1.818J/2.65J/10.391J/11.371J/22.811J/ESD166J

SUSTAINABLE ENERGY

2.650J/10.291J/22.081J

INTRODUCTION TO SUSTAINABLE ENERGY

Prof. Michael W. Golay
Nuclear Engineering Dept.

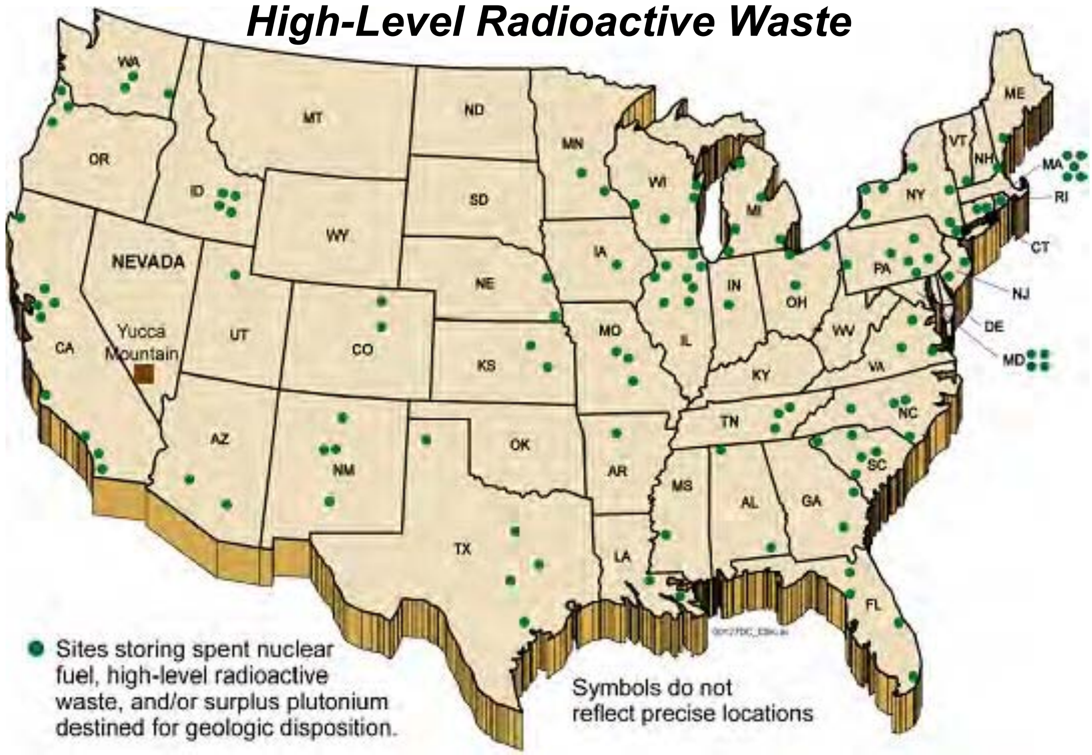
NUCLEAR WASTES AND YUCCA MOUNTAIN

NUCLEAR WASTE

Defense Complex Clean-Up

Support of Nonproliferation Initiatives, e.g. Disposal of DOE Foreign Research Reactor Spent Fuel

Locations of Spent Nuclear Fuel and High-Level Radioactive Waste



Commercial Spent Nuclear Fuel

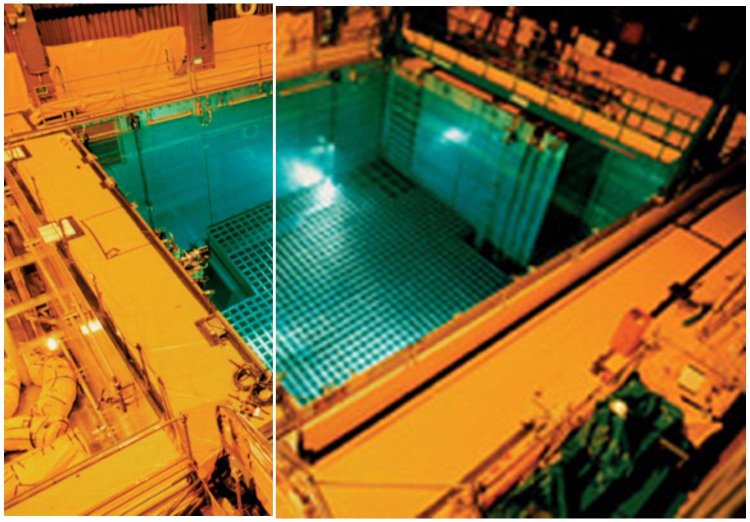
Disposition of Naval Reactor Spent Nuclear Fuel

Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

SPENT NUCLEAR FUEL

- 39 states with nuclear waste
- Five DOE sites with nuclear waste

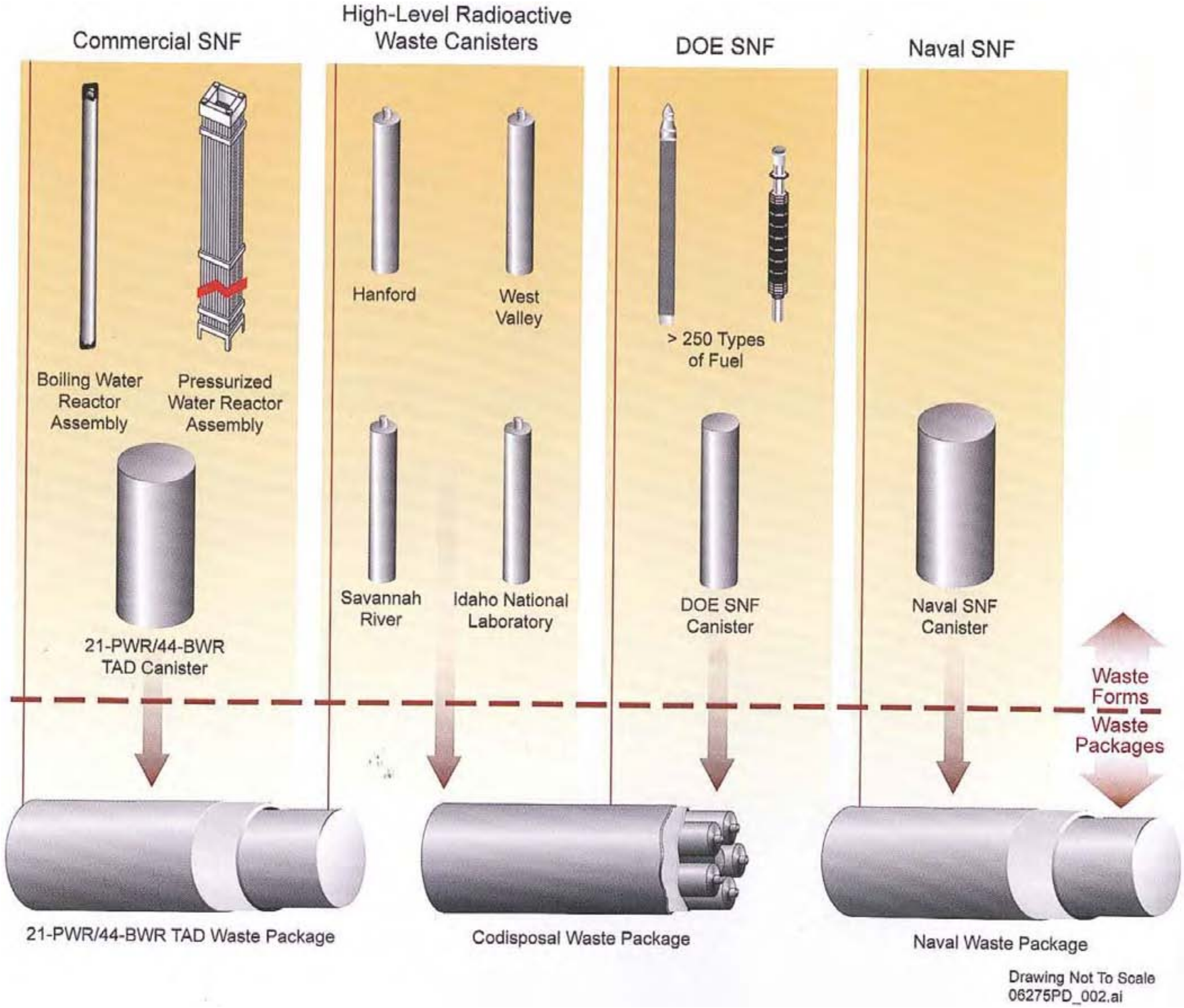
Spent-fuel pools



Dry cask storage

Photos of spent fuel pool and dry cask storage from the U.S. Nuclear Regulatory Commission.

WASTE FORMS AND PACKAGES



Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

TRANSPORTATION CASK

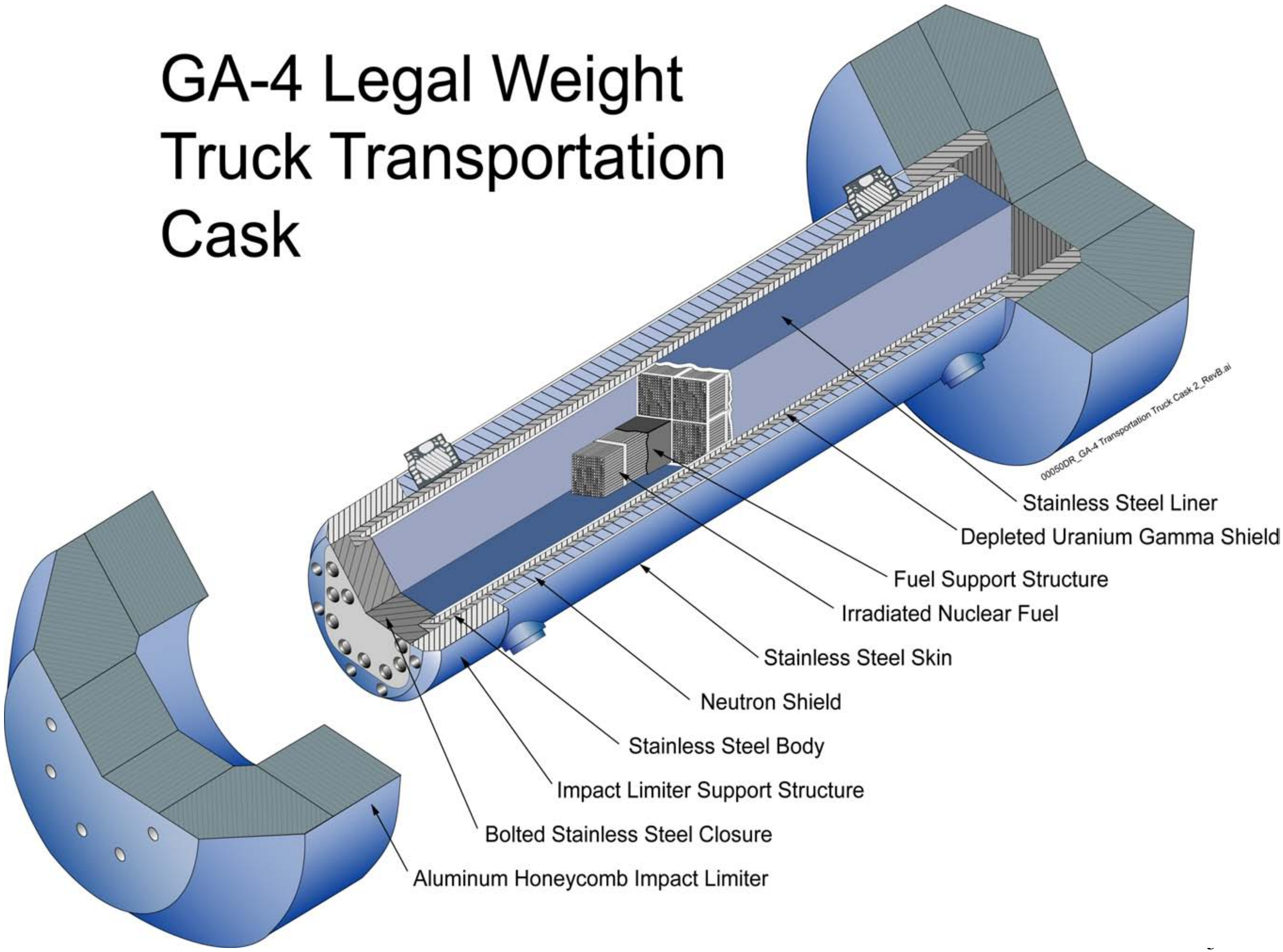


Image by U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

TIMELINE FOR NUCLEAR WASTE DISPOSAL

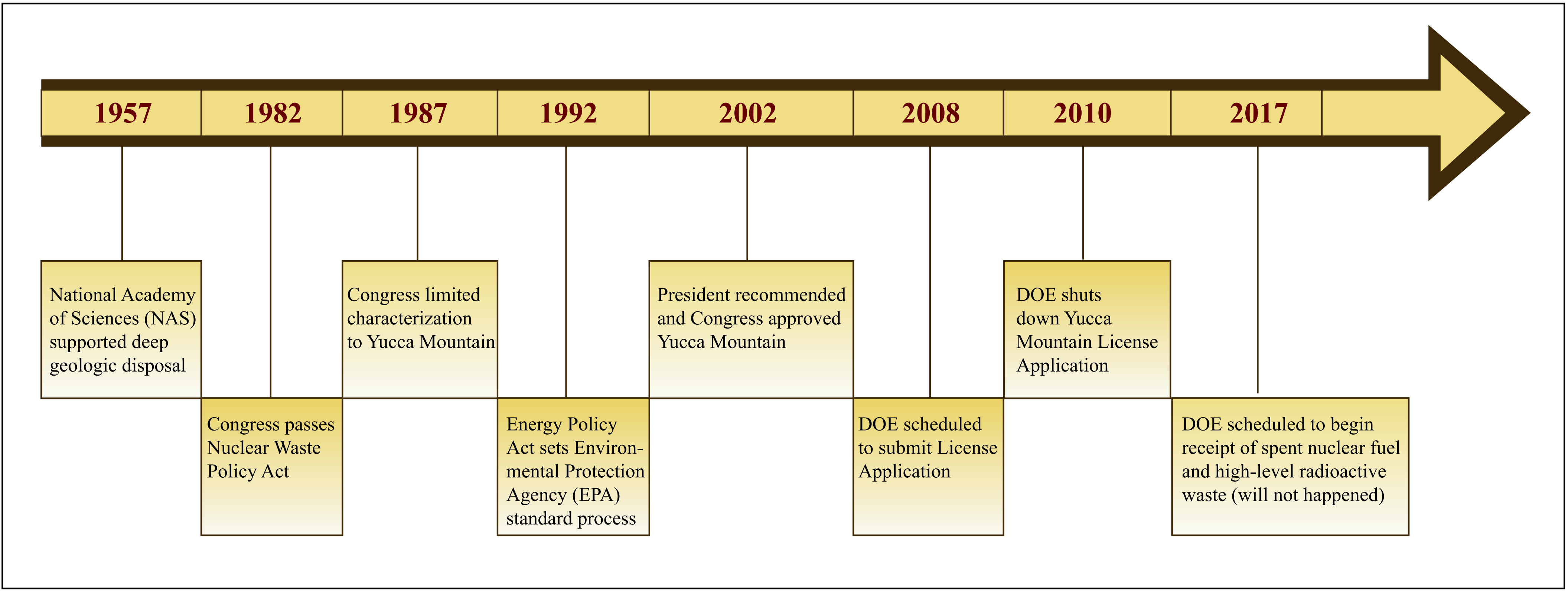
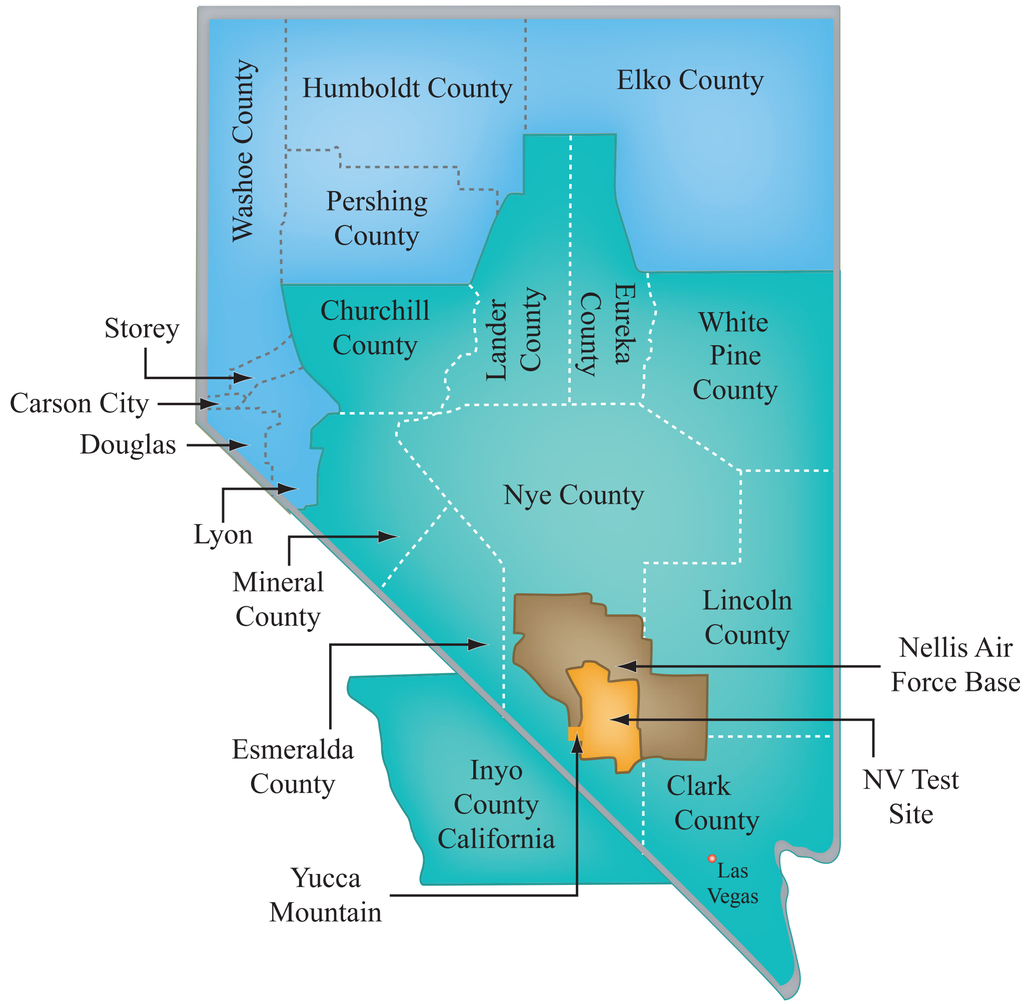


Image by MIT OpenCourseWare.

YUCCA MOUNTAIN, NEVADA



- Counties designated as affected units of local government
- 100 miles northwest of Las Vegas in Nye County
- Located on Western boundary of the Nevada Test Site, a U.S. Department of Energy (DOE) facility

Image by MIT OpenCourseWare.

YUCCA MOUNTAIN SITE

Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

YUCCA MOUNTAIN SUBSURFACE OVERVIEW

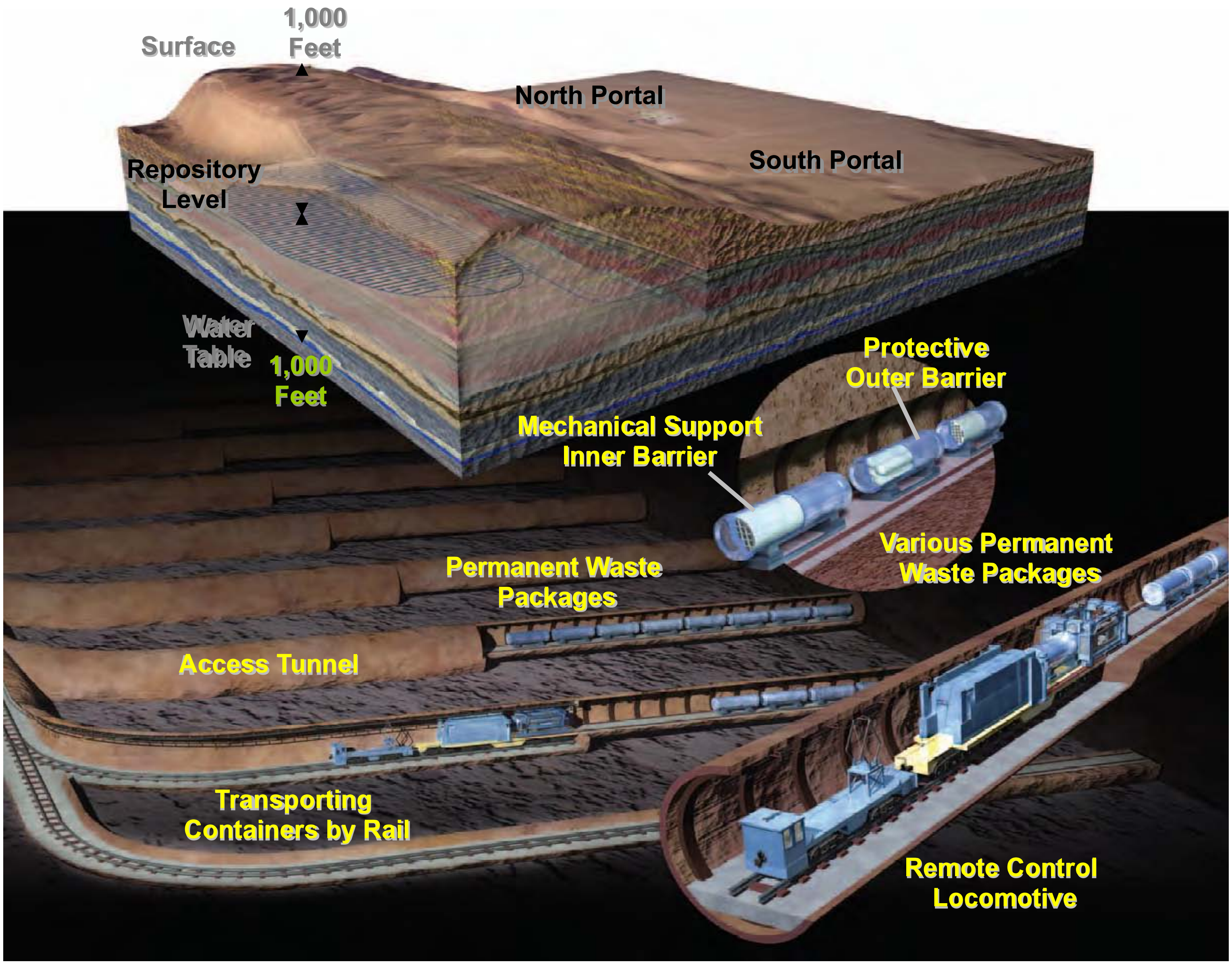
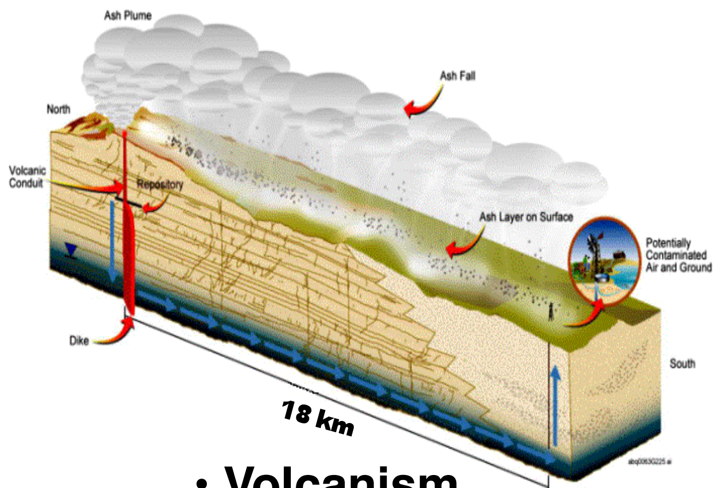
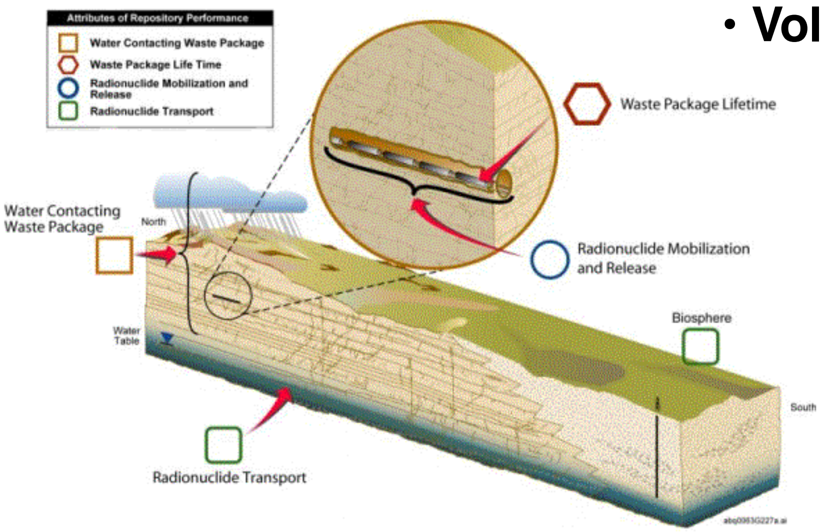


Image by U.S. Office of Civilian Radioactive Waste Management.

HYPOTHETICAL SCENARIOS

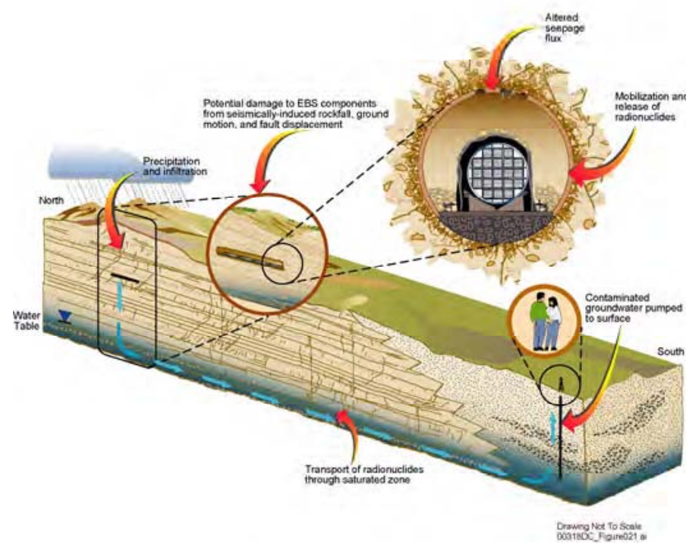


• **Volcanism**



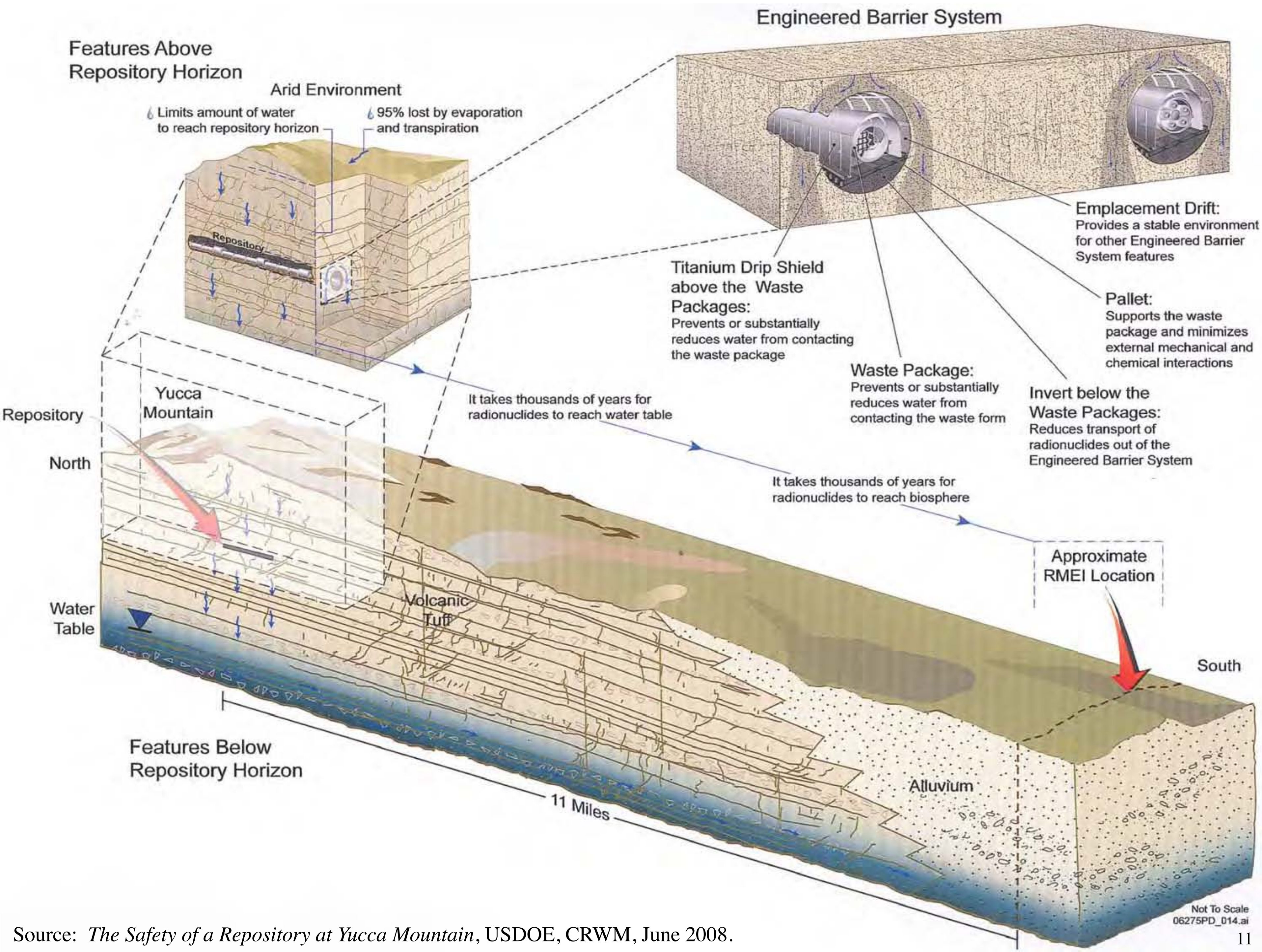
• **Nominal**

•**Early defects**



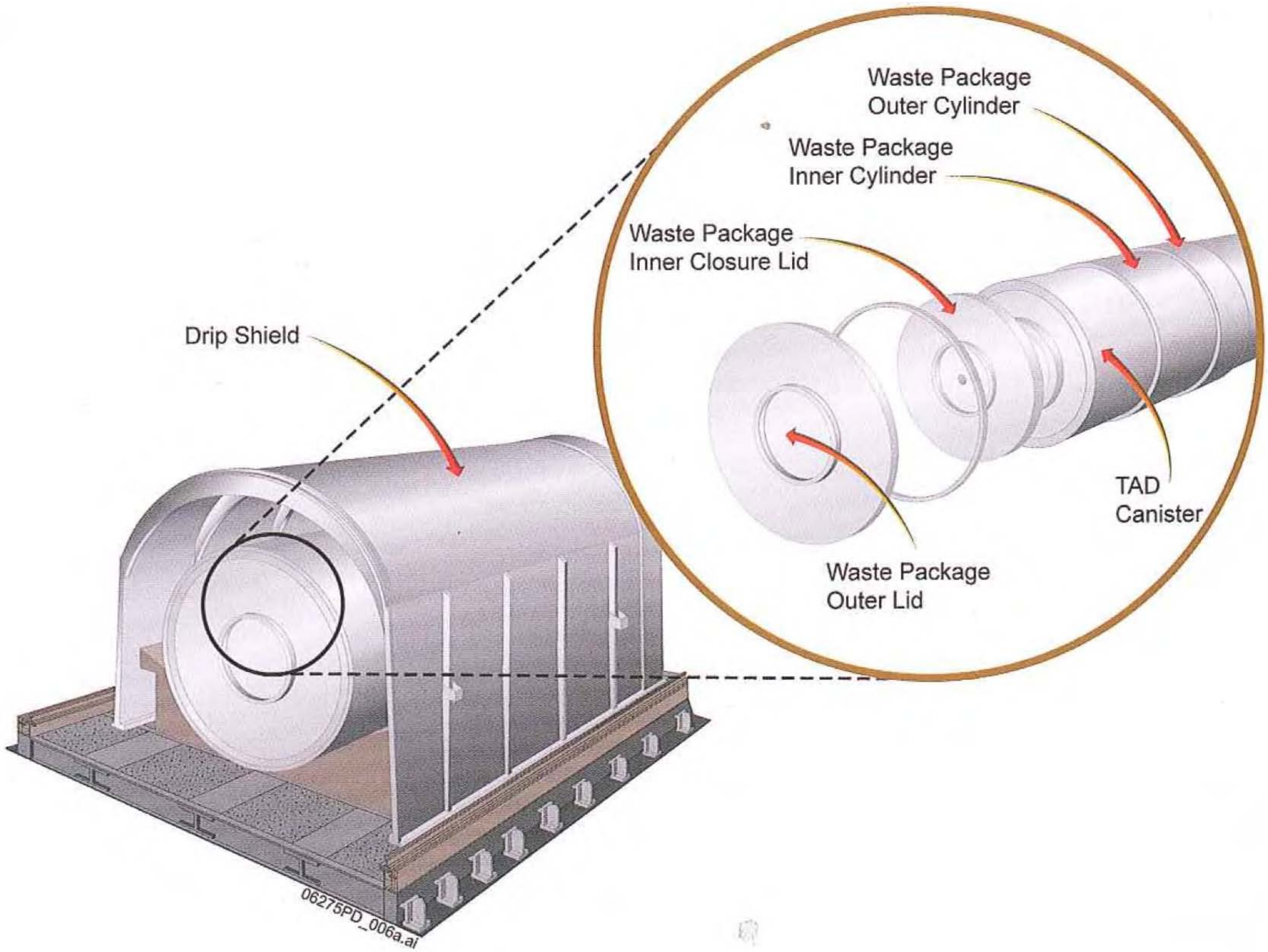
•**Seismic**

Source: U.S. Department of Energy.



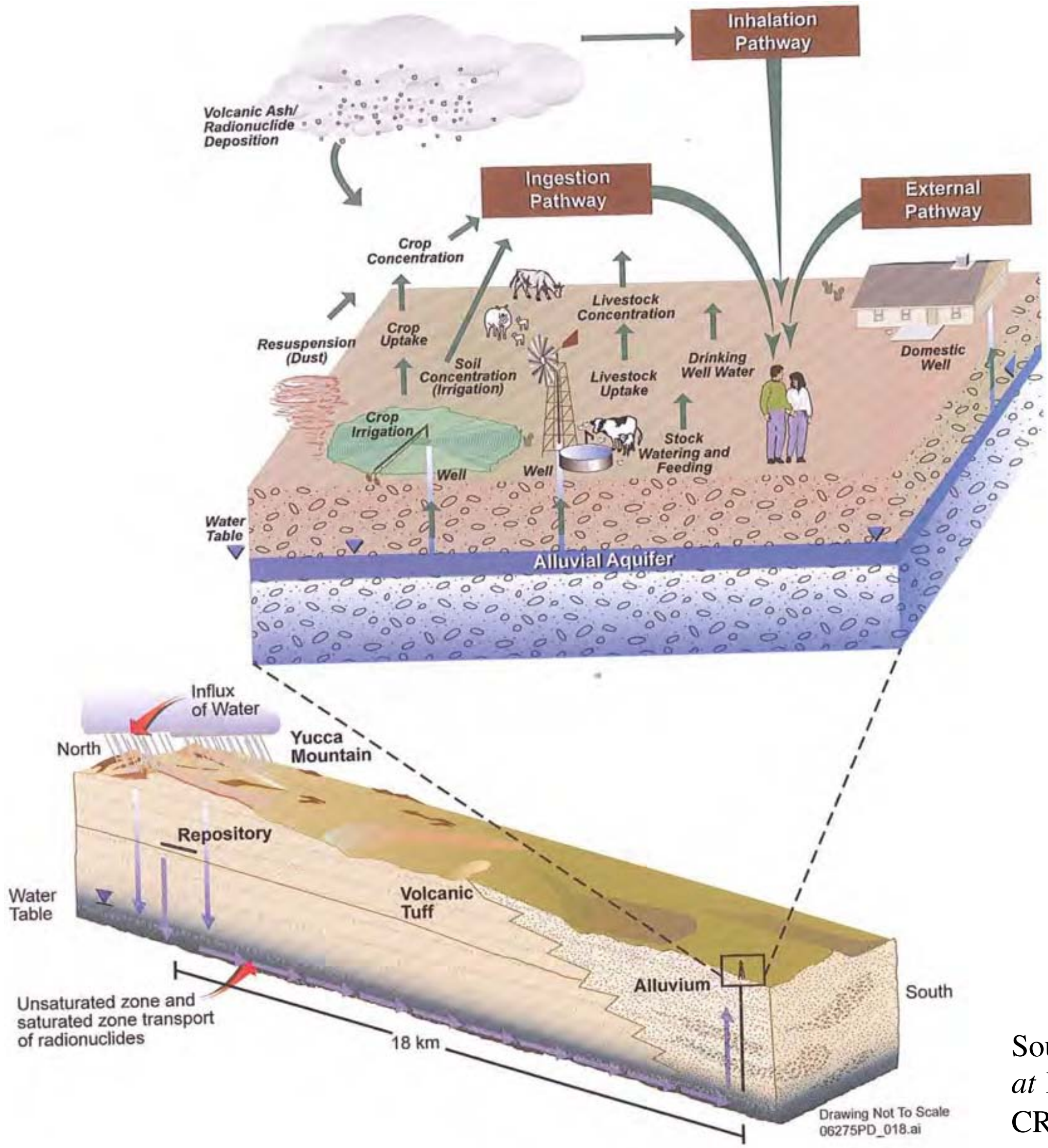
Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

CANISTER PLACED INSIDE WASTE PACKAGE



Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

LOCATION AND CHARACTERISTICS OF REASONABLE MAXIMALLY EXPOSED INIDVIDUAL AND FEATURES OF NATURAL SYSTEM BELOW REPOSITY THAT LIMIT MOVEMENT OF RADIONUCLIDES TO THAT LOCATION



Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

Yucca Mountain: Predicted average annual dose for 10,000 years

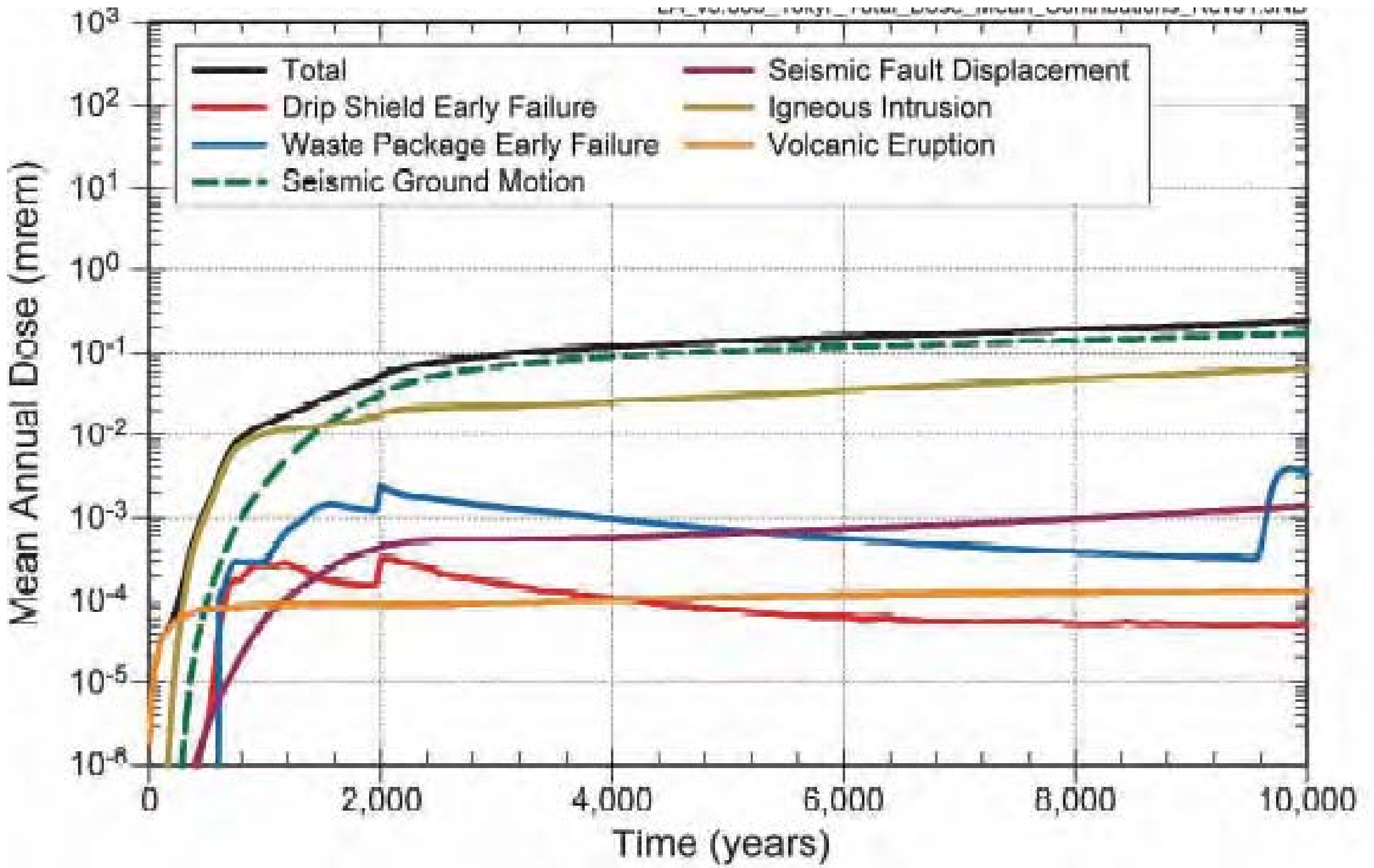


Fig. F-17 in *Draft Supplemental Environmental Impact Statement for a Geologic Repository at Yucca Mountain.* U.S. Department of Energy, October 2007, DOE/EIS-0250F-S1D.

Yucca Mountain: Predicted median annual dose for 1,000,000 years

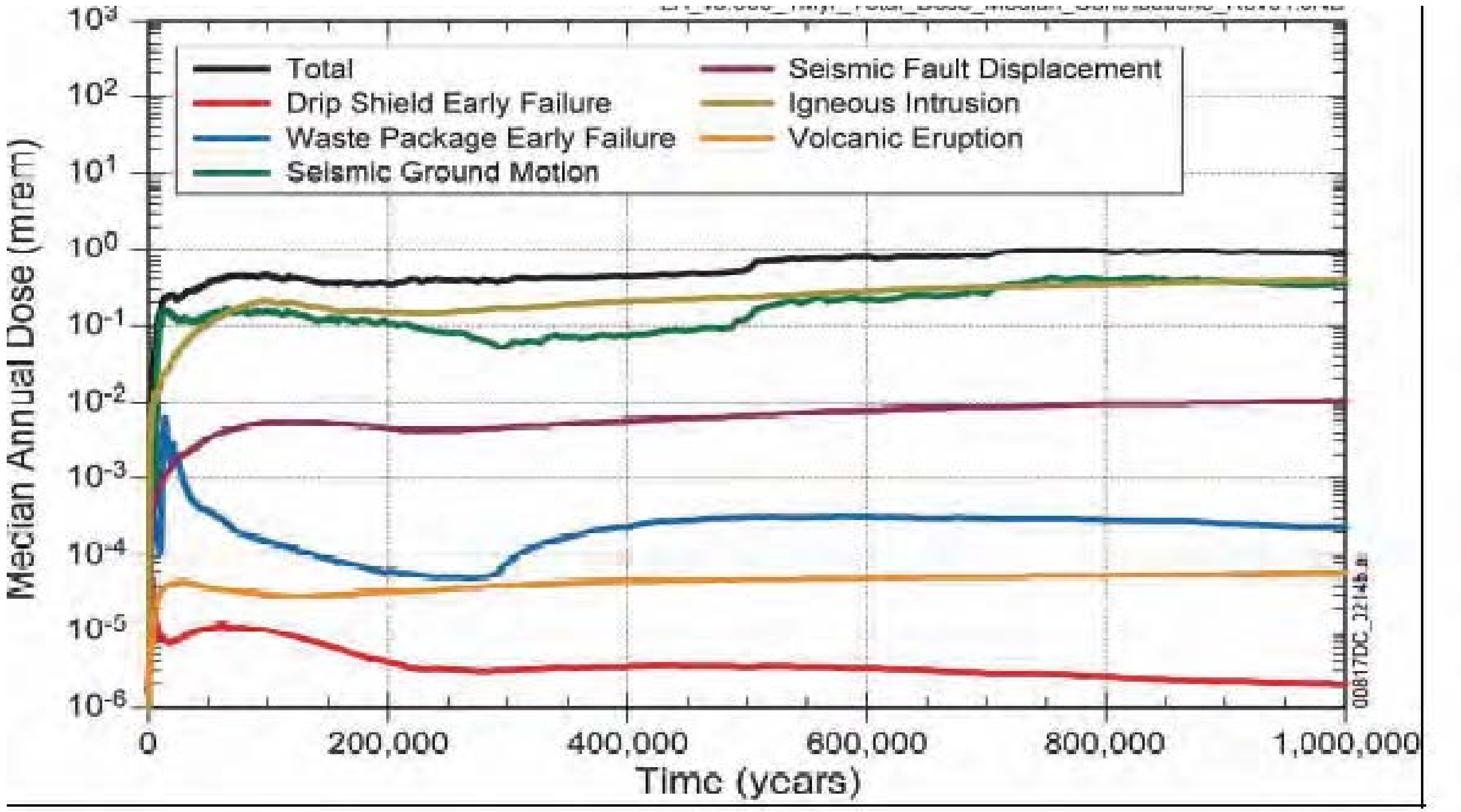


Fig. F-17 in *Draft Supplemental Environmental Impact Statement for a Geologic Repository at Yucca Mountain.* U.S. Department of Energy, October 2007, DOE/EIS-0250F-S1D.

POSTCLOSURE PERFORMANCE RESULTS

	Mean	Median	95th Percentile
Individual Protection Standard	No more than 15 mrem	No more than 350 mrem[a]	None (95th percentile is provided here for comparison only)
First 10,000 years	0.24 mrem		0.67 mrem
Time of occurrence	10,000 years		10,000 years
Post-10,000 years[b]		0.9 mrem	9.1 mrem
Time of occurrence		~800,000 years	1,000,000 years
Human Intrusion Standard		No more than 350 mrem[a]	
Post-10,000 years[b]		0.01 mrem	
Time of occurrence		~202,000 years	

NOTE: [a]Proposed
[b]Within the proposed period of geologic stability, defined as 1 million years.

	Combined ^{226}Ra and ^{228}Ra Concentration	Gross Alpha Activity Concentration	Dose from Combined Beta- and Photon-Emitting Radionuclides
Groundwater Protection Standard: Limit for Activity Concentration or Annual Dose	5 pCi/L	15 pCi/L	4 mrem
Performance Results: Projected Maximum Mean Activity Concentration or Annual Dose	$<10^{-6}$ pCi/L	10^{-4} pCi/L	Whole body: ~0.06 mrem Thyroid: ~0.26 mrem
Natural Background Level	0.5 pCi/L	0.5 pCi/L	Background level excluded in regulatory requirement

Source: *The Safety of a Repository at Yucca Mountain*, USDOE, CRWM, June 2008.

NUCLIDES OF INTEREST

Summary of Activities (Ci/MTU) for Radionuclides of Interest as a Function of Post-Irradiation Time

(NOTE: Nuclides whose contribution to the specific activity of the fuel is less than 0.001 Ci/MTU at a post-irradiation time of 150 days are left blank.)

Power = 30MW; Burnup = 33,000 MWd: Flux = 2.92×10^{13} n/cm^2-sec

Z	Radionuclide	Half-life*	Curies/Metric Ton Uranium: Discharge**	160 days**	1 year**	10 years**
1	H-3	12.26y	7.09E02	6.91E02	6.7E02	4.03E02
4	Be-10	2.7×10^6y	-	-	-	-
6	C-14	5770y	-	-	-	-
20	Ca-41	1.1×10^5y	-	-	-	-
27	Co-60	5.27y	-	-	-	-
28	Ni-59	8×10^4y	-	-	-	-
34	Se-79	7×10^4y	3.98E-01	3.98E-01	3.98E-01	3.98E-01
36	Kr-85	10.4y	1.13E04	1.10E04	1.06E04	5.96E03
37	Rb-87	4.7×10^{10}y	-	-	-	-
38	SR-89	50.4d	7.18E05	8.51E04	5.53E03	5.15E-16
	SR-90	28y	7.76E04	7.68E04	7.57E04	6.07E04
39	Y-90	64.2h	8.07E04	7.68E04	7.58E04	6.07E04
	Y-91	57.5d	9.38E05	1.43E05	1.28E04	1.89E-13
40	Zr-93	9.5×10^5y	1.89E00	1.89E00	1.89E^0	1.89E00
	Zr-95	65d	1.37E06	2.49E05	2.80E04	1.67E-11
41	Nb-93m	3.7y	1.45E-01	1.83E-01	2.31E-01	8.40E-01
	Nb-95	35d	1.38E06	4.73E05	5.95E04	3.61E-11
42	Mo-93	10^4y	-	-	-	-
43	Tc-99	2.1×10^5y	1.43E01	1.43E01	1.43E01	1.43E01
44	Ru-103	40d	1.22E06	7.41E04	2.05E03	2.09E-22
	Ru-106	1.0y	5.45E05	4.03E05	2.73E05	5.50E02
46	Pd-107	7×10^6y	1.10E-01	1.10E-01	1.10E-01	1.10E-01
47	Ag-110m	249d	3.68E03	2.37E03	1.35E03	1.66E-01
50	Sn-126	10^5y	5.46E-01	5.46E-01	5.46E-01	5.46E-01
51	Sb-125	2.0y	8.7E03	7.89E03	6.83E03	6.78E02
52	Te-127m	105d	1.54E04	5.77E03	1.57E03	1.30E-06
	Te-129	67.3m	3.37E05	1.42E03	2.17E01	0.0
53	I-129	1.72×10^7y	3.71E-02	3.74E-02	3.74E-02	3.74E-02
	I-131	8.05d	8.61E05	9.23E-01	1.99E-08	0.0
55	Cs-134	2.19y	2.46E05	2.12E05	1.76E05	8.38E03
	Cs-135	2.0×10^6y	2.86E-01	2.86E-01	2.86E-01	2.86E-01
	Cs-137	30y	1.08E05	1.07E05	1.05E05	8.56E04

Appendix A in Bishop, William P., and Frank J. Miraglia, Jr. *Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle*. U.S. Nuclear Regulatory Commission, October 1976, NUREG-0116/WASH-1248 Supplement 1.

NUCLIDES OF INTEREST, cont'

Z	Radionuclide	Half-life	Discharge	160 days	1 year	10 years
58	Ce-144	285d	1.11E06	7.52E05	4.56E05	1.51E02
61	Pm-147	2.5y	1.02E05	9.73E04	8.39E04	7.75E03
63	Eu-154	16y	6.99E03	6.86E03	6.69E03	4.53E03
	Eu-155	1.7y	7.48E03	6.33E03	5.11E03	1.63E02
82	Pb-210	21y				
84	Po-210	138d				
86	Rn-220	51.5s	1.50E-03	2.29E-03	3.40E-03	1.60E-02
	Rn-222	3.82d				
88	Ra-224	3.64d	1.50E-03	2.29E-03	3.40E-03	1.60E-02
	Ra-225	14.8d				
	Ra-226	1622y				
ACTINIDES						
90	Th-228	1.91y	1.49E-03	2.27E-03	3.38E-03	1.60E-02
	Th-229	7340y				
	Th-230	80y				
	Th-232	14y				
	Th-234	24.1d	3.14E-01	3.14E-01	3.14E-01	3.14E-01
91	Pa-226	1.8m				
92	U-233	1.62×10^5y				
	U-234	2.48×10^5y	7.51E-01	7.55E-01	7.59E-01	8.30E-01
	U-235	7.13×10^8y	1.71E-02	1.71E-02	1.71E-02	1.71E-02
	U-236	2.39×10^7y	2.88E-01	2.88E-01	2.88E-01	2.88E-01
	U-238	4.51×10^9y	3.14E-01	3.14E-01	3.14E-01	3.14E-01
TRU						
93	Np-237	2.2×10^6y	3.33E-01	3.40E-01	3.40E-01	3.43E-01
94	Pu-236	285y	3.50E-01	3.16E-01	2.75E-01	3.08E-02
	Pu-238	89y	2.72E03	2.82E03	2.86E03	2.70E03
	Pu-239	2.44×10^4y	3.18E02	3.23E02	3.23E02	3.23E02
	Pu-240	6.58×10^3y	4.77E02	4.77E02	4.77E02	4.79E02
	Pu-241	13y	1.05E05	1.03E05	1.00E05	6.53E04
	Pu-242	3.79×10^5y	1.38E00	1.38E00	1.38E00	1.38E00
	Pu-244	7.6×10^7y				
95	Am-241	458y	8.59E01	1.59E02	2.50E02	1.41E03
	Am-242	16h	6.34E04	9.14E00	9.12E00	8.75E00
	Am-243	7.95×10^3y	1.81E01	1.82E01	1.82E01	1.82E01
96	Cm-242	163d	3.34E04	1.70E04	7.12E03	7.18E00
	Cm-243	35y	3.71E00	3.68E00	3.68E00	2.99E00
	Cm-244	17.6y	2.44E03	2.40E03	2.35E03	1.67E03
	Cm-247	4×10^7y				

* Handbook of Chemistry and Physics, 45th Edition, Section B

** ORNL-4628, "ORIGEN-The ORNL Isotope Generation and Depletion Code", May 1973, Tables A-7 and A-9.

Appendix A in Bishop, William P., and Frank J. Miraglia, Jr. *Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle*. U.S. Nuclear Regulatory Commission, October 1976, NUREG-0116/WASH-1248 Supplement 1.

BUILDUP OF REACTION PRODUCTS

Images removed due to copyright restrictions.
Please see Fig. 1, 2, 9-11 in Cohen, Bernard L. "The Disposal of Radioactive Wastes from Fission Reactors." *Scientific American* 236 (June 1977): 21-31.

DISPOSAL OPTIONS

- Sub-Seabed
- Ice Sheets
- Space
- Deep Bore Holes
- Geologic repositories for storing highly radioactive materials have been chosen by the National Academy of Science in several assessments versus the alternative means of storage or disposal of highly radioactive materials.

Source: S.A. Simonson, “Waste Technology Issues,” undated.

TECHNICAL PERFORMANCE CRITERIA

- The bases for determining the performance of a geologic repository are established by regulations
- The regulations establish numerical release limits that are presumed to be

1) Self consistent between regulating agencies
   - NRC within 5 km of repository
   - EPA beyond 5 km
2) Based upon equivalency of different radionuclide risks with regard to dose to man
3) Consistent with other societal risks
   - Current basis is indirectly related to demonstrating a total system performance probability of less than one chance in 10 of causing 1000 excess deaths per 10,000 years

Source: S.A. Simonson, “Waste Technology Issues,” undated.

TECHNICAL PERFORMANCE OF A GEOLOGIC REPOSITORY

- In essence, the performance of a geologic repository system boils down to a very detailed risk assessment of all of the physical and processes that could occur that may result in releases of radionuclides to the environment using predictions extrapolated to many thousands of years into the future.
- First, Scenario of Likely Events Must be Identified For the Chosen Repository Location (Yucca Mountain)
- Natural, High Probability
  - Natural Degradation of Engineered Barriers and Waste Forms
  - Movement of Radionuclides in Ground Water or Air
- Natural, Low Probability
  - Volcanism
  - Earthquakes
- Human Intrusion
  - Drilling
  - Mining

Source: S.A. Simonson, "Waste Technology Issues," undated.

SUB-SYSTEM INVESTIGATIONS

For Each of the Events, Predictive Models Must Be Developed Incorporating the Following Sub-System Models:

- Natural Barriers and Repository Influences
  - Radionuclide Transport in Ground Water
  - Radionuclide Transport as Vapors and Gases
  - Water Infiltration into Repository
- Engineered Barriers and Waste Forms

Source: S.A. Simonson, "Waste Technology Issues," undated.

HIGH-LEVEL WASTE

DEFINITION: Wastes Arising from the Primary Decontamination Steps in the Reprocessing of Spent Fuel

PRUEX Process:

Nitric Acid

↓

Spent Fuel → Shearing → Dissolution → Solvent Extraction → High-Level Waste

Solvent Extraction → Uranium + Plutonium

↓

Uranium Plutonium Separation → Uranium

Uranium Plutonium Separation → Plutonium

Source: S.A. Simonson, "Waste Technology Issues," undated.

TUTORIAL: SOLVENT EXTRACTION

Reaction:

$$UO_2^{2+}(aq) + 2NO_3^-(aq) + 2TB(org) \Leftrightarrow UO_2(NO_3)_2 \cdot 2TBP(org)$$

$$Pu^{4+}(aq) + 4NO_3^-(aq) + 2TB(org) \Leftrightarrow Pu(NO_3)_4 \cdot 2TBP(org)$$

Results in a Distribution of Uranium and Plutonium:

$$D_i \, \frac{\text{concentration of i in organic phase}}{\text{concentration of i in the aqueous phase}}$$

and a Net Separation of Uranium and Plutonium from the Fission Products:

$$\alpha = \frac{D_{\text{product}}}{D_{\text{impurity}}}$$

D's for Uranium and Plutonium are Much Higher Than the Fission Products, Thus a Separation (large α) is Made at Greater Than 99% in One Pass of Solvent Extraction.

Source: S.A. Simonson, "Waste Technology Issues," undated.

REPROCESSING CONTINUED

After Separation, Uranium is Separated from the Plutonium by Chemically Changing the Aqueous Solution and Repeating the Solvent Extraction

Approximately 1% of the Spent Fuel is Plutonium of Which 70% is Fissile (7 g/kg spent fuel)

ECONOMICS:

Cost of Reprocessing	~$1300/kg
Cost of Fuel Fabrication	~$ 350/kg
Energy Value of Plutonium	~$ 200/kg
Uranium Credit	~$ 60/kg

Therefore, Marginal to Uneconomic to Reprocess at Current Facilities, Particularly When Uranium is Very Inexpensive

Fission Products and Actinide Wastes are Sent for Processing Into Glass Logs for Permanent Disposal

Source: S.A. Simonson, “Waste Technology Issues,” undated.

WHY GLASS?

Historical Perspective of High-Level Waste Glass:

- Natural Analogs
- High Durability (10X better than spent fuel in retaining radionuclides
- High Waste Loading (up to 30 wt% waste vs. 5% for spent fuel)
- Predictability of Degradation

Source: S.A. Simonson, "Waste Technology Issues," undated.

NUCLEAR WASTE MANAGEMENT SYSTEM

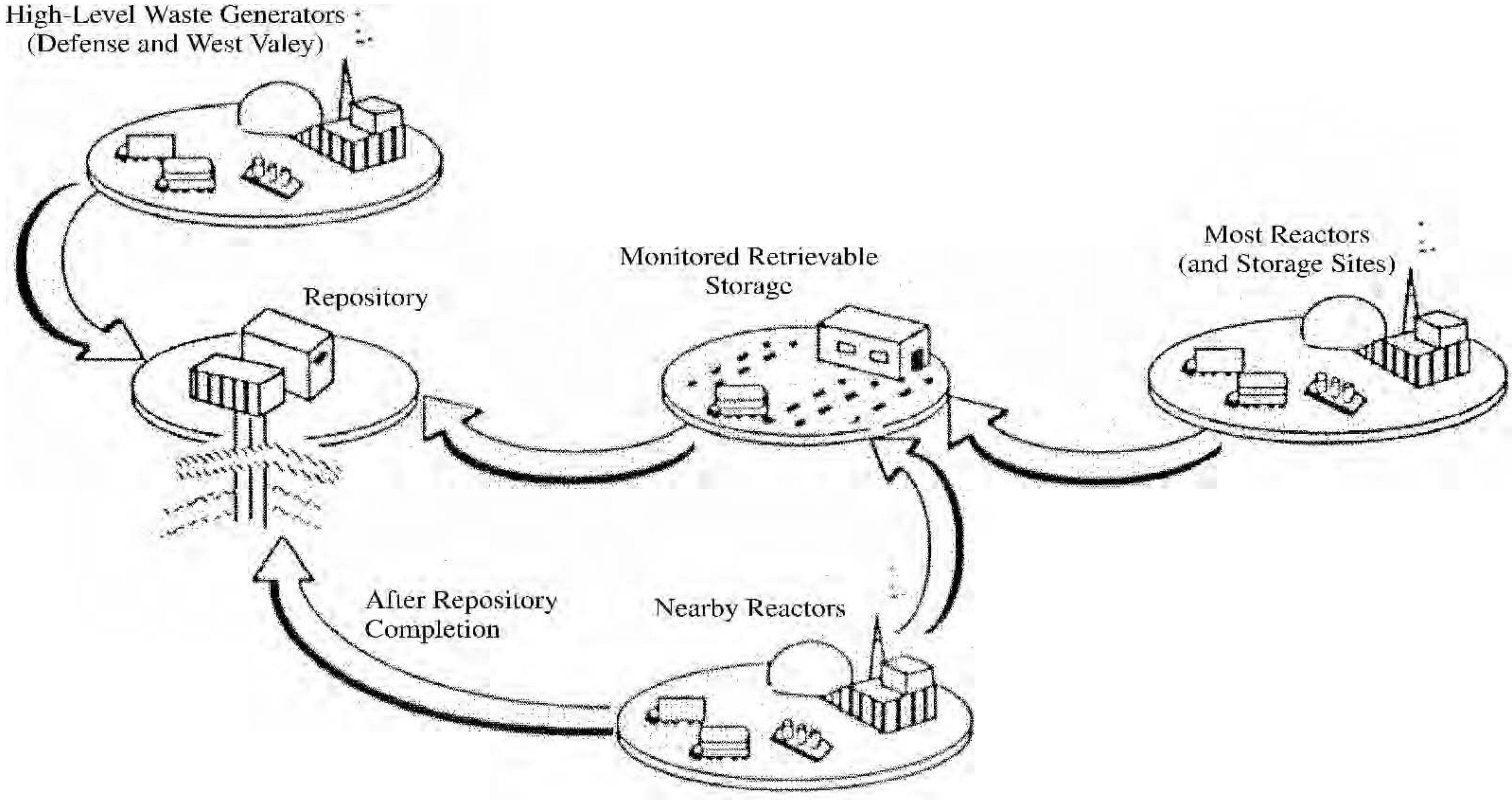
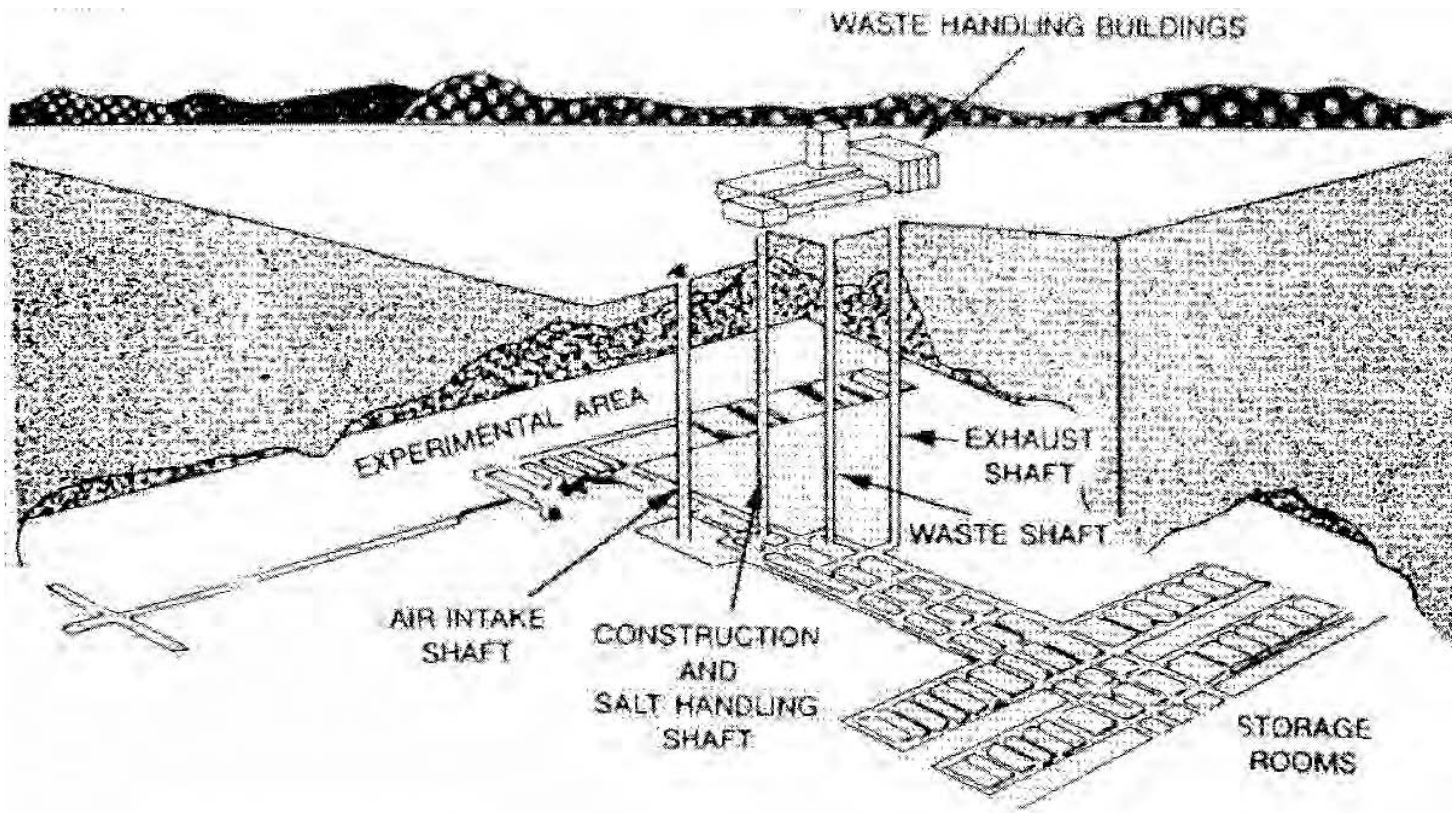


Image by U.S. Department of Energy.

Source: S.A. Simonson, "Waste Technology Issues," undated.

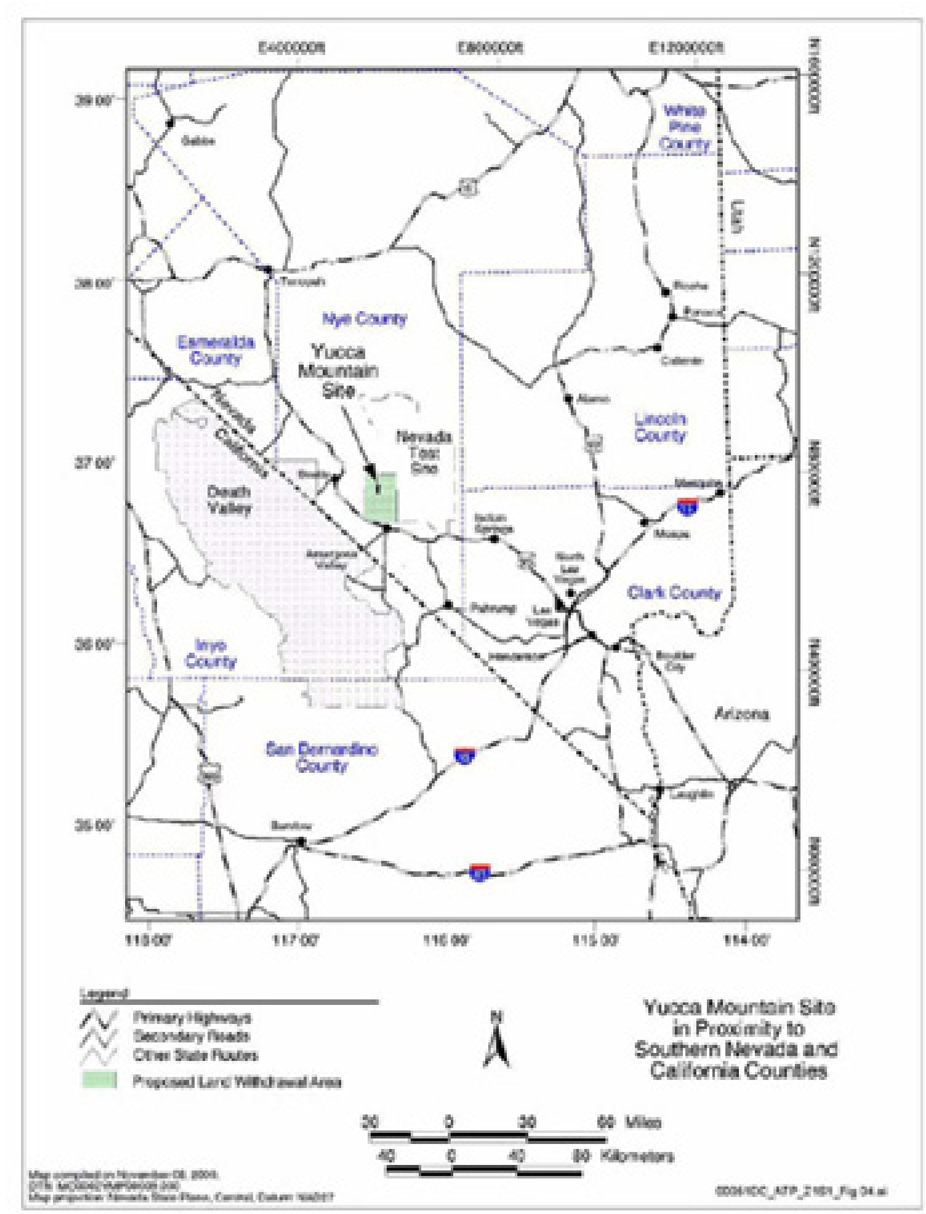
WASTE ISOLATION PILOT PLANT: ITS CAPACITY, ESTIMATED OPERATIONAL COST, AND ESTIMATED LIFETIME



Total waste capacity:	6 million cubic feet
Current accumulated waste volume:	2.12 million cubic feet
Construction cost to date:	$700 million
Estimated cost for 25-year operation:	$2.5 billion
Estimated total time to fill the WIPP repository:	20 - 30 years

Fig. 2-3 in *Complex Cleanup: The Environmental Legacy of Nuclear Weapons Production*. U.S. Congress, Office of Technology Assessment, February 1991, OTA-O-484.

SOUTHERN NEVADA REGION



Source: Fig. 1-5 in "Yucca Mountain Science and Engineering Report." U.S. Department of Energy, Office of Civilian Radioactive Waste Management (February 2002): DOE/RW-0539-1.

INTERESTED PARTIES

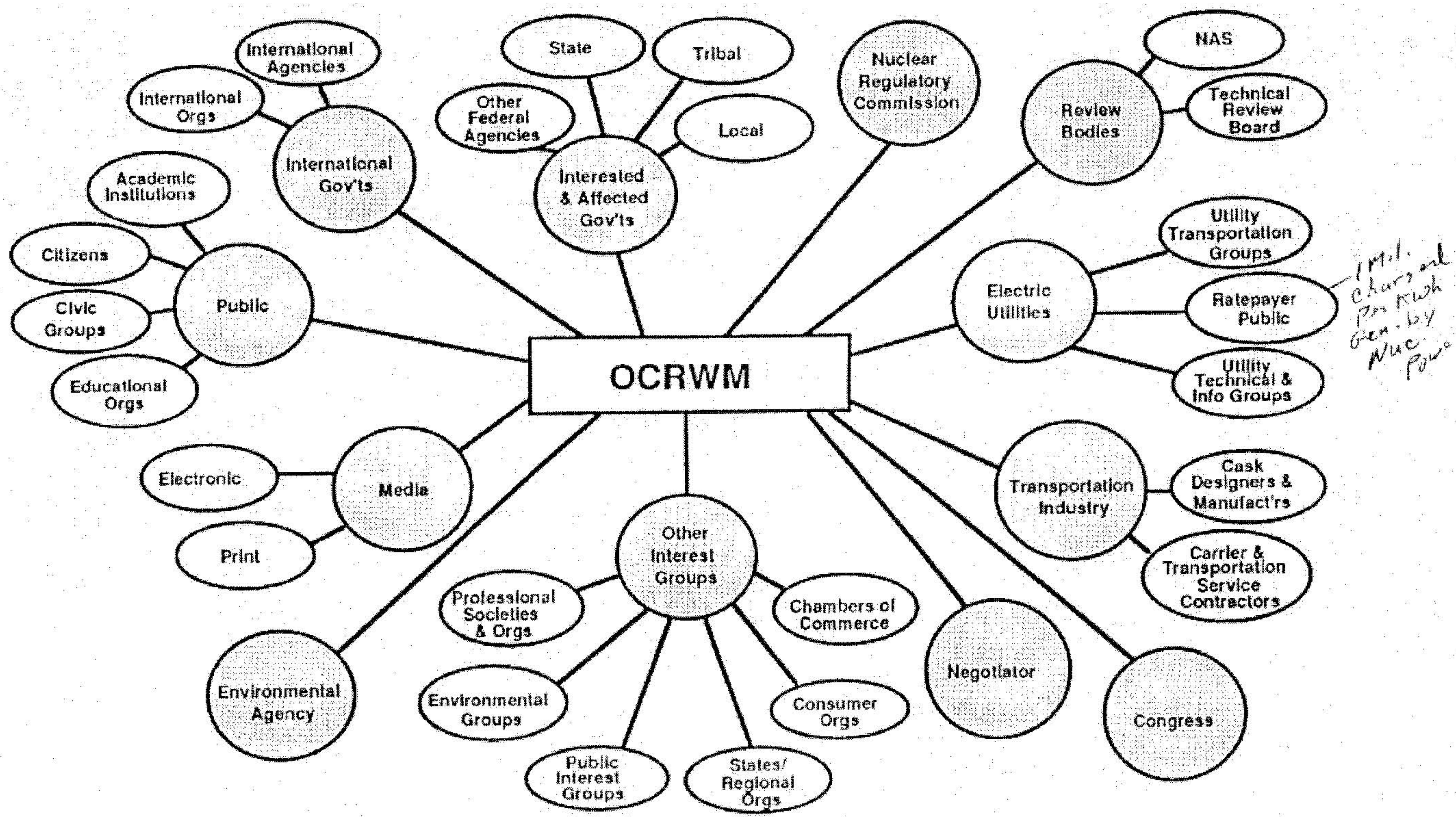


Image by U.S. Department of Energy.

Source: S.A. Simonson, "Waste Technology Issues," undated.

OBSERVATIONS

- Complex, First-of-a-Kind Project
- Public Acceptance Dominates
- Numerous Oversight Entities
- Incredible Meetings Schedule
- Fire Drills Dominate Strategic Planning
- Radioactive Waste People are Competent and Hardworking
- DOE Bureaucracy is a Major Challenge

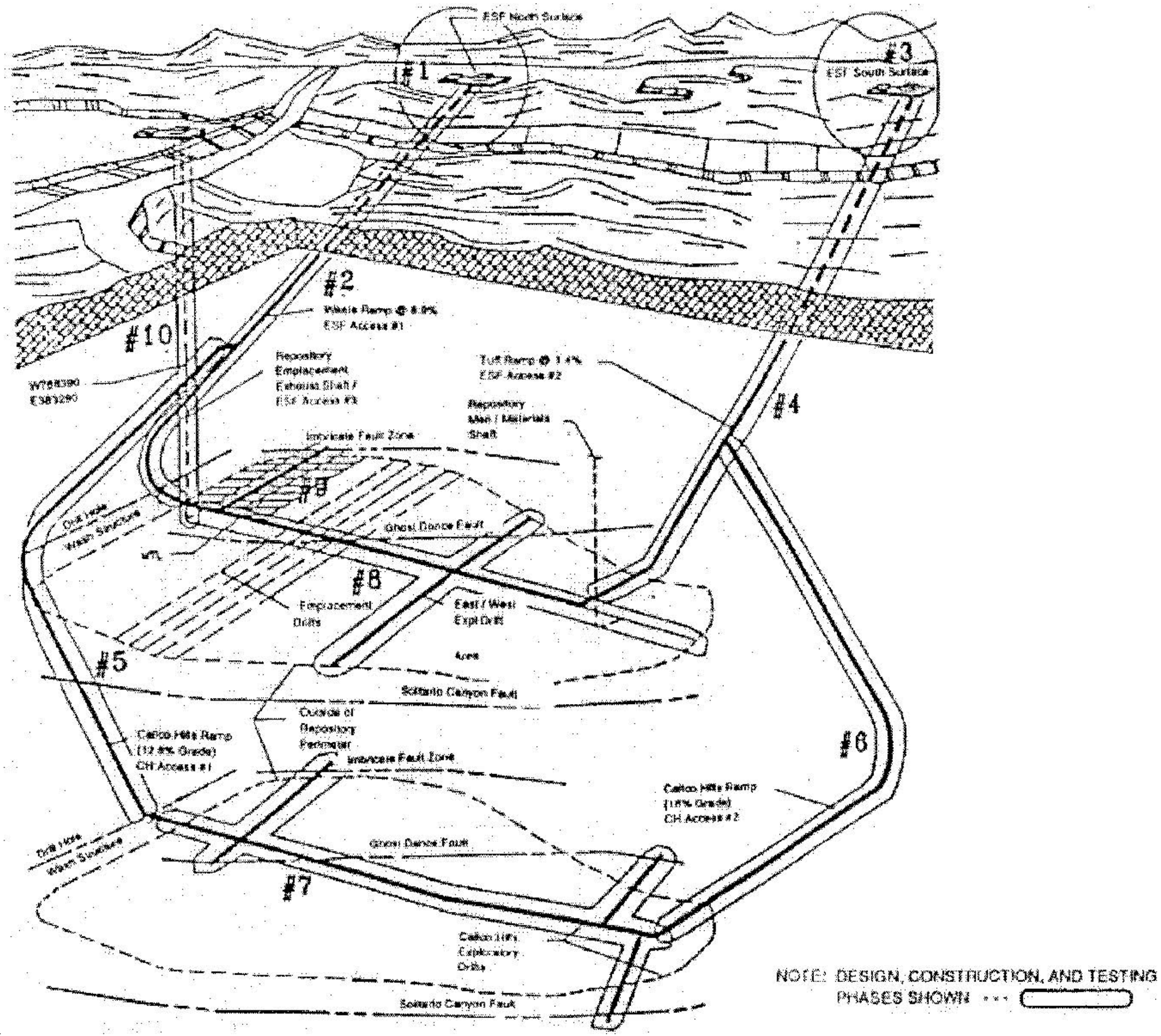
Source: S.A. Simonson, “Waste Technology Issues,” undated.

OBSERVATIONS (Continued)

- The M&O Welcomed by DOE/Community
- High Expectations
- Large, High Visibility Tasks Being Assigned
- M&O Identity and Team Integration is Good
- TRW/Team Identity and Reputation Will Be Applied
- M&O is Viewed as Different
  - Broadly capable
  - Mission/goal oriented
  - Experienced/up-to-speed
  - Not a support contractor

Source: S.A. Simonson, "Waste Technology Issues," undated.

EXPLORATORY STUDIES FACILITY



NOTE: This is pictorial only and not drawn to scale.

Source: S.A. Simonson, "Waste Technology Issues," undated.

Slide 7 in Petrie, Edgar H. "Exploratory Shaft Facility Alternatives Study - Resumption of Design Activities." U.S. Department of Energy, Office of Civilian Radioactive Waste Management, March 7, 1991.

CANISTERS

YUCCA MOUNTAIN COUNTRYSIDE

YUCCA MOUNTAIN COUNTRYSIDE

YUCCA MOUNTAIN COUNTRYSIDE

YUCCAS AT YUCCA MOUNTAIN

YUCCA MOUNTAIN COUNTRYSIDE, METEOROLOGICAL STATION

YUCCA MOUNTAIN COUNTRYSIDE

YUCCA MOUNTAIN TUNNEL ENTRANCE, RAIL ENGINE

YUCCA MOUNTAIN EXCAVATION PILE

YUCCA MOUNTAIN ENTRANCE

YUCCA MOUNTAIN ENTRANCE

YUCCA MOUNTAIN TUNNEL

YUCCA MOUNTAIN TUNNEL

YUCCA MOUNTAIN TUNNEL

NPR IN ACTION

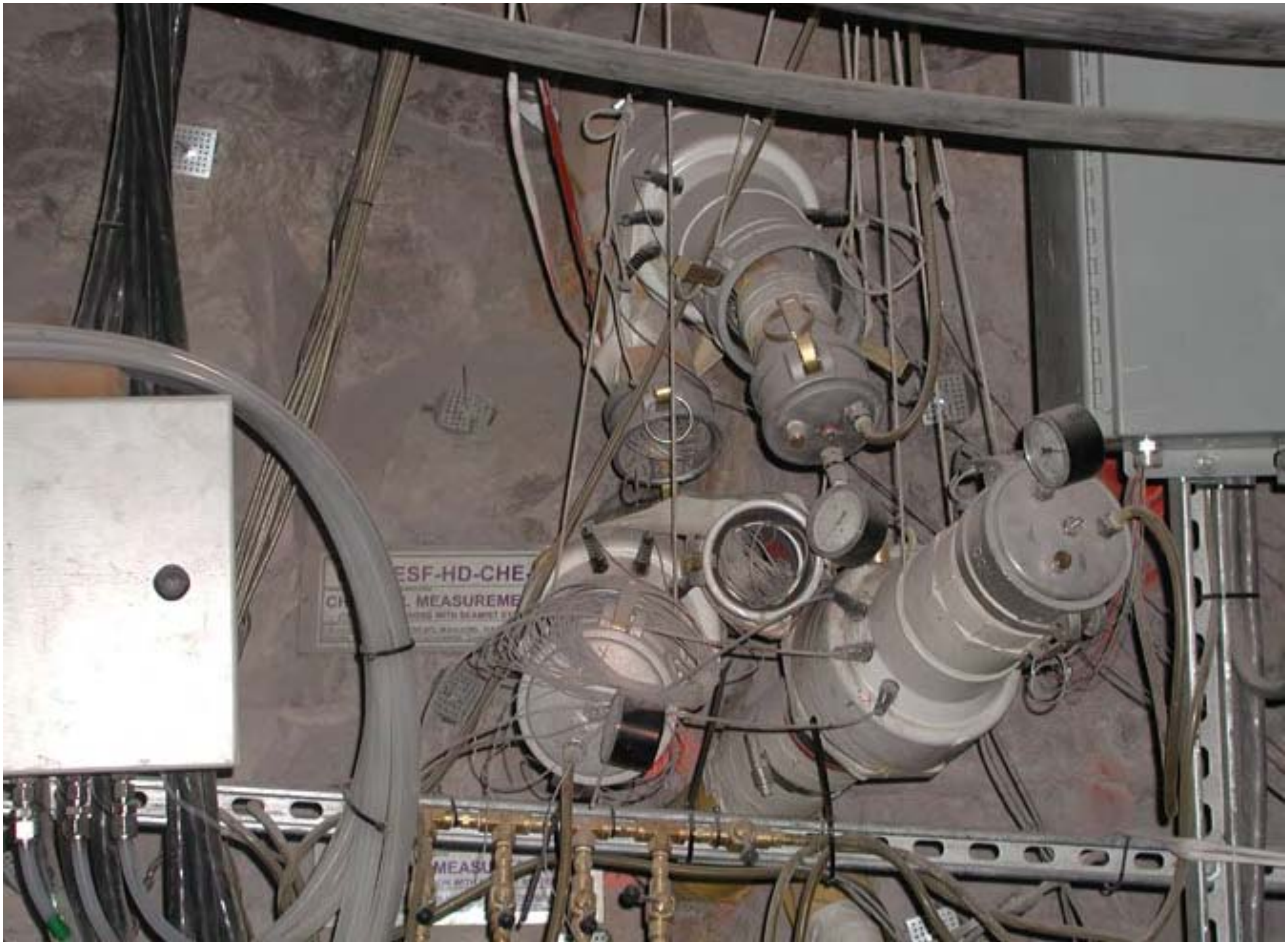
TUNNEL HEATING MEASUREMENT

TUNNEL HEATING MEASUREMENT, VISITING ENGINEER

TUNNEL HEATING MEASUREMENT

TUNNEL HEATING MEASUREMENT, THERMAL PROBES

TUNNEL HEATING MEASUREMENT, CHEMICAL PROBES



YUCCA MOUNTAIN WATER SUPPLY, SYMBOL OF FEDERAL-STATE RELATIONSHIP