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Considering Uncertainty and Risk in Public Protection Decisions

Nuclear/Radiological Communications Working Group

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What is FRMAC?

- Federal Radiological Monitoring and Assessment Center (FRMAC)
- Provides timely, high-quality predictions, measurements, analyses, and assessments to promote efficient and effective emergency response for the protection of the public from the consequences of nuclear or radiological incidents
- Generates data products to aid decision makers in interpreting measurements and models in terms of published federal Protective Action Guides (PAGs)
- These data products are often maps that help decision makers determine where protective actions (e.g., sheltering, evacuation, or relocation of the public) may be warranted

Uncertainty Analysis Project

- DOE NNSA Consequence Management (CM) has been asked for many years to quantify the uncertainty in our data products
- FY17-18 project is a first attempt at quantifying uncertainty of the Derived Response Level (DRL) values that are used for CM data products
- Ultimate goal is to quantify the confidence in the values used to produce CM data products to ensure that appropriate public protection decisions are supported by defensible analysis
- Uncertainty analyses can help CM identify major sources of uncertainty and motivate additional studies to minimize these sources of uncertainty

Data Product Terminology

- Protective Action Guide (PAG) = a projected dose to an individual from a release of radioactive material at which a specific protective action to reduce or avoid that dose is recommended
- Derived Response Level (DRL) = a level of radioactivity in the environment that would be expected to produce a dose equal to the corresponding PAG

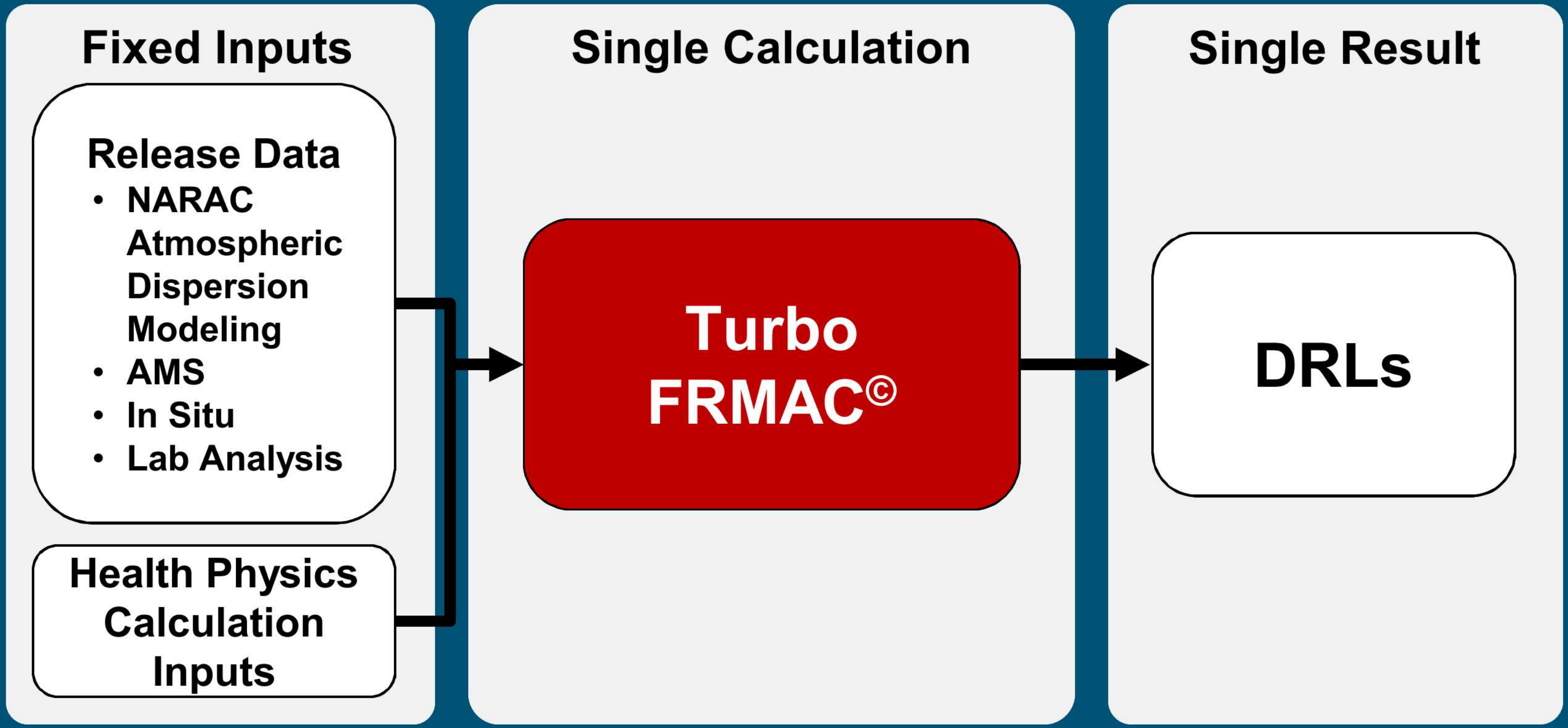
Time Phase	Duration	Dose Pathways Included	PAG
Early Phase (Total Dose)	4 days after release	Plume and Ground	1 rem
Early Phase (Avoidable Dose)	4 days after release	Ground	1 rem
First Year	1 year after release	Ground	2 rem

Uncertainty Analysis Scenarios

- Detonation of Cesium-137 and/or Americium-241 radiological dispersal device
- Source term of sufficient quantity to create an activity per area equal to the DRL at a hypothetical location downwind
- Public Protection DRL calculation was performed for the Early Phase (Total Dose), Early Phase (Avoidable Dose) and First Year time phases using all FRMAC defaults, as specified in FRMAC Assessment Manual, Vol. 1

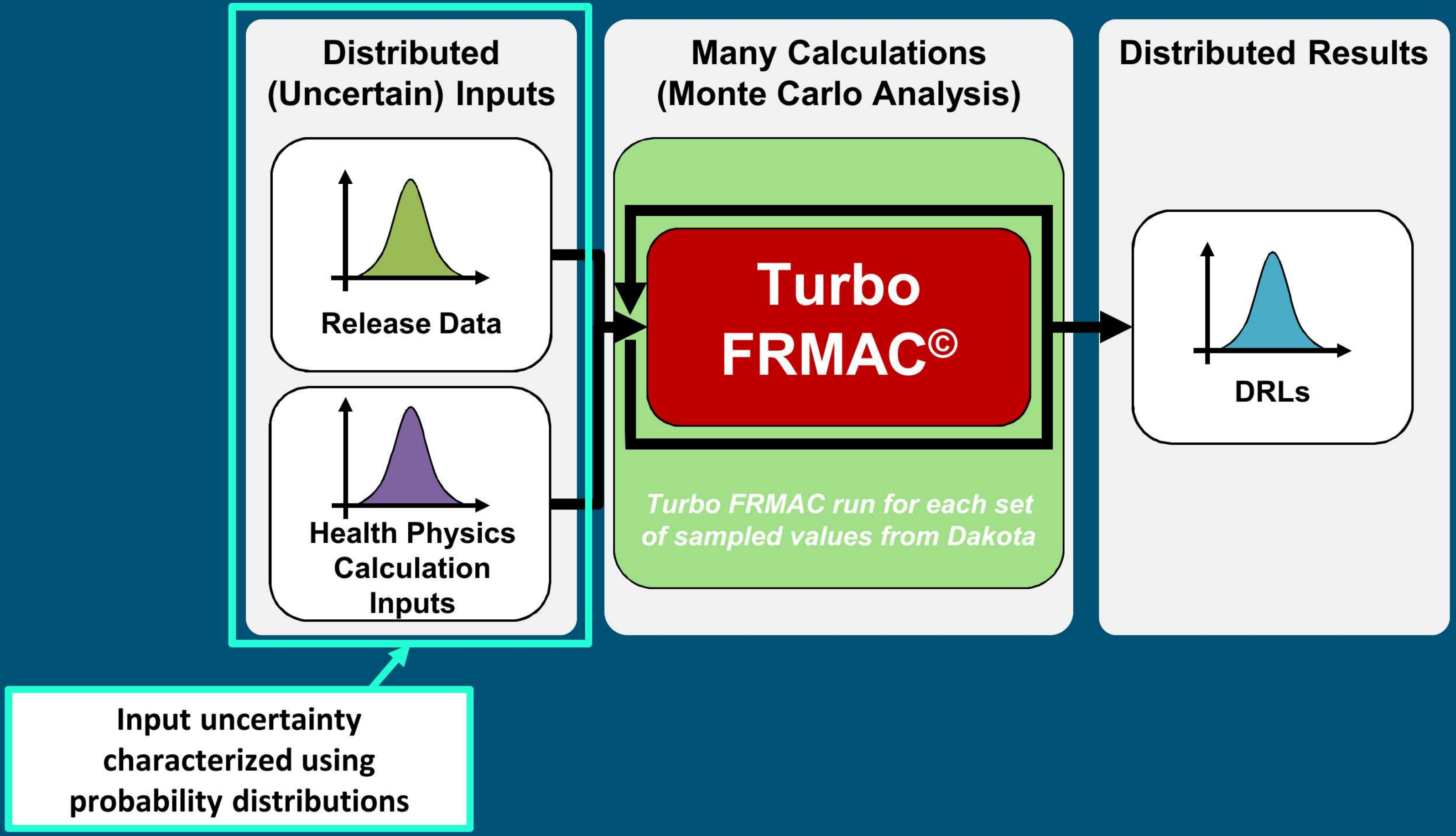
Current Response Process

- Response calculations use fixed inputs to run a single calculation with a single result



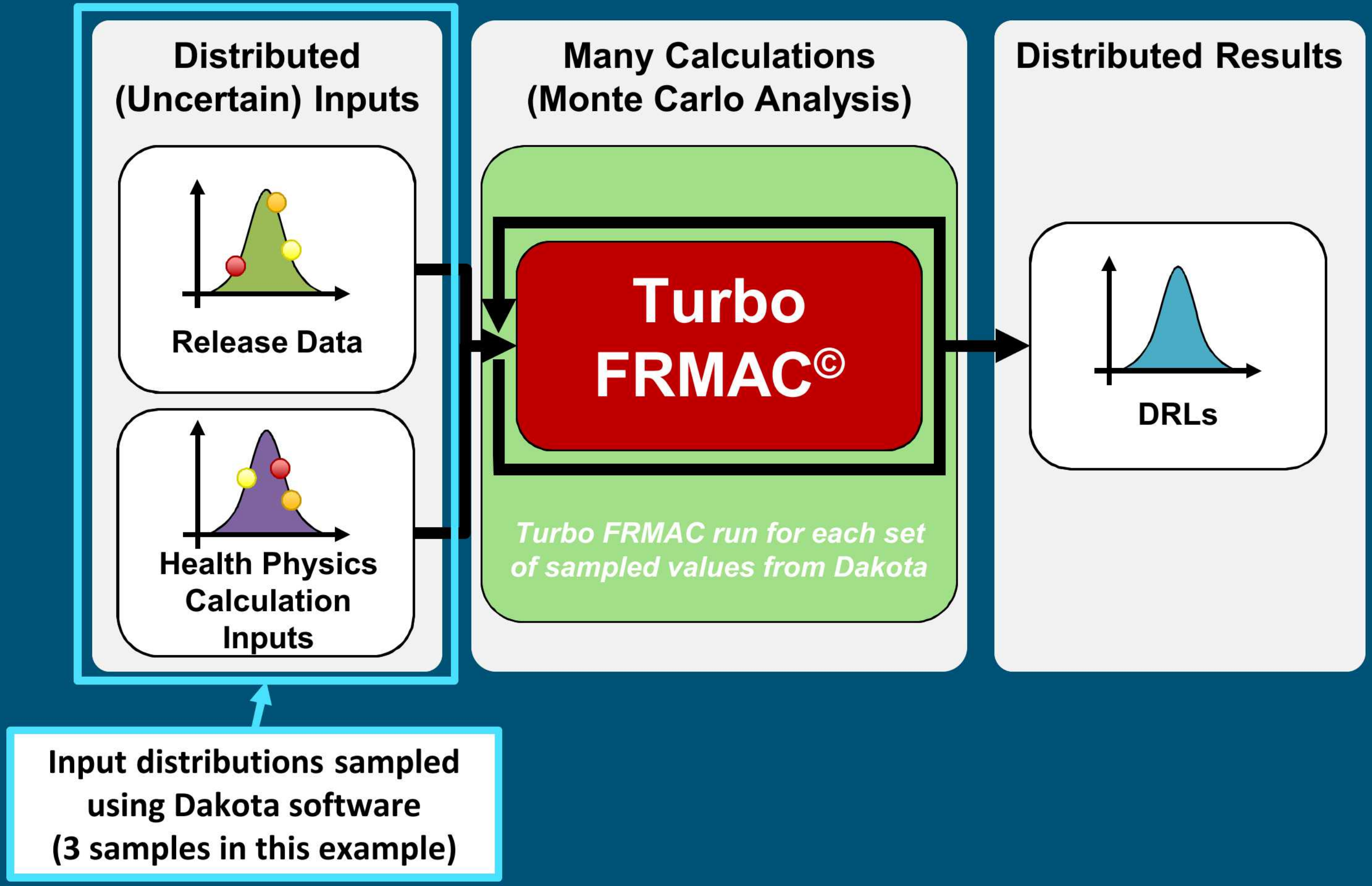
Uncertainty Propagation

- Monte Carlo analysis used to propagate uncertainty from inputs through the model to the outputs



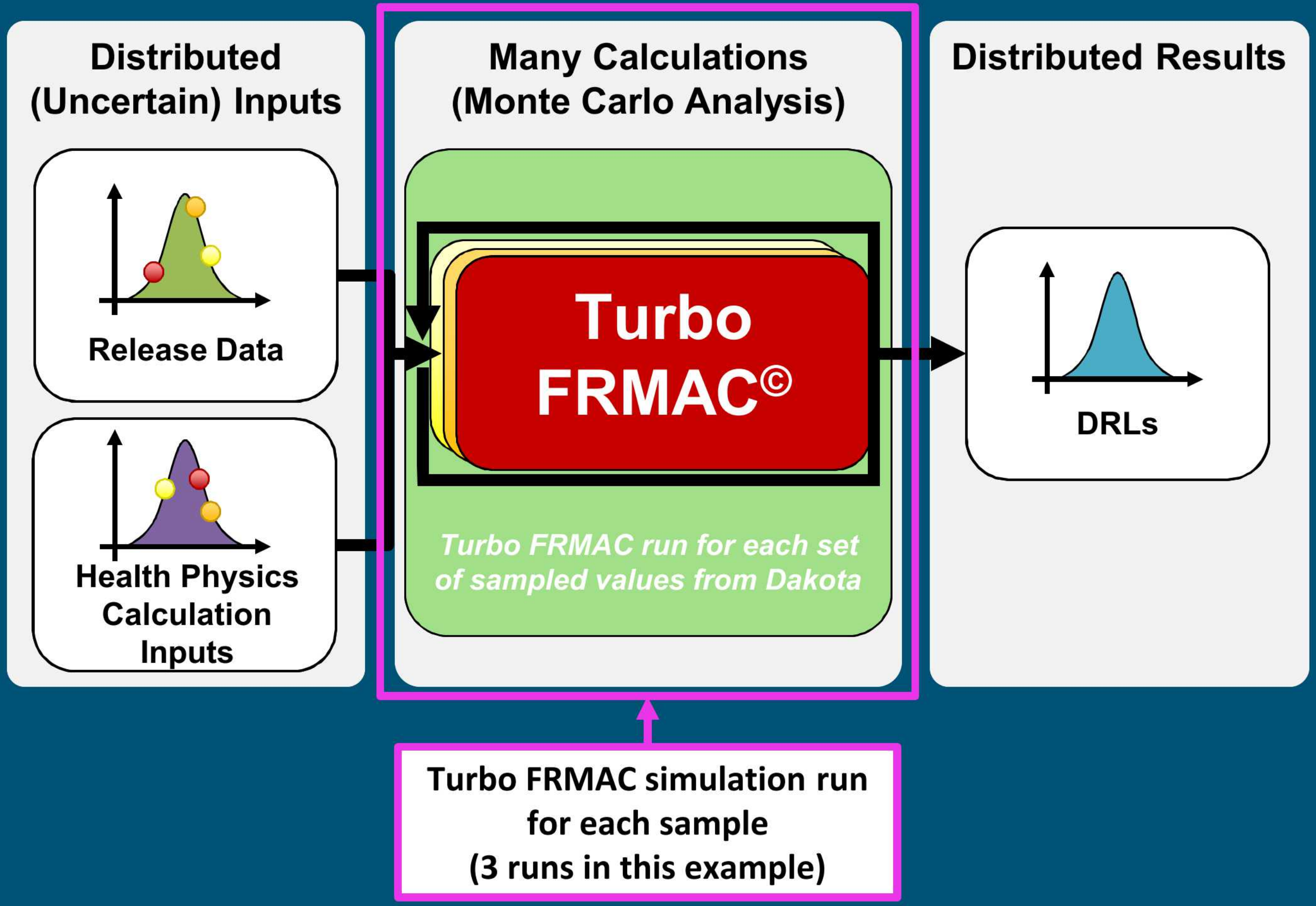
Uncertainty Propagation

- Input probability distributions characterize uncertain inputs and are sampled using Sandia's Dakota software



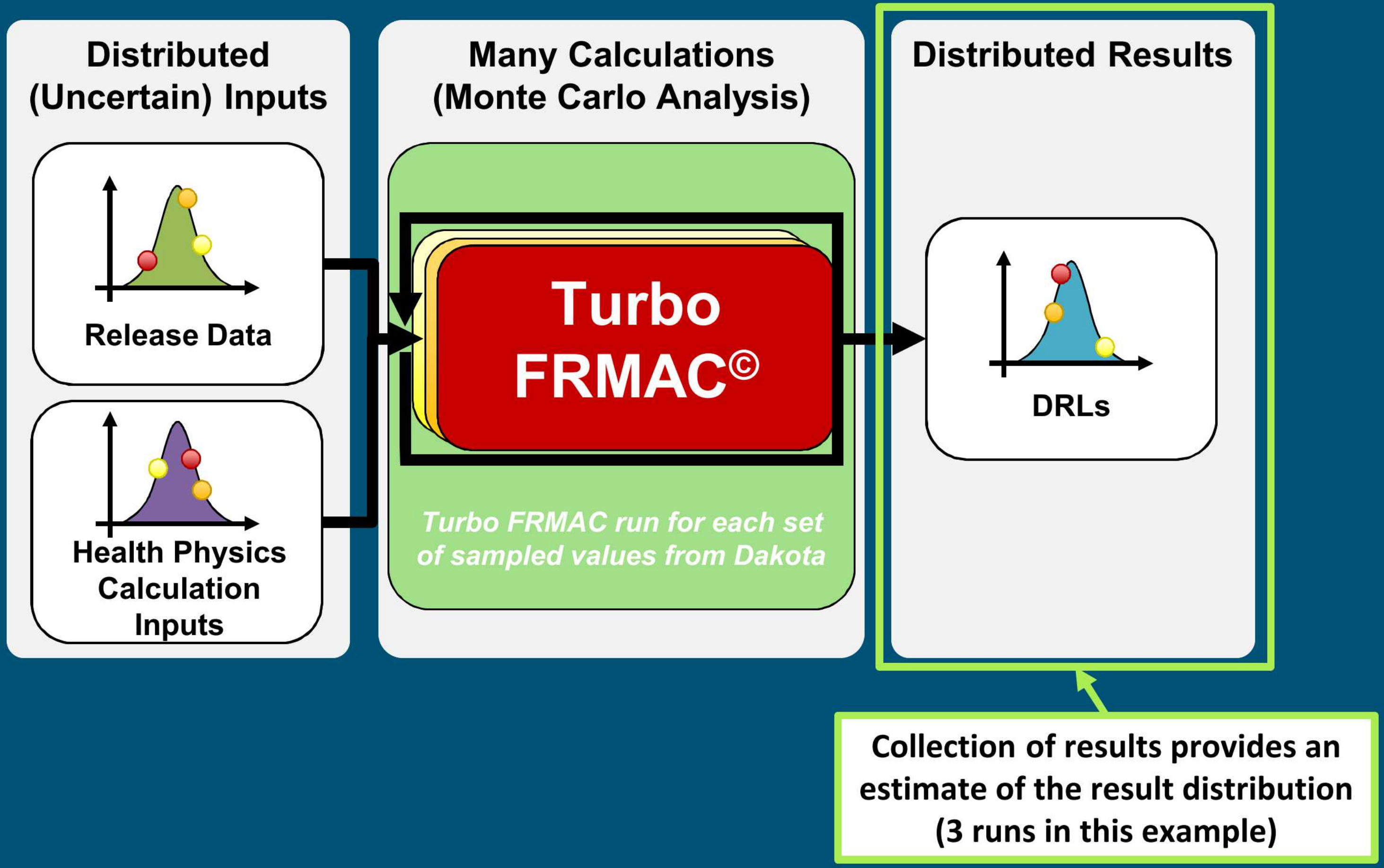
Uncertainty Propagation

- Turbo FRMAC simulation run for each sample taken from input distributions



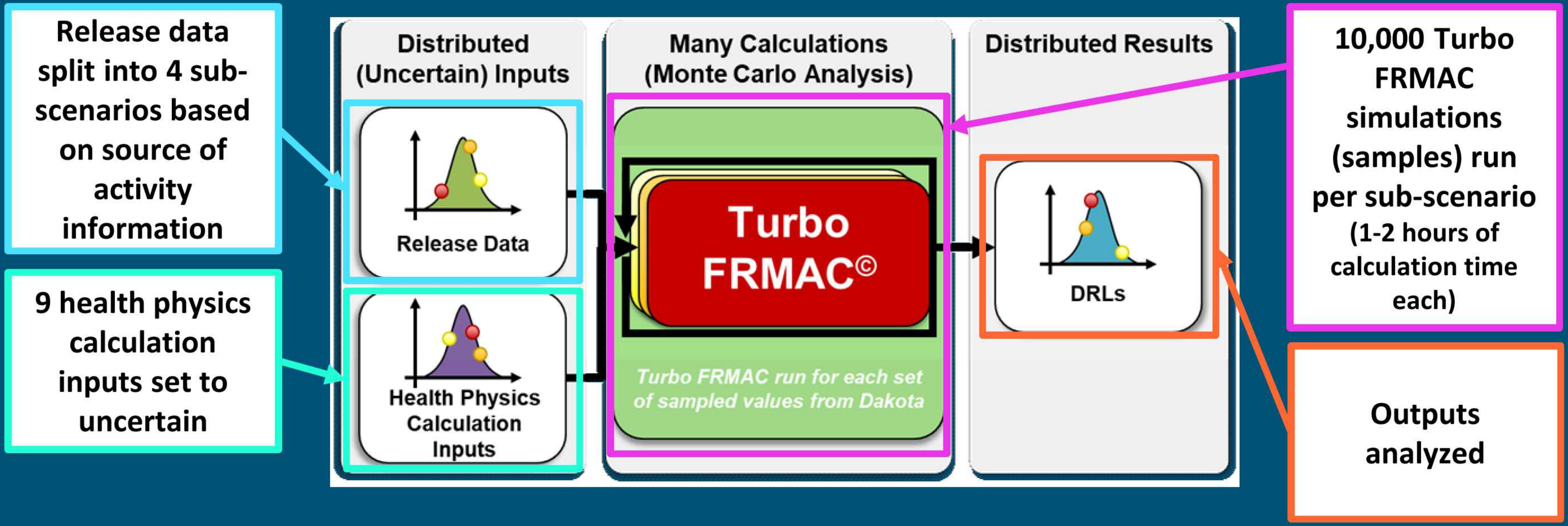
Uncertainty Propagation

- Collection of results from each simulation provides an estimate of the distribution of the result of interest (DRL)



Uncertainty Propagation

- Monte Carlo analysis used to propagate uncertainty from inputs through the model to the outputs
- Samples from input distributions taken using Latin hypercube sampling (LHS)
- A large sample size is needed to create a precise estimate of the output distribution
- Collection of results from each simulation provides an estimate of the distribution of the result of interest (DRL)



Sources of Uncertainty

- DRLs are calculated based on measured or projected concentrations of radionuclides in the environment
- The concentration sources considered in this analysis include:
  - NARAC atmospheric dispersion modeling
  - Aerial Measuring System (AMS) measurements
  - In Situ deposition measurements
  - Laboratory Analysis
- Nine uncertain inputs that contribute to uncertainty in the health physics calculations of Public Protection DRLs were assigned probability distributions
- Input distributions were selected based on uncertainty information from published data and/or expert opinion

Input Distribution Summary

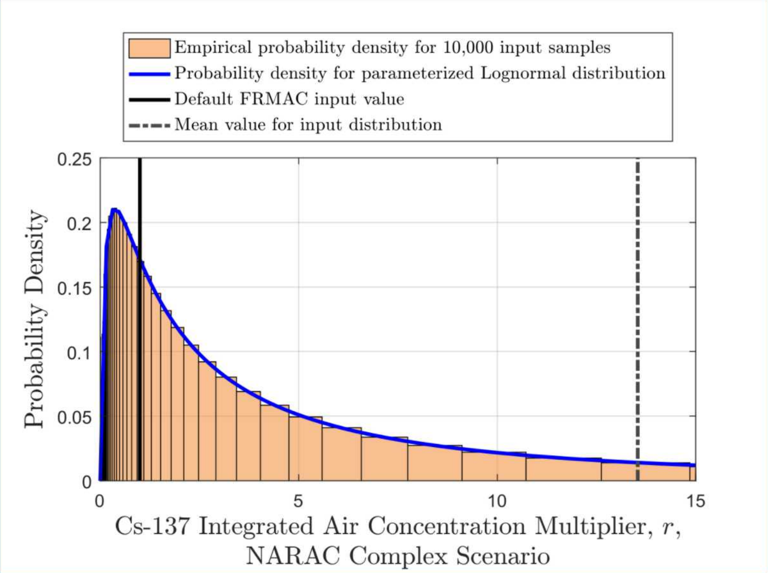
Input	Default Value	Distribution Type	Mean	SD	Mode	Lower Bound	Upper Bound	Units
Air Concentration Uncertainty Multiplier – NARAC*	1	Lognormal+	4.06	4.69				---
Activity per Area‡	330	Normal	DRL	Varies				µCi/m^2
Deposition Velocity	3.00E-3	Triangular			3.00E-3	3.00E-4	3.00E-2	m/s
Breathing Rate – Light Exercise, Adult Male	1.50	Normal	1.75	0.42		0.54	3.00	m^3/hr
Breathing Rate – Activity-Averaged, Adult Male	0.92	Triangular			0.92	0.54	1.50	m^3/hr
Ground Roughness Factor	0.82	Normal	0.82	0.082		0	1	--
Resuspension Coefficient Multiplier§	1	Lognormal+	1	4.2				--
Weathering Coefficient Multiplier§	1	Lognormal+	1	1.2				--
Deposition External Dose Coefficient Multiplier	1	Triangular			0.8	0.5	1.5	--
Cs-137 Inhalation Dose Coefficient Multiplier**	1	Lognormal+	1	1.5		1.67	7.02	--
Am-241 Inhalation Dose Coefficient Multiplier++	1	Lognormal+	1	2		1.38	22.8	--
Plume External Dose Coefficient Multiplier	1	Triangular			0.8	0.5	1.5	--

For more information on these input probability distributions, please see SAND2018-0329 and SAND2018-13984

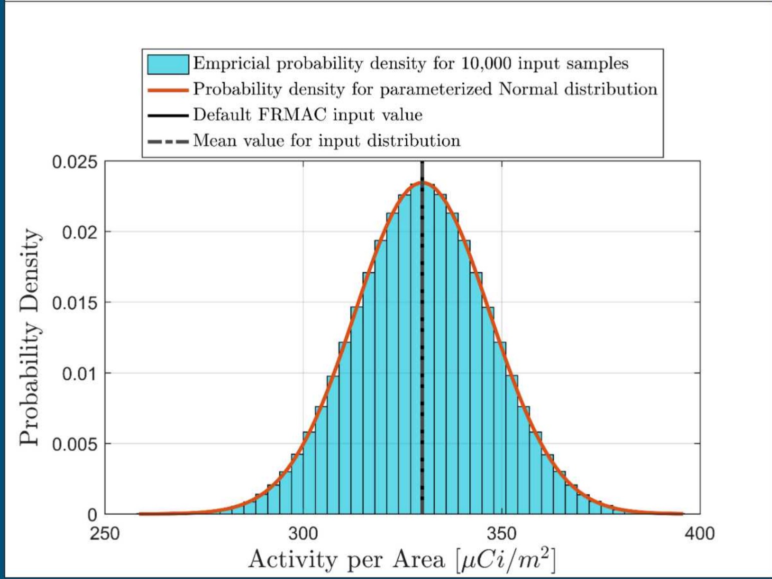
Input Distribution Examples

- Distribution forms and parameters describe the possible values for an input and are sampled for each simulation
- Figures below show examples of assigned distributions

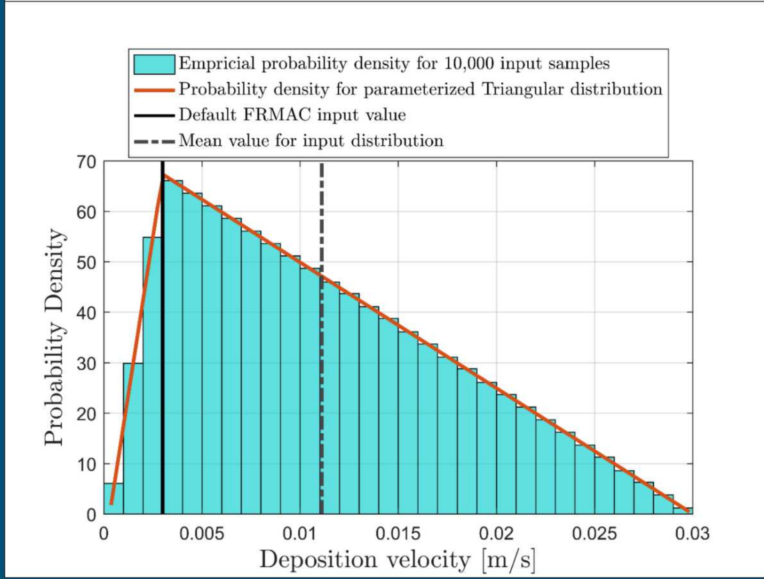
Lognormal distribution for Air Concentration Multiplier



Normal distribution for Activity per Area



Triangular distribution for Deposition Velocity



Uncertainty Analysis Results

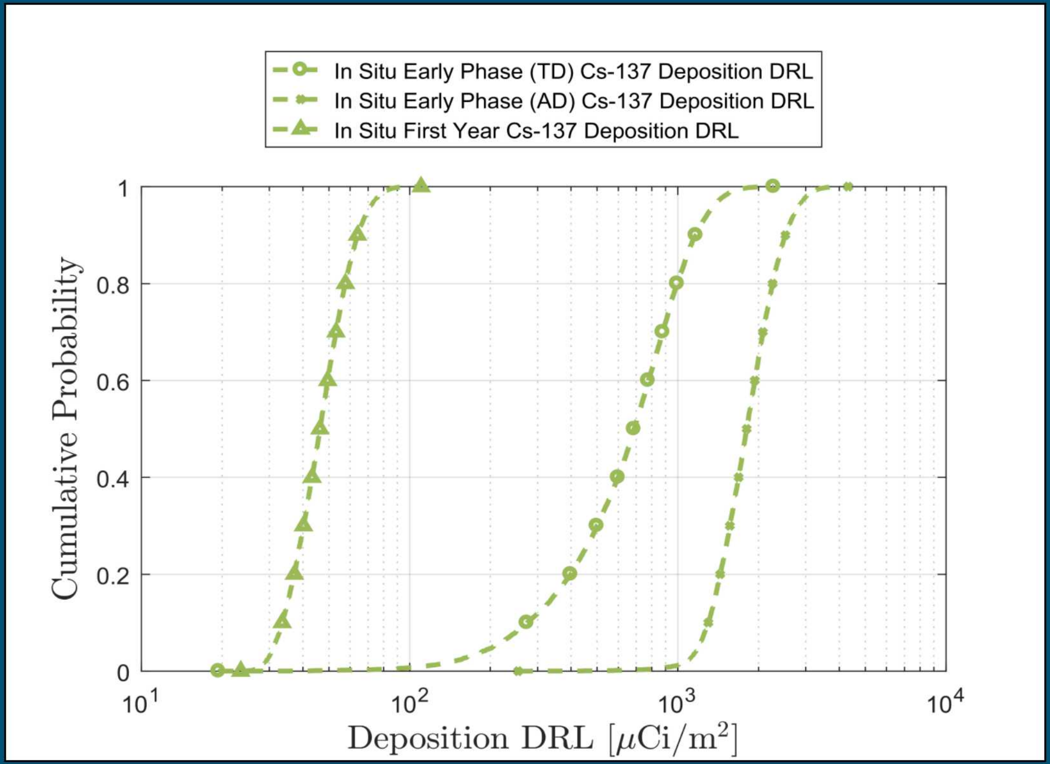
- Performed 10,000 simulations for each source of radioactivity concentration data and each scenario to generate a set of results for each output of interest
- Output results include DRLs and dose parameters. Only radionuclide-specific Deposition DRL results are presented as this is the most commonly used quantity for CM data products
- Presented results should be considered examples derived from a proof of concept of simulation methods and should not be explicitly applied or used to draw conclusions about the full range of potential uncertainties in data products

Uncertainty Analysis Results – Cs-137 Deposition DRL (μCi/m^2)

Scenario	Default	Mean	5th	50th	95th		Mean/ Default	95th/ 5th
Early Phase (Total Dose)	3.31E+02	7.10E+02	2.05E+02	6.87E+02	1.31E+03		2.15	6.42
Early Phase (Avoidable Dose)	1.70E+03	1.86E+03	1.20E+03	1.80E+03	2.75E+03		1.10	2.30
First Year	42.0	47.8	31.1	46.3	69.6		1.14	2.24

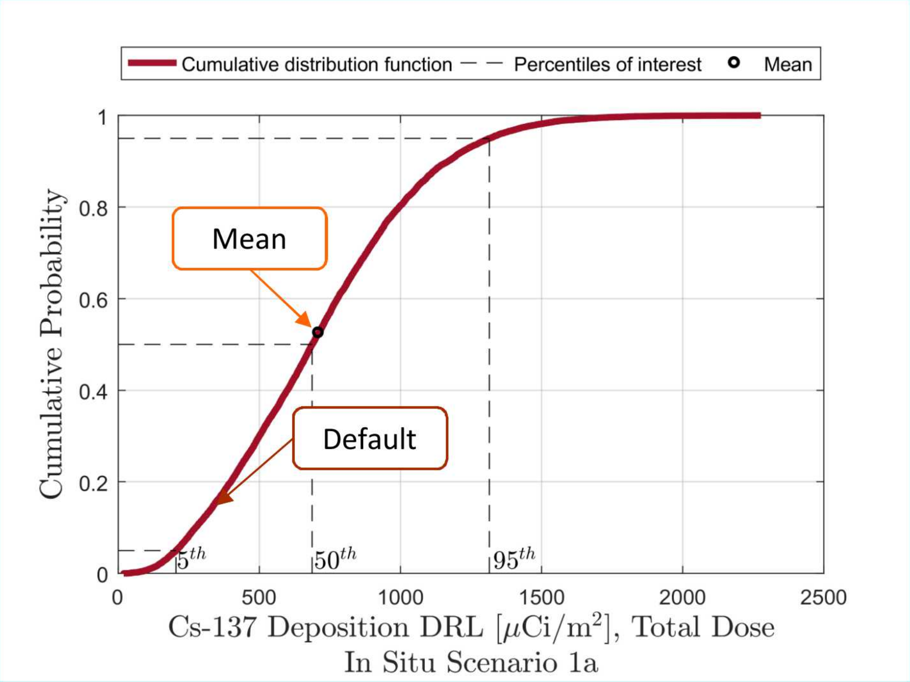
Results shown for Single Radionuclide In Situ simulations

- Cs-137 Deposition DRL is more uncertain when dose from the plume is included
- Mean and Default are similar when the plume is excluded



Uncertainty Analysis Results – Mean vs. Default

- CM's default Deposition DRL is conservative because it is less than the mean result derived from the uncertainty analyses
- Note: This conservatism was observed only for the scenarios considered in this project

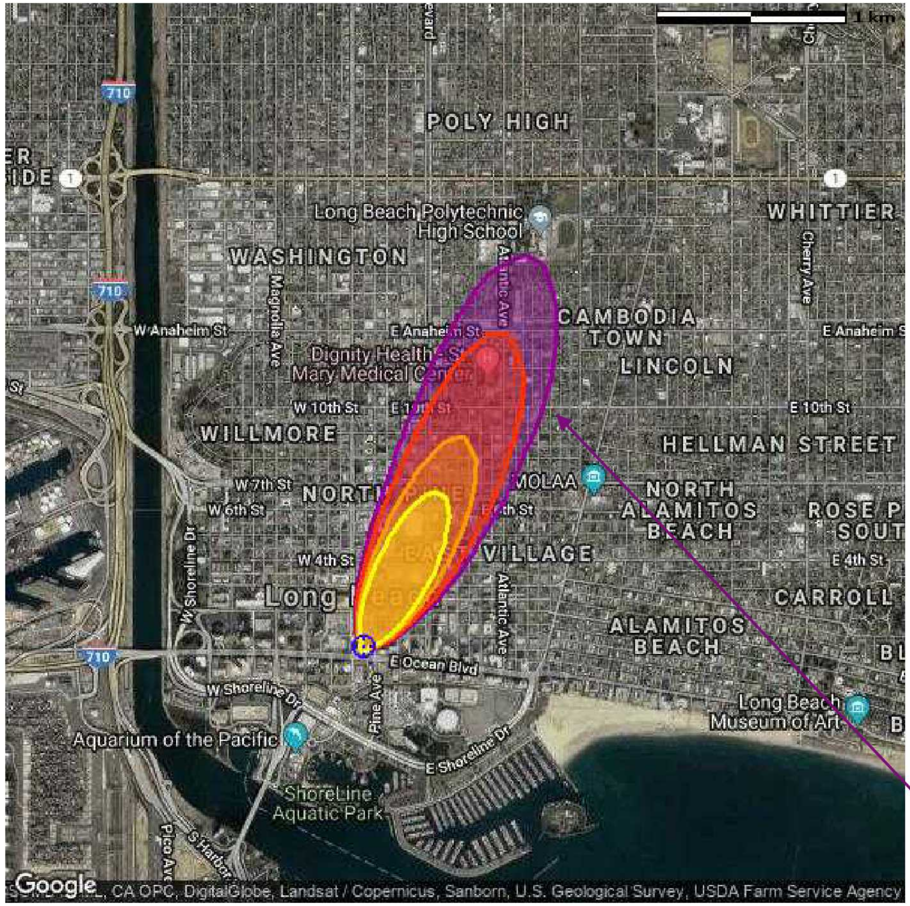


Results shown for Early Phase (Total Dose)

Example for Demonstration Only

CM Uncertainty Analysis Project
Cs-137 Early Phase (Total Dose) DRL

Hypothetical Surface Contamination from Deposited Radionuclides



Concentration Levels			
	Description	(uCi/m2) Extent Area	Population
	95th Percentile	>1,310 0.9km 0.2 km2	6,190
	Mean	>710 1.2km 0.3 km2	7,860
	Default	>330 1.8km 0.7 km2	14,000
	5th Percentile	>205 2.2km 1.1 km2	18,000
Areas and counts in the table are cumulative. Population Source = LandScan USA V1.0.			

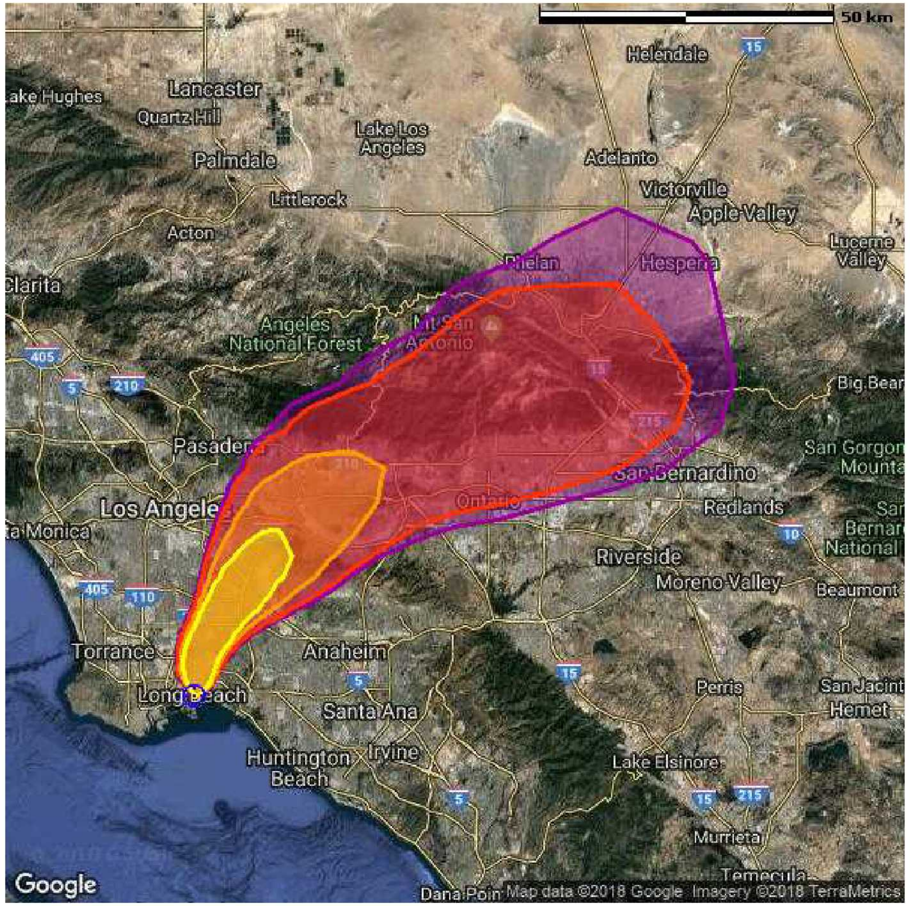
Decision makers may interpret the 5th percentile contour as meaning that there is a 5% chance that someone outside of this area could receive a dose that exceeds the PAG if a protective action is not taken

Example for Demonstration Only

Example for Demonstration Only

CM Uncertainty Analysis Project
Am-241 Early Phase (Total Dose) DRL

Hypothetical Surface Contamination from Deposited Radionuclides



Concentration Levels

	Description	(uCi/m2) Extent Area	Population
(yellow)	95th Percentile	>0.5 31.4km 211 km2	728,000
(orange)	Mean	>0.2 50.0km 621 km2	1.78E6
(red)	Default	>0.05 99.8km 2,410 km2	3.10E6
(purple)	5th Percentile	>0.03 114km 3,331 km2	3.51E6

Areas and counts in the table are cumulative. Population Source = LandScan USA V1.0.

For this scenario, the default DRL contour covers nearly four times the area and double the population than the mean DRL contour

- Protective action recommendations based on default method would result in a significantly larger impacted population when compared to the mean
- Distribution of DRL values represented by 5th and 95th percentiles shows that extreme values encompassing areas that are much larger and much smaller than the default, respectively, are possible

Example for Demonstration Only

Using Uncertainty Analyses to Guide Public Protection Decisions

- What is the acceptable level of uncertainty in the projected doses of public protection decisions?
  - Does it change if small or large numbers of people are impacted?
  - Does it change if small or large land areas are impacted?
  - Who determines what is the acceptable level of uncertainty?
- CM can draw the contours identifying the evacuation and relocation areas very differently based on the acceptable uncertainty in the projected DRL
- Many impacts in addition to projected radiation doses must be considered when determining if populations should be evacuated or relocated
  - Potential impacts include non-radiological hazards and socioeconomic risk
  - Recent studies have indicated that large populations were unnecessarily relocated following the Chernobyl and Fukushima nuclear power plant accidents[1]

[1] *J-value assessment of relocation measures following the nuclear power plant accidents at Chernobyl and Fukushima Daiichi*, Waddington I, Thomas PJ, Taylor RH, Vaughan GJ, *Process Safety and Environmental Protection,* 112, 16-49, 2017 (among other related articles in this issue)

Questions for You

- Should uncertainty analysis results be used to inform protective action decisions?
- How should uncertainty analysis results be used during a response?
- Who is the ultimate consumer of this information (e.g., Decision Makers, ROSS)?
- How would you like to see this sort of information presented?

Conclusion

- We are working on incorporating the risks associated with non-radiological hazards in our analyses
- We are working with Decision Makers and Communicators to understand how we can help them make better informed public protection decisions
- We welcome any thoughts and suggestions

Thank you!

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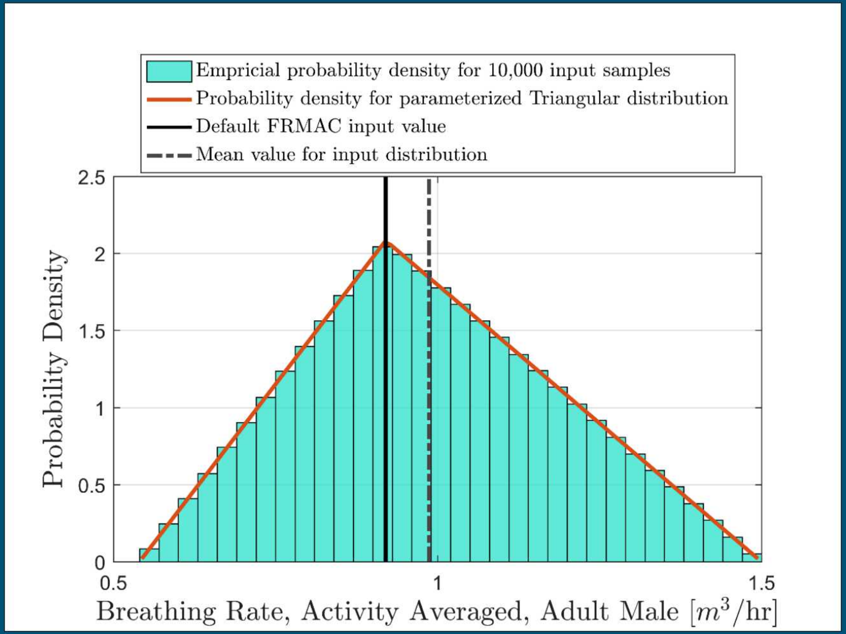
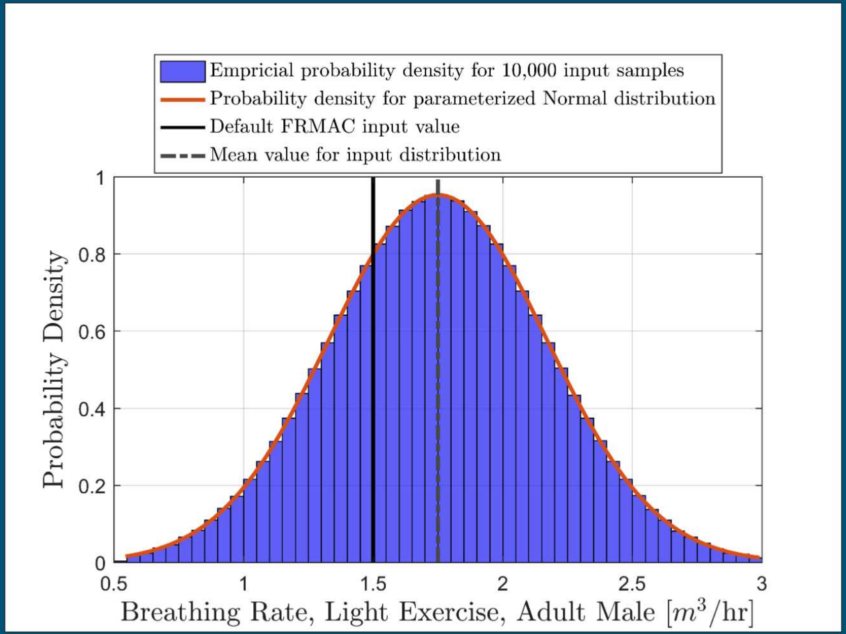
Additional Slides

Input Distribution References

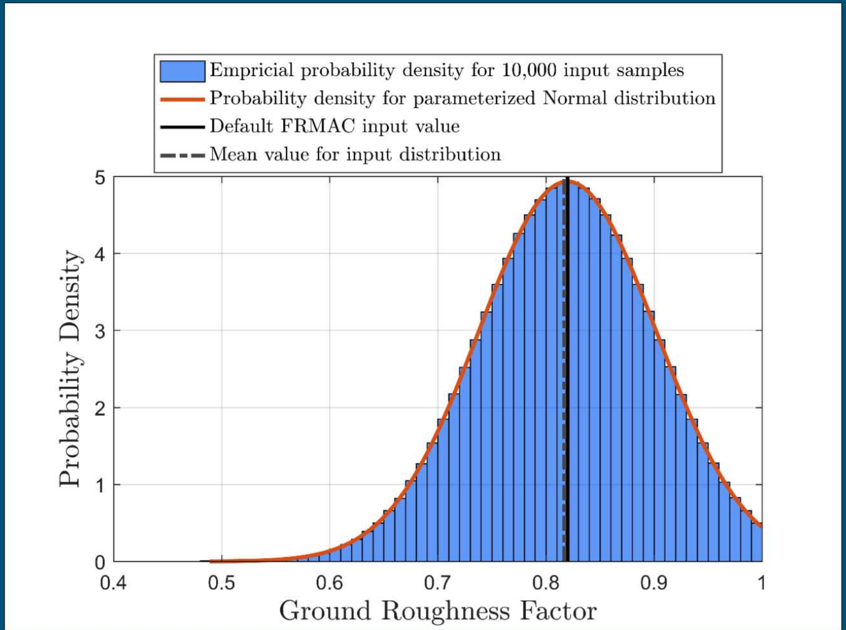
Input	Reference
Air Concentration Uncertainty Multiplier – NARAC	Developed in collaboration with FRMAC scientists at RSL and NARAC
Activity per Area – In Situ	
Activity per Area – AMS	
Activity per Area – Laboratory Analysis	
Deposition Velocity	*Evaluation of Severe Accident Risks: Quantification of Major Input Parameters*, NUREG/CR-4551, Vol. 2, Rev. 1, Part 7, U.S. Nuclear Regulatory Commission, Washington, DC, 1990
Breathing Rate – Light Exercise, Adult Male	Developed using information from 2011 EPA Exposure Factors Handbook
Breathing Rate – Activity-Averaged, Adult Male	Based on approach used by RESRAD for a similar parameter - *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes*, NUREG/CR-6697, ANL/EAD/TM-98, Argonne National Laboratory, Argonne, IL, 2000
Ground Roughness Factor	No uncertainty information available. Developed based on 10% measurement uncertainty described in Beck, H.L., *Exposure Rate Conversion Factors for Radionuclides Deposited on the Ground*, EML-378, U.S. Department of Energy Environmental Measurements Laboratory, New York, NY, 1980
Resuspension Coefficient Multiplier	Maxwell, R. and Anspaugh, L., "An Improved Model for Prediction of Resuspension" in *Health Physics*, Vol. 101, pp. 722-730, December 2011
Weathering Coefficient Multiplier	No uncertainty information available. Developed based on information in Anspaugh reference: Golikov, V.Y., Balonov, M.I., Jacob, P., "External Exposure of the Population Living in Areas of Russia Contaminated Due to the Chernobyl Accident" in *Radiat Environ Biophys*, Vol. 41, pp. 185-193, 2002
Deposition External Dose Coefficient Multiplier	Eckerman, K., *Radiation Dose and Health Risk Estimation: Technical Basis for the State-of-the-Art Reactor Consequence Analysis Project*, Oak Ridge National Laboratory, Oak Ridge, TN, 2012
Inhalation Dose Coefficient Multipliers	
Plume External Dose Coefficient Multiplier	Assigned per conversation with Keith Eckerman on March 20, 2017



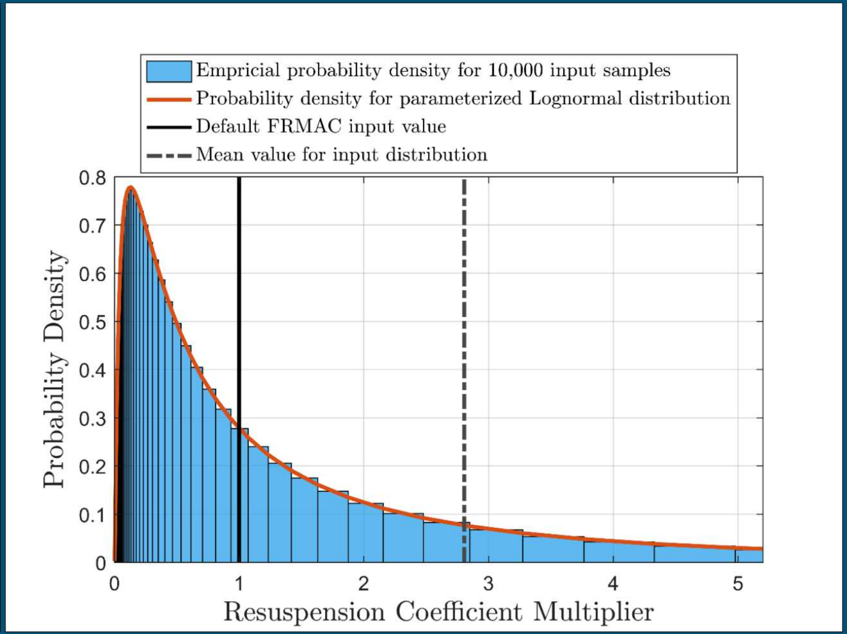
Empricial probability density for 10,000 input samples
Probability density for parameterized Triangular distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Breathing Rate, Activity Averaged, Adult Male [m^3/hr]



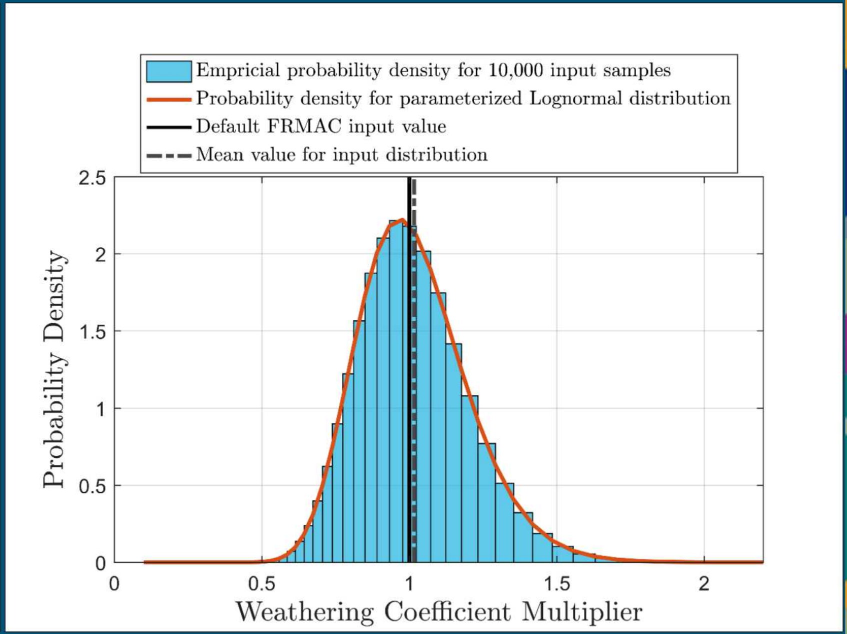
Empricial probability density for 10,000 input samples
Probability density for parameterized Normal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Breathing Rate, Light Exercise, Adult Male [m^3/hr]



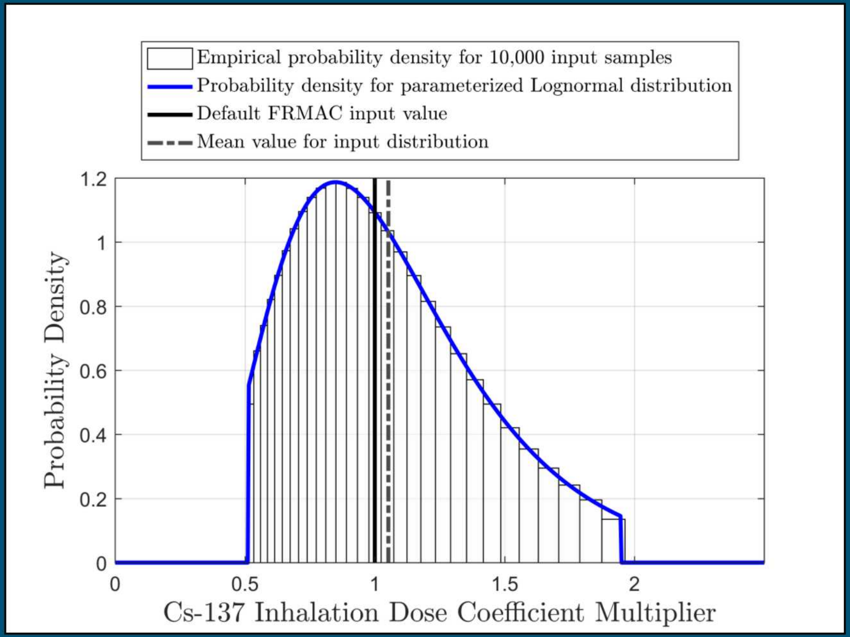
Empricial probability density for 10,000 input samples
Probability density for parameterized Normal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Ground Roughness Factor

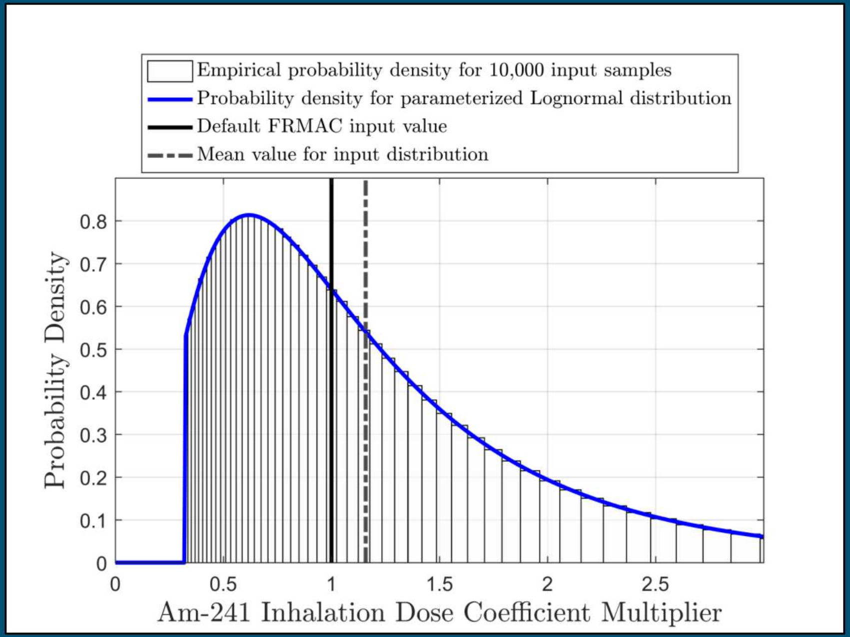


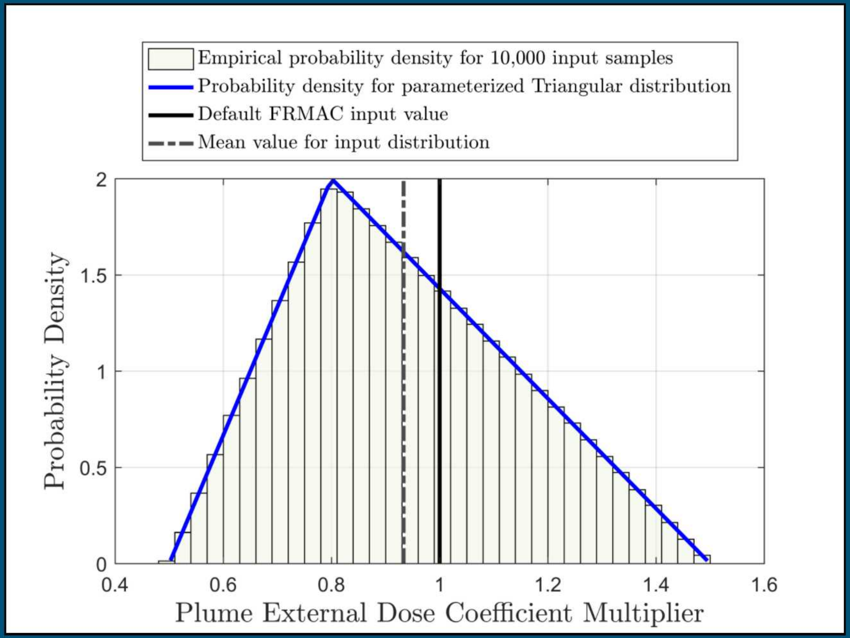
Empricial probability density for 10,000 input samples
Probability density for parameterized Lognormal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Resuspension Coefficient Multiplier

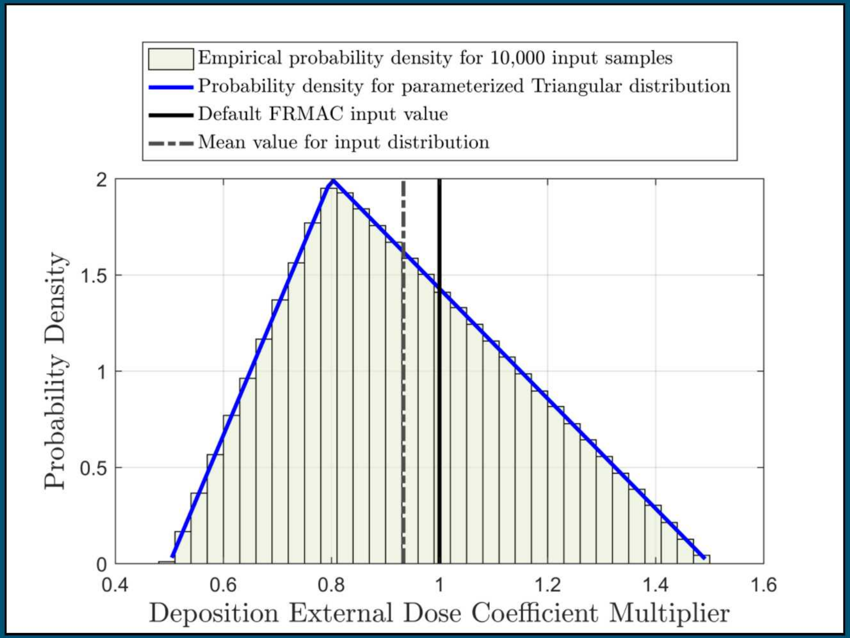


Empricial probability density for 10,000 input samples
Probability density for parameterized Lognormal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Weathering Coefficient Multiplier


Empirical probability density for 10,000 input samples
Probability density for parameterized Lognormal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Cs-137 Inhalation Dose Coefficient Multiplier
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2


Empirical probability density for 10,000 input samples
Probability density for parameterized Lognormal distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Am-241 Inhalation Dose Coefficient Multiplier
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1
1.5
2
2.5


Empirical probability density for 10,000 input samples
Probability density for parameterized Triangular distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Plume External Dose Coefficient Multiplier
0
0.5
1
1.5
2
0.4
0.6
0.8
1
1.2
1.4
1.6

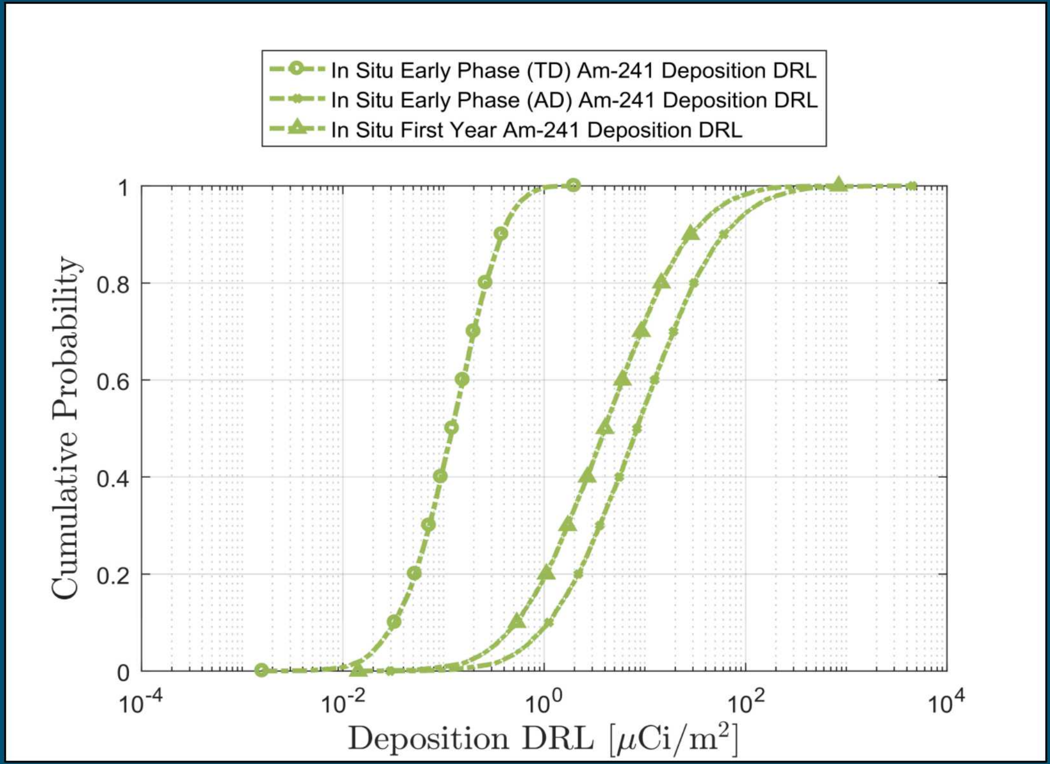

Empirical probability density for 10,000 input samples
Probability density for parameterized Triangular distribution
Default FRMAC input value
Mean value for input distribution
Probability Density
Deposition External Dose Coefficient Multiplier
0
0.5
1
1.5
2
0.4
0.6
0.8
1
1.2
1.4
1.6

Uncertainty Analysis Results – Am-241 Deposition DRL (µCi/m^2)

Scenario	Default	Mean	5th	50th	95th		Mean/ Default	95th/ 5th
Early Phase (Total Dose)	4.64E-02	1.74E-01	2.17E-02	1.23E-01	4.98E-01		3.76	22.9
Early Phase (Avoidable Dose)	8.66	28.1	6.38E-01	8.35	1.10E+02		3.24	173
First Year	4.15	12.4	3.07E-01	4.01	50.5		2.98	164

Results shown for Single Radionuclide In Situ simulations

- Am-241 Deposition DRL is more uncertain when dose from the plume is <u>excluded</u>
- Deposition DRL is more uncertain for Am-241 than Cs-137



Sensitivity Analysis Results

- Sensitivity analysis methods tell us how much of the uncertainty in the output is explained by the uncertainty in the input
- Linear rank regression technique applied for the purposes of this project
  - Inputs ranked in terms of importance by standardized rank regression coefficient (SRRC) value
  - Results verified using scatterplots comparing inputs and outputs
- Results showed that deposition velocity is the most important contributor to DRL uncertainty in the case of a single-radionuclide source term DRL calculation that includes the plume
- When the plume is not included, the DRL uncertainty is driven by the most uncertain inputs to the primary dose pathway
- These observations can be used to motivate additional studies to better characterize these inputs and in turn reduce the overall uncertainty in the DRL results

Sensitivity Analysis Results – Cs-137 Deposition DRL

Early Phase (Total Dose), R^2 = 0.931	
Variable Name	**R^2**
Deposition Velocity	0.654
Cs-137 Inhalation Dose Coefficient Multiplier	0.786
Breathing Rate, Light Exercise, Adult Male	0.854
Weathering Coefficient Multiplier	0.893
Deposition External Dose Coefficient Multiplier	0.922
Ground Roughness Factor	0.927
Resuspension Coefficient Multiplier	0.931
Cs-137 Activity per Area	0.931
Plume External Dose Coefficient Multiplier	0.931
Breathing Rate, Activity Averaged, Adult Male	0.931

Early Phase (Avoidable Dose), R^2 = 0.901	
Variable Name	**R^2**
Deposition External Dose Coefficient Multiplier	0.716
Ground Roughness Factor	0.827
Resuspension Coefficient Multiplier	0.895
Cs-137 Inhalation Dose Coefficient Multiplier	0.899
Breathing Rate, Activity Averaged, Adult Male	0.900
Breathing Rate, Light Exercise, Adult Male	0.901
Cs-137 Activity per Area	0.901
Deposition Velocity	0.901
Plume External Dose Coefficient Multiplier	0.901
Weathering Coefficient Multiplier	0.901

Results shown for Single Radionuclide In Situ simulations

- Sensitivity results show that the inputs that contribute the most uncertainty to the Cs-137 Deposition DRL are:
  - Deposition velocity when dose from the plume is included
  - Groundshine inputs when dose from the plume is excluded

Sensitivity Analysis Results – Am-241 Deposition DRL

Early Phase (Total Dose), R^2 = 0.942	
Variable Name	**R^2**
Deposition Velocity	0.516
Am-241 Inhalation Dose Coefficient Multiplier	0.849
Breathing Rate, Light Exercise, Adult Male	0.905
Weathering Coefficient Multiplier	0.938
Resuspension Coefficient Multiplier	0.942
Breathing Rate, Activity Averaged, Adult Male	0.942
Deposition External Dose Coefficient Multiplier	0.942
Ground Roughness Factor	0.942
Am-241 Activity per Area	0.942
Plume External Dose Coefficient Multiplier	0.942

Early Phase (Avoidable Dose), R^2 = 0.980	
Variable Name	**R^2**
Resuspension Coefficient Multiplier	0.833
Am-241 Inhalation Dose Coefficient Multiplier	0.951
Breathing Rate, Activity Averaged, Adult Male	0.967
Breathing Rate, Light Exercise, Adult Male	0.980
Ground Roughness Factor	0.980
Am-241 Activity per Area	0.980
Deposition Velocity	0.980
Deposition External Dose Coefficient Multiplier	0.980
Plume External Dose Coefficient Multiplier	0.980
Weathering Coefficient Multiplier	0.980

Results shown for Single Radionuclide In Situ simulations

- Sensitivity results show that the inputs that contribute the most uncertainty to the Am-241 Deposition DRL are:
  - Deposition velocity when dose from the plume is included
  - Resuspension inhalation inputs when dose from the plume is excluded

Convergence Results

Output Name	Lower Bound of 95% CI	Mean	Upper Bound of 95% CI
Dose Rate DRL [mrem/hr]	4.68E-01	4.93E-01	5.18E-01
Cs-137 Deposition DRL [µCi/m^2]	8.53E+01	8.99E+01	9.46E+01
Cs-137 Integrated Air DRL [µCi-s/m^3]	1.22E+04	1.32E+04	1.41E+04
Cs-137 Resuspension Inhalation DP [mrem]	1.44E+01	1.66E+01	1.90E+01
Cs-137 Groundshine DP [mrem]	2.17E+02	2.32E+02	2.51E+02
Cs-137 Total DP [mrem]	2.30E+02	2.49E+02	2.72E+02
Am-241 Deposition DRL [µCi/m^2]	2.19E+01	2.29E+01	2.41E+01
Am-241 Integrated Air DRL [µCi-s/m^3]	3.25E+03	3.49E+03	3.76E+03
Am-241 Resuspension Inhalation DP [mrem]	1.42E+05	1.67E+05	1.98E+05
Am-241 Groundshine DP [mrem]	8.62E+00	9.26E+00	9.99E+00

- 95% Confidence Intervals (CI) are interpreted as follows: ‘there is a 95% confidence that the true value of the mean falls within this interval.’
- Results show that estimate of the mean is well characterized by the 10,000 LHS samples used to quantify the uncertainties