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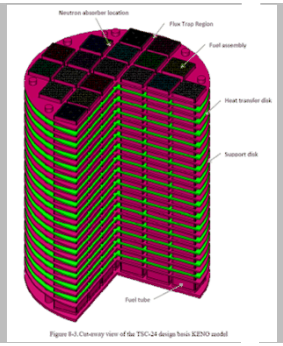

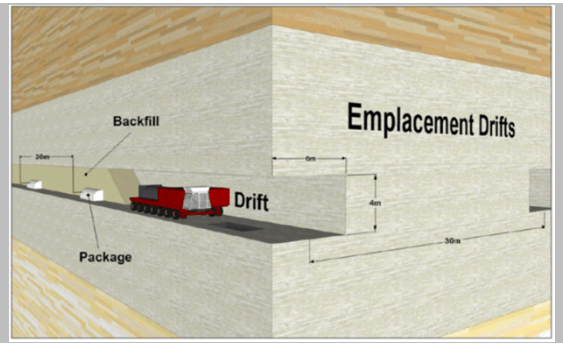

Geologic Disposal Cost Estimates in the U.S.

Ernest Hardin

IAEA Consultancy Meeting on DGR Cost Estimation Methods
October, 2016

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U.S. DEPARTMENT OF ENERGY

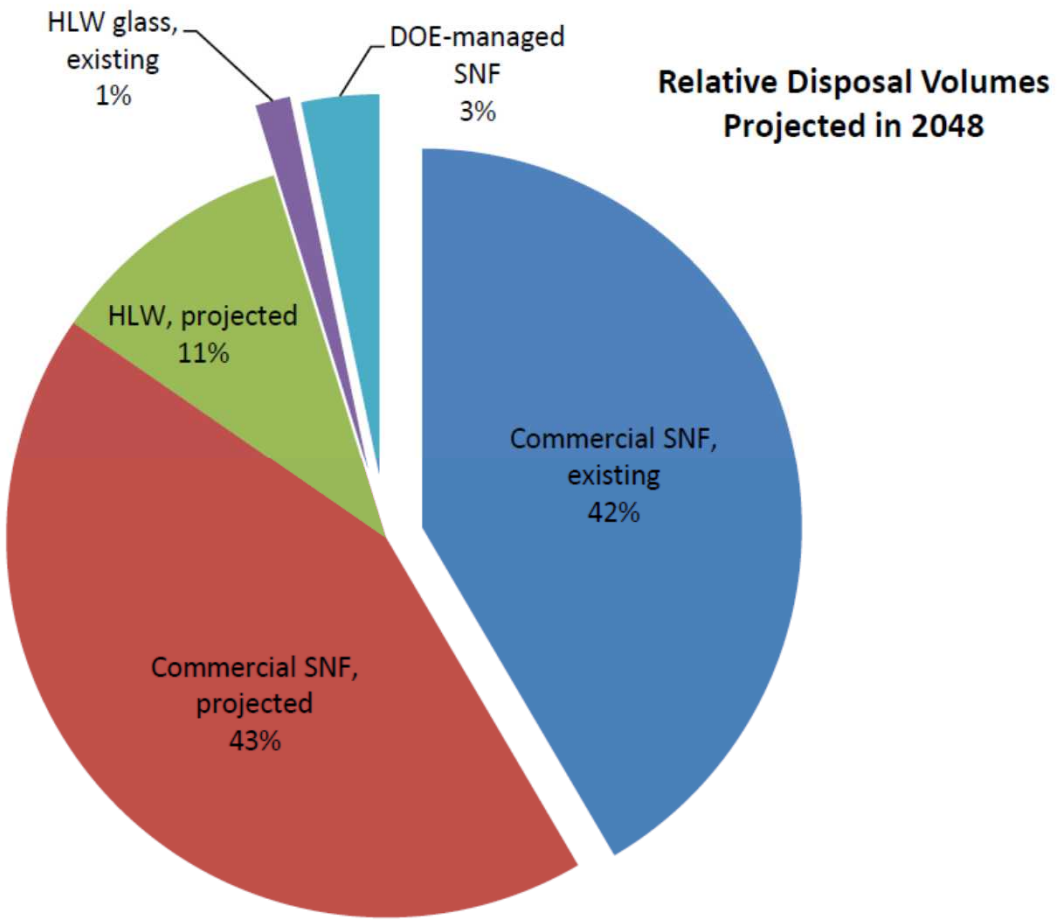
NNSA National Nuclear Security Administration

Outline

- Disposal inventories
- Estimation method
- Examples: WIPP and Yucca Mountain
- Risk/uncertainty analyses
- Funding geologic disposal activities in the U.S.
  - WIPP development
  - Yucca Mountain development
  - Yucca Mountain life cycle
- Generic disposal concept cost estimates

Total Projected U.S. SNF and HLW Inventory (2014)

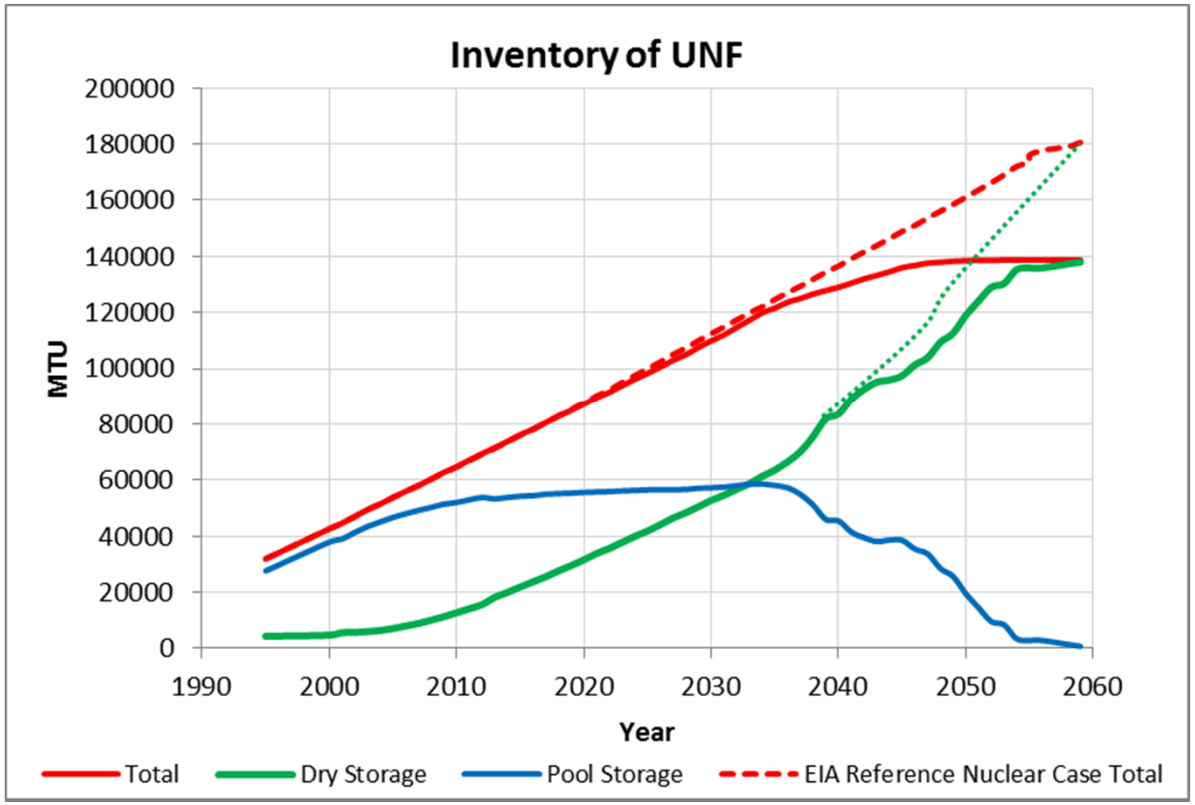
- Normalized based on estimated volume
- Assumptions
  - All commercial SNF disposed in DPC-based packages
  - Based on existing NPPs with 60-yr life extensions (140,000 MTU total)
  - Calcine waste is hot-isostatic pressed with RCRA additives
  - ~3,500 m^3 of naval SNF remains to be generated



Source: SNL (Sandia National Laboratories) 2014. *Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High- Level Radioactive Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. FCRD-UFD-2013-000371, Revision 1 (3 volumes).

Projected Commercial Spent Fuel Accumulation in the U.S.

Pool Storage and Dry Storage



- CALVIN-TSL logistics simulator (Nutt et al. 2012)
- Existing power plants with 20-year life extensions (60-yr total life)
- Burnup increase to maximum 5% enrichment
- Transfer to dry storage during operations and at reactor shutdown
- EIA reference case → Some new builds

Estimation Methods (1/5)

- **Government (Department of Energy) orders & guides***
  - Management & Operating contract model
  - Engineering/procurement/construction model
- **Engineering build-up ← Work Breakdown Structure**
- **Risk/uncertainty analysis**
  - Technology readiness level (TRL; NASA, ESA, API, et al.)
  - Contingency (typ. ±30% on engineering estimates at conceptual level)
  - Monte Carlo analysis for contingency or management reserve

* DOE G 430.1-1, *Cost Estimating Guide*

DOE Order 5700.2, *Cost Estimating, Analysis and Standardization*

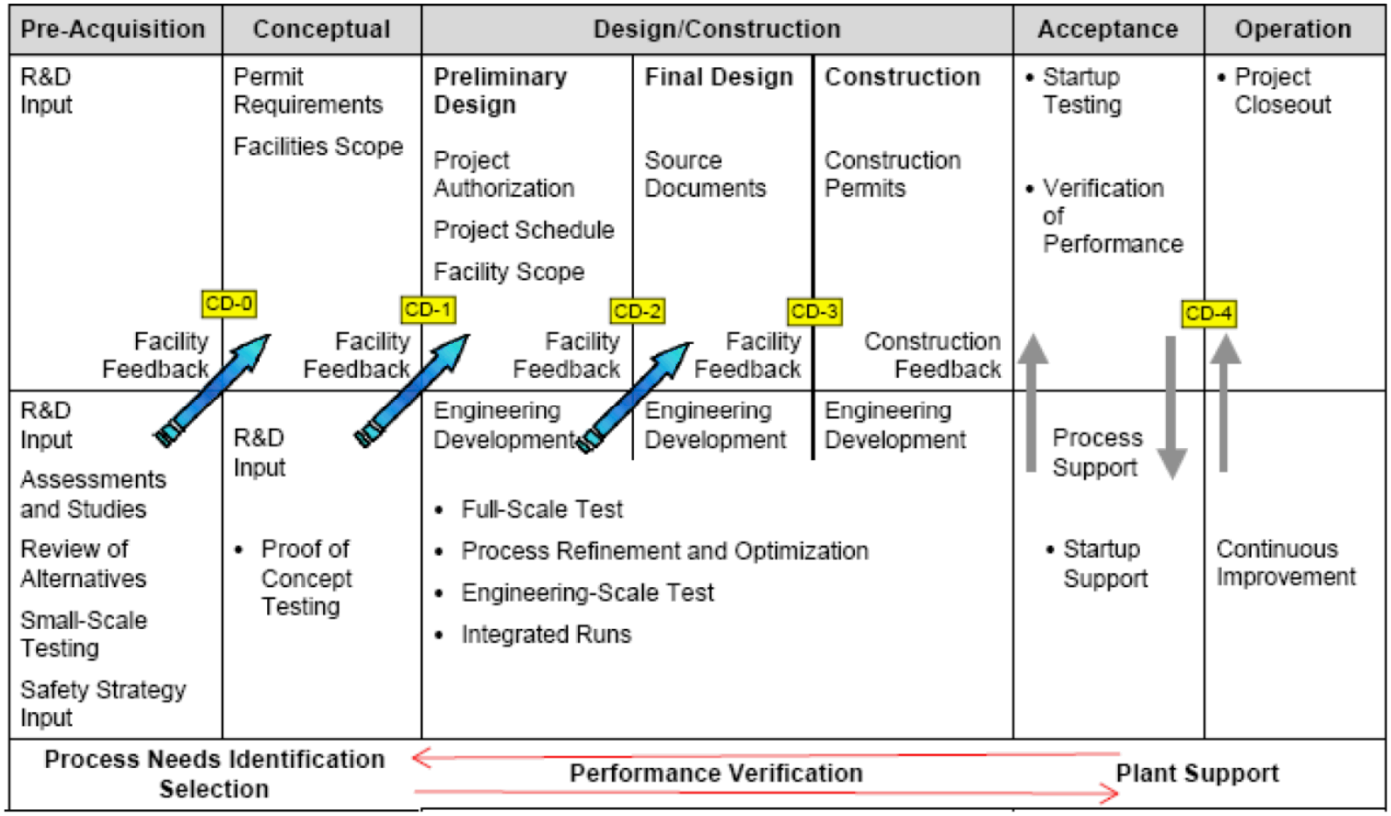
DOE Order 4700.1, *Project Management System*

DOE Order 413.3B, *Program and Project Management (PM) for the Acquisition of Capital Assets* (>$50M)

Estimation Methods (2/5)

- **Four types of cost estimates (capital projects, E-P-C):**
  - Preliminary/feasibility (support critical decision CD-0)
  - Budget/conceptual design at 10% to 15% complete (cost ±30%, CD-1)
  - Title I preliminary design at 25% to 35% complete (cost ±20%, CD-2)
  - Title II final design at 60% to 100% complete (definitive cost –5% to +15%, CD-3)

Life Cycle of a Project Phase



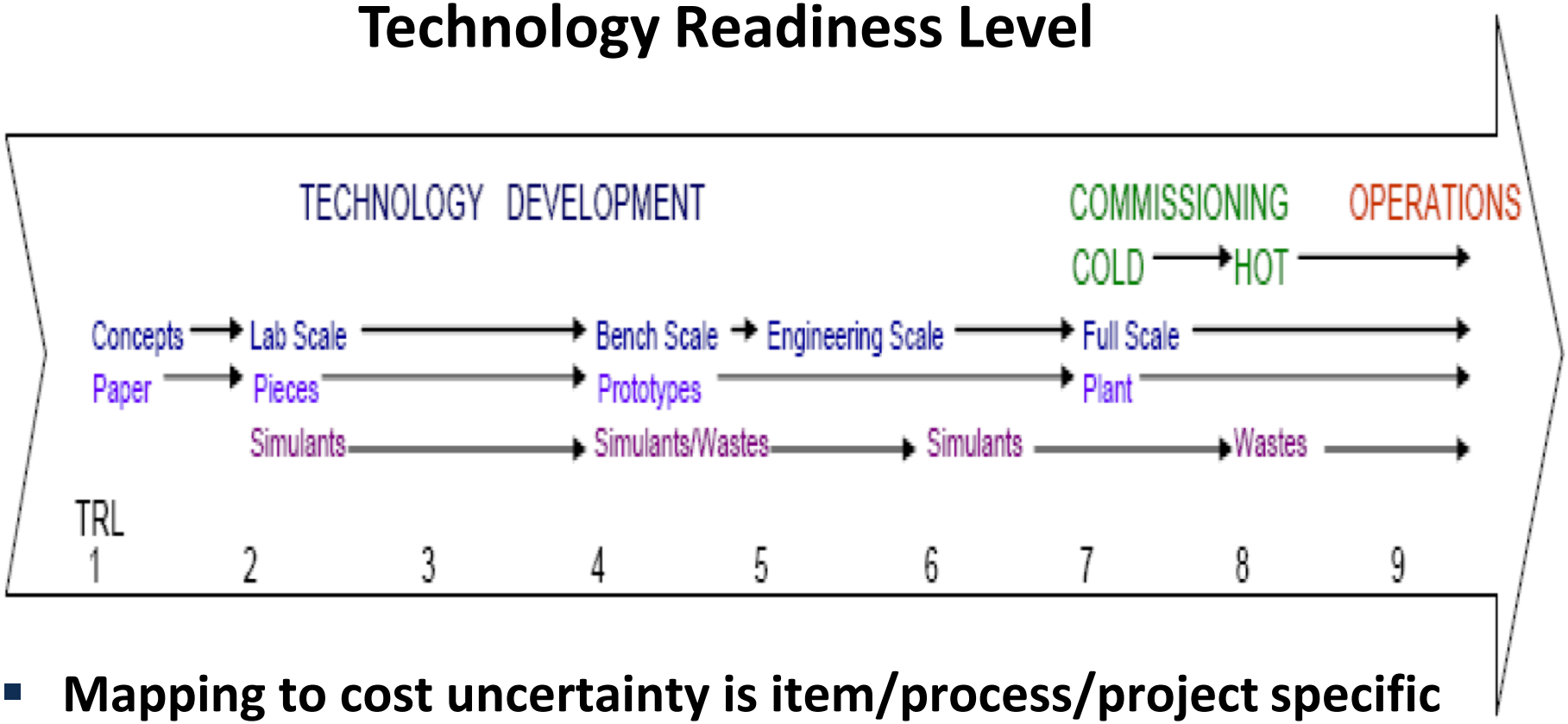
Estimation Methods (3/5)

- **Environmental management/restoration projects:**
  - **Assessment phase estimates**
    - Planning -50% to +100%
    - Preliminary -30% to +70%
    - Detailed -25% to +55%
  - **Cleanup phase estimates**
    - Planning -50% to +100%
    - Feasibility -30% to +80%
    - Preliminary -30% to +60%
    - Detailed -10% to +25%

Objective: Generate point estimates for each phase, such that these range limits are equally probable

- **More similar to geologic repository development than conventional E-P-C**
  - Historically not used for Yucca Mountain Project

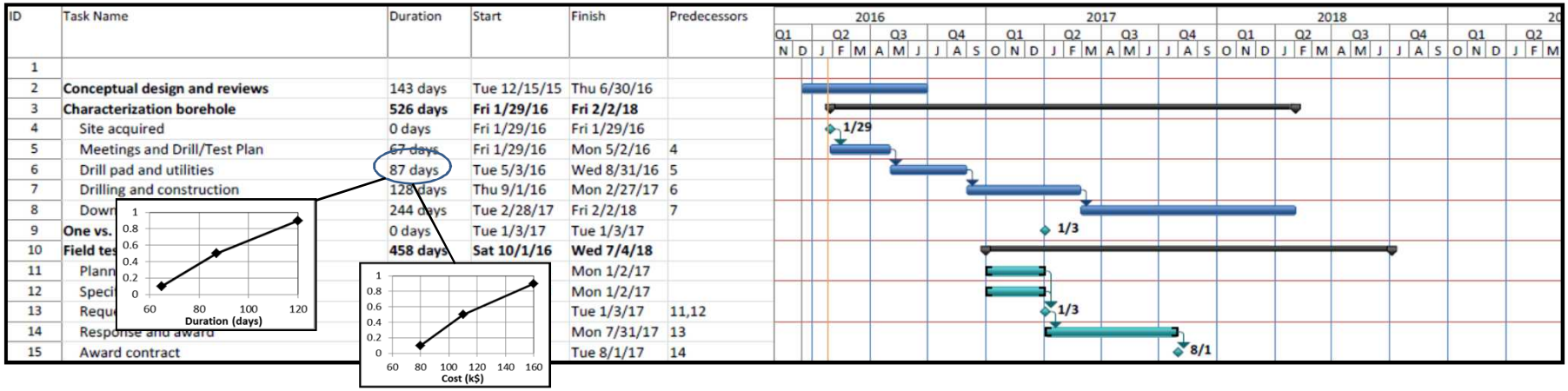
Estimation Methods (4/5)
Technology Readiness Level



- **Mapping to cost uncertainty is item/process/project specific**

Source: DOE Guide 413.2-4, *Technology Readiness Assessment Guide*

Estimation Methods (5/5)

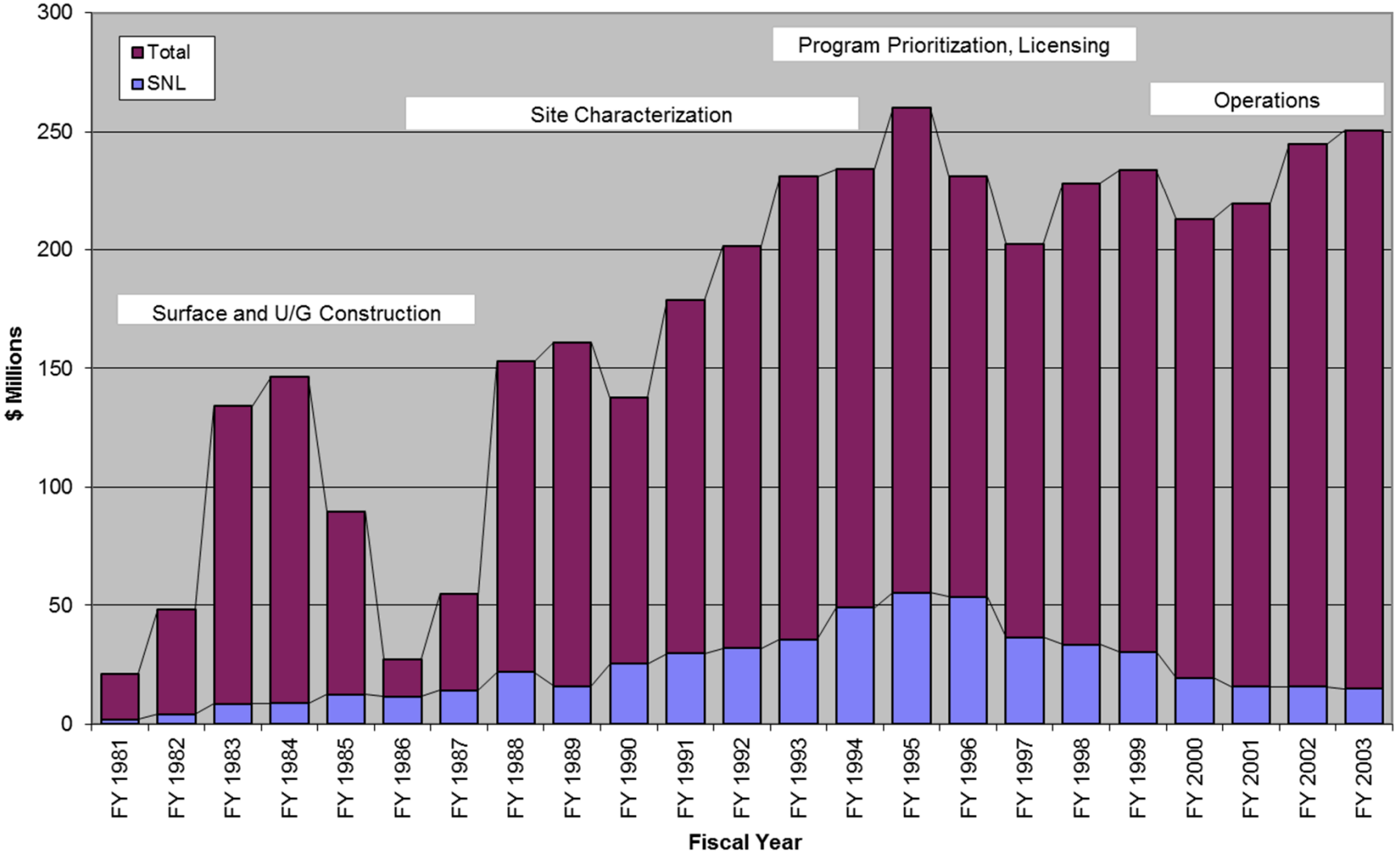


- **Monte Carlo Analysis**
  - Fully integrated schedule (all activities in internal milestones tied)
  - Resource loaded (key resource availability vs. time across all activities)
  - Budget allocated to schedule items
  - Define uncertainty functions for duration and cost, for every activity
  - Adjust WBS level for analysis, and define correlations among activities
  - Generate successive realizations of schedule/cost sampling all functions
  - Central Limit Theorem: Result converges to normal distribution
- **Example: Yucca Mountain science program ~12,000 schedule lines**

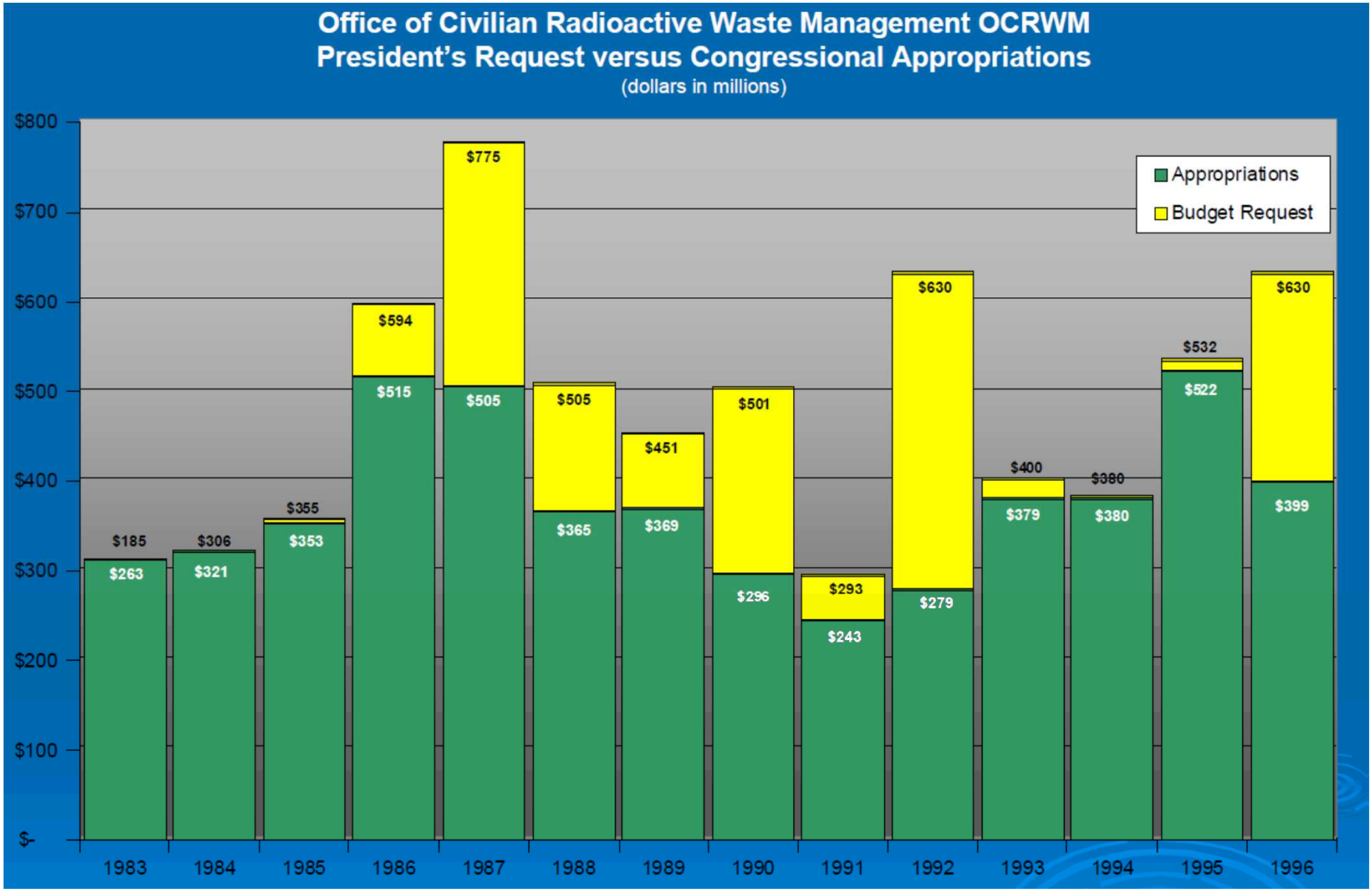
WIPP Funding History

Phases thru 5 years of disposal operations

TRU waste capacity: 175,000 m^3 Approx. cost thru 2016: $9B (2016$)



Yucca Mountain Project Development Funding (1/3)



Yucca Mountain Project Development Funding (2/3)

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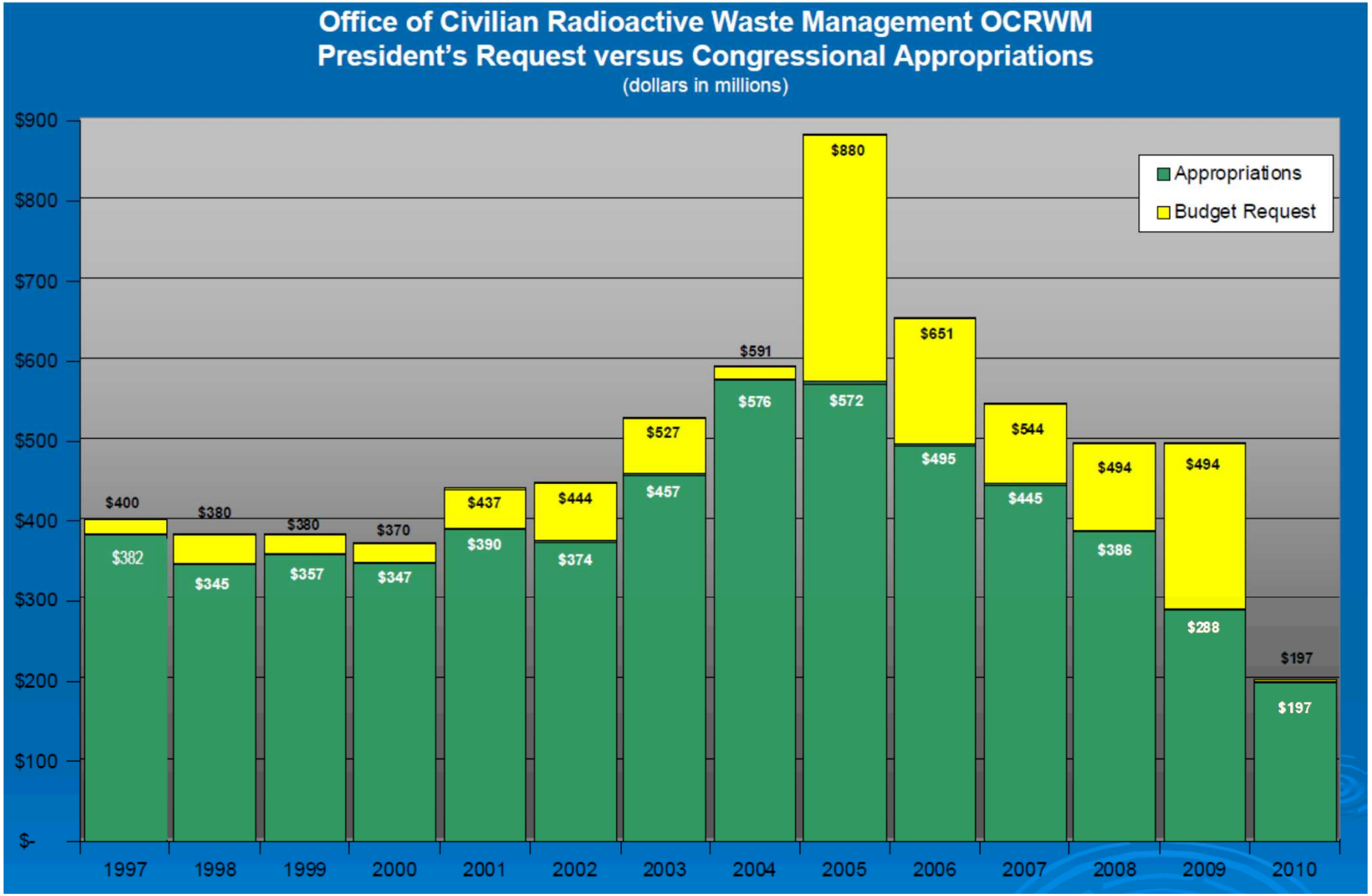

Yucca Mountain Project Development Funding (3/3)

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PROGRAM APPROPRIATIONS HISTORY (a)
NUCLEAR WASTE DISPOSAL AND DEFENSE NUCLEAR WASTE DISPOSAL APPROPRIATIONS (b)
(dollars in thousands)

	FY 1997	FY 1998	FY 1999	(e) FY 2000	(f) FY 2001	(g) FY 2002	FY 2003	FY 2004	FY 2005	(h) FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY83-FY10 Total
OCRWM (By Appropriation)															
ENERGY SUPPLY R&D, CIVILIAN WASTE R&D		-304	-151												333,962
NUCLEAR WASTE FUND APPROPRIATION	182,000	156,000	168,465	235,601	190,654	94,916	144,058	188,879	343,232	148,500	99,206	187,269	145,390	98,400	6,790,946
DEFENSE NUCLEAR WASTE APPROPRIATION	200,000	190,000	189,000	111,574	199,725	279,795	312,952	387,699	229,152	346,500	346,500	199,171	143,000	98,400	3,974,298
TOTAL (OCRWM)	**382,000**	**346,000**	**357,465**	**347,175**	**390,379**	**374,711**	**457,010**	**576,578**	**572,384**	**495,000**	**445,706**	**386,440**	**288,390**	**196,800**	**11,099,661**
NON-OCRWM															
NRC	11,000	15,000	17,000	19,150	21,600	23,650	24,738	32,905	68,498	45,657	45,826	29,025	49,000	0	452,049
NWTRB	2,531	2,600	2,600	2,600	2,900	3,100	3,179	3,158	3,152	3,572	3,591	3,621	3,811	0	44,226
NWN															
Total (NON-OCRWM)	**13,531**	**17,600**	**19,600**	**21,750**	**24,500**	**26,750**	**27,917**	**36,063**	**71,650**	**49,229**	**49,417**	**32,646**	**52,811**	**0**	**699,625**

Total appropriation $11.8B ($ in year of expenditure)

Yucca Mountain Project Development: Community Impact Funding

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- **Affected Units of Local Government^ - Oversight**
  - Initiated: 1989
  - Total to Date (actual): $119,923,319
- **State of Nevada – Oversight**
  - Initiated: 1983
  - Total to Date (actual): $97,616,609
- **Payments Equal to Taxes**
  - Initiated: 1983
  - Total to Date (actual): $146,991,657
- **Nevada System of Higher Education**
  - Initiated: 1984
  - Total to Date (actual): $124,046,990
- **Clark County , NV Transportation Grant**
  - Initiated: 2004
  - Total to Date (actual): $2,000,000
- **Inyo County, CA (Death Valley Regional Ground Water Monitoring Program**
  - Initiated: 2002
  - Total to Date (actual): $4,450,000
- **Nye County, NV Science & Verification Program**
  - Initiated: 1996
  - Total to Date (actual): $31,416,868
- **Nye County, NV Cooperative Agreement**
  - Initiated: 2004
  - Total to Date (actual): $430,000

Total Funding to AULGs, the State of Nevada, affected Tribes, the Nevada System of Higher Education, and other financial and technical assistance since 1983: $526,875,443.

*The AULGs are the ten counties designated "affected" by the Secretary of Energy in accordance with the Nuclear Waste Policy Act.

U.S. Nuclear Waste Fund Status

Sandia National Laboratories

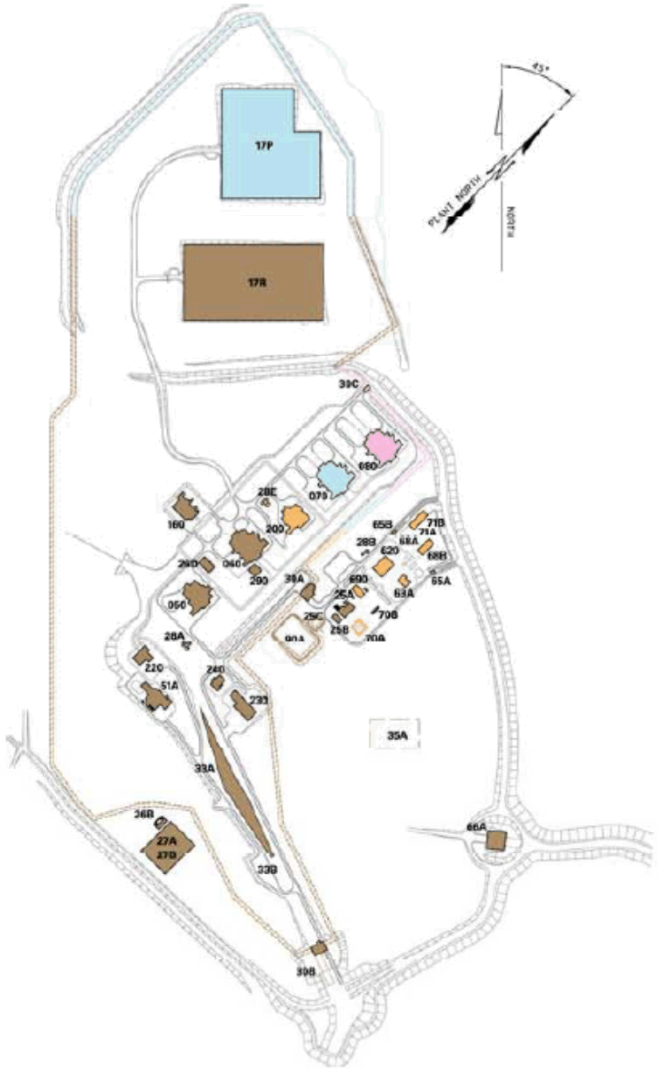
Nuclear Waste Fund Income Sources and Disbursements[1]

Nuclear Waste Fund Income Sources (dollars in thousands)

	Spent Nuclear Fuel Fees			Defense Fees	Treasury Loan				
Fiscal Year	One-Mil Fees [2,4]	One-Time Fees [2]	Cumulative Fees[2]	High-Level Waste Fees [2]	Principal (Payment)	Investment Returns[3,5]	Total Annual Income	Annual Disbursements[6]	NWF Balance
1983	74	0	74	0	254	0	327	178	149
1984	330	0	404	0	5	0	334	276	207
1985	367	1,427	2,198	0	-258	-74	1,462	316	1,353
1986	362	6	2,566	0	0	73	441	399	1,395
1987	435	6	3,007	0	0	89	530	469	1,456
1988	498	6	3,511	0	0	165	669	402	1,723
1989	513	6	4,030	0	0	196	715	349	2,089
1990	570	6	4,606	0	0	161	737	337	2,489
1991	594	6	5,206	5	0	241	846	322	3,013
1992	560	6	5,772	8	0	268	842	350	3,505
1993	466	11	6,249	0	0	296	773	294	3,984
1994	418	4	6,671	0	0	210	632	310	4,306
1995	615	0	7,286	0	0	246	861	408	4,759
1996	633	1	7,920	0	0	212	846	209	5,396
1997	596	0	8,516	0	0	471	1,067	159	6,304
1998	600	0	9,116	0	0	743	1,343	211	7,436
1999	662	0	9,778	0	0	106	768	175	8,029
2000	702	0	10,480	0	0	883	1,585	289	9,325
2001	689	0	11,169	0	0	1,243	1,932	199	11,058
2002	712	0	11,881	0	0	1,862	2,574	120	13,512
2003	731	0	12,612	0	0	446	1,177	154	14,535
2004	732	0	13,344	0	0	1,315	2,047	193	16,389
2005	736	0	14,080	0	0	1,178	1,914	324	17,979
2006	752	0	14,832	0	0	542	1,294	192	19,081
2007	754	0	15,586	0	0	794	1,548	236	20,393
2008	763	0	16,349	0	0	1,117	1,880	226	22,047
2009	770		17,119			1,054	1,824	223	23,648
FY10 thru 1/31/2010	327					391	718	90	24,276
Cum-to-date	15,961	1,485	17,446	13	0	14,228	31,686	7,410	24,276
Forecast for End of FY 2010	769	0	17,118	0	0	1,172	1,941	220	25,369

Hardin, E.L., Geologic Disposal Cost Estimates (SAND2016-*****)

Yucca Mountain Total Cost Summary (1/3)



LEGEND			
Initial Operating Capability			
Phase 1			
050	Wet Handling Facility	26D	Emergency Diesel Generator Facility
060	Canister Receipt and Closure Facility 1	27A	Switchyard (138kV)
51A	Initial Handling Facility	27B	13.8kV Switchgear Facility
17R	Aging Pad R	28A	Fire Water Facility
160	Low-Level Waste Facility	28B	Fire Water Facility
220	Heavy Equipment Maintenance Facility	30A	Central Security Station
230	Warehouse and Non-Nuclear Receipt Facility	30B	Cask Receipt Security Station
240	Central Control Center Facility	33A	Rail Car Buffer Area
25A	Utility Facility	33B	Truck Buffer Area
25B	Cooling Tower	35A	Septic Tank and Leach Field
25C	Evaporation Pond	66A	Helicopter Pad
20B	Standby Diesel Generator Facility	290	Aging Overpack Staging Facility
90A	Storm Water Retention Pond		
Full Operating Capability			
Phase 2			
200	Receipt Facility	68B	Materials/Yard Storage
28E	Fire Water Facility	690	Vehicle Maintenance and Motor Pool
620	Administration Facility	70A	Diesel Fuel Oil Storage
63A	Fire, Rescue and Medical Facility	70B	Fueling Stations
65A	Administration Security Station	71A	Craft Shops
65B	Administration Security Station	71B	Equipment/Yard Storage
68A	Warehouse/Central Receiving		
Phase 3			
070	Canister Receipt and Closure Facility 2	17P	Aging Pad P
Phase 4			
080	Canister Receipt and Closure Facility 3	30C	North Perimeter Security Station

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Figure 2-2. Primary Repository Surface Facilities

Yucca Mountain Total Cost Summary (2/3)

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Table 2-3. Repository Engineering, Procurement, and Construction Costs (in Millions of 2007$)

Cost Element	Historical Costs (2003 – 2006)	Future Costs (2007 – 2053)	Total Costs (2003 – 2053)
Licensi			40
Surface			50
Waste			40

Table 2-4. Repository Operations Costs (in Millions of 2007$)

Cost Element	Future Costs (2017 – 2073)

Table 2-1. Repository Costs by Phase (in Millions of 2007$)

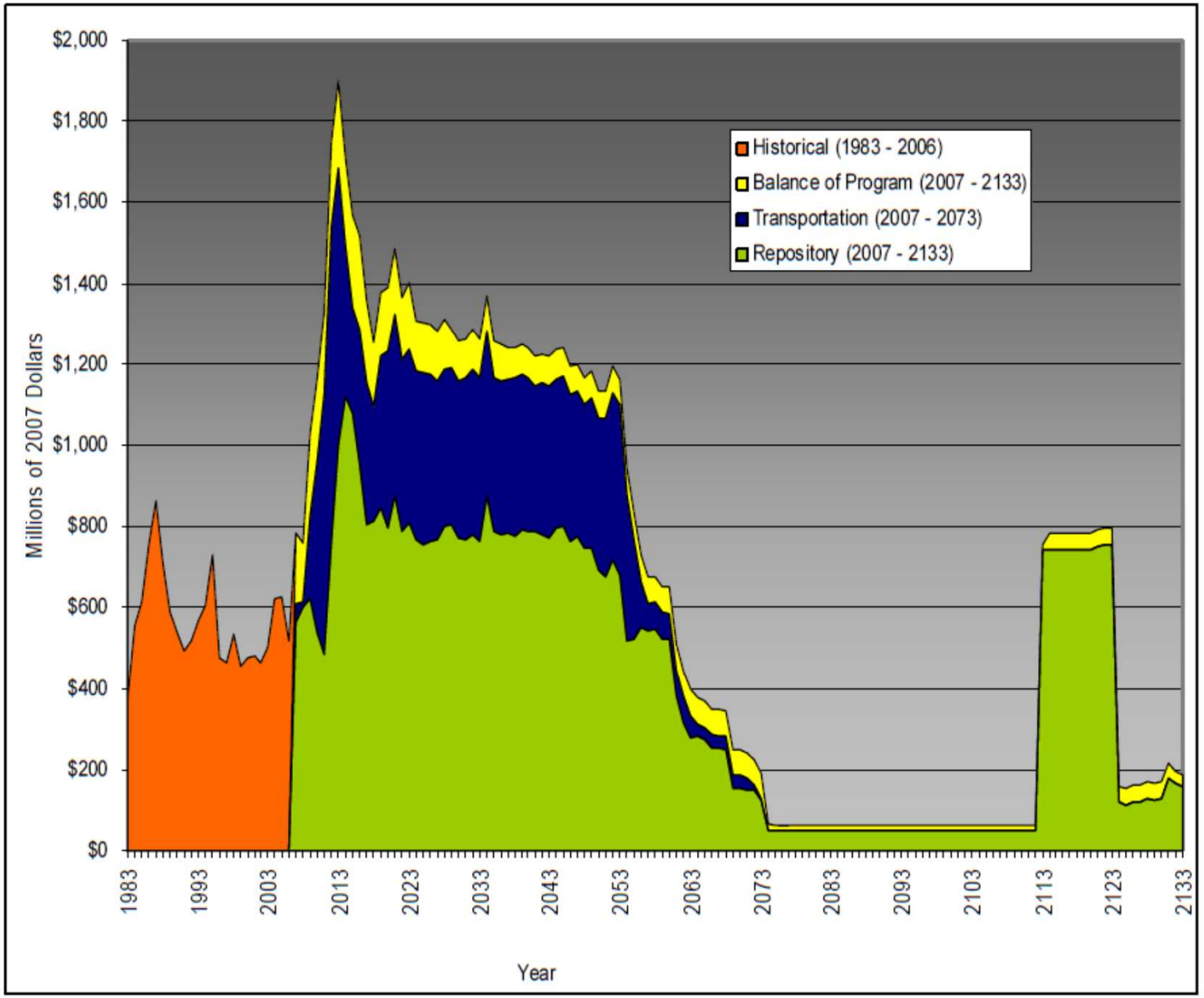
Cost Element	Historical (1983 – 2006)	Future Costs (2007 – 2133)	Total Costs (1983 – 2133)
Development & Evaluation (1983 – 2002)	8,330	0	8,330
Engineering, Procurement & Construction (2003 – 2053)	1,580	16,550	18,130

Table 1-1. Summary of the 2007 TSLCC Estimate – 2007 Dollars (in Millions of 2007$)

Cost Element	Historical Costs (1983 – 2006)	Future Costs (2007 – 2133)	Total Costs (1983 – 2133)
Repository	9,910	54,820	64,730
Transportation	780	19,480	20,250
Balance of Program	2,860	8,340	11,200
Total	**13,540**	**82,640**	**96,180**

NOTE: Row and column totals may not add due to rounding.

Yucca Mountain Total Cost Summary (3/3)



Cost Estimates for Disposal of U.S. Commercial SNF (1/2)

Generic (non-site specific) Cost Analysis

# Waste Packages Required		4-PWR/9- or 12-BWR	12-PWR/ 21-BWR	21-PWR/ 44-BWR	DPC Direct
"Enclosed"					
Crystalline	Based on KBS-3V (SKB 2011)	**82,583**	(Note 1)	(Note 2)	(Note 2)
Argillaceous	Based on ANDRA (2005) (for SNF in horiz. boreholes)	**82,583**	(Note 1)	(Note 2)	(Note 2)
	Based on NAGRA (2002, 2003) (for in-drift, self-shielded pkgs, with immediate backfilling)	(Note 3)	**28,792**	(Note 2)	(Note 2)
Salt	U.S. reference (in-drift)	**82,583**	**28,792**	**16,157**	**~10,000**
"Open"					
Hard Rock (e.g., Crystalline)	Unsaturated, unbackfilled, open (YM concept, DOE 2008a)	(Note 4)	**28,792**	**16,157**	**~10,000**
	Saturated, backfilled, open	(Note 4)	**28,792**	**16,157**	**~10,000**
Argillaceous	Backfilled, open	(Note 4)	**28,792**	**16,157**	**~10,000**

Notes:

1. T_{peak}> 100°C; canister handling problematic for borehole emplacement.
2. T_{peak}>> 100°C.
3. Assume cost is similar to borehole emplacement.
4. Open-mode ventilation not needed to meet thermal goals (use enclosed concepts).

Cost Estimates for Disposal of U.S. Commercial SNF (2/2)

Total Inventory 140,000 MTU Range ~200 to 800 k$/MTU

Estimated Life-Cycle Repository Cost (2016 $B)		4-PWR/9- or 12-BWR	12-PWR/ 21-BWR	21-PWR/ 44-BWR	DPC Direct
"Enclosed"					
Crystalline	Based on KBS-3V (SKB 2011)	**$63 – 85B**			
Argillaceous	Based on ANDRA (2005) (for SNF in horiz. boreholes)	**$83 – 116B**			
	Based on NAGRA (2002, 2003) (for in-drift, self-shielded pkgs, with immediate backfilling)		**$51 – 69B**		
Salt	U.S. reference (in-drift)	**$44 – 60B**	**$30 – 42B**	**$25 – 34B**	**$32 – 44B**
"Open"					
Hard Rock (e.g., Crystalline)	Unsaturated, unbackfilled, open (YM concept, DOE 2008)		**$60 – 80B**	**$44 – 59B**	**$44 – 59B**
	Saturated, backfilled, open		**$57 – 76B**	**$42 – 57B**	**$40 – 54B**
Argillaceous	Backfilled, open		**$60 – 81B**	**$46 – 62B**	**$44 – 60B**

Sources:

Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1)*. SAND2016-0235.

SRNL (Savannah River National Lab) 2015. *Generic Repository Cost Estimates.* FCRD-UFD-2015-000740 Rev. 0.