HEALTH PHYSICS SOCIETY 2026

HPS 2026

6-9 July 2026 • National Harbor, MD

Bayesian Analysis of Uncertainty in ^{239}Pu Biokinetic Predictions: A Study of Former Nuclear Workers

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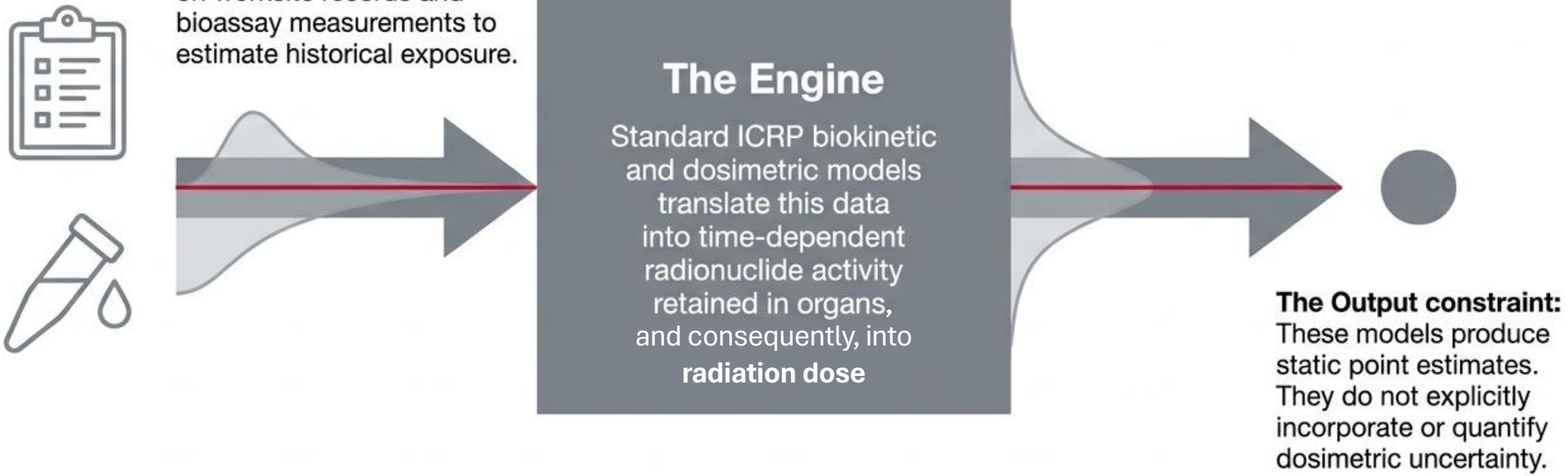
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USTUR-0730-26A

"Learning from Plutonium and Uranium Workers"

Standard Paradigm: Bypassing Uncertainty



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The Bayesian Shift and the Core Validation Problem



https://en.wikipedia.org/wiki/Thomas_Bayes

The Shift

Epidemiological risk modeling is increasingly adopting Bayesian analysis methods to provide a posterior distribution of dose estimates rather than a single point value.

The Assumption

It is assumed that this Bayesian posterior distribution contains the true dose.

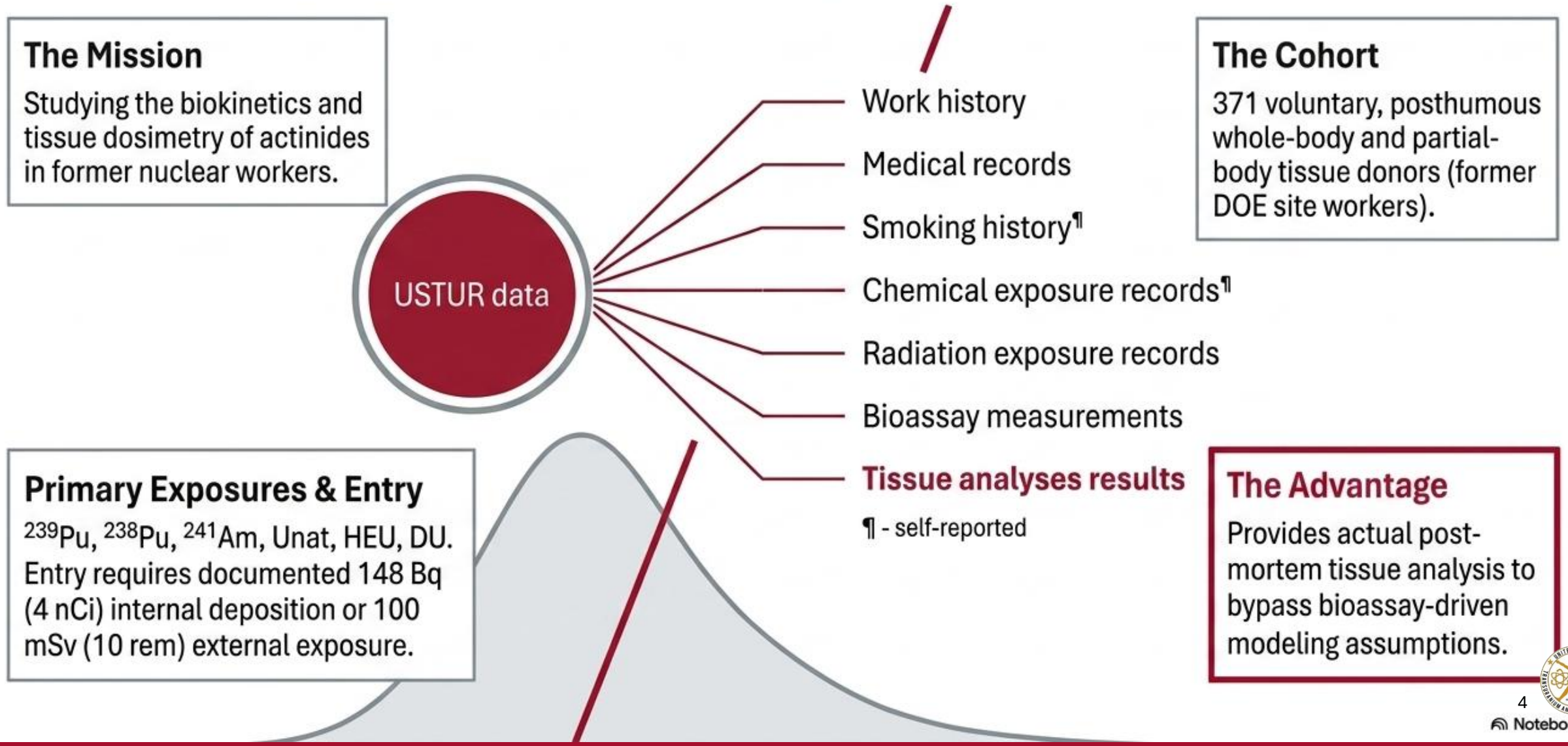
The Test

Because radiation dose is directly related to time-dependent radionuclide activity in tissues, we can use uncertainties in predicted organ activities as a direct surrogate to test uncertainties in dose estimation

The Question: When we test these probability distributions against actual human autopsy data, do they hold up?

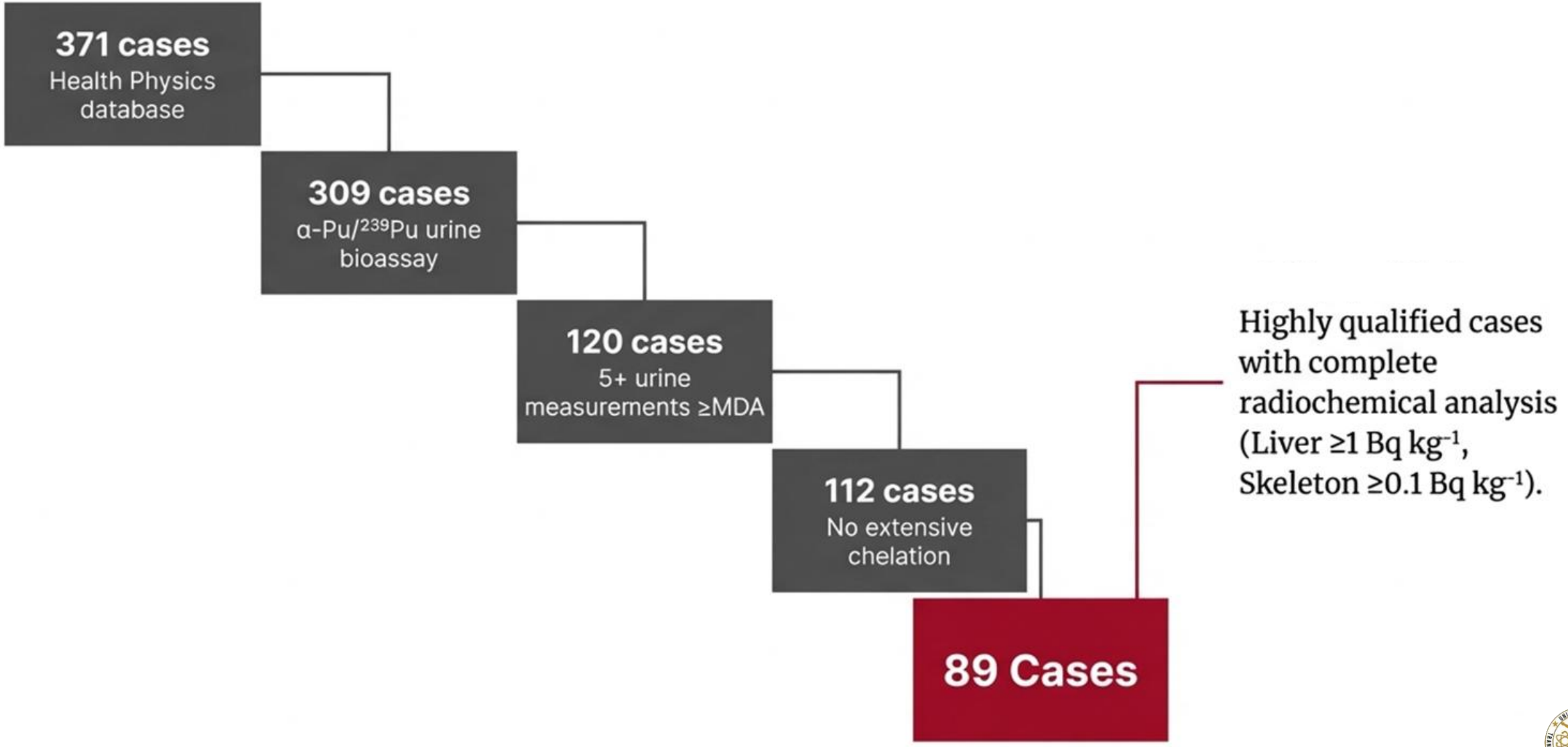
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United States Transuranium and Uranium Registries



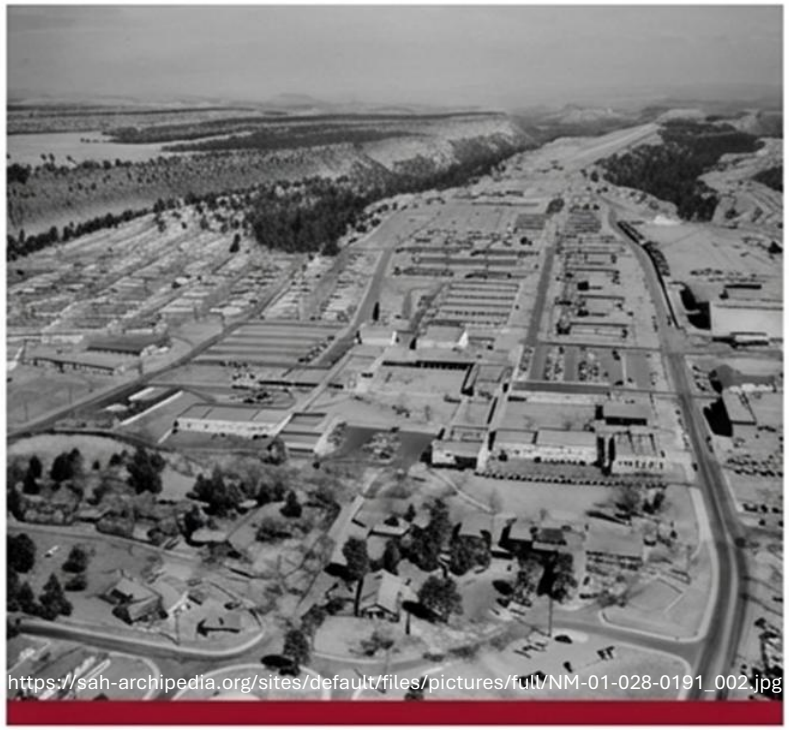
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Qualified Case Selection



Study Group: 35 Cases from Three Worksites


https://vgoinc.com/wp-content/uploads/2018/05/Hanford-1.jpg


https://sah-archipedia.org/sites/default/files/pictures/full/NM-01-028-0191_002.jpg


https://coloradoencyclopedia.org/article/rocky-flats-nuclear-facility

Hanford (n = 15)

Pu production for nuclear weapons, 1943–1989.

Los Alamos (n = 10)

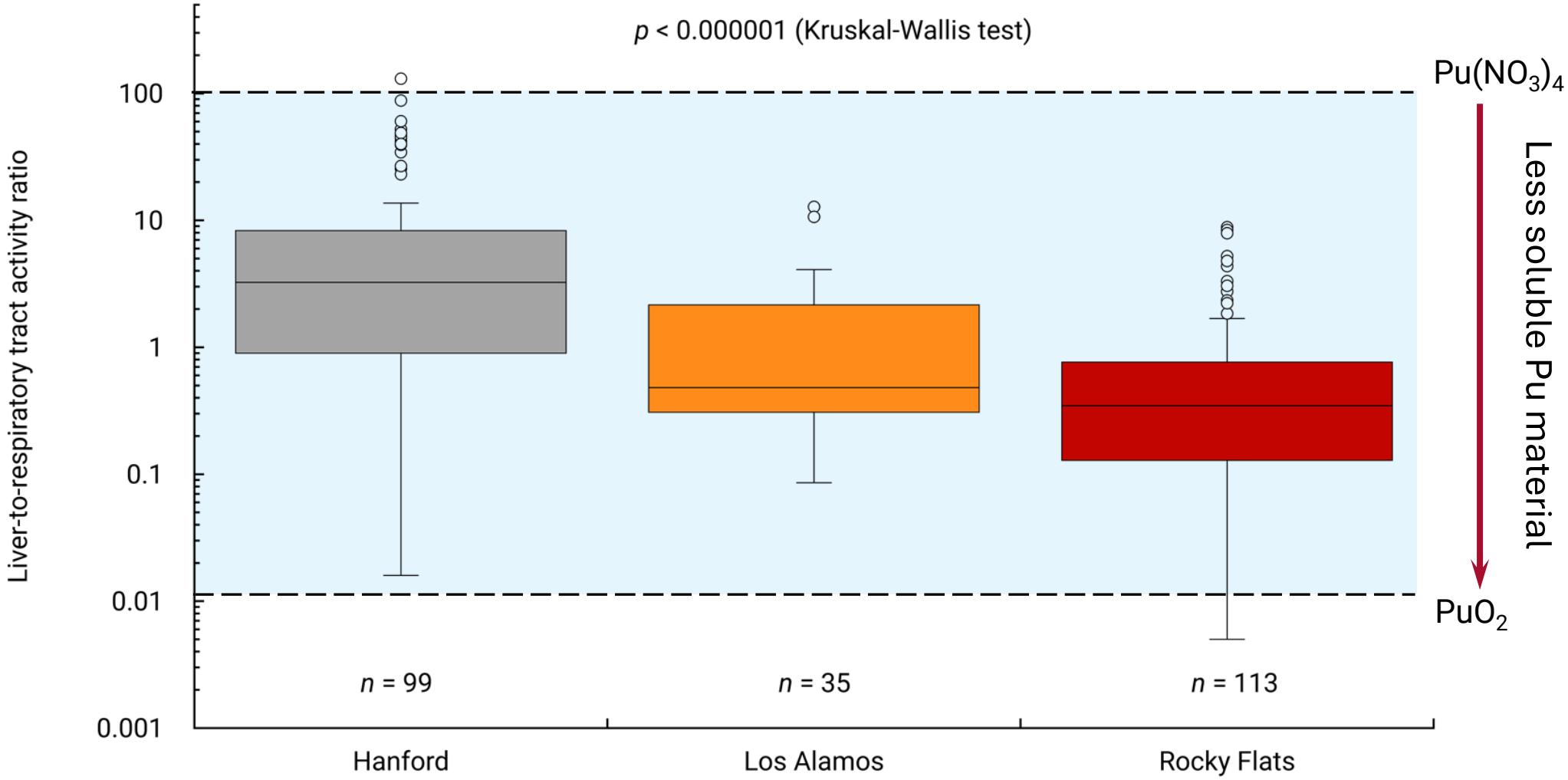
Pu processing and applications, 1943–present.

Rocky Flats (n = 10)

Production of Pu triggers and Pu recovery, 1952–1992.

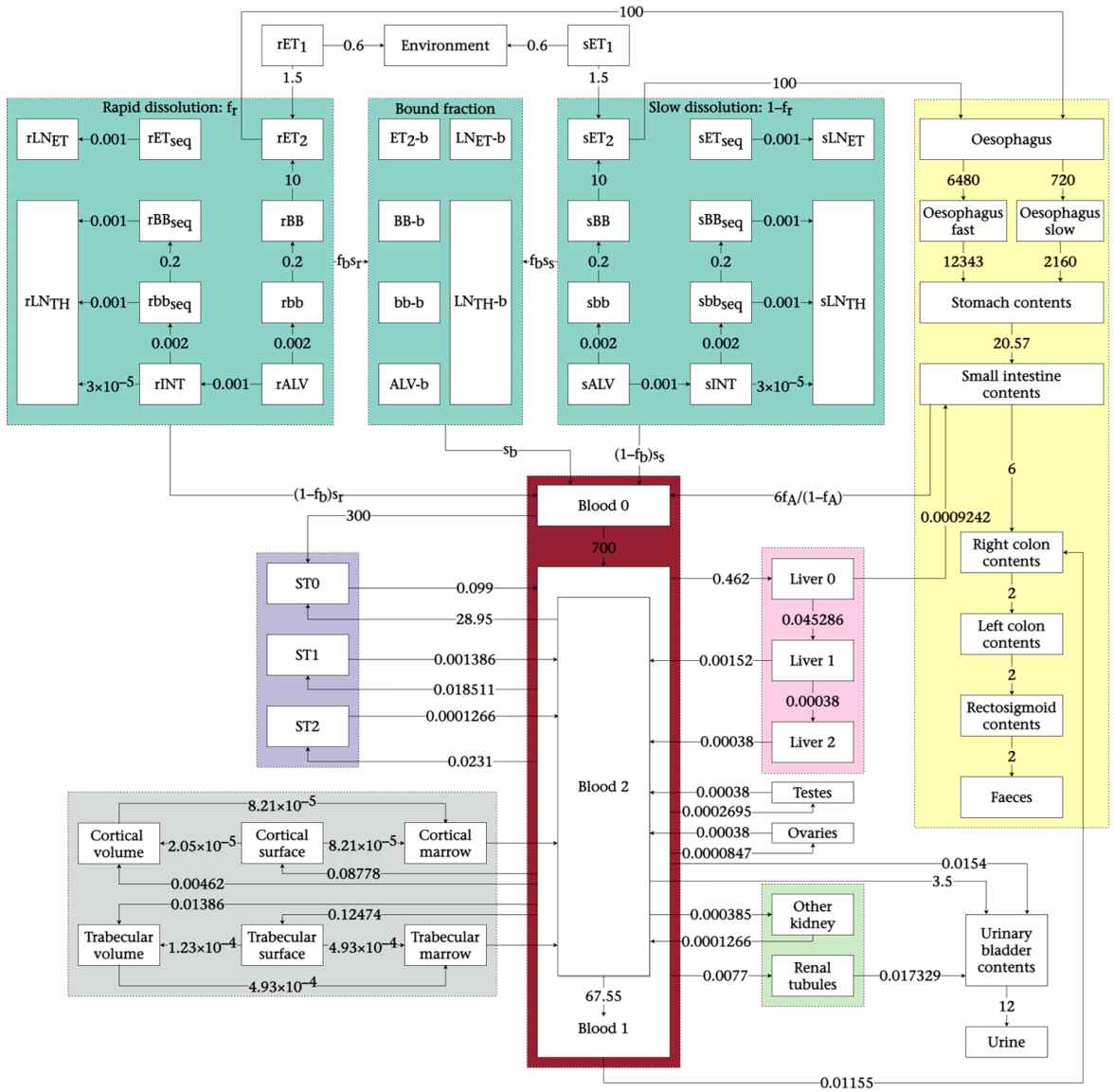
Distinct Operational and Material Physico-chemical Profiles

Material Solubility by Worksites

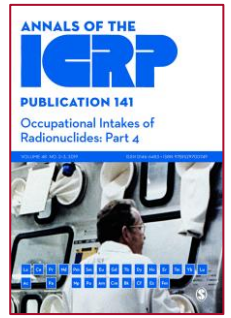


Podium Presentation at IRPA/HPS Meeting, Orlando, FL, July 7 – 12, 2024

Analytical Engine: USTUR-iRAD



Biokinetic Framework:
Built on the latest ICRP OIR models



Software Architecture:
Adaptable, object-oriented code written in Python 3.9



Dr. Martin Šefl

Takeaway:
Flexible computing environment capable of running complex uncertainty simulations

Avtandilashvili, M., Šefl, M., Zhou, J.Y., Tolmachev S.Y.
Scientific Reports 15:20476; 2025
https://doi.org/10.1038/s41598-025-04799-3

Computational Workflow

System employs **Latin hypercube sampling** of parameters from **prior distributions**

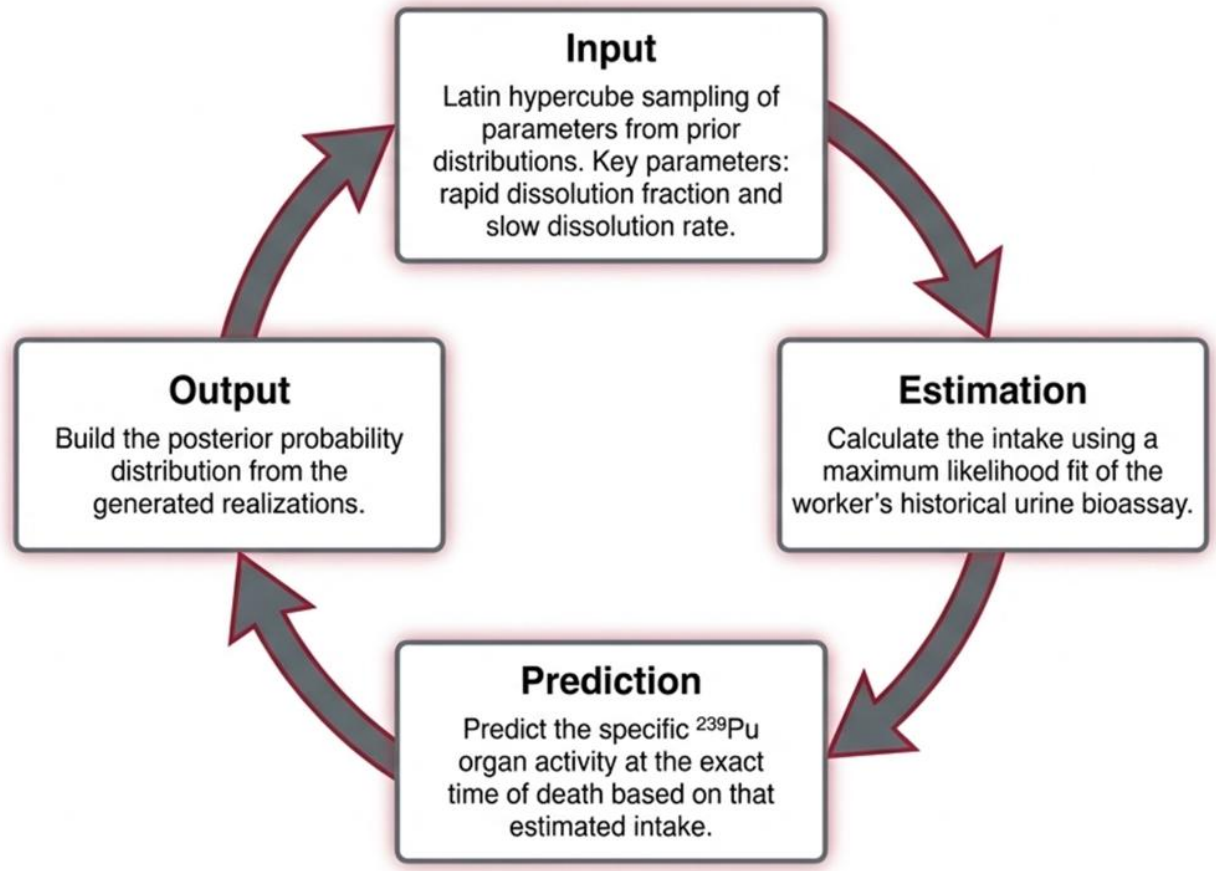
Scale: 10,000 distinct realizations generated for every single case

For each realization:

1. Estimate intake using maximum likelihood fit of the urine bioassay
2. Predict organ activity at the time of death based on estimated intake

Intake scenario assumption:

Chronic inhalation over the employment

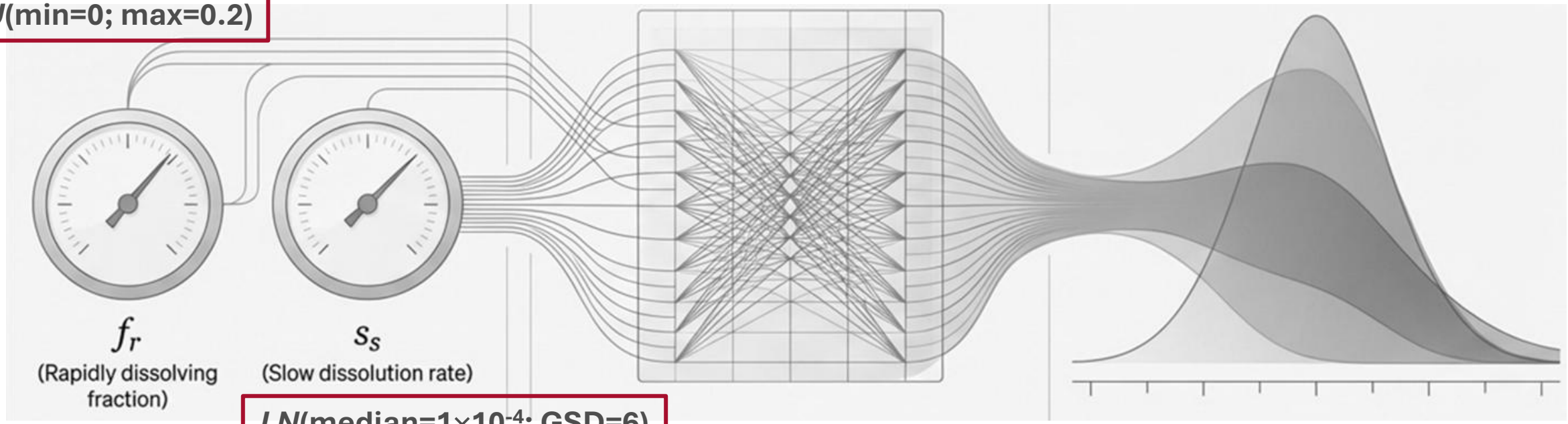


Establishing the Boundaries: Prior Distributions

Human Respiratory Tract Model:

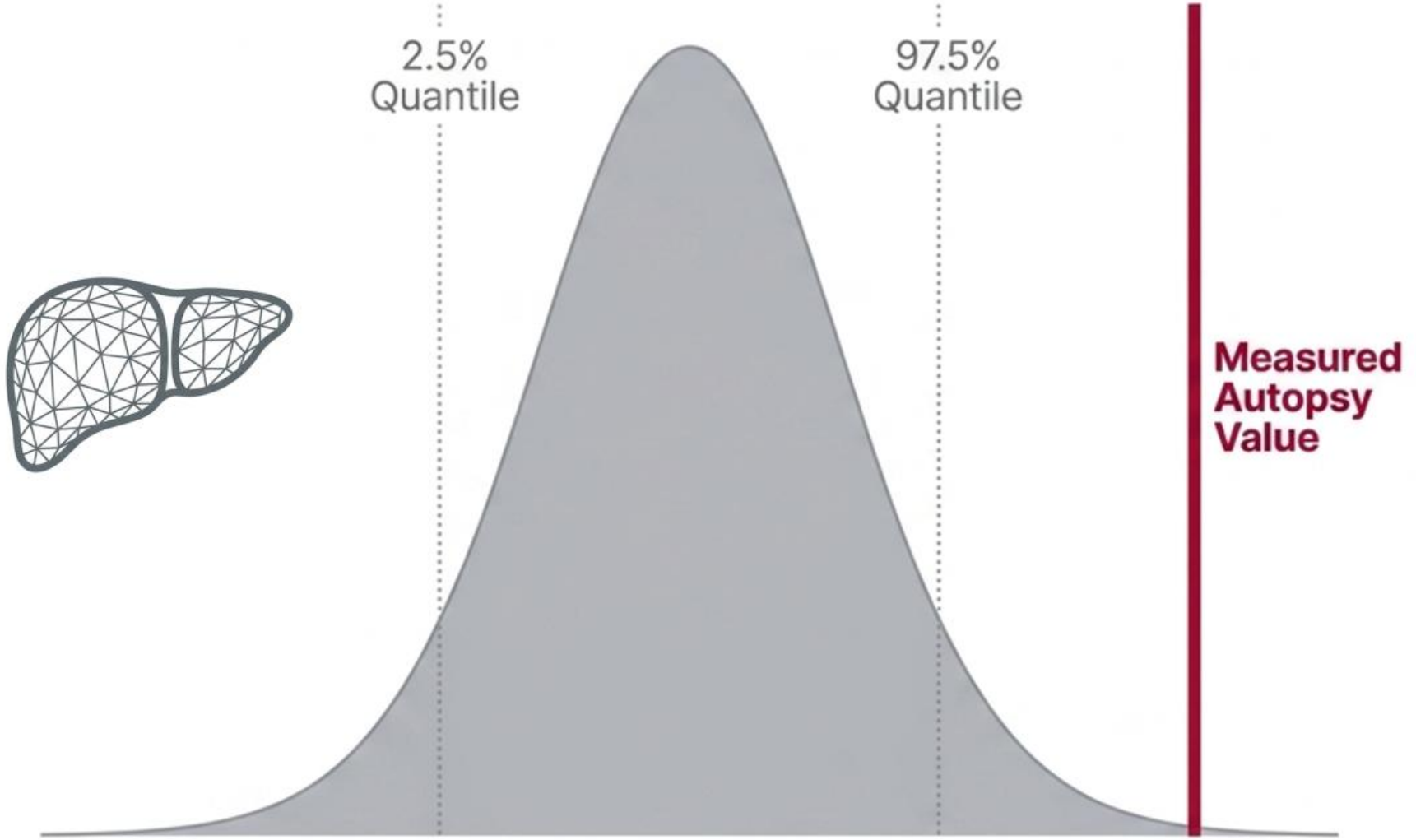
- Two absorption parameters, f_r and s_s, selected for sampling
- Particle transport rates *INT*→LN_{TH}, *ALV*→*INT*, *ALV*→*bb*, and k_{PT} scaling factor for the remaining parameters tested, but default values ultimately used

***U*(min=0; max=0.2)**



***LN*(median=1×10^{-4}; GSD=6)**

Reality Check 1: Liver Predictions Fail to Capture Reality



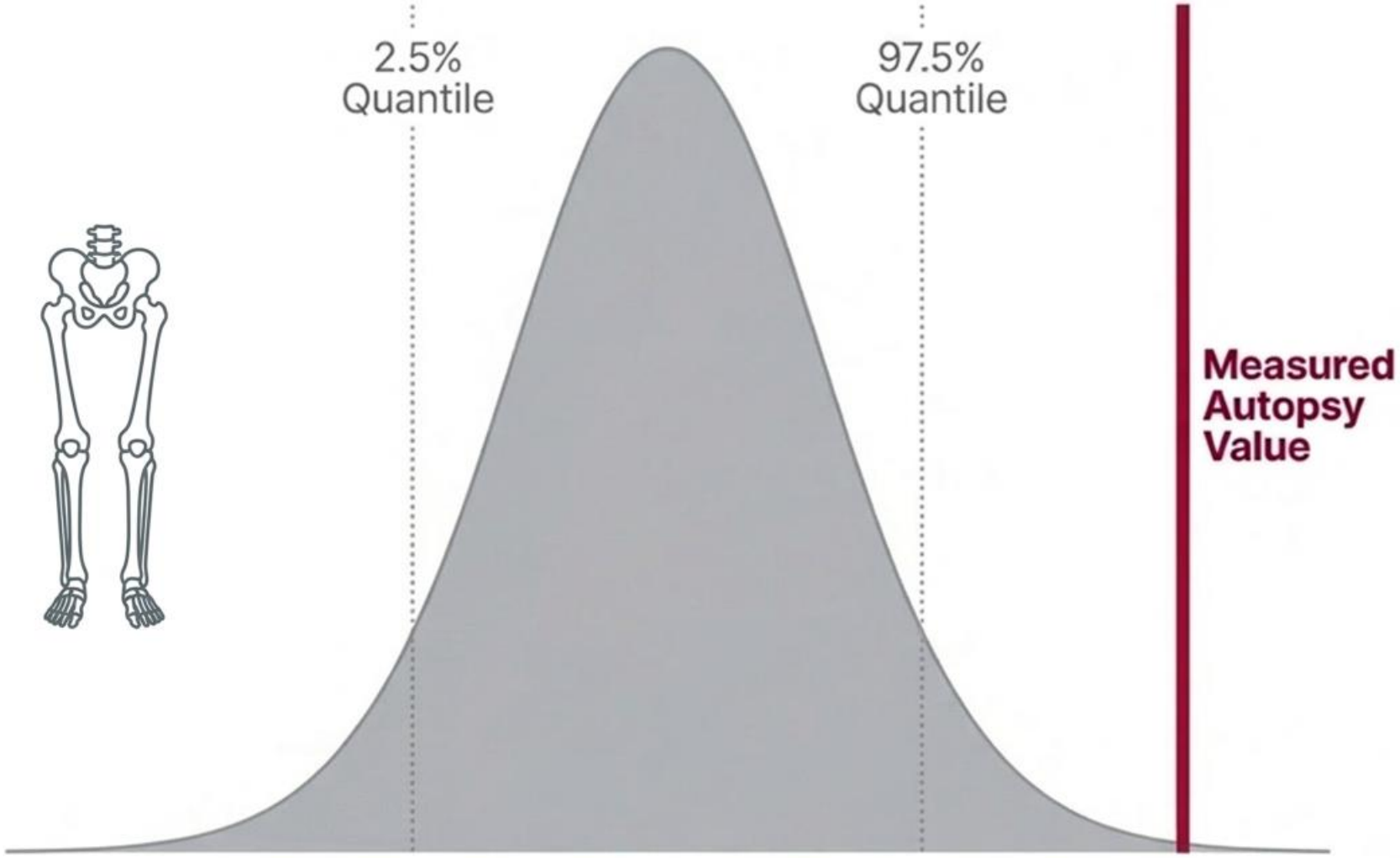
The Test: Liver activity predicted from historical urine bioassays vs. post-mortem measured reality.

The Result: The predicted distribution fundamentally fails to cover the measured value in a vast number of cases.

The Data: For 26 out of 35 individual cases, the actual measured liver activity fell entirely outside the 95% credible interval of the model prediction.

Conclusion: The models are missing the ground truth.

Reality Check 2: Systematic Underprediction in the Skeleton



The Test: Skeletal activity predicted from bioassays vs. post-mortem measurement.

The Result: Similar to the liver, the uncertainty ranges modeled a posteriori simply do not capture the true ^{239}Pu organ activities.

The Data: For 31 out of 35 individual cases, the measured skeleton activity lay entirely outside the 95% credible interval.

Observation: The failure isn't isolated to soft tissue; skeleton (primary long-term retention site) is also systematically mischaracterized by the predictive distributions.

Reality Check 3: Unusable Margins in the Respiratory Tract



The Test:
Respiratory tract activity predictions.

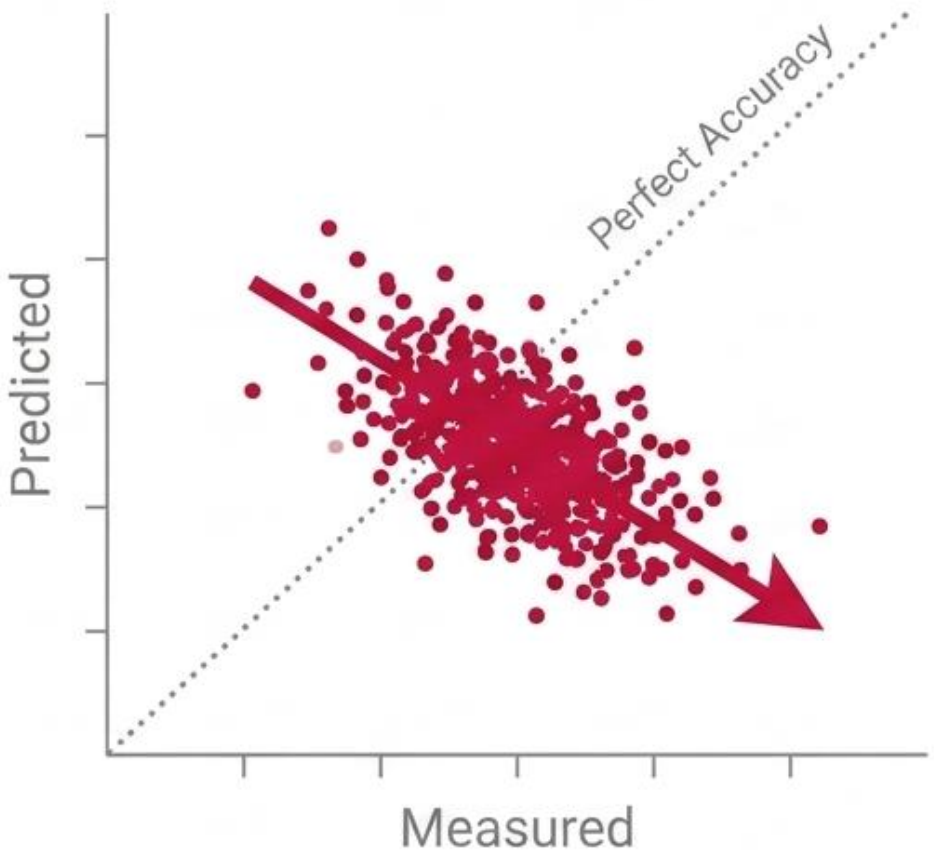


The Result:
While the true value sometimes falls inside the boundaries, the predictive distributions so wide they lose practical utility.

The Data:
Geometric mean of the 2.5% and 97.5% quantile range is an astonishing 997.

Conclusion:
An uncertainty range this broad provides no decision-useful information for retrospective dosimetry or radiation protection.

The Synthesis: Correlated Bias over Random Variability



Correlated Bias

The bias in model predictions was highly correlated across organs. We observed systematic patterns, including correlated under- or overprediction of liver and skeleton activities across individuals.

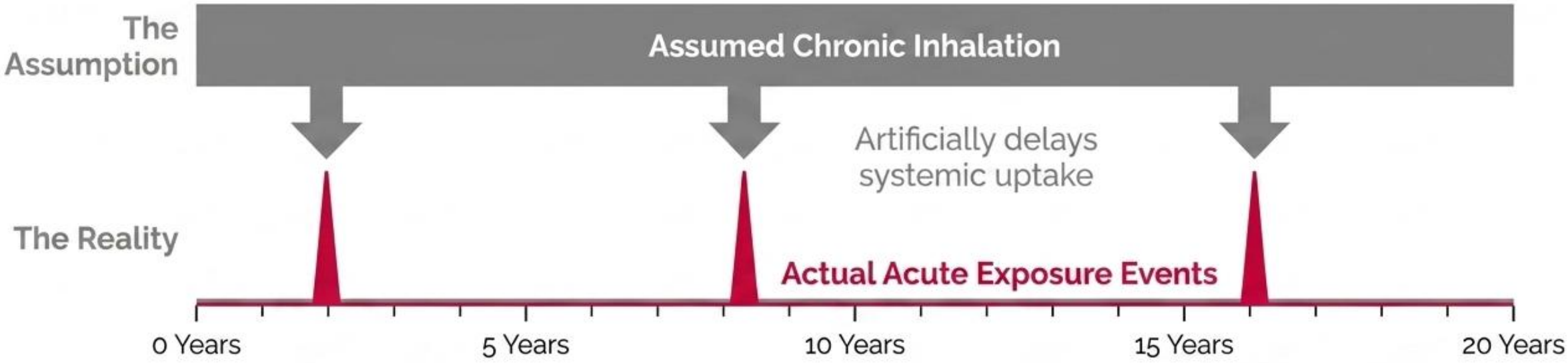
Not Just Noise

These patterns cannot be explained by random biological variability alone.

The Missing Biology

Even when differences in material solubility (Pu-nitrate *vs*. PuO_2) were correctly inferred, substantial discrepancies remained. This reflects well-documented inter-individual variability in plutonium retention and partitioning that current reference models completely ignore.

Mechanical Failure: The “Chronic Intake” Constraint



The Assumption:

Standard assumption of chronic inhalation over employment forces model predictions to make the math work.

The Reality:

This assumption artificially distributes the intake over time.

The Consequence:

By constraining the timing of systemic uptake, the model inherently contributes to a downward bias in predicted skeletal activities. The math breaks the biology.

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Conclusions: Limits of Posterior Predictions from Urine Bioassay Alone

The Core Challenge

Modeled uncertainty ranges frequently fail to capture true 239Pu organ activities. This directly challenges the foundational assumption that Bayesian posterior dose distributions inherently contain the “true dose”.

The Safety Concern

In approximately half of the evaluated cases, the model predictions were not conservative. From a global radiation protection standpoint, underpredicting retained dose is a critical vulnerability.

The Path Forward

The empirical evidence from USTUR autopsy data demonstrates a need for improved dose modeling by incorporating realistic intake timing assumption and accounting for true biological variability in long-term organ retention and partitioning

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Thank you for your attention!
Questions?



https://brand.wsu.edu/imagery/

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