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Coal-fired power plants constitute a significant source of energy production for the United States, and are projected to do so for decades to come. Most of the scrutiny coal-fired power plants receive is in the form of environmental concerns regarding green house gas emissions of carbon dioxide, sulfur dioxide, and others. It is known that coal fly ash released through the stacks of coal power plants contains concentrated levels of naturally-occurring radiation, such as Radium-226. However, since the source of radiation is natural and the activity levels are low, there are no nuclear regulatory requirements imposed on coal plants.

The focus of this study was to use the Nuclear Regulatory Commission's (NRC) facility release criteria to determine whether the concentration of naturally occurring Radium-226 present in soil surrounding the Centralia Power Plant is elevated relative to soil collected 80 kilometers away.

The non-parametric Wilcoxon Rank Sum test was used to compare twenty-eight soil samples collected within 3.4 kilometers of the Centralia Power Plant stacks against an equal number of reference samples collected in Port Orchard, Washington. It was determined that the average concentration of Radium-226 in soil near the power plant was 1.59 pCi/g, while the average concentration in reference soil was 0.59 pCi/g. The study suggests that the area around the power plant would fail to pass the release criteria of a NRC Multi-Agency Radiation Survey and Site Investigation (MARSSIM) Class 3 survey unit. If it is true that coal fired power plants increase background radiation levels measurably, but not at a level sufficient to cause alarm, it may be sensible to revise the strict emissions standards for nuclear facilities or increase requirements for utilities other than nuclear.

Evaluating the Presence of Radium-226 in Soil Surrounding a Coal-Fired Power Plant using the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)

by
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APPROVED:

Major Professor, representing Radiation Health Physics

Head of the Department of Nuclear Engineering & Radiation Health Physics

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Thomas A. Herring, Author

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I am also more grateful than words can say to my dear wife, Carrie, whose patience and encouragement these past two years have been both heroic and inspiring.

Above all, I am grateful to God, who, though lacking nothing in Himself, chose to create me nonetheless. And with each new glimmer of understanding in this life, I echo the humble sentiments of Johannes Kepler: “I am merely striving to think God's thoughts after Him.”

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INTRODUCTION

Coal-Fired Power

In 2010, approximately 45 percent of U.S. electricity was generated by coal power (U.S. Dept. of Energy, Electric Power Annual 2010). According to projections made by the U.S. Department of Energy, America's dependency on coal power is not expected to change dramatically over the next two decades: "Coal maintains the largest share of total [electricity] generation in 2035 in all the cases, varying only from 42 percent to 44 percent across all the cases (Annual Energy Outlook 2011, Figure [1])."

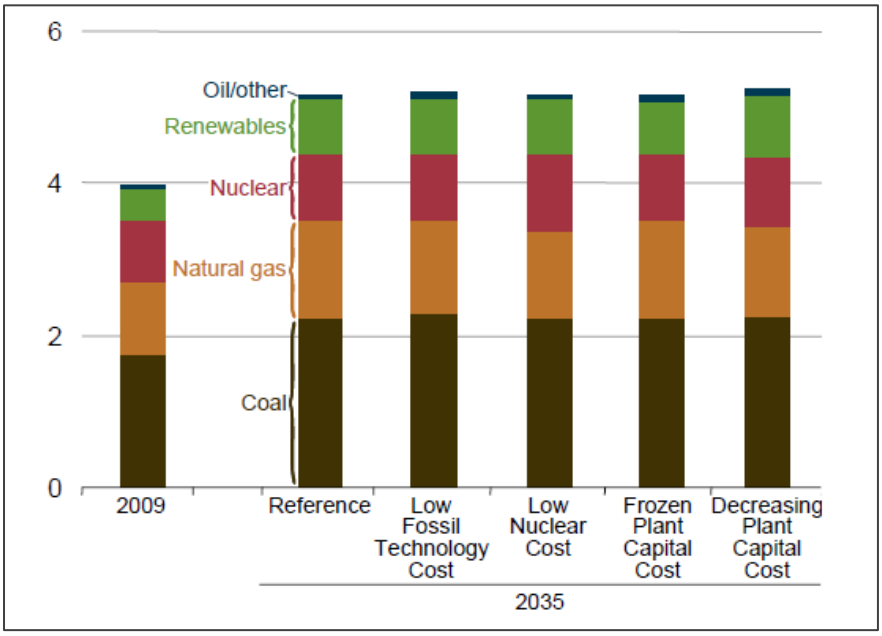

Figure 1, U.S. electricity generation by fuel in five cases, 2009 and 2035 (billion kilowatt hours). © U.S. Energy Information Administration, Annual Energy Outlook 2011.

Even when factoring in potential regulatory reforms in nine different scenarios the DOE outlook is that “coal remains the largest single source of generation through 2035 in all but one [case]” (p. 50). The only case where coal decreases as an energy source assumes CO_2 emissions rise in price from $25 per ton in 2013 to $77 per ton in 2035. This projection of coal-fired electricity generation is in spite of the fact that the median age of all coal burning units in use today is 45 years old, and that many are 70 and 80 years old (SourceWatch, 2011). Figure 2 provides a graphical representation of the number of coal burning units operating today by the year in which they were originally built.

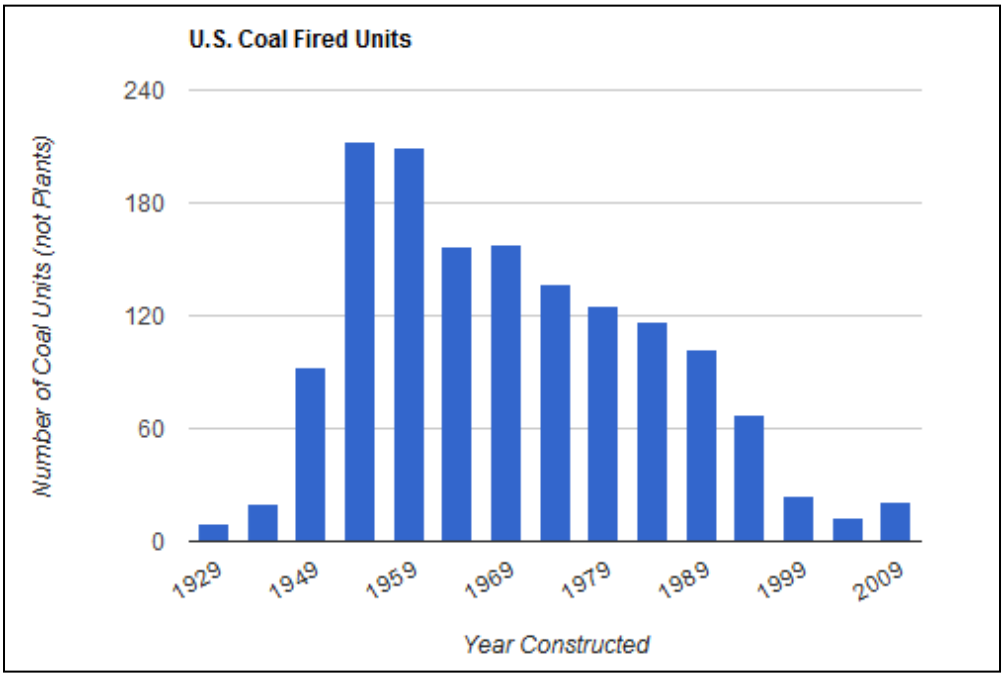

Figure 2, Number of existing coal units in the United States by the year they were constructed. Data obtained from Sourcewatch.org and the U.S. Energy Information Administration.

Coal fuel can be in the form of anthracite, bituminous, subbituminous, lignite, waste coal, and coal synthetic fuel, and is distinguished by the amount of heat each type produces. The two types most commonly used are bituminous and subbituminous which, according to the U.S. Energy Information Administration together comprise more than 90% of coal burned in the United States (Figure 3). They are characterized by a high carbon content ranging from 35-86% (U.S. Dept. of Energy, Today in Energy, 2011).

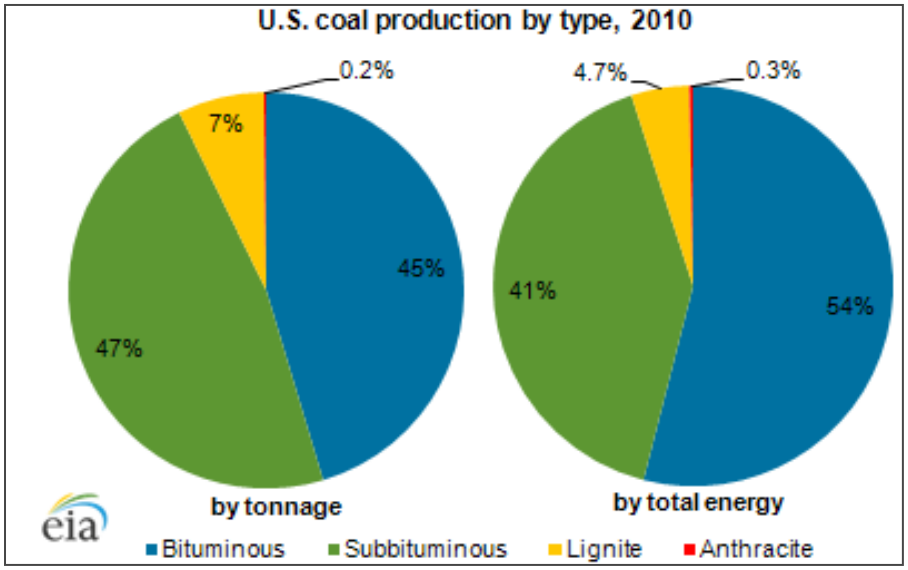

Figure 3, U.S. coal production by type, 2010. © U.S. Energy Information Administration, IEA Coal Information 2010.

Most coal fired power plants operate by crushing mined coal into a fine powder and then feeding the powder into a combustion unit where it serves as a fuel for heat generation. The heat is transferred to steam which drives a turbine, generating electric power. The steam is then cooled down through the use of pond or river water, and the condensed fluid is returned to the boiler in the form of water to begin the process again.

Coal which has combusted is reduced to ash, with a volume of about one-tenth that of the original coal, thereby increasing the concentration of those metals originally present in the coal (U.S. EPA, Coal Ash, 2011). Roughly 40% of the ash takes the form of 'bottom ash' which collects as residue along the walls of the furnace and is treated as waste. The remaining 60%, referred to as 'top ash' or 'fly ash', is a fine particle residue which rises with the flue gases, and is exhausted through a stack to the atmosphere.

Centralia Power Plant

The Centralia Big Hanaford Power Plant located about 140 kilometers north of Portland, Oregon, in Centralia, Washington, is one of more than 600 coal-fired plants in the nation, and has been in operation since the early 1970's. The plant is owned by TransAlta Centralia Generation LLC; its ownership has changed hands several times over the years. The plant is equipped with two tangentially-fired pulverized coal boilers, manufactured by Combustion Engineering, which have a combined output of 1,340 MW of electric power (CH2MHILL, BART Analysis for Centralia Power Plant, 2-1). In 2001, the construction of natural gas-fired units began, and today the plant operates with five combined cycle gas turbine units (CCGT), supplying an additional 248 MW of electric power to the Pacific Northwest ("Centralia Power Plant New CCGT Unit, WA, USA," 2011). Facing increasing political pressure from environmental activists and Washington State lawmakers, a deal was announced in March 2011 that TransAlta would shut down both of its coal boilers by 2025 ("TransAlta Agrees to Phase Out Coal Plant, Senate Approves Deal with 36-13 Vote," 2011).

The power plant's greenhouse gas emissions were the driving force behind the planned closure of the two coal boilers (Washington State Dept. of Ecology, "Memorandum of Understanding Between the State of Washington and TransAlta Centralia Generation LLC," 2010), and has been a focus for activists and government regulators for years. From 2000 to 2002, in accordance with federal and state Best Available Retrofit Technology (BART) regulations, Centralia Power Plant installed scrubbers to reduce the emission of Sulfur Dioxide (SO_2) to the atmosphere (CH2MHILL, BART Analysis for Centralia Power Plant, ES-1). However, the agreement reached in 2011 called for additional controls of greenhouse gas emissions from the plant. As Washington State Governor Christine Gregoire explained in March:

> *"In 2013, TransAlta will install additional air pollution control technology to further reduce emissions of nitrogen oxides at the plant. This technology is called selective non-catalytic reduction (SNCR). The TransAlta plant is the state's largest single industrial source of nitrogen oxide emissions. Nitrogen oxides are one of the causes of visibility-limiting regional haze in national parks and on federal lands" ("TransAlta Agrees to Phase Out Coal Plant, Senate Approves Deal with 36-13 Vote," 2011).*

While the thermal radiation effects of sulfur dioxide, nitrous oxide, and other greenhouse gases emitted from the 470-foot stacks remains the issue of greatest concern for environmentalists and public officials, any effects from a second type of radiative energy have been largely ignored. The purpose of this study is to examine whether the radioactivity concentrations of Radium-226 in soil surrounding the Centralia Power Plant are measurably higher than the concentrations found in reference soil collected eighty kilometers away in Port Orchard, Washington. The non-parametric Wilcoxon Rank Sum statistical test

used in the Nuclear Regulatory Commission's Multi-Agency Radiation Survey and Site Investigation Manual will be applied to the data to make this determination.

Naturally Occurring Radiation in Sub-Bituminous Coal

Coal is known to contain trace quantities of naturally occurring radionuclides, such as Uranium, Thorium, and Radium. When burned, the organic constituents of the coal are removed and the trace quantities of radionuclides are concentrated, called technologically enhanced naturally occurring radioactive material (TENORM). Still, coal ash typically contains less than 20% TENORM, with stable elements such as silicon, aluminum, iron and calcium making up the remaining 80 to 90 percent (U.S. EPA, Coal Ash, 2011).

According to the Environmental Protection Agency, the average radiation level present in coal fly ash is 5.8 pCi/g, and approaches 10 pCi/g at the high end of the spectrum (see Table 1).

Table 1, EPA Radiation Protection, Coal Ash

Wastes	**Radiation Level (pCi/g)**		
	Low	Average	High
Bottom Ash	1.6	3.5-4.6	7.7
Fly Ash	2	5.8	9.7

In comparison, according to data compiled by the same federal agency, the average radiation level in soil ranges from 0.2 - 4.2 pCi/g (U.S. EPA,TENORM Sources, 2011). However, it is true that advanced scrubbers and filtration devices installed on stacks today dramatically reduce emissions of ash

and only 2% to 5% is typically released to the atmosphere (U.S. EPA, Coal Ash, 2011). Yet even a small fraction of ash released from a plant that burns over one million tons of coal per year (Washington State Dept. of Ecology, BART Determination Support Document for TransAlta Centralia Generation, LLC Power Plant Centralia, Washington, 2010, p. 3) can add up to significant quantities over time.

A rough, conservative calculation yields approximately 1,200 tons of ash released from Centralia Power Plant to the atmosphere each year.[1] Of this, approximately 20% is TENORM, or 240 tons of fly ash per year which has the potential to cause a measurable increase in local background radiation levels.

Assuming a consumption of 1,000,000 tons of coal per year, using the EPA average of 5.8 pCi/g in fly ash, Centralia Power Plant may emit as much as 1.26 mCi of naturally occurring radiation each year.

A study conducted by Oak Ridge National Laboratory researchers J. P. McBride, R. E. Moore, J. P. Witherspoon, and R. E. Blanco in 1978 found that the estimated whole-body and bone dose commitments in man-rem due to coal fired plants exceeded that of nuclear power plants. In making their estimates, it was assumed that 100% of the food is grown and consumed at 500 meters from the plant, and a coal plant release of 1% of the total ash in the coal burned.

Concern about the release of naturally occurring radiation was also expressed by Alex Gabbard in 1993 when he wrote in the Oak Ridge National Lab Review:

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[1] 1,000,000 tons of coal/year X 10% ash X 60% Fly Ash X 2% unfiltered = 1,200 tons of ash released/year.

> *"For comparison, according to NCRP Reports No. 92 and No. 95, population exposure from operation of 1000-MWe nuclear and coal-fired power plants amounts to 490 person-rem/year for coal plants and 4.8 person-rem/year for nuclear plants. Thus, the population effective dose equivalent from coal plants is 100 times that from nuclear plants."*

Reflecting on the implications of this wide disparity between nuclear plants and coal plants of radiation exposure to the general public, Gabbard asked the question:

> *"Considering that the U.S. nuclear power industry has been required to invest in expensive measures to greatly reduce releases of radioactivity from nuclear fuel and fission products to the environment, should coal-fired power plants be allowed to do so without constraints?"*

The question posed by Gabbard is the supporting motivation for this study. The industry standard for the release of nuclear facilities is the Multi-Agency Radiation Survey & Site Investigation Manual (MARSSIM) developed by the Nuclear Regulatory Commission (NRC), so MARSSIM was used to examine the soil surrounding Centralia Power Plant.

MARSSIM

A variety of methods are available for determining whether there is a significant health risk associated with the emission of TENORM from a coal fired plant. The federal limits for radioactivity concentrations present in soil from the emissions of nuclear facilities are governed by the Nuclear Regulatory Commission (NRC). In 2000 the NRC developed NUREG-1575, more commonly known as the Multi-Agency Radiation Survey & Site Investigation Manual (MARSSIM). The purpose for developing MARSSIM was to provide regulatory guidance to nuclear facilities for their decommissioning, and determine the criteria for resolving whether or not a site meets the release criterion and can be released to the public for unrestricted use. As stated in 10 CFR 20.1402,

> *"A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and that the residual radioactivity has been reduced to levels that are as low as reasonable achievable (ALARA)."*

Since data collection and measurement will always contain some uncertainty it is not possible to attain 100% confidence in any decision to release or restrict a site for public use. Therefore, statistical methods are necessary "to provide a quantitative estimate of the probability that the release criterion is not exceeded at a particular site" (MARSSIM 2.5.1).

Though not governed by the NRC in any way, the purpose of this study was to use MARSSIM as a means of evaluating the levels of residual naturally

occurring radioactivity distinguishable from background radiation found in the vicinity of the coal-fired Centralia Power Plant.

MARSSIM recommends using the "Data Life Cycle" for planning, implementation, and evaluation of results when determining whether a site is acceptable for unrestricted use (MARSSIM Roadmap, Data Life Cycle). Formally then, the Data Life Cycle process is broken into four independent phases: planning, implementing, assessing, and decision making.

Planning

In the planning stage, a series of planning steps for establishing data quality and survey designs are established. This process is referred to as the Data Quality Objectives (DQO) Process.

> *"The DQO Process provides systematic procedures for defining the criteria that the survey design should satisfy, including what type of measurements to perform, when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform" (MARSSIM 2.3.1).*

At a minimum, paragraph 2.3.1 requires the following information from the DQO Process:

1. Classify and specify boundaries of survey units
2. State the null hypothesis (H_o)
3. Specify a gray region (Δ) where consequences of decision errors are relatively minor
4. Define Type I and Type II decision errors
5. Estimate the standard deviation (σ) of the measurements in the survey unit (typically estimated from preliminary survey data)
6. Specify the relative shift (defined as the gray region divided by the standard deviation Δ/σ)
7. Specify the detection limit for all measurement techniques
8. Calculate the number of measurements needed (N) and specify the measurement locations required to demonstrate compliance
9. Specify the documentation requirements for the survey

Implementation

During the implementation phase, data is collected using standardized and documented measurement techniques, and quality control steps are set in place to ensure results are accurate and measurement uncertainty is known and controlled.

> *"Systematic errors, also called bias, accumulate during the measurement process and result from faults in sampling designs and procedures, analytical procedures, sample contamination, losses, interactions with containers, deterioration, inaccurate instrument calibration, and other sources" (MARSSIM 4.9.1).*

Assessment

In the assessment phase, the data is evaluated to determine whether or not the objectives of the survey were met. The assessment phase may be broken down into three phases: data verification, data validation, and Data Quality Assessment (MARSSIM 2.3.3).

Data verification ensures the stated requirements of the planning phase were implemented, data validation ensures that the results support the objectives of the quality assurance project plan, and data quality assessment is the "scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use (MARSSIM 2.3.3).

Decision Making

After the survey data has been assessed, a decision is made as to whether or not the null hypothesis can be rejected. For nuclear facilities being released to the public this is done in coordination with an NRC regulator.

Clearly, in this preliminary investigation that is not the case, still the objectives of this MARSSIM application remain the same: “To make technically defensible decisions with a specified level of confidence” (MARSSIM 2.3).

CENTRALIA POWER PLANT SURVEY

The radioactivity concentration in soil due to the emissions of a nuclear facility which would result in a dose of 25 mrem per year above background to a member of the public is the Derived Concentration Guideline Level, or DCGL. There are two types of DCGLs defined in MARSSIM, the nonparametric statistical test $DCGL_W$ (*Wilcoxon Rank Sum)* and the $DCGL_{EMC}$ (*Elevated Measurement Comparison*). The $DCGL_W$ applies to an entire survey unit or area of interest if it is suspected that residual radioactivity is evenly distributed, while the $DCGL_{EMC}$, as the name implies, is used only when an area of elevated activity is located within a larger area (MARSSIM 2.2).

Figure 4, Centralia Power Plant emission stacks. Photo taken 9/24/2011.

The conditions which satisfy the decommissioning objectives described in MARSSIM are as follows:

1. *The uniform residual contamination above background is below the $DCGL_W$.*
2. *Individual measurements or samples, representing small areas of residual radioactivity, do not exceed the $DCGL_{EMC}$ for areas of elevated residual radioactivity. These small areas of residual radioactivity may exceed the $DCGL_W$ established for average residual radioactivity levels in a survey unit, provided these areas of residual radioactivity satisfy the criteria of the responsible regulatory agency (MARSSIM 4.2).*

The $DCGL_W$ for a single nuclide can be determined from either a default screening level provided by the NRC, or from less conservative site-specific dose modeling (if approved by an NRC regulator). However, "For the majority of MARSSIM users, the DCGL will simply be obtained using…default parameters" (MARSSIM 4.2) and therefore for the purposes of this study the nuclide-specific screening level for Radium-226 provided in Appendix H of NUREG-1757 Volume 2 was used. The screening levels were calculated using the dose modeling DandD code developed by the Nuclear Regulatory Commission (Section H.2.3, "Acceptable Screening Tools").

Dose modeling used to calculate the DCGLs is based on 15 centimeters of soil depth. Thus, the soil samples collected in this study were also taken at a depth of 15 centimeters.

Survey Units

The typical process for nuclear facility decommissioning entails a historical assessment of the site, including a thorough record review of radiological spills, effluent releases, surveys, licensing documents, personnel interviews, aerial photographs, etc. This information would then be used to

characterize the site and provide a basic understanding of where the areas of greatest contamination potential are located. Field surveys could then be conducted under a graded approach with increased focus on those areas where contamination is most likely to be found.

Under the MARSSIM approach, areas are classified as either impacted or non-impacted. Non-impacted areas “have no reasonable potential for residual contamination and require no further evidence to demonstrate compliance with the release criterion” (MARSSIM 2.5.2). Impacted areas are assigned a classification according to their potential for contamination, as Class 1, Class 2, or Class 3. The area classification determines the degree of radiological survey scrutiny it will receive. In a Class 1 area, it is expected that contamination will exceed the Derived Concentration Guideline Level. In Class 2 areas, individual measurements should not exceed the $DCGL_W$, though there is a potential for contamination at a significant fraction of the $DCGL_W$. And in Class 3 areas, there is little potential for contamination and individual measurements should not exceed a significant fraction of the $DCGL_W$ (e.g., 20%, [MARSSIM 5.5.2.6]). If a survey unit is misclassified, the potential for making a decision error (Type I or Type II) increases.

Based on the classification potential for contamination, a site is divided up into the various survey units just discussed, which are then assessed independent of each other. MARSSIM recommends a maximum land area survey unit size of 2,000 m^2 for Class 1 units and 10,000 m^2 for Class 2 units. Class 3 survey units have no size restrictions (MARSSIM 4.6).

In a Class 1 survey unit, any discrete measurements which are above the $DCGL_W$ and above a predetermined statistical parameter (e.g., 3σ) for the measurements should be investigated. Additionally, a measurement which is found to be above the $DCGL_{EMC}$ should likewise be investigated. The derived concentration guideline level for the elevated measurement comparison is given by the equation:

$$DCGL_{EMC} = A_m \, x \, DCGL_W$$

where A_m is the "area factor" for the area of the systematic grid (MARSSIM 8.5.1). Use of the $DCGL_{EMC}$ applies only to Class 1 survey units, since measurements taken in Class 2 and Class 3 areas are not expected to exceed the $DCGL_W$ (MARSSIM 5.5.2.6). Any measurement taken in a Class 2 or Class 3 area which exceeds the $DCGL_W$ should be flagged for further investigation.

Since coal-fired plants are not regulated by the NRC it was assumed that there is little or no potential for contamination (in this case, of concentrated naturally occurring radionuclides), and that individual measurements of soil would not exceed a significant fraction of the $DCGL_W$. Therefore, for the purposes of this study we regarded all of the area surrounding the Centralia Power Plant as a Class 3 survey area.

Radionuclide of Concern and Detection Equipment

Samples were counted in a four-inch thick lead cave (with copper and tin lining) using a High Purity Germanium (HPGe) detector manufactured by

Canberra Industries. The HPGe detector has a 50% efficiency rating at 1332 keV, relative to a 3 X 3 inch thallium activated sodium iodide, (NaI(Tl)) detector. Spectral analysis was performed using Canberra Industries Genie-VMS software. The fly ash released from the coal plant contains multiple radionuclides with Radium-226 being the radionuclide of interest. Uranium-235, which is also present in fly ash, has a gamma energy peak at approximately the same energy as the Radium-226 gamma peak (185.7 keV versus 186.2 keV). Therefore, the nuclide library file used in sample analysis also included the Uranium-235 143.8 keV peak in order to determine what part of the peak at approximately 186 keV should be assigned to Radium-226.

Since the soil sample analysis is nuclide-specific and the radionuclide of interest, Ra-226 is found in background at levels which approach the DCGL, the Wilcoxon Rank Sum Test was used (MARSSIM 2.5.1.2).

The DCGL for various nuclides can be given by the Screening Values provided in Table H.2 of NUREG-1757. A concentration for Ra-226+C of 0.6 pCi/g is provided. The “+C” indicates a value for a radionuclide with its decay products present in equilibrium. Since the half life of Ra-226 is very long (1602 years) as compared to its decay products, most notably Rn-222 ($t_{1/2}$ = 3.8 days), secular equilibrium is reached within a period of approximately 30 days. Thus, the concentration value for Ra-226+C (and not the value for Ra-226 alone) was used.

As this study designates all of the area in the vicinity of the coal plant stacks as a Class 3 survey unit, MARSSIM requires that samples be distributed randomly. When land regulated by the NRC is sampled for free release and

unrestricted use under MARSSIM, the random, unbiased sample points are selected using a detailed grid and a computer program or a table of random numbers. However, sampling in this study is restricted by private property rights and trespassing laws. Soil samples were therefore collected along the shoulders of public roads - land which is owned by the county. Seven survey sites were chosen at random and samples were taken in groups of four, ranging from 460 meters to 3.4 kilometers away from the two Centralia Power Plant stacks.

Null Hypothesis, Decision Errors and Relative Shift

The null hypothesis (H_0) tested by the Wilcoxon Rank Sum (WRS) test is, "The residual radioactivity in the survey unit exceeds the release criterion ($DCGL_W$)" (MARSSIM 2.5.1). It is assumed to be true unless proven otherwise by the WRS test. The result of the WRS test determines whether the survey unit as a whole meets the criterion, while the Elevated Measurement Comparison (in a Class 1 survey unit) determines whether individual measurements require remediation (MARSSIM paragraph 8.4.1).

Any survey that does not sample 100% of the land surface area will have some statistical probability of making a decision error. There are two possible decision errors – that the Null Hypothesis is rejected when it is true (defined as a Type I error) and that the Null Hypothesis is accepted when it is false (a Type II error). The maximum acceptable probability that the statistical test will incorrectly conclude that the median level of contamination in a survey unit is below the $DCGL_W$ (a Type I error) is set by the regulator. This probability value is referred to as *alpha* and is usually set at 5% by the regulator. The licensee establishes

the maximum acceptable probability of a Type II error – the probability that the statistical test will incorrectly conclude that the median level of contamination (above background) in a survey unit is *above* the $DCGL_W$. This value is referred to as *beta*. For this study we set the value of beta also at 5%.

A gray region (Δ) between the DCGL and the Lower Bound of the Gray Region (LBGR) must be specified. The LBGR is set at the expected mean contamination concentration of the survey unit. During a typical Final Status Survey, the LBGR would be determined after characterization data is obtained in each survey unit. In this case, of course, characterization data was not available, an expected mean concentration is not available, and therefore to obtain a relative shift in the desired range (approximately 1), the LBGR was set at 0.25 pCi/g.

The standard deviation of contaminant would normally be calculated for both the reference area and the survey unit, again using characterization surveys. In the absence of any survey data, MARSSIM recommends a standard deviation of 0.3 to be used (MARSSIM 5.5.2.2).

Thus, using the $DCGL_W$ of 0.6 pCi/g, the relative shift becomes:

$$\frac{\Delta}{\sigma} = \frac{0.6 - 0.25}{0.3} = 1.16$$

Number of Measurements Needed (N)

Once the relative shift has been determined, and *alpha* and *beta* have been selected, the number of samples required to be collected is provided in NUREG-1757 Table 5.3. To conduct a MARSSIM survey properly, sampling must be conservative. One may not collect fewer samples than required, and

since a smaller relative shift results in a greater number of samples taken, relative shift values must always be rounded down. Referencing Table 5.3 of NUREG-1757, a relative shift of 1.1 with *alpha* set at 0.05 and *beta* set at 0.05 gives an N/2 value of 28. Therefore, MARSSIM directs that 28 samples should be collected in the reference area, and 28 samples collected in the survey area.

MATERIALS AND METHODS

Sample Collection

In conducting soil sampling at both the survey site and the reference site the same sampling tools and processes were used. Soil was collected at a depth of 15 centimeters, using a standard bulb planter with a steel tube approximately 8 centimeters in diameter. To ensure standard soil sampling depth, the tube was marked with electrical tape at 15 cm.

Figure 5, Bulb planter used for collecting core soil samples. (Marked at 15 cm with electrical tape.)

For loose or sandy soil, a hand trowel was used to collect soil that would not adhere to the walls of the bulb planter. For hard, compacted soil, a rubber mallet was used to drive the core-sampler down to the standard depth.

In some cases the core sample could be transferred directly to a 500 mL bottle using a funnel. In cases where the soil was very compacted or moist, the

soil was first removed from the bulb planter into a collection tray where it was broken down further by hand, and then transferred to the 500 mL bottle using a funnel (see Figure 6). Plant life, grass, leaves, and debris were all removed prior to placing the soil in the bottle, to avoid skewing results from, for example the concentration of various radionuclides by plant biota. Similarly, rocks and gravel greater than ½ an inch diameter were also removed.

Figure 6, Collecting soil using a collection tray. Tray used to break down compacted samples and transfer to a 500 mL bottle using a funnel.

To minimize any potential of cross-contamination, all sampling equipment was cleaned between sample locations. For dry soil samples, this only entailed scraping or brushing the soil off, but for moist soil samples, tools were cleaned using paper towel.

Weather Data

Wind statistics obtained from Centralia Airport based on observations taken between December 2009 and September 2011 daily from 7am to 7pm show an average wind speed of 9 miles per hour. Wind direction is somewhat evenly distributed over the course of a year, however the predominant direction is out of the South. During the month of September 2011 when sampling was conducted, the average wind speed was 8 miles per hour, and the dominant wind direction was out of the West (Windfinder , 2011).

Soil Data

The composition of soil data was retrieved from soil data maps maintained by the Natural Resource Conservation Service (NRCS), an agency of the United States Department of Agriculture. Descriptions and attributes of the soil collected at the survey site and the reference areas are provided in Table 2.

Table 2, Soil data

	Survey Unit Soil	Reference Soil A	Reference Soil B	Reference Soil C	Reference Soil D
Elevation	212-251 feet	155-171 feet	81-155 feet	190-201 feet	238-264 feet
Mean annual precipitation	60-75 inches	30-55 inches	35-55 inches	37 inches	30-55 inches
Composition	Buckpeat and similar soils: 100%	Harstine and similar soils: 85% Minor components: 2%	Shalcar and similar soils: 85% Minor components: 15%	Kitsap silt loam soils: 85% Minor components: 2%	Harstine and similar soils: 85% Minor components: 2%
Slope	30-65%	6-15%	0-1%	8-15%	6-15%
Depth to restrictive feature	80+ inches	20-35 inches	80+ inches	80+ inches	20-35 inches
Drainage class	Well drained	Moderately well drained	Very poorly drained	Moderately well drained	Moderately well drained
Capacity of the most limiting layer to transmit water	Moderately high to high (0.57-1.98 in/hr)	Very low to moderately low (0.00-0.06 in/hr)	Moderately high to high (0.57-1.98 in/hr)	Moderately low to moderately high (0.06-0.20 in/hr)	Very low to moderately low (0.00-0.06 in/hr)
Depth to the water table	24-39 inches	24-39 inches	0 inches	18-30 inches	24-39 inches
Available water capacity	High (about 11.7 inches)	Very low (about 3.0 inches)	Very high (about 19.9 inches)	High (about 11.4 inches)	Very low (about 3.0 inches)
Typical Profile	0-19 in: Silty loam 19-60 in: Silty clay loam	0-33 in: Gravelly sandy loam 33-60 in: Very gravelly sandy loam	0-32 in: Muck 32-60 in: Stratified loamy sand to silty clay loam	0-35 in: Silty clay loam 35-60 in: Stratified silt to silty clay loam	0-33 in: Gravelly sandy loam 33-60 in: Very gravelly sandy loam

Most of the property surrounding the power plant was owned by the parent company, TransAlta, and restricted from access by the public. Thus all survey samples were collected along county roads, a few feet beyond the edge of the pavement. All sample areas were tracked using a handheld GPS device. Three sample areas were less than 1 kilometer from the stacks, one sample area was 1.5 km East, one sample area was 3.3 km Northeast, and two sample areas were 3.2 and 3.4 km Southwest of the power plant exhaust stacks.

All sample bottles were labeled according to sample area and sample number. At the power plant survey site, seven independent sampling areas were chosen, numbered 1 through 7. In each area, four core soil samples were taken at several meters apart from each other, labeled “A” through “D”. For example, the four sample bottles for the first area were labeled 1-A, 1-B, 1-C, and 1-D. All survey site descriptions and GPS coordinates are provided in Table 3.

Table 3, Centralia Power Plant Survey Sheet

CENTRALIA POWER PLANT - SURVEY FIELD SHEET			
Sample Numbers	**GPS Coordinates**	**Topographic Description**	**Geographic Description**
1-A through 1-D	N 46.77639 W 122.82630 Elevation 248 ft.	Grassy area, surrounded by trees, small bushes, and a low hill	3.3 km NE (46.0°) of CPP stacks Map Marker "A"
2-A through 2-D	N 46.75482 W 122.83759 Elevation 238 ft.	Grassy area, flat with a few trees. Line of sight to the plant	1.5 km E (94.3°) of CPP stacks Map Marker "B"
3-A through 3-D	N 46.75356 W 122.85224 Elevation 250 ft.	Grassy area, samples taken in drainage ditch along Big Hanaford Rd.	484 m ExSE (127.1°) of CPP stacks Map Marker "C"
4-A through 4-D	N 46.75449 W 122.86330 Elevation 251 ft.	Line of sight to stacks, grassy area with bushes near the base of a hill	460 m W (250°) of CPP stacks Map Marker "D"
5-A through 5-D	N 46.75495 W 122.86906 Elevation 243 ft.	Adjacent railroad tracks off Big Hanford Rd., grass and gravel area	0.9 km W (260.1°) of CPP stacks Map Marker "E"
6-A through 6-D	N 46.72700 W 122.87091 Elevation 212 ft.	End of Tietzel Rd., major hill coverage, clay and gravel soil composition	3.4 km SxSW (197.8°) of CPP stacks Map Marker "F"
7-A through 7-D	N 46.72965 W 122.87297 Elevation 222 ft.	On Tietzel Rd., flat area, hill coverage, samples taken in drainage ditch	3.2 km SxSW (202.2°) of CPP stacks Map Marker "G"

The seven sample sites are shown in Figure 7, each represented by a red marker. Samples were collected close enough to each other at each site that a single GPS coordinate is sufficiently accurate. Marker “A” corresponds to sample site “1”, marker “B” corresponds to sample site “2”, and so on. The two Centralia Power Plant emission stacks are located between markers “C” and “D” (Google Maps, ACME Mapper 2.0, 2011).

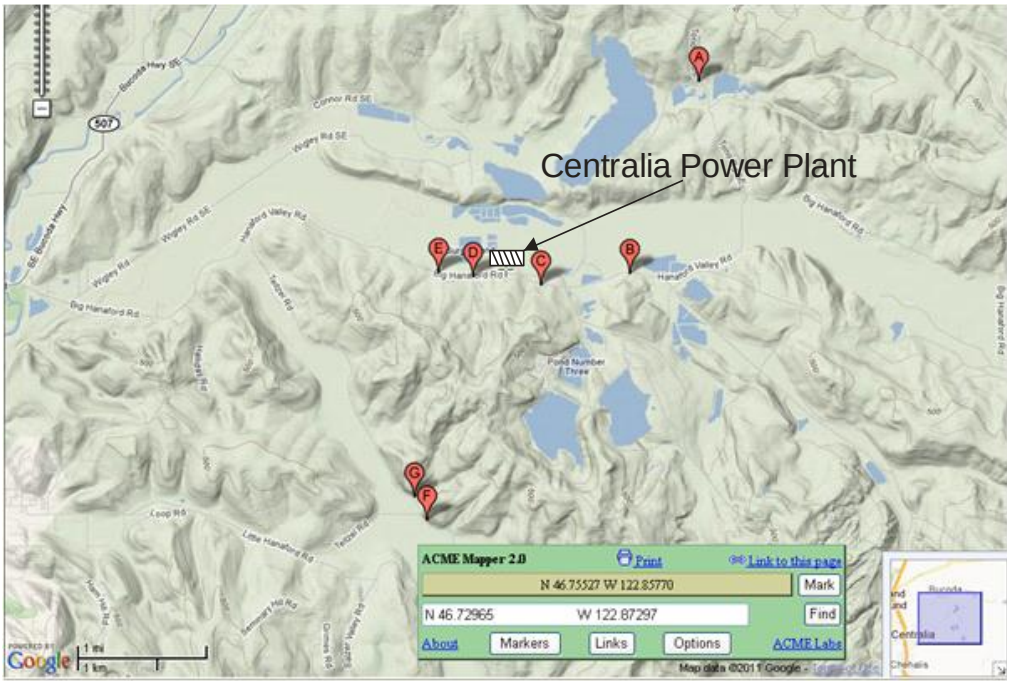

Figure 7, Terrain map, Centralia Power Plant Sample Locations at markers “A” through “F”. © 2011 Google.

Figure 8, CPP sample location 1 at marker “A”. © 2011 Google.

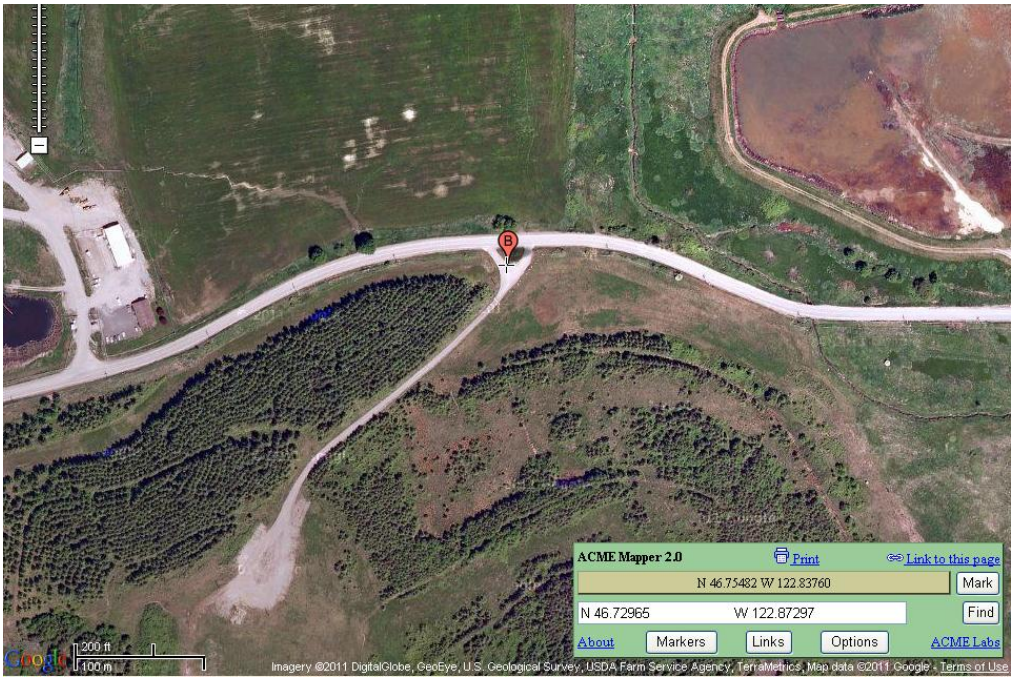

Figure 9, CPP sample location 2 at marker “B”. © 2011 Google.

Figure 10, CPP sample location 3 at marker “C”. Stacks visible in the upper left corner of map. © 2011 Google.

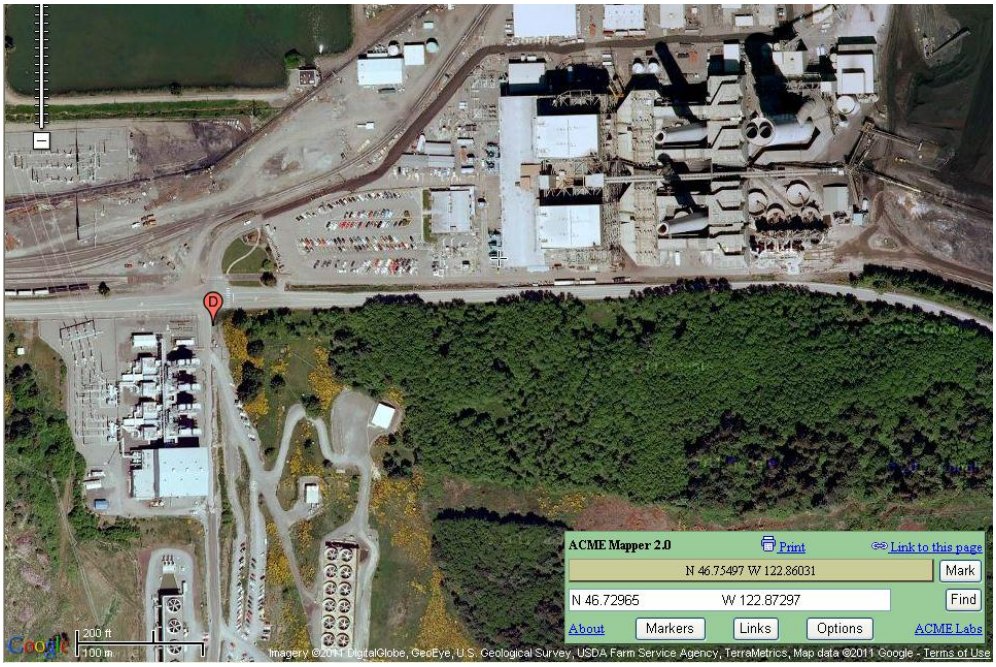

Figure 11, CPP sample location 4 at marker “D”. Stacks visible in the upper right corner of map. © 2011 Google.

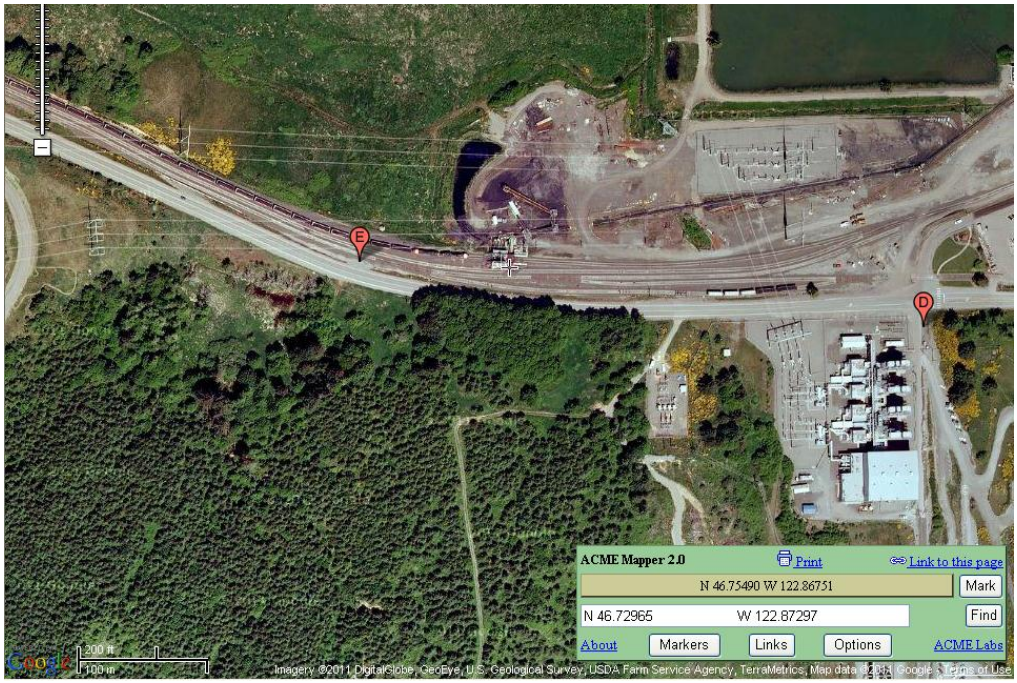

Figure 12, CPP sample location 5 at marker “E”. © 2011 Google.

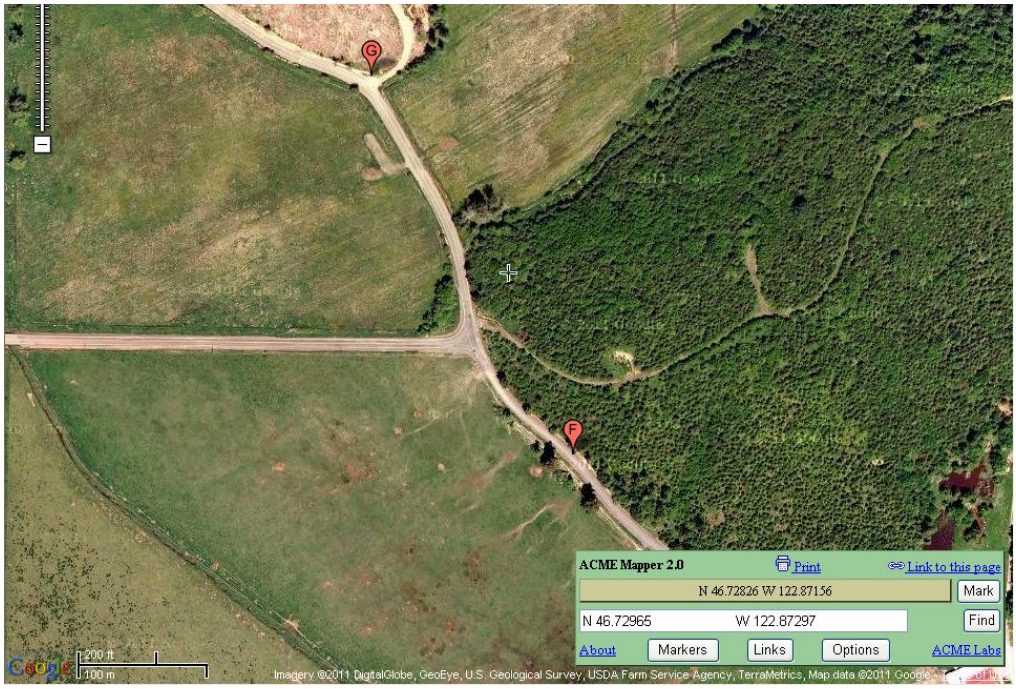

Figure 13, CPP sample locations 6 and 7 at markers “F” and “G”. © 2011 Google.

In collecting reference samples, four independent sampling areas were chosen, labeled “A” through “D”. In each reference area, seven core samples were taken at several meters apart from each other, numbered 1 through 7. To minimize confusion, reference samples also received a designation with the letter “R”. Thus, the labeling convention used for reference sample bottles was R-A-1, R-A-2, and so on. Reference site descriptions and GPS coordinates are provided in Table 4.

Table 4, Reference Samples Survey Sheet

PORT ORCHARD REFERENCE SAMPLES - SURVEY FIELD SHEET				
Sample Numbers	**GPS Coordinates**	**Topographic Description**	**Geographic Description**	**Comments**
R-A-1	N 47.52992 W 122.64178 Elevation 155 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "A"	Taken on flat shoulder adjacent the road
R-A-2	N 47.52993 W 122.64176 Elevation 162 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "A"	Taken on flat shoulder adjacent the road
R-A-3	N 47.52980 W 122.64184 Elevation 166 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "A"	Taken on flat shoulder adjacent the road
R-A-4	N 47.52969 W 122.64183 Elevation 171 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "B"	Taken on flat shoulder adjacent the road
R-A-5	N 47.52959 W 122.64177 Elevation 164 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "B"	Taken on flat shoulder adjacent the road
R-A-6	N 47.52950 W 122.64176 Elevation 159 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "B"	Taken on flat shoulder adjacent the road
R-A-7	N 47.52937 W 122.64177 Elevation 166 ft.	Flat area, grassy, surrounded by trees	West Ave. Map Marker "B"	Taken on flat shoulder adjacent the road

Table 4, continued

PORT ORCHARD REFERENCE SAMPLES - SURVEY FIELD SHEET				
Sample Numbers	**GPS Coordinates**	**Topographic Description**	**Geographic Description**	**Comments**
R-B-1	N 47.50015 W 122.58395 Elevation 155 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "C"	Moist, dense soil in flat area of park
R-B-2	N 47.50007 W 122.58376 Elevation 106 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "C"	Moist, dense soil in flat area of park
R-B-3	N 47.50000 W 122.58355 Elevation 96 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "D"	Moist, dense soil in flat area of park
R-B-4	N 47.49983 W 122.58342 Elevation 91 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "D"	Moist, dense soil in flat area of park
R-B-5	N 47.49962 W 122.58346 Elevation 93 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "E"	Moist, dense soil in flat area of park
R-B-6	N 47.49950 W 122.58364 Elevation 88 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "E"	Moist, dense soil in flat area of park
R-B-7	N 47.49938 W 122.58414 Elevation 81 ft.	Flat area, grassy, surrounded by trees and lake	Long Lake Park Map Marker "F"	Moist, dense soil in flat area of park

Table 4, continued

PORT ORCHARD REFERENCE SAMPLES - SURVEY FIELD SHEET				
Sample Numbers	**GPS Coordinates**	**Topographic Description**	**Geographic Description**	**Comments**
R-C-1	N 47.48507 W 122.64775 Elevation 193 ft.	Flat area, grassy	Lider Rd. Map Marker "G"	Taken along side road in drainage ditch
R-C-2	N 47.48512 W 122.64792 Elevation 201 ft.	Flat area, grassy	Lider Rd. Map Marker "G"	Taken along side road in drainage ditch
R-C-3	N 47.48516 W 122.64796 Elevation 190 ft.	Flat area, grassy	Lider Rd. Map Marker "H"	Taken along side road in drainage ditch
R-C-4	N 47.48522 W 122.64815 Elevation 192 ft.	Flat area, grassy	Lider Rd. Map Marker "H"	Taken along side road in drainage ditch
R-C-5	N 47.48510 W 122.64757 Elevation 191 ft.	Flat area, grassy	Lider Rd. Map Marker "I"	Taken along side road in drainage ditch
R-C-6	N 47.48505 W 122.64741 Elevation 193 ft.	Flat area, grassy	Lider Rd. Map Marker "I"	Taken along side road in drainage ditch
R-C-7	N 47.48492 W 122.64712 Elevation 198 ft.	Flat area, grassy	Lider Rd. Map Marker "I"	Taken along side road in drainage ditch

Table 4, continued

PORT ORCHARD REFERENCE SAMPLES - SURVEY FIELD SHEET				
Sample Numbers	**GPS Coordinates**	**Topographic Description**	**Geographic Description**	**Comments**
R-D-1	N 47.51794 W 122.65601 Elevation 238 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "J"	Field soil dry, compact
R-D-2	N 47.51783 W 122.65607 Elevation 242 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "J"	Field soil dry, compact
R-D-3	N 47.51759 W 122.65620 Elevation 248 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "K"	Field soil dry, compact
R-D-4	N 47.51736 W 122.65648 Elevation 248 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "K"	Field soil dry, compact
R-D-5	N 47.51716 W 122.65680 Elevation 255 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "L"	Field soil dry, compact
R-D-6	N 47.51696 W 122.65669 Elevation 264 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "L"	Field soil dry, compact
R-D-7	N 47.51687 W 122.65651 Elevation 263 ft.	Flat area, grassy, surrounded by trees	Field adjacent school Map Marker "M"	Field soil dry, compact

The four reference areas are shown in Figure 14. Within each reference area soil samples were collected at greater distances from each other (20-50 meters) than were the Centralia Power Plant survey samples. Nevertheless, some samples were taken too close to each other for the ACME Mapper 2.0 program to distinguish them. In such cases, samples are denoted on the map with the same letter as the next closest sample.

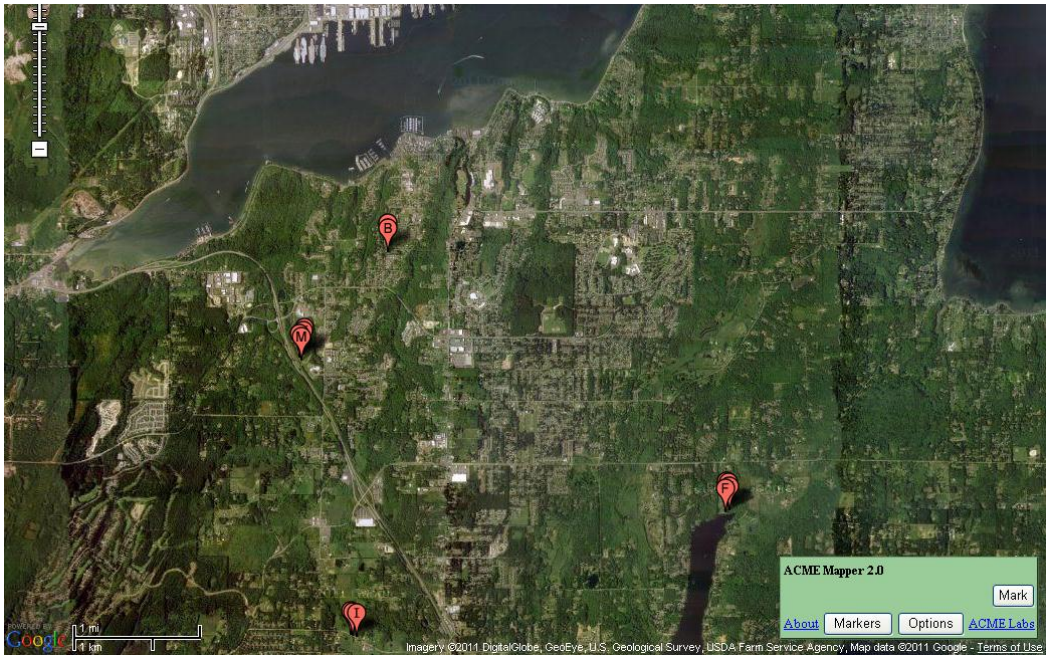

Figure 14, All Reference Area Sample Locations, Port Orchard, Washington. © 2011 Google.

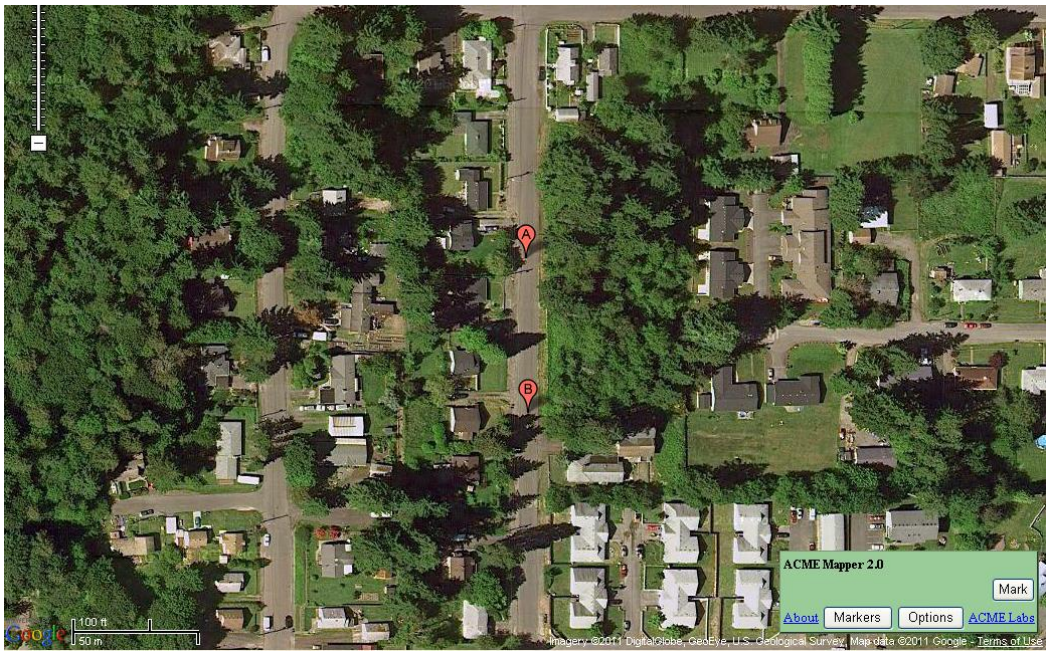

Figure 15, Reference Area A. Seven samples were collected along the shoulder of West Avenue between markers “A” and “B”. © 2011 Google.

Figure 16, Reference Area B. Seven samples were collected at Long Lake Park near markers “C” through “F”. © 2011 Google.

Figure 17, Reference Area C. Seven samples were collected along the shoulder of Lider Road near markers “I” through “H”. © 2011 Google.

Figure 18, Reference Area D. Seven samples were collected in the field behind Cedar Heights Jr. High School near markers “J” through “M”. © 2011 Google.

SAMPLE PREPARATION AND ANALYSIS

The soil samples were weighed using a precision balance, accurate to a tenth of a gram. A tare weight was measured using an empty 500 mL bottle, and subtracted from all soil sample gross weight measurements.

Gamma spectroscopic analysis was performed on each of the soil samples using a high purity germanium (HPGe) detector. Spectroscopic sample analysis was split between two HPGe detectors. To minimize any bias in the results due to qualitative differences between the detectors, each detector was used to analyze one half of the survey samples and one half of the reference samples.

Measuring the activity of a radionuclide in a sample is achieved by first converting the net photopeak area in to a count rate. Once a count rate has been obtained, the efficiency of the detector at that gamma ray energy (and a given source geometry) can then be used to determine the total activity in the sample.

An analytic fit of the data in the vicinity of the peak yields a Gaussian peak with a small additive component representing the low-energy tailing of the peak. The background continuum under the peak is subtracted out to give the net peak area, or the total counts measured. The total counts are then divided by the count time to give a sample count rate (Knoll, 1989, p. 575).

To determine whether a sample contains radioactivity, a count rate is chosen which is above the count rate of a blank sample (in this case, a 500 mL bottle of water). This count rate is the decision level (L_c) and any sample analysis which exceeds the decision level is considered to have detectable activity.

If the count rate of a blank sample exceeds the decision level only 5% of the time, then the net count rate of a sample must be greater than the net count rate of the blank by 1.645 standard deviations (1.645σ) to be detected (based on statistical confidence intervals under a Normal Curve) . The decision level considers only a type I or alpha error: claiming the sample contains activity when it does not, also known as a false positive. A 95% confidence level means that a sample containing no activity will wrongly be identified as containing activity 5% of the time.

A type II or beta error occurs in counting statistics when activity is present in the sample above the decision level, but it is not identified. The type II error is considered along with the type I error in determining the lower limit of detection (LLD) which is given by the equation:

$$LLD = 3.29\sqrt{r_b t_b\left(1+\frac{t_g}{t_b}\right)+3}$$

Where r_b is the background count rate, t_b is the background count time, and t_g is the gross sample count time.

The minimum detectable activity (MDA) of a counting system is defined as the smallest quantity of radioactivity present in a sample which can be measured. The MDA is dependent on the counting efficiency of a system and on the lower limit of detection. It is given by the following equation:

$$MDA = \frac{3.29\sqrt{r_b t_b\left(1+\frac{t_g}{t_b}\right)+3}}{Kt}$$

Where K is a factor including detector efficiency, chemical yield and transformation rate into the desired units (in this case, pCi/g) and t is the sample counting time.

For radionuclide-specific soil sample analysis, the decision level L_c for the detector must be below the DCGL, which for Ra-226+C is 0.6 pCi/g. A decision level of 0.5 pCi/g was chosen, and to ensure it would be reached for soil sample analysis, a background sample of 500 mL de-ionized water was used to determine the necessary count time of two hours. All soil samples were set for gamma spectroscopic analysis for two hours. Sample results sheets were reviewed for errors and anomalies, and pertinent data was tabulated in Appendix A.

Quality Assurance

A scale check using a 100 g check weight was performed prior to sample weighing. Both HPGe detectors had successful calibration checks performed using a known radioactive source (Na-22 and Eu-155) prior to and immediately following sample analysis.

Sample placement on each detector was automated, so geometric differences between sample counting were minimal. A mass quantity error of 1% was incorporated into the radioactivity concentration analysis of each sample.

RESULTS

Survey Area, Centralia, WA

It was found that all but one of the twenty-eight survey samples had detectable Ra-226. The highest level found was 3.2 +/- 1.5 pCi/g (5.3 x $DCGL_W$). The average concentration of Ra-226 in the survey soil was 1.59 pCi/g, (2.7 x $DCGL_W$) and the median concentration was 1.37 pCi/g (see Table 5). Uranium-235 was not detected in any of the soil samples.

Figure 19 shows the average concentrations of Ra-226 with their uncertainties found in each of the seven areas (four soil samples per area) sampled near the Centralia Power Plant.

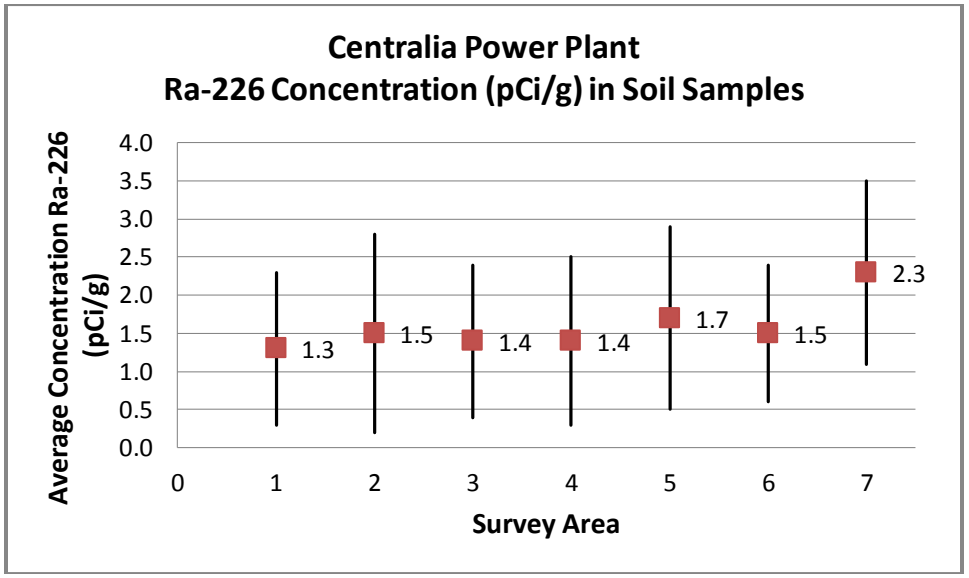

Figure 19, CPP average Ra-226 soil concentration in each survey area.

Figure 20 shows the same average concentrations of Ra-226 with their uncertainties, but the seven sample areas are listed in order of distance from the

power plant stacks, nearest to farthest. Sample collection area 4 was closest to the power plant (460 m), while sample area 6 was furthest away (3400 m).

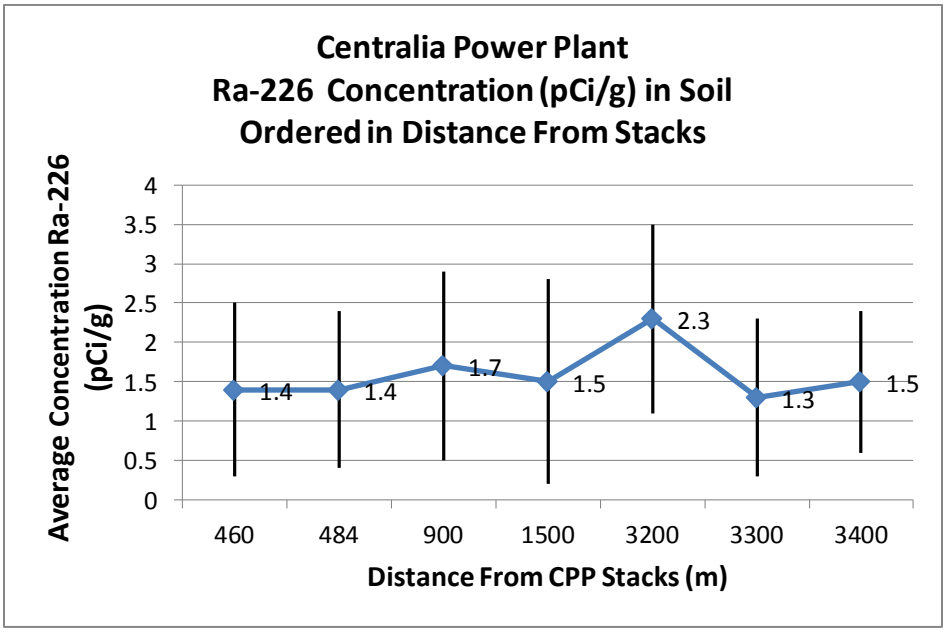

Figure 20, CPP average Ra-226 soil concentration ordered in distance from stacks.

Also of note, six survey samples (21%) contained detectable Cs-137, a radionuclide which is not associated with coal-fire emissions, but is commonly detected in environmental samples as a result of nuclear testing, and accidents such as occurred at Chernobyl, Ukraine in 1986 and Fukushima-Daiichi, Japan in 2011. The highest level of Cs-137 identified in Centralia, Washington was 0.223 +/- 0.060 pCi/g, with an average concentration among those samples which had detectable cesium-137 of 0.122 pCi/g.

Reference Area, Port Orchard, WA

In fourteen of the twenty-eight reference samples, Ra-226 was identified, while U-235 was not detected in any of the samples. The highest concentration of radium was 1.5 +/- 1.1 pCi/g, and the average concentration of all reference samples was just below the $DCGL_W$ at 0.59 pCi/g. The median concentration was 0.56 pCi/g.

Figure 21 shows the average concentrations of Ra-226 with their uncertainties found in each of the four reference areas (seven soil samples per area) sampled near Port Orchard, Washington.

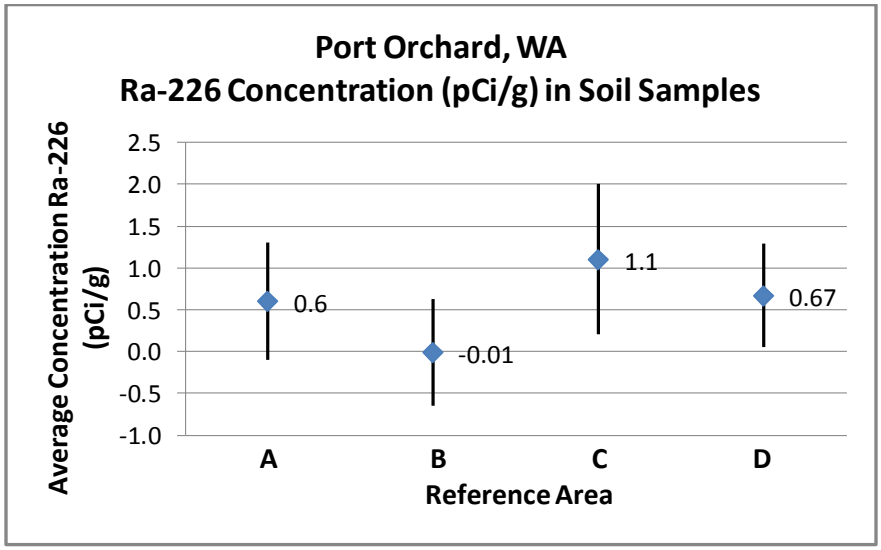

Figure 21, Port Orchard average Ra-226 soil concentration in each survey area.

Cesium-137 was detected in twenty-one of the twenty-eight reference samples (75%). Despite being more prevalent in the soil, the highest concentration found in Port Orchard, Washington was only 0.197 +/- 0.047 pCi/g, with a detectable average concentration of 0.073 pCi/g.

Table 5, Centralia Power Plant and Reference Sample radioactivity concentrations

	Centralia Power Plant Samples pCi/g	Reference Samples pCi/g
Average Ra-226	**1.59**	**0.59**
Median Ra-226	**1.37**	**0.56**
Maximum Ra-226	**3.2**	**1.5**
Minimum Ra-226	**0.61**	**-0.55**
Range Ra-226	**2.59 (3.87σ)**	**2.05 (3.66 σ)**
σ Ra-226	**0.67**	**0.56**
Combined Range Ra-226	**3.75 (4.75σ)**	
Combined σ Ra-226	**0.79**	
Average Cs-137	0.122	0.073
Maximum Cs-137	0.223	0.197

DISCUSSION

It is clear that the soil which was sampled around the coal-fired power plant had elevated levels of radium relative to that found in soil taken from the reference area. Whether or not those levels are statistically significant from a radiological perspective can be determined using the non-parametric Wilcoxon Rank Sum test. Because the area was treated as a Class 3 survey unit, the Elevated Measurement Comparison is not performed against each measurement. Rather, sample points above the $DCGL_W$ of 0.6 pCi/g would be flagged for further investigation.

Comparing our measured standard deviation of 0.79 with our assumed value of 0.3 it is clear that, under normal NRC release criteria, unnecessary remediation may result as there is an increased risk of a Type II error. This is only a concern if the statistical test indicates that the null hypothesis is accepted.

Since the gamma spectroscopic analysis was nuclide specific, and our radionuclide of concern is found in background, MARSSIM directs us to use the non-parametric Wilcoxon Rank Sum (WRS) statistical test (MARSSIM 8.4.1).

The purpose of the WRS test is to determine whether or not residual activity in a survey unit (as a whole) exceeds the $DCGL_W$. The advantage of the nonparametric WRS test, as NUREG-1575 notes, is that it does not assume that the data are normally or log-normally distributed.

In the section “Reporting Survey Results” (MARSSIM 2.3.5) we are instructed to, whenever possible, report actual results of an analysis together with its uncertainty even when a measurement is below the detection limit. “Even

negative results and results with large uncertainties can be used in the statistical tests to demonstrate compliance" (MARSSIM 2.3.5).

Only one soil sample from the survey unit was less than detectable, but exactly half of the reference samples were below the detection limit. While the non-parametric WRS test can be used with as much as 40% of the results reported as non-detects, "it is better to report the actual results and avoid the possibility of exceeding this limit" (MARSSIM 2.3.5). For this reason, all analysis results for Ra-226 concentrations, including negative concentrations, are recorded in Appendix A.

The Null Hypothesis tested by the WRS test is that, "The median concentration in the survey unit exceeds that in the reference area by more than the $DCGL_W$" (MARSSIM 8.4.1). We assume the Null Hypothesis is true, and we perform the WRS test to determine whether or not the Null Hypothesis should be rejected. MARSSIM provides us with the six steps (MARSSIM 8.4.2) used to apply the WRS:

1. Obtain the adjusted reference area measurements, Z_i, by adding the $DCGL_W$ to each reference area measurement, X_i. $Z_i = X_i + DCGL_W$
2. The *m* adjusted reference sample measurements, Z_i from the reference area and the *n* sample measurements, Y_i, from the survey unit are pooled and ranked in order of increasing size from 1 to *N*, where $N = m + n$.
3. If several measurements are tied (i.e., have the same value), they are all assigned the average rank of that group of tied measurements.
4. If there are *t* "less than" values, they are all given the average of ranks from 1 to t. Therefore, they are all assigned the rank $t(t+1)/(2t) = (t+1)/2$, which is the average of the first *t* integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as "less than" values.
5. Sum the ranks of the adjusted measurements from the reference area, W_r. Note that since the sum of the first *N* integers is $N(N+1)/2$, one can equivalently sum the ranks of the measurements from the survey unit, W_s, and compute $W_r = N(N+1)/2 - W_s$.

6. Compare W_r with the critical value given in Table I.4 for the appropriate values of *n*, *m*, and α. If W_r is greater than the tabulated value, reject the hypothesis that the survey unit exceeds the release criterion.

Table I.4 only includes values up to m = 20, n =20. For survey or reference sample quantities exceeding 20, and where there are many ties, MARSSIM gives the following equation:

$$\text{Critical Value} = m(n+m+1)/2 + z\sqrt{\frac{nm}{12}\left[(n+m+1) - \sum_{j=1}^{g}\frac{t_j(t_j^2-1)}{(n+m)(n+m-1)}\right]}$$

Where g is the number of groups of tied measurements and t_j is the number of tied measurements in the jth group (MARSSIM I-10).

z is the (1-α) percentile of a standard normal distribution, which, for an α value of 0.05, MARSSIM provides as 1.645.

Thus, for our values the equation becomes

$$\text{Critical Value} = 28(57)/2 + 1.645\sqrt{\frac{(28)(28)}{12}\left[(57) - \sum_{j=1}^{6}\frac{t_j(t_j^2-1)}{(56)(55)}\right]}$$

$$\text{Critical Value} = 798 + 1.645\sqrt{65.33\ (57-1.12)}$$

$$\text{Critical Value} = 897.4$$

As shown in Appendix A, the value of W_r (sum of the ranks of the adjusted reference area measurements) is 674, which is less than our critical value, 897.4. Therefore, we fail to reject (i.e., we accept) the hypothesis that the survey unit exceeds the release criterion.

CONCLUSION

If coal fired power plants were forced to adhere to the standards which are currently applied to nuclear power plants, this environmental study of the concentration of Radium-226 in surface soil suggests that the area surrounding the Centralia Power Plant would likely fail the Wilcoxon Rank Sum test as a MARSSIM Class 3 survey unit. The levels of naturally occurring Radium-226 found in 28 soil samples collected within 3.4 kilometers of the exhaust stacks were measurably higher than the same number of reference samples collected in similar soil from Port Orchard, Washington. This study also indicates that if the area near the coal power plant were regarded as a radiologically controlled area, it may need to be classified into multiple Class 1 survey units, since the levels of Ra-226 present in surface soil were commonly found to be above the $DCGL_W$ screening level of 0.6 pCi/g. This would entail grid-sampling of 100% of each survey unit (each survey unit having a suggested maximum area of 2,000 m^2), and establishing a $DCGL_{EMC}$ (MARSSIM 4.6 and 8.5.1).

The concentrations of radium found in this academic investigation indicate that fly ash being emitted from the Centralia Power Plant may be increasing the background radiation levels to the general public by as much as 25 to 50 millirem (mrem) per year.[2] Assuming the preliminary findings of this investigation are correct, an increased dose to the public of 25 to 50 mrem annually is comparatively small. According to the American Nuclear Society, for

[2] $DCGL_{Ra\text{-}226}$ = 0.6 pCi/g. The average concentration of Ra-226 in surface soil near the Centralia Power Plant was 1.0 pCi/g higher than that found in reference soil from Port Orchard, WA. (1.0/0.6) x 25 mrem/year = 41.7 mrem.

instance, choosing to live in Flagstaff, Arizona – or anywhere else in the Colorado Plateau area – rather than along the Atlantic coast will increase one's dose by an average of 47 mrem a year (Radiation Dose Chart , 2011).

While it is true that the findings of this study suggest that, in the hypothetical, the Centralia Power Plant may not pass NRC release criteria, the converse may also be said. Namely, if the radioactive emissions of a coal fired power plant pose a sufficiently minimal risk to the public to not require regulation, why should the regulation of radioactive emissions from a nuclear facility be any more stringent? Undoubtedly, any difference in standards is grounded in political realities and the public perception of nuclear sites versus non-nuclear sites. But radionuclides found in nature are – all other things being equal – no more beneficial or harmful to humanity than those produced within the confines of a nuclear reactor core. Statutes enacted and regulations enforced using one standard for "nuclear" facilities and a different standard for "non-nuclear" facilities only reinforces the unfounded fears commonly associated with radioactivity and nuclear power today.

Regulatory bodies should review the data from non-nuclear facilities such as the Centralia Power Plant and consider a more standardized approach to those regulations imposed upon nuclear facilities.

Survey Improvements

MARSSIM does not provide explicit guidance concerning the steps to be taken if it is shown that a survey unit fails (MARSSIM 8.5.3). However, the first

step is to verify the results of the Final Status Survey. In this case, there are several items that could be improved upon which may yield a different outcome.

Many of the reference samples analyzed did not identify Radium-226. It is possible that the soil sampled in the reference area is not representative of the soil in Centralia, Washington. Sampling closer to the power plant, but still several kilometers upwind might show natural Ra-226 concentrations higher than what was found in Port Orchard, Washington. Supporting this possibility is the fact that Uranium-235 was not identified in any soil sample collected. This was unexpected since fly ash is known to contain trace quantities of uranium and radium. The direct sampling of fly ash released from the stacks would also provide valuable information about naturally occurring radioactivity concentrations be released to the atmosphere.

Performing the gamma spectroscopic analysis for a longer count time (e.g., twelve hours instead of two) would lower the decision levels L_c and the associated Ra-226 uncertainties. Samples with lower radium concentrations would be detected, giving more accurate data.

Another improvement would be to dry the soil samples using a convection oven. Removing the water content would reduce the variability in mass measurements (directly associated with radioactivity concentration) between samples taken in moist and dry areas.

Slightly more accurate data could also be obtained by calibrating the HPGe detectors using a Ra-226 and U-235 source, instead of a Na-22 and Eu-155 source. Using the radium and uranium source would give a precise energy

calibration for the gamma energies of interest, namely 186.2 keV for radium and the 187.5 keV and 143.8 keV energies for uranium.

Arguably the best improvement in this study would be to conduct sampling around the power plant in areas where Ra-226 (and U-235) is most likely to be found. Most of the property in the immediate area surrounding the Centralia Power Plant stacks is owned by TransAlta Corporation. It was not possible to sample in the direct path of the plume as a result of restricted access. Better sampling locations would be North of the stacks in the flat, grassy fields, and along the hill bordering the South side of the Plant. Only then could a truly representative and unbiased survey be conducted offering the most reliable conclusions.

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APPENDIX A

Soil Samples									
Sample Number	Gross Weight	Tare Weight	Net Weight	Ra-226 (pCi/g)	Ra-226 Uncertainty (pCi/g)	Area	Adjusted Ra-226 Data	Ranks	Reference Area Ranks
1-A	817.9	58.0	759.9	1.03	0.81	S	1.03	20	0
1-B	650.2	58.0	592.2	1.9	1.0	S	1.90	45	0
1-C	636.9	58.0	578.9	1.3	1.2	S	1.30	25.5	0
1-D	557.9	58.0	499.9	0.87	0.96	S	0.87	13	0
2-A	514.5	58.0	456.5	1.5	1.3	S	1.50	34	0
2-B	496.9	58.0	438.9	2.4	1.6	S	2.40	53	0
2-C	444.0	58.0	386.0	1.3	1.2	S	1.30	25.5	0
2-D	365.0	58.0	307.0	0.98	0.98	S	0.98	18	0
3-A	655.5	58.0	597.5	0.61	0.67	S	0.61	5	0
3-B	522.3	58.0	464.3	1.3	1.0	S	1.30	25.5	0
3-C	552.7	58.0	494.7	2.2	1.2	S	2.20	51	0
3-D	660.2	58.0	602.2	1.4	1.2	S	1.40	31.5	0
4-A	691.9	58.0	633.9	0.93	0.88	S	0.93	17	0
4-B	674.1	58.0	616.1	1.51	0.92	S	1.51	35.5	0
4-C	492.1	58.0	434.1	1.8	1.4	S	1.80	44	0
4-D	449.4	58.0	391.4	1.2	1.2	S	1.20	23	0
5-A	407.6	58.0	349.6	3.2	1.5	S	3.20	56	0
5-B	566.4	58.0	508.4	1.3	1.3	S	1.30	25.5	0
5-C	766.2	58.0	708.2	1.34	0.83	S	1.34	30	0
5-D	577.4	58.0	519.4	1.11	0.99	S	1.11	22	0
6-A	654.3	58.0	596.3	0.83	0.81	S	0.83	11	0
6-B	751.0	58.0	693.0	1.09	0.79	S	1.09	21	0
6-C	614.8	58.0	556.8	2.1	1.1	S	2.10	49.5	0
6-D	568.9	58.0	510.9	2.04	0.84	S	2.04	48	0
7-A	533.3	58.0	475.3	2.9	1.3	S	2.90	55	0
7-B	532.4	58.0	474.4	2.3	1.0	S	2.30	52	0
7-C	386.7	58.0	328.7	2.7	1.6	S	2.70	54	0
7-D	511.2	58.0	453.2	1.4	1.0	S	1.40	31.5	0

APPENDIX A (cont.)

Soil Samples									
Sample Number	Gross Weight	Tare Weight	Net Weight	Ra-226 (pCi/g)	Ra-226 Uncertainty (pCi/g)	Area	Adjusted Ra-226 Data	Ranks	Reference Area Ranks
R-A-1	565.0	58.0	507.0	0.006	0.51	R	0.606	4	4
R-A-2	486.3	58.0	428.3	0.40	0.64	R	1.00	19	19
R-A-3	724.0	58.0	666.0	0.28	0.41	R	0.88	14.5	14.5
R-A-4	462.1	58.0	404.1	1.2	1.2	R	1.80	43	43
R-A-5	510.2	58.0	452.2	0.31	0.59	R	0.91	16	16
R-A-6	633.4	58.0	575.4	1.03	0.77	R	1.63	39	39
R-A-7	534.7	58.0	476.7	1.16	0.89	R	1.76	42	42
R-B-1	444.2	58.0	386.2	-0.55	0.62	R	0.05	1	1
R-B-2	523.0	58.0	465.0	0.28	0.57	R	0.88	14.5	14.5
R-B-3	514.9	58.0	456.9	0.21	0.57	R	0.81	9.5	9.5
R-B-4	411.5	58.0	353.5	0.21	0.74	R	0.81	9.5	9.5
R-B-5	375.3	58.0	317.3	-0.32	0.78	R	0.28	2	2
R-B-6	439.8	58.0	381.8	0.24	0.67	R	0.84	12	12
R-B-7	548.7	58.0	490.7	-0.15	0.54	R	0.45	3	3
R-C-1	556.8	58.0	498.8	1.5	1.1	R	2.10	49.5	49.5
R-C-2	507.8	58.0	449.8	1.05	0.93	R	1.65	40	40
R-C-3	587.7	58.0	529.7	0.72	0.72	R	1.32	28.5	28.5
R-C-4	534.2	58.0	476.2	1.13	0.84	R	1.73	41	41
R-C-5	542.2	58.0	484.2	1.00	0.91	R	1.60	38	38
R-C-6	585.0	58.0	527.0	0.72	0.73	R	1.32	28.5	28.5
R-C-7	701.1	58.0	643.1	1.36	0.80	R	1.96	46	46
R-D-1	568.7	58.0	510.7	0.18	0.52	R	0.78	7.5	7.5
R-D-2	804.2	58.0	746.2	0.10	0.39	R	0.70	6	6
R-D-3	716.4	58.0	658.4	0.18	0.43	R	0.78	7.5	7.5
R-D-4	690.2	58.0	632.2	0.91	0.78	R	1.51	35.5	35.5
R-D-5	649.9	58.0	591.9	0.89	0.71	R	1.49	33	33
R-D-6	745.3	58.0	687.3	1.43	0.77	R	2.03	47	47
R-D-7	652.6	58.0	594.6	0.99	0.75	R	1.59	37	37
SUM =								1596	674