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Uncertainty Propagation in ICRP 66 Human Respiratory Tract Model

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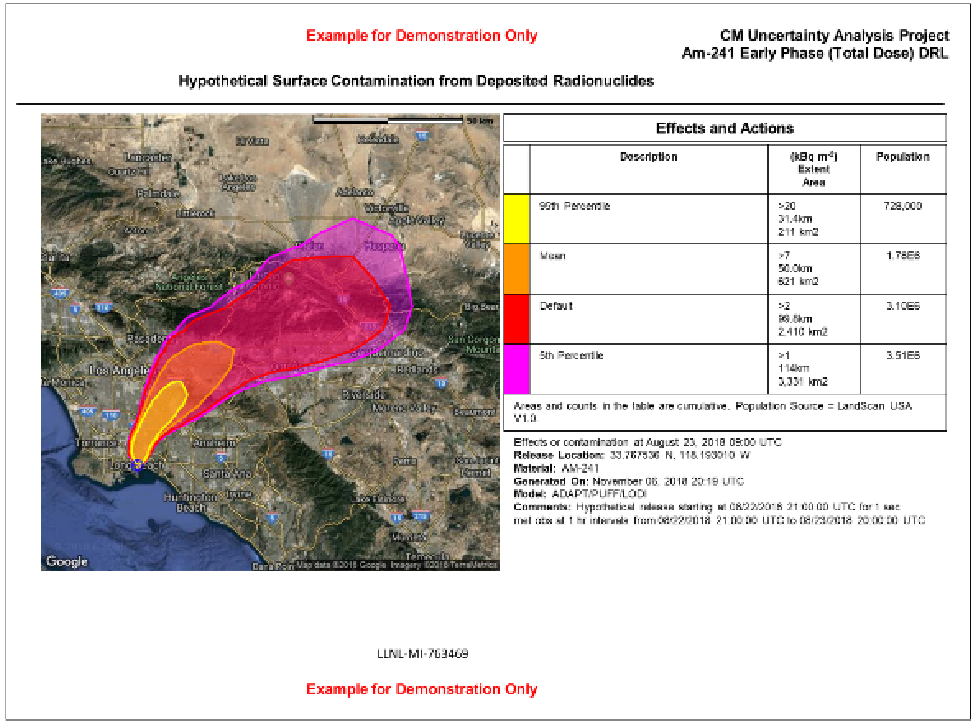
Background

Sandia National Laboratories (SNL) recently developed a methodology to characterize uncertainty in Derived Response Levels (DRLs) used as contours on map products developed by the DOE Consequence Management (CM) program in support of the Federal Radiological Monitoring and Assessment Center (FRMAC)

Proof-of-concept sensitivity analyses showed that **dose coefficient uncertainty** can contribute large uncertainty to overall DRL uncertainty

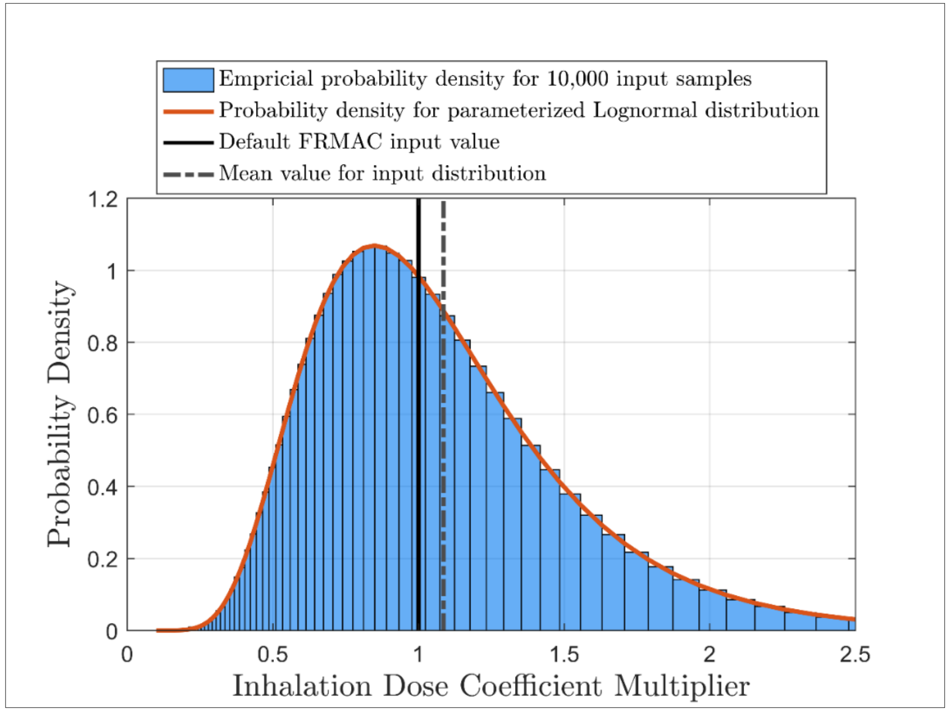


Cochran LD, Eckert AC, Hunt B, Kraus T. Uncertainty Analysis of Consequence Management Data Products. Health Phys. 2020 Apr;118(4):382-395. doi: 10.1097/HP.0000000000001133.

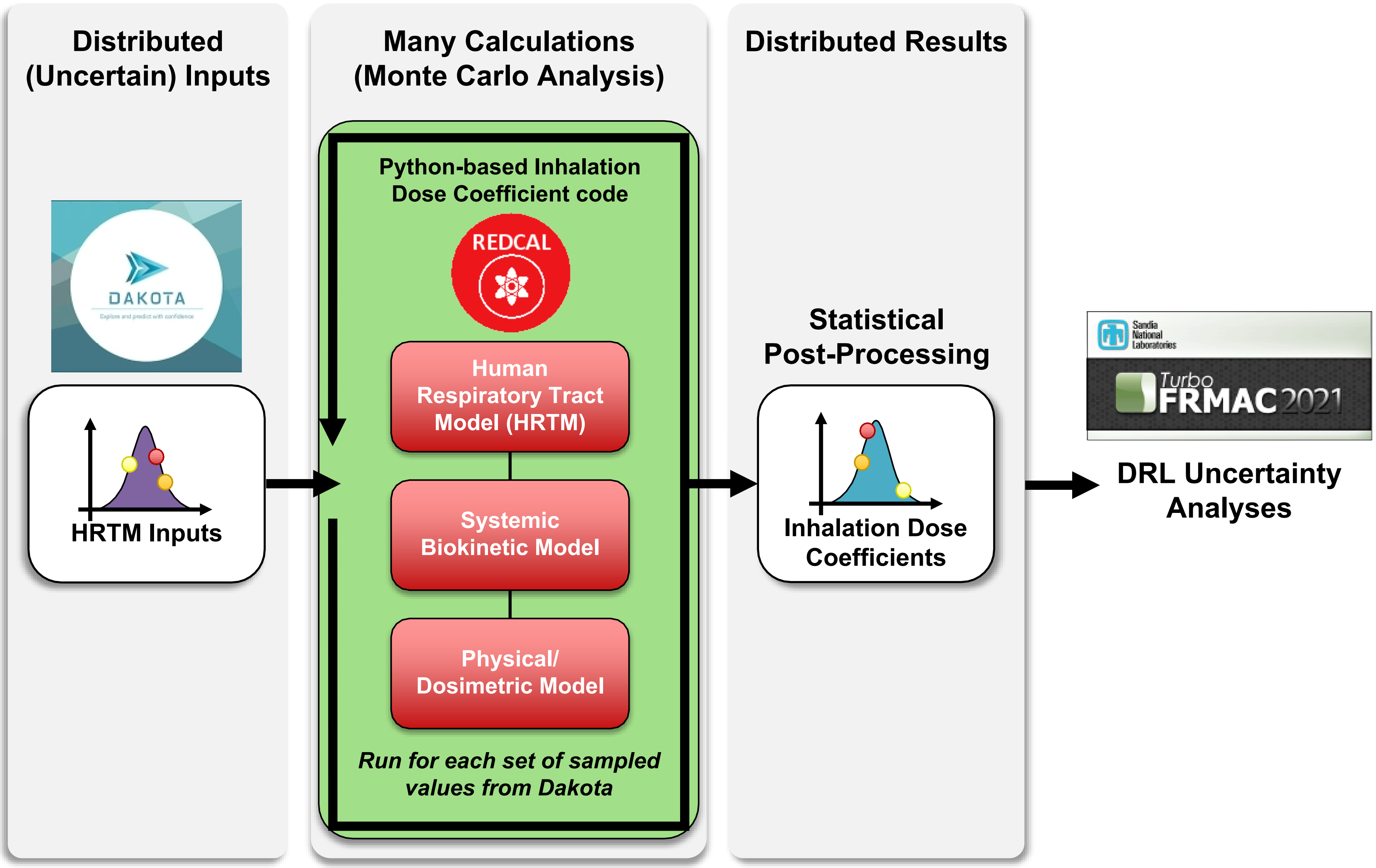
Current Project

Methodology requires sampling DRL input probability distributions, but inhalation dose coefficient uncertainties are available only for a subset of radionuclides relevant to a nuclear power plant release

Goal is to **develop a framework for propagating uncertainty through the human respiratory tract model** (HRTM) and use it to generate inhalation dose coefficient probability distributions for radionuclides that represent a broader set of incidents to which DOE CM could potentially respond (e.g., radiological dispersal device, improvised nuclear device)



Uncertainty Analysis Framework



Input Sampling Methodology

Distributions for uncertain inputs were identified via literature review

Input probability distributions are sampled using **SNL's Dakota software**

Static sampling currently employed: Specify input distributions, generate entire *Monte Carlo* sample, use a script to run REDCAL code for each case

- Possible future direction: Have Dakota call REDCAL and receive results, to permit wider suite of studies

Uncertain inputs are considered independent, with certain constraints (e.g., sum to 1) handled via REDCAL HRTM algorithm rather than sampling distributions

Python Code Framework – Radiological Exposure Dosimetry Calculator (REDCAL)

Inhalation
- Particle Size Distribution
- Inhalation rate & breathing method (nasal, oral, mixed)
- Chemical Form and clearance type
- Lung Model 66

Deposition in Lung Model
- Solubility fractions & rates calculated by clearance type (f/m/s)
- Deposition within respiratory compartments
- Deposition based off deposition efficiencies during inhalation and exhalation (ICRP 66 Tables 12 & 13)

Clearance and Retention in Lungs
- Transfer coefficients between respiratory compartments (blood absorption and GI transfer calculated)
- Tracking dissolved material
- Tracking sequestered material
- Retention in lung compartments
- Distributions chosen for most parameters

Systemic Biokinetics
- ICRP 60/66 model values
- Systemic transfer coefficients determine ODE
- Excretion method and rates
- Compartments with long retention

Time Integrate Activity/ Decay (NNT)
- Integrate with respect to time (up to 50 years, Committed period)
- Organ/Tissue activity calculated, integral yields total number of decays within each compartment (source strength term for dose calculation)
- Calculated within systemic kinetics module

Organ Absorbed Dose (Gy)
- Specific Abosrbed Fractions (SAF) multiplies source strength for dose computation
- ICRP 107 decay data (energy and type)
- SAF library for radionuclides
- Convert absorbed dose to equivalent dose with radiation weighting factor

Committed Equivalent & Effective Dose
- ICRP 60 tissue weighting factos, 61 remainder formulation
- Committed Dose period defined by upper bound of integral

Evaluated Inputs

Parameter	Consideration	Basis & Impact
Particle size	Uncertain (lognormal)	Aerosol generation results in range of particle sizes
Breathing rate	Uncertain (public versus worker parameter range)	Regional deposition based on activity-dependent ventilation rate
Deposition fractions (Regional and compartmental)	Uncertain (function of aerosol parameters)	Method of transport determines method of deposition (sedimentation/impaction)
Lung model rates (Absorption/Clearance values, dissolution rates)	Uncertain (distribution around type: F/M/S)	Dissolution rates greatly impact the dose values to the lungs
Anatomical differences in lung geometry and volume (scaling factors)	Static values (reference values ICRP 66)	Volume scaling impacts flow through airways and thus deposition. Would like CFD modeling to determine the impact
Dosimetry values (Tissue Weighting factors, Specific Absorbed Fractions (SAF))	Static values (tissue weights from ICRP 60)	Changes in SAF value require radiation transport runs with new organ geometry and organ volumes

Regional Deposition Efficiency Distributions

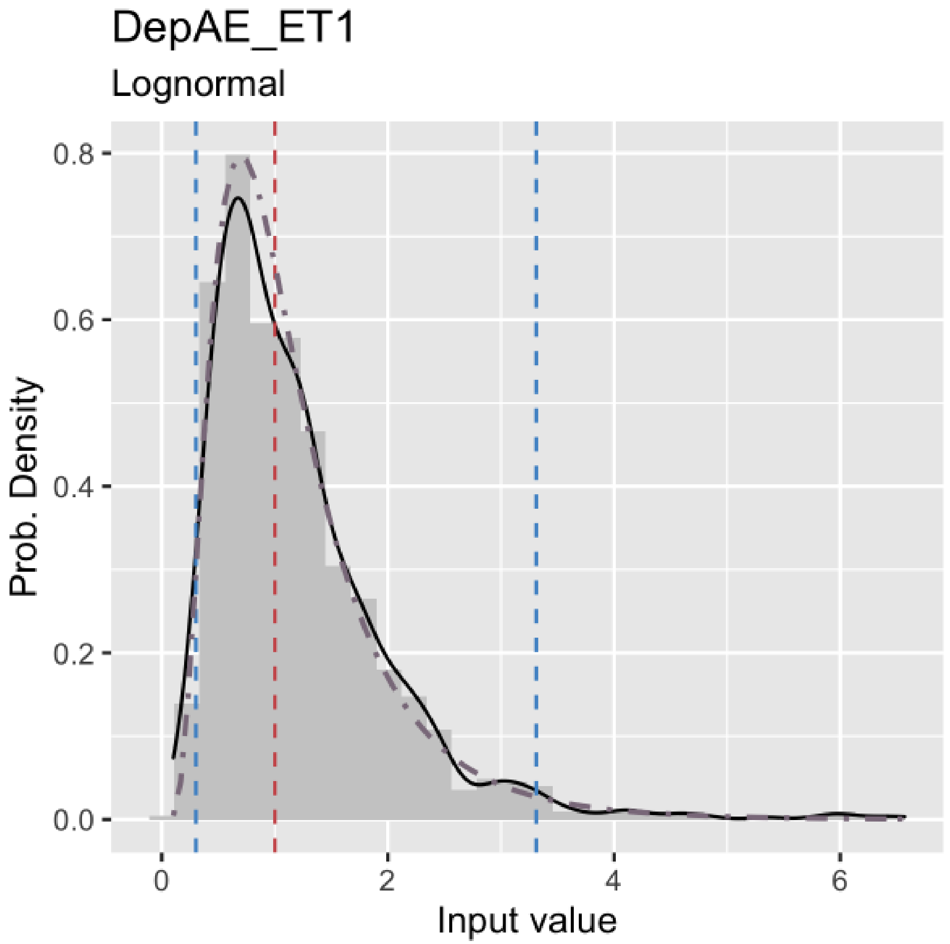
Input	Description	Reference Value	Units	Distribution Type	Mean	SD
$C_{ae}(ET_1)$	Random variable for aerodynamic deposition efficiency in ET_1	1.00	unitless	Lognormal	1.00	1.82
$C_{ae}(ET_2)$	Random variable for aerodynamic deposition efficiency in ET_2	1.00	unitless	Lognormal	1.00	1.82
$C_{ae}(BB)$	Random variable for aerodynamic deposition efficiency in BB	1.00	unitless	Lognormal	1.00	1.58
$C_{ae}(bb)$	Random variable for aerodynamic deposition efficiency in bb	1.00	unitless	Lognormal	1.00	1.58
$C_{ae}(AI)$	Random variable for aerodynamic deposition efficiency in AI	1.00	unitless	Lognormal	1.00	1.30
$C_{th}(ET_1)$	Random variable for thermodynamic deposition efficiency in ET_1	1.00	unitless	Lognormal	1.00	1.18
$C_{th}(ET_2)$	Random variable for thermodynamic deposition efficiency in ET_2	1.00	unitless	Lognormal	1.00	1.18
$C_{th}(BB)$	Random variable for thermodynamic deposition efficiency in BB	1.00	unitless	Lognormal	1.00	1.23
$C_{th}(bb)$	Random variable for thermodynamic deposition efficiency in bb	1.00	unitless	Lognormal	1.00	1.23
$C_{th}(AI)$	Random variable for thermodynamic deposition efficiency in AI	1.00	unitless	Lognormal	1.00	1.23

The means and standard deviations listed for lognormal distributions on this table are the geometric mean and geometric standard deviation (SD), respectively.

c converted to geometric standard deviation assuming $(c)^{1/2}$ as noted in Bolch WE, Farfán EB, Huh C, Huston TE, Bolch WE. Influences of parameter uncertainties within the ICRP 66 respiratory tract model: particle deposition. Health Phys. 2001 Oct;81(4):378-94.
doi: 10.1097/00004032-200110000-00003

Example Sampling

Random variable for aerodynamic deposition efficiency in ET1



Histogram (grey) with empirical density of sampled input (black) and theoretical density (dark purple)

Geometric mean (red) and 2 SD bounds (blue) indicated with vertical lines

1000 samples generated for initial cases, to be refined based on run time and precision needs

Compartmental Deposition Fraction Distributions

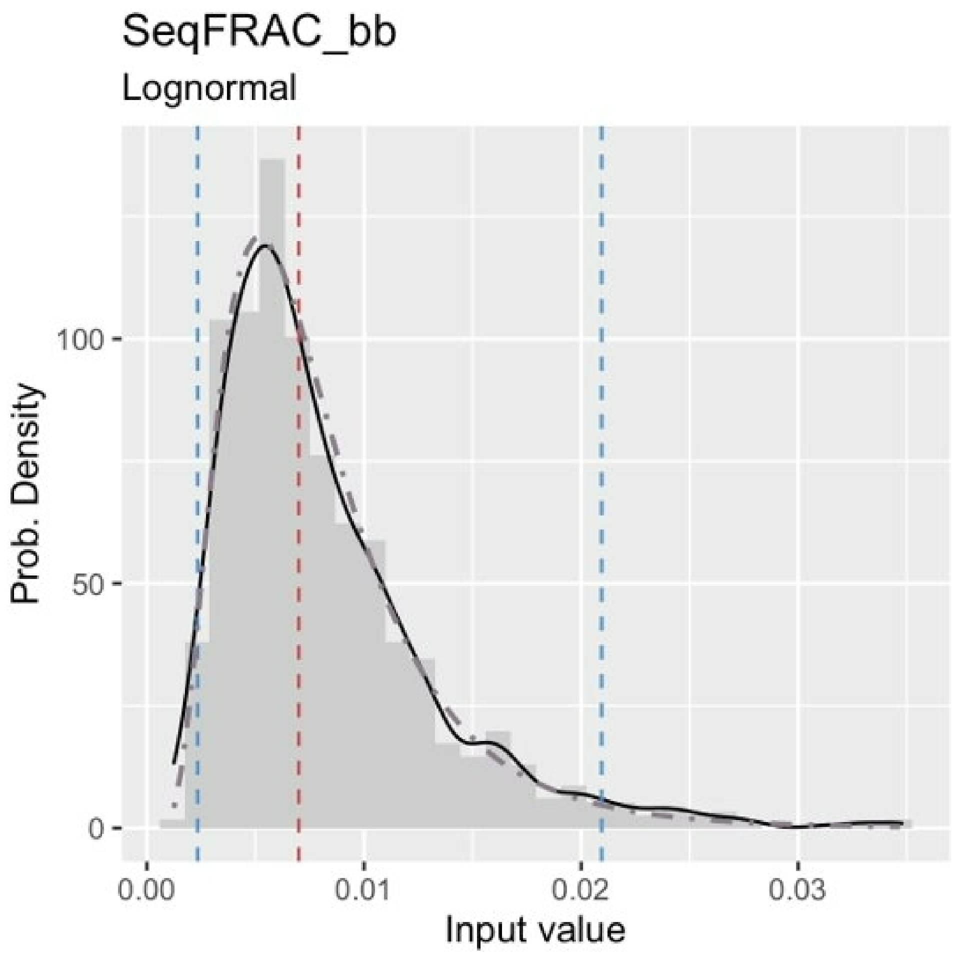
Input	Description	Reference Value	Units	Distribution Type	Mean	SD
$f_d(ET_{seq})$	Fraction of deposition in ET_{seq} compartment	0.0005	unitless	Lognormal	0.0005	1.73
$f_d(BB_{seq})$	Fraction of deposition in BB_{seq} compartment	0.007	unitless	Lognormal	0.007	1.73
$f_d(bb_{seq})$	Fraction of deposition in bb_{seq} compartment	0.007	unitless	Lognormal	0.007	1.73
$E(f_s)$	Random error term to introduce uncertainty in f_s, the slow-clearing fraction from BB and bb regions	N/A	unitless	Normal	0	0.1
$f_d(AI_1)$	Fraction of deposition in AI_1 compartment	0.3	unitless	Lognormal	0.3	1.10

The means and standard deviations listed for lognormal distributions on this table are the geometric mean and geometric standard deviation (SD), respectively.

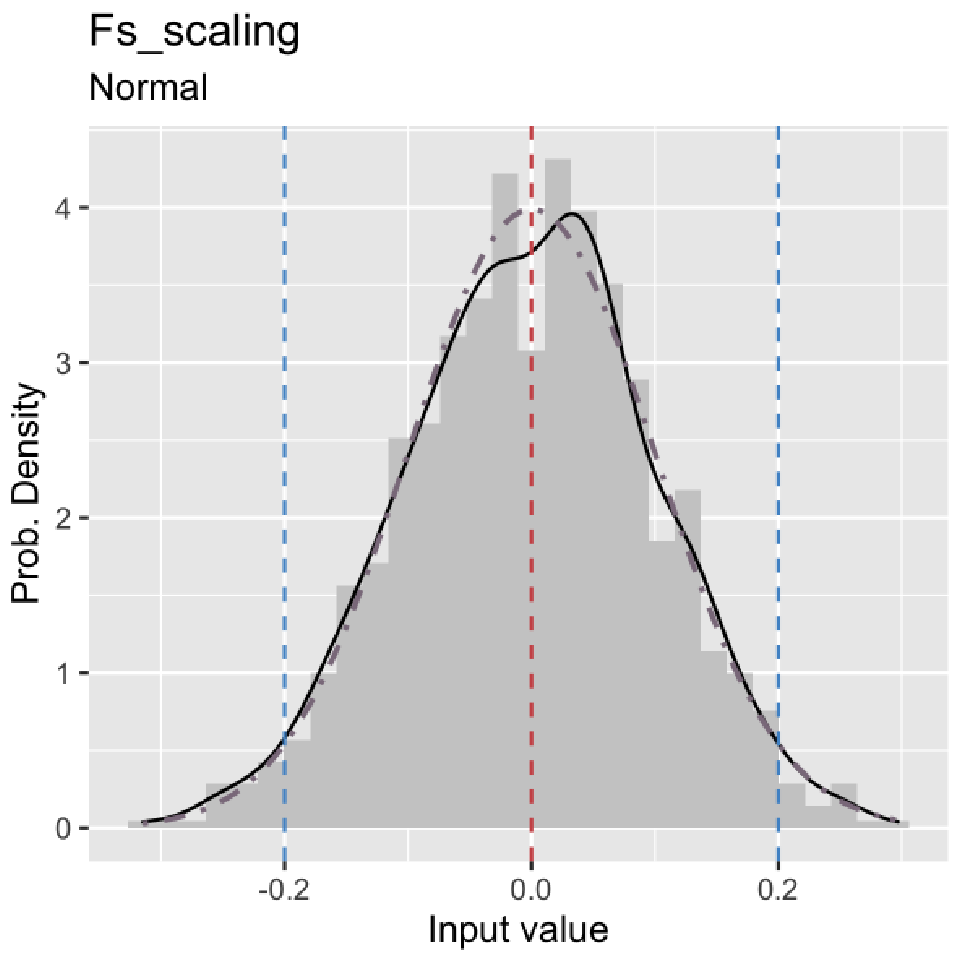
Slow-clearing fraction information based on Bolch WE, Huston TE, Farfán EB, Vernetson WG, Bolch WE. Influences of parameter uncertainties within the ICRP-66 respiratory tract model: particle clearance. Health Phys. 2003 Apr;84(4):421-35.
doi: 10.1097/00004032-200304000-00002

Example Sampling

Fraction of deposition in bb_{seq} compartment



Random error term to introduce uncertainty in f_s, the slow-clearing fraction from BB and bb regions



Fractional Clearance Rate Distributions

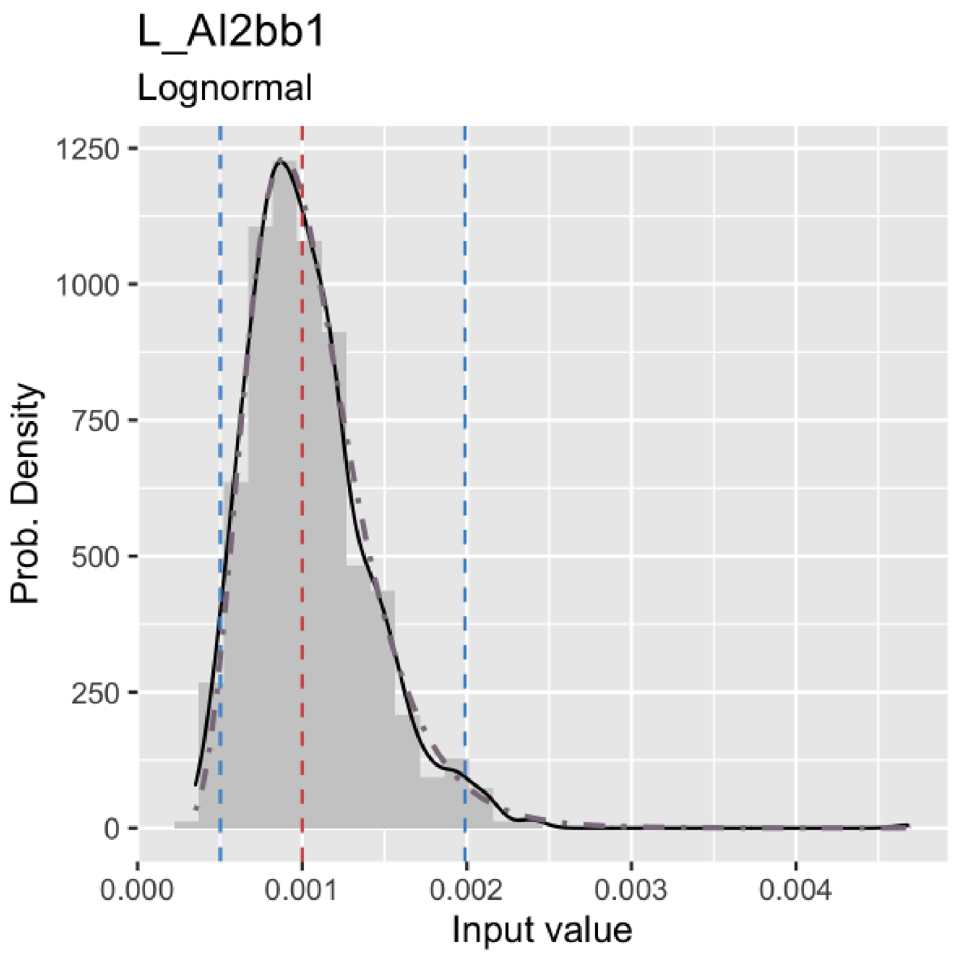
Input	Description	Reference Value	Units	Distribution Type	Mean	SD
$m_{2,4}$	Fractional clearance rate constant for mechanical clearance from AI_2 to bb_1	0.001	d^{-1}	Lognormal	0.001	1.41
$m_{3,4}$	Fractional clearance rate constant for mechanical clearance from AI_3 to bb_1	0.0001	d^{-1}	Lognormal	0.0001	1.73
$m_{3,10}$	Fractional clearance rate constant for mechanical clearance from AI_3 to LN_{TH}	0.00002	d^{-1}	Lognormal	0.00002	1.41
$m_{4,7}$	Fractional clearance rate constant for mechanical clearance from bb_1 to BB_1	2	d^{-1}	Lognormal	2	1.41
$m_{5,7}$	Fractional clearance rate constant for mechanical clearance from bb_2 to BB_1	0.03	d^{-1}	Lognormal	0.03	1.73
$m_{6,10}$	Fractional clearance rate constant for mechanical clearance from bb_{seq} to LN_{TH}	0.01	d^{-1}	Lognormal	0.01	1.73
$m_{7,11}$	Fractional clearance rate constant for mechanical clearance from BB_1 to ET_2	10	d^{-1}	Lognormal	10	1.22
$m_{8,11}$	Fractional clearance rate constant for mechanical clearance from BB_2 to ET_2	0.03	d^{-1}	Lognormal	0.03	1.73
$m_{9,10}$	Fractional clearance rate constant for mechanical clearance from BB_{seq} to LN_{TH}	0.01	d^{-1}	Lognormal	0.01	1.73
$m_{11,15}$	Fractional clearance rate constant for mechanical clearance from ET_2 to GI Tract	100	d^{-1}	Lognormal	100	1.73
$m_{12,13}$	Fractional clearance rate constant for mechanical clearance from ET_{seq} to LN_{ET}	0.001	d^{-1}	Lognormal	0.001	1.73
$m_{14,16}$	Fractional clearance rate constant for mechanical clearance from ET_1 to Env	1	d^{-1}	Lognormal	1	1.73

The means and standard deviations listed for lognormal distributions on this table are the geometric mean and geometric standard deviation (SD), respectively.

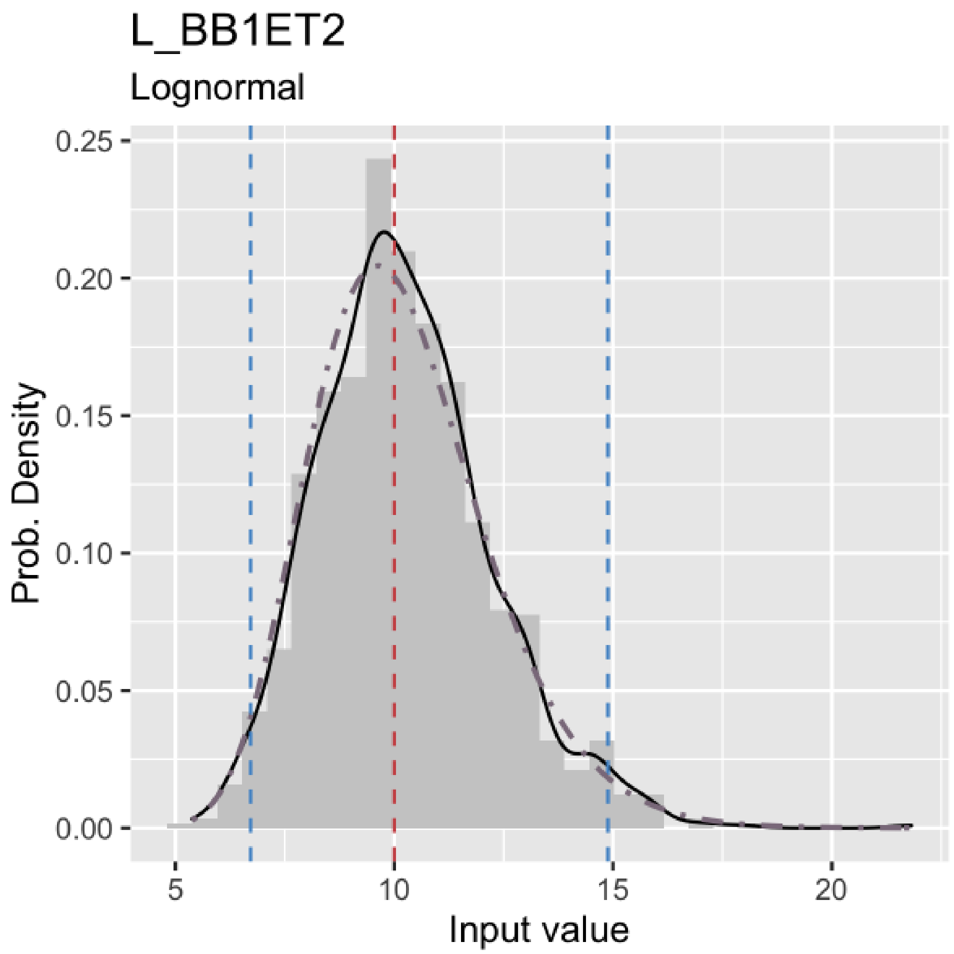
Assigned uncertainty factors based on Bolch WE, Huston TE, Farfán EB, Vernetson WG, Bolch WE. Influences of parameter uncertainties within the ICRP-66 respiratory tract model: particle clearance. Health Phys. 2003 Apr;84(4):421-35.
doi: 10.1097/00004032-200304000-00002

Example Sampling

Fractional clearance rate constant for mechanical clearance from AI_2 to bb_1



Fractional clearance rate constant for mechanical clearance from BB_1 to ET_2



Initial Cases

Initial cases will include radionuclides of high interest to CM/FRMAC that cover a range of radiation emission types, lung clearance types, and half-lives

- Am-241 Moderate
- Co-60 Moderate
- Cs-137 Fast
- I-131 Fast
- Sr-90/Y-90 Slow/Moderate

Initial cases will consider the following particle sizes but will be expanded to cover particle sizes for which dose coefficients are currently available (0.001 – 30 µm AMAD)

- 1 µm (public)
- 5 µm (occupational)

Conclusion

The dose coefficient probability distributions resulting from this work will enable DRL uncertainty analyses for the full range of incidents to which CM could potentially respond

In addition, the dose coefficient uncertainty quantification framework and radionuclide-specific probability distributions resulting from this work will be **useful for uncertainty analyses by the broader radiological dose assessment community** (i.e., outside of CM-specific applications)

Questions?

Thank you!

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