emphasis was placed on modeling the uncertainty associated with the organ-specific dose estimates in the Fernald Dosimetry Reconstruction Project (RAC, 1998a). This modeling was accomplished using a complex Monte Carlo algorithm that produced a range of possible values for the estimates that reflected the uncertainty in the components of the dose estimation process. The estimates of the maximum FMPC-related dose for each organ that we call the nominal estimates of maximum dose, however, were produced by setting each uncertain input parameter in the dose estimation algorithm to its median value. In general, these nominal maximum dose estimates should be quite close to the median value for a set of possible maximum doses that would be produced using the full Monte Carlo approach (Devine et al, 1998). Due to computational constraints resulting from both the structure of the dose reconstruction computer software and the number of age and time period of exposure combinations that need to be considered when estimating the maximum dose, we could not simply extend the dose reconstruction Monte Carlo process to produce multiple possible values for the maximum organ doses. As an alternative, we chose to model the level of uncertainty that is likely to be associated with the nominal maximum dose estimates.

We assumed that the uncertainty associated with the maximum organ-specific dose estimates for a hypothetical individual within each 12 areas that comprise the assessment domain could be described using the mathematical model

$$D_i^j \; ? \; D_i \; * \; K^j \qquad .$$

In this equation, D_i is the nominal maximum dose estimate associated with area i where i = 1, 2, 3, … 12. The value K^j in the equation is what we will call the uncertainty factor and D_i^j is the possible value for the true maximum dose produced in the jth repetition of the Monte Carlo simulation process. To develop each D_i^j, we multiplied the nominal maximum dose estimate by an uncertainty factor specific to that repetition. Therefore, since 5,000 possible values for the true maximum dose were generated in the Monte Carlo process, 5,000 values of K were also used. For each repetition of the Monte Carlo simulation, a random value for K was generated by assuming that the natural log of K follows a normal distribution with mean zero and variance of 0.45. The value for the mean was selected so that the median of K would be close to one. We desire the median value of K to be close to one so that the collection of generated possible values for the maximum dose will have a median value that is close to the nominal maximum dose estimate. The assumed variance was set so that the ratio of the 95th percentile to the 5th percentile of the range of values produced in the Monte Carlo process would be roughly 3. We wanted this ratio to roughly equal 3 to be consistent with the uncertainty ranges reported for organ-specific dose estimates given for a collection of hypothetical exposure scenarios in the Fernald Dosimetry Reconstruction Report (RAC, 1998a).

We used a constant uncertainty factor for each repetition of estimating the collection of maximum doses in the Monte Carlo process to preserve the correlation structure among the uncertainties for the collection of 12 area-specific maximum dose estimates (Devine et al, 1998). Sampling a common uncertainty factor and then generating a collection of 12 area-specific maximum dose estimates was repeated for each of the 5,000 repetitions of the Monte Carlo process.

Estimating the Maximum Organ Dose for a Hypothetical Individual Exposed to Contaminated Well Water

Some off-site wells, located to the south of the FMPC facility, were identified in the Fernald Dosimetry Reconstruction Project as being contaminated with uranium beginning in the mid to late 1960s (RAC, 1998a). Due to this additional source of contamination, we would expect that people using these wells would have received larger organ-specific radiation doses than those residents of the same area who did not. However, the ground water plume carrying this contamination affected a relatively small portion of the assessment population. To address this important pathway and yet reflect the relatively small number of people affected, we produced separate estimates of the maximum organ doses for a hypothetical individual exposed to contaminated well water.

In the dose reconstruction project, a well referred to as Well 15 was identified as having the highest measured concentrations of radioactive contaminants among private off-site wells (RAC, 1998a). As a result, we used the contamination levels estimated for this well to derive the estimates of the maximum dose for a hypothetical person exposed to well water contaminated with radioactive material. The location of Well 15 is illustrated with a star symbol in Figure 3.

We estimated the maximum dose for the hypothetical person who used contaminated well water for the other hypothetical residents of the assessment domain. However, in estimating maximum dose that included exposure to contaminated well water, we assumed that the hypothetical individual resided within the geographic cell that contained Well 15. In addition, we assumed that the hypothetical person drank and irrigated with water obtained from the well. On the basis of the results of the Fernald Dosimetry Reconstruction Project (RAC, 1998a), we assumed that the well was contaminated with radioactive material from 1965 onward. The assumptions on the lifestyle characteristics of the hypothetical individual assumed to have maximum exposure to radioactive material released from the site, including exposure to contaminated well water, are listed in the third column of Table 2. Note that, except for the source of drinking water and water used for irrigation, the assumptions for the hypothetical person assumed to have been exposed to contaminated well water are the same as those for the 12 hypothetical individuals not assumed to have been so exposed.

We estimated the uncertainty concerning the maximum organ-specific dose for the hypothetical individual who was exposed to contaminated well water using a Monte Carlo process identical to that used to describe the uncertainty in the maximum dose estimates for the 12 areas in the domain. Thus, we produced 5,000 possible values for the maximum organ-specific doses for the hypothetical individual who was exposed to water from a contaminated well.

Estimating the Increase in the Lifetime Risk of Developing Cancer per Sievert of Radiation Dose Received

Estimates of the increase in the lifetime risk of dying from or developing various types of cancer per sievert of radiation dose received have been developed by a number of expert committees and organizations (NAS, 1990; ICRP, 1991; NCRP, 1993; Evans et al., 1993; EPA, 1993; Puskin and Nelson, 1995; UNSCEAR, 1988). These estimates are primarily based on epidemiologic studies of Japanese populations exposed as a result of the nuclear bombings of Hiroshima and Nagasaki and, to a lesser extent, on studies of other human populations exposed to ionizing radiation. The results of these epidemiologic studies have been used, for example, by the International Council for Radiation Protection (ICRP) and the National Council for Radiation Protection and Measurements (NCRP), to produce estimates of the increase in the lifetime risk of dying from cancer per sievert dose.

To be consistent with both common practice in radiation protection and with previous risk estimation activities related to FMPC-related exposure (RAC, 1998a), when possible we used values for the increase in the lifetime risk per sievert dose derived by the ICRP (ICRP, 1991) and supported by the NCRP (NCRP, 1993) to develop our screening level estimates of FMPC-related risk. However, we adjusted the ICRP's estimated increase in the risk for bone cancer per unit dose to reflect the fact that the our bone dose estimates are for radiation dose to the bone surface rather than an average dose to the entire skeleton (Puskin and Nelson, 1995; Evans et al, 1993; Puskin, Nelson and Nelson, 1992). In addition, the ICRP did not specifically estimate the increase in the kidney cancer risk per sievert of radiation dose received. However, the Environmental Protection Agency (EPA) (EPA, 1994; Puskin and Nelson, 1995) has presented an estimate for the increase in the kidney cancer risk per unit dose that is consistent with earlier estimates of kidney cancer risk related to FMPC radiation exposure (RAC, 1998a). Therefore, we used the EPA estimate in our assessment. We also used an EPA estimate for the increase in the risk of dying from breast cancer

per unit dose in our assessment as opposed to that value for breast cancer reported by the ICRP (Puskin and Nelson, 1995; EPA, 1994). We used this estimate for two reasons. First, the EPA derived the estimate using the cancer experience resulting from radiation exposure in a North American population as opposed to a Japanese population. As a result, their estimate is likely to be more appropriate for the population surrounding the FMPC site. In addition, their estimate is somewhat greater than the ICRP's, and, because our goal was to develop plausible maximum values for FMPC-related risk, we deemed it appropriate to use this larger value. These values for the increase in the risk of dying from cancer per sievert of dose received are listed in the second column of Table 3.

To meet the goals of our risk estimation, we had to modify the estimates given in the second column of Table 3 to reflect the probability of developing, as opposed to dying from, a radiation-induced cancer. We made this adjustment from mortality risk to cancer occurrence risk using a value called the lethality fraction. This number is an estimate of the proportion of the people who develop the particular cancer who will eventually die as a direct result of that cancer. The lethality fraction estimates used in this report were developed by the ICRP (ICRP, 1991) and are listed in the third column of Table 3. Using these values, the estimates for increase in the risk of developing cancer in a specific organ per sievert of dose received that we used to estimate FMPC-related risk were obtained by dividing the increase in risk of mortality per unit dose estimates by the organ-specific lethality fraction.

Table 3. Values for Increase in the Risk of Dying from Specified Cancers per Sievert of Radiation Dose Received, Lethality Fractions*, and the Increase in the Lifetime Risks of Developing Cancer per Sievert of Radiation Dose Received that are Used to Estimate FMPC-Related Cancer Risks

Cancer Type	Increase in the Lifetime Risk of Dying from the Cancer per Sievert of Radiation Dose Received (x 10,000)	Estimated Lethality Fraction[###]	Increase in the Lifetime Risk of Developing Cancer per Sievert of Radiation Dose Received (x 10,000)[**]	
			Median[+]	(90% (Credibility Interval) [++]
Kidney Cancer	5.5[#]	0.65	8.4[@]	(2.8 - 24.8)
Female Breast Cancer	92[#]	0.50	186	(62 - 554)
Bone Cancer	0.7[##]	0.70	.99	(0.32 – 3.0)
Leukemia	50[###]	0.99	51	(17, 151)

* The lethality fraction is an estimate of the proportion of people who develop a specified type of cancer and will eventually die from it.

** Summarizes the range of uncertain values for the increase in the risk of developing cancer per sievert of dose that will be multiplied by the maximum dose estimates in Tables 6, 8, 10, and 12 to estimate the lifetime risk of selected cancers due to IMPC-related radiation exposure.

[###] ICRP (1991)

[+] We produced 5,000[+] possible values for the increase in the risk of developing cancer per sievert of radiation dose received were produced to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

[++] 90% of the 5,000 generated values for the increase in the risk of developing cancer per sievert dose fall between the upper and lower limits of the 90% credibility interval.

[#] EPA (1994)

[@] This estimate implies that if 10,000 people received 1 seivert of radiation dose, (for example, to the kidney), we would estimate that 8.4 (or 8) of them would develop kidney cancer due to this dose.

[##] The ICRP reported increase in the risk of dying from bone cancer per sievert dose received of 5×10^{-4} (ICRP, 1991). We divided this number by 7.5 to reflect the fact that we used estimates of radiation to the bone surface rather than the average radiation dose to the entire bone (Puskin, Nelson, and Nelson, 1995).

Just as we are uncertain about the true value of the maximum dose in each of the areas, we are also uncertain about the true values of the increase in risk of developing cancer per unit dose. The estimates given in Table 3 are subject to the statistical variation one would expect in estimates derived from epidemiologic studies of human populations. In addition, there is uncertainty concerning the use of risk estimates developed in studies of populations who received high radiation doses at a high rate, for example due to the explosion of a nuclear device, to estimate the risk in populations exposed to lower amounts of radiation over a longer period of time. Another source of uncertainty is possible differences in characteristics, for example dietary habits, between the populations in which estimates of the increase in risk per unit dose were developed and the population for which we wished to estimate risk. A committee of the NCRP has addressed these sources of uncertainty by estimating a range of possible values for the increase per sievert in the lifetime risk of dying of any radiation induced cancer (NCRP, 1997). The ratio of the 95th percentile to the median value of these possible estimates was about 2.5 to 3. To model the uncertainty in the values of the increase in lifetime risk of developing a cancer per sievert dose, we used a Monte Carlo process similar to that used to model the uncertainty in the estimated maximum doses. Using this process, we produced a collection of 5,000 possible values for the increase in risk per unit dose for each of the cancers addressed in this report. To mirror the uncertainty in the estimated risk of death due to any cancer, we developed this Monte Carlo process so the ratio of the 95th percentile to the median of the possible values of the increase in cancer risk per sievert was approximately 3. We again used the median values and the 90% credibility interval to summarize the collection of 5,000 possible values for the increase in the lifetime risk of developing the cancers in this report per sievert of FMPC-related radiation dose. These medians and intervals are listed in the last column of Table 3. Notice that the median value for the collection of increase in risk per unit dose values is quite close to the value obtained by dividing the ICRP and EPA estimates of the increase in risk of dying per sievert of dose by the estimated lethality fractions.

Modeling the Uncertainty in the Increase in the Lifetime Risk of Developing a Radiation Induced Cancer per Sievert of Dose Received.

Let *IR* be the increase in cancer risk per sievert dose received for one of the organs listed in Table 3. For the *j*th repetition of the Monte Carlo process, we generate a possible value of the true increase in risk per sievert dose as

$$IR^j \; ? \; IR * M^j$$

where IR^j is the possible value for the true increase in risk per sievert dose and M^j is an uncertainty factor designed to reflect our lack of knowledge. The NCRP conducted an analysis of the uncertainty likely to be associated with the general application of Japanese atomic bomb survivor data to estimating the increase in the lifetime risk of dying from any radiation induced cancer per sievert of whole body dose (NCRP, 1997). In this analysis, the NCRP estimated a range up to about 3 between the 95th percentile and the median of the distribution of possible values for the increase in risk per unit dose. To be consistent with this estimate, we assume that the uncertainty associated with the increase in the lifetime risk of cancer per sievert dose for the estimates shown in Table 3 is of similar magnitude. To reflect this assumption, we generated 5,000 values for *M* by assuming that the natural log of *M* follows a normal distribution with mean zero and variance 0.45. The values for *M* used in each repetition of the Monte Carlo uncertainty process were generated independently for each of the organ-specific estimates of the increase in risk per sievert. For each organ, within each repetition, the ratio of the increase in the risk of cancer death per sievert and the lethality fraction provided in Table 3 was multiplied by the generated value for *M* to produce a possible realization for the true organ-specific increase in the lifetime risk of developing cancer per sievert of radiation dose.

Estimating the Lifetime Risk of Developing Cancer for a Hypothetical Individual Receiving the Maximum Dose Within each of the 12 Areas of the Assessment Domain

Five thousand possible values for the lifetime risk of developing kidney cancer, breast cancer, bone cancer, and leukemia were developed by multiplying each of the possible values for the maximum area-specific organ dose by a generated possible value for the increase in the lifetime risk of developing that cancer per sievert of radiation dose received. The resulting collection of estimates reflects the lifetime risk of developing cancer for a group of hypothetical individuals each receiving the maximum dose in a given area of the assessment domain. For each organ and area, we used the median value and the 90% credibility interval to summarize this range of possible values for lifetime risk at the maximum dose.

We also developed possible values for the lifetime risk of developing cancer in each organ considered for the hypothetical individual assumed to have been exposed to contaminated well water. These risk estimates were derived in the same manner as those for the maximally exposed individuals in each of the 12 areas except that the maximum dose estimate for each organ included the dose resulting from drinking and irrigating with contaminated well water.

Estimating the Increase in Lifetime Risk of Developing Cancer for a Hypothetical Individual Receiving the Maximum FMPC-Related Radiation Dose

Let D_i^j be the possible value for the maximum dose for one of the organs being considered generated for a hypothetical person who resided in area *i*, where *i* = 1, 2, 3, …12, for the *j*th repetition of the Monte Carlo process. In addition, we will assume that IR^j is the possible value for the increase in lifetime risk of developing cancer in that organ per sievert of radiation dose. The superscript *j* associated with the increase in risk per unit dose again designates that value as being the realization generated in the *j*th repetition of the Monte Carlo process. The *j*th realization for the lifetime risk of developing the cancer of interest, which we will designate as LR_i^j is then estimated as

$$LR_i^j \; ? \; D_i^j * IR^j \qquad .$$

Because we have 5,000 realizations for the possible values of the 12 area-specific maximum doses and 5,000 realizations for the increase in the lifetime risk of developing cancer per sievert, we produced 5,000 possible values for the estimated lifetime risk of developing the cancer for hypothetical persons who received the maximum dose in each of the 12 areas. For each organ and area, this range of possible values for lifetime risk at the maximum dose is summarized using the median value and the 90% credibility interval.

Estimates of the lifetime risks of developing cancer for a hypothetical individual receiving the maximum radiation dose who was exposed to contaminated well water were developed in an identical manner to the estimates for the hypothetical persons who were not exposed to well water.

Estimating the Percentage Increase in the Background Lifetime Risk of Developing Cancer due to Radiation Exposure from the FMPC

Although the screening level estimates of the lifetime risk of developing cancer for hypothetical individuals having the estimated maximum FMPC-related radiation dose provide a measure of the potential upper bound for the effects of these exposures, the percentage increase in the lifetime risk of developing cancer over that which would be expected in the absence of FMPC exposures is perhaps more meaningful. The percentage increase in the lifetime risk for an individual receiving the maximum dose is defined as the lifetime risk resulting from FMPC radiation exposure divided by the background lifetime risk of developing the cancer times 100.

The background risk is the lifetime risk of developing cancer that would occur in the absence of any radiation exposure from the FMPC. The estimates of the lifetime background risk of developing the cancers addressed in this report are listed in Table 4. We developed these estimates using a life table modeling approach developed by the National Cancer Institute (Feuer and Wun, 1996). The estimates are based on information on cancer occurrence among segments of the U.S. population collected in the Surveillance, Epidemiology and End Results (SEER) Program (NCI, 1998), on mortality data from the National Center for Health Statistics (NCHS, 1981-83), and on population estimates from the Bureau of the Census (Bureau of the Census, 1981-83).

Table 4. Estimates of the Background* Lifetime Risk of Developing Selected Cancers Used in the Report

Type of Cancer	Background Lifetime Risk@
Kidney	0.008
Breast	0.1
Bone	0.0007
Leukemia	0.008 **

* For the purposes of this report, we considered the background risk to be the average risk of developing one of the cancers considered sometime during a person's lifetime if that person was not exposed to radioactive materials released from the FMPC site

@ Background risk values are based on data from 1981-1983.

** The background risk estimate for leukemia excludes chronic lymphocytic leukemia. We exclude this type of leukemia because studies of populations exposed to radiation have not shown a relationship between this exposure and the risk of developing this type of leukemia.

Estimating the Percentage Increase in the Lifetime Risk of Developing Cancer for a Hypothetical Individual Exposed to the Maximum FMPC-Related Radiation Dose

Let *BR* be the background lifetime risk of developing kidney, breast, or bone cancer or the background lifetime risk of developing leukemia. By background lifetime risk, we mean an average person's lifetime risk of developing that cancer if there had been no exposure to radiation released from the FMPC. The estimated percentage increase in the hypothetical individual's risk of developing the cancer in area *i* of the assessment domain was calculated as

$$PI_i^j \; ? \; \frac{LR_i^j}{BR} * 100 \quad .$$

In the above equation, PI_i^j represents the estimated percentage increase in the lifetime risk of developing the cancer for the hypothetical individual in area *i*, *i* = 1, 2, …12, who received the maximum radiation dose to the organ of interest. As stated previously, LR_i^j is the estimated increase in that hypothetical individual's lifetime risk of developing cancer resulting from FMPC-related radiation exposure. Notice that both PI_i^j and LR_i^j have superscripts corresponding to the *j*th repetition of the Monte Carlo process. Just as with the estimates of the increase in the lifetime risk of developing cancer among hypothetical individuals receiving the maximum dose, the estimated percentage increase in the lifetime risk over the background is uncertain. To reflect this uncertainty, 5,000 possible values for the percentage increase in lifetime risk of developing cancer for hypothetical individuals receiving the maximum FMPC-related radiation dose were produced in the Monte Carlo process. Again, the uncertainty concerning the percentage increase estimates will be summarized by presenting the median and 90% credibility interval.

We estimated the median and 90% credibility interval for the percentage increase in the lifetime risk for a hypothetical individual receiving the maximum dose who was assumed to be exposed to contaminated well water in exactly the same way as was done for those not exposed to contaminated well water.

Estimating an Upper Bound for the Number of Cancer Cases that May Result from Exposure to Radionuclides Released from the FMPC from 1951 through 1988

To further interpret the estimates of the screening level lifetime cancer risks given in this report, we developed what we call upper bound estimates for the number of cancer cases that may result from the FMPC-related radiation exposures addressed in this report. By an upper bound estimate, we mean the maximum number of cancer cases that may result given our screening level risk estimates. To get these upper bound estimates, we made the unrealistic assumption that everyone who resided within any of the 12 geographic areas for any length of time between 1951 and 1988 received the estimated maximum organ dose for that area. This assumption is unrealistic because it is not likely that all individuals who resided in a given area for any length of time during this period received the estimated maximum dose. By making this unrealistic assumption, however, we obtain an estimated number of cancer cases that is very likely to be larger than the actual number of cancers that may result from FMPC-related radiation exposure.

The first step in deriving these upper bound risk estimates is to estimate the number of people who resided within each of the areas of the assessment domain for any length of time from 1951 through 1988. As part of the assessment of the risk of lung cancer mortality associated with radiation exposure to the communities surrounding the FMCP, we developed estimates of the number of persons who resided, for any length of time from 1951 through 1988, in each of the 12 areas making up the assessment domain (Devine et al, 1998). Because we could not actually count the number of people within each area, these population estimates are uncertain. The population estimates used in this report are based on those developed earlier (Devine et al, 1998) and incorporate this uncertainty. Again, we summarized the uncertainty associated with the population estimates using median values and 90% credibility intervals. These medians and intervals for the estimated number of persons who resided within the 12 areas for any length of time during the plant's operational years are given in Table 5.

Table 5. Estimated Number of People Who Resided for any Length of Time From 1951 through 1988 within the 12 Areas of the Assessment Domain

DIRECTION FROM THE SITE	DISTANCE FROM THE SITE (kilometers)	ESTIMATED NUMBER OF RESIDENTS #	
		Median*	(90% Credibility Interval)**
Northeast	**1 – 4**	4,409	(2,685 – 7,356)
	4 – 7	3,799	(2,350 – 6,213)
	7 – 10	2,870	(1,750 – 4,689)
Southeast	**1 – 4**	896	(555 – 1,466)
	4 – 7	3,499	(2,150 – 5,685)
	7 – 10	8,038	(4,897 – 13,087)
Southwest	**1 – 4**	1,357	(829 – 2,205)
	4 – 7	2,202	(1,349 – 3,597)
	7 – 10	5,528	(3,372 – 9,054)
Northwest	**1 – 4**	834	(508 – 1,370)
	4 – 7	3,757	(2,307 – 6,148)
	7 – 10	6,946	(4,263 – 11,360)
Total	---	45,909***	(38,896 – 54,343)

We assume that one half of the population are women.

* We produced 5 ,000 possible values for the number of residents per area and the total number of residents in the assessment domain in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates for the number of residents fall between the upper and lower limits of the 90% credibility interval.

*** Because of the Monte Carlo approach used to model uncertainty, the median value for the total population estimate will not necessarily equal the sum of the median population estimates for each of the areas.

The upper bound estimates for the number of cancer cases associated with exposure to radioactive material released from the FMPC were developed by multiplying the estimated lifetime risk for each area in the assessment domain by the estimated number of people who resided in that area as listed in Table 5. Again, it should be noted that this implies, incorrectly, that everyone who resided in the area for any length of time from 1951 through 1988 received the maximum dose. Because both the estimated values for the lifetime risk of developing cancer and for the number of residents per area are uncertain, the estimated upper bound for the number of cancer cases is also uncertain. We produced 5,000 possible values for this upper bound estimate using the Monte Carlo approach for each of the areas within the assessment domain

Upper bound estimates for the total number of cancer cases in the assessment domain resulting from exposure to radioactive material released from the FMCP site were obtained by summing the area-specific upper bound estimates. This sum represents an upper bound estimate for the total number of cancer cases that may occur within the assessment domain if everyone who resided in each of the areas received the same dose as the hypothetical maximally exposed individual. Because the area-specific upper bound estimates are uncertain, their sum is also uncertain. The uncertainty associated with the upper bound estimates for the total number of cancers within the assessment domain is summarized using the median and the 90% credibility interval.

Estimates of the upper bound number of cases among those exposed to contaminated well water were produced by multiplying the estimated lifetime risk for the hypothetical person assumed to have had this additional source of radiation exposure by the sum of the number of people estimated to have resided in areas 1 to 4 kilometers from the site in both the southeast and southwest directions. These areas are highlighted in the map of the assessment domain shown in Figure 3. It is highly unlikely that all residents of these two areas were exposed to contaminated well water or that those who were exposed received the maximum dose estimated for the hypothetical individuals who had this exposure. We assumed that everyone in these two areas received the maximum dose in order to produce an estimate of the number of cancer cases resulting from this exposure that is likely to be larger than the true number of FMPC-related cancer cases that may occur among residents of the assessment domain exposed to contaminated well water.

For the purposes of comparison, we also estimated the expected background number of cases for each of the cancers considered. These estimates reflect the number of cases of kidney cancer, female breast cancer, bone cancer, and leukemia we might expect to occur among the populations of each of the areas within the assessment domain if there had been no exposure to radioactive materials released from the FMPC site. These background estimates were obtained by multiplying the cancer-specific background lifetime risk estimates, given in Table 4, by the estimated number of residents within each of the areas. The total number of expected background cancer cases in the assessment domain was estimated by summing the area-specific background estimates. Because the estimated population size within each area is uncertain, so is the estimated background number of cancer cases. As with the other uncertain values, the uncertainty associated with the estimated background number of cancer cases is summarized by using median values and 90% credibility intervals.

The background number of cancer cases among people assumed to have been exposed to contaminated well water was obtained by multiplying the lifetime background cancer risks in Table 4 by the sum of the estimated populations in the two areas 1 to 4 kilometers from the site in the southeast and southwest directions.

Estimating of the Upper Bounds for Number of Cancer Cases Related to the Release of Radioactive Material from the FMPC from 1951 through 1988

To develop the upper bound estimates for the number of cancer cases in each of the areas, we first had to estimate the number of people who resided in each area for any length of time from 1951 though 1988. A previous set of estimates for these area-specific population sizes and their associated uncertainties were developed in Phase I of the Fernald Risk Assessment Project (Devine et al, 1998). By examining these estimates, we determined that the ratio of the 95th percentile of the range of possible population sizes to the median value was about 1.2 for each of the 12 areas within the assessment domain. Therefore, 5,000 possible values for the population size of each of the areas were generated using the equation

$$P_i^j \; ? \; P_i * Q_i^j \qquad .$$

In this equation, P_i is the median value for the population in area i, i = 1, 2, 12 produced in the Phase I Report and P_i^j represents the possible value for the number of residents in area i generated in the jth repetition of the Monte Carlo process. The uncertainty factor, Q_i, was assumed to follow a lognormal distribution such that the mean of the natural log of Q_i is zero. The variance of the assumed distribution for Q_i was selected to provide a ratio of 1.2 between the 95th percentile and the median value. Notice that Q_i has a subscript designating it as being specific to area i. This designation signifies that the uncertainty associated with the population size estimates was assumed to be independent among areas.

Let P_i^j be the estimated number of residents in area i, for any length of time from 1951 through 1988, generated in the jth repetition of the Monte Carlo process. Our goal is to produce an estimate of the number of cancer cases in this area that may result from exposure to radioactive material released from the FMPC site that is likely to be larger than the actual number of cases that may occur. This upper bound estimate for the number of cancer cases was derived as

$$UBC_i^j \; ? \; P_i^j * LR_i^j$$

where UBC_i^j is the jth possible value for the upper bound estimate of the number of cancer cases in area i produced in the Monte Carlo process and LR_i^j is the jth possible value for areas i's screening level lifetime risk. To reflect the uncertainty associated with the estimated upper bound for the number of FMPC radiation-related cancer cases, 5,000 possible values for the screening level estimates were produced for each area in the assessment domain.

Within each repetition of the Monte Carlo process, the area-specific estimate for the upper bound number of cancer cases were summed to produce an upper bound estimate for the total number of FMPC radiation related cancer cases that may result within the entire assessment domain. This estimate should be interpreted as the number of FMPC-related cancer cases that may result in the unlikely situation that all persons who lived for any length of time from 1951 through 1988 within the assessment domain received the estimated maximum dose. Because this is not likely to be the case, the estimated total number of cases is, again, an upper bound estimate that can be used to focus future, potentially more realistic, risk estimation efforts.

Estimates of the upper bound for the number of cases that may result in those exposed to contaminated well water were produced for each cancer by multiplying the estimated risk to a hypothetical person receiving the maximum dose resulting from this exposure by the sum of the number of persons estimated to have resided in areas 1 to 4 kilometers southeast and southwest of the site for any length of time from 1951 through 1988.

Chapter

5

Results

In this chapter, we present a collection of tables containing our estimates of the maximum FMPC-related radiation dose for the kidneys, female breast, bone surface, and bone marrow for 12 hypothetical individuals, one from each of the areas within the assessment domain. In addition, we present estimates of the lifetime risk of developing kidney cancer, breast cancer, bone cancer, and leukemia associated with the maximum dose values. For interpretation purposes, we also list our estimates of the percentage increase in the lifetime risk of developing these cancers above that we would expect if there had been no radiation exposure from the FMPC site. We also provide a similar list of estimates reflecting the additional radiation dose resulting from exposure to contaminated well water. Because all of these estimates are subject to uncertainty, we summarize the range of possible values estimated for the dose, risk, percentage increase in risk, and number of cases using medians and 90% credibility intervals.

As a final summary of our evaluation, we present upper bound estimates for the number of cases of kidney cancer, female breast cancer, bone cancer, and leukemia that may result from exposure to radioactive material released from the FMPC site during its operating years among all residents of the assessment domain. Because the numbers of cancer cases presented in this report are upper bound estimates, they are likely to be larger than the true number that may occur in this assessment population as a result of exposure to radiation released from the FMPC site.

Kidney Cancer

Estimates of the Maximum Lifetime Kidney Dose (in Sieverts) Resulting from Exposure to Radioactive Materials Released from the FMPC from 1951 through 1988

Table 6 contains the median values and the 90% credibility intervals for the estimated maximum radiation dose to the kidneys for hypothetical individuals who resided within the 12 areas of the assessment domain. Estimates of maximum kidney dose tend to be greater for those who lived closer to the site. In addition, the estimated maximum doses are larger in areas to the east of the facility than in those to the west. This difference in estimated dose depending on the assumed location of residence for the hypothetical individuals reflects the direction of the prevailing winds in the region (RAC, 1998a). The median values for the maximum kidney dose to a hypothetical individual range from 0.06 sieverts in the area closest to the site to the northeast to 0.008 sieverts in the area 7 to 10 kilometers to the northwest.

Table 6. Estimates of the Maximum Lifetime Kidney Dose Equivalent (in Sieverts), Excess Lifetime Risk of Developing Kidney Cancer, and Percentage Increase in the Lifetime Risk of Kidney Cancer Resulting from Exposure to Radioactive Material Released from the FMPC from 1951 through 1988 for Hypothetical Individuals Residing in the 12 Geographic Areas Within the Assessment Domain and for an Individual Assumed to Have Been Exposed to Contaminated Well Water

Direction From FMPC	Distance (kilometers) from FMPC	Maximum Kidney Dose Equivalent (in Sieverts)		Excess Lifetime Risk Resulting from Maximum Dose (x 1000)		Percentage Increase in Lifetime Risk (%)	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	0.06	(0.02 – 0.17)	0.05	(0.01 – 0.22)	0.60	(0.13 – 2.77)
	4-7	0.02	(0.008 – 0.07)	0.02	(0.004 – 0.09)	0.25	(0.05 – 1.17)
	7-10	0.02	(0.005 – 0.05)	0.01	(0.003 – 0.06)	0.17	(0.04 – 0.77)
Southeast	1-4	0.05	(0.02 – 0.15)	0.04	(0.009 – 0.19)	0.52	(0.11 – 2.38)
	4-7	0.02	(0.007 – 0.06)	0.02	(0.004 – 0.08)	0.23	(0.05 – 1.03)
	7-10	0.01	(0.005 – 0.04)	0.01	(0.003 – 0.06)	0.15	(0.03 – 0.69)
Southwest	1-4	0.04	(0.01 – 0.11)	0.03	(0.007 – 0.14)	0.39	(0.08 – 1.79)
	4-7	0.01	(0.005 – 0.04)	0.01	(0.003 – 0.06)	0.15	(0.03 – 0.71)
	7-10	0.01	(0.003 – 0.03)	0.008	(0.002 – 0.04)	0.10	(0.02 – 0.47)
Northwest	1-4	0.03	(0.009 – 0.08)	0.02	(0.005 – 0.10)	0.28	(0.06 – 1.28)
	4-7	0.01	(0.004 – 0.03)	0.01	(0.002 – 0.04)	0.12	(0.02 – 0.54)
	7-10	0.008	(0.003 – 0.02)	0.007	(0.001 – 0.03)	0.09	(0.02 – 0.39)
WELL 15 (directly South)	1-2	0.07	(0.02 – 0.20)	0.06	(0.01 – 0.28)	0.73	(0.15 – 3.50)

* We produced 5,000 possible values for the maximum dose, the lifetime cancer risk resulting from that dose, and the percentage increase in the lifetime cancer risk over background in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Estimates of the Excess Lifetime Risk and the Percentage Increase in the Lifetime Risk Resulting from the Maximum Dose for Hypothetical Individuals in 12 Areas Within the Assessment Domain

Median values and 90% credibility intervals for the lifetime risk of developing kidney cancer that may result from these maximum doses are also provided in Table 6. As an example of how to interpret these numbers, consider the hypothetical individual with the highest estimated risk. This person is assumed to have lived 1 to 4 kilometers northeast of the site. The median value for this individual's lifetime risk of developing kidney cancer as a result of the maximum radiation dose is estimated to be 0.00005. What this means is that this hypothetical individual's chance of developing kidney cancer as a result of FMPC radiation exposure is about 1 in 20,000. Alternatively, we may put this more simply by saying, if 100,000 people experienced the same maximum radiation dose to the kidney as this individual, we would expect about 5 additional cases of kidney cancer to occur in this group.

The actual value of the estimated lifetime risk of developing kidney cancer as a result of receiving the maximum dose is somewhat difficult to interpret. To put this estimate into context, we can look at how much the maximum exposure to FMPC-related radioactive material increases the lifetime risk of kidney cancer over the risk that would be expected if the exposure had not occurred. This lifetime risk in the absence of FMPC-related exposure is called the background risk. Estimates of the percentage by which the lifetime risk is increased because of the estimated maximum exposure are provided in the last column of Table 6. If we again consider the hypothetical individual assumed to have lived in the area 1 to 4 kilometers northeast of the site, we see that this individual's lifetime risk of developing kidney cancer is estimated to increase by a median value of 0.6% as a result of receiving the maximum estimated dose. The 90% credibility interval for this individual's percentage increase in lifetime risk is 0.1% to about 3%. As with the estimates of maximum kidney dose, the estimated values for the percentage increase in lifetime risk tend to be larger for areas closer to the site and for areas to the east of the facility. Notice that the median percentage increase in the lifetime risk of developing kidney cancer for individuals receiving the maximum FMPC-related radiation dose is less than 1% for all 12 areas within the assessment domain.

Estimates of the Maximum Dose (in Sieverts), Excess Lifetime Risk, and Percentage Increase in the Lifetime Risk resulting from Exposure to Contaminated Well Water

The last row in Tables 6 lists the estimated median and 90% credibility intervals for the maximum kidney dose for a hypothetical individual assumed to have been exposed to radiation-contaminated well water, the lifetime risk of developing kidney cancer resulting from that dose, and the percentage increase in the lifetime risk due to the FMPC-related radiation exposure over the background risk. The median value for the maximum kidney dose among people exposed to contaminated well water is 0.07 sieverts with a 90% credibility interval of 0.02 sieverts to 0.2 sieverts. By comparing this dose to the 0.04 sieverts estimated for our hypothetical person residing 1 to 4 kilometers southwest of the site, the area that contains Well 15, we see that accounting for contaminated well water has increased the median estimate of the maximum kidney dose by 75%. Finally, the median value for the estimated percentage increase in the lifetime risk of developing kidney cancer is 0.7%, and the 90% credibility interval is about 0.2% to 4% when we include exposure to contaminated well water in our maximum dose estimate.

Estimates of the Number of Kidney Cancer Cases Resulting from the Maximum FMPC-Related Radiation Dose for Each of the Areas

As we discussed in the Methods chapter of this report, we not only estimated the percentage increase over background in the lifetime risk of developing cancer for maximally exposed hypothetical individuals, but, we also estimated an upper bound for the number of cancer cases that could result from this maximum exposure. We call this estimate an upper bound because it was developed under the unrealistic assumption that everyone who resided within any of the 12 geographic areas within the assessment domain for any length of time from 1951 though 1988 received the estimated maximum lifetime dose for that area. As a result, these upper bounds estimates should be viewed as possible, yet unlikely, values for the number of cancer cases that could result from FMPC-related radiation exposure.

Upper bound estimates for the number of cases of kidney cancer resulting from exposure to radioactive material released from the FMPC site for each of the 12 geographic areas within the assessment domain are provided in Table 7. For comparison, the table also contains median values and 90% credibility intervals for the background number of kidney cancers we would expect in

each area if there had been no exposure to radioactive material released from the site. The median estimates for the area-specific background number of kidney cancer cases range from 7 to 64. The median upper bound estimate for the number of additional kidney cancer cases that may occur as a result of FMPC radiation exposure is 0 in all areas. If we consider the upper limit of the 90% credibility interval to be our uppermost estimate for the number of cases of kidney cancer that could result from this maximum exposure, then across the 12 geographic areas this uppermost estimate ranges from 0 to 1 additional case. It is important to bear in mind that estimates of the number of cancer cases will not follow the patterns seen for our estimates of maximum dose, risk, and percentage increase. This is because the upper bound estimate for the number of cases is determined by multiplying the estimated size of the population in a geographic area (provided in Table 5) by the excess lifetime risk estimates given in Table 6. The number of cases that may result from exposure to contaminated well water is provided later in this Chapter in Table 15.

Table 7. Upper Bound Estimates of the Number of Kidney Cancer Cases that May Occur as a Result of Exposure to Radioactive Material Released from the FMPC from 1951 through 1988 for the 12 Geographic Areas Within the Assessment Domain

Direction From FMPC	Distance (kilometers) from FMPC	Background Number of Kidney Cancer Cases [#@]		Upper Bound Estimate for Number of Kidney Cancer Cases Resulting from FMPC Radiation Exposure [#@]	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	35	(22 – 59)	0	(0 –1)
	4-7	30	(19 – 50)	0	(0 –0)
	7-10	23	(14 – 38)	0	(0-0)
Southeast	1-4	7	(4 – 12)	0	(0-0)
	4-7	28	(17 – 46)	0	(0-0)
	7-10	64	(39 – 105)	0	(0-0)
Southwest	1-4	11	(7 – 18)	0	(0-0)
	4-7	18	(11 – 29)	0	(0-0)
	7-10	44	(27 – 42)	0	(0-0)
Northwest	1-4	7	(4 – 11)	0	(0-0)
	4-7	30	(19 – 49)	0	(0-0)
	7-10	56	(34 – 91)	0	(0-0)

[#] Median values and 90% credibility intervals for the estimated number of people who resided in each of the areas for any length of time from 1951 through 1988 are listed in Table 5.

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the number of background cases and the number of cases resulting from FMPC radiation exposures in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

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Female Breast Cancer

Estimates of the Maximum Lifetime Breast Dose (in Sieverts) Resulting from Exposure to Radioactive Materials Released from the FMPC from 1951 through 1988

Estimates of the maximum dose to the breast are contained in Table 8 for hypothetical women residing in each of the 12 geographic areas of the Fernald assessment domain. Even when exposure is maximized, dose to the breast is small. Median values across the 12 areas range from 0.001 to 0.006 sieverts.

Table 8. Estimates of the Maximum Lifetime Female Breast Dose Equivalent (in Sieverts), Excess Lifetime Risk of Developing Breast Cancer, and Percentage Increase in the Lifetime Risk of Breast Cancer Resulting from Exposure to Radioactive Material Released from the FMPC from 1951 Through 1988 for Hypothetical Individuals Residing in the 12 Geographic Areas Within the Assessment Domain and for an Individual Assumed to have been Exposed to Contaminated Well Water

Direction From FMPC	Distance (kilometers) from FMPC	Maximum Breast Dose Equivalent (in Sieverts)		Excess Lifetime Risk Resulting from Maximum Dose (x 1000)		Percentage Increase in Lifetime Risk (%)	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	0.004	(0.001 – 0.01)	0.08	(0.02 – 0.38)	0.07	(0.02 – 0.38)
	4-7	0.002	(0.001 – 0.01)	0.03	(0.006 – 0.16)	0.03	(0.006 – 0.16)
	7-10	0.001	(0.0004 – 0.003)	0.02	(0.004 – 0.11)	0.02	(0.004 – 0.11)
Southeast	1-4	0.004	(0.001 – 0.01)	0.08	(0.02 – 0.40)	0.08	(0.02 – 0.40)
	4-7	0.002	(0.001 – 0.005)	0.03	(0.006 – 0.15)	0.03	(0.006 – 0.15)
	7-10	0.001	(0.0004 – 0.003)	0.02	(0.004 – 0.10)	0.02	(0.004 – 0.10)
Southwest	1-4	0.006	(0.002 – 0.02)	0.10	(0.02 – 0.53)	0.10	(0.02 – 0.53)
	4-7	0.001	(0.0003 – 0.003)	0.02	(0.003 – 0.09)	0.02	(0.003 – 0.09)
	7-10	0.001	(0.0002 – 0.002)	0.01	(0.002 – 0.05)	0.01	(0.002 – 0.05)
Northwest	1-4	0.006	(0.002 – 0.02)	0.11	(0.02 – 0.57)	0.11	(0.02 – 0.57)
	4-7	0.001	(0.0003 – 0.003)	0.02	(0.004 – 0.10)	0.02	(0.004 – 0.10)
	7-10	0.001	(0.0002 – 0.002)	0.01	(0.002 – 0.06)	0.01	(0.002 – 0.06)
WELL 15 (directly South)	1-2	0.002	(0.001 – 0.005)	0.03	(0.007 – 0.15)	0.03	(0.007 – 0.15)

* We produced 5,000 possible values for the maximum dose, the lifetime cancer risk resulting from that dose, and the percentage increase in the lifetime cancer risk over background in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Estimates of the Excess Lifetime Risk of Developing and the Percentage Increase in the Lifetime Risk Resulting from the Maximum Dose for 12 Areas Within the Assessment Domain

The median values for the estimated lifetime risk of breast cancer resulting from these maximal doses range from 0.00001 in the areas 7 to 10 kilometers southwest and nortwest of the site to 0.0001 in the area 1 to 4 kilometers to the southwest. The median values for the estimated percentage increase in the lifetime risk of developing breast cancer over the background lifetime risk are less than or equal to 0.1% for all areas. If we use the upper limit of the 90% credibility interval as an estimate of the uppermost percentage increase in the lifetime risk of breast cancer related to FMPC exposure, then these results indicate that this uppermost percentage increase in less than 0.6% across all areas.

Estimates of the Maximum Dose (in Sieverts), Excess Lifetime Risk, and Percentage Increase in the Lifetime Risk for a Woman Resulting from Exposure to Contaminated Well Water

The last row of Table 8 contains the estimated maximum dose for a hypothetical female exposed to well water contaminated with radioactive material released from the FMCP site. The median estimated breast dose resulting from this maximum exposure is 0.002 sieverts, and the upper bound of the 90% credibility interval for this maximum dose is 0.005 sieverts. This maximal dose to a hypothetical female increases her lifetime risk of developing breast cancer by an estimated median value of 0.03% (90% credibility interval; 0.007% to 0.15%) over the expected lifetime risk in the absence of FMPC-related radiation exposure.

Estimates of the Number of Breast Cancer Cases Resulting from the Maximum FMPC-Related Radiation Dose for Women Residing in the Assessment Domain

Table 9 contains our upper bound estimates of the number of female breast cancer cases that may occur in each of the 12 geographic areas. As was done with kidney cancer, we considered the upper limit of our credibility interval to be the upper bound on our estimate of the number of cancer cases that could result from these maximum exposures. Within each of the 12 geographic areas our upper bound estimate for the number of additional cases that may occur was 1 or less. In comparison, our median estimate of the background number of breast cancer cases in these area-specific populations, in other words the number that would occur in the absence of FMPC-related exposure, ranged from 42 to 402.

Table 9. Upper Bound Estimates of the Number of Female Breast Cancer Cases that May Occur as a Result of Exposure to Radioactive Material Released from the FMPC from 1951 Through 1988 for the 12 Geographic Areas Within the Assessment Domain

Direction From FMPC	Distance (kilometers) from FMPC	Background Number of Female Breast Cancer Cases [# @]		Upper Bound Estimate for Number of Female Breast Cancer Cases Resulting from FMPC Radiation Exposure [# @]	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	221	(134 – 368)	0	(0 – 1)
	4-7	190	(118 – 311)	0	(0 – 0)
	7-10	144	(88 – 235)	0	(0 – 0)
Southeast	1-4	45	(28 – 73)	0	(0 – 0)
	4-7	175	(108 – 284)	0	(0 – 0)
	7-10	402	(245 – 654)	0	(0 – 0)
Southwest	1-4	68	(42 – 110)	0	(0 – 0)
	4-7	110	(68 – 180)	0	(0 – 0)
	7-10	276	(169 – 453)	0	(0 – 0)
Northwest	1-4	42	(25 – 69)	0	(0 – 0)
	4-7	188	(115 – 307)	0	(0 – 0)
	7-10	347	(213 – 568)	0	(0 – 0)

[#] Median values and 90% credibility intervals for the estimated number of persons who resided in each of the areas for any length of time from 1951 through 1988 are listed in Table 5. For breast cancer, these population estimates should be divided by 2 to reflect the estimated number of women residents.

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the number of background cases and the number of cases resulting from FMPC radiation exposures in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Bone Cancer

Estimates of the Maximum Lifetime Bone Dose (in Sieverts) Resulting from Exposure to Radioactive Materials Released from the FMPC from 1951 through 1988

The estimated maximum lifetime bone dose equivalent values provided in Table 10, are higher than those estimated for any other organ in this report. This is to be expected since uranium, thorium, and the other radionuclides released from the FMPC tend to accumulate in the bone. As was noted for kidney dose, the estimates of the maximum dose tend to be higher for the hypothetical persons who were assumed to have resided closer to and east of the site. The highest estimated dose is for the hypothetical individual residing in the cell 1 to 4 kilometers northeast of the site. The median value for the bone dose for this maximally exposed person is 0.49 sieverts, and the 90% credibility interval ranges from 0.16 to 1.43 sieverts.

Table 10. Estimates of the Maximum Lifetime Bone Surface Dose Equivalent (in Sieverts), Excess Lifetime Risk of Developing Bone Cancer, and Percentage Increase in the Lifetime Risk of Bone Cancer Resulting from Exposure to Radioactive Material Released from the FMPC from 1951 through 1988 for Hypothetical Individuals Residing in the 12 Geographic Areas Within the Assessment Domain and for an Individual Assumed to Have Been Exposed to Contaminated Well Water

Direction From FMPC	Distance (kilometers) from FMPC	Maximum Bone Dose Equivalent (in Sieverts)		Excess Lifetime Risk Resulting from Maximum Dose (x 1000)		Percentage Increase in Lifetime Risk (%)	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	0.49	(0.16 – 1.43)	0.05	(0.01 – 0.23)	7.10	(1.44 – 32.33)
	4-7	0.21	(0.07 – 0.61)	0.02	(0.004 – 0.10)	3.02	(0.61 – 13.75)
	7-10	0.14	(0.05 – 0.40)	0.01	(0.003 – 0.06)	1.99	(0.40 – 9.06)
Southeast	1-4	0.42	(0.14 – 1.23)	0.04	(0.009 – 0.19)	6.09	(1.23 – 27.73)
	4-7	0.19	(0.06 – 0.54)	0.02	(0.004 – 0.08)	2.66	(0.54 – 12.13)
	7-10	0.13	(0.04 – 0.36)	0.01	(0.003 – 0.06)	1.80	(0.36 – 8.18)
Southwest	1-4	0.30	(0.10 – 0.88)	0.03	(0.006 – 0.14)	4.36	(0.88 – 19.84)
	4-7	0.13	(0.04 – 0.37)	0.01	(0.003 – 0.06)	1.85	(0.38 – 8.44)
	7-10	0.09	(0.03 – 0.25)	0.009	(0.002 – 0.04)	1.24	(0.25 – 5.67)
Northwest	1-4	0.20	(0.07 – 0.59)	0.02	(0.004 – 0.09)	2.93	(0.59 – 13.34)
	4-7	0.10	(0.03 – 0.28)	0.01	(0.002 – 0.05)	1.40	(0.28 – 6.37)
	7-10	0.07	(0.02 – 0.21)	0.01	(0.001 – 0.03)	1.02	(0.21 – 4.65)
WELL 15 (directly South)	1-2	0.44	(0.15 – 1.35)	0.04	(0.009 – 0.22)	6.28	(1.33 – 30.88)

* We produced 5,000 possible values for the maximum dose, the lifetime cancer risk resulting from that dose, and the percentage increase in the lifetime cancer risk over background in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Estimates of the Excess Lifetime Risk of and the Percentage Increase in the Lifetime Risk Resulting from the Maximum Dose for 12 Areas Within the Assessment Domain

The chance that the hypothetical maximally exposed individual residing 1 to 4 kilometers northeast of the site will develop bone cancer as a result of receiving the maximum FMPC-related radiation dose to the bone surface is about 1 in 20,000 or 0.00005. This translates into an estimated 7% increase in the lifetime risk of developing bone cancer above the background risk (90% credibility interval: 1% to 32%). The lowest percentage increase in the estimated lifetime risk is for the hypothetical person residing 7 to 10 kilometers to the northwest who had a 1% increase over background (90% credibility interval: 0.2% to 5%).

Estimates of the Maximum Dose (in Sieverts), Excess Lifetime Risk, and Percentage Increase in the Lifetime Risk Resulting from Exposure to Contaminated Well Water

The estimated median value for the maximum bone surface dose for a hypothetical person exposed to contaminated well water is 0.44 sieverts (90% credibility interval: 0.15 to 1.35 sieverts). Based on this range of values for the maximum bone surface dose, we estimate about a 6% increase in the lifetime risk of developing bone cancer over what we would expect if the exposure had not occurred. The 90% credibility interval for the percentage increase in the lifetime risk of developing bone cancer for a hypothetical person whose exposure includes contaminated well water ranges from 1% to 31%.

Estimates of the Number of Bone Cancer Cases Resulting from the Maximum FMPC-Related Radiation Dose Estimates for Each of the Areas in the Assessment Domain

Bone cancer is a very rare disease as demonstrated by the low background number of bone cancer cases expected to occur in the 12 areas within the assessment domain (Table 11). Therefore, the percentage increase estimates listed in Table 10 translate into few additional cases of this cancer that may occur as a result of exposure to radiation released from the FMPC. If we assume everyone residing within each of the 12 geographic areas received the maximum dose estimated for that area, then we estimate that no more than 1 additional case of bone cancer may occur in each area.

Table 11. Upper Bound Estimates of the Number of Bone Cancer Cases that May Occur as a Result of Exposure to Radioactive Material Released from the FMPC from 1951 through 1988 for the 12 Geographic Areas Within the Assessment Domain

Direction From FMPC	Distance (kilometers) from FMPC	Background Number of Bone Cancer Cases [#@]		Upper Bound Estimate for Number of Bone Cancer Cases Resulting from FMPC Radiation Exposure [#@]	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	3	(2 – 5)	0	(0 – 1)
	4-7	3	(2 –4)	0	(0 – 0)
	7-10	2	(1 – 3)	0	(0 – 0)
Southeast	1-4	1	(0 – 1)	0	(0 – 0)
	4-7	3	(2 – 4)	0	(0 – 0)
	7-10	6	(3 – 9)	0	(0 – 0)
Southwest	1-4	1	(1 – 2)	0	(0 – 0)
	4-7	2	(1 – 3)	0	(0 – 0)
	7-10	4	(2 – 6)	0	(0 – 0)
Northwest	1-4	1	(0 – 1)	0	(0 – 0)
	4-7	3	(2 – 4)	0	(0 – 0)
	7-10	5	(3 – 8)	0	(0 – 0)

[#] Median values and 90% credibility intervals for the estimated number of persons who resided in each of the areas for any length of time from 1951 through 1988 are listed in Table 5.

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the number of background cases and the number of cases resulting from FMPC radiation exposures in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Leukemia

Estimates of the Maximum Lifetime Bone Marrow Dose (in Sieverts) Resulting from Exposure to Radioactive Materials Released from the FMPC from 1951 through 1988

Table 12 contains a summary of the maximum bone marrow dose for the 12 hypothetical individuals receiving the maximum FMPC-related radiation dose within each assessment domain area. The median value estimated for the maximum bone marrow dose of a hypothetical person assumed to have lived 1 to 4 kilometers northeast of the site was 0.04 sieverts. In comparison, the median value estimated for the bone marrow dose to a similar maximally exposed hypothetical individual residing 7 to 10 kilometers northwest of the site was 0.01 sieverts.

Table 12. Estimates of the Maximum Lifetime Bone Marrow Dose Equivalent (in Sieverts), Excess Lifetime Risk of Developing Leukemia, and Percentage Increase in the Lifetime Risk of Leukemia Resulting from Exposure to Radioactive Material Released from the FMPC from 1951 Through 1988 or Hypothetical Individuals Residing in the 12 Geographic Areas Within the Assessment Domain and for an Individual Assumed to have been Exposed to Contaminated Well Water

Direction From FMPC	Distance (kilometers) from FMPC	Maximum Bone Marrow Dose Equivalent (in Sieverts)		Excess Lifetime Risk Resulting from Maximum Dose (x 1000)		Percentage Increase in Lifetime Risk (%)	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	0.04	(0.01 – 0.13)	0.21	(0.05 – 1.04)	2.68	(0.58-13.05)
	4-7	0.02	(0.01 – 0.06)	0.10	(0.02 – 0.46)	1.19	(0.26 – 5.80)
	7-10	0.01	(0.004 – 0.04)	0.07	(0.01 – 0.32)	0.82	(0.18 – 4.00)
Southeast	1-4	0.04	(0.01 – 0.11)	0.19	(0.04 – 0.91)	2.34	(0.51 - 11.39)
	4-7	0.02	(0.01 – 0.05)	0.09	(0.02 – 0.42)	1.07	(0.23 – 5.22)
	7-10	0.01	(0.004 – 0.04)	0.06	(0.01 – 0.29)	0.76	(0.16 – 3.68)
Southwest	1-4	0.03	(0.01 – 0.09)	0.15	(0.03 – 0.72)	1.84	(0.40 – 8.98)
	4-7	0.01	(0.004 – 0.04)	0.06	(0.01 – 0.30)	0.77	(0.17 – 3.75)
	7-10	0.01	(0.003 – 0.03)	0.04	(0.01 – 0.21)	0.55	(0.12 – 2.66)
Northwest	1-4	0.02	(0.01 – 0.07)	0.11	(0.02 – 0.53)	1.36	(0.29 – 6.62)
	4-7	0.01	(0.003 – 0.03)	0.05	(0.01 – 0.24)	0.62	(0.13 – 3.02)
	7-10	0.01	(0.003 – 0.02)	0.04	(0.01 – 0.18)	0.47	(0.10 – 2.31)
WELL 15 (directly South)	1-2	0.10	(0.03 –0.30)	0.50	(0.10 – 2.53)	6.27	(1.26 – 31.67)

* We produced 5,000 possible values for the maximum dose, the lifetime cancer risk resulting from that dose, and the percentage increase in the lifetime cancer risk over background in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Estimates of the Excess Lifetime Risk and the Percentage Increase in the Lifetime Risk Resulting from the Maximum Dose for 12 Areas Within the Assessment Domain

As would be expected, the geographic pattern for the estimated percentage increase in the lifetime risk of developing leukemia for hypothetical individuals receiving the maximum bone marrow dose mirrored that of the maximum dose estimates. The largest estimated percentage increase in lifetime risk, with a median value of 3% and a 90% credibility interval of 0.6% to 13%, occurs in the area closest to the site in the northeast direction. The smallest estimated percentage increase in lifetime risk (median 0.5% and 90% credibility interval: 0.1% to about 2%) occurs in the area furthest from the site in the northwest direction.

Estimates of the Maximum Dose (in Sieverts), Excess Lifetime Risk, and Percentage Increase in the Lifetime Risk Resulting from Exposure to Contaminated Well Water

Possible values for the maximum bone marrow dose for a hypothetical individual exposed to well water contaminated with radioactive material released from the FMPC site ranged from 0.03 sieverts to 0.30 sieverts (last row, Table 12). This range of possible values for the maximum bone marrow dose results in a median estimated percentage increase in the lifetime risk of developing leukemia for a hypothetical individual exposed to contaminated well water of about 6% (90% credibility interval: 1% to 32%).

Estimates of the Number of Leukemia Cases Resulting from the Maximum FMPC-Related Radiation Dose for each of the Areas in the Assessment Domain

The estimates presented in Table 13 indicate that the upper bound on the number of cases of leukemia that may occur as a result of Fernald-related radiation exposures ranges from about 1 to 5 within the 12 geographic areas being evaluated. These results are higher than those presented previously for the other cancer sites, where the upper bound has consistently been 1 or fewer additional cases.

Table 13. Upper Bound Estimates of the Number of Leukemia Cases that May Occur as a Result of Exposure to Radioactive Material Released from the FMPC from 1951 through 1988 for the 12 Geographic Areas Within the Assessment Domain

Direction From FMPC	Distance (kilometers) from FMPC	Background Number of Leukemia Cases [#] [@]		Upper Bound Estimate for Number of Leukemia Cases Resulting from FMPC Radiation Exposure [#] [@]	
		Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Northeast	1-4	35	(22 – 59)	1	(0 – 5)
	4-7	30	(19 – 50)	0	(0 – 2)
	7-10	23	(14 – 38)	0	(0 – 1)
Southeast	1-4	7	(4 – 12)	0	(0 – 1)
	4-7	28	(17 – 46)	0	(0 – 2)
	7-10	64	(39 – 105)	0	(0 – 2)
Southwest	1-4	11	(7 – 18)	0	(0 – 1)
	4-7	18	(11 – 29)	0	(0 – 1)
	7-10	44	(27 – 72)	0	(0 – 1)
Northwest	1-4	7	(4 – 11)	0	(0 – 0)
	4-7	30	(19 – 49)	0	(0 – 1)
	7-10	56	(34 – 91)	0	(0 – 1)

[#] Median values and 90% credibility intervals for the estimated number of persons who resided in each of the areas for any length of time from 1951 through 1988 are listed in Table 5.

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the number of background cases and the number of cases resulting from FMPC radiation exposures in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Upper Bound Estimates of the Number of Cancer Cases that May Have Occurred or May Occur in the Assessment Population Resulting from Exposure to Radioactive Material Released from the FMPC Site

As described previously, we estimated an upper bound for the number of cancer cases that could result from this maximum exposure for each of the 12 geographic areas being considered. These estimates are upper bounds because they are based on the unrealistic assumption that everyone who resided within any of the 12 areas of the assessment domain for any length of time from 1951 though 1988 received the estimated maximum lifetime dose for that area. Thus, these estimates should be viewed as possible, yet unlikely, values for the maximum number of cancer cases that could result from FMPC-related radiation exposure. The true number of kidney cancer, female breast cancer, bone cancer, and leukemia cases that may occur in the assessment population as a result of exposure to radioactive material released from the FMPC site is likely to be less than the estimates given in this report.

Upper bound estimates of the number of cancer cases that may result in the entire Fernald assessment population from FMPC-related radiation exposure are given in Table 14. These estimates do not include the increase in the number of cancer cases among those assumed to have been exposed to contaminated well water. The background number of kidney cancer, female breast cancer, bone cancer, and leukemia cases that we would expect in the assessment population if there had been no radiation exposure from the former FMCP are also provided for comparison. Notice that, even though the upper bound estimates given for each area in the previous tables in this chapter may be zero, the upper bound estimates for the <u>total</u> number of cancers can be greater than zero because the estimated number of cancer cases for a given area was rounded to the nearest whole number for presentation in Tables 7, 9, 11, and 13. For example, an estimate of 0.092 cases was rounded to a reported value of 0 cases. In estimating the total number of cases for the assessment domain, we added unrounded area-specific estimates, which resulted in upper bound estimates greater than zero for the total number of cases in the assessment domain.

Because of the unrealistic assumptions on which these estimates are based, the upper bound estimates presented in this report are likely to be larger than the true number of cancer cases that may have or may yet occur in the assessment population as a result of exposure to FMPC-related radiation. As a result, one can reasonably assume, on the basis of these maximized estimates, that

the number of cancer cases in the assessment population attributable to FMPC exposures should not exceed the upper limit of the credibility interval shown in the right column of Table 14. That is, 4 or fewer additional cases of kidney cancer, 3 or fewer additional cases of female breast cancer, 4 or fewer additional cases of bone cancer and 18 or fewer additional cases of leukemia may occur among people residing within 10 kilometers of the site for any length of time from 1951 though 1988, who were not also exposed to well water.

Table 14. Upper Bound Estimates of the Number of Cases of Selected Cancers that May Result from Exposure to Radioactive Material Released from the FMPC Site, Excluding Exposure to Contaminated Well Water, Among People Who Resided Within 10 Kilometers (6.2 miles) of the Facility for any Length of Time from 1951 through 1988

TYPE OF CANCER	Expected Number of Background Cases[#@]		Upper Bound Estimate for Number of Cases Related to FMPC Radiation Exposure[#@]	
	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Kidney Cancer	367	(311 - 435)	1	(0 - 4)
Breast Cancer	2,296	(1,945 – 2,717)	1	(0 - 3)
Bone Cancer	32	(27 - 38)	1	(0 - 4)
Leukemia	367	(311 - 435)	4	(1 - 18)

[#] The median value for the estimated number of people who resided in the assessment domain for any length of time from 1951 through 1988 is 45,909, and the 90% credibility interval is 38,896 to 54,343. For evaluating the estimated number of female breast cancers, the median estimated number of women in this population is 22,955, and the 90% credibility interval is 19,448 to 27,172 (see Table 5).

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the upper bound on the number of cases and the background number of cases in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Upper bound estimates of the number of cases of cancer that may result from FMPC-related radiation exposure among people receiving additional exposure by using water from site-contaminated wells are given in Table 15. These estimates were produced only for the populations assumed to have lived for any length of time from 1951 through 1988 in the two areas 1 to 4 kilometers from the site to the southeast and to the southwest (see Figure 3). Again, it is not likely that everyone who resided in these two areas for any length of time from 1951 through 1988 was exposed to contaminated well water. Therefore, the estimates given in Table 15 should be interpreted as upper bounds since they are likely to be larger than the true number of cancer cases that may occur among people in these two areas as a result of exposure to radioactive material released from the site, including that in contaminated well water. With this in mind, we estimate 1 or fewer additional case of kidney cancer, female breast cancer, and bone cancer may occur as a result of FMPC-related radiation exposure which includes contaminated well water in the combined population of the areas 1 to 4 kilometers southeast to southwest of the site. Similarly, the estimates indicate that 6 or less additional cases of leukemia may to occur among this portion of the assessment population potentially exposed to well water contaminated with radioactive material released from the site.

Table 15. Upper Bound Estimates for the Number of Cases of Selected Cancers that May Result from Exposure to Radioactive Material Released from the FMPC Site, Including Contaminated Well Water, Among People Who Resided 1 -4 Kilometers to the Southeast and Southwest of the Facility for any Length of Time from 1951 through 1988

TYPE OF CANCER	Expected Number of Background Cases[#@]		Upper Bound Estimate for Number of Cases Related to FMPC Radiation Exposure[#@]	
	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Kidney Cancer	18	(13 – 26)	0	(0 – 1)
Breast Cancer	115	(81 – 165)	0	(0 – 0)
Bone Cancer	2	(1 – 2)	0	(0 – 1)
Leukemia	18	(13 – 26)	1	(0 – 6)

[#] The median value for the estimated people who resided in the two areas 1 to 4 kilometers to the southeast and southwest of the site for any length of time from 1951 through 1988 is 2,294 and the 90% credibility interval is 1,610 to 3,298. For evaluating the estimated number of female breast cancers, the median estimated number of women in this population is 1,147 and the 90% credibility interval is 805 to 1,649 (see Table 5).

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the upper bound on the number of cases and the background number of cases in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

A comparison of the upper bound estimates from Table 15 with similar estimates given in Tables 7, 9, 11 and 13 for the areas 1 to 4 kilometers to the southeast and southwest of the site indicates that exposure from contaminated well water has a greater effect on the estimated number of FMPC radiation-related cancer cases in these areas than does exposure from other water sources such as Paddy's Run Creek. Therefore, we can substitute the upper bound estimates of the number of cases among those assumed to have been exposed to contaminated well water in these two areas for the estimated number of cases in these areas among those not having this exposure into our derivation of the upper bound case estimates for the entire assessment domain. The resulting upper bound estimates can be interpreted as the total number of FMPC-related cases that may occur among all members of the assessment domain, including those exposed to contaminated well water. These

estimates are given in Table 16. It is important to remember when comparing the summary estimates in Table 16 with those in Tables 14 and 15 that the medians and the limits of the 90% credibility intervals for the sum of uncertain values will not necessarily equal the sum of the medians or the sum of the credibility interval limits.

The estimated number of background cases in Table 16 is the same as that given in Table 14 because, in both tables, we are illustrating the number of cases of these types of cancer we would expect in the assessment population in the absence of any radiation exposure from the FMPC. By combining the upper level estimates across those assumed to have been exposed to contaminated well water and those not assumed to have had this exposure, we estimate that it is likely that 4 or fewer additional cases of kidney cancer, 3 fewer additional cases of female breast cancer, and 4 or fewer additional cases of bone cancer may occur in the assessment population as a result of exposure to radioactive material released from the FMPC site from 1951 through 1988. Similarly, we estimate an uppermost bound of 23 additional cases of leukemia may result from exposure to radioactive material released from the site among persons who resided within 10 kilometers (6.2 miles) of the facility for any length of time from 1951 through 1988. Because of the assumptions used to develop these estimates and the fact that we define our uppermost estimate of the number of cases as the upper limit of the 90% credibility interval, the actual number of cases of these types of cancer that may occur in the assessment population as a result of FMCP-related radiation exposure is likely to be lower than the estimates presented in this report.

Table 16. Upper Bound Estimates of the Number of Cases of Selected Cancers that May Result from Exposure to Radioactive Material, Including Exposure to Contaminated Well Water, Released from the FMPC Site Among People who Resided Within 10 Kilometers (6.2 miles) of the Facility for any Length of Time from 1951 through 1988

TYPE OF CANCER	Expected Number of Background Cases[#] [@]		Upper Bound Estimate for Number of Cases Related to FMPC Radiation Exposure[#] [@]	
	Median*	(90% Credibility Interval)**	Median*	(90% Credibility Interval)**
Kidney Cancer	367	(311 – 435)	1	(0 – 4)
Breast Cancer	2,296	(1,945 – 2,717)	1	(0 – 3)
Bone Cancer	32	(27 – 38)	1	(0 – 4)
Leukemia	367	(311 – 435)	5	(3 – 23)

[#] The median value for the estimated number of persons who resided in the assessment domain for any length of time from 1951 through 1988 is 45,909 and the 90% credibility interval is 38,896 to 54,343. For evaluating the estimated number of female breast cancers, the median estimated number of women in this population is 22,955 and the 90% credibility interval is 19,448 to 27,172 (see Table 5).

@ The number of cases have been rounded to the nearest whole number. For example, if the number of cases is less than 0.5, then the number of cases is rounded to 0.

* We produced 5,000 possible values for the upper bound on the number of cases and the background number of cases in order to reflect the uncertainty associated with these values. The median is that value greater than one half of the estimates and less than the other half.

** 90% of the 5,000 estimates fall between the upper and lower limits of the 90% credibility interval.

Chapter

6

Interpreting the Screening Level Cancer Risk Estimates

In interpreting the screening level estimates of the lifetime risk of developing cancer, the percentage increase in lifetime risk, and the upper bound estimates for the number of cancer cases that may result from FMPC-related radiation exposure presented in this report, one should keep in mind the assumptions used to develop them. The risk estimates reflect the lifetime risk of developing kidney cancer, female breast cancer, bone cancer, and leukemia among hypothetical individuals who were assumed to have received the maximum plausible dose of radiation released from the FMPC site during the facility's years of operation. Similarly, the upper bound estimates of the number of cases of these types of cancers that may result from this exposure were based on the unrealistic assumption that everyone who resided in one of the areas of the assessment domain received the estimated maximum dose for that area. One of our goals in developing these estimates was to direct CDC's future risk estimation and other public health activities related to past FMPC-related radiation exposure. When interpreting our results one should also remember that the estimated screening level risks and upper bound numbers of cancer cases are not intended to reflect the true level of risk in the affected community. It is likely that the true number of cancer cases, of the types addressed in this report, that may result from FMPC-related radiation exposure will be lower than the estimates presented in Table 16. Alternatively, we can say that the true number of cases of kidney cancer, female breast cancer, bone cancer, and leukemia that may occur in the assessment population as a result of exposure to radioactive material released from the FMPC site from 1951 through 1988 is not likely to be greater than the estimates provided in this table. Therefore, these estimates may provide area residents with a reference point with which to evaluate their own potential cancer risk related to radiation released from the FMPC site.

Limitations of the Approach Used to Estimate the Screening Level Lifetime Cancer Risks

Estimates of the Lifetime Risk of Developing Cancer Did not Include the Additional Risk Incurred by People who Worked at the FMPC Site

A key point to remember when evaluating the screening level estimates of risk presented in this report is that these estimates reflect risk among hypothetical individuals receiving the maximum organ-specific dose as a result of living within 10 kilometers (6.2 miles) of the facility for any length of time from 1951 through 1988. They do not reflect the additional risk incurred by people who were also employed at the site. We could not estimate the risk for such people because the dose estimation software developed in the Fernald Dosimetry Reconstruction Project for use in estimating radiation dose at locations up to 10 kilometers from the site did not allow us to reliably estimate dose for locations within the site boundary (particularly within the site's production area) (RAC, 1998b). The National Institute for Occupational Safety and Health (NIOSH) has a number of current investigations underway at Fernald to examine potential associations between worker exposure to site-related chemicals and radionuclides and the risk of adverse health effects.

Potential for Underestimating the Maximum Organ Specific Doses

The estimates of the screening level lifetime cancer risks and the upper bounds for the number of FMPC-related cancer cases given in this report are based on plausible values for the maximum organ doses resulting from exposure to radioactive material released from the site. We developed these estimates by assuming a collection of lifestyle characteristics that tend to increase exposure to site-related radiation. These assumptions, while plausible, are unlikely to reflect the true lifestyles of the majority of the assessment population. Our estimates of maximum dose could be raised even further, however, by making even more unrealistic assumptions about these hypothetical individuals. For example, we could have assumed that the hypothetical individuals spent 100% of their time outdoors. This type of unrealistic assumption, while producing higher estimates of dose, is not consistent with our goal of producing plausible estimates for the organ-specific maximum doses.

Setting all uncertain parameters in the dose estimation model, for example the amount of material released from the site, to their maximum value rather than their median value as we did for this report, could also have increased our estimates of the maximum dose. Again, however, this approach would have been inconsistent with our attempt to estimate plausible values for the maximum dose. We have modeled the uncertainty associated with our maximum dose estimates to have an upper bound for the 90% credibility interval that is 2 times larger than the median estimated value. As a result, we used a large range of possible values for the maximum doses in our Monte Carlo process. This range is likely to include the majority of possible values for the maximum dose that could be generated both by using the upper bounds of the uncertainty of the dose estimation parameters and by making implausible assumptions on the lifestyle characteristics of the hypothetical individuals for whom we estimate dose.

Estimates of the upper bounds for the number of cancer cases potentially related to exposure to radiation from the FMPC site are likely to be larger than the actual number of cases that may result from this exposure among people in the assessment population. This likely overestimation reflects the unrealistic assumption that everyone who ever resided in any of the areas of the assessment domain for any length of time from 1951 through 1988 received the estimated maximum dose for that area.

Estimates of the Lifetime Risk of Developing Cancer per Sievert used in the Report

Estimates of the increase in the lifetime risks of developing cancer per sievert of radiation dose received that we used in this report are listed in Table 3. These estimates were derived from epidemiologic investigations of the cancer experience of human populations exposed to ionizing radiation, primarily studies of atomic bomb survivors and individuals exposed to radiation for medical reasons. The type of exposure experienced by these populations may be quite different from that of the assessment population considered in this report. For example, the radiation exposure received by survivors of the bombings at Hiroshima and Nagasaki was primarily external whereas main exposure pathway among the FMPC assessment population is internal resulting from inhalation and ingestion of radioactive materials released from the site (RAC, 1998a). In addition, the radiation exposure experienced by the atomic bomb survivors resulted in doses substantially larger than those estimated for even the maximally exposed hypothetical individual within the assessment domain. Furthermore, the radiation exposure experienced by the population who

resided within 10 kilometers (6.2 miles) of the FMPC site was incurred continuously over the years of plant operations as opposed to the instantaneous exposure experienced by the atomic bomb survivors. The use of the cancer risks associated with exposure to high doses delivered over a short period of time that have been observed in epidemiologic studies to estimate the risk for people exposed to lower doses over long time periods is an area of current research and discussion in the scientific community. However, both the ICRP (ICRP, 1991) and EPA (EPA, 1994) risk estimates used in this report include adjustments, where these groups have deemed it warranted based on available information, to account for the potential effects of these differences in exposure experience.

Another potentially important factor to consider in applying estimates of the increase in cancer risk per unit dose derived from one population to assess radiation-induced cancer risk in a second population is the difference in characteristics between the two populations. For example, for some cancers, the risk of dying from the disease per sievert of dose received appears to be related to the background risk of dying from that cancer if there was no radiation exposure. In some situations, this potential dependence of the increase in risk per unit dose on the background risk could make use of risk observed in Japanese populations inappropriate for use in estimating the risk in the FMPC assessment population. The rate of breast cancer, for example, is substantially lower among Japanese women than among women who reside in North America. This difference in the background risk of breast cancer is one reason that we chose to use EPA's increase in risk per sievert dose estimate for this outcome (EPA, 1994). This choice reflects the fact that the EPA developed their estimate of the lifetime increase in the risk of dying from breast cancer per sievert of radiation dose received using mostly data from a North American population of women who received diagnostic and therapeutic doses of x-rays.

Underestimation of the Uncertainty Associated with the Screening Level Estimates of Lifetime Cancer Risk

When evaluating the results presented in this report, one should keep in mind the uncertainty associated with the screening level risk estimates. We have attempted to incorporate information about the uncertainty associated with the components that contributed to the final screening level risk estimates and upper bound estimates of the number of potential cancer cases. These components include uncertainty about the true level of the maximum dose, uncertainty associated with the increase in the risk of developing cancer per sievert of radiation dose received, and

uncertainty concerning the size of the population that resided within the assessment domain. This list, however, is by no means exhaustive of all the potential uncertainties associated with estimating these values. For example, we did not consider uncertainty associated with either the background lifetime risks of developing the cancers considered in this report or the proportion of those cancers that result in death (the lethality fractions presented in Table 3). The uncertainties associated with these values, however, are likely to be small relative to those already incorporated in our estimation of the 90% credibility intervals developed for this report.

For those components of uncertainty that are included in the final estimates, we used mathematical models to estimate the magnitude of the lack of precision. While these models were based on observed information whenever possible, they are themselves uncertain. For example, in estimating the uncertainty associated with the increase in the lifetime risk of developing the cancers per sievert of radiation dose received, we used a value estimated for the increase in the risk of cancer induced death resulting from any cancer per unit dose (NCRP, 1997). While it is likely that the true level of uncertainty for the increase in the risk of developing cancer per sievert dose for individual organs may be substantially larger than this range, these types of organ-specific uncertainty estimates have not been separately developed.

The Risk of Kidney Disease Resulting from the Chemical Properties of Uranium is Not Addressed in this Report

In this screening level evaluation of how FMPC exposures may affect the kidneys of people who resided within the assessment domain, we only considered the radioactive properties of contaminants released from the FMPC site during its years of operation. Ingestion of uranium was the primary pathway responsible for the estimated radiation dose to the kidneys resulting from this exposure (RAC, 1998a). However, the chemical characteristics of ingested uranium may also have detrimental health effects on the kidney (Morris and Meinhold, 1995). The Agency for Toxic Substances and Disease Registry (ATSDR) is estimating the potential health effects associated with the chemical properties of uranium and other elements released from the FMPC site. We have shared the methods and results of this report and those of the Fernald Dosimetry Reconstruction Project, with ATSDR for inclusion in its assessment.

Chapter 7

Recommendations

On the basis of the results of this screening assessment, we do not recommend a more detailed analysis of radiation-related risk for kidney cancer, bone cancer, female breast cancer or leukemia. Even though we used methods designed to maximize potential risk, we estimated that Fernald-related radiation exposure may result in 4 or fewer additional cases of kidney cancer, female breast cancer, and bone cancer. We also estimated that 23 or fewer additional cases of leukemia may have occurred or may occur in the assessment population as a result of their exposure to radioactive material released from the FMPC from 1951 to 1988. These upper bound estimates include the effects of exposure to contaminated well water. Our recommendation was developed with input from the Fernald Health Effects Subcommittee, who reviewed the draft report of this risk analysis.

This report deals with exposures that occurred in the past. While there is no way to reduce these exposures, there are actions individuals can take if they are concerned about their own or their family members' risk of cancer:

- CDC recommends individuals who smoke should quit. Although most people are familiar with the link between smoking and lung cancer, few realize that smoking is also linked with cancers at other body sites. About 25% - 30% renal cell (kidney) cancers are attributed to cigarette smoking (ACS, 1999c). In addition, scientists believe about 20% of the most common type of leukemia in adults, acute myelogenous leukemia, is due to smoking (ACS, 1999b).

- The Department of Health and Human Services' Preventive Services Task Force recommends that women aged 50-69 be screened for breast cancer every 1-2 years with mammography alone or mammography and an annual clinical breast exam. Younger and older women, particularly those at higher risk because they have had a previous breast cancer or because they have a family history of the disease, should consult with their health care providers. Early detection through mammography remains the most effective way for a woman to reduce her risk of dying

from breast cancer. The goal of early detection is to find a cancer when it is most treatable. A mammogram can detect a breast tumor about two years before it can be felt by a woman or by her physician (ACOG, 1999). More information about breast cancer screening can be obtained by calling the Ohio Department of Health's Breast and Cervical Cancer Prevention Program at 1-888-PAP-MAMM (1-888-727-6266) or 513-584-4342.

- Finally, it makes sense for individuals to eat a healthful diet and to exercise. "Existing scientific evidence suggests that about one-third of cancer deaths that occur in the US each year are due to dietary factors" (ACS, 1999). Dietary factors have been suggested as risk factors for both breast and kidney cancer, and both cancers have been linked to obesity. Recommended dietary changes include reduction in the amount of fatty foods consumed and an increase in the amount of fruits and vegetables.

References

American Cancer Society (ACS). Cancer Facts & Figures – 1999. Atlanta, GA: ACS, 1999a.

ACS. Cancer Facts: Chronic Leukemias; Renal Cell Cancer. Atlanta, GA: ACS, 1999b.

ACS. Cancer Facts: Renal Cell Cancer. Atlanta, GA: ACS, 1999c.

American College of Obstetrics and Gynecology (ACOG). Women's Health Columns: When Should You Get a Mammogram? information from website at: www.acog.org/from_home/publications/womans_health/wh10-13-7.htm, 1999.

Archer VE, Wagoner JK, Lundin FE. Cancer mortality among uranium mill workers. J Occup Med 15:11-14, 1973.

Boice JD Jr, Land CE, Preston DL. Ionizing Radiation. In: Cancer Epidemiology and Prevention (Schottenfeld D and Fraumeni JF Jr, eds) . New York, NY: Oxford University Press, 1996.

Boice JD Jr, Preston DL, Davis FG, Monson RR. Frequent chest x-ray fluoroscopy and breast cancer incidence among tuberculosis patients in Massachusetts. Radiat Res 125:214-222, 1991.

Bureau of the Census. 1981-1983 Intercensal population estimates by age [Machine-readable public use data tapes]. Washington, DC: US Department of Commerce, Bureau of the Census, 1981-1983.

Checkoway H, Pearce N, Crawford-Brown DJ, Cragle DL. Radiation doses and cause-specific mortality among workers at a nuclear materials fabrication plant. Am J Epidemiol 127:255-266, 1988.

Centers for Disease Control and Prevention (CDC). Fernald Health Effects Subcommittee (FHES) meeting minutes, May 1998.

CDC. FHES meeting minutes, August 1997.

CDC. National Center for Health Statistics (NCHS). Vital Statistics mortality data, underlying cause of death, 1981-1983. [Machine-readable public use data tapes]. Hyattsville, MD: CDC, 1981-1983.

Curtis RE, Hankey BF, Myers MH, Young JL. Risk of leukemia associated with the first course of cancer treatment: an analysis of the Surveillance, Epidemiology and End Results Program experience. J Natl Can Inst 72(3): 531-44, 1984.

Davis FG, Boice JD Jr, Hrubee Z, Monson RR. Cancer mortality in a radiation-exposed cohort of Massachusetts tuberculosis patients. Cancer 49:6130-6136, 1989.

Devine OJ, Qualters JR, Morrissey JL, Wall PA. Estimation of the Impact of the Former Feed Materials Production Center (FMPC) on Lung Cancer Mortality in the Surrounding Community. Atlanta, GA: Centers for Disease Control and Prevention, 1998.

Dupree EA, Cragle DL, McLain RW, Crawford-Brown DJ, Teta MJ. Mortality among workers at a uranium processing facility, the Linde Air Products Company Ceramics Plant, 1943-1949. Scand J Work Environ Health 13:100-107, 1987.

Evans JS, Abrahamson S, Bender MA, et al. Health Effects Models for Nuclear Power Plant Accident Consequence Analysis. Part I: Introduction, Integration, and Summary. NUREG/CR-4214, Rev. 2, Part 1, ITRI-141. Washington, DC: U.S. Nuclear Regulatory Commission, 1993.

Dupree Ellis, EA. Briefing on Study Results, September, 1998.

Feuer EJ, Wun LM. DEVCAN: Probability of DEVeloping CANcer software, Version 3.3. Bethesda, MD: National Cancer Institute, 1996.

Hoffman DA, Lonstein JE, Morin MM, et al. Breast cancer in women with scoliosis exposed to multiple diagnostic x rays. J Natl Cancer Inst 81:1307-1312, 1989.

Howe GR, McLaughlin J. Breast cancer mortality between 1950 and 1987 after exposure to fractionated moderate-dose-rate ionizing radiation in the Canadian Fluoroscopy Cohort Study and a comparison with breast cancer mortality in the Atomic Bomb Survivors Study. Radiat Res 145:694-707, 1996.

Inskip PD, Monson RR, Wagoner JK, et al. Cancer mortality following radium treatment for uterine bleeding. Radiat Res 123:331-344, 1990.

Inskip PD, Kleinerman RA, Stovall M, et al. Leukemia, lymphoma and multiple myeloma after pelvic radiotherapy for benign disease. Radiat Res 135:108-24, 1993.

International Commission on Radiological Protection (ICRP). 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP 21(1-3). Oxford, UK: Pergamon Press, 1991.

Kleinerman RA, Boice JD Jr, Storm HH, et al. Second primary cancer after treatment for cervical cancer. An international cancer registries study. Cancer 76:442-452, 1995.

Morris SC, Meinhold AF. Probabilistic risk assessment of nephrotoxic effect of uranium in drinking water. Health Phys 69:897-908, 1995.

National Academy of Sciences (NAS). National Research Council (NRC) Committee on the Biological Effects of Ionizing Radiation. Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V Report). Washington, DC: National Academy Press, 1990.

NAS. NRC. Committee on the Biological Effects of Ionizing Radiation. Health Effects of Radon and Other Internally Deposited Alpha-Emitters (BEIR IV Report). Washington, DC: National Academy Press, 1988.

National Cancer Institute (NCI). Surveillance, Epidemiology, and End Results (SEER) Cancer Incidence Public-Use Database, 1973-1995. August 1997 Submission. Bethesda, MD: NCI., Cancer Statistics Branch, 1998.

National Council on Radiation Protection and Measurements (NCRP). NCRP Report No. 128. Radionuclide Exposure of the Embryo/Fetus. Bethesda, MD: NCRP, 1998 .

NCRP. NCRP Report No. 126. Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection. Bethesda, MD: NCRP, 1997.

NCRP. NCRP Report No. 115. Risk Estimates For Radiation Protection. Bethesda, MD: NCRP, 1993.

Pierce DA, Shimizu Y, Preston DL, Vaeth M, Mabuchi K. Studies of mortality of atomic bomb survivors. Report 12, Part I. Cancer: 1950-1990. Radiat Res 146:1-27, 1996.

Polednak AP, Frome EL. Mortality among men employed between 1943 and 1947 at a uranium-processing plant. J Occup Med 23(3): 169-178, 1981.

Preston DL, Kusumi S, Tomonaga M, et al. Cancer incidence in atomic bomb survivors. Part III: Leukemia, lymphoma and multiple myeloma, 1950-1987. Radiat Res 137:S68-S97, 1994.

Puskin JS, Nelson CB. Estimates of radiogenic cancer risks. Health Phys 69(1):93-101, 1995.

Puskin JS, Nelson NS, Nelson CB. Bone cancer risk estimates. Health Phys 63(5):579-580, 1992.

Radiologic Assessments Corporation (RAC). Task 6: Radiation Doses and Risk to Residents from FMPC Operations from 1951-1988. Volume II (Final Report). Neeses, SC: RAC, 1998a.

RAC. Computer modules for estimating organ-specific doses. Neeses, SC: RAC, 1998b.

Thompson DE, Mabuchi K, Ron E, et al. Cancer incidence in atomic bomb survivors. Part II: Solid tumors, 1958-1987. Radiat Res 137:S17-S67, 1994.

Tokunaga M, Land CE, Tokuoka S, et al. Incidence of female breast cancer among atomic bomb survivors, 1950-1985. Radiat Res 138:209-223, 1994.

United Nations Scientific Committee on the Effects of Atomic Radiation. (UNSCEAR). Sources, Effects and Risks of Ionizing Radiation. 1988 Report to the General Assembly, with annexes. New York, NY: United Nations, 1988.

U.S. Environmental Protection Agency (EPA). Estimating Radiogenic Cancer Risks. EPA 402-R-93-076. Washington, DC: EPA, 1994.

U.S. Preventive Services Task Force. 1995 Guide to Clinical Preventive Services, 2nd Edition. Washington, DC: U.S. Department of Health and Human Services, 1995.

Vose D. Quantitative Risk Analysis. A Guide to Monte Carlo Simulation Modelling. Chichester, England: John Wiley & Sons, 1996.

Weiss HA, Darby SC, Doll R. Cancer mortality following x-ray treatment for ankylosing spondylitis. Int J Cancer 59:327-338, 1994.

Weiss HA, Darby SC, Fearn T, Doll R. Leukemia mortality after x-ray treatment for ankylosing spondylitis. Radiat Res 142:1-11, 1995.