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Dose Modeling and Statistical Assessment of Hot Spots for Decommissioning Applications

Eric Warner Abelquist
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Eric Warner Abelquist entitled "Dose Modeling and Statistical Assessment of Hot Spots for Decommissioning Applications." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

Laurence F. Miller, Major Professor

We have read this dissertation and recommend its acceptance:

Kevin G. Robinson, Ronald E. Pevey, Lawrence W. Townsend

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Dose Modeling and Statistical Assessment of Hot Spots for Decommissioning Applications

A Dissertation Presented for
the degree of
Doctor of Philosophy,
The University of Tennessee, Knoxville

Eric Warner Abelquist
August 2008

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I have had the privilege to work at one of the best companies, with the finest people, for more than fifteen years now. My friends and colleagues at the Oak Ridge Associated Universities have had a profound impact on my career. We have worked together on many projects, reliably executing our role as the independent verification contractor for the DOE and NRC on scores of decommissioning projects. We have gained valuable experience by solving technical problems in decommissioning through application of our expertise in environmental and decommissioning survey procedures, application and innovation of field survey instrumentation, and laboratory analyses of media samples. Our leadership position in the decommissioning industry was recognized by our role in the development of MARSSIM and solidified through our efforts to establish the first MARSSIM training course in 1997—and built upon by offering more than 70 MARSSIM courses since that time. It is precisely this collaborative effort with the ORAU team that prepared me to perform this dissertation research. My sincere thanks go out to all my friends and colleagues at ORAU over the past 15 years.

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ABSTRACT

A primary goal of this research was to develop a technically defensible approach for modeling the receptor dose due to smaller “hot spots” of residual radioactivity. Nearly 700 combinations of environmental pathways, radionuclides and hot spot sizes were evaluated in this work. The hot spot sizes studied ranged from 0.01 m^2 to 10 m^2, and included both building and land area exposure pathways. Dose modeling codes RESRAD, RESRAD-BUILD, and MicroShield were used to assess hot spot doses and develop pathway-specific area factors for eleven radionuclides. These area factors are proposed for use within the existing Multiagency Radiation Survey and Site Investigation Manual (MARSSIM) context of final status survey design and implementation. The research identified pathways that are particularly “hot spot sensitive”—i.e., particularly sensitive to changes in the areal size of the contaminated area. The external radiation pathway was the most hot spot sensitive for eight of the eleven radionuclides studied. These area factors were evaluated both when the receptor was located directly on the soil hot spot and ranged from 6.6 to 11.4 for 1 m^2 hot spot; and ranged from 650 to 785 when the receptor was located 6 m from the 1 m^2 hot spot. The external radiation pathway was also the most sensitive of the building occupancy pathways. For the smallest building hot spot studied (100 cm^2), the area factors were approximately 1100 for each of the radionuclides. A Bayesian statistical approach for assessing the acceptability of hot spots is proposed. A posterior distribution is generated based on the final status survey data that provides an estimate of the 99^{th} percentile of the contaminant distribution. Hot spot compliance is demonstrated by comparing the upper tolerance limit—— defined as the 95% upper confidence level on the 99^{th} percentile of the contaminant distribution in the survey unit—with the $DCGL_{99th}$ value. The $DCGL_{99th}$ is the hot spot dose limit developed using the dose modeling research to establish area factors mentioned above. The proposed approach provides a hot spot assessment approach that considers hot spots that may be present, but not found. Examples are provided to illustrate this approach.

PREFACE

Decommissioning of sites and buildings is contemplated when facilities have reached the end of their useful life. Decommissioning is a complex activity that involves characterizing the contaminated areas, remediating those areas that exceed acceptable contamination guidelines, and performing radiological surveys to demonstrate that the site has been successfully cleaned up. In the United States, this activity is regulated by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency (EPA), as well as individual states. Recent decommissioning projects have included nuclear power reactors such as Maine Yankee, Big Rock Power and Trojan Nuclear Plants, and US Department of Energy (DOE) weapons complex sites such as Fernald and Rocky Flats. The organization that I work for, Oak Ridge Associated Universities is often requested by the regulators to perform independent verification to assess the adequacy of cleanup at these decommissioning sites.

An important aspect of decommissioning is determining how clean is clean enough. As mentioned above, the NRC and the EPA are the two principal federal agencies responsible for the cleanup and decommissioning of radioactively contaminated sites. The NRC's release criteria for unrestricted release are promulgated in Subpart E of 10 CFR 20.1402; they include a dose limit to an average member of the critical group of 25 mrem/y, and that the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA). The EPA's release criteria are risk-based rather than dose-based. Specifically, the EPA uses an acceptable lifetime excess cancer risk of 10E-6 to 10E-4 to assess whether a site should be released or not. Typically, individual states use the same release criteria as the NRC, though in some states more restrictive release criteria have been adopted—e.g., Connecticut has a release criterion of 19 mrem/y, New Jersey uses 15 mrem/y and Massachusetts has adopted 10 mrem/y. The DOE has a basic dose limit of 100 mrem/y for members of the public from all sources, and for a single source such as a decommissioning site has stated that NRC's 25 mrem/y is reasonable (USDOE 2002).

A common feature of the regulatory release criteria mentioned above is that they are not measurable quantities, at least not directly. This is the role of dose modeling—to translate the dose- or risk-based release criteria to measurable concentrations of radioactivity in soil and on building surfaces. Dose modeling considers how future receptors might be exposed to residual radioactivity that remains following the decommissioning of a site or building. Specific exposure scenarios such as the residential farmer or building occupant scenarios are postulated, and environmental pathways commensurate with each scenario are used to calculate translate the release criterion to a measurable quantity. These measurable quantities are called derived concentration guideline levels (DCGLs). So demonstrating compliance with DCGLs is the same thing as demonstrating

compliance with release criteria.

Various software tools exist to facilitate dose modeling in support of decommissioning. The most widely used modeling codes in the decommissioning industry are likely RESRAD for soil areas and RESRAD-BUILD for building surfaces, both written and maintained by Argonne National Laboratory. These software tools allow the quick calculation of DCGLs by modeling the transport of radionuclides through the environment to the future receptor via various pathways such as direct external radiation, ingestion of drinking water, plant and animal products, and inhalation of contaminated dust. Modeling parameters associated with each of the pathways are needed in order to perform these calculations. These parameters can be classified as physical (e.g., resuspension factor), metabolic (e.g., breathing rate) or behavioral (e.g., time spent gardening), and they can be default or site-specific values. Therefore, pathway modeling considers various scenarios and exposure pathways to convert dose or risk into measurable concentrations.

RESRAD and RESRAD-BUILD are used to calculate DCGLs that equate to the appropriate release criteria for the site. This is performed by modeling unit concentration (e.g., 1 pCi/g for soil) for a particular radionuclide, and then calculating the receptor dose based on the defined scenario(s), exposure pathways, models, and parameter distributions. The dose that results for unit concentration is then scaled to the dose-based release criterion (e.g., 25 mrem/y) to directly calculate the radionuclide concentration (DCGL) that corresponds to the release criterion. It is important to note that this radionuclide concentration is typically taken to be more or less uniformly distributed over the survey unit (i.e., on the order of 1,000 to 10,000 m^2).

Radiological surveys in support of decommissioning are planned at the same time as DCGLs are being developed for the site. MARSSIM, which stands for the Multiagency Radiation Survey and Site Investigation Manual, is the industry standard for decommissioning surveys. It has been the buzzword in the D&D arena since the document was published in December 1997. The MARSSIM's popularity is due to the broad agency support it has received from the EPA, DOE, NRC and Department of Defense (DoD). These agencies prepared MARSSIM to provide consistent methods for conducting radiological surveys to support decommissioning. The MARSSIM provides guidance on the planning, implementation, and evaluation of decommissioning radiological surveys—historical site assessment, scoping, characterization, and final status surveys. It is geared toward the final status survey—which demonstrates that dose-based or risk-based release criteria for decommissioning sites have been satisfied. A brief description of the MARSSIM survey types follows.

The historical site assessment (HSA) is not a survey per se. It can be described as an effort to collect as much background information on the site as possible.

Examples of HSA information includes site inspection reports, routine operational survey reports, documentation of off-normal occurrences and effluent releases, and interviews with former employees. Objectives of the HSA are to identify potential sources of contamination, differentiate areas of different contamination potential, and provide input to scoping and characterization survey designs. The scoping and characterization surveys build upon the HSA data by collecting both random and judgmental samples from all potential areas of concern. The objectives of these preliminary surveys are to determine the nature and extent of contamination to allow effective planning for remediation and waste disposal activities, as well as to provide site data for dose modeling input for site-specific DCGLs, and input to the final status survey design.

The MARSSIM provides many details on final status survey design. The first steps in the design are to identify the contaminants and to classify all site areas according to contamination potential—with the underlying premise being that the greater the contamination potential, the greater the survey coverage (i.e., greater scan and sampling density). Areas that have no reasonable potential for residual contamination are classified as non-impacted areas. These areas have no radiological impact from site operations and are typically identified early in decommissioning. Areas with reasonable potential for residual contamination are classified as impacted areas. Impacted areas are further subdivided into one of three classifications (USNRC 2000a):

- Class 1 areas: Areas that have, or had prior to remediation, a potential for radioactive contamination (based on site operating history) or known contamination (based on previous radiation surveys) above the DCGL. Simply stated, Class 1 areas are likely to have hot spots.

- Class 2 areas: Areas that have, or had prior to remediation, a potential for radioactive contamination or known contamination, but are not expected to exceed the DCGL.

- Class 3 areas: Any impacted areas that are not expected to contain any residual radioactivity, or are expected to contain levels of residual radioactivity at a small fraction of the DCGL, based on site operating history and previous radiation surveys.

Once classified as Class 1, Class 2, and Class 3 areas, each area is further divided into survey units based on the guidance offered in the MARSSIM. A survey unit is a physical area consisting of structure or land areas of specified size and shape for which a separate decision will be made as to whether or not that area exceeds the release criterion. Survey units range in size from 2,000 to 10,000 m^2 or more for land areas and 100 to 1,000 m^2 or more for building surfaces.

The final status survey consists of two general activities—radiological scanning to identify any elevated radiation levels in the survey unit, and random systematic sampling over the survey unit (soil samples for land areas and surface activity measurements for building surfaces). Two statistical tests are used to plan and evaluate final status survey sampling data—Wilcoxon Rank Sum when the contaminants are present in natural background, and the Sign test when contaminants are not present in background. A second evaluation is performed on judgmental samples that were collected at likely areas of contamination or based on scanning results. These judgmental samples are commonly referred to as "hot spots" (radionuclide concentrations that exceed the DCGL) identified in the survey unit. This is called the elevated measurement comparison test in MARSSIM, and it should not be confused with a statistical test.

At this point it is necessary to return to the discussion on release criteria and DCGLs. Recall that DCGLs are radionuclide-specific concentrations that equate to the release criterion. MARSSIM defines two potential DCGLs based on the area of contamination. If the residual radioactivity is evenly distributed over a large area (e.g., survey unit), MARSSIM looks at the average activity over the entire area. This DCGL is called the $DCGL_W$ and it is derived based on an average concentration over a large area. It is the DCGL used in the statistical tests. Conversely, if the residual radioactivity appears as small areas of elevated activity (i.e., hot spots) within a larger area, typically smaller than the area between measurement locations, MARSSIM considers the results of individual measurements. This DCGL is called the $DCGL_{EMC}$ and it is defined as the DCGL used for the elevated measurement comparison (EMC); it is derived separately for these hot spots. Modeling codes such as RESRAD and RESRAD-BUILD are used to derive the DCGLs, both the $DCGL_W$ and $DCGL_{EMC}$. There is a simple relationship between the DCGLs—the $DCGL_{EMC}$ equals the $DCGL_W$ times the area factor. The area factor is the magnitude by which the concentration within the small area of elevated activity (hot spot) can exceed the $DCGL_W$ while maintaining compliance with the release criterion. [Note: My dissertation research focuses on the calculation of these area factors and therefore the $DCGL_{EMC}$.]

Upon completion of the final status survey, the WRS or Sign test is used to test the data against the $DCGL_W$ to determine if the mean of the contaminant distribution in the survey unit satisfies the release criteria. The elevated measurement comparison is then performed to demonstrate that identified hot spot concentrations do not exceed the $DCGL_{EMC}$ for small areas of elevated concentration. Both tests must be satisfied before the survey unit passes.

My experience in implementing and reviewing MARSSIM final status surveys has left me with two specific perspectives on hot spots: 1) the acceptable hot spot limits seem to have a weak technical basis, and 2) hot spots are frequently missed during the final status survey. This dissertation addresses hot spots

associated with decommissioning projects, particularly during the final status survey. There were basically two primary thrusts of this research. The first fundamental aspect of this research addresses how acceptable DCGLs for hot spots ($DCGL_{EMC}$) are determined. The receptor dose due to hot spots (contaminated areas ranging in size from 0.01 to 10 m^2) was studied. The RESRAD and RESRAD-BUILD codes were used extensively in this process to assess hot spot doses. The outcome of this first area of research was the development of pathway-specific area factors for eleven radionuclides. These area factors are proposed for use within the existing MARSSIM context of survey design and implementation. Specifically, the advance in the state of the art is the rigorous assessment of hot spot dose modeling and development of comprehensive area factors. It is hoped that regulatory agencies will review the technical approach described herein, and consider adopting these area factors for application in MARSSIM survey designs and implementation.

It is important to point out that this dissertation required the heavy use of example calculations, particularly for the assessment of how the modeling codes handled various hot spot sizes. These examples are necessary to describe the process and including them in the body of the text helps the overall flow of the document as results and conclusions for each pathway are discussed.

The second fundamental aspect of this research was the development of a statistical assessment approach for hot spots that assesses the acceptability of multiple hot spots in the survey unit. This proposed approach does not necessarily depend on the results of the primary research thrust explained above. Rather, it's more of a big picture approach that places hot spots in the overall context of the contaminant distribution in a survey unit. That is, while the MARSSIM describes a two-pronged approach for separately demonstrating compliance with both the mean contaminant concentration and elevated areas (hot spots), this research proposes an integrated contaminant distribution concept where compliance is demonstrated for the contaminant distribution as a whole. That is, both the mean and upper percentiles (e.g., 99^{th} percentile) of the contaminant distribution are compared to the $DCGL_W$ and $DCGL_{99th}$ in order to demonstrate compliance. Note: The development of the $DCGL_{99th}$ should consider the very same dose modeling concerns used to establish the area factors in the first research area (i.e., the upper 99^{th} percentile concentrations are by definition the hot spots). The value of this approach is two-fold. First, it addresses the issue of how to handle hot spots that may exist in the survey unit, but have not been found. Second, it inherently handles multiple hot spots because they are characterized and accounted for in the overall contaminant distribution that is being assessed for compliance with release criteria. It is hoped that regulatory agencies will consider this consolidated view of hot spots as well.

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CHAPTER 1 INTRODUCTION AND GENERAL DESIGN OF RESEARCH

1.1 Dose Modeling to Establish Release Criteria

Dose modeling is performed to calculate future receptor doses to demonstrate compliance with the specified release criteria for decommissioning. Specifically, dose modeling is conducted to determine measurable quantities called derived concentration guideline levels (DCGLs) that correspond to the release criteria. Site release criteria can sometimes be called “cleanup criteria,” “clearance levels,” “authorized limits,” or simply “guidelines”. The final status survey assesses whether the residual radioactivity, following any necessary site remediation, complies with these DCGLs, and thus allows the D&D site to conclude that release criteria have been met.

A common assumption in dose modeling is that the contamination is more or less uniformly distributed over a parcel of land or building surface area. The hypothetical dose to future land users and/or building occupants is based on land use and building occupancy scenarios. For example, one of the more conservative land use scenarios is the residential farmer scenario. A less conservative scenario would be the industrial worker scenario. Some regulatory agencies, such as the Department of Energy (DOE) and Nuclear Regulatory Commission (NRC), require the evaluation of several land uses as part of the process of determining the appropriate DCGL. Once a reasonable scenario is selected, environmental pathways are considered, detailing how the future occupant might be exposed to radiation dose. The usual pathways include external radiation exposure, inhalation and inadvertent ingestion.

Potentially more than 100 modeling parameters can be specified to complete the exercise of determining the future receptor dose. Examples of these parameters might include the extent of clean soil cover above the source term, size of contaminated area, or distribution coefficient for radionuclides in the land areas. Similarly, the inhalation rate, resuspension factor (used to predict how much surface contamination becomes airborne), and occupancy factor (used to estimate an individual’s exposure time) are important parameters for building scenarios. In summary, dose assessments are used to demonstrate compliance with the release criteria and generally rely on (1) models for transport of radionuclides through the environment to a receptor, and (2) the parameters used in those models.

One common aspect of all current dose modeling efforts is that the source terms are usually taken to be relatively large, and uniform—e.g., the Multiagency

Radiation Survey and Site Investigation Manual[1] (MARSSIM) suggests survey unit sizes on the order of 2000 to 10,000 m^2 for land areas and 100 to 1000 m^2 for building surfaces. Other guidance such as the uranium mill tailings standards (40 CFR 192) specifies 100 m^2 for land, as does the DOE O 5400.5 (USDOE 1990), while both DOE O 5400.5 and Regulatory Guide 1.86 (USAEC 1974) specify 1 m^2 units for building area. Understanding that residual contamination is very often not uniform, but rather spotty, DCGLs are needed for smaller areas of contamination (commonly called hot spots). The MARSSIM calls the limit for hot spots the $DCGL_{EMC}$—or DCGL for the elevated measurement comparison. So while the need to have $DCGL_{EMC}$s is well-founded, the current approach in MARSSIM used to generate the $DCGL_{EMC}$ is not completely technically sound.

The MARSSIM recommends running RESRAD and RESRAD-BUILD codes at successively smaller areas (e.g., from the RESRAD default of 10,000 m^2 to 1 m^2), and taking the ratio of dose generated by the modeling code for the default area to that generated for the smaller areas studied (USNRC 2000a). While this approach is a reasonable first cut at generating hot spot limits, a careful study of hot spot dose modeling is warranted. For example, the external radiation pathway is modeled by an infinite plane source in RESRAD. The practical effect of reducing the size of the contaminated area from an entire survey unit to a much smaller area is that the receptor is assumed to spend all of their outdoor time directly on a small hot spot. NUREG-1757 (USNRC 2006) recognizes that potential limitations of the current method of determining DCGL values may exist. The NUREG suggests that it is worthwhile to consider alternate risk scenarios when determining acceptable residual radioactivity levels of discrete particles. Simply stated, the dose modeling scenarios used in RESRAD[2] and RESRAD-BUILD may not be strictly applicable for contaminated areas of 1 m^2 or smaller—scenarios, pathways, and modeling parameters for nominal hot spot sizes are questionable, and should be addressed.

The primary objective of this research is to develop a technically defensible approach for modeling the receptor dose due to hot spots. The dissertation addresses how environmental pathways and parameters are impacted by hot spot source terms. The research identifies pathways and parameters that are particularly "hot spot sensitive"—those pathways and parameters in particular were studied to determine the best way for considering their contribution to receptor dose.

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[1] The MARSSIM is a multiagency consensus document that was developed collaboratively by DOD, DOE, EPA, and the NRC to describe a consistent approach for planning and performing final status surveys.

[2] RESRAD and RESRAD-BUILD are the industry standard dose modeling codes, and in particular, are essentially the only codes used to establish hot spot limits ($DCGL_{EMC}$). Therefore, the dissertation research focused exclusively on these modeling codes.

Fundamentally, the work addressed in this dissertation is to base the determination of acceptable hot spot release criteria on dose, but not by simply reducing the size of the contaminated area to smaller and smaller hot spot sizes. Rather, hot spot release criteria were developed by considering the best estimate of dose from first principles described below. An overarching issue that is addressed during implementation of the hot spot release criteria is the requirement for receptor doses to be as low as reasonably achievable (ALARA). An example of implementing ALARA for hot spots is that once found, the hot spot is remediated (regardless of dose).

This research focused on two primary use scenarios—building occupancy and residential farmer. Each of these scenarios consists of a number of pathways that can deliver dose to the receptor. The following pathways were studied in this dissertation work. Subsequently, some of the pathways considered were deemed not to be particularly hot spot sensitive

1.11 Resident Farmer Scenario for Contaminated Soil Sites

This scenario accounts for potential exposure to residual radioactive contamination in soil. For this scenario, the soil contamination is assumed to be contained in a surface layer. The resident farmer is defined as a person who lives on the site following license termination, grows some portion of their diet on the site, and drinks water from an on-site well. The pathways that were evaluated in this dissertation that apply to the resident farmer include:

- direct exposure to external radiation from contaminated soil
- inhalation exposure to resuspended soil
- direct ingestion of soil
- ingestion of drinking water from a groundwater source
- ingestion of plant products grown in contaminated soil
- ingestion of plant products irrigated with contaminated groundwater
- ingestion of animal products grown onsite (i.e., after animals ingest contaminated drinking water, plant products, and soil)
- ingestion of fish from a contaminated surface water source

1.12 Building Occupant Scenario for Reuse of Structures

This scenario accounts for exposure to fixed and removable thin layer or surface contamination sources within a structure. The building occupant is defined as a person who works in a commercial building following license termination. The pathways that were evaluated in this dissertation that apply to the building occupant include:

- external exposure to penetrating radiation from surface sources

- inhalation of resuspended surface contamination
- inadvertent ingestion of surface contamination

1.2 General Design of Hot Spot Dose Modeling Research

This work included a detailed look at how hot spots of various sizes actually produce receptor doses for specified environmental and building pathways. The radionuclides evaluated in this work were chosen for modeling due to their varying decay modes, and the fact that they represent a wide range of physical and chemical characteristics that affect environmental transport—e.g., deposition, resuspension, volatilization, plant uptake, and solubility. The radionuclides include C-14, Co-60, Sr-90, Tc-99, I-129, Cs-137, Ra-226 (series in equilibrium), Th-232 (series in equilibrium), U-238 (processed uranium), Pu-239, and Am-241. The hot spot sizes considered were 10 m^2, 3 m^2, 1 m^2, 0.5 m^2, 0.1 m^2 and 0.01 m^2. The smallest hot spot size (0.01 m^2) may be effectively considered to represent a discrete particle (10 cm × 10 cm) within a soil matrix. Further, each hot spot source term was considered to exist on the soil surface, at a depth of 15 cm, and have no clean soil cover.

The modeling currently performed to derive DCGLs does not directly apply to hot particles treated as distributed over an area. NUREG/CR-5512 is a fundamental guidance document for environmental pathway modeling, it further expands on this point: “When more complex situations arise, such as the presence of inhomogeneous, buried sources in soil, site-specific modeling or the use of external exposure measurements may better describe the situation and should be used instead of simple model representations…” (USNRC 1992a). The exposure pathways are based on mobility and resuspension factors for an evenly distributed contaminant. In addition, when the area of concern becomes increasingly small, such as 1 m^2 or smaller, the resident farmer scenario and its environmental pathways may no longer be realistic. Further evaluation of this issue was performed to provide a stronger technical basis for determining the acceptability of leaving hot spots behind.

Once the hot spot dose modeling approach was developed, the research focused on how this approach can be integrated into the MARSSIM final status survey design. The survey approach for assessing the acceptability of hot spots, and specifically, for handling multiple hot spots was reviewed. A new methodology for assessing the acceptability of hot spots is proposed. This approach seeks to define the overall hot spot criteria in the context of the contaminant distribution, recognizing that both the mean and overall shape of the distribution are important factors in determining the receptor dose. Specifically, the 99^{th} percentile of the estimated contaminant distribution is compared to a proposed hot spot limit called the $DCGL_{99th}$ (explained in detail in Chapter 6).

CHAPTER 2 LITERATURE REVIEW

A detailed review of the available literature pertinent to release criteria, dose modeling, and radiological surveys in support of decommissioning was performed. A primary study question that framed the literature review was "What is the release criterion for hot spots and how is it currently determined?" Several regulatory and/or guidance documents were reviewed, including the Atomic Energy Commission (AEC, predecessor agency to the Nuclear Regulatory Commission) Regulatory Guide 1.86, Department of Energy O 5400.5, RESRAD manual (ANL 2001), and most recently, the Multiagency Radiation Survey and Site Investigation Manual. Each of these documents has addressed hot spots to some degree, with the greatest detail covered by the MARSSIM. Certainly the level of rigor in establishing hot spot limits has increased over last few decades.

2.1 General Approaches for Hot Spot Criteria

Two general approaches are currently used for determining hot spot criteria. First, the hot spot criteria are administratively established as some multiple of the average guideline. For example, Regulatory Guide 1.86 sets the hot spot limit at three times the average limit. Another example of administratively set hot spot criteria can be found in DOE 5400.5 where the soil hot spot limit is calculated by multiplying the average guideline by as factor of $(100/A)^{0.5}$, where A is the area of the hot spot.

Radiological survey approaches such as those described in NUREG/CR-5849 (USNRC 1992b) and DOE Order 5400.5 (USDOE 1990) provide an administrative limit for hot spots that based on the $(100/A)^{0.5}$ factor. For example, if A equals 10 m^2, then the hot spot limit is 3.16 times the average DCGL. This means that if the hot spot area is 10 m^2, then the allowable limit that can be averaged over that area is equal to 3.16 times the average guideline for the entire survey unit, which in this case is 1000 m^2. Because neither the average guideline nor the hot spot limit is based on dose or risk using this approach, there is usually no connection between the average guideline value and the hot spot limit. That is, the hot spot limit is not based on the dose limit; it is simply a multiplier above the average guideline. Note: The factor of 100 in the $(100/A)^{0.5}$ factor represents the averaging area for demonstrating compliance. Larger averaging areas (e.g., 1000 to 5000 m^2) are commonly used in survey guidance, and would increase the hot spot limit accordingly. Note: The $(100/A)^{0.5}$ factor was derived as the function that conservatively bounds the receptor dose from water-independent pathways. An analysis in the 1980s indicated that this factor is "very conservative for some radionuclides and less so for others but is always

more restrictive than the method based on the dose limit".[3]

The second approach currently used to establish hot spot criteria is to use the area factor approach presented in MARSSIM. This involves extrapolating the dose modeling approach for relatively large parcels of land and building area to small hot spot sizes. The MARSSIM allows for residual radioactivity levels that could be above the average Derived Concentration Guideline Level ($DCGL_W$); however, the levels are limited to the maximum radioactivity level specified by a defined area called the $DCGL_{EMC}$ or elevated measurement comparison. The basic premise in MARSSIM is that the residual contamination is distributed relatively uniformly and, therefore, the statistical tests do not directly consider the presence of discrete particles. Since hot spots are routinely identified during the conduct of final status surveys, a careful evaluation of the dose impacts of these discrete particles is needed. It is noted that various researchers have developed technical basis documents to address scanning surveys using both conventional scanning and *in situ* gamma ray spectroscopy (ISGRS) and their ability to detect discrete sources of radioactivity.

Of all the guidance documents researched, the MARSSIM presents the most detailed approach for determining values for the $DCGL_{EMC}$. The MARSSIM suggests a modification to the $DCGL_W$ using a correction factor that accounts for the difference in the size of the contaminated area, and the resulting change in dose. The area factor (AF) is the magnitude by which the concentration within the small area of elevated activity (hot spot) can exceed $DCGL_W$ while maintaining compliance with the release criterion. Specifically, the MARSSIM recognizes that the RESRAD code defaults to a land area of 10,000 m^2—it is this area that the $DCGL_W$ is determined. The area factors are then computed by taking the ratio of the dose or risk per unit concentration generated by RESRAD for the default 10,000 m^2 to that generated for other contaminated areas (i.e., 1, 3, 10 m^2). If the DCGL for residual radioactivity distributed over 10,000 m^2 is multiplied by this value, the resulting concentration distributed over the specified smaller area delivers the same calculated dose (USNRC 2000a).

This simplistic approach, though detailed, overlooks the problem that some pathways are not meant to be evaluated at area sizes substantially less than 100 or 1000 m^2. The assumptions that logically hold for larger land areas and building surface areas—such as the "unlimited reservoir" of contamination for the inhalation pathway—may not support the dose modeling technical basis as the area is reduced to the size of typical hot spots.

It should be noted that receptor dose depends on both the average contamination in the survey unit, as well as the distribution of activity, including

[3] Meeting minutes prepared on September 1986 by Andrew Wallo, III, project engineer, The Aerospace Corporation.

hot spots. Note that MARSSIM equation 8-2 (shown below) addresses the sum of the fractions rule for hot spots (USNRC 2000a):

$$\frac{\delta}{DCGL_W} + \frac{(average\,conc\,in\,elevated\,area - \delta)}{(area\,factor\,for\,elevated\,area) \times (DCGL_W)} < 1$$

where δ is the average residual radioactivity in the survey unit.
In practice, MARSSIM equation 8-2 allows for relatively few hot spots to remain in a survey unit.

2.2 Historic Release Criteria Documents

The release criteria documents that were written prior to the mid 1990s were largely generic in nature. These generic release criteria can be defined as guidance provided by regulatory agencies that did not account for site-specific characteristics. Examples of generic release criteria are the Atomic Energy Commission's Regulatory Guide 1.86, "Termination of Operating Licenses for Nuclear Reactors" (USAEC 1974) and DOE Order 5400.5, "Radiation Protection of the Public and the Environment" (USDOE 1990). By comparison, site-specific criteria are usually derived by the licensee or stakeholder using various scenarios and site characteristics (e.g., depth of contamination, size of contaminated area, depth to groundwater depth, etc.). Site-specific release criteria are usually based on a risk- or dose-based criterion, such as 25 mrem/y, and depends on modeling (e.g., RESRAD or RESRAD-BUILD) to translate the dose criterion to measurable guidelines.

The historic regulatory guidance documents were not dose-based. Rather, the guidelines provided in Regulatory Guide 1.86 were generally based on considerations related to the detection capabilities of commercially available survey instruments at that time (early 1970s). NRC guidance included Regulatory Guide 1.86 for reactor licensees and "Guidelines for decontamination of facilities and equipment prior to release for unrestricted use or termination of license for byproduct, source, or special nuclear material" for non-reactor licenses (USNRC 1987). Table 1 provides the Regulatory Guide 1.86 surface activity guidelines and conditions for implementation. Removable surface activity guidelines are not shown in the table, but are 20% of the average surface activity guidelines for each grouping.

It is important to understand that surface activity levels are allowed to be averaged over 1 m^2, but no surface activity levels can exceed the maximum surface activity specified for a 100 cm^2 area. The latter represent explicit hot spot limits.

Table 1 Regulatory guide 1.86 surface contamination criteria.

Radionuclide	Average Surface Activity in 1 m^2 (dpm/100 cm^2)	Maximum Surface Activity in 100 cm^2 (dpm/100 cm^2)
U-nat, ^{235}U, ^{238}U and associated decay products	5,000	15,000
Transuranics, ^{226}Ra, ^{228}Ra, ^{230}Th, ^{228}Th, ^{231}Pa, ^{227}Ac, ^{125}I, ^{129}I	100	300
Th-nat, ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U, ^{126}I, ^{131}I, ^{133}I	1,000	3,000
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except Sr-90 and others noted above	5,000	15,000

Concerning volumetric contamination guidelines, the NRC's Branch Technical Position (BTP), "Disposal or onsite storage of thorium or uranium wastes from past operations" (USNRC 1981) provides the guidelines for unrestricted release of uranium and thorium in soil. The guidelines for disposal in Option 1 are "set sufficiently low that no member of the public is expected to receive a radiation dose commitment from disposed materials in excess of 1 millirad per year to the lung or 3 millirads per year to the bone from inhalation and ingestion, under any foreseeable use of the material or property" (USNRC 1981). Most interesting in regard to hot spots is that the guidelines are stated in terms of maximum allowable concentrations. That is, any concentrations found to exceed the maximum allowable concentrations needed to be remediated before the wastes were buried. Thus there were no explicit hot spot limits in NRC BTP on disposal of uranium and thorium waste.

DOE Order 5400.5 also provides release criteria for soil contaminated with Ra-226, Ra-228, Th-230, and Th-232. The guidelines and conditions for each of these contaminants are as follows: 5 pCi/g, averaged over the first 15 cm of soil below the surface; and 15 pCi/g, averaged over 15-cm thick layers of soil more than 15 cm below the surface. These guidelines represent allowable residual

concentrations above background averaged across any 15-cm thick layer to any depth and over any contiguous 100 m^2 surface area. Further, if the average concentration in any surface or below-surface area, less than or equal to 25 m^2, exceeds the authorized limit of guideline by a factor of $(100/A)^{½}$, where A is the area or the elevated region in square meters, limits for "hot spots" are also be applicable. Note: This concept is now referred to as an area factor in MARSSIM.

Sometimes groundwater can be an important environmental medium when assessing the possible exposure pathways at a D&D site. EPA's 40 CFR Part 141, National Primary Drinking Water Standards for Radionuclides[4], provides guidance on the acceptable levels of radioactivity in drinking water. It is important to recognize that the EPA drinking water standards are applicable to public drinking water systems, rather than groundwater concentrations, and are enforced at the drinking water tap. The standards provide for maximum contaminant levels of 5 pCi/l for combined Ra-226 and Ra-228, 15 pCi/l for gross alpha activity, and a limit for beta-gamma emitters based on 4 mrem per year. Note that these guidelines are stated as "maximum limits". This implies that there are no hot spot values for concentrations that may exceed the maximum contaminant value—these are "not to exceed" values.

In conclusion, the hot spot guidelines in the historic release criteria documents were sometimes an arbitrary factor (i.e., 3) of the average guideline, or as in the case of DOE 5400.5, a multiplier based on the size of the hot spot relative to the unit averaging area. A couple of the historic guidance documents provided guidelines that were maximum limits, which meant that there were no explicit hot spot limits.

2.3 Dose-Based Release Criteria

The fundamental objective of a final status survey is to demonstrate that the established release criteria have been met. Therefore, one of the single most important aspects of final status survey planning is to have a clear understanding of the decommissioning release criteria that apply to a particular D&D project. For years, D&D professionals used the well-known historic guidelines mentioned in the previous section for planning and implementing final status surveys. However, since the promulgation of the NRC's license termination rule, D&D professionals are using new decommissioning release criteria for building surfaces and land areas.

The Nuclear Regulatory Commission promulgated decommissioning criteria in Subpart E, "Radiological Criteria for License Termination" 10 CFR Part 20 in July 21, 1997 (USNRC 1997). Under Subpart E, a licensee may terminate a license

[4] Federal Register: Volume 65, Number 236:76707-76753; December 7, 2000

for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a total effective dose equivalent to an average member of a critical group that does not exceed 25 millirems per year, and the residual radioactivity has been reduced to levels that are as low as reasonably achievable. The implementation date for this rule was August 20, 1998, with a one year grandfather period. The NRC has issued numerous guidance documents to support this rulemaking effort and has identified the need to consolidate guidance documents into a central resource. This resource is three-volume NUREG that encompasses guidance from regulatory guides, NUREGs, decommissioning licensing conditions, and generic decommissioning communications generated over the past several years. This comprehensive three-volume set is referred to as NUREG-1757, "Consolidated Decommissioning Guidance" (USNRC 2006). NUREG-1757 provides detailed guidance on dose modeling, final status surveys, ALARA and restricted use scenarios.

In a Federal Register Notice dated November 18, 1998 the NRC provided a screening table of unrestricted release values (DCGLs) for building surface contamination of common beta/gamma emitting radionuclides (FR 1998). The screening table was derived using the DandD screening code, Version 1, and its default input parameters. The DCGL values correspond to surface concentrations of radionuclides contamination that would be deemed in compliance with the unrestricted use dose criterion of 25 mrem/y.

NRC issued a second Federal Register Notice dated December 7, 1999, in which the NRC noted several areas where DandD, Version 1, was overly conservative (FR 1999). The explanation provided for this conservatism was that Version 1 used a common default parameter set for all radionuclides, rather than being tailored for each radionuclide. NRC later corrected the excessive conservatism in Version 2.0 of the DandD code by using default parameter values based on the specific radionuclides being modeled. Additionally, the NRC contracted with Argonne National Laboratory to develop probabilistic dose modeling versions of RESRAD and RESRAD-BUILD.

The NRC provided additional information in a Federal Register Notice on June 13, 2000 concerning the use of screening values (default DCGLs) to demonstrate compliance with release criteria (FR 2000). In this FRN, the NRC referenced Vol. 3 of NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning, Parameter Analysis, Draft Report for Comment," (USNRC 1999a). The conditions for demonstrating compliance with surface soil DCGLs include, in part:

- residual radioactivity is contained in the top layer of the surface soil (i.e., a thickness of approximately 15 centimeters)
- unsaturated zone and the groundwater are initially free of

radiological contamination
- vertical saturated hydraulic conductivity at the specific site is greater than the infiltration rate.

The conditions for demonstrating compliance with building surface DCGLs include, in part:

- residual radioactivity is contained in the top layer of the building surface (i.e., there is no volumetric contamination);
- fraction of removable surface contamination does not exceed 10%

On this final point, the NRC explains that when the fraction of removable contamination is undetermined or greater than 10%, licensees may assume that 100% of the surface contamination is removable, and therefore the screening values should be decreased by a factor of ten.

The NRC also states in the June 13, 2000 FRN that NUREG/CR-5512, vol. 3 can be used to determine acceptable DCGLs. For example, Table 5.19 (using a P_{crit} = 0.90) may be used for building surface activity DCGLs. These DCGLs are generic screening DCGLs and as such, are purposefully conservative. A P_{crit} value of 0.90 means that the DCGL is derived to overestimate the receptor dose—i.e., so that the derived dose for 90% of the screening cases will not be underestimated.

To summarize, decommissioning release criteria have been evolving over the past few decades, and it is important to have a clear understanding of the past and present release criteria. For many D&D projects, the release criteria are now dose-based, as opposed to the former guidelines found in guidance documents such as Regulatory Guide 1.86.

2.4 Dose Modeling—Scenarios, Pathways, and Parameters

Environmental pathway modeling provides a mechanism to calculate the expected radioactivity in various environmental media that result from the transport from an initial source term (e.g., soil concentration), as a function of time. For example, given an initial surface activity on building surfaces, how are the potential doses delivered? To determine the dose, the possible exposure pathways must be evaluated—direct radiation, inhalation, and ingestion—as well as the physical parameters used to calculate the transportation of radioactivity for each pathway.

NUREG-1757, Appendix I describes an alternative approach for demonstrating compliance with release criteria (USNRC 2006). Rather than use MARSSIM to demonstrate compliance with DCGLs developed from dose modeling codes, the licensee performs dose assessments that focus on the determination of doses

corresponding to specified radionuclide concentrations. The approach requires a thorough source term abstraction to delineate the spatial extent of residual radioactivity and to represent the spatial variability of the residual radioactivity. Specifically, characterization of the existing radiological conditions should be sufficient to estimate both the distribution and total radioactivity of the source term across the site. Dose modeling can then be performed using this source term abstraction. Clearly, the presence of hot spots impacts both the distribution and the total radioactivity.

2.41 Scenarios and Pathways

NUREG/CR-5512 (USNRC1992a) states that the intent of the exposure scenarios is to account for the vast majority of the potential future uses of lands and structures, while discounting a small fraction of highly unlikely future use scenarios. This prudently conservative approach likely overestimates the receptor dose to a degree, but not as much if the worst case scenarios were used.

The particular scenario and its associated environmental pathways are specified in order to calculate the receptor dose that can result from building surface or soil contamination. Receptor dose pathways can range from inhaling air that contains resuspended contaminated soil, ingesting drinking water from a contaminated well, fish from a contaminated pond, or consume plant and animal products that are grown in contaminated soil.

NUREG-1549 (USNRC 1998) introduced a decision framework that provides a methodology for dose assessments used in demonstrating compliance with release criteria. The decision framework provided licensees a flexible approach for demonstrating compliance. Licensees were offered three options to achieve site release: 1) perform activities that reduce uncertainty in either the source term or modeling code; 2) perform activities that reduce contamination remediation; or 3) perform activities that reduce exposure (e.g., land use restrictions). While NUREG-1549 was prepared as a possible alternative to the standard MARSSIM final status survey approach, it has not enjoyed widespread use.

2.42 Pathway Modeling Parameters

Pathway modeling parameters are well described in the following two references: 1) Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil, ANL/EAIS-8 (ANL 1993) and 2) Residual Radioactive Contamination from Decommissioning, Parameter Analysis, NUREG/CR-5512, vol. 3 (USNRC 1999a). The ANL handbook provides parameter definitions, typical ranges and variations, and measurement methodologies for more than 50 modeling parameters. Examples of parameters include soil density, hydraulic conductivity and gradient, inhalation rate, thickness of the contaminated zone

and the fraction of time spent indoors onsite.

NUREG/CR-5512, vol. 3 recognizes three general types of modeling parameters: behavioral, metabolic and physical parameters. Behavioral parameters can be defined as those parameters that depend on the characteristics of the critical group. For example, behavioral parameters include the time that individuals spend in various locations in on-site buildings and land areas, area of land used for gardening, and consumption rates for fruit, grains, seafood, milk and water. The only metabolic parameter considered in this NUREG is the breathing rate, which is usually a function of either being indoors (light activity) or outdoors (moderate activity or gardening). Physical parameters describe the physical characteristics of the site and can be determined by site-specific data collection or by citing relevant data in the literature, such as the annual rainfall amounts at the D&D site. Common examples of physical parameters include the resuspension factor in a building, thickness of the soil contamination layer, crop yields, moisture content of soil, and soil density.

For probabilistic dose modeling it is important to have a reasonable understanding of the uncertainty associated with each of these parameter values. A valuable strategy is to determine which parameters for a specified scenario are important—i.e., sensitive to small changes in parameter values—as this is a critical input to the process of assessing which parameters might be most sensitive to hot spots.

2.5 Dose Modeling Codes

RESRAD, RESRAD-Build and DandD are currently the most popular choices for dose modeling. It is useful to understand some of the major differences between the these codes. Perhaps the best documents to consult concerning the differences between RESRAD and DandD are two NRC documents: NUREG/CR-5512, vol. 4 (USNRC 1999b) and NUREG-1757, vol. 2 , rev. 1 (USNRC 2006). NUREG/CR-5512, vol. 4 states that the fundamental difference between the two codes is that RESRAD is a general purpose environmental dose assessment model, while DandD is specifically designed to model the four scenarios described in NUREG/CR-5512, vol. 1.

2.51 RESRAD and RESRAD-BUILD Models

The RESRAD code for land areas is the centerpiece of the RESRAD family of codes. The RESRAD code has been used by many D&D professionals for more than a decade. The principal application of RESRAD is to calculate the dose rate to a receptor from a specified source term, considering a number of exposure pathways. The pathways include external gamma, inhalation, agricultural (plant, meat and milk ingestion), soil ingestion, aquatic foods, drinking water, and radon. Each of these pathways can be turned off, provided that sufficient justification

exists for not considering a specific exposure pathway.

The primary scenario in RESRAD-BUILD is that of the office worker. This is considered to be a long term scenario, which involves direct radiation, inhalation and ingestion exposure pathways. This modeling code is certainly more complex than the corresponding scenario in the DandD code, but one cannot help but wonder if the complexity offered is really useful. With RESRAD-BUILD, the building can be divided into three rooms, along with controls on ventilation between the rooms, and with the outside air. Of course, this complexity helps with the movement of loose contamination that can become airborne and therefore move throughout the rooms of the building.

Finally, in RESRAD-BUILD, not only can the user provide the location and number of discrete sources, but also defines certain source characteristics that impact the receptor dose. These include the removal fraction, time for source removal, release fraction of material to the indoor air, and the direct ingestion rate. Another plus for RESRAD-BUILD is that the size of the contaminated area can be varied, which allows the calculation of area factors—something that is either impossible, or very difficult for DandD.

2.52 DandD Model

The DandD model has four possible scenarios that can be run. These include building occupancy and building renovation for surface contamination on building interiors, and residential occupancy and drinking water scenarios for land areas.

The DandD model (ver. 1) was developed as a screening computer code. It was intended to be used with conservative default parameters to provide licensees an acceptable method for demonstrating compliance with the unrestricted release criteria. The NRC fully anticipated that pathway analysis/dose assessment codes other than DandD would more than likely be necessary for some D&D sites. Subsequently, the NRC developed DandD, ver. 2 to address the excessive conservatism associated with DandD, ver. 1.

DandD, ver. 2 can perform probabilistic modeling of dose assessments, and it includes a sensitivity analysis module. This model implements the methodology and information contained in NURE/CR-5512, vol. 1 and also uses the parameter probability distribution functions described in NUREG/CR-5512, vol. 3. NUREG-1757, vol. 2 describes the attributes of the DandD ver. 2 model in great detail.

2.6 Determination of DCGLs and Area Factors

Ultimately, the modeling codes are used to generate DCGLs and area factors. A few examples are provided to illustrate how these values can be calculated.

2.61 Dose Modeling to Obtain DCGLs

The $DCGL_W$, based on pathway modeling, is the uniform residual radioactivity concentration level within a survey unit that corresponds to the release criterion. The $DCGL_{EMC}$ is the residual radioactivity concentration present in smaller areas of elevated activity (i.e. hot spots) that also corresponds to the same release criterion. The survey unit sizes selected should be generally consistent with the size of contaminated areas used in the modeling to obtain the $DCGL_W$.

Dose assessments to the potentially exposed population using one of the computer models discussed previously usually begins by calculating the dose due to unit activity on building surfaces (1 dpm/100 cm^2) or in soil (1 pCi/g). The $DCGL_W$ based on a particular dose criterion, say 25 mrem/y, is determined by direct ratio. For example, assume that the dose from 1 pCi/g of Cs-137 using RESRAD, with default parameters, was 1.76 mrem/y. Then the DCGL based on 25 mrem/y is simply 25 mrem/y divided by 1.76 mrem/y per pCi/g, or 14 pCi/g.

Lastly, there is a specific $DCGL_{EMC}$ for each particular hot spot area—for example, if the hot spot area for a particular radionuclide is 10 m^2 the $DCGL_{EMC}$ may be 32 pCi/g, and if the hot spot for the same radionuclide was now confined to only 3 m^2, the $DCGL_{EMC}$ may be 85 pCi/g (note that the smaller the size of the hot spot area, the higher the radionuclide concentration may be that equates to the release criterion). This increase in the allowable concentration in the smaller area is called the area factor. Again, dose modeling is used to determine the magnitude of these area factors as a function of the contaminated area size.

2.62 Dose Modeling to Obtain Area Factors

To obtain area factors, the RESRAD code can be used to calculate the dose for a given input activity and the default contaminated area size (i.e., 2,000 m^2). Then the code is run for successively smaller contaminated area sizes and the resultant dose rates recorded. The dose rate for the smaller contamination area will always be at least as big as that for the default contaminant size. The area factor for a specific contaminant area is simply the dose rate for the smaller contaminant area by the initial dose rate for the default contaminant area. The calculation of area factors can be performed for the desired number of contaminant areas.

In addition to the contaminant area size, the only other parameter that is changed during the determination of area factors is the length of the contaminant area

parallel to the aquifer. It may also be argued that the fraction of food originating from these smaller contaminant zones should also be changed. Or perhaps, the area factors should be based only on the direct radiation exposure pathway.

The following example illustrates the calculation of area factors using RESRAD-BUILD to generate area factors for building surfaces. Essentially, the area factors are determined by calculating the $DCGL_W$ based on a source area of 100 m^2, and then running the code for a number of smaller contamination areas, keeping all other parameters constant. The area factors for Cs-137 (Table 2) show that as the size of the hot spot is reduced, the area factor increases.

Table 2 Area factors for Cs-137 based on RESRAD-Build model.

Source Area (m^2)	Dose Rate (mrem/y)	Area Factor
100	1.25E-5	1
36	8.26E-5	1.51
25	7.05E-6	1.77
16	5.72E-6	2.19
9	4.22E-6	2.96
4	2.53E-6	4.94
1	8.45E-7	14.8

CHAPTER 3 DOSE MODELING OF HOT SPOTS IN SOIL

This research effort involved a detailed look at how hot spots of various areal sizes produce receptor doses for specified environmental and building pathways. Dose modeling of hot spots was performed from first principles. The dose from hot spots was calculated directly for a number of pathways, rather than relying on the MARSSIM area factor approach described in the previous chapter—i.e., calculating the receptor dose for successively smaller contaminated areas.

Additionally, the use of probabilistic risk assessments for determining hot spot doses was considered. For example, the likelihood of encountering a hot spot in a given area was studied, assuming that all areas of a survey unit are equally likely to be occupied by a future receptor. One aspect of this research was to use Crystal Ball to simulate the distribution of some parameters used to develop hot spot limits. For instance, the distribution of distances between receptor and hot spot within a survey unit was evaluated. This allowed sampling from a receptor-to-hot spot distance distribution to obtain a receptor dose distribution.

RESRAD was integral to the dissertation research principally due to the fact that it is the only modeling code used to obtain area factors needed to derive hot spot limits. In that context, going back to first principles for some pathways really meant taking a closer look at how the RESRAD code calculated receptor dose, and more specifically, how the receptor dose was related to the size of the contaminated area. An important aspect of this research was to clearly understand how the RESRAD modeling code handles hot spots when calculating receptor dose.

Pathway-specific conclusions are provided at the end of each section. For example, the primary conclusion for the external radiation pathway is that hot spot doses are much smaller under likely field conditions than assessed under the current practice outlined in MARSSIM. Another interesting point confirmed from this research is that when the predominant pathway is one based on source term inventory, regardless of whether the total activity is spread over 100 m^2 or concentrated in 0.1 m^2, the same amount of activity delivers the same dose. Therefore in this situation, hot spots are only important in the sense that they contribute to the total source term.

3.1 Direct Exposure to External Radiation

The first pathway evaluated is the direct exposure to external radiation from contaminated soil. The receptor dose from a widely distributed source term to the dose from a hot spot of particular size is compared—this ratio of receptor

doses allows calculation of the hot spot limit for that size hot spot. An example case for a hot spot size equal to 10 m^2 of Co-60 in a 1000 m^2 survey unit was evaluated. The actual hot spot dose determined from first principles was compared to the current practice of obtaining area factors described in MARSSIM (refer to Chapter 2), as well as to the result obtained using the MicroShield code. The receptor dose from several smaller hot spot sizes was also calculated; results are tabulated in Appendix C.

3.11 RESRAD Area Factor Approach for Direct Radiation Pathway

The RESRAD area factor approach, described in the MARSSIM, is the conventional approach being used at many decommissioning sites in the U.S. today. This approach uses a correction factor that accounts for the difference in the size of the contaminated area, and the resulting change in dose. The area factor is the magnitude by which the concentration within the small area of elevated activity (hot spot) can exceed $DCGL_W$ while maintaining compliance with the release criterion. The area factors are computed by taking the ratio of the dose or risk per unit concentration generated by RESRAD for the assumed contaminated area (survey unit size on the order of 1000 to 10,000 m^2) to that generated for smaller hot spot sizes (e.g., usually 10 m^2 or smaller).

The potential shortcoming in this widely used approach is that simply reducing the size of the contaminated area, and using RESRAD to calculate dose for this smaller footprint, fails to consider fact that some environmental pathways should be re-evaluated for source terms that are on the order of the size of hot spots—not the typical 1000s of square meters modeled for survey units. This is best understood after reviewing how RESRAD calculates the average guideline ($DCGL_W$). It will then be easier to see how it is related to the hot spot dose and area factor. Appendix A in the RESRAD Manual (ANL 2001) provides a very helpful dose modeling description for the external ground radiation pathway.

First, let's describe how RESRAD calculates the receptor dose from the external ground radiation pathway for a uniformly contaminated area (i.e., size of the survey unit). In general, the effective dose equivalent limit (in mrem/y) is converted to a soil concentration by means of dose to source ratios (DSRs). The DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the external ground radiation pathway the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j} \qquad (3-1)$$

where:
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem/y per

pCi/g; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

Note that i and j are index labels for principal radionuclides—i is the index used for radionuclides that exist initially at time t, and j refers to radionuclides in decay chain of radionuclide i.

The DCF is the effective dose equivalent to the receptor at 1 m above the ground surface from exposure to unit concentration of the radionuclide present in a uniformly contaminated zone. The DCFs in RESRAD were taken from Federal Guidance Report 12 (Eckerman and Ryman 1993). For Co-60, the DCF is 16.21 mrem/y per pCi/g.

The source factor is essentially a correction factor for the source term that accounts for ingrowth and radioactive decay, and contaminated zone erosion due to leaching. The ETF for the external radiation pathway is the ratio of the effective dose equivalent for the actual source to the effective dose equivalent for the standard source. The standard source is a uniformly contaminated zone of infinite depth and lateral extent with no soil cover.

RESRAD was run assuming that Co-60 contamination was present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was modeled. Unit concentration (1 pCi/g) was input in the modeling code. The default occupancy factor is 0.6, which accounts for an outdoor time fraction of 0.25 plus an indoor time fraction of 0.5 that is weighted by a 70% indoor shielding factor. The resulting DSR from the RESRAD run was 7.336 mrem/y per pCi/g. The dose was evaluated by RESRAD to be 7.336 mrem/y at time t = 0 years. The ground radiation pathway was responsible for 99.56% of the total dose, while the plant pathway was roughly the remaining about 0.4%. The $DCGL_W$ based on 25 mrem/y can be calculated as follows: 25 mrem/y/(7.336 mrem/y/1 pCi/g), which yields a value of 3.4 pCi/g.

RESRAD was run again to calculate the area factor, and therefore the $DCGL_{EMC}$, for a 10 m^2 hot spot. The dose from this smaller contaminated area is certainly expected to be less than the dose resulting from the entire survey unit being uniformly contaminated; the dose in this case is 3.212 mrem/y. This time the external ground radiation pathway is responsible for 99.99% of the total dose, with the plant pathway contributing the other 0.01%.

The area factor is calculated by dividing the dose from the larger contaminated area (7.336 mrem/y) by the dose due to the smaller hot spot area (3.212 mrem/y). This ratio is 2.3 and it is the area factor for a 10 m^2 hot spot of Co-60.

The $DCGL_{EMC}$ for the 10 m^2 Co-60 hot spot is therefore 2.3 times 3.4 pCi/g, or 7.8 pCi/g. Hence, the hot spot limit using this approach is 2.3 times the average guideline.

Before calculating the hot spot dose from first principles, it is worthwhile to understand a little more about how RESRAD calculated the hot spot dose from this smaller area. Of the three primary factors defined earlier to determine the DSR for the external radiation pathway, the environmental transport factor is directly impacted by the size of the contaminated area. The other two factors do not depend on the contamination area—i.e., the DCF is defined based on infinite lateral extent, and the source factor is not a function of the contaminated area size. The RESRAD Manual provides the following equation for the ETF for the external radiation pathway (ANL 2001):

$$ETF_i = FO \times FS_i \times FA_i \times FCD_i \qquad (3-2)$$

where:
FO is the occupancy and shielding factor
[FO = f_{otd} + (f_{ind} × F_{sh})), where f_{otd} and f_{ind} are outdoor and indoor time fractions, respectively, and F_{sh} is the indoor shielding factor];
FS is the shape factor (to account for non-circular contaminated areas);
FA is the radionuclide-specific area factor; and
FCD is the depth and cover factor.

Assuming that the only difference in the model is the size of the contaminated area, the occupancy and shielding factor, shape factor, and depth and cover factor are not particularly significant in their role for hot spot dose calculations in RESRAD. The significant factor is clearly the radionuclide-specific area factor, FA.

The area factor, FA, is derived in RESRAD using a point-kernel dose integral over source thickness (T), radius (R), distance from receptor midpoint above ground surface (T_a = 1 m), and thickness of cover material (C_d). Specifically, FA is the ratio of the dose integrals for the hot spot geometry and the infinite lateral extent geometry:

$$FA_{\gamma} = \frac{D[R = r, T_a = 1m, T, C_d]}{D[R = \infty, T_a = 1m, T, C_d]} \qquad (3-3)$$

Notice that the FA parameter is calculated based on the actual size of the contaminated area (using radius r), and divided by an infinite lateral extent geometry. The FA parameter for the 1000 m^2 contaminated area was determined by RESRAD to be 0.936 (therefore 1000 m^2 is nearly an infinite area in this regard). The FA for the 10 m^2 hot spot area is 0.412. The ratio of the FA

parameters is calculated to determine to what degree the difference in receptor dose contribution is due to source geometry: 0.936/0.412 = 2.3, which is exactly the area factor that was calculated above. Therefore, the ratio of these parameters for the two source geometries shows that for the external radiation pathway, FA is solely responsible for determining the area factor.

3.12 MicroShield Area Factor Calculation

MicroShield was used to calculate the exposure rate, with buildup, for the case of uniform Co-60 contamination present to a depth of 15 cm over the 1000 m^2 survey unit. Again, unit concentration in pCi/g was input. The exposure rate result was 2.160E-3 mR/h. The annual dose can be calculated assuming the same outdoor fraction as used by RESRAD (0.25), and recognizing that 1 mR in air is equivalent to 1 mrem in tissue for gamma emitters:

$$Dose = (2.160E-3 mR/h)(8760 h/y)(0.25) = 4.73 mrem/y$$

Once again MicroShield is run to calculate the area factor for a 10 m^2 hot spot. The receptor is assumed to be located at the center of the hot spot. The exposure rate in this case is 9.406E-4 mR/h. This result is converted to annual dose as follows:

$$Dose = (9.406E-4 mR/h)(8760 h/y)(0.25) = 2.06 mrem/y$$

As before, the area factor is calculated by dividing the dose from the larger contaminated area (4.73 mrem/y) by the dose due to the smaller hot spot area (2.06 mrem/y). This ratio is 2.3—the exact same area factor as obtained from the RESRAD code. Therefore, the MicroShield calculation confirms the RESRAD result that the area factor for a 10 m^2 hot spot of Co-60 is 2.3 times the average guideline. Again, it is important to remember that these results are for the case of the receptor located directly on the hot spot.

3.13 Calculation of Hot Spot Dose Based on First Principles

The following derivation applies to a receptor located at some distance from a 10 m^2 hot spot.[5] The hot spot is assumed to be 15 cm deep (no soil cover), and the receptor dose is calculated at a height of 1 m above the ground surface. Initially, buildup was not included in the derivation to permit comparison to the MicroShield results without buildup, but ultimately buildup was included in the dose calculations. It should also be noted that exposure rate in air is the actual quantity being calculated by MicroShield, and so it was for the hand-calculation

[5] The calculation of exposure rate from first principles shown in this section relied heavily on notes taken in the spring semester of 1990 from the University of Lowell Radiological Sciences course 98.532 Introduction to Radiation Shielding.

herein. The equation used to calculate exposure rate is as follows:

$$X_p = (\phi)(E_\gamma)(\frac{\mu_{en}}{\rho})(\frac{e^-}{\overline{w}}) \qquad (3-4)$$

where
φ is the gamma ray fluence at the receptor location,
E_γ is the average gamma energy emitted from the radionuclide,
μ_{en}/ρ is the energy absorption coefficient in air,
e^- is the charge on an electron, and
w-bar is the average energy needed to create an ion pair in air.

The gamma fluence from a point source (assuming no attenuation in air) is given by:

$$\phi = \frac{S}{4\pi r^2} \qquad (3-5)$$

where S is the source strength in units such as gammas per second.

The 10-m^2 hot spot has a radius of R = 1.784 m, and a depth y in soil of 15 cm. The receptor dose is calculated at a distance T_a = 1 m above the soil surface. The Co-60 source term is assumed to be 1 pCi/g, uniformly distributed within the hot spot soil volume. Assuming a soil density of 1.6 g/cm^3, this source term can be expressed as follows:

$$S_V = (1\,pCi/g)(1.6\,g/cm^3)(2.22\,dpm/\,pCi)(1\min/60\,s)(2\gamma/dis) = 0.117\gamma/cm^3 s$$

The receptor dose is calculated using the point kernel technique. A differential volume element, dV, is identified as 2πrdrdy (Figure 1). The distance from the differential volume source to the receptor dose point is ρ. This distance varies with the radius (r) and the soil depth, y. Figure 1 illustrates the hot spot to receptor geometry used to calculate external radiation exposure.

Specifically, this is written

$$\rho^2 = (T_a + y)^2 + r^2$$

Now, from the position of the differential volume source, z is defined as the soil distance the gamma ray traverses on its way to the receptor dose point.

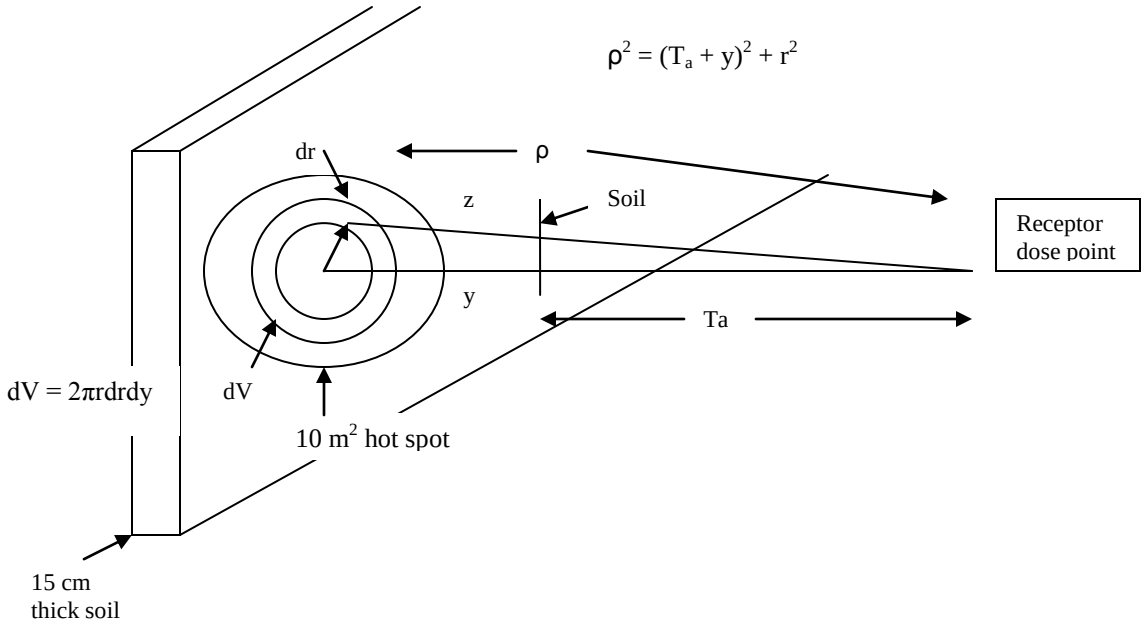

Figure 1 Geometry used to calculate external radiation exposure at receptor location.

Recognizing the similar right triangles, z is expressed in the following equation

$$\frac{\rho - z}{\rho} = \frac{T_a}{T_a + y},$$

and solving for z yields

$$z = \frac{\rho\, y}{T_a + y}$$

Taking the partial derivatives with respect to ρ and r of the following equation (holding the depth y constant):

$$\rho^2 = (T_a + y)^2 + r^2$$

this yields

$$2\rho\, d\rho = 2r\, dr$$

Substituting into the differential volume element expression:

$$dV = 2\pi r\, dr\, dy = 2\pi\rho\, d\rho\, dy$$

Next, the expression is shown for differential exposure rate at the receptor dose location, without buildup:

$$dX_P = \frac{k\, S_V\, dV\, e^{-\mu z}}{4\pi\rho^2} \qquad (3-6)$$

where k is a conversion factor used to convert the gamma fluence to exposure rate. Specifically, k is calculated for an energy absorption coefficient (μ_{en}/ρ) for air of 0.0266 cm^2/g, based on average Co-60 gamma energy per photon of 1.25 MeV:

$$k = (0.0266\frac{cm^2}{g})(1.25\frac{MeV}{\gamma})(\frac{1R}{2.58E-4C/kg})(\frac{1.6E-19C}{33.7eV})(\frac{1E6eV}{MeV})\times$$
$$(\frac{1000g}{kg})(\frac{3600s}{h})(\frac{1000mR}{R})$$

Combining terms, the following value for k is obtained:

$$k = 2.203E-3\frac{cm^2\ s\ mR}{\gamma\, h}$$

Substituting the expressions for dV and z into equation (3-6) and canceling like terms:

$$dX_P = \frac{k\, S_V}{2}\frac{e^{-\mu(\frac{\rho y}{T_a+y})}}{\rho}\, d\rho\, dy$$

Integrating the above expression to yield the exposure rate at the receptor location:

$$X_P = \frac{k\, S_V}{2}\int_0^T \int_{T_a+y}^{\sqrt{(T_a+y)^2+R^2}} \frac{e^{-\mu(\frac{\rho y}{T_a+y})}}{\rho}\, d\rho\, dy \qquad (3-7)$$

where the limits of integration on y are 0 to T (soil contamination depth), and integration limits on ρ are $T_a + y$ (when r = 0), and $((T_a + y)^2 + R^2)^{0.5}$, when r = R.

Maple (mathematics software package) was used to perform the double integration of the point kernel above. To solve, it was necessary to split the

integral into two single integrals and appropriately account for the limits of integration (Maple output provided in Appendix A). The result was 5.817E-4 mR/h at the receptor dose location. This compared quite favorably to the MicroShield result (also without buildup) of 5.925E-4 mR/h.

Two observations can be made from the above exercise. First, going back to first principles to calculate exposure rate at the receptor location provides a clear picture of the physics and approach involved in the calculation. Second, the resulting small relative percent difference (1.9%) when compared to the MicroShield result validates the MicroShield code. The calculations behind the MicroShield approach can be understood, and used to calculate the exposure rate at other receptor locations relative to the hot spot. Indeed, going forward, both MicroShield and RESRAD were used to calculate the receptor dose for the situation where the receptor is not located directly on the hot spot.

Now radiation buildup is introduced into the exposure rate calculation. The buildup factors used by both RESRAD and MicroShield (Ver. 5) were considered. RESRAD uses the energy absorption buildup factor for length measured in mean free paths (Trubey 1991).[6] Conversely, the MicroShield User's Manual states that for most geometries, buildup factors are obtained from tables of buildup factors, and interpolation is performed as necessary. The user's manual cites exceptions for the infinite plane and infinite slab geometries, where Taylor buildup formula is used. The approach used in the hand calculation was performed using Taylor's three parameter buildup formula (Chilton 1984):

$$B = Ae^{-\alpha_1 \mu r} + (1-A)e^{-\alpha_2 \mu r} \qquad (3-8)$$

The soil composition modeled in RESRAD and MicroShield has an effective atomic number (z_{eff}) of approximately 10.5. The Taylor buildup factor coefficients provided for ordinary concrete were used to account for buildup because coefficients are not available for soil. Concrete is considered to be a reasonable surrogate for soil due to its similarity to soil in terms of effective atomic number (z_{eff} for ordinary concrete is 11).[7] Specifically, buildup coefficients (A, α_1, and α_2) were provided for gamma energies that bound the gamma energy of concern (1.25 MeV). Interpolation between gamma energies of 1 and 2 MeV was performed to determine the coefficients for 1.25 MeV. Morgan and Turner (1967) state that interpolation is possible because "buildup factors are smoothly varying functions of both atomic number and energy…". The interpolated coefficients were as follows: A = 23.652; α_1 = -0.06485; and α_2 = -0.01170.

[6] New gamma-ray buildup factor data for point kernel calculations: ANS-6.4.3 standard reference data; NUREG-5740; 1991.

[7] Morgan and Turner, Principles of Radiation Protection; Table 9-3 Parameters for the Taylor Form of the Buildup Factor, p. 273.

The Taylor buildup formula and coefficients were incorporated into the exposure rate expression as follows:

$$X_P = \frac{k\,S_V}{2}\int_0^T \left(A\int_{T_a+y}^{\sqrt{(T_a+y)^2+R^2}} \frac{e^{-(1+\alpha_1)(\frac{\mu\rho y}{T_a+y})}}{\rho}\,d\rho + (1-A)\int_{T_a+y}^{\sqrt{(T_a+y)^2+R^2}} \frac{e^{-(1+\alpha_2)(\frac{\mu\rho y}{T_a+y})}}{\rho}\,d\rho \right) dy \qquad (3-9)$$

Maple was used to perform the double integration of the point kernel above (Appendix A provides the Maple output). To solve, it was necessary to evaluate each inside integral separately, and then to integrate the sum over the depth variable y. The result was 1.077E-3 mR/h at the receptor dose location. This compared reasonably well with the MicroShield result with buildup of 9.401E-4 mR/h (~12.7% relative percent difference). The difference is likely due to the approach MicroShield calculates buildup versus how it was performed in the hand calculation.

3.14 Comparison using RESRAD, MicroShield and Hand Calculations

RESRAD calculated an annual receptor dose to the 10 m^2 hot spot of 3.212 mrem/y. This was based on an outdoor fraction of 0.25, and recognizing that 99.99% of the total dose came from the external pathway. Also, the receptor was assumed to be located directly above the hot spot for 0.25 × 8760 hours per year. This result can be compared to that obtained using MicroShield (using the buildup result). The annual dose was calculated assuming the same outdoor fraction—the result was 2.06 mrem/y. Thus, the difference between the RESRAD and MicroShield results was approximately 36%.

Finally, the receptor annual dose is calculated using the hand calculation, making the same assumptions as stated above:

$$Dose = (1.0774E-mR/h)(8760h/y)(0.25) = 2.36 mrem/y$$

The hand calculation based on first principles resulted in a receptor dose value that was between that determined from RESRAD and MicroShield.

Therefore, comparable results are obtained using three different techniques for calculating the receptor dose to a 10 m^2 hot spot: 3.212, 2.06, and 2.36 mrem/y. While this general consistency of results is encouraging from a perspective of calculation validation, the fact remains that assuming that the receptor is located directly on the hot spot for all of their time spent outdoors is very conservative, not to mention unrealistic.

3.15 Receptor Located Some Distance from the Hot Spot

The next step was to evaluate the receptor dose from a 10 m^2 hot spot when the receptor is located some distance from the hot spot. An arbitrary distance of 6 m was selected to evaluate both RESRAD and MicroShield calculations of the annual receptor dose from a 10 m^2 Co-60 hot spot. The RESRAD annual dose was 9.506E-2 mrem/y (99.66% from external radiation pathway). As before, this result was based on an outdoor fraction of 0.25, and the receptor was assumed to located 6 m from the hot spot for 0.25 × 8760 hours per year. Note: The RESRAD feature "Shape of the Contaminated Zone" was used to draw the contaminated area, and then position the receptor using the mouse. It can be a bit tricky to create a 10 m^2 hot spot and then to position the receptor precisely 6 m from the hot spot.

MicroShield (considering buildup) was then used to calculate the receptor dose the same distance from the hot spot. Again, the annual dose was calculated assuming the same outdoor fraction, and recognizing that 1 mR in air is similar to 1 mrem in tissue for gamma emitters:

$$Dose = (2.737E-5\, mR/h)(8760 h/y)(0.25) = 5.994E-2\ mrem/y$$

The difference between the RESRAD and MicroShield results is about 37%. Differences in the determination of radiation buildup and occupancy factor values are likely causes for this difference. Ultimately this difference is not that important. Rather, the hot spot area factors are of interest, and they depend on the relative decrease in dose for each method used.

For example, given the receptor dose based on a 6 m distance from the hot spot, the RESRAD area factor is calculated. Specifically, the area factor is calculated by dividing the dose from the 1000 m^2 contaminated area (7.336 mrem/y) by the dose due to the smaller hot spot area located 6 m from the receptor (9.506E-2 mrem/y). This ratio is 77, and it represents the area factor for a 10 m^2 hot spot of Co-60 assuming that the receptor is 6 m from the hot spot. The $DCGL_{EMC}$ for the 10 m^2 Co-60 hot spot in this case was 77 times 3.4 pCi/g, or 262 pCi/g. Again, the important outcome is that the hot spot limit using this approach is 77 times the average guideline.

The MicroShield area factor is then calculated for the same distance. As before, the area factor is calculated by dividing the dose from the 1000 m^2 contaminated area (4.73 mrem/y) by the dose due to the smaller hot spot area located 6 m from the receptor (5.992E-2 mrem/y). The area factor turns out to be 79, which is close to the result determined by RESRAD.

So, the area factor for a 10 m^2 hot spot is 2.3 when the receptor is located directly on the hot spot, and 77 (or 79) when the receptor is 6 m from the hot spot. What is a technically defensible approach for determining a reasonable

receptor-to-hot spot distance? One approach is to use probabilistic modeling to determine a distribution of distances to evaluate.

3.16 Proposal to More Realistically Assess Hot Spot Dose

The proposal is to use a probabilistic approach for assessing receptor distance from the hot spot location, and to use that distance in the determination of hot spot area factor. This approach provides a more realistic assessment of the receptor dose from hot spots by considering the probability of getting dose from these small source terms. The current area factor approach assumes the worst case that receptor has the misfortune of spending all allotted outdoor time perched on the hot spot. This is very unlikely, and should not form the basis for determining hot spot doses. In that regard, it is important to point out the significant conservatism of assuming that the receptor spends all of their time on the hot spot when outdoors.

A comparison to the inhalation pathway is instructive. RESRAD uses an environmental transport factor (ETF) to calculate inhalation dose to a receptor located at some distance from the source of the airborne contamination. That is, RESRAD does not assume that the receptor is located at the hot spot location for purposes of inhalation pathway calculations. [Many screening calculations do indeed assume the receptor is located directly over the hot spot, and assume that the receptor inhales the radioactivity that is resuspended without the benefit of airborne dispersion]. Rather, RESRAD uses the transport (e.g., wind) of radioactivity to provide some measure of atmospheric dispersion (dilution) of the airborne radioactivity before it is inhaled by the receptor. So, a parallel assumption for the external radiation pathway would be that the receptor is NOT located directly on the hot spot, but rather some distance from the hot spot.

One possibility as to why RESRAD handles receptor dose from hot spots in this manner is that it is an unintended consequence of the usual receptor-to-source geometry where the receptor is assumed to be located above an infinite plane source. This is the geometry used in Federal Guidance Report No. 12 to obtain the dose coefficients for contaminated soil (Eckerman and Ryman 1993), and these dose coefficients are used in the RESRAD code. So the default approach in RESRAD is to position the receptor directly over the source (Note: RESRAD does allow the user to change this receptor-to-source geometry). As long as the source is large (on the order of 10s to 100s of square meters), it doesn't matter where the receptor is located, the external radiation exposure at the receptor location is essentially constant. However, for a small radiation source (i.e., hot spot size), it no longer makes sense to assume that the receptor is located directly above the source. Rather, it is more appropriate to assume that the receptor is likely to be some distance from the hot spot over the course of time the receptor spends outdoors.
Furthermore, the NRC has adopted a philosophy of being "prudently

conservative" when it comes to dose modeling. Background discussion in Appendix I of NUREG-1757 (USNRC 2006) states that the Commission directed NRC staff to address areas of excessive conservatism, and to use a probabilistic approach for calculating the total effective dose equivalent. This proposed approach is consistent with the NRC's stated philosophy—it will result in a much lower dose from potential hot spots present.

The idea is to generate a distribution of distances (*l*), and use this variable to calculate a distribution of doses that result when considering that the receptor will usually be located at varying distances from the hot spot. The receptor can be located at any location (x_1, y_1) within the survey unit, and the same goes for the hot spot (x_2, y_2). The distance between the receptor and hot spot is given by:

$$l=\sqrt{(y_1-y_2)^2+(x_1-x_2)^2} \qquad (3-10)$$

Assume a Class 1 survey unit of 1000 m^2 with square dimensions of 31.6 m × 31.6 m. The minimum distance between the receptor and hot spot is zero (current assumption in practice), and the maximum distance in this case is the diagonal in the survey unit (44.7 m).

Crystal Ball was used to generate 1000 trials of random locations for the receptor and hot spot location. A uniform distribution was assumed for sampling each of the two pairs of coordinates, with a minimum of zero and maximum of 44.7 m. The Crystal Ball output is provided in Table 3.

Table 3 Distribution of receptor-to-hot spot distances (m) using Crystal Ball.

Statistic	Forecast Value	Fit Value: Beta Distribution
Mean	16.8	16.8
Median	16.65	16.57
Standard Deviation	7.86	7.86
Minimum	0.33	-2.28
Maximum	38.19	39.86

Figure 2 shows the Crystal Ball output trials as well as the best fit to these data, which was a beta distribution. The average distance between receptor and hot

spot based on this simulation was 16.8 m, with a standard deviation of 7.86 m. The minimum and maximum distances were 0.33 and 38.2 m, respectively. Obviously, the most conservative distance to select would be zero—and that is precisely what is being done today. A reasonably conservative distance might be the 10% percentile value of the distribution—for this simulation the 10% percentile is 6.01 m. That is, only 10% of the expected receptor-to-hot spot distances are less than 6 m, while 90% are greater than 6 m.

3.17 External Radiation Pathway Results

Results from the RESRAD and MicroShield runs are provided in Appendix B for Co-60 as an example of the code output. A summary of this output is provided in Tables 27 to 34 in Appendix C which show the hot spot area factors as a function of radionuclide, hot spot size, and receptor distance from the hot spot for both RESRAD and MicroShield. The reference survey unit size is 1000 m^2. Note that only MicroShield was used to calculate the dose for the situation where the receptor is located 6 m from the hot spot. It should also be noted that the RESRAD code does not allow the calculation of doses for hot spot sizes smaller than 1 m^2 areas. [8] Otherwise, the RESRAD and MicroShield area factors are generally comparable for the case where the receptor is located directly on the hot spot.

The consistency of area factors independent of radionuclide was interesting. For example, the area factor ranged from roughly 7 to 11 for a 1 m^2 hot spot, from 12 to 21 for a 0.5 m^2 hot spot, and 60 to 100 for a 0.1 m^2 hot spot.

The assumption that the receptor might be located 6 m from the hot spot on average had a significant impact on the resulting area factors. Also note how consistent the area factors are across the range of different radionuclides: area factors ranged from 650 to 785 for a 1 m^2 hot spot and from 1150 to 1280 for a 0.5 m^2 hot spot.

3.18 External Radiation Pathway Conclusions

The primary conclusion based on the external radiation pathway is that hot spot doses are much smaller under likely field conditions than assessed under current

[8] This situation was discussed with Dr. Charley Yu (ANL) in March 2008. Dr. Yu agreed that RESRAD had this limitation and his proposal to fix RESRAD for hot spots less than 1 m^2 was to use either extrapolation or simply assume that the dose will be linearly proportional to area for area less than 1 m^2. This new area factor method for areas less than 1 m^2 will be available in upcoming versions of RESRAD and RESRAD-Offsite.

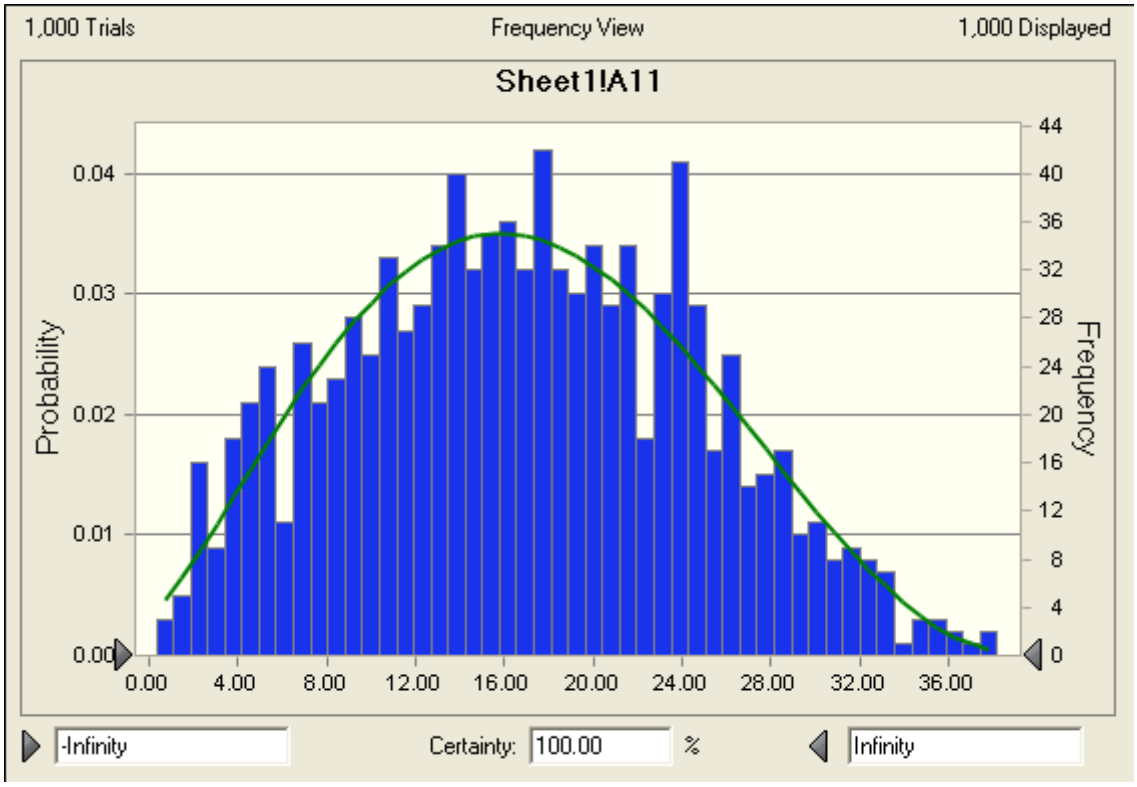

Figure 2 Output from Crystal Ball simulation of receptor to hot spot distances.

regulatory criteria. This is particularly true for the assumption that the receptor is located 6 m from the hot spot. The area factors for the eight radionuclides evaluated when the receptor was located directly on the hot spot ranged from 6.6 to 11.4 for 1 m^2 hot spot; and ranged from 650 to 785 when the receptor was located 6 m from the 1 m^2 hot spot. Thus, allowing the receptor to be on average 6 m from the hot spot over the exposure time results in area factors that are much greater than currently allowed. However, these larger area factors are still more restrictive than those area factors that scale directly with the size of the contaminated area (where the area factor for 1 m^2 area is 1000).

It is worth emphasizing that the area factors for external radiation pathway are generally the same regardless of the radionuclide. For example, the area factor ranged from roughly 7 to 11 for a 1 m^2 hot spot, from 12 to 21 for a 0.5 m^2 hot spot, and 60 to 100 for a 0.1 m^2 hot spot. From an application perspective, it might be beneficial to consider establishing the area factors for the external radiation pathway based on the most limiting radionuclide—which was Am-241 or I-129, depending on the model (RESRAD or MicroShield) used to generate the area factor.
MicroShield was used to calculate area factors for hot spot sizes less than 1 m^2;

this is particularly helpful for the design and implementation of final status surveys. Hot spots on the order of 0.1 m^2 are commonly identified during field surveys. As discussed in Chapter 6, the upper tail of the contaminant (e.g., 99th percentile) can often be considered to consist of smaller areas of contamination. So it is reasonable to consider a DCGL based on the 99th percentile as the $DCGL_{EMC}$ for a small hot spot, such as 0.1 m^2.

In conclusion, the impact of this dissertation work is that the current hot spot limits being used at many cleanup sites are overly restrictive, and may result in the decommissioning industry paying for something that provides very little value. Substantial reductions in cleanup and survey costs are possible if hot spot criteria are established on a stronger technical basis—e.g., using area factors for hot spot sizes less than 1 m^2 when the hot spot size warrants, and possibly considering that the receptor may be some distance from the hot spot.

3.2 Inhalation Exposure to Resuspended Soil

The second pathway evaluated is the inhalation exposure due to resuspended contaminated soil. The receptor dose from a widely distributed source term to the dose from a hot spot of particular size is compared—this ratio of receptor doses allows calculation of the hot spot limit for that size hot spot. A detailed look at how hot spots of various sizes actually produce receptor doses for the inhalation exposure to resuspended soil is considered in this section. The hot spot sizes considered are 10 m^2, 3 m^2, 1 m^2, 0.5 m^2, 0.1 m^2 and 0.01 m^2. An example case for a hot spot size equal to 10 m^2 of Pu-239 in a 1000 m^2 survey unit was evaluated.

3.2.1 RESRAD Area Factor Approach for Inhalation Exposure Pathway

Resuspension is the physical mechanism of re-injecting particulates that have been deposited on the ground from an atmospheric deposition event back into the atmosphere. Once the particulates have been resuspended, they are dispersed as they travel toward the receptor. An air transport and dispersion model is used to calculate dispersion coefficients throughout the area of interest for unit releases from each of the resuspension sources. Note that resuspension rates from contaminated soil can increase due to the amount of soil exposed (lack of vegetative cover), size of the area involved, and the resuspension mechanisms (ERG 2004).

The inhalation exposure pathway involves two phenomena to deliver receptor dose: 1) soil contamination becomes airborne, and 2) receptor inhalation of airborne concentration of radionuclides for some duration. The first phenomenon considers the airborne concentration near the source due to resuspension of the

contamination, and the second considers the dilution of the airborne concentration as it moves to the receptor location via air dispersion. Appendix B in the RESRAD User's Manual describes the dose modeling description for the inhalation exposure to resuspended soil pathway (ANL 2001).

This section describes how RESRAD calculates the receptor dose from the inhalation pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). As with the external radiation pathway, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the inhalation exposure to resuspended soil pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j} \qquad (3-11)$$

where
DCF_j is the dose conversion factor for the j^{th} radionuclide in mrem per pCi;
$BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j;
ETF_j is the environmental transport factor for the j^{th} radionuclide at time, t; and
$SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.
[Note that i and j are index labels for principal radionuclides—i refers to radionuclides that exist initially at time t, and j refers to radionuclides that exist in decay chain of radionuclide i.]

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by an individual from inhalation exposure of unit radioactivity of the radionuclide present. The DCFs in RESRAD were taken from FGR-11 (USEPA 1988). For example, the DCF for Pu-239 is 0.429 mrem/pCi. The source factor is essentially a correction factor for the source term that accounts for ingrowth, radioactive decay, and leaching.

The environmental transport factor for the inhalation exposure pathway is the ratio of the annual intake of the i^{th} principal radionuclide by dust inhalation to the concentration of that radionuclide in the soil. Of the three primary factors used to determine the DSR for the inhalation exposure pathway, the environmental transport factor is impacted by the mass loading of airborne contaminated particles and the size of the contaminated area—called the area factor in RESRAD. The RESRAD Manual provides the following equation for the ETF for the inhalation exposure pathway:

$$ETF_i = ASR_i \times FA_i \times FCD_i \times FO_i \times FI_i \qquad (3-12)$$

where
ASR is the air-to-soil concentration ratio, which also equals the mass loading of airborne contaminated soil particles (RESRAD default is 1E-4 g/ m^3);
FA is the area factor;
FCD is the depth and cover factor
[FCD = 1 when contaminated zone thickness exceeds the depth of the soil mixing layer];
FO is the occupancy factor
[FO = f_{otd} + (f_{ind} × F_{dust})), where f_{otd} and f_{ind} are outdoor and indoor time fractions, respectively, and F_{dust} is the indoor dust filtration factor]; and
FI is the annual intake of air (8400 m^3/y).

RESRAD uses a constant mass loading factor for estimating the airborne concentration near the source. By way of comparison, the NRC's DandD model uses a resuspension factor model to describe the process by which the dust becomes airborne. RESRAD models dilution of the airborne concentration using a zero release height Gaussian plume model. This approach is embodied in the area factor, which depends on the particle size, wind speed, and size of the contaminated area. Least squares regression was used to fit the area factor in RESRAD, with the resultant equation shown below:

$$FA = \frac{a}{1 + b(\sqrt{A})^c} \qquad (3-13)$$

where
A is the size of the contaminated area (m^2);
a, b, c are coefficients of least squares regression that are provided as a function of wind speed.

As an illustrative example, RESRAD was run for a source term of Pu-239 contamination (1 pCi/g) that was present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The outdoor time fraction was 0.25, and when combined with an indoor time fraction of 0.5 and dust filtration factor of 0.4, an occupancy factor of 0.45 is obtained for the inhalation pathway. The resulting DSR from the RESRAD run is 0.1702 mrem/y per pCi/g (this result considers all pathways). The receptor dose, from all pathways based on 1 pCi/g soil contamination, is therefore 0.1702 mrem/y at time t = 0 years. The inhalation exposure pathway accounts for 12.65% of the dose—the inhalation pathway was responsible for delivering a dose of 0.02154 mrem/y. The soil ingestion and plant pathways were responsible for 56.7% and 30.2% of the receptor dose, respectively. The $DCGL_W$ based on 25 mrem/y can be calculated: 25

mrem/y/(0.1702 mrem/y/1 pCi/g) = 147 pCi/g.

RESRAD was then used to calculate the area factor, and therefore the $DCGL_{EMC}$, for a 10 m^2 hot spot. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The dose from this smaller contaminated area was 0.01474 mrem/y. This time the inhalation exposure pathway was responsible for 89.4% of the total dose, or 0.01317 mrem/y; the soil ingestion and plant pathways contributed 6.55% and 3.48%, respectively. It is noteworthy that the inhalation exposure pathway contribution jumped from 12.65% to nearly 90% as the contaminated area size was reduced from 1000 m^2 to 10 m^2.

The area factor is calculated by dividing the dose (from all pathways) from the larger contaminated area (0.1702 mrem/y) by the dose due to the smaller hot spot area (0.01474 mrem/y). This ratio is 11.5 and it is the area factor for a 10 m^2 hot spot of Pu-239. The $DCGL_{EMC}$ for this 10 m^2 Pu-239 hot spot is therefore 11.5 times 147 pCi/g, or 1700 pCi/g. Therefore, the hot spot limit using this approach is 11.5 times the average guideline. However, the inhalation pathway is of particular interest.

Focusing exclusively on the inhalation pathway for delivering receptor dose, the area factor based on the inhalation exposure pathway alone is calculated. Recall that the inhalation pathway dose for the 1000 m^2 survey unit was 0.02154 mrem/y. The inhalation pathway dose for the 10 m^2 hot spot was 0.01317 mrem/y. The area factor based on the inhalation exposure pathway is simply 0.02154 mrem/y divided by 0.01317 mrem/y, or 1.64. This means that the smaller hot spot area still results in a sizeable inhalation dose relative to the large 1000 m^2 survey unit.

The inhalation pathway area factor result is checked against the RESRAD area factor (FA). Note that RESRAD uses a default particle size of 1 μm and wind speed of 2 m/s. The linear regression coefficients for these defaults are a = 1.6819, b = 25.5076, and c = -0.2278. For a survey unit area of A = 1000 m^2, FA is given by:

$$FA = \frac{1.6819}{1 + 25.5076(\sqrt{1000})^{-0.2278}} = 0.1333$$

The FA parameter is determined for a hot spot area A = 10 m^2 using the same equation. The result is FA = 0.0816. Next, the ratio of the FA parameters is obtained, 0.1333 divided by 0.0816, or 1.63. This is virtually the same result obtained by taking the ratio of the inhalation exposure pathway doses shown above (i.e., 1.64). This means that the difference in receptor dose (as a result of changing contaminated area sizes) is due entirely to the FA parameter.

It is instructive to see how RESRAD calculates the inhalation pathway dose for the 10 m^2 hot spot. Recall that the DCF for Pu-239 is 0.429 mrem/pCi. The ETF is calculated:

$$ETF = (1E-4\,g/m^3)\times(0.0816)\times(1)\times(0.45)\times(8400 m^3/y) = 3.08E-2\ g/y$$

Now the inhalation pathway dose from the 10 m^2 hot spot is calculated:

$$D_{inh} = (0.429 mrem/pCi)\times(3.08E-2\,g/y)\times(1\,pCi/g) = 0.0132 mrem/y$$

This calculation shows how the RESRAD area factor (FA) parameter operates according to the size of the contaminated area (although rather weakly), and confirmed the hot spot inhalation pathway dose calculation. It is reasonable to conclude that for Pu-239, the inhalation exposure pathway delivers nearly the same dose from a 10 m^2 contaminated area as it does from the soil concentration in a 1000 m^2 area (difference is only factor of 1.63). That is, even with100 times more activity in 1000 m^2 survey unit than in the 10 m^2 hot spot, the inhalation dose from the survey unit is only 1.63 times greater. This seems to be a bit non-intuitive, and certainly conservative.

One might expect that the inhalation receptor dose would generally scale with size of contaminated area, similar to the approach in RESRAD-BUILD. Indeed, the Eastern Research Group (ERG 2004) reports that source term "emission rates might increase, depending on the amounts of soil exposed, the size of the area involved, and the resuspension mechanisms." The receptor dose based on first principles was considered next.

3.2.2 Calculation of Inhalation Pathway Dose Based on First Principles

The inhalation pathway dose was first calculated for a receptor located in a 1000 m^2 survey unit uniformly contaminated with Pu-239 to a depth of 15 cm (no soil cover). The default parameters selected are the same as those used in RESRAD—namely a mass loading factor of 1E-4 g/ m^3, occupancy factor of 0.45, and an annual intake of air equal to 8400 m^3/y. The inhalation dose can be calculated as follows:

$$D_{inh} = (1\,pCi/g)\times(1E-4\,g/m^3)\times(8400 m^3/y)\times(0.429 mrem/pCi)\times(0.45) = 0.162\ mrem/y$$

This inhalation dose calculated above is much higher than that determined by RESRAD (by a factor of 7.5) for the same contamination size of 1000 m^2 (0.0215 mrem/y). Indeed, the RESRAD result is 0.133 times the inhalation pathway dose calculated from first principles. The difference is due to the application of an area factor in RESRAD that serves to dilute the airborne concentration that the

receptor inhales. The hand calculation makes the conservative assumption that the airborne concentration predicted by multiplying the soil concentration by the mass loading factor is the same concentration breathed by the receptor. This is analogous to simple screening techniques that assume that the airborne concentration at the receptor is equal to the airborne concentration at the point of release (a conservative approach indeed).

Both mechanical disturbances (tilling fields) and wind erosion can generate airborne concentrations. The distance between the point of generation and the receptor location is variable. It may be that the Gaussian plume model aspect of FA parameter may adequately consider the receptor distance from the hot spot. That is, the dilution afforded by the FA parameter effectively accounts for the variable receptor to hot spot distance. The FA parameter in RESRAD adds realism by diluting the airborne concentration that reaches the receptor location. Therefore, the FA factor will be used in the calculation of receptor inhalation dose using first principles—the revised inhalation dose for a 1000 m^2 contaminated area is 0.0216 mrem/y. Therefore, the RESRAD and hand calculation of inhalation dose for a 1000 m^2 contaminated area are essentially equal.

3.2.3 Proposal to More Realistically Assess Hot Spot Dose

As a point of interest, the FA parameter for a 1 m^2 hot spot for the same conditions is 0.0634, which yields a factor of 2.1 when divided into the FA for the 1000 m^2 area (0.1333). So, while the FA parameter accounts for the size of the contaminated area, it does so very weakly. This simple example shows that the inhalation dose is only reduced by a factor of 2.1 as the contaminated area is reduced from 1000 m^2 to 1 m^2.

ERG (2004) discusses resuspension of contamination in the context of open field areas that have either unlimited or limited wind erosion potential. An unlimited potential area can be characterized by a smooth field, lacking vegetation, and covered with a thick reservoir of loose sandy soil (unlimited reservoir). Conversely, a limited potential area can be characterized by a heterogeneous field covered with a high density of gravel, rocks, or vegetation. Considering these definitions, it seems that small hot spots would be classified as having limited wind erosion potential—primarily due to the fact that they do not possess an unlimited reservoir of contamination available for resuspension. Once winds begin to resuspend contamination, “the supply of erodible particles is quickly exhausted…” (ERG 2004). Therefore, it seems reasonable to conclude that the source term available for inhalation pathway depends more strongly on the contaminated area size than credited by the RESRAD approach.

To increase the effect of contaminated area on the inhalation dose, a simple reduction term defined by dividing the hot spot area by the survey unit area is proposed. This simply reduces the radionuclide source term available to deliver

inhalation dose to the receptor.

Now the inhalation pathway dose to a receptor is calculated from a 10 m^2 hot spot. As before, assume that the contaminant is Pu-239 to a depth of 15 cm (no soil cover). Assume that the same default parameters as used in RESRAD—namely a mass loading factor of 1E-4 g/ m^3, occupancy factor of 0.45, and an annual intake of air equal to 8400 m^3/y. The FA parameter for a 10 m^2 hot spot for default conditions described above is 0.0816, and the source term reduction factor is 10/1000, or 0.01. This calculation assumes that the airborne contamination that the receptor breathes is directly proportional to the hot spot size. The inhalation dose can be calculated as follows:

$$D_{inh} = (1\,pCi/g) \times (0.0816) \times (0.01) \times (1E-4\,g/m^3) \times (8400 m^3/y) \times (0.429 mrem/pCi) \times (0.45) = 1.32E-4\ mrem/y$$

This receptor dose is less than the 0.0216 mrem/y dose calculated for the 1000 m^2 survey unit due to the source term reduction factor (0.01) and the ratio of the FA parameters (0.0816/0.133, or 0.613). This calculation assumes that the source term reduction factor effectively accounts for the fact that the receptor inhalation dose delivered from a hot spot reflects the reduced total source term in a hot spot. This source term reduction factor, along with the FA parameter, considers the size of the contaminated area on the determination on receptor inhalation dose. The area factor for a 10 m^2 Pu-239 hot spot is determined by dividing the 1000 m^2 dose (0.0216 mrem/y) by the 10 m^2 hot spot dose (1.32E-4 mrem/y)—which results in an area factor of 163.

3.2.4 Inhalation Pathway Results

Key output pages from the Co-60 RESRAD runs as an example are provided in Appendix B. Tables 35 to 45 in Appendix D illustrate the hot spot area factors as a function of radionuclide, hot spot size, and receptor distance from the hot spot for both RESRAD and the hand calculation. The area factors calculated using the RESRAD code were the same for all of the radionuclides studied with the exception of C-14. This means that the manner in which the soil contamination becomes airborne and then transported to the receptor location is independent of the particular radionuclide. Again, with the exception for C-14, these area factors had a very small range, from 1.64 to 3.49 for hot spots ranging in size from 10 m^2 to 0.01 m^2.

The area factors calculated using the hand calculations were significantly larger. These area factors were consistent for all eleven radionuclides studied, ranging from a low of 163 for a 10 m^2 hot spot, to 3.50E5 for a 0.01 m^2 hot spot. It is clear that based on the hand calculations, the inhalation pathway area factors are much larger than the corresponding external radiation pathway area factors. For

example, the inhalation area factor for Cs-137 for 1 m^2 is 2100, while the area factor for external radiation for Cs-137 is about 11. Therefore, the inhalation pathway area factors are not hot spot sensitive using the hand calculation approach.

3.2.5 Inhalation Pathway Conclusions

The inhalation doses for hot spots calculated by RESRAD are more than 100 times greater than the results obtained from the hand calculations (refer to Tables 35 to 45 in Appendix D). Area factors calculated using the hand calculations are correspondingly much greater than those calculated using the RESRAD code. This is due to the hand calculation approach of dividing the hot spot area by the survey unit area—which simply reduces the radionuclide source term available to deliver inhalation dose to the receptor.

As mentioned earlier, it seems that the RESRAD inhalation pathway calculations do not effectively account for the smaller source term presented by hot spots. In other words, the receptor dose from hot spots depends more strongly on the contaminated area size than credited by the RESRAD approach.

The inhalation pathway may or may not be considered “hot spot sensitive” depending on whether the RESRAD or hand calculation approach is used to generate area factors—under the hand calculation approach, this pathway is not hot spot sensitive.

3.3 Ingestion-Based Pathways

The residential farmer scenario accounts for potential exposure to residual radioactive contamination in soil and other environmental media. The resident farmer is defined as a person who lives on the site following license termination, grows some portion of their food on the site, and drinks water from an on-site well. The residential farmer receives radiation dose from direct exposure to external radiation from contaminated soil and inhalation exposure from resuspended soil, as well as from the ingestion-based pathways. This section focuses on the hot spot dose from the following six ingestion-based pathways:

- direct ingestion of soil
- ingestion of drinking water from a groundwater source
- ingestion of plant products grown in contaminated soil
- ingestion of plant products irrigated with contaminated groundwater
- ingestion of animal products grown onsite (i.e., after animals ingest contaminated drinking water, plant products, and soil)
- ingestion of fish from a contaminated surface water source

The ingestion-based pathways can be further categorized by water-dependent and water-independent pathways. For example, water-independent pathways include the direct ingestion of soil and ingestion of plant products grown in contaminated soil. Water-dependent pathways include ingestion of drinking water, ingestion of plant products irrigated with contaminated groundwater, and ingestion of fish from a contaminated surface water source. The ingestion of animal products grown onsite includes both water-dependent and water-independent pathways—the time of exposure dictating which exposure pathway is more significant. Note that water-dependent pathways are not important until the contamination reaches the groundwater or surface water body.

The overall objective was to evaluate how hot spots impact receptor dose via different environmental pathways. For each of these six ingestion-based pathways, RESRAD was studied to determine how the modeling code handles the dose calculation for hot spots (ANL 2001). If the RESRAD approach seemed viable for how it handles hot spots, then hand calculations were performed to validate the RESRAD calculations. It was important to understand the difference between "water independent" and "water dependent" pathways in RESRAD. If the water-dependent pathways deliver dose in a manner consistent with total radioactivity inventory, then hot spots only need to be considered to the extent that they contribute to the total source term. This point was considered in the following ingestion-based pathways.

3.3.1 Direction Ingestion of Soil

The direct ingestion of soil exposure pathway involves the ingestion of contamination by future site occupants. This is a water-independent pathway where the receptor dose might occur when a person comes in contact with contaminated soil, and subsequently proceeds to eat without washing his hands. This results in the incidental ingestion of contamination. The RESRAD default for the annual intake of soil in this fashion is 36.5 g/y. Appendix F in the RESRAD Manual provides a description of this pathway (ANL 2001).

<u>RESRAD Area Factor Approach for Ingestion of Soil Pathway</u>

A description of how RESRAD calculates the receptor dose from the soil ingestion pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit) is considered in this section. As with the external radiation pathway, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). The DSRs are expressed in terms of four factors: dose conversion factors (DCFs), branching factor, environmental transport factors (ETFs), and source factors (SFs). For the soil ingestion pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j} \qquad (3-14)$$

where
DCF_j is the dose conversion factor for the j^{th} radionuclide in mrem per pCi;
$BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j;
ETF_j is the environmental transport factor for the j^{th} radionuclide at time, t; and
$SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by an individual from ingestion exposure of unit radioactivity of the radionuclide present. Note that the DCF values for soil ingestion are the same as those for the food ingestion pathways. The DCFs in RESRAD were taken from FGR-11 (USEPA 1988). For example, the DCF for Cs-137 is 5.0E-5 mrem/pCi. The source factor is essentially a correction factor for the source term that accounts for ingrowth, radioactive decay, and leaching.

The ETF accounts for environmental factors such as the size of the contaminated area, cover depth, and wind erosion. The ETF for the soil ingestion pathway is the ratio of the annual intake of the i^{th} principal radionuclide by soil ingestion to the concentration of that radionuclide in the soil. Of the four factors used to determine the DSR for the ingestion of soil pathway, the environmental transport factor has the greatest impact from hot spots. Specifically, the ETF is impacted by both the annual intake of soil and the size of the contaminated area—called the area factor in RESRAD. The RESRAD Manual provides the following equation for the ETF for the soil ingestion pathway (ANL 2001):

$$ETF_j = FSI \times FA \times FCD \times FO \qquad (3-15)$$

where:
FSI is the annual intake of soil (RESRAD default is 36.5 g/y);
FA is the area factor
[FA for soil ingestion pathway is based in the following decision rule for size of contaminated area, A:
FA = A/1000, for 0 < A < 1000 m^2, otherwise FA = 1 for A > 1000 m^2];
FCD is the depth and cover factor
[FCD = 1 when the thickness of the contaminated zone is equal to or exceeds the depth of the soil mixing layer]; and
FO is the occupancy factor
[The default FO = 0.75 based on the assumption that 50% of a person's time is spent indoors and 25% of the time is spent outdoors in the contaminated area].

As an illustrative example, RESRAD was used to model Cs-137 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The DSR for the soil ingestion pathway (water-independent) was 1.35E-3 mrem/y per pCi/g. The soil ingestion pathway accounts for only 0.08% of the dose—the external radiation pathway delivered about 98% of the total receptor dose.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the soil ingestion pathway. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The soil ingestion dose from this smaller contaminated area was 1.35E-5 mrem/y for a 1 pCi/g Cs-137 source term.

The area factor is calculated by dividing the plant dose from the larger contaminated area (1.35E-3 mrem/y) by the dose due to the hot spot area (1.35E-5 mrem/y). This ratio is 100 and it is the area factor for a 10 m^2 hot spot of Cs-137 for the soil ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the soil ingestion pathway. In each case it was apparent that the hot spot dose (and therefore area factor) scaled directly with the hot spot size. That is, if the hot spot size is reduced by a factor of 1000, then the hot spot dose is reduced by a similar factor, and therefore the area factor is 1000. Refer to Tables 46 to 56 in Appendix E for receptor doses and area factors for all of the radionuclides and hot spot sizes for this pathway.

Conceptually, considering that the future occupant is likely to randomly occupy different locations within a survey unit, then it seems reasonable that the receptor dose would scale directly with the fraction of the survey unit actually contaminated. So, the hot spot dose is essentially based on the total amount or inventory of radioactivity being in contact with a future receptor, and ultimately ingested by the future receptor.

Hand Calculation Verification of Ingestion of Soil Pathway Dose

The soil ingestion dose for Cs-137 uniformly distributed in a 1000 m^2 survey unit was calculated using the RESRAD equations described above. The calculations were performed at time t = 0. Equation 3-15 can be used to calculate the environmental transfer factor. The parameter values for each of the variables in the ETF equation were defined earlier. Only the area factor needs to calculated to permit calculation of the ETF. The FA is calculated based on the size of the contaminated area using the following rule:

$$FA = \frac{A}{1000}, \quad where\ 0 < A < 1000 m^2$$

and

$$FA = 1, \quad where\, A > 1000 m^2$$

Since A is 1000 m^2, then FA equals 1.

Therefore calculate ETF directly:

$$ETF = (36.5 g/y) \times (1) \times (1) \times (0.75) = 27.4 g/y$$

Next, calculate the DSR for this example of Cs-137 in a 1000 m^2 survey unit:

$$DSR = (5.0E-5 mrem/pCi) \times (27.4 g/y) = 1.37E-3 \frac{mrem/y}{pCi/g}$$

This result compares to the RESRAD result of 1.35E-3 mrem/y per pCi/g.

Therefore, the RESRAD calculation of receptor dose was validated for the soil ingestion pathway for Cs-137 in a 1000 m^2 survey unit. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. Clearly, the FA parameter is significant in assessing how hot spots impact receptor dose. Again, the receptor dose varies directly with the hot spot area. This result seems reasonable for the reasons stated earlier. Thus, it appears that RESRAD model adequately handles hot spots for this pathway.

Soil Ingestion Pathway Conclusions

The area factors calculated in Tables 46 to 56 (Appendix E) indicate that the receptor dose varies directly with the size of the contaminated area. Thus, when the hot spot is 1/1000 of the survey unit area, the area factor is 1000. The RESRAD FA parameter is significant in assessing how hot spots impact receptor dose. The RESRAD model adequately handles hot spots for this pathway.

Hand calculations were performed to confirm the RESRAD results. For a number of radionuclides the receptor dose results were very close; for a few radionuclides the difference was significant. However, the important result is that for the soil ingestion pathway, both the RESRAD and hand calculations indicate that area factors scale directly with size of the contaminated area. As such, this pathway is not considered to be “hot spot” sensitive.

3.3.2 Ingestion of Drinking Water

This section begins with a general discussion on the approach used for the water-dependent pathways. First, note that the ingestion of drinking water is a water-dependent pathway, and as such, receptor dose will be delayed until

radionuclides in soil can migrate to the groundwater and then reach a point of water withdrawal (e.g., well or pond). The water-dependent pathways are described by two segments—a water pathway segment and a food chain pathway segment. The water pathway segment connects the soil contamination zone with the point of water withdrawal (e.g., irrigation, drinking, or aquatic foods); the food chain segment connects the radionuclide concentration in water to the food chain and ultimately human exposure.

The drinking water pathway is assessed by multiplying the water/soil concentration ratio by the annual quantity of contaminated water (from well or surface water) consumed by the receptor. RESRAD assumes that a ground water well is located in the center, or at down-gradient edge, of the contaminated zone. Further, the pond is assumed to be contaminated by water transported to the surface after percolating through the contaminated zone.

Time is an important consideration in the calculation of dose via water-dependent pathways. The time it takes for each radionuclide to reach the groundwater and produce dose via the plant irrigation pathway will be different. Therefore, the approach used for hot spot dose assessment was to run RESRAD for time periods ranging from 0 to 5000 years for each radionuclide assumed to have contaminated area of 1000 m^2. RESRAD graphical output of total dose as a function of time (in years) was then reviewed to determine the time when the dose reached a peak due to the groundwater pathway. The following results per radionuclide were observed: Uranium (about 700 years), Tc-99 (3 years), Ra-226 (about 700 years), I-129 (3 years), C-14 (2 years), and Am-241 (about 150 years). Five radionuclides did not exhibit a peak dose due to groundwater breakthrough: Co-60, Sr-90, Cs-137, Th-232 and Pu-239. That is, these radionuclides do not contribute to receptor dose via the ingestion of contaminated drinking water. Note that for the water-independent pathways, the hot spot dose assessment, and calculation of area factors, was performed at time $t = 0$.

Focusing on the six radionuclides that do have a water-dependent pathway dose component, it was observed that the time for maximum dose to occur for a particular radionuclide was dependent on the size of the contaminated area. For example, consider the C-14 and the time for maximum dose as a function of contaminated area size shown in Table 4.

So, the time for C-14 to reach a maximum dose via water-dependent pathways varies with the size of the contaminated area, ranging from roughly 1 to 3 years. The hot spot dose calculation and area factor determination will use the time for maximum dose for each of the contaminated area sizes. In addition to C-14, Tc-99 and I-129 have water-dependent dose maxima that are also their global maxima.

Table 4 Time for maximum drinking water pathway dose for C-14 hot spots.

C-14 Contaminated Area (m^2)	Time for Maximum Dose (years)
1000	2.389
10	1.038
3	1.145
1	0.883
0.5	0.884
0.1	0.821
0.01	0.946

Ra-226, U-238, and Am-241 have global dose maxima at different times than their water-dependent dose maxima. Therefore, a different approach was used to determine the time for the water-dependent pathway to achieve a dose maximum. For each of these three radionuclides, RESRAD was first run with only the drinking water and fish ingestion pathways turned on. This was done for each contaminated area size. Once the time for maximum dose was determined for these two water-dependent pathways, RESRAD was re-run with all pathways turned on and set for that time to achieve the water-dependent dose maximum. The results for Am-241 are provided in Table 5 to illustrate this approach. The Am-241 results indicate that the time to reach a maximum varies slightly with the size of the contaminated area. The smaller the contaminated area, the sooner it produces a maximum dose.

RESRAD Area Factor Approach for Ingestion of Drinking Water Pathway

The drinking water pathway involves two phenomena to deliver receptor dose. The first step is the leaching of radionuclides from the contaminated zone to the groundwater. The physical mechanism is adsorption—radionuclides adsorbed to soil particulates are leached by infiltrating water. The contamination is then transported through the unsaturated zone to the saturated zone (groundwater).

RESRAD uses two segments: 1) a water pathway segment that extends from the contamination zone to a point of where receptor dose begins, and 2) a food chain pathway that extends from point of entry of a radionuclide from water to receptor exposure. Appendices D and E in the RESRAD User's Manual provides a description of the dose modeling for these water-dependent pathways (ANL 2001).

RESRAD employs two groundwater models for calculating the water/soil concentration: a mass balance (MB) model and a non-dispersion (ND) model. The mass balance model assumes that radionuclides released from the contaminated zone are withdrawn from a well located at the center of the

Table 5 Time for maximum drinking water pathway dose for Am-241 hot spots.

Am-241 Area (m^2)	Time (years) for Maximum Dose
1000	164
10	151
3	139
1	133
0.5	130
0.1	128
0.01	126

contaminated zone. The non-dispersion model assumes no dispersion of the contamination as it passes through the vadose zone to the saturated zone, and that the well is located at the down-gradient edge of the contaminated zone. Important note: The mass balance model is used for contaminated areas 1,000 m^2 or less, while the non-dispersion model can be used for contaminated areas of any size. The breakthrough times are the same for both models, while the rise times and dilution factors are different (ANL 2001).

This section provides a general overview of how RESRAD calculates the receptor dose from the drinking water pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). The groundwater pathway involves terms such as the breakthrough time, rise time, and dilution factor. As with the other environmental pathways in RESRAD, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the drinking water ingestion pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j} \qquad (3-16)$$

where
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem per pCi; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose

equivalent that is incurred by the receptor from ingestion of unit radioactivity of the radionuclide present. As previously noted, the DCFs in RESRAD were taken from Federal Guidance Report No. 11. For example, the DCF for Am-241 is 3.640E-3 mrem/pCi. The source factor is essentially a correction factor for the source term that accounts for ingrowth and radioactive decay, as well as leaching.

The following discussion is a general overview of the RESRAD water-dependent model. The model components include 1) radionuclide leaching from the contaminated zone, 2) relationship between radionuclide content in water at point of use to parameters that describe the leaching and transport processes, and 3) water transport parameters such as breakthrough time, rise time and dilution.

The ETF for the drinking water ingestion pathway is used to calculate the amount of contaminated material ingested by the receptor in a year (units are g/y). Equation D-23 in the RESRAD Manual provides the following equation for the ETF for the water-dependent ingestion pathway:

$$ETF_{ij,7}(t) = DF_7 \times FDW \times [WSR_{ij,1}(t) \times FD1 + WSR_{ij,2}(t) \times (1 - FD1)] \quad (3-17)$$

where
DF_7 is the annual intake of drinking water (default is 510 L/y);
FDW is the fraction of drinking water from the site (default is 1.0);
$WSR_{ij,1}$ is the ratio of well water to soil concentration ratio at time t (pCi/L per pCi/g, or simply g/L);
$WSR_{ij,2}$ is the ratio of surface water to soil concentration ratio at time t (pCi/L per pCi/g, or simply g/L); and
FD1 is the fraction of well water used for drinking (default is 1.0).

The point of this present assessment is to determine how the size of the contaminated area impacts the drinking water pathway. Appendix F provides an overview of the model equations for the drinking water pathway that depend on the size of the contaminated area.

RESRAD was then used to calculate hot spot doses and area factors for Am-241 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The time for the receptor dose to reach a maximum was 164 y. The DSR for the drinking water pathway (water-dependent) was 1.95 mrem/y per pCi/g.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the drinking water pathway. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The time for the receptor dose to reach a maximum for this smaller hot spot area was 151 y.

The drinking water pathway dose from this smaller contaminated area was 0.479 mrem/y for a 1 pCi/g Am-241 source term.

The area factor is calculated by dividing the plant dose from the larger contaminated area (1.95 mrem/y) by the dose due to the hot spot area (0.479 mrem/y). This ratio is 4.06 and it is the area factor for a 10 m^2 hot spot of Am-241 for the drinking water ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the drinking water pathway. The area factor continued to increase with successively smaller hot spots, but there was no immediately obvious relationship with area (as was the case with the FA for the direct ingestion of soil pathway described in the previous section). Refer to Tables 57 to 62 in Appendix F for receptor doses and area factors for the radionuclides that have water-dependent pathway dose components. Specifically, these include C-14, Tc-99, I-129, Ra-226, U-238 and Am-241.

It turns out that the area factor is impacted by one parameter—WSR. This parameter is sensitive to area—although in a somewhat complicated fashion. The following section will describe the calculation details of this pathway.

Validation of Drinking Water Pathway Dose

The drinking water pathway dose is assessed in this section. Specifically, the dose for Am-241 uniformly distributed in a 1000 m^2 survey unit was calculated using the RESRAD equations described above. The calculations were performed at time t = 164 y. The first step is to calculate dose environmental transfer factor:

$$ETF_{ij,7}(t) = DF_7 \times WSR_{ij,1}(t)$$

The drinking water intake is 510 L/y.

The RESRAD default for the source of contaminated drinking water is 100% well-water (i.e., no drinking water comes from contaminated surface water). The RESRAD calculated value for $WSR_{ij,1}$ (groundwater) is 1.049 g/L.

Now, all the necessary intermediate results to calculate the ETF for the drinking water pathway are available:

$$ETF_{ij,7} = (510\ L/y)(1.049 g/L) = 535.0\ g/y$$

Finally the DSR is calculated for this example of Am-241 in a 1000 m^2 survey unit:

$$DSR = 3.64E-3 mrem/pCi \times 535.0\ g/y = 1.947\ \frac{mrem/y}{pCi/g}$$

This result matches the RESRAD output of 1.95 mrem/y per pCi/g.

Therefore, it was possible to validate the RESRAD calculation of receptor dose for the drinking water pathway for Am-241 in a 1000 m^2 survey unit. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. The WSR parameter is impacted by the hot spot size. Taking a ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.049 divided by 0.2579, the parameter ratio of 4.06 is obtained. This is the same value as the area factor calculated earlier.

It is worthwhile to look at the WSR in more detail to see how it depends on area. The water/soil concentration, WSR_{ij} (t), is expressed as follows (ANL 2001):

$$WSR_{ij}(t) = \frac{\sum_k \frac{\lambda_j \times r_{kj}(t) \times f}{I \times A \times constant}}{S_i(0)}$$

As discussed in Appendix F, the dilution factor (f) is dependent on the contaminated area, as is r_{kj}, and of course, the area A. The point here is that the WSR term is a rather complex function of contaminated area, A.

RESRAD provides the following equations for determining the ND model dilution factor:

$$f_1 = \frac{z}{d_w}, \quad when\ \ d_r \le \frac{A}{l}\ and\ z \le d_w;$$

and

$$f_1 = \frac{AI}{U_w}, \quad when\ \ d_r > \frac{A}{l}\ and\ z \le d_w$$

where
U_w is the well pumping rate(default is 250 m^3/y);
z is the effective aquifer contamination depth (m);
d_w is the distance of well intake below the water table (default is 10 m);
l is the length of the contamination zone parallel to the aquifer (set equal to the

square root of the contaminated area, A).

The first step is to determine which equation is the appropriate one to use. Calculate the effective pumping width, d_r. For the 1000 m^2 area, d_r is calculated:

$$d_r = \frac{U_W}{V_{wfr}\, d_w} = \frac{250 m^3/y}{(2\ m/y)(10m)} = 12.5m$$

where
V_{wfr} is the water flow rate per unit cross-sectional area (default is 2 m/y).

The aquifer contamination depth at the well, z, is given by:

$$z = \frac{(I)(l)}{V_{wfr}} = \frac{0.5 m/y \sqrt{1000 m^2}}{(2\ m/y)} = 7.90m$$

Use the first equation to calculate the dilution factor:

$$f_1 = \frac{7.9m}{10m} = 0.79,\ \ because\ d_r \le \frac{A}{l}\ and\ z \le d_w$$

Perform the same set of calculations for the A = 10 m^2. In this case, d_r is greater than A/l, so use the second equation for dilution factor:

$$f_1 = \frac{10 m^2 \times 0.5 m/y}{250 m^3/y} = 2.0E-2$$

Recall that the ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.049 divided by 0.2579, yielded a parameter ratio of 4.06. The ratio of dilution factors, 0.79 divided by 2.0E-2, results in 39.5, and the inverse ratio of areas is 0.01, resulting in a ratio of 0.395 just considering those two components. Therefore, it is reasonable to conclude that the area embodied by the radionuclide release at the point of use, $r_{kj}(t)$ in the WSR equation yields a ratio of 10.3, since when that is multiplied by the 0.395 yields the overall ratio of 4.06. This explains the complex area dependence on WSR.

Drinking Water Pathway Conclusions

One conclusion for the drinking water pathway is that the area factors for the six radionuclides that deliver receptor dose via this pathway are more restrictive than

those that scale directly with the size of the contaminated area. That is, the area factors for the soil ingestion pathway for a 1 m^2 area were 1000 for all radionuclides. The drinking water pathway area factors for 1 m^2 area ranged from 90 to 119 for C-14, Tc-99, and I-129, and ranged from 20.3 to 21.9 for Ra-226, U-238, and Am-241. It is important to remember that area factors for this pathway were calculated based of the individual time that a maximum occurs for the water-dependent pathway for a particular contaminated area size. Given that the maximum for the external radiation pathway occurs at time t = 0, the area factor for a particular radionuclide will have a local maximum at t = 0, and another at the water-dependent time for maximum dose.

Hand calculations were performed to better understand how the size of the contaminated area impacted the RESRAD calculation of receptor dose for this pathway. It is interesting to note that while the area factors for the drinking water are more restrictive than those that scale directly with contaminated area size, they are less restrictive than the external radiation pathway (for receptor located directly on the hot spot) area factor. The drinking water pathway is therefore regarded as mildly "hot spot" sensitive.

3.3.3 Ingestion of Plant Products Grown in Contaminated Soil

The ingestion of plant products grown in soil accounts for four food pathways: plant foods, meat, milk, and aquatic foods. The plant food pathway category can be divided into the following four subcategories: 1) root uptake from crops grown in the contaminated area, 2) foliar deposition uptake from the settling of contaminated dust on the plants, 3) root uptake from contaminated irrigation water, and 4) foliar uptake from overhead irrigation with contaminated water. In this section the focus is on the water-independent plant food ingestion pathways—i.e., those pathways that deliver receptor dose via two common phenomena: 1) root uptake in contaminated soil, and 2) foliar deposition of contaminated dust. The first phenomenon considers the plant update of contamination via its root system, and the second considers the resuspension of contaminated material and its settling on plants. Appendix D in the RESRAD User's Manual provides a description of the dose modeling for the plant food ingestion pathway (ANL 2001).

<u>RESRAD Area Factor Approach for Ingestion of Plant Products Grown in Contaminated Soil Pathway</u>

First, let's begin with description of how RESRAD calculates the receptor dose from the plant food ingestion pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). As with the other environmental pathways in RESRAD, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport

factors (ETFs), and source factors (SFs). For the plant food ingestion pathway, again start with the familiar dose to soil concentration ratio, DSR_i, calculation:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j}$$

where
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem per pCi; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by the receptor from ingestion of unit radioactivity of the radionuclide present. As previously noted, the DCFs in RESRAD were taken from FGR-11. For example, the DCF for Co-60 is 2.69E-5 mrem/pCi. Note: When more than one f_1 value is provided in FGR-11, the most conservative (i.e., highest value) DCF was selected. The source factor is essentially a correction factor for the source term that accounts for ingrowth and radioactive decay, as well as leaching.

The ETF for the plant food ingestion pathway is used to calculate the amount of contaminated material ingested by the receptor in a year (units are g/y). Equation D-1 in the RESRAD Manual provides the following equation for the ETF for the plant food ingestion pathway (ANL 2001):

$$ETF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times \sum_k DF_{pk} \times FSR_{ij,pqk}(t) \qquad (3-28)$$

where:
p is the primary pathway index for the plant (p=3);
q is the secondary index for root uptake (q=1), foliar deposition (q=2), ditch irrigation (q=3), overhead irrigation (q=4), livestock water (q=5), and livestock intake of soil (q=6);
FA_p is the area factor for the p^{th} primary pathway;
FCD_{pq} is the cover and depth factor for the pq^{th} ingestion pathway at time t,
k is the food class index—fruits, non-leafy vegetables and grains (k=1), and leafy vegetables (k=2);
DF_{pk} is the dietary factor which represents the annual consumption of k^{th} food class for the pth food pathway (in g/y); and
$FSR_{ij,pqk}(t)$ is the food-to-soil concentration ratio at time t of radionuclide j to the soil concentration of radionuclide i at time 0, for the pq^{th} ingestion pathway and k^{th} food class.

Obviously this pathway is much more complex than the external radiation and inhalation pathways. Also note that the livestock water subpathway (q=5) and livestock soil intake subpathway (q=6) occur only for the meat (p=4) and milk (p=5) pathways.

RESRAD was used to model Co-60 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The DSR for the plant ingestion pathway (water-independent) was 2.912E-2 mrem/y per pCi/g. The plant food ingestion pathway accounts for only 0.4% of the dose—the external radiation pathway delivered 99.6% of the total receptor dose.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the plant food ingestion pathway. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The plant pathway dose from this smaller contaminated area was 2.912E-4 mrem/y for a 1 pCi/g Co-60 source term.

The area factor is calculated by dividing the plant dose from the larger contaminated area (2.912E-2 mrem/y) by the dose due to the hot spot area (2.912E-4 mrem/y). This ratio is 100 and it is the area factor for a 10 m^2 hot spot of Co-60 for the plant food ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the plant food ingestion pathway. In each case it was apparent that the hot spot dose (and therefore area factor) scaled directly with the hot spot size. That is, if the hot spot size is reduced by a factor of 1000, then the hot spot dose is reduced by a similar factor, and therefore the area factor is 1000. Refer to Tables 63 to 73 in Appendix G for hot spot receptor doses and area factors for all of the radionuclides and hot spot sizes for this pathway.

Conceptually, considering that the crops are grown fairly uniform across a future survey unit, then it seems reasonable that the receptor dose would scale directly with the fraction of the survey unit actually contaminated. So, the hot spot dose is essentially based on the total amount or inventory of radioactivity getting into the plant food chain, and ultimately ingested by a receptor.

<u>Validation of Ingestion of Plant Products Grown in Contaminated Soil Pathway Dose</u>

As an example, the plant food ingestion dose for Co-60 uniformly distributed in a 1000 m^2 survey unit was calculated using the RESRAD equations described above. Perform the calculations at time t = 0. Recall that the environmental transfer factor is given by:

$$ETF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times \sum_k DF_{pk} \times FSR_{ij,pqk}(t)$$

The area factor for the primary pathway (p =3 for plant), FA_3, is calculated based on the size of the contaminated area using the following rule:

$$FA_3 = \frac{A}{2000}, \quad where\ 0 \le A \le 1000 m^2$$

and

$$FA_3 = 0.5, \quad where\ A > 1000 m^2$$

Since A is 1000 m^2, then FA_3 equals 0.5.

It is appropriate to note at this point that FA_3 is the function that best illustrates how the dose is a function of hot spot size.

The cover and depth factor, FCD_{pq}, has potentially different values depending on the particular secondary index (q). That is, for root uptake (q = 1), FCD is given by:

$$FCD_{31} = \frac{T(t)}{d_r} = \frac{0.15 m}{0.9 m} = 0.1667,$$

where T(t) is the thickness of the contaminated zone (0.15 m), and d_r is the maximum root depth (RESRAD default is 0.9 m).

For foliar deposition (q = 2), FCD_{32} is calculated by dividing T(t) by d_m, the depth of the soil mixing layer (RESRAD default is 0.15 m). Since both T(t) and d_m are equal to 0.15 m, FCD_{32} is equal to 1.

The dietary factors, DK_{31} and DK_{32}, are 160 kg/y for fruits, non-leafy vegetables and grains, and 14 kg/y for leafy vegetables, respectively.

Calculation of the food/soil concentration ratios (FSR) for plant foods is quite different for root uptake and foliar deposition. The FSR for root uptake is simply a vegetable/soil transfer factor tabulated in Table D.3 of the RESRAD Manual. Further, these transfer factors are used for both fruits, leafy vegetables, and grains (k=1), and for non-leafy vegetables. That is, FSR_{j311} equals FSR_{j312} , which for cobalt is 8.0E-2. The units are dimensionless—i.e., vegetable wet weight concentration divided by dry soil concentration.

The FSR for foliar deposition is calculated using the following equation:

$$FSR_{j32k} = FA_2 \times FAR_{j32k} \times ASR_3 \qquad (3-29)$$

where FA_2 is the area factor for dilution of resuspended contaminated dust, FAR_{j32k} is the plant food/air concentration ratio for radionuclide transfer by airborne foliar deposition (m^3/g), and ASR_3 is the mass loading factor (default is 1E-4 g/m^3).

Recall that for FA_2, RESRAD uses a default particle size of 1 μm and wind speed of 2 m/s. The linear regression coefficients for these defaults are a = 1.6819, b = 25.5076, and c = -0.2278, and for a survey unit area of A = 1000 m^2, FA_2 is given by:

$$FA_2 = \frac{1.6819}{1 + 25.5076(\sqrt{1000})^{-0.2278}} = 0.1333$$

The last piece of this puzzle is the equation for FAR_{j32k} :

$$FAR_{j32k} = 3.16E4 \frac{(v_{dj} \times f_r \times T_{jvk})[1 - e^{(-\lambda_w t_{ek})}]}{Y_{vk} \times \lambda_w} \qquad (3-30)$$

where v_{dj} is the deposition velocity (default is 1E-3 m/s for most elements); f_r is the fraction of deposited radionuclides retained on the vegetation (default is 0.25); T_{jvk} is the foliage-to-food radionuclide transfer coefficient (T_{jv1} = 0.1 and T_{jv2} = 1.0), λ_w is the weathering removal constant for vegetation (default is 20 y^{-1}), t_{ek} is the time of exposure of the k^{th} food class to contamination during growing season (t_{e1} = 0.17 y and t_{e2} = 0.25 y), and Y_{vk} is the wet weight crop yield (Y_{v1} = 0.7 kg/m^2 and Y_{v2} = 1.5 kg/m^2).

Next, perform hand calculations to confirm the RESRAD results. First calculate FAR_{j321} and FAR_{j322}:

$$FAR_{j321} = 3.16E4 \frac{(1E-3 \times 0.25 \times 0.1)[1 - e^{(-20 \times 0.17)}]}{0.7 \times 20} = 5.45E-2$$

and

$$FAR_{j322} = 3.16E4 \frac{(1E-3 \times 0.25 \times 1)[1 - e^{(-20 \times 0.25)}]}{1.5 \times 20} = 0.262$$

Next, use the above results to calculate FSR_{j321} and for FSR_{j322} :

$$FSR_{j321} = FA_2 \times \ FAR_{j321} \times ASR_3 = 0.1333 \times 5.45E-2 \times 1E-4 = 7.27E-7$$

and

$$FSR_{j322} = FA_2 \times \ FAR_{j322} \times ASR_3 = 0.1333 \times 0.262 \times 1E-4 = 3.49E-6$$

All the necessary intermediate results are available to calculate the ETF for p, q and k:

$$ETF_{31} = 0.5 \times 0.1666 \times [(160E3)(8.0E-2) + (14E3)(8.0E-2)] = 1.16E3 \ g/y$$

and

$$ETF_{32} = 0.5 \times 1 \times [(160E3)(7.27E-7) + (14E3)(3.49E-6)] = 8.26E-2 \ g/y$$

Thus, ETF_{31} is much greater than ETF_{32}.

Finally calculate the DSR for this example of Co-60 in a 1000 m^2 survey unit:

$$DSR = 2.69E-5 \, mrem/pCi \times 1.16E3 \, g/y = 3.12E-2 \frac{mrem/y}{pCi/g}$$

This result compares to the RESRAD result of 2.912E-2 mrem/y per pCi/g.

Therefore, the RESRAD calculation of receptor dose for the plant food ingestion pathway for Co-60 in a 1000 m^2 survey unit was validated. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. Clearly, the FA_3 parameter is significant in assessing how hot spots impact receptor dose. Again, the receptor dose varies directly with the hot spot area. This result seems reasonable for the reasons stated earlier.

Ingestion of Plant Products Grown in Contaminated Soil Pathway Conclusions

With the exception of C-14, the area factors calculated in the above tables indicate that the receptor dose varies directly with the size of the contaminated area. Thus, when the hot spot is 1/1000 of the survey unit area, the area factor is 1000. The RESRAD FA_3 parameter is significant in assessing how hot spots impact receptor dose. Again, it is reasonable to conclude that the RESRAD model adequately handles hot spots for this pathway.

Hand calculations were performed to confirm the RESRAD results. The hand calculation results were quite similar for Co-60, Sr-90, Cs-137, U-238, Pu-239

and Am-241. The results were reasonably close for I-129, Ra-226, and Th-232. There was roughly an order of magnitude difference in the Tc-99 results, and three to four orders of magnitude difference for the C-14 results. The underlying cause for this discrepancy is that the RESRAD code uses a more complex dose model for C-14 than for other radionuclides, while the hand calculations treated C-14 in the same manner as the other radionuclides.

However, notwithstanding the C-14 results, for the ingestion of plant products grown in contaminated soil pathway, both the RESRAD and hand calculations indicate that area factors scale directly with size of the contaminated area. As such, this pathway is also not considered to be "hot spot" sensitive.

3.3.4 Ingestion of Plant Products Irrigated with Contaminated Groundwater

It is important to note at the outset that the ingestion of plant products irrigated with contaminated groundwater has many parallels with the drinking water pathway. Both are water-dependent pathways, and as such, receptor dose will be delayed until radionuclides in soil can migrate to the groundwater and then reach a point of water withdrawal (e.g., well or pond) for ultimate water use. The water-dependent pathways are described by two segments—a water pathway segment and a food chain pathway segment. The water pathway segment connects the soil contamination zone with the point of water withdrawal (e.g., irrigation, drinking, or aquatic foods); the food chain segment connects the radionuclide concentration in water to the food chain and ultimately human exposure.

This pathway delivers dose via ditch irrigation and overhead irrigation. Ditch irrigation pathway involves the contribution from root uptake of contaminated irrigation water by plant foods. Overhead irrigation represents a sub-pathway for foliar uptake. Irrigation water may come from either a well or pond. RESRAD assumes that a ground water well is located in the center, or at down-gradient edge, of the contaminated zone (ANL 2001). Further, the pond is assumed to be contaminated by water transported to the surface after percolating through the contaminated zone.

Time is an important consideration in the calculation of dose via water-dependent pathways. The time it takes for each radionuclide to reach the groundwater and produce dose via the plant irrigation pathway will be different. [This was the same issue treated previously in the drinking water pathway analysis.] Therefore, the approach used for hot spot dose assessment was to run RESRAD for time periods ranging from 0 to 5000 years for each radionuclide assumed to have contaminated area of 1000 m^2. RESRAD graphical output of total dose as a function of time (in years) was then reviewed to determine the time when the dose reached a peak due to the groundwater pathway. Recall that the following results per radionuclide were observed: Uranium (about 700 years), Tc-99 (3

years), Ra-226 (about 700 years), I-129 (3 years), C-14 (2 years), and Am-241 (about 150 years). Five radionuclides did not exhibit a peak dose due to groundwater breakthrough: Co-60, Sr-90, Cs-137, Th-232 and Pu-239. That is, these radionuclides do not contribute to receptor dose via the ingestion of plant products irrigated with contaminated water. Note that for the water-independent pathways, the hot spot dose assessment, and calculation of area factors, was performed at time t = 0. Refer to Tables 34 and 35 for results of the time for maximum dose as a function of hot spot size for C-14 and Am-241, respectively.

RESRAD Area Factor Approach for Ingestion of Plant Products Irrigated with Contaminated Water Pathway

The plant irrigation ingestion pathway involves three phenomena to deliver receptor dose: 1) radionuclides from soil contamination migrate from the unsaturated to saturated zone (water table), 2) contaminated ground water is then used to irrigate crops via ditch or overhead irrigation, and 3) the receptor ingests plant food products. Two subcategories are of interest: 1) root uptake from contaminated irrigation water, and 2) foliar uptake from overhead irrigation with contaminated water. Appendices D and E in the RESRAD User's Manual provides a description of the dose modeling for these water-dependent pathways (ANL 2001).

RESRAD employs two groundwater models for calculating the water/soil concentration: a mass balance (MB) model and a non-dispersion (ND) model. The mass balance model assumes that radionuclides released from the contaminated zone are withdrawn from a well located at the center of the contaminated zone. The non-dispersion model assumes no dispersion of the contamination as it passes through the vadose zone to the saturated zone, and that the well is located at the down-gradient edge of the contaminated zone. Important note: The MB model is used for contaminated areas 1,000 m^2 or less, while the ND model can be used for contaminated areas of any size. The breakthrough times are the same for both models, while the rise times and dilution factors are different.

This section provides a general overview of how RESRAD calculates the receptor dose from the plant irrigation ingestion pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). The groundwater pathway involves terms such as the breakthrough time, rise time, and dilution factor. As with the other environmental pathways in RESRAD, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the plant irrigation ingestion pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j}$$

where:
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem per pCi; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by the receptor from ingestion of unit radioactivity of the radionuclide present. As previously noted, the DCFs in RESRAD were taken from Federal Guidance Report No. 11 (USEPA 1988). For example, the DCF for Am-241 is 3.640E-3 mrem/pCi. The source factor is essentially a correction factor for the source term that accounts for ingrowth and radioactive decay, as well as leaching.

The following discussion is a general overview of the RESRAD water-dependent model. The model components include 1) radionuclide leaching from the contaminated zone, 2) relationship between radionuclide content in water at point of use to parameters that describe the leaching and transport processes, and 3) water transport parameters such as breakthrough time, rise time and dilution.

The ETF for the plant irrigation ingestion pathway is used to calculate the amount of contaminated material ingested by the receptor in a year (units are g/y). Equation E-1 in the RESRAD User's Manual provides the following equation for the ETF for the water-dependent ingestion pathway (ANL 2001):

$$ETF_{ij,pqr}(t) = WEF_{ij,pqr}(t) \times WSR_{ij,r}(t) \qquad (3-31)$$

where:
p is the primary pathway index for the plant (p=3);
q is the secondary index for ditch irrigation (q=3), overhead irrigation (q=4), livestock water (q=5), and livestock intake of soil (q=6);
r is the water pathway segment—contaminated zone to well water (r = 1) and contaminated zone to surface water (r = 2);
$WEF_{ij,pqr}$ is the water exposure factor at time t for the j^{th} radionuclide transported through the pqr^{th} pathway from point of water use to point of exposure (in L/y); and
$WSR_{ij,r}$ is the water/soil concentration ratio at time t for the r^{th} water pathway segment—units are pCi/L per pCi/g, or simply g/L.

The point of this present discussion is to determine how the size of the contaminated area impacts the plant irrigation pathway. Therefore, only those model equations that depend on the size of the contaminated area will be studied in any detail. The reader is referred to the discussion in Appendix F on the drinking water pathway model equations—the same equations apply for the plant irrigation pathway.

Once the groundwater becomes contaminated, the next step is to consider how the receptor receives a dose via the plant irrigation pathway. Recall that the environmental transport factor is given by:

$$ETF_{ij,pqr}(t) = WEF_{ij,pqr}(t) \times WSR_{ij,r}(t)$$

The water exposure factor, WEF, represents the ratio of the annual radionuclide intake in food that is contaminated through a water-dependent pathway to the radionuclide concentration in water. The units for the WEF are L/y and it is calculated:

$$WEF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times \sum_k DF_{pk} \times FWR_{jpqk} \qquad (3-32)$$

where
FA_p is the area factor for the p^{th} primary pathway;
FCD_{pq} is the cover and depth factor for the pq^{th} ingestion pathway at time t,
k is the food class index—fruits, non-leafy vegetables and grains (k=1), and leafy vegetables (k=2);
DF_{pk} is the dietary factor which represents the annual consumption of k^{th} food class for the p^{th} food pathway (in g/y); and
FWR_{jpqk} is the food/water concentration ratio (L/g).

The FWR equation depends on the nature of the plant irrigation—ditch or overhead. The FWR for ditch irrigation is calculated:

$$FWR_{j33k} = \frac{(I_{rr} \times B_{jv})[1 - e^{(-L_j t_{ek})}]}{\rho_e \times L_j} \qquad (3-33)$$

where
I_{rr} is the irrigation rate (default is 0.2 m/y);
t_{ek} is the time of exposure of the kth food class to contamination during growing season (t_{e1} = 0.17 y and t_{e2} = 0.25 y);
B_{jv} is the vegetable/soil transfer factors;
L_j is the leach rate constant (y^{-1}); and
ρ_e is the effective surface density of soil (default is 225 kg/m^2).

The FWR for overhead irrigation is calculated:

$$FWR_{j34k} = \frac{(I_{rr} \times f_r' \times T_{jvk})[1-e^{(-\lambda_w t_{ek})}]}{Y_{vk} \times \lambda_w} + [FWR_{j33k} \times (1-f_r')] \qquad (3-34)$$

where
f'_r is the fraction of deposited radionuclides retained on vegetation (default is 0.25);
T_{jvk} is the foliage-to-food radionuclide transfer coefficient (T_{jv1} = 0.1 and T_{jv2} = 1.0);
λ_w is the weathering removal constant for vegetation (default is 20 y^{-1}); and
Y_{vk} is the wet weight crop yield (Y_{v1} = 0.7 kg/m^2 and Y_{v2} = 1.5 kg/m^2).

RESRAD was used to model Am-241 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The time for the receptor dose to reach a maximum was 164 y. The DSR for the plant irrigation pathway (water-dependent) was 1.50E-1 mrem/y per pCi/g.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the plant irrigation pathway. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The time for the receptor dose to reach a maximum for this smaller hot spot area was 151 y. The plant irrigation pathway dose from this smaller contaminated area was 3.68E-4 mrem/y for a 1 pCi/g Am-241 source term.

The area factor is calculated by dividing the plant dose from the larger contaminated area (1.50E-1 mrem/y) by the dose due to the hot spot area (3.68E-4 mrem/y). This ratio is 406 and it is the area factor for a 10 m^2 hot spot of Am-241 for the plant irrigation ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the plant irrigation ingestion pathway. The area factor continued to increase with successively smaller hot spots, but there was no immediately obvious relationship with area (as was the case with the FA_3 for the plant soil pathway described earlier). Refer to Tables 74 to 79 in Appendix H for receptor doses and area factors for hot spot sizes for this pathway.

It turns out that the area factor is impacted by two parameters—FA_3 and WSR. Both of these parameters are sensitive to area—FA_3 directly, and WSR in a more complicated fashion. The following section will describe the calculation details of this pathway.

<u>Validation of Ingestion of Plant Products Irrigated with Contaminated Water Pathway Dose</u>

The food ingestion dose from the plant irrigation pathway is assessed in this section. Specifically, the plant irrigation dose for Am-241 uniformly distributed in a 1000 m^2 survey unit was calculated using the RESRAD equations described above. Perform the calculations at time t = 164 y. The first step is to specify the overall equations used to calculate dose. This includes the environmental transfer factor and water exposure factor:

$$ETF_{ij,pqr}(t) = WEF_{ij,pqr}(t) \times WSR_{ij,r}(t)$$

$$WEF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times \sum_k DF_{pk} \times FWR_{jpqk}$$

The area factor for the primary pathway (p = 3 for plant), FA_3, is calculated based on the size of the contaminated area using the following rule:

$$FA_3 = \frac{A}{2000}, \quad where\ 0 \le A \le 1000 m^2$$

and

$$FA_3 = 0.5, \quad where\ A > 1000 m^2$$

Since A is 1000 m^2, then FA_3 equals 0.5.

So, as before, FA is one of the parameters that influences receptor dose is a function of hot spot size.

The cover and depth factor, FCD_{pq}, is 1 for both ditch (q = 3) and overhead (q = 4) irrigation. That makes sense because the radionuclides that are transported from the contamination zone to the saturated zone are independent of the depth of contamination—i.e., the infiltrating water transports the contamination to the aquifer regardless of contamination depth.

The dietary factors, DK_{31} and DK_{32}, are 160 kg/y for fruits, non-leafy vegetables and grains, and 14 kg/y for leafy vegetables, respectively.

The plant-food/water concentrations (FWR) depend on several groundwater hydrogeological parameters, as well as the food class and the irrigation method. The following interim results were obtained from the RESRAD code (Table 6).

Next, calculate the water exposure factor for the ditch and overhead irrigation methods. First calculate WEF for the ditch irrigation:

$$WEF_{ij,33}(t) = (0.5)[(160E3\frac{g}{y})(1.1235E-7\frac{L}{g}) + (14E3\frac{g}{y})(1.6454E-7\frac{L}{g})] = 1.01E-2\ \frac{L}{y}$$

Table 6 Plant-food/water concentrations for irrigation type and food class.

Irrigation Type	Food Class	FWR (L/g)
Ditch	k=1	1.1235E-7
Ditch	k=2	1.6454E-7
Overhead	k=1	3.4522E-4
Overhead	k=2	1.6554E-3

Now, WEF for overhead irrigation:

$$WEF_{ij,34}(t) = (0.5)[(160E3\,g/y)(3.4522E-4\,L/g) + (14E3\,g/y)(1.655E-3\,L/g)] = 39.2\,\frac{L}{y}$$

The RESRAD default for the source of contaminated irrigation water is 100% well-water (i.e., no irrigation water comes from contaminated surface water). The RESRAD calculated value for $WSR_{j,1}$ (groundwater) is 1.049 g/L.

Now all the necessary intermediate results are available to calculate the ETF for the ditch and overhead irrigation:

$$ETF_{33} = WEF_{33} \times WSR = (1.01E-2\,L/y)(1.049\,g/L) = 1.064E-2\ g/y$$

and

$$ETF_{34} = WEF_{34} \times WSR = (39.2\,L/y)(1.049\,g/L) = 41.13\ g/y$$

Note that the overhead irrigation transfer factor is much greater than the ditch irrigation factor.

Finally calculate the DSR for this example of Am-241 in a 1000 m^2 survey unit:

$$DSR = 3.64E-3\,mrem/pCi \times (1.064E-2 + 41.13)\,g/y = 0.1497\,\frac{mrem/y}{pCi/g}$$

This result matches the RESRAD output of 0.1497 mrem/y per pCi/g.

Therefore, the RESRAD calculation of receptor dose for the plant irrigation ingestion pathway for Am-241 in a 1000 m^2 survey unit was validated. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. Clearly, the FA_3 parameter is an important parameter in assessing how hot spots impact receptor dose. This parameter

alone accounts for a factor of 100 of the overall area factor of 406. The other parameter that is impacted by the hot spot size is WSR. Taking the ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.049 divided by 0.2579, yields a parameter ratio of 4.06. When multiplying this by the 100 from FA_3 the overall area factor is 406.

It is worthwhile to look at the WSR in more detail to see how it depends on area. Recall that the water/soil concentration, WSR_{ij} (t), is expressed as follows:

$$WSR_{ij}(t) = \frac{\sum_k \frac{\lambda_j \times r_{kj}(t) \times f}{I \times A \times cons\tan t}}{S_i(0)}$$

As previously noted, the dilution factor (f) is dependent of the contaminated area, as is r_{kj}, and of course, the area A. The point here is that the WSR term is a rather complex function of contaminated area, A.

Again, it is useful to study how the WSR parameter depends on the dilution factor for the ND model and the MB model (difference largely depends on the distance of the well from the contaminated zone). RESRAD provides the following equations for determining the ND model dilution factor:

$$f_1 = \frac{z}{d_w}, \quad when \;\; d_r \le \frac{A}{l} \; and \; z \le d_w;$$

and

$$f_1 = \frac{A\,I}{U_w}, \quad when \;\; d_r > \frac{A}{l} \; and \; z \le d_w$$

where
U_w is the well pumping rate (default is 250 m^3/y);
z is the effective aquifer contamination depth (m);
d_w is the distance of well intake below the water table (default is 10 m); and
l is the length of the contamination zone parallel to the aquifer (set equal to the square root of the contaminated area, A).

The first step is to determine which equation is the appropriate one to use. Calculate the effective pumping width, d_r. For the 1000 m^2 area, d_r is calculated:

$$d_r = \frac{U_W}{V_{wfr}\, d_w} = \frac{250 m^3/y}{(2\ m/y)(10 m)} = 12.5 m$$

where
V_{wfr} is the water flow rate per unit cross-sectional area (default is 2 m/y).

The aquifer contamination depth at the well, z, is given by:

$$z = \frac{(I)(l)}{V_{wfr}} = \frac{0.5 m/y \sqrt{1000 m^2}}{(2\ m/y)} = 7.90 m$$

Use the first equation to calculate the dilution factor:

$$f_1 = \frac{7.9 m}{10 m} = 0.79,\ \ because\ d_r \le \frac{A}{l}\ and\ z \le d_w$$

Perform the same set of calculations for the A = 10 m^2. In this case, d_r is greater than A/l, so use the second equation for dilution factor:

$$f_1 = \frac{10 m^2 \times 0.5 m/y}{250 m^3/y} = 2.0E-2$$

Recall that the ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.049 divided by 0.2579, yielded a parameter ratio of 4.06. The ratio of dilution factors, 0.79 divided by 2.0E-2, results in 39.5, and the inverse ratio of areas is 0.01, resulting in a ratio of 0.395 just considering those two components. Therefore it is reasonable to conclude that the area embodied by the radionuclide release at the point of use, $r_{kj}(t)$ in the WSR equation yields a ratio of 10.3, since when that is multiplied by the 0.395 yields the overall ratio of 4.06. This shows the complex area dependence on WSR.

Plant Irrigation Pathway Conclusions

One conclusion for the plant irrigation water pathway is that the area factors for the six radionuclides that deliver receptor dose via this pathway are very large compared to those that scale directly with the size of the contaminated area. That is, the area factors for the soil ingestion pathway for a 1 m^2 area were 1000 for all radionuclides. The plant irrigation pathway area factors for 1 m^2 area ranged from 8.9E4 to 1.6E6 for C-14, Tc-99, and I-129, and ranged from 2.0E4 to 2.2E4 for Ra-226, U-238, and Am-241.

Hand calculations were performed to better understand how the size of the contaminated area impacted the RESRAD calculation of receptor dose for this pathway. It is clear the area factors for the plant irrigation pathway are less restrictive than the other pathways studied. Therefore, the plant irrigation water pathway is certainly not “hot spot” sensitive

3.3.5 Ingestion of Animal Products Grown Onsite

The ingestion of animal products grown onsite largely refers to the consumption of meat and milk. Both the water-dependent and water-independent pathways are involved, therefore, one approach for assessing hot spot size impact on receptor dose is to separately assess the water-independent meat and milk pathways and the water-dependent meat and milk pathways. In both cases the detailed pathways include animal ingestion of contaminated fodder, water and soil—all of which leads to contaminated meat and milk that is ingested by the future receptor. In general, the plant irrigation hot spot doses (evaluated in the previous section) are one to three orders of magnitude higher than the water-dependent meat/milk pathways. This is due to the fact that the meat/milk pathways involve an additional pathway segment in the transfer of radionuclides from contaminated soil to ultimate receptor radionuclide intake.

RESRAD Area Factor Approach for Ingestion of Animal Products Grown Onsite Pathway

RESRAD accounts for the water-independent meat/milk pathways and the water-dependent meat/milk pathways slightly differently. For the water-independent food pathways, the animal ingests plants that are grown in contaminated soil. This involves the root uptake from crops grown in the contaminated area and foliar deposition uptake from the settling of contaminated dust on the plants, as well as the livestock direct ingestion of soil. For the water-dependent food pathways, irrigation water is assumed to contaminate the plants, which are then ingested by the animal. And the livestock consumption of contaminated water is also a possible water-dependent pathway. Appendices D and E in the RESRAD User's Manual describe the meat and milk pathways (ANL 2001).

First, let's begin with description of how RESRAD calculates the receptor dose from the animal products pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). As with the other environmental pathways in RESRAD, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the animal products ingestion pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j}$$

where:
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem per

pCi; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by the receptor from ingestion of unit radioactivity of the radionuclide present. As previously noted, the DCFs in RESRAD were taken from FGR-11 (USEPA 1988). The source factor is essentially a correction factor for the source term that accounts for ingrowth and radioactive decay, as well as leaching.

The ETF for the animal product pathway is used to calculate the amount of contaminated material ingested by the receptor in a year (units are g/y). Equation D-1 in the RESRAD Manual provides the following equation for the ETF for the animal product ingestion pathway (ANL 2001):

$$ETF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times DF_{p1} \times FSR_{ij,pq}(t) \qquad (3-35)$$

where:
p is the primary pathway index for the meat (p=4) and milk (p=5);
q is the secondary index for root uptake (q=1), foliar deposition (q=2), ditch irrigation (q=3), overhead irrigation (q=4), livestock water (q=5), and livestock intake of soil (q=6);
FA_p is the area factor for the p^{th} primary pathway;
FCD_{pq} is the cover and depth factor for the pq^{th} ingestion pathway at time t,
DF_{p1} is the dietary factor for meat (63 kg/y) and milk (92 L/y) which represents the annual consumption of meat and milk, respectively; and
$FSR_{ij,pq}(t)$ is the food-to-soil concentration ratio at time t for meat and milk to the soil.

The food/soil concentration ratios can be calculated:

$$FSR_{ij,pq}(t) = FQR_{jp} \times FI_{pq} \times QSR_{ij,pq}(t) \qquad (3-36)$$

where
FQR_{jp} is the radionuclide transfer factor for meat and milk in d/kg;
FI_{pq} is the daily intake of fodder (q=1,2,3, or 4), water (q=5), or soil (q=6) by livestock; and
$QSR_{ij,pq}(t)$ is the fodder-to-soil concentration ratio for meat and milk when q = 1 and 2; fodder or livestock-water concentration when q=3, 4 or 5; and for livestock soil intake QSR is 1.

RESRAD provides values of FQR in Table D.4 (ANL 2001). The livestock fodder intake default values are 68 kg/d for meat and 55 kg/d for milk, and livestock water intake is 50 L/d and 160 L/d for meat and milk, respectively.

The equations for fodder/soil concentration ratios are time dependent for the water-dependent pathways, and time-independent for the water-independent pathways. The formulas for QSR are described below.

For root uptake by fodder:

$$QSR_{ij,41} = QSR_{ij,51} = B_{jv} \qquad (3-37)$$

where B_{jv} is the vegetable/soil transfer factor for rot uptake.

For foliar deposition on fodder:

$$QSR_{ij,42} = QSR_{ij,52} = FA_2 \times FAR_{j323} \times ASR_3 \qquad (3-38)$$

where FA_2 is the area factor for dilution of resuspended contaminated dust, FAR_{j32k} is the plant food/air concentration ratio for radionuclide transfer by airborne foliar deposition (m^3/g), and ASR_3 is the mass loading factor (default is 1E-4 g/m^3).

For ditch irrigation of fodder:

$$QSR_{ij,43}(t) = QSR_{ij,53}(t) = FWR_{j333} \times FIRW \times [WSR_{ij,1}(t) \times FI1 + WSR_{ij,2}(t) \times (1 - FI1)] \qquad (3-39)$$

where FWR is the plant-food/water concentration ratio, FIRW is the fraction of irrigation water obtained from contaminated sources (default is 1.0), and $WSR_{ij,1}$ and $WSR_{ij,2}$ are the water/soil concentration ratios for well water and surface water, respectively.

The FWR equation depends on the nature of the plant irrigation—ditch or overhead. The FWR for ditch irrigation is calculated:

$$FWR_{j33k} = \frac{(I_{rr} \times B_{jv})[1 - e^{(-L_j t_{ek})}]}{\rho_e \times L_j} \qquad (3-40)$$

where
I_{rr} is the irrigation rate (default is 0.2 m/y);
t_{ek} is the time of exposure of the kth food class to contamination during growing season (t_{e1} = 0.17 y and t_{e2} = 0.25 y);
B_{jv} is the vegetable/soil transfer factors;

L_j is the leach rate constant (y^{-1}); and
ρ_e is the effective surface density of soil (default is 225 kg/m^2).

For overhead irrigation of fodder:

$$QSR_{ij,44}(t) = QSR_{ij,54}(t) = FWR_{j334} \times FIRW \times [WSR_{ij,1}(t) \times FI1 + WSR_{ij,2}(t) \times (1 - FI1)] \quad (3-41)$$

The FWR for overhead irrigation is calculated:

$$FWR_{j34k} = \frac{(I_{rr} \times f_r' \times T_{jvk})[1 - e^{(-\lambda_w t_{ek})}]}{Y_{vk} \times \lambda_w} + [FWR_{j33k} \times (1 - f_r')] \quad (3-42)$$

where
f'_r is the fraction of deposited radionuclides retained on vegetation (default is 0.25);
T_{jvk} is the foliage-to-food radionuclide transfer coefficient (T_{jv1} = 0.1 and T_{jv2} = 1.0);
λ_w is the weathering removal constant for vegetation (default is 20 y^{-1}); and
Y_{vk} is the wet weight crop yield (Y_{v1} = 0.7 kg/m^2 and Y_{v2} = 1.5 kg/m^2).

For the intake of contaminated livestock water:

$$QSR_{ij,45}(t) = QSR_{ij,55}(t) = FLW \times [WSR_{ij,1}(t) \times FL1 + WSR_{ij,2}(t) \times (1 - FL1)] \times 1E-3 \quad (3-43)$$

where FLW is the fraction of livestock water obtained from contaminated sources (default is 1.0), and FL1 is the fraction of well water used for watering livestock (default is 1.0).

RESRAD was used to model Am-241 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The time was set at 164 years to coincide with the maximum dose for the water-dependent pathway. The DSR for the milk ingestion pathway was 9.12E-6 mrem/y per pCi/g. The DSR for the meat ingestion pathway was 1.04E-4 mrem/y per pCi/g.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the milk and meat ingestion pathways. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The milk ingestion pathway dose from this smaller contaminated area was 2.25E-8 mrem/y for a 1 pCi/g Am-241 source term. The meat ingestion pathway dose

from this smaller contaminated area was 2.57E-7 mrem/y for a 1 pCi/g Am-241 source term.

The area factor is calculated by dividing the milk (or meat) dose from the larger contaminated area by the dose due to the hot spot area. This ratio is 406 and it is the area factor for a 10 m^2 hot spot of Am-241 for the milk ingestion pathway; the ratio was also 406 for the meat ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the milk and meat ingestion pathways. There was no apparent direct relationship between hot spot dose (and therefore area factor) and the contaminated area size, other than the expected result that larger area factors resulted with smaller hot spots.

The water-independent milk and meat pathways were assessed at time t =0. This time it was apparent that the hot spot dose (and therefore area factor) scaled directly with the hot spot size. That is, if the hot spot size is reduced by a factor of 1000, then the hot spot dose is reduced by a similar factor, and therefore the area factor is 1000. Refer to Tables 80 to 96 in Appendix I for receptor doses and area factors for all of the radionuclides and hot spot sizes for the milk and meat pathways, for both the water-dependent and water-independent pathways.

Conceptually for the water-independent pathways, considering that the crops are grown fairly uniform across a future survey unit, then it seems reasonable that the receptor dose would scale directly with the fraction of the survey unit actually contaminated. So, the hot spot dose is essentially based on the total amount or inventory of radioactivity getting into the plant food chain, and ultimately ingested by a receptor. For the water-dependent pathways, the relationship is not so straightforward.

Validation of Animal Products Pathway Dose

The milk ingestion dose was calculated for Am-241 uniformly distributed in a 1000 m^2 survey unit using the RESRAD equations described above. The calculations were performed at time t = 164 years (water-dependent). Recall that the environmental transfer factor is given by:

$$ETF_{ij,pq}(t) = FA_p \times FCD_{pq}(t) \times DF_{p1} \times FSR_{ij,pq}(t)$$

The area factor for the primary pathway (p = 5 for milk), FA_5, is calculated based on the size of the contaminated area using the following rule:

$$FA_5 = \frac{A}{20000}, \quad where\ 0 \le A \le 20{,}000 m^2$$

and

$$FA_5 = 1, \quad where A > 20{,}000 m^2$$

Since A is 1000 m^2, then FA_5 equals 0.05. Obviously FA_5 for the milk (and meat) ingestion pathways is a parameter influenced by the hot spot size.

The cover and depth factor, FCD_{pq}, is 1 for both ditch (q = 3) and overhead (q = 4) irrigation. That makes sense because the radionuclides that are transported from the contamination zone to the saturated zone are independent of the depth of contamination—i.e., the infiltrating water transports the contamination to the aquifer regardless of contamination depth.

The calculation of FSR_{5q} is performed for ditch irrigation, overhead irrigation, and livestock water. Begin with ditch irrigation:

$$FSR_{ij,53}(t) = FQR_{j5} \times FI_{53} \times QSR_{53}(t)$$

where RESRAD defaults for FQR is 2.0E-6 d/kg and FI is 55 kg/d, and

$$QSR_{ij,53}(t) = FWR_{j333} \times FIRW \times [WSR_{ij,1}(t) \times FI1 + WSR_{ij,2}(t) \times (1 - FI1)]$$

Recognizing that FIRW (fraction of irrigation water obtained from contaminated sources) has a default value of 1.0, and default for FI1 (fraction of well water used for irrigation) is 1.0, QSR is given by:

$$QSR_{ij,53}(t) = (5.31E-8 L/g) \times (1) \times [1.049 g/L] = 5.57E-8$$

Therefore,

$$FSR_{ij,53}(t) = (2.0E-6 d/kg) \times (55 kg/d) \times (5.57E-8) = 6.13E-12$$

Next overhead irrigation is considered:

$$FSR_{ij,54}(t) = FQR_{j5} \times FI_{54} \times QSR_{54}(t)$$

where same RESRAD defaults for FQR is 2.0E-6 d/kg and FI is 55 kg/d, and

$$QSR_{ij,54}(t) = FWR_{j343} \times FIRW \times [WSR_{ij,1}(t) \times FI1 + WSR_{ij,2}(t) \times (1 - FI1)]$$

Again, FIRW and FI1 are both 1.0, so

$$QSR_{ij,54}(t) = (1.814E-3\,L/g) \times (1) \times [1.049\,g/L] = 1.90E-3$$

Therefore,

$$FSR_{ij,54}(t) = (2.0E-6\,d/kg) \times (55\,kg/d) \times (1.90E-3) = 2.09E-7$$

Finally calculate FSR for livestock water:

$$FSR_{ij,55}(t) = FQR_{j5} \times FI_{55} \times QSR_{55}(t)$$

where same RESRAD defaults for FQR is 2.0E-6 d/kg and FI is 160 L/d, and

$$QSR_{ij,55}(t) = FLW \times [WSR_{ij,1}(t) \times FL1 + WSR_{ij,2}(t) \times (1 - FL1)] \times 1E-3$$

where FLW (fraction of livestock water obtained from contaminated sources) and FL1 (fraction of well water used for watering livestock) are both 1.0, so

$$QSR_{ij,55}(t) = (1) \times [1.049\,g/L] \times (1E-3\,L/g) = 1.049E-3$$

Therefore,

$$FSR_{ij,55}(t) = (2.0E-6\,d/kg) \times (160\,L/d) \times (1.049E-3) = 3.36E-7$$

Now the environmental transfer factor can be calculated for the three sub-pathways (q = 3, 4 and 5). Also note that the dietary factor for milk is 92 L/y (or 92E3 g/y).

The ETF for ditch irrigation is calculated:

$$ETF_{ij,53}(t) = FA_p \times FCD_{pq}(t) \times DF_{p1} \times FSR_{ij,pq}(t) =$$
$$(0.05) \times (1) \times (92E3\,g/y) \times (6.13E-12) = 2.82E-8\,g/y$$

For overhead irrigation:

$$ETF_{ij,54}(t) = (0.05) \times (1) \times (92E3\,g/y) \times (2.09E-7) = 9.63E-4\,g/y$$

For livestock water:

$$ETF_{ij,55}(t) = (0.05) \times (1) \times (92E3\,g/y) \times (3.36E-7) = 1.54E-3\,g/y$$

Finally calculate the DSR for this example of Am-241 in a 1000 m^2 survey unit:

$$DSR = 3.64E-3\,mrem/\,pCi \times (2.82E-8 + 9.63E-4 + 1.54E-3)\,g/\,y = 9.11E-6\,\frac{mrem/\,y}{pCi/\,g}$$

This result matches the RESRAD output of 9.12E-6 mrem/y per pCi/g.

Therefore, it was possible to validate the RESRAD calculation of receptor dose for the milk ingestion pathway for Am-241 in a 1000 m^2 survey unit. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. Clearly, the FA_5 parameter is an important parameter in assessing how hot spots impact receptor dose. This parameter alone accounts for a factor of 100 of the overall area factor of 406. The other parameter that is impacted by the hot spot size is WSR. Taking a ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.049 divided by 0.2579, yields a parameter ratio of 4.06. When multiplying this by the 100 from FA_5 the overall area factor of 406. The WSR parameter and its impact on the area factor was evaluated in the plant irrigation section—this assessment is the same for this present pathway, and all water-dependent pathways for that matter.

Animal Product Pathway Conclusions

The first conclusion for the animal product pathway pertains to the water-dependent pathways where the area factors for the six radionuclides that deliver receptor dose via this pathway are very large compared to those that scale directly with the size of the contaminated area. That is, the area factors for the pathways that scale directly with hot spot size have an area factor of 1000 for a 1 m^2 area. The water-dependent animal product pathway area factors for 1 m^2 area ranged from 2.0E4 to 1.5E5.

Hand calculations were performed to validate the RESRAD calculation of receptor dose for the milk ingestion pathway for Am-241 in a 1000 m^2 survey unit. This assessment was not only useful for validation, but also permitted a better understanding of how the size of the contaminated area impacted the RESRAD calculation of receptor dose for this pathway. It is clear the area factors for the water-dependent animal products pathway are less restrictive than the other pathways studied. Therefore, this pathway is certainly not “hot spot” sensitive.

The second conclusion pertains to the water-independent animal product pathway—the area factors calculated in the above tables indicate that the receptor dose varies directly with the size of the contaminated area. Thus, when the hot spot is 1/1000 of the survey unit area, the area factor is 1000. Area factors for the water-independent animal product pathway scale directly with size of the contaminated area. As such, this pathway is also not considered to be “hot spot” sensitive.

3.3.6 Ingestion of Fish from a Contaminated Surface Water Source

First, note that this is a water-dependent pathway, and as discussed previously (i.e., for the drinking water pathway), receptor dose will be delayed until radionuclides in soil can migrate to the surface water body and then reach a point of water withdrawal (e.g., pond or river). The water-dependent pathways are described by two segments—a water pathway segment and a food chain pathway segment. The water pathway segment connects the soil contamination zone with the point of water withdrawal (e.g., irrigation, drinking, or aquatic foods); the food chain segment connects the radionuclide concentration in water to the food chain and ultimately human exposure.

The aquatic food (fish, crustaceans, and mollusks) pathway is assessed by multiplying the annual quantity of contaminated aquatic food consumed by the bioaccumulation factor and the surface water/soil concentration ratio. RESRAD assumes that the pond is contaminated by water transported to the surface after percolating through the contaminated zone.

Time is an important consideration in the calculation of dose via water-dependent pathways. The time it takes for each radionuclide to reach the groundwater and produce dose via the fish ingestion pathway will be different. The following times for each radionuclide to reach a peak dose were observed: Uranium (about 700 years), Tc-99 (3 years), Ra-226 (about 700 years), I-129 (3 years), C-14 (2 years), and Am-241 (about 150 years). Five radionuclides did not exhibit a peak dose due to groundwater breakthrough: Co-60, Sr-90, Cs-137, Th-232 and Pu-239. That is, these radionuclides do not contribute to receptor dose via the fish ingestion pathway. Note that for the water-independent pathways, the hot spot dose assessment, and calculation of area factors, was performed at time t = 0.

Focusing on the six radionuclides that do have a water-dependent pathway dose component, it was observed that the time for maximum dose to occur for a particular radionuclide was dependent on the size of the contaminated area. Refer to Tables 34 and 35 for examples of time for maximum dose to be achieved for C-14 and Am-241, respectively.

<u>RESRAD Area Factor Approach for Ingestion of Fish from a Contaminated Surface Water Source Pathway</u>

The fish ingestion pathway involves two pathway segments to deliver receptor. First, a groundwater pathway segment that extends to the edge of the contamination zone to a location where surface seepage occurs, and 2) a surface water segment where the contaminated groundwater mixes with uncontaminated surface water (pond). Receptor dose occurs when the future resident ingests contaminated aquatic delights. Appendices D and E in the RESRAD User's Manual provides a description of the dose modeling for these

water-dependent pathways (ANL 2001). Also, the drinking water pathway section describes the two RESRAD groundwater models for calculating the water/soil concentration: a mass balance (MB) model and a non-dispersion (ND) model.

This section provides a general overview of how RESRAD calculates the receptor dose from the fish ingestion pathway for a uniformly contaminated area (e.g., 1000 m^2 survey unit). The groundwater pathway involves terms such as the breakthrough time, rise time, and dilution factor. These terms were described in the drinking water pathway section. As with the other environmental pathways in RESRAD, the effective dose equivalent limit is converted to a soil concentration by means of dose to source ratios (DSRs). Recall that the DSRs are expressed in terms of three primary factors: dose conversion factors (DCFs), environmental transport factors (ETFs), and source factors (SFs). For the fish ingestion pathway, the dose to soil concentration ratio, DSR_i, for the i^{th} radionuclide in mrem/y per pCi/g is given by:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j}$$

where:
DCF_j is the dose conversion factor for the j^{th} principal radionuclide in mrem per pCi; $BRF_{i,j}$ is the fraction of total decay of radionuclide i that results in ingrowth of radionuclide j; ETF_j is the environmental transport factor for the j^{th} principal radionuclide at time, t; and $SF_{i,j}$ is the source factor that accounts for ingrowth and decay and leaching of the j^{th} principal radionuclide originating from the transformation of the i^{th} principal radionuclide at time t.

The DCF is the dose to exposure ratio—i.e., the committed effective dose equivalent that is incurred by the receptor from ingestion of unit radioactivity of the radionuclide present. As previously noted, the DCFs in RESRAD were taken from Federal Guidance Report No. 11 (USEPA 1988). For example, the DCF for Am-241 is 3.640E-3 mrem/pCi. The source factor is essentially a correction factor for the source term that accounts for ingrowth, radioactive decay, and leaching.

The ETF for the fish ingestion pathway is used to calculate the amount of contaminated material ingested by the receptor in a year (units are g/y). RESRAD (equation D.21 in RESRAD User's Manual) provides the following equation for the ETF for the water-dependent ingestion pathway (ANL 2001):

$$ETF_{ij,6}(t) = FR_6 \times (\sum_k DF_{6k} \times FWR_{j6k}) \times WSR_{ij,2}(t) \qquad (3-44)$$

where:

FR_6 is the fraction of aquatic food consumed that is contaminated (default is 0.5);
DF_{6k} are dietary factors for annual consumption of fish (k=1) and crustaceans/mollusks (k=2) in kg/y;
FDW is the fraction of drinking water from the site (default is 1.0);
FWR_{j6k} is the bioaccumulation factor in L/kg for fish/water concentration and crustaceans/mollusks/ water concentration; and
$WSR_{ij,2}$ is the ratio of surface water to soil concentration ratio at time t (pCi/L per pCi/g, or simply g/L).

Similar to the drinking water and plant irrigation pathways, the size of the contaminated area has an impact on the fish ingestion pathway. The radionuclide release rate is directly related to the size of the contaminated area. The RESRAD groundwater model equations that impact the hot spot dose by virtue of the contaminated area size are discussed in the drinking water pathway.

RESRAD was used to model Am-241 contamination (1 pCi/g) present to a depth of 15 cm over the 1000 m^2 survey unit. No soil cover was assumed. The time for the receptor dose to reach a maximum was 164 y. The DSR for the fish ingestion pathway was 2.57E-3 mrem/y per pCi/g.

RESRAD was then used to calculate the area factor for a 10 m^2 hot spot for the fish ingestion pathway. All of the parameters were the same with the exception of the contaminated area size and the length parallel to the aquifer. The time for the receptor dose to reach a maximum for this smaller hot spot area was 151 y. The fish ingestion pathway dose from this smaller contaminated area was 2.49E-4 mrem/y for a 1 pCi/g Am-241 source term.

The area factor is calculated by dividing the plant dose from the larger contaminated area (2.57E-3 mrem/y) by the dose due to the hot spot area (2.49E-4 mrem/y). This ratio is 10.3 and it is the area factor for a 10 m^2 hot spot of Am-241 for the fish ingestion pathway.

The area factor for successively smaller hot spot areas (3, 1, 0.5, 0.1, and 0.01 m^2) were calculated for the fish ingestion pathway. The area factor continued to increase with successively smaller hot spots, but there was no immediately obvious relationship with area. Refer to Tables 97 to 102 in Appendix J for receptor doses and area factors for the radionuclides and hot spot sizes for this pathway.

It turns out that the area factor is impacted by one parameter—WSR. This parameter is sensitive to area—although in a somewhat complicated fashion. The following section will describe the calculation details of this pathway.

Validation of Fish Ingestion Pathway Dose

The fish ingestion pathway dose is assessed in this section. Specifically, the dose for Am-241 uniformly distributed in a 1000 m^2 survey unit was calculated using the RESRAD equations described above. The calculations were performed at time t = 164 y. The first step is to calculate dose environmental transfer factor:

$$ETF_{ij,6}(t) = FR_6 \times (\sum_k DF_{6k} \times FWR_{j6k}) \times WSR_{ij,2}(t)$$

The dietary factors for fish and crustaceans/mollusks are 5.4 kg/y and 0.9 kg/y, respectively. The bioaccumulation factors for americium are 30.0 L/kg and 1000 L/kg, respectively for fish and crustaceans/mollusks.

The RESRAD calculated value for $WSR_{ij,2}$ (surface water) is 1.328E-3 g/L.

All the necessary intermediate results are available to calculate the ETF for the fish ingestion pathway:

$$ETF_{ij,6} = 0.5 \times [(5.4 kg/y)(30 L/kg) + (0.9 kg/y)(1000 L/kg)] \times 1.328E-3 g/L = 0.705 g/y$$

Finally calculate the DSR for this example of Am-241 in a 1000 m^2 survey unit:

$$DSR = 3.64E-3 mrem/pCi \times 0.705 g/y = 2.567E-3 \frac{mrem/y}{pCi/g}$$

This result matches the RESRAD output of 2.57E-3 mrem/y per pCi/g.

Therefore, the RESRAD calculation of receptor dose for the fish ingestion pathway for Am-241 in a 1000 m^2 survey unit was validated. Looking at these calculations in detail allows a better understanding of how the hot spot area impacts the calculation of dose. The WSR parameter is impacted by the hot spot size. Taking a ratio of the WSR for 1000 m^2 to the WSR for 10 m^2, 1.328E-3 divided by 1.289E-4, yields a parameter ratio of 10.3. This is the same value as the area factor calculated earlier.

It is worthwhile to look at the WSR in more detail to see how it depends on area. Recall that the water/soil concentration, WSR_{ij} (t), is expressed as follows:

$$WSR_{ij}(t) = \frac{\sum_k \frac{\lambda_j \times r_{kj}(t) \times f}{I \times A \times cons\tan t}}{S_i(0)}$$

As previously noted, the dilution factor (f) is dependent of the contaminated area, as is r_{kj}, and of course, the area A.

The dilution factor for the surface water pathway is calculated differently than for the groundwater pathway. RESRAD provides the following equation for determining the surface water dilution factor:

$$f_2 = \frac{A}{A_w}$$

where
A_w is the area of the watershed (default is 10^6 m^2).

So, the dilution factor based on a contaminated area of 1000 m^2 is given by:

$$f_2 = \frac{1000 m^2}{1E6\ m^2} = 1E-3$$

Perform the same calculation for the A = 10 m^2 to get the dilution factor:

$$f_2 = \frac{10 m^2}{1E6\ m^2} = 1E-5$$

Recall that the ratio of the WSR for 1000 m^2 to the WSR for 10 m^2 yielded a parameter ratio of 10.3. The ratio of dilution factors, 1E-3 divided by 1E-5, results in 100, and the inverse ratio of areas is 0.01—resulting in a ratio of 1 (these two area components effectively cancel out). Therefore it is reasonable to conclude that the area embodied by the radionuclide release at the point of use, $r_{kj}(t)$ in the WSR equation yields a ratio of 10.3, since that is the overall ratio of WSR for 1000 m^2 to the WSR for 10 m^2. This is the same conclusion reached for the drinking water and plant irrigation pathways—in fact, it is consistent for all of the water-dependent pathways.

Fish Ingestion Pathway Conclusions

One conclusion for the fish ingestion pathway is that the area factors for the six radionuclides that deliver receptor dose via this pathway are more restrictive than those that scale directly with the size of the contaminated area. That is, the area factors for the soil ingestion pathway for a 1 m^2 area were 1000 for all radionuclides. The fish ingestion pathway area factors for 1 m^2 area ranged from 226 to 307 for C-14, Tc-99, and I-129, and ranged from 51.4 to 74.7 for Ra-226, U-238, and Am-241. It is important to remember that area factors for this pathway were calculated based of the individual time that a maximum occurs for

the water-dependent pathway for a particular contaminated area size. Given that the maximum for the external radiation pathway occurs at time t = 0, the area factor for a particular radionuclide will have a local maximum at t = 0, and another at the water-dependent time for maximum dose.

Hand calculations were performed to better understand how the size of the contaminated area impacted the RESRAD calculation of receptor dose for this pathway. It is interesting to note that while the area factors for the fish ingestion pathway are more restrictive than those that scale directly with contaminated area size, they are less restrictive than the external radiation pathway (for receptor located directly on the hot spot) area factor. The fish ingestion pathway is therefore regarded as mildly "hot spot" sensitive.

3.3.7 Ingestion-Based Pathway Conclusions

The receptor dose impact from hot spots via these six environmental pathways is largely related to total source term. For example, the radioactivity present in the drinking water originates from the activity in the survey unit that is transported to the groundwater, and eventually to the drinking water. Also, there is a time lag for some pathways like the plant products irrigated with contaminated water because it might take hundreds of years for example for the contamination to travel to the groundwater. The results of this section point to another somewhat obvious conclusion— hot spot dose assessment is more of a near term concern than for some future time (after breakthrough when they have reached the groundwater). That is, external radiation pathway seems to be more limiting.

Based on upon careful assessment of RESRAD, hot spot dose from the six ingestion pathways are either 1) linearly dependent on area—e.g., direct soil ingestion, ingestion of plant products grown in contaminated soil, and water-independent animal product pathways; or 2) based on total inventory of radioactivity—e.g., ingestion of plant products irrigated with contaminated water, water-dependent animal products consumption, drinking water, and fish ingestion. Considering the first set of pathways, recall that the ETF term in the dose calculation contains the FA parameter that causes the ingestion dose to be dependent on the size of the contaminated area. Specifically, the area relationships are as follows: A/1000 (direct soil ingestion), A/2000 (ingestion of plant products), and A/20,000 (ingestion of meat and dairy products).

The soil ingestion, water-independent animal product, and ingestion of plant products grown in contaminated soil all have area factors that scale directly with size of the contaminated area. As such, these pathways are not considered to be "hot spot" sensitive. The plant irrigation and water-dependent animal product pathway are the least restrictive, and have the largest area factors (even larger than those that scale directly with the size of the contaminated area). The drinking water and fish ingestion pathways are "mildly hot spot sensitive", having

area factors somewhat smaller than those that scale directly with the size of the contaminated area.

Finally, what can conclude about the cattle grazing at a rate of 50 m^2 per day—how do hot spots contribute to receptor dose? Well, as mentioned above, the ingestion dose scales directly with the size of the contaminated area. So if the contaminated area is only 1 m^2, the milk ingestion dose scales proportionately. Therefore, for a survey unit size of 1000 m^2 the hot spot ingestion dose would be 1/1000 of that derived for the case when the entire survey unit is contaminated. The idea is that the cattle graze essentially randomly throughout the survey unit, so on average, the hot spot represents just 1/1000 of the total grazing area. It seems that this is a reasonable way to model hot spots for this pathway. Besides, the external radiation and drinking water pathways are more limiting, so the cattle grazing on small hot spots argument turns out not to be that important.

CHAPTER 4 DOSE MODELING OF HOT SPOTS IN BUILDINGS

The building occupancy scenario accounts for receptor exposure to fixed and removable surface contamination sources within a structure. This residual radioactivity is assumed to remain following decontamination and decommissioning activities have been completed, including the final status survey. The building occupant is defined as a person who works in a commercial building following license termination. This section focuses on the hot spot dose from the following building occupancy pathways:

- external radiation
- inhalation of resuspended surface contamination
- inadvertent ingestion of surface contamination

Dose modeling of hot spots on building surfaces was performed from first principles. A detailed look at how hot spots of various sizes actually produce receptor doses for the above building occupancy pathways is considered in this section. The hot spot sizes considered are 3 m^2, 1 m^2, 0.5 m^2, 0.1 m^2 and 0.01 m^2. The default survey unit considered in this assessment is a floor area of 100 m^2. The smallest hot spot size (0.01 m^2) may be effectively considered to represent a discrete particle (10 cm × 10 cm) present on a building surface. Further, each hot spot source term will be considered to exist on the building surface; that is, the contamination is not considered to be present within the volume of the material surface.

Perhaps the most important aspect of using RESRAD-BUILD for this dissertation work is that it allows for the size of the contaminated area to be varied, which allows the calculation of area factors. The RESRAD-BUILD User's Manual describes the exposure scenarios and specifically, the dose modeling description for the inhalation exposure to building contamination (ANL 2003).

Both RESRAD-BUILD and MicroShield codes were used to assess hot spot doses from building contamination, with MicroShield being used specifically for the external radiation pathway. Building occupancy is the primary scenario in RESRAD-BUILD—e.g., an office worker spends roughly 2000 hours per year working in a building that may have residual radioactivity present. The pathways considered in RESRAD-BUILD include external radiation, inhalation and ingestion exposure pathways. RESRAD-BUILD offers the ability to model a building that can include up to three rooms, along with controls on ventilation between the rooms, and with the outside air. For this assessment it was assumed the receptor works in a single-room warehouse building.

For each of the three pathways, RESRAD-BUILD (and MicroShield for the external radiation pathway) was studied to determine how the code handled the

hot spot dose calculation. Receptor dose results were tabulated for RESRAD-BUILD, MicroShield and hand calculation area factors.

4.1 External Radiation Pathway

The receptor dose from the external radiation pathway primarily depends on the radionuclide and the characteristics of its emitted radiation, quantity of radioactivity on the building surface (a time-dependent term due to physical removal and radioactive decay), geometry of the source term, source-to-receptor distance, and exposure duration. The approach used to assess this pathway's dependence on hot spots involved both RESRAD-BUILD and MicroShield codes to calculate dose when the receptor was located directly over the hot spot. Additionally, MicroShield was used for the case when the receptor was positioned one meter from the hot spot.

Unlike the RESRAD code which does not permit hot spot sizes less than 1 m^2, RESRAD-BUILD was used to calculate hot spot doses for areas as small as 0.01 m^2. This smallest hot spot size (equal to 100 cm^2) is also the conventional averaging area for a single direct measurement of surface activity, as well as the nominal size of many radiation detectors used to measure surface activity. Note: Of the 11 radionuclides considered in this dissertation, three were not included in the external radiation dose evaluation because they do not have gamma or x-ray emissions (C-14, Sr-90, and Tc-99).

4.1.1 RESRAD-BUILD Area Factor Approach for External Radiation Pathway

It's beneficial to understand how RESRAD-BUILD calculates the hot spot dose from the external radiation exposure pathway. This approach is discussed in Appendix F of the RESRAD-BUILD manual. Specifically, the RESRAD-BUILD approach for the calculation of external radiation dose from an area source is to treat the source as a volume source of small thickness (0.01 cm) with unit density. The external radiation dose is estimated by assuming that the floor is an area source with the receptor located 1 m above the floor. The external dose at time t, $D_i(t)$, is calculated as follows:

$$D_i(t) = (ED/365) \times F_{in} \times F_i \times \overline{C}_S(t) \times DCF \times F_G \qquad (4-1)$$

where:
ED is the exposure duration in days;
F_{in} is the fraction of time spent indoors;
F_j is the fraction of time spent in compartment i;
$C_S(t)$ is the average volume source concentration in pCi/g over the exposure duration;

DCF is the dose conversion factor from FGR-12 for an infinite volume source; and
F_G or the geometrical factor, is the ratio of the dose for the actual source geometry to the dose for the standard source—contaminated soil of infinite depth and lateral extent with no clean cover. This geometrical factor is effectively the product of the depth-and-cover factor (F_{CD}), an area and material factor (F_{AM}), and the off-set factor ($F_{OFF-SET}$).

Again, although the source is technically a volume source, the thickness of 0.01 cm in reality should be viewed as a building surface source. In other words, the contamination is not assumed to be present within the volume of the building surface materials. Appendix F in the RESRAD-BUILD manual describes the various geometrical factors in sufficient detail (ANL 2003). For instance, the F_{AM} is derived using the point-kernel method considering the actual source geometry, source thickness, and gamma energies.

RESRAD-BUILD was run assuming that Ra-226 contamination (series assumed to be in secular equilibrium) was uniformly present on the floor over a 100 m^2 survey unit. Unit concentration (1 pCi/m^2) was input. The default indoor time fraction is 0.5 and exposure duration was 365 days. For this analysis, the source was positioned at the center of the room by specifying source coordinates at 5 m, 5 m, 0 (these are x, y, and z coordinates). The receptor was positioned at the same x and y coordinates as the source (e.g., 5 m and 5 m), with z coordinate equal to 1 m—so the receptor dose location was 1 m above the center of the source. The resulting dose from the model was 2.41E-5 mrem/y.

Next, RESRAD-BUILD was run to calculate the area factor for a 0.1 m^2 hot spot—a factor of 1000 smaller contaminated area. The dose from this smaller contaminated area is certainly expected to be less than the dose resulting from the entire survey unit being uniformly contaminated; the dose in this case is 2.17E-7 mrem/y. The area factor is calculated by dividing the dose from the larger contaminated area (2.41E-5 mrem/y) by the dose due to the smaller hot spot area (2.17E-7 mrem/y). This ratio is 110 and it is the area factor for a 0.1 m^2 hot spot of Ra-226.

The key parameter responsible for the difference in hot spot doses is the geometrical factor. Given that RESRAD-BUILD uses a point-kernel approach, it is not surprising that MicroShield, which also uses a point-kernel calculation, produces similar results. This is discussed in the following section.

4.1.2 MicroShield Area Factor Calculation

MicroShield was used to calculate the exposure rate, with buildup, for the case of uniform Ra-226 (series in equilibrium) contamination present on the surface of a 100 m^2 survey unit. The disk geometry in the MicroShield model was used.

Again, unit concentration in pCi/m^2 was converted to 1E-10 µCi/cm^2 and was input. The exposure rate result was 9.98E-9 mR/h. The annual dose can be calculated assuming the same exposure duration and indoor fraction as used by RESRAD (8760 hours per year times 0.5 indoor fraction), and recognizing that 1 mR in air is equivalent to 1 mrem in tissue for gamma emitters:

$$Dose = (9.98E-9\, mR/h)(8760 h/y)(0.5) = 4.37E-5\ mrem/y$$

Note that the MicroShield result is about 1.8 times greater than the RESRAD-BUILD result. This may be due to the fact that RESRAD-BUILD is assuming that some of the surface activity is being removed over the duration period due to abrasion and radioactive decay.

Now run MicroShield again to calculate the area factor for a 0.1 m^2 hot spot. The receptor is assumed to be located at the center of the hot spot. The exposure rate in this case is 8.98E-11 mR/h. This result can be converted to annual dose as follows:

$$Dose = (8.98E-11 mR/h)(8760 h/y)(0.5) = 3.93E-7\ mrem/y$$

The area factor is calculated by dividing the dose from the larger contaminated area (4.37E-5 mrem/y) by the dose due to the smaller hot spot area (3.93E-7 mrem/y). This ratio is 110—the same area factor as obtained from the RESRAD code. Therefore, the MicroShield calculation confirms the RESRAD result that the area factor for a 0.1 m^2 hot spot of Ra-226 is 110 times the average guideline. Again, it is important to remember that these results are for the case of the receptor located directly on the hot spot.

4.1.3 Receptor Location 1 m Distance from the Hot Spot

One aspect of this research is the use of probabilistic risk assessments for determining hot spot doses. This might include assessing the likelihood of encountering a hot spot in a given area, given that all areas of a survey unit are equally likely to be occupied by a future receptor. Similar to the approach presented for the external radiation pathway for soil, a distribution of receptor-to-hot spot distances can be generated using Crystal Ball. Based on the output, a reasonably conservative distance could be selected (e.g. 1 m).

The next step was to evaluate the receptor dose from a 0.1 m^2 hot spot when the receptor is located some distance from the hot spot. An arbitrary distance of 1 m was selected to evaluate MicroShield calculations of the annual receptor dose from a 0.1 m^2 Ra-226 hot spot. The MicroShield exposure rate was 4.56E-11 mR/h. As before, this result was based on an indoor fraction of 0.5, and the receptor was assumed to located 1 m from the hot spot for 0.5 × 8760 hours per year. The MicroShield result (considering buildup) was as follows:

$$Dose = (4.56E-11 mR/h)(8760 h/y)(0.5) = 2.00E-7\ mrem/y$$

For example, given the receptor dose based on a 1 m distance from the hot spot, the area factor was calculated. Specifically, the area factor is calculated by dividing the dose from the 100 m^2 contaminated area (4.37E-5 mrem/y) by the dose due to the smaller hot spot area located 1 m from the receptor (2.00E-7 mrem/y). This ratio is 220, and it represents the area factor for a 0.1 m^2 hot spot of Ra-226 assuming that the receptor is 1 m from the hot spot. Tables 103 to 110 in Appendix K show the external radiation doses and area factors as a function of radionuclide, hot spot size, and receptor distance from the hot spot for both RESRAD-BUILD and MicroShield. Results of the RESRAD-BUILD runs are provided in Appendix B for Co-60 as an example of the code output.

So, the area factor for a 0.1 m^2 hot spot is 110 when the receptor is located directly on the hot spot, and 220 when the receptor is 1 m from the hot spot. This general relationship holds for all eight radionuclides deliver dose via the external radiation pathway—i.e., the area factor for a 0.1 m^2 hot spot is roughly 100 when receptor located directly on the hot spot, and about 200 when the receptor is 1 m away. For a 100 cm^2 (0.01 m^2) hot spot the area factors are consistent for all radionuclides studied—about 1100 when receptor on hot spot, and roughly 2200 when receptor is 1 m away from the hot spot. Probabilistic modeling can be used as a technically defensible approach for determining a reasonable distribution of receptor-to-hot spot distances based on the survey unit size.

4.1.4 External Radiation Pathway Conclusions

The area factors calculated for the external radiation pathway are remarkably similar for each of the radionuclides[9]. For example, for the receptor located directly over a 0.1 m^2 hot spot, the area factors ranged from 107 to 115 for RESRAD-BUILD and ranged 111 to 114 for MicroShield. It may be reasonable to consider an area factor of 100 for all radionuclides. For the case of the receptor located 1 m from the 0.1 m^2 hot spot, the area factors ranged from 217 to 222. Therefore, conclude that for the external radiation pathway, the area factor is largely independent of the radionuclide (i.e., area factor only depends on the size of the hot spot).

For the smallest hot spot studied (0.01 m^2 or 100 cm^2), the area factors were approximately 1100. This compares to an area factor of 3 cited in both Regulatory Guide 1.86 and DOE Order 5400.5. Thus, the area factors calculated based on dose modeling are much larger than the historical factor of three area factor used for decades. Therefore, conclude that this pathway is indeed “hot spot” sensitive.

[9] The exception being for Pu-239—the area factor is significantly different for RESRAD-BUILD and MicroShield.

4.2 Inhalation Pathway

Receptor dose from the inhalation exposure pathway is determined by performing three sets of calculations: 1) the mechanical removal of material from the source and the rate of release of radionuclides into the indoor air; 2) the indoor airborne concentration of the radionuclides released into the air; and 3) the inhalation of airborne radioactive dust and the associated effective dose equivalent. The RESRAD-BUILD calculation of radionuclide release rate, $I_i(t)$ in pCi/h, into the compartment is shown below (ANL 2003):

$$I_i(t) = \frac{f_R \, f \, Q_s(t)}{24 T_R} \qquad (4-2)$$

where:
f_R is the removable fraction of the source material;
f is the fraction of removed material that becomes airborne (also called air release fraction);
T_R is time to remove material from the source (source lifetime, in days); and
$Q_s(t)$ is the total radionuclide activity (pCi) in the source at time t.
Note that once the exposure time t exceeds T_R, the radionuclide release rate becomes zero— ($I_i(t) = 0$).

The following RESRAD-BUILD default values were used in this assessment: removal fraction ($f_R = 0.5$), time for source removal ($T_R = 365$ days), and fraction of material released to the indoor air (f = 0.1). Sullivan et al. (2008) note that the removal fraction is a key parameter (along with resuspension) for determining inhalation dose.

The indoor airborne concentration, C_i, is calculated in RESRAD-BUILD using the indoor air quality model. This model factors in the radionuclide release rate shown above, and simulates the transport of radiological contaminants inside a building with air exchange between compartments and with outdoor air using a mass balance of the contaminant. The air quality model assumes that particulates in the indoor air are well mixed; therefore, the pollutant concentration is assumed to be the same for every point in the air within the compartment.

The total committed effective dose equivalent $D_{inh}(t)$ from time t to t + ED (exposure duration, usually one year) due to inhalation compartment can be calculated as follows:

$$D_{inh} = F_{in} \times F_i \times IR \times C_i \times ED \times DCF_{inh} \qquad (4-3)$$

where:
F_{in} is the fraction of time spent indoors (default is 0.5);
F_i is the fraction of indoor time that is spent at compartment i (dimensionless);
IR is the inhalation rate (default is 18 m^3/d);
C_i is the average radionuclide concentration (pCi/m^3) over the exposure duration, ED; and DCF_{inh} is the inhalation dose conversion factor for the radionuclide (mrem/pCi).

As one might expect, RESRAD and RESRAD-BUILD use the same dose conversion factors.

4.2.1 RESRAD-BUILD Area Factor Approach for Inhalation Exposure Pathway

RESRAD-BUILD (Version 3.22) was used to calculate the receptor dose from the inhalation pathway for a uniformly contaminated area (e.g., 100 m^2 survey unit). Specifically, RESRAD-BUILD was used to determine the receptor dose from an area source of 1 pCi/m^2 (2.22E-2 dpm/100 cm^2) of Am-241 on building surfaces. The default room size in this model is 36 m^2, which was increased to 100 m^2. The source contamination area was also assumed to be 100 m^2. RESRAD-BUILD allows the user to specify both the receptor and contamination source locations in the building. For this analysis, the source was positioned at the center of the room by specifying source coordinates at 5 m, 5 m, 0 (these are x, y, and z coordinates). The receptor was positioned at the same x and y coordinates as the source (e.g., 5 m and 5 m), with z coordinate equal to 1 m—effectively 1 m above the center of the source. Note: For the inhalation and ingestion pathways it does not matter where the receptor is located in the room because the model assumes that the air is homogenously mixed in each compartment.

The RESRAD-BUILD analysis used all default parameter values with the exception being the size of the room (used 100 m^2 rather than 36 m^2). The hot spot source term was an area source of 1 pCi/m^2. The resulting inhalation pathway receptor dose from the RESRAD-BUILD run was 4.15E-3 mrem/y.

RESRAD-BUILD was then used to calculate the area factor for the inhalation pathway for a 0.1 m^2 hot spot. All of the parameters were the same with the exception of the contaminated area size. The dose from this smaller contaminated area was 4.15E-6 mrem/y. It is interesting to note that the inhalation pathway dose scales directly with size of the contaminated area. As the contaminated area size was reduced from 100 m^2 to 0.1 m^2 (factor of 1000 reduction), the receptor dose from the inhalation pathway similarly was reduced by a factor of 1000. Thus, RESRAD-BUILD calculation of inhalation dose scales directly with the total radioactivity in the source.

Therefore, the area factor is calculated by dividing the inhalation pathway dose

from the larger contaminated area (4.15E-3 mrem/y) by the dose due to the smaller hot spot area (4.15E-6 mrem/y). This ratio is 1000 and it is the area factor for a 0.1 m^2 hot spot of Am-241.

Before leaving the RESRAD-BUILD calculation, the calculation of inhalation dose for the 100 m^2 Am-241 source term using this model was examined. Recall that the RESRAD-BUILD result was 4.15E-3 mrem/y. Studying these calculations in greater detail allows a better understanding of how the hot spot area impacts the calculation of dose. Start with the calculation of radionuclide release rate at t = 0, $I_i(t)$, given that the total radionuclide activity in the source (Q_s) at this time is 100 pCi:

$$I_i(t) = \frac{f_R \, f \, Q_s(t)}{24 T_R} = \frac{(0.5)(0.1)(100\,pCi)}{(24h/d)(365d)(3600s/h)} = 1.585E-7\,pCi/s$$

This compares to the RESRAD-BUILD interim result of 1.59E-7 pCi/s. Obviously Q_s depends on the hot spot size in order to determine the total radionuclide activity—i.e., unit activity concentration of 1 pCi/m^2 multiplied by contaminated area size (100 m^2).

RESRAD-BUILD calculates the indoor airborne concentration (C_i) using its indoor air quality model that accounts for factors such as the radionuclide release rate (calculated above), room dimensions, resuspension rate and building air exchange rate. The resulting airborne concentration of Am-241 calculated by RESRAD-BUILD air quality model is 2.85E-6 pCi/m^3.

Finally, calculate the total committed effective dose equivalent from time t = 0 to t = 1 y (exposure duration of 1 y) using the following equation:

$$D_{inh} = F_{in} \times F_i \times IR \times C_i \times ED \times DCF_{inh} \qquad (4-4)$$

$$D_{inh} = (0.5)(1)(18m^3/d)(2.85E-6\,\frac{pCi}{m^3})(1y)(0.444\frac{mrem}{pCi})(365d/y) = 4.16E-3\,mrem$$

Therefore, working through the equation provided a better understanding of the RESRAD-BUILD inhalation dose calculation for Am-241. Clearly, the Q_s total radionuclide activity parameter is the key in assessing how hot spots impact receptor dose.

The area factor for other hot spot areas (3, 1, 0.5, and 0.01 m^2) was calculated for the inhalation pathway. In each case it was apparent that the hot spot dose (and therefore area factor) scaled directly with the hot spot size. That is, if the hot spot size is reduced by a factor of 1000, then the hot spot dose is reduced by a similar factor, and therefore the area factor is 1000. Refer to Tables 111 to 121

in Appendix L for the receptor doses and area factors for each of the radionuclides and hot spot sizes for this pathway.

4.2.2 Calculation of Inhalation Pathway Dose Based on First Principles

The inhalation pathway dose will first be calculated for a receptor located in a 100 m^2 floor survey unit uniformly contaminated (1 pCi/m^2) with Am-241. The approach used here will be somewhat different from the RESRAD-BUILD approach—namely the resuspension factor was used to predict how much of the surface contamination becomes airborne. The inhalation dose will be calculated first from the surface activity level, using the following pathway equation

$$D_{inh} = A_s \times \frac{A}{SU} \times RF \times BR \times t \times DCF_{inh} \qquad (4-5)$$

where:
A_s is the surface activity level in pCi/m^2;
A is the contaminated area size in m^2;
SU is the survey unit size in m^2 —therefore A/SU represents the fraction of the survey unit area represented by the hot spot;
RF is the resuspension factor (use 1E-6 m^{-1} based on NUREG-1720 recommendation);
BR is the breathing rate (assume 33.6 m^3/d); and
t is the exposure time (97.5 days—based 45 hours per week, 52 weeks per year)

Federal Guidance Report No. 11 (USEPA 1988) provides the inhalation DCF for Am-241 as 0.444 mrem/pCi. The inhalation dose from Am-241 on 100 m^2 building floor surface is calculated as follows:

$$D_{inh} = 1\frac{pCi}{m^2} \times \frac{100m^2}{100m^2} \times 1E-6\,m^{-1} \times 33.6\frac{m^3}{d} \times 97.5\frac{d}{y} \times 0.444\frac{mrem}{pCi} = 1.45E-3\ mrem/y$$

This result is fairly close to the RESRAD-BUILD inhalation pathway dose of 4.15E-3 mrem/y. The hand calculation based on first principles is admittedly much simpler than the RESRAD-BUILD approach. A few factors are responsible for the difference. First, the hand calculation assumes that the receptor is located in the immediate vicinity of the hot spot and that the airborne concentration in the receptor's breathing zone is simply given by the product of the resuspension factor and the total activity in the hot spot. Second, the exposure duration for RESRAD-BUILD is 182.5 days (assumption is that occupant spends 0.5 time indoors), while the hand calculation assumes 97.5 days (based on a more typical work week). Third, the RESRAD-BUILD model uses a lower breathing rate of 18 m^3/d versus 33.6 m^3/d for the hand calculation.

However, these latter two factors are a wash. Multiplying the exposure duration by the breathing rate in each case yields a total volume of air inhaled of 3285 m^3 for RESRAD-BUILD compared to 3276 m^3 for the hand calculation. Perhaps most importantly, in both instances, the airborne contamination that the receptor breathes is related to the hot spot size, i.e., hot spot dose for the inhalation pathway is a function of total activity, just as RESRAD-BUILD assumes in its modeling approach.

The next step is to calculate the inhalation pathway dose to a receptor from a 0.1 m^2 hot spot. Obviously the total activity source term is much smaller, even though the surface activity level is still 1 pCi/m^2. The inhalation dose in this case is 1.45E-6 mrem/y. Therefore, the hot spot dose is directly related to the size of the contaminated area, A.

4.2.3 Inhalation Pathway Conclusions

As indicated in the above tables for the inhalation pathway of the building occupancy scenario, hot spot doses and area factors are generally consistent between the RESRAD-BUILD code and hand calculations. This is due to the fact that both RESRAD-BUILD and the hand calculation approach divide the hot spot area by the survey unit area—which reduces the radionuclide source term available to deliver inhalation dose to the receptor. That is, for both approaches, the airborne contamination inhaled by the receptor is directly proportional to the hot spot size.

It is interesting to compare the area factors obtained from the external radiation pathway (previous section), with those calculated for the inhalation pathway. Recall that for the receptor located directly over a 0.1 m^2 hot spot, the external radiation pathway area factors ranged from 107 to 115 for RESRAD-BUILD and ranged 111 to 114 for MicroShield. For the same 0.1 m^2 hot spot, the inhalation pathway area factor is 1000—a consequence of the fact that as the size of the contaminated area is reduced from 100 m^2 to 0.1 m^2 (reduced by factor of 1000), the hot spot dose is similarly reduced by a factor of 1000, and therefore, the area factor is 1000. Therefore, conclude that this pathway is not “hot spot” sensitive.

4.3 Ingestion Pathway

The ingestion pathway of the building occupancy scenario considers two components of the receptor dose from the inadvertent ingestion pathway: 1) the inadvertent ingestion of radioactive material contained in removable material directly from the source (sometimes referred to as direct ingestion), and 2) the inadvertent ingestion of airborne radioactive particulates deposited on building surfaces (also called secondary ingestion).

4.3.1 RESRAD-BUILD Area Factor Approach for Inadvertent Ingestion Exposure Pathway

RESRAD-BUILD calculates the total ingestion dose by the sum of the direct and secondary ingestion pathway components, $D_{i,l}$ and $D_{i,d}$. The inadvertent ingestion dose from the direct ingestion of loose material is calculated as follows (ANL 2003):

$$D_{i,l}(t) = (24 \times ED \times F_{in} \times F_i) \times ER_l \times f_R \times Q_s(t) \times DCF_{ing} \qquad (4-6)$$

where:
ED is the exposure duration (365 d);
F_{in} is the fraction of time spent indoors (default is 0.5);
F_i is the fraction of indoor time that is spent at compartment i (dimensionless);
ER_l is the ingestion rate of loose material directly from the source as a fraction of the source per unit time (default is 3.06E-6 h^{-1});
f_R is the removable fraction of the source material (default is 0.5); and
$Q_s(t)$ is the total average radionuclide activity over the exposure duration, ED, in the source (pCi) at time t.

Note: The RESRAD-BUILD output indicates that the default value for direct ingestion is 0 h^{-1} (ER_l =0). This means that the inadvertent ingestion dose is exclusively due to secondary ingestion.

The inadvertent ingestion dose from the secondary ingestion of airborne radioactive particulates deposited on building surfaces is calculated:

$$D_{i,d}(t) = (24 \times ED \times F_{in} \times F_i) \times SER \times C_{di}(t) \times DCF_{ing} \qquad (4-7)$$

where:
SER is the surface ingestion rate of dust particulates deposited on horizontal surfaces (default is 1.0E-4 m^2/h); and
$C_{di}(t)$ is the average surface concentration (in pCi/m^2) deposited on horizontal surfaces over the exposure duration, ED, starting at time t; and
DCF_{ing} is the ingestion dose conversion factor (mrem/pCi).

RESRAD-BUILD (Version 3.22) was used to calculate the receptor dose from the inadvertent ingestion pathway for a uniformly contaminated area (e.g., 100 m^2 survey unit). Specifically, RESRAD-BUILD was used to determine the receptor dose from an area source of 1 pCi/m^2 of Am-241 on building surfaces. The survey unit size was assumed to be 100 m^2; the source contamination area was also specified as 100 m^2. The source was positioned at the center of the room by specifying source coordinates at 5 m, 5 m, 0 m. The receptor was positioned at the same x and y coordinates as the source (e.g., 5 m and 5 m), with z

coordinate equal to 1 m—effectively 1 m above the center of the source. Note: For the inhalation and ingestion pathways it does not matter where the receptor is located in the room because the model assumes that the air is homogenously mixed in each compartment.

The RESRAD-BUILD analysis used all default parameter values with the exception being the size of the room (used 100 m^2 rather than 36 m^2). The hot spot source term was an area source of 1 pCi/m^2. The resulting inadvertent ingestion pathway receptor dose from the RESRAD-BUILD run was 9.06E-5 mrem/y.

RESRAD-BUILD was then used to calculate the area factor for the ingestion pathway for a 0.1 m^2 hot spot. All of the parameters were the same with the exception of the contaminated area size. The dose from this smaller contaminated area was 9.06E-8 mrem/y. It is interesting to note that the inadvertent ingestion pathway dose scales directly with size of the contaminated area. As the contaminated area size was reduced from 100 m^2 to 0.1 m^2 (factor of 1000 reduction), the receptor dose from the ingestion pathway similarly was reduced by a factor of 1000. Therefore, the area factor is calculated by dividing the ingestion pathway dose from the larger contaminated area (9.06E-5 mrem/y) by the dose due to the smaller hot spot area (9.06E-8 mrem/y). This ratio is 1000 and it is the area factor for a 0.1 m^2 hot spot of Am-241.

Before leaving the RESRAD-BUILD calculation, it is worthwhile to take a closer look at the calculation of ingestion dose for the 100 m^2 Am-241 source term using this model. Recall that the RESRAD-BUILD ingestion dose result was 9.06E5 mrem/y, and it equals the secondary ingestion of airborne radioactive particulates deposited on building surfaces (because the direct ingestion of loose material is equal to zero). The inadvertent ingestion dose from the ingestion of airborne radioactive particulates deposited on building surfaces is calculated using eqn 4-7:

$$D_{i,d}(t) = (24 \times ED \times F_{in} \times F_i) \times SER \times C_{di}(t) \times DCF_{ing}$$

Each of the variables in eqn 4-7 is known, with the exception of $C_{di}(t)$. The latter variable is determined using the RESRAD-BUILD air quality model. That is, RESRAD-BUILD calculates the airborne concentration of Am-241, which depends on the radionuclide release rate, room dimensions, resuspension rate and building air exchange rate. The average surface contamination deposited on horizontal surfaces, C_{di}, is then calculated from the airborne concentration. The radioactivity available to settle out as surface contamination is a function of the total source term. A better understanding of the RESRAD-BUILD ingestion dose calculation for Am-241 was achieved. The parameter important in assessing how hot spots impact receptor dose includes C_{di} in the above equation.

The area factor for other hot spot areas (3, 1, 0.5, and 0.01 m^2) was calculated for the ingestion pathway. In each case it was apparent that the hot spot dose (and therefore area factor) scaled directly with the hot spot size. That is, if the hot spot size is reduced by a factor of 1000, then the hot spot dose is reduced by a similar factor, and therefore the area factor is 1000. Refer to Tables 122 to 132 in Appendix M for receptor doses and area factors for the radionuclides and hot spot sizes for this pathway.

4.3.2 Calculation of Ingestion Pathway Dose Based on First Principles

The ingestion pathway dose will first be calculated for a receptor located in a 100 m^2 floor survey unit uniformly contaminated (1 pCi/m^2) with Am-241. The approach used here will be a little different from the RESRAD-BUILD approach. Namely, use the effective transfer rate for ingestion (GO). NUREG/CR-5512, vol. 3 (USNRC 1999a) defines the parameter GO as the effective transfer rate of contamination from building surfaces via hands, food and other items to the mouth—a process called secondary ingestion. The default value for GO is 1E-4 m^2/h. Note that GO is essentially the same parameter as SER used by RESRAD-BUILD. The ingestion dose is calculated using the following pathway equation:

$$D_{ing} = A_s \times \frac{A}{SU} \times GO \times t \times DCF_{ing} \qquad (4-8)$$

where:
A_s is the surface activity level in pCi/m^2;
A is the contaminated area size in m^2;
SU is the survey unit size in m^2—therefore A/SU represents the fraction of the survey unit area represented by the hot spot;
t is the exposure time (97.5 days—based 45 hours per week, 52 weeks per year); and
DCF_{ing} is the dose conversion factor for ingestion.

Federal Guidance Report No. 11 (USEPA 1988) provides the inhalation DCF for Am-241 as 3.64E-3 mrem/pCi. The ingestion dose from Am-241 on 100 m^2 building floor surface is calculated as follows:

$$D_{ing} = \frac{1\,pCi}{m^2} \times \frac{100 m^2}{100 m^2} \times \frac{1E-4 m^2}{h} \times \frac{97.5 d}{y} \times \frac{24 h}{d} \times \frac{3.64E-3 mrem}{pCi} = 8.52E-4\ mrem/y$$

This compares to the RESRAD-BUILD ingestion pathway dose of 9.06E-5 mrem/y. Thus, the hand calculation is about nine times greater than the

RESRAD-BUILD calculation. The two primary reasons for the difference between the RESRAD-BUILD and hand calculation results are the exposure time and surface contamination available for secondary ingestion. First, the RESRAD-BUILD model assumes the receptor has an exposure time of 4380 hours per year (assuming that 100% of indoor time is spent in the compartment of concern), while the hand calculation uses 2340 hours. Second, the RESRAD-BUILD model uses an air quality model to determine the surface contamination that settles on horizontal surfaces. In this calculation the surface contamination turns out to be 5.7E-2 pCi/m^2. The hand calculation simply assumes that the surface contamination available for secondary ingestion is the initial source term on the surface (1 pCi/m^2). Overall, even though the hand calculation uses less receptor exposure time, the larger surface contamination term (by a factor of more than 17); the hand calculation produces a receptor ingestion dose that is nearly a factor of ten greater that that calculated with RESRAD-BUILD.

The next step is to calculate the inhalation pathway dose to a receptor from a 0.1 m^2 hot spot. Obviously the total activity source term is much smaller, even though the surface activity level is still 1 pCi/m^2. The ingestion dose in this case is 8.52E-7 mrem/y. Therefore, the hot spot dose is directly related to the size of the contaminated area, A.

4.3.3 Ingestion Pathway Conclusions

As indicated in Tables 122 to 132 for the ingestion pathway of the building occupancy scenario, the hot spot doses are nearly a factor of ten greater for the hand calculations compared to the RESRAD-BUILD results. Possible explanations were discussed earlier in this section. However, even though the hot spot doses are difference, the area factors are very consistent between the RESRAD-BUILD code and hand calculations.

As with the inhalation pathway area factors, the ingestion pathway area factors are directly proportional to the hot spot size. For a 0.1 m^2 hot spot, the ingestion pathway area factor is 1000—a consequence of the fact that as the size of the contaminated area is reduced from 100 m^2 to 0.1 m^2 (reduced by factor of 1000), the hot spot dose is similarly reduced by a factor of 1000, and therefore, the area factor is 1000. Therefore, conclude that this pathway is not “hot spot” sensitive.

4.4 Building Occupancy Scenario Conclusions

Overall, the receptor dose impact from hot spots via the three building occupancy pathways is either directly related to total source term (e.g., inhalation and ingestion pathways), or a more complex relationship holds (external radiation pathway). For example, the hot spot dose via the inhalation and ingestion pathways scales directly with the size of the contaminated area. A larger hot spot source term (total radioactivity), results in a larger receptor dose.

It is illustrative to compare the area factors obtained from the external radiation pathway, with those calculated for the inhalation and ingestion pathways. Recall that for the receptor located directly over a 0.01 m^2 hot spot, the external radiation pathway area factors ranged from 1060 to 1130 for RESRAD-BUILD and ranged 1100 to 1130 for MicroShield. The area factors for the other two pathways were 10,000. Therefore, the conclusion is that the external radiation pathway is the most limiting of the pathways, and it is certainly hot spot sensitive.

It is important to review the area factor results in the context of the particular radionuclide being considered. That is, the results evaluated so far have taken each pathway by itself. Based on that approach, the external radiation pathway is more limiting (i.e., smaller area factors) than the inhalation and ingestion pathways. However, specific radionuclides typically deliver dose via a combination of pathways. For example, both Co-60 and Cs-137 deliver the majority of their dose via the external radiation pathway. So, considering an assumed hot spot size of 100 cm^2 (0.01 m^2) of Co-60 and Cs-137, the area factor would be expected to be close to that obtained for the external radiation pathway alone. Indeed, the area factors for Co-60 and Cs-137 are 1220 and 1340, respectively. Several radionuclides have area factors for a 0.01 m^2 hot spot that are 10,000 (or very close to 10,000). These radionuclides include C-14, Sr-90, Tc-99, Th-232, U-238, Pu-239, and Am-241—and while some of these radionuclides may have a small external radiation dose component, their dominant dose pathway is inhalation or ingestion (or both). Finally, two radionuclides represent a mix between the external radiation pathway and the inhalation/ingestion pathways—I-129 has an area factor of 6240 and Ra-226 has an area factor of 7300. Therefore, when establishing area factors for radionuclides it is necessary to consider the relative dose contribution provided by each pathway.

CHAPTER 5 UNCERTAINTY ASSESSMENT

The objective of uncertainty assessment is to determine the factors that contribute to the hot spot dose uncertainty. In the context of the external radiation pathway the goal was to identify the input parameters that are responsible for most of the uncertainty in receptor dose. Considering that the external radiation pathway is the primary hot spot pathway of interest, a number of questions were addressed in this evaluation. For example, how much uncertainty exists in the hot spot dose result? What parameters contribute to the uncertainty, and how significant is the uncertainty in each parameter compared to the total uncertainty? The uncertainties in dose assessments can be addressed using a variety of approaches. One approach is to use the Monte Carlo for Neutral Particles (MCNP) code to validate the external radiation pathway doses obtained using MicroShield. In this regard MCNP can be used to calculate the receptor dose from the external radiation pathway, and thereby providing an estimate of the dose uncertainty.

Various aspects of uncertainty assessment were performed in this research. First, MCNP was used to assess the uncertainties in dose calculations for the external radiation pathway. The direct exposure to external radiation from contaminated soil was evaluated using RESRAD, MicroShield, and a hand calculation returning to first principles. MCNP was used to validate the calculation of receptor doses from the external radiation pathway. This offered an approach for estimating the uncertainty involved with the point kernel methods used by MicroShield. The approach used to model external radiation geometry using MCNP is discussed in the next section.

Next, bounding uncertainty analyses were performed for a number of representative pathways by calculating hot spot doses for the case when the hot spot is on the surface (no depth), and for the case when the hot spot extends to a depth of 15 cm. This provides an assessment of the impact that depth has on hot spot dose.

Finally, the uncertainties in source distributions were evaluated to study their impact on receptor dose calculations. Opportunities to make use of real data (e.g., survey data to evaluate contaminant distributions) to validate the models and approaches used in this work were sought.

5.1 MCNP Modeling of External Radiation Pathway

The hot spot dose modeling research discussed in Chapters 3 and 4 indicates that the hot spot dose is most impacted by the external radiation pathway. This fact justified the in-depth uncertainty assessment for this pathway—especially

that involving MCNP simulations.

The MCNP Code, developed and maintained by Los Alamos National Laboratory, is an internationally recognized code for analyzing the transport of neutrons and gamma rays by the Monte Carlo method. MCNP stands for Monte Carlo for neutral particles (NP). The code deals with transport of neutrons, gamma rays, and coupled transport, i.e., transport of secondary gamma rays resulting from neutron interactions.

5.1.1 MCNP Approach to Validate MicroShield Results

The approach used to model the external radiation geometry using MCNP is described in this section. This assessment includes the radionuclides, hot spot sizes and receptor distance from the hot spot. The input files for the modeling code and MCNP output are discussed in detail. The ultimate objective is to compare the MicroShield results to the MCNP results as an approach for assessing the uncertainty in these codes.

The geometry modeled for assessing the external radiation dose to the receptor is fairly straightforward. The receptor is initially positioned directly above (at height of 1 m) a hot spot that is located in an infinite slab of soil. The hot spot areal size is varied using same dimensions evaluated previously, but the depth is a constant 15 cm. Three radionuclides are studied using MCNP: Co-60, Cs-137, and Am-241. These radionuclides provide a good range of energies, from 0.060 MeV for Am-241 to 1.332 MeV for the second Co-60 emission. The materials modeled include soil and air; the elemental compositions and mass fractions for these materials were obtained from Federal Guidance Report 12 (Eckerman and Ryman1993).

The MCNP input file is used to describe the source-to-receptor geometry, specific materials and radiation sources, and format and types of results needed from the calculation. Specific problem geometries are developed by defining cells that are bounded by one or more surfaces, and cells can be filled with a specific material or defined as a void.

The cell, surface, and data cards are the fundamental components of the MCNP input file. The MCNP manual (LANL 2003) uses the word “card” to describe a single line of input that can consist of up to 80 characters. A “section” consists of one or more cards. The input file structure is shown below.

- Title Card
- Cell Cards
- Blank Line Delimiter
- Data Cards
- Blank Line Terminator (optional)

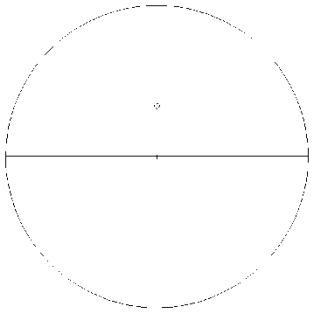

Figure 3 MCNP geometry showing receptor tally cell above soil surface.

An example is used to describe the MCNP approach used to validate the external radiation results obtained from MicroShield. Specifically, the MCNP calculation of receptor dose from Co-60 for a receptor located directly over the hot spot is described in detail (Figure 3). For this example, the number of photons incident on a tally cell (represents the receptor) was calculated from a uniform cylindrical volume source that has a surface area of 0.1 m^2 and depth of 15 cm. The source is Co-60, which is characterized by two gamma emissions of nearly 100% yield with gamma energies of 1.173 and 1.332 MeV.

The MCNP5 input file for this example is as follows:

```
External Dose from Co-60
c Co-60 0.1 m2 survey unit
1 1 -1.6 -1 -2 $soil below x-y axis and inside sphere
2 2 -0.001293 1 -2 3   $air
3 2 -0.001293 -3 $tally cell, air
4 0 2
c end of cell cards

C Beginning of surfaces
1 PZ 0 $ Plane surface on x-y axis
2 so 300 $ sphere surface centered at origin
3 sz 100 5 $tally sphere at 1 m height, 5 cm radius
c End of surfaces
```

```
mode p
IMP:P 1 1 1 0
SDEF par=2 erg=D1 POS=0 0 -7.5 cel=1 rad=D2 ext=D3 AXS=0 0 1
SI1 L 1.173 1.332 $two Co-60 energies
SP1 0.9986 0.9998 $ photon yields for each energy
SI2 0 17.84
SP2 -21 1
SI3 7.5

 F6:p 3 $tally is energy deposition in cell 3
 FM6 116.79
 c FM6 constant specific to hot spot size; converts to mR/h
 c M1 is soil based on FGR-12 composition
 M1 1000 -0.021 6000 -0.016 8000 -0.577 13000 -0.05
    14000 -0.271 19000 -0.013 20000 -0.041 26000 -0.011
 c M2 is air based on FGR-12 composition
 M2 1000 -0.00064 6000 -0.00014 7000 -0.75086
    8000 -0.23555 18000 -0.01281
 NPS 1000000
```

The first step for developing any input file is to give it a title card. In this example the title card is simply “External Dose from Co-60.” A comment card immediately follows that explains that this particular input file is for a 0.1 m^2 hot spot.

Cell cards were defined next. In this simple geometry four cell cards were defined. It is first necessary to define a few surfaces before cells can be described. First, consider a plane surface on the x-y axis. Above this surface an air-filled cell is defined, while a soil-filled cell is defined below this surface. The surface cards are used to define the boundaries of the cells. A sphere centered at the origin surrounds the both the air and soil cells, essentially creating a hemisphere of air above a lower hemisphere of soil. The sphere has a radius of 300 cm. Any particles leaving the sphere enter a void, and are “killed”, i.e., no longer are those particle histories tracked. A tally cell is defined as a 5 cm sphere located 1 m above the hot spot, which is centered at the origin of the coordinate system. Therefore, definitions include cell 1 as the soil, cell 2 as the air, cell 3 as the tally cell (described later), and cell 4 as the void surrounding the 300 cm sphere. The negative value located after the material number indicates the material density in grams per cubic centimeter. When a cell contains a void, no density value is needed.

The cylindrical source is defined using the “SDEF” card. The center of the source in x, y, z coordinate system is 0, 0, 7.5 cm (in soil). The radius for the 0.1 m^2 hot spot is 17.84 cm. The par=2 means that the code is transporting photons (as opposed to neutrons). The “erg = D1” function defines the energies and yields of the gamma emissions. The radius of the source must be defined as a distribution (“rad=D2”) between 0 and 17.84 cm, with the SP2 card showing “-21 1” meaning that source particles will be distributed along the radius of the disc

with a power law to the first power, the desired distribution for particles within a circular area in the x-y plane. The “ext=D3” on the SI3 card describes the height of the cylinder, with 7.5 cm describing the center.

The material cards for this example are defined next. The material cards are placed in the data section of the input deck after the surface cards with a blank line delimiter placed between the surface cards and the data cards. Air is used to transport the particles that leave the soil. As previously mentioned, air and soil have compositions as defined in FGR-12. Tables 7 and 8 show these data.

The negative values in the material data section of the input file indicate mass fractions. If weight fractions on a material card do not sum to unity, MCNP will normalize them.

Tally and tally multiplier cards are described next. The F6:p tally is for energy deposition in cell 3. The coordinates for this cell were provided earlier in the cell description of the input file. Recall that the tally cell represents the receptor location—basically a 5-cm radius sphere (of air) located at 1 m above the hot spot. The F6:p tally results are in units of Mev/g deposited in the cell.

Table 7 Mass fractions used for soil composition.

Element	Mass Fraction
H	0.021
C	0.016
O	0.577
Al	0.050
Si	0.271
K	0.013
Ca	0.041
Fe	0.011

Table 8 Mass fractions used for air composition.

Element	Mass Fraction
H	0.00064
C	0.00014
N	0.75086
O	0.23555
Ar	0.01281

The tally multiplier, FM6, is shown next. The MCNP result in MeV/g (energy deposition in cell) must be multiplied by the volume (1.5E4 cm^3) and source strength (1 pCi/g which results in 0.1184 gammas per cm^3 per second. This result (V*S) of 1776 is then multiplied by conversion factors of 1.602E-8 rad/(MeV/g), 1000 mrad/rad, 3600 s/h, and 1 R per 0.877 rad in air. This leads directly to our tally multiplier of 116.79. Note that it is directly dependent on the size of the hot spot.

Three more data cards are mentioned for completion—the mode of the problem ("mode"), the cell importances ("imp"), and the number of particle histories to run ("nps"). For this example only photons are transported ("mode p"). The photons are transported inside cells 1 through 3, and they are killed once they reach cell 4. Since the entries on the "imp" card correspond to the order of the cells on the input card, the values for the "imp" card are 1, 1, 1 and 0, in that order. For this example, one million particles ("nps 1000000") were run. One blank line must be placed after the last data card to signal the end of the input file.

The input file from this input file is now complete. The command line for running this input file is given as: `mcnp5 i=Co01 o=Co01out`

On the command line, the "i=Co01" entry indicates the name that the input file is given inside the MCNP5 directory. The "o=Co01out" entry defines the output file once it is created. By default, this output file is placed in the same directory as the input file. This run of 1,000,000 histories only took about 1 minute to complete. Perhaps somewhat surprising was that only 5 photons interacted in the tally cell. The result was 2.22E-5 mR/h with a relative error of 2.65%. For comparison, the MicroShield result was 2.15E-5 mR/h.

5.1.2 MCNP Validation Results for Co-60, Cs-137 and Am-241

MCNP results were determine for three representative radionuclides—Co-60, Cs-137, and Am-241. These radionuclides offer a range of gamma radiation energies from 60 keV to 1.33 MeV. MCNP exposure rate results were compared to those obtained from MicroShield in Tables 9 to 11.

5.1.3 MCNP Conclusions

The MCNP code was used to validate the MicroShield exposure rate results for three radionuclides—Co-60, Cs-137, and Am-241. For the case of the receptor located directly above the hot spot, the exposure rates were very similar. The largest relative percent error was 18%, and most were no more than 3 to 4% relative percent error. So for this geometry, MCNP certainly provided a validation of the MicroShield results. The uncertainty in the exposure rate measurements for this geometry generally ranges from 2 to 10%.

The MCNP code was also used to validate the MicroShield results for the receptor located 6 m away from the hot spot. The comparison between MCNP and MicroShield was not so good for this geometry. The relative percent error between the two approaches was typically 50% or more, and for the smallest three hot spot sizes, ranged from 120% to 740%. For these largest discrepancies MicroShield consistently overestimated the exposure rate. The likely reason for this discrepancy is that the MicroShield code treats the scattered photon fluence as having the same photon energy as the primary flux. Obviously this approximation introduces increasing error as the buildup contribution to the total exposure rate increases. The uncertainty in the exposure rate measurements for this geometry (expressed as relative percent error) is much greater, ranging from a factor of two to a factor of eight for smaller hot spot sizes.

The bottom line concerning this MCNP assessment is that the area factors provided in Appendix C for the 6 m receptor distance are even larger than reported. This is because the MCNP exposure rate results were consistently lower than the corresponding MicroShield results, meaning that the 6 m distance area factors are greater by a proportional amount.

Note that for most of the assessments, the MCNP relative error ranged from 1.5% to 12%, with the larger errors associated with the 6 m receptor distance from the hot spot. These MCNP errors were sufficiently small to permit valid comparisons with the MicroShield results.

5.2 Depth of Contamination, Outdoor Fraction and Receptor Distance

The next part of the uncertainty assessment for the external radiation pathway focused on three parameters: 1) depth of contamination, 2) outdoor fraction, and 3) distance of receptor from the hot spot. Both Crystal Ball and JMP software codes are used in these analyses. Simulations using the Crystal Ball software code were used to model the parameter distributions. This allowed an assessment of the impact that depth has on hot spot dose, and in particular, the uncertainty.

5.2.1 Depth of Contamination and its Uncertainty

The depth of contamination is the first parameter evaluated in this uncertainty assessment. The radionuclide concentration in the hot spot was assumed to vary from just being on the soil surface (0.1 cm depth) to a depth of 15 cm. Given the range of the depth of contamination data (0.1 to 15 cm), a uniform distribution is the least-biased parameter distribution. The mean of this distribution is simply (0.1 + 15)/2 = 7.55 cm. The standard deviation, s, is given by:

Table 9 MCNP vs. MicroShield exposure rate results for Co-60 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MicroShield (mR/h)	2.16E-3	9.41E-4	4.56E-4	1.89E-4	1.01E-4	2.15E-5	2.18E-6
MCNP (mR/h)	1.82E-3	8.62E-4	4.47E-4	1.91E-4	1.09E-4	2.22E-5	2.25E-6
MCNP (relative error)	9.54%	4.22%	3.21%	2.85%	2.68%	2.65%	2.62%
MicroShield/MCNP	1.186	1.092	1.021	0.991	0.932	0.968	0.970
Relative Percent Error	18.6%	9.17%	2.08%	-0.9%	-6.81%	-3.24%	-3.02%
Receptor 6 m From Hot Spot							
MicroShield (mR/h)	2.17E-3	2.74E-5	8.68E-6	3.32E-6	1.89E-6	5.36E-7	7.26E-8
MCNP (mR/h)	1.94E-3	1.55E-5	5.01E-6	1.69E-6	8.00E-7	1.68E-7	1.81E-8
MCNP (relative error)	8.95%	10.12%	3.10%	9.89%	7.18%	9.77%	9.40%
MicroShield/MCNP	1.117	1.770	1.732	1.963	2.364	3.186	4.004
Relative Percent Error	11.7%	77.0%	73.2%	96.3%	136%	219%	300%

Table 10 MCNP vs. MicroShield exposure rate results for Cs-137 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MicroShield (mR/h)	4.98E-4	2.28E-4	1.13E-4	4.69E-5	2.51E-5	5.35E-6	5.42E-7
MCNP (mR/h)	4.43E-4	2.11E-4	1.12E-4	4.79E-5	2.63E-5	5.56E-6	5.58E-7
MCNP (relative error)	9.29%	2.28%	1.72%	1.52%	1.46%	1.42%	1.40%
MicroShield/MCNP	1.124	1.080	1.001	0.997	0.957	0.961	0.972
Relative Percent Error	12.4%	8.02%	0.079%	-2.26%	-4.25%	-3.86%	-2.81%
Receptor 6 m From Hot Spot							
MicroShield (mR/h)	5.01E-4	6.01E-6	1.93E-6	7.46E-7	4.29E-7	1.27E-7	1.83E-8
MCNP (mR/h)	5.13E-4	3.16E-6	1.16E-6	4.05E-7	1.71E-7	3.42E-8	3.64E-9
MCNP (relative error)	8.56%	10.80%	9.96%	9.82%	10.56%	10.37%	10.11%
MicroShield/MCNP	0.976	1.902	1.667	1.843	2.512	3.720	5.018
Relative Percent Error	-2.45%	90.2%	66.7%	84.3%	151%	272%	402%

Table 11 MCNP vs. MicroShield exposure rate results for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MicroShield (mR/h)	5.74E-6	3.14E-6	1.72E-6	7.65E-7	4.20E-7	9.10E-8	9.28E-9
MCNP (mR/h)	5.97E-6	3.08E-6	1.74E-6	7.63E-7	4.37E-7	9.11E-8	8.94E-9
MCNP (relative error)	10.66%	4.36%	3.17%	2.78%	2.58%	2.53%	2.55%
MicroShield/MCNP	0.963	1.022	0.987	1.003	0.961	0.999	1.037
Relative Percent Error	-3.74%	2.16%	-1.31%	0.255%	-3.90%	-0.066%	3.74%
Receptor 6 m From Hot Spot							
MicroShield (mR/h)	5.90E-6	6.31E-8	2.09E-8	8.50E-9	5.03E-9	1.65E-9	4.09E-10
MCNP (mR/h)	6.59E-6	4.91E-8	1.44E-8	1.15E-8	2.27E-9	5.54E-10	4.87E-11
MCNP (relative error)	10.28%	11.88%	11.88%	11.91%	12.25%	11.30%	11.56%
MicroShield/MCNP	0.896	1.287	1.452	0.736	2.221	2.975	8.386
Relative Percent Error	-10.4%	28.7%	45.2%	-26.4%	122%	198%	739%

$$s = \sqrt{\frac{(15-0.1)^2}{12}} = 4.3\ cm$$

The output from 1000 runs of Crystal Ball for the depth distribution had a mean of 7.52 cm and a standard deviation of 4.36 cm. This closely matched the expected mean and standard deviation.

It is useful to note that the uniform probability density function assumes that all depths between 0.1 and 15 cm are equally likely. The frequency output in Crystal Ball illustrates the probabilistic variability of the depth of contamination when sampled from a uniform distribution (Figure 4).

5.2.2 Calculation of Exposure Rate and its Uncertainty

MicroShield was used to calculate the exposure rate for a receptor located directly above a 10 m^2 hot spot of Co-60. Again, the depth of contamination was varied from 0.1 cm (surface) to 15 cm. The concentration was held constant at 1 pCi/g Co-60. [In a later section of this chapter the source distribution was varied via the lognormal distribution to consider the impact of hot spots on the average receptor dose.] MicroShield exposure rate results for a number of depths are provided in the Table 12.

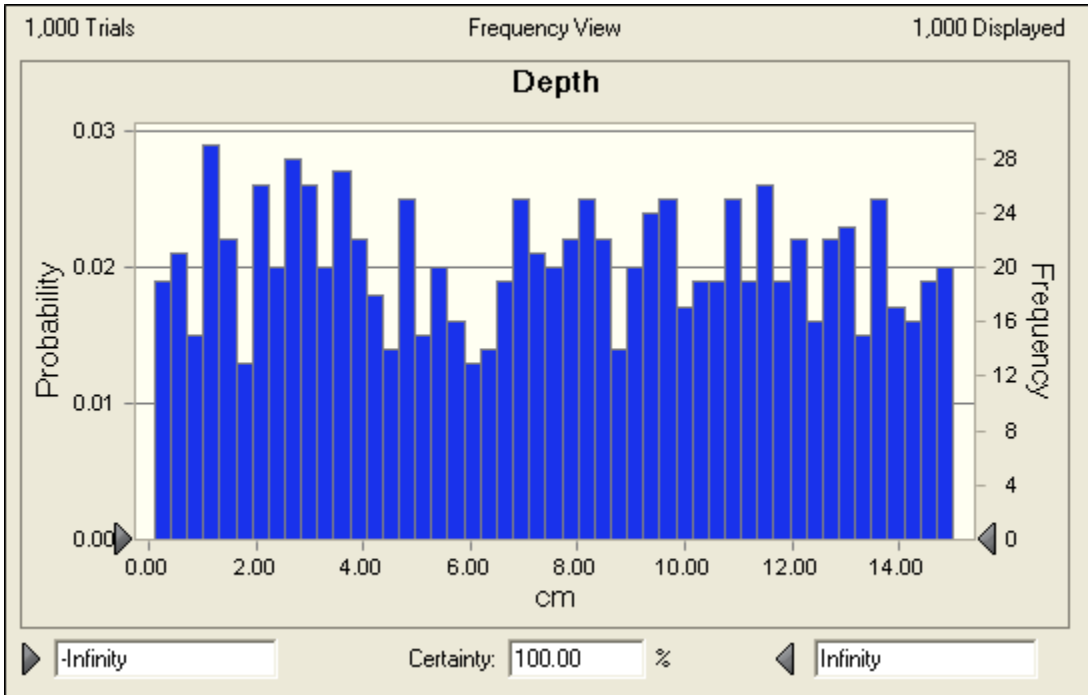

Figure 4 Depth of contamination parameter as sampled from a uniform

distribution.
Table 12 MicroShield exposure rates as a function of depth and source term.

Depth (cm)	Exposure Rate (mR/h)
0.1	9.29E-6
1	9.13E-5
3	2.63E-4
5	4.11E-4
7	5.43E-4
10	7.16E-4
15	9.41E-4

As an aside, the annual receptor dose from this Co-60 hot spot was calculated using RESRAD, MicroShield, and by hand calculation using Maple to solve a double integral. Comparable results were obtained using these different techniques for calculating the receptor dose to a 10 m^2 hot spot at the 15 cm depth—3.212, 2.06, and 2.36 mrem/y, respectively. The MCNP analysis in the previous section provided an estimate of the MicroShield uncertainty for the case when the receptor is located directly above the hot spot.

The reason that the exposure rate increases with depth is due to the fact that the total source term increases as the depth increases (since concentration is constant, as depth increases, the total source term increases). The exposure rate reaches a maximum of 1.38E-3 mR/h at a depth of roughly 80 cm.

The exposure rate versus depth data were then analyzed using JMP statistical software. The data were best fit by a polynomial equation as indicated in the JMP output in Figure 5. The individual uncertainties related to each MicroShield calculation (not assessed) are included in the random error associated with the linear regression—these include calculation error (e.g., MicroShield), as well as errors due to other predictors affecting exposure rate that are not included in the model.

The regression analysis had an R^2 value of 0.9999 indicating a very good fit. The second-order polynomial equation describing exposure rate (in mR/h) as a function of depth (in cm) is given by:

$$\dot{X} = -1.867E-6(Depth)^2 + 9.0362E-5(Depth) + 3.429E-6$$

Note: The intercept term is statistically equal to zero since the lower and upper 95% interval includes zero.

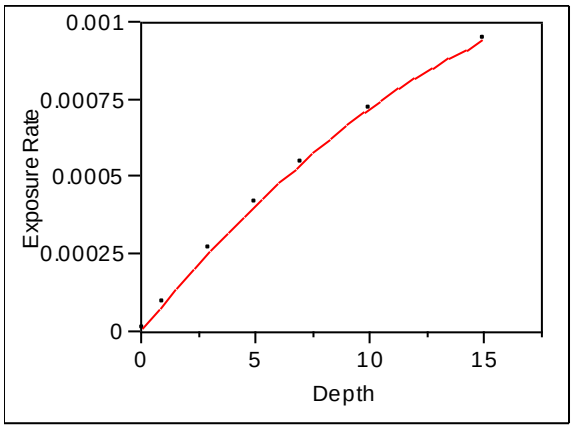

Figure 5 Exposure rate vs. depth regression plot.

At this point the exposure rate was calculated due to 10 m^2 hot spot of Co-60 that exists at some depth profile that ranges from 0.1 to 15 cm. The exposure rate data were multiplied by 1000 to convert units from mR/h to µR/h. Crystal Ball was used to simulate varying depths, and for each depth value selected, the exposure rate was calculated using the polynomial equation provided above. The Crystal Ball output statistics indicate a mean exposure rate of 0.54 µR/h, with a standard deviation of 0.27 µR/h. A simple measure of uncertainty in this distribution is the relative standard deviation: 0.27/0.54 equals 50%. The exposure rate distribution shown in Figure 6 reflects both the uncertainty in the depth, as well as the uncertainty in the model that predicts exposure rate as a function of depth. Recall that the exposure rate ranged from 0.00929 to 0.9406 µR/h—about the same range that results from the Crystal Ball simulation.

5.2.3 Outdoor Fraction and its Uncertainty

The outdoor fraction parameter was considered next. The time spent outdoors at the residence of concern (i.e., potentially contaminated property), called the outdoor fraction, is classified by NUREG/CR-5512, vol. 3 as a behavioral parameter. Table 6.7 in NUREG/CR-5512 provides data describing the time spent outdoors at a residence (USNRC 1999a)—the mean is 40.2, 24-hour days per year with a standard deviation of 40.6, 24-hour days per year. These statistics can be divided by 365.25 days per year to yield outdoor fractions of 0.11 for both the mean and standard deviation. This parameter can be described by a beta density function specified with an expected value (mean), standard deviation, minimum (0% time outdoors), and maximum (100% time outdoors).

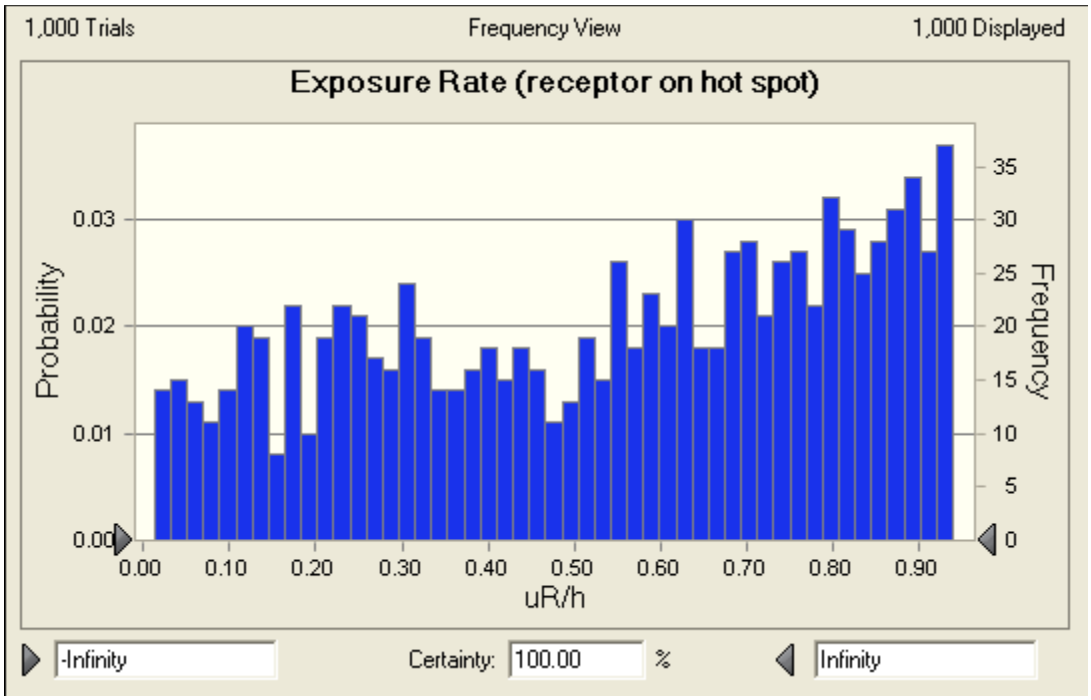

Figure 6 Simulation of exposure rate distribution as a function of depth.

Crystal Ball was used to model the outdoor time fraction using the beta probability density function (Figure 7). The alpha and beta values needed for the beta distribution can be determined from the mean and standard deviation according to the following equations (Tamhane and Dunlop 2000):

$$\mu = \frac{\alpha}{\alpha + \beta} = 0.11 \qquad (5-1)$$

and

$$\sigma = \sqrt{\frac{\alpha \cdot \beta}{(\alpha + \beta)^2 (\alpha + \beta + 1)}} = 0.11 \qquad (5-2)$$

Figure 8 shows that the output from the beta distribution of outdoor time fraction resulted in a mean and standard deviation of 0.11, and with a minimum and maximum of 0 and 0.70, respectively. It is interesting to note that the maximum outdoor time fraction from the simulation of 1,000 trials was 0.70 (not very close to the theoretical maximum of 1). Also, the relative standard deviation for this distribution is: 0.11/0.11 or 100%

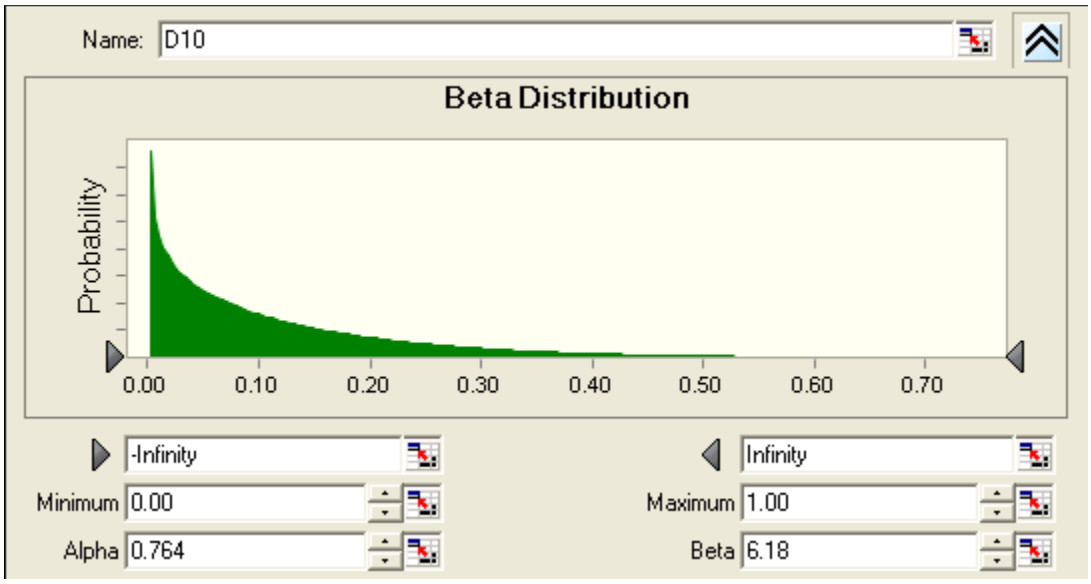

Figure 7 Outdoor fraction modeled with a beta distribution.

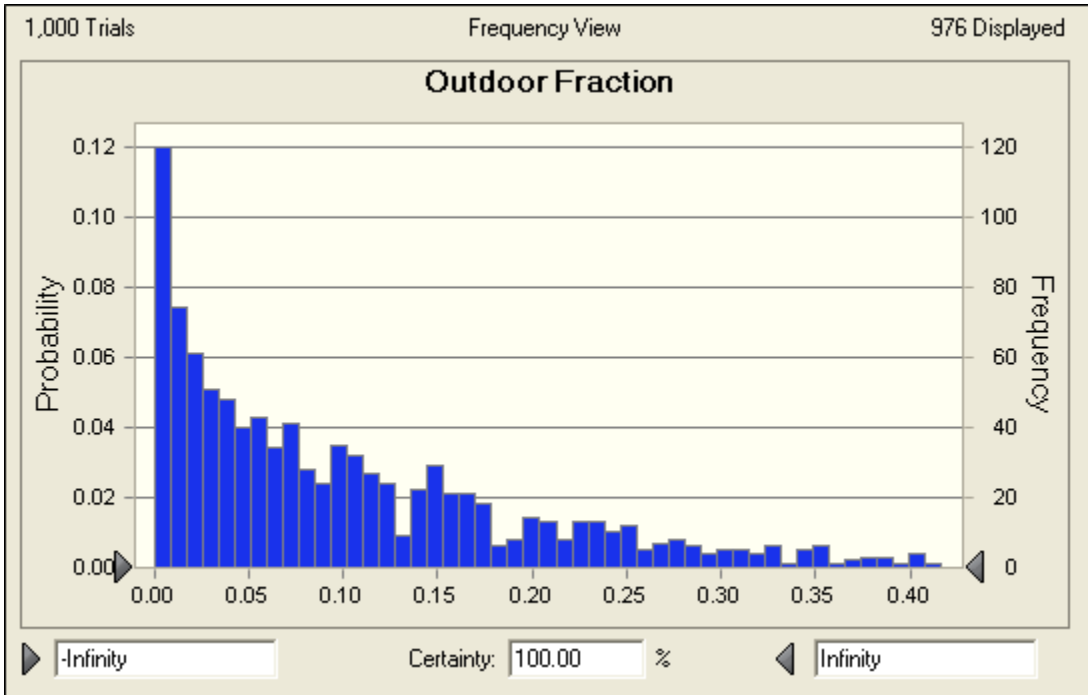

Figure 8 Outdoor fraction simulation results.

5.2.4 Annual Receptor Dose from External Radiation Pathway

Finally, the annual receptor dose is calculated by multiplying the exposure rate in mR/h by the outdoor time fraction. For example, MicroShield is used to calculate the exposure rate when the hot spot contamination is present to a depth of 15 cm over the 10 m^2 hot spot—the exposure rate result is 9.41E-4 mR/h. The annual dose can be calculated assuming the same outdoor fraction as used by RESRAD (0.25):

$$Annual\,Dose = (9.41E-4\,mR/h)(8760\,h/y)(0.25) = 2.06\,mrem/y$$

This Crystal Ball output provides the following statistics for the annual receptor dose:

• Mean	0.51
• Median	0.29
• Standard Deviation	0.62
• Variance	0.38
• Minimum	0.00
• Maximum	3.91

The relative standard deviation is used as a simple measure of uncertainty; the relative standard deviation in the annual receptor dose was 122%. The annual dose ranges from a minimum of 0 to a maximum of 3.91 mrem/y, for the case when the receptor is directly over the hot spot. Also, note that the shape of this distribution is very similar to the outdoor fraction, indicating that outdoor fraction has a significant influence on the annual dose distribution (Figure 9).

Indeed, Crystal Ball corroborates this expectation that the annual receptor dose is more sensitive to outdoor fraction than it is to hot spot depth. As evident in the Figure 10 below, the uncertainty in the outdoor fraction represents more than 80% of the overall uncertainty in the annual dose from the external pathway. It is important to recognize that the uncertainty in a behavioral parameter like outdoor fraction can often be much greater than the uncertainty in the dose measurement (refer to the MCNP validation of MicroShield in the previous section).

5.2.5 Source Term Distribution Contribution to Uncertainty

So far the source term (1 pCi/g) has been treated as if it were a constant, with no uncertainty. Various source term distributions are considered in this section to assess the source distribution's impact on the receptor dose variability. Crystal Ball was used to simulate sampling from different source term distributions, including a normal and lognormal distribution.

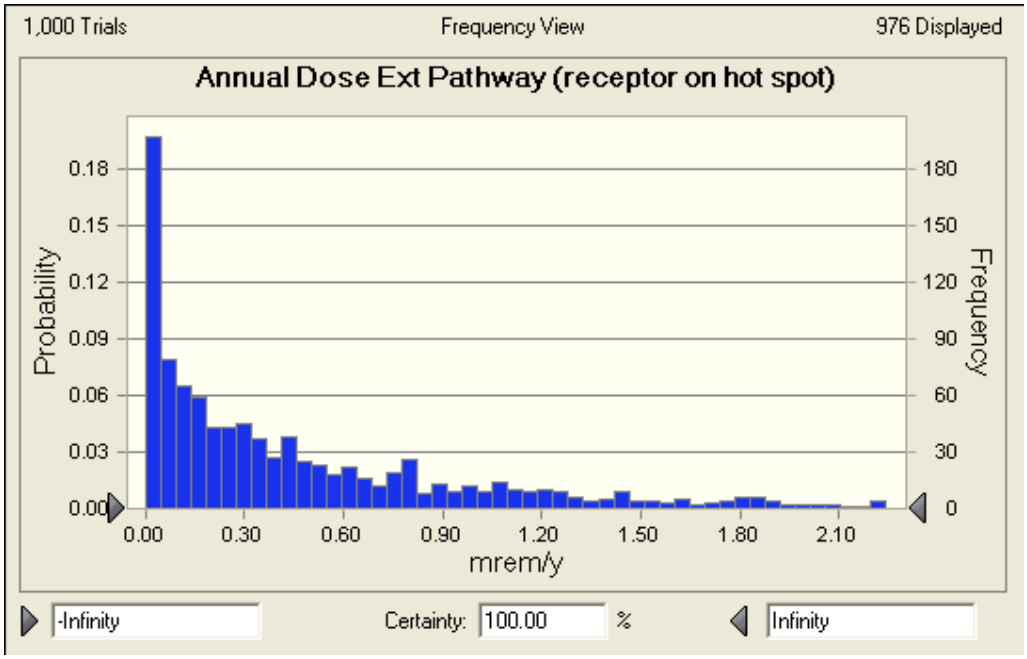

Figure 9 Annual dose distribution from Crystal Ball simulation.

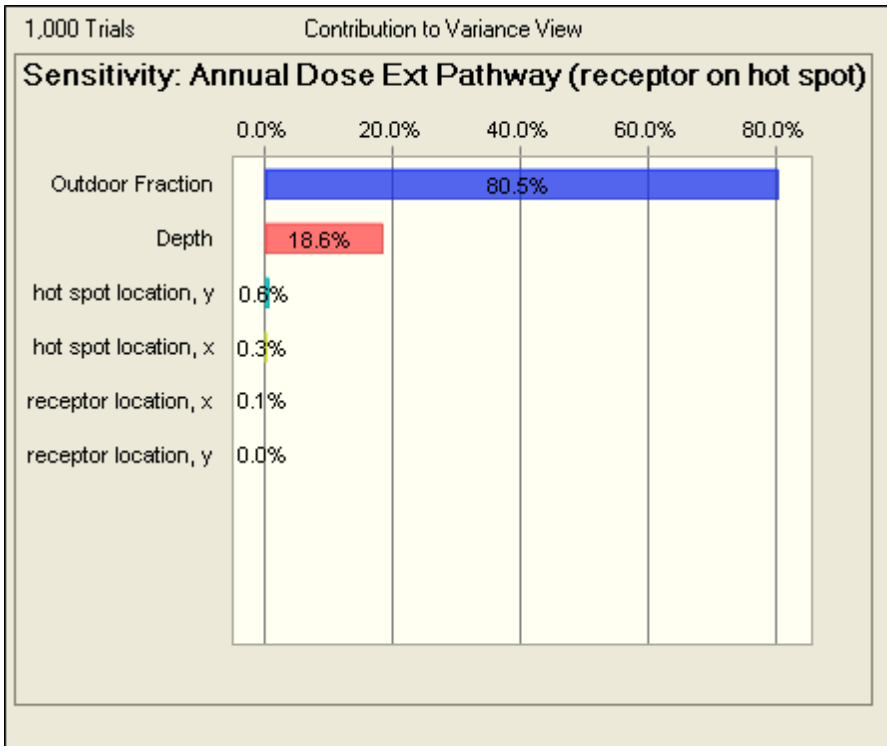

Figure 10 Parameter sensitivity output from Crystal Ball.

Kamboj et al. (2005) described an approach for using RESRAD to identify sensitive parameters in dose assessments. The paper discusses dominant pathways and sensitive parameters for several common radionuclides, and makes the point that probabilistic analyses use parameter distributions to identify the variability in dose estimates resulting from the variability in the modeling parameters. It is reasonable to extend this approach to the source term and its variability. Indeed, in that sense, the source term may be the most sensitive parameter of all. It's important to note that the modeling approach in NUREG-1549 (USNRC 1998) described this approach—develop the source term via characterization and then directly model the receptor dose.

For the normal distribution, a mean and standard deviation equal to 1 and 0.2 pCi/g was assumed, respectively. Crystal Ball ran 1000 simulations from this normal distribution, and the annual receptor dose was calculated using an outdoor fraction of 0.25 and recognizing from earlier MicroShield analyses that for a 10 m^2 Co-60 hot spot at a 15 cm depth, the exposure rate is 9.41E-4 mR/h.

The output statistics of the annual receptor dose in mrem/y were as follows:

- Mean 2.06
- Median 2.05
- Standard Deviation 0.42
- Variance 0.17
- Minimum 0.90
- Maximum 3.32

The relative standard deviation of annual dose for the normal distribution case was 20.4%. Figure 11 shows the annual dose from a normal distribution.

Next, a lognormal distribution was simulated with mean and standard deviation equal to 1 and 0.2 pCi/g, respectively. The output statistics of the annual receptor dose in mrem/y were as follows:

- Mean 2.07
- Median 2.02
- Standard Deviation 0.43
- Variance 0.18
- Minimum 1.07
- Maximum 3.89

The relative standard deviation of annual dose for the lognormal distribution case was 20.8%.

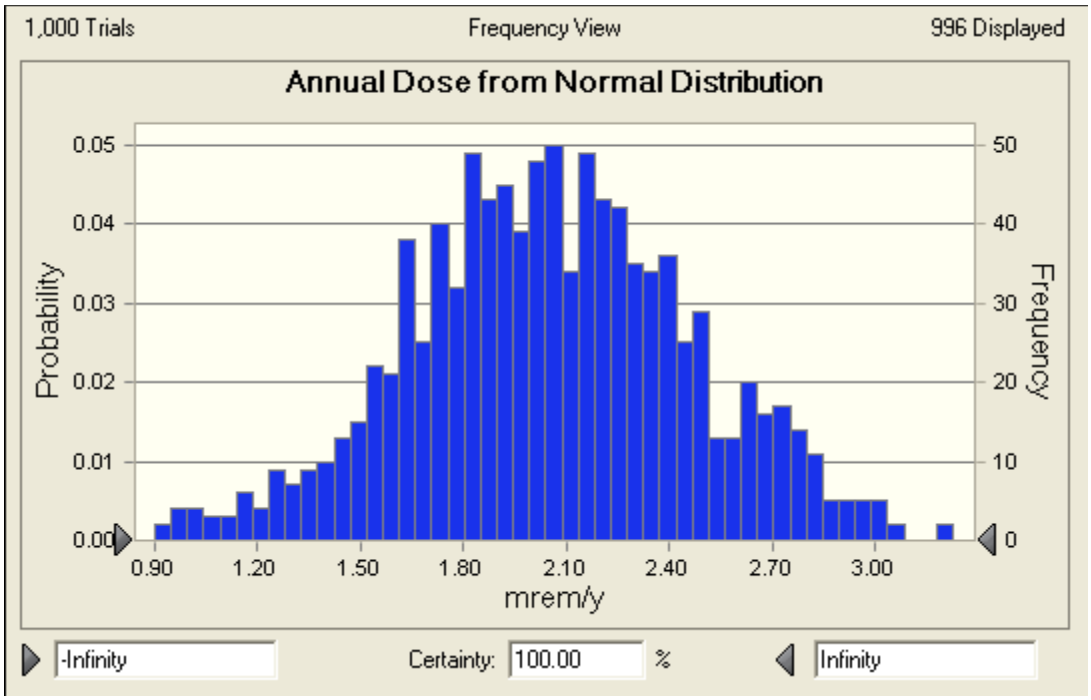

Figure 11 Annual dose distribution for source term with normal distribution.

It is clear from these two figures that the lognormal distribution adds a little more variability to the annual receptor dose compared to the normal distribution (Figure 12). Specifically, the maximum annual dose for the normal distribution was 3.32 mrem/y, while the maximum dose was 3.89 mrem/y for the lognormal distribution. Overall, the relative standard deviation for the two distributions was similar—20.4% versus 20.8%.

Finally, the source term was modeled using the maximum extreme value distribution. Crystal Ball explains this distribution as one that is commonly used to describe the largest value of a response over a period of time, such as 100-year floods, rainfall, and earthquakes. This seems to fit with the situation where hot spots comprise the upper values of the source term distribution. The parameters for the maximum extreme value distribution are likeliest and scale—1 and 0.2 pCi/g were selected for these distribution parameters. The output statistics of the annual receptor dose in mrem/y were as follows:

- Mean 2.29
- Median 2.20
- Standard Deviation 0.54
- Variance 0.29
- Minimum 1.22
- Maximum 5.55

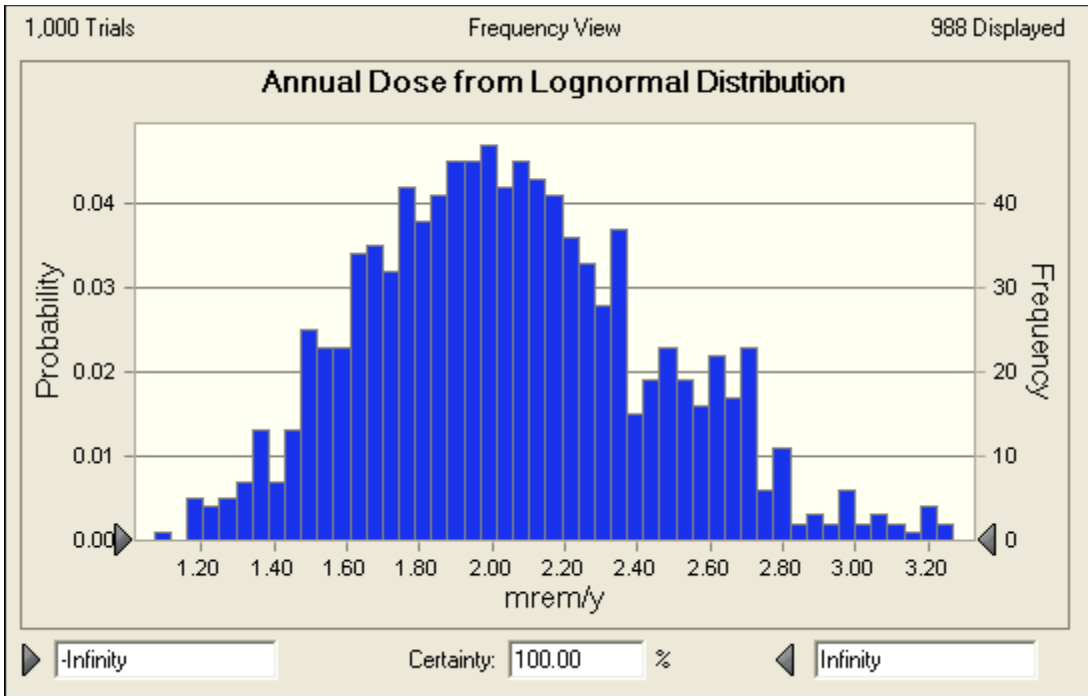

Figure 12 Annual dose distribution for source term with lognormal distribution.

The relative standard deviation of annual dose for the maximum extreme distribution case was 23.6%. The maximum value of receptor dose (5.55 mrem/y) can be thought of as the largest hot spot concentration sampled in the survey unit. The positive skew of this distribution impacts the mean annual receptor dose (Figure 13).

While all three of the distributions had similar relative standard deviations (20.4% to 23.6%), the maximum extreme distribution is perhaps the most representative of a Class 1 survey unit that contains a number of hot spots. The mean dose for the normal and lognormal distributions were nearly identical (2.06 and 2.07 mrem/y), while the maximum extreme distribution had a mean dose of 2.29 mrem/y. The maximum dose for each distribution was 3.32, 3.89, and 5.55 mrem/y, respectively for the normal, lognormal, and maximum extreme distributions. Therefore, the maximum extreme distribution illustrates the effect that hot spots can have on both the mean dose and the maximum dose.

5.2.6 Receptor Distance from Hot Spot

The next step was to evaluate the receptor dose from a 10 m^2 hot spot when the receptor is located some distance from the hot spot. A distribution of distances (*l*) was generated that represents the likelihood that a future receptor will usually be located at varying distances from the hot spot. The receptor can be located at

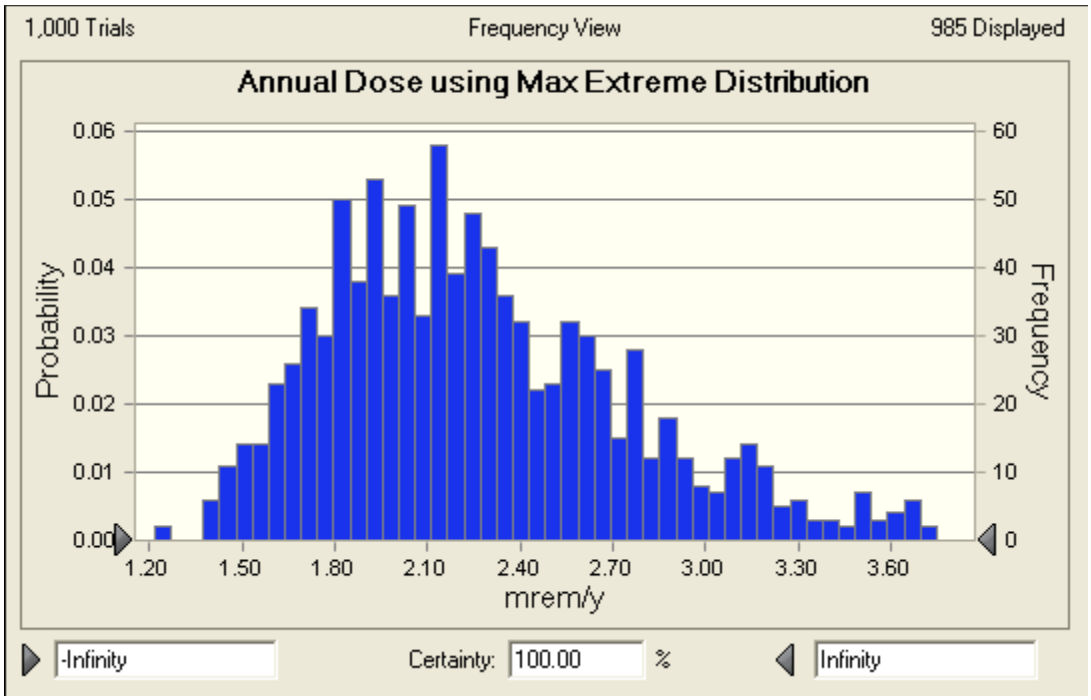

Figure 13 Annual dose distribution for source term with maximum extreme distribution.

any location (x_1, y_1) within the survey unit, and the same goes for the hot spot (x_2, y_2). The distance between the receptor and hot spot is given by:

$$l=\sqrt{(y_1-y_2)^2+(x_1-x_2)^2} \qquad (5-3)$$

Consider a Class 1 survey unit of 1000 m^2 with square dimensions (31.6 m × 31.6 m). The minimum distance is obviously zero, and the maximum distance in this case is the diagonal in the survey unit (44.7 m).

Crystal Ball was used to generate 1000 trials of random locations for the receptor and hot spot location. A uniform distribution was assumed for sampling each of the two pairs of coordinates, with a minimum of zero and maximum of 31.6 m. The Crystal Ball output is shown on Figure 14.

The average distance between receptor and hot spot based on this simulation is 16.4 m, with a standard deviation of 7.82 m. The minimum and maximum distances were 0.57 and 38.8 m, respectively.

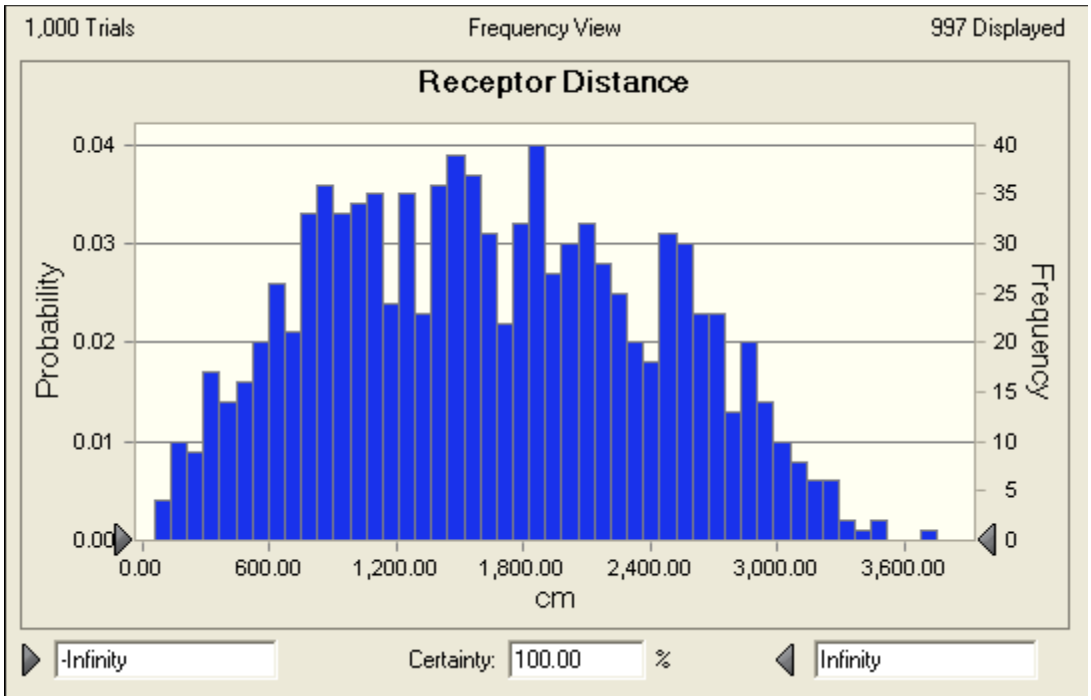

Figure 14 Receptor distance distribution from hot spot.

5.2.7 Exposure Rate Calculation as a Function of Depth and Distance

MicroShield was used to calculate the exposure rate as a function of both depth and distance. The exposure rate data in mR/h are shown in Table 13.

The next step was to use JMP to model exposure rate as a function of two predictors: depth and receptor distance (Figure 15). It was a challenge to generate a reasonably good regression model that can predict exposure rates based on simulated depth and receptor distance values—the key was taking the natural log of the exposure rate prior to fitting the data.

The regression equation from the JMP output was:

$$\ln(\dot{X}) = -10.288 + 0.593 Depth - 0.0049 Distance - 0.027(Depth)^2 + 7.32E-7 Distance^2$$

At this point the exposure rate was modeled as a function of both depth and receptor distance using the above regression equation. Crystal Ball was used to simulate varying depths and distances; exposure rates were calculated using the regression equation shown above. The statistics (shown below) from Crystal Ball indicate a mean exposure rate of 0.01 µR/h, with a standard deviation of 0.0.04 µR/h. Again, using the relative standard deviation as a simple measure of

Table 13 Exposure rate as a function of both depth and receptor distance.

Depth (cm)	Receptor Distance (m)						
	0	1	3	6	10	16	40
0.1	9.290E-6	8.073E-6	2.350E-6	5.736E-7	2.019E-7	7.700E-8	1.131E-8
1	9.127E-5	7.888E-5	2.268E-5	5.346E-6	1.781E-6	6.184E-7	6.016E-8
3	2.634E-4	2.249E-4	6.278E-5	1.335E-5	3.824E-6	1.095E-6	8.275E-8
5	4.107E-4	3.560E-4	9.574E-5	1.828E-5	4.704E-6	1.269E-6	1.012E-7
7	5.430E-4	4.719E-4	1.221E-4	2.131E-5	5.206E-6	1.404E-6	1.194E-7
10	7.161E-4	6.191E-4	1.518E-4	2.415E-5	5.793E-6	1.604E-6	1.468E-7
15	9.406E-4	8.032E-4	1.837E-4	2.737E-5	6.711E-6	1.936E-6	1.929E-7

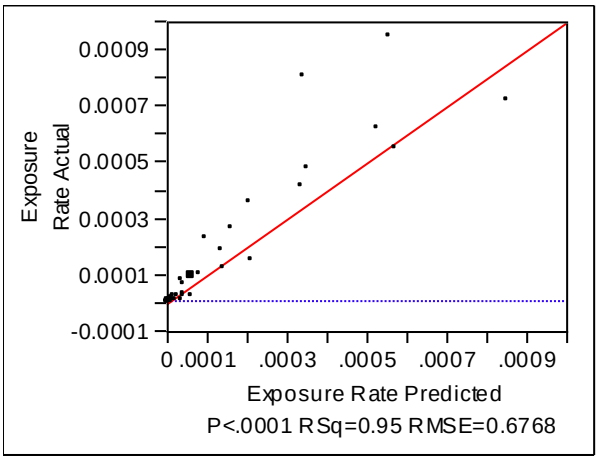

Figure 15 Regression fit of exposure rate data.

uncertainty: 0.04/0.01 or 400%! Adding the variability of distance has a substantial impact on the exposure rate calculation (which of course is entirely expected).

This Crystal Ball output provides the following statistics for the exposure rate in μR/h:

- Mean 0.01
- Median 0.00
- Standard Deviation 0.04
- Variance 0.00
- Minimum 0.00
- Maximum 0.55

5.2.8 Annual Receptor Dose from External Radiation Pathway as Function of Depth and Distance

Lastly, the annual receptor dose and its uncertainty were calculated by multiplying the exposure rate (based on depth and distance) by the outdoor time fraction. This Crystal Ball output, shown on Figure 16, provides the following statistics for the exposure rate in μR/h:

- Mean 0.01
- Median 0.00
- Standard Deviation 0.05
- Variance 0.00
- Minimum 0.00
- Maximum 0.76

The relative standard deviation is 0.05/0.01 or 500%. Recall that prior to including the distance the relative standard deviation in the annual receptor dose was 122%. So, distance adds a tremendous amount of uncertainty in the determination of annual receptor dose. The annual dose ranges from a minimum of 0 to a maximum of 0.76 mrem/y.

5.2.9 Parameter Uncertainty Assessment Conclusions

This aspect of the dissertation work assessed the receptor dose uncertainty associated with the external radiation pathway due to a 10-m^2 hot spot. The parameters considered in this uncertainty assessment included the depth of contamination, outdoor time fraction, source term distribution and receptor distance from the hot spot.

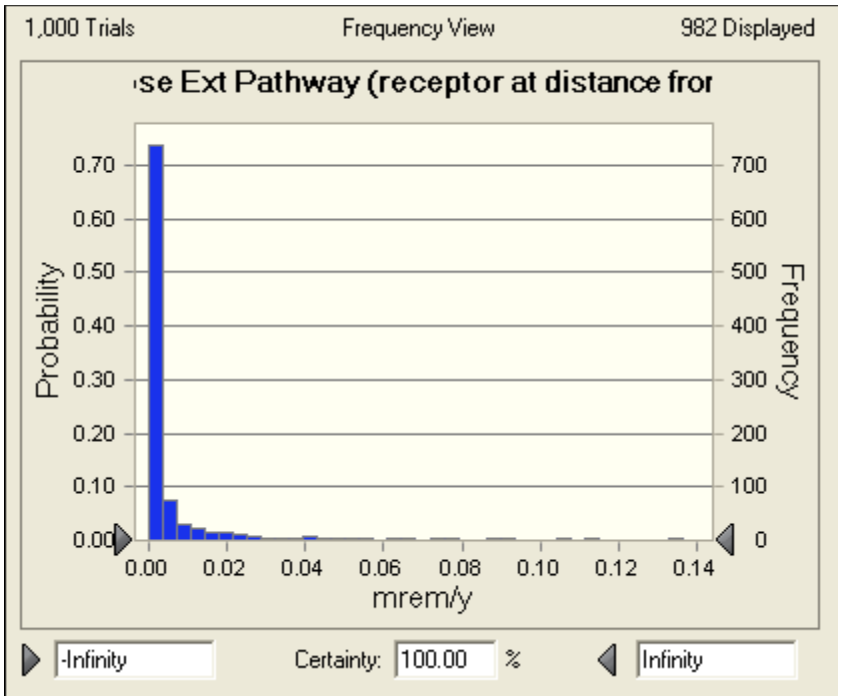

Figure 16 Annual dose distribution for receptor at distance from hot spot.

The first assessment only considered depth and outdoor fraction—i.e., receptor distance was zero (receptor directly over hot spot). The uncertainty in the annual dose was dominated by the outdoor fraction (80%) over the depth (~20%). Also, the relative standard deviation for the annual receptor dose in this case was 122%—mean of 0.51 mrem/y and 0.62 mrem/y standard deviation.

Next, three source term distributions were evaluated—normal, lognormal, and maximum extreme distributions. The relative standard deviations, respectively, were 20.4%, 20.8%, and 23.6%. The conclusion for this aspect of the uncertainty assessment was that the particular source term distribution is not a major contributor to the receptor dose uncertainty.

The final assessment added the receptor distance from the hot spot to the other parameters. The receptor distance parameter had a mean and standard deviation of 16.4 m and 7.8 m, respectively. The distance had a significant impact on the annual dose. The mean and standard deviation of the annual dose were 0.01 and 0.05 mrem/y, respectively (500% relative standard deviation).

So, the two input parameters that have the greatest impact on the annual receptor dose are 1) the receptor distance from the hot spot, and 2) the outdoor fraction. It is important to put these results in proper context. For most dose modeling efforts, the greatest uncertainty in the future receptor dose relates to

the pathways and parameters related to particular scenarios (e.g., outdoor fraction and estimated receptor distance from hot spot). The uncertainty of field and laboratory measurements (e.g., routinely less than 10%) used to characterize the source term are often trivial compared to the modeling parameter uncertainty. NCRP Report No. 76 (p. 219) sums it up well. “The models and parameters… are only mathematical approximations of real environmental situations and processes. Furthermore, the parameters used in these models are highly variable. Therefore, it is important to consider the level of uncertainty associated with model calculations (NCRP 1984).”

CHAPTER 6 STATISTICAL APPROACH FOR HOT SPOT ASSESSMENT

The U.S. Nuclear Regulatory Commission defines release criteria for license termination following cleanup in 10 CFR 20 Subpart E (USNRC 1997). Specifically, the limit is based on the annual total effective dose equivalent (TEDE) received during a year to an average member of the critical group. Dose modeling is performed to establish the relationship between residual radioactivity remaining at a site and future receptor dose. The modeling considers specific scenarios and environmental pathways, and modeling parameters such as crop yields for vegetables and individual breathing rates. These model parameters have various distributions, often determined empirically based on experimentation (USNRC 1999a). The radioactive source term also has a particular distribution that should be considered in the overall assessment of receptor dose (refer to section 5.2.5 that addresses this point). Specifically, the source term should be characterized in terms of its location (mean or median) and scale (standard deviation) parameters, the latter being particularly influenced by the presence of hot spots. At a minimum, hot spot limits need to be clearly defined to provide guidelines for consistent interpretation and serve as an achievable goal for decommissioning release criteria.

The Multiagency Radiation Survey and Site Investigation Manual has been used for designing and implementing final status surveys at numerous decommissioning sites since its publication in the late 1990s (USNRC 2000a). The final status survey design includes a nonparametric statistical approach to demonstrate that the average contamination level in the survey unit satisfies release criteria, in addition to provisions for identifying and remediating hot spots that exceed the release criteria. Specifically, the MARSSIM recommends that potential hot spots in a Class 1 survey unit that could exceed the derived concentration guideline levels for small elevated areas of radioactivity have a reasonably good probability of being detected. Soil sampling on a specified grid size, in conjunction with gamma radiation surface scanning, is necessary to obtain an adequate assurance level that these hot spots are not missed during the final status survey. While this survey approach has served the decommissioning industry well, a notable shortcoming is the lack of guidance on how to handle the hot spots that remain undetected following the final status survey. In other words, even the most diligent scan surveys are likely to miss some hot spots, while less effective scans might result in many hot spots remaining at the conclusion of survey activities.

This section presents a statistical compliance approach to address detected (and undetected) hot spots potentially present in a survey unit. This approach may be thought of as an upper limit test on hot spots, recognizing that both the contaminant mean and overall distribution (particularly the higher concentrations

due to hot spots) are important parameters for demonstrating that the cleanup has achieved the release criteria. To implement this test, dose modeling must be performed to generate the derived concentration guideline level for the average residual radioactivity level (referred to as the $DCGL_W$), and also the derived guideline level for residual radioactivity that equates to the 99th percentile of receptor dose. Once the dose modeling effort provides this $DCGL_{99th}$, the 99th percentile of the contaminant distribution was compared to this upper concentration limit. Thus, it is necessary to have an overall understanding of the contaminant distribution to make this determination on hot spot acceptability.

One difficulty with this approach is that a large number of samples are required to adequately characterize the upper tail of the distribution. That is, with relatively few data, the uncertainty in the upper percentiles of distributions is great. Mulhausen and Damiano (1998) make the point that "if a decision must be made with a few measurements (e.g., 10), confidence is highest for the estimate of the mean, lower for the estimate of the variance, and lowest for estimates of lower or upper percentiles." In this regard, consider adopting a Bayesian statistical approach that would allow one to construct a posterior distribution of the contaminant concentration in a survey unit. The posterior distribution considers both prior knowledge of the radiological characteristics of the survey unit and sampling data generated during the final status survey. The 99th percentile of the contaminant distribution is then obtained from the posterior distribution.

6.1 Background

Environmental contamination data frequently follow a right skewed distribution, which can at times be approximated by a lognormal distribution. In some cases, the contamination distribution may be highly skewed such that the data remain skewed even after a log-transform. Indeed, the EPA notes that the distribution of contamination data can be strongly skewed so that it contains a few very high values (USEPA 2002a). Because the future receptor could be exposed to these higher values or hot spots, the final status survey should appropriately take hot spots into account.

When considering hot spots, it is of interest to use the sample data to calculate an upper bound on the population mean, as well as upper percentiles of the distributions (e.g., 98th, 99th, etc.). So the idea is to have a better understanding of the overall distribution of environmental contamination—i.e., not just the mean concentration, but also the upper percentiles of the distribution that are impacted by hot spots.

In the context of cleanup, most of the data can be described by a normal or lognormal distribution, with some number of hot spots that are part of the overall distribution. It is important to recognize the distinction between an upper confidence level of the distribution mean and an upper percentile of the entire

distribution. Now if the distribution is normally distributed, then the 99th percentile of the distribution is given by the mean plus 2.576 times the standard deviation of the distribution. However, when hot spots are present, the distribution may not be taken to be normally distributed.

The current final status survey approach on many environmental/radiological cleanup projects is to randomly sample the survey unit to obtain an estimate of the mean, coupled with radiological scans to identify hot spots. The hot spots are evaluated separately from the mean during the compliance assessment. A shortcoming of this two-pronged survey approach is that it doesn't provide a mechanism for addressing the hot spots that were not found. That is, did the survey identify 70% of the hot spots present? Or perhaps only 50% or 30% were found.

Clearly, hot spots can be viewed as the higher (highest) radiological concentrations from the distribution of concentrations obtained from a survey unit. They are part of the true contamination distribution, and as such, occupy the right-hand tail of the distribution. Imagine an unrealistically high sampling density—e.g., collecting a soil sample on a 1–foot grid in a 1000 m^2 survey unit. This would produce more than 11,000 systematic soil samples and would reveal virtually all of the hot spots present in the survey unit. Rank ordering the concentration data from this mammoth data set and producing a histogram would quickly reveal the 99th percentile of the contaminant distribution. This value might then be compared to a regulatory limit to assess whether the upper tail of the distribution satisfied release criteria.

Figure 17 shows the distribution of Cs-137 soil concentrations in a survey unit at a recent decommissioning site. The underlying distribution appears to be log-normal and the upper tail of the distribution clearly indicates the presence of hot spots. The average concentration in this survey unit was shown to meet release criteria using the nonparametric Sign test described in MARSSIM. The lingering question is whether the hot spots present in this survey unit satisfy the release criteria. That is, consider a statistical test that is specifically suited to demonstrate that the upper level of the distribution is acceptable. For example, if all hot spots are not found, is it possible to establish a contaminant distribution using the hot spots found to conclude with reasonable confidence that the 99th percentile of the distribution is below the $DCGL_{99th}$?

The proposed compliance approach is to demonstrate compliance with both the mean and 99th percentile of the contaminant distribution by comparing these values to the $DCGL_W$ and $DCGL_{99th}$, respectively. The development of the $DCGL_{99th}$ should consider the dose modeling approach used to establish the hot spot area factors described in Chapters 3 and 4. The key is recognizing that at the time of the final status survey, the upper percentile concentrations are by

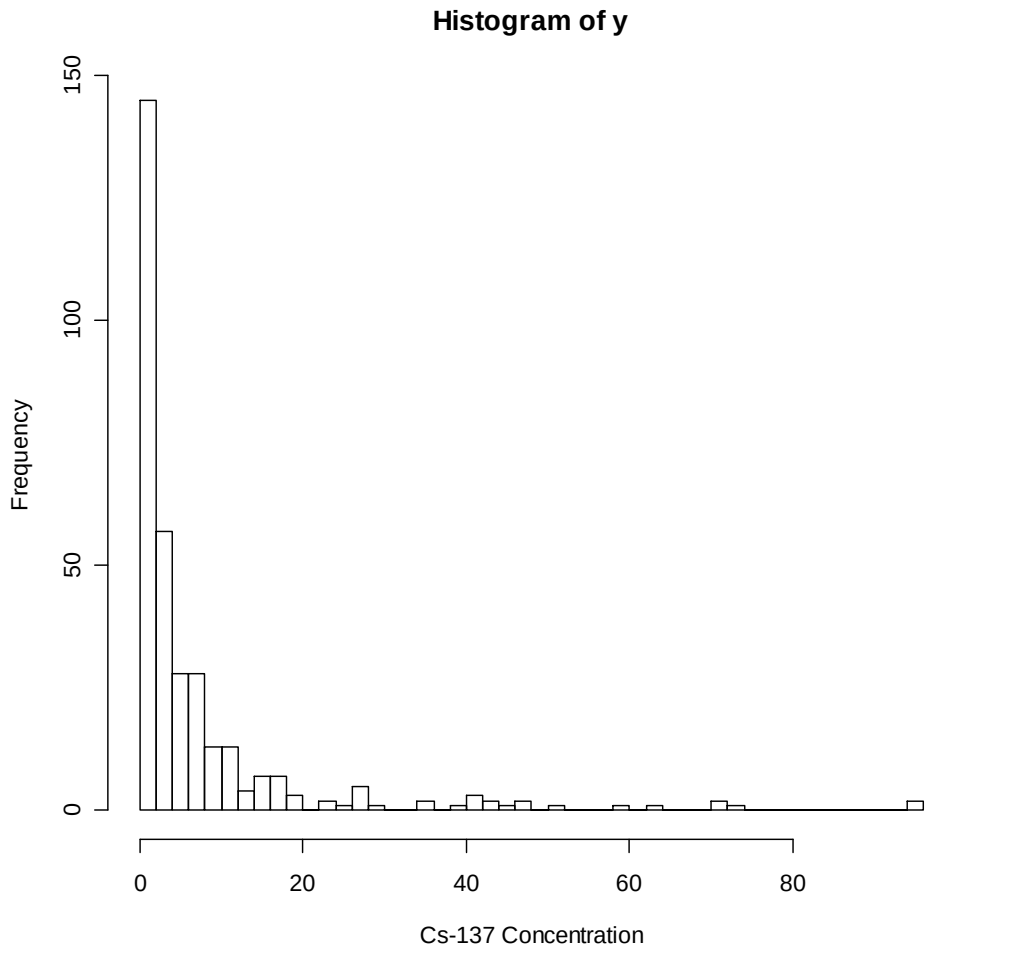

Figure 17 Histogram of Cs-137 concentrations (pCi/g).

definition, hot spots (assuming that hot spots are indeed present in the survey unit). That is, in general, for the concentration to be considered an extreme value concentration (99th percentile), it necessarily has to be associated with a relatively small area as compared to the survey unit area. For example, assume that the survey unit area is 1000 m^2; a reasonable hot spot size might be 0.1 m^2 or less. Therefore, the $DCGL_{99th}$ might be defined as the concentration equal to the $DCGL_W$ times the area factor for a 0.1 m^2 area. For example, if the $DCGL_W$ for Co-60 is 5.3 pCi/g, and the area factor for a 0.1 m^2 hot spot is 100 (Table C-1), then the $DCGL_{99th}$ for Co-60 is 530 pCi/g. So compliance would be achieved by demonstrating that the mean concentration is less than the $DCGL_W$ (5.3 pCi/g), and the 99th percentile of the distribution is less than the $DCGL_{99th}$ (530 pCi/g). Note that this approach also handles multiple hot spots, as the multiple hot spots are treated as part of the distribution.

6.2 Bayesian Statistical Approach

A Bayesian statistical approach for assessing hot spots is proposed in this dissertation. The general approach is to use the final status survey results to construct a posterior distribution of radionuclide concentrations in the survey unit. Specifically, the posterior distribution can be used to predict the upper percentiles (hot spots) that may exist in the survey unit. An upper limit test is proposed where the 99th percentile of the radionuclide distribution is compared to the $DCGL_{99th}$ (i.e., 99th percentile of the DCGL distribution). For example, the upper tolerance limit (UTL) defined as the 95% upper confidence level on the 99th percentile can be used to demonstrate compliance (Mulhausen and Damiano 1998).

A brief background on Bayesian statistics is presented in the next section, followed by the specific details of the proposed approach for hot spot compliance. More fully developed examples using real data sets are provided in Appendix O.

6.2.1 Background on Bayesian Statistics

A few Bayesian terms—prior, likelihood and posterior—are defined as an introduction to Bayesian statistics. First, the prior distribution is defined as the distribution that reflects the state of existing knowledge about the parameter(s) before the data are collected. Sorensen and Gianola (2002) define the likelihood function, denoted $L(\theta|y)$, as any function of the parameter θ that is proportional to $f(y|\theta)$. It is a mathematical function of the parameter for fixed data; it is not a probability density, so the different values θ takes in the likelihood cannot be interpreted in the customary probabilistic sense. Finally, the posterior distribution is the distribution that reflects the state of knowledge about the parameter(s) after the data have been observed. For example, after the final status survey has

been completed and soil concentration data have been obtained, the posterior distribution is constructed. Thus, the Bayesian approach treats θ as a random variable; the data (used to generate the likelihood function) are used to update the prior distribution to obtain the posterior distribution of θ.

Bayes's theorem simply reflects the dynamics of applying observed data (likelihood) to current knowledge (prior distribution), to update our knowledge (posterior distribution). Let's assume that the prior distribution is given by f(θ) and observed data are given by y. The posterior distribution of θ is given by f(θ|y). Bayes's theorem can be written as follows:

$$f(\theta \mid y) = \frac{f(\theta) f(y \mid \theta)}{\int_{-\infty}^{\infty} f(\theta) f(y \mid \theta) d\theta} \qquad (6-1)$$

The integral in the denominator normalizes the posterior distribution, so that the integral of the posterior distribution is equal to 1. This integral is often difficult to solve, even with numerical techniques.

One of the challenges in applying the Bayesian statistical approach is converting the current knowledge into a prior distribution. For example, what is the expected contamination status of a particular survey unit? New information is available once the final status survey (FSS) has been performed. The question is how the FSS data—both soil samples and scanning data—can be combined with the prior distribution. The basic task of the Bayesian analysis is to construct a model for the relationship between the parameters (θ) and observed data (y), and then calculate the posterior probability distribution of parameters conditional on the data, f(θ|y).

A criticism of Bayesian analyses is that the prior distribution is often subjective, e.g., based on expert knowledge or professional opinion. Leonard and Hsu (1999) address the issue of subjective probabilities and point to the situation where the particular outcome may be rare, perhaps occurring only once. Because it cannot be replicated, there is no possibility for measuring probabilities by repeated sampling (via the usual frequentist approach). Thus, these probabilities cannot be measured by repeated sampling, and they are called "subjective". To alleviate the problems associated with subjective priors, a non-informative prior distribution is often assumed. A non-informative prior distribution assigns the same probability to each possible value of the parameter(s). The impact that the non-informative prior distribution has on the posterior distribution depends on how much data are collected. For example, if the sample size is relatively large, the choice of the prior distribution will have a minimal impact on the posterior distribution.

In most problems, posterior distribution is not available in closed form, and the resulting integrals are usually impossible to solve analytically, or difficult using standard techniques for numerical integration. Approximate integration techniques used in Bayesian statistics involve Gaussian integration, Laplace approximation, or numerical integration based on stochastic approaches (e.g., Monte Carlo). Markov chain Monte Carlo (MCMC) algorithms are attractive solutions for the calculation of the posterior density. Two common MCMC algorithms are the Gibbs and Metropolis-Hastings samplers. These samplers can be used to estimate the posterior contaminant distribution—in particular, the 99^{th} percentile of the distribution. The use of MCMC techniques emerged in the late 1980s as the core of Bayesian computing, and it has since revolutionized the field (Marin and Robert 2007).

The basic idea behind MCMC is to produce a Markov chain whose stationary distribution (π) is sufficiently similar to the posterior distribution of interest. The Markov chain provides an invariant distribution that has a density given by π that sufficiently describes the posterior distribution. Of fundamental importance in using the MCMC technique is whether the chain converges to a limiting distribution (e.g. π), regardless of any reasonable (legal) starting distribution. Further, once the Markov chain has reached a stage where π is stationary, it must retain this distribution in subsequent moves (Sorensen and Gianola 2002).

The sampling approach for MCMC to enable posterior distribution evaluation generally consists of two steps: 1) constructing an algorithm for simulating a long chain of draws from the posterior distribution, and 2) basing inferences on posterior summaries of the parameters calculated from the samples. The Gibbs sampler works by choosing value(s) for the initial state of the distribution and iterating through the distribution by updating each of the full conditionals until the distribution converges on a stationary posterior distribution. The algorithms for each sampler are shown below.

Gibbs Sampler Algorithm:

- Repeatedly samples each parameter from its full conditional posterior distribution given the current values of the other parameters.
- Samples converge to a stationary distribution that is the joint posterior distribution.
- Requires algorithm for sampling from full conditional distributions.

Metropolis-Hastings Sampler Algorithm:

- Sample a candidate for a parameter from a candidate generating density (e.g., normal, lognormal) centered on the previous value of the parameter.
- Accept the candidate with probability equal to the minimum of one and the ratios of the posterior probabilities at the new and old values of the

parameter multiplied by a correction for asymmetric candidate generating densities.

- Repeat for all the parameters and for a large number of iterations.

The mean, standard deviation and 99th percentile of this stationary distribution are the desired values in either case.

The next two sections detail the Bayesian analysis of the posterior distribution for normal data sets. The first example discusses the normal distribution when the standard deviation is known, and no hot spots are present. The second example considers the normal distribution when the mean and standard deviation are unknown, and hot spots are present. The second example illustrates why the normal distribution is not a particularly good choice for the posterior distribution when hot spots are present.

Bayesian analysis—normal distribution with conjugate prior (no hot spots)

A simple example of normal distributions in the absence of hot spots was considered. This is referred to as the conjugate prior for normal distributions, where the standard deviation is known. The 99th percentile can be directly obtained because the posterior distribution will be normal (i.e., 99th percentile is given by 2.576 times the standard deviation).

For a random sample obtained from a normal distribution with unknown mean and known variance (τ^2), the likelihood is written:

$$l(\theta|y) \propto \exp[-\frac{1}{2\tau^2}\sum_{i=1}^{n}(y_i-\theta)^2] \qquad (6-2)$$

The likelihood expression above represents the likelihood of parameter θ given the observed data y. Assuming a conjugate prior, which is a reasonable assumption for most contaminant situations, the following posterior density on parameter θ is obtained:

$$\pi(\theta|y) \propto \exp[-\frac{1}{2\sigma^2}(\theta-\mu)^2 - \frac{n}{2\tau^2}(\theta-\bar{y})^2] \qquad (6-3)$$

It is important to note that the parameter θ is the mean of the distribution, and as such, in the context of the posterior distribution given above, it is a function of both the sampling data and the prior information. Indeed, the first term in the exponential can be thought of as the prior piece of the posterior, while the second term represents the likelihood piece obtained from sampling.

Leonard and Hsu (1999) provide explicit expressions for the determination of the

posterior mean (θ^*) and variance (v), as follows:

$$\theta^* = \frac{n\bar{y} + \kappa\mu}{n + \kappa} \qquad (6-4)$$

$$\upsilon = \frac{\tau^2}{n + \kappa} \qquad (6-5)$$

where κ is given by τ^2/σ^2 .

It was stated earlier that the Gibbs and Metropolis-Hastings samplers allow inferences to be made on posterior distributions that are analytically challenging to solve directly. This is not the case for the present example. In fact, a simple R code[10] was written to solve the posterior mean of θ for a number of sample values. The mean, standard deviation and 99th percentile on the distribution (assuming that the posterior distribution is normal) were 1.51, 0.42, and 2.59, respectively. The plot of the posterior mean was indeed normally distributed. If the posterior distribution is normally distributed, then the 99th percentile of the distribution can be calculated directly from the standard deviation. In this case the 99th percentile equals 2.59.

It is instructive to demonstrate how the Metropolis-Hastings (MH) sampler can be used to solve this problem. R code was written for the MH sampler to solve for the posterior mean and variance of θ (Appendix N). The statistical output from the MH sampler compares well to the exact values calculated earlier—the mean and standard deviation were 1.53 and 0.42, respectively.

A plot of the θ values for each iteration is shown on Figure 18. This plot indicates the value of θ at each of the 5000 stages, which represent a time series of values. At each stage, a sample is obtained from the proposed distribution (normal distribution in this example), and it is accepted as the new value of the Markov chain state only if the value moves the chain closer to an equilibrium state. The plot indicates that the chain reaches an equilibrium state rather quickly, and that for most of the subsequent iterations the candidate values are essentially sampled from a stationary distribution. A burn-in period is often used when the initial iterations indicate lack of convergence, in which case the sampler statistics are only calculated after the burn-in. The statistics associated with the stationary distribution can be used to draw inferences from the posterior distribution.

[10] R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

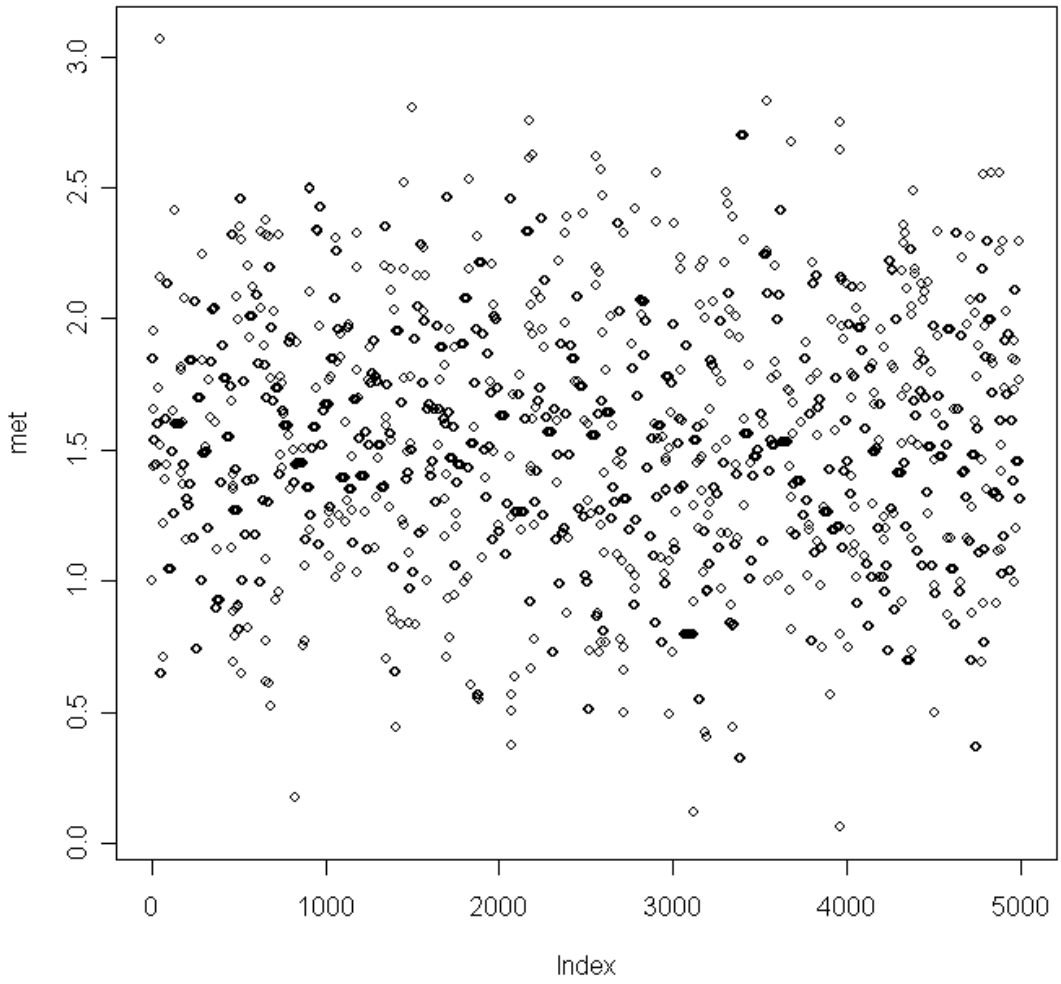

Figure 18 Plot of Metropolis-Hastings sampler results.

The validity of the conclusion on the 99th percentile depends on the normality assumption regarding the likelihood and the prior distribution. The histogram for θ suggests that the posterior distribution is normally distributed (Figure 19).

Bayesian analysis—normal distribution with mean and standard deviation unknown (hot spots present)

A more realistic situation is the case where both the mean and standard deviation are unknown. The approach will be to assume a flat prior (uniform) distribution on the mean, along with a standard non-informative prior ($1/\sigma^2$) on the standard deviation. The presence of hot spots will certainly impact the standard deviation of the distribution—and if the posterior distribution cannot be assumed to be normally distributed, then the 99th percentile of the distribution is no longer 2.576 times the standard deviation.

The joint posterior distribution of the mean and variance in this circumstance is characterized by a normal component and an inverse gamma distribution component. The proposed approach is to use a non-informative prior coupled with final status survey data to calculate a posterior distribution. The posterior distribution will then be used to determine the 99th percentile, which ultimately allows comparison to a hot spot limit specified at the 99th percentile.

The data set consists of 333 soil sample concentrations of Cs-137 collected during a final status survey in multiple class 1 survey units. While Figure 17 clearly indicates a right-skew to the data set, results are presented as an example of the methodology.

This example assumes a normal data model with unknown mean and variance, where $y \sim N(\mu, \sigma^2)$, and both μ and σ are unknown random variables. The Gibbs sampler can be used to explore the posterior distribution that results from the normal model with unknown mean and variance.

So, given a normally distributed estimate of a parameter μ, with unknown mean and variance—a flat (uniform) prior for μ and a "Jeffreys" prior $1/\sigma^2$ for σ^2 are assumed. The posterior density is proportional to the prior times the likelihood:

$$\pi(\mu,\sigma^2|y) \propto \pi(\mu,\sigma^2)\pi(y|\mu,\sigma^2) \qquad (6-6)$$

Thus, the posterior is expressed as the following

$$\pi(\mu,\sigma^2|y) \propto (\sigma)^{-2}\left(\frac{1}{2\pi\sigma^2}\right)^{n/2}\exp\left(-\frac{1}{2\sigma^2}(n-1)s^2+n(\bar{y}-\mu)^2\right) \qquad (6-7)$$

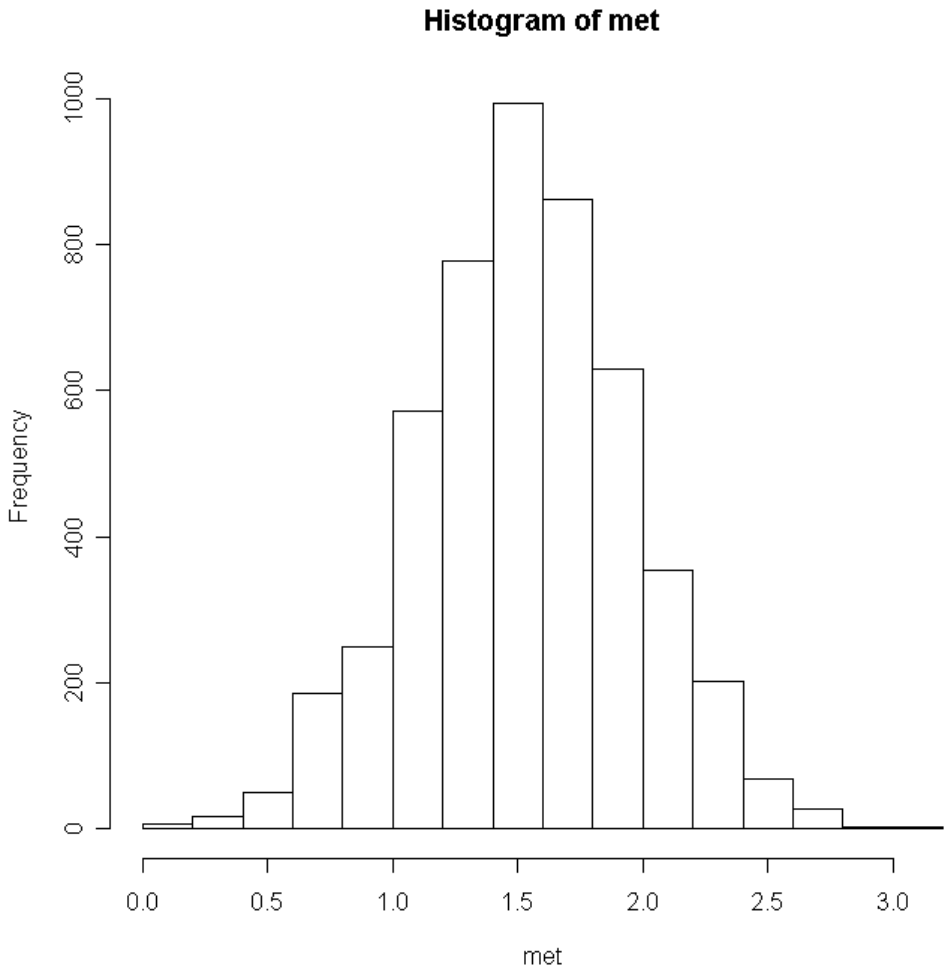

Figure 19 Histogram of posterior mean values from Metropolis-Hastings sampler.

where s^2 is the sample variance given by

$$s^2 = \frac{1}{n-1}\sum (y_i - \bar{y})^2 \qquad (6-8)$$

It can be shown that the conditional posterior distribution for the mean is as follows:

$$\pi(\mu \left| \sigma^2, y \right.) \sim N(\bar{y}, \frac{\sigma^2}{n}) \qquad (6-9)$$

This is readily seen to be a normal with mean y-bar, and variance σ^2/n.

The marginal distribution of the mean can be obtained by integrating out the variance. Again, it can be show that this results in a t-distribution with n-1 degrees of freedom

$$\pi(\mu \left| y \right.) \sim t_{n-1}(\bar{y}, \frac{s^2}{n}) \qquad (6-10)$$

The marginal distribution of the variance can be obtained by integrating over the mean. The result is an inverse chi-square density.

$$\sigma^2 \left| y \right. \propto \frac{\sum (y_i - \mu)^2}{\chi^2} \propto inversegamma(\frac{n-1}{2}, \frac{(n-1)s^2}{2}) \qquad (6-11)$$

Note that the programming language R has a function for drawing samples from a chi-square distribution. As shown in the above equation, the value of σ^2 was obtained by dividing the summation term by the sampled chi-square value. This allows σ^2 to be sampled at each Gibbs step, as shown below.

$$\sigma^{2(1)} \left| y \right. \sim \ invgamma(\frac{n-1}{2}, \frac{(n-1)s^2}{2})$$

$$\mu^{(1)} \left| \sigma^2, y \right. \sim N(\bar{y}, \frac{\sigma^{2(1)}}{n})$$

-
-
-

$$\sigma^{2(t)} \left| y \right. \sim \ invgamma(\frac{n-1}{2}, \frac{(n-1)s^2}{2})$$

$$\mu^{(t)} \left| \sigma^2, y \sim N(\bar{y}, \frac{\sigma^{2(t)}}{n}) \right.$$

The mean and standard deviation of the data set (333 samples) is 7.44 and 13.7, respectively. The empirical estimate of the 99th percentile of the data is 71.7. The Gibbs sampler code for this example (written in R) is provided in Appendix N. The posterior distribution statistics were essentially identical to the actual data—the mean was 7.42 and the standard deviation was 13.7. Now, given that this is a normal data model, the 99th percentile was calculated by summing the mean and 2.576 times the standard deviation. This result is 42.7—clearly an underestimate of the actual 99th percentile for this large sample data set. This indicates that the normal model for the posterior distribution does not possess sufficiently thick tails to adequately represent the upper percentiles of the true distribution (for this example data set). That is, the presence of hot spots in the data set suggests that a normal posterior distribution is not a good choice due to its light (narrow) tails. The next section introduces the use of a more robust model to handle heavier-tailed distributions.

6.2.2 Bayesian Hot Spot Assessment Using Robust t Distribution

A Bayesian statistical approach is considered for describing the contaminant distribution (including hot spots). The resulting posterior distribution can then be used to make inferences on the 99th percentile of the contaminant distribution, which will provide an assessment of whether the hot spots comply with release criteria. As noted in the previous section, the posterior distribution is obtained from a prior distribution and likelihood function based on sampling data.

The likelihood function based on sampling data is usually normal (or lognormal) with some frequency of hot spots that results in a right skewed distribution. Thus, after performing a final survey sampling campaign that includes both random sampling and judgmental sampling for hot spots, the expected result is a normal or lognormal underlying distribution, with a number of hot spots characterizing the upper tail of the distribution. This concept of viewing hot spots as part of the overall contaminant distribution provides a more comprehensive assessment of future receptor dose because the upper percentiles of the contaminant distribution include the contribution from hot spots.

This approach is admittedly conservative in that it combines the random data (e.g., from systematic sampling) and judgmental data (e.g., collected as a result of radiation scanning) on an equally-weighted basis. For example, suppose that 15 samples were collected randomly for the MARSSIM statistical test and two judgmental samples were collected at potential hot spot locations identified via scanning. This combined data set of 17 random and judgmental data samples is equally weighted, and the data set is used to estimate the 99th percentile of the

contaminant distribution. Again, this is a conservative approach for estimating the 99th percentile.

Returning to the point of the last section, a posterior distribution that incorporates hot spots must necessarily have thicker (wider) tails than the normal distribution. The t distribution is such a distribution, and it was used to estimate parameters of the posterior distribution, such as the mean and 99th percentile.

Albert (2007) notes that "when there is a possibility of outliers, a good strategy assumes the observations are distributed from a population with tails that are heavier than the normal form." Well, the possibility of outliers certainly holds for the situation of potential hot spots in a Class 1 survey unit. And the t distribution with small degrees of freedom is a good example of a heavy-tailed distribution. With this background, a more robust model can be used that assumes that the data are sampled from a t distribution with location μ and scale parameter σ, and known degrees of freedom v. Assuming a non-informative prior distribution (e.g., uniform distribution), the posterior distribution is given by Albert (2007):

$$\pi(\mu,\sigma|y) \propto \left(\frac{1}{\sigma}\right)\prod_{i=1}^{n}\frac{1}{\sigma}\left(1+\frac{(y_i-\mu)^2}{\sigma^2}\right)^{-(\nu+1)/2} \qquad (6-12)$$

Albert observes that the posterior can be expressed by the mixture of conditional distributions that are conducive to coding in a Gibbs sampler:

$$y|\lambda \sim N(\mu,\frac{\sigma}{\lambda})$$

$$\lambda \sim gamma(\nu/2,\nu/2)$$

In this hierarchical model, the data vector y represents a mixture of normal distributions with the scale parameter λ introducing additional variation (i.e., gamma distributed) in the scale parameter. Both the mean and variance are represented by a non-informative uniform prior:

$$(\mu,\sigma) \propto (1/\sigma)$$

The Gibbs sampler code was written with these conditional distributions representing the robust t posterior distribution.

Prior to performing the robust t analysis it was necessary to perform a Box-Cox transformation to normalize the data. The Box-Cox procedure automatically identifies a transformation from the family of power transformations on the data (Kutner et al. 2004). This is a standard technique implemented when performing

linear regression analysis. Note that the log transform is a special case of the Box-Cox transform. The family of power transformations is of the form (Kutner et al. 2004):

$$y' = y^T$$

where T is the transform parameter determined from the data.
The Box-Cox procedure includes the following common transforms:

T = 2	$y' = y^2$
T = 0.5	y' = sqrt(y)
T = 0	y' = ln(y)
T = -0.5	y' = 1/sqrt(y)
T = -1	y' = 1/y

The Box-Cox procedure uses the method of maximum likelihood to estimate the transform parameter T. The Box-Cox function was downloaded from a library package in R called "car".

Another challenge was to specify appropriate v (degrees of freedom) based on the transformed data. The robust t model introduces additional variability via the λ scale parameter as a function of the degrees of freedom. When the degrees of freedom are low (less than 20), the scale parameter introduces significant variability in the posterior distribution. When the transformed data reasonably match a normal distribution, the degrees of freedom v can be higher to reflect the fact that the distribution is near normal. Specifically, the normal deviate for the 99^{th} percentile is 2.326. The t distribution deviate for 4, 40, and 100 degrees of freedom is 3.747, 2.423, and 2.364, respectively.

Before running the Gibbs sampler code to generate the statistics of the posterior distribution, it is necessary to perform the Box-Cox transform on the data. First, recall the histogram of the 333 samples indicated a strong right-skewed distribution. Taking the Box-Cox transform of the data (using R) substantially reduced the skewness in the data, transforming the data to match a normal distribution (Figure 20). [The transform parameter T calculated using the Box-Cox was 0.0944.]

A Shapiro-Wilk normality test was performed on the transformed data to provide a test of normality. The null hypothesis for this test is that the data have a normal distribution. The test statistics were as follows:

Shapiro-Wilk normality test:
W = 0.9933, p-value = 0.1483

The p-value indicates that the null hypothesis cannot be rejected at the 10% level

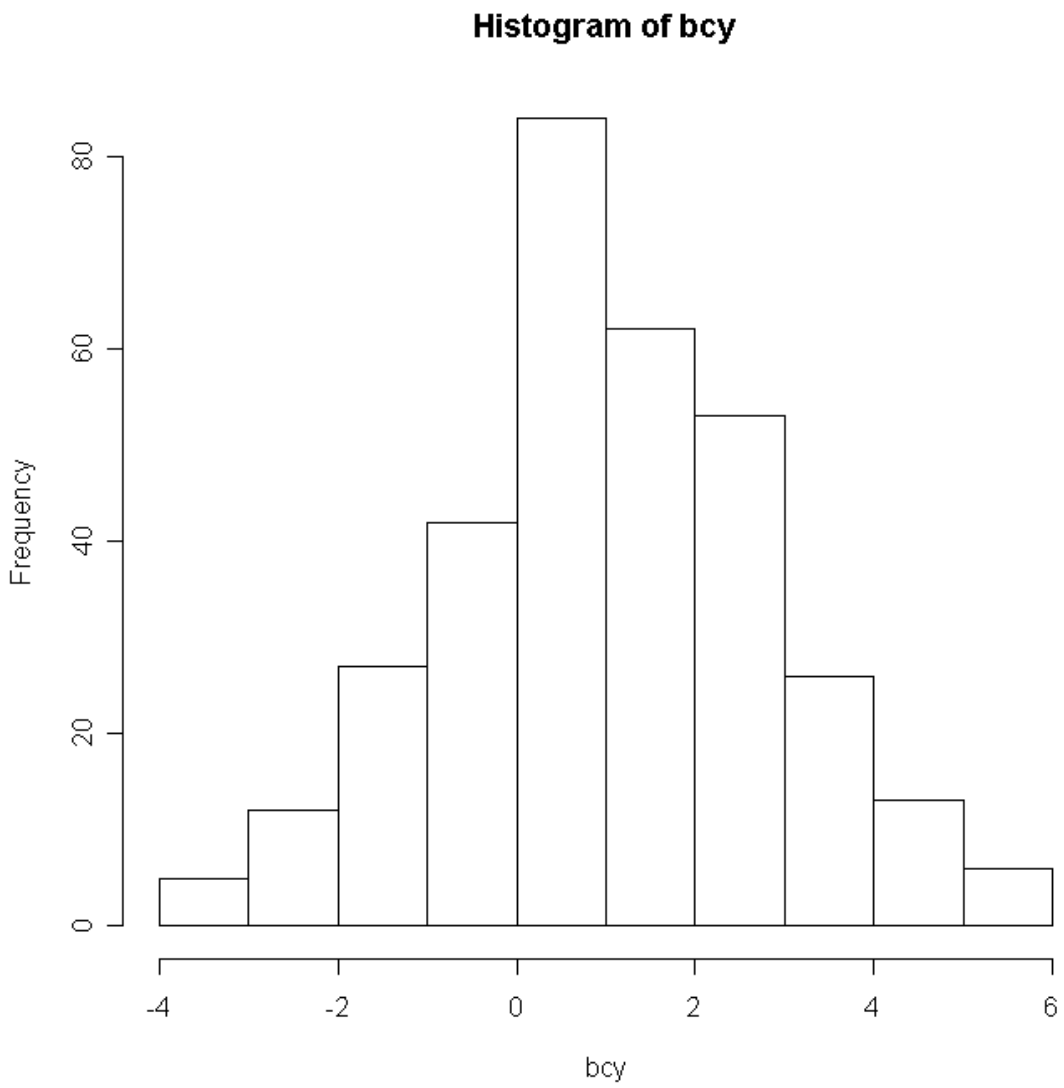

Figure 20 Box-Cox transform of soil concentration data.

Table 14 Final survey data and robust t posterior distribution for large sample.

Statistic	FSS Data	Posterior Distribution
Mean	7.44	2.70
95th	37.7	30.8
99th	71.7	77.5
UTL	----	96.5

of significance; conclude that the transformed data are likely to be from a normal distribution.

The Gibbs sampler code for the robust t distribution model is provided in Appendix N. A value for v of 40 was used in this analysis because the transformed data were reasonably close to a normal distribution. The posterior distribution output of the Gibbs sampler is compared to the 333 samples from the final status survey in Table 14. The methodology was to transform the data using Box-Cox procedure, calculate the 99th percentile of the posterior distribution using a Gibbs sampler, and then back-transform the results to concentration data.

The posterior distribution in this example slightly spreads the data further into the tails at the 99th percentile. At the 99th percentile, the final status survey data distribution has a value of 71.7 pCi/g, while the corresponding posterior distribution result is 77.5 pCi/g. The upper tolerance limit (UTL) represents the 95% upper confidence level on the 99th percentile—it was 96.5 pCi/g. Specifically, the Gibbs sampler code produced a distribution of results at the 99th percentile—the mean of the 99th percentile was 77.5 pCi/g, and the 95% upper confidence level for this percentile was 96.5 pCi/g. The UTL is directly compared to the $DCGL_{99th}$, and compliance with the hot spot criteria would be demonstrated as long as the UTL is less than the $DCGL_{99th}$.

Therefore, the posterior t distribution accounts for hot spots that may exist in the survey unit, but have not been identified. This is appealing from the context of regulatory compliance. Assuming that all the hot spots have been identified, the 99th percentile of the actual data (71.7 pCi/g) would not be questioned. However, finding all of the hot spots is seldom the case. Rather, the more appropriate question is how many hot spots have been missed and remain in the survey unit. This approach provides confidence to conclude that: 1) more hot spots are likely (upper end of the distribution), and that the best estimate of the 95% upper confidence level for the 99th percentile is 96.5 pCi/g. Finally, the hot spot assessment is performed by comparing the UTL concentration to the $DCGL_{99th}$. The proposed hot spot assessment approach is summarized next.

6.2.3 Proposed Hot Spot Assessment

The ultimate goal of the final status survey is to demonstrate that the contaminant concentration in the survey unit meets the release criterion (e.g., 25 mrem/y). The MARSSIM final status survey design specifies that two aspects of the contaminant distribution must be assessed in order to demonstrate compliance with release criteria—i.e., the mean and the upper tail of the distribution (hot spots). Indeed, the FSS design specifies random samples in the survey unit to determine the mean concentration, and radiation scanning to identify and assess any hot spots present in the survey uniform.

As mentioned earlier, the second component of this compliance approach depends on the hot spots being identified so that they can then be assessed for compliance purposes. As many final status survey practitioners would attest, finding most of the hot spots can be a real challenge. Therefore, it is reasonable to conclude that the MARSSIM approach generally works well for assessing hot spots, but it does have two shortcomings: 1) it does not account for the fact that scanning is not likely to find ALL of the hot spots present, and 2) its approach for handling multiple hot spots identified in the survey unit is not consistent with a dose- or risk-based approach used to establish DCGLs in the first place.

The proposed approach for hot spot assessment is to recognize the connection between the average and upper tail of the contaminant distribution in the survey unit, and to use a compliance test that compares the upper tail (e.g., 99^{th} percentile) to the $DCGL_{99th}$. That is, it is recognized that the hot spots are a further continuum of the contaminant distribution—i.e., the upper tail of the distribution. Under this approach, the hot spots identified, as well as those not identified, are considered in the compliance demonstration. Further, those that are identified should be considered for remediation as part of an ALARA assessment.

To summarize, the assessment aspect of this proposal is to use a Bayesian statistical approach to determine the posterior distribution, particularly the 99^{th} percentile of the data distribution, and then compare the 95% upper confidence level on the 99^{th} percentile (defined as the Upper Tolerance Limit) with the $DCGL_{99th}$. The $DCGL_{99th}$ can be determined from the area factors generated in Chapters 3 and 4 for a particular hot spot size (e.g., 0.1 m^2). Appendix O provides three examples of the proposed hot spot assessment for final status survey data.

<u>Summary of Proposed Approach for FSS Design and Assessment:</u>

1) Determine sample size *n* using MARSSIM approach
2) Collect *n* samples and any judgmental samples from FSS
3) Perform nonparametric statistical test (on random data alone) to demonstrate average contamination in the survey unit satisfies release criteria

4) Combine random and judgmental data and use robust t methodology to generate posterior distribution
5) Compare the 95% upper confidence level of the 99th percentile (from the posterior distribution) to the $DCGL_{99th}$ to assess compliance with hot spots
6) Remediate identified hot spots based on ALARA considerations

It is also interesting to point out that this approach is particularly helpful in situations where the scan minimum detectable concentration (MDC) is not sufficiently sensitive to identify hot spots of concern. [This is usually the case for non-radiological contaminants in the environment]. In this circumstance, the posterior distribution provides an estimation of the levels of hot spots that likely exist in the survey unit, but cannot be readily found due to a poor scan MDC. The decision-maker can then decide whether to release the survey unit having knowledge of the likely magnitude of unidentified hot spots remaining in the survey unit.

6.3 Bayesian Statistical Approach Conclusions

A Bayesian statistical approach was proposed to demonstrate how hot spots potentially remaining in a survey unit can be shown to satisfy release criteria. A robust t posterior distribution model provided an estimate of the 99th percentile of the contaminant distribution. Markov chain Monte Carlo provided a useful tool for exploring the posterior distribution, and specifically for drawing inferences about models and parameters. In that regard, a Gibbs sampler programmed in R language was used to generate statistics of the posterior distribution. Hot spot compliance is demonstrated by comparing the upper tolerance limit (i.e., 95% upper confidence level on the 99th percentile) of the contaminant distribution in the survey unit with the $DCGL_{99th}$ value. This proposed approach would improve the MARSSIM hot spot assessment approach by providing a comprehensive compliance methodology that considers hot spots that may be present, but not found. The worked examples in Appendix O illustrate the approach for hot spot assessment for three different final status survey data scenarios.

The proposed survey approach for assessing the acceptability of hot spots also addresses the issue of multiple hot spots. That is, the contaminant distribution that results from the Bayesian analysis inherently accounts for multiple hot spots in the survey unit. For example, the range of contaminant concentrations that exist between the 98th percentile and the 99.5th percentile are likely to be defined as hot spots in a Class 1 survey unit. Therefore, these “multiple” hot spots (whether they are identified or not) are handled during the assessment of the overall contaminant distribution. Thus, the proposed approach seeks to define the overall hot spot criteria in the context of the contaminant distribution, recognizing that both the mean and overall shape of the distribution are important factors in determining the receptor dose. The hot spot assessment involves a simple comparison of the upper tolerance limit with the $DCGL_{99th}$.

CHAPTER 7 APPLICATION TO NON-RADIOLOGICAL CONTAMINANTS

The dissertation research objective regarding non-radiological contaminants was to explore how release criteria and cleanup standards are established for a number of contaminants, and specifically, to evaluate the applicability of the radiological hot spot limit concept to non-radiological contaminants. Technical approaches for setting non-radiological hot spot limits were considered. The principal study questions included: How do other disciplines handle hot spot concentrations of contaminants? Do environmental scientists and industrial hygienists have an approach for determining acceptability of chemical hot spots? The research goals were to research how non-radiological hot spots impact receptor exposures, and propose an approach for how hot spot limits might be set. Using the results obtained for radiological contaminants and the hot spot sensitive pathways, the equations used to establish preliminary remediation goals (PRGs) were evaluated to consider proposed non-radiological hot spot limits.

7.1 Background

The environmental pathway equations for radiological and non-radiological contaminants are similar. Comparable situations exist for both radiological and non-radiological contamination—the respective concentration limits (PRGs and DCGLs) assume that the contamination is uniform across the survey or exposure unit, while in many cases the contamination is likely to be spotty and contain hot spots. Strictly speaking, there are no hot spot limits for non-radiological (chemical) contaminants. Yet, it is reasonable to expect that the non-radiological contamination present in an exposure unit is just as spotty, and non-uniformly distributed, as radioactive contamination tends to be.

The general compliance approach for non-radiological contaminants is to first assess whether compliance can be demonstrated with PRGs. A conceptual site model should be prepared to support this process. The primary condition for the use of PRGs is that the exposure pathways and site conditions match those modeled to generate the PRGs. If some concentrations exceed the PRG, then a risk assessment is performed across the entire exposure unit. No remediation is warranted provided that the risk from chemical concentrations is within the acceptable risk range—if outside risk range, then cleanup is needed. Another option for addressing elevated chemical concentrations might be to average the data over an exposure unit to demonstrate compliance. This is usually a weighted average, and it is often specified in the record of decision (ROD) for the cleanup project. In other cases, the preliminary remediation goals are assessed

as “not to exceed” values.[11] Developing hot spot limits for non-radiological contaminants might support the consistent application of PRGs at Superfund sites.

7.2 CERCLA and RCRA Regulations

There are many regulations that govern the release of sites potentially contaminated with non-radiological contaminants. Perhaps two of the more familiar cleanup regulations for non-radiological contaminant are those promulgated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). The following excerpts are from the CERCLA section on degree of cleanup. Rather than establishing individual cleanup standards, CERCLA ensures that cleanup activities are based on cleanup standards and criteria established by other laws (USEPA 2008): “*Remedial actions selected under this section… shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and of control of further release at a minimum which assures protection of human health and the environment.”* The second excerpt provides an example on the degree of cleanup required*, “Such remedial action shall require a level or standard of control which at least attains Maximum Contaminant Level Goals established under the Safe Drinking Water Act and water quality criteria established under section 304 or 303 of the Clean Water Act, where such goals or criteria are relevant and appropriate…”*

The EPA recently published the “Final Guidance on Completion of Corrective Action Activities at RCRA Facilities” in the Federal Register.[12] This guidance covers a number of issues related to the completion of corrective action activities at RCRA facilities. The ultimate goal of these corrective actions is to satisfy the ‘‘protection of human health and the environment’’. In this regard, the RCRA and CERCLA cleanup programs have roughly the same approach to cleanup.

Remedial actions conducted at CERCLA (and RCRA) sites are designed to be protective of human health and the environment. The overall CERCLA remedial process is similar to the MARSSIM process. A comparison of the two cleanup approaches is provided in Appendix F of the MARSSIM (USNRC 2000a). Cleanup levels under both programs are developed based on radiation dose or risk assessments. While the MARSSIM has DCGLs that are based on acceptable radiation dose limits, CERCLA establishes preliminary remediation goals (PRGs) that combine current human health toxicity values with exposure pathways to estimate contaminant concentrations in environmental media. The

[11] EPA Region 9 recognizes that applying the PRGs as a “max” soil concentration is not a universally accepted approach, from User’s Guide and Background Technical Document for USEPA Region 9’s Preliminary Remediation Goals (PRG) Table (http://www.epa.gov/region09/waste/sfund/prg/index.html)

[12] Federal Register. Vol. 68, No. 37; February 25, 2003

EPA generally sets remediation levels for: 1) carcinogens at a level that represents an excess upper bound lifetime cancer risk to an individual of between 1E-4 to 1E-6; and for 2) non-carcinogens such that the cumulative risks from exposure will not result in adverse effects to human populations (USEPA 2002b). Therefore, PRGs represent chemical concentrations in air, soil, and water that correspond to fixed levels of risk—e.g., 1E-6 excess cancer risk or non-cancer hazard quotient[13] (HQ) of 1. It is important to understand that PRGs are implemented as initial cleanup goals—a comprehensive risk assessment following remedial actions is often needed at CERCLA sites.

Similar to the preliminary remediation goals are the risk-based soil screening levels (SSLs) for contaminants in soil. The EPA's soil screening guidance user's guide (EPA 1996a) provides a methodology to calculate the SSLs that combines contaminant toxicity information with exposure pathway assumptions. The standard scenario is based on the reasonable maximum exposure (RME) for a residential setting—the approach "estimates the RME for chronic exposures on a site-specific basis by combining an average exposure-point concentration with reasonable conservative values for intake and duration" (EPA 1996a). The SSLs are not to be interpreted as cleanup standards—rather, where contaminant concentrations exceed SSLs, further investigation should be performed, but not necessarily cleanup. For the migration to groundwater pathway (from soil), the SSLs are back-calculated from groundwater concentration limits that are based on the maximum contaminant levels (MCLs) or health-based limits (i.e., cancer risk of 1E-6 or an HQ of one) (USEPA 2002b).

7.3 Chemical Toxicity and Risk for Non-Radiological Contaminants

The following non-radiological contaminants are discussed in this section: arsenic, asbestos, beryllium, lead, mercury, PCBs, and trichloroethylene (TCE). The chemical hazard/risk, likely exposure pathway, and exposure limits are described for each contaminant in this section, and the information is used to propose hot spot limits consistent with routes of exposure.

The EPA Integrated Risk Information System (IRIS) database provides toxicity information for a number of the contaminants. The EPA IRIS is a "database of human health effects that may result from exposure to various substances found in the environment. IRIS was initially developed for EPA staff in response to a growing demand for consistent information on chemical substances for use in

[13] EPA defines the hazard quotient as the ratio of a single substance exposure level over a specified time period to a reference dose for that substance derived from a similar exposure period (USEPA 1991).

risk assessments, decision-making and regulatory activities."[14]

The Agency for Toxic Substances and Disease Registry (ATSDR) provides exposure and health risk information for many hazardous substances. This information includes a summary and interpretation of available toxicological information and epidemiologic evaluations on a hazardous substance in order to ascertain the levels of significant human exposure for the substance and the associated acute, sub-acute, and chronic health effects.

Arsenic

Arsenic can enter the body by inhalation, ingestion (e.g., drinking water), and skin contact. ATSDR reports that "breathing high levels of inorganic arsenic can give you a sore throat or irritated lungs" and that ingesting very high levels of arsenic can be lethal (ATSDR 2007).

Asbestos

Inhalation of asbestos fibers is the pathway of greatest risk. Asbestos fibers can lead to lung cancer and asbestosis, which has a relatively long latent period for disease to be manifested. When the health consequence is longer term rather than acute, the exposure to hot spots of contamination can be significant (ATSDR 2001).

Beryllium

Inhalation of beryllium can result in acute beryllium disease if beryllium air levels are high enough (greater than 1000 µg/m^3). Some exposed workers (1-15%) become sensitive to beryllium. These individuals may develop an inflammatory reaction in the respiratory system. This condition is called chronic beryllium disease (CBD), and can occur years after exposure to higher than normal levels of beryllium (greater than 0.2 µg /m^3) (ATSDR 2002).

Lead

The effects of lead are the same whether it enters the body through breathing or swallowing. Lead can affect almost every organ and system in your body. The main target for lead toxicity is the nervous system, both in adults and children (ATSDR 2007). Exposure pathways include inhalation, ingestion of drinking water, and eating foods contaminated with lead. Inhalation is the most common route of entry, followed by ingestion. Remediation of lead in paint is a concern.

[14] U.S. Environmental Protection Agency. Integrated Risk Information System (IRIS). Office of Research and Development; National Center for Environmental Assessment: http://www.epa.gov/iris.

Mercury

Exposure to mercury occurs from breathing contaminated air, ingesting contaminated water and food, and having dental and medical treatments. Examples include eating fish or shellfish contaminated with methyl mercury, and breathing vapors in air from spills, incinerators, and industries that burn mercury-containing fuels (ATSDR 1999).

PCBs

Polychlorinated biphenyls are mixtures of up to 209 individual chlorinated compounds (known as congeners). PCBs are either oily liquids or solids that are colorless to light yellow, and they can exist as a vapor in air. Many commercial PCB mixtures are known in the U.S. by the trade name Aroclor (ATSDR 2001).

PCB routes of entry include ingestion, inhalation, and skin exposure. The main dietary sources of PCBs are fish (especially sport fish caught in contaminated waters), meat, and dairy products (ATSDR 2001).

TCE

Trichloroethylene is a colorless liquid that has been widely used as a solvent for cleaning and degreasing metal parts. Drinking or breathing high levels of trichloroethylene may cause nervous system effects, liver and lung damage, abnormal heartbeat, coma, and possibly death (ATSDR 2003).

7.4 Methodology for Establishing Preliminary Remediation Goals

The exposure routes of concern for each of the identified contaminants were discussed in the previous section. The pathway information, coupled with the chemical toxicity and other characteristics of the identified contaminants, are used by the EPA and other regulators to establish exposure limits. Recognizing this methodology, a general framework for hot spot limits for non-radiological contaminants is proposed. The basis of this approach is to develop the relationship between the hot spot sensitive pathways for radiological contaminants and potential hot spot sensitive pathways for non-radiological contaminants. As with the radiological pathway analyses, it is expected that some pathways for non-radiological contaminants will not be hot spot sensitive.

The scope of the research required reading and understanding materials that form the underlying basis of the current non-radiological cleanup standards. For example, this included CERCLA and RCRA statutes, as well as a host of primarily EPA guidance documents. The specific approach was to assess the routes of exposure for a number of non-radiological contaminants—dermal absorption, inhalation, direct exposure, ingestion—in order to understand how

hot spots impact receptor exposure. The first pathway considered was the residential use of water, where the contaminant is assumed to be in the water (as opposed to the situation where the contaminant is initially in the soil and has to be transported to the groundwater). Next, three soil pathways were identified for further study: drinking water (i.e., contamination migrating from soil to groundwater), direct ingestion of soil, and inhalation of fugitive dust. For each pathway, equations for both carcinogenic and non-carcinogenic health effects were evaluated.

The stated purpose of the EPA's Risk Assessment Guidance for Superfund (RAGS) is to assist risk assessors and remedial project managers at CERCLA sites in developing preliminary remediation goals (USEPA 1991). Specifically, it provides guidance on the use of risk-based calculations to establish chemical concentration limits using toxicity values and exposure pathway information. For example, RAGS provides risk equations for groundwater, surface water and soil pathways. Interestingly, the document does not consider more complex pathways involving plant and animal product consumption—" …equations do not address pathways such as plant and animal uptake of contaminants from soil with subsequent human ingestion" (USEPA 1991).

7.4.1 Groundwater and Surface Water PRGs

The first example considered is the residential land use scenario in RAGS used to calculate risk-based PRGs for groundwater and surface water. The risk from groundwater or surface water is based on combining two exposure pathways: direct ingestion and inhalation of volatiles from household water use. The risks from these two exposure pathways are combined, and the calculated PRG is derived to be sufficiently protective of exposures from both pathways. For residential water, the PRG equation based on carcinogenic effects is as follows:

$$C = \frac{TR \times BW \times AT \times 365d/y}{EF \times ED \times [(SF_i \times K \times IR_a) + (SF_o \times IR_w)]} \qquad (7-1)$$

where
C is the chemical concentration in water (mg/L)
TR is the target excess individual cancer risk (1E-6),
BW is adult body weight (default is 70 kg),
AT is averaging time (70 y),
SF_i is the inhalation cancer slope factor for a particular chemical $(mg/kg\text{-}d)^{-1}$,
SF_o is the oral cancer slope factor for a particular chemical $(mg/kg\text{-}d)^{-1}$,
EF is exposure frequency (350 d/y),
ED is exposure duration (30 y),
IR_a is the daily indoor inhalation rate (default is 15 m^3/d),
IR_w is the daily water ingestion rate (default is 2 L/d), and

K is the volatilization factor (unitless).

The PRG equation based on non-carcinogenic effects is given by:

$$C = \frac{THI \times BW \times AT \times 365d/y}{EF \times ED \times [(\frac{1}{RfD_i} \times K \times IR_a) + (\frac{1}{RfD_o} \times IR_w)]} \qquad (7-2)$$

where
THI is the target hazard index (unitless, default is 1),
BW is adult body weight (default is 70 kg),
RfD_i is the inhalation chronic reference dose (mg/kg-d), and
RfD_o is the oral chronic reference dose (mg/kg-d).

It is important to recognize the PRG equations above assume that the chemical contaminant is present in the household water from the outset (time t = 0). These equations do not lend themselves to the calculation of non-radiological hot spots, at least not directly. Consider that the PRG-level chemical concentration in water (mg/L) delivers a specified target risk. This risk is based on a total intake of the particular chemical. Conceptually, a short-term increase in the chemical concentration in the water will deliver the risk over some specified averaging time if the daily water ingestion rate is commensurately reduced, such that the overall chemical intake is maintained constant. It is precisely this concept that allows one to consider the possibility of deriving non-radiological hot spots.

7.4.2 Soil Screening Levels

For chemical contamination in soil, EPA recommends the use soil screening levels (SSLs). Specifically, the EPA states that the "models, equations, and assumptions presented in the Soil Screening Guidance to address inhalation exposures supersede those described in RAGS HHEM, Part B for resident soils" (USEPA 1996a). The SSLs represent soil concentration levels that correspond to a target risk (carcinogen) or hazard quotient (non-carcinogen), and they can be used as PRGs provided that the conditions found at the site are sufficiently similar to the assumed conditions used to develop the SSLs (USEPA 2002b).

The EPA's Soil Screening Guidance discusses three pathways for exposure from contaminated soil: 1) direct ingestion, 2) dermal contact, and 3) inhalation of fugitive dusts (USEPA 1996b). It is noteworthy that there is no analog to the external radiation pathway for chemicals. Appendix A in EPA's Supplemental Guidance for Developing Soil Screening Levels for Superfund sites (USEPA 2002b) provides generic SSLs for 109 chemicals under residential and non-residential (i.e., commercial/industrial) exposure scenarios. Generic SSLs for

three of the soil pathways in this appendix—inhalation of volatiles in outdoor air, inhalation of fugitive dust, and migration to ground water—were calculated using the same equations and default values for exposure assumptions found in the Soil Screening Guidance (USEPA 1996b). SSL calculations for direct ingestion, inhalation of fugitive dust, and migration to groundwater pathways are considered next.

Direct Ingestion Soil Screening Levels

The soil screening guidance (USEPA 1996a) provides the following SSL equation[15] for the direct ingestion pathway for non-carcinogenic contaminants:

$$SSL = \frac{THQ \times BW \times AT \times 365 d/y}{1/R_f D_o \times 1E-6\, kg/mg \times EF \times ED \times IR} \qquad (7-3)$$

where
SSL is soil screening level in mg/kg,
THQ is the target hazard quotient (default = 1),
BW is body weight (15 kg),
AT is averaging time (6 y),
R_fD_o is oral reference dose in mg/kg-d,
EF is exposure frequency (350 d/y),
ED is exposure duration (6 y), and
IR is ingestion rate of soil (200 mg/d).

This SSL is based on the "childhood only" exposure scenario because a number of studies have shown that inadvertent ingestion of soil is common among children 6 years old and younger (USEPA 1996a).

The SSL equation for direct ingestion pathway for carcinogenic contaminants is given by:

$$SSL = \frac{TR \times AT \times 365 d/y}{SF_o \times 1E-6\, kg/mg \times EF \times IF_{soil\,adj}} \qquad (7-4)$$

where
TR is the target cancer risk (1E-6),
SF_o is the oral slope factor in $(mg/kg\text{-}d)^{-1}$, and
$IF_{soil\ adj}$ is the age-adjusted soil ingestion factor (in mg-y/kg-d).

[15] EPA updated the direct ingestion pathway calculation to provide SSLs based on the combined soil ingestion and dermal absorption exposure pathway in USEPA 2002b. For the purposes of this work, the original direct ingestion SSL equation in USEPA 1996a was used.

Inhalation Soil Screening Levels

The next soil pathway considered is the inhalation of fugitive dusts pathway. The EPA guidance states that inhalation is usually not as limiting as direct ingestion (USEPA 1996b). The soil screening guidance provides the following SSL equation for the inhalation of fugitive dusts pathway for non-carcinogenic contaminants:

$$SSL = \frac{THQ \times AT \times 365 d/y}{\left(\frac{1}{R_f C} \times \frac{1}{PEF}\right) \times EF \times ED \times IR} \qquad (7-5)$$

where
SSL is soil screening level in mg/kg,
THQ is the target hazard quotient (default = 1),
AT is averaging time (30 y),
R_fC is the inhalation reference concentration (mg/m^3),
EF is exposure frequency (350 d/y),
ED is exposure duration (30 y), and
PEF is the particulate emission factor (default is 1.32E9 m^3/kg).

The particulate emission factor relates the concentration of contaminant in soil to the concentration of dust particles in air. The PEF represents the annual average emission rate based on wind erosion. The EPA states that this pathway should be compared to chronic health criteria; it is not appropriate for evaluating acute exposures (USEPA 1996a).

The PEF consists of two separate models, an emission model to estimate emissions of the contaminant from the soil, and a dispersion model to simulate dispersion of the contaminant in the atmosphere. It is based on the "unlimited reservoir" model to estimate particulate emissions via wind erosion. The equation provided for the PEF is shown below:

$$PEF = \frac{Q/C \times 3600 s/h}{0.036 \times (1-V) \times (U_m/U_t)^3 \times F(x)} \qquad (7-6)$$

where
Q/C is the inverse of mean concentration at the center of a 0.5-acre square source (default is 90.80 g/m^2-s per kg/m^3),
V is fraction of vegetative cover (default is 50%),
U_m is mean annual wind speed (default is 4.69 m/s),
U_t is equivalent threshold value of wind speed at 7 m (default is 11.32 m/s), and
F(x) is function dependent on U_m/U_t derived using an approach cited in Cowherd

et al. 1985.

The soil screening guidance provides the following SSL equation for the inhalation pathway for carcinogenic contaminants:

$$SSL = \frac{TR \times AT \times 365 d/y}{URF \times 1000 \mu g/mg \times EF \times ED \times 1/PEF} \qquad (7-7)$$

where
TR is the target cancer risk (1E-6),
AT is averaging time (70 y),
URF is the inhalation unit risk factor for a particular chemical $(\mu g/mg)^{-1}$,
EF is exposure frequency (350 d/y),
ED is exposure duration (30 y), and
PEF is the particulate emission factor (default is 1.32E9 m^3/kg).

Migration to Groundwater Soil Screening Levels

The final soil pathway considered is the migration to groundwater pathway. This pathway considers contaminants in soil that have the potential to contaminate groundwater. The migration of contaminants from soil to groundwater begins with the release of the contaminant from soil to leachate, followed by transport of the contaminant through the soil and aquifer to a receptor well. The simplified model essentially consists of two steps: 1) the acceptable groundwater concentration is multiplied by a dilution factor to obtain the target soil leachate concentration, and 2) the partition equation is used to calculate the total soil concentration that corresponds to the soil leachate concentration (USEPA 1996a). The SSL partitioning equation is given by:

$$SSL = C_w \times \left[k_d + \frac{(\theta_w + \theta_a H')}{\rho_b} \right] \qquad (7-8)$$

where
C_w is target soil leachate concentration (mg/L),
k_d is the soil-water partition coefficient (L/kg),
θ_w is water-filled soil porosity (L-water/L-soil),
θ_a is the air-filled soil porosity (L-air/L-soil),
ρ_b is the dry soil bulk density (kg/L), and
H' is Henry's law constant.

Basically, the migration to groundwater SSLs are back-calculated from an acceptable target soil leachate concentration using a dilution-attenuation factor (DAF). USEPA 2002b provides generic SSLs using DAFs of both 20 and 1. The

DAF of 20 accounts for reductions in contaminant concentration due to natural processes occurring in the subsurface. The DAF of one assumes no dilution or attenuation between the source and the receptor well. The EPA notes that a DAF of 1 "should be used at sites where little or no dilution or attenuation of soil leachate concentrations is expected; this will be the case at sites with characteristics such as shallow water tables, fractured media, karst topography, or source size greater than 30 acres" (USEPA 2002b).

The EPA notes that a "DAF of 20 is protective for sources up to 0.5 acres in size" (USEPA 1996b). Table 5 in USEPA 1996b provides data illustrating the variation in DAF with size of source area. The smallest source considered was 0.02 acres (about 80 m^2), and the corresponding DAF at the 95^{th} percentile is 946. This means that smaller sources (0.02 acres in this case) can have SSL concentrations 946/20, or 47 times the SSL based on a default DAF of 20. This result has application regarding the development of non-radiological hot spot limits.

7.5 Proposed Non-Radiological Hot Spot Limits

It is beneficial to recognize that radiological and non-radiological contaminants and their respective cleanup criteria are generally treated in the same way. NCRP Report 146 (2004), "Approaches to risk management in remediation of radioactively contaminated sites" provides an overview of the EPA and NRC approaches for demonstrating that sites have met release criteria. Both regulatory agencies establish their respective release criteria in terms of risk or dose levels, and then perform pathway modeling in consideration of relevant scenarios. Ultimately, measureable concentration limits in various media that correspond to the release criteria are derived. Many sites contaminated with radioactivity use the RESRAD modeling code, while Superfund sites often use the preliminary remediation goal (PRG) calculator. In either case, the result is a concentration limit that corresponds to the release criteria. Under the MARSSIM approach, the average concentration limit is called the $DCGL_W$, and it is statistically compared to the average concentration in the survey unit. The comparable average concentration limit at Superfund sites is the PRG, which is often implemented as an average limit across an exposure limit—although in some cases it has been implemented as a "not to exceed" concentration.

Recognizing that elevated concentrations of radioactivity (hot spots) often exist at cleanup sites, the MARSSIM established the $DCGL_{EMC}$. This hot spot limit is used to assess the acceptability of these smaller contaminant source terms. A case can be made for the derivation of non-radiological hot spot limits in much the same fashion as for radioactive hot spots. The key is recognizing the similarity of equations used to obtain SSLs (and PRGs) and DCGLs—i.e., in the same way that the DCGL equations are modified to account for hot spot source terms, the SSL equations can be modified to derive non-radiological area factors.

Thus, larger concentrations of non-radiological contaminants in a smaller area might be acceptable provided that the overall risk is consistent with that derived for the SSL (or PRG) concentration present over the entire exposure unit.

The EPA's soil screening guidance report states that a default 0.5 acre (about 2,000 m^2) source area is used to calculate the generic SSLs (USEPA 1996b). The same report further notes that commenters on the draft Soil Screening Guidance suggested that most contaminated soil sources were 0.5 acre or less. This is largely consistent with that experienced for radioactive contaminant source terms at decommissioning sites. Interestingly, the draft soil screening guidance had a default contamination area of 30 acres (120,000 m^2). The EPA performed an assessment of the impact of reducing the contaminant area; they found that decreasing the source area from 30 acres to 0.5 acre increases the inhalation SSLs by about a factor of two.

The "unlimited reservoir" model used to derive the SSLs for the inhalation pathway hardly seems appropriate for small source terms (i.e., less than 10 m^2). Recall the discussion in Chapter 3 concerning the inhalation pathway and radiological area factors. The argument was made that the size of the contaminated area should have a more pronounced effect on the area factor, and inhalation dose. The same argument can be made for non-radiological contaminants via the inhalation pathway—the area factors, and therefore the SSLs, should increase significantly with the reduction in the size of the hot spot.

For the migration to ground water pathway, the EPA noted that the source area affects the DAF, which also directly affects the final SSLs and is not chemical-specific (USEPA 1996b). The reduced source area impacts the dilution factor in a complicated fashion that affects the infiltration to the aquifer, mixing zone depth, hydraulic conductivity, among other parameters. One overall impact, depending on the value of the aquifer's Darcy velocity, is that the reduced source term from 30 to 0.5 acres increases the dilution factor (and thus the SSL) by a factor of 3.1 (USEPA 1996b). Obviously, hot spots on the order of 10 m^2 or less are of particular interest in this research.

The direct ingestion pathway in soil for non-carcinogenic contaminants is used to demonstrate in greater detail how non-radiological hot spot limits can be derived. Recall the risk-based soil screening levels equation from the EPA's soil screening guidance user's guide (USEPA 1996a):

$$SSL = \frac{THQ \times BW \times AT \times 365 d/y}{1/R_f D_o \times 1E-6\, kg/mg \times EF \times ED \times IR} \qquad (7-9)$$

The corresponding RESRAD equations for direct soil ingestion pathway for radiological contaminants are given by the following equations:

$$DSR_i = \sum_j DCF_j \times BRF_{i,j} \times ETF_j \times SF_{i,j} \qquad (7-10)$$

where the DSR is the dose to source ratio that depends on the dose conversion factor (DCF), branching factor, environmental transport factor (ETF), and source factor (SF). The ETF depends on the size of the contaminated area, FA, as follows:

$$ETF_j = FSI \times FA \times FCD \times FO \qquad (7-11)$$

where FA is the area factor based in the following decision rule for size of contaminated area, A: FA = A/1000, for 0 < A < 1000 m^2, otherwise FA = 1 for A greater than 1000 m^2.

The future occupant is assumed to randomly occupy different locations within a survey unit. Further, it seems reasonable that the receptor dose would scale directly with the fraction of the survey unit actually contaminated. The radiological hot spot dose is essentially based on the total amount or inventory of radioactivity being in contact with a future receptor, and ultimately ingested by the future receptor.

Considering the SSL concentration for non-radiological contaminants calculated in equation 7-9, how can the equation be modified to account for hot spot source terms? Note that the dose for the radiological contaminant for the soil ingestion pathway scaled directly with the size of the contaminated area. For example, if the hot spot size was 1 m^2, then the FA parameter is given as A/1000, or 1/1000. A similar reduction for the non-radiological SSL concentration is suggested—but in this case the exposure frequency (EF) is modified from its default value of 350 d/y. The future receptor is likely to be much less exposed to a non-radiological hot spot than when the entire exposure unit is assumed to be contaminated at the PRG concentration. A reasonable estimate of the reduced exposure frequency is the simple ratio of hot spot area to the exposure unit area.

For example, if the exposure unit is 10,000 m^2 and the hot spot is 10 m^2, then the exposure frequency of 350 d/y is reduced by a factor of 10/10000, or 0.001. This results in a hot spot-modified EF of 0.35 d/y, and reflects the fact that a future receptor has a much smaller exposure frequency to a relatively small hot spot in the exposure unit. The modified EF of 0.35 d/y goes in the denominator of eqn 7-9, so the hot spot SSL concentration in this case is 1000 times larger than the SSL derived for the entire exposure unit. The result is that the risk scales directly with the size of the non-radiological hot spot.

This approach assumes that the increased hot spot concentration does not exceed an acute risk level for the particular contaminant. The non-radiological

hot spot will still be based on chronic health effects. For example, a hot spot concentration of 1000 times the PRG may be acceptable from a chronic risk perspective, but the acute health risk needs to be assessed as well. An interesting paper by Schulz and Griffin (2001) reported that an acute PRG for arsenic in soil was calculated using a shorter exposure duration. The acute PRG for arsenic was 2,564 ppm, while the chronic PRG, based on lifetime exposure duration, was 260 ppm. An acute PRG should be calculated to ensure that there are no adverse health effects from the short term exposure (Schulz and Griffin 2001).

The SSL equations for each of the pathways evaluated can be modified to account for source areas on the order of hot spots. The pathways and DCGL equations used for radiological contaminants can serve as a guide for calculating non-radiological area factors. The next section provides an example of non-radiological hot spot compliance, where the 99th percentile of arsenic concentrations in soil evaluated using the statistical methodology in Chapter 6 are compared to proposed non-radiological hot spot concentrations for arsenic.

7.6 Example of Non-Radiological Hot Spot Compliance

Mulhausen and Damiano (1998) argue the case for considering both the mean and upper percentile aspects of contaminant distributions. Focusing on the mean contamination "provides an average exposure estimate that is directly related to average dose", while focusing on the upper percentiles "provides insight to the upper extremes of exposure …and may be useful for evaluating agents with primarily acute effects…" This is precisely the point addressed in Chapter 6. The statistical approach described in Chapter 6 can be applied to the non-radiological hot spot assessment as well as radiological hot spots.

The EPA recommends using the 95th upper confidence level on the mean, as opposed to the mean, for demonstrating compliance with the PRG or SSL (USEPA 2002a). This is a conservative approach for demonstrating compliance with the average contamination level in an exposure unit, but it does not address the upper tail of the contaminant distribution that is impacted by non-radiological hot spots. Whenever hot spots are possibly present in an exposure unit (e.g., based on site history or preliminary survey information), the data quality objectives process should consider a comprehensive approach for evaluating the risk impact posed by the non-radiological hot spots. The following example demonstrates the approach used to obtain non-radiological area factors, and how actual site data can be shown to comply with the proposed non-radiological hot spot limit using robust t distribution. That is, the 99th percentile of the contaminant distribution is compared to the hot spot limit.

Consider a remediation site where the primary soil contaminant is arsenic, and that the site-specific PRG for arsenic is 16 mg/kg. Assume that the critical

exposure pathway used to derive this PRG is direct ingestion of soil. This assumption is based on the generic SSLs provided for arsenic (USEPA 1996b): 0.4 mg/kg for ingestion, 750 mg/kg for inhalation of fugitive particulates, and 29 mg/kg for migration to groundwater (using DAF of 20). It is important to note that these generic SSLs correspond to a cancer risk level of 1E-6. Thus, it seems reasonable to calculate area factor for arsenic based on direct ingestion pathway.

The direct ingestion pathway in soil for carcinogenic contaminants is used to assess the proposed arsenic area factor. Recall the risk-based soil screening levels equation from the EPA's soil screening guidance user's guide (USEPA 1996a):

$$SSL = \frac{TR \times AT \times 365 d/y}{SF_o \times 1E-6\, kg/mg \times EF \times IF_{soil\,adj}}$$

As discussed in the previous section, the exposure frequency is reduced in recognition of the smaller contaminant source term. Recall that the default exposure frequency is 350 d/y. A reasonable estimate of the reduced exposure frequency is the simple ratio of hot spot area to the exposure unit area. For this example, assume that the hot spot size of interest is 100 m^2 and the exposure unit is 10,000 m^2. The exposure frequency of 350 d/y is reduced by a factor of 100/10000, or 0.01. This results in a hot-spot-modified EF of 3.5 d/y, and reflects the fact that a future receptor has a much smaller exposure frequency to a relatively small hot spot in the exposure unit. The modified EF of 3.5 d/y results in a hot spot concentration of 100 times larger than the PRG derived for the entire exposure unit. The hot spot PRG is 1600 mg/kg in this case.

Twenty-five soil samples were collected and analyzed for arsenic. The mean and 99th percentile concentrations were 10.3 and 22.8 mg/kg, respectively. The data ranged from 3.9 to 23 mg/kg, with five concentrations greater than the 16 mg/kg PRG average release criterion. The Bayesian analysis (refer to Chapter 6 for details on this approach) results shown in Table 15.

The robust t posterior distribution in this case is greater than the arsenic survey data at the 95th and 99th percentiles, largely as a result of the variability in the data. The actual data had a 99th percentile value of 22.8 mg/kg, while the 99th percentile of the posterior distribution was 40.1 mg/kg. The upper tolerance limit (UTL) was 65.4 mg/kg—meaning that the 95% upper confidence level on the 99th percentile of the contaminant distribution is still much less than the arsenic hot spot PRG of 1600 mg/kg for a 100 m^2 hot spot.

Table 15 Robust t posterior distribution for arsenic in soil data.

Statistic	Survey Data	Posterior Distribution
Mean	10.3	8.8
95th	21.4	24.2
99th	22.8	40.1
UTL	----	65.4

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

One of the major conclusions of this work is that dose modeling of hot spots using the current practice (i.e., RESRAD code) likely overestimates the future receptor dose for the external radiation and inhalation pathways. The dose modeling of hot spots for the ingestion pathways result in area factors that either scale with size of the contaminated area or are based on source inventory, and as such, the results are not likely to be overestimated. From an implementation standpoint, it is of interest to know the dominant pathway for the radionuclide under consideration. For example, Co-60 in soil delivers nearly 100% of its dose via the direct radiation pathway, so dose estimates for Co-60 hot spots are likely overestimated. C-14 on the other hand delivers 90% of its dose via the plant pathway (water-independent), so it is not likely to have an overestimated hot spot dose.

The primary conclusion based on the external radiation pathway is that hot spot doses are much smaller under likely field conditions than assessed under current regulatory criteria. This is particularly true for the assumption that the receptor is located 6 m from the hot spot. The area factors for the eight radionuclides evaluated when the receptor was located directly on the hot spot ranged from 6.6 to 11.4 for 1 m^2 hot spot; and ranged from 650 to 785 when the receptor was located 6 m from the 1 m^2 hot spot. Therefore, allowing the receptor to be on average 6 m from the hot spot over the exposure time results in area factors that are much greater than currently allowed. However, these larger area factors are still more restrictive than those area factors that scale directly with the size of the contaminated area (where the area factor for 1 m^2 area is 1000). The external radiation pathway is certainly “hot spot sensitive”.

The inhalation pathway also has hot spot doses that are much smaller under likely field conditions than assessed using the RESRAD modeling code. Area factors calculated based on first principles are much greater than currently calculated using the RESRAD code. This is due to the proposed hand calculation approach of dividing the hot spot area by the survey unit area—which simply reduces the radionuclide source term available to deliver inhalation dose to the receptor. The inhalation pathway may or may not be considered “hot spot sensitive” depending on whether the RESRAD or hand-calculation approach is used to generate area factors—under the hand-calculation approach, this pathway is not hot spot sensitive.

The soil ingestion, water-independent animal product, and ingestion of plant products grown in contaminated soil all have area factors that scale directly with size of the contaminated area. As such, these pathways are not considered to be “hot spot” sensitive. The plant irrigation and water-dependent animal product pathway are the least restrictive, and have the largest area factors (even larger than those that scale directly with the size of the contaminated area). The

drinking water and fish ingestion pathways are “mildly hot spot sensitive”, having area factors somewhat smaller than those that scale directly with the size of the contaminated area. The external radiation pathway is the limiting pathway in terms of area factor for eight of the eleven radionuclides. The drinking water pathway is the most important pathway for one radionuclide, and has secondary importance for several of the radionuclides evaluated.

A general conclusion supported by these results is that the external radiation pathway is clearly the most limiting pathway, and as such, an argument can be made that this pathway alone should be used to establish area factors and corresponding hot spot limits. This argument is further supported by the fact that the other two hot spot sensitive pathways, drinking water and fish ingestion, are water-dependent pathways that require hundreds of years to reach groundwater (and deliver dose) for many of the radionuclides of concern. Recommendation: As long as the total source term estimate accounts for the contribution from hot spot(s) in the survey unit, **the specific limitation on individual hot spot concentration can be established considering the external pathway alone.**

The receptor dose impact from hot spots via the three building occupancy pathways is either directly related to total source term (e.g., inhalation and ingestion pathways), or a more complex relationship holds (external radiation pathway). For example, the hot spot dose via the inhalation and ingestion pathways scales directly with the size of the contaminated area, which means that the greater the hot spot source term, the greater the receptor dose. The external radiation pathway is the most limiting of the pathways, and it is certainly “hot spot sensitive”. For the external radiation pathway, the area factor is largely independent of the radionuclide (i.e., area factor only depends on the size of the hot spot). For the smallest hot spot studied (0.01 m^2 or 100 cm^2), the area factors were approximately 1100. This compares to an area factor of 3 cited in both Regulatory Guide 1.86 and DOE Order 5400.5. Thus, the area factors calculated based on dose modeling are much larger than the historical factor of three area factor used for decades.

The MCNP code was used to validate the MicroShield exposure rate results for three radionuclides—Co-60, Cs-137, and Am-241. For the case of the receptor located directly above the hot spot, the exposure rates were very similar. The largest relative standard error was 18%, and most were no more than 3 to 4% relative standard error. The uncertainty in the exposure rate measurements for this geometry generally ranges from 2 to 10%.

The MCNP code was also used to validate the MicroShield results for the receptor located 6 m away from the hot spot. The comparison between MCNP and MicroShield was not so good for this geometry. The relative standard error between the two approaches was typically 50% or more, and for the smallest three hot spot sizes, ranged from 120% to 740%. For these largest

discrepancies MicroShield consistently overestimated the exposure rate. The uncertainty in the exposure rate measurements for this geometry (as expressed by the relative standard error) is much greater, ranging from a factor of two to a factor of eight for the smaller hot spot sizes.

The uncertainty assessment identified the two input parameters that have the greatest impact on the annual receptor dose: 1) the receptor distance from the hot spot, and 2) the outdoor fraction. It is important to put these results in proper context. For most dose modeling efforts, the greatest uncertainty in the future receptor dose relates to the pathways and parameters related to particular scenarios (e.g., outdoor fraction and estimated receptor distance from hot spot). In general, the uncertainty of field and laboratory measurements (e.g., routinely less than 10%) used to characterize the source term are often trivial compared to the modeling parameter uncertainty.

A Bayesian statistical approach was proposed to demonstrate how hot spots potentially remaining in a survey unit can be shown to satisfy release criteria. A robust t posterior distribution model provided an estimate of the 99^{th} percentile of the contaminant distribution. Markov chain Monte Carlo provides a useful tool for exploring the posterior distribution, and specifically for drawing inferences about models and parameters. In that regard, a Gibbs sampler programmed in R was used to generate statistics of the posterior distribution. Hot spot compliance is demonstrated by comparing the 99^{th} percentile of the contaminant distribution in the survey unit with the $DCGL_{99th}$ value. This proposed approach would supplement the MARSSIM final status survey data reduction approach that is based on assessing only those hot spots that have been identified. The proposed approach provides a hot spot assessment approach that considers hot spots that may be present, but not found.

Some recommendations for future work:

- Use MCNP to directly model the receptor external dose from multiple hot spots, at various locations.

- RESRAD has reported been revised (spring 2008) to handle hot spots less than 1 m^2. The proposed resolution was to either use extrapolation or simply assume that the dose will be linearly proportional to area for area less than 1 m^2. As a follow-up, testing this linear proportionality relationship in RESRAD to results obtained from MicroShield would be valuable.

- Statistical approach in this work combines the random and judgmental data on an equal weighting for the Bayesian statistical approach. An improvement would be to use scanning data from the survey units to better define the overall shape of the contaminant distribution.

- Evaluate the impact of variable receptor distances from the hot spot was assumed to be accounted for by the dilution afforded by the FA factor. This assumption might be the focus of future work. Obviously, the greater the distance the receptor is from the hot spot, the smaller the airborne concentration in the receptor's breathing zone.

The dose modeling and statistical assessment of hot spots was thoroughly evaluated in this dissertation work. Tables 16 to 26 provide a summary of the pathway-specific area factors for each of the radionuclides studied. One impact of this dissertation work is that the current hot spot limits being used at many cleanup sites in the U.S. are unduly restrictive, and may result in the decommissioning industry paying for something that provides very little value. Substantial reductions in cleanup and survey costs are within reach if hot spot criteria are established on a stronger technical basis. It is hoped that regulatory agencies will review the technical approach described herein, and consider adopting these area factors for application in MARSSIM survey designs and implementation.

Table 16 Summary of pathway-specific area factors for C-14.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	NA	NA	NA	NA	NA	NA	NA
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	12.0	37.5	115	229	1090	1.1E4
Plant Products (contaminated soil)	1	1.45	4.85	14.5	29.1	145	1450
Plant Products (irrigation)	1	9100	1.5E5	1.6E6	7.3E6	2.2E8	2.5E10
Meat (water-dependent)	1	163	1.9E4	1.5E4	6.3E5	1.6E7	1.6E9
Milk (water-dependent)	1	1240	1.3E4	1.2E5	4.8E5	1.1E7	1.1E9
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	31.3	103	295	592	2870	2.9E4

Table 17 Summary of pathway-specific area factors for Co-60.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	2.30	4.73	11.4	21.3	100	990
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	NA	NA	NA	NA	NA	NA	NA
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	NA	NA	NA	NA	NA	NA	NA
Meat (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Milk (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	NA	NA	NA	NA	NA	NA	NA

Table 18 Summary of pathway-specific area factors for Sr-90.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	NA	NA	NA	NA	NA	NA	NA
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	NA	NA	NA	NA	NA	NA	NA
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	NA	NA	NA	NA	NA	NA	NA
Meat (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Milk (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	NA	NA	NA	NA	NA	NA	NA

Table 19 Summary of pathway-specific area factors for Tc-99.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	NA	NA	NA	NA	NA	NA	NA
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	12.4	40.4	119	238	1190	1.2E4
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	1	1270	1.4E4	1.2E5	4.9E5	1.2E7	1.2E9
Meat (water-dependent)	1	1280	1.5E4	1.3E5	5.0E5	1.3E7	1.3E9
Milk (water-dependent)	1	1240	1.4E4	1.2E5	4.8E5	1.2E7	1.2E9
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	31.8	105	307	614	3070	3.1E4

Table 20 Summary of pathway-specific area factors for I-129.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	1.76	3.14	6.93	12.6	57.6	575
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	9.03	30.3	90.0	176	881	8810
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	1	912	1.0E4	8.9E4	3.6E5	9.0E6	9.0E8
Meat (water-dependent)	1	924	1.0E4	8.9E4	3.7E5	9.3E6	9.3E8
Milk (water-dependent)	1	905	1.0E4	9.0E4	3.6E5	8.9E6	8.9E8
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	23.0	76.9	226	453	2260	2.3E4

Table 21 Summary of pathway-specific area factors for Cs-137.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	2.18	4.42	10.6	19.8	93.1	918
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	NA	NA	NA	NA	NA	NA	NA
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	NA	NA	NA	NA	NA	NA	NA
Meat (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Milk (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	NA	NA	NA	NA	NA	NA	NA

Table 22 Summary of pathway-specific area factors for Ra-226.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	2.26	4.63	11.1	20.8	97.8	964
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	4.01	8.81	21.9	40.9	196	1930
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	1	401	2940	2.2E4	8.2E4	2.0E6	1.9E8
Meat (water-dependent)	1	401	2930	2.2E4	8.2E4	2.0E6	1.9E8
Milk (water-dependent)	1	400	2860	2.1E4	8.0E4	1.9E6	1.9E8
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	10.2	22.6	56.8	105	505	4930

Table 23 Summary of pathway-specific area factors for Th-232.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	2.31	4.74	11.4	21.3	100	990
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	NA	NA	NA	NA	NA	NA	NA
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	NA	NA	NA	NA	NA	NA	NA
Meat (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Milk (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	NA	NA	NA	NA	NA	NA	NA

Table 24 Summary of pathway-specific area factors for U-238.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	2.09	4.14	9.78	18.2	85.1	837
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	4.35	9.30	21.1	36.8	158	1450
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	1	435	3100	2.1E4	7.4E4	1.6E6	1.5E8
Meat (water-dependent)	1	469	3360	2.3E4	8.0E4	1.8E6	1.6E8
Milk (water-dependent)	1	414	2940	2.0E4	7.0E4	1.5E6	1.4E8
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	15.3	32.9	74.7	130	561	5140

Table 25 Summary of pathway-specific area factors for Pu-239.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	1.92	3.63	8.41	15.5	72.4	713
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	NA	NA	NA	NA	NA	NA	NA
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	NA	NA	NA	NA	NA	NA	NA
Meat (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Milk (water-dependent)	NA	NA	NA	NA	NA	NA	NA
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	NA	NA	NA	NA	NA	NA	NA

Table 26 Summary of pathway-specific area factors for Am-241.

	Hot Spot Size (m^2)						
Pathway	1000	10	3	1	0.5	0.1	0.01
External Radiation	1	1.83	3.35	7.50	13.7	63.1	619
Inhalation	1	163	621	2100	4540	2.71E4	3.50E5
Soil Ingestion	1	100	333	1000	2000	1.0E4	1.0E5
Drinking Water	1	4.06	8.77	20.3	35.8	158	1430
Plant Products (contaminated soil)	1	100	333	1000	2000	1.0E4	1.0E5
Plant Products (irrigation)	1	406	2920	2.0E4	7.2E4	1.6E6	1.4E8
Meat (water-dependent)	1	406	2930	2.0E4	7.2E4	1.6E6	1.5E8
Milk (water-dependent)	1	406	2930	2.0E4	7.2E4	1.6E6	1.5E8
Meat (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Milk (water-independent)	1	100	333	1000	2000	1.0E4	1.0E5
Fish Ingestion	1	10.3	22.2	51.4	90.6	399	3630

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APPENDICES

Appendix A: Maple Output

Results of Double Integration of Point Kernel Exposure Rate

Exposure Rate for 1 m above 10 m^2 hot spot; No Buildup

```
T := 15; Ta := 100; Sv := .117; L := 178.4; k := 0.2203e-2; mu
   := 0.923e-1;
```

$$T := 15$$

$$Ta := 100$$

$$Sv := 0.117$$

$$L := 178.4$$

$$k := 0.002203$$

$$\mu := 0.0923$$

```
> zi := Ta + y;
```

$$zi := 100 + y$$

```
>
>
> zf := zi*sqrt(1 + L^2/(Ta + y)^2, symbolic);
```

$$zf := (100 + y)\sqrt{1 + \frac{31826.56}{(100 + y)^2}}$$

```
x := (Int(exp(-mu·rho·y/(Ta + y))/rho, rho = zi..zf));
```

$$\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.0923\,\rho\,y}{100+y}}}{\rho}\,d\rho$$

```
W := int(x, y = 0..T);
```

$$\int_0^{15}\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.0923\,\rho\,y}{100+y}}}{\rho}\,d\rho\,dy$$

```
assuming real
```

$\xrightarrow{\text{assuming real}}$ 4.513416135 (result of double integration)

```
evalf(k·Sv/2·W);
```

$$5.8167 \times 10^{-4}$$

Exposure Rate for 1 m above 10 m^2 Hot Spot, With Buildup

$T := 15;$

$$15$$

$Ta := 100$

$$100$$

$Sv := 0.117$

$$0.117$$

$L := 178.4$

$$178.4$$

$A := 23.652; \alpha 1 := -0.06485; \alpha 2 := -0.0117($

$$23.652$$

$$-0.06485$$

$$-0.0117($$

$k := 2.203E-3;$

$$0.00220$$

$\mu := 0.0923;$

$$0.0923$$

$zi := Ta + y;$

$$zi := 100 + y$$

>

>

> $zf := zi * \mathrm{sqrt}(1 + L\text{^}2/(Ta + y)\text{^}2, symbolic);$

$$zf := (100 + y)\sqrt{1 + \frac{31826.56}{(100 + y)^2}}$$

$$G := A \cdot Int\left(\frac{\exp\left(-(1 + \alpha 1)\cdot\left(\frac{\mathrm{mu}\cdot\mathrm{rho}\cdot y}{Ta + y}\right)\right)}{\mathrm{rho}}, \mathrm{rho} = zi\,..zf\right); H := (1 - A)\cdot Int\left(\frac{\exp\left(-(1 + \alpha 2)\cdot\left(\frac{\mathrm{mu}\cdot\mathrm{rho}\cdot y}{Ta + y}\right)\right)}{\mathrm{rho}}, \mathrm{rho} = zi\,..zf\right);$$

$$23.652\left(\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.086314345\,\rho\,y}{100+y}}}{\rho}\,d\rho\right)$$

$$-22.652\left(\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.091220090\,\rho\,y}{100+y}}}{\rho}\,d\rho\right)$$

$W := int((G+H), y = 0..T);$

$$\int_0^{15}\left(23.652\left(\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.086314345\,\rho\,y}{100+y}}}{\rho}\,d\rho\right) - 22.652\left(\int_{100+y}^{(100+y)\sqrt{1+\frac{31826.56}{(100+y)^2}}} \frac{e^{-\frac{0.091220090\,\rho\,y}{100+y}}}{\rho}\,d\rho\right)\right) dy$$

$\xrightarrow{\text{assuming real}}$ 8.36030666

$evalf\left(\frac{k \cdot Sv}{2} \cdot W\right);$

$$1.0774 \times 10^{-3}$$

Appendix B: Co-60 Output from RESRAD, RESRAD-BUILD, and MicroShield

RESRAD Output for Co-60 in 1000 m^2 survey unit

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	7.304E+00	0.9956	1.030E-05	0.0000	0.000E+00	0.0000	2.912E-02	0.0040	2.227E-03	0.0003	2.850E-04	0.000	6.871E-04	0.0001
Total	7.304E+00	0.9956	1.030E-05	0.0000	0.000E+00	0.0000	2.912E-02	0.0040	2.227E-03	0.0003	2.850E-04	0.000	6.871E-04	0.0001

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	7.336E+00	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	7.336E+00	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 10 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	3.211E+00	0.9999	6.299E-06	0.0000	0.000E+00	0.0000	2.912E-04	0.0001	2.227E-05	0.0000	2.850E-06	0.000	6.871E-06	0.0000
Total	3.211E+00	0.9999	6.299E-06	0.0000	0.000E+00	0.0000	2.912E-04	0.0001	2.227E-05	0.0000	2.850E-06	0.000	6.871E-06	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	3.212E+00	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	3.212E+00	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 3 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground mrem/yr	Ground fract.	Inhalation mrem/yr	Inhalation fract.	Radon mrem/yr	Radon fract.	Plant mrem/yr	Plant fract.	Meat mrem/yr	Meat fract.	Milk mrem/yr	Milk fract.	Soil mrem/yr	Soil fract.
Co-60	1.515E+00	0.9999	5.526E-06	0.0000	0.000E+00	0.0000	8.737E-05	0.0001	6.681E-06	0.0000	8.550E-07	0.000	2.061E-06	0.0000
Total	1.515E+00	0.9999	5.526E-06	0.0000	0.000E+00	0.0000	8.737E-05	0.0001	6.681E-06	0.0000	8.550E-07	0.000	2.061E-06	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water mrem/yr	Water fract.	Fish mrem/yr	Fish fract.	Radon mrem/yr	Radon fract.	Plant mrem/yr	Plant fract.	Meat mrem/yr	Meat fract.	Milk mrem/yr	Milk fract.	All Pathways* mrem/yr	All Pathways* fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	1.516E+00	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	1.516E+00	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 1 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground mrem/yr	Ground fract.	Inhalation mrem/yr	Inhalation fract.	Radon mrem/yr	Radon fract.	Plant mrem/yr	Plant fract.	Meat mrem/yr	Meat fract.	Milk mrem/yr	Milk fract.	Soil mrem/yr	Soil fract.
Co-60	6.472E-01	0.9999	4.901E-06	0.0000	0.000E+00	0.0000	2.912E-05	0.0000	2.227E-06	0.0000	2.850E-07	0.000	6.871E-07	0.0000
Total	6.472E-01	0.9999	4.901E-06	0.0000	0.000E+00	0.0000	2.912E-05	0.0000	2.227E-06	0.0000	2.850E-07	0.000	6.871E-07	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water mrem/yr	Water fract.	Fish mrem/yr	Fish fract.	Radon mrem/yr	Radon fract.	Plant mrem/yr	Plant fract.	Meat mrem/yr	Meat fract.	Milk mrem/yr	Milk fract.	All Pathways* mrem/yr	All Pathways* fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.473E-01	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.473E-01	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 0.5 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	6.468E-01	1.0000	4.542E-06	0.0000	0.000E+00	0.0000	1.456E-05	0.0000	1.113E-06	0.0000	1.425E-07	0.000	3.435E-07	0.0000
Total	6.468E-01	1.0000	4.542E-06	0.0000	0.000E+00	0.0000	1.456E-05	0.0000	1.113E-06	0.0000	1.425E-07	0.000	3.435E-07	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.469E-01	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.469E-01	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 0.1 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	6.468E-01	1.0000	3.803E-06	0.0000	0.000E+00	0.0000	2.912E-06	0.0000	2.227E-07	0.0000	2.850E-08	0.000	6.871E-08	0.0000
Total	6.468E-01	1.0000	3.803E-06	0.0000	0.000E+00	0.0000	2.912E-06	0.0000	2.227E-07	0.0000	2.850E-08	0.000	6.871E-08	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.468E-01	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.468E-01	1.0000

*Sum of all water independent and dependent pathways.

RESRAD Output for Co-60 in 0.01 m^2 hot spot

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Independent Pathways (Inhalation excludes radon)

Radio-Nuclide	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	6.468E-01	1.0000	2.946E-06	0.0000	0.000E+00	0.0000	2.912E-07	0.0000	2.227E-08	0.0000	2.850E-09	0.000	6.871E-09	0.0000
Total	6.468E-01	1.0000	2.946E-06	0.0000	0.000E+00	0.0000	2.912E-07	0.0000	2.227E-08	0.0000	2.850E-09	0.000	6.871E-09	0.0000

Total Dose Contributions TDOSE(i,p,t) for Individual Radionuclides (i) and Pathways (p)
As mrem/yr and Fraction of Total Dose At t = 0.000E+00 years

Water Dependent Pathways

Radio-Nuclide	Water		Fish		Radon		Plant		Meat		Milk		All Pathways*	
	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.	mrem/yr	fract.
Co-60	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.468E-01	1.0000
Total	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.0000	0.000E+00	0.000	6.468E-01	1.0000

*Sum of all water independent and dependent pathways.

RESRAD-BUILD Output for Co-60 in 100 m^2 survey unit

```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 09:50:44 **
 Title : Co-60 100 m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 100m.bld
 Evaluation Time:  0.00000000E+00  years
```

RESRAD-BUILDDose Tables

Source Information

```
 Source:  1
        Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
        Geometry::  Type: Area        Area:1.00E+02 [m2]  Direction: z
        Pathway ::
             Direct Ingestion Rate:    0.000E+00 [1/hr]
             Fraction released to air: 1.000E-01
             Removable fraction:       5.000E-01
             Time to Remove:           3.650E+02 [day]


         Contamination::     Nuclide    Concentration
                                          [pCi/m2]
                             CO-60       1.000E+00
```

Source Contributions to Receptor Doses

[mrem]

	Source 1	Total
Receptor 1	3.61E-05	3.61E-05
Total	3.61E-05	3.61E-05

Pathway Detail of Doses

[mrem]

Source: 1

Receptor	External	Deposition	Immersion	Inhalation	Radon	Ingestion
1	3.18E-05	2.07E-06	1.71E-08	1.67E-06	0.00E+00	5.43E-07
Total	3.18E-05	2.07E-06	1.71E-08	1.67E-06	0.00E+00	5.43E-07

RESRAD-BUILD Output for Co-60 in 3 m^2 hot spot

```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 09:58:53 **
 Title : Co-60 3m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 3m.bld
 Evaluation Time:  0.00000000E+00  years

                RESRAD-BUILDDose Tables

      ========  Source Information  ========


 Source:  1
         Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
         Geometry::  Type: Area        Area:3.00E+00 [m2]  Direction: z
         Pathway ::
              Direct Ingestion Rate:    0.000E+00 [1/hr]
              Fraction released to air: 1.000E-01
              Removable fraction:       5.000E-01
              Time to Remove:           3.650E+02 [day]


          Contamination::     Nuclide    Concentration
                                           [pCi/m2]
                              CO-60       1.000E+00

                    Source Contributions to Receptor Doses

                                    [mrem]

                 Source   Total
                    1
 Receptor  1    6.26E-06 6.26E-06
 Total          6.26E-06 6.26E-06
                           Pathway Detail of Doses

                                  [mrem]

Source:  1
    Receptor    External  Deposition Immersion  Inhalation   Radon    Ingestion
       1       6.13E-06   6.22E-08   5.13E-10   5.02E-08   0.00E+00   1.63E-08
   Total       6.13E-06   6.22E-08   5.13E-10   5.02E-08   0.00E+00   1.63E-08
```

RESRAD-BUILD Output for Co-60 in 1 m^2 hot spot

```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 10:02:10 **
 Title : Co-60 1m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 1m.bld
 Evaluation Time:  0.00000000E+00  years

                RESRAD-BUILDDose Tables

 ========  Source Information  ========

 Source:  1
         Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
         Geometry::  Type: Area        Area:1.00E+00 [m2]  Direction: z
         Pathway ::
              Direct Ingestion Rate:    0.000E+00 [1/hr]
              Fraction released to air: 1.000E-01
              Removable fraction:       5.000E-01
              Time to Remove:           3.650E+02 [day]


          Contamination::     Nuclide    Concentration
                                           [pCi/m2]
                              CO-60       1.000E+00

                    Source Contributions to Receptor Doses
                    ======================================
                                    [mrem]

                  Source   Total
                     1
 Receptor  1     2.57E-06 2.57E-06
 Total           2.57E-06 2.57E-06
                           Pathway Detail of Doses
                           =======================
                                   [mrem]

Source:  1
    Receptor    External  Deposition Immersion  Inhalation   Radon    Ingestion
       1       2.53E-06   2.07E-08   1.71E-10   1.67E-08   0.00E+00   5.43E-09
   Total       2.53E-06   2.07E-08   1.71E-10   1.67E-08   0.00E+00   5.43E-09
```

RESRAD-BUILD Output for Co-60 in 0.5 m^2 hot spot

```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 10:09:58 **
 Title : Co-60 0_5m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 0_5m rev.bld
 Evaluation Time:  0.00000000E+00  years
```

RESRAD-BUILDDose Tables

Source Information

```
 Source:  1
        Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
        Geometry::  Type: Area        Area:5.00E-01 [m2]  Direction: z
        Pathway ::
             Direct Ingestion Rate:    0.000E+00 [1/hr]
             Fraction released to air: 1.000E-01
             Removable fraction:       5.000E-01
             Time to Remove:           3.650E+02 [day]
```

Contamination::	Nuclide	Concentration [pCi/m2]
	CO-60	1.000E+00

Source Contributions to Receptor Doses

[mrem]

	Source 1	Total
Receptor 1	1.37E-06	1.37E-06
Total	1.37E-06	1.37E-06

Pathway Detail of Doses

[mrem]

Source: 1

Receptor	External	Deposition	Immersion	Inhalation	Radon	Ingestion
1	1.35E-06	1.04E-08	8.55E-11	8.36E-09	0.00E+00	2.72E-09
Total	1.35E-06	1.04E-08	8.55E-11	8.36E-09	0.00E+00	2.72E-09

RESRAD-BUILD Output for Co-60 in 0.1 m^2 hot spot

```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 10:12:30 **
 Title : Co-60 0_1m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 0_1m.bld
 Evaluation Time:  0.00000000E+00  years
```

RESRAD-BUILDDose Tables

Source Information

```
 Source:  1
        Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
        Geometry::  Type: Area        Area:1.00E-01 [m2]  Direction: z
        Pathway ::
             Direct Ingestion Rate:    0.000E+00 [1/hr]
             Fraction released to air: 1.000E-01
             Removable fraction:       5.000E-01
             Time to Remove:           3.650E+02 [day]

         Contamination::     Nuclide    Concentration
                                          [pCi/m2]
                             CO-60       1.000E+00
```

Source Contributions to Receptor Doses

[mrem]

	Source 1	Total
Receptor 1	2.91E-07	2.91E-07
Total	2.91E-07	2.91E-07

Pathway Detail of Doses

[mrem]

Source: 1

Receptor	External	Deposition	Immersion	Inhalation	Radon	Ingestion
1	2.86E-07	2.07E-09	1.71E-11	1.67E-09	0.00E+00	5.43E-10
Total	2.86E-07	2.07E-09	1.71E-11	1.67E-09	0.00E+00	5.43E-10

RESRAD-BUILD Output for Co-60 in 0.01 m^2 hot spot

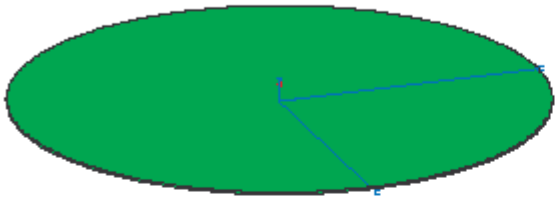
```
** RESRAD-BUILD Dose Program Output, Version 3.22 06/06/08 10:14:55 **
 Title : Co-60 0_01m2 survey unit
 Input File : C:\Program Files\RESRAD_Family\BUILD\Co-60 0_01m.bld
 Evaluation Time:  0.00000000E+00  years

                RESRAD-BUILDDose Tables

                Source Information

 Source:  1
         Location::  Room :  1  x:   5.00 y:   5.00  z:   0.00 [m]
         Geometry::  Type: Area        Area:1.00E-02 [m2]  Direction: z
         Pathway ::
              Direct Ingestion Rate:    0.000E+00 [1/hr]
              Fraction released to air: 1.000E-01
              Removable fraction:       5.000E-01
              Time to Remove:           3.650E+02 [day]

          Contamination::     Nuclide    Concentration
                                           [pCi/m2]
                              CO-60       1.000E+00

                    Source Contributions to Receptor Doses
                                    [mrem]

                  Source   Total
                     1
 Receptor  1     2.95E-08 2.95E-08
 Total           2.95E-08 2.95E-08

                          Pathway Detail of Doses
                                  [mrem]

Source:  1
    Receptor    External  Deposition Immersion  Inhalation   Radon    Ingestion
       1       2.91E-08   2.07E-10   1.71E-12   1.67E-10   0.00E+00   5.43E-11
   Total       2.91E-08   2.07E-10   1.71E-12   1.67E-10   0.00E+00   5.43E-11
```

MicroShield v5.05 (5.05-00302)
OAK RIDGE ASSOCIATED UNIVRSITIES

Page : 1
DOS File : CO_WIDE.MS5
Run Date: June 6, 2008
Run Time: 10:30:11 AM
Duration : 00:00:00

File Ref: _____
Date: _____
By: _____
Checked: _____

Case Title: Co-60 uniform in SU
Description: Co-60 uniform in 1000 m2 SU; Soil FGR-12
Geometry: 8 - Cylinder Volume - End Shields



Source Dimensions

Height	15.0 cm	5.9 in
Radius	1.8e+3 cm	58 ft 6.4 in

Dose Points

	X	Y	Z
# 1	0 cm	115 cm	0 cm
	0.0 in	3 ft 9.3 in	0.0 in

Shields

Shield Name	Dimension	Material	Density
Source	1.50e+08 cm³	Soil FGR-12	1.6
Air Gap		Air	0.00122

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Co-60	2.3997e-004	8.8788e+006	1.6000e-006	5.9200e-002

Buildup
The material reference is : Source

Integration Parameters

Radial	20
Circumferential	10
Y Direction (axial)	10

Results

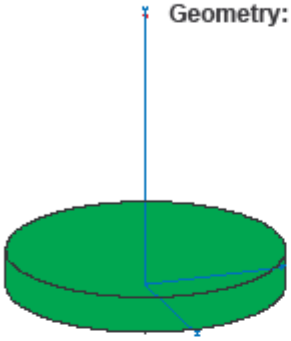
Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.6938	1.448e+03	2.423e-05	5.176e-05	4.678e-08	9.993e-08
1.1732	8.879e+06	3.122e-01	5.691e-01	5.580e-04	1.017e-03
1.3325	8.879e+06	3.740e-01	6.585e-01	6.489e-04	1.142e-03
TOTALS:	1.776e+07	6.863e-01	1.228e+00	1.207e-03	2.160e-03

MicroShield v5.05 (5.05-00302)
OAK RIDGE ASSOCIATED UNIVRSITIES

Page : 1
DOS File : CO_1M_HS.MS5
Run Date: June 6, 2008
Run Time: 10:53:27 AM
Duration : 00:00:00

File Ref: _____
Date: _____
By: _____
Checked: _____

Case Title: Co-60 1 m2 hot spot
Description: Co-60 hot spot 1 m2 ; Soil FGR-12
Geometry: 8 - Cylinder Volume - End Shields



Source Dimensions

Height	15.0 cm	5.9 in
Radius	56.4 cm	1 ft 10.2 in

Dose Points

	X	Y	Z
# 1	0 cm	115 cm	0 cm
	0.0 in	3 ft 9.3 in	0.0 in

Shields

Shield Name	Dimension	Material	Density
Source	1.50e+05 cm³	Soil FGR-12	1.6
Air Gap		Air	0.00122

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Co-60	2.3984e-007	8.8740e+003	1.6000e-006	5.9200e-002

Buildup
The material reference is : Source

Integration Parameters

Radial	20
Circumferential	10
Y Direction (axial)	10

Results

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.6938	1.448e+00	2.797e-06	4.848e-06	5.400e-09	9.359e-09
1.1732	8.874e+03	3.367e-02	5.021e-02	6.017e-05	8.972e-05
1.3325	8.874e+03	3.958e-02	5.721e-02	6.867e-05	9.925e-05
TOTALS:	1.775e+04	7.325e-02	1.074e-01	1.288e-04	1.890e-04

MicroShield v5.05 (5.05-00302)
OAK RIDGE ASSOCIATED UNIVRSITIES

Page : 1
DOS File : CO_01_HS.MS5
Run Date: June 6, 2008
Run Time: 10:59:39 AM
Duration : 00:00:00

File Ref: _____
Date: _____
By: _____
Checked: _____

Case Title: Co-60 0.1 m2 hot s
Description: Co-60 hot spot 0.1 m2 ; Soil FGR-12
Geometry: 8 - Cylinder Volume - End Shields

Source Dimensions

Height	15.0 cm	5.9 in
Radius	17.84 cm	7.0 in

Dose Points

	X	Y	Z
# 1	0 cm	115 cm	0 cm
	0.0 in	3 ft 9.3 in	0.0 in

Shields

Shield Name	Dimension	Material	Density
Source	1.50e+04 cm³	Soil FGR-12	1.6
Air Gap		Air	0.00122

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Co-60	2.3997e-008	8.8788e+002	1.6000e-006	5.9200e-002

Buildup
The material reference is : Source

Integration Parameters

Radial	20
Circumferential	10
Y Direction (axial)	10

Results

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.6938	1.448e-01	3.252e-07	5.529e-07	6.278e-10	1.068e-09
1.1732	8.879e+02	3.892e-03	5.716e-03	6.955e-06	1.021e-05
1.3325	8.879e+02	4.569e-03	6.510e-03	7.927e-06	1.130e-05
TOTALS:	1.776e+03	8.461e-03	1.223e-02	1.488e-05	2.151e-05

Appendix C: Direct Exposure to External Radiation

Table 27 External radiation doses and area factors for Co-60 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	2.1	4.4	9.8	NA	NA	NA
RESRAD Dose (mrem/y)	7.3	3.2	1.5	0.65	0.65	0.65	0.65
RESRAD AF	1	2.27	4.82	11.3	11.3	11.3	11.3
MicroShield Dose (mrem/y)	4.7	2.1	1.0	0.41	0.22	4.7E-2	4.7E-3
MicroShield AF	1	2.30	4.73	11.4	21.3	100	990
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	4.7	6.0E-2	1.9E-2	7.3E-3	4.1E-3	1.2E-3	1.6E-4
MicroShield AF	1	79.3	250	650	1150	4050	30,000

Table 28 External radiation doses and area factors for I-129 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	NA	NA	NA	NA	NA	NA	NA
RESRAD Dose (mrem/y)	1.1E-3	6.0E-4	3.0E-4	1.5E-4	1.5E-4	1.5E-4	1.5E-4
RESRAD AF	1	1.77	3.50	7.03	7.03	7.03	7.03
MicroShield Dose (mrem/y)	8.1E-3	4.6E-3	2.6E-3	1.2E-3	6.4E-4	1.4E-4	1.4E-5
MicroShield AF	1	1.76	3.14	6.93	12.6	57.6	575
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	7.8E-3	6.4E-5	2.3E-5	9.9E-6	6.1E-6	2.2E-6	5.8E-7
MicroShield AF	1	122	340	785	1280	3620	13,600

Table 29 External radiation doses and area factors for Cs-137 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	2.4	5.0	11.0	NA	NA	NA
RESRAD Dose (mrem/y)	1.7	0.78	0.37	0.16	0.16	0.16	0.16
RESRAD AF	1	2.21	4.67	10.8	10.8	10.8	10.8
MicroShield Dose (mrem/y)	1.1	0.50	0.25	0.10	5.5E-2	1.2E-2	1.2E-3
MicroShield AF	1	2.18	4.42	10.6	19.8	93.1	918
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	1.1	1.3E-2	4.2E-3	1.6E-3	9.4E-4	2.8E-4	4.0E-5
MicroShield AF	1	83.3	260	672	1170	3930	27,400

Table 30 External radiation doses and area factors for Ra-226 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	7.8	21.3	54.8	NA	NA	NA
RESRAD Dose (mrem/y)	5.3	2.3	1.1	0.47	0.47	0.47	0.47
RESRAD AF	1	2.28	4.82	11.2	11.3	11.3	11.3
MicroShield Dose (mrem/y)	3.3	1.4	0.71	0.29	0.16	3.3E-2	3.4E-3
MicroShield AF	1	2.26	4.63	11.1	20.8	97.8	964
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	3.3	4.1E-2	1.3E-2	5.0E-3	2.8E-3	8.2E-4	1.1E-4
MicroShield AF	1	80.2	252	658	1150	4020	28,900

Table 31 External radiation doses and area factors for Th-232 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	3.2	6.2	12.5	NA	NA	NA
RESRAD Dose (mrem/y)	7.6	3.3	1.6	0.67	0.67	0.67	0.67
RESRAD AF	1	2.29	4.85	11.3	11.3	11.3	11.3
MicroShield Dose (mrem/y)	4.7	2.0	0.99	0.41	0.22	4.7E-2	4.7E-3
MicroShield AF	1	2.31	4.74	11.4	21.3	100	990
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	4.7	6.0E-2	1.9E-2	7.2E-3	4.1E-3	1.2E-3	1.6E-4
MicroShield AF	1	78.6	249	652	1150	4070	29,700

Table 32 External radiation doses and area factors for U-238 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	11.1	18.3	30.6	NA	NA	NA
RESRAD Dose (mrem/y)	4.6E-2	2.2E-2	1.0E-2	4.5E-3	4.5E-3	4.5E-3	4.5E-3
RESRAD AF	1	2.13	4.46	10.2	10.2	10.2	10.2
MicroShield Dose (mrem/y)	2.0E-2	9.5E-3	4.8E-3	2.0E-3	1.1E-3	2.3E-4	2.4E-5
MicroShield AF	1	2.09	4.14	9.78	18.2	85.1	837
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	2.0E-2	2.4E-4	7.6E-5	3.0E-5	1.7E-5	5.2E-6	8.5E-7
MicroShield AF	1	85.5	265	679	1180	3870	23,700

Table 33 External radiation doses and area factors for Pu-239 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	NA	NA	NA	NA	NA	NA	NA
RESRAD Dose (mrem/y)	1.6E-4	8.2E-5	4.0E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5
RESRAD AF	1	1.98	4.11	9.08	9.09	9.09	9.09
MicroShield Dose (mrem/y)	6.3E-5	3.3E-5	1.7E-5	7.5E-6	4.0E-6	8.7E-7	8.8E-8
MicroShield AF	1	1.92	3.63	8.41	15.5	72.4	713
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	6.4E-5	6.9E-7	2.3E-7	9.1E-8	5.3E-8	1.7E-8	3.3E-9
MicroShield AF	1	92.2	280	703	1210	3720	19,200

Table 34 External radiation doses and area factors for Am-241 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
MARSSIM AF	1	96.3	139.7	208.7	NA	NA	NA
RESRAD Dose (mrem/y)	2.1E-2	1.3E-2	6.4E-3	3.1E-3	3.1E-3	3.1E-3	3.1E-3
RESRAD AF	1	1.61	3.22	6.60	6.60	6.60	6.60
MicroShield Dose (mrem/y)	1.3E-2	6.9E-3	3.8E-3	1.7E-3	9.2E-4	2.0E-4	2.0E-5
MicroShield AF	1	1.83	3.35	7.50	13.7	63.1	619
Receptor 6 m From Hot Spot							
MicroShield Dose (mrem/y)	1.3E-2	1.4E-4	4.6E-5	1.9E-5	1.1E-5	3.6E-6	9.0E-7
MicroShield AF	1	93.5	283	694	1170	3580	14,400

Appendix D: Inhalation Exposure to Resuspended Soil

Table 35 Inhalation pathway doses and area factors for C-14 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	3.2E-6	3.2E-7	1.8E-7	1.0E-7	7.3E-8	3.3E-8	1.1E-8
Area Factor	1	9.95	18.1	31.2	43.8	96.3	289
Hand Calculation (mrem/y)	1.1E-7	6.4E-10	1.7E-10	5.0E-11	2.3E-11	3.9E-12	3.0E-13
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 36 Inhalation pathway doses and area factors for Co-60 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.0E-5	6.3E-6	5.5E-6	4.9E-6	4.5E-6	3.8E-6	3.0E-6
Area Factor	1	1.64	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	1.1E-5	6.8E-8	1.8E-8	5.3E-9	2.4E-9	4.1E-10	3.2E-11
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 37 Inhalation pathway doses and area factors for Sr-90 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	6.3E-5	3.8E-5	3.4E-5	3.0E-5	2.8E-5	2.3E-5	1.8E-5
Area Factor	1	1.64	1.86	2.10	2.27	2.71	3.49
Hand Calculation (mrem/y)	6.6E-5	4.0E-7	1.1E-7	3.1E-8	1.5E-8	2.4E-9	1.9E-10
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 38 Inhalation pathway doses and area factors for Tc-99 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	4.0E-8	2.5E-8	2.2E-8	1.9E-8	1.8E-8	1.5E-8	1.2E-8
Area Factor	1	1.63	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	4.2E-7	2.6E-9	6.8E-10	2.0E-10	9.3E-11	1.6E-11	1.2E-12
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 39 Inhalation pathway doses and area factors for I-129 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.3E-6	7.7E-7	6.8E-7	6.0E-7	5.6E-7	4.7E-7	3.6E-7
Area Factor	1	1.63	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	8.8E-6	5.4E-8	1.4E-8	4.2E-9	1.9E-9	3.2E-10	2.5E-11
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 40 Inhalation pathway doses and area factors for Cs-137 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.6E-6	9.7E-7	8.5E-7	7.5E-7	7.0E-7	5.9E-7	4.5E-7
Area Factor	1	1.64	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	1.6E-6	9.8E-9	2.6E-9	7.7E-10	3.6E-10	5.9E-11	4.6E-12
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 41 Inhalation pathway doses and area factors for Ra-226 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.6E-3	9.7E-4	8.5E-4	7.5E-4	7.0E-4	5.8E-4	4.5E-4
Area Factor	1	1.63	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	1.6E-3	9.8E-6	2.6E-6	7.6E-7	3.5E-7	5.9E-8	4.6E-9
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 42 Inhalation pathway doses and area factors for Th-232 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.0E-1	6.1E-2	5.4E-2	4.8E-2	4.4E-2	3.7E-2	2.9E-2
Area Factor	1	1.63	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	1.0E-1	6.1E-4	1.6E-4	4.8E-5	2.2E-5	3.7E-6	2.9E-7
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 43 Inhalation pathway doses and area factors for U-238 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	6.2E-3	3.8E-3	3.3E-3	2.9E-3	2.7E-3	2.3E-3	1.8E-3
Area Factor	1	1.63	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	6.3E-3	3.9E-5	1.0E-5	3.0E-6	1.4E-6	2.3E-7	1.8E-8
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 44 Inhalation pathway doses and area factors for Pu-239 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	2.2E-2	1.3E-2	1.2E-2	1.0E-2	9.5E-3	8.0E-3	6.2E-3
Area Factor	1	1.64	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	2.2E-2	1.3E-4	3.5E-5	1.0E-5	4.8E-6	8.0E-7	6.2E-8
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Table 45 Inhalation pathway doses and area factors for Am-241 hot spots in soil.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	2.1E-2	1.3E-2	1.1E-2	1.0E-2	9.3E-3	7.8E-3	6.1E-3
Area Factor	1	1.64	1.86	2.10	2.27	2.71	3.50
Hand Calculation (mrem/y)	2.2E-2	1.4E-4	3.6E-5	1.1E-5	4.9E-6	8.3E-7	6.4E-8
Area Factor	1	163	621	2100	4540	2.71E4	3.50E5

Appendix E: Direct Ingestion of Soil

Table 46 Soil ingestion pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.9E-6	1.9E-8	5.6E-9	1.9E-9	9.4E-10	1.9E-10	1.9E-11
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	5.7E-5	5.7E-7	1.7E-7	5.7E-8	2.9E-8	5.7E-9	5.7E-10
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 47 Soil ingestion pathway doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	6.9E-4	6.9E-6	2.1E-6	6.9E-7	3.4E-7	6.9E-8	6.9E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	7.4E-4	7.4E-6	2.2E-6	7.4E-7	3.7E-7	7.4E-8	7.4E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 48 Soil ingestion pathway doses and area factors for Sr-90 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	4.0E-3	4.0E-5	1.2E-5	4.0E-6	2.0E-6	4.0E-7	4.0E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	4.2E-3	4.2E-5	1.3E-5	4.2E-6	2.1E-6	4.2E-7	4.2E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 49 Soil ingestion pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	3.9E-6	3.9E-8	1.2E-8	3.9E-9	1.9E-9	3.9E-10	3.9E-11
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	4.0E-5	4.0E-7	1.2E-7	4.0E-8	2.0E-8	4.0E-9	4.0E-10
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 50 Soil ingestion pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.1E-3	1.1E-5	3.3E-6	1.1E-6	5.4E-7	1.1E-7	1.1E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	7.6E-3	7.6E-5	2.3E-5	7.6E-6	3.8E-6	7.6E-7	7.6E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 51 Soil ingestion pathway doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.4E-3	1.4E-5	4.1E-6	1.4E-6	6.7E-7	1.4E-7	1.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	1.4E-3	1.4E-5	4.1E-6	1.4E-6	6.8E-7	1.4E-7	1.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 52 Soil ingestion pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	2.3E-1	2.3E-3	7.0E-4	2.3E-4	1.2E-4	2.3E-5	2.3E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	2.4E-1	2.4E-3	7.1E-4	2.4E-4	1.2E-4	2.4E-5	2.4E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 53 Soil ingestion pathway doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	1.4E-1	1.4E-3	4.1E-4	1.4E-4	6.8E-5	1.4E-5	1.4E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	1.4E-1	1.4E-3	4.1E-4	1.4E-4	6.8E-5	1.4E-5	1.4E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 54 Soil ingestion pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	7.4E-3	7.4E-5	2.2E-5	7.4E-6	3.7E-6	7.4E-7	7.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	7.6E-3	7.6E-5	2.3E-5	7.6E-6	3.8E-6	7.6E-7	7.6E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 55 Soil ingestion pathway doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	9.7E-2	9.7E-4	2.9E-4	9.7E-5	4.8E-5	9.7E-6	9.7E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	9.7E-2	9.7E-4	2.9E-4	9.7E-5	4.9E-5	9.7E-6	9.7E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 56 Soil ingestion pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Inh Dose (mrem/y)	9.4E-2	9.4E-4	2.8E-4	9.4E-5	4.7E-5	9.4E-6	9.4E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	1.0E-1	1.0E-3	3.0E-4	1.0E-4	5.0E-5	1.0E-5	1.0E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Appendix F: Ingestion of Drinking Water

Impact of contaminated area size on drinking water pathway

The first equation considered is the radionuclide release rate due to radionuclides leaching from the contaminated zone

$$\dot{R}_i(t) = L_i \times \rho_b^{(cz)} \times A \times T(t) \times S_i(t) \qquad (F-1)$$

where
L_i is the leach rate for radionuclide i in y^{-1};
ρ_b is the bulk density of the contaminated zone in kg/m^3;
A is the area of the contaminated zone in m^2;
T(t) is the thickness of the contaminated zone (m) at time t; and
S_i is the average concentration of radionuclide i in the contaminated zone at time t (pCi/g).

It is important to recognize from equation F-1 that the radionuclide release rate is directly related to the size of the contaminated area, A.

The leach rate constant is defined as the fraction of available radionuclide i that is leached out per unit time. It is calculated

$$L_i = \frac{I}{\theta^{(cz)} \times T_0 \times R_{d_i}^{(cz)}} \qquad (F-2)$$

where:
I is the infiltration rate (m/y) based on the evapotranspiration coefficient, runoff coefficient, precipitation rate, and irrigation rate;
θ is the volumetric water content of the contaminated zone;
T_0 is the initial thickness of the contaminated zone; and
R_{di} is the retardation factor in the contaminated zone which depends on the distribution coefficient (k_d), volumetric water content and bulk soil density.

The water/soil concentration ratio, WSR_{ij} (t) is determined as follows:

$$WSR_{ij}(t) = \frac{W_{ij}(t)}{S_i(0)} \qquad (F-3)$$

where W_{ij} (t) is the average radionuclide concentration in water at time t of the jth principal radionuclide (pCi/L) attributed to the soil concentration at time t = 0, $S_i(0)$. Note that RESRAD model calculates W_{ij} (t) as the sum of all contributions from the decay products of the original contamination $S_i(0)$.

RESRAD defines a transfer function, $G_{kj}(t)$, that uses a convolution integral to account for the release of radionuclides from the contamination zone to the unsaturated zone, and ultimately through the saturated zone to the point of water use. The radionuclide release at point of use is given by:

$$r_{kj}(t) = \dot{R}_{ik}(t) * G_{jk}(t) = \int_0^t \dot{R}_{ik}(t') \times G_{kj}(t - t')\, dt' \qquad (F-4)$$

The water/soil concentration, WSR_{ij} (t), can be expressed as follows:

$$WSR_{ij}(t) = \frac{\sum_k \frac{\lambda_j \times r_{kj}(t) \times f}{I \times A \times cons\tan t}}{S_i(0)} \qquad (F-5)$$

where λ_j is the radionuclide decay constant, f is the dilution factor, the constant accounts for unit conversions, and other variables are as previously defined. Considering the above equation, the dilution factor, described below, is dependent of the contaminated area, as is r_{kj}, and of course, the area A. The point here is that the WSR term is a rather complex function of contaminated area, A.

Finally, consider the water transport parameters as they apply to the groundwater pathway and the surface water pathway. These parameters include the breakthrough time, rise time and dilution factor. The breakthrough time is the time following the release of the site at which radionuclides first appear in the water at the point of use. The rise time is the time following breakthrough for the radionuclide concentration to achieve a maximum. The dilution factor represents the ratio between the concentration in the water at the point of use (e.g., irrigation or drinking water) to the concentration in the infiltrating water as it leaves the unsaturated zone.

The breakthrough time for the groundwater pathway is simply the radionuclide transport time through the unsaturated zone. RESRAD assumes that once the

radionuclide reaches the water table (saturated zone), it immediately enters the well—that is, transport time through the aquifer is zero. The RESRAD Manual aptly notes that both the hydraulic conductivity and distribution coefficient are critical hydrogeological parameters that impact the breakthrough time, and as such, recommends that site-specific values should be used for these parameters (ANL 2001).

The rise time calculation depends on the groundwater model used—mass balance or non-dispersion. The rise time for the ND model is equal to the time for the radionuclide to be transported from the upgradient edge of the contaminated zone to the downgradient edge of the saturated zone. For the mass balance model, the rise time is zero because the well is assumed to be located in the center of the contaminated zone.

RESRAD assumes that water flow is vertically downward from the contaminated zone through the unsaturated zone, to the saturated zone. The dilution factor is potentially impacted by the size of the contaminated area. For MB model the dilution factor is given by:

$$f_1 = \frac{A \times I}{U_w}, \quad if \ A \times I < U_w; otherwise f_1 = 1; \qquad (F-6)$$

where A is the area of the contaminated zone, I is the infiltration rate (m/y), and U_w is the well pumping rate or annual volume of water withdrawn from the well (default is 250 m^3/y).

The dilution factor for the ND model can be much smaller than that calculated for the MB model, depending primarily on the distance of the well from the contaminated zone. RESRAD provides the following equations for determining the ND model dilution factor:

$$f_1 = \frac{z}{d_w}, \quad when \ d_r \le \frac{A}{l} \ and \ z \le d_w; \qquad (F-7)$$

and

$$f_1 = \frac{AI}{U_w}, \quad when \ d_r > \frac{A}{l} \ and \ z \le d_w \qquad (F-8)$$

where z is the effective aquifer contamination depth (m), d_w is the distance of well intake below the water table (m), and *l* is the length of the contamination zone parallel to the aquifer.

The surface water pathway in RESRAD consists of an on-site groundwater pathway that extends to the edge of the contaminated zone, an off-site groundwater pathway that extends from the edge of the contaminated zone to a location where surface seepage occurs, and a surface water segment where the contaminated groundwater mixes with the surface water. The breakthrough time and rise time are the same as that for the groundwater pathway. However, the dilution factor for the surface water pathway is the ratio of the annual volume of water that percolates through the contaminated zone to the annual total inflow of water. The basis for this determination of dilution factor is that the surface water is a pond characterized by a steady-state inflow and outflow, and that the annual inflow of radioactivity into the pond is equal to the annual amount of radioactivity leaching from the contaminated zone. The dilution factor is calculated:

$$f_2 = \frac{A}{A_w} \qquad (F-9)$$

where A is the size of the contaminated area (default is 10,000 m^2) and A_w is the area of the watershed (default is 1E6 m^2). As an aside, this relationship between survey unit area and hot spot area is precisely the relationship proposed to handle the inhalation pathway dilution factor addressed earlier.

The preceding discussion is a relatively simple level description of the groundwater model; many important details were largely omitted. Again, the point is to understand the RESRAD groundwater model in sufficient detail to assess how the contaminated area size comes into play.

Once the groundwater becomes contaminated, the next step is to consider how the receptor receives a dose via the drinking water pathway. Recall that the environmental transport factor is given by:

$$ETF_{ij,7}(t) = DF_7 \times FDW \times [WSR_{ij,1}(t) \times FD1 + WSR_{ij,2}(t) \times (1 - FD1)]$$

Recognizing that FDW (fraction of drinking water from the site) and FD1 (fraction of well water used for drinking) are both 1.0 by default, the ETF is simply:

$$ETF_{ij,7}(t) = DF_7 \times WSR_{ij,1}(t) \qquad (F-10)$$

Therefore the annual intake of drinking water (510 L/y) is multiplied by the by the WSR parameter.

Table 57 Drinking water pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	4.1E-2	3.4E-3	1.1E-3	3.6E-4	1.8E-4	3.8E-5	3.8E-6
Area Factor	1	12.0	37.5	115	229	1090	1.1E4
Time for Max Dose (years)	2.4	1.0	1.1	0.9	0.9	0.8	0.9

Table 58 Drinking water pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	9.0E-2	7.3E-3	2.2E-3	7.6E-4	3.8E-4	7.6E-5	7.6E-6
Area Factor	1	12.4	40.4	119	238	1190	1.2E4
Time for Max Dose (years)	3.3	1.2	1.0	0.9	0.9	0.9	0.9

Table 59 Drinking water pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	12	1.4	4.0E-1	1.4E-1	6.9E-2	1.4E-2	1.4E-3
Area Factor	1	9.03	30.3	90.0	176	881	8810
Time for Max Dose (years)	5.3	1.9	1.7	1.8	1.5	1.5	1.5

Table 60 Drinking water pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	8.4E-1	2.1E-1	9.5E-2	3.8E-2	2.1E-2	4.3E-3	4.4E-4
Area Factor	1	4.01	8.81	21.9	40.9	196	1930
Time for Max Dose (years)	605	573	529	508	498	494	491

Table 61 Drinking water pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	7.6E-2	1.7E-2	8.1E-3	3.6E-3	2.1E-3	4.8E-4	5.2E-5
Area Factor	1	4.35	9.30	21.1	36.8	158	1450
Time for Max Dose (years)	916	396	365	349	340	334	330

Table 62 Drinking water pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	2.0	4.8E-1	2.2E-1	9.6E-2	5.4E-2	1.2E-2	1.4E-3
Area Factor	1	4.06	8.77	20.3	35.8	158	1430
Time for Max Dose (years)	164	151	139	133	130	128	126

Appendix G: Ingestion of Plant Products Grown in Contaminated Soil

Table 63 Ingestion of plant products grown in contaminated soil pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	5.9E-3	8.2E-6	1.7E-6	4.4E-7	1.9E-7	3.1E-8	2.8E-9
Area Factor	1	716	3460	1.4E4	3.1E4	1.9E5	2.1E6
Hand Calculation (mrem/y)	1.7E-1	2.2E-2	6.4E-3	2.2E-3	1.1E-3	2.2E-4	2.2E-5
Area Factor	1	1.45	4.85	14.5	29.1	145	1450

Table 64 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	2.9E-2	2.9E-4	8.7E-5	2.9E-5	1.5E-5	2.9E-6	2.9E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	3.1E-2	3.1E-4	9.4E-5	3.1E-5	1.6E-5	3.1E-6	3.1E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 65 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Sr-90 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	6.3E-1	6.3E-3	1.9E-3	6.3E-4	3.2E-4	6.3E-5	6.3E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	6.7E-1	6.7E-3	2.0E-3	6.7E-4	3.3E-4	6.7E-5	6.7E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 66 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.1E-2	1.1E-4	3.4E-5	1.1E-5	5.6E-6	1.1E-6	1.1E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	1.1E-1	1.1E-3	3.2E-4	1.1E-4	5.3E-5	1.1E-5	1.1E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 67 Ingestion of plant products grown in contaminated soil pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.3E-2	1.3E-4	3.8E-5	1.3E-5	6.4E-6	1.3E-6	1.3E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	8.0E-2	8.0E-4	2.4E-4	8.0E-5	4.0E-5	8.0E-6	8.0E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 68 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	2.9E-2	2.9E-4	8.6E-5	2.9E-5	1.4E-5	2.9E-6	2.9E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	2.9E-2	2.9E-4	8.7E-5	2.9E-5	1.5E-5	2.9E-6	2.9E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 69 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.8	1.8E-2	5.4E-3	1.8E-3	9.0E-4	1.8E-4	1.8E-5
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	6.2	6.2E-2	1.9E-2	6.2E-3	3.1E-3	6.2E-4	6.2E-5
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 70 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	8.8E-1	8.8E-3	2.6E-3	8.8E-4	4.4E-4	8.8E-5	8.8E-6
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	3.0	3.0E-2	9.1E-3	3.0E-3	1.5E-3	3.0E-4	3.0E-5
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 71 Ingestion of plant products grown in contaminated soil pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	9.8E-3	9.8E-5	2.9E-5	9.8E-6	4.9E-6	9.8E-7	9.8E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	1.0E-2	1.0E-4	3.0E-5	1.0E-5	5.0E-6	1.0E-6	1.0E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 72 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	5.1E-2	5.1E-4	1.5E-4	5.1E-5	2.6E-5	5.1E-6	5.1E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	5.2E-2	5.2E-4	1.5E-4	5.2E-5	2.6E-5	5.1E-6	5.1E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 73 Ingestion of plant products grown in contaminated soil pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	5.0E-2	5.0E-4	1.5E-4	5.0E-5	2.5E-5	5.0E-6	5.0E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Hand Calculation (mrem/y)	5.3E-2	5.3E-4	1.6E-4	5.3E-5	2.7E-5	5.3E-6	5.3E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Appendix H: Ingestion of Plant Products Irrigated with Contaminated Groundwater

Table 74 Plant irrigation pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	2.8E-3	3.1E-7	1.9E-8	1.8E-9	3.9E-10	1.3E-11	1.1E-13
Area Factor	1	9100	1.5E5	1.6E6	7.3E6	2.2E8	2.5E10
Time for Max Dose (years)	2.4	1.0	1.1	0.9	0.9	0.8	0.9

Table 75 Plant irrigation pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.1E-2	8.7E-6	7.8E-7	9.0E-8	2.3E-8	9.0E-10	9.0E-12
Area Factor	1	1270	1.4E4	1.2E5	4.9E5	1.2E7	1.2E9
Time for Max Dose (years)	3.3	1.2	1.0	0.9	0.9	0.9	0.9

Table 76 Plant irrigation pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	9.4E-1	1.0E-3	9.3E-5	1.1E-5	2.6E-6	1.1E-7	1.1E-9
Area Factor	1	912	1.0E4	8.9E4	3.6E5	9.0E6	9.0E8
Time for Max Dose (years)	5.3	1.9	1.7	1.8	1.5	1.5	1.5

Table 77 Plant irrigation pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	6.5E-2	1.6E-4	2.2E-5	3.0E-6	7.9E-7	3.3E-8	3.4E-10
Area Factor	1	401	2940	2.2E4	8.2E4	2.0E6	1.9E8
Time for Max Dose (years)	605	573	529	508	498	494	491

Table 78 Plant irrigation pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	5.8E-3	1.3E-5	1.9E-6	2.8E-7	7.9E-8	3.7E-9	4.0E-11
Area Factor	1	435	3100	2.1E4	7.4E4	1.6E6	1.5E8
Time for Max Dose (years)	916	396	365	349	340	334	330

Table 79 Plant irrigation pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.5E-1	3.7E-4	5.1E-5	7.4E-6	2.1E-6	9.5E-8	1.0E-9
Area Factor	1	406	2920	2.0E4	7.2E4	1.6E6	1.4E8
Time for Max Dose (years)	164	151	139	133	130	128	126

Appendix I: Ingestion of Animal Products Grown Onsite

Table 80 Animal product (water-dependent) pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.8E-4	1.1E-7	9.1E-9	1.2E-9	2.8E-10	1.1E-11	1.1E-13
Area Factor	1	163	1.9E4	1.5E4	6.3E5	1.6E7	1.6E9
Milk Ing Dose (mrem/y)	5.2E-4	4.1E-7	3.9E-8	4.3E-9	1.1E-9	4.5E-11	4.5E-13
Area Factor	1	1240	1.3E4	1.2E5	4.8E5	1.1E7	1.1E9

Table 81 Animal product (water-dependent) pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.0E-5	8.1E-9	7.1E-10	8.2E-11	2.1E-11	8.2E-13	8.2E-15
Area Factor	1	1280	1.5E4	1.3E5	5.0E5	1.3E7	1.3E9
Milk Ing Dose (mrem/y)	2.2E-4	1.8E-7	1.6E-8	1.8E-9	4.6E-10	1.8E-11	1.8E-13
Area Factor	1	1240	1.4E4	1.2E5	4.8E5	1.2E7	1.2E9

Table 82 Animal product (water-dependent) pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	9.1E-2	9.9E-5	8.8E-6	1.0E-6	2.5E-7	9.8E-9	9.8E-11
Area Factor	1	924	1.0E4	8.9E4	3.7E5	9.3E6	9.3E8
Milk Ing Dose (mrem/y)	2.9E-1	3.2E-4	2.8E-5	3.2E-6	8.1E-7	3.2E-8	3.2E-10
Area Factor	1	905	1.0E4	9.0E4	3.6E5	8.9E6	8.9E8

Table 83 Animal product (water-dependent) pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	7.6E-4	1.9E-6	2.6E-7	3.5E-8	9.3E-9	3.9E-10	3.9E-12
Area Factor	1	401	2930	2.2E4	8.2E4	2.0E6	1.9E8
Milk Ing Dose (mrem/y)	8.7E-4	2.2E-6	3.1E-7	4.2E-8	1.1E-8	4.6E-10	4.6E-12
Area Factor	1	400	2860	2.1E4	8.0E4	1.9E6	1.9E8

Table 84 Animal product (water-dependent) pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	3.2E-5	6.9E-8	9.6E-9	1.4E-9	4.1E-10	1.9E-11	2.1E-13
Area Factor	1	469	3360	2.3E4	8.0E4	1.8E6	1.6E8
Milk Ing Dose (mrem/y)	1.0E-4	2.4E-7	3.4E-8	5.0E-9	1.4E-9	6.6E-11	7.3E-13
Area Factor	1	414	2940	2.0E4	7.0E4	1.5E6	1.4E8

Table 85 Animal product (water-dependent) pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.0E-4	2.6E-7	3.6E-8	5.1E-9	1.4E-9	6.7E-11	7.0E-13
Area Factor	1	406	2930	2.0E4	7.2E4	1.6E6	1.5E8
Milk Ing Dose (mrem/y)	9.1E-6	2.3E-8	3.1E-9	4.5E-10	1.3E-10	5.8E-12	6.3E-14
Area Factor	1	406	2930	2.0E4	7.2E4	1.6E6	1.5E8

Table 86 Animal product (water-independent) pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	4.0E-4	5.8E-7	1.2E-7	3.1E-8	1.4E-8	2.3E-9	2.0E-10
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	7.7E-5	1.2E-7	2.6E-8	6.9E-9	3.1E-9	5.4E-10	4.9E-11
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 87 Animal product (water-independent) pathway doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	2.2E-3	2.2E-5	6.7E-6	2.2E-6	1.1E-6	2.2E-7	2.2E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	2.9E-4	2.9E-6	8.6E-7	2.9E-7	1.4E-7	2.9E-8	2.9E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 88 Animal product (water-independent) pathway doses and area factors for Sr-90 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.5E-2	1.5E-4	4.3E-5	1.5E-5	7.2E-6	1.5E-6	1.5E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	4.4E-3	4.4E-5	1.3E-5	4.4E-6	2.2E-6	4.4E-7	4.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 89 Animal product (water-independent) pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	5.4E-6	5.4E-8	1.6E-8	5.4E-9	2.7E-9	5.4E-10	5.4E-11
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	4.7E-5	4.7E-7	1.4E-7	4.7E-8	2.4E-8	4.7E-9	4.7E-10
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 90 Animal product (water-independent) pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	8.9E-4	8.9E-6	2.7E-6	8.9E-7	4.4E-7	8.9E-8	8.9E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	1.4E-3	1.4E-5	4.3E-6	1.4E-6	7.1E-7	1.4E-7	1.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 91 Animal product (water-independent) pathway doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	4.4E-3	4.4E-5	1.3E-5	4.4E-6	2.2E-6	4.4E-7	4.4E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	1.6E-3	1.6E-5	4.7E-6	1.6E-6	7.9E-7	1.6E-7	1.6E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 92 Animal product (water-independent) pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.5E-2	1.5E-4	4.5E-5	1.5E-5	7.5E-6	1.5E-6	1.5E-
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	1.1E-2	1.1E-4	3.3E-5	1.1E-5	5.5E-6	1.1E-6	1.1E-7
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 93 Animal product (water-independent) pathway doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	4.8E-3	4.8E-5	1.5E-5	4.8E-6	2.4E-6	4.8E-7	4.8E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	5.7E-3	5.7E-5	1.7E-5	5.7E-6	2.8E-6	5.7E-7	5.7E-8
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 94 Animal product (water-independent) pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	1.5E-4	1.5E-6	4.6E-7	1.5E-7	7.6E-8	1.5E-8	1.5E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	3.9E-4	3.9E-6	1.2E-6	3.9E-7	1.9E-7	3.9E-8	3.9E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 95 Animal product (water-independent) pathway doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	5.7E-4	5.7E-6	1.7E-6	5.7E-7	2.8E-7	5.7E-8	5.7E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	8.3E-6	8.3E-8	2.5E-8	8.3E-9	4.1E-9	8.3E-10	8.3E-11
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Table 96 Animal product (water-independent) pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
Meat Ing Dose (mrem/y)	2.8E-4	2.8E-6	8.4E-7	2.8E-7	1.4E-7	2.8E-8	2.8E-9
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5
Milk Ing Dose (mrem/y)	1.6E-5	1.6E-7	4.8E-8	1.6E-8	8.1E-9	1.6E-9	1.6E-10
Area Factor	1	100	333	1000	2000	1.0E4	1.0E5

Appendix J: Ingestion of Fish from a Contaminated Surface Water Source

Table 97 Fish ingestion pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.4E-2	4.6E-4	1.4E-4	4.8E-5	2.4E-5	5.0E-6	5.0E-7
Area Factor	1	31.3	103	295	592	2870	2.9E4
Time for Max Dose (years)	2.4	1.0	1.1	0.9	0.9	0.8	0.9

Table 98 Fish ingestion pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.3E-5	4.0E-7	1.2E-7	4.1E-8	2.1E-8	4.1E-9	4.1E-10
Area Factor	1	31.8	105	307	614	3070	3.1E4
Time for Max Dose (years)	3.3	1.2	1.0	0.9	0.9	0.9	0.9

Table 99 Fish ingestion pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	3.3E-3	1.5E-4	4.4E-5	1.5E-5	7.4E-6	1.5E-6	1.5E-7
Area Factor	1	23.0	76.9	226	453	2260	2.3E4
Time for Max Dose (years)	5.3	1.9	1.7	1.8	1.5	1.5	1.5

Table 100 Fish ingestion pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.5E-3	1.5E-4	6.7E-5	2.7E-5	1.5E-5	3.0E-6	3.1E-7
Area Factor	1	10.2	22.6	56.8	105	505	4930
Time for Max Dose (years)	605	573	529	508	498	494	491

Table 101 Fish ingestion pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	1.5E-5	9.8E-7	4.5E-7	2.0E-7	1.2E-7	2.7E-8	2.9E-9
Area Factor	1	15.3	32.9	74.7	130	561	5140
Time for Max Dose (years)	916	396	365	349	340	334	330

Table 102 Fish ingestion pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)						
Receptor on Hot Spot	1000	10	3	1	0.5	0.1	0.01
RESRAD Ing Dose (mrem/y)	2.6E-3	2.5E-4	1.2E-4	5.0E-5	2.8E-5	6.4E-6	7.1E-7
Area Factor	1	10.3	22.2	51.4	90.6	399	3630
Time for Max Dose (years)	164	151	139	133	130	128	126

Appendix K: External Radiation Pathway in Building

Table 103 External radiation doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	3.2E-5	6.1E-6	2.5E-6	1.4E-6	2.9E-7	2.9E-8
RESRAD-BUILD AF	1	5.19	12.6	23.6	111	1090
MicroShield Dose (mrem/y)	6.2E-5	1.2E-5	4.9E-6	2.6E-6	5.6E-7	5.7E-8
MicroShield AF	1	5.19	12.6	23.5	111	1100
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	6.2E-5	8.2E-6	2.8E-6	1.4E-6	2.8E-7	2.8E-8
MicroShield AF	1	7.49	21.8	43.4	217	2170

Table 104 External radiation doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	7.1E-7	1.3E-7	5.5E-8	2.9E-8	6.2E-9	6.3E-10
RESRAD-BUILD AF	1	5.33	13.0	24.3	115	1130
MicroShield Dose (mrem/y)	3.1E-6	6.0E-7	2.5E-7	1.3E-7	2.8E-8	2.8E-9
MicroShield AF	1	5.26	12.8	23.9	113	1110
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	3.1E-6	4.1E-7	1.4E-7	7.1E-8	1.4E-8	1.4E-9
MicroShield AF	1	7.57	22.0	43.9	219	2190

Table 105 External radiation doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	8.0E-6	1.5E-6	6.3E-7	3.4E-7	7.2E-8	7.3E-9
RESRAD-BUILD AF	1	5.20	12.6	23.6	111	1100
MicroShield Dose (mrem/y)	1.7E-5	3.2E-6	1.3E-6	7.0E-7	1.5E-7	1.5E-8
MicroShield AF	1	5.20	12.6	23.6	111	1100
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	1.6E-5	2.2E-6	7.5E-7	3.8E-7	7.6E-8	7.5E-9
MicroShield AF	1	7.50	21.8	43.5	217	2170

Table 106 External radiation doses and area factors for Ra-226 hot spots in soil.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	2.4E-5	4.6E-6	1.9E-6	1.0E-6	2.2E-7	2.2E-8
RESRAD-BUILD AF	1	5.21	12.6	23.6	111	1100
MicroShield Dose (mrem/y)	4.4E-5	8.4E-6	3.5E-6	1.9E-6	3.9E-7	4.0E-8
MicroShield AF	1	5.20	12.6	23.6	111	1100
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	4.3E-5	5.8E-6	2.0E-6	1.0E-6	2.0E-7	2.0E-8
MicroShield AF	1	7.50	21.8	43.5	217	2170

Table 107 External radiation doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	3.5E-5	6.5E-6	2.7E-6	1.4E-6	3.0E-7	3.1E-8
RESRAD-BUILD AF	1	5.20	12.6	23.7	111	1100
MicroShield Dose (mrem/y)	6.1E-5	1.2E-5	4.8E-6	2.6E-6	5.5E-7	5.6E-8
MicroShield AF	1	5.20	12.6	23.6	111	1100
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	6.0E-5	8.1E-6	2.8E-6	1.4E-6	2.8E-7	2.8E-8
MicroShield AF	1	7.50	21.8	43.5	217	2170

Table 108 External radiation doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	3.1E-7	6.0E-8	2.5E-8	1.3E-8	2.8E-9	2.9E-10
RESRAD-BUILD AF	1	5.07	12.2	22.9	108	1070
MicroShield Dose (mrem/y)	3.5E-7	6.7E-8	2.8E-8	1.5E-8	3.1E-9	3.2E-10
MicroShield AF	1	5.25	12.7	23.8	112	1110
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	3.5E-7	4.6E-8	1.6E-8	7.9E-9	1.6E-9	1.6E-10
MicroShield AF	1	7.56	22.0	43.8	219	2190

Table 109 External radiation doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.5E-8	5.3E-9	2.4E-9	1.3E-9	2.8E-10	2.8E-11
RESRAD-BUILD AF	1	5.19	12.6	23.6	111	1090
MicroShield Dose (mrem/y)	1.2E-9	2.3E-10	9.4E-11	5.0E-11	1.1E-11	1.1E-12
MicroShield AF	1	5.30	12.9	24.1	114	1120
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	1.2E-9	1.6E-10	5.4E-11	2.7E-11	5.5E-12	5.4E-13
MicroShield AF	1	7.63	22.2	44.2	221	2210

Table 110 External radiation doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	5.9E-7	1.2E-7	4.8E-8	2.6E-8	5.5E-9	5.6E-10
RESRAD-BUILD AF	1	5.03	12.2	22.8	107	1060
MicroShield Dose (mrem/y)	7.8E-7	1.5E-7	6.0E-8	3.2E-8	6.8E-9	6.9E-10
MicroShield AF	1	5.33	13.0	24.2	114	1130
Receptor 1 m From Hot Spot						
MicroShield Dose (mrem/y)	7.7E-7	1.0E-7	3.5E-8	1.7E-8	3.5E-9	3.5E-10
MicroShield AF	1	7.67	22.3	44.4	222	2220

Appendix L: Inhalation Pathway in Building

Table 111 Inhalation pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	2.0E-8	5.9E-10	2.0E-10	9.8E-11	2.0E-11	2.0E-12
Area Factor	1	33.4	100	200	1000	1.0E4
Hand Calculation (mrem/y)	6.9E-9	2.1E-10	6.9E-11	3.4E-11	6.9E-12	6.9E-13
Area Factor	1	33.4	100	200	1000	1.0E4

Table 112 Inhalation pathway doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.7E-6	5.0E-8	1.7E-8	8.4E-9	1.7E-9	1.7E-10
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	7.2E-7	2.2E-8	7.2E-9	3.6E-9	7.2E-10	7.2E-11
Area Factor	1	33.3	100	200	1000	1.0E4

Table 113 Inhalation pathway doses and area factors for Sr-90 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.2E-5	3.5E-7	1.2E-7	5.9E-8	1.2E-8	1.2E-9
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	4.3E-6	1.3E-7	4.3E-8	2.1E-8	4.3E-9	4.3E-10
Area Factor	1	33.3	100	200	1000	1.0E4

Table 114 Inhalation pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	7.8E-8	2.3E-9	7.8E-10	3.9E-10	7.8E-11	7.8E-12
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	2.7E-8	8.2E-10	2.7E-10	1.4E-10	2.7E-11	2.7E-12
Area Factor	1	33.3	100	200	1000	1.0E4

Table 115 Inhalation pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.6E-6	4.9E-8	1.6E-8	8.2E-9	1.6E-9	1.6E-10
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	5.7E-7	1.7E-8	5.7E-9	2.9E-9	5.7E-10	5.7E-11
Area Factor	1	33.3	100	200	1000	1.0E4

Table 116 Inhalation pathway doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	2.9E-7	8.6E-9	2.9E-9	1.4E-9	2.9E-10	2.9E-11
Area Factor	1	33.4	100	200	1000	1.0E4
Hand Calculation (mrem/y)	1.1E-7	3.1E-9	1.1E-9	5.2E-10	1.1E-10	1.1E-11
Area Factor	1	33.3	100	200	1000	1.0E4

Table 117 Inhalation pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	2.9E-4	8.7E-6	2.9E-6	1.5E-6	2.9E-7	2.9E-8
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	1.0E-4	3.1E-6	1.0E-6	5.2E-7	1.0E-7	1.0E-8
Area Factor	1	33.3	100	200	1000	1.0E4

Table 118 Inhalation pathway doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.8E-2	5.3E-4	1.8E-4	8.9E-5	1.8E-5	1.8E-6
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	6.5E-3	2.0E-4	6.5E-5	3.3E-5	6.5E-6	6.5E-7
Area Factor	1	33.3	100	200	1000	1.0E4

Table 119 Inhalation pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.2E-3	3.5E-5	1.2E-5	5.9E-6	1.2E-6	1.2E-7
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	4.1E-4	1.2E-5	4.1E-6	2.1E-6	4.1E-7	4.1E-8
Area Factor	1	33.3	100	200	1000	1.0E4

Table 120 Inhalation pathway doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	4.0E-3	1.2E-4	4.0E-5	2.0E-5	4.0E-6	4.0E-7
Area Factor	1	33.5	100	200	1000	1.0E4
Hand Calculation (mrem/y)	1.4E-3	4.2E-5	1.4E-5	7.0E-6	1.4E-6	1.4E-7
Area Factor	1	33.3	100	200	1000	1.0E4

Table 121 Inhalation pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	4.2E-3	1.2E-4	4.2E-5	2.1E-5	4.2E-6	4.2E-7
Area Factor	1	33.5	100	200	1000	1.0E4
Hand Calculation (mrem/y)	1.5E-3	4.4E-5	1.5E-5	7.3E-6	1.5E-6	1.5E-7
Area Factor	1	33.3	100	200	1000	1.0E4

Appendix M: Ingestion Pathway in Building

Table 122 Ingestion pathway doses and area factors for C-14 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	5.2E-8	1.6E-9	5.2E-10	2.6E-10	5.2E-11	5.2E-12
Area Factor	1	33.2	100	200	1000	1.0E4
Hand Calculation (mrem/y)	4.9E-7	1.5E-8	4.9E-9	2.5E-9	4.9E-10	4.9E-11
Area Factor	1	33.3	100	200	1000	1.0E4

Table 123 Ingestion pathway doses and area factors for Co-60 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	5.4E-7	1.6E-8	5.4E-9	2.7E-9	5.4E-10	5.4E-11
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	6.3E-6	1.9E-7	6.3E-8	3.2E-8	6.3E-9	6.3E-10
Area Factor	1	33.3	100	200	1000	1.0E4

Table 124 Ingestion pathway doses and area factors for Sr-90 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	3.7E-6	1.1E-7	3.7E-8	1.8E-8	3.7E-9	3.7E-10
Area Factor	1	33.4	100	201	1000	1.0E4
Hand Calculation (mrem/y)	3.6E-5	1.1E-6	3.6E-7	1.8E-7	3.6E-8	3.6E-9
Area Factor	1	33.3	100	200	1000	1.0E4

Table 125 Ingestion pathway doses and area factors for Tc-99 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	3.7E-8	1.1E-9	3.7E-10	1.8E-10	3.7E-11	3.7E-12
Area Factor	1	33.5	100	201	1000	1.0E4
Hand Calculation (mrem/y)	3.4E-7	1.0E-8	3.4E-9	1.7E-9	3.4E-10	3.4E-11
Area Factor	1	33.3	100	200	1000	1.0E4

Table 126 Ingestion pathway doses and area factors for I-129 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	6.9E-6	2.1E-7	6.9E-8	3.5E-8	6.9E-9	6.9E-10
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	6.5E-5	1.9E-6	6.5E-7	3.2E-7	6.5E-8	6.5E-9
Area Factor	1	33.3	100	200	1000	1.0E4

Table 127 Ingestion pathway doses and area factors for Cs-137 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.2E-6	3.6E-8	1.2E-8	6.0E-9	1.2E-9	1.2E-10
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	1.2E-5	3.5E-7	1.2E-7	5.9E-8	1.2E-8	1.2E-9
Area Factor	1	33.3	100	200	1000	1.0E4

Table 128 Ingestion pathway doses and area factors for Ra-226 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	2.1E-4	6.2E-6	2.1E-6	1.0E-6	2.1E-7	2.1E-8
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	2.0E-3	6.0E-5	2.0E-5	1.0E-5	2.0E-6	2.0E-7
Area Factor	1	33.3	100	200	1000	1.0E4

Table 129 Ingestion pathway doses and area factors for Th-232 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	1.1E-4	3.4E-6	1.1E-6	5.7E-7	1.1E-7	1.1E-8
Area Factor	1	33.4	100	201	1000	1.0E4
Hand Calculation (mrem/y)	1.2E-3	3.5E-5	1.2E-5	5.8E-6	1.2E-6	1.2E-7
Area Factor	1	33.3	100	200	1000	1.0E4

Table 130 Ingestion pathway doses and area factors for U-238 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	6.9E-6	2.1E-7	6.9E-8	3.4E-8	6.9E-9	6.9E-10
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	6.5E-5	1.9E-6	6.5E-7	3.2E-7	6.5E-8	6.5E-9
Area Factor	1	33.3	100	200	1000	1.0E4

Table 131 Ingestion pathway doses and area factors for Pu-239 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	8.8E-5	2.7E-6	8.8E-7	4.4E-7	8.8E-8	8.8E-9
Area Factor	1	33.4	100	200	1000	1.0E4
Hand Calculation (mrem/y)	8.3E-4	2.5E-5	8.3E-6	4.1E-6	8.3E-7	8.3E-8
Area Factor	1	33.3	100	200	1000	1.0E4

Table 132 Ingestion pathway doses and area factors for Am-241 hot spots.

	Hot Spot Size (m^2)					
Receptor on Hot Spot	100	3	1	0.5	0.1	0.01
RESRAD-BUILD Dose (mrem/y)	9.1E-5	2.7E-6	9.1E-7	4.5E-7	9.1E-8	9.1E-9
Area Factor	1	33.3	100	200	1000	1.0E4
Hand Calculation (mrem/y)	8.5E-4	2.6E-5	8.5E-6	4.3E-6	8.5E-7	8.5E-8
Area Factor	1	33.3	100	200	1000	1.0E4

Appendix N : Metropolis-Hastings Sampler and Gibbs Sampler Codes in R Programming Language

```
#Metropolis-Hastings sampler for a normal posterior based
# on normal proposal distribution
# Posterior density is normal
ybar=1.5
tau=3
n=50
f<-function(theta,mu,sigma) exp(-(1/(2*sigma^2))*(theta-mu)^2-
(n/(2*tau^2)*(theta-ybar)^2))
# Initiation procedure
met<-numeric(5000)
last<-1   # current vector in chain is called last
# Run chain using a normal distribution
mu=2
sigma=3
# Command cand<-rnorm(1,mu,sigma) generates a single random normal
# variable that is a proposed value for theta
for (i in 1:5000) {
cand<-rnorm(1,mu,sigma)
alpha<-
f(cand,mu,sigma)/f(last,mu,sigma)*(dnorm(cand,mu,sigma)/dnorm(last,mu,s
igma))
if (runif(1)<min(alpha,1)) last<-cand
met[i]<-last}
hist(met)
plot(met)
#To assess the individual results and statistics of the MH sampler
met
summary(met)
var(met)
```

```
# Gibbs Sampler for normally distributed estimates of a parameter μ,
with unknown variance
# Assume a flat (uniform) prior for μ and a "Jeffreys" prior
# 1/sigma^2 for sigma^2
# Produce 1 sample of mu from normal distribution
samplemu<- function(xbar,sdev,N){
rnorm(1,xbar,sdev/sqrt(N))
}
# Produce 1 sample of std dev from marginal chi-sq distribution
samplesd = function(X,mu,N){
sqrt(sum((X-mu)^2)/rchisq(1,N))
}
# Initialize sampling chain
samplen = function(n=1000,mu=0,sdev=1){
xbar = mean(X)
N = length(X)
mus = rep(NaN,n)
sdevs = rep(NaN,n)
# n sampling steps
for(i in 1:n) {
mus[i] = mu = samplemu(xbar,sdev,N)
sdevs[i] = sdev = samplesd(X,mu,N)
}
p99th=mus+2.576*sdevs
list(mu=mus,sdev=sdevs,p99th=p99th) # result
}
#Use data set...333 samples
X<-scan("c:\\abelquie\\UT NE\\R Code\\Cs Data.txt")
# Now sample n times and look at marginal distributions
z<-samplen(1000)
#"list(z)" to see posterior values
#Likelihood (FSS Data) statistics
summary(X)
sd(X)
#posterior statistics for mean and standard deviation
summary(z$mu)
sd(z$mu)
summary(z$sd)
# 99th percentile of posterior
summary(z$p99th)
```

```
# Robust modeling using t distribution with conditional distributions
# Assume a flat (noninformative) prior on mu and sigma

#Use large data set...333 samples
y<-scan("c:\\Abelquie\\UT NE\\R Code\\Cs Data.txt")

library(LearnBayes)
library(car)

box.cox.powers(y[y>0])  #Find the optimal value of p for Box-Cox

bcy=box.cox(y[y>0],0.0944)  #Apply transform once find optimal p

FSSbcq=quantile(bcy,seq(.95,.995,.005))

# Using 40 degrees of freedom following normal transform

FSSbc=robustt(bcy,40,10000)  #normal model

FSSbc95 = FSSbc$mu+sqrt(FSSbc$s2)*qt(0.95,40)
FSSbc99 = FSSbc$mu+sqrt(FSSbc$s2)*qt(0.99,40)
FSSbcmean = FSSbc$mu

summary(FSSbcmean)
summary(FSSbc95)
summary(FSSbc99)

#Transforming Back.
box.cox.inv=function(x,p){
answer=(x*p+1)^{1/p}
}

#Transform sample of 99pctiles back and get interval for the results.

FSSbvinv95 = box.cox.inv(FSSbc95,.0944)
summary(FSSbvinv95)

FSSbvinv99 = box.cox.inv(FSSbc99,.0944)
summary(FSSbvinv99)

FSSbvinvmean = box.cox.inv(FSSbcmean,.0944)
summary(FSSbvinvmean)

quantile(FSSbvinv99,c(.05,.95))

FSSq = quantile(y[y>0],c(.95,.975,.99,.995))  #actual quantiles.
```

Appendix O: Hot Spot Assessment Examples for Final Status Survey Data

The robust t model can be used to estimate the 99th percentile for final status survey data. This model was used to process three real data sets from final status surveys. First however, a simulated normal random sample of 15 samples was evaluated, first assuming no hot spots were found, and then assuming two hot spots were identified and added to the data set.

The posterior distribution output of the Gibbs sampler is compared to the 15 normally distributed samples assumed to have a mean of 12 and standard deviation of 5. So even in the absence of hot spots, the posterior distribution spreads the data further into the tails at the 95th and 99th percentiles. It is worth noting that the Box-Cox transform in this case was 0.9, indicating that not much of a transformation was needed to make the data normal (as expected). At the 99th percentile, the final status survey data distribution has a value of 21.24 pCi/g (Table 133). The corresponding posterior distribution result is 24.90 pCi/g. The robust t model nearly matches the mean of the data distribution, and its tails are somewhat heavier. The upper tolerance limit, defined as the 95% upper confidence level on the 99th percentile, was 30.67 pCi/g.

Performing this analysis on the same FSS data set, except that two hot spot results (38 and 62 pCi/g) were added. Considering the addition of two hot spots, the 99th percentile of the posterior distribution is expected to shift much further to the right.

The posterior distribution output of the Gibbs sampler is now compared to the 15 normally distributed samples plus two hot spots added to the data set:. Clearly, considering the presence of two hot spots added to the data set, the posterior distribution spreads the data further into the tails. At the 99th percentile, the final status survey data distribution has a value 58.16 pCi/g (Table 134). The corresponding posterior distribution using the robust t methodology is 89.77

Table 133 Final survey data and robust t posterior distribution for small sample, no hot spots.

Statistic	FSS Data	Posterior Distribution
Mean	12.42	12.33
95th	19.89	20.97
99th	21.24	24.90
UTL	----	30.67

pCi/g. The UTL that world be used to demonstrate compliance with the $DCGL_{99th}$ is 181.0 pCi/g. The robust t model again nearly matches the location (mean) of the data distribution, but the 99th percentile is greater than the data, owing to the fact that the presence and magnitude of hot spots adds to the variability of the contaminant distribution.

Now consider three realistic FSS data sets—two from soil areas, and one from a building surface survey unit. The first data set represents 15 soil sample results analyzed for U-238 from a Class 2 survey unit (hot spots not expected). The FSS data ranged from 0.95 to 2.08 pCi/g, with two concentrations barely exceeding the $DCGL_W$ of 2.0 pCi/g (see data set at the end of this appendix). The Bayesian analysis results are shown in Table 135. The robust t posterior distribution in this case is slightly greater than the final status survey data at the 99th percentile. The FSS data had a 99th percentile value of 2.07 pCi/g, while the 99th percentile of the posterior distribution was 2.74 pCi/g. The UTL was calculated as 3.76 pCi/g. Hot spot compliance would be demonstrated by comparing the UTL to the $DCGL_{99th}$ value (which will pass provided that the area factor is at least 2).

The second soil data set involves 45 soil samples with Cs-137 results that exhibit a strong skew to the right, as illustrated in Figure 21. The mean and standard deviation of the FSS data are 9.0 pCi/g and 17.2 pCi/g, respectively (Table 136).

Table 136 indicates that the robust t posterior distribution increased the 99th percentile predicted to remain in the survey unit. The FSS data had a 99th

Table 134 Final survey data and robust t posterior distribution for small sample and two hot spots.

Statistic	FSS Data	Posterior Distribution
Mean	16.84	13.44
95th	42.80	46.70
99th	58.16	89.77
UTL	----	181.0

Table 135 Robust t posterior distribution for U-238 final status survey data.

Statistic	FSS Data	Posterior Distribution
Mean	1.41	1.37
95th	2.05	2.17
99th	2.07	2.74
UTL	----	3.76

Table 136 Robust t posterior distribution for Cs-137 final status survey data.

Statistic	FSS Data	Posterior Distribution
Mean	9.00	2.35
95th	42.80	50.74
99th	77.29	149.7
UTL	----	278.9

percentile value of 77.29 pCi/g, while the 99th percentile of the posterior distribution was 149.7 pCi/g. The UTL that would be used for hot spot compliance purposes is 278.9 pCi/g. This significant increase in the tails of the posterior distribution is largely due to the shape of the distribution and the number of samples in the FSS data.

The final data set consists of 56 surface activity measurements. The data ranged from less than zero to 2980 dpm. In fact, roughly half of the data are negative values, indicating that the radioactivity levels at those surface locations are statistically equal to background (i.e., zero net radioactivity). This is a common situation encountered in Class 1 survey units, where even though the potential exists for hot spots, much of the random statistical data are at background levels. The Bayesian analysis results are shown in Table 137.

The robust t posterior distribution in this case is not much greater than the FSS data at the 99th percentile. The FSS data had a 99th percentile value of 2760 dpm/100 cm^2, while the 99th percentile of the posterior distribution was 3230 dpm/100 cm^2. This is another example were the posterior distribution had a relatively minor impact on the FSS data at the 99th percentile. Hot spot compliance would be demonstrated by comparing the UTL of 6420 dpm/100 cm^2 to the $DCGL_{99th}$ value.

An important observation from these three examples is that high values of the 99th percentile occur when the data exhibit high variability and the sample size is low (e.g., less than 20).

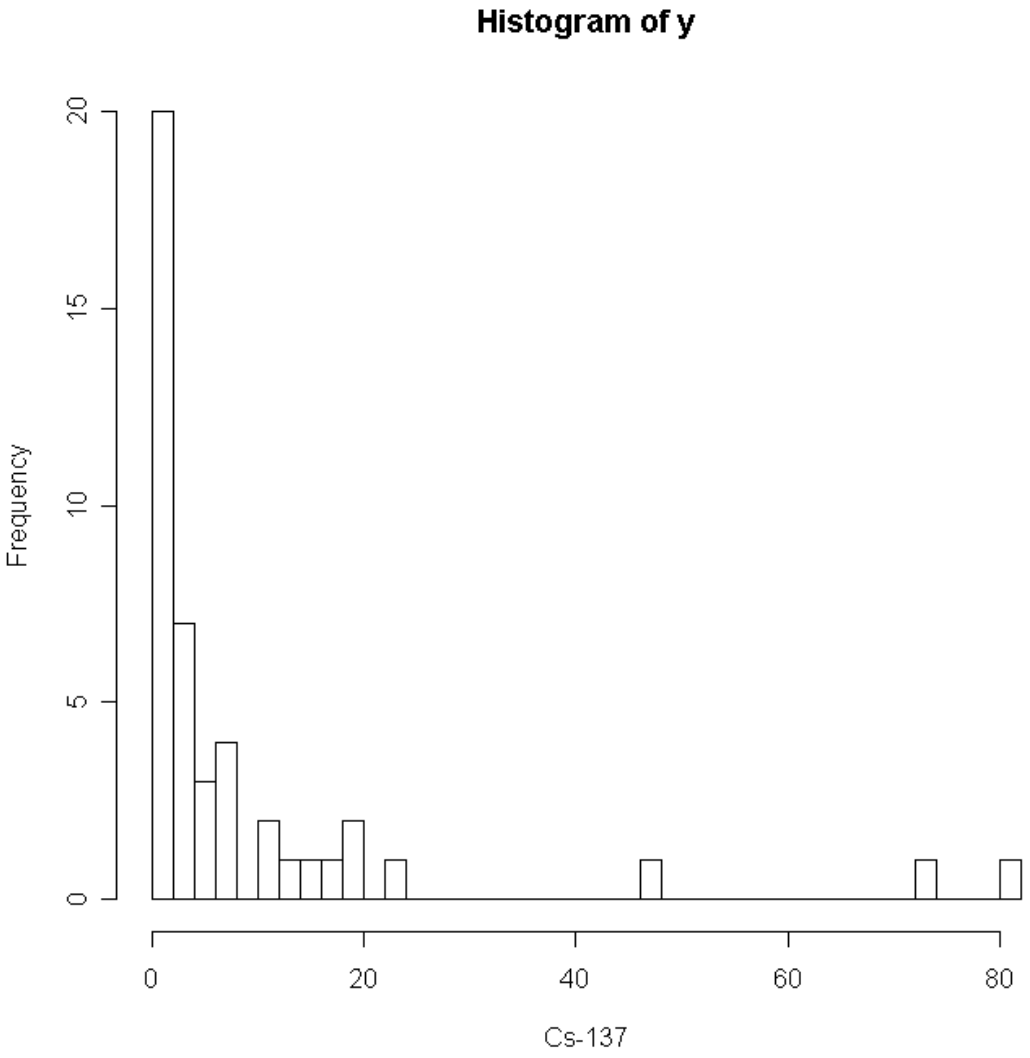


Figure 21 Histogram of FSS data showing Cs-137 concentrations.

Table 137 Robust t posterior distribution for surface activity data.

Statistic	FSS Data	Posterior Distribution
Mean	90	180
95th	1650	1380
99th	2760	3230
UTL	----	6420

FSS Data Sets Used in Examples

Cs-137 Data (45 samples)

14.700
6.880
17.000
47.800
5.650
0.008
0.008
0.051
0.056
0.044
0.189
0.065
0.990
18.500
3.720
1.800
0.180
6.100
72.700
0.200
2.980
20.000
10.300
3.220
0.410
12.900
0.770
5.520
1.570
3.650
1.850
4.660
2.710
80.900
3.490
3.200
1.820
22.800
11.100
6.570
7.170
0.480
0.420
0.071
0.058

Surface Activity Data (56 Samples)

117
122
310
243
379
501
-285
-397
-248
-136
-179
-156
-238
-144
-161
-233
104
84
-64
40
50
141
-139
-119
-92
32
37
-57
-82
-126
-203
-109
-60
-112
-82
-7
-37
-129
-84
-119
5
2143
2975
392
348
174
223
243
136
358
233
215
143
197
-653
-586

U-238 Data (15 samples)

1.58
0.96
1.19
1.16
1.38
1.64
2.08
1.48
1.34
1.13
1.62
1.5
1.12
2.04
0.95

VITA

Eric Abelquist is the Vice President and Director of the Independent Environmental Assessment and Verification program for the Oak Ridge Associated Universities (ORAU). In this capacity Mr. Abelquist provides health physics technical assistance, including independent verification of decommissioning sites, for the NRC and DOE. He contributed to the preparation of the Multiagency Radiation Survey and Site Investigation Manual (MARSSIM) and subsequently authored a textbook: *Decommissioning Health Physics: A Handbook for MARSSIM Users* in 2001. He has a B.S. and M.S. in Radiological Sciences and Protection from the University of Lowell (Lowell, MA). He received a PhD in Nuclear Engineering from The University of Tennessee in 2008. Eric lives in Knoxville with his wife Sandy, and their three children, Alyssa, Elizabeth, and Gunnar.