



Uncertainties in Internal Dosimetry

An Idea Whose Time Has Come?



Tom LaBone

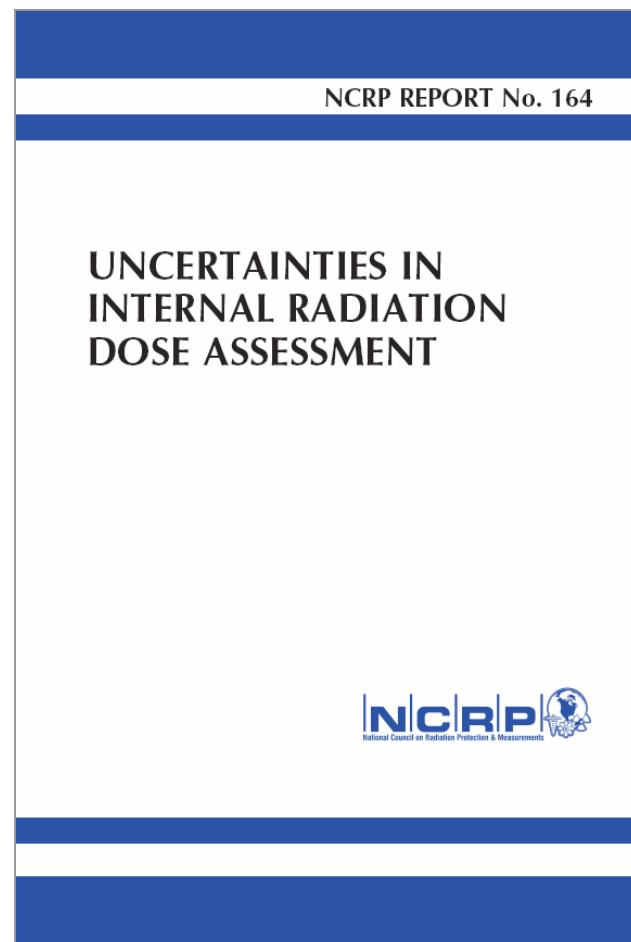
Savannah River Chapter of
Health Physics Society
Aiken, SC
May 16, 2014

“It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so.”

Mark Twain

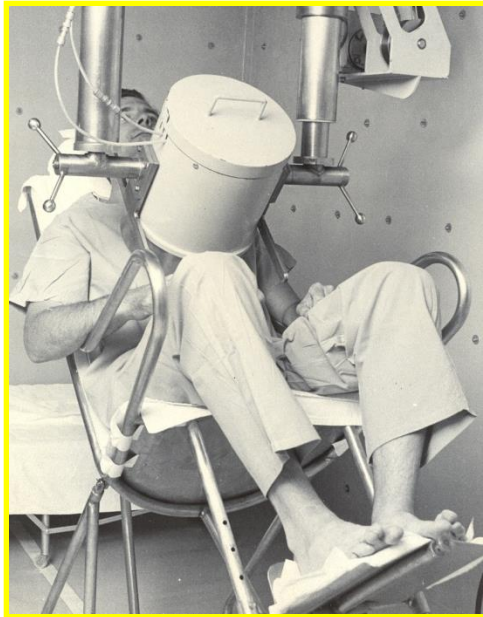
NCRP 164 (2010)

- “The dose limits that are recommended by the ICRP for regulatory purposes are based on the use of values of dose per unit intake that are to be applied without consideration of uncertainty.”
- “Nevertheless, it is scientifically and ethically necessary to assess the possibility that persons with assigned estimates of internal dose did not in fact receive much larger doses.”
- “This is the reason to evaluate the uncertainties in assigned dose.”



Cs-137 Chest Counter

This “chest counter” ...

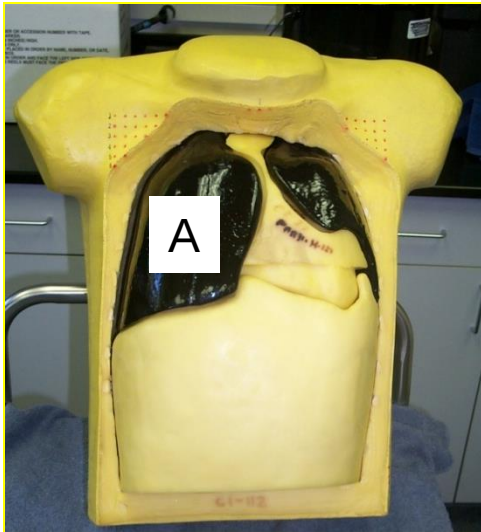


...is calibrated with this phantom...

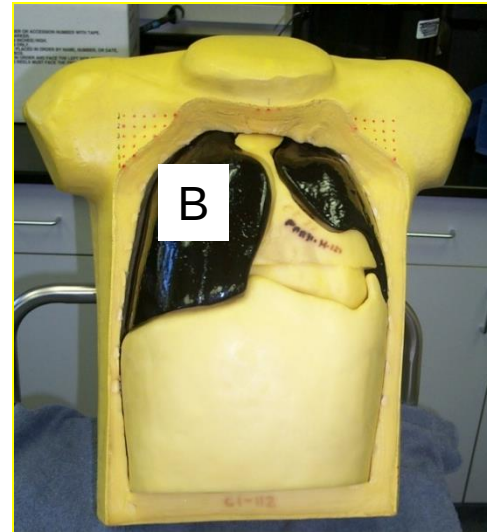
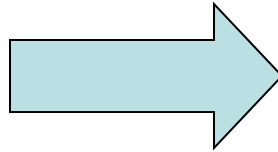


... and is used to count this person

Analytical Uncertainty



Calibrate with these
standard lungs in
this phantom



Now quantify these
unknown lungs in the
same phantom

Analytical Uncertainty

- *Guide to the Expression of Uncertainty in Measurement*, ISO/IEC Guide 98, 1995.
 - referred to as the “GUM”
 - provides guidance on calculating and reporting the uncertainty in a measurement
- Quantifying Uncertainty in Analytical Measurement, EURACHEM/CITAC Guide CG 4, 2000
 - GUM methodology tailored to radiochemistry
- *Multi-Agency Radiological Laboratory Analytical Protocols Manual* (MARLAP), NUREG-1576
 - Provides useful guidance on all aspects of analyzing samples

Measurand

- Measurand
 - a detailed description of a particular quantity that is determined by measurement
- The measurand here is taken to be
 - quantity of Cs-137 that is present in a set of unknown lungs placed in a Livermore chest phantom with a 2 cm thick chest wall
 - as determined by a 8x8 inch NaI detector
 - collimated with 3 cm of lead
 - placed in contact with the midline of the chest at the height of the arm pits
 - calibrated with a NIST traceable Cs-137 standard lung set
 - having a resolution for the 662 keV gamma of 10%
 - using the Canberra Abacos-2k spectrum analysis software with parameters specified elsewhere

Influence Quantity

- Influence quantity
 - quantity that is not the measurand but affects the result of the measurement
 - e.g., the temperature at which the chest counts are made
- Influence quantities are eliminated by incorporating them into the definition of the measurand
- Note that it is not possible to eliminate or even identify all influence quantities
 - the goal is to account for the ones that significantly impact the measurement

Corrected Result

- The measurement is performed and found to be 3700 Bq
 - this realized quantity, the corrected result, should be viewed as being our best estimate of the measurand rather than the measurand
- The corrected result is not the value of the measurand because of
 - random variation of observations
 - inadequate corrections of systematic effects
 - incomplete knowledge of the physical system

Accuracy

- Accuracy of measurement
 - closeness of the agreement between the result of a measurement and a “true” value of the measurand
- The “true” value of the measurand is the result we might get from highly accurate instruments and a completely specified measurand
- The true value of a measurand is not knowable, so the accuracy is not knowable
 - accuracy is a qualitative term

Errors

- The error in a measurement is defined as

$$\text{error} = \text{measured value} - \text{true value}$$

- Since the true value is unknowable, the error is also unknowable
- Errors can be classified by how they influence the measurement
 - random and systematic errors

Types of Errors

- Random errors result from random effects in the measurement
 - the magnitude and sign of a random error changes from measurement to measurement
 - measurements cannot be corrected for random errors
 - ...but random errors can be quantified and reduced
- Systematic errors results from systematic effects in the measurement
 - the magnitude and sign of a systematic error is constant from measurement to measurement
 - measurements can be corrected for known systematic errors
 - ...but the correction introduces additional random errors

Uncertainty

- It is not very useful to say “the unknown lung set contains 3700 Bq of Cs-137 with an unknown error”
- So, let us use a quantity that can be estimated to use in place of error - uncertainty
 - *Uncertainty* is a parameter associated with a measurement that characterizes the dispersion of values that can reasonably be attributed to the measurand
 - The GUM gives a detailed methodology for calculating and reporting the uncertainty

So What is Uncertainty?

- Uncertainty is usually presented as an interval in which we are reasonably confident the best value of the measurand lies, consistent with presently available knowledge
 - Professional judgment usually plays a large role in the estimation of uncertainty
 - Uncertainty can be viewed as a formal way for the analyst to convey his beliefs to the customer

Analytical Uncertainty

- According to GUM
 - The reported result is a point estimate of the best estimate of the measurand
 - The uncertainty is a “credible” interval around the point estimate
- You should ask for and be given results and uncertainties based on the GUM methodology
- You should have an idea of what is included in the analytical uncertainty
- In the case of the unknown lungs, the best estimate of the measurand was reported by the lab to be (3700 ± 370) Bq
 - the *combined standard uncertainty* is 370 Bq

Coverage Interval

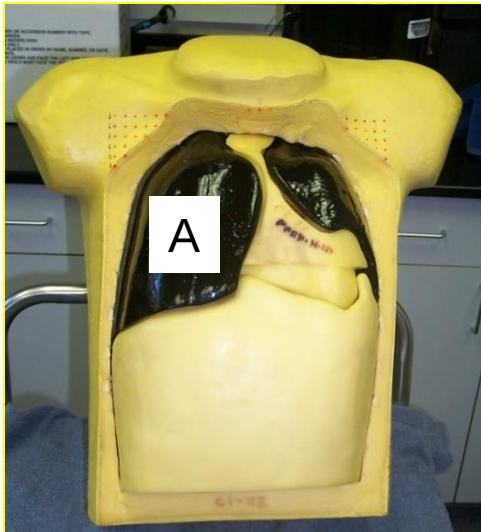
Combined standard uncertainty ~ 68% coverage interval

$$3700 \pm 370 = (3330, 4070)$$

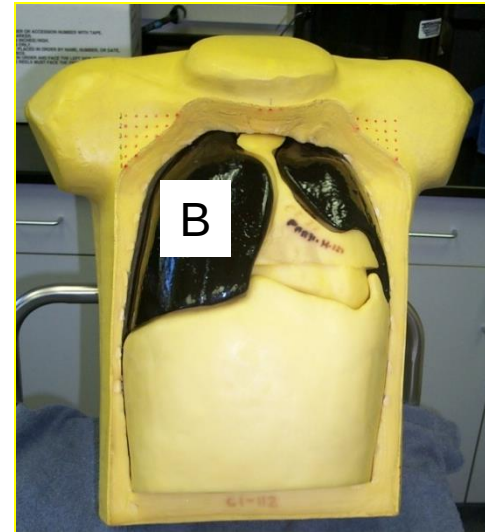
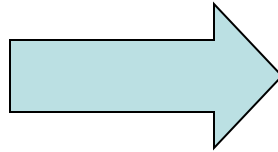
Expanded uncertainty ~95% coverage interval

$$3700 \pm (2 \times 370) = (2960, 4440)$$

I am ~95% certain that the true value of the measurand is in the interval from 2960 Bq to 4440 Bq



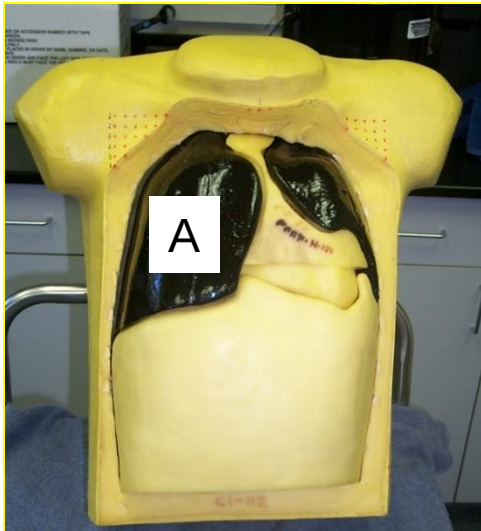
Calibrate with these
standard lungs in
this phantom



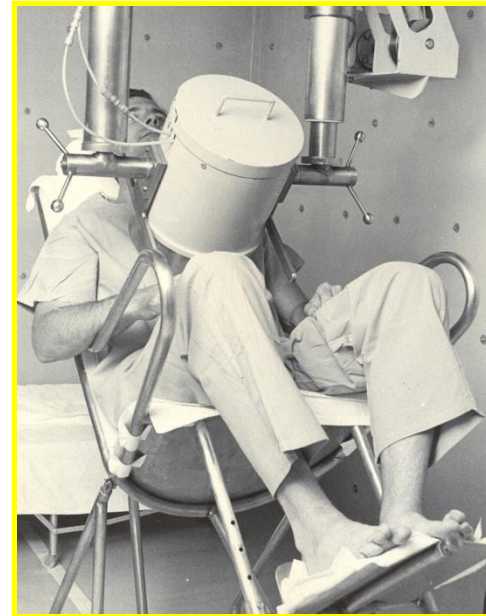
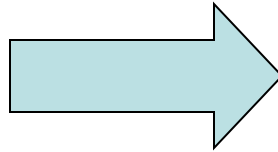
These unknown lungs
contain 3700 ± 370 Bq,
combined standard uncertainty

Bioassay Compartment

- The analytical uncertainty is the uncertainty associated with counting the phantom
- Now, assume we do a “chest count” of an individual at $t = 10$ days after an acute exposure and a result and csu of (3700 ± 370) Bq of Cs-137 is reported
 - What is the measurand here?
 - Is it the same for the phantom and the person?
 - What is included in the uncertainty?



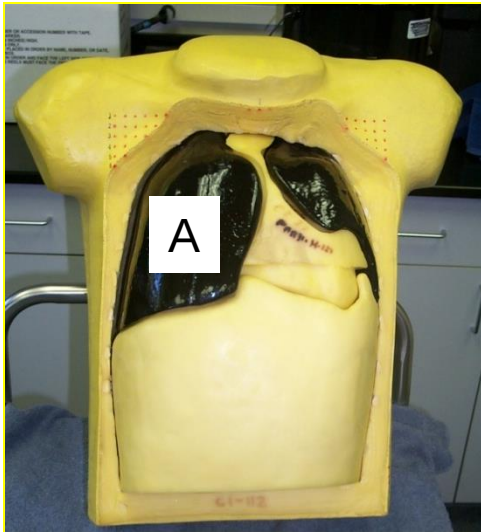
Calibrate with these
standard lungs in
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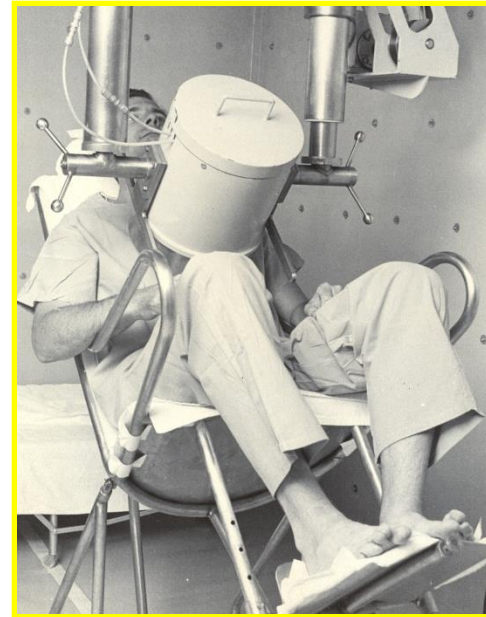
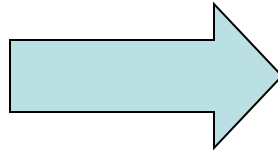
This person has a reported
chest burden of 3700 ± 370 Bq,
combined standard uncertainty

Uncertainty in Bioassay

- Uncertainties reported with chest counts are often just the analytical uncertainty
 - You should check on what is included in the reported uncertainty
- The measurand for the person is usually assumed to be the same as the measurand for the phantom, which may be grossly incorrect
 - e.g., Cs-137 in the person is likely to have different distribution than the Cs-137 in the phantom
- There are uncertainties in the chest count above and beyond the analytical uncertainty
 - a relative csu of 30% will be used here



Calibrate with these
standard lungs in
this phantom



This person has a reported
chest burden of 3700 ± 1110 Bq,
combined standard uncertainty

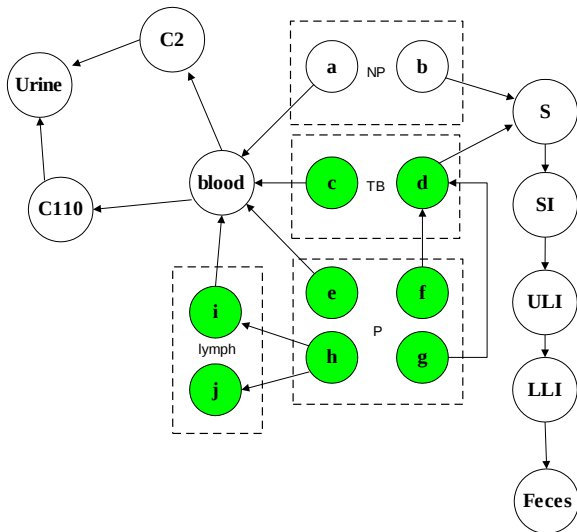
Mapping Uncertainty

- The intake of Cs-137 is calculated by dividing the results of the chest count $M(t)$ by the appropriate intake retention fraction $m(t)$

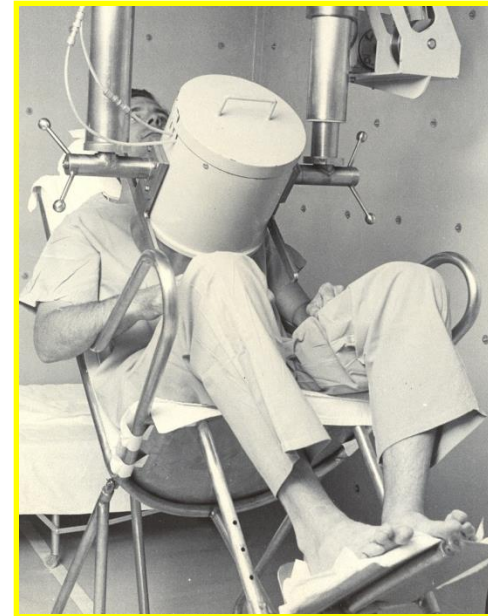
$$I = \frac{M(10)}{m(10)}$$

- The IRF $m(10)$ is composed of a combination of biokinetic compartments
 - the structure of the biokinetic compartments defines our model of how material moves in the body
- To calculate the intake we need to properly “map” (associate) biokinetic compartments to what the chest counter is seeing

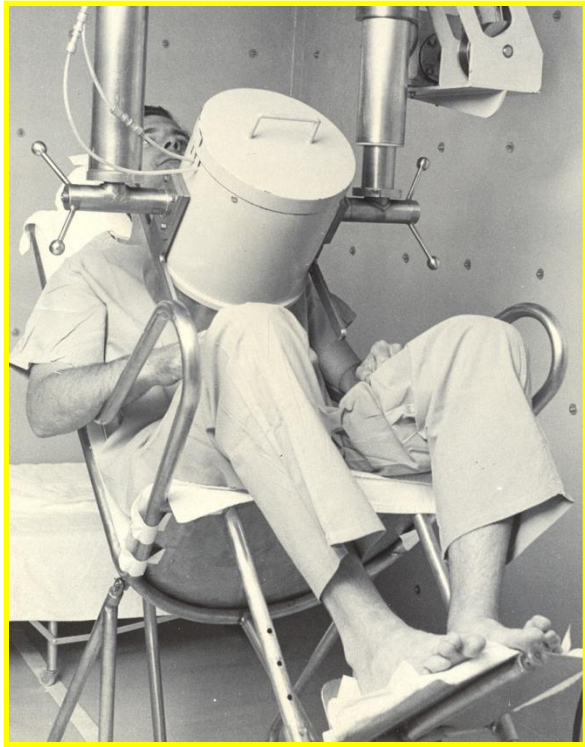
ICRP 30 Cs-137 Biokinetic Model



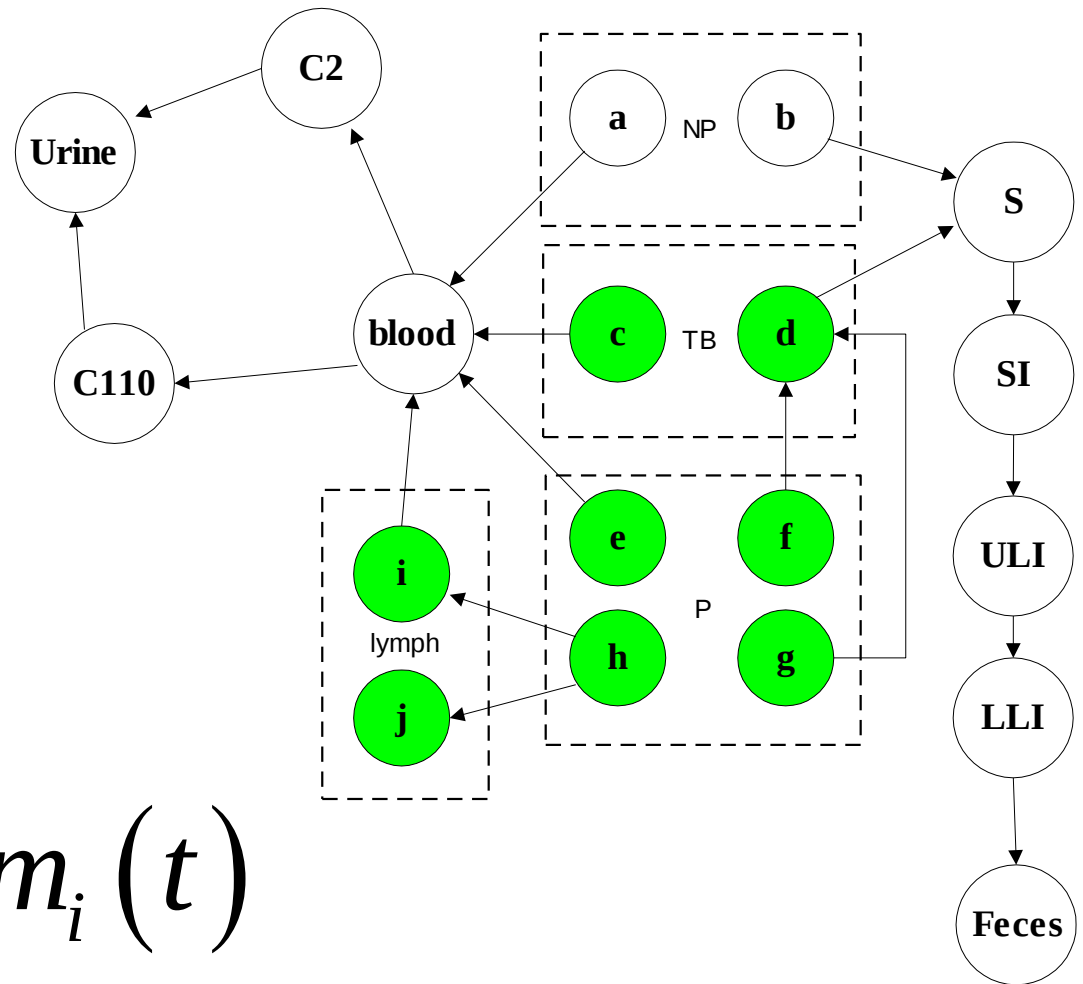
How is the 3700 Bq distributed in the model and what is the associated uncertainty?



This person has a reported chest burden of 3700 ± 1110 Bq, combined standard uncertainty



ICRP 30 Cesium-137 Biokinetic Model



$$m_{chest}(t) = \sum_{i=c}^j m_i(t)$$

NUREG CR/4884 IRF
for Class D 1 μm
AMAD Cs-137

CLASS D	AMAD = 1 MICRON	HALFLIFE= 1.10E+04 DAYS	CESIUM 137		
TIME AFTER SINGLE INTAKE	FRACTION OF INITIAL INTAKE IN:				
DAYS	SYSTEMIC ORGANS	LUNGS	NASAL PASSAGES	GI TRACT	TOTAL BODY
1.00E-01	3.90E-01	2.26E-01	3.03E-04	2.17E-02	6.38E-01
2.00E-01	4.33E-01	2.01E-01	2.96E-07	2.28E-03	6.36E-01
3.00E-01	4.55E-01	1.79E-01	0.00E+00	4.15E-04	6.35E-01
4.00E-01	4.73E-01	1.60E-01	0.00E+00	1.85E-04	6.33E-01
5.00E-01	4.88E-01	1.43E-01	0.00E+00	1.21E-04	6.31E-01
6.00E-01	5.02E-01	1.27E-01	0.00E+00	8.47E-05	6.29E-01
7.00E-01	5.14E-01	1.13E-01	0.00E+00	5.98E-05	6.28E-01
8.00E-01	5.25E-01	1.01E-01	0.00E+00	4.23E-05	6.26E-01
9.00E-01	5.34E-01	8.96E-02	0.00E+00	2.99E-05	6.24E-01
1.00E+00	5.43E-01	7.97E-02	0.00E+00	2.12E-05	6.22E-01
2.00E+00	5.81E-01	2.42E-02	0.00E+00	7.04E-07	6.06E-01
3.00E+00	5.85E-01	7.13E-03	0.00E+00	3.82E-08	5.92E-01
4.00E+00	5.79E-01	2.05E-03	0.00E+00	0.00E+00	5.81E-01
5.00E+00	5.71E-01	5.80E-04	0.00E+00	0.00E+00	5.72E-01
6.00E+00	5.64E-01	1.62E-04	0.00E+00	0.00E+00	5.64E-01
7.00E+00	5.58E-01	4.47E-05	0.00E+00	0.00E+00	5.58E-01
8.00E+00	5.53E-01	1.22E-05	0.00E+00	0.00E+00	5.53E-01
9.00E+00	5.48E-01	3.32E-06	0.00E+00	0.00E+00	5.48E-01
1.00E+01	5.43E-01	8.96E-07	0.00E+00	0.00E+00	5.43E-01
2.00E+01	5.08E-01	0.00E+00	0.00E+00	0.00E+00	5.08E-01

$$m(10) = 8.96 \times 10^{-7}$$

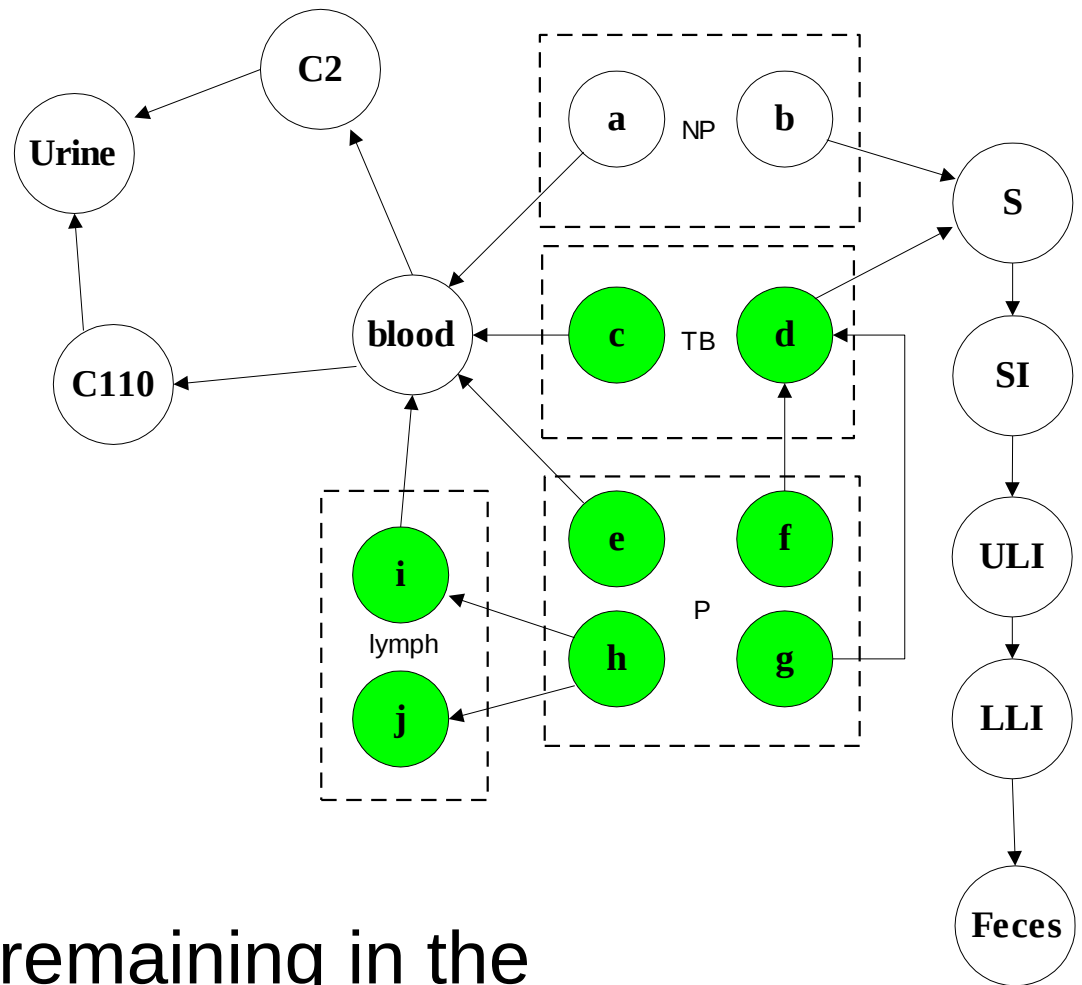
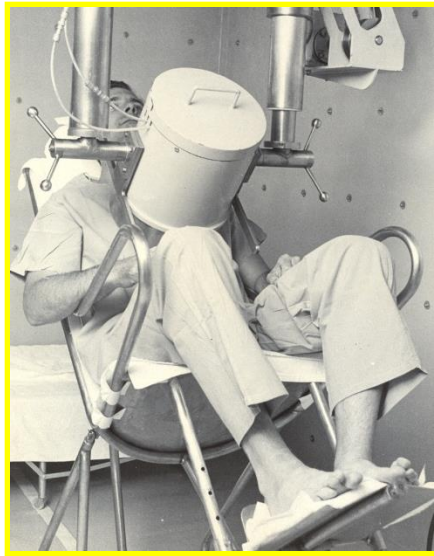
Really Big Intake?

$$M(10) = (3.7 \pm 1.1) \times 10^3 \text{ Bq}$$

$$m(10) = 8.96 \times 10^{-7} \quad (\text{assume no uncertainty})$$

$$I = \frac{(3.7 \pm 1.1) \times 10^3 \text{ Bq}}{8.96 \times 10^{-7}} = (4.1 \pm 1.2) \times 10^9 \text{ Bq}$$

This is what might be called a naïve calculation because it does not account for all sources of uncertainty



There is no Cs-137 remaining in the lungs at $t = 10$ days and the “chest counter” is seeing some portion of C110 and C2 and not just the lung biokinetic compartment

Model Specification Error

- At this point we are assuming that the biokinetic model has no uncertainty
- However, as a result of associating the chest count result with the wrong compartments of the biokinetic model we have generated an incorrect intake estimate
- Note that the uncertainty reported for the intake does not accurately reflect the enormity of our crime
 - There is a large uncertainty in our uncertainty

Reasonable Adjustment

The DOE bomab phantom has 16970 grams out of 58705 grams in the thorax bottle

Thus ~0.289 of the Cs-137 in the systemic whole body is in the view of the “chest” counter

$$m(10) = 8.96 \times 10^{-7} + (0.289 \times 0.543)$$

$$m(10) = 0.157$$

$$I = \frac{3700 \text{ Bq}}{0.157} = 2.357 \times 10^4 \text{ Bq}$$

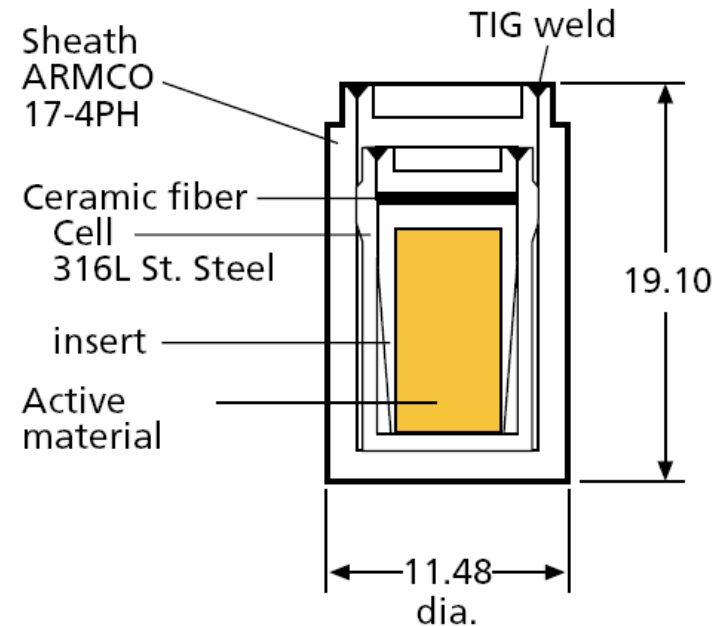
How do I determine the uncertainty in this intake estimate?



Other Sources of Uncertainty

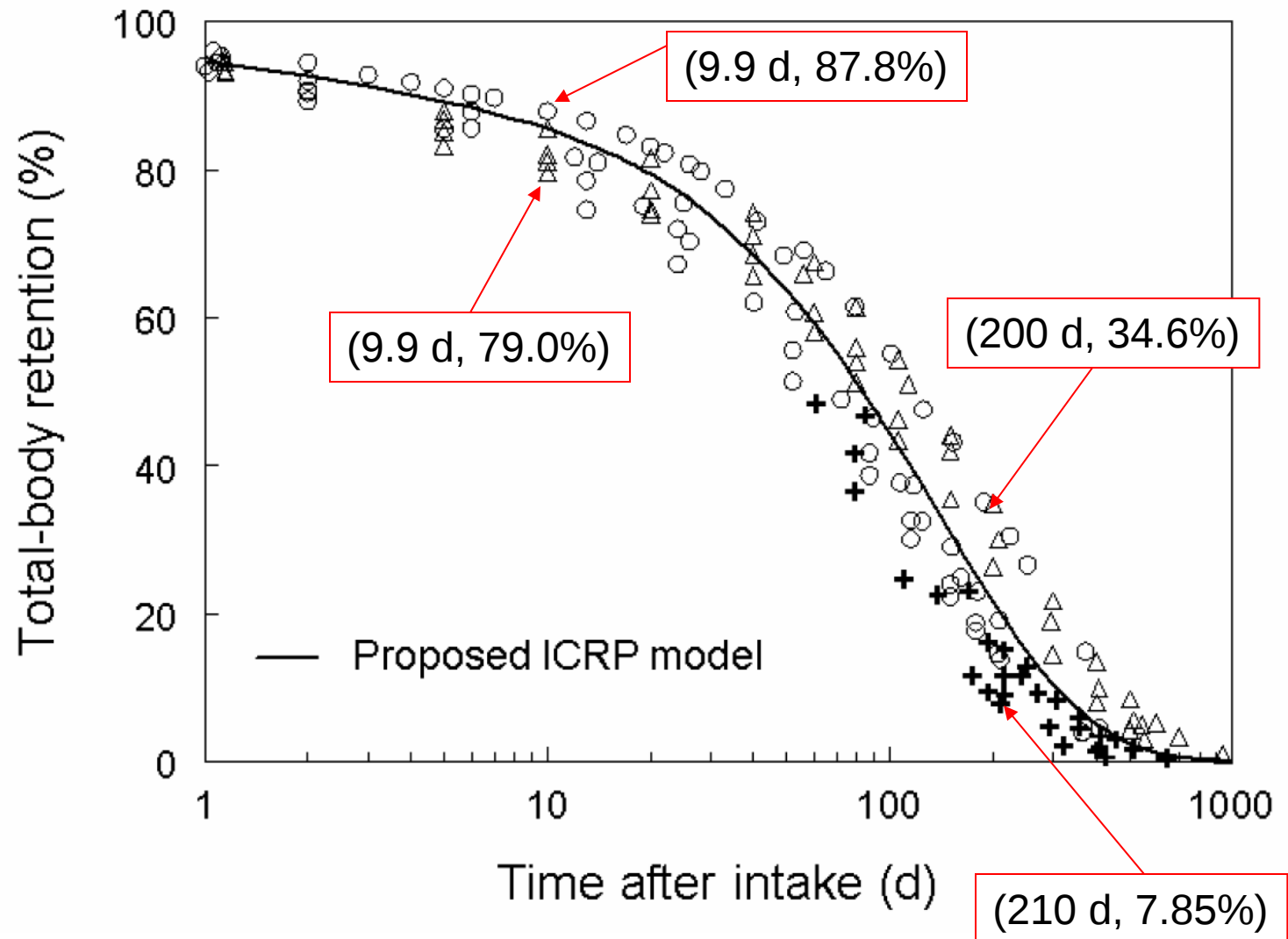
- Uncertainty in associating biokinetic models with bioassay measurements
- Uncertainty resulting from when we
 - don't recognize that the intake occurred
 - don't know when the intake occurred
 - don't know the chemical or physical form of the assimilated material
- Uncertainty in biokinetic models

What uncertainty would have resulted if the material was Class Y Cs-137 and we had assumed Class D Cs-137?

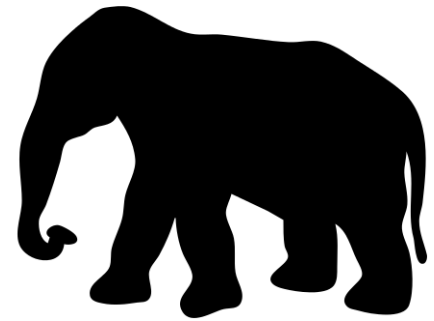


integrity of the source. The Cs-137 ceramic is manufactured by firing a special Cs-137 compound, finely homogenized SiO_2 and strengthening agents in special casts. A uniform solid ceramic matrix is formed, incorporating the Cesium-137 radionuclide. This matrix is insoluble in almost every ordinary solvent, and

Uncertainty in Cs-137 Systemic Model



Elephants in the Room

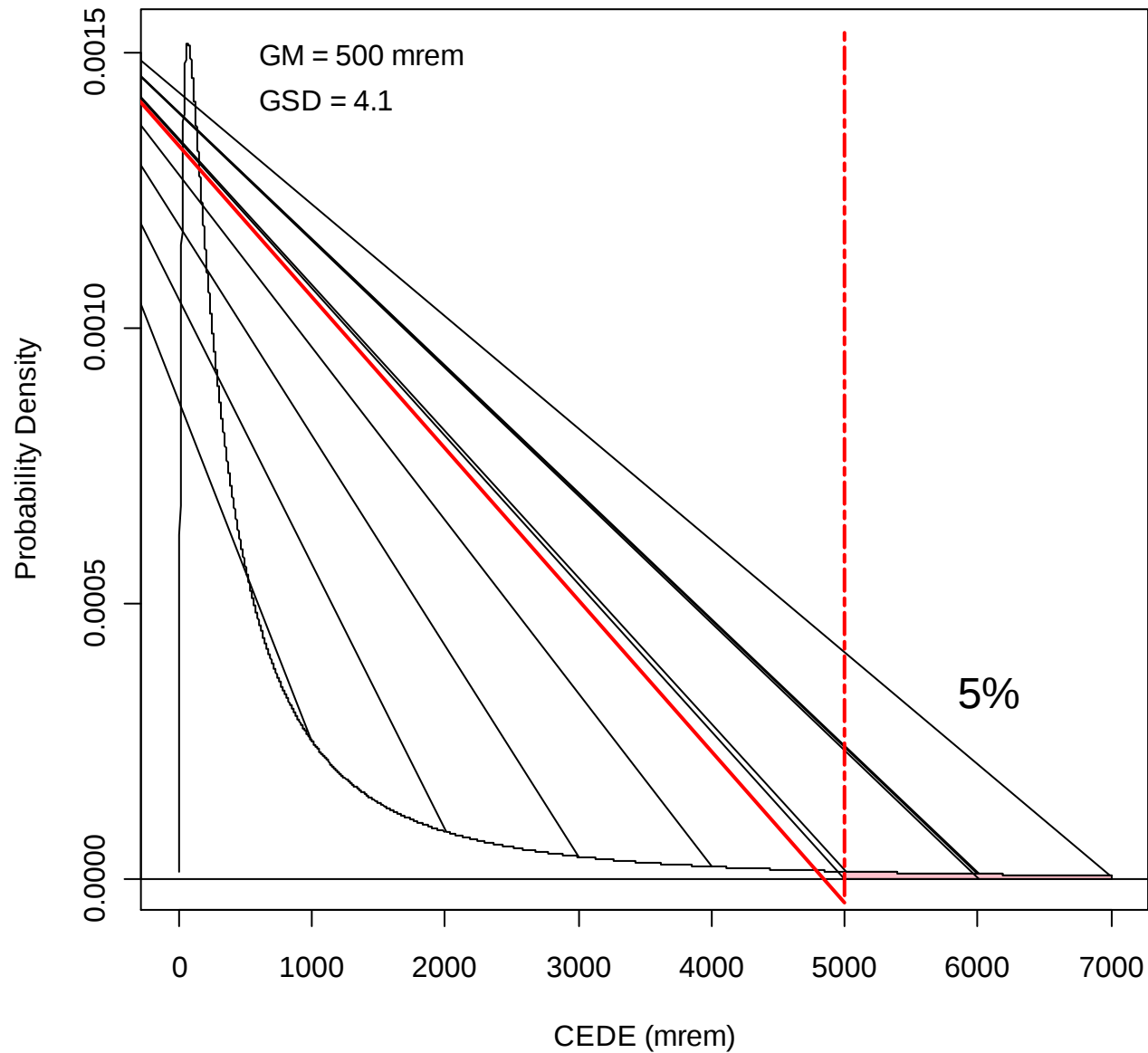


- How do we go about calculating an uncertainty that accounts for all significant sources of uncertainty?
- How large can the uncertainty in an internal dose get before it is unusable?
- How will regulators view (and use) the uncertainty in an internal dose?
- How will the recipient of an internal dose respond to the uncertainty in that dose?

Maximum Acceptable Uncertainty

- USNRC TEDE dose limit is 5 rem/year
- You are required to monitor a worker if he is likely to exceed ~ 0.5 rem/year (monitoring level)
- So, the 95% coverage interval on internal dose shall not exceed a factor of 10 at the monitoring level (0.5 rem)
 - if the uncertainty is any larger the worker has a reasonable probability of exceeding the dose limit before you decide to monitor him
 - this assumes that we have no problems recognizing that the intake occurred

What Now?

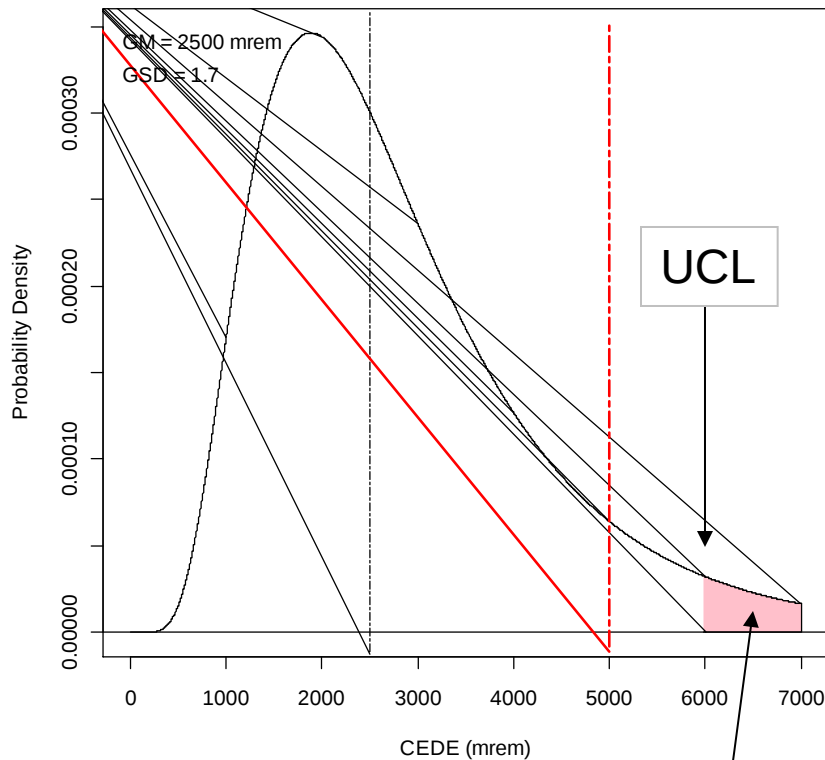


Regulators

- How would the USNRC incorporate the uncertainty in an internal dose into the regulations?
- At Superfund sites the USEPA apparently compares the upper 95th confidence level of the mean concentration of a contaminate to the regulatory limit
- Let's try something like that on for size

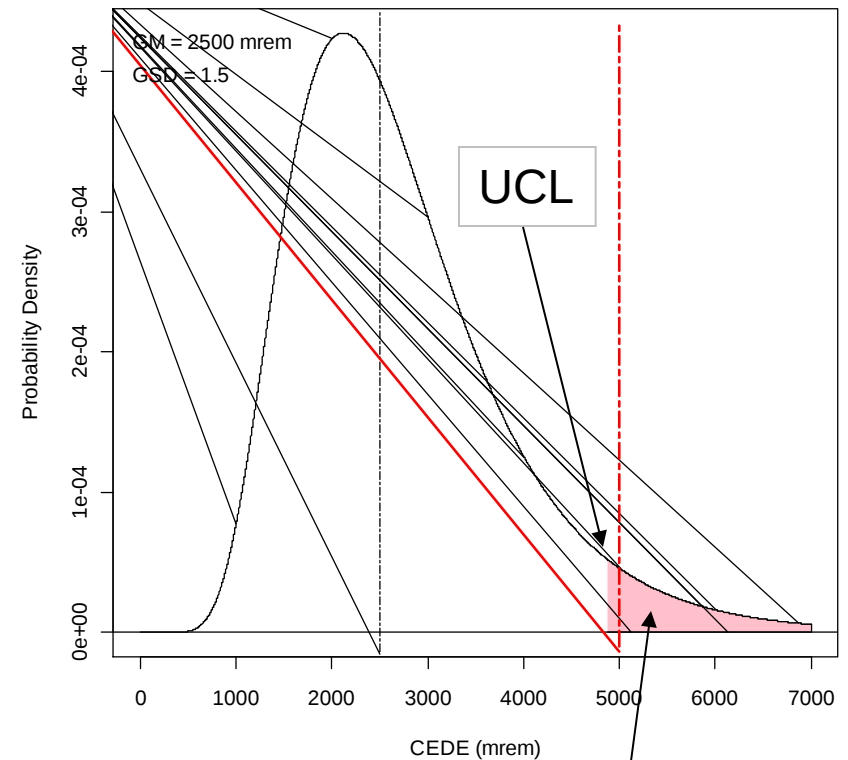
If Uncertainty Mattered to the NRC

You are in Big Trouble



5%

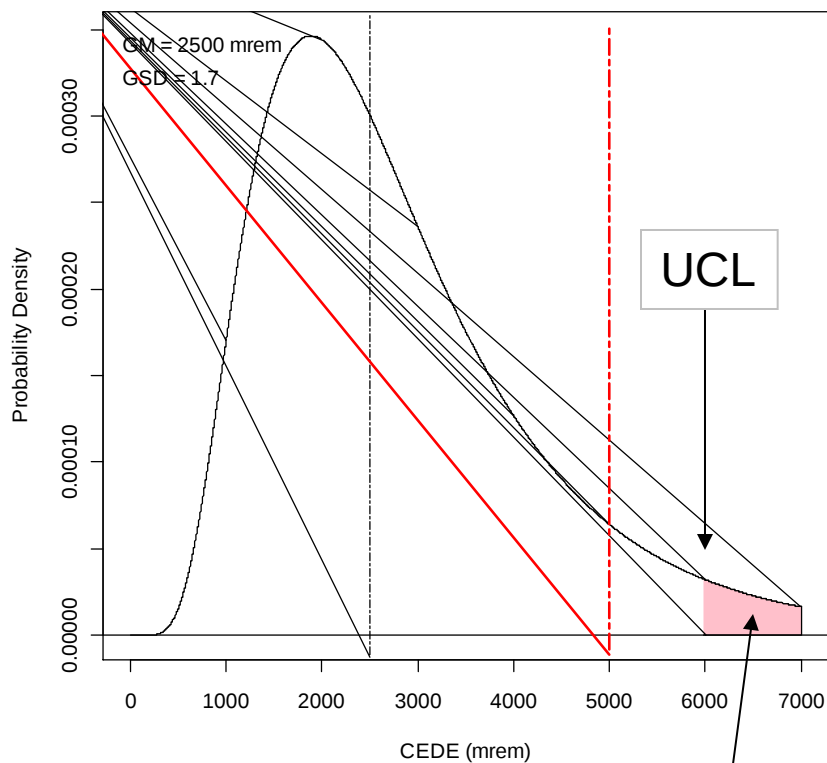
You are a Lower Deity



5%

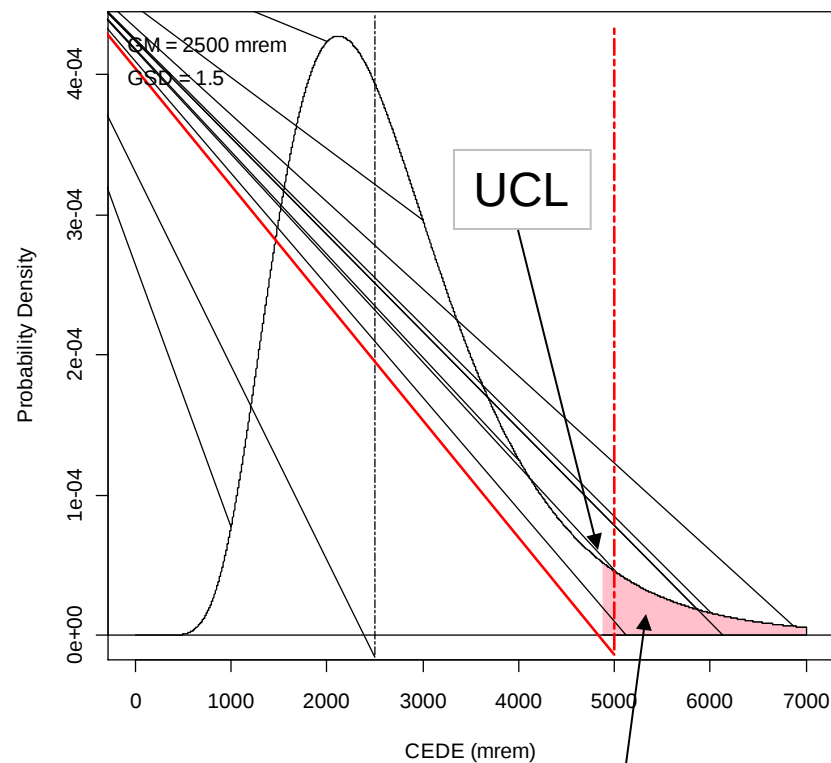
If Uncertainty Mattered to the Worker

You are in Big Trouble



5%

You are in Big Trouble



5%

My Recommendation

- Uncertainty in occupational internal doses should be studied to help us design and implement internal dosimetry programs that minimize the amount of uncertainty in reported intakes and doses
- Uncertainty in occupational internal doses should not be
 - reported to workers (unless requested)
 - formally incorporated into the regulations