Goals, Challenges, and Successes of Managing Fusion Active Materials

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8th International Symposium on Fusion Nuclear Technology
ISFNT-8
October 1-5, 2007
Heidelberg, Germany

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 waste 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 lanfill.

- **Why?**
  - Limited capacity of existing low-level waste repositories
  - Political difficulty of building new repositories
  - 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.

Geological Disposal

- Majority of fusion power plants will generate only low-level waste (LLW) that requires near-surface, shallow-land burial if all fusion materials are carefully chosen to minimize long-lived radioactive products.

- In specific cases, even though reprocessing seemed technically feasible, disposal scheme emerged as preferred option for economic reasons.

- In all countries, LLW represents about 90% of all fission radwaste volume.

- Few countries are likely to have deep-mined geological repository. HLW Hanford facility has been in operation in US since 1960. In 1990s, only one such repository was granted license: U.S. Waste Isolation Pilot Plant (WIPP).

- No HLW facility in Europe or Japan.

Ten LLW Repositories in US, EU, J

- **US:**
  - **Barnwell repository*** in South Carolina – Class A, B, C LLW
  - **Richland repository** in Washington – Class C LLW
  - **Clive repository** in Utah – Class A LLW
  - Many nuclear facilities are currently storing their LLW (and HLW) onsite because of limited and expensive offsite disposal options.

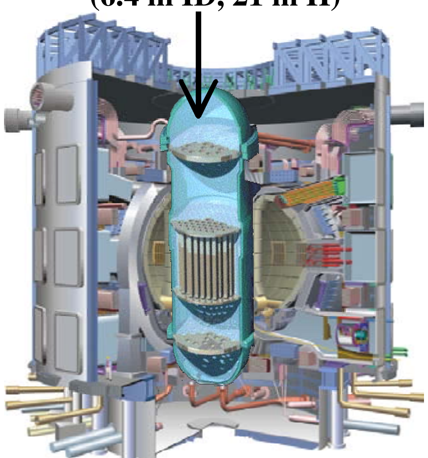
- **Europe:**
  - **LILW repository** in **France** (CSA), **Spain** (El Cabril), **Sweden** (SFR), **United Kingdom** (Drigg), and **Finland** (at each nuclear power plant site)
  - **VLLW repository** in **France**.

- **Japan:**
  - One repository in **Rokkasho** for LLW(II).

* Barnwell facility may limit in 2008 amount of LLW that they currently accept.

Fusion Generates Large Amount of LLW that would Fill Repositories Rapidly

Economic Simplified Boiling Water Reactor - Gen-III$^+$
ESBWR Vessel
(6.4 m ID, 21 m H)



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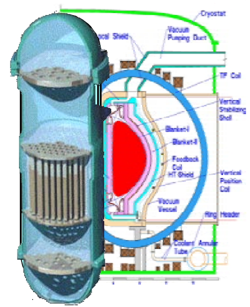
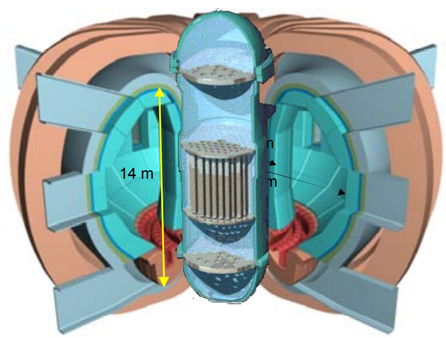
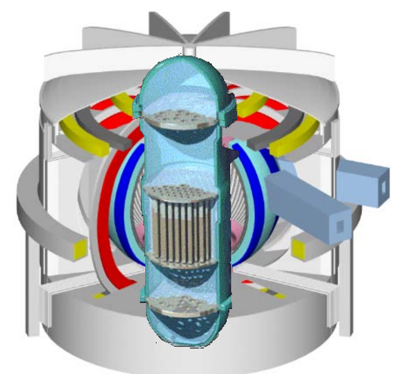


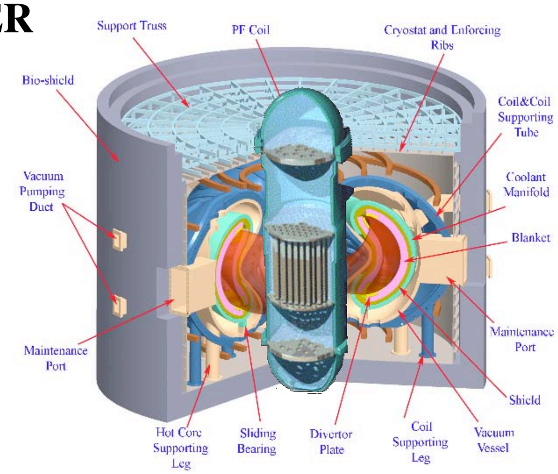
ARIES-AT



PPCS



VECTOR



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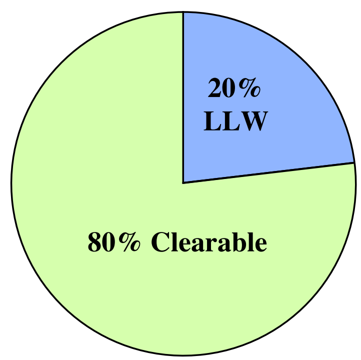
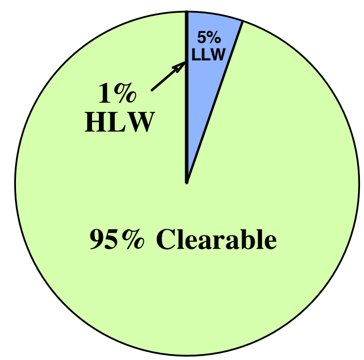


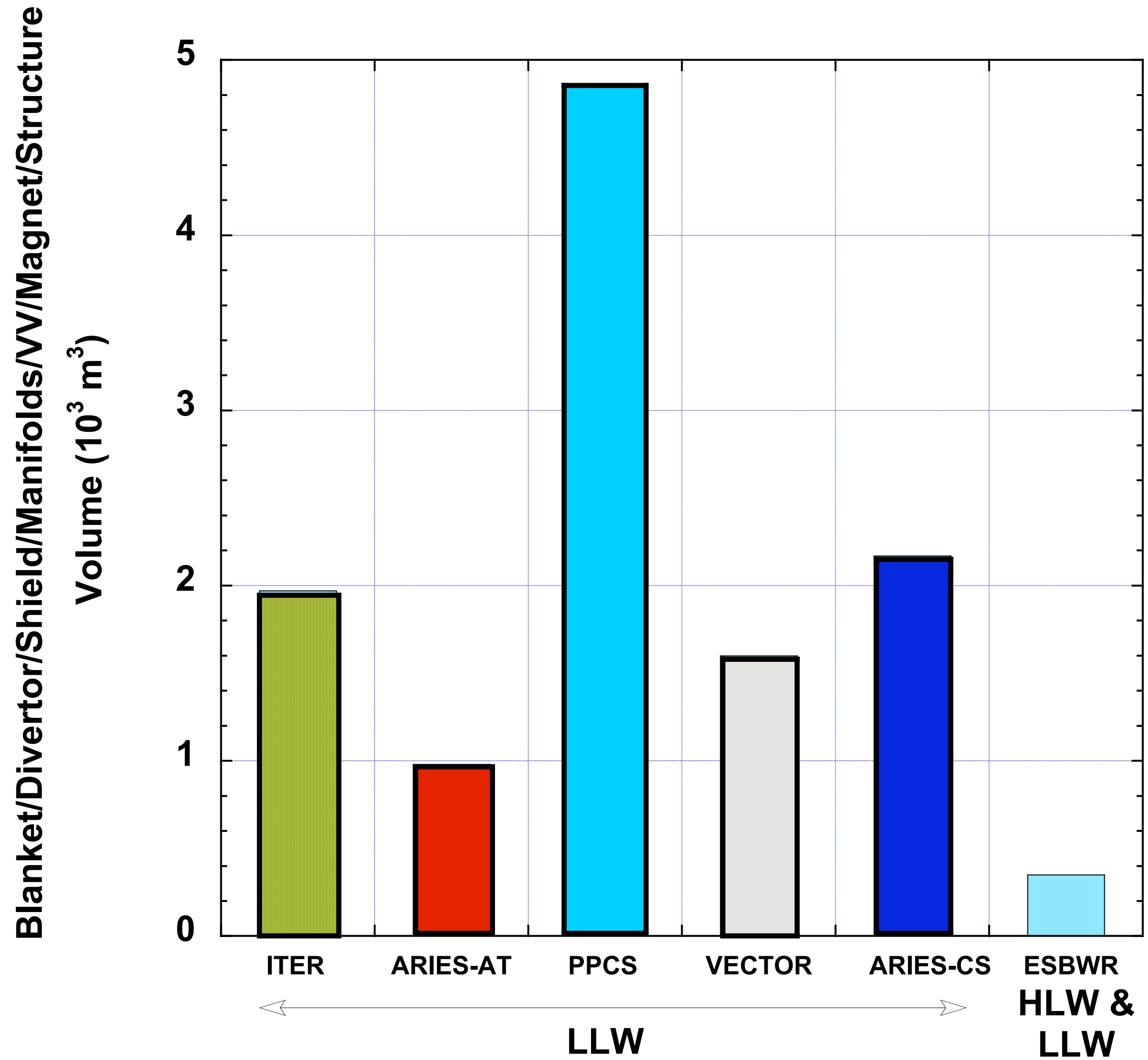
Fusion



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

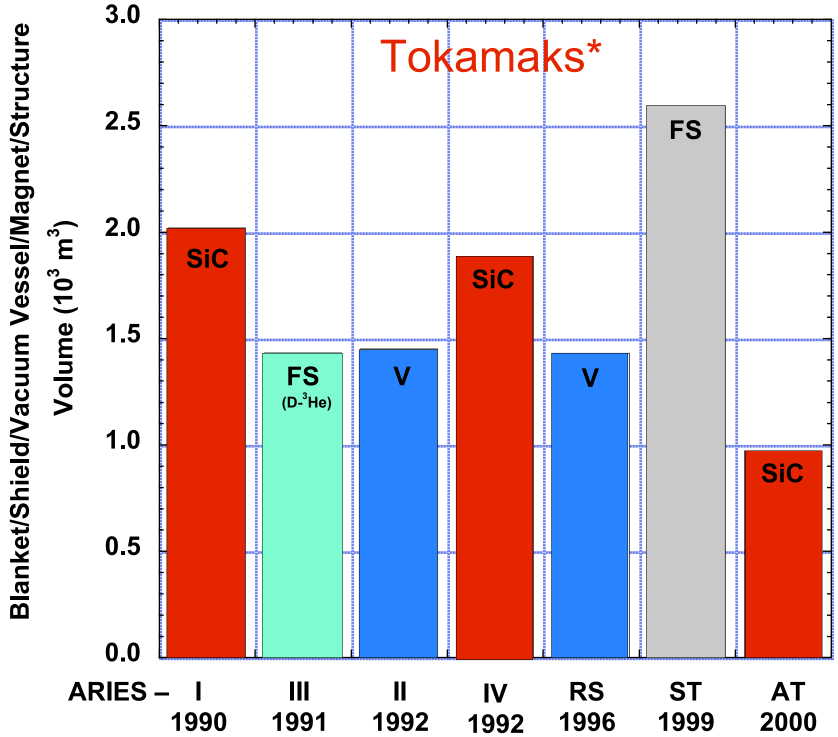
  C – Clear slightly-irradiated materials

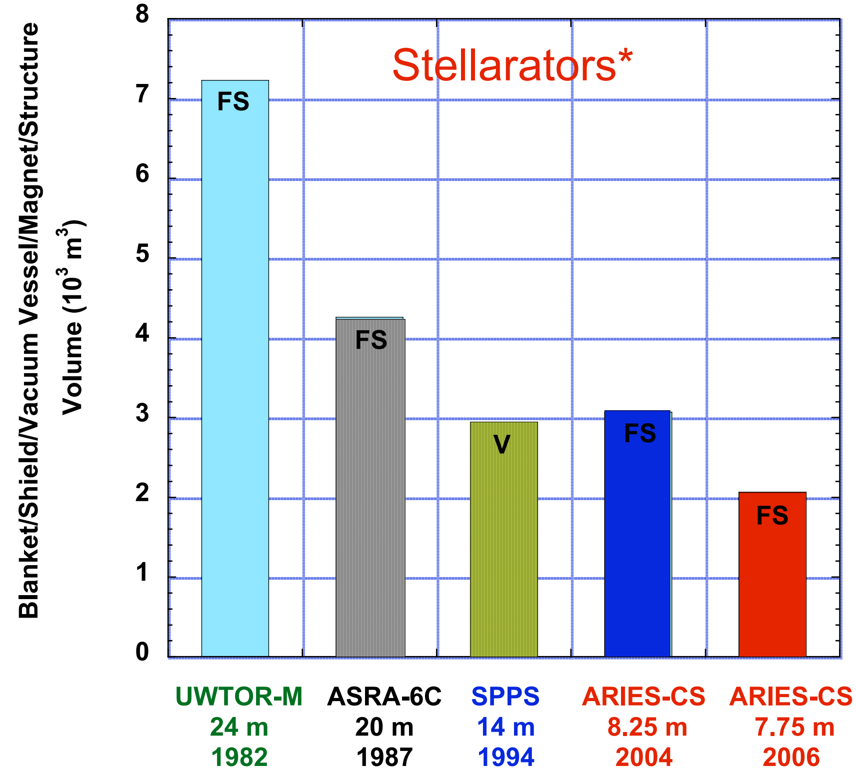
  B – Burn active fusion byproducts, if any, in fusion devices[@].

@ 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



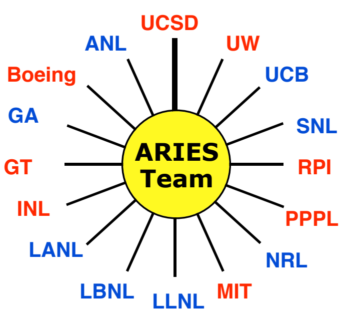


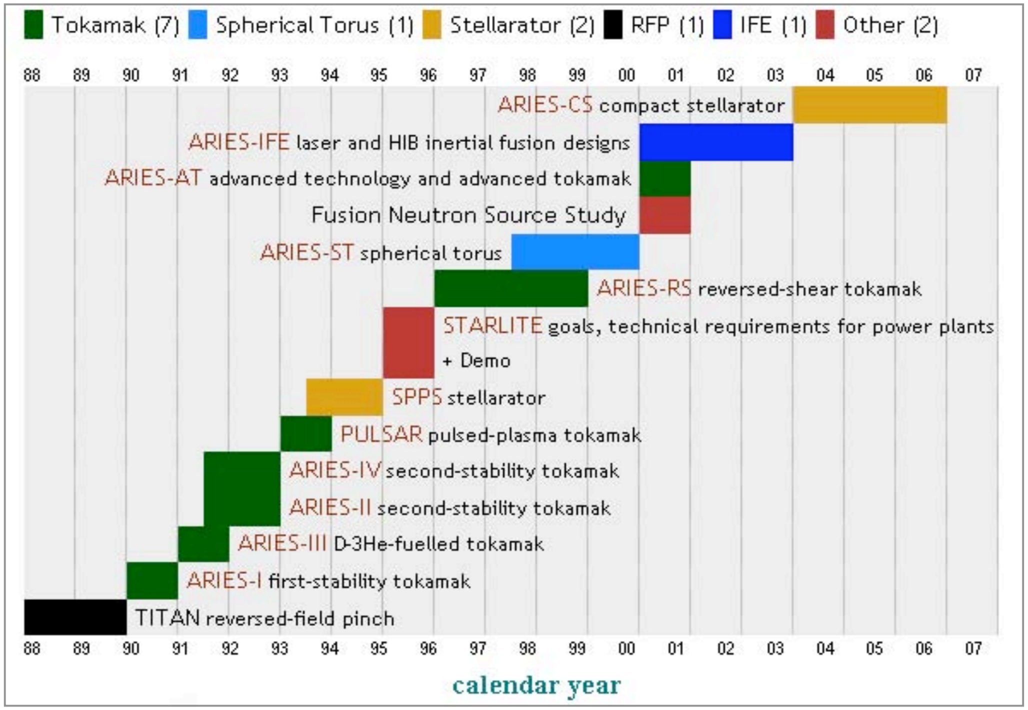
Tokamak waste volume halved over 10 y study period

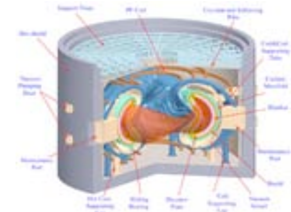
Stellarator waste volume dropped by 3-fold over 25 y study period

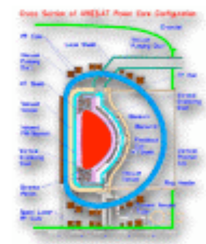
* Actual volumes of components (not compacted, no replacements).

ARIES Designs
(1988-2007)






ARIES-CS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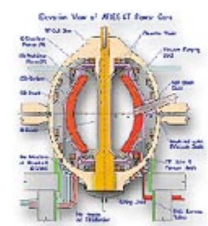
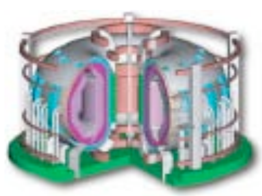
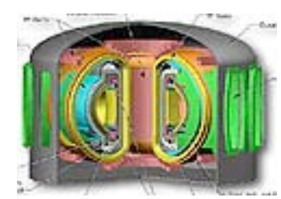

ARIES-ST


ARIES-I


ARIES-III


ARIES-IV


SPPS


ARIES-RS

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	**Targets#**	no (for economic reasons)	yes / no	**yes** (as Class A LLW)
Z-Pinch-IFE	**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).

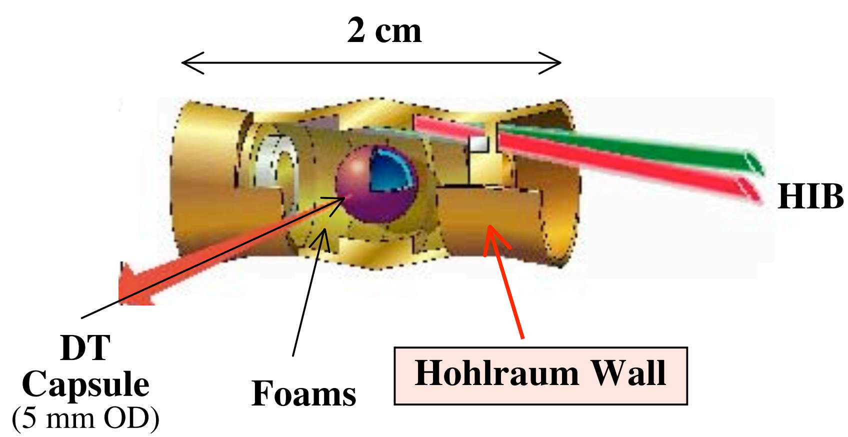
* L. El-Guebaly, P. Wilson, and M. Sawan, "Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant," to be published in *Fusion Science & Technology*.

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**

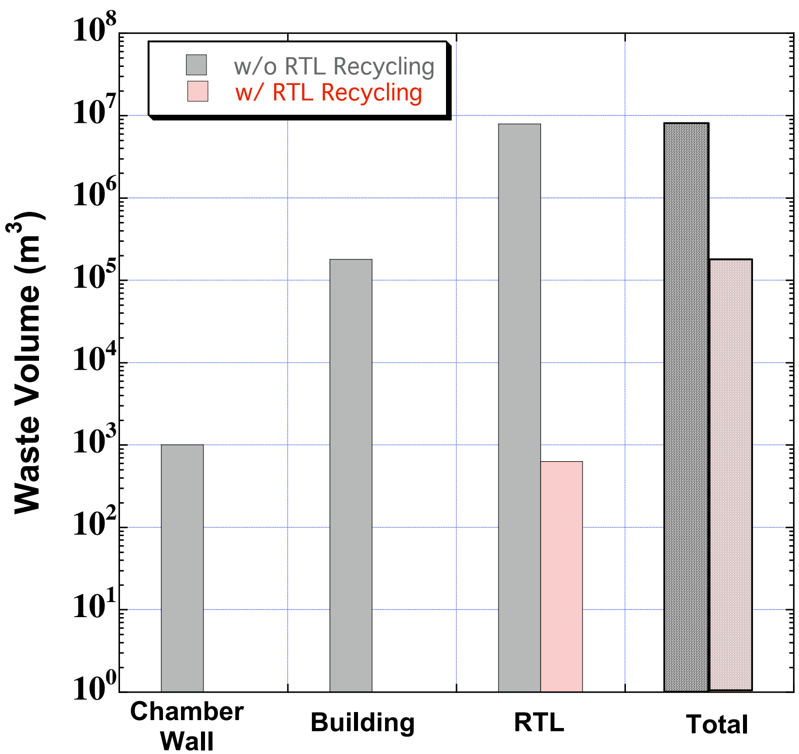
Preferred Option

- **Recycling** of hohlraum walls **doubles COE.**
- Hohlraum walls represent **< 1% of waste stream.**
- Once-through use generates **Class A** LLW.
- **Target factory designers prefer dealing with non-radioactive hohlraum wall materials.**

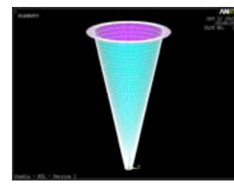


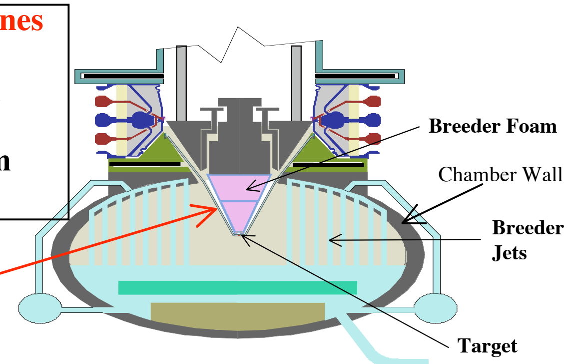
ARIES-IFE Target

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

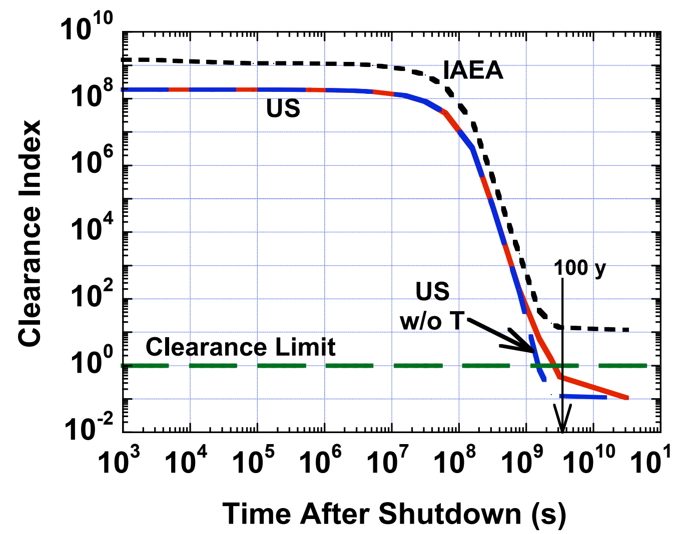


Recyclable Transmission Lines
Top diameter = 1 m
Bottom diameter = 0.1 m
Length = 2 m
Total thickness = 0.142 cm
50 kg / RTL





Z-Pinch Chamber

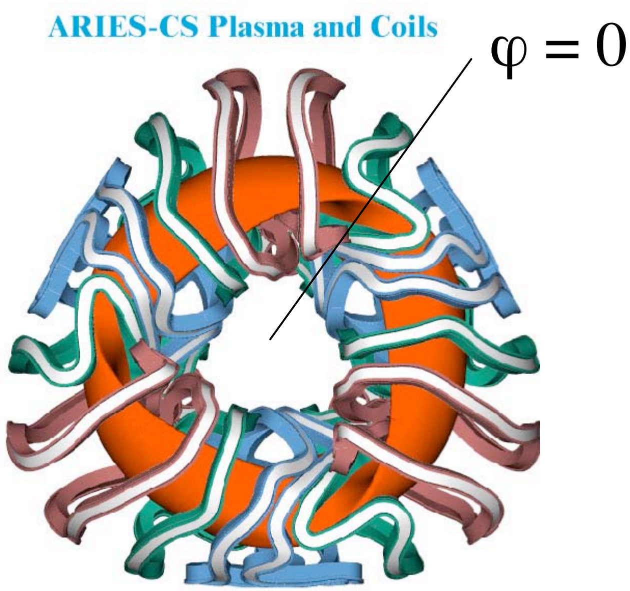


No recycling during 40 FPY
Total RTL volume = 7 M m^3

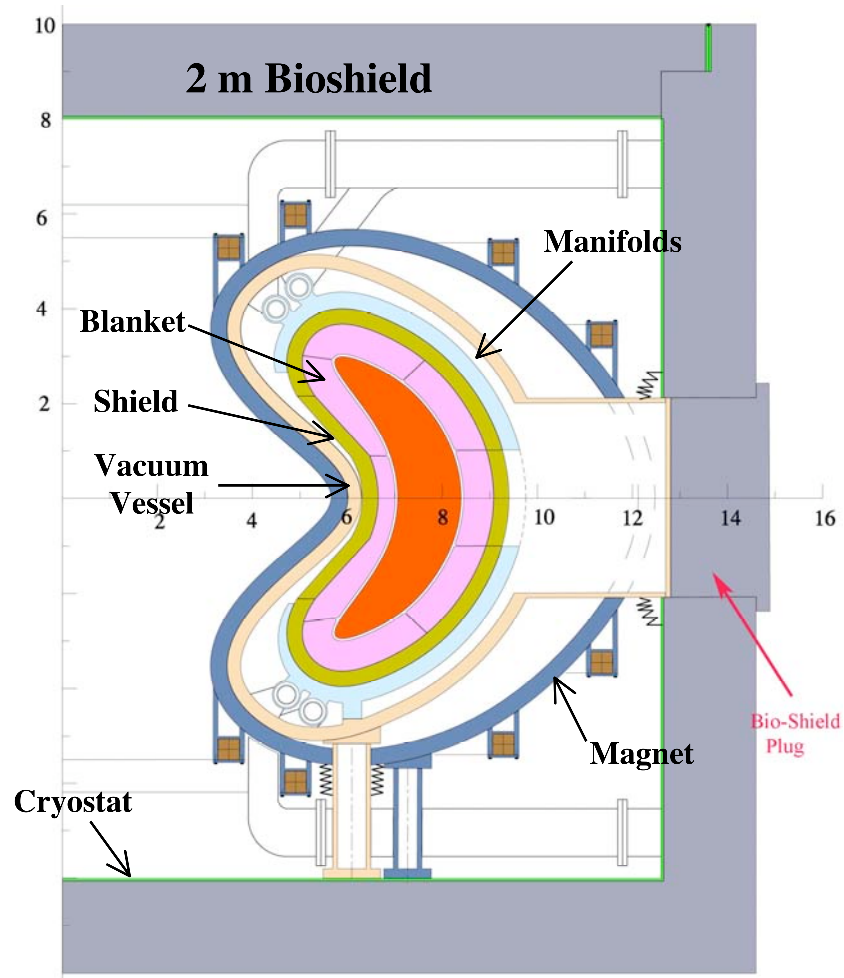
With recycling
1.1 day RTL inventory
Total RTL volume = 0.0005 M m^3

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

ARIES Compact Stellarator

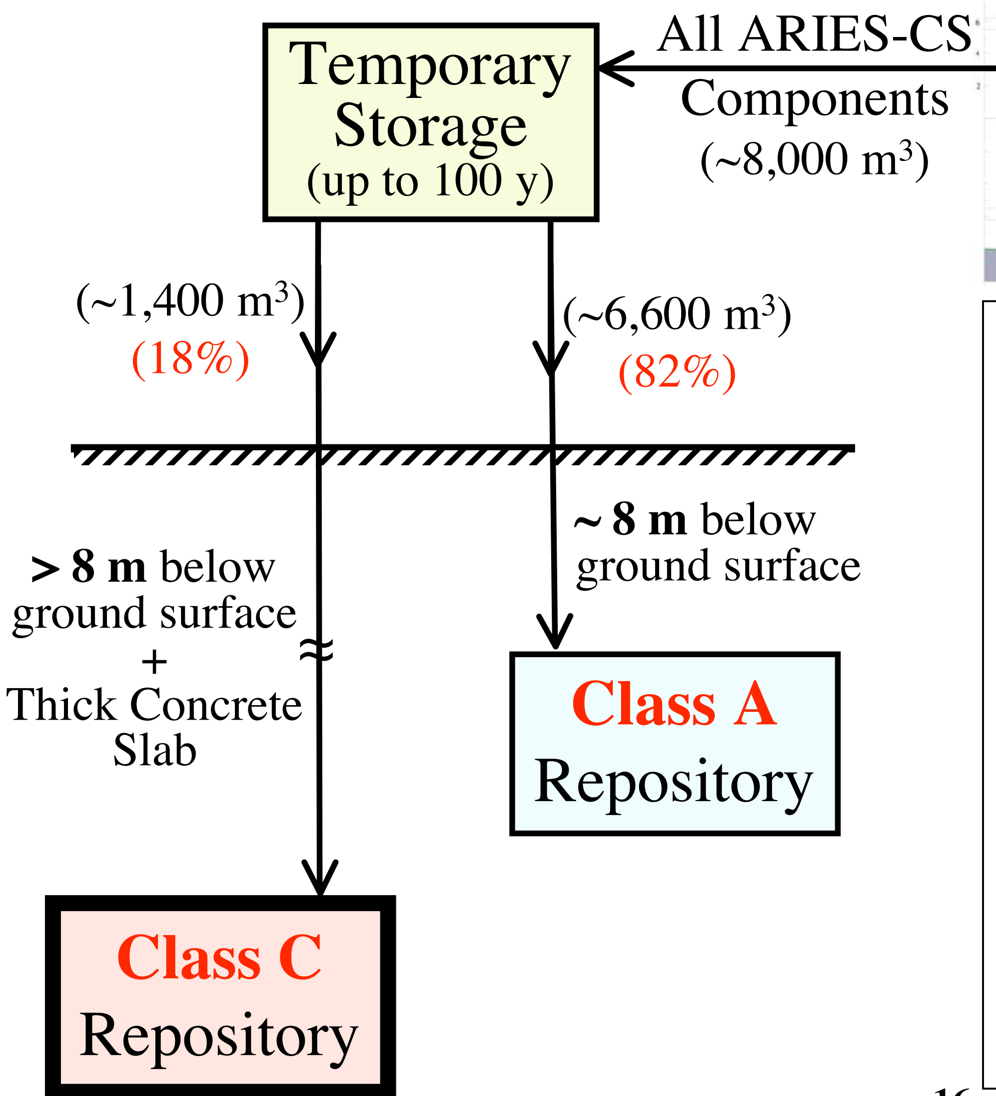


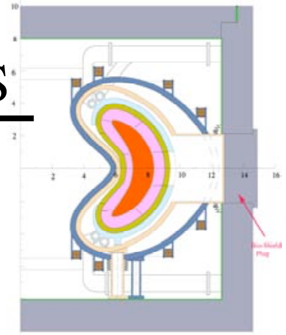
- 3 Field Periods.
- LiPb/He/FS System.
- 7.75 m Major Radius.
- 2.6 MW/m^2 Average NWL.
- 3 FPY Replaceable FW/Blanket.
- 40 FPY Permanent Components.
- ~78 mills/kWh COE ($2004).



ARIES-CS Cross Section @ φ = 0

ARIES-CS LLW Classification for Geological Disposal



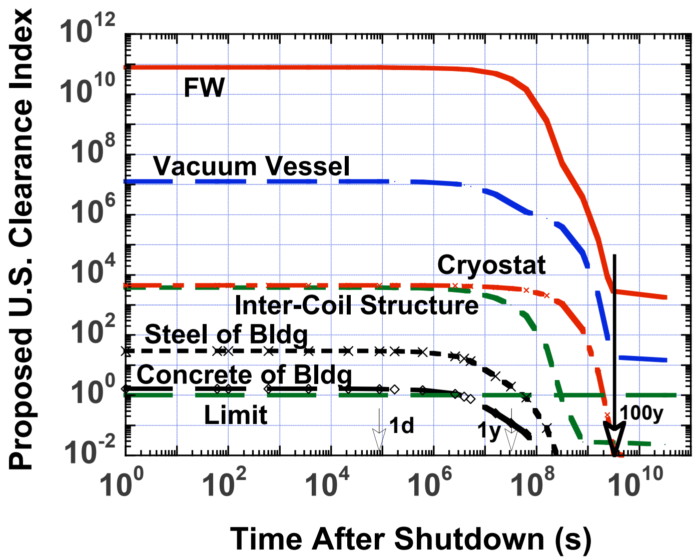


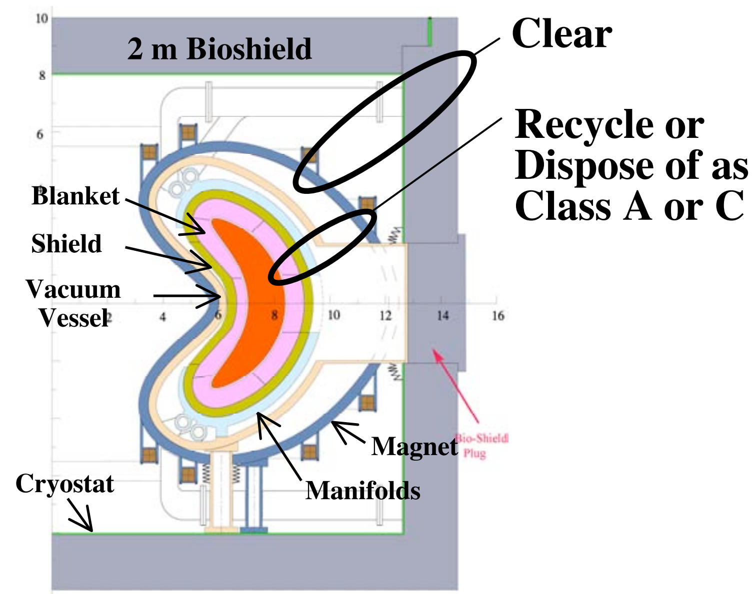
Least hazardous type of waste

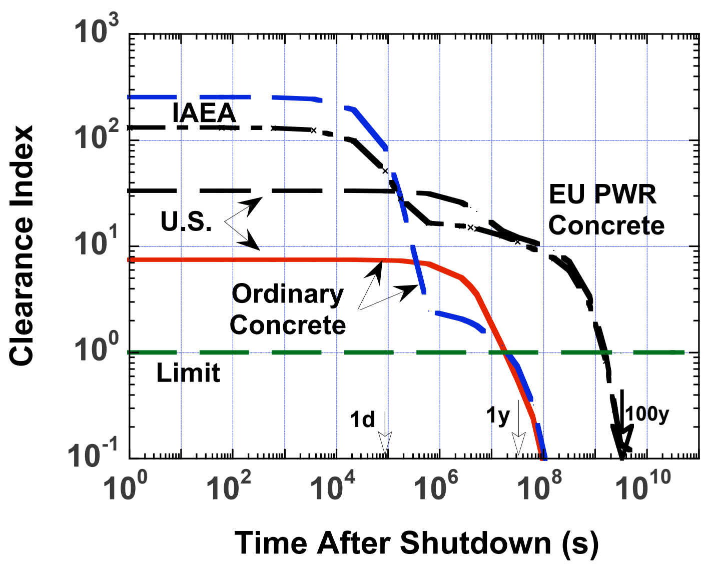
	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		**no**
Shield/Manifolds	√		**no**
Vacuum Vessel		√	**no**
Magnet:			
Nb_3Sn	√		**no**
Cu Stabilizer		√	√
JK2LB Steel*		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

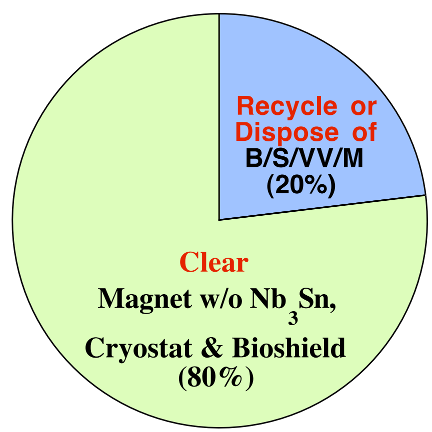
* Preferred over Incoloy-908 for clearance considerations.

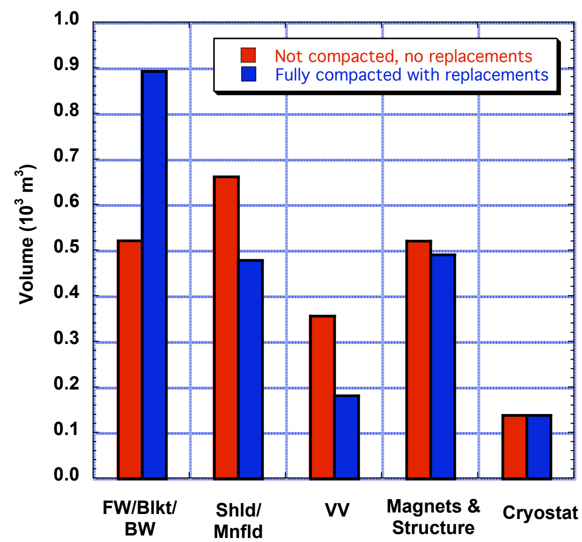
80% of ARIES-CS Active Materials can be Cleared in < 100 y after Decommissioning



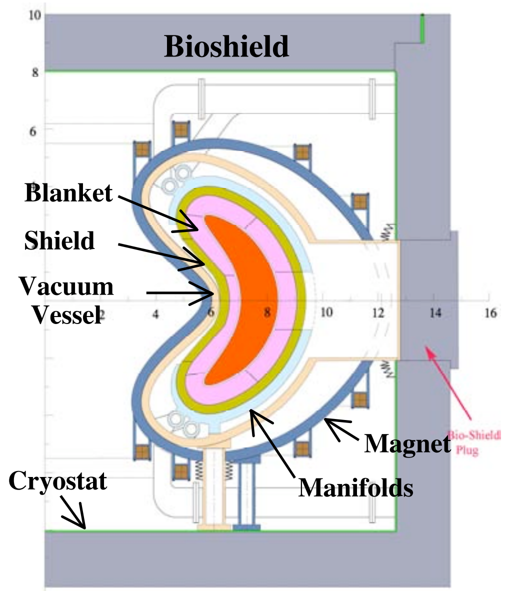


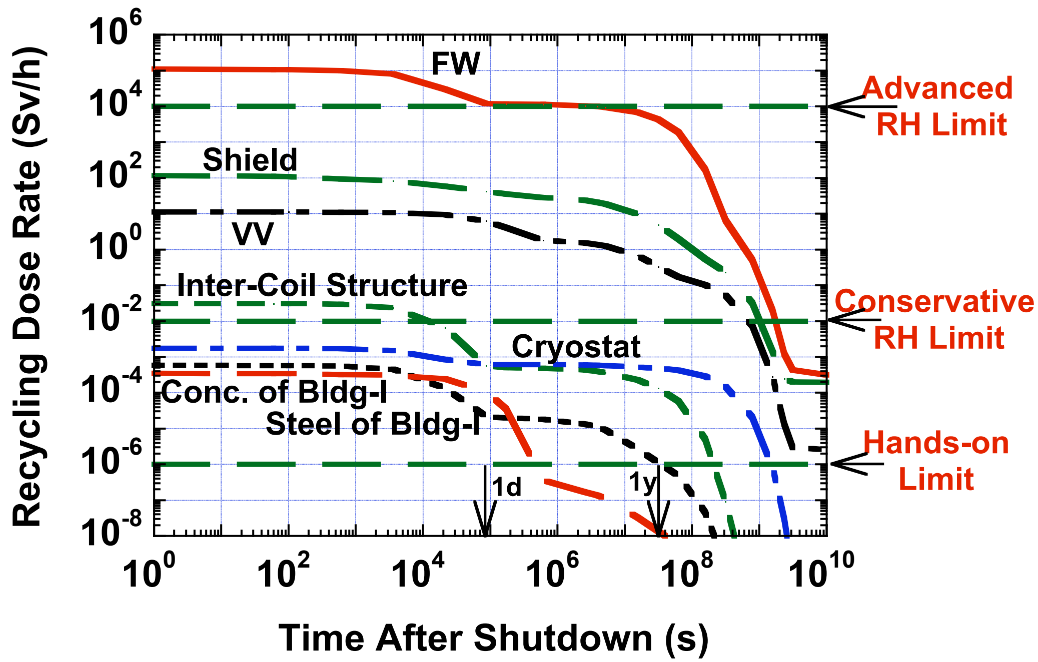






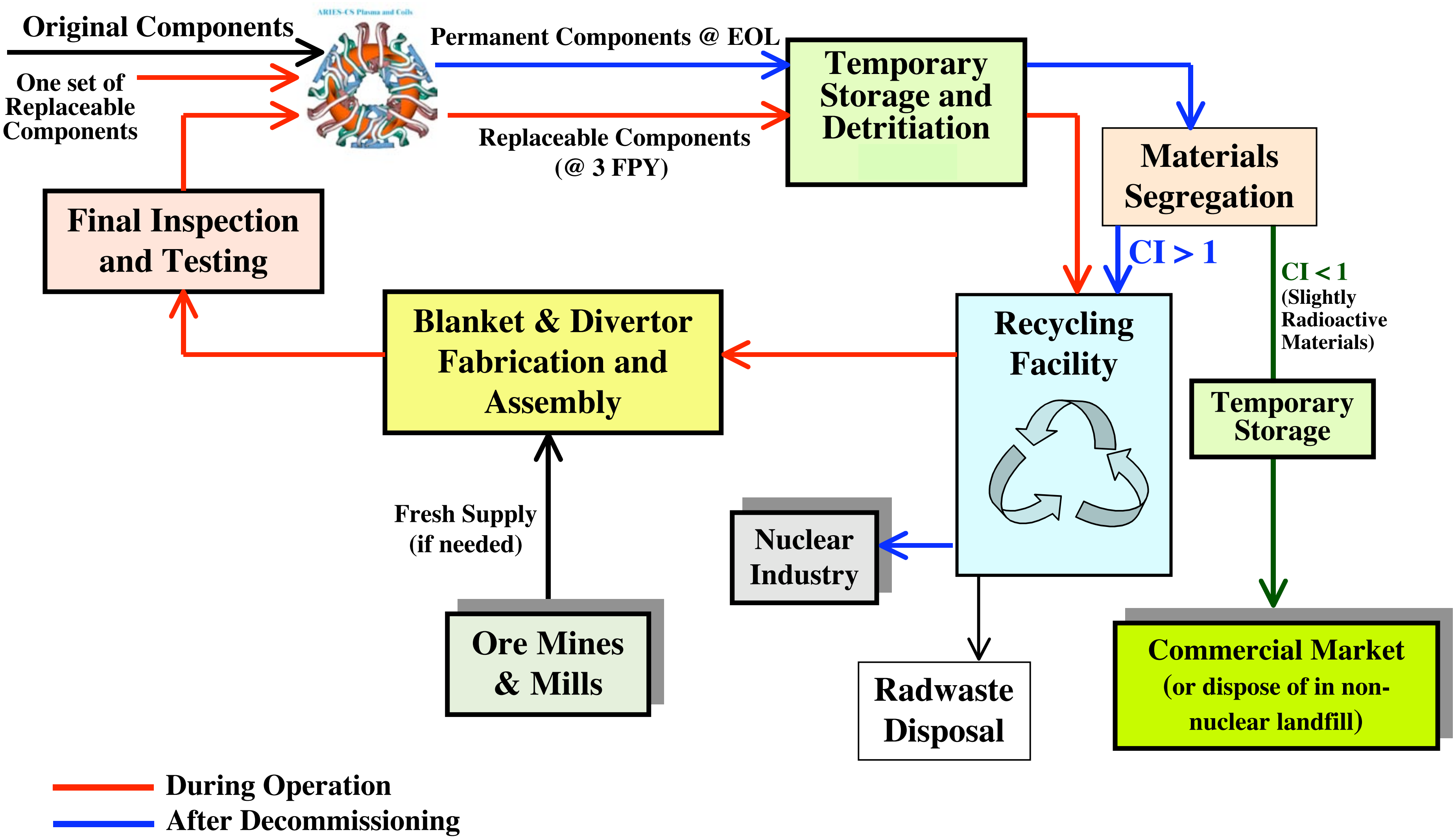
All ARIES-CS Components can Potentially be Recycled in < 1 y Using Advanced RH Equipment





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

Recycling & Clearance Flow Diagram



General Observations

- US, EU, and J 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 recycling

  ⇒ detritiation prior to recycling is necessary for fusion components.
- Several **critical issues** still need further investigation for all three options:
  - Disposal
  - Recycling
  - Clearance

Disposal Issues

- Large volume to be disposed of (7,000 - 8,000 m^3 per 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 activated materials
- 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)*
- Large interim storage facility
- 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
- Any materials for disposal? Volume? Radwaste level?
- Properties of recycled materials? Any structural role? Reuse as filler?
- Aspects of radioisotopes buildup by subsequent reuse and radiotoxicity buildup
- Recycling plant capacity and support ratio
- Acceptability of nuclear industry to recycled materials
- Recycling infrastructure.

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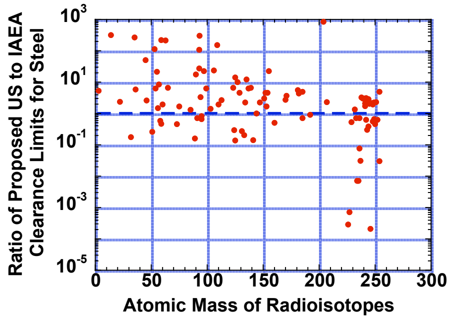
* Ref.: R. Pampin, R.A. Forrest, R. Bestwick, Consideration of strategies, industry experience, processes and time scales for the recycling of fusion irradiated material, UKAEA report FUS-539 (2006).

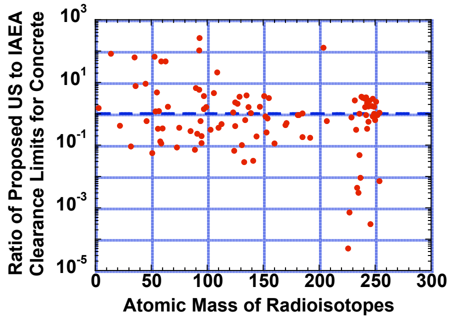
Clearance Issues

- 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 fusion-specific clearance limits



- Large interim storage facility

- Clearance infrastructure

- Availability of clearance market (some experience already exists in several E.U. countries: Sweden, Germany, Spain, and Belgium. Currently, U.S. industries do 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 with 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
  - 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.

EU Recycling R&D Program

- Ongoing EU studies focus on R&D issues that should be addressed in order to recycle as much materials as possible in safe, economical, and environmentally friendly manner*.

- Studies comprise review of current status and state-of-the art methods to recycle typical materials and components of EU Power Plant Conceptual Studies (PPCS).

- **Main conclusions**:
  - Recycling of fusion materials is a challenge.
  - Material treatment includes detritiation, segregation of various materials, cutting, crushing, melting, re-fabrication, refurbishing of liquid breeders, and packaging/shipping.
  - Solutions and routes to follow should be developed ASAP in order to tackle arising issues.

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* Refs.: V. Massaut et.al., "State-of-the-Art of Fusion Material Recycling and Remaining Issues," to be published n Fusion Engineering & Design.
L.Ooms and V. Massaut, "Feasibility of Fusion Waste Recycling," SCK-CEN Report, R-4056, 276/05-01 (2005).
R. Pampin, R.A. Forrest, R. Bestwick, "Consideration of Strategies, Industry Experience, Processes and Time Scales for the Recycling of Fusion Irradiated Material," UKAEA report FUS-539 (2006).

Recommendations

Regarding the huge amount of activated materials involved in fusion power plants,

Fusion designers should:

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

Nuclear industry and organizations should:

- Continue developing advanced radiation-resistant remote handling equipment capable of handling 10,000 Sv/h or more
- **Accept recycled materials** from dismantled nuclear facilities
- National and international organizations (US-NRC, IAEA, etc.) continue their efforts to convince industrial and environmental groups that **clearance** can be conducted safely with no risk to public health
- Regulatory agencies take into account <u>fusion-specific</u> and advanced nuclear materials and issue official guidelines for unconditional release of clearable materials.