



Activated Fusion Radwaste Disposition/Recycling/Clearance

Laila El-Guebaly

Fusion Technology Institute

University of Wisconsin-Madison

<https://fti.neep.wisc.edu/fti.neep.wisc.edu/ncoe/home.html>

laila.elguebaly@wisc.edu

U.S. contact person for IEA Task on Fusion Radioactive Waste Studies

Chair of IPAC for IAEA Workshop on Fusion Radwaste Management (Oct 2021)

L. Cadwallader, B. Merrill (INL), A. Rowcliffe (ORNL)



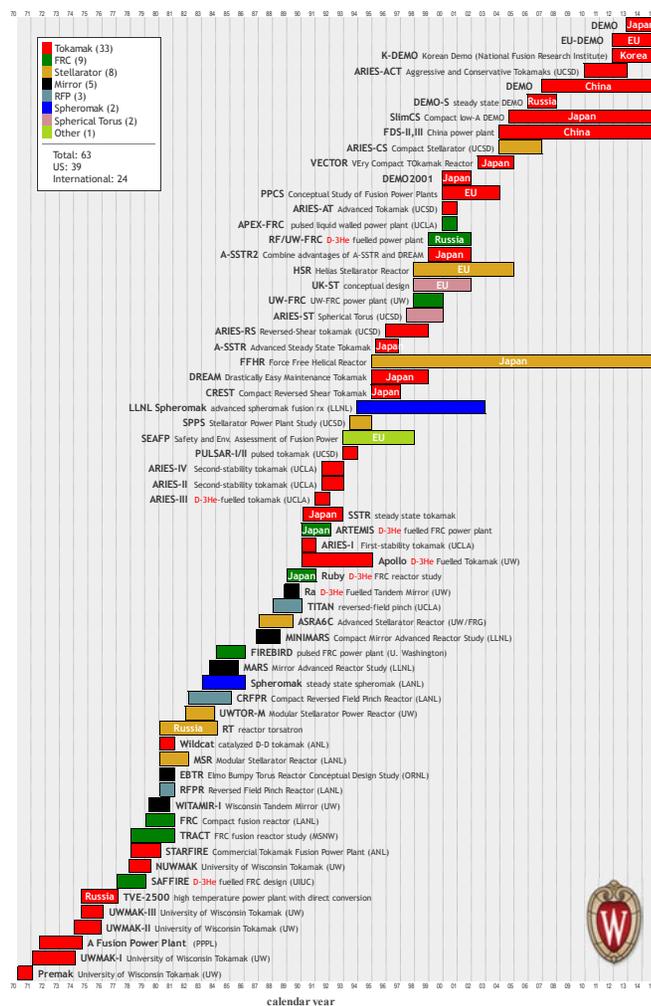
Kickoff Meeting for ARPA-E GAMOW Program

January 21-22, 2021



> 60 Conceptual Designs Developed Since 1970 to Identify and Resolve Physics/Technology Challenges

MFE Power Plant Studies, Worldwide



Most studies and experiments are currently devoted to **D-T fuel cycle** – least demanding to reach ignition.

Stress on fusion safety stimulated research on fuel cycles other than D-T, based on ‘advanced’ reactions, such as D-D, D-³He, P-¹¹B, and ³He-³He.

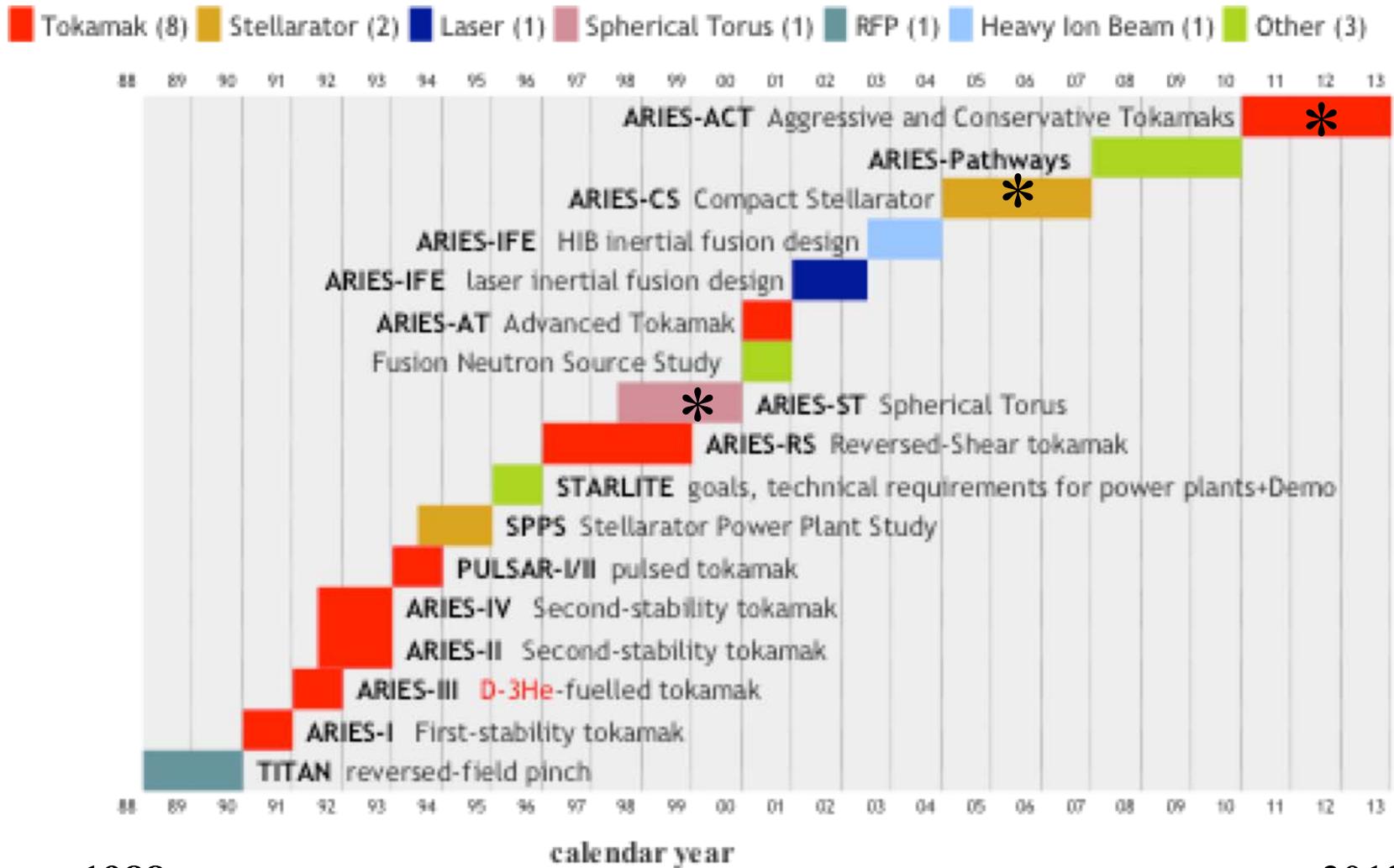
Majority of designs provide CAD drawings, info on volume/mass of all fusion power core (FPC) components (first wall → magnet) and their support structures.

- Without going much into great details, these conceptual designs assess viability of new concepts as economically competitive energy sources, critically evaluate strengths and limitations, and ultimately guide national science and technology R&D programs.



The US ARIES Project (1988–2013)

Examined several Fusion Concepts



1988

2013



Essential Criteria for Attractive Power Plants

Nine essential criteria embody U.S. vision for end goal of attractive fusion power plants. These criteria provide key insights on strategic directions that U.S. program should pursue to demonstrate the feasibility of fusion during development phase and to ultimately develop attractive and economically competitive power plants that will be acceptable to utilities, industries, and public.

1. Economically competitive compared to other sources of electric energy
2. Stable electric power production with load-following capacity and range of unit sizes
3. Steady state operation with well-controlled transients and high system availability
4. Tritium self-sufficiency with closed fuel cycle
5. Reduced-activation, radiation-resistant structural and functional materials to extend safe service lifetime, and reduce cost, radwaste stream, and radiation hazards
6. RAMI: Reliability, availability, maintainability, and inspectability for all components
7. Easy to license by regulatory agencies
8. Intrinsic safety, **minimal environmental impact**, and wide public acceptance:
 1. No need for evacuation plan even during severe accident
 2. No local or global environmental impacts
 3. Minimal occupational exposure to radiation/toxicity
 4. Routine emissions and tritium leakage below allowable levels
 5. Inclusion of proliferation safeguards by design
9. **Integral radwaste management and decommissioning plan**
 1. **Minimize radioactive waste by design, recycling, and clearance (release of allowed materials)**
 2. **No high-level waste; only Class C low-level waste or better.**



Motivation

- In recent decades, fusion designers have become increasingly aware of the challenging problem facing fusion, as the large amount of low-level waste (LLW; WDR* <1) generated during operation and after decommissioning will fill U.S. repositories rapidly. **Concerns:** lack of waste repositories; very difficult to build new repositories; high disposal cost; radwaste burden for future generations.
- More environmentally attractive means stimulated search for new approach to **keep radioactive volume to a minimum** via developing fusion-specific **recycling**** and **clearance#** approaches that help advance fusion's social acceptance.
- **Why?**
 - **Proper handling of activated materials through recycling/clearance is important for public acceptability of fusion energy.** **Positive attributes:** minimize fusion environmental impact, free ample space in repositories, reclaim valuable resources (through less mining of materials), and save millions of dollars for high disposal cost (as cost of recycling is cheaper).
 - **Such strategy has near-term implications on U.S. materials program** in terms of relaxing strict LLW requirements with which material community is currently working (limited number of elements with extremely low impurities and high cost).

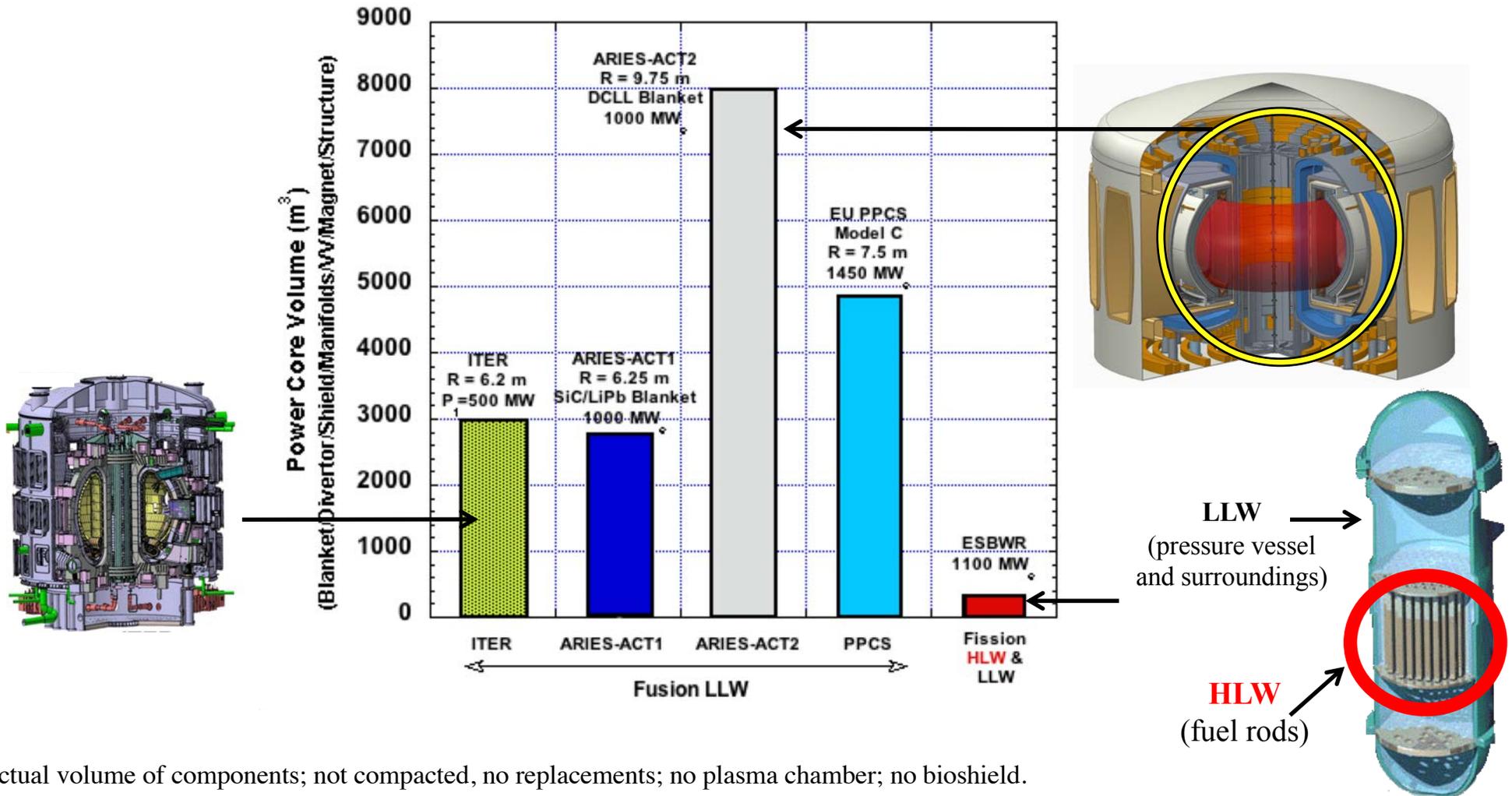
• Waste Disposal Rating

** Reuse within nuclear industry.

Slightly activated materials containing traces of radioactivity (< 1% of background radiation) could be cleared and released to commercial market to fabricate as consumer products.



Unlike Fission, Fusion Generates Only LLW, but in Large Quantity*



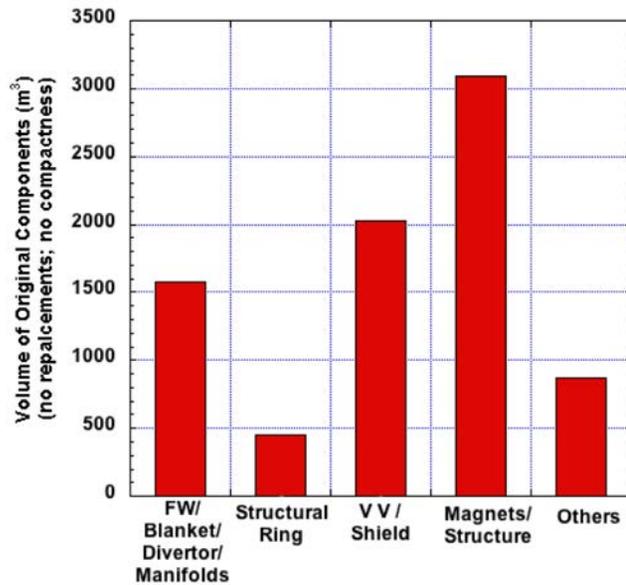
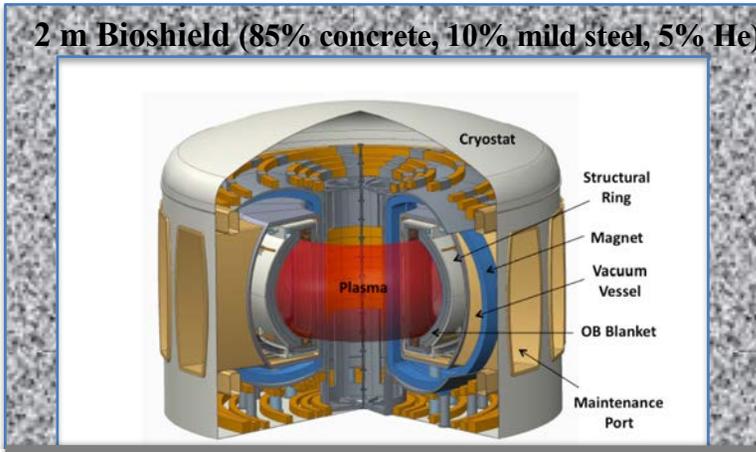
Actual volume of components; not compacted, no replacements; no plasma chamber; no bioshield.

* Fusion designs not employing low-activation structures (such as ARC) will generate HLW.

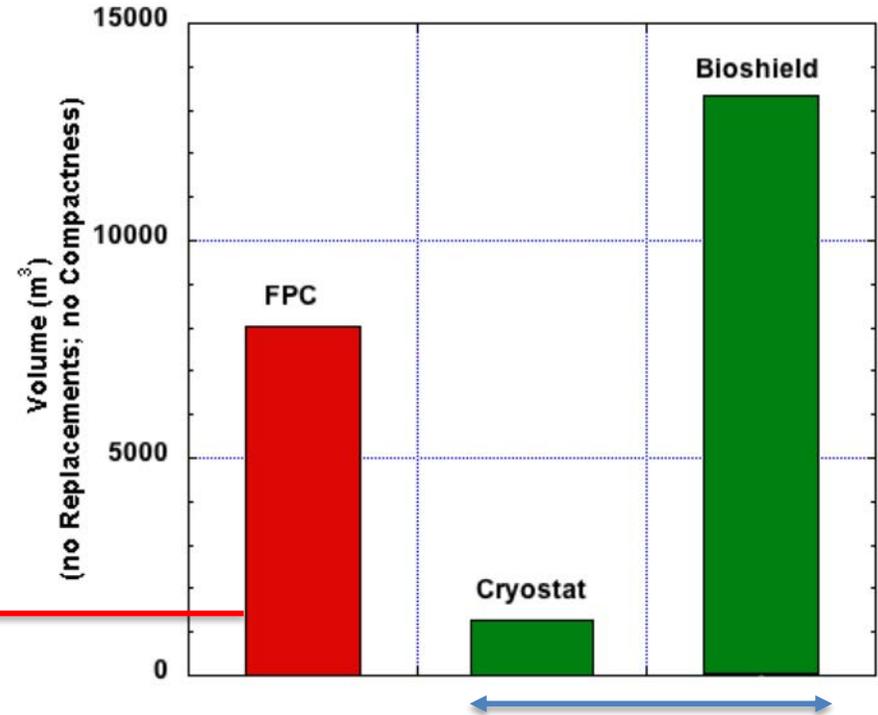


Breakdown of ARIES-ACT2 Volume

2 m Bioshield (85% concrete, 10% mild steel, 5% He)



ARIES-ACT2



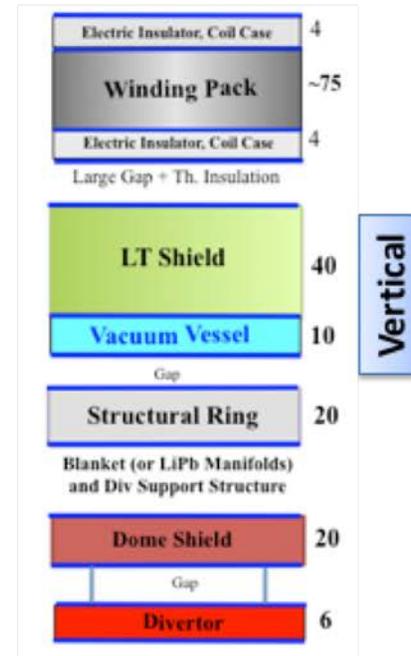
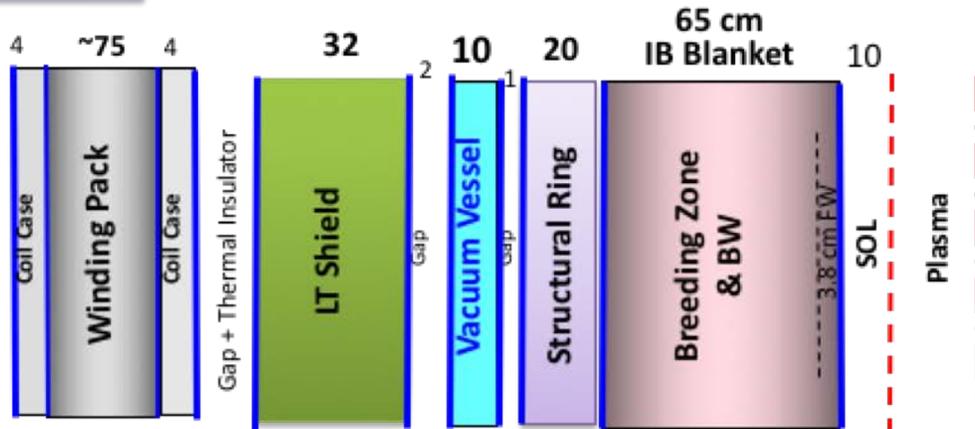
~ 35% disposable or recyclable
(40% Class C LLW, 60% Class A LLW)

~ 65%
(Clearable)

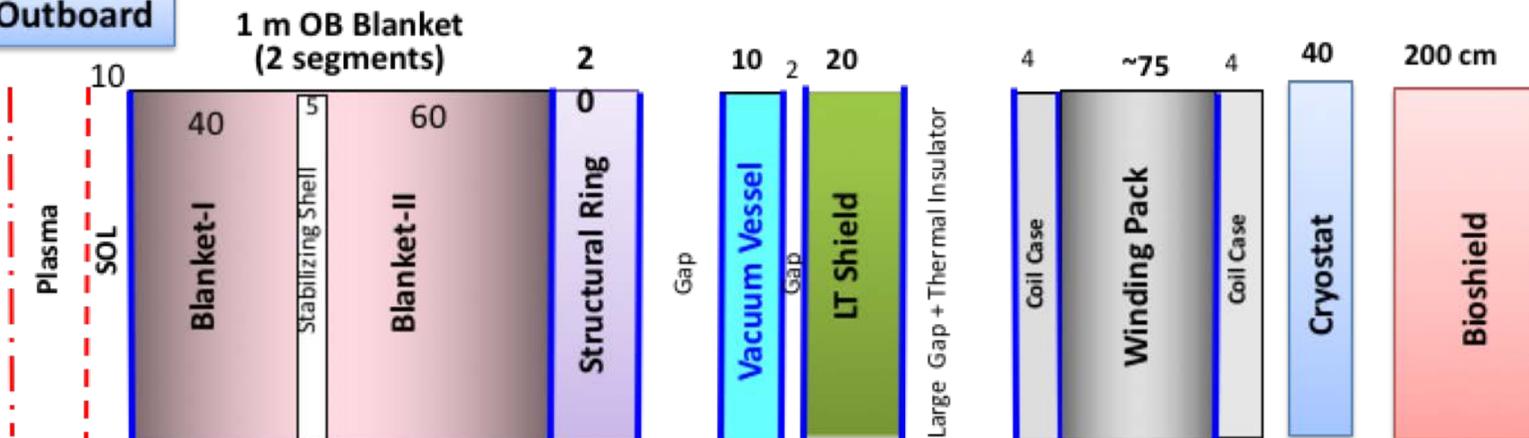


ARIES-ACT2 Radial/Vertical Build

Inboard



Outboard



Activation of Fusion Materials

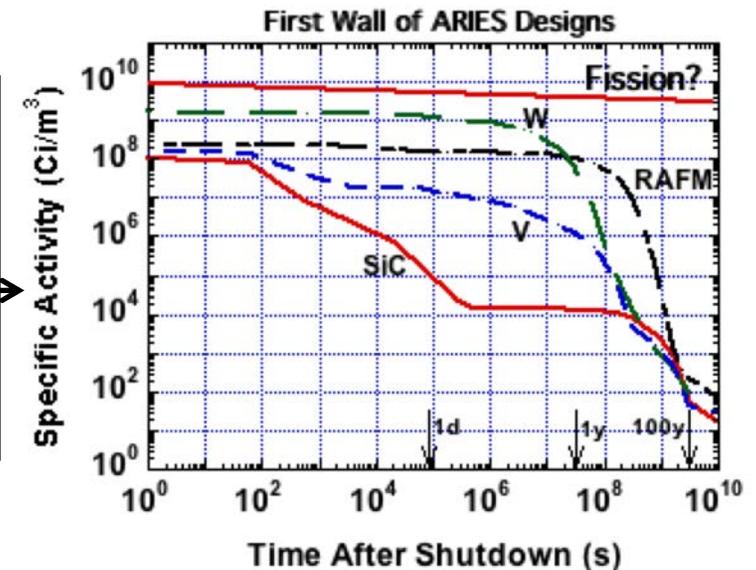


Activation of Fusion Materials

FPC radwaste is mostly steel.

Example: ARIES-ACT2 inventory: ~8000 m³ Steel and other solids; ~2,000 m³ PbLi breeder

- Candidate **reduced activation structural materials**:
RAFM steel, V-4Cr-4Ti, W alloys, SiC/SiC composites.
- Each structural material exhibits unique activation property during operation.
- SiC/SiC composites decay by several orders of magnitude within few days – salient feature for SiC/SiC.



Tritium Breeders:

- Liquid metals and molten salts are contaminated by their own radioactive byproducts.
- Activated corrosion products present major safety concern for occupational exposure during operation and releases to environment in case of accident.
- It is essential to continuously filter and purify all liquid breeders, molten salts, and coolants to avoid contaminating sub-systems and assure safe operation.
- At end of operation, liquid metals and molten salts **will not be disposed of**, but rather will be refurbished to adjust its Li content before **reuse as breeder in other fusion devices**.

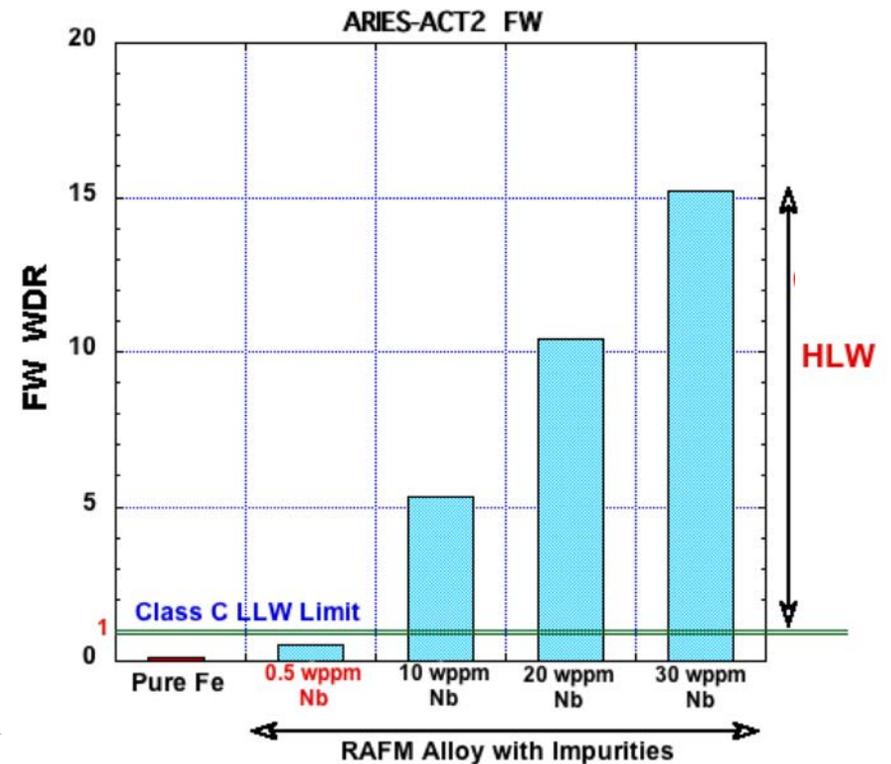
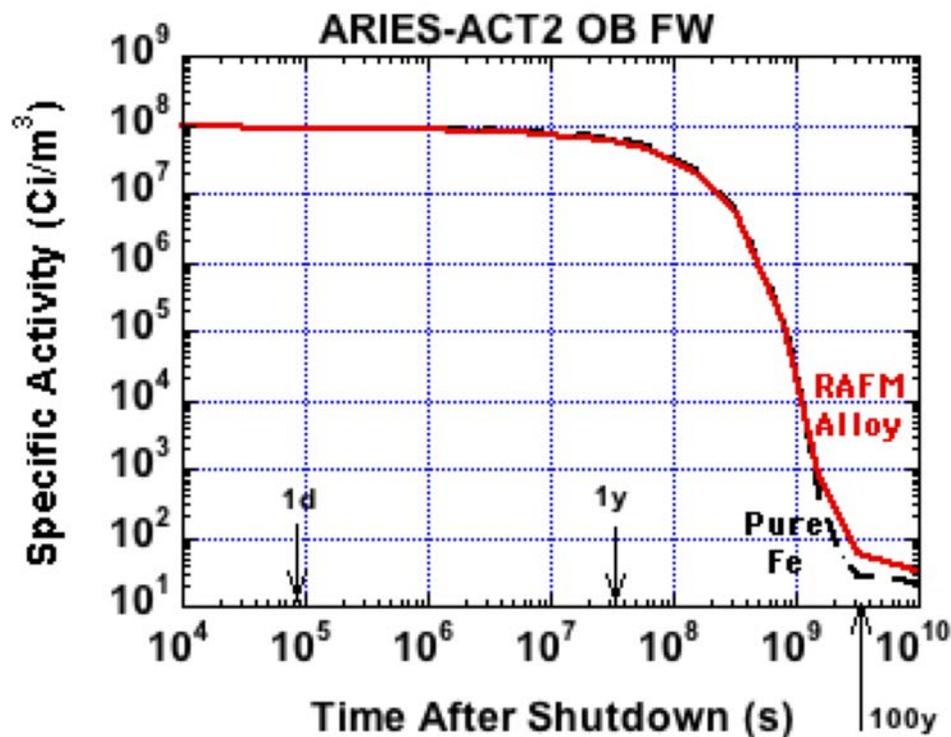


Activation of Steel Structure

Reduced-activation structural materials:

- **Careful choice of alloying elements** is essential to generate Class C LLW or better
 - ⇒ Avoid using Ni, Mo, Nb, Al, Re, etc. that generate long-lived radionuclides.
- **Impurities** (Nb, Mo, Ag, Al, Re, etc.) **must be controlled** to low level to avoid generating HLW.
- Alloying elements and impurities affect activity at > 50 y after shutdown.
- **Nb** impurity impacts WDR* greatly and should be kept **below 0.5 wppm**. **Cost?**

* Waste Disposal Rating



The Disposal Option



Managing Fusion Radioactive Materials – *The Disposal Option*

- The waste disposal rating (WDR) represents a metric for fusion waste classification:
 - **WDR < 1 means Class C LLW**
 - WDR < 0.1 means waste may qualify as Class A LLW
 - WDR > 1 means HLW*.
- WDR is evaluated at 100 y after shutdown for fully compacted components to classify the waste according to:
 - **Nuclear Regulatory Commission (NRC) 10CFR61 limits**
The NRC waste classification is based largely on radionuclides that are produced in fission reactors, hospitals, research laboratories, and food irradiation facilities.
 - **Fetter's waste disposal limits***
In the early 1990s, Fetter and others performed analyses to determine the specific activity limits for Class CLLW considering all radionuclides of interest to fusion using a methodology similar to that of 10CFR61. Although Fetter's calculations carry no regulatory acceptance yet, they are fusion-relevant as they include numerous fusion-specific radioisotopes.
- **All fusion components should meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion radwaste.**
- As expected, there are commonalities and differences between NRC and Fetter's limits.

• HLW official definition by NRC: spent fission fuel and residues of treatment of spent fission fuel.
In fusion designs, HLW is used for components with WDR > 1.



NRC vs. Fetter's Specific Activity Limits for Radionuclides

Periodic Table of the Elements

8 radionuclides highlighted in red: C-14, N-13, O-15, P-32, S-35, Se-75, I-131, and Po-210.

Periodic Table of the Elements

20 radionuclides highlighted in red: C-14, N-13, O-15, P-32, S-35, Se-75, I-131, Po-210, and 13 other isotopes.

NRC 10CFR61 developed specific activity limits for only 8 radionuclides (excluding actinides), presenting a weak basis for selecting reduced-activation materials for fusion and qualifying them as Class C LLW for near surface disposal

Fetter expanded list of NRC 10CFR61 radionuclides and determined specific activity limits for fusion-relevant isotopes with $5y < t_{1/2} < 10^{12}y$, assuming waste form is metal. NRC did NOT endorse Fetter's limits yet.

US Code of Federal Regulations, Title 10, Energy, Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, US Government Printing Office, January 2014.

S. FETTER, E. T. CHENG, and F. M. MANN, "Long Term Radioactive Waste from Fusion Reactors: Part II," Fusion Engineering and Design, 13, 239 (1990).



The Root of the Disposal Challenge

- Fusion generates large quantity of LLW (> 20,000 m³; including bioshield).
- Existing U.S. LLW sites cannot handle T-containing fusion radwaste.
- Disposal cost is high and continues to increase with time.
- Most commercial repositories will be closed by 2050.
- LLW requirements mandate strict control of impurities ⇒ expensive fusion materials.
- Disposing sizable fusion materials in repository is NOT environmentally attractive, nor economic solution.

What we suggest...

- Avoid the geologic disposal of fusion LLW.
- Promote recycling and clearance of **ALL** fusion materials.

- *L. El-Guebaly, "Nuclear Assessment to Support ARIES Power Plants and Next Step Facilities: Emerging Challenges and Lessons Learned," Fusion Science and Technology, Vol 74, #4, 340-369 (2018).*
- *L.A. El-Guebaly and L. Cadwallader, "Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy." Chapter in book: Radioactive Waste: Sources, Management and Health Risks. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).*
- *Zucchetti, M., Di Pace, L., El-Guebaly, L., Kolbasov, B. N., Massaut, V., Pampin, R. & Wilson, P. (2009). "The Back End of the Fusion Materials Cycle," Fusion Science and Technology, 52, 109-139.*



Key Issues and Needs for Disposal

Some issues/needs are related to activation areas inside FPC (that could be addressed by fusion designers), while others are related to areas outside FPC, requiring industrial, national lab, and fission experiences, DOE-OFES and NRC involvements. Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclides, radiation level, component size, weight, etc.).

Issues:

- Large volume of radwaste (mostly Class A and Class C LLW, but some designs (like ARC) generate HLW)
- High disposal cost that continues to increase (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal)
- No commercial HLW repositories exist in the U.S. (or elsewhere); fission power plants store their HLW onsite
- Limited capacity of existing LLW repositories
- Political difficulty of siting new repositories limits their capacity
- Prediction of repositories' conditions for long time into future
- Radwaste burden for future generations.

Needs:

- Revised fusion-specific activity limits for LLW, GTCC, and HLW issued by NRC
- Rigorous time-dependent methodology for flowing coolants and breeders
- Large capacity and low-cost interim storage facility with decay heat removal capability
- Repositories designed for T-containing materials
- Reversible disposal process and retrievable waste (to gain public acceptance and ease licensing).

Recycling and Clearance Options



Numerous Fusion Materials Proposed for Recycling Since Early 1980s

- Potential for hands-on recycling of fusion materials was recognized in 1980 STARFIRE report [C.C. Baker et al., “STARFIRE—a commercial tokamak fusion power plant study,” ANL Report ANL/FPP-80-1(1980)].
- In early 1990s-present, several fusion materials have been assigned to recycling for economic and limited resource reasons:
 - All liquid breeders [PbLi, Li, Flibe] (large quantities; e.g., 2000 m³ PbLi in ARIES-ACT2)
 - Vanadium (costly) [T.J. Dolan and G.J. Butterworth, “Vanadium recycling,” *Fusion Technology*, **26** (1994) 1014-1020]
 - Copper [G.J. Butterworth et al., “Recycling of copper used in fusion power plants,” *Fusion Engineering and Design*, **38** (1998) 441-458]
 - Beryllium [B.N. Kolbasov et al., “On Use of Beryllium in Fusion Reactors: Resources, Impurities and Necessity of Detritiation after Irradiation,” *Fusion Engineering and Design*, **109** (2016) 480-484]
 - Steel RTL of Z-pinch (large quantity) [L. El-Guebaly, P. Wilson, and M. Sawan, “Activation and Waste Stream Analysis for RTL of Z-Pinch Power Plant,” *Fusion Science and Technology*, **52**, No. 4, 1027-1031 (2007)]
- In 2000, ARIES System Studies* raised concerns regarding large radioactive inventory of fusion power plants, calling for recycling and clearance as potential solutions.
- The recycling and clearance approaches became more technically feasible with development of advanced radiation-hardened remote handling (RH) tools that can handle highly irradiated materials (with 10,000 Sv/hr at first wall of fusion power plants), along introduction of clearance category by NRC and IAEA in 2003-2004 for slightly radioactive materials.
- We suggest expanding the above list to include ALL fusion materials:
 - RAFM steel, W alloys, and other structures
 - Magnet materials (largest inventory in FPC)
 - Bioshield (largest inventory in entire plant, but clearable).

* L. El-Guebaly, “Evaluation of Disposal, Recycling, and Clearance Scenarios for Managing ARIES Radwaste after Plant Decommissioning,” *Nuclear Fusion* **47** (2007) 485-488.

* L.A. El-Guebaly and L. Cadwallader, “Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy.” Chapter in book: *Radioactive Waste: Sources, Management and Health Risks*. Susanna Penton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).



Recycling/Clearance Criteria

Recycling (reuse of materials within nuclear industry):

- **Dose to remote handling (RH) equipment**, determining needs for hands-on, conventional, or advanced tools and interim storage period necessary to meet dose limit.
- Decay heat level during reprocessing
- Economics of fabricating complex shapes remotely
- Physical properties of recycled products
- Efficiency of detritiation system.

Clearance (Unconditional release of slightly radioactive materials to commercial market for reuse):

- Clearable materials are handled as if they are no longer radioactive, reused without restriction, and recycled into consumer products (chairs, tables, bridges, dams, concrete walls, cement roads, etc.).
- Clearable materials (with **Clearance Index < 1**) contain traces of radioactivity with very low dose < 10 $\mu\text{Sv/y}$ (< 1% of background radiation).
- In 2003, NRC declared that materials with low concentrations of radioactivity could be deregulated. **NRC NUREG-1640 document*** contains clearance limits for 115 radioisotopes of steel, copper, aluminium, and concrete wastes.
- In 2004, **IAEA*** issued clearance guidelines for 257 elements.
- More recently in 2016, DOE developed Technical Standard to support the clearance and release of materials, equipment, and items from accelerator facilities*.

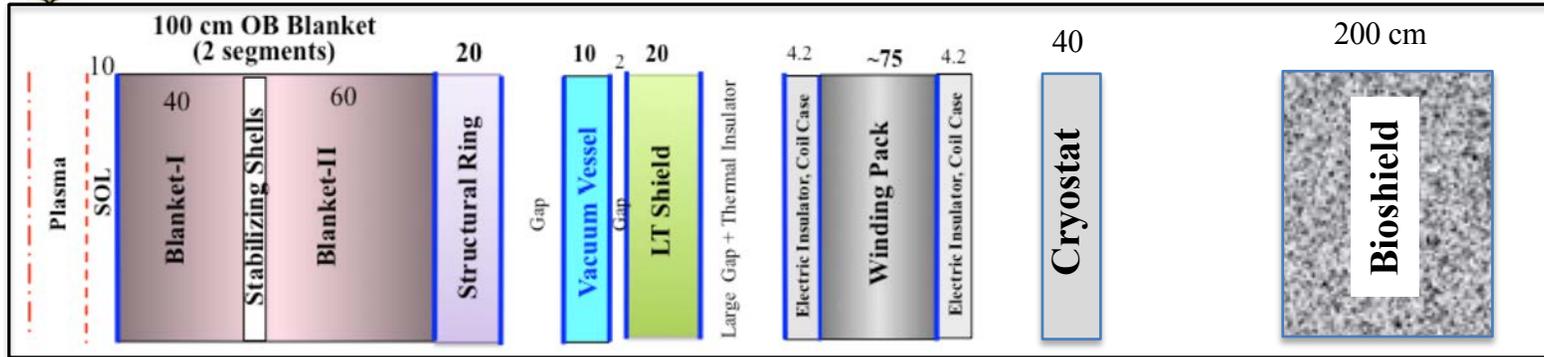
• Anigstein, R. et al., "Radiological Assessments for Clearance of Materials from Nuclear Facilities," volume 1, NUREG-1640, US Nuclear Regulatory Commission, June 2003. Available at: <http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/>.

• U.S. Department of Energy, "Clearance And Release Of Personal Property From Accelerator Facilities," DOE-STD-6004-2016 (March 2016).

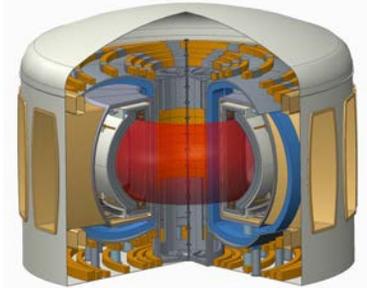
• International Atomic Energy Agency, Application of the concepts of exclusion, exemption and clearance, IAEA Safety Standards Series, No. RS-G-1.7 (2004). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf.



ARIES Project Examined Recycling Option for Several Fusion Designs

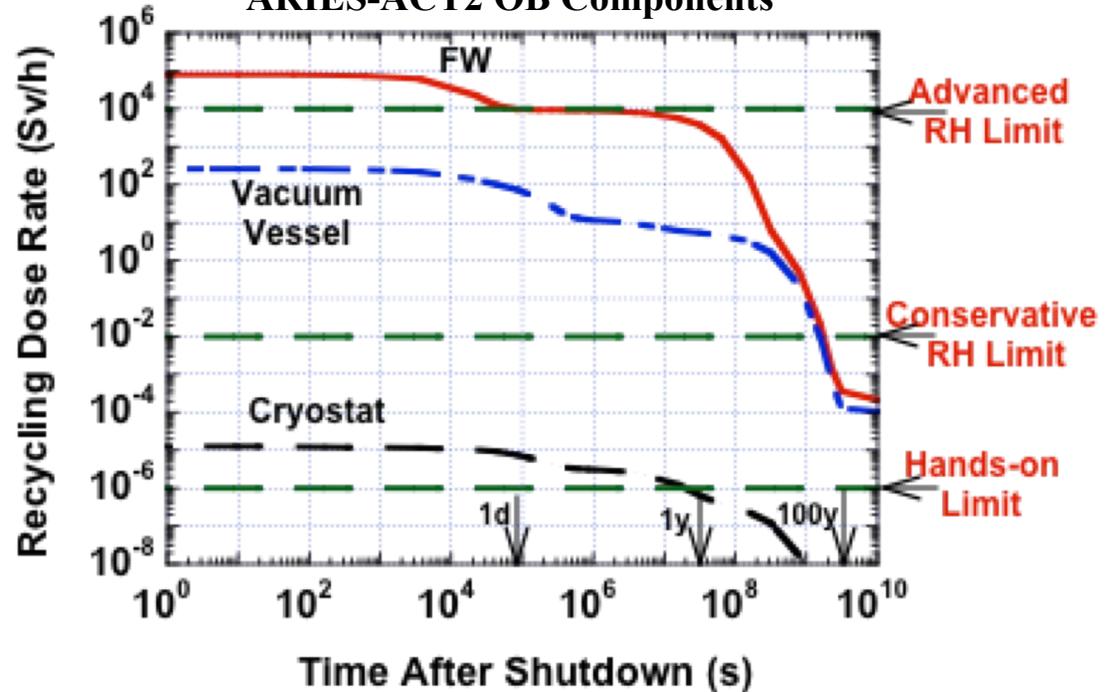


ARIES-ACT2



All FPC components can potentially be recycled in < 1y with advanced RH equipment

ARIES-ACT2 OB Components





Key Issues and Needs for Recycling

Some issues/needs are related to activation areas inside FPC (that could be addressed by fusion designers), while others are related to areas outside FPC, requiring industrial, national lab, and fission experiences, DOE-OFES and NRC involvements. Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclides, radiation level, component size, weight, etc.).

Issues:

- Separation of various activated materials from complex components
- Radiochemical or isotopic separation processes for some materials, if needed
- Treatment and remote re-fabrication of radioactive materials. Any residual He that affects rewelding?
- Radiotoxicity and radioisotope 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?
- Energy demand for recycling process
- Cost of recycled materials
- Recycling plant capacity and support ratio

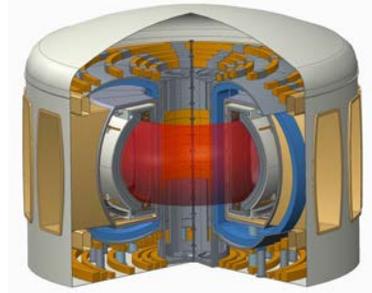
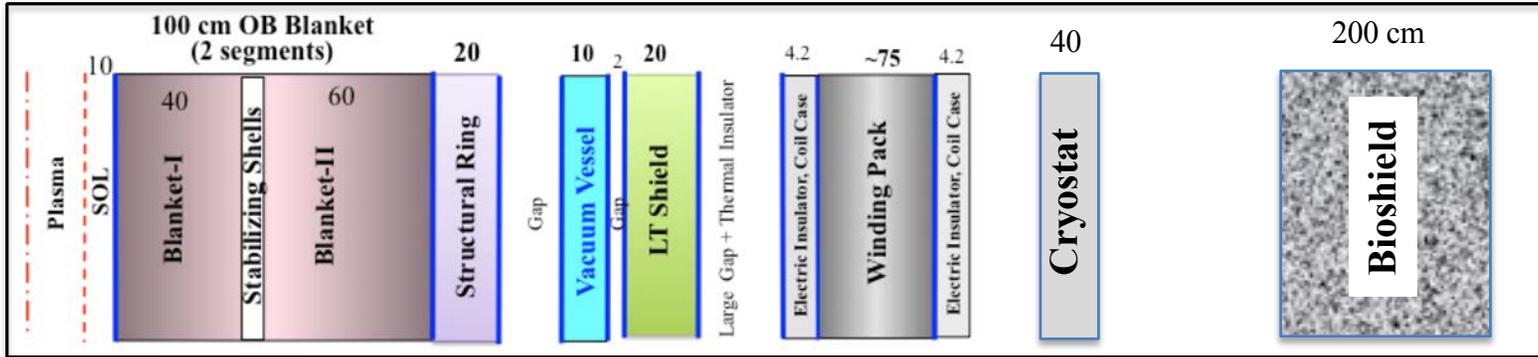
Needs:

- NRC to regulate the use of recycled materials from dismantled nuclear facilities
- R&D program to address recycling issues
- Radiation-resistant remote handling equipment
- Rigorous time-dependent radiotoxicity of recycled liquid breeders
- Reversible assembling process of components and constituents (to ease separation of materials after use)
- Efficient detritiation system to remove T before recycling
- Large capacity and low-cost interim storage facility with decay heat removal capability
- Nuclear industry should accept recycled materials
- Recycling infrastructure.

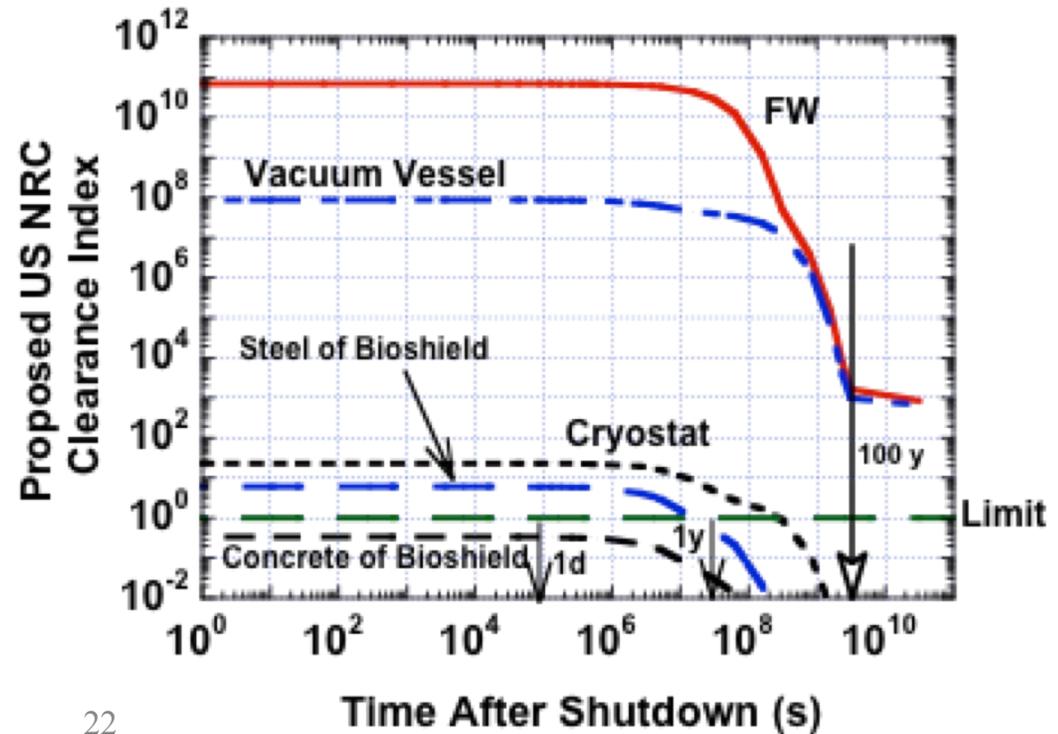


ARIES Project Examined Clearance Option for Several Fusion Designs

ARIES-ACT2



Only cryostat, bioshield, and some magnet constituents (not shown) can be cleared in 10 y after decommissioning





Key Issues and Needs for Clearance

Some issues/needs are related to activation areas inside FPC (that could be addressed by fusion designers), while others are related to areas outside FPC, requiring industrial, national lab, and fission experiences, DOE-OFES and NRC involvements. Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclides, radiation level, component size, weight, etc.).

Issues:

- Discrepancies* between proposed NRC & IAEA clearance standards
- Impact on clearance index prediction of missing radioisotopes (such as ^{10}Be , ^{26}Al , ^{32}Si , $^{91,92}\text{Nb}$, ^{98}Tc , $^{113\text{m}}\text{Cd}$, $^{121\text{m}}\text{Sn}$, ^{150}Eu , $^{157,158}\text{Tb}$, $^{163,166\text{m}}\text{Ho}$, $^{178\text{n}}\text{Hf}$, $^{186\text{m},187}\text{Re}$, ^{193}Pt , $^{208,210\text{m},212}\text{Bi}$, and ^{209}Po)
- Radioisotope buildup and release by subsequent reuse.

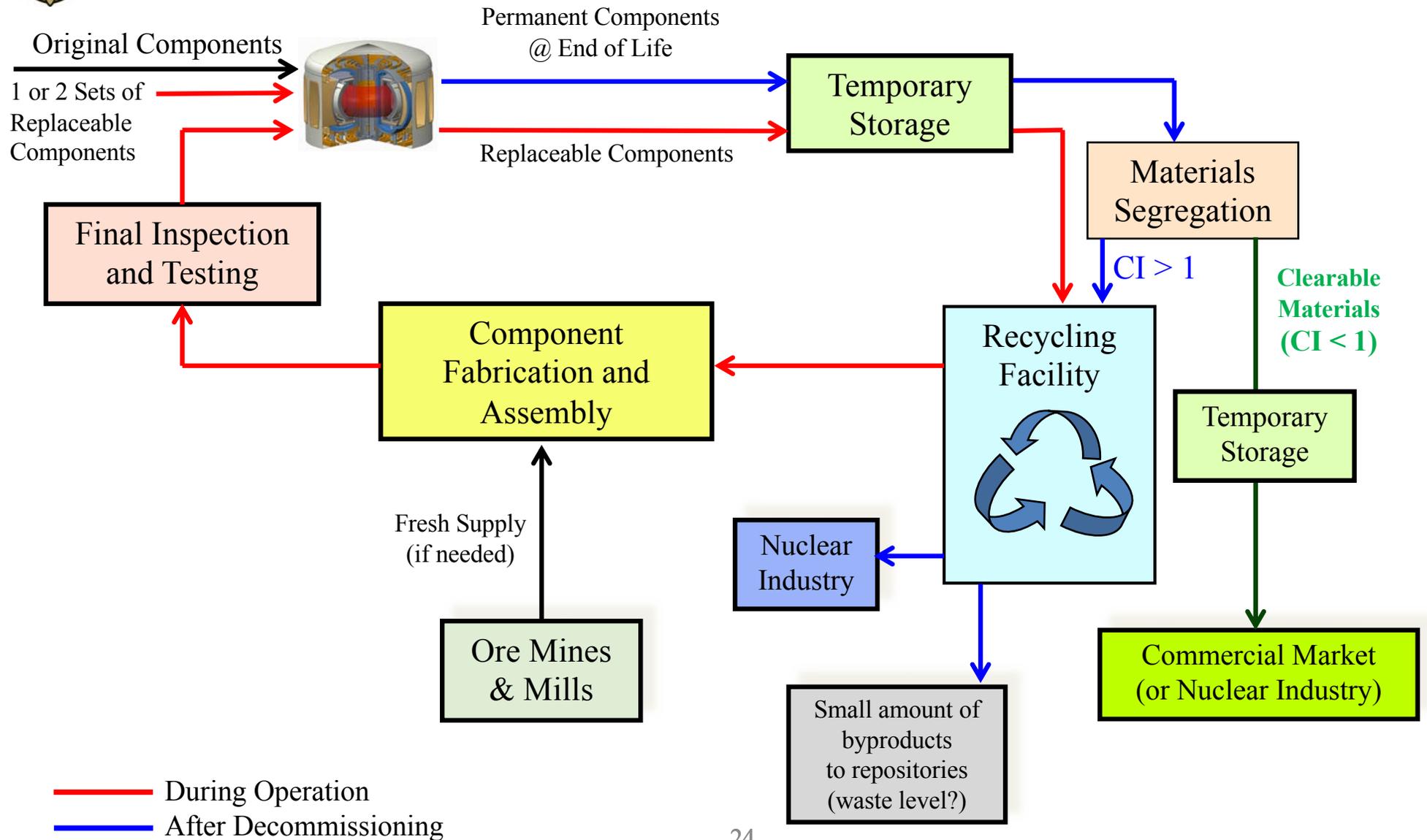
Needs:

- NRC clearance limits for fusion activated materials
- Accurate measurements and reduction of impurities that deter clearance of in-vessel components
- Reversible assembling process of components and constituents
- Large capacity and low-cost interim storage facility
- Clearance infrastructure
- Clearance market.

* El-Guebaly, L., Wilson, P. and Paige, D. (2006). "Evolution of clearance standards and implications for radwaste management of fusion power plants," *Fusion Science and Technology*, 49, 62-73.

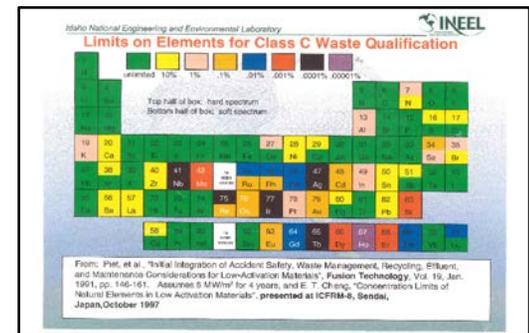


Recycling & Clearance Flow Diagram



Significant impact on materials program...

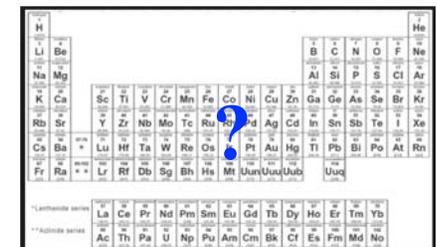
Recycling/Clearance Approaches could Revise Strict Compositional Limitations for Fusion Materials



1990s INL Chart for
Class C waste disposal

Opening up design space for more material choices...

Since recycling requirements are quite different from that for disposal, restrictions imposed on many alloying elements and impurities (like Al, Mo, Nb, Re, Ni, Cu, Ir, Ag, etc.) could be lifted out or relaxed considerably.



Recycling Chart
(to be developed)



Potential Game-Changers for New Fusion Materials

- Since all fusion materials could potentially be recycled, we suggest **revisiting strict compositional boundaries** within which materials community is currently working.
- Recycling/clearance guidelines seem to be **less restrictive** for fusion material selection and development.
- **Potential impacts of recycling/clearance:**
 - Can tolerate **higher level of impurities** \Rightarrow **Less costly fusion materials**
 - **No restrictions on alloying elements.** For example:
 - **ORNL:** developing **corrosion resistance high-Cr ODS** for PbLi blanket alloying with **Al** \Rightarrow higher FW/blanket operating temperature reaching 700-800°C \Rightarrow higher η_{th} .
 - **PNNL/UCSB:** Considering **Tungsten Heavy Alloys (W-Ni-Fe)** with high **Ni** content. Such alloys with 2-9 wt.% Ni exhibit great mechanical properties, with promising toughness, strength, and ductility properties for divertor applications.
 - **Purdue Univ.:** Examining variety of **structural materials for divertor structure: Nb, Mo, Ta, Zr, and Hf**, in addition to W.
 - Alloying **W** with **Re** to improve ductility of divertor structure.
 - Reconsidering for fusion applications:
 - **316-SS** of ITER (w/ **Ni, Mo** \Rightarrow HLW)
 - **Inconel-718** of ARC (w/ **Ni, Nb, Mo** \Rightarrow HLW).



Remarks and Outlook

- It is just a matter of time to develop the recycling and clearance technologies and their official regulations that are essential to support fusion deployment.
- Fusion program should be set up to change what is now impractical and costly waste disposal option into a valued commodity through the further development of recycling and clearance approaches for fusion radioactive materials.
- These approaches will relax the strict LLW requirements and expand the compositional boundaries within which materials community is currently working.
- While there is no official NRC regulations for recycling/clearance of fusion activated materials, some progress has been made in other nuclear fields in U.S. and abroad.
- Such developments will be of great importance to fusion, but adaptation to fusion environment and needs is necessary (radionuclides, radiation level, component size, weight, etc.).
- **In the meantime, fusion designers should undertake issues important for social acceptance of fusion:**
 - Minimize volume of radioactive materials by clever design and develop transformative, innovative technologies to achieve this goal
 - Integrate recycling and clearance approaches at early stage of fusion designs
 - Develop reversible assembling process for components and constituents (to ease separation of materials after use)
 - Continue addressing issues and needs for disposal/recycling/clearance approaches through dedicated **R&D program** *(some issues/needs are related to activation areas inside FPC (that could be addressed by fusion designers), while others are related to areas outside FPC, requiring industrial, national lab, and fission experiences, DOE-OFES and NRC involvements. Many of the identified issues/needs are addressed by the fission industry).*

R&D Priorities

Funding agencies (DOE-OFES and Private Company)
Regulator (NRC)
National labs and Industries
Activation code developer (UW)



R&D Priorities for Fusion Radwaste Management

- **DOE-OFES:**
 - Fund R&D programs that advance fusion's social acceptance, such as minimizing radwaste stream via recycling and clearance.
 - Integrate recycling and clearance rules into revised DOE Fusion Safety Standards to support new fusion facilities, such as Pilot Plant, DEMO, Power Plants, and others developed by private fusion companies.
 - Start program to **develop recycling/clearance related technologies** and couple this effort with private industry through ARPA-E, INFUSE, and/or SBIR initiatives.
 - More specifically, some of the fusion radwaste approaches could have implications/benefits for private fusion companies, assuming recycling/clearance approaches can be successfully developed to reduce final radwaste burdens/risks.



R&D Priorities for Fusion Radwaste Management (Cont.)

- **NRC:**

- Issue fusion-specific disposal, recycling and clearance standards that include ALL radioisotopes encountered in fusion.

- **Disposal:**

- Reassess definitions of waste categories for fusion LLW, GTCC, and HLW
- Issue specific activity limits for all radionuclides generated by fusion (> 50)
- Take more pragmatic view of different risks associated with fusion radwaste (mostly steel) in comparison to fission and other nuclear radwastes (majority of fusion stable structural steels have a relatively low risk profile regardless of their absolute activation).
- Develop new strategy for disposition of T-containing fusion radwaste (with significantly higher T than in fission waste).



R&D Priorities for Fusion Radwaste Management (Cont.)

- **NRC:**

- **Recycling:**

- Support acceptability of nuclear industry to recycled materials
- Develop criteria for recyclable activated materials
- Regulate the use of recycled materials from dismantled nuclear facilities
- Examples of U.S. recycling activities:
 - Tons of metals and concrete from fission plants have been recycled for reuse within nuclear industry. This is small compared to fusion LLW, but it is a good start.
 - In 2010, DOE required decontamination of 15,300 tons of radioactive nickel and recycling into products that are used in radiologically-controlled applications.
 - To avoid high disposal cost, ORNL Y-12 Team investigated possibility of recycling ~10 tons of Be metal to reuse as tiles for ITER's first wall. Testing program to qualify Be (from U.S. weapons program) is underway [1,2].

1. W. Rogerson, S. Brown (Y-12 NSC at ORNL) et al., "Qualification of Unneeded US Weapons Program Beryllium Metal for ITER," presented at 21st TOFE (2014).

2. W. Rogerson, R. Hardesty, "Qualifying Nuclear Weapons Enterprise Legacy Metal for ITER," presented at 28th SOFE (2019).

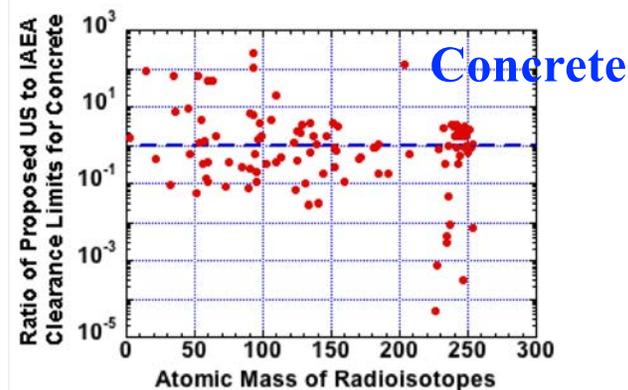
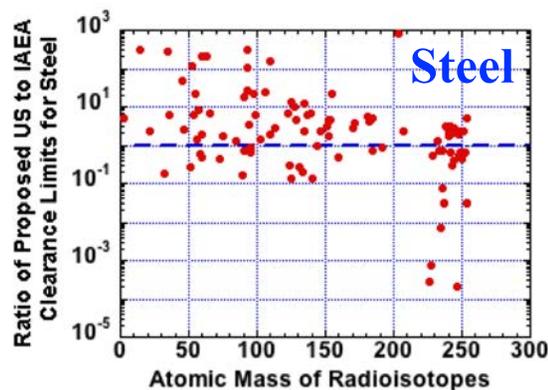


R&D Priorities for Fusion Radwaste Management (Cont.)

- **NRC:**

- **Clearance:**

- Identify clearance limits for missing radioisotopes generated by fusion*:
 ^{10}Be , ^{26}Al , ^{32}Si , $^{91,92}\text{Nb}$, ^{98}Tc , $^{113\text{m}}\text{Cd}$, $^{121\text{m}}\text{Sn}$, ^{150}Eu , $^{157,158}\text{Tb}$, $^{163,166\text{m}}\text{Ho}$, $^{178\text{n}}\text{Hf}$, $^{186\text{m},187}\text{Re}$, ^{193}Pt , $^{208,210\text{m},212}\text{Bi}$, and ^{209}Po .
- Many discrepancies* between NRC & IAEA# clearance standards (that impact CI and storage period)
 - Clearance of slightly radioactive materials from DOE managed facilities has been going on in a case-by-case basis.
 - Since 1990s, many European projects* (in Sweden, Belgium and Spain) cleared materials in industrial quantities (mostly metals and concrete rubble).
- Any future effort to reach international agreement or harmonized regulation for clearance? (as steel products and scrap are routinely sold internationally)



• El-Guebaly, L., Wilson, P. and Paige, D. (2006). "Evolution of clearance standards and implications for radwaste management of fusion power plants," *Fusion Science and Technology*, 49, 62-73.

• El-Guebaly, L., Massaut, V., Tobita, K. & Cadwallader, L. (2008). "Goals, Challenges, and Successes of Managing Fusion Active Materials," *Fusion Engineering and Design*, 83, 928-935.

International Atomic Energy Agency, *Application of the concepts of exclusion, exemption and clearance*, IAEA Safety Standards Series, No. RS-G-1.7 (2004).

Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf



R&D Priorities for Fusion Radwaste Management (Cont.)

- **National Labs and Industries:**

- Accurate measurements and reduction of impurities that disqualify LLW disposal or deter clearance of in-vessel components
- Continue developing advanced radiation-resistant RH equipment capable of handling $> 10,000$ Sv/h to recycle (and maintain) fusion components
 - At INL EBR-II, RH equipment operated well at high doses around 10,000 Sv/h since 1960s through 1990s*. Adaptation of such equipment to fusion environment and needs is essential.
- Develop efficient chemical and/or radioisotope separation processes for fusion recyclable materials.
- Assess efficiency of detritiation system that removes majority of tritium before disposal and recycling.

* L.A. El-Guebaly and L. Cadwallader, "Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy." Chapter in book: *Radioactive Waste: Sources, Management and Health Risks*. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).



R&D Priorities for Fusion Radwaste Management (Cont.)

- **National Labs and Industries:**

- Determine quality and physical properties of recycled products.

- Limited scale recycling has been proven feasible*:

- After melting, slag tends to collect majority of radionuclides. When slag is removed, resulting ingots contained only very low level of radioactivity.
- INL, SRNL, and industrial company fabricated shielding casks out of recycled stainless steel and Pb*:
 - Composition adjustments after slag removal produced metal alloys with properties very similar to those of fresh alloys
 - Casks were designed, built, and tested for strength and impact
 - Prototype casks functioned well and are still in use since 1996.
- In Europe, Belgium, UK, and Italy addressed recycling of fusion activated materials:
 - L. Ooms, 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).
 - V. Massaut, R. Bestwick, K. Brodén, L. Di Pace, L. Ooms, R. Pampin, State of the art of fusion material recycling and remaining issues, Fusion Engineering and Design 82 (2007) 2844-2849.
 - L. Di Pace et al., Feasibility Studies of DEMO Potential Waste Recycling by Proven Existing Industrial-Scale Processes, Fusion Engineering and Design 146 (2019) 107-110.

* L.A. El-Guebaly and L. Cadwallader, "Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy." Chapter in book: *Radioactive Waste: Sources, Management and Health Risks*. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).



R&D Priorities for Fusion Radwaste Management (Cont.)

- **Economics:**

- Evaluate disposal cost (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal in repositories)
- For COE evaluation, develop D&D costing algorithm for fusion radwaste (proportional to LLW or HLW volume/mass to replace 0.5 mills/kWh – single value for all designs)
- Cost of recycled breeders and replenishment of Li enrichment
- Cost of remote fabrication with conventional techniques using recycled materials
 - INL and industrial firm recycled activated Pb bricks for nuclear industry. Cost of Pb LLW disposal was ~\$5/pound while cost of recycling was cheaper: ~\$4.3/pound including fabrication into brick shapes*.
 - Russian study concluded that recycling is cheaper than disposal[#].
- Cost of remote fabrication with AMT (Advanced Manufacturing Technologies) using recycled materials.

* L.A. El-Guebaly and L. Cadwallader, “Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy.” Chapter in book: *Radioactive Waste: Sources, Management and Health Risks*. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).

Bartenev, S. A., Kvasnitskij, I. B., Kolbasov, B. N., Romanov, P. V., Romanovskij, V. N. (2004). “Radiochemical reprocessing of V-Cr-Ti alloy and its feasibility study,” *Journal of Nuclear Materials*, 329-333, 406-410



R&D Priorities for Fusion Radwaste Management (Cont.)

- **Activation Codes and Data:**

- Continue developing state-of-the-art, time-dependent activation codes (such as ALARA*) and cross section data that allow designers to determine the radiation environment with high accuracy and examine radwaste management options (disposal, recycling and clearance) during the design process.
- Potential updates for ALARA:
 - Software modernization: newest methods, algorithms and infrastructure
 - Support for newer activation data sets: FENDL3/A
 - Better integration into 3-D analysis workflows, using PyNE
 - Integrate ALARA with DAGMC (that couples CAD with 3-D MCNP).

• P. WILSON and D. HENDERSON, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis: A Complete Package for Analysis of Induced Activation," University of Wisconsin Fusion Technology Institute Report. Volume I - UWFD-1070. Volume II - UWFD-1071 (1998).

• RSICC distributed (<https://rsicc.ornl.gov/codes/ccc/ccc7/ccc-723.html>)

• DAGMC Users Guide, University of Wisconsin-Madison Fusion Technology Institute (2008); <http://svalinn.github.io/DAGMC/usersguide/>



Upcoming IAEA Workshop on Fusion Radwaste Management

First Workshop on Waste Management for Fusion

**IAEA Headquarters
Vienna, Austria**

Preliminary dates: ~~May 20-22, 2020~~
~~Feb 24-26, 2021~~
October 6-8, 2021

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<https://nucleus.iaea.org/sites/fusionportal/Pages/Waste.aspx>



Resources

- **UW Neutronics Center of Excellence:** <https://fti.neep.wisc.edu/fti.neep.wisc.edu/ncoe/home.html>
- **UW Fusion Technology Institute:** <https://fti.neep.wisc.edu/fti.neep.wisc.edu/index.html>
UW FTI personnel have been designing conceptual MFE and IFE power plants and experimental facilities for over 45 years. We collaborated with research teams at national institutions and international organizations and participated in 60 projects. The UWFD series of technical reports details the research of the FTI from 1971 to the present. Over 800 authors have contributed more than 1400 reports. Nearly all are posted online at: <https://fti.neep.wisc.edu/fti.neep.wisc.edu/pubs.html>
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