State-of-the-Art Scheme for Managing Fusion Activated Materials: US Strategy and Regulations

L. El-Guebaly and L. Cadwallader
University of Wisconsin-Madison
Idaho National Laboratory

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with participation from China

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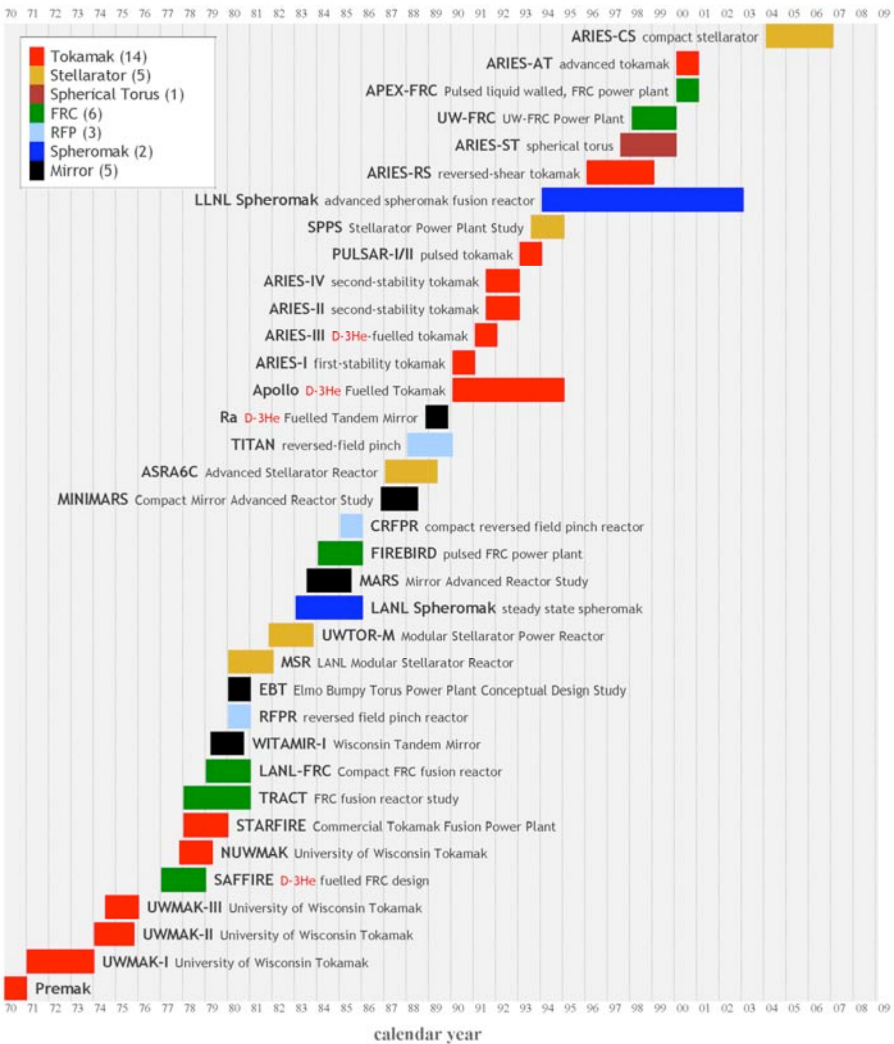
US Developed > 35 MFE Power Plant Studies Over Past 40 years



- There is worldwide interest in building fusion power plants by 2030-2050.
- **Pressing Q**: what should we do with activated materials generated during operation and after decommissioning?
- Geological disposal is NOT environmentally attractive option.
- We propose **integrated** management strategy that can handle the **sizable** activated materials generated by fusion and minimize radwaste burden for future generations.

Options for Radwaste Management

- **Disposal in space** – not feasible
- **Ice-sheet disposal** @ north/south pole – not feasible
- **Seabed disposal** (reconsidered 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. A lesson learned for fusion…)

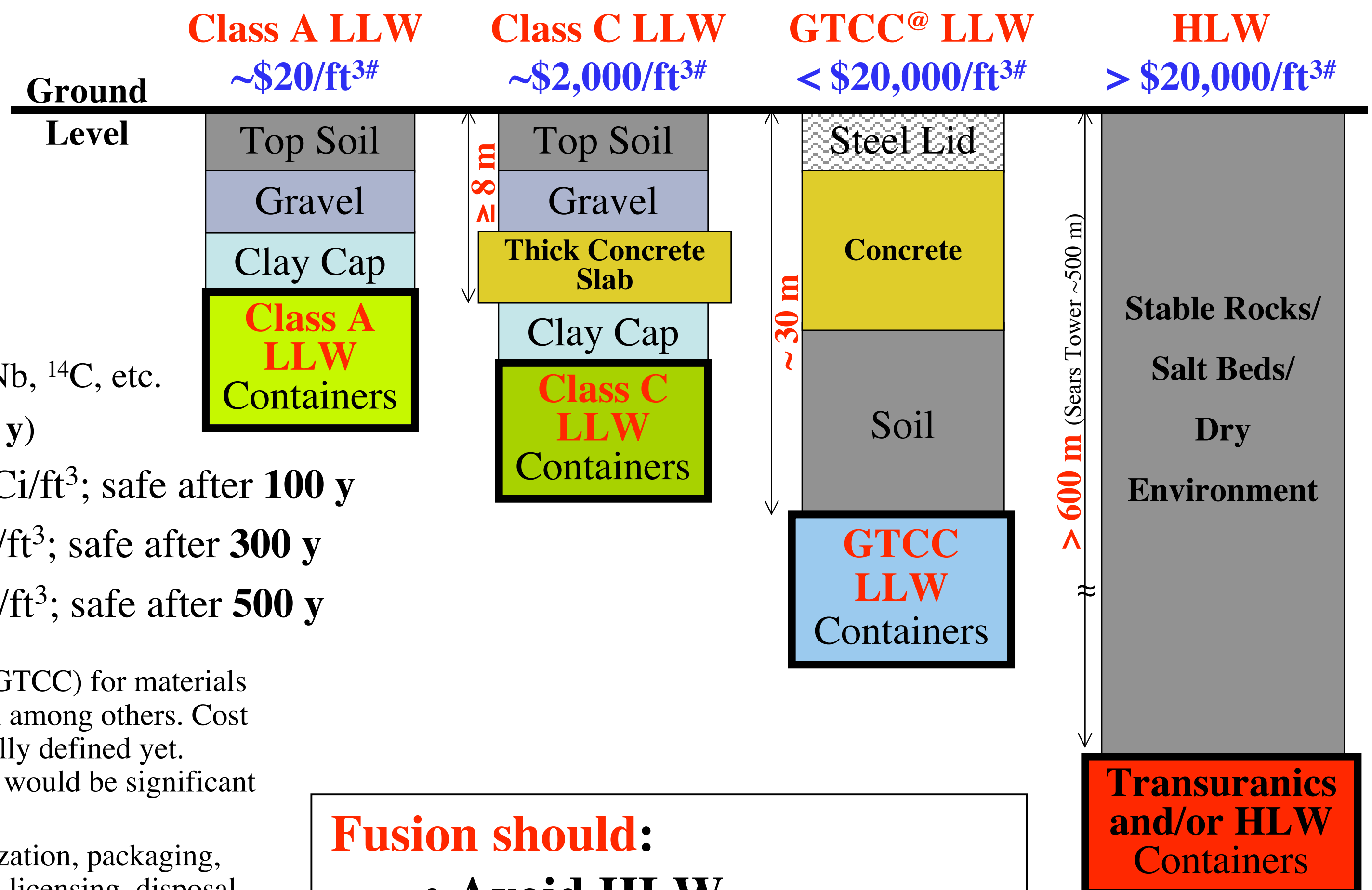
- **Transmutation of long-lived fission and fusion* radionuclides** (⇒ proliferation concerns for fission only)
- new **Recycling / reprocessing** (reuse within nuclear industry)
- new **Clearance** (release to commercial market if materials are slightly radioactive)

* 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.

Geological Disposal

The big picture… and problems

Radwaste Disposal in Geological Repositories is Costly, Specially 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:

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

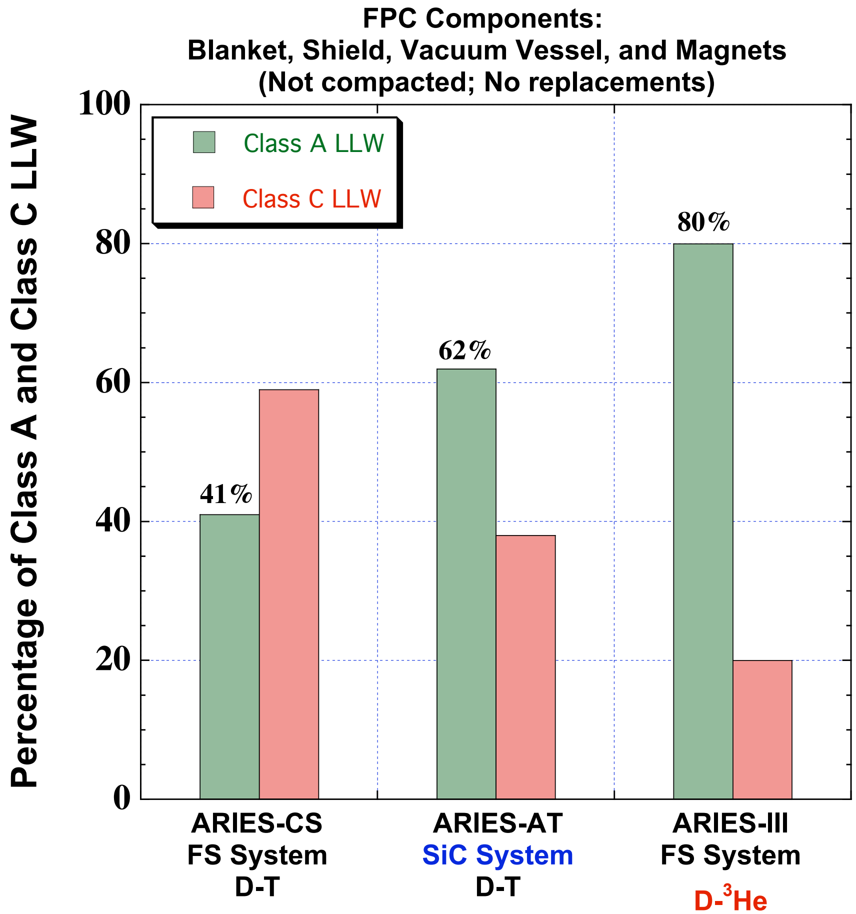
@ Greater Than Class C Waste (GTCC) for materials containing ^{60}Co, ^{63}Ni, and ^{59}Ni among others. Cost effective option, but not formally defined yet. Saving and ease of disposition would be significant compared to HLW.

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; $**96**B in 2008.

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

Fusion Generates Only Low-Level Waste
(Class A or C)

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



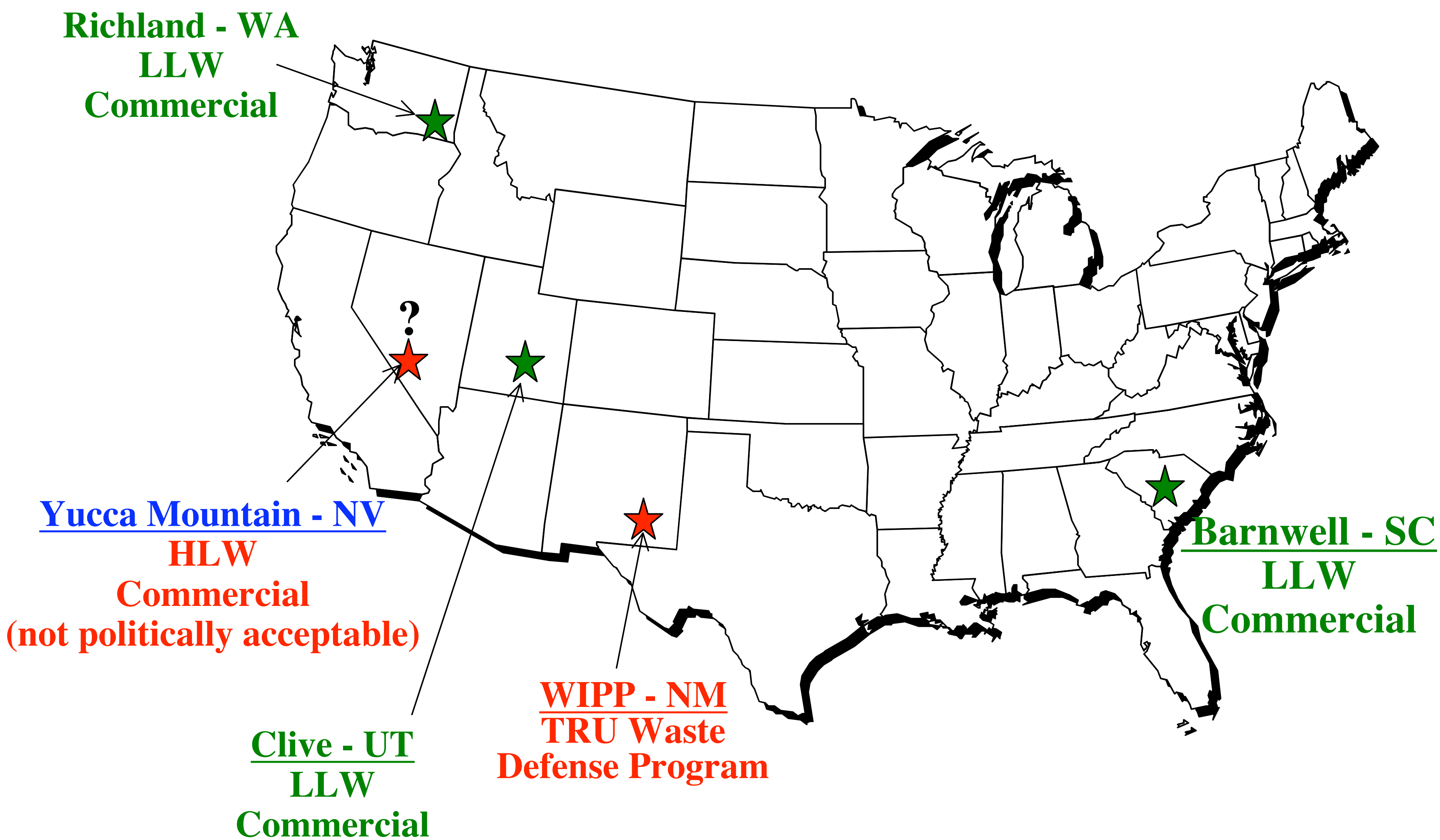
Status of Geological Disposal

- **Operational commercial repositories**:

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

- Worldwide, LLW represents ~ 90% of radwaste volume.
- At present, many US utilities store LLW, GTCC, and HLW at 121 temporary locations in 39 states because of limited and/or expensive offsite disposal options.
- Some suggested keeping fission waste onsite for century until US find more permanent solution.
- Several states tried to develop new disposal sites, but changed their mind because of strong opposition from public and environmentalists.
- **Wisconsin Law**: Before building new nuclear power plant in WI, federally-licensed nuclear waste dump should be available to dispose of **all** nuclear waste from WI reactors.

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



US Commercial LLW Repositories

- **Barnwell facility** in SC:
  - 1971 – 2038.
  - Receives Class A, B, C LLW.
  - Supports east-coast reactors and hospitals.
  - 1,000,000 m^3 capacity ⇒ **can accommodate 125 fusion power plants.**
  - 90% Full.
  - **In July 2008, Barnwell facility closed to all LLW received from outside Compact States**: CT, NJ, SC.
  - 36 states lost access to Barnwell, having no place to dispose 91% of their Class B & C LLW.
  - NRC now allows storing LLW onsite for extended period.
- **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 US Class A waste volume, but does not accept sealed sources or biological tissue waste – a great concern for biotech industry.

US Needs National Solution for LLW and HLW Disposal Problems

Recycling and Clearance

The solution…

(Relatively easy to apply from science perspectives, but
real challenge from policy, regulatory, and public acceptance perspectives)

Handling Radioactive Materials is Important to Future of Fusion Energy

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

- **New Strategy** should be developed for fusion, calling for major rethinking, education, and research to make this new strategy a reality:
  - Avoid geological disposal
  - Minimize volume of radwaste by:
    - Clever designs
    - Promoting new concepts:

      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). This is currently performed on case-by-case basis for US nuclear facilities. Clearable materials are safe, containing 10 μSv/y (< 1% of background radiation).

- **Why?**
  - Limited capacity of existing LLW repositories
  - Political difficulty of building new ones
  - Tighter environmental controls.

Benefits to Magnetic Fusion Energy

- Broad application to any fusion concept:
  - MFE or IFE
  - Experimental devices
  - Demo
  - Power plants.

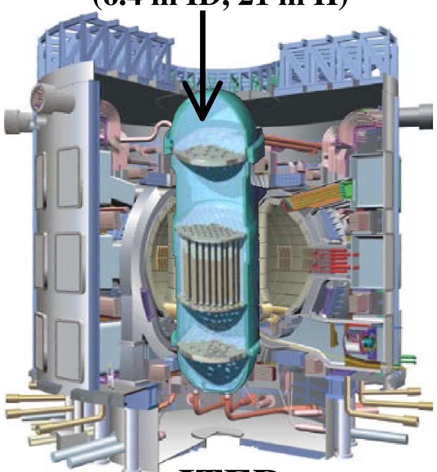
- Solve fusion large radwaste problem (see next VG).

- Minimize radwaste burden for future generations.

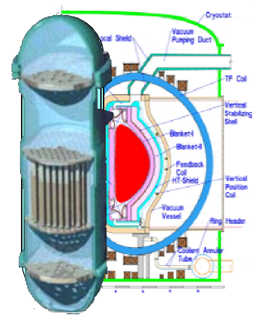
- Promote fusion as nuclear energy source with minimal environmental impact.

Fusion Generates Large Amount of LLW that would Rapidly Fill Repositories

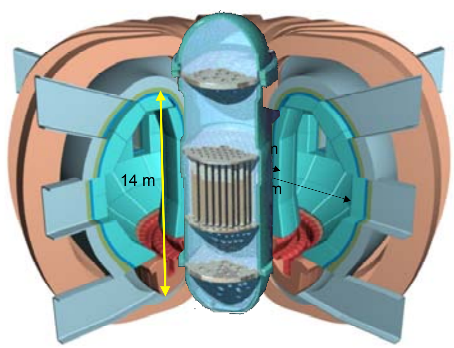
ESBWR Vessel
(6.4 m ID, 21 m H)



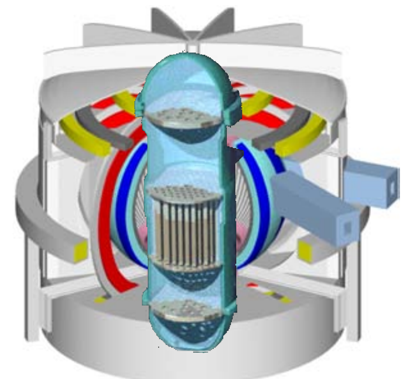
ITER



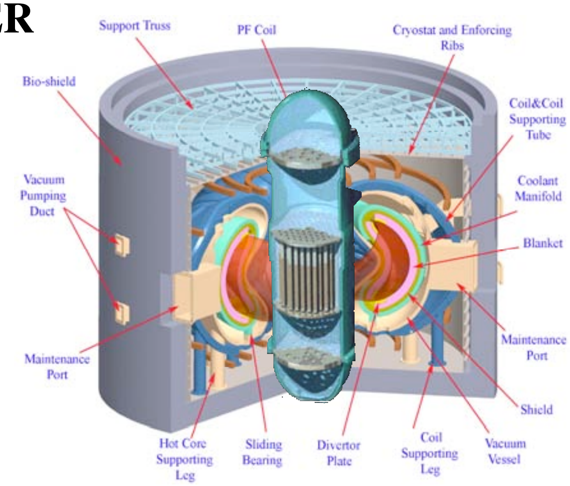
ARIES-AT



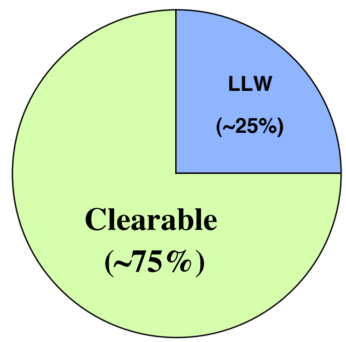
PPCS
Europe



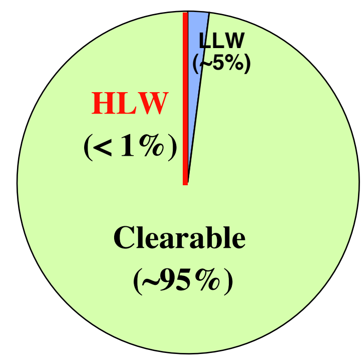
VECTOR
Japan



ARIES-CS



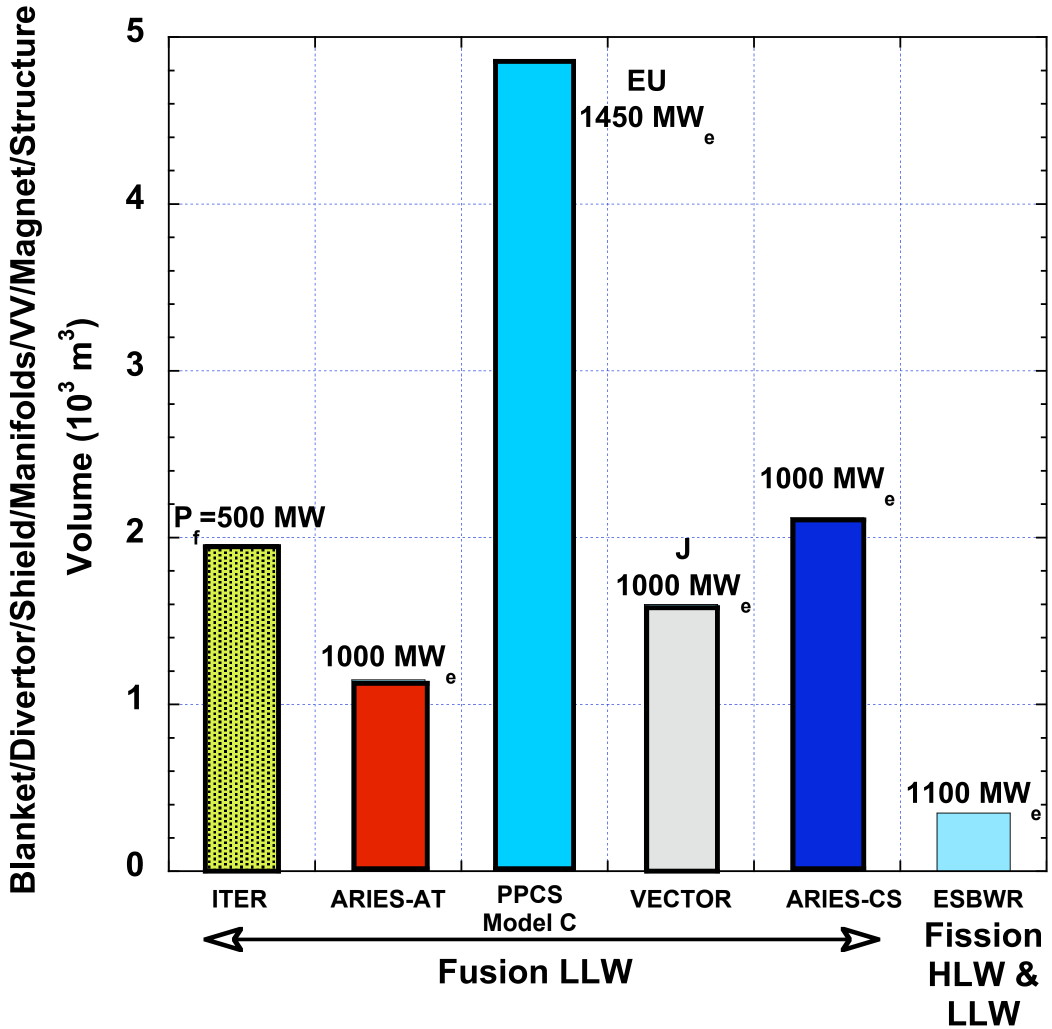
Fusion



Fission

Radwaste Volume Comparison

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



Radwaste Minimization

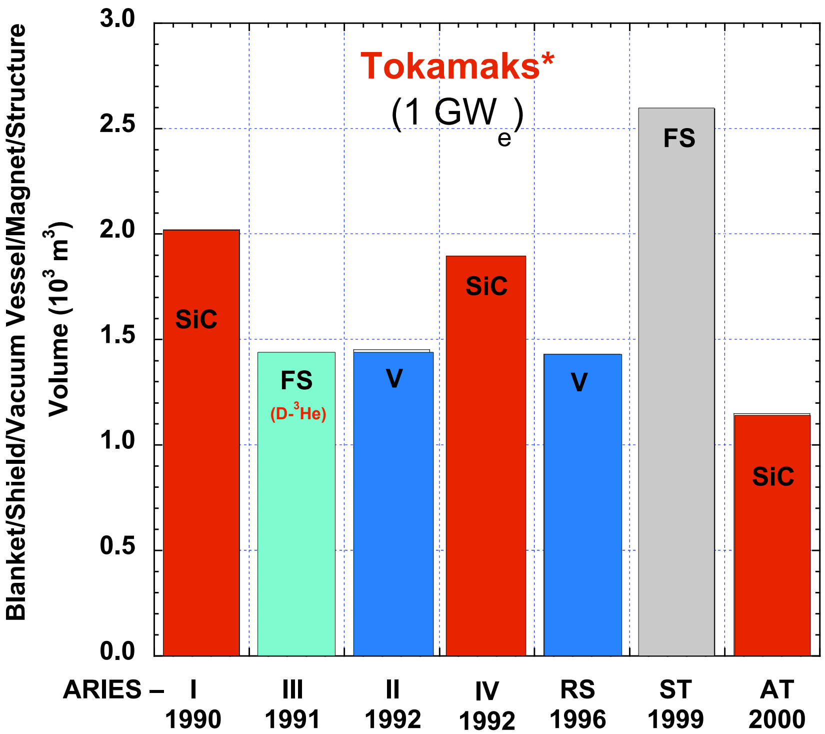
(Recommended for <u>all</u> fusion concepts.

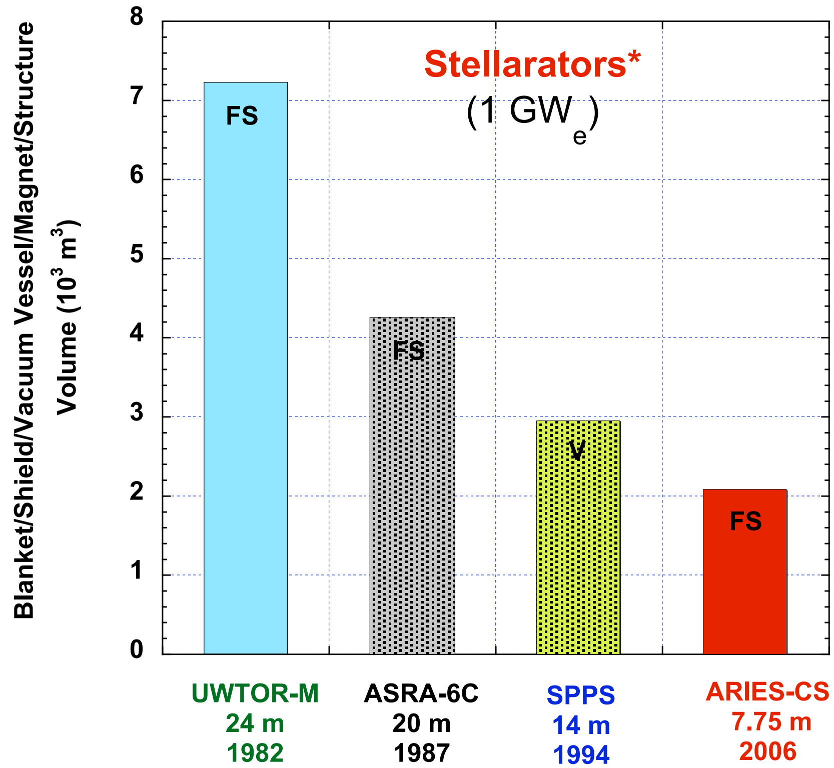
<u>Only knob we have for worst case scenario</u>:

no changes to today's US waste management strategy (disposal)

⇒ Continue developing low-activation materials for fusion applications to avoid HLW generation)

ARIES Project Committed to Radwaste Minimization by Design





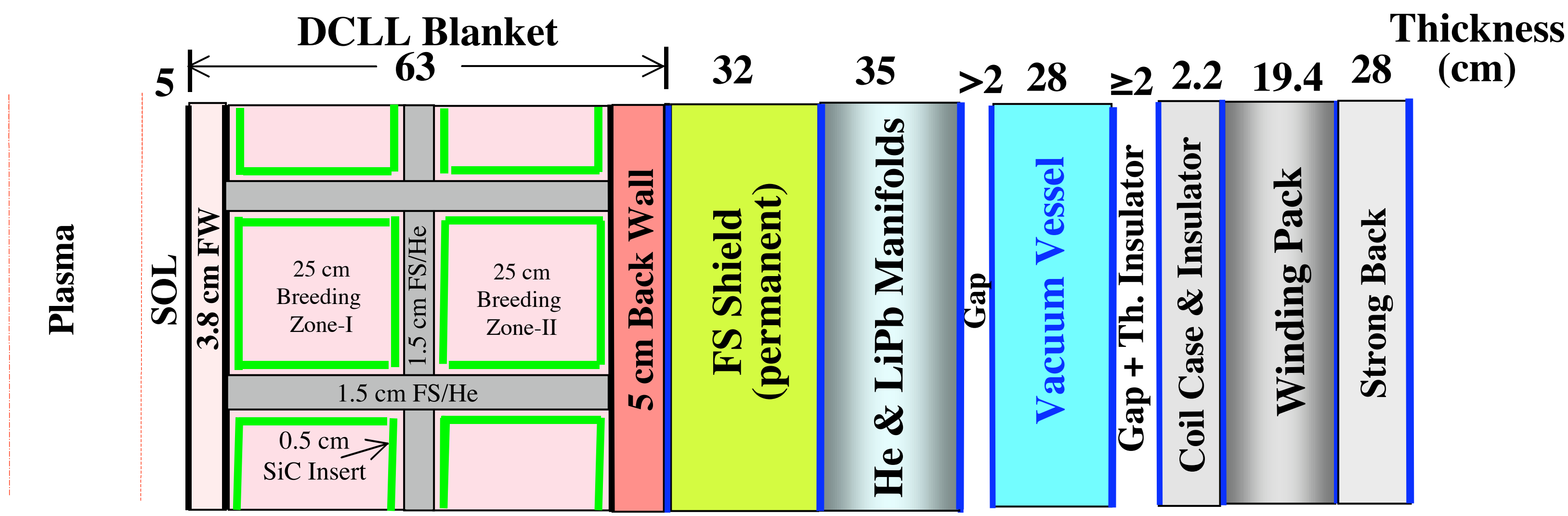
Tokamak radwaste volume
~ halved over 10 y study period

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

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

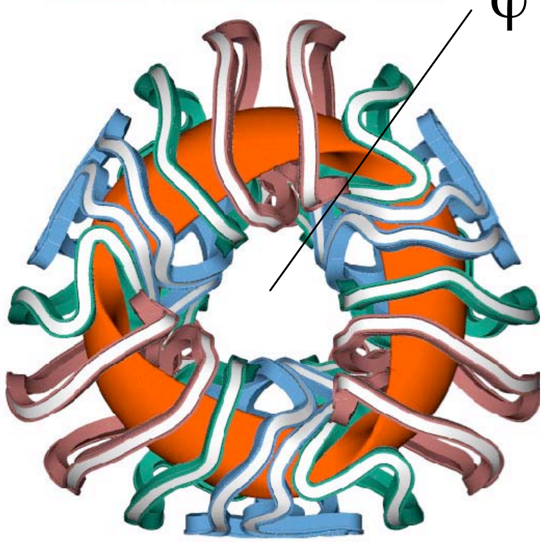
Disposal, Recycling, and Clearance

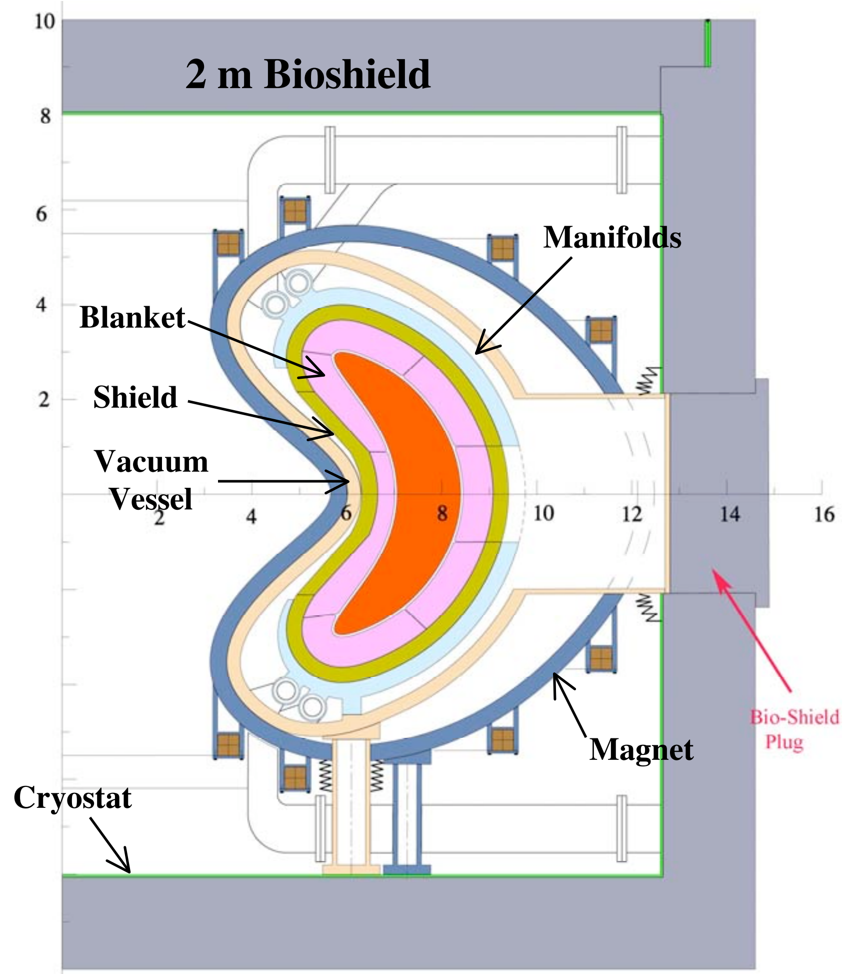
Applied to most recent power plant study (ARIES-CS) with DCLL system



ARIES Compact Stellarator

ARIES-CS Plasma and Coils



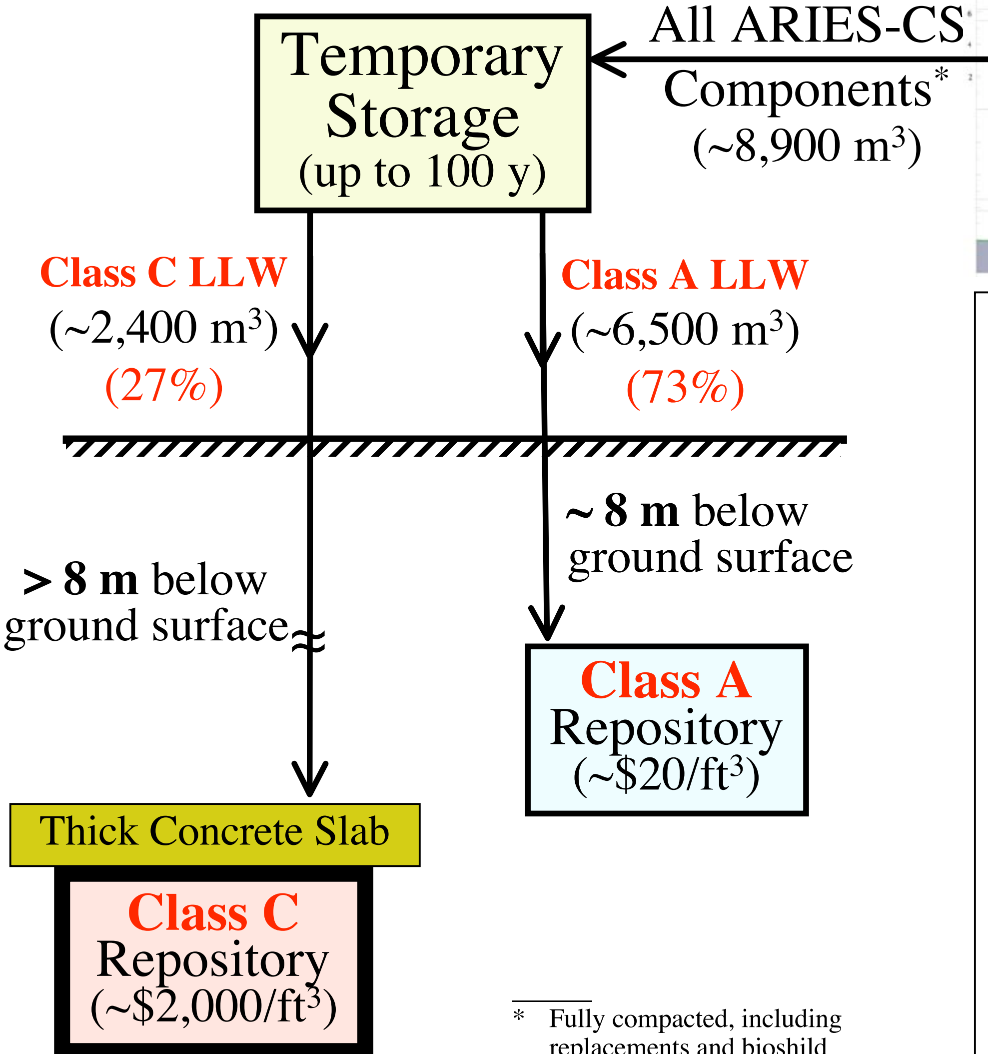


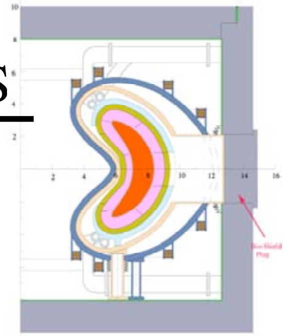
ARIES-CS Cross Section @ φ = 0

ARIES-CS:

- 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





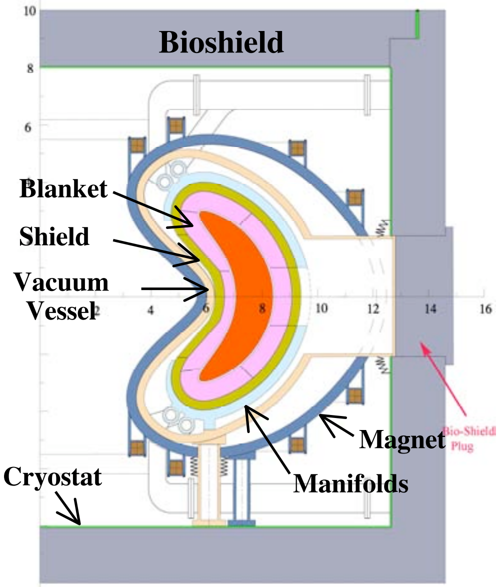
* Fully compacted, including replacements and bioshield

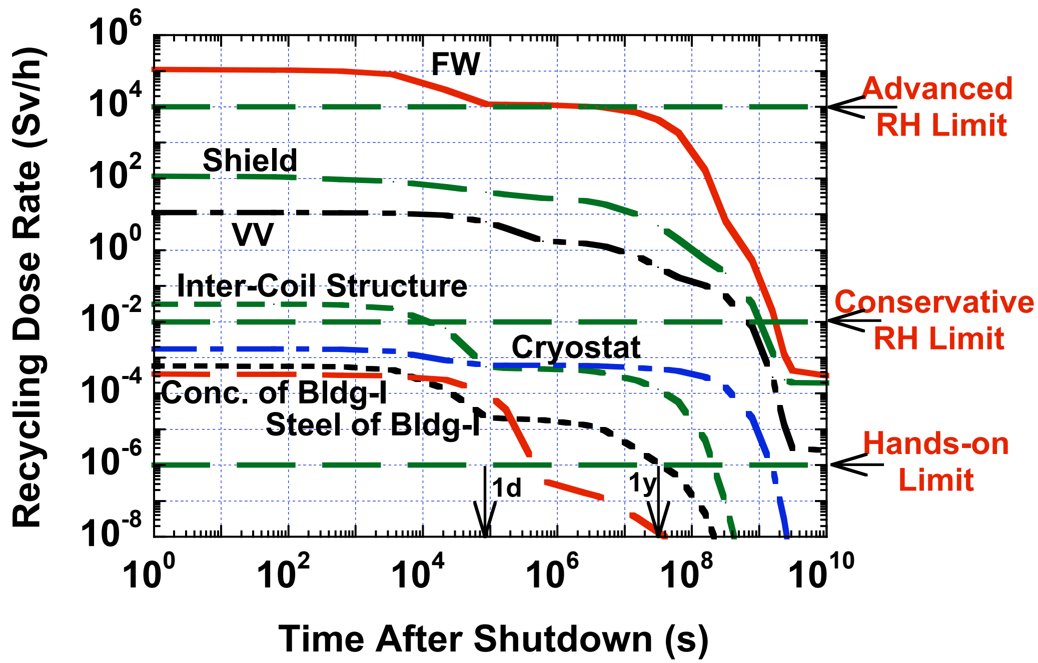
Least Hazardous Type of Waste

	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.

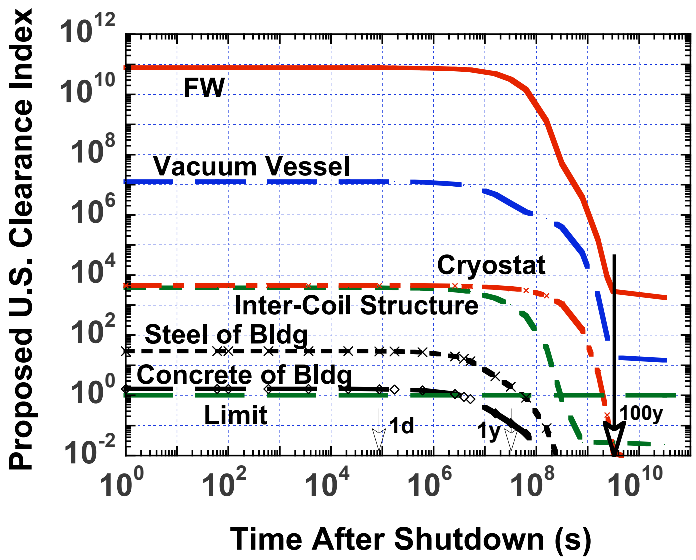
All ARIES-CS Components can Potentially be Recycled in < 1 y Using Advanced RH Equipment

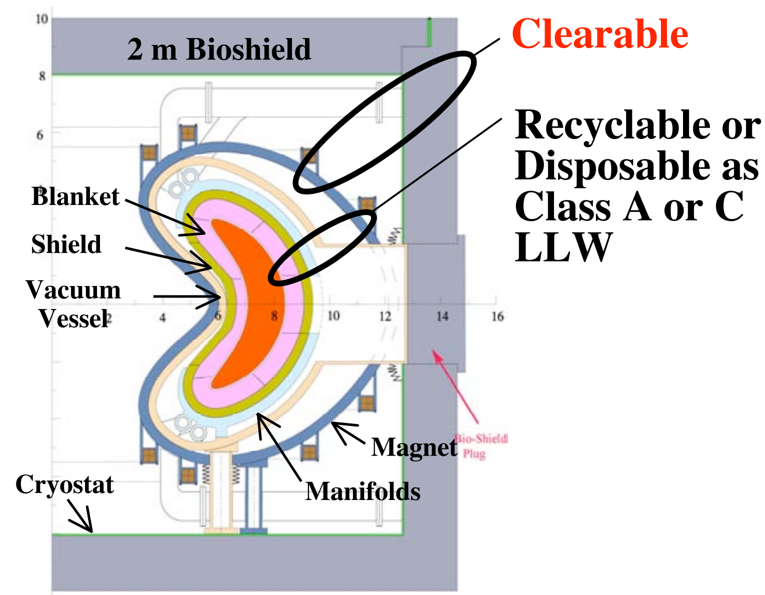


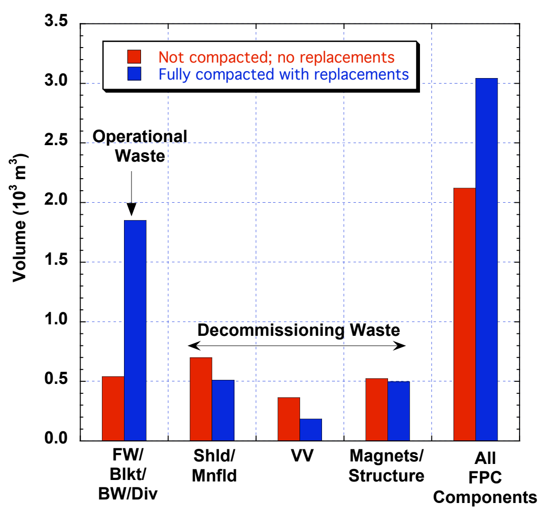


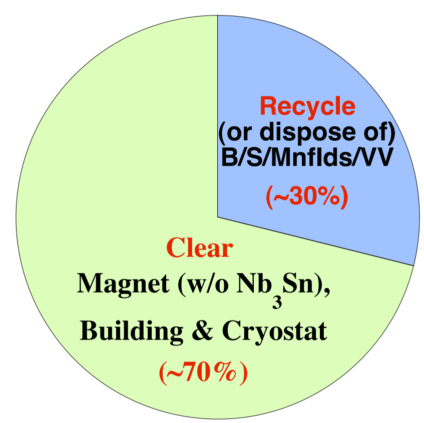
- At early cooling periods (<10 y):
  - Main contributor to dose of FS-based components is ^{54}Mn from Fe
  - Impurities have no contribution to recycling dose.
- Developing advanced recycling tools could relax stringent specifications imposed on some impurities.
- Advanced RH equipment will be developed in 20-50 years to support fission AFCI and MOX fuel reprocessing systems.

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

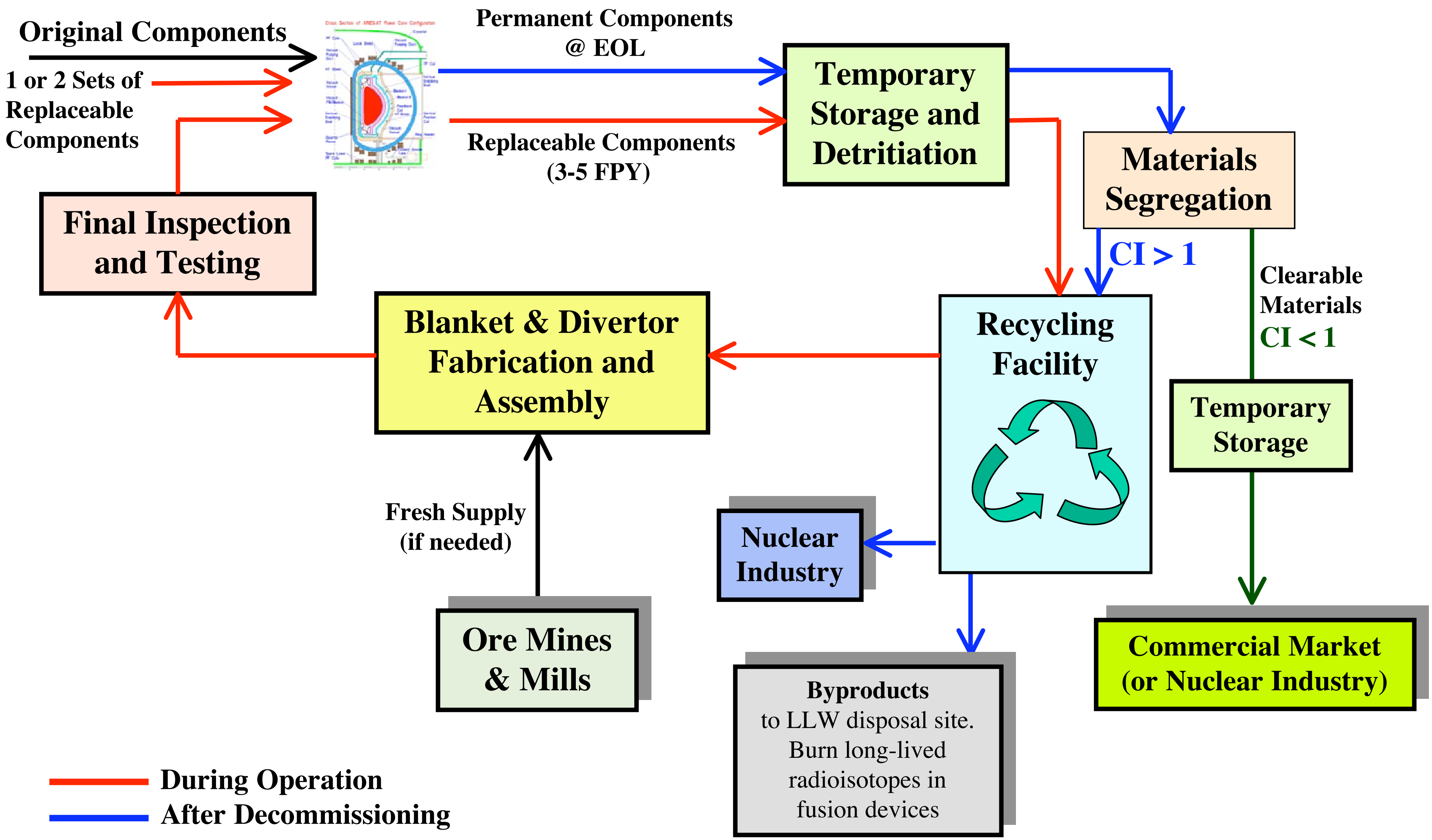








Recycling & Clearance Flow Diagram



General Observations

- Several fusion studies indicated recycling and clearance are technically feasible, providing effective means to minimize radwaste volume.
- Recycling and clearance should be pursued despite lack of details at present.
- Fusion recycling technology will benefit from fission developments and accomplishments in 20-50 y (in support of MOX fuel and AFCI programs).
- Fusion materials contains tritium that may introduce complications to recycling and disposal

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

Key Issues and Needs for Disposal

Issues:

- Only low-level waste ⇒ continue developing low-activation materials
- Accurate measurements and reduction of impurities that prevent shallow land burial
- Large volume to be disposed of ($\geq$ 8,000 m^3 per 1 GW_e plant, including bioshield)
- High disposal cost (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal)
- Any toxic waste (such as Be, V, and Mo) or mixed waste?
- Limited capacity of existing LLW repositories
- Political difficulty of building new repositories
- Prediction of repository's conditions for long time into future[#]
- Radwaste burden for future generations.

Needs:

- Official specific activity limits for fusion LLW issued by legal authorities[*]
- Fusion-specific repositories designed for T-containing materials
- Reversible LLW repositories (to gain public acceptance).

DOE data shows water infiltration will corroded radwaste packages and radioactivity will leak and contaminate groundwater.

* NRC may not get involved until Demo is designed and needs to be regulated.

Key Issues and Needs for Recycling

Issues:

- Dismantling and separation of various materials from complex components (such as magnets)
- Treatment and remote re-fabrication of radioactive materials
- Radiochemical or isotopic separation processes for some materials, if needed
- Aspects of radioisotope/radiotoxicity buildup and release by subsequent reuse
- Properties of recycled materials? Any structural role? Reuse as filler?
- Handling of T containing materials during recycling
- Management of secondary waste. Any materials for disposal? Volume? Radwaste level? Burn of long-lived products in fusion facilities*?
- Energy demand for recycling process
- Cost of recycled materials
- Recycling plant capacity and support ratio

Needs:

- R&D program to address recycling issues
- Radiation-resistant remote handling equipment for fusion use
- Reversible assembling process of components and constituents (to ease separation of materials after use)
- Efficient detritiation system
- Large and low-cost interim storage facility with decay heat removal capacity#
- Nuclear industry should accept recycled materials
- Recycling infrastructure.

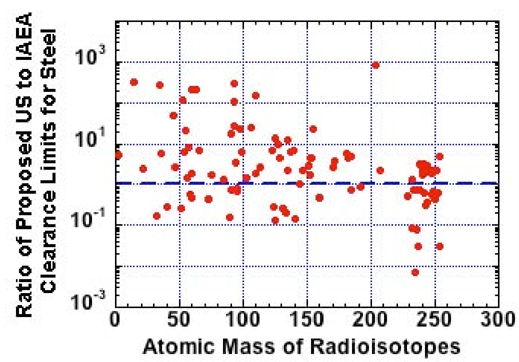
* L. El-Guebaly, "Managing Fusion High Level Waste – a Strategy for Burning the Long-Lived Products in Fusion Devices," *Fusion Engineering and Design* **81** (2006) 1321-1326.
# e.g., heat pipes.

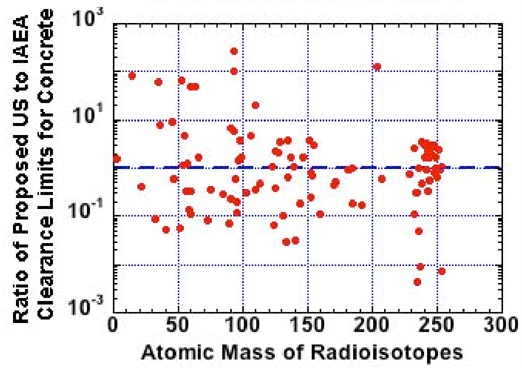
Key Issues and Needs for Clearance

Issues:

- Discrepancies between proposed US-NRC & IAEA clearance standards#
- Impact on clearance index prediction of missing fusion 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)
- Concerns for radioisotope buildup and release by subsequent reuse.





Needs:

- Official fusion-specific clearance limits issued by legal authorities*
- Accurate measurements and reduction of impurities that deter clearance of in-vessel components
- Reversible assembling process of components and constituents
- Large and low-cost interim storage facility
- Clearance infrastructure
- Clearance market (Some experience exists in several EU countries: Sweden, Germany, Spain, and Belgium. At present, US industry does not support unconditional clearance claiming it could erode public confidence in US products and damage US markets).

\# 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).

* NRC may not get involved until Demo is designed and needs to be regulated.

US Industrial Experience Demonstrates Economical and Technical Feasibility of Recycling at High Doses

- US recycled tons of metals and concrete from fission plant D&D.
- **In 1960s**, ANL-West Hot Fuel Examination Facility developed radiation resistant tools to handle fission fuel rods for Experimental Breeder Reactor (EBR-II). RH equipment operated successfully at **10,000 Sv/h** (needed for fusion).
- 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.
- Advanced recycling technology exists in US. Adaptation to fusion needs is highly desirable (radiation level, size, weight, etc.).

What We Suggest

Fusion program should start developing **NOW**

recycling approach before designing/building Demo (by 2030-2050)

and

clearance approach before decommissioning power plants (by ~2100),

hoping that US will be progressive with respect to

recycling/clearance perspectives

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Technology Readiness Levels

Concept Development

TRL	Issue-Specific Definition	Facility Needs
1	• Develop activation code and cross section data library. • Perform activation analysis for advanced power plants to define waste disposal rating and recycling/clearance potential for low-activation materials (ferritic steel, vanadium alloy, and SiC/SiC composites). • Identify alloying elements and impurities that violate Class C LLW disposal requirement using NRC and Fetter's waste disposal limits. • Provide feedback to materials community to modify composition by altering alloying elements and controlling undesirable impurities that produce HLW.	
2	• Determine cooling periods that allow recycling and clearance of materials in < 100 years from plant decommissioning. • Identify alloying elements and impurities that lead to excessive recycling dose and delay clearance of sizable components using proposed NRC clearance guidelines. • Provide preliminary feedback to materials community on alloying elements and impurities that lead to excessive recycling doses or deter clearance of in-vessel components. • Couple CAD, 3-D neutronics, and activation codes to map dose around torus.	
3	• Verify and experimentally validate prediction of activation models and cross section data. • Reexamine modified alloys and calculate their activation responses in realistic fusion environment to assure satisfying recycling and proposed NRC clearance requirements. • Develop preliminary, unofficial clearance limits for fusion-specific radioisotopes.	V&V Codes & Data: Integral experiments on mockups with 14 MeV neutron source, e.g., FNS (in Japan) and FNG (in Italy). New facility to be built in US. IFMIF (small mockups < 6 liters). Neutron-producing fusion experiments (such as JET or JT-60) for activation cross section validation

Technology Readiness Levels (Cont.)

Proof of Principle

TRL	Issue-Specific Definition	Facility Needs
4	• Small-scale tests on irradiated mockups to demonstrate segregation of various materials, crushing, melting, and refabrication of components. • Verify that slag from melting collects majority of radionuclides. Identify waste classification of slag. • Bench scale tests to validate efficiency of detritiation system. • Laboratory-scale tests of recycling processes of fusion materials.	Fission nuclear industries at INL and Oak Ridge, Tennessee. Recycling and detritiation facilities at Savannah River National Laboratory.
5	• Large scale tests conducted to validate predictions of activity and doses over longer irradiation periods in prototypical environment (neutron, heating, etc) for both highly irradiated and slightly irradiated components. • Development of radiation-resistant remote handling equipment that can withstand high fusion doses > 10,000 Sv/h.	Integral experiments with intense 14 MeV neutron source
6	• Full scale test to validate activation and dose calculations at prototypical neutron flux and fluence. • NRC* to develop clearance (and disposal) standards for fusion-specific radioisotopes • Reevaluate clearance index for clearable components using newly developed NRC fusion-specific clearance standards. • Develop recycling infrastructure.	Integral experiments with multiple, intense 14 MeV neutron sources

Technology Readiness Levels (Cont.)

Proof of Performance

TRL	Issue-Specific Definition	Facility Needs
7	• Prototype tests of full size components conducted in D-T fusion machines to demonstrate the successful recycling of fusion radioactive materials within the nuclear industry.	Component Testing Facility (fusion-relevant nuclear environment). Change out of components will generate recyclable materials.
8	• Successful operation over long time of components made of recyclable materials in fusion machine. • Recycling demonstrated for all components (including bioshield) after facility decommissioning.	Component Testing Facility (fusion-relevant nuclear environment)
9	• Successful operation demonstrated for prototypical sizes of components made of recyclable materials during fusion Demo operation. • Develop clearance infrastructure and establish clearance market for slightly radioactive materials generated in the future by fusion power plants.	Demo

Where Are We?

US:

- **TRL of 1-2,** with missing elements**:**
  - ARIES studies indicated shallow land burial, recycling, and clearance are technically feasible for power plants employing low-activation materials (FS, V, SiC)
- Limited scale recycling within nuclear, non-fusion industry has been proven feasible at INL and industrial firms
- Free-release has been performed only on a case-by-case basis during non-fusion decommissioning projects since 1990s
- In next 20-50 y, recycling technology will benefit greatly from fission developments and accomplishments in support of more challenging MOX fuel and AFCI programs.

Worldwide:

- Growing international effort in support of recycling/clearance in EU, RF, JA
- European, Russian, and Chinese studies indicated feasibility of recycling and clearance
- Clearance market for **fission** activate materials currently **exists** in Germany, Spain, Sweden, Belgium, and other European countries
- **TRL of 1-5,** with missing elements.

2007 FESAC Supports US Position on Fusion Recycling/Clearance

- **Quote from Page 70 of 2007 FESAC report:**

  "Beyond the need to avoid the production of high-level waste, there is a need to establish a more complete waste management strategy that examines all the types of waste anticipated for Demo and the anticipated more restricted regulatory environment for disposal of radioactive material. **Demo designs should consider recycle and reuse as much as possible.** Development of suitable waste reduction **recycling and clearance strategies is <u>required</u> for the expected quantities of power plant relevant materials**. Of particular concern over the longer term could also be the need to detritiate some of the waste prior to disposal to prevent tritium from eventually reaching underground water sources. This may require special facilities for the large anticipated fusion components. The **fission industry will be developing recycling techniques** for the Global Nuclear Energy Partnership (**GNEP**) and the US Nuclear Regulatory Commission (**NRC**) **is developing guidelines for the release of clearable materials** from fission reactor wastes both of which may be of value to fusion."

Reference:

M. Greenwald et al., "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy," A Report to the Fusion Energy Sciences Advisory Committee, October 2007.

Maturation of Recycling and Clearance Approaches

Fusion designers should:

- Minimize radwaste volume by clever designs
- Promote environmentally attractive scenarios such as recycling and clearance, avoiding geological disposal
- Continue addressing critical issues for all three options
- Continue developing low-activation materials (specifications could be relaxed for some impurities while more stringent specs will be imposed on others to maximize clearance)
- Accurately measure and reduce impurities that deter clearance of in-vessel components
- Address technical and economical aspects before selecting the most suitable radwaste management approach for any fusion component.

Nuclear industry and regulatory organizations should:

- Continue developing advanced radiation-resistant remote handling equipment capable of handling > 10,000 Sv/h that can be adapted for fusion use
- Consider fusion-specific materials and issue official guidelines for unconditional release of clearable materials
- 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.

Maturation of Recycling and Clearance Approaches (Cont.)

- **Tools**:
  - **Activation code and data**
    - Continue improving ALARA pulsed activation code*
    - Verification and validation of ALARA code to NRC requirements
    - Validation of activation cross section data
  - **Simulation and modeling** (taking advantages to recent advances in computational science)
    - Coupling of CAD and 3-D neutronics code to enable full simulation of fusion power core with penetrations and gaps
    - Coupling of 3-D neutronics and ALARA activation codes to accurately predict activation source term in all components and map doses around torus during operation and after shutdown
  - **Supporting theories:**
    - Realistic approach(s) to estimate recycling dose
  - **Standards**:
    - Fusion-specific clearance (and disposal) standards issued by NRC

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