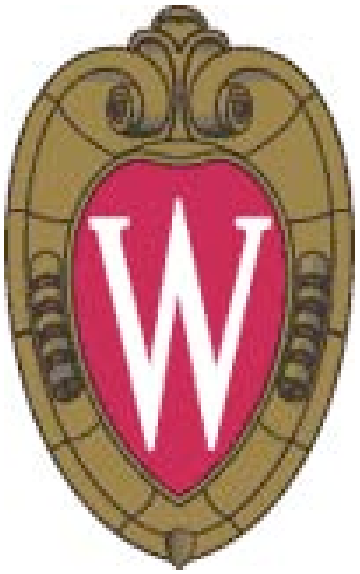

Lifecycle Waste Disposal and Decommissioning Costs for ARIES Systems Code

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ARIES-Pathways Project Meeting

May 28-29, 2008

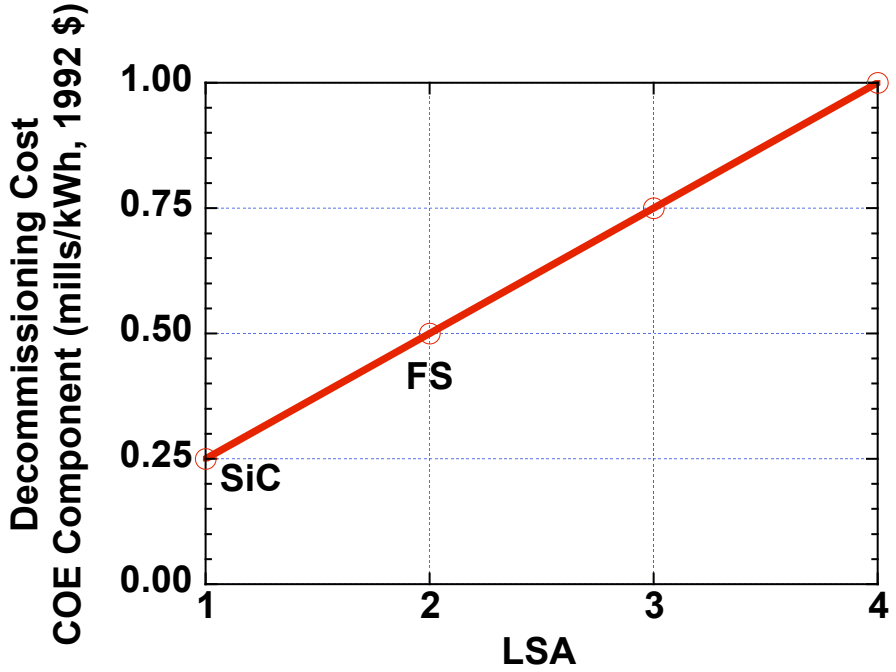
UW-Madison

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** (⇒ 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).

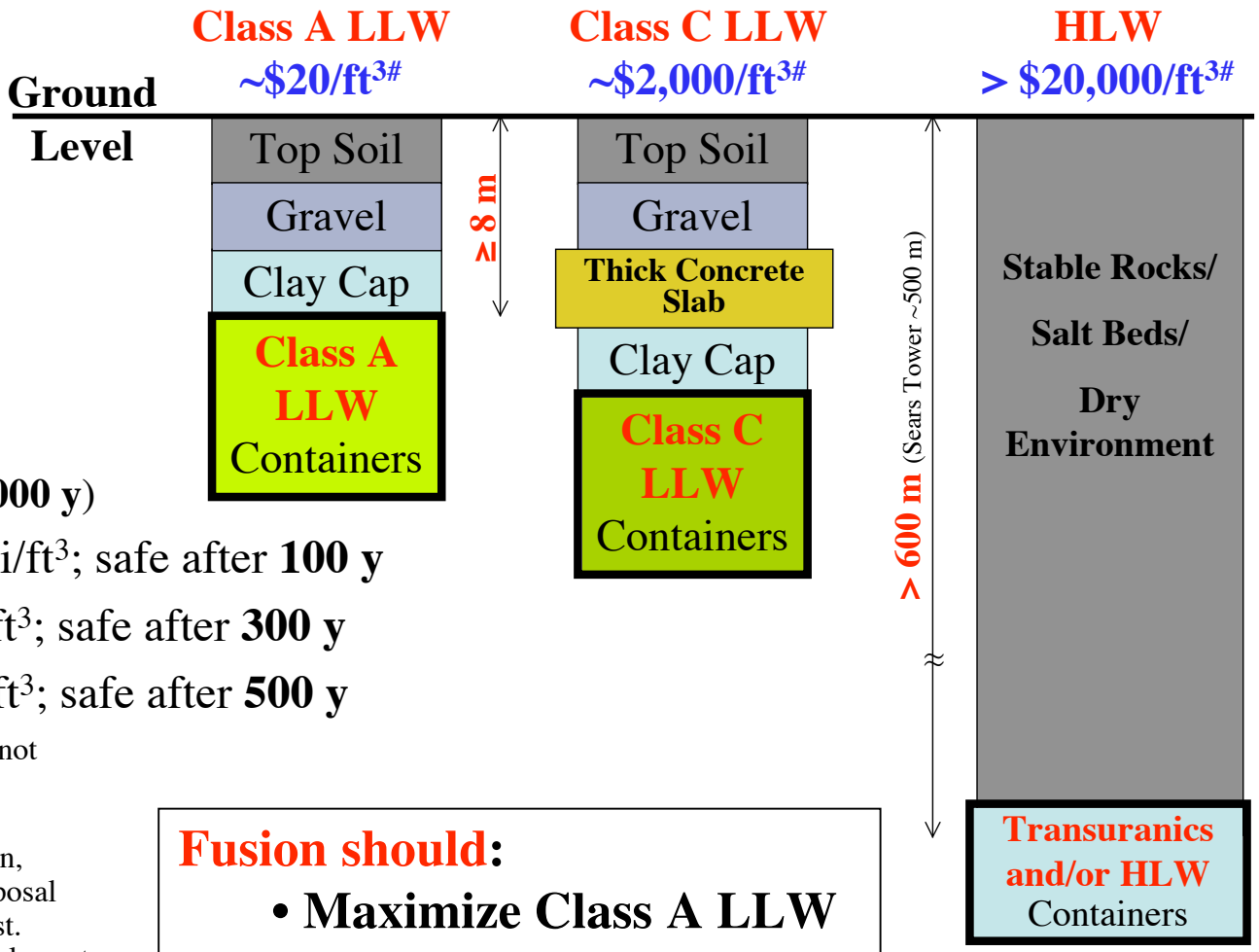


Waste Lifecycle Cost (commercial values; 2003 $)

- 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 \$/ft^3 for **Class A** LLW
  2,000 \$/ft^3 for **Class C** LLW
  > 20,000 \$/ft^3 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@



HLW (e.g., transuranics, ^{94}Nb, ^{14}C, etc.; active > **5,000 y**)

LLW*:

- **Class A:** < 0.1 Ci/ft^3; safe after **100 y**
- **Class B:** < 2 Ci/ft^3; safe after **300 y**
- **Class C:** < 7 Ci/ft^3; safe after **500 y**

Fusion should:

- **Maximize Class A LLW**
- **Minimize Class C LLW**
- **Avoid 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: $**8**B in 1983; $**57**B in 2001; $**70**B in 2007.

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

Status of Geological Disposal

- **Worldwide operational, <u>commercial</u> 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 m^3 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 m^3 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.

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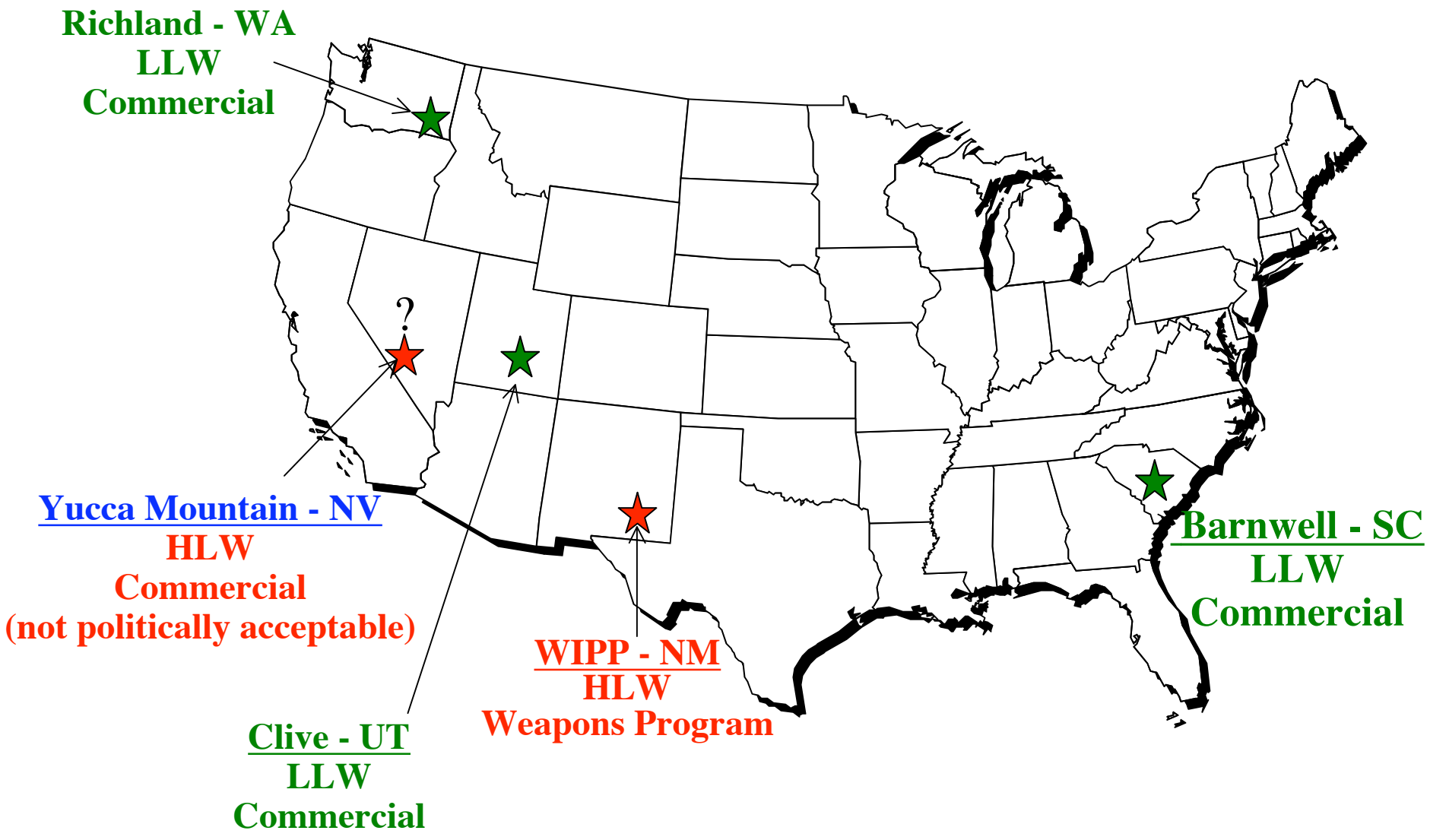
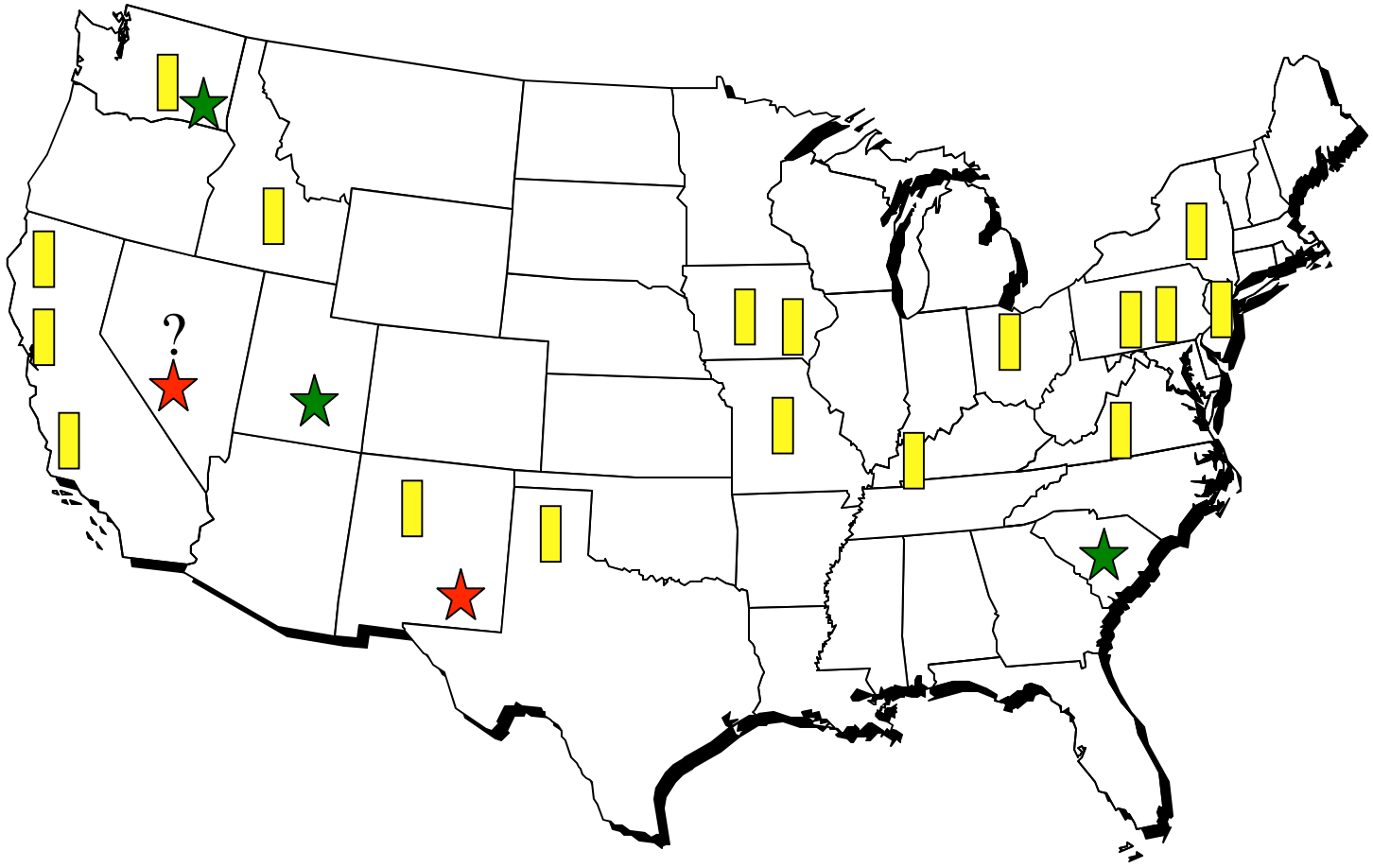
* "Time is Running out for a Permanent LLW Solution," Nuclear News (Dec 2004).
N. Zacha, "Low-Level Radioactive Waste Disposal: Are We Having a Crisis Yet?," Nuclear News August 2007).

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

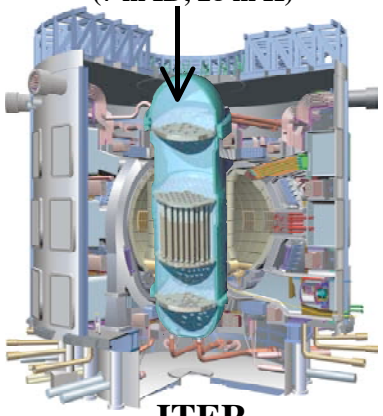


DOE Controls ~17 Small-Scale Disposal Sites at National Labs Conducting Nuclear Weapons Research and Production Programs



As near-term solution, DOE opened its disposal facilities to commercial LLW

Fission – Fusion Power Core Comparison



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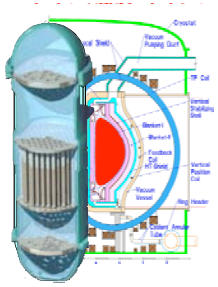
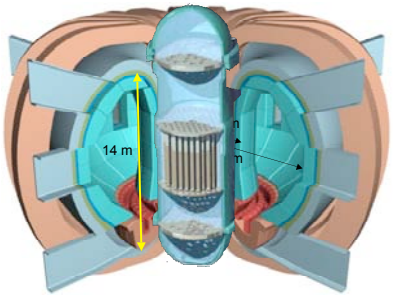
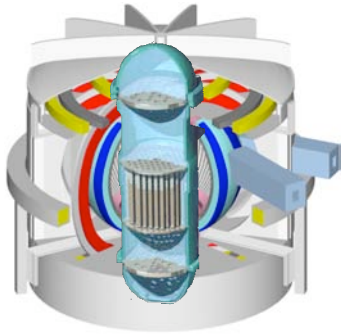


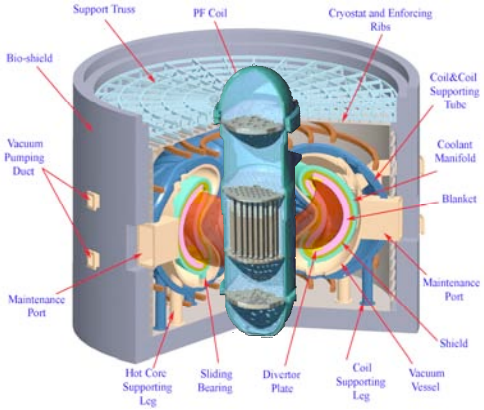
ARIES-AT



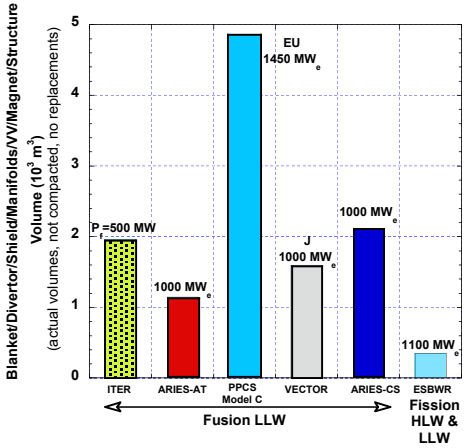
PPCS
Europe

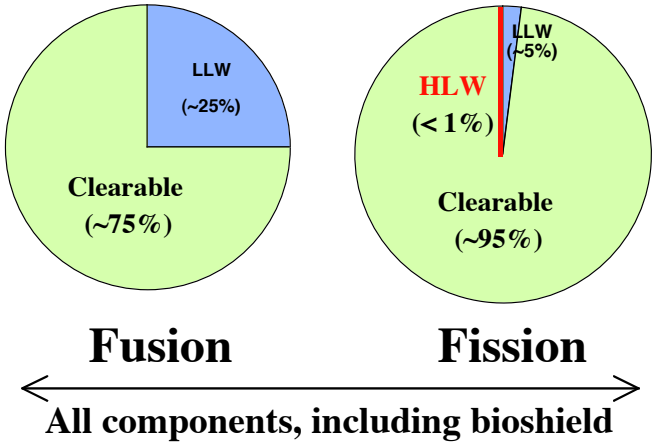


VECTOR
Japan

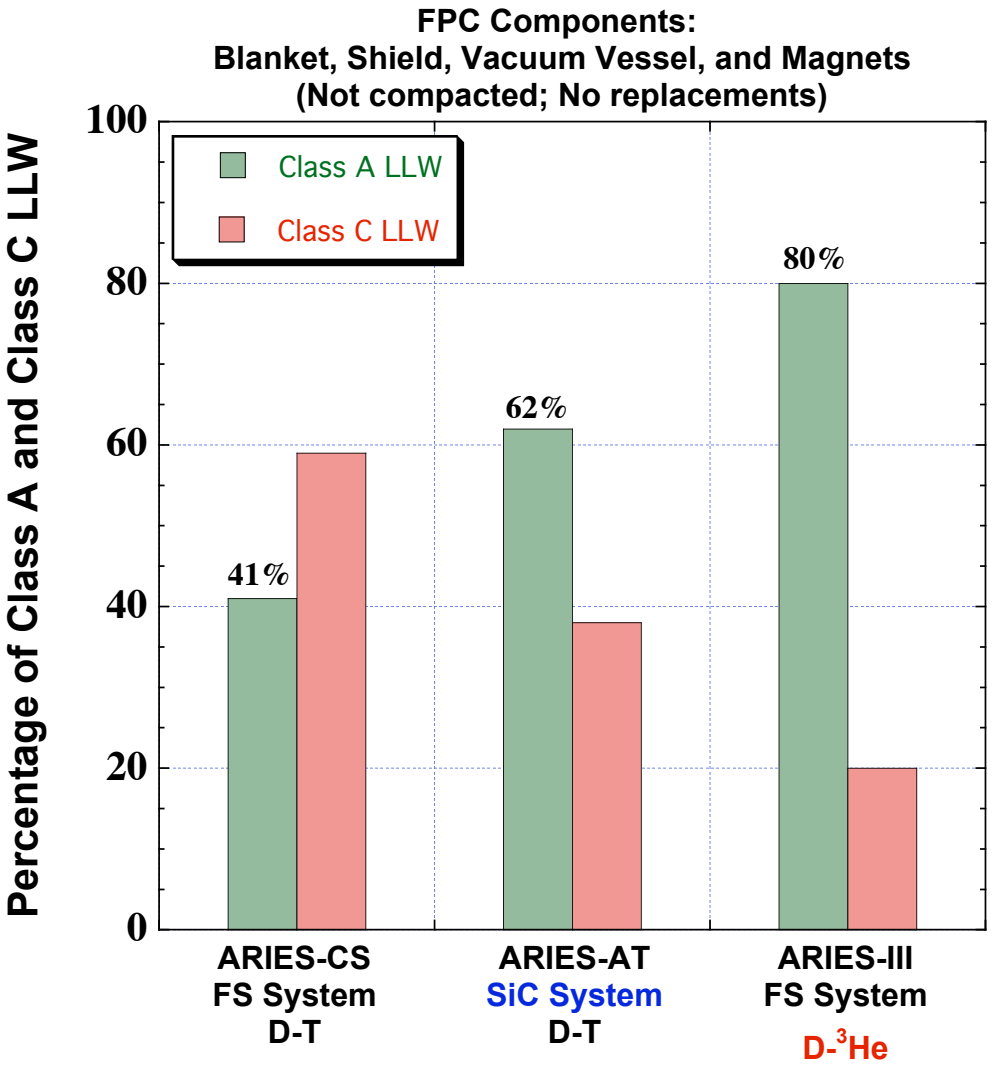


ARIES-CS

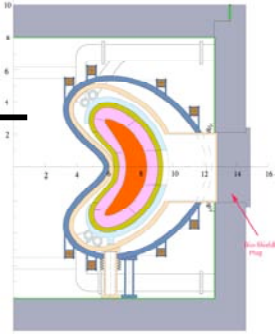




Fusion Generates Only LLW



ARIES-CS LLW Classification for Geological Disposal



All ARIES-CS Components* (~8,900 m³)

Temporary Storage (up to 100 y)

Class C LLW (~2,400 m³) (27%)

Class A LLW (~6,500 m³) (73%)

> 8 m below ground surface

~ 8 m below ground surface

Class A Repository (~$20/ft³)

Thick Concrete Slab

Class C Repository (~$2,000/ft³)

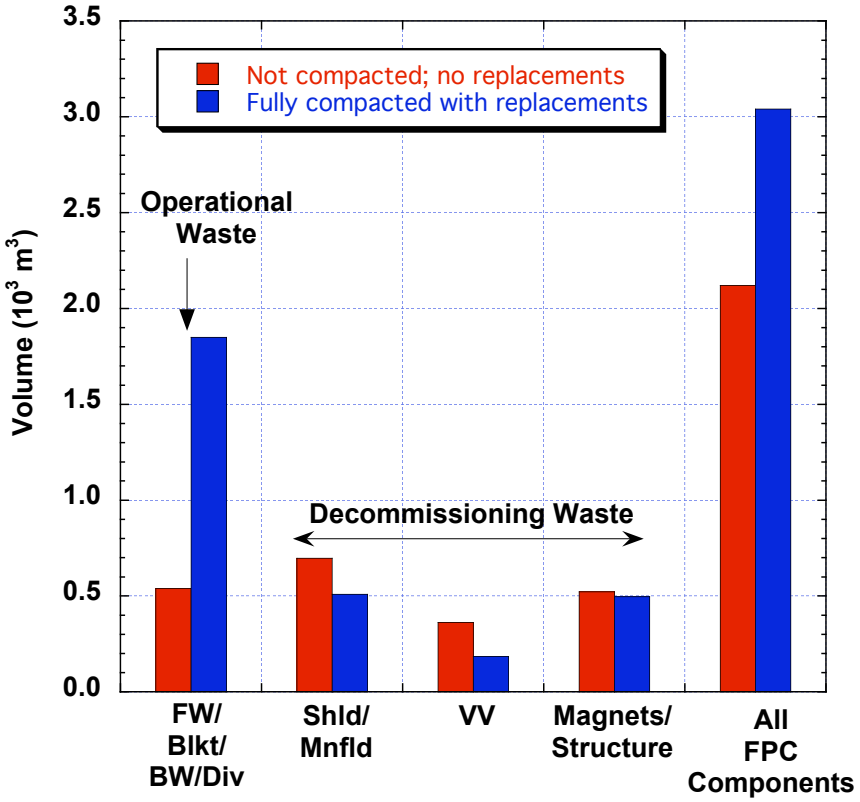
* Balance-of-plant equipment and external components (e.g., HX,turbines, cooling towers, etc.) not included.

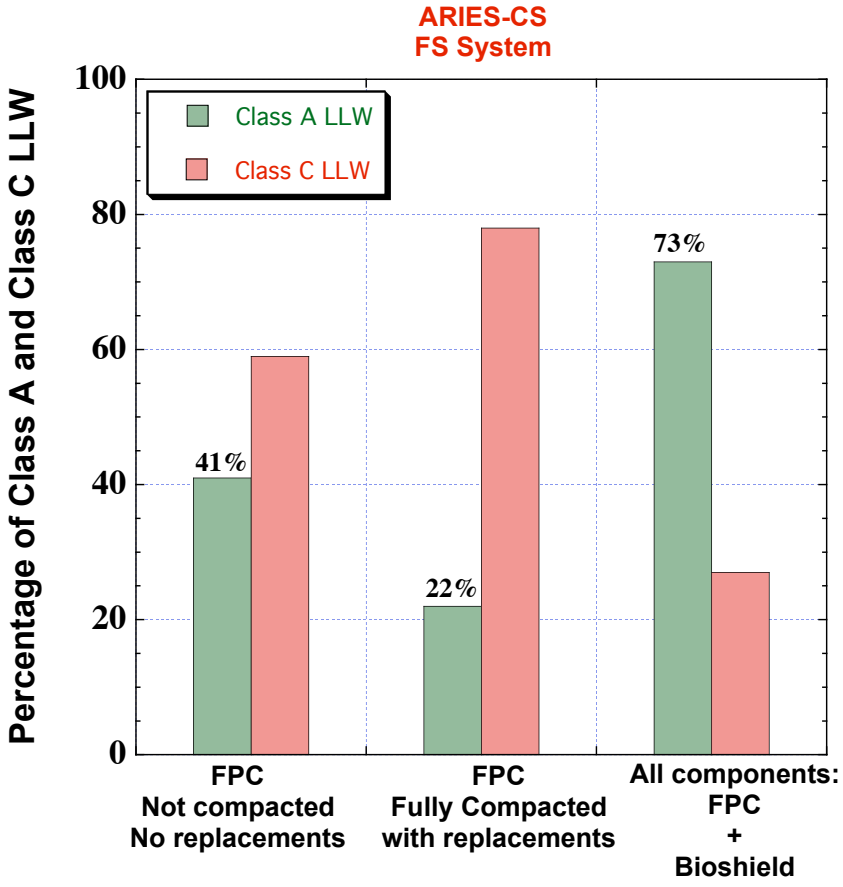
Least Hazardous Type of Waste

	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		**no**
Shield/Manifolds	√		**no**
Vacuum Vessel		√	**no**
Magnet:			
Nb_3Sn	√		**no**
Cu Stabilizer		√	√
JK2LB Steel*		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

* Preferred over Incoloy-908 for clearance considerations.

Breakdown of ARIES-CS LLW

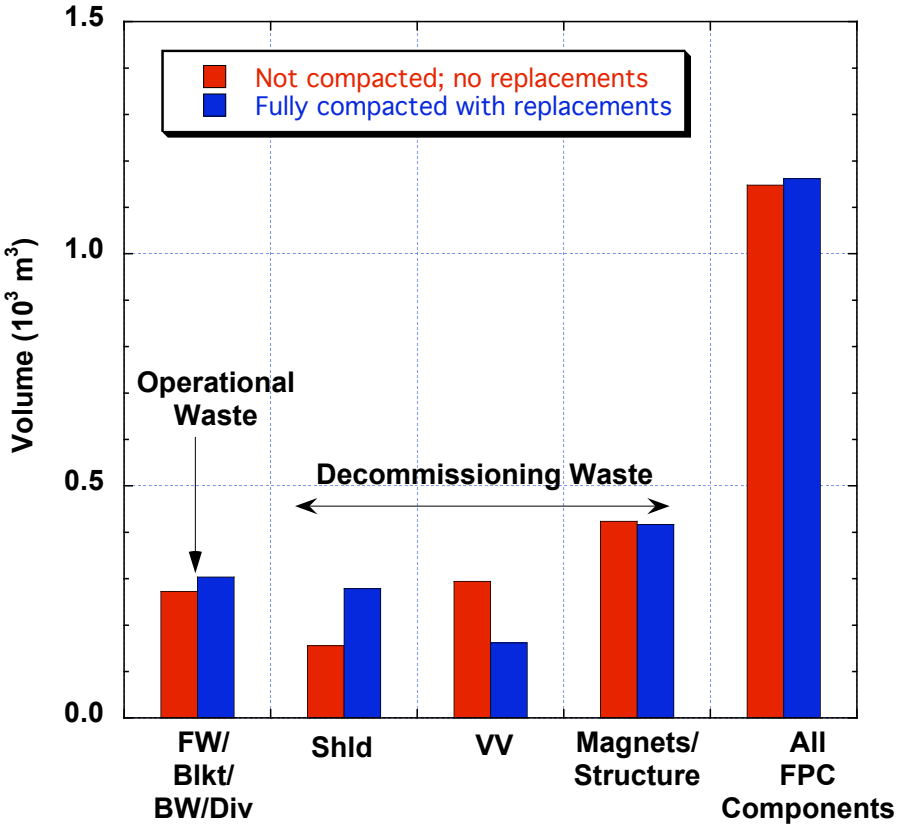


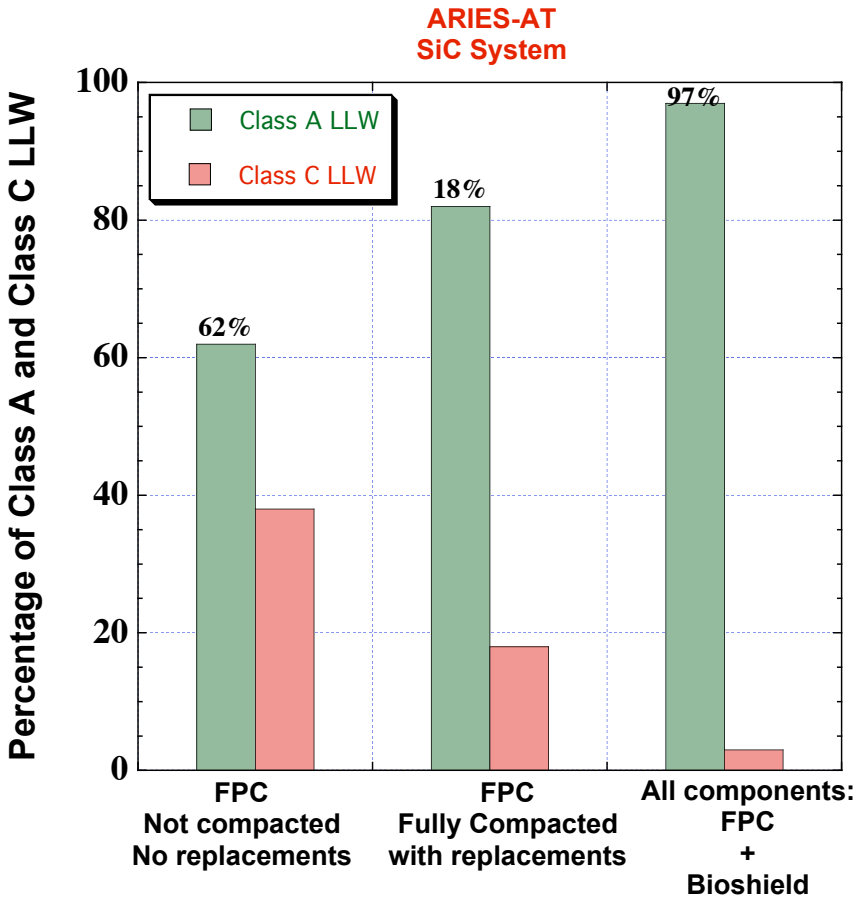


63 cm thick LiPb/He/FS blanket

Not segmented

Breakdown of ARIES-AT LLW





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	**2.3×10^5** (73%)	**8.4×10^4** (27%)	**3.1×10^5**
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	**2.8×10^5** (97%)	**7.3×10^3** (3%)	**3.1×10^5**
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 $)**

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* 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: $**8**B in 1983; $**57**B in 2001; $**70**B 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.

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