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Error Analysis of CM Data Products Sources of Uncertainty

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1 INTRODUCTION

This goal of this project is to address the current inability to assess the overall error and uncertainty of data products developed and distributed by DOE's Consequence Management (CM) Program. This is a widely recognized shortfall, the resolution of which would provide a great deal of value and defensibility to the analysis results, data products, and the decision making process that follows this work. A global approach to this problem is necessary because multiple sources of error and uncertainty contribute to the ultimate production of CM data products. Therefore, this project will require collaboration with subject matter experts across a wide range of FRMAC skill sets in order to quantify the types of uncertainty that each area of the CM process might contain and to understand how variations in these uncertainty sources contribute to the aggregated uncertainty present in CM data products. The ultimate goal of this project is to quantify the confidence level of CM products to ensure that appropriate public and worker protections decisions are supported by defensible analysis.

This project seeks to develop a probabilistic framework to characterize the CM process and the interrelated nature of error and uncertainty propagation that contributes to the overall uncertainty in CM data products. This framework will be developed for a single CM data product that will serve as a proof of concept. The first step of this work is the identification of error and uncertainty sources for this specific data product. The purpose of this report is to describe each of these identified sources of error and uncertainty.

This scope of this TI project is limited to the analysis of the uncertainty associated with Public Protection Derived Response Levels (DRLs), which are used to evaluate the radiological impacts to members of the public from exposure to radioactive material. A Derived Response Level (DRL) is a level of radioactivity in the environment that would be expected to produce a dose equal to the corresponding Protective Action Guide (PAG). The CM data products for which Public Protection DRLs are calculated are used to help decision makers determine where protective actions (e.g., sheltering, evacuation, or relocation of the public) may be warranted.

To create a finished product, ready for distribution to decision makers, health physics calculations are performed to estimate the likely dose that may be received by the public following a radiological release. These calculations rely on data which may be collected from one of several methods: analytical results from laboratories, results from Aerial Measurement Systems, or field measurements made by ground-based monitoring teams. Results of the calculations are then applied to create contours on a data grid developed using NARAC plume predictions.

The goal of this analysis is to characterize uncertainty in the CM data product development process. This does not require the characterization of uncertainty inherent to the situation under analysis; sources of uncertainty such as the type of release, location of release, weather, etc., will be held constant for this project in order to allow for the examination of the impact of sources of uncertainty within the analysis process itself. A demonstration scenario has been selected for this analysis with the following characteristics:

- Detonation of an RDD on level terrain within a stable wind class
- Cs-137 is the only radionuclide in the source term
- Default particle size distribution

The following sections describe the sources of error and uncertainty identified in each portion of the CM analysis process. Calculation terms that contribute to uncertainty in the health physics calculations of Public Protection DRLs are described in Section 2. Sources of uncertainty in data collection are given in Section 3. Detailed information on possible sources of uncertainty in NARAC plume predictions is given in Section 4.

2 PUBLIC PROTECTION DRL SOURCES OF UNCERTAINTY

Public Protection DRLs can be based upon integrated air activity, areal activity, dose rate, and exposure rate. The parameters used in the calculation of these DRLs are listed in Table 1 and are either constant or time-varying inputs. The analysis is limited to a single age group (Adult) and organ (Whole Body), and the Early Phase (Total Dose) which includes dose from all four primary pathways: inhalation of radioactive material during plume passage, external exposure (plume submersion) during plume passage, inhalation of resuspended material deposited by a release, and external exposure (groundshine) from material deposited by a release.

The following terms contribute to the uncertainty in health physics analyses underlying the DRL calculation. See Method 1.1 in the FRMAC Assessment Manual for details on the use of these terms.

Table 1: Public Protection Derived Response Levels (DRL) Calculation Parameter List.

Term	Units	Definition	Fixed/Varies	Calculation
$\tilde{A}$	$\frac{\mu Ci \cdot s}{m^3}$	Integrated air activity of radionuclide *i* in a release.	TBD by Data Collection or prediction	$DRL_{\tilde{A}}$, *Pl_InhDP*, *Pl_ExDP*
BR_{AA}	$\frac{m^3}{s}$	Activity-Averaged Breathing Rate, the average volume of air breathed per unit time by an adult male (ICRP94, Table B.16B).	Varies	*Dp_InhDP*
BR_{LE}	$\frac{m^3}{s}$	Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP94, Table 6).	Varies	*Pl_InhDP*
Dp_ExDC	$\frac{mrem \cdot m^2}{\mu Ci \cdot hr}$	Deposition External Dose Coefficient, the external dose rate from radionuclide *i* per unit activity deposited on the ground.	Varies	*Dp_ExDP*, *Dp_MExDF*
Dp	$\frac{\mu Ci}{m^2}$	Deposition, the activity of radionuclide *i* per unit area of ground (areal activity).	TBD by Data Collection or prediction	DRL_{Dp}, *Dp_MExDF* , *KP*, *WP*
GRF	unitless	Ground Roughness Factor, a constant (0.82) that compensates for the fact that the external exposure is not coming from an infinite flat plane (An02).	Varies	*Dp_ExDP*, *Dp_MExDF*
InhDC	$\frac{mrem}{\mu Ci}$	Inhalation Dose Coefficient, the committed dose coefficient for inhalation of radionuclide *i*.	Varies	*Pl_InhDP*, *Dp_InhDP*

Term	Units	Definition	Fixed/Varies	Calculation
K	m^{-1}	Resuspension Factor, the fraction of radioactive material transferred from the surface to the breathing zone at given time t after initial deposition.	Varies	KP
PAG	mrem	Protective Action Guide for total dose.	Fixed	$DRL_{\tilde{A}}$, DRL_{Dp}
Pl_ExDC	$\frac{\text{mrem}\cdot\text{m}^3}{\mu\text{Ci}\cdot\text{s}}$	Plume External Dose Coefficient, the external dose rate from submersion in radionuclide i in the plume.	Varies	Pl_ExDP
$XDCF_C$	$\frac{\text{mrem}}{\text{mR}}$	Exposure to Dose Conversion Factor (chronic), the constant used to convert external exposure (mR) to deep tissue (1 cm) dose (mrem), 1.0.	Considering known	DRL_{XR}
WF	unitless	Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind).	Varies	DRL_{Dp}, Dp_MExDF
Y_α	$\frac{\mu\text{Ci}_\alpha}{\mu\text{Ci}_{nt}}$	Yield, the alpha activity per total (nuclear transformation) activity of radionuclide i.	Considering known	$DRL_{\alpha,\tilde{A}}$, $DRL_{\alpha,Dp}$
Y_β	$\frac{\mu\text{Ci}_\beta}{\mu\text{Ci}_{nt}}$	Yield, the beta activity per total (nuclear transformation) activity of radionuclide i.	Considering known	$DRL_\beta,\tilde{A}$, $DRL\beta_{,Dp}$

3 DATA COLLECTION SOURCES OF UNCERTAINTY

The health physics dose calculations are based on measured or projected concentrations of radionuclides in the environment. Measured values can be provided through multiple sources, including analytical laboratory results or field measurements obtained either through aerial measuring systems or ground-based monitoring teams. Projections are usually obtained from atmospheric modelling calculations performed using NARAC plume projections.

Sources of uncertainty in measurement values are discussed in this section. Sources of uncertainty from NARAC modelling projections are discussed in Section 4.

3.1 Laboratory Analysis

The information detailed in this section describes the sources of uncertainty within the laboratory analysis function and was provided by FRMAC Lab Analysis Subject Matter Experts (SMEs). The evaluation is based on the scenario described in the introduction. Based on this scenario, an evaluation was conducted for the sources of uncertainly that could be identified and quantified for the laboratory sample analysis of ground deposition samples.

A discussion of the methodology employed by the FRMAC Lab Analysis regarding uncertainty is contained in the FRMAC Lab Analysis Manual, Appendix B [1]. The manual describes two principle factors that contribute to the overall uncertainty in sample analytical results: **sample count time** and **background count rate**. In this case, overall uncertainty is inversely proportional to both sample count time and background count rate. Thus, relatively high sample count times and background count rates would produce relatively low overall uncertainties.

For default ground deposition analyses, FRMAC requests laboratories to provide results that meet or are below a Critical Level (L_c) of 10% of the Analytical Action Level (AAL) determined by the FRMAC Assessment scientists. In meeting this specified detection level, the relative uncertainty in the sample results are estimated to be **~10%**. This estimate is based on a range of typical count times and background count rates. The table below demonstrates how the relative uncertainty at the AAL varies based on count time and background count rate.

Table 2: Relative Uncertainty Estimates at 10% of the Default Analytical Action Level

Background count rate (CPM)	Sample Count Time (minutes)		
	1	10	100
.001	138%	78.2%	44.3%
1	25.4%	15.1%	11.1%
10	15.1%	9.9%	7.5%
100	9.9%	7.5%	6.6%

The following equation is used to calculate the relative uncertainty at the AAL:

$$\frac{\sigma_{R_{AAL}}}{R_{AAL}} = \frac{R_{L_C}}{R_{AAL}} \frac{1}{k} \sqrt{\left(\frac{R_{AAL}}{R_{L_C}}\right)\left(k\sqrt{\frac{1}{R_B T_S}}\right) + 1}$$

k = 1.645

$$\frac{R_{L_C}}{R_{AAL}} = 10\%$$

where:

$\frac{\sigma_{R_{AAL}}}{R_{AAL}}$ = relative uncertainty at the Analytical Action Level

R_{L_C} = count rate at the Critical Level (L_C)

R_{AAL} = count rate at the Analytical Action Level

R_B = background count rate

T_S = sample count time

k = normal deviate for a 1-sided confidence level (1.645 the 95% confidence level)

3.2 Aerial Measuring System

Due to the heavy involvement of AMS personnel in the Presidential Inauguration, this portion of the report has not been completed. This information will be included in an updated report to be completed as soon as possible following the Inauguration.

3.3 Field Monitoring

The sources of uncertainty for the field monitoring portion of the CM data product analysis flow are given in this section. For the purposes of this project, the field monitoring portion of this process uses an on-site (in-situ) gamma spectroscopy measurement of radioactive material deposited on the ground.

The sources of uncertainty in this measurement are given as follows:

- **Efficiency calibration data**: When a detector is characterized, several energy spectra are collected using NIST traceable radioactive sources. The efficiency is determined by comparing the measured counts in spectrum peaks with the gamma rays expected from the sources. The number of counts in the spectrum peaks are dependent upon the strength of the sources and the collection time, and the uncertainty in the number of counts is related to the number of counts. Some gamma rays will be more abundant than others, thus the uncertainty of the efficiency for the peaks will differ.
- **Efficiency calibration parameterization**: After the efficiency is measured at several discrete energies, the points are fit to a function. The functional form is used for the efficiency from this point forward. The function is obtained by least squares minimization, thus it does not necessarily pass through the measured points.
- **Efficiency calibration interpolation/integration**: For in-situ measurements of freshly deposited material, the material is assumed to be uniformly distributed on the surface of the ground. The peaks in the spectrum come from gamma rays coming from the half sphere below the detector. The detector is not spherically symmetric, so the efficiency must be determined as a function of angle. The number of gamma rays hitting the detector also varies as a function of the angle. The efficiency is not measured for an infinite plane source, but is calculated based on point source measurements plus interpolation across energies and angle, and integration of the expected single from the half sphere.
- **Statistical uncertainty on the measurement**: The number of counts in a gamma ray peak will depend upon the amount of activity on the ground and the collection time. The uncertainty on the measurement is related to the counts in the spectrum peak.

4 NARAC Plume Predictions Sources of Uncertainty

This section documents the major categories of uncertainty specifically impacting the National Atmospheric Release Advisory Center (NARAC) atmospheric plume modeling results. Individual parameters/inputs have been grouped into major categories based on their impact on NARAC products. The following subsections provide descriptions of each of these parameters. In Section 4.1, static data sets that are utilized for NARAC plume modeling are discussed. Meteorological sources of uncertainty that need to be considered are documented in Section 4.2. Sources of model physics uncertainty are discussed in Section 4.3 while sources of uncertainty associated with radiological source terms are identified in Section 4.4. In Section 4.5, the uncertainty parameters associated with model data post processing are discussed.

Based on the demonstration scenario selected for this TI project, the primary category of uncertainty that will impact NARAC plume predictions will be limited to model physics because the terrain, meteorology, and source term are assumed to be known and well represented in the model prediction.

4.1 Static data inputs

The following parameters listed below are database driven static inputs utilized for NARAC plume predictions:

- **Terrain elevation**: Provides data to generate a gridded representation of surface topography that is utilized by the NARAC atmospheric model to simulate terrain influenced wind flow.
- **Land use/land cover**: Spatially varying data that identifies the dominant land use category (e.g. water, forest, desert) and characteristics for a given model grid cell that can have a large impact on dry deposition rates for particles and gases.
- **Building data**: Provides individual building geometries as an input to high resolution models such as computational fluids dynamics codes that are capable of resolving building aware wind flow.
- **Population data**: Provides a gridded, spatially varying representation of population density to estimate the number of people potentially influenced by a hazardous atmospheric release scenario.

4.2 Meteorological inputs

The parameters listed below are meteorological inputs utilized for NARAC plume predictions:

- **Wind speed**: The rate of wind flow distance per unit of time; critical input to describing the rate at which hazardous atmospheric contaminants are transported away from a release location.
- **Wind direction**: Typically denotes the direction from which the wind is blowing and is an important input to accurately modeling the geographic region(s) that will be impacted by an atmospheric release.
- **Friction velocity:** A representation of mechanical turbulence that is generated by wind shear that impacts near surface plume spread.
- **Atmospheric stability**: Parameter such as the Pasquill-Gifford stability class or Obukhov length scale that describes the degree of horizontal and vertical plume spread due to atmospheric diffusion.
- **Planetary boundary layer height**: Layer above the Earth's surface that defines the depth of significant vertical mixing.
- **Precipitation rate**: Provides the average volume of water that falls on a unit area over a unit time and is a critical parameter to accurately calculating deposition due to precipitation scavenging.
- **Precipitation phase**: Describes the microphysics phase of precipitation (i.e. liquid, ice, graupel), which can impact precipitation scavenging rates.

4.3 Model physics

The parameters listed below are model physics inputs utilized for NARAC plume predictions:

- **Wind adjustment**: Mass conservation algorithm that converts irregularly spaced weather observations to a gridded, terrain aware wind field; accuracy is highly dependent on the density and representativeness of available meteorological observations.
- **Standard deviation of cross-wind velocity component (σ_v^2)**: Parameterization of the degree of horizontal turbulence and plume diffusion.
- **Calculation of eddy diffusivity (K_z)**: Describes vertical turbulent mixing that will result in atmospheric plume spread.
- **Gravitational settling**: The downward velocity of particles due to the Earth's gravitational force; highly dependent on particle diameter, particle density, air density and viscosity of medium (air).
- **Non-settling velocity**: Downward flux rate of gases and particles onto a surface due to phenomenon other than gravitational settling such as impaction, interception and Brownian motion.
- **Precipitation scavenging**: Removal of atmospheric particles and gases due to uptake or collision with rain droplets or ice; precipitation scavenging is highly dependent on the rainfall rate and radionuclide species dependent scavenging coefficients; separate in-cloud and below cloud physical processes are separately parameterized.
- **Cloud rise model**: Physics developed to simulate the time evolution of particles within a cloud resulting from an explosion; one key output is cloud stabilization height.
- **Particle physics**: First principles physics or parameterizations that calculate particle phenomenon such as nucleation, agglomeration and activation.

4.4 Radiological source term

The parameters listed below are radiological source term inputs utilized for NARAC plume predictions:

- **Source amount**: Defines the amount of radiological material that is released to the atmosphere.
- **Radionuclide source/mixture**: Provides the specific radionuclide or mix of multiple nuclides that are released to the atmosphere.
- **Particle size distribution**: Provides the relative amount (usually by mass) of particles present according to size.
- **Source geometry**: Describes the spatial distribution of released atmospheric material as a function of release mechanism (e.g. surface point release, explosion, fire).
- **Field measurement accuracy**: NARAC develops source term estimates based on radiological field measurements when available; the skill of the developed source term is dependent on field measurement accuracy.

4.5 Model data post-processing

The parameters listed below are model data post-processing inputs utilized for NARAC plume predictions:

- **Dose conversion factors**: Coefficients to convert radiation exposure via cloud shine, ground shine, and inhalation to committed effective dose equivalent and dose equivalent for individual organs; idealized exposure conditions are typically assumed such as a semi-infinite plane with uniform radionuclide concentrations

- **Data comparison issues**: The horizontal resolution of simulated concentration grid cells are insufficient to match the resolution of radiological field measurements leading to poor source term estimates; also, running with an insufficient number of dispersion tracer particles can lead to poor statistical sampling and inaccurate model to data comparisons.

5 SUMMARY

The sources of error and uncertainty described for each part of the CM data product development process contribute to overall uncertainty in these data products. The identification of these sources of error and uncertainty is the first step in developing an understanding of this overall uncertainty. Each of these sources of uncertainty will be characterized mathematically and fit into a probabilistic framework that can be used to characterize uncertainty in the final CM data product.

6 REFERENCES

[1] FRMAC Lab Analysis Manual, Appendix B, SAND2013-10382P, December 2013.