



Lifecycle Waste Disposal and Decommissioning Costs for ARIES Systems Code

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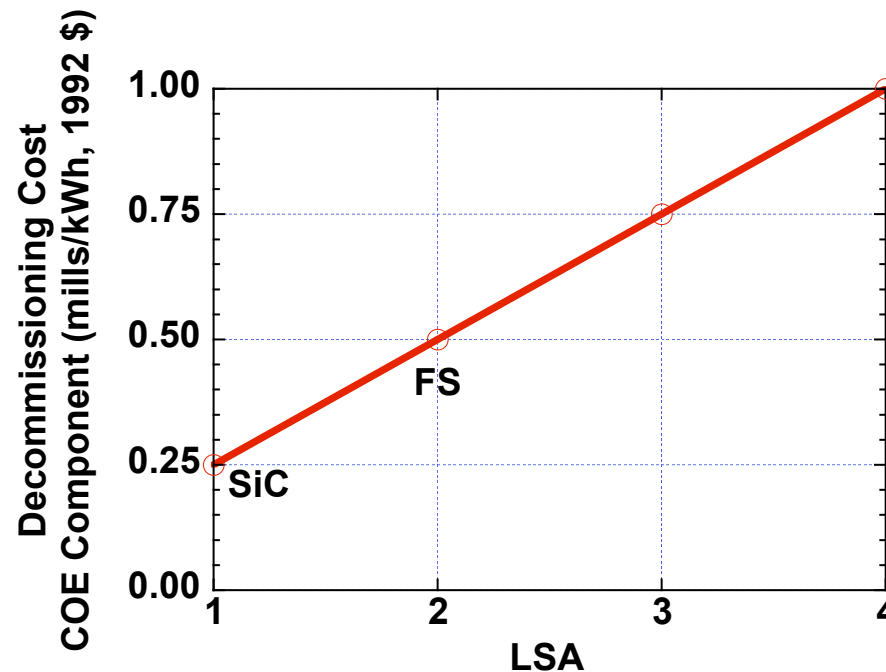


Options for Radwaste Management

- Disposal in space – not feasible
- Ice-sheet disposal @ north/south pole – not feasible
- **Seabed disposal** (coming back by MIT)
- **Geological disposal** (preferred US option over past 50 y. Before 1980, NRC did not look at back-end of fuel cycle when considering environmental impact statement for reactor applications.)
- **Transmutation of long-lived radionuclides** ($\Rightarrow$ proliferation concerns)
- **Recycling / reprocessing** (reuse within nuclear industry)
- **Clearance** (release to commercial market if materials are slightly radioactive)

Background Info

- All fusion **materials are carefully chosen** to minimize long-lived radioactive products (e.g., low-activation ferritic steel (FS), vanadium, and SiC structures).
- ARIES System Code (ASC) considers 0.25 – 1 mill/kWh for decommissioning cost, depending on LSA factor.
- Decommissioning cost accounts for decontamination, dismantling, and radwaste management (**disposal**, recycling, and/or clearance).



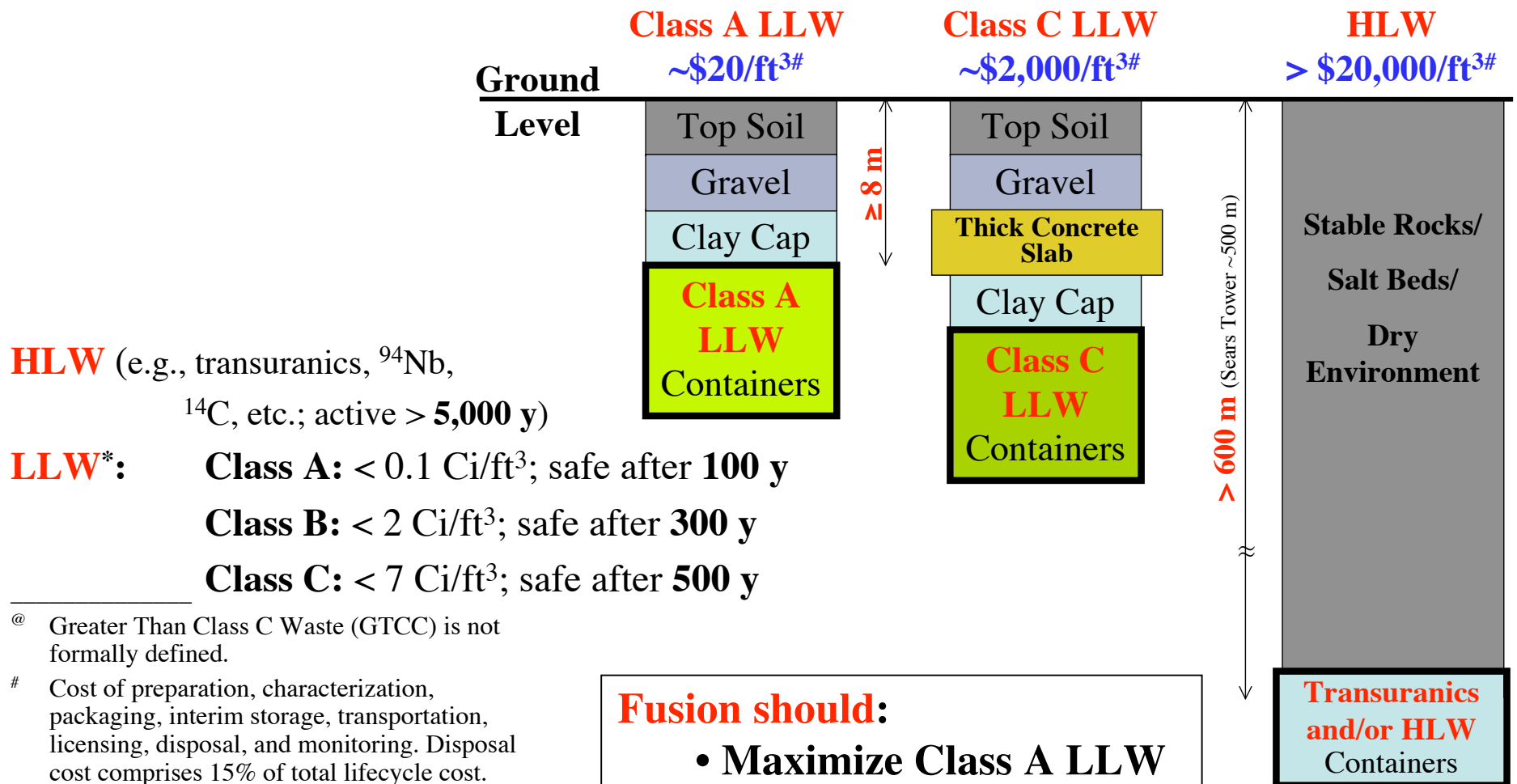


Waste Lifecycle Cost (commercial values; 2003 \$)

- It includes costs of:
 - Waste preparation
 - Characterization
 - Packaging
 - Interim storage
 - Transportation
 - Licensing
 - **Disposal**
 - Monitoring.
- **Disposal** cost:
 - Comprises 15% of total lifecycle cost
 - Has gone up substantially over past several years
 - Vary somewhat based on location of disposal site and nature of Class C wastes.
- HLW* disposal cost is big unknown.
- **Waste lifecycle costs:** \$20 \$/ft³ for **Class A LLW**
2,000 \$/ft³ for **Class C LLW**
> 20,000 \$/ft³ for **HLW***.
- **DOE costs** are higher than commercial costs by 3-5 fold for everything DOE does (construct buildings, tear down buildings, labor multiplier of 3x, etc.).

* HLW legal definition: spent fission fuel and residues of treatment of spent fission fuel. In fusion designs, HLW is used for components with Waste Disposal Rating > 1. This may include the Greater Than Class C (GTCC) waste – not formally defined yet by NRC.

NRC Classification of LLW and HLW[@]



[@] Greater Than Class C Waste (GTCC) is not formally defined.

Cost of preparation, characterization, packaging, interim storage, transportation, licensing, disposal, and monitoring. Disposal cost comprises 15% of total lifecycle cost. Yucca Mountain HLW repository lifecycle cost estimates: \$8B in 1983; \$57B in 2001; \$70B in 2007.

* From fusion, research labs, hospitals, food irradiation facilities, etc.

Status of Geological Disposal

- Worldwide operational, commercial repositories:

	US	Europe	Japan
LLW	3	6	1
HLW	---	---	---

- Currently, LLW represents ~ 90% of radwaste volume
- Several states tried to develop new disposal sites, but changed their mind because of strong opposition from public and environmentalists
- At present, many US utilities store LLW and HLW on site because of limited and/or expensive offsite disposal options
- US needs national solution for LLW and HLW disposal problems.



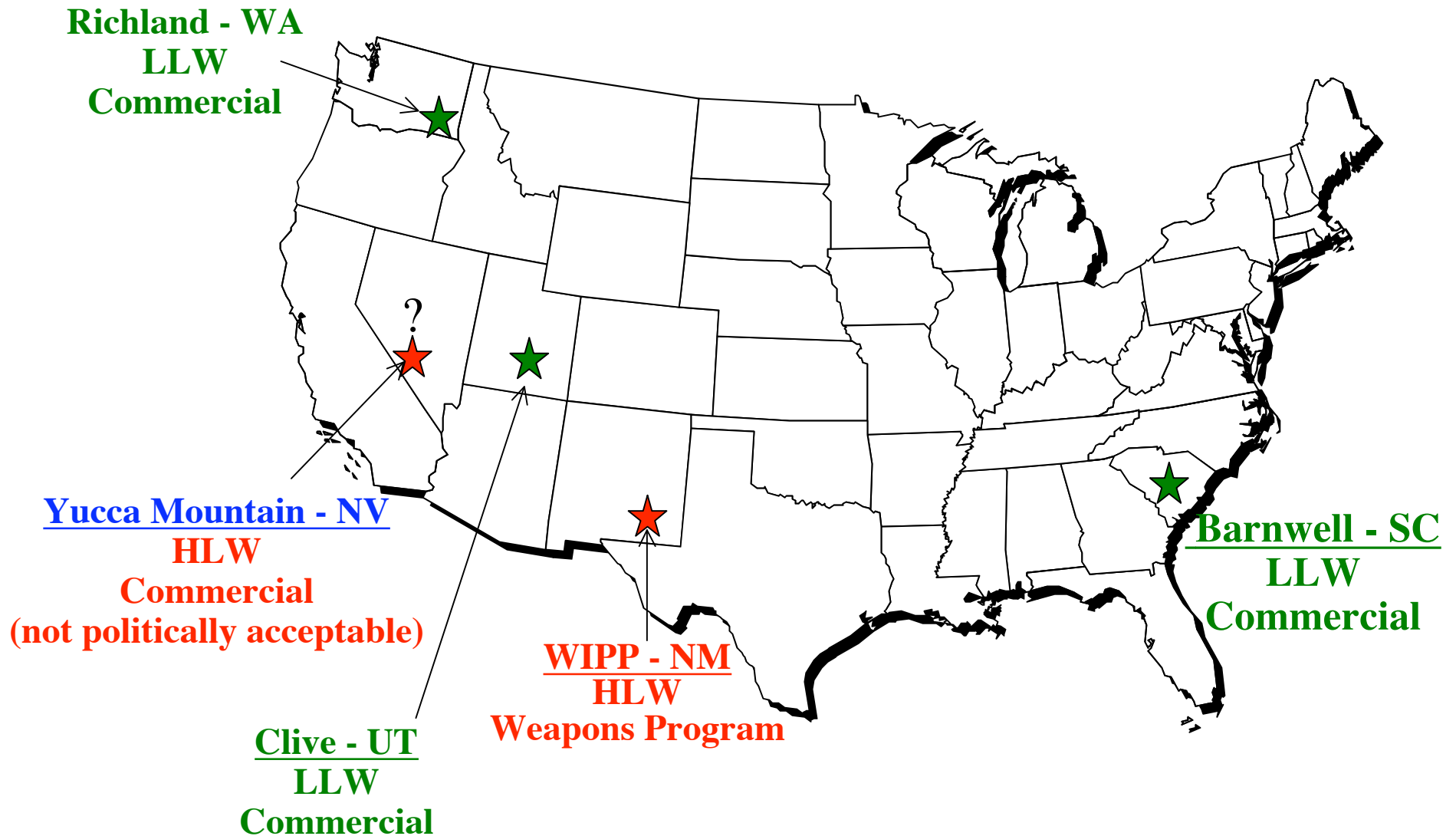
US Commercial LLW Repositories

- **Barnwell facility** in SC:
 - 1971 – 2038.
 - Receives Class A, B, C LLW from outside compact.
 - Supports east-coast reactors and hospitals.
 - 1000,000 m³ capacity ⇒ can accommodate 125 fusion power plants.
 - **90% Full.**
 - In July 2008, Barnwell will limit amount of LLW received from outside compact*.
 - 36 states will lose access to Barnwell in July 08, having no place to dispose 91% of their Class B & C LLW.
- **Richland facility** in WA:
 - Class C LLW.
 - Supports 11 northwest states.
 - 125,000 m³ capacity ⇒ can accommodate 15 fusion power plants.
- **Clive facility** in Utah:
 - Receives nationwide Class A LLW only.
 - Disposes 98% of U.S. Class A waste volume, but does not accept sealed sources or biological tissue waste – a great concern for biotech industry.

* “Time is Running out for a Permanent LLW Solution,” Nuclear News (Dec 2004).

N. Zacha, “Low-Level Radioactive Waste Disposal: Are We Having a Crisis Yet?,” Nuclear News August 2007).

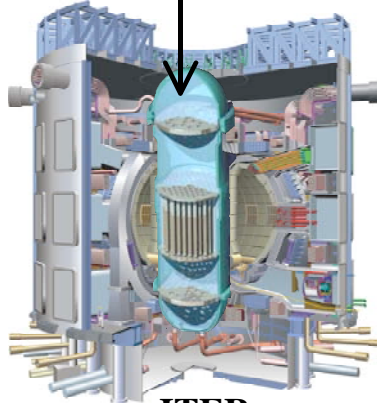
4-5 Large-Scale Repositories in US: 3 for LLW & 1-2 for HLW



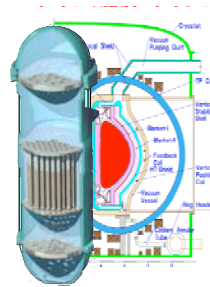


Fission – Fusion Power Core Comparison

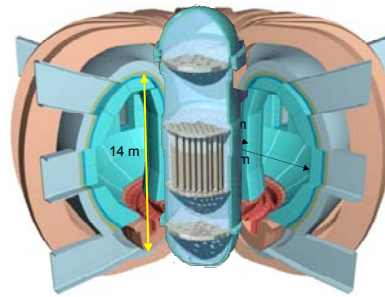
ESBWR Vessel
(7 m ID, 28 m H)



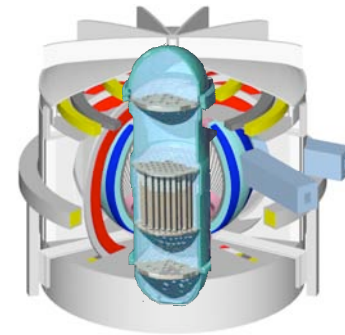
ITER



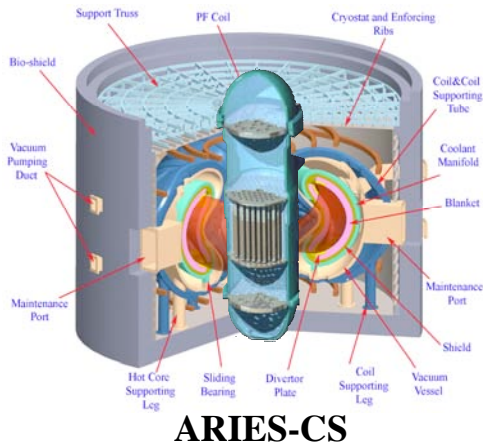
ARIES-AT



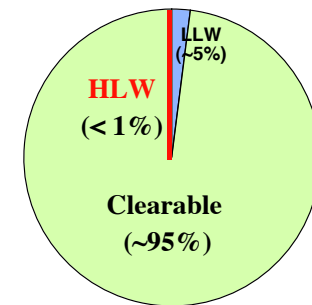
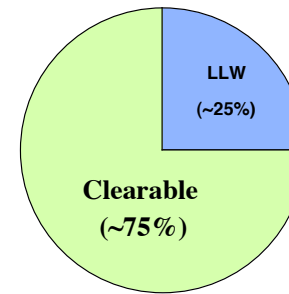
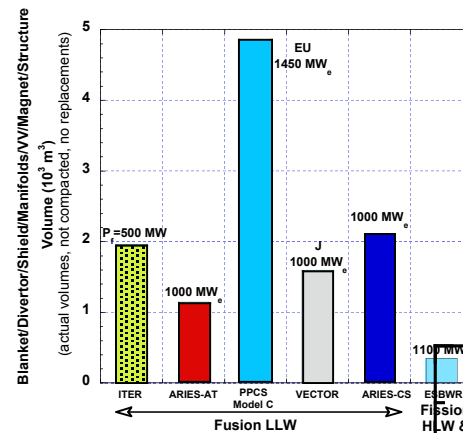
PPCS
Europe



VECTOR
Japan



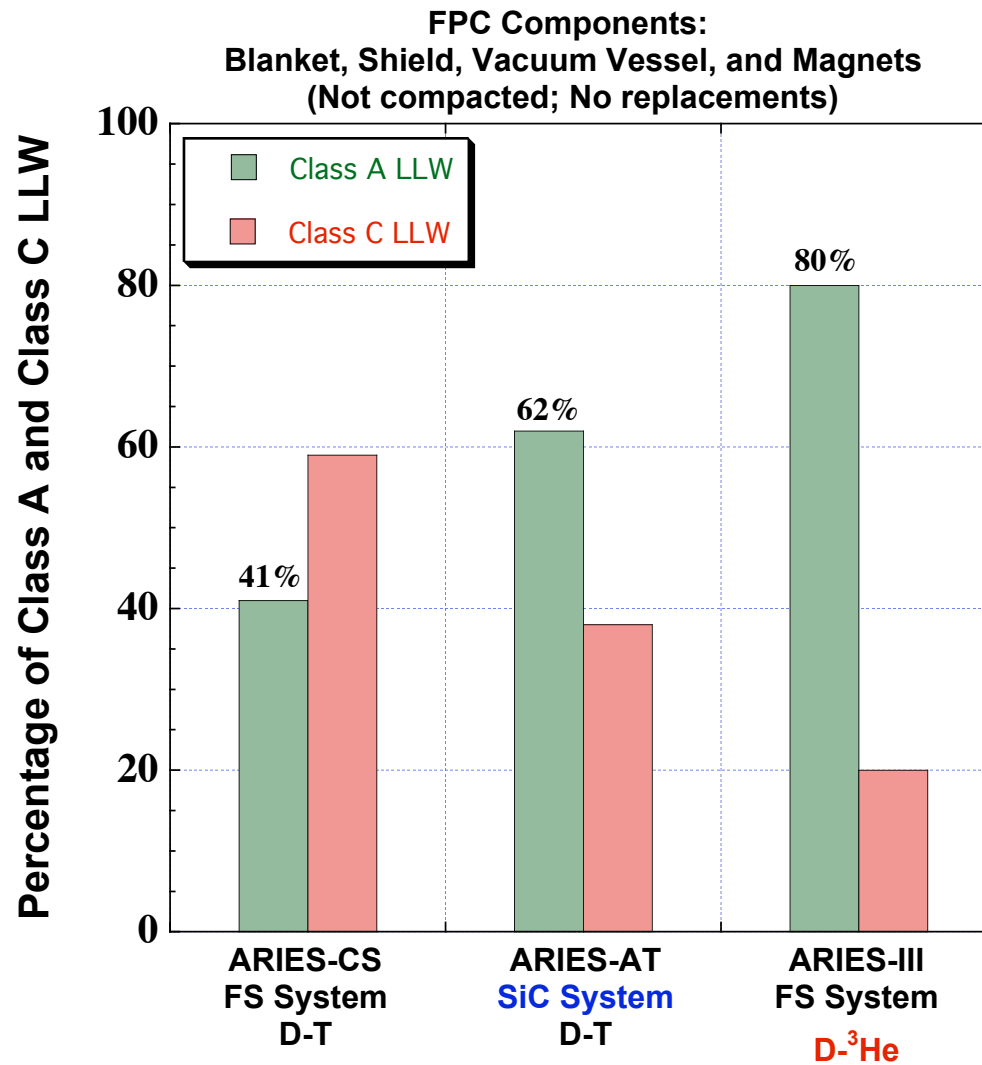
ARIES-CS



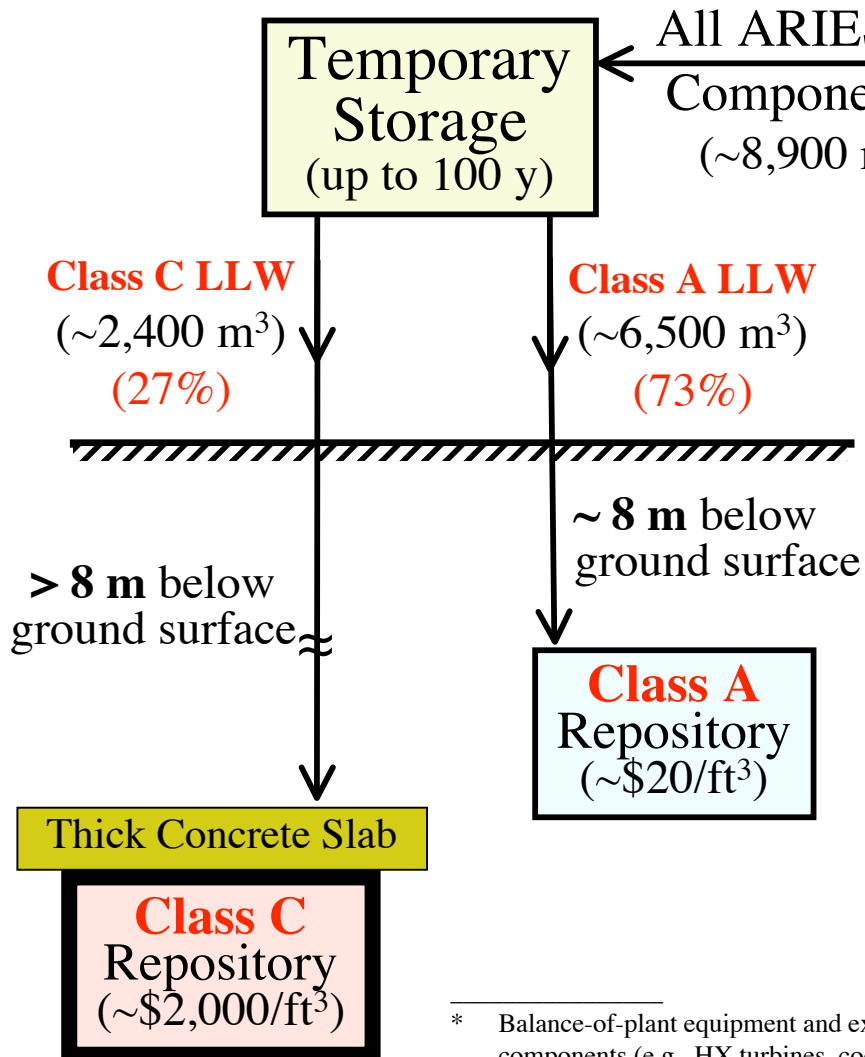
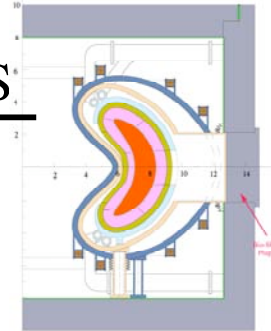
Fusion **Fission**

← All components, including shield →

Fusion Generates Only LLW



ARIES-CS LLW Classification for Geological Disposal



* Balance-of-plant equipment and external components (e.g., HX, turbines, cooling towers, etc.) not included.

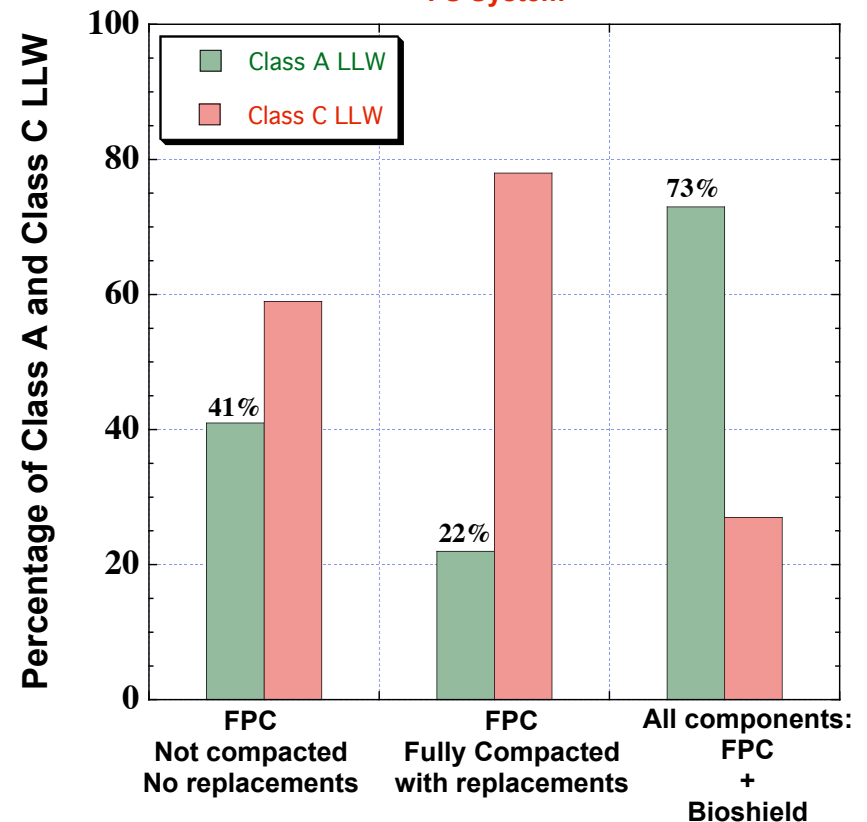
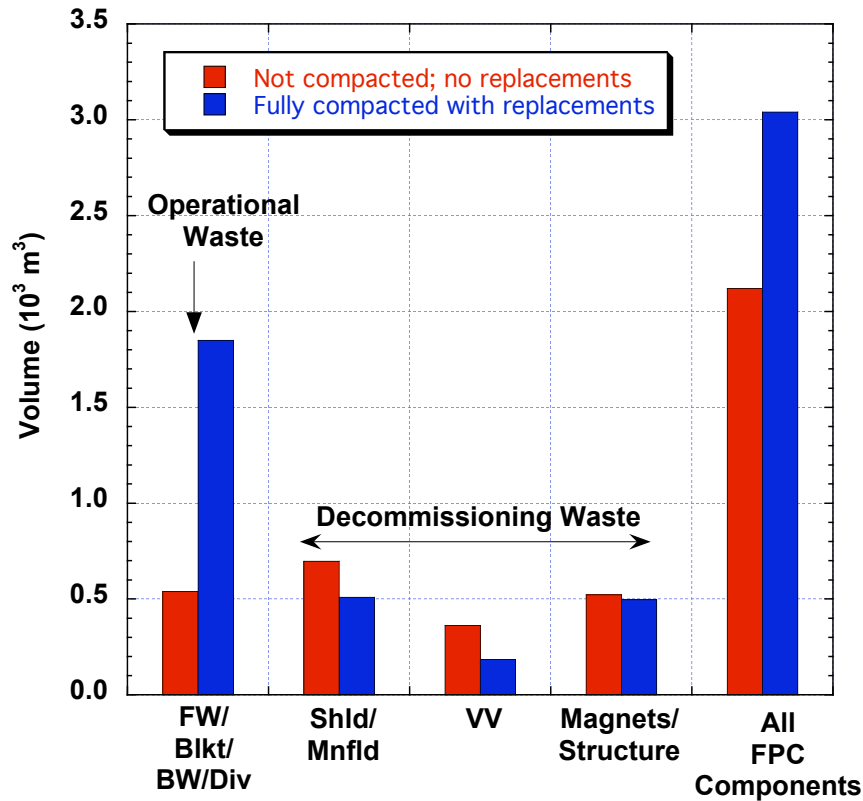
Least Hazardous
Type of Waste

	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	✓		no
Shield/Manifolds	✓		no
Vacuum Vessel		✓	no
Magnet:			
Nb ₃ Sn	✓		no
Cu Stabilizer		✓	✓
JK2LB Steel*		✓	✓
Insulator		✓	✓
Cryostat		✓	✓
Bioshield		✓	✓

* Preferred over Incoloy-908 for clearance considerations.

Breakdown of ARIES-CS LLW

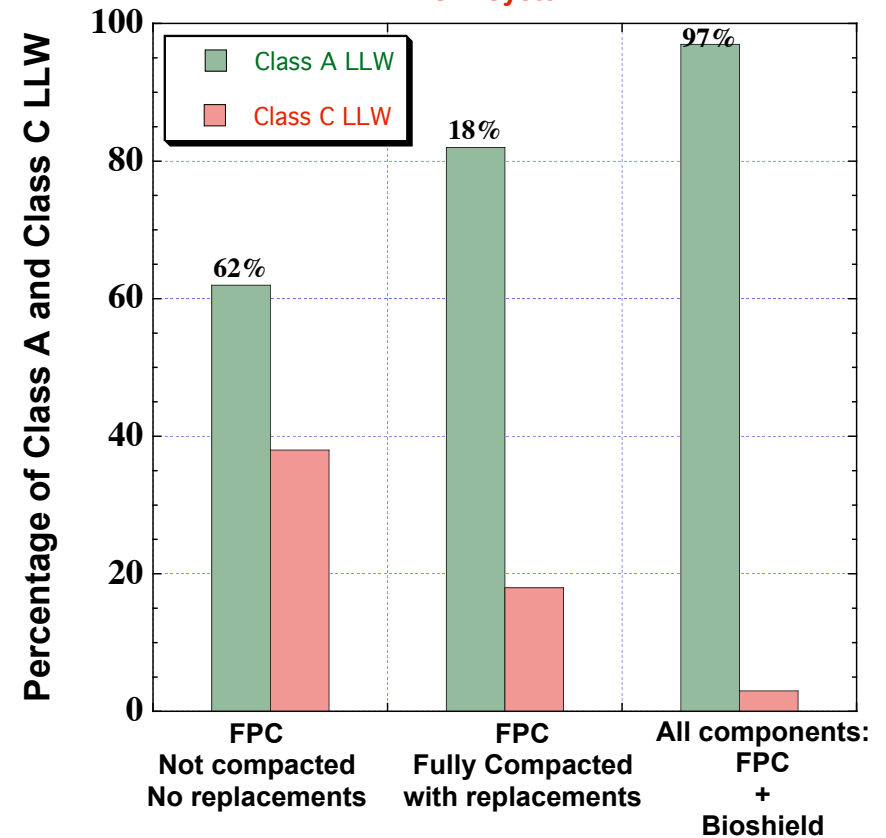
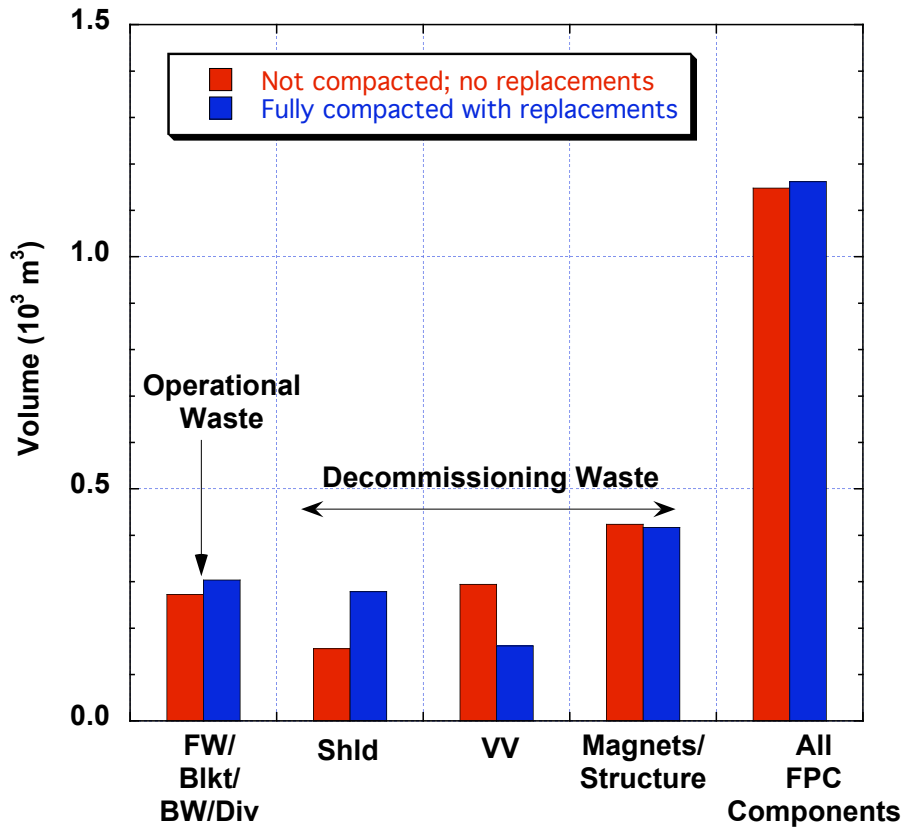
ARIES-CS
FS System



63 cm thick LiPb/He/FS blanket
Not segmented

Breakdown of ARIES-AT LLW

ARIES-AT
SiC System



75 cm thick OB LiPb/SiC blanket
Two segments: 30 & 45 cm



Decommissioning Project

- Starts at end of plant operational life to reduce amount of radioactive materials at site and ensure public health and safety as well as protection of environment.
- Project may take 6-10 y to complete, depending on plant size.
- Procedures include:
 - Detailed timeline
 - Type and magnitude of contaminants (waste volume, type, level, etc.)
 - Dismantling process: cutting, removal of components and equipment, and size reduction
 - Decontamination process: removal of contaminated materials from facility and shipping to waste processing facility, storage, or disposal site
 - **Radwaste management** (disposal*, recycling, and/or clearance. Preparation, characterization, packaging, interim storage, transportation, licensing, disposal, and monitoring).
- Applications submitted to NRC for license to operate new plant should include decommissioning funding plans:
 - Demonstrating detailed and financial plans for decommissioning before beginning of construction
 - Setting aside decommissioning funds (outside licensee's control) **from day one** of plant operation. This is included in all costing codes as "Decommissioning Cost" – a component of COE.

* Disposal cost of operational waste (from replaceable components) should be added to O&M annual funds, not to decommissioning bank account.



ARIES-CS Waste Lifecycle Cost (all Components: FPC + Bioshield)

	Class A LLW	Class C LLW	Total
Radwaste Volume:			
m ³	6,500	2,400	9,800
ft ³	2.3 x 10 ⁵ (73%)	8.4 x 10 ⁴ (27%)	3.1 x 10 ⁵
Waste Lifecycle Cost (\$M):	5 (@ \$20/ft ³)	170 (@ \$2000/ft ³)	175
Annual Cost[#] (\$M/y)			3.7
COE Component* (mills/kWh)			0.5
Decommissioning Cost* (mills/kWh):			> 0.5 (0.5 in ASC for LSA=2)

**For FS system, waste lifecycle cost is dominated by
Class C LLW disposal cost (27% of total volume)**

[#] per 47 y (40 FPY with 85% availability).

* Annual cost (\$/y) = COE (mills/kwh) x 8760 (h/y) x Availability (decimal fraction) x P_e (MW_e).



ARIES-AT Waste Lifecycle Cost (all Components: FPC + Bioshield)

	Class A LLW	Class C LLW	Total
Radwaste Volume:			
m ³	7,900	210	8,110
ft ³	2.8 x 10 ⁵ (97%)	7.3 x 10 ³ (3%)	3.1 x 10 ⁵
Waste Lifecycle Cost (\$M):	6 (@ \$20/ft ³)	15 (@ \$2000/ft ³)	21
Annual Cost[#] (\$M/y)			0.45
COE Component* (mills/kWh)			0.06
Decommissioning Cost* (mills/kWh):			>> 0.06 (0.25 in ASC for LSA=1)

For SiC system, waste lifecycle cost is relatively small.
Disposal cost for Class C LLW (3% of total volume) is 70% of total cost.

[#] per 47 y (40 FPY with 85% availability).

* Annual cost (\$/y) = COE (mills/kwh) x 8760 (h/y) x Availability (decimal fraction) x P_e (MW_e).



Decommissioning Cost

- Decommissioning fund covers costs of:
 - Dismantling, decontamination, and radwaste management (300-400 \$M)
 - Site restoration: returning the site to condition agreed upon with NRC for either restricted or unrestricted use (~ \$50M).
- Size of fund should be adjusted periodically to account for changes in:
 - Cost of labor
 - Cost of energy
 - Cost of LLW disposal
 - New specifications in regulations
 - Technological advancements.
- Decommissioning fund varies with:
 - Plant size and type
 - Geological location: local labor and waste burial costs
 - Specific processes and methods used for decommissioning.



Decommissioning Cost (Cont.)

Fission Examples:

Trend:

	BWR	PWR
P_e (MW _e)	1100	1100
Location	Midwestern Region	Western Region
D cost* (2004 \$M)	465	280

Actual Cases:

	Big Rock Point	Yankee Rowe	Fort St. Vrain	Haddam Neck	Maine Yankee	Rancho Seco	Trojan
P_e (MW _e)	67	175	330	619	830	913	1130
	BWR	PWR	HT Gas	PWR	PWR	PWR	PWR
Location	Michigan	Massachusetts	Colorado	Connecticut	Maine	California	Oregon
D cost (\$M)	290	306	189	345 + 82 [#] = 427	325 + 53 [#] = 378	441	252 + 110 [#] = 362
	(1997 \$)	(1995 \$)	(1990 \$)	(1996 \$)	(1997 \$)	(1995 \$)	(1993 \$)

* Costs are reduced by using waste vendor to reduce volume of radioactive waste requiring disposal

[#] Spent fuel storage cost. Present fleet of US nuke plants assigns 1 mill/kWh for spent fuel disposal.
Yucca Mountain HLW repository lifecycle cost estimates: \$8B in 1983; \$57B in 2001; \$70B in 2007.



Recommended ARIES Decommissioning Cost

- Scaling from NRC data for fission plants:

D cost (2004 \$)	300 – 400 \$M w/o spent fuel*
Annual cost (for 47 y plant with 85% availability)	6.4 – 8.5 \$M
COE component	0.9 – 1.2 mills/kWh
- Fission waste w/o spent fuel: ~95% Class A and ~5% Class C with close similarity to fusion SiC-based System.
- D cost for ARIES-SiC could be around 1 mill/kWh.
- Adding ~0.5 mills/kWh (difference between fusion FS and SiC disposal costs)
D cost for fusion FS system could be ~1.5 mills/kWh.

* Present fleet of US nuke plants assigns 1 mill/kWh for spent fuel disposal.

Yucca Mountain HLW repository lifecycle cost estimates: \$8B in 1983; \$57B in 2001; \$70B in 2007.



Recommended ARIES Decommissioning Cost (Cont.)

- At present, ASC assigns 0.25 and 0.5 mills/kWh (1992 \$) for LSA=1 and LSA=2 D costs, respectively.
- It is reasonable to consider:
 - 1 mill/kWh for SiC-based system with LSA=1
 - 1.5 mill/kWh for FS-based system with LSA=2
- These 2004 \$ values should be updated frequently to reflect changes to D cost.
- In practice, disposal cost of operational waste (from replaceable components) should be added to O&M annual funds, not to decommissioning bank account.

