Evaluation of Disposal, Recycling, and Clearance Scenarios for Managing ARIES Radwaste after Plant Decommissioning

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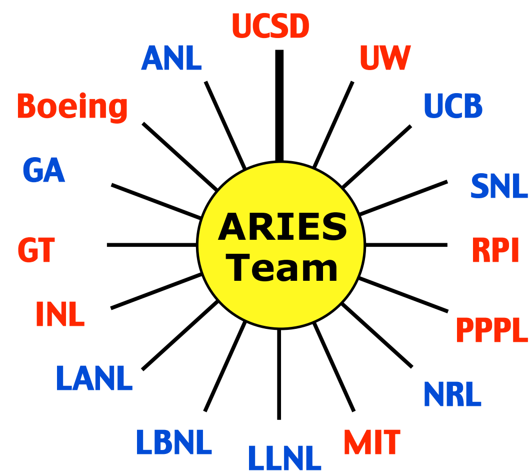
The ARIES Project

ARIES Mission

Perform advanced integrated design studies of long term fusion energy embodiments to identify key R&D directions and provide vision for the U.S. fusion program.

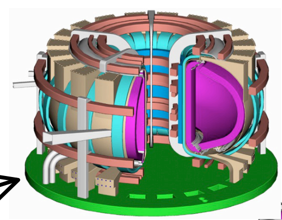
ARIES Goal

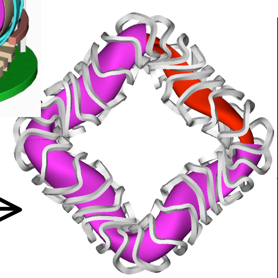
Demonstrate that fusion power can be a safe, clean, and economically attractive option.

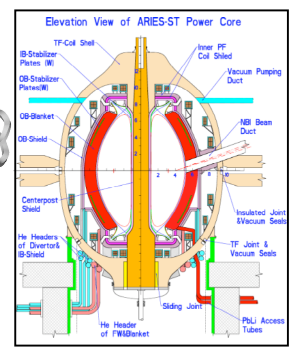


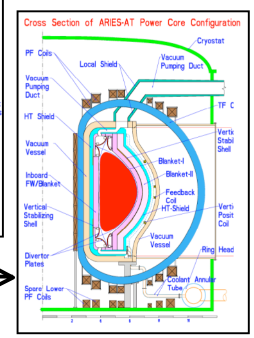
ARIES team examined numerous concepts as 1 GWe Power Plants:

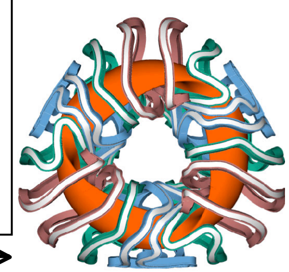
- **TITAN** reversed-field pinch (1988)
- **ARIES-I** first-stability tokamak (1990)
- **ARIES-III** D-^{3}He-fueled tokamak (1991)
- **ARIES-II and -IV** second-stability tokamaks (1992)
- **Pulsar** pulsed-plasma tokamak (1993)
- **SPPS** stellarator (1994)
- **Starlite** study (1995) (goals & technical requirements for power plants & Demo)
- **ARIES-RS** reversed-shear tokamak (1996)
- **ARIES-ST** spherical torus (1999)
- Fusion neutron source study (2000)
- **ARIES-AT** advanced technology and advanced tokamak (2000)
- **ARIES-IFE** laser and HIB inertial fusion designs (2000-2003)
- **ARIES-CS** compact stellarator (2003-2006)











ARIES Power Plants Demonstrate Adequate Performance in Several Safety Areas

Environmental impact:

- **Minimal radioactive releases**# during normal and abnormal operations.
- **No high-level waste**.
- **Low activation materials** with strict impurity control
  → minimal long-term environmental impact.

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, etc).

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

- 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.

Recent Trend in Radwaste Management

- **Options**:
  - **Disposal** in repositories: LLW (WDR < 1) or HLW (WDR > 1)
  - **Recycling** – reuse within nuclear facilities (dose < 3000 Sv/h)
  - **Clearance** – release slightly-radioactive materials to commercial market if CI < 1.

- Tighter environmental controls and the political difficulty of building new repositories worldwide may force fusion designers to promote recycling and clearance, avoiding geological disposal **no radwaste burden on future generations**.

- There's **growing international effort** in support of this new trend.

- Recycling may not be economically feasible for all fusion components.

- Recycling of liquids and solids may generate limited amount of radioactive waste that needs special treatment.

Adopt MRCB Philosophy

M – Minimize volume of active materials by design

D. Petti, B. Merrill, R. Moore, G. Longhurst, L. El-Guebaly, E. Mogahed, D. Henderson, P. Wilson, and A. Abdou, "ARIES-AT safety design and analysis," Fusion Engineering and Design, **80**, 111-137 (Jan 2006).

L. El-Guebaly, "Development of Radwaste Volume Minimization Schemes for ARIES Power Plants," to be published.

R – Recycle <u>if</u> economically and technologically feasible

L. El-Guebaly, P. Wilson, D. Henderson, A. Varuttamaseni, and the ARIES Team, "Recycling of IFE Target Materials versus One-Shot Use Scenario: Key Issues and Preferred Option," University of Wisconsin Fusion Technology Institute Report, UWFDM-1183 (November 2002). Available at: http://fti.neep.wisc.edu/pdf/fdm1183.pdf

L. El-Guebaly, P. Wilson, M. Sawan, D. Henderson, and A. Varuttamaseni, "Radiological Impact of IFE Target and RTL Recycling Option: A Comparative Study," University of Wisconsin Fusion Technology Institute Report, UWFDM-1227 (July 2004). Available at: http://fti.neep.wisc.edu/pdf/fdm1227.pdf

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L. El-Guebaly, P. Wilson, M.E. Sawan, "Recycling and Clearance of the Slightly Activated RTLs of the 2005 Z-Pinch Design," University of Wisconsin Fusion Technology Institute Report, UWFDM-1284 (October 2005). Available at: http://fti.neep.wisc.edu/pdf/fdm1284.pdf

M. Zucchetti, L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, K. Tobita, "The Feasibility of Recycling and Clearance of Active Materials from Fusion Power Plants," ICFRM-12 conference at Santa Barbara (Dec. 4-9, 2005). To be published in Journal of Nuclear Materials.

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D. Petti et al., "Future Directions in U.S. Fusion Safety & Environmental Program," 8th IAEA TM on Fusion Power Plant Safety (July 10-13, 2006, Vienna, Austria).

C – Clear slightly-irradiated materials

L. El-Guebaly, D. Henderson, A. Abdou, and P. Wilson, "Clearance Issues for Advanced Fusion Power Plants", Fusion Technology, <u>39</u>, No. 2, 986-990 (2001).

L. El-Guebaly, P. Wilson, and D. Paige, "Status of US, EU, and IAEA Clearance Standards and Estimates of Fusion Radwaste Classifications," University of Wisconsin Fusion Technology Institute Report, UWFDM-1231 (December 2004). Available at: http://fti.neep.wisc.edu/pdf/fdm1231.pdf

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L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, K. Tobita, M. Zucchetti, "Current Challenges Facing Recycling and Clearance of Fusion Radioactive Materials," University of Wisconsin Fusion Technology Institute Report, UWFDM-1285 (Nov 2005). Available at: http://fti.neep.wisc.edu/pdf/fdm1285.pdf

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L. El-Guebaly, R. Pampin, and M. Zucchetti, "Insights from Clearance Assessments of Fusion Power Plants: ARIES and PPCS," University of Wisconsin Fusion Technology Institute Report, UWFDM-1292 (July 2006). Available at: http://fti.neep.wisc.edu/pdf/fdm1292.pdf

B – Burn long-lived radionuclides in fusion devices

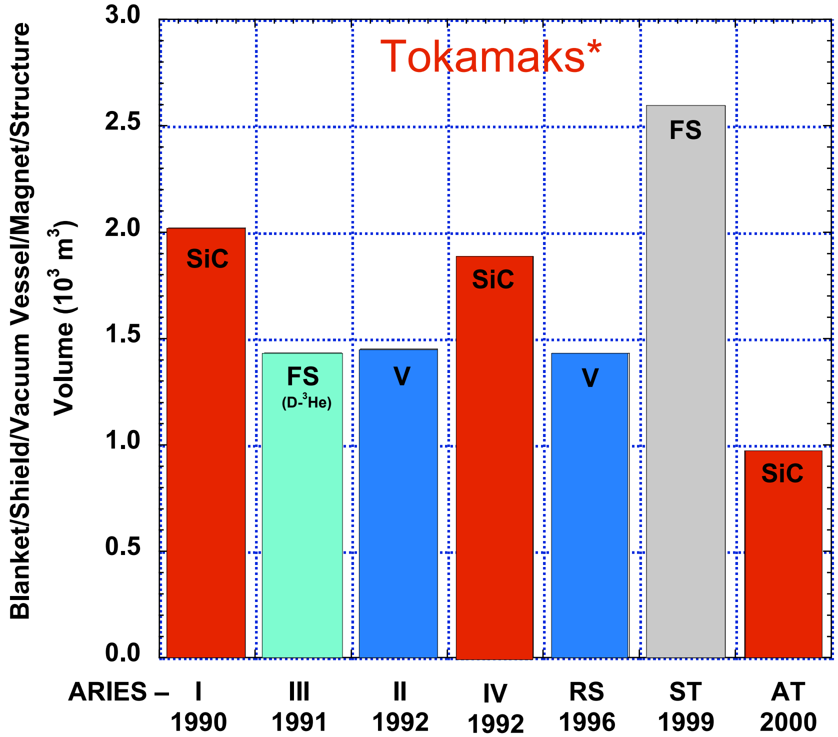
L.A. El-Guebaly, "Need for Special Burning Module in Fusion Devices to Transmute Fusion High-Level Waste," University of Wisconsin Fusion Technology Institute Report, UWFDM-1155 (June 2002). Available at: http://fti.neep.wisc.edu/pdf/fdm1155.pdf

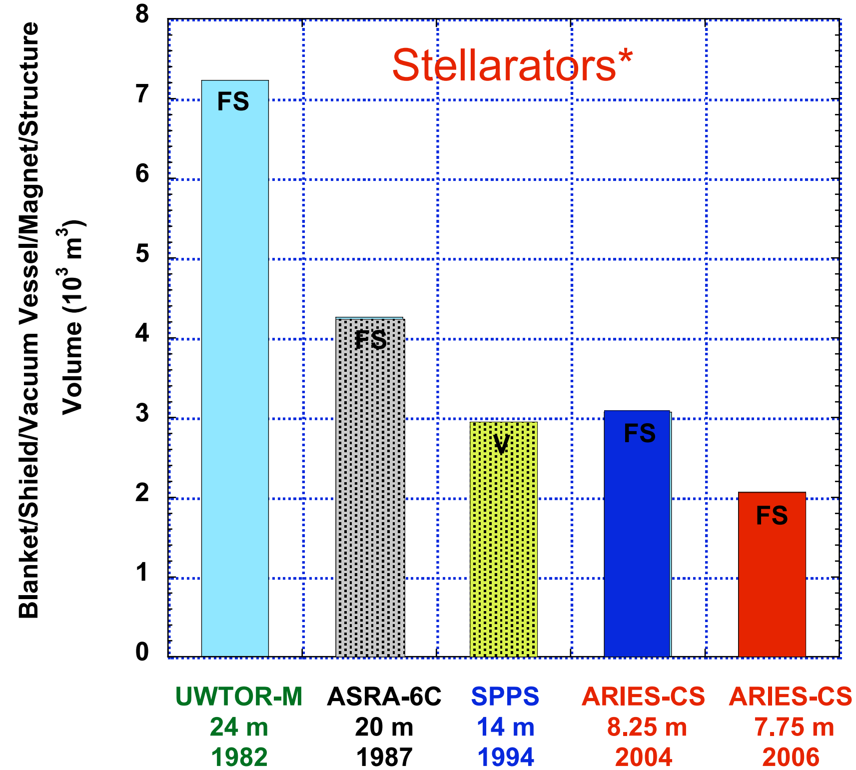
L. El-Guebaly, "Managing Fusion High Level Waste – a Strategy for Burning the Long-Lived Products in Fusion Devices," Fusion Engineering and Design, 81 (2006) 1321-1326.

Radwaste Minimization

Tokamaks and Stellarators

ARIES Project Committed to Waste Minimization





Tokamak waste volume halved over 10 y study period

Stellarator waste volume dropped by factor of 3 over 25 y study period

* Actual volumes (not compacted, no replacements).

Disposal, Recycling, and Clearance

IFE and MFE designs

Disposal, Recycling, Clearance Applied to Recent Fusion Designs

(red bold indicates preference)

	Components	Recycle?	Clear?	Dispose of @ EOL?
IFE:				
ARIES-IFE	Targets	no (for economic reasons)	yes / no	**yes** (as Class A)
Z-Pinch	RTL*	**yes** (a must during operation)	yes	yes (as Class A)
Any design	all	**yes**	yes / no	yes (as Class A/C)
MFE:				
ARIES-CS	all	**yes**	yes / no	yes (as Class A/C; Reference for ARIES project)

* Recyclable Transmission Lines.

Codes and Data

- **DANTSYS** neutral-particle transport code (1, 2, 3-D).

- **ALARA** **pulsed activation code***:
  – Explicit modeling of 85% availability.
  – Exact modeling of IFE pulses (> 10,000).

- **IAEA FENDL-2** **nuclear data**:
  175 neutron and 42 gamma group structure.

- **Standards and Guidelines**:
  NRC and Fetter's waste disposal limits.
  ANS □attenuation coefficients.
  2003 U.S. NRC proposed clearance limits.
  2004 IAEA clearance limits.

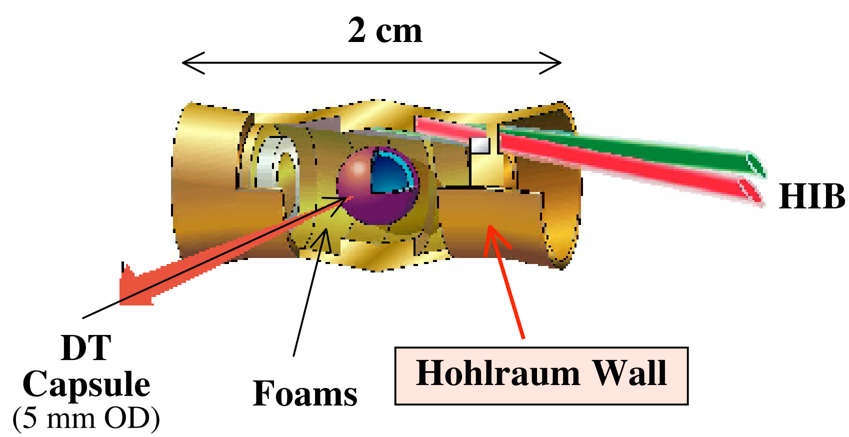
* P. Wilson and D. Henderson, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis Code Technical Manual," University of Wisconsin Fusion Technology Institute, UWFDM-1070 (January 1998). Available at: http://fti.neep.wisc.edu/pdf/fdm1070.pdf

Economics Prevent Recycling of ARIES-IFE-HIB Targets

	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**

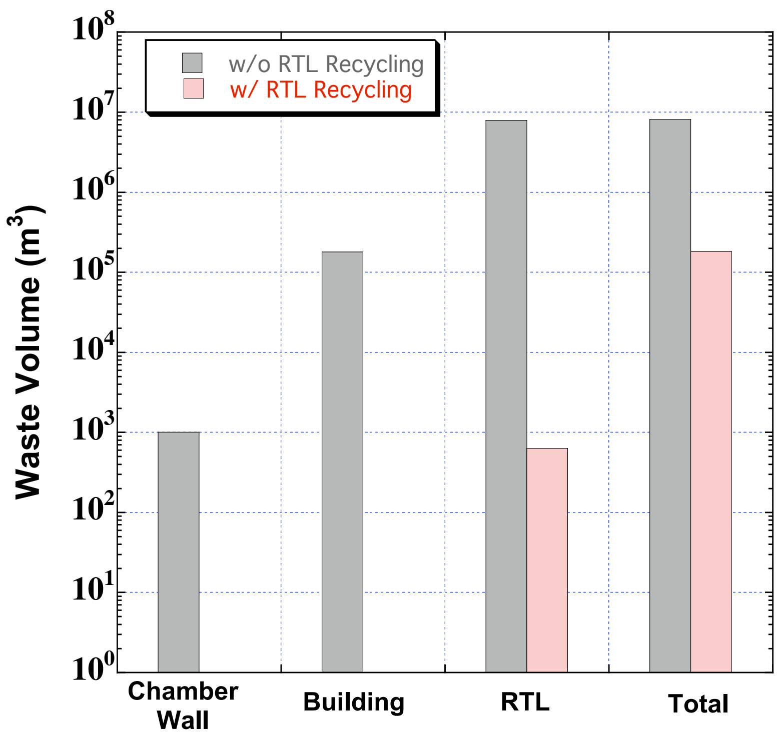
Preferred Option (One-Shot Use Scenario)

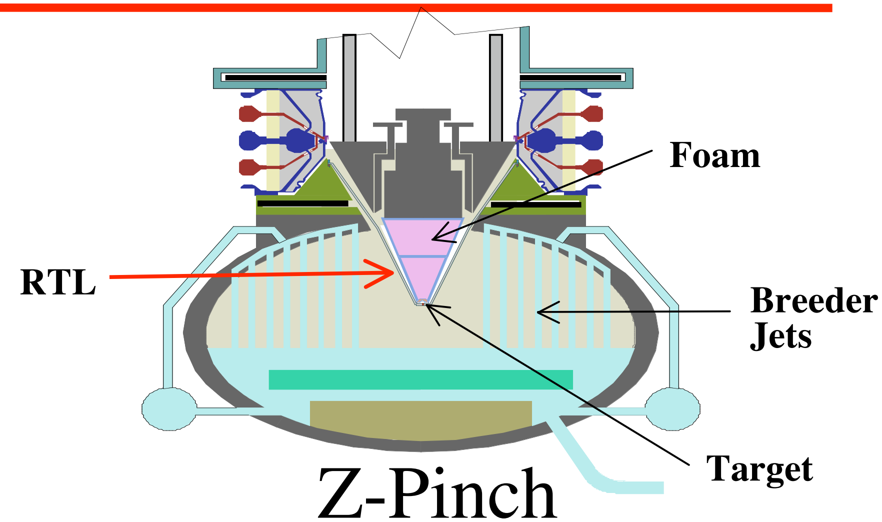
- Hohlraum wall materials represent < 1% of waste stream.
- Once-through use generates Class A LLW. Few materials (Au, Hg, Ta) have CI < 1.
- Target factory designers prefer dealing with non-radioactive hohlraum wall materials.

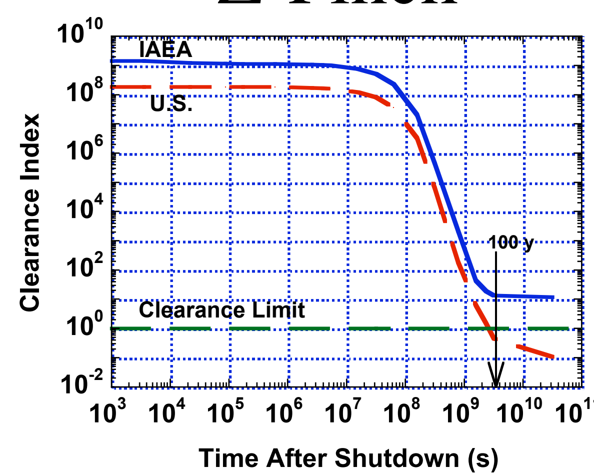


ARIES-IFE Target

Recycling is a "Must" Requirement for RTL to Minimize Waste Stream and Enhance Economics







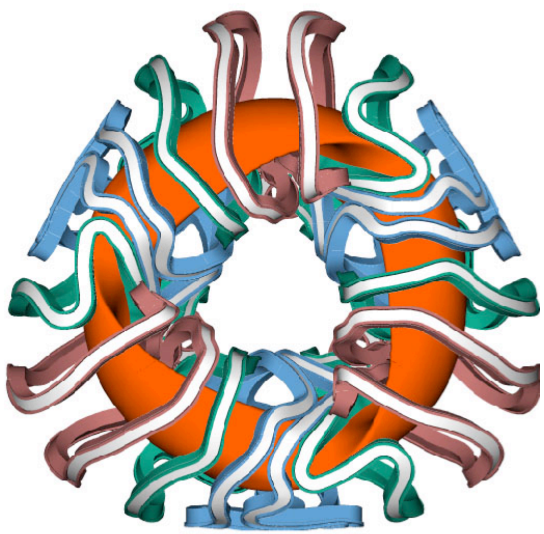
No recycling for 40 FPY
Total RTL mass = 70 M Tons

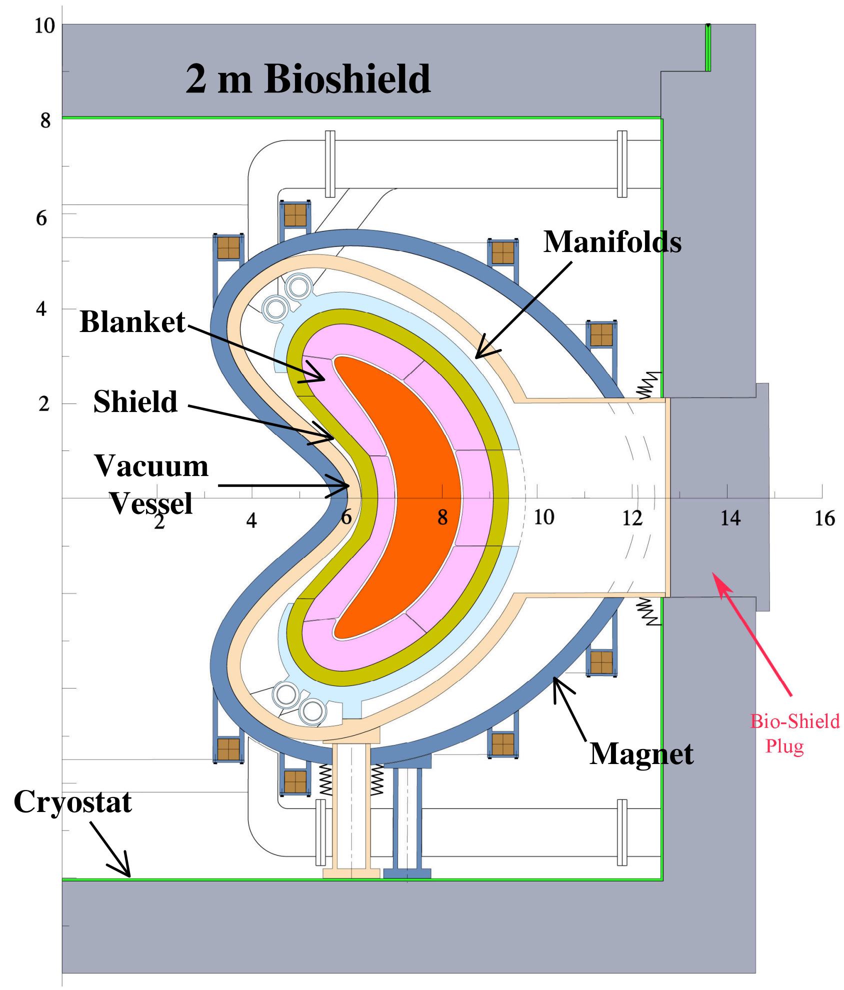
With recycling
1.1 day RTL inventory
Total RTL mass = 0.005 M Tons

RTL could be cleared after 85 y following decommission

ARIES Compact Stellarator

ARIES-CS Plasma and Coils





3 Field Periods.

LiPb/FS/He System.

7.75 m Major Radius.

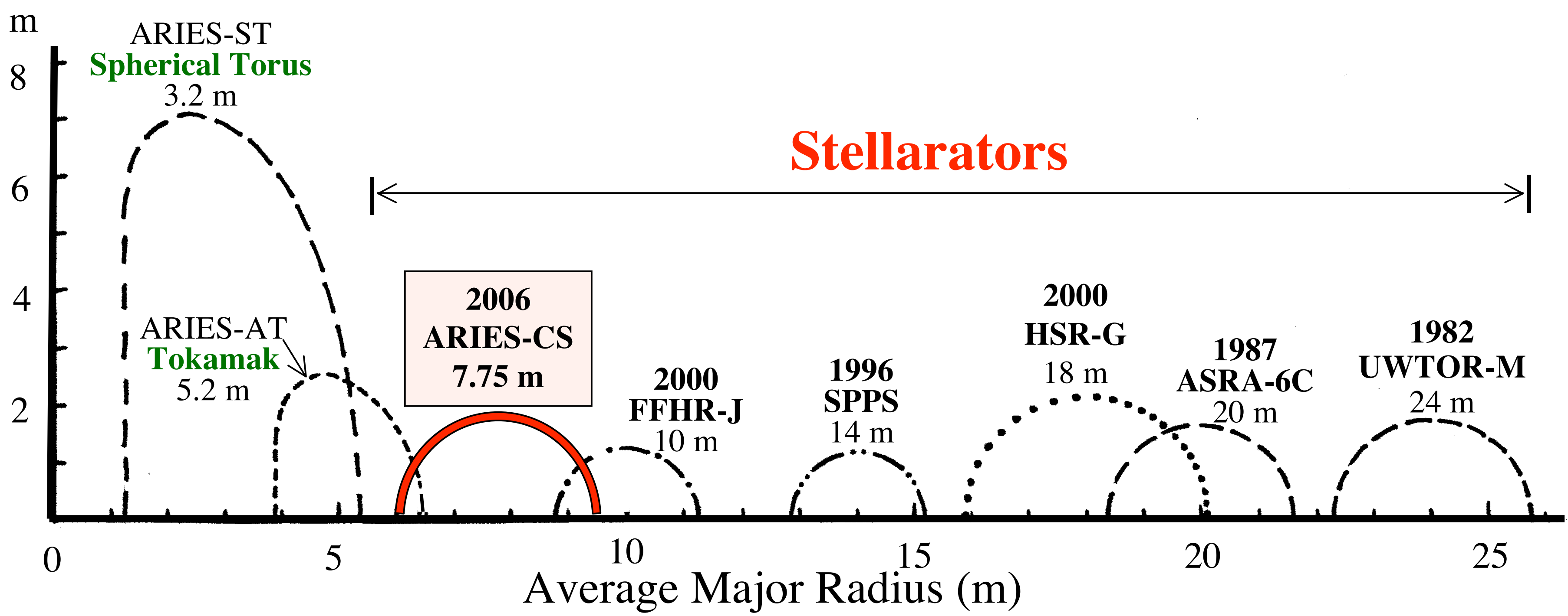
2.6 MW/m^2 Average NWL.

3.9 FPY Replaceable FW/Blanket.

40 FPY Permanent Components.

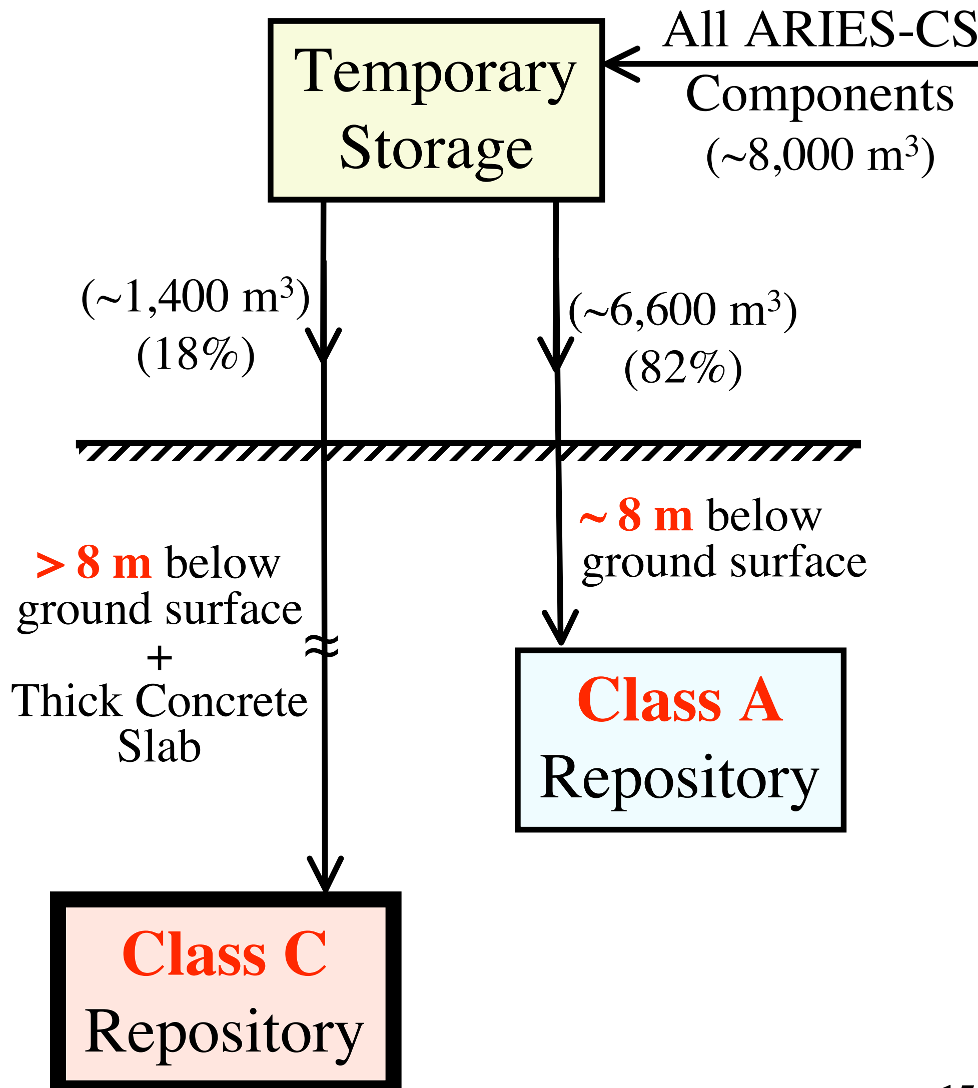
~70 mills/kWh COE ($2004).

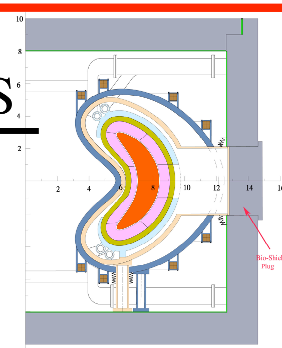
ARIES-CS



Stellarator major radius more than halved by advanced physics and technology, dropping from 24 m for UWTOR-M to 7-8 m for ARIES-CS, approaching R of advanced tokamaks.

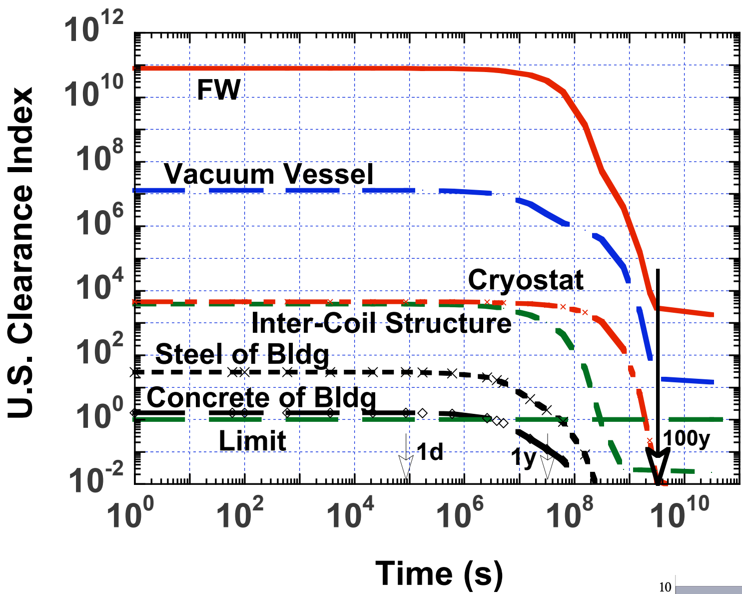
ARIES-CS LLW Classification for Geological Disposal

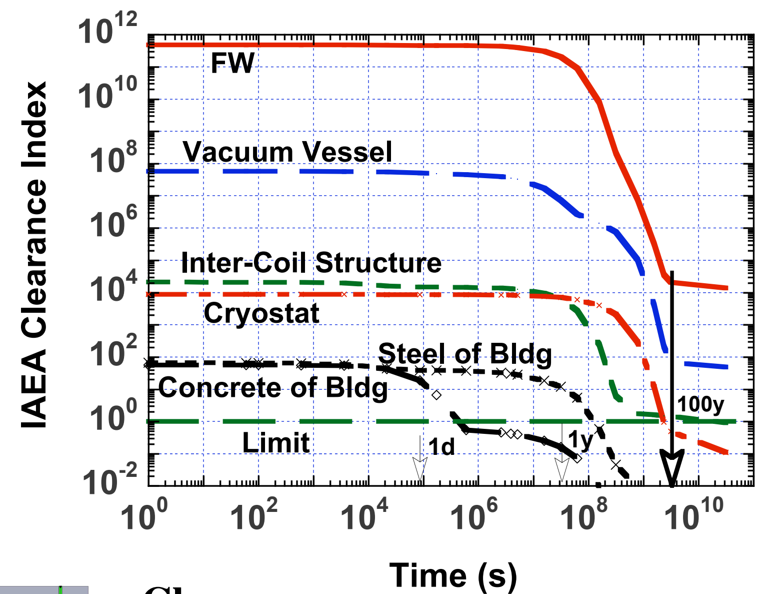


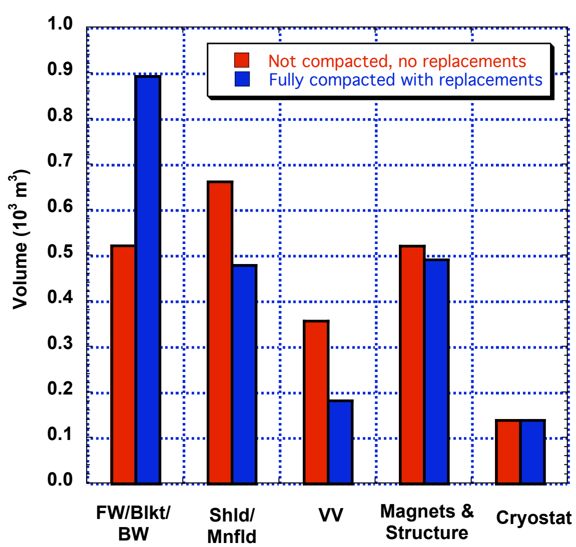


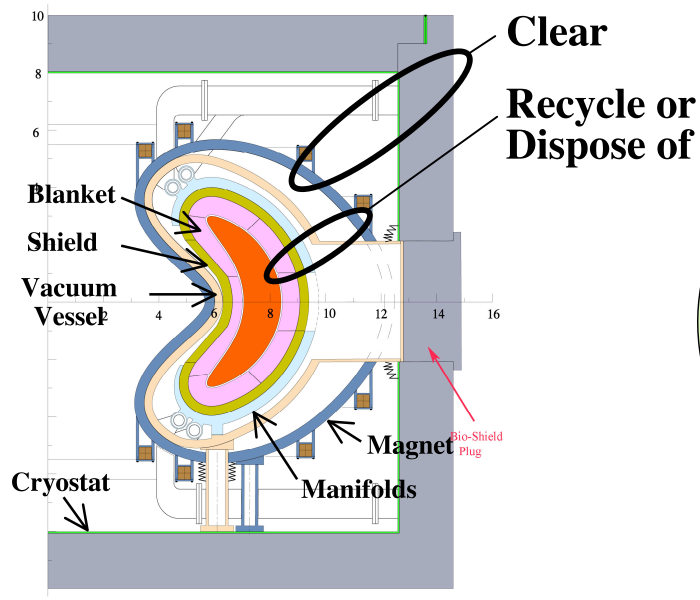
	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		no
Shield/Manifolds	√		no
Vacuum Vessel		√	no
Magnet:			
Nb_3Sn	√		no
Cu Stabilizer		√	√
JK2LB Steel		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

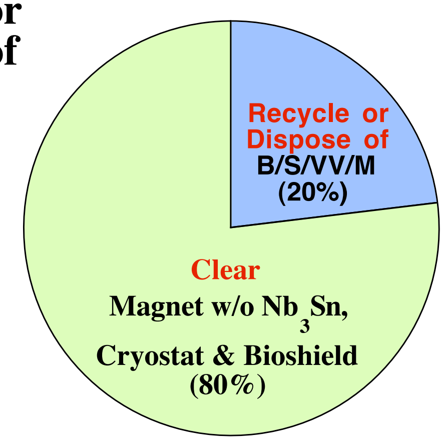
80% of ARIES-CS Active Materials can be Cleared in < 100 y after Decommission









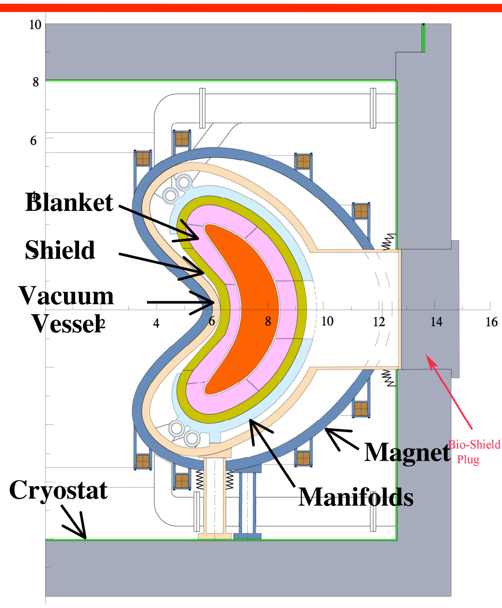


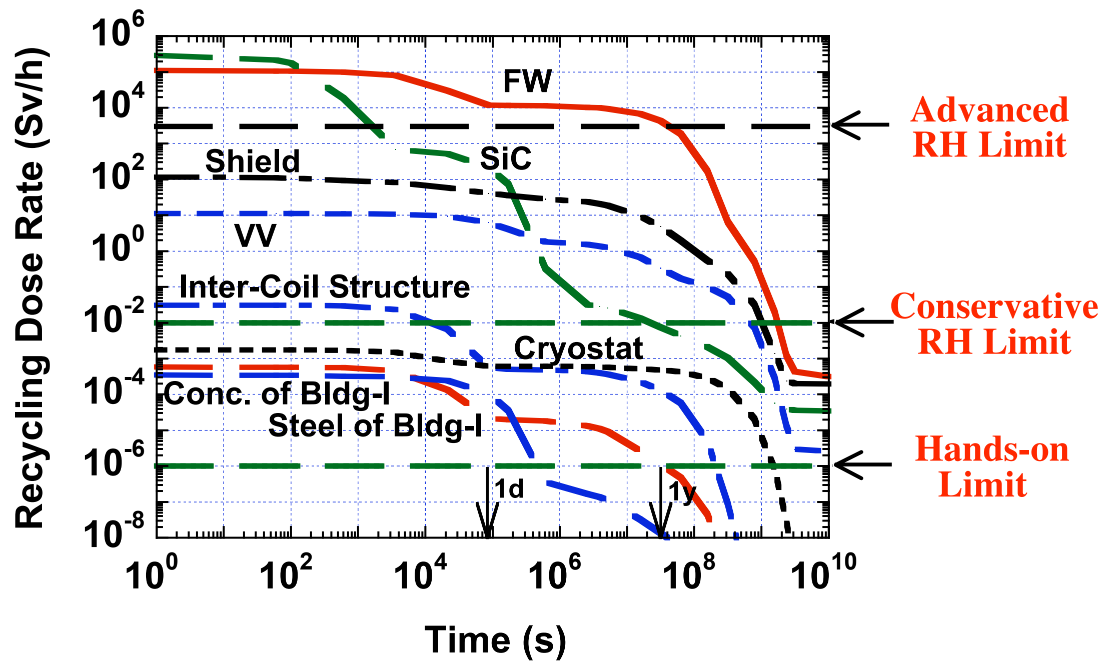
Inconsistencies in Clearance Standards Result in Widely Varying Storage Periods

	U.S.	IAEA
Cu Stabilizer	**20 y** ^{60}Co	**~ 100 y** ? ^{63}Ni
Inter-coil Structure (JK2LB)	**10 y** ^{54}Mn	**~ 500 y** ? ^{14}C, ^{63}Ni
Cryostat (304 SS)	**64 y** ^{60}Co	**70 y** ^{63}Ni, ^{60}Co
Bioshield:		
Mild Steel	**3.5 y** ^{54}Mn, ^{55}Fe, ^{60}Co	**7 y** ? ^{54}Mn, ^{55}Fe
Concrete	**0.6 y** ^{22}Na, ^{54}Mn, ^{59}Fe, ^{41}Ca	**0.6 y** ^{54}Mn, ^{22}Na, ^{45}Ca, ^{55}Fe

Contributors to CI originate from main material and alloying elements, not from impurities.

All ARIES-CS Components can be Recycled in 1-2 y Using Advanced and Conventional RH Equipment





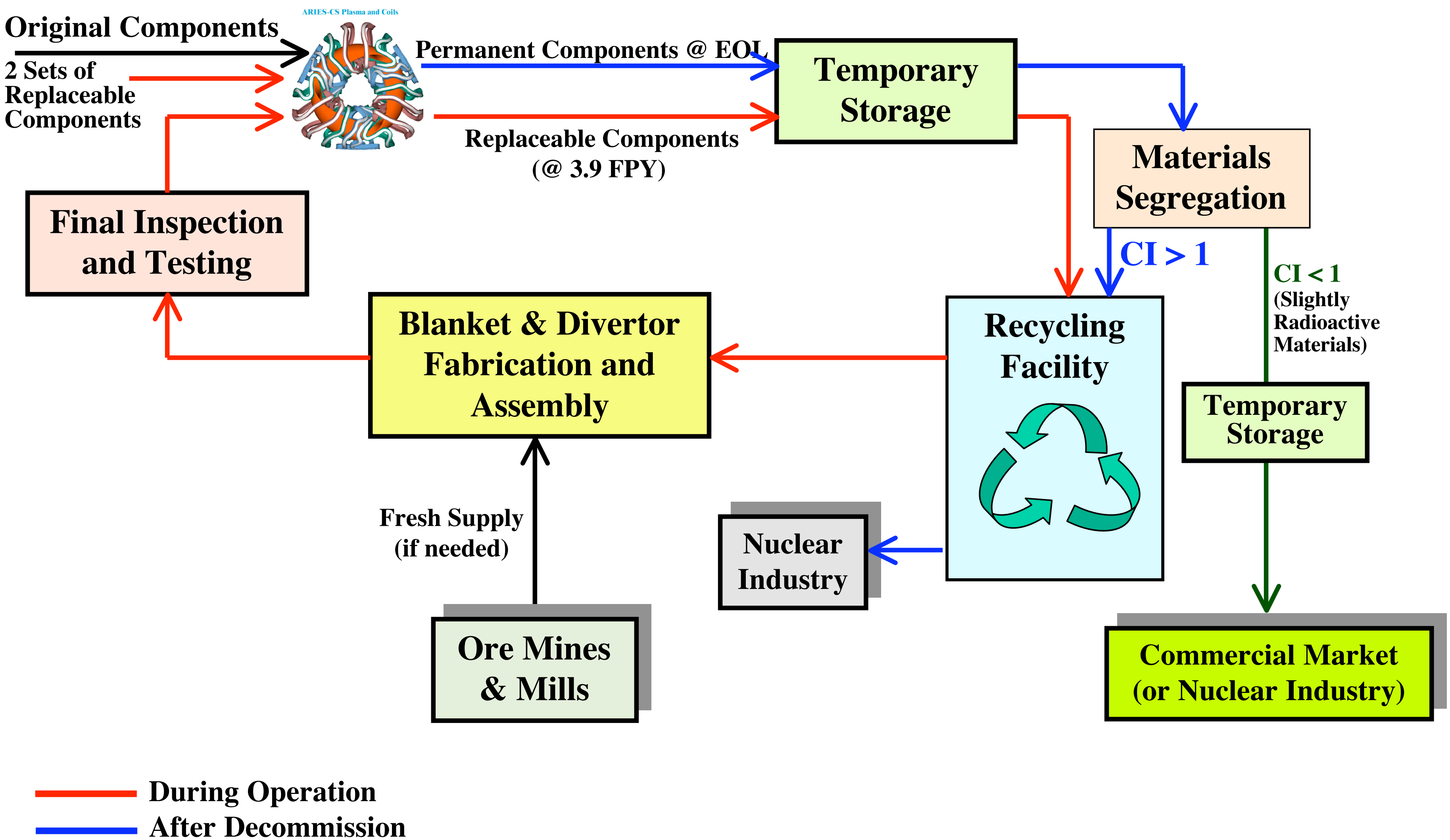
FS-based components:

- ^{54}Mn (from Fe) is main contributor to dose.
- Store components for few years to decay before recycling.
- After several life-cycles, advanced RH equipment could handle shield, manifolds, and VV.

SiC-based components:

- ^{58,60}Co, ^{54}Mn, and ^{65}Zn contributors originate from impurities.
- Strict impurity control may allow hands-on recycling.

Recycling & Clearance Flow Diagram



Disposal Issues

- Large volume to be disposed of (7,000 - 8,000 m^3 per plant, including bioshield).
- High disposal cost (for preparation, packaging, transportation, licensing, and disposal).
- Existing LLW repositories may become limited.
- Political difficulty of building new repositories.
- Tighter environmental controls.
- Radwaste burden for future generations.

Recycling Issues

- Development of radiation-hardened RH equipment (> 3000 Sv/h).
- Energy demand and cost of recycling process.
- Chemical or isotopic separation processes, if needed.
- Any materials for disposal? Volume? Waste level?
- Properties of recycled materials?
- Recycling plant capacity and support ratio.

Clearance Issues

- No clearance market anywhere in the world. (U.S. industries do not support clearance claiming it could erode public confidence in their products and damage their markets).

- Discrepancies between clearance standards.

- Lack of consideration for numerous fusion radioisotopes.

- Impact of missing radioisotopes on CI prediction.

Conclusions

- Power plant designs should minimize radwaste assigned for geological disposal and adopt MRCB philosophy:
  - Minimize volume of active materials by design
  - Promote recycling/clearance
  - Burn long-lived radioisotopes, if needed, to avoid disposal.

- Recycling offers significant advantage for waste minimization. It should be pursued despite lack of details at present. Fusion recycling technology will benefit from fission developments and accomplishments in 50-100 y.

- As clearance is highly desirable, national and international organizations (NRC, IAEA, etc.) should continue their efforts to convince industrial and environmental groups that clearance can be conducted safely with no risk to public health.

- These recommendations help earn public acceptance for fusion as government agencies **and** public ask for energy sources that:
  - are safe no evacuation plan
  - generate little or no waste no burden for future generations
  - do not deplete natural resources recycle all radwaste
  - have minimal environmental impact avoid geological disposal.