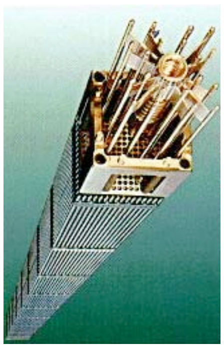
NUCLEAR WASTE MANAGEMENT

April 26, 2004

PWR Fuel Assembly

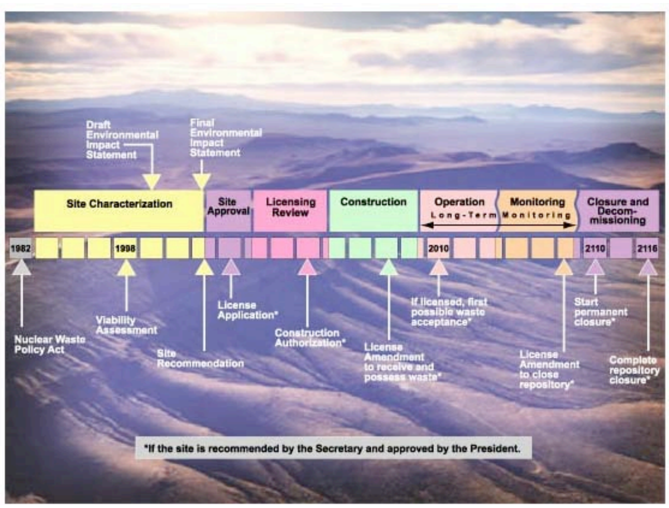


Deep divisions of opinion about the feasibility of nuclear waste disposal . . . .

- The critics:
  - Risks are very high
  - Absence of demonstrated disposal technology after 40+ years proves that nuclear power is fundamentally flawed
  - Irresponsible to generate more waste while the problem remains unsolved

- The advocates
  - 'High-level waste is a non-risk . . . .'
  - 'It is embarrassingly easy to solve the technical problems, yet impossible to solve the political problems . . .'

– Harold Lewis, *Technological Risk,* 1990



Source: DOE Office of Civilian Radioactive Waste Management, Yucca Mountain Project Home Page, http://www.ymp.gov/timeline/index.htm

DOE Yucca Mountain Project website

Key policy issues posed by nuclear waste

- the balance of authority between federal, state, and local jurisdictions
- intertemporal equity and our obligations -- economic and environmental -- to future generations
- the assessment of technical risk and the ‘verification’ of system performance when no true verification is possible
- Public management of large-scale programs

History of nuclear waste management includes false starts and failures

- 1972: U.S. Atomic Energy Commission abandons repository project at a salt mine in Lyons, KA. Promotes Retrievable Surface Storage Facility (RSSF) as 100-year interim solution.
- 1975: RSSF abandoned. Geologic disposal adopted as preferred alternative.
- 1977: Spent fuel reprocessing indefinitely deferred.
- Complex national geologic repository site selection process initiated, then abandoned. Yucca Mountain picked instead.
- DOE contracts with utilities to take possession of utility spent fuel beginning in 1998, but fails to do so.
- Leaks of high-level radioactive waste from tanks at DOE sites in Washington and South Carolina.
- Disclosures of contamination and excessive radiation doses to workers throughout DOE nuclear complex over a period of decades.
- Continuing conflict between federal, state, and local jurisdictions over siting, regulatory issues

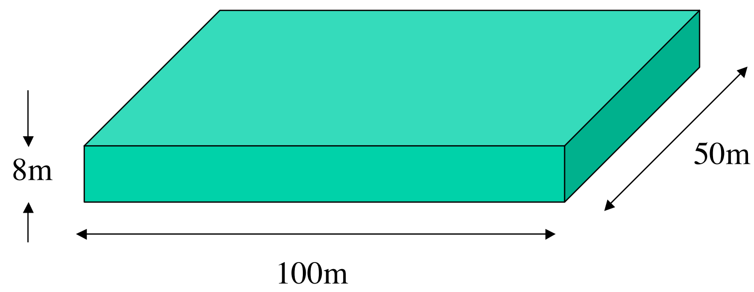
Nuclear Waste Types

Waste type		Description	Annual waste generation from a 1000 MWe LWR (m^3/yr) (includes contribution from fuel cycle stages)
High-level waste	HLW	a. Unreprocessed spent fuel assemblies b. Highly radioactive primary waste stream from reprocessing (containing virtually all fission products and most transuranics except plutonium)	~ 10
Transuranic waste	TRU	Non-high-level waste contaminated with long-lived transuranics above 100 nanocuries per gram (10^{-7} curies/gm)	~ n.a.
Uranium mill tailings		Residues from uranium mining and milling operations containing low concentrations of naturally occurring radioactive materials	~ 100,000
Low level waste	LLW	All non-high-level, non-TRU wastes; wide variation in physical and chemical forms, activity levels, etc (gloves, I-X resins, etc.)	~ 20 (PWR) ~ 80 (BWR)
Wastes from decontamination and decommissioning	D&D	Waste contaminated with small amounts or radioactivity from D&D (mostly LLW)	~ 400 (annualized)
Mixed waste		Contains both radioactive materials and hazardous chemicals	
Effluents		Contaminated materials below 'de minimus' levels permitting direct discharge to environment	

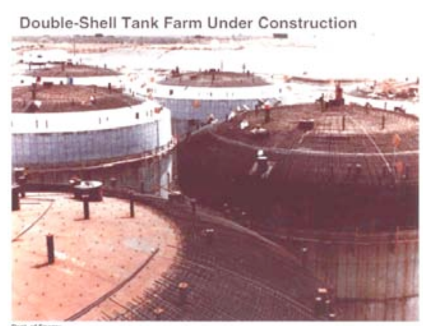
How much spent fuel?

U.S. power reactor fleet:

10 (m^3/reactor-year) x 40 (years) x 100 reactors ~ 40,000 m^3

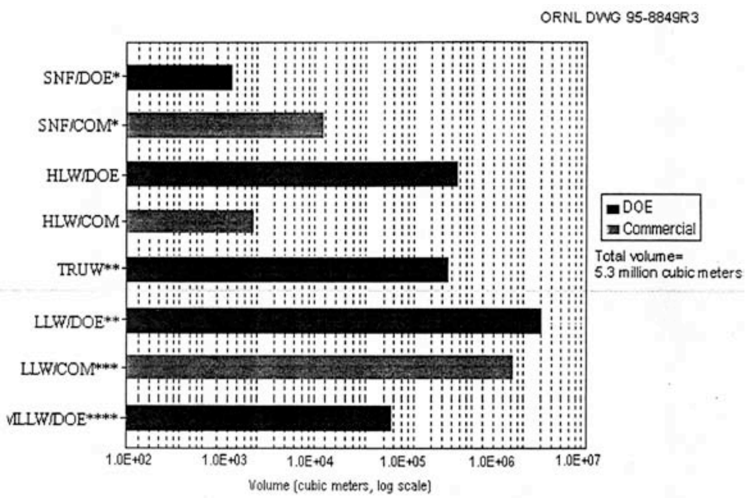


DOE/Defense high level waste mostly stored in tanks at Hanford and Savannah River



Current inventories of high-level waste

	Commercial spent fuel	DOE defense high-level waste
Volume	~20,000 m^3	~340,000 m^3
Radioactivity	~ 35 x 10^9 curies	~ 0.7 x 10^9 curies



¹Permanently discharged reactor fuel. Includes spacing between fuel assembly rods.
²DOE wastes include both retrievably stored and buried materials.
³Includes contributions from disposed wastes only.
⁴Includes retrievably stored RCRA and TSCA materials only.

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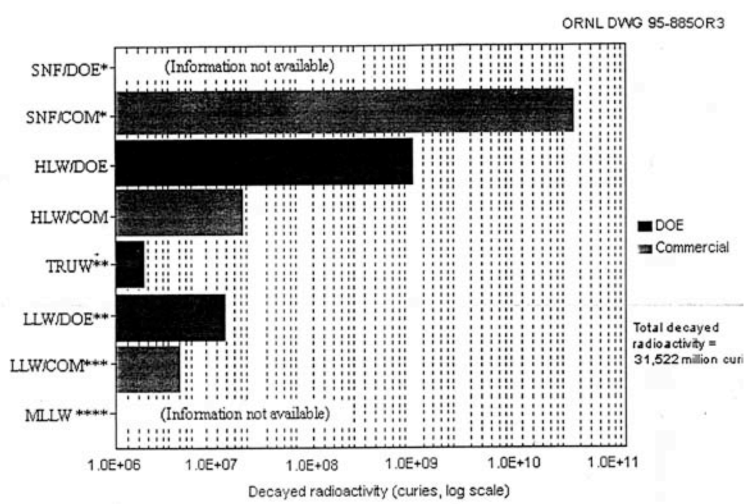

*Estimate of commercial LWR fuel permanently discharged.
**DOE wastes include both retrievably stored and buried materials.
***Includes contributions from disposed wastes only.

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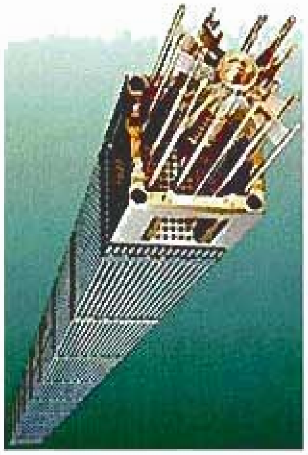
How hazardous is spent fuel?



Surface radiation dose 1 meter from 5-year-old PWR spent fuel assembly in air: 25,000-50,000 rems/hr

LD50 dose: 400-500 rems

Table 8.7 Elemental constituents in uranium fuel discharged from a PWR†

	g/Mg	Ci/Mg	W/Mg
Actinides			
Uranium	9.54×10^5	4.05	4.18×10^{-2}
Neptunium	7.49×10^2	1.81×10^1	5.20×10^{-2}
Plutonium	9.03×10^3	1.08×10^5	1.52×10^2
Americium	1.40×10^2	1.88×10^2	6.11
Curium	4.70×10^1	1.89×10^4	6.90×10^2
Subtotal	9.64×10^5	1.27×10^5	8.48×10^2
Fission products			
Tritium	7.17×10^{-2}	6.90×10^2	2.45×10^{-2}
Selenium	4.87×10^1	3.96×10^{-1}	1.50×10^{-4}
Bromine	1.38×10^1	0	0
Krypton	3.60×10^2	1.10×10^4	6.85×10^1
Rubidium	3.23×10^2	1.90×10^3	0
Strontium	8.68×10^2	1.74×10^5	4.50×10^2
Yttrium	4.53×10^2	2.38×10^5	1.05×10^3
Zirconium	3.42×10^3	2.77×10^5	1.45×10^3
Niobium	1.16×10^1	5.21×10^5	2.50×10^3
Molybdenum	3.09×10^3	0	0
Technetium	7.52×10^2	1.43×10^1	9.67×10^{-3}
Ruthenium	1.90×10^3	4.99×10^5	3.13×10^2
Rhodium	3.19×10^2	4.99×10^5	3.99×10^3
Palladium	8.49×10^2	0	0
Silver	4.21×10^1	2.75×10^3	4.16×10^1
Cadmium	4.75×10^1	5.95×10^1	2.13×10^{-1}
Indium	1.09	3.57×10^{-1}	1.04×10^{-3}
Tin	3.28×10^1	3.85×10^4	1.56×10^2
Antimony	1.36×10^1	7.96×10^3	2.74×10^1
Tellurium	4.85×10^2	1.34×10^4	1.66×10^1
Iodine	2.12×10^2	2.22	8.98×10^{-3}
Xenon	4.87×10^3	3.12	3.04×10^{-3}
Cesium	2.40×10^3	3.21×10^5	2.42×10^3
Barium	1.20×10^3	1.00×10^5	3.93×10^2
Lanthanum	1.14×10^3	4.92×10^2	8.16
Cerium	2.47×10^3	8.27×10^5	7.87×10^2
Praseodymium	1.09×10^3	7.71×10^5	5.73×10^3
Neodymium	3.51×10^3	9.47×10^2	2.65×10^{-1}
Promethium	1.10×10^2	1.00×10^5	9.17×10^1
Samarium	6.96×10^2	1.25×10^3	2.18
Europium	1.26×10^2	1.35×10^4	7.19×10^1
Gadolinium	6.29×10^1	2.32×10^1	3.34×10^{-2}
Terbium	1.25	3.02×10^2	2.54
Dysprosium	6.28×10^{-1}	0	0
Subtotal	3.09×10^4	4.18×10^6	1.96×10^4
Total	9.95×10^5	4.31×10^6	2.04×10^4

†Quantities are expressed per metric ton of uranium in the fresh fuel charged to the reactor. Average fuel exposure = 33 MWd/kg. Average specific power = 30 MW/Mg. 150 days after discharge.

Waste Decay Behavior

Radioactivity units:

1 Becquerel (Bq) = 1 disintegration per second

1 Curie = 3.7×10^{10} Bq

Spent fuel radioactivity = $\sum \lambda_i N_i(t)$ (Becquerels/MTHM)

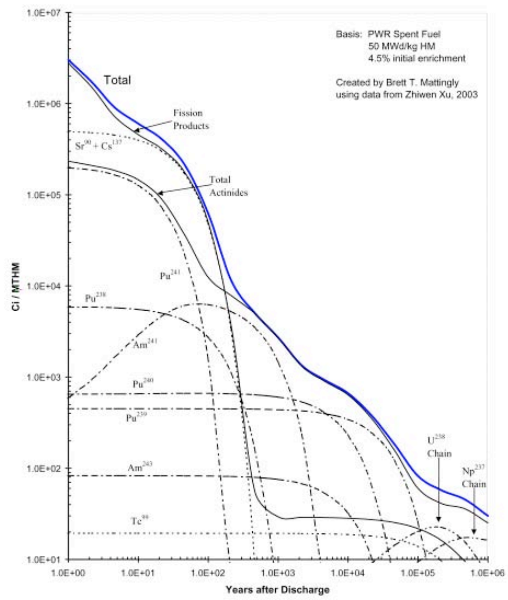
where

$\lambda_i (t)$ = decay constant for isotope i (sec^{-1}) = (ln 2) / $t_{1/2}$

$N_i(t)$ = # of atoms of isotope i per MTHM

= $N_i(0)\, e^{-\lambda t}$

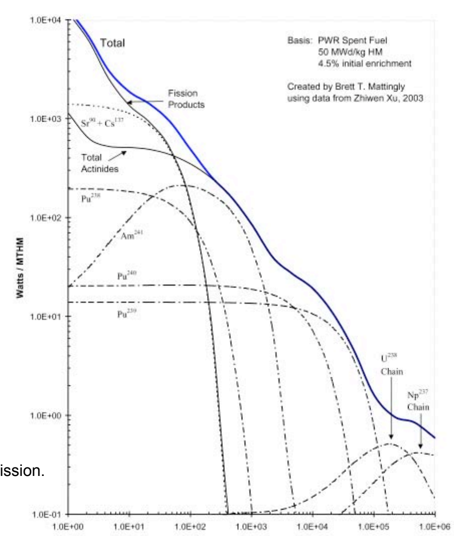
Figure 1. Activity Profile of Spent Fuel



Courtesy of Brett Mattingly. Used with permission.

Decay behavior (contd.)

Figure 2. Decay Heat Profile of Spent Nuclear Fuel

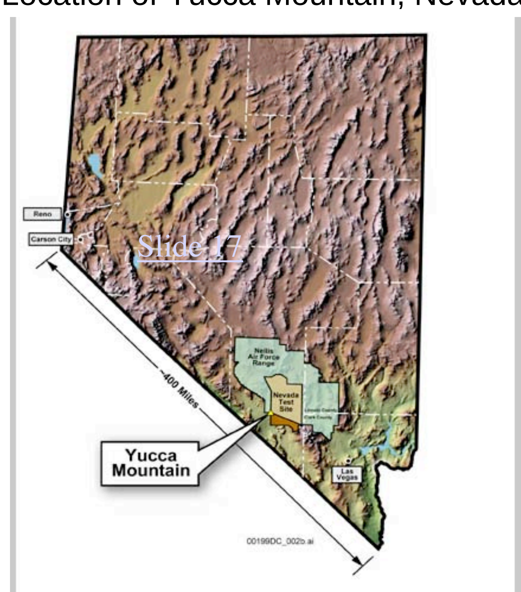


Courtesy of Brett Mattingly. Used with permission.

Disposition alternatives for high level waste

- Surface or near-surface engineered storage
- Geologic repositories
- Deep borehole disposal
- Sub-seabed disposal
- Ice-sheet disposal
- Extra-terrestrial disposal
- Waste partitioning
  - Reprocessing and recycling of economically useful species
  - Partitioning and transmutation of long-lived species
- (Do nothing)

Location of Yucca Mountain, Nevada



Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml

Yucca Mountain Site

- 100 miles NW of Las Vegas
- Volcanic tuff
  - Layers of consolidated, compacted ashfalls from volcanic eruptions occurring more than 10 million years ago
  - Underlying the tuff is sedimentary carbonate rock
- Repository horizon in ‘unsaturated zone’, about 300 meters below the surface, and 300-500 meters above the water table
- Two major aquifers in the saturated zone below Yucca Mountain, one in tuff, one in carbonate rock.

Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml

Yucca Mountain, Nevada

Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml.

Aerial view of the crest of Yucca Mountain, NV

Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml.

Another aerial view of Yucca Mountain (from the South)

View of Yucca Mountain from the south

Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml

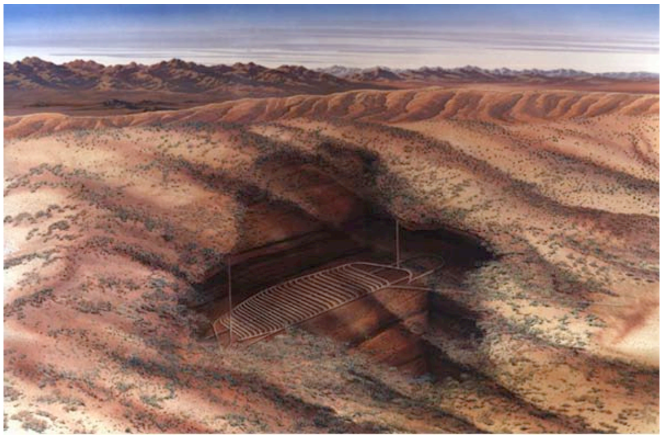
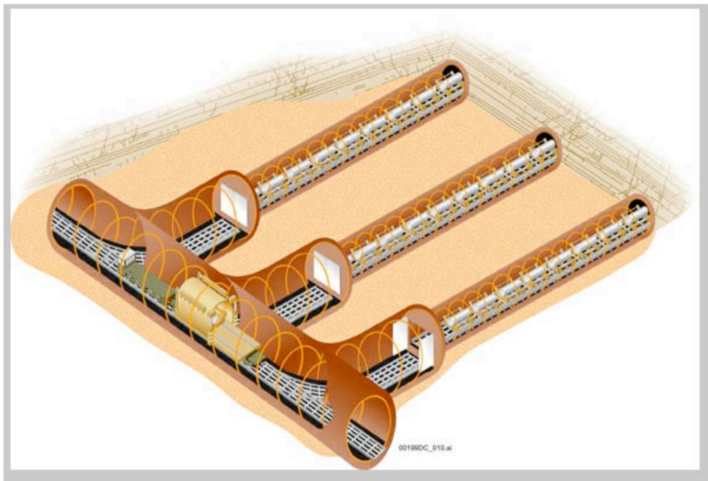


Figure 8.5 Artist's rendition of the Yucca Mountain repository

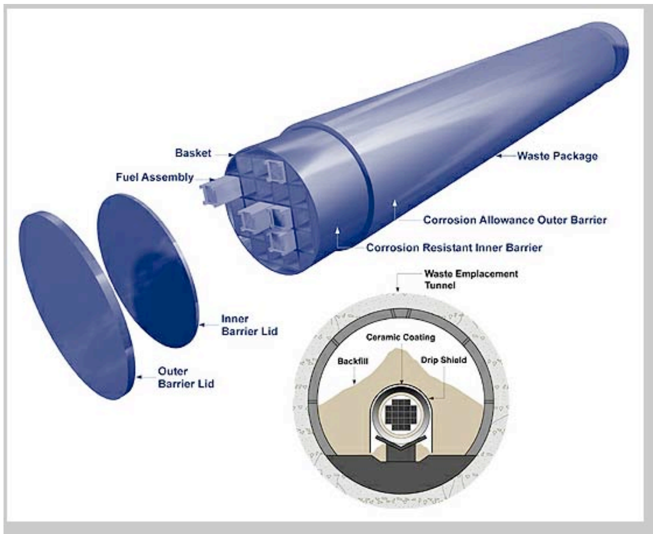
Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml.

The repository will be series of emplacement 'drifts' where waste packages will be emplaced and monitored.



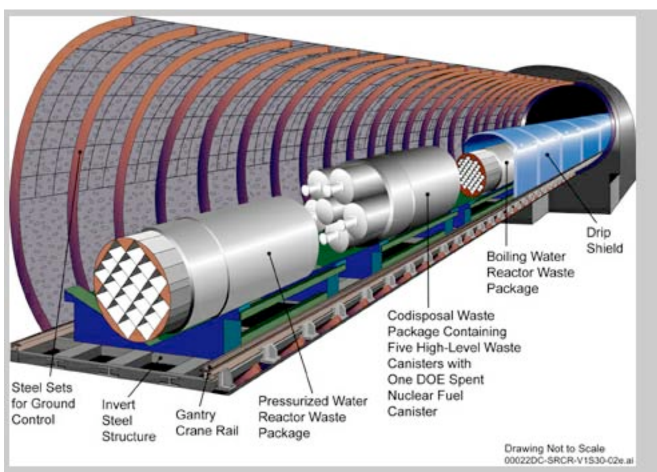
Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml.

Waste Package Placement



Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml

Cutaway of drift with three types of waste packages



Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml.
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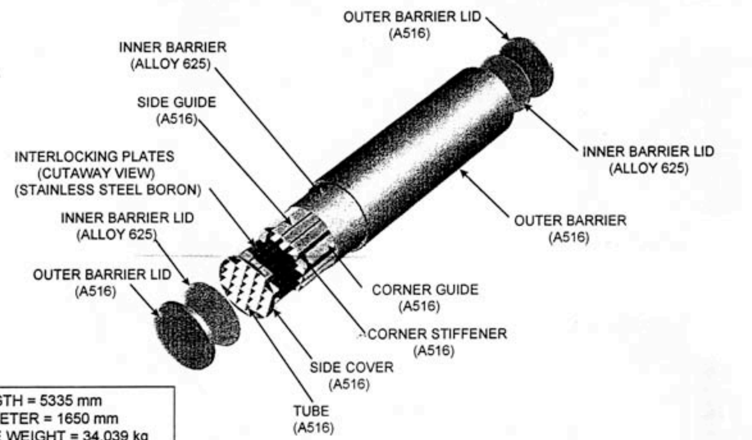
21-PWR UCF Disposal Container



LENGTH = 5335 mm
DIAMETER = 1650 mm
TARE WEIGHT = 34,039 kg
LOADED WEIGHT = 50,423 kg

Civilian Radioactive Waste Management System
Management & Operating Contractor

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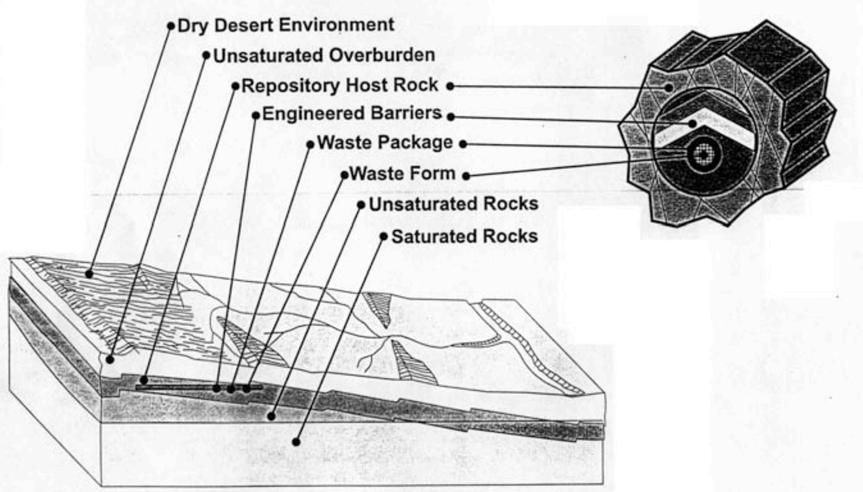
Schematic of Components Affecting Total System Performance



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For how long should the waste be confined?

- 'Radiotoxicity' -- a crude measure of waste hazard:
  - the total volume of water that would be required to dilute each of the radionuclides in 1 MT of spent fuel down to the safe drinking water concentration
- The radiation protection authorities have specified 'maximum permissible concentrations' of individual radionuclides in water (and air) so that an individual obtaining total intake of water (or air) would not receive more than maximum allowable radiation dose (50 millirem/yr)
- We can then define a time-dependent <u>ingestion hazard index</u>:

$$\textit{Ingestion hazard index at time } t = \sum_i^{all\ radionuclides} \left(\frac{\lambda_i N_i(t)}{MPC_i^{water}} \right)$$

Example for $Sr-90$:

$ICRP-72$ *ingestion dose coefficient* $= 2.8 \times 10^{-8}\ Sv/Bq$

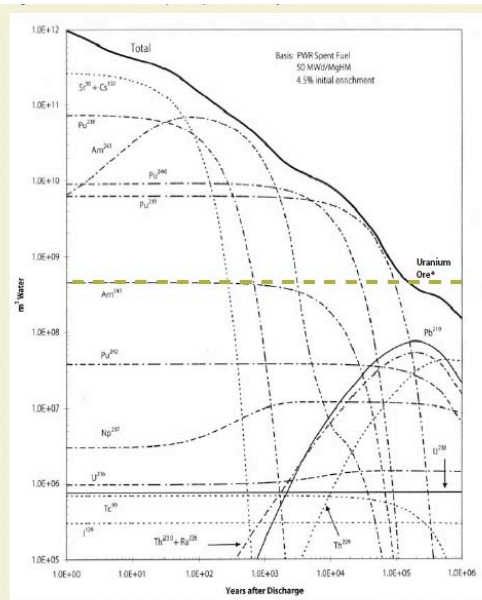
Thus, total allowable annual intake for committed effective dose of $5 \times 10^{-4}\ Sv$ (*i.e.* 50 *mrem*)

$$= \frac{5 \times 10^{-4}}{2.8 \times 10^{-8}} = 1.786 \times 10^{4}\ Bq/yr$$

Maximum allowable concentration of $Sr-90$

$$= \frac{1.786 \times 10^{4} (Bq/yr)}{0.002 (m^3/day) \times 365 (d/yr)} = 2.45 \times 10^{4}\ Bq/m^3$$

<u>Radiotoxicity decay profile for spent PWR fuel (m^3/MTHM)</u>



The radiotoxicity index corresponds to an ingested dose of 50 mrem/year and was calculated using ICRP-72 adult dose coefficients (1996)

* Amount of ore mined to produce 1 MT fuel @ 4.5% U-235 enrichment

Deutsch, John, Ernest Moniz et al. "The Future of Nuclear Power: An Interdisciplinary MIT Study." Massachusetts Institute of Technology, 2003 (ISBN 0-615-12420-8). Available at http://web.mit.edu/nuclearpower/. p. 60

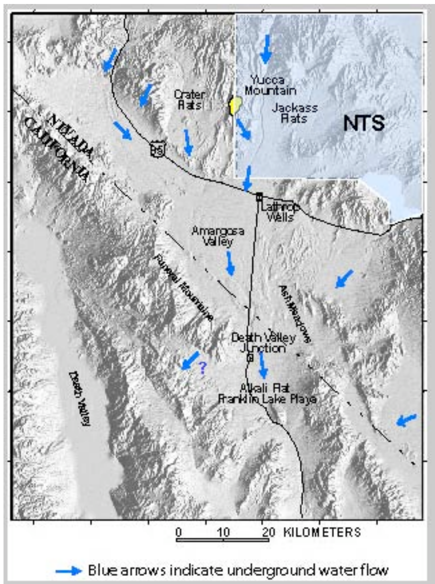
Potential failure modes for geologic repositories

- Natural degradation over time of the natural and engineered barriers in the repository
  - Dissolution and transport of radionuclides in groundwater
  - Natural exhumation processes
    - Tectonic processes (e.g., folding, faulting, magmatic intrusions, volcanism)
    - Erosion (wind, water, glaciation)
- Breaching of barriers by human activity

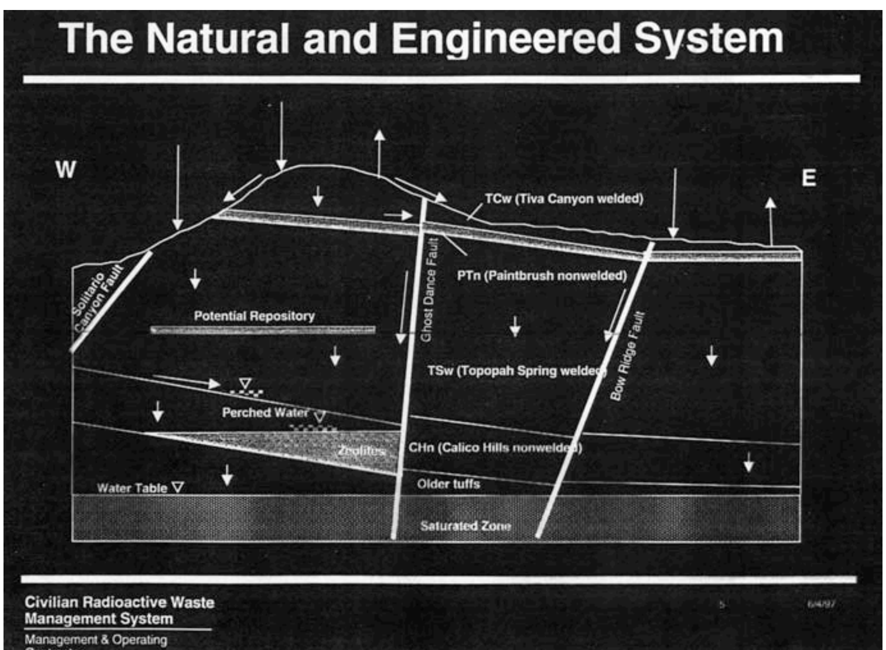
Performance Assessments of Repository System

- Rate of inflow of groundwater into the repository
  - Hydrology-- current and long-term, fracturing, faulting, thermal stresses in host rock
- Rate of corrosion of canister, other barriers, and primary waste form
  - temperature, oxidation/reduction conditions, materials properties of waste package
- Radionuclide transport in groundwater
  - hydrology, sorption on rock surfaces, actinide chemistry
- Biosphere transport
  - potable water supplies, irrigation water, demography -- current and long-term

Groundwater hydrology of Yucca Mountain region



Source: U.S. Dept of Energy, http://ocrwm.doe.gov/newsroom/photos/photos_graphics.shtml



International Programs in High-Level Waste Management

- All the leading nuclear countries have adopted the geologic repository approach for HLW disposal
- No country has yet established an operating repository
- There are important differences in technical strategies
  - Spent fuel vs. reprocessed HLW
    - Spent fuel (U.S., Canada, Finland)
    - Reprocessed, vitrified HLW (UK, France). (Japan and Russia have announced prohibitions on direct disposal of spent fuel
    - Store spent fuel temporarily and decide later
  - Candidate geologic media
  - Geochemical environment
  - Reliance on engineered vs. natural barriers to radionuclide transport
  - Thermal design of facility (including age of waste at emplacement)

High-level waste disposal plans of leading nuclear countries

Country	Management Responsibility	Preferred Geologic Medium	Earliest anticipated repository opening date	Status
United States	DOE	Volcanic tuff	2010	Site selected (Yucca Mountain, NV); application for construction license underway
Finland	Power companies (Posiva Oy)	Crystalline bedrock	2020	Site selected (Olkiluoto, SW Finland) – decision ratified by Parliament in May 2001
Sweden	Power companies (SKB)	Crystalline rock	2020	Searching for a suitable site
Switzerland	Power company cooperative (Nagra)	Crystalline rock or clay	2020 or later	Searching for a suitable site
France	Independent public authority (ANDRA)	Granite or clay	2020 or later	Developing repository concept
Canada	Crown corporation (AECL)	Granite	2025 or later	Reviewing repository concept
Japan	National agency (NUMO)	Not selected	2030	Searching for suitable site
United Kingdom	Under review	Not selected	After 2040	Delaying decision until 2040
Germany	Federal contractor company (DBE)	Salt	No date specified	Moratorium on repository development for 3-10 years

Comparison of U.S. and Finnish Repository Programs

U.S.	Finland
• Direct disposal of spent fuel	• Direct disposal of spent fuel
• Stainless steel canister + Alloy 22 shell	• Cast iron canister + copper mantle
• 'Drip shield'; no backfill	• Bentonite backfill
• Unsaturated zone	• Saturated zone
• Oxidizing environment	• Reducing environment
• Package surface temperature > 100C	• Low temperature operating condition
• Reliance on engineered barriers increasing	• Primary reliance on engineered barriers

<u>Finnish high-level waste repository</u>

Figure A-7.B.1 KBS-3 Repository Concept

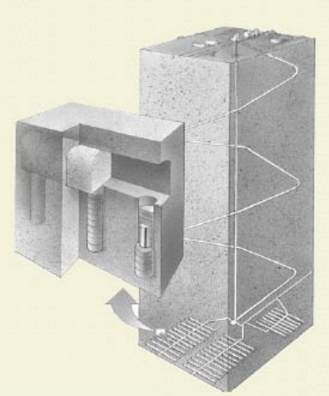
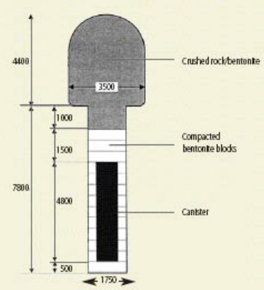
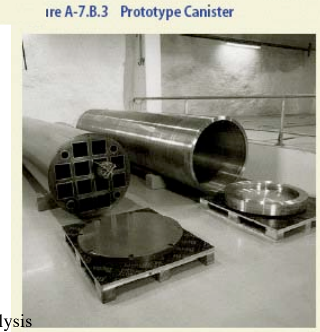


Figure A-7.B.2 Deposition Hole for Okliluoto Waste Canister



(from TILA-99, dimensions in mm)

ıre A-7.B.3 Prototype Canister



(Holds 12 assemblies from the Olkiluoto BWR power plant)

Deutsch, John, Ernest Moniz et al. "The Future of Nuclear Power: An Interdisciplinary MIT Study." Massachusetts Institute of Technology, 2003 (ISBN 0-615-12420-8). Available at http://web.mit.edu/nuclearpower/. p. 159

Three key issues

- The repository site selection process
- The interim spent fuel management system
- Regulation of high level waste repositories

History of U.S. repository siting efforts

1957: National Academy of Sciences recommends geologic disposal; identifies salt rock as the preferred medium

1972: U.S. Atomic Energy Commission abandons repository project at a salt mine in Lyons, KA. Research on alternative methods, including other geologic media, deep seabed, etc. begins. AEC promotes RSSF as 100-year interim solution.

1975: RSSF abandoned. Geologic disposal adopted as preferred alternative.

1978: President Carter affirms principle of not handing responsibility for disposal to future generations, as well as feasibility of geologic disposal. Advocates 'consultation and concurrence' policy towards states.

1982: Nuclear Waste Policy Act -- lays out comprehensive screening process leading to 2 sites in West and East; establishes Nuclear Waste Fund, financed by 0.1 cent/kwh nuclear electricity levy; directs DOE to begin accepting spent fuel from utilities in 1998.

History of U.S.repository siting efforts (continued)

1985: President Reagan abandons site search in east

1987: Nuclear Waste Policy Act Amendments -- direct DOE to focus all site investigation at Yucca Mountain, NV; ended 2nd repository screening activity

1987- Nevada opposes DOE site characterization efforts. Courts rule in favor of DOE.

1998: DOE 'Viability Assessment' finds no technical 'showstoppers' to proceeding with Yucca Mountain site

1999: DOE issues Draft Environmental Impact Statement concluding that disposal at Yucca Mountain would be safer than leaving the waste where it is.

2002: President approves proceeding with YM as nation's first repository

2010: Repository scheduled to open, but . .. .

2036: Repository loading scheduled to be completed

Lifecycle cost of repository, including construction, operation, closure, and postclosure monitoring estimated at $45-50 billion.

Some Possible Scenarios at Yucca Mountain

- The site will be selected; the Federal government will be found to have the necessary legal authority, and will proceed to design, license, and build a repository.
- The site will be selected, the Federal government will be found to have the necessary legal authority, but the project will be stopped by political and other roadblocks.
- The site will be selected, but the Federal government's effort to pre-empt state authority will ultimately be found unconstitutional and the project will be stopped.

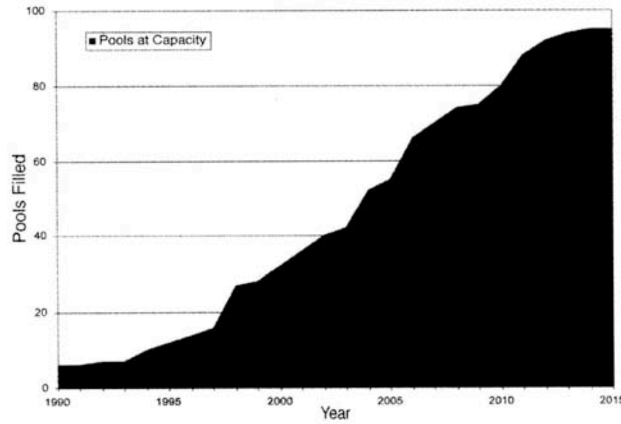


Figure 4: U.S. Reactor Fuel Pool Storage Capacity Exhaustion (Kazimi and Todreas, 1999)

An Interim Storage Facility for Spent Fuel?

- Advocates:
  - Provide breathing room for reactors running out of on-site storage space
  - Will provide more time to understand repository science and engineering, find an acceptable repository site, explore disposal alternatives (including transmutation), etc.
- Opponents:
  - Will become a de facto alternative to disposal
  - Will be no easier to site than a repository
  - Will reduce momentum to develop a repository
- 1987 legislation -- ties MRS construction to approval of final site; prohibits siting MRS in Nevada; subsequent Congressional efforts to overturn this and build MRS in Nevada vetoed by Clinton.
- Senate legislation introduced this year would prevent 'irreversible action relating to disposal of spent nuclear fuel' and provide more funding for partitioning and transmutation.

Regulating Geologic Repositories

- Standards -- who will decide?
- Standards -- how safe is safe enough?
- Verification -- how sure must we be?

Performance Standards for HLW Repositories: Who's in charge?

- Authority to set criteria and standards and to license high level waste repositories vested in the Federal government
- Jurisdiction is divided; boundaries often ill-defined
  - EPA responsible for promulgating 'generally applicable standards' for protection of the general environment
  - NRC responsible for:
    - establishing criteria and standards for the facility itself
    - Responsible for licensing the facility
  - DOE responsible for implementation, including demonstrating compliance with EPA and NRC standards and regulations
- Constant tension between agencies; occasionally open warfare . . .
- Legal challenges
- Congress increasingly involved in technical standard-setting . . .
- Alignment of EPA, NRC and DOE standards largely achieved by 2001

Congress becoming increasingly active

- NWPA of 1982:
  - EPA shall promulgate generally applicable standards for protection of the general environment from offsite releases . .
  - NRC shall promulgate technical requirements and criteria . . .not inconsistent with any comparable standards of EPA
- Energy Policy Act of 1992
  - Requires EPA to promulgate a standard specifically for Yucca Mountain, to be consistent with findings and recommendations of a study to be performed by the National Academy of Sciences
- NAS -- 1996 study
  - Risk at 10^{-5} to 10^{-6} at calculated peak risk, whenever it occurs (200,000-300,000 years) -- 2-20 mrem/yr
- S.104,1997
  - EPA standard shall limit lifetime risk, to the average member of the critical group, of premature death from cancer . . .to approximately, but not greater than 1 in 1000. (~30 mrem/yr)
  - Shall not have release limits or contaminant levels for individual nuclides
- HR 1270, 1997 (proposed)
  - NRC rule should be less than 100 mrem/yr to average member of gen. pop

Some key issues that any technical standard must address:

- Allowable risk from repository relative to natural background risks (how safe is safe enough?)
- Assumptions about future human activities and lifestyles
- How far into the future is it reasonable to project disposal system performance?

EPA Standards for HLW Repositories

- General disposal standard (40 CFR 191) issued in 1993
  - Effort took 15 years
  - Subject to challenges, remanding, overrides by the courts and Congress before final issuance
- In 1992 Congress enacted legislation specifically exempting Yucca Mountain from 40 CFR 191 standards, and directing EPA to develop specific standards for Yucca Mountain
  - Yucca Mountain standards to be consistent with the findings and recommendations of the National Academy of Sciences
- EPA issues Yucca Mountain standard (40 CFR 197) in 1999

Generic EPA Standard for Disposal of HLW, Spent Fuel and TRU Waste (10 CFR 191)

- Population risk standard: Health impacts for the first 10,000 years for a repository containing 100,000 metric tons of heavy metal should not exceed 1000 fatal cancers
  - Cancer risk based on assumed incidence of 5.75×10^{-4} fatal cancers per rem of population dose.(linear, non-threshold dose-response model)
  - Risks to future generations from a geologic respository for high-level wastes during the first 10,000 years should be no greater than the risks from an equivalent amount of unmined uranium ore.
- Individual protection requirement
  - Annual effective dose equivalent, for all pathways of exposure, should be no greater than 15 mrem/year, for 10,000 years.*
- Additional ground water protection limits
  - Concentration of radioactivity in any underground source of drinking water should not exceed Maximum Contaminant Levels of Safe Drinking Water Act.

* Natural background: 300 mrem/yr

EPA Site-Specific Disposal Standards for Yucca Mountain (10 CFR 197; issued in 1999)

- Individual protection standard
- Groundwater protection standard
- Human intrusion standard

EPA Disposal Standards for Yucca Mountain (10 CFR 197; finalized June 2001)

- Individual protection standard
  - No greater than **15 mrem** per year for the maximally-exposed individual during first 10,000 years
  - Equivalent to an annual fatal cancer risk of 8.5×10^{-6} per year to the maximally-exposed individual
  - EPA: "Determining the appropriate dose level is ultimately a question of both science and public policy"
  - National Academy of Sciences:"The level of protection established by a standard is a statement of the level of the risk that is acceptable to society. Whether posed as 'How safe is safe enough?' or as 'What is an acceptable level?', the question is not solvable by science'
  - Total dose limit recommended by ICRP from all sources of radiation, except from background and medical procedures: 100 mrem/year
    - (Other sources in the area -- Nevada Nuclear Testing Site, LLW and TRU waste)
  - EPA: "To avoid unsupportable speculation regarding human activities and conditions, we believe it is appropriate to assume that . . parameters describing human activities and interactions with the repository (e.g., the level of human knowledge and technical capability, human physiology and nutritional needs, general lifestyles and food consumption patterns of the population, and potential pathways through the biosphere leading to radiation exposure or humans) **will remain as they are today** (emphasis added)

- Controlled Area:
  - Maximum of 300 km^2 of surface area above repository
  - No more than 5 km from edge of repository footprint (except in predominant direction of groundwater flow)

Why 10,000 years?

- National Academy of Sciences:
  - "There is no scientific basis for limiting the time period of the individual risk standard to 10,000 years or any other value."
  - The probabilities and consequences of the relevant features, events and processes "... are sufficiently boundable so that these factors can be included in performance assessments that extend over periods on the order of about one million years."
- EPA:
  - "We believe that such an approach is not practical for regulatory decisionmaking, which involves more than scientific performance projections using computer models."
  - "We have included a 10,000-year compliance period in regulations for non-radioactive hazardous waste."

How to verify compliance with the EPA's standards?

- This is the task of the NRC
- NRC will requires DOE to demonstrate compliance with this standard using performance assessment (systematic analysis of events, processes, and features affecting isolation performance)
- Future human activities and biosphere conditions?
  - EPA: "To avoid unsupportable speculation regarding human activities and conditions, we believe it is appropriate to assume that . . parameters describing human activities and interactions with the repository (e.g., the level of human knowledge and technical capability, human physiology and nutritional needs, general lifestyles and food consumption patterns of the population, and potential pathways through the biosphere leading to radiation exposure or humans) **will remain as they are today** (emphasis added)
- Treatment of unlikely events
  - "Events that are very unlikely (less than 1 in 10,000 over 10,000 years) can be excluded [from the performance assessment]"

How to determine compliance with standards?

§ 191.15 Individual protection requirements.

(a) Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system, to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts).

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(c) Compliance assessments **need not provide complete assurance** that the requirements of paragraph (a) of this section will be met. Because of the long time period involved and the nature of the processes and events of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, **what is required is a reasonable expectation, on the basis of the record before the implementing agency**, that compliance with paragraph (a) of this section will be achieved. (Emphasis added)

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[58 FR 66414, Dec. 20, 1993]

NRC Requirements

- Consistency with EPA standards
  - Individual protection
  - Groundwater contamination in the accessible environment
  - Human intrusion
- Multibarrier approach
- Future human activities and biosphere conditions
  - "Characteristics of the reference biosphere and the reasonably maximally exposed individual are to be based on current human behavior and biospheric conditions in the region"
- Treatment of unlikely events
  - "Events that are very unlikely (less than 1 in 10,000 over 10,000 years) can be excluded [from the performance assessment]"

NRC regulations prescribe a multibarrier approach

- Rationale for multibarrier approach
  - Geologic barriers: "Although there is an extensive geologic record ranging from thousands to millions of years, this record is subject to interpretation and includes many uncertainties."
  - Engineered barriers: "Although the composition and configuration of engineered structures can be defined with a degree of precision not possible for natural barriers, it is recognized that except for a few archaeological and natural analogs, there is a limited experience base for the performance of complex, engineered structures over periods longer than a few hundred years . . ."
  - "These uncertainties are addressed by requiring the use of a multiple barrier approach; specifically an engineered barrier system is required in addition to the natural barriers provided by the geologic setting."

Selected NRC Technical Criteria for High Level Waste Disposal (10 CFR 60) -- 1984

- NRC took a 'defense-in-depth' approach to setting repository performance standards. Minimum performance standards were prescribed for each of the major elements of the repository (i.e., the waste package, the underground facility, and the geologic setting)
- Performance requirements:
  - substantially complete containment of HLW within the waste packages for from 300 to 1000 years
  - subsequently, the total release rate of radionuclides from the engineered barrier system (i.e., waste packages + underground structure) shall not exceed 10^{-5}/yr of the waste inventory present after 1000 years
  - pre-waste emplacement groundwater travel time from the repository to the accessible environment shall be at least 1000 yrs

  \+ many additional qualitative siting and design criteria

NRC Regulatory Requirements for Yucca Mountain specifically (10 CFR 63 -- Nov. 2001)

- Fundamentally different from 10 CFR 60
  - 10 CFR 60 relied on several quantitative subsystem performance objectives
  - NRC no longer believes that this is the best approach for ensuring compliance with overall environmental standards
- 10 CFR 63 is based instead on only one quantitative standard: demonstrating compliance with the individual dose limit of 15 mrem/yr for 10,000 years.
- Requires DOE to demonstrate compliance with this standard using performance assessment (systematic analysis of events, processes, and features affecting isolation performance)
  - 10 CFR 63 specifies performance assessment methodology

Lessons from history of nuclear waste regulation

- Some key technical issues have no 'right answer' ('transcientific questions')
- Setting standards and regulations is not solvable by science. It is ultimately a question of public policy.
- Implementation of regulations will require the exercise of technical judgements by technical experts. Proof of compliance with standards in the normal sense is not achievable.
- Regulation does not occur in a political vacuum; it is a public process. The credibility in the public domain of the technical experts who will be called upon to make these judgments will be crucial.
- Public credibility, once lost, is extremely difficult to restore.
- Because the regulatory process (both standard-setting and implementation) is a public process, it will also be affected by public perceptions of risk