



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Fuel Cycle Research and Development

**Performance Metrics for Storage and
Disposal of Used Nuclear Fuel and
High-Level Radioactive Waste**

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January 28-29, Albuquerque, NM**



Outline

- **Regulatory performance metrics and approaches to evaluating compliance**
 - Storage
 - Disposal
- **Metrics for inputs to storage and disposal performance analyses**
- **Other potential metrics for storage and disposal**
 - E.g., mass and activity flux, radiotoxicity flux and concentration
- **Displaying performance metrics from Monte Carlo analyses**
 - E.g., peak of mean vs. mean of peaks
- **Storage and disposal metrics in the context of fuel cycle systems analysis**



Regulatory Performance Metrics: Storage

- **10 CFR Part 72: Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste**
 - Normal operations: ALARA, with annual dose limit of 25 mrem at site boundary
 - § 72.104(a): *During normal operations and anticipated occurrences, the annual dose equivalent to any real individual who is located beyond the controlled area must not exceed 0.25 mSv (25 mrem) to the whole body, 0.75 mSv (75 mrem) to the thyroid and 0.25 mSv (25 mrem) to any other critical organ...*
 - § 72.104(b) *Operational restrictions must be established to meet as low as is reasonably achievable objectives...*
 - Design Basis Accidents: up to 5 rem total effective dose equivalent at site boundary
 - § 72.106(b) *Any individual located on or beyond the nearest boundary of the controlled area may not receive from any design basis accident the more limiting of a total effective dose equivalent of 0.05 Sv (5 rem), or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 0.5 Sv (50 rem).*
 - Decommissioning: in accordance with 10 CFR 20 subpart E
 - *ALARA, annual dose limit of 25 mrem at any location*



Regulatory Performance Metrics: Disposal

- **40 CFR Part 191 and 10 CFR Part 60 (all US repositories other than Yucca Mountain)**
 - Primary standard is a probabilistic 10,000-year cumulative release limit, normalized to initial inventory
 - *Oversimplifying, there must be less than one chance in 10 of releasing 1/10,000 of the initial inventory of Pu in 10,000 years*
 - Individual dose limit (0.15 mSv/yr [15 mrem/yr]) for undisturbed performance only
 - Groundwater protection standards for undisturbed performance only
 - 10 CFR Part 60 imposes specific subsystem requirements
- **40 CFR Part 197 and 10 CFR Part 63 (specific to Yucca Mountain, following 1995 binding recommendations from the National Academies of Science)**
 - Primary standard is a probabilistic estimate of mean annual dose to an individual member of the public
 - *0.15 mSv/yr (15 mrem/yr) up to 10,000 years*
 - *1.0 mSv/yr (100 mrem/yr) from 10,000 years to 1,000,000 years*
 - Human intrusion standards are treated separately and are limited to groundwater pathways
 - Groundwater protection standards apply for undisturbed performance
- **International Atomic Energy Agency Geological Disposal of Radioactive Waste Safety Standards WS-R-4**
 - “...not more than 0.3 mSv [30 mrem] in a year or a risk constraint of the order of 10^{-5} per year”
 - “Care needs to be exercised in using the criteria beyond the time where uncertainties become so large that the criteria may no longer serve as a reasonable basis for decision making”

Metrics for Inputs to Storage and Disposal Analyses

■ Storage

- Characteristics of used fuel and HLW
 - *Mass and volume of used fuel and HLW*
 - *Physical characteristics of used fuel and HLW*
 - *Radionuclide inventory*
 - *Heat output*
 - *Characterization of Special Nuclear Material level of significance (10 CFR 73)*
- Conceptual facility design
- Generic site characteristics

■ Disposal

- Characteristics of spent fuel and HLW
 - *Mass and volume of spent fuel and HLW*
 - *Physical characteristics of spent fuel and HLW*
 - *Radionuclide inventory*
 - *Heat output*
- Conceptual facility design
- Generic site characteristics

Potential Metrics for Storage and Disposal (other than dose)

■ Intermediate performance measures of potential interest

- Storage
 - *Degradation rate of fuel form and container internals*
 - *Degradation rate of containers*
- Disposal
 - *Time-dependent temperature history of disposal region*
 - *Time-dependent water flux in disposal region*
 - *Degradation rate of engineered barriers*
 - *Time-dependent radionuclide concentrations at various locations within the disposal system*
 - *Cumulative releases of radionuclides at various locations within the disposal system*



Evaluating Alternative Metrics for Disposal

- **E.g., European Commission “SPIN” (safety and performance indicators) report (2002) provides systematic evaluation of**
 - “Safety Indicators” at system level
 - *Effective dose rate*
 - *Radiotoxicity concentration in biosphere water*
 - *Radiotoxicity flux from geosphere*
 - *Time-integrated radiotoxicity flux from geosphere*
 - *Radiotoxicity outside geosphere*
 - *Relative activity concentration in biosphere water*
 - *Relative activity flux from geosphere*
 - “Performance Indicators” at subsystem level
 - *Activity in compartments, activity flux from compartments, and time-integrated activity flux*
 - *Radiotoxicity in compartments, radiotoxicity flux from compartments, and time-integrated radiotoxicity flux*
 - *Radiotoxicity outside compartments*
 - *Activity concentration in biosphere water and waste package water*
 - *Transport times through compartments*
 - *Proportion of not-totally isolated waste*
 - *Time-integrated flux from geosphere divided by initial inventory*
 - *Concentration in biosphere water divided by concentration in waste package water*

Evaluating Alternative Metrics for Disposal (cont.)

- **Subsystem level “Performance Indicators” relevant to the Used Fuel Disposition (UFD) Campaign**
 - Intermediate metrics from the system-level analyses
 - *Radionuclide mass and activity flux at component boundaries*
 - *Time-integrated radionuclide mass and activity flux at component boundaries*
 - Performance of specific components within a disposal system
 - *Waste form degradation rates*
 - *Waste package degradation rates*
 - *Transport times within groundwater release pathways, for sorbing and nonsorbing species*



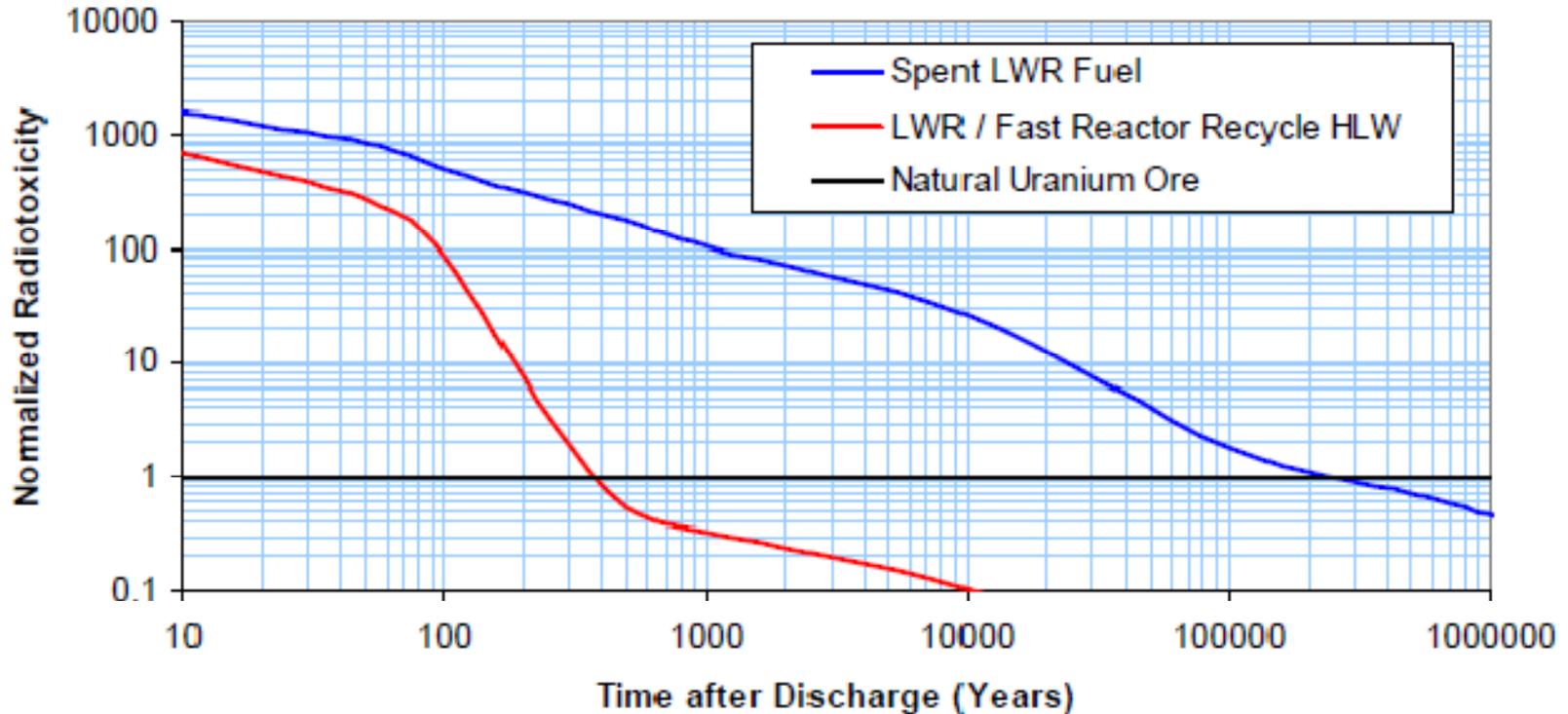
Evaluating Alternative Metrics for Disposal (cont.)

■ System level “Safety Indicators” relevant to the UFD Campaign

- Annual dose remains the most useful metric for comparing disposal concepts
 - *Unavoidably introduces uncertainty about dilution and biosphere pathways*
 - *Biosphere uncertainty can be removed by using aqueous concentration as a metric*
- Cumulative (e.g., time-integrated) metrics require a finite performance period, and are incompatible with “peak-dose” standards because they increase monotonically through time for long-lived species
- Radiotoxicity (defined as activity times dose conversion) of the waste form is not useful for evaluating waste form or disposal-system performance
 - *It is, however, a widely used metric for evaluating impacts of alternative fuel cycle options on the waste stream, and it may be helpful for disposal options to offer a comparable metric*
 - *Has units of dose (sieverts or rems) per unit mass of waste, or can be dimensionless normalized to radiotoxicity of equivalent mass of initial uranium ore*
- Radiotoxicity concentration and radiotoxicity flux may be useful for comparison purposes to initial radiotoxicity of the waste form



Radiotoxicity of Used Fuel



Example display of radiotoxicity, showing activity in a unit mass of used fuel × ingestion dose conversion factors, normalized to radiotoxicity of the comparable mass of initial uranium ore

(Fig. 6 of GNEP-TIO-AI-AI-RT-2008-000268 Rev 2)

Radiotoxicity as a Disposal Metric

■ Radiotoxicity flux

- Has units of dose per time
- Can be normalized to unit mass of initial waste form and expressed as an annual release fraction of initial radiotoxicity to provide comparison to fuel cycle options study metric
- Can be displayed for component boundaries in disposal system
 - *E.g., waste from radiotoxicity annual release fraction, waste package radiotoxicity annual release fraction, etc.*

■ Radiotoxicity concentration

- Has units of dose per volume
- Requires specification of a reference volume (i.e., of water)
- Can be displayed for multiple components in disposal system
- Can be directly compared to initial waste form radiotoxicity if initial unit mass of waste is converted to volume

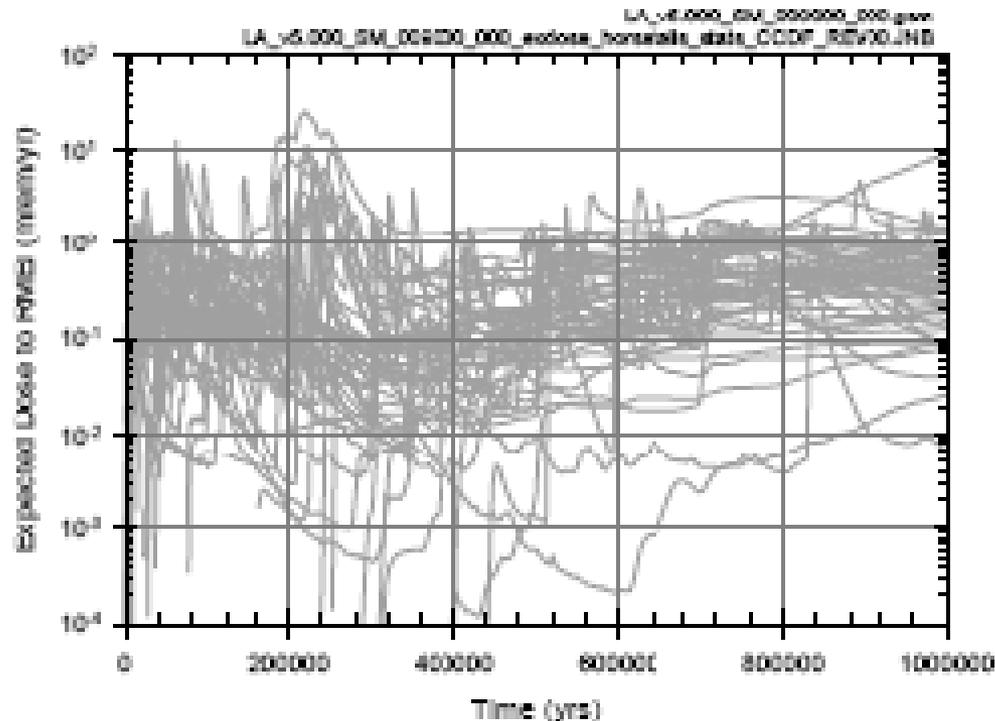
■ Advantages:

- Comparability to fuel cycle options study metrics
- Removes uncertainty associated with biosphere pathway assumptions



Displaying Performance Metrics from Monte Carlo Analyses

- Individual realizations from Monte Carlo analyses may show very different results, with peak values occurring at different times



Representative calculation from Yucca Mountain TSPA-LA (SNL 2008, MDL-WIS-PA-000005 Rev 00, Figure J8-42(b), showing 50 realizations of 1,000,000 estimated annual dose resulting from nominal corrosion processes and seismic ground motion



Monte Carlo Means as Performance Metrics

■ What information to display from multiple realizations?

- The full set of results is useful for analysis, but summary measures are essential metrics for decision-making
- Means, medians, and various percentiles are all proposed
- Means are the most common summary metric, and they are the required metric for US disposal regulations

■ Which Mean?

- Mean of the peaks
 - **The peak value of the metric is determined over the entire simulation duration for each realization for a given combination of input parameter values. The mean of the individual peaks from each realization, regardless of the time at which it occurs, is then determined.**
 - **The mean of the peaks is a summary measure of the largest values regardless of when they occur**
- Peak of the mean
 - **The mean value of the metric is determined at each time step by summing over all realizations. The highest value of the mean during the simulation period is then determined**
 - **The peak of the mean is a summary measure of the largest value estimated for any specified time**
- The two metrics convey different information, and there can be times when either may be appropriate but...
 - ***The peak of the mean annual dose is the metric required for EPA and NRC disposal regulations***

Storage and Disposal Metrics in the Context of Fuel Cycle Systems Analysis

■ Upstream analyses provide input to storage and disposal analyses

- For each fuel cycle option, UFD Campaign needs
 - *Identification of waste categories*
 - *Estimates of volumes*
 - *Radionuclide inventories*
 - *Thermal output*
 - *Initial form and physical characteristics*
 - *Schedule*
- For specific waste forms, UFD Campaign needs
 - *Physical and chemical characteristics*
 - *Degradation characteristics for a broad range of thermal, chemical, and mechanical damage conditions*
 - *Thermal output*
 - *Radionuclide inventory*

Storage and Disposal Metrics in the Context of Fuel Cycle Systems Analysis (cont.)

- **UFD analyses will provide metrics to iterative systems analyses, in parallel with other components of FC R&D program, to evaluate alternative fuel cycle options**
 - System-level metrics
 - *Risk to humans, expressed as estimated mean annual dose to individuals*
 - *Radiotoxicity flux or concentration, for comparison to used fuel radiotoxicity*
 - Intermediate-level subsystem metrics
 - *Radionuclide mass and activity flux at component boundaries*
 - *Time-integrated radionuclide mass and activity flux at disposal concept component boundaries*
 - Performance of specific components within a disposal system
 - *Waste form degradation rates*
 - *Waste package degradation rates*
 - *Transport times within groundwater release pathways, for sorbing and nonsorbing species*
- **Additional system analysis metrics applicable to all parts of fuel cycle**
 - Cost
 - Schedule

■ Questions and discussion?