Toward the Ultimate Goal of Radwaste-Free Fusion: Recycling and Clearance, Avoiding Geological Disposal

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Background Info

Fusion fuel cycles:

$D + T \rightarrow n\ (14.07\ \text{MeV}) + {}^{4}He\ (3.52\ \text{MeV})$

Advanced Fuel Cycles

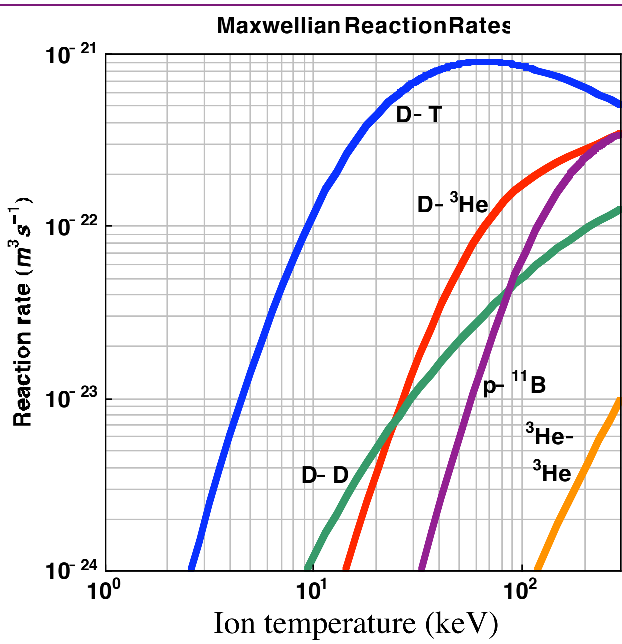
$D + D \rightarrow n\ (2.45\ \text{MeV}) + {}^{3}He\ (0.82\ \text{MeV})$

$\rightarrow p\ (3.02\ \text{MeV}) + T\ (1.01\ \text{MeV})$

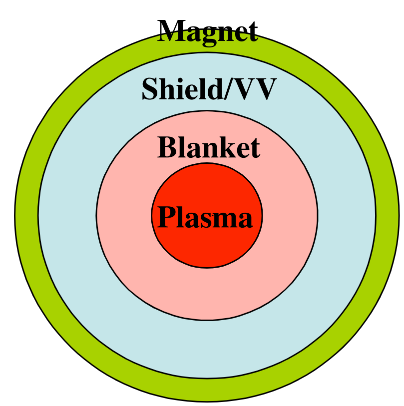
$D + {}^{3}He \rightarrow p\ (14.68\ \text{MeV}) + {}^{4}He\ (3.67\ \text{MeV})$

$p + {}^{11}B \rightarrow 3\ {}^{4}He\ (8.68\ \text{MeV})$

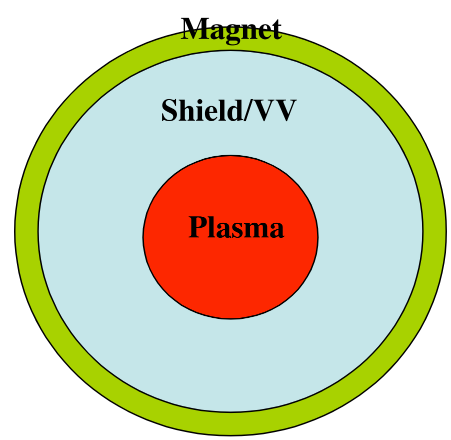
${}^{3}He + {}^{3}He \rightarrow 2\ p + {}^{4}He\ (12.86\ \text{MeV})$



- D-T fusion is easiest to achieve but produces large amount of energetic neutrons
- Neutrons activate materials surrounding plasma
- Proper choice of materials reduces radioactivity
- Researchers explored fuel cycles other than D-T to alleviate fusion radwaste problems.

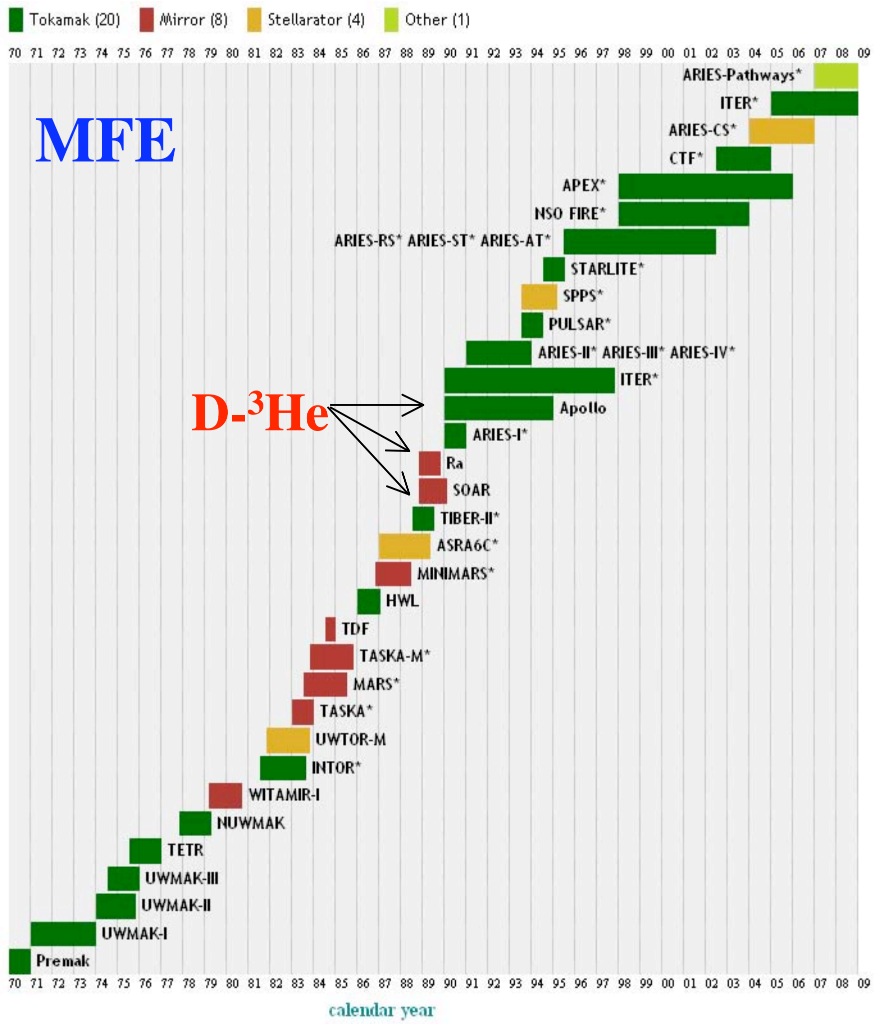


D-T Design Components

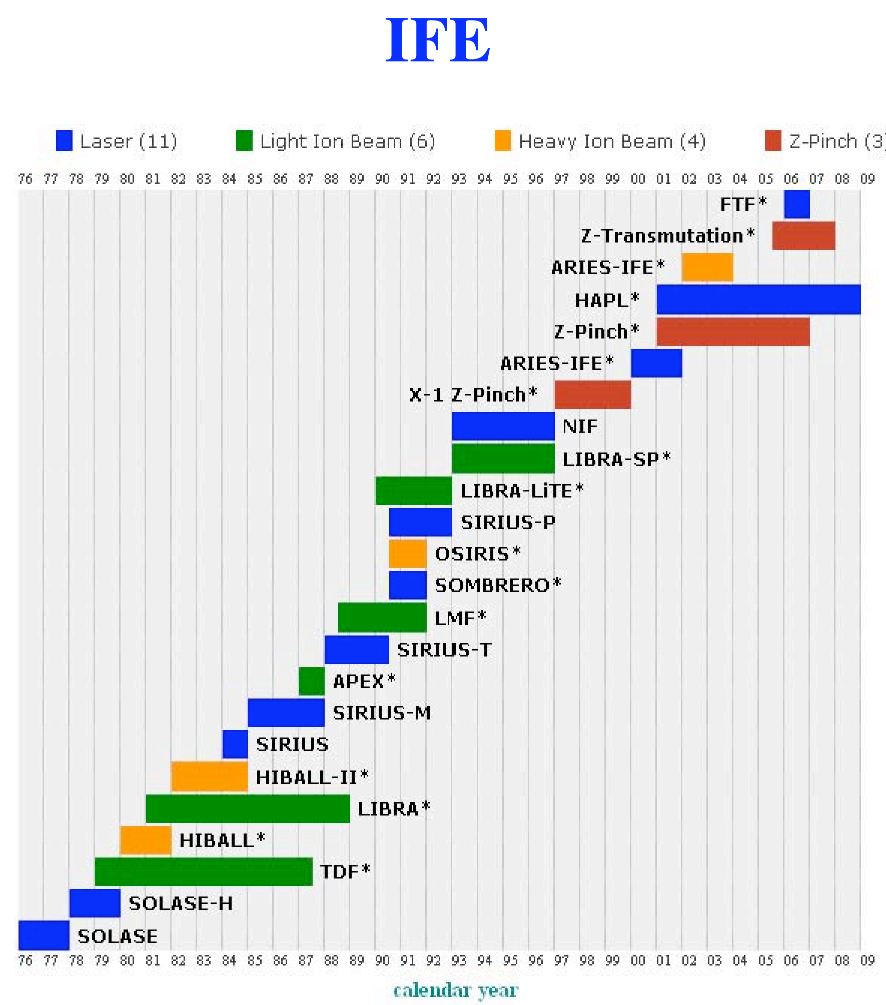


D-^{3}He Design Components

FTI Developed and Actively Participated in 33 MFE & 24 IFE Studies during ~40 y

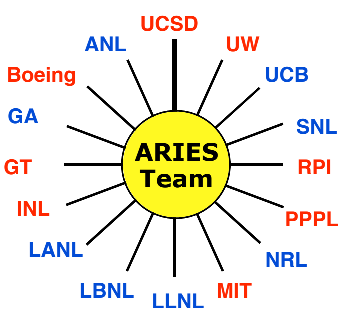


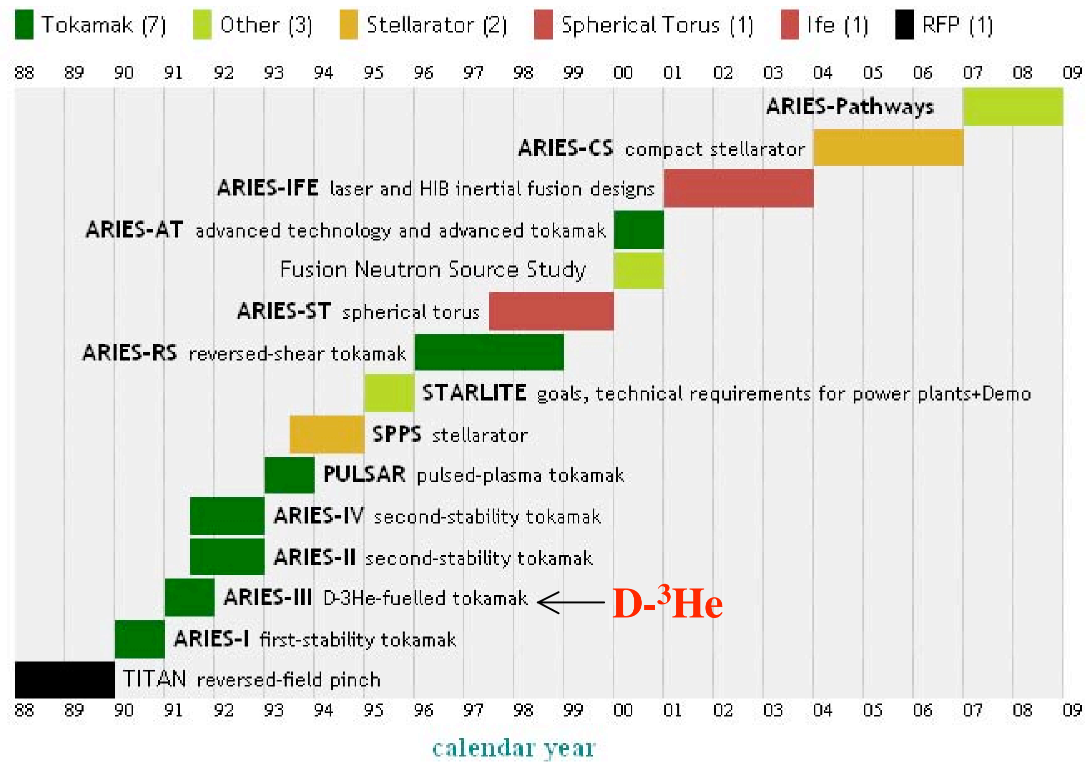
*in conjunction with other universities, national and international labs

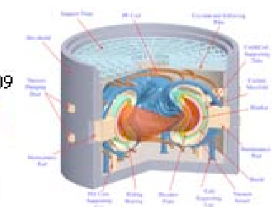


*in conjunction with other universities, national and international labs

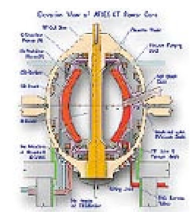
Over Past 20 y, Multi-Institutional ARIES Team Developed > 10 Advanced Designs

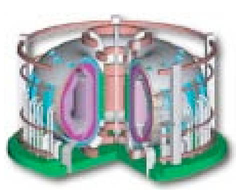





ARIES-CS

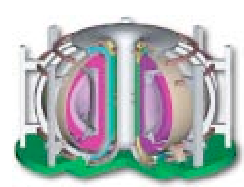

ARIES-AT


ARIES-ST

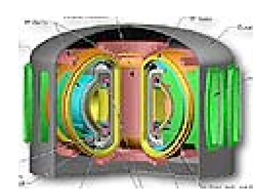

ARIES-I


ARIES-III

D-^{3}He


ARIES-IV


SPPS


ARIES-RS

Fusion Demonstrates Adequate Performance in Several Safety and Environmental Areas

Environmental impact:

- **Minimal radioactive releases**[#] during normal and abnormal operations.
- **Low activation materials** with strict impurity control
  - ⇒ minimal long-term environmental impact
- **Minimal low-level waste** (LLW)
- **No high-level waste** (HLW)

Occupational and public safety:

- **No evacuation plan** following abnormal events (early dose at site boundary < 1 rem[*]) to avoid disturbing public daily life.
- **Low dose** to workers and personnel during operation and maintenance activity (< 2.5 mrem/h).
- **Public safety** during normal operation (bio-dose << 2.5 mrem/h) and following credible accidents:
  - LOCA, LOFA, LOVA, and by-pass events.
  - External events (seismic, hurricanes, tornadoes, airplane crash, etc.).

No energy and pressurization threats to confinement barriers (VV and cryostat):

- Decay heat problem solved by design
- Chemical reaction avoided
- No combustible gas generated
- Chemical energy controlled by design
- Overpressure protection system
- Rapid, benign plasma shutdown.

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* 1 rem (= 10 m Sv) accident dose stated in Fusion Safety Standards, DOE report, DOE-STD-6002-96 (1996).

\# Such as T, volatile activated structure, corrosion products, and erosion dust. Or, from liquid and gas leaks.

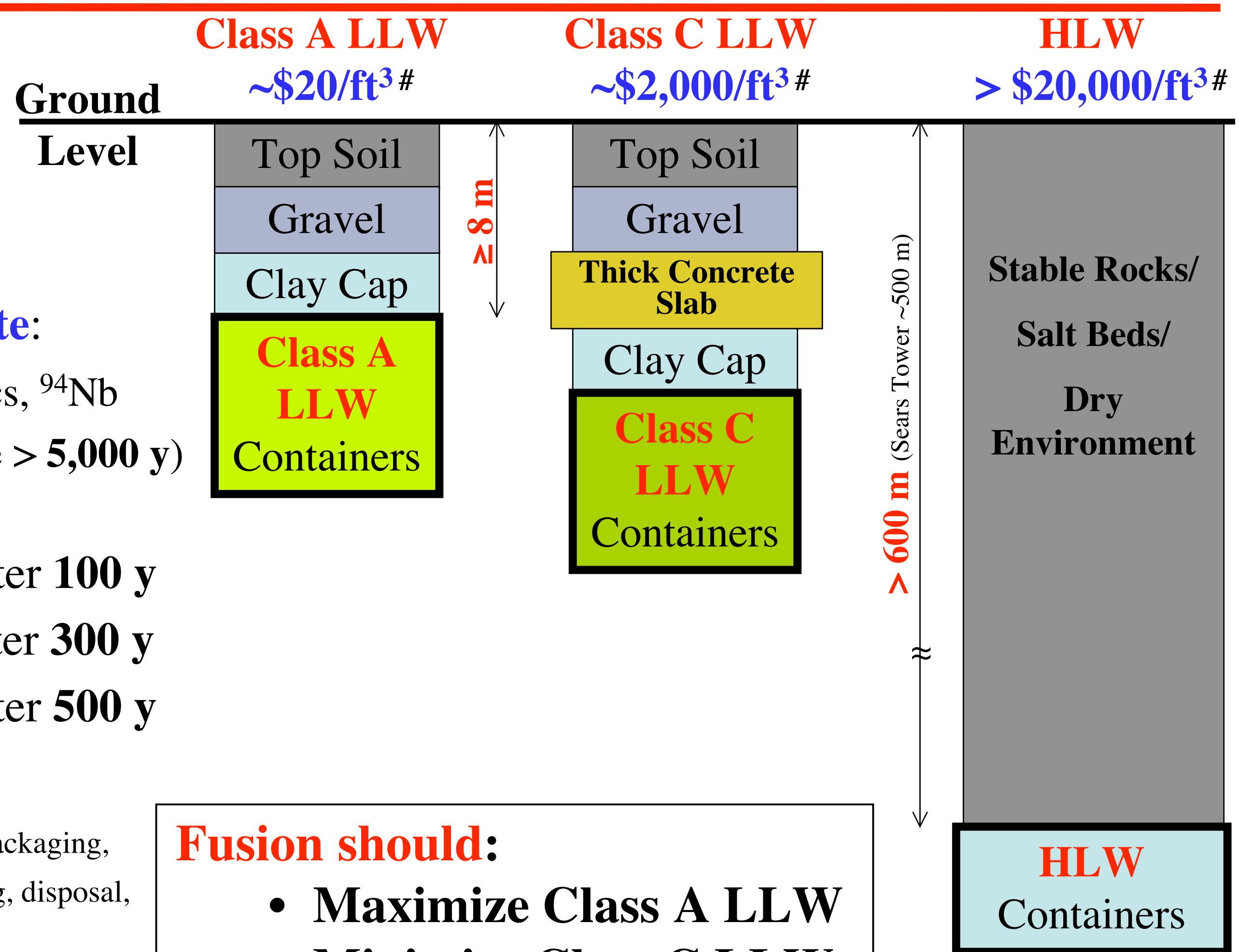
Options for Radwaste Management

- Disposal in space
- Ice-sheet disposal
- Seabed disposal
- Transmutation of long-lived radionuclides (⇒ proliferation concerns)
- **Geological disposal** (preferred US option over past 50 y)
- Recycling / reprocessing (reuse within nuclear industry)
- Clearance (release to commercial market if materials are slightly radioactive)

NRC Classification of LLW and HLW

US Classification of radwaste:

- **HLW** (e.g., transuranics, ^{94}Nb ^{14}C, etc.; active > **5,000 y**)
- **LLW***:
  - **Class A** - safe after **100 y**
  - **Class B** - safe after **300 y**
  - **Class C** - safe after **500 y**



Cost of preparation, characterization, packaging, interim storage, transportation, licensing, disposal, and monitoring.

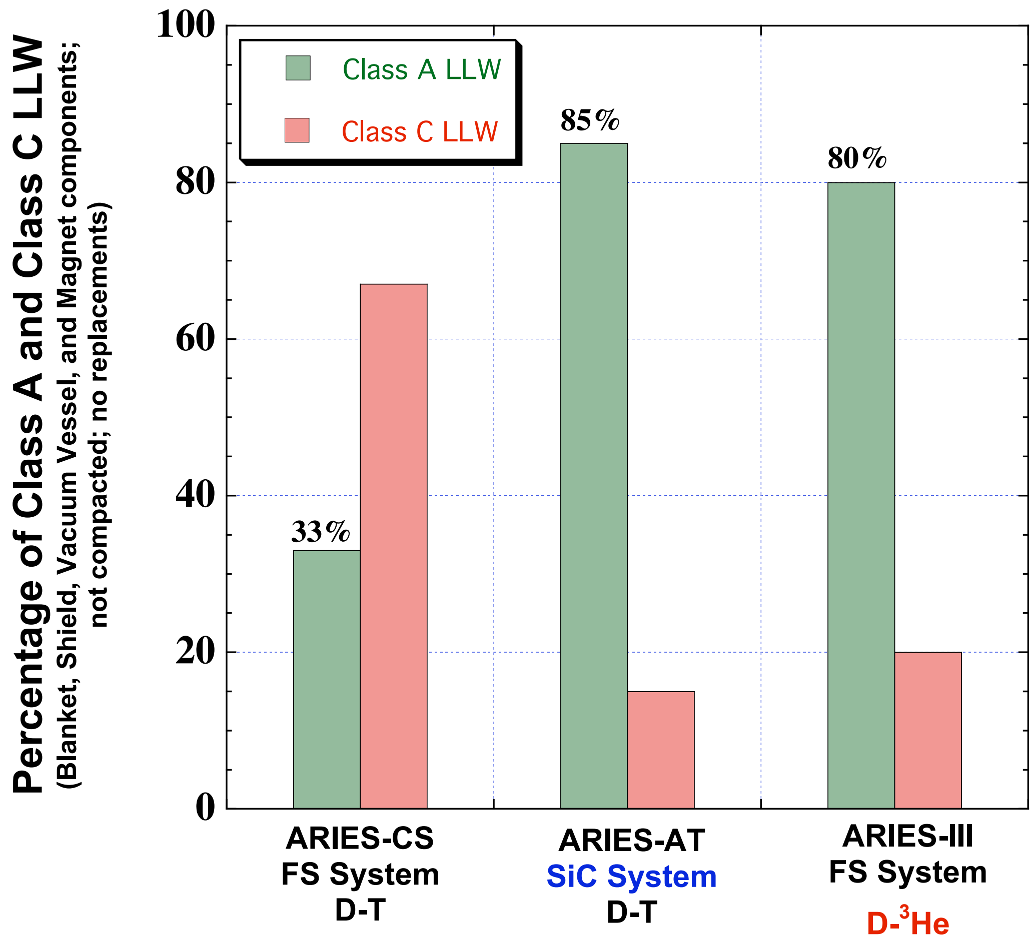
* From fusion, research labs, hospitals, food irradiation facilities, etc.

Fusion should:

- **Maximize Class A LLW**
- **Minimize Class C LLW**
- **Avoid HLW**

Fusion Generates Only LLW

All fusion materials are carefully chosen to minimize long-lived radioactive products (e.g., low-activation ferritic steel (FS), vanadium, and SiC structures)



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

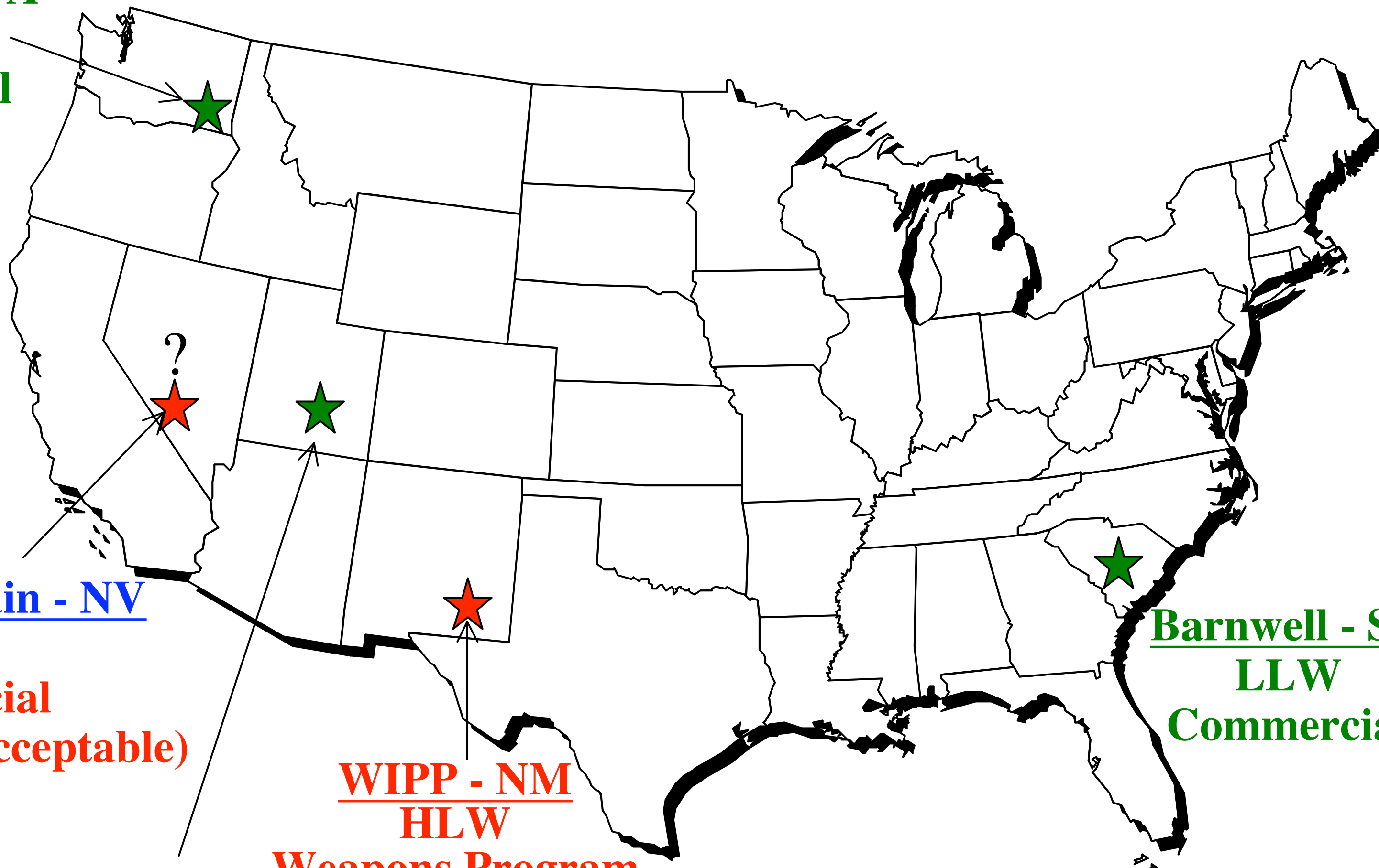
- Largest US repository (Barnwell in SC) may limit LLW received in July 2008

- 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

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

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



DOE controls ~15 small-scale disposal sites at national labs, conducting nuclear weapons research and production programs

US Needs National Solution for LLW and HLW Disposal Problems

Recycling and Clearance

The solution…

Handling Fusion Radioactive Materials is Important to Future of Fusion Energy

- **Background**: Majority of earlier fusion power plants designed focused on disposal of active materials in repositories, adopting fission radwaste management approach preferred in 1970's.

- **New Strategy**: Develop new framework for fusion:
  – Minimal radwaste should be disposed of in ground
  – Promote:
    - Recycling – reuse within nuclear industry, if technically and economically feasible
    - Clearance – unconditional release to commercial market to fabricate as consumer products (or dispose of in non-nuclear landfill).
      Clearable materials are safe, containing < 1% of background radiation.

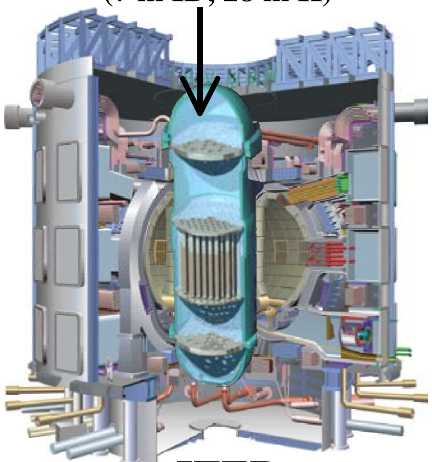
- **Why?**
  – Limited capacity of existing low-level waste repositories
  – Political difficulty of building new ones
  – Tighter environmental controls
  – Minimize radwaste burden for future generations.

- **Applications**: Any fusion concept (MFE & IFE); power plants and experimental devices.

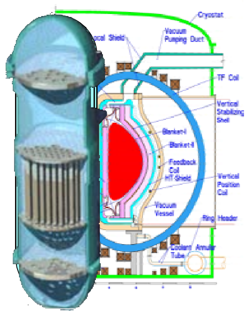
- **Impact**: Promote fusion as nuclear source of energy with minimal environmental impact.

Fusion Generates Large Amount of LLW that would Fill Repositories Rapidly

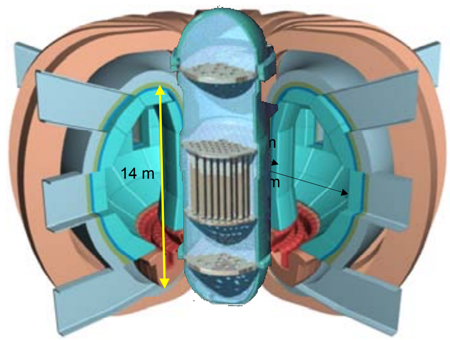
ESBWR Vessel (7 m ID, 28 m H)



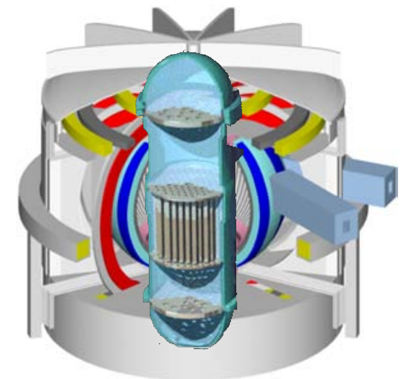
ITER



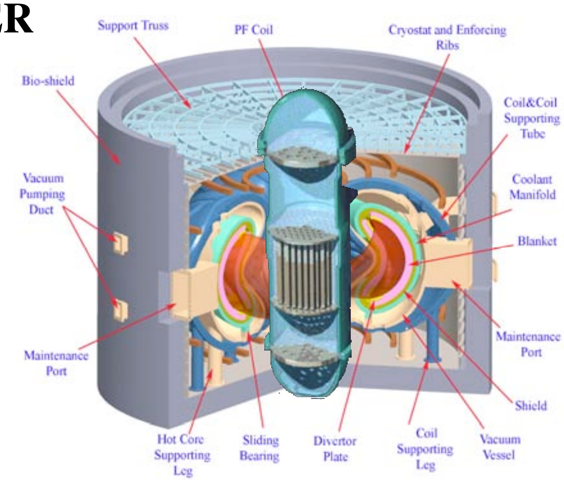
ARIES-AT



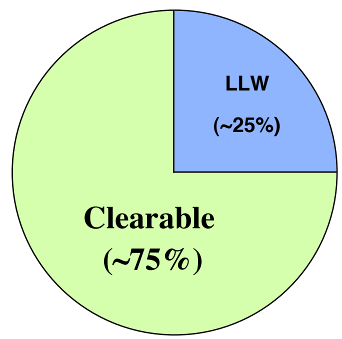
PPCS Europe



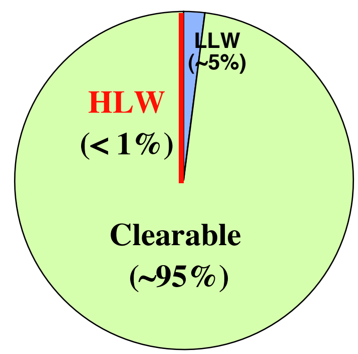
VECTOR Japan



ARIES-CS



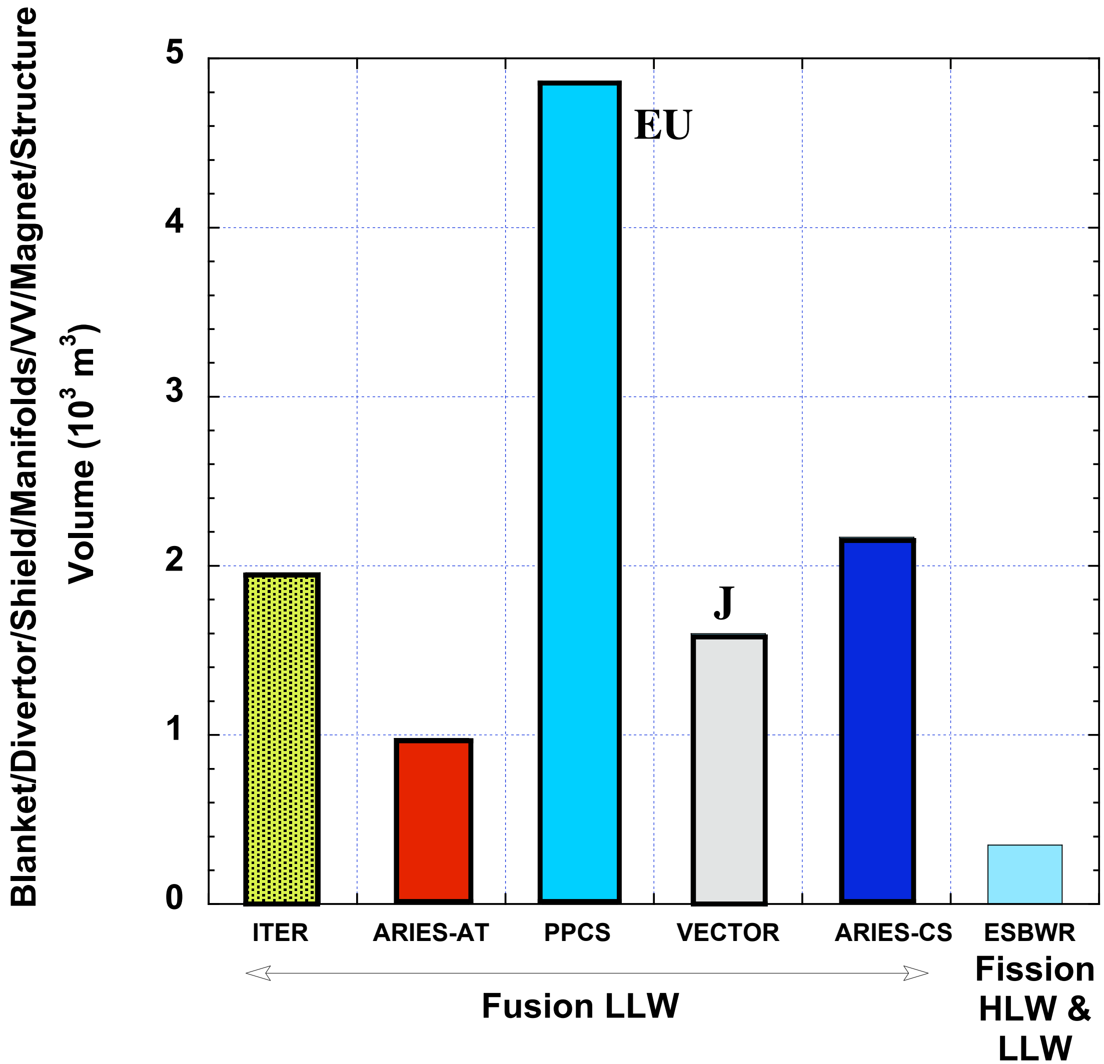
Fusion



Fission

Radwaste Volume Comparison

(Actual volumes of components; not compacted, no replacements)



What We Suggest

- **Business as usual is not environmentally attractive option for fusion. Something should be done.**

- Fusion designs should adopt **MRCB** philosophy:

  M – Minimize volume of active materials by clever designs

  R – Recycle, if economically and technologically feasible

  C – Clear slightly-irradiated materials

  B – Burn long-lived fusion byproducts, if any, in fusion devices*.

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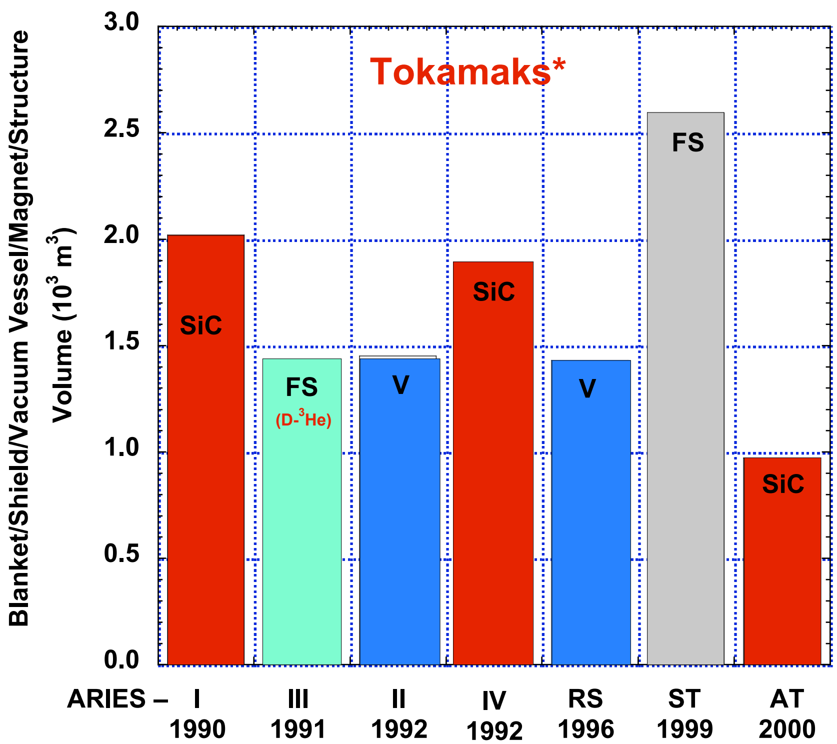
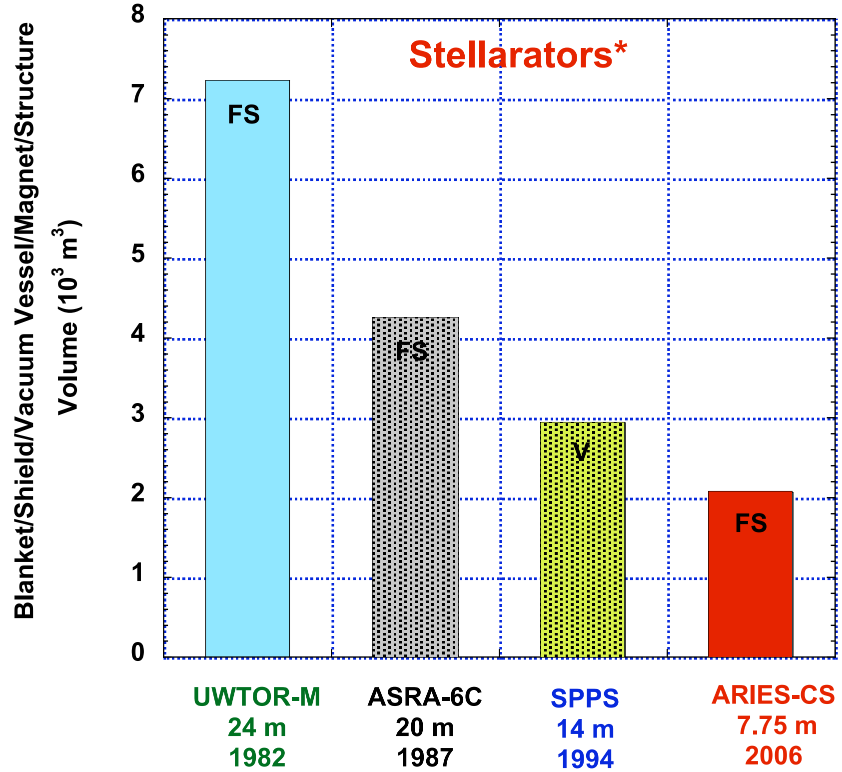
* L. El-Guebaly, "Managing Fusion High Level Waste – a Strategy for Burning the Long-Lived Products in Fusion Devices," *Fusion Engineering and Design*, **81** (2006) 1321-1326.

Radwaste Minimization

ARIES Project Committed to Radwaste Minimization by Design





Tokamak waste volume halved over 10 y study period

Stellarator waste volume dropped by 3-fold over 25 y study period

* Actual volumes of components (not compacted, no replacements).

Disposal, Recycling, and Clearance

Disposal, Recycling, Clearance Approaches Applied to Recent US Fusion Studies

(**red** indicates preference)

	Components	Recycle?	Clear?	Dispose of @ EOL?
MFE:				
ARIES-CS@	**all**	yes	yes / no	yes (as Class A & C LLW)
IFE:				
ARIES-IFE (Heavy Ion Beam)	**Targets**#	no (for economic reasons)	yes / no	yes (as Class A LLW)
Z-Pinch	**RTL*** (carbon steel)	yes (a *must* requirement)	yes	yes (as Class A LLW)

@ L. El-Guebaly et al., "Designing ARIES-CS Compact Radial Build and Nuclear System: Neutronics, Shielding, and Activation," to be published in *Fusion Science and Technology*.

L. El-Guebaly, P. Wilson, D. Henderson, and A. Varuttamaseni, "Feasibility of Target Materials Recycling as Waste Management Alternative," *Fusion Science & Technology*, **46**, No. 3, 506-518 (2004).

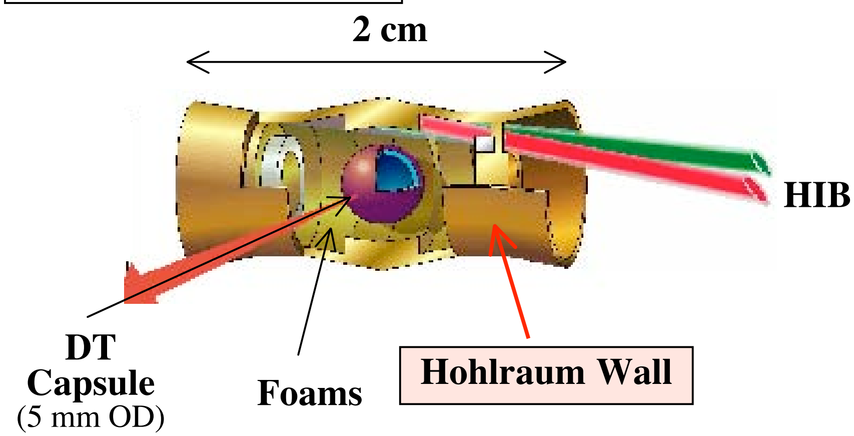
* L. El-Guebaly, P. Wilson, and M. Sawan, "Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant," *Fusion Science & Technology* **52**, No. 3, 1027-1031 (2007).

Economics Prevent Recycling of ARIES-IFE-HIB Hohlraum Wall#

	One-Shot Use Scenario	Recycling Scenario
Cost per Target	**$ 0.4**	**$ 3.15**
Incremental Change to COE	~ 10 mills/kWh	~ 70 mills/kWh
Cost of Electricity (COE)	**~ 70 mills/kWh**	**~ 130 mills/kWh**

Preferred Option

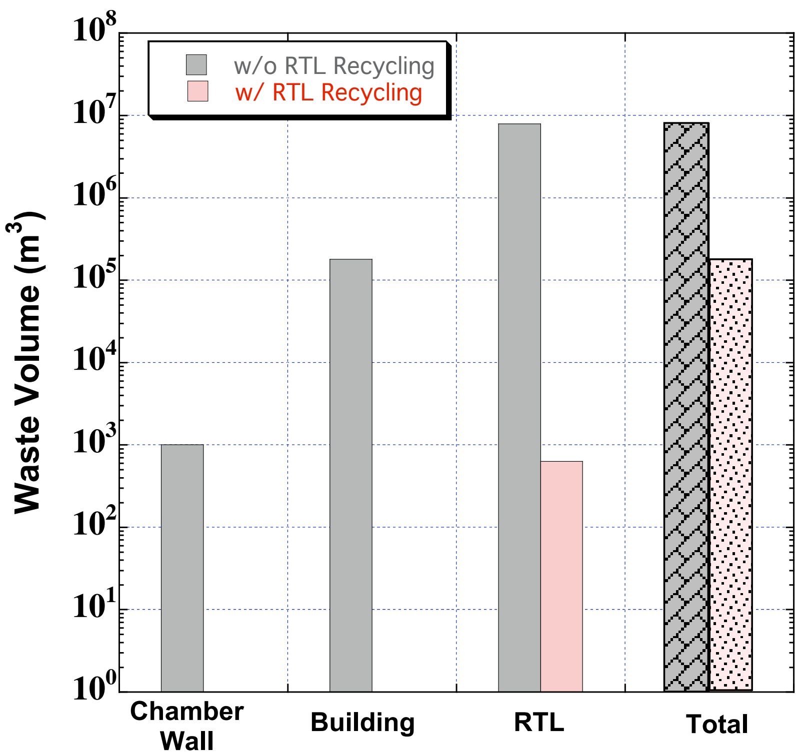
- **Recycling** of hohlraum walls **doubles COE**.
- Hohlraum walls represent **< 1% of radwaste stream.**
- Once-through use generates **Class A** LLW.
- **Target factory designers prefer dealing with non-radioactive hohlraum wall materials.**
- Single fusion-specific repository (designed for T-containing materials) is needed for such fusion components and secondary waste.



ARIES-IFE Target

L. El-Guebaly, P. Wilson, D. Henderson, and A. Varuttamaseni, "Feasibility of Target Materials Recycling as Waste Management Alternative," *Fusion Science & Technology*, **46**, No. 3, 506-518 (2004).

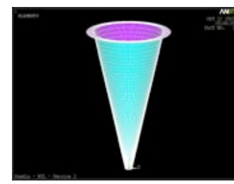
Recycling is a "Must" Requirement for RTL of Z-Pinch to Minimize Radwaste Stream and Enhance Economics*

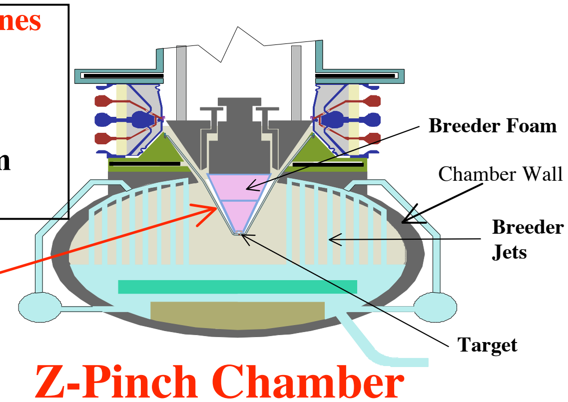


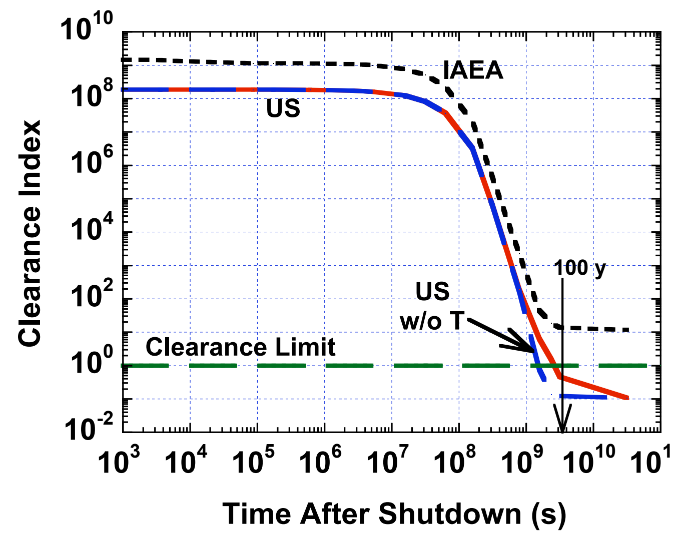
No recycling during 40 FPY
Total RTL volume = 7 M m^3

With recycling
1.1 day RTL inventory
Total RTL volume = 0.0005 M m^3

Recyclable Transmission Lines
Top diameter = 1 m
Bottom diameter = 0.1 m
Length = 2 m
Total thickness = 0.142 cm
50 kg / RTL



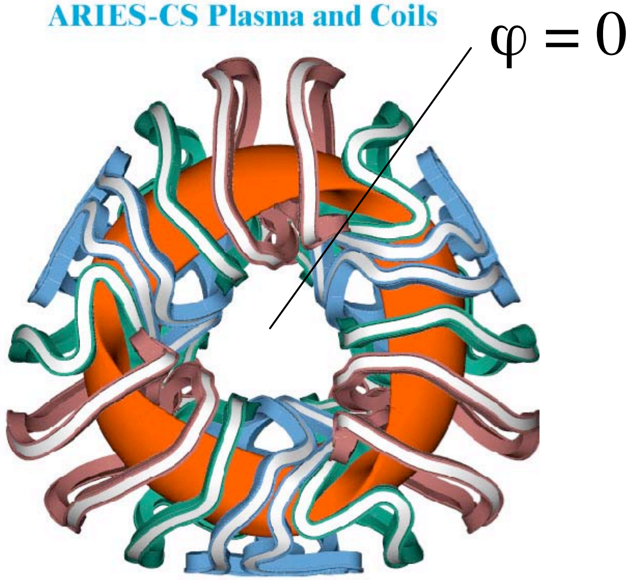


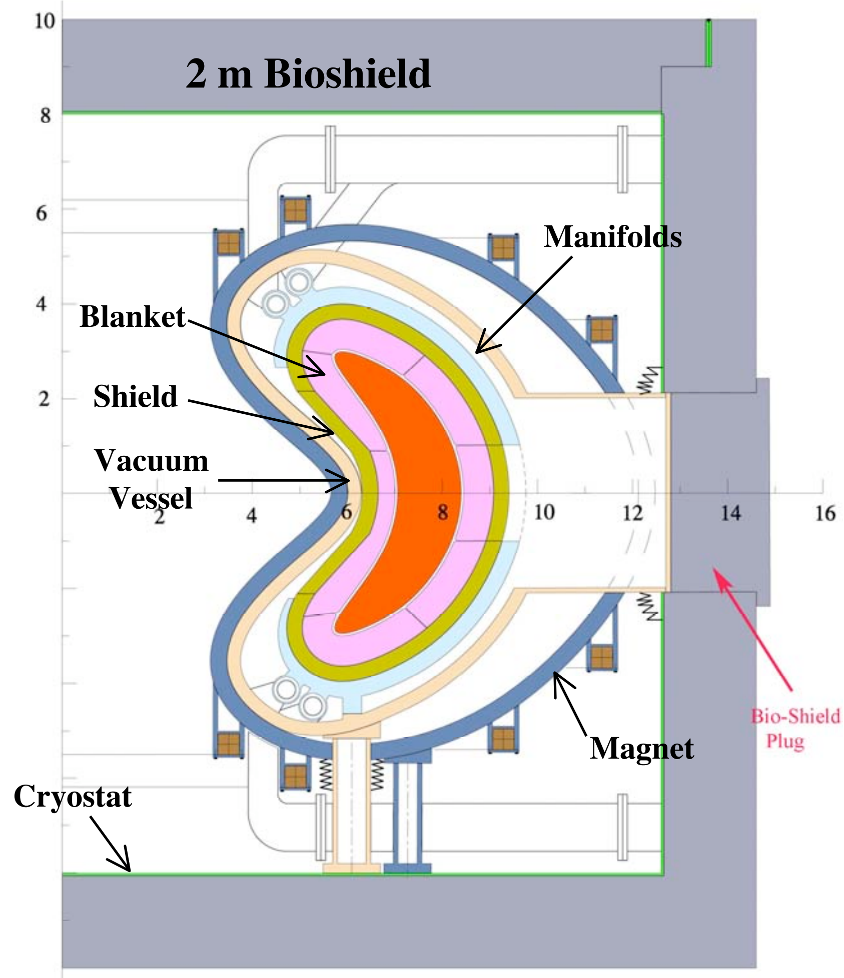


RTL waste could be stored for 50-100 y after plant decommissioning, then cleared (released to commercial market for reuse)

* L. El-Guebaly, P. Wilson, and M. Sawan, "Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant," *Fusion Science & Technology* **52**, No. 3, 1027-1031 (2007).

ARIES Compact Stellarator





ARIES-CS Cross Section @ $\varphi = 0$

3 Field Periods.

LiPb/He/FS System.

7.75 m Major Radius.

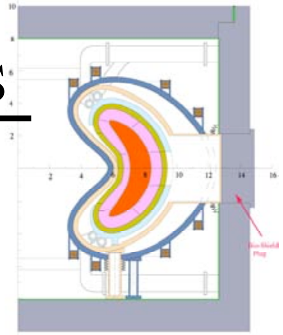
2.6 MW/m^2 Average NWL.

3 FPY Replaceable FW/Blanket/Div.

40 FPY Permanent Components.

~78 mills/kWh COE ($2004).

ARIES-CS LLW Classification for Geological Disposal



All ARIES-CS Components (~8,900 m^3) → **Temporary Storage** (up to 100 y)

Class C LLW (~2,400 m^3) (27%)

> 8 m below ground surface

Thick Concrete Slab

Class C Repository (~\$2,000/ft^3)

Class A LLW (~6,500 m^3) (73%)

~ 8 m below ground surface

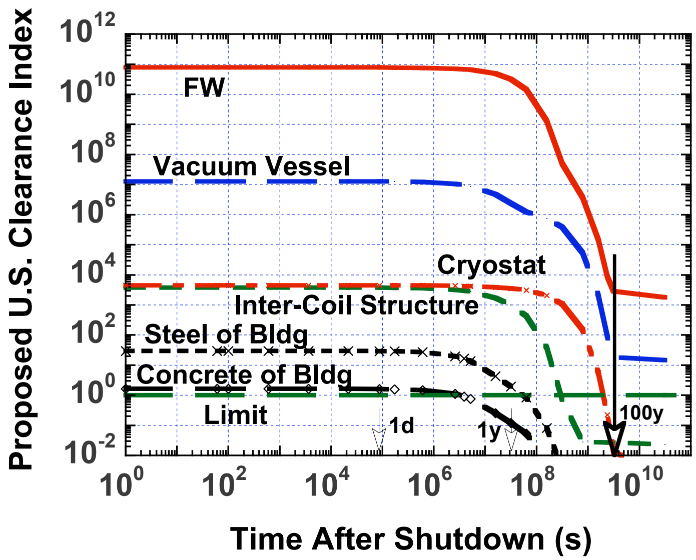
Class A Repository (~\$20/ft^3)

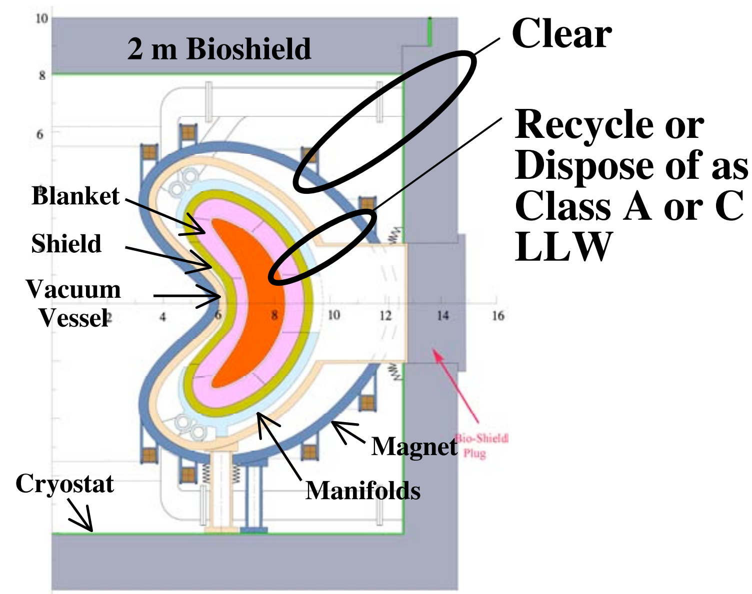
Least Hazardous Type of Waste

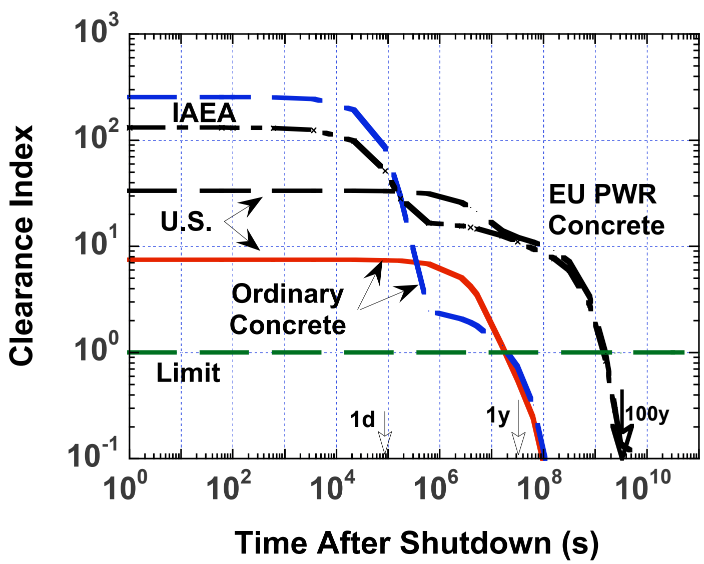
	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		**no**
Shield/Manifolds	√		**no**
Vacuum Vessel		√	**no**
Magnet:			
Nb_3Sn	√		**no**
Cu Stabilizer		√	√
JK2LB Steel*		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

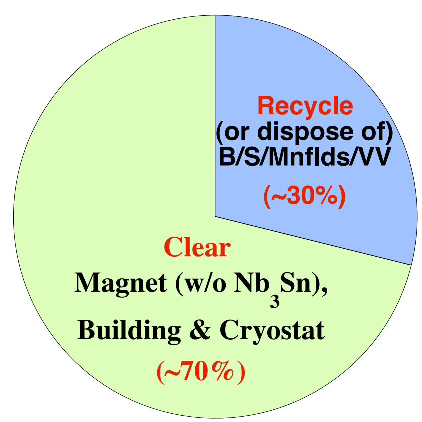
* Preferred over Incoloy-908 for clearance considerations.

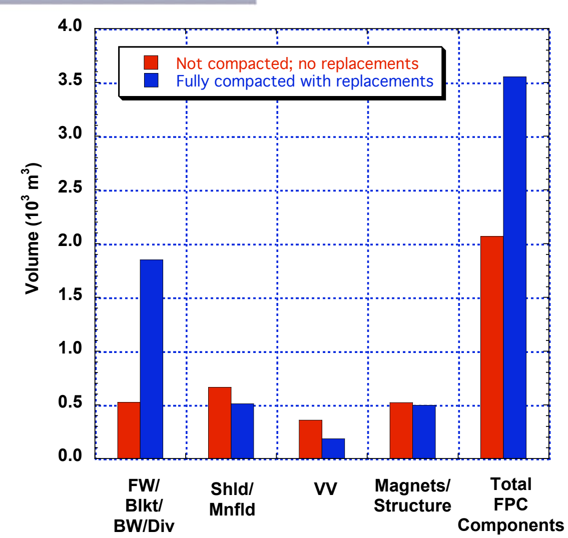
70% of ARIES-CS Active Materials can be Cleared in < 100 y after Decommissioning



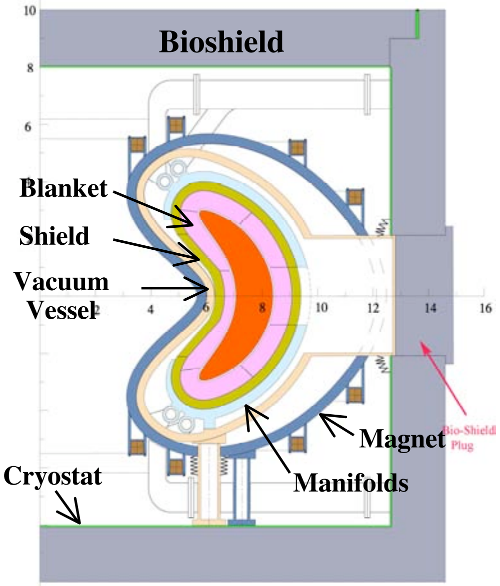


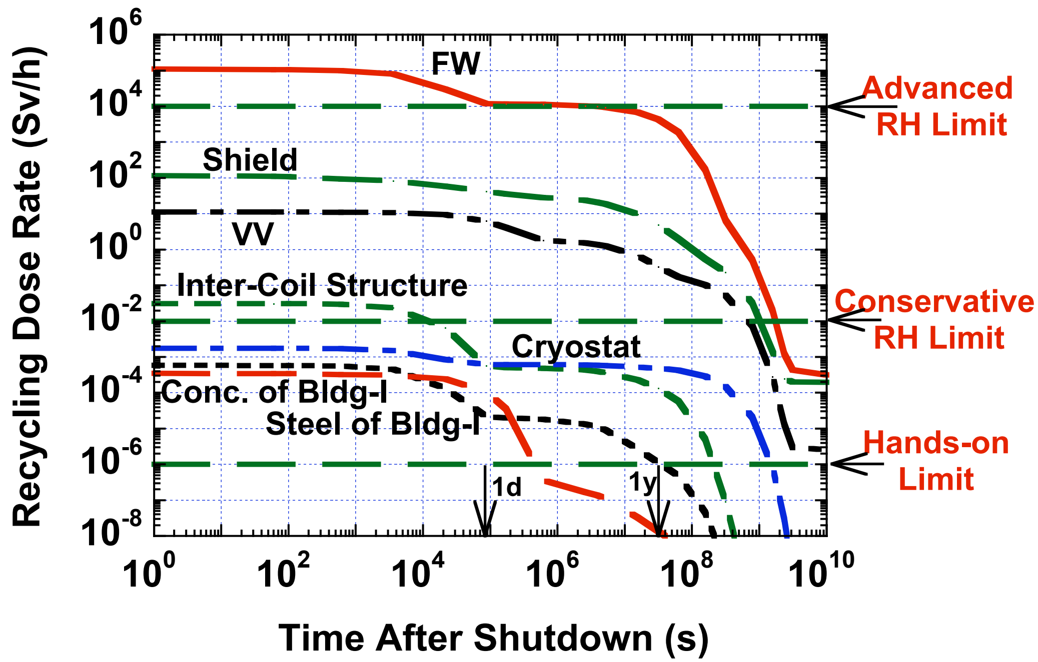






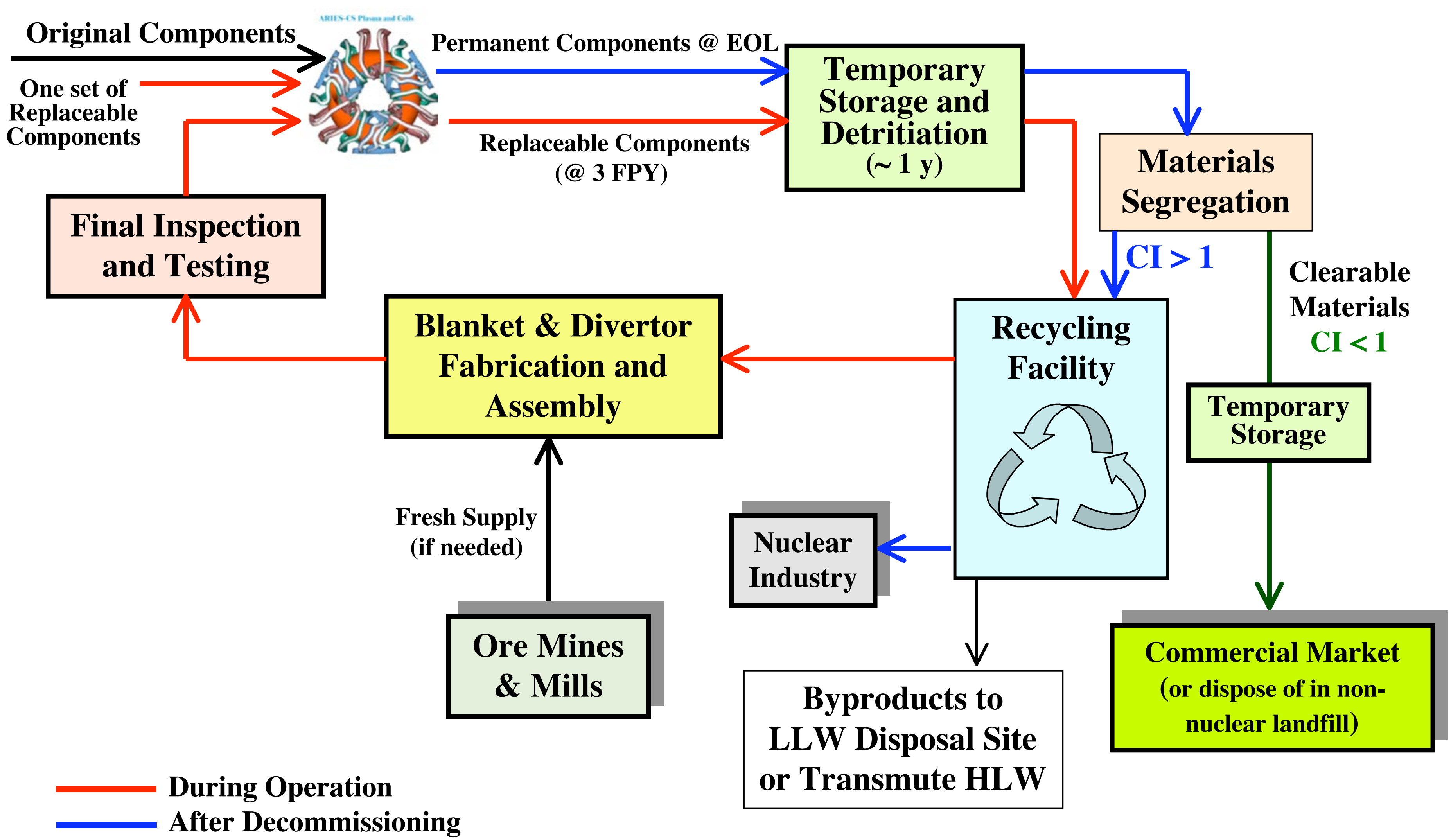
All ARIES-CS Components can Potentially be Recycled in < 1 y Using Advanced RH Equipment





- At early cooling periods (<10 y):
  - Main contributor to dose of FS-based components is ^{54}Mn from Fe
  - Impurities have no contribution to recycling dose.
- Developing advanced recycling tools could relax stringent specifications imposed on fusion material impurities.
- Development of more advanced tools is foreseen to support fission GNEP initiative and MOX fuel reprocessing system.

Recycling & Clearance Flow Diagram



General Observations

- Fusion studies indicated recycling and clearance are technically feasible, providing effective means to minimize radwaste volume.

- They should be pursued despite lack of details at present.

- Fusion recycling technology will benefit from fission developments and accomplishments in 50 – 100 y.

- Fusion materials contains tritium that may introduce serious complications to disposal and recycling

  $\Rightarrow$ detritiation prior to recycling is necessary for fusion components.

- Several **critical issues** need further investigation for all three options:
  - Disposal
  - Recycling
  - Clearance.

Disposal Issues

- Large volume to be disposed of (≥ 8,000 m^3 per 1 GW_e plant, including bioshield)
- Immediate or deferred dismantling?
- High disposal cost (for preparation, packaging, transportation, licensing, and disposal).
- Limited capacity of existing LLW repositories
- Need for fusion-specific repositories designed for T-containing materials
- Need for specific activity limits for fusion LLW issued by legal authorities
- Political difficulty of building new repositories
- Tighter environmental controls
- Radwaste burden for future generations.

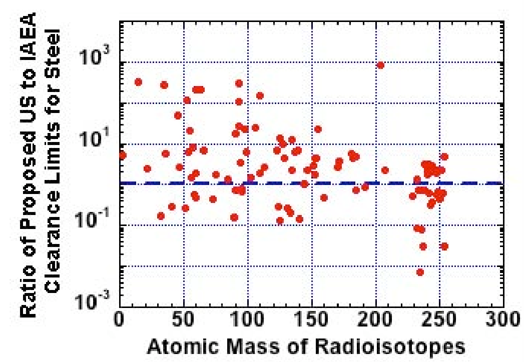
Recycling Issues

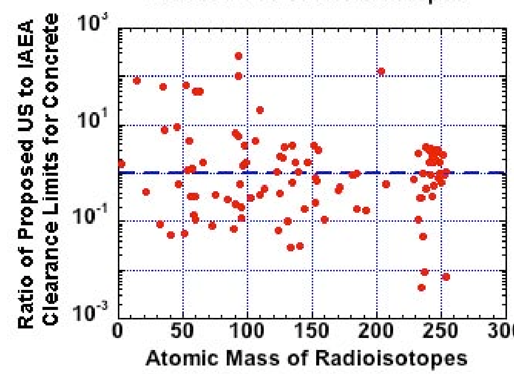
- Development of radiation-resistant RH equipment (≥ 10,000 Sv/h) for fusion use
- Large and low-cost interim storage facility with decay heat removal capacity[#]
- Dismantling and separation of various materials from complex components
- Energy demand for recycling process
- Cost of recycled materials
- Treatment and complex, remote re-fabrication of radioactive materials
- Radiochemical or isotopic separation processes for some materials, if needed
- Efficiency of detritiation system
- Management of secondary waste. Any materials for disposal? Volume? Radwaste level?
- Properties of recycled materials? Any structural role? Reuse as filler?
- Aspects of radioisotope and radiotoxicity buildup by subsequent reuse
- Recycling plant capacity and support ratio
- Acceptability of nuclear industry to recycled materials
- Recycling infrastructure.

[#] e.g., heat pipes.

Clearance Issues

- Discrepancies between US-NRC & IAEA clearance standards*





- Impact on CI prediction of missing radioisotopes (such as ^{10}Be, ^{26}Al, ^{32}Si, ^{91,92}Nb, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, ^{157,158}Tb, ^{163,166m}Ho, ^{178n}Hf, ^{186m,187}Re, ^{193}Pt, ^{208,210m,212}Bi, and ^{209}Po).

- Need for official fusion-specific clearance limits issued by legal authorities

- Large and low-cost interim storage facility

- Clearance infrastructure

- Availability of clearance market (Europe is ahead of US in recycling/clearance. Some experience already exists in several EU countries: Sweden, Germany, Spain, and Belgium. Currently, US industry does not support unconditional clearance claiming it could erode public confidence in their products and damage their markets).

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* L. El-Guebaly, P. Wilson, and D. Paige, "Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants," *Fusion Science & Technology*, **49**, 62-73 (2006).

US Industrial Experience Demonstrates Technical and Economical Feasibility of Recycling

- INL and industrial firm recycled activated Pb bricks for nuclear industry. Cost of Pb LLW disposal was ~$5/pound while cost of recycling was ~$4.3/pound including fabrication into brick shapes.
  Savings:
  - Recycling versus disposal cost
  - Disposal volume over entire lifecycle
  - Not requiring purchase of new Pb bricks.

- INL and industrial company fabricated shielding casks out of recycled SS:
  - Casks were designed, built, and tested for strength and impact
  - Slag from melting tends to collect some radionuclides
  - Composition adjustments after slag removal produced metal alloys with properties very similar to those of fresh alloys
  - Prototype casks functioned well and are still in use since 1996.

- In 1960s, ANL-West Hot Fuel Examination Facility developed tools to handle fission fuel rods for Experimental Breeder Reactor (EBR-II).
  RH equipment operated well at 10,000 Sv/h.

Recommendations

Regarding sizable amount of activated materials involved in fusion power plants,

Fusion designers should:

- Minimize radwaste volume by clever design
- Promote environmentally attractive scenarios such as recycling and clearance, avoiding geological burial
- Investigate critical issues for all three options
- Address technical and economical aspects before selecting most suitable radwaste management approach for any fusion component
- Continue developing low-activation materials. Stringent specifications on impurities could be relaxed by developing advanced recycling tools.

Nuclear industry and regulatory organizations should:

- Continue developing advanced radiation-resistant remote handling equipment capable of handling 10,000 Sv/h or more that can be adapted for fusion use
- **Accept recycled materials** from dismantled nuclear facilities
- Continue national and international efforts to convince industrial and environmental groups that **clearance** can be conducted safely with no risk to public health
- Consider <u>fusion-specific</u> and advanced nuclear materials and issue official guidelines for unconditional release of clearable materials.