Overview of Environmental Aspect of Future Fusion Power Plants

(an issue that could influence the public acceptability of fusion energy if remained unaddressed)

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USBPO Webinar Series on Burning Plasma Concepts and their Implications

September 15, 2022

Worldwide Effort to Develop Fusion Energy for Next Generations

- **Seven** magnetic fusion energy (MFE) concepts developed since 1950s:

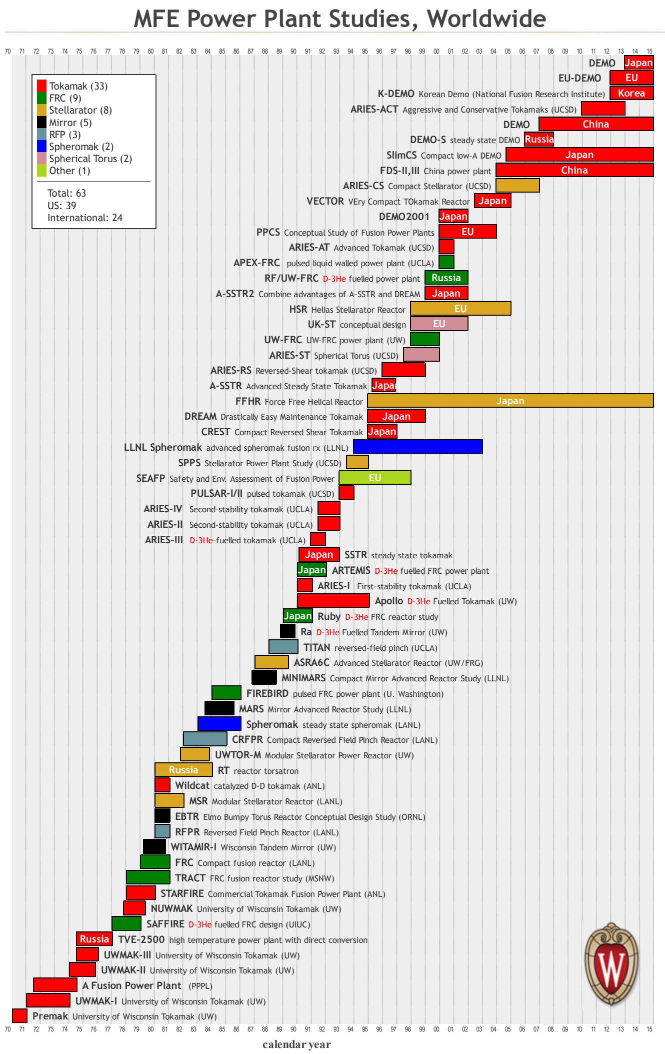
Tokamaks	Field-reversed configurations (FRC)
Stellarators	Reversed-field pinches (RFP)
Spherical tokamak (ST)	Spheromaks
	Tandem mirrors (TM).

- At the present time, main concept supporting pathway from ITER to power plant is D-T tokamak.

- Private sector will develop several fusion concepts in 2030s and examine other fuel cycles, not only D-T.

- Several countries developed roadmaps with end goal of operating 1st fusion power plant by 2050**.** These roadmaps take different pathways, depending on:
  - Degree of extrapolation beyond ITER
  - Readiness of fusion **materials** with verifiable irradiated design properties
  - What **technologies** remain to be developed and matured for viable 1st power plant?
    (or build 1st plant and then solve remaining problems: materials, safety, etc., if it can be licensed and supported by utilities)
  - What **other facilities** will be needed between ITER and 1st power plant?

More Than 60 Conceptual MFE Designs* Developed Since 1970 to Identify and Resolve Physics/Technology Challenges



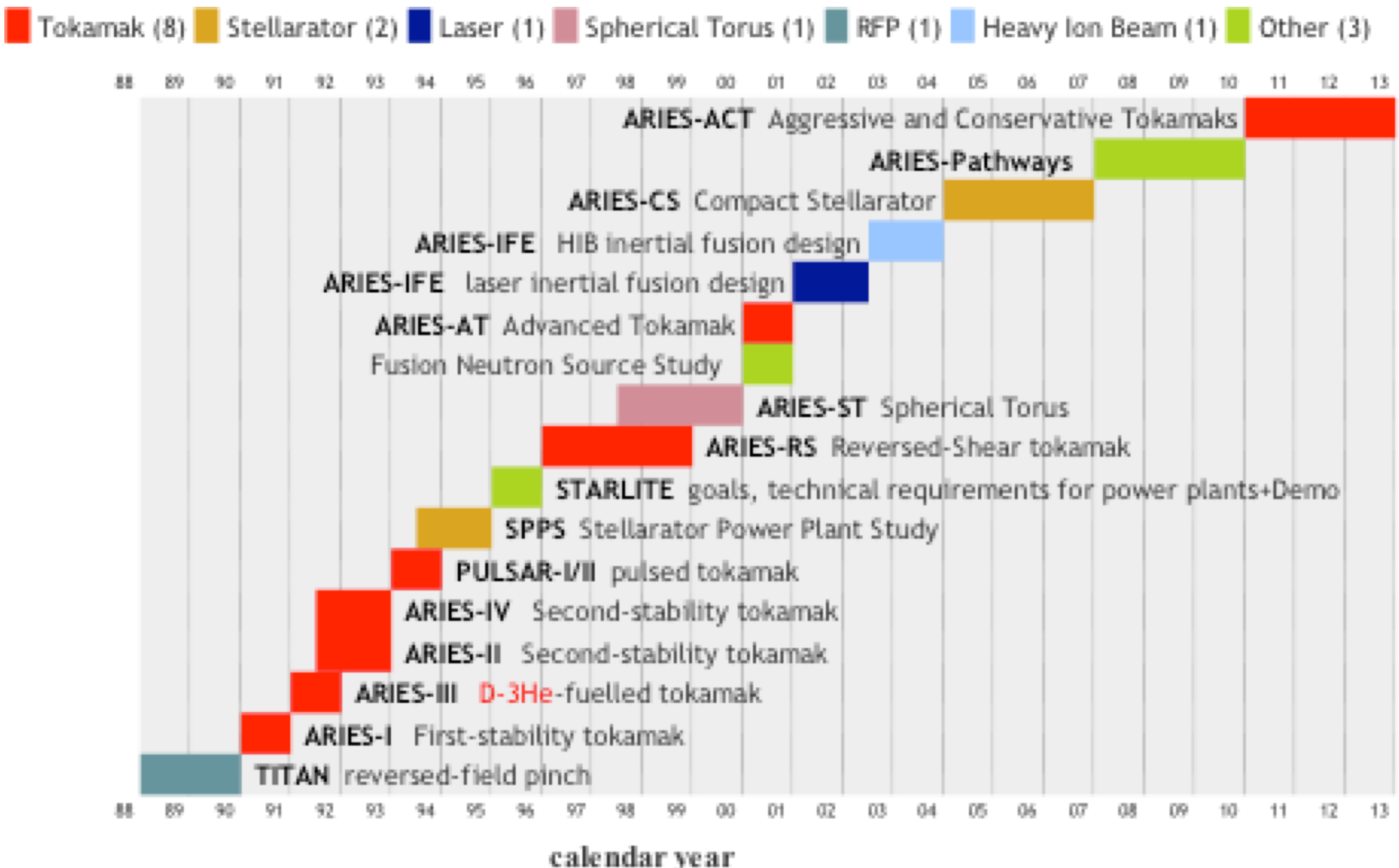
Most studies and experiments are currently devoted to **D-T fuel cycle** – least demanding to reach ignition.

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

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.

U.S. ARIES Project (1988–2013) Examined Several Fusion Concepts with Commercial Perspective in Mind

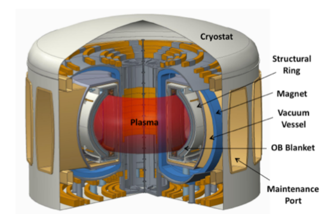


1988 **2013**

ARIES-ACT

Tokamak

(with reduced activation structure)



http://qedfusion.org/aries.shtml

The ARIES project focused mainly on the device. Less attention was given to the BOP.

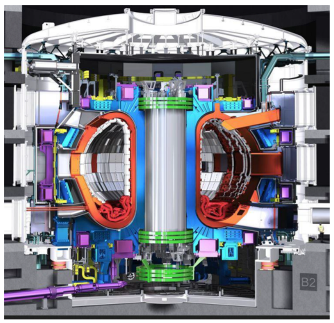
Fusion has long been thought for its safety and environmental advantages over other energy sources.

Majority of Fusion designs employ reduced-activation materials to generate low-level waste
(under strict alloying elements and impurity control),
but in large quantity compared to fission.

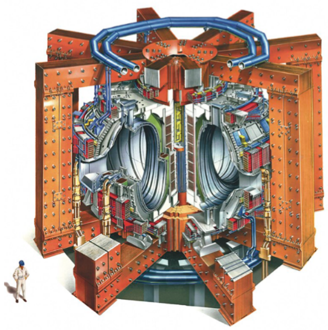
This is serious environmental issue that could influence public acceptability of fusion energy and should be solved ***at any price****.*

Worldwide Pathways to Fusion Energy

ITER



JET



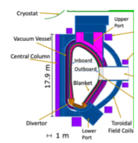
+ TFTR, DIII-D, EAST, JT-60SA, KSTAR, etc.

+ Supporting R&D activities:
Materials Testing Facility, Blanket Development Program, Divertor and PMI Testing Facilities, Code Development and Simulations, etc.

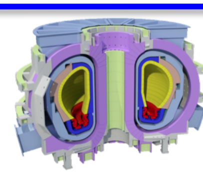
US FNSF or Pilot Plant

US-DEMO ?

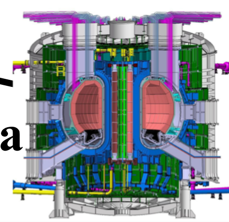
EU-DEMO



JA-DEMO

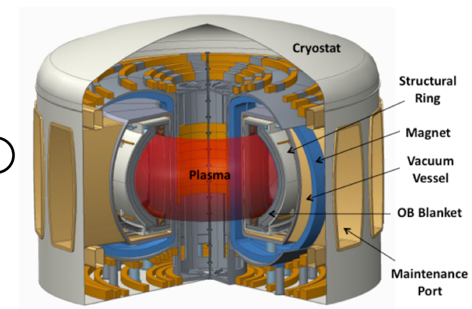


China



CFETR Phase I	DEMO Phase II

1st Power Plant by 2050



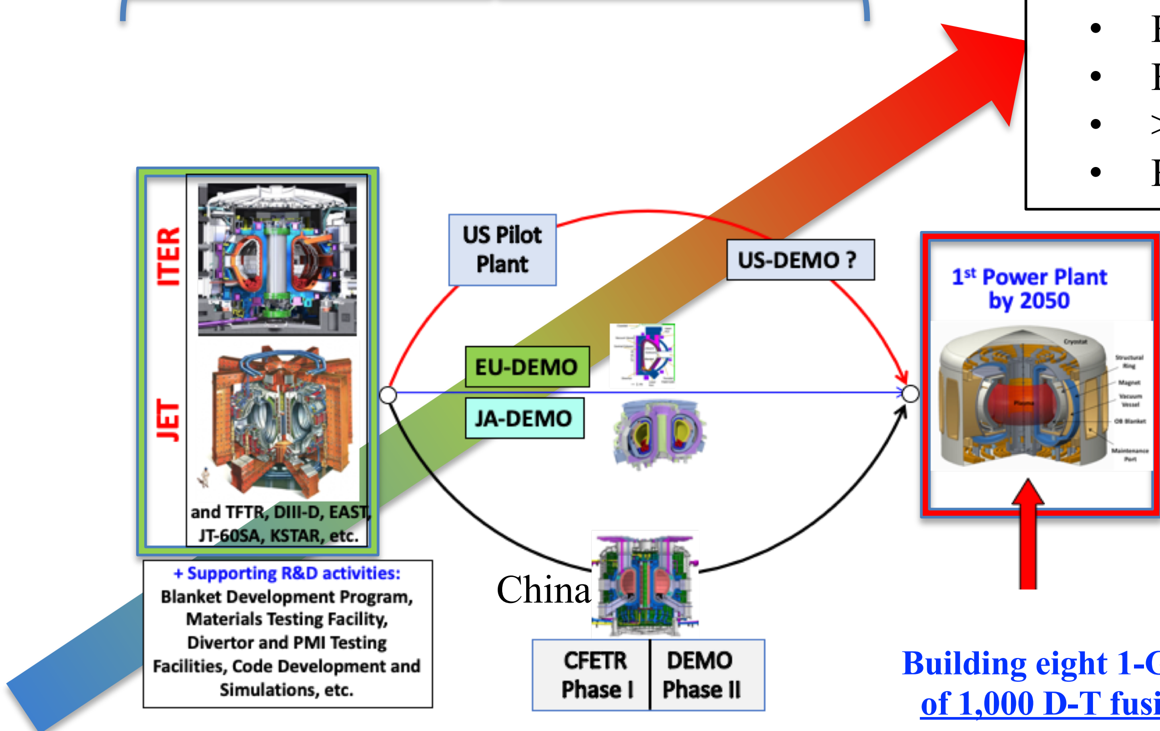
Advanced or Conservative Physics and/or Technology?

Radioactivity Level Varies Widely with Designs

One-of-a-kind Devices

High Radioactivity **(Power Plant):**

- High radwaste inventory
- High fusion power (2-3 GW)
- High NWL ($\geq$ 1 MW/m^2)
- High availability (85%)
- > 50 y lifetime
- High n fluence ($\geq$ 20 MWy/m^2)



This leads to RWM* challenges that require serious effort to manage radwaste.

Low Radioactivity **(ITER):**

- Relatively low radwaste inventory
- 500 MW fusion power
- Low NWL (0.5 MW/m^2)
- 20 y lifetime
- Low availability
- Low n fluence (0.3 MWy/m^2)

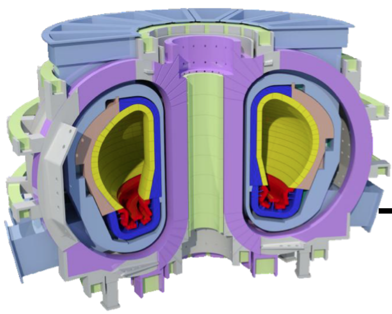
Building eight 1-GW$_e$ fusion plants annually, fleet of 1,000 D-T fusion power plants could provide ~10% of world electricity demand by ~2200.

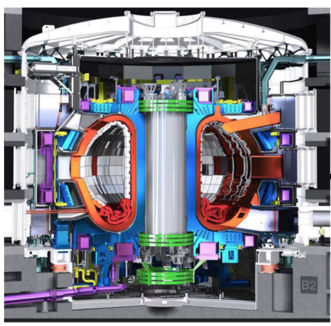
Resources Will Eventually be Limited

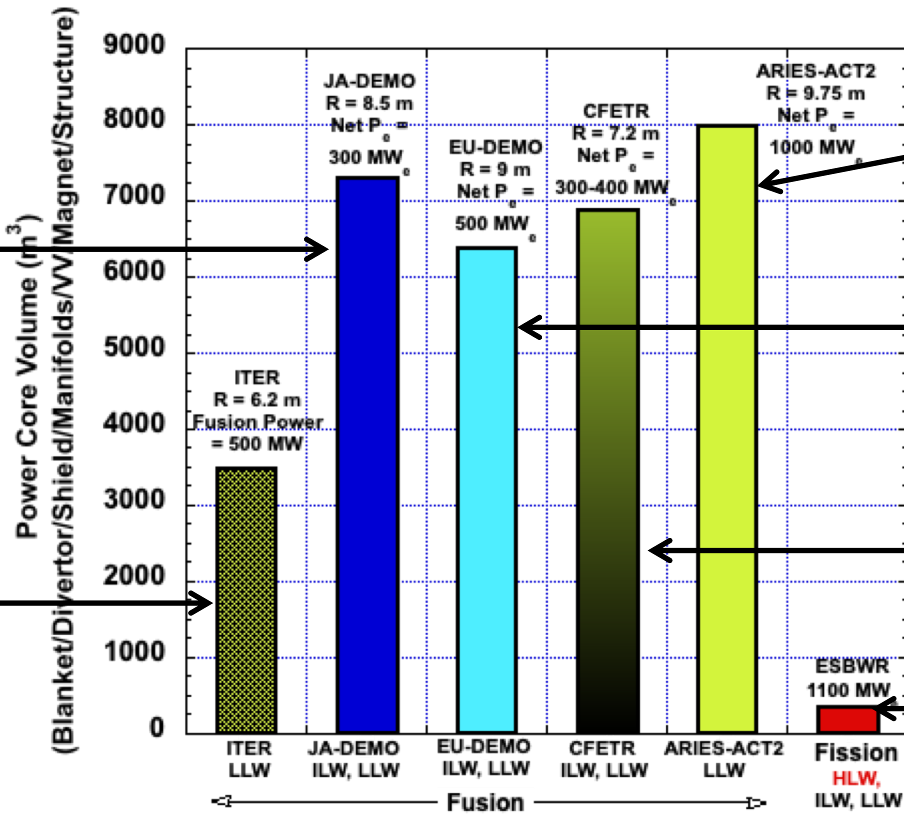
Luigi Di Pace, "Suitable Recycling Techniques for DEMO Activated Metals." IAEA TECDOC on Fusion RWM, to be published in 2023.

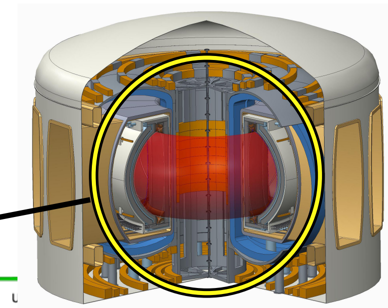
* Radioactive waste (radwaste) management

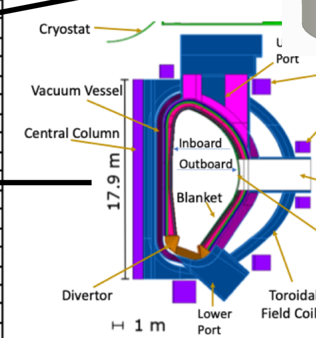
Fusion Designs Employing Reduced-Activation Materials Could Generate Only LLW#, but in Large Quantity Compared to Fission

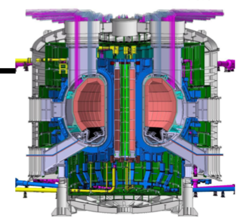


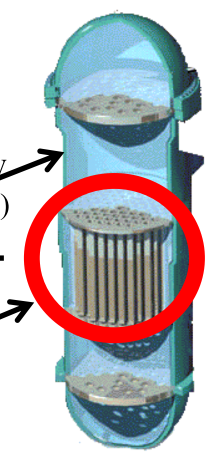












Actual volume of fusion power components in ITER, JA, EU, China, and US ARIES designs; not compacted, no replacements; no plasma chamber; no cryostat/bioshield.

What would be the public reaction to sizable fusion radwaste?

Options for Managing Radioactive Materials

- **Geological "land based" disposal** – default option for fission waste for many nations.

- **Transmutation of long-lived radionuclides**
(⇒ proliferation concerns for fission, not for fusion).
- **Disposal in space** – not feasible due to international treaties.
- **Ice-sheet disposal** @ north/south pole – not feasible due to international treaties.
- **Ocean disposal** (1947-1993; Prohibited in 1994).

Others came and mostly disappeared

- **Recycling** / reprocessing (reuse within nuclear industry).
- **Clearance** (release to commercial market if materials are slightly radioactive, containing 10 μSv/y (< 1% of background radiation)).

Activated materials – not counted as radwaste

Each option faces its own set of challenges

The Disposal Option

- Environmental concerns
- U.S. disposal classifications
- Status of U.S. repositories
- Key issues and needs for fusion.

Environmental Concerns and Facts

- Land-based disposal has been the preferred U.S. option for LLW from commercial nuclear facilities since 1960s.

- **Concerns**:
  - For LLW, the issue is land disposal sites oversight for 100 years
  - Water is prime carrier for wastes. If water infiltrates, it will corrode waste containers
  - Over time, radioactivity could leak, contaminate groundwater, and eventually reach humans
  - Of particular concern for fusion is the need to detritiate some of fusion radwaste prior to disposal to prevent tritium from eventually reaching underground water sources.

Waste Disposal Rating – Metric for Waste Classification

NRC 10 CFR Part61* classifies the waste at 100 years after shutdown according to its waste disposal rating (WDR), which is the ratio of specific activity (in Ci/m^3) to allowable limit, summed over all radioisotopes:

- **WDR < 1** means Class C LLW (using Class C limits)
- **WDR < 0.1** means waste may qualify as Class A LLW

  (to be re-evaluated using Class A limits)
- **WDR > 1** means GTCC.

Most fusion radwaste qualify as Class A or Class C LLW. Some radwaste may qualify as GTCC# with WDR >>1.

- US Code of Federal Regulations, Title 10, Energy, Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (2020). https://www.nrc.gov/reading-rm/doc-collections/cfr/part060/full-text.html.

NRC is currently preparing the regulatory basis for disposal of GTCC waste# (LLW that contains radionuclide concentrations exceeding Class C limits). The Draft Regulatory Basis for the Disposal of GTCC and Transuranic Waste is available at ADAMS Accession No. ML19059A403. https://www.nr c.gov/waste/llw-disposal/llw-pa/gtcc-transuranic-waste-disposal.html

Many Radionuclides of Interest to Fusion are Not in NRC 10 CFR Part 61

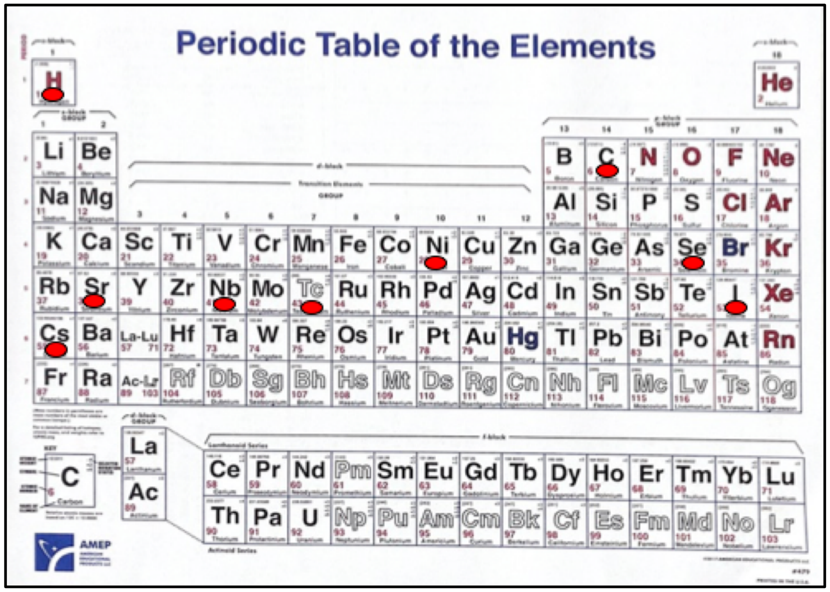
In early 1990s, Fetter et al.* expanded the NRC 10CFR61 list considerably and performed analyses to determine the Class C specific activity limits for many radionuclides of interest to fusion using a methodology similar to that of NRC. Although Fetter's calculations carry no regulatory endorsement by NRC, they are useful to fusion designers because they include many fusion-specific radioisotopes:

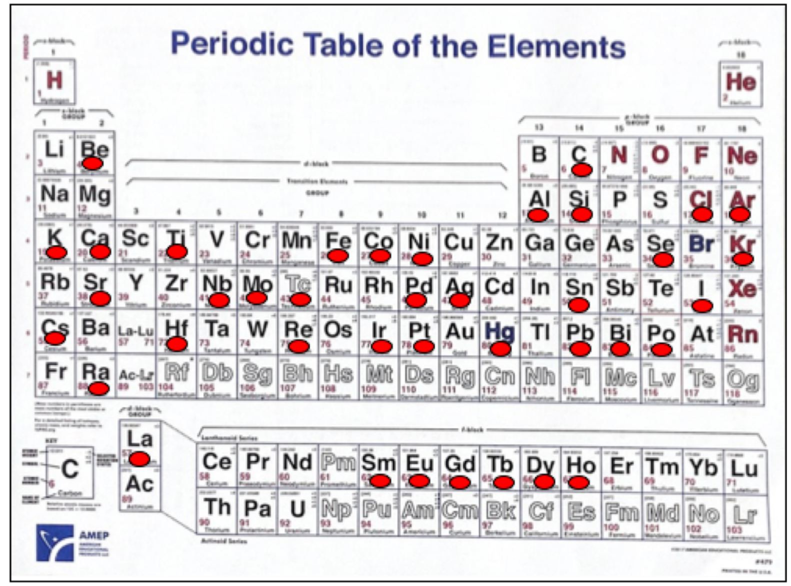
- Class C limits for **53** radionuclides of interest to fusion
- **No** limits available for Class A LLW
- **Not** in regulation form yet
- Approved by U.S. Fusion Safety Standing Committee#

- *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).*

 # DOE STANDARD, Safety of Magnetic Fusion Facilities: Guidance, DOE-STD-6003-96 (1996). Currently under revision. https://www.standards.doe.gov/standards-documents/6000/6003-astd-1996/@@images/file.

NRC vs. Fetter's Specific Activity Limits for Radionuclides





NRC 10CFR61 developed specific activity limits for only **9/11** elements/radioisotopes*, presenting a weak basis for selecting reduced-activation materials for fusion and their qualification as Class A and C LLW

US Code of Federal Regulations, Title 10, Energy, Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (2020).

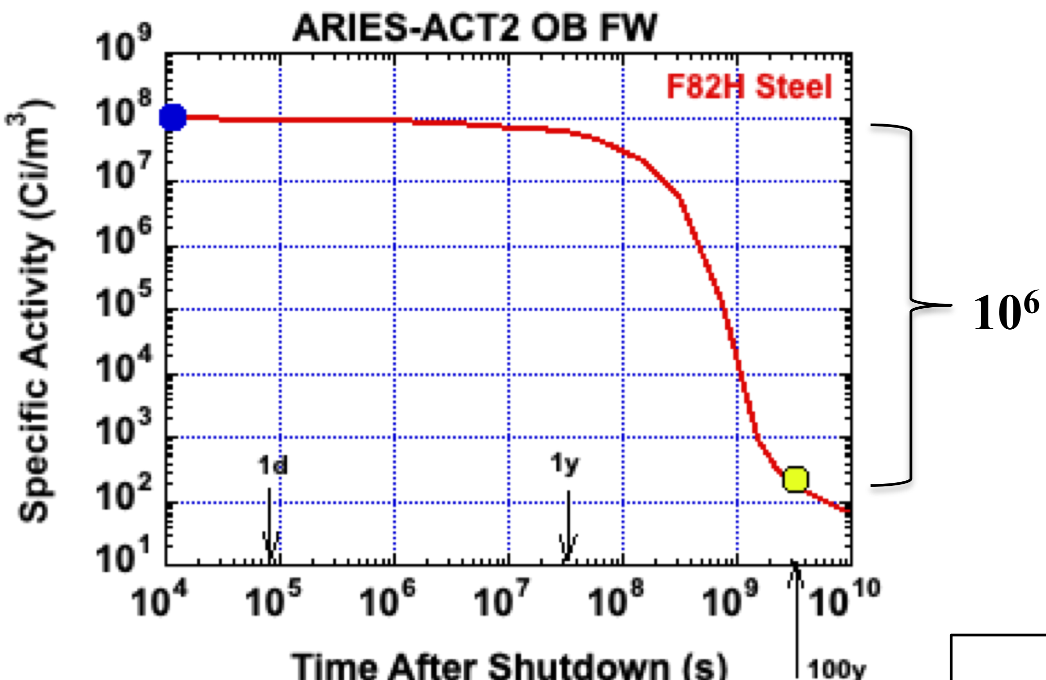
Fetter expanded list of NRC 10CFR61 radionuclides and determined specific activity limits for <u>fusion-relevant isotopes</u> **39/53** elements/radioisotopes* with $5y < t_{1/2} < 10^{12}y$, assuming waste form is metal.

*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).*

* Excluding actinides and fission products.

Fusion Radionuclide Profile

@ shutdown:
56/367
elements/radioisotopes with wide range of activities and half-lives



@ 100 y after shutdown:
38/71
elements/radioisotopes with various activities and half-lives

Missing Radioisotopes Introduce Uncertainty in WDR Evaluation of Fusion Components

- Many fusion radioisotopes are missing in both NRC and Fetter’s disposal limits.

- Impact of missing radioisotopes on WDR prediction is unknown.

Interim measures:
- All fusion components should meet both NRC and Fetter's limits until NRC develops official guidelines for fusion radwaste.
- ARIES project reports highest value of both evaluations.

Worldwide Materials Program Developed Reduced-Activation Materials for Fusion Applications

Why?

- To qualify fusion radwaste as LLW (with WDR < 1)
- Minimize hazard and release risk
- Allow multiple recycling of radioactive materials before reaching dose limit.

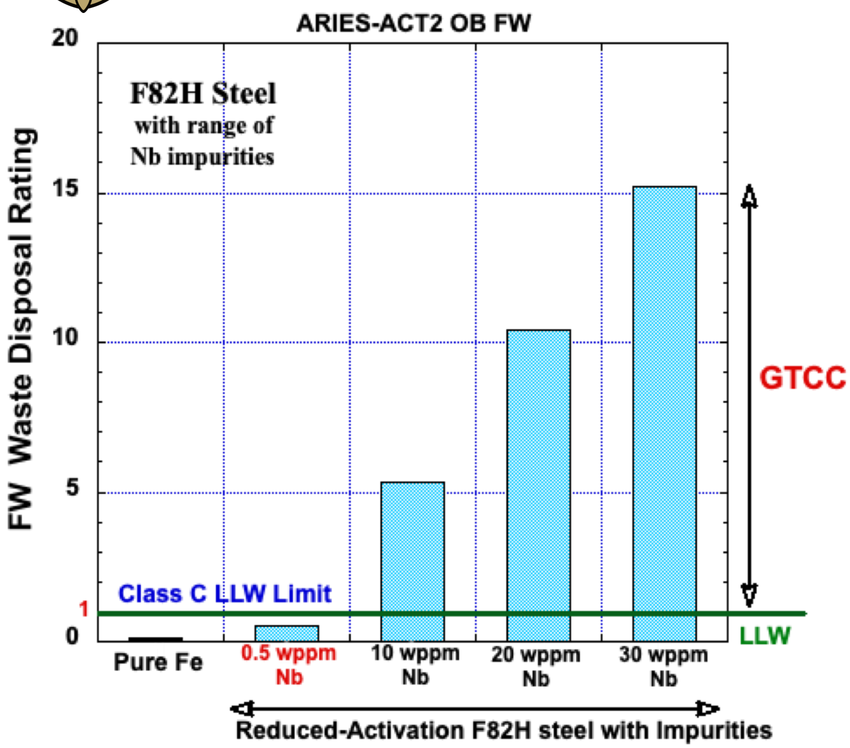
Compositional limitations for fusion designs:

- Avoid (as much as practically possible) alloying with Al, N, Ni, C, Cu, Nb, Mo, Re, Ag, etc. that generate long-lived radionuclides.
- Specific impurities (such as Nb, Mo, Ag, Re, etc.) must be controlled to low level to generate only LLW.

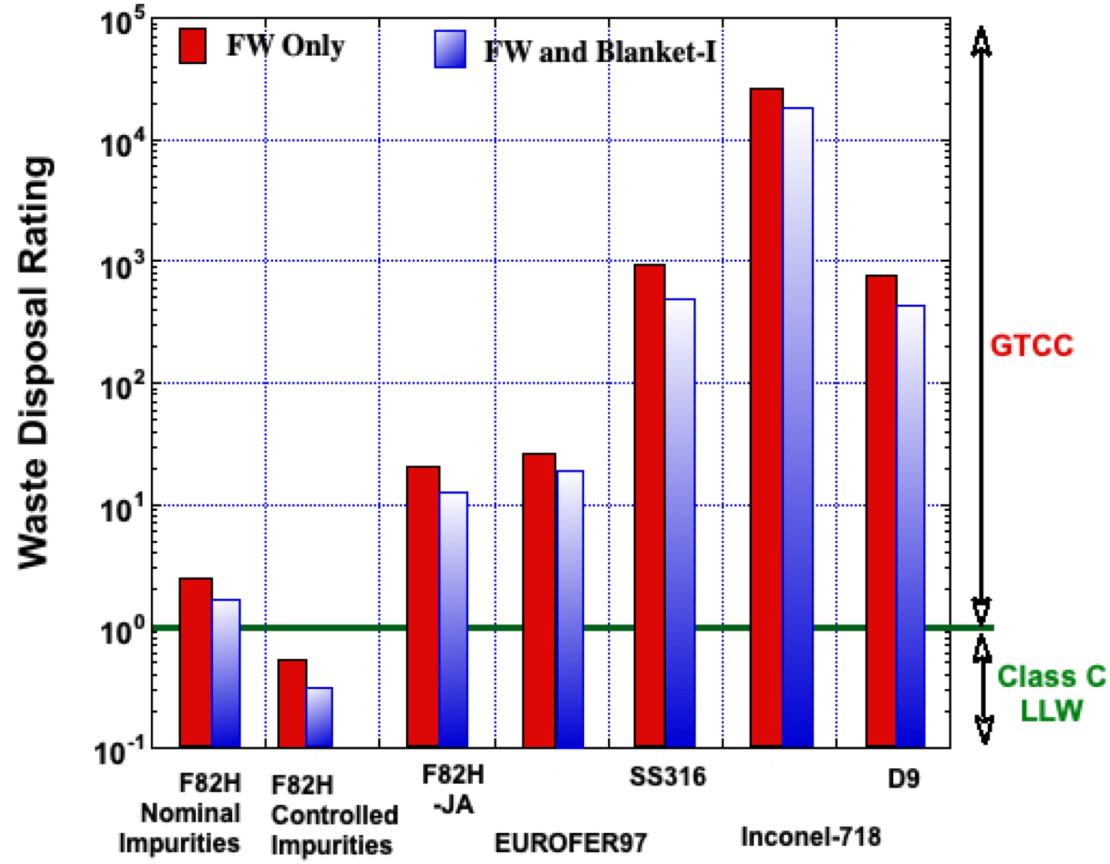
- Nb impurity impacts WDR greatly and should be kept below 1 wppm.

- Impact of such limitations on cost of reduced-activation materials is unknown and should be assessed.

Examining Alternate Steels for ARIES-ACT2 FW and Blanket



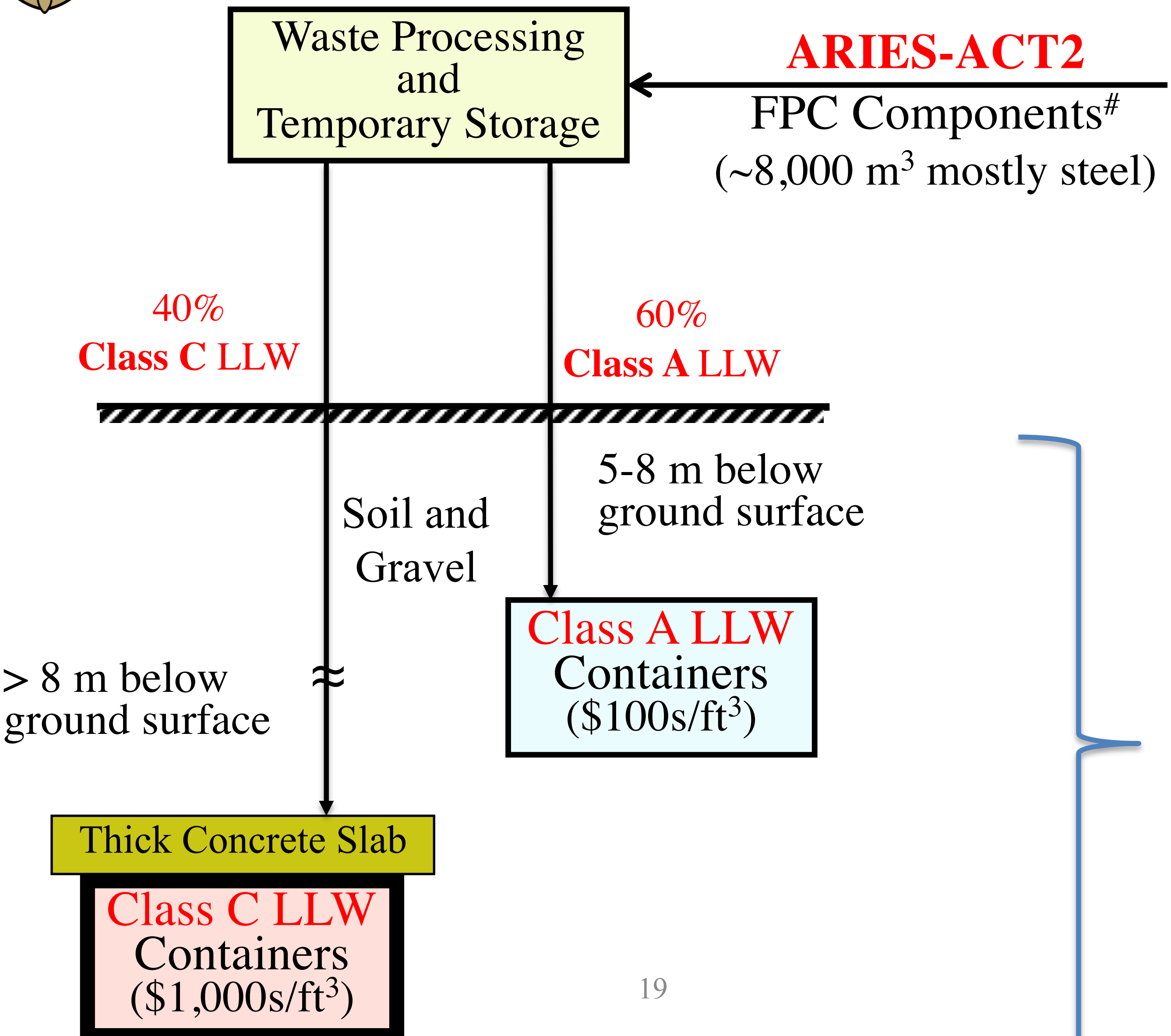
Nb impurity has major impact on WDR

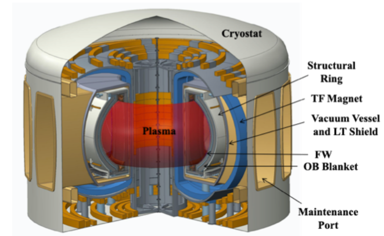


<u>To meet U.S. LLW design requirements:</u>

- Limit Nb impurity to < 1 wppm in F82H and EUROFER97 – both reduced-activation steels.
- Avoid using three steels: SS316 (of ITER) and Inconel-718, and D9 (of ARC design).

Radwaste of All ARIES Designs Classifies as LLW with Strict Alloying Elements and Impurity Control



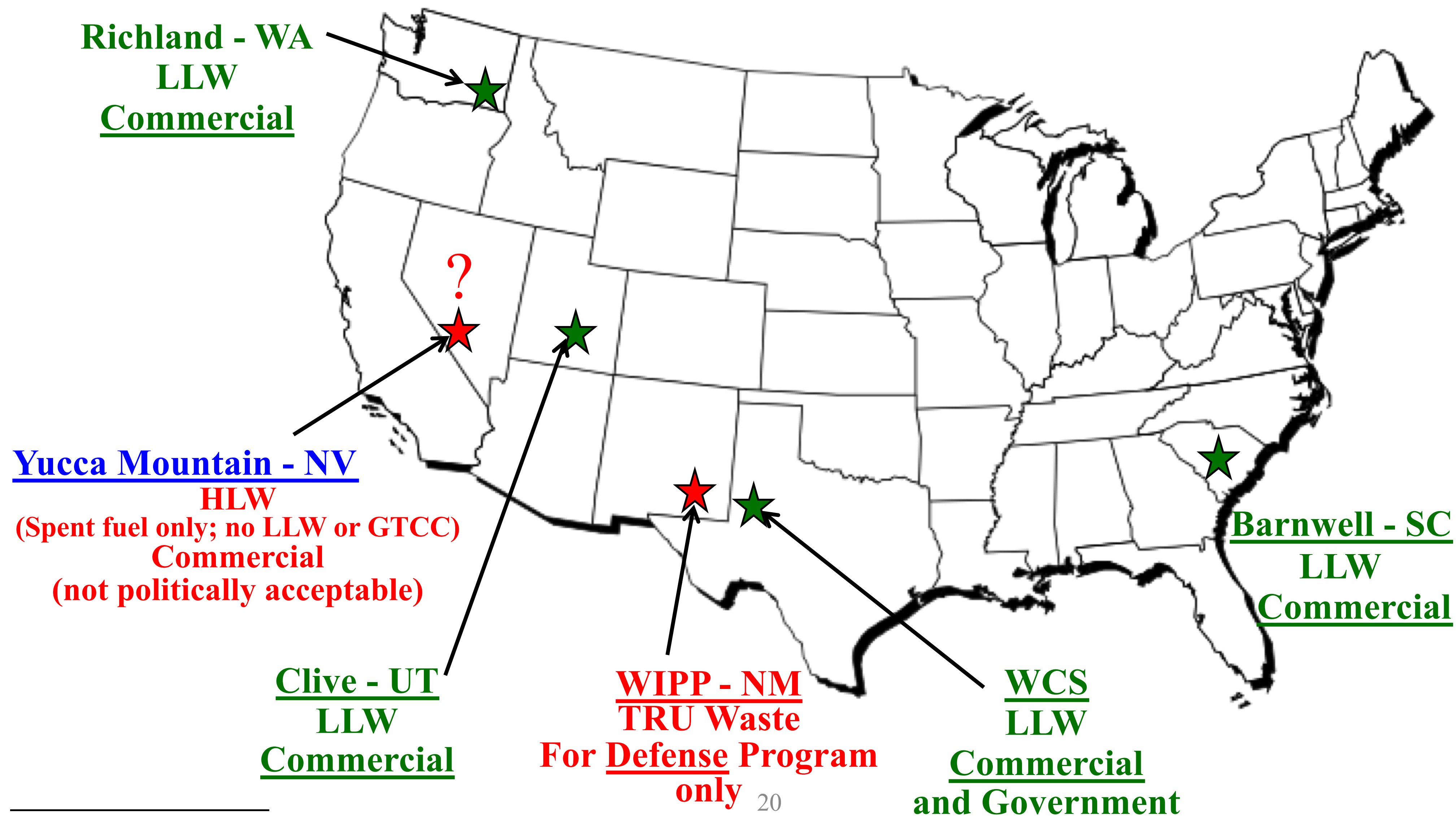


\# Excluding bioshield and cryostat, balance-of-plant equipment, and external components (e.g., HX, turbines, cooling towers, etc.).

Will be disposed of in commercial LLW repositories.

Where?

Locations of Four Large-Scale LLW Commercial Repositories in U.S.



https://www.nrc.gov/waste/llw-disposal/licensing/locations.html

3 out of 4 Commercial LLW Repositories will be Closed by ~2050

- Barnwell facility in SC:
  - 1971 – 2038
  - Receives Class A, B, C LLW
  - Supports east-coast reactors and hospitals
  - 870,000 m^3 capacity
  - 90% Full
  - In July 2008, Barnwell facility closed to all LLW received from outside 3 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.
- 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
  - 4,571,000 m^3 capacity
  - Closure by 2024.
- Richland facility in WA:
  - Class A, B, C LLW
  - Supports 11 northwest states
  - 1,700,000 m^3 capacity
  - Closure by 2056.
- WCS (Waste Control Specialists) in TX:
  - Newest facility for disposal, storage and treatment of LLW from all 50 states.
  - Class A, B, C LLW.

Limited option for disposal will drive disposal cost high

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 GTCC)
- Impact on WDR prediction of missing fusion radioisotopes in NRC and Fetter's limits
- High disposal cost that continues to increase with time (for preparation, characterization, packaging, interim storage, transportation, licensing, and disposal)
- Limited capacity of existing LLW repositories
- No commercial HLW repositories exist in the U.S. (or elsewhere); fission power plants store their HLW onsite
- Political difficulty of siting new land disposal sites limits their capacity
- Prediction of repositories' conditions for long time into future
- Radwaste burden for future generations.

Needs:

- Revised fusion-specific activity limits and disposal protocols for LLW and GTCC issued by NRC
- Disposal sites designed for tritiated radwaste
- Reversible disposal process and retrievable waste (to gain public acceptance and ease licensing)
- Large capacity and low-cost interim storage facility with decay heat removal capability.

Key Takeaways:

Existing U.S. LLW sites cannot handle <u>tritiated</u> fusion radwaste

Disposing <u>sizable</u> fusion materials in repository is NOT environmentally attractive, nor economic solution

Shallow land burial waste management strategy may NOT be practical when large quantities of fusion waste is to be managed in 21st century*

* D. Petti, "SNOWMASS Hot Topic – Chamber Science and Technology, "Re-Evaluation of the Use of Low Activation Materials in Waste Management Strategies for Fusion." (1999).

What We Suggest...

- **New strategy** should be developed to limit radwaste for fusion energy, calling for rethinking, education, and research to make it a reality.

- **Focus on**:
  - Minimizing the waste by clever design
  - Limiting radwaste requiring disposal
  - Emphasizing recycling* and clearance# to minimize waste.
  - Developing fusion-specific disposal class and regulations by NRC for any remaining fusion radwaste.

- **Why**?
  - Fusion generates large quantity of LLW (mostly steel and concrete)
  - Limited capacity of existing LLW repositories
  - Political difficulty of building new repositories (for both LLW and HLW)
  - Stricter regulations and tighter environmental controls
  - Uncertain geological conditions over long time
  - Minimize radwaste burden for future generations
  - Reclaim resources by recycling and clearance
  - Promote fusion as energy source with minimal environmental impact
  - Gain public acceptability for fusion
  - Support decommissioning goals of U.S. and IAEA in 21st century.

- *Reclaim resources and reuse within nuclear industry.*

 # 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 U.S. nuclear facilities. Clearable materials are safe, containing 10 µSv/y (< 1% of background radiation).

Decommissioning Goal for 21st Century

Many organizations have given some attention to the issue of reducing the amount of radioactive waste generated when decommissioning nuclear plants

U.S.:

- **Department of Energy*, NRC, and Fusion Safety Standing Committee** (currently under revision):
  - A goal of decommissioning U.S. nuclear facilities is to minimize waste volumes, recycle, and clear as much of materials as practical. Reasons:
    - Reclaim use of metal resources
    - Reduce the volume of LLW requiring disposal.

- *Related references:*

Hrncir, T., et al., (2013). "The impact of radioactive steel recycling on the public and professionals," Journal of Hazardous Materials, 254-255, 98-106.
US Department of Energy, "Recycle of Scrap Metals Originating from Radiological Areas," DOE/EA-1919 (2012). https://www.energy.gov/nepa/ea-1919-recycle-scrap-metals-originating-radiological-areas.
Radiological Assessments for Clearance of Equipment and Materials from Nuclear Facilities, Draft NUREG-1640, Nuclear Regulatory Commission, Washington, D.C. (1998).
ANIGSTEIN, R. et al., "Radiological Assessments for Clearance of Materials from Nuclear Facilities," volume 1, NUREG-1640, US Nuclear Regulatory Commission (2003). 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 (2016). https://www.standards.doe.gov/standards-documents/6000/6004-astd-2016.

Decommissioning Goal for 21st Century (Cont.)

- **U.S. 1999 Snowmass Report on Fusion Chamber Science and Technology***:
  - A waste management strategy focused solely on low activation materials does not address the entirely of the radioactive waste picture for fusion. We recommend a strategy that is balanced with respect to minimizing both the hazards (via low activation materials) and the volume (via reduction of ex-vessel activation). As such, we propose the following minimum design goals:
    - To reduce the overall radioactive waste volume by limiting vessel/ex-vessel activation so that the bulkier large volume components can be cleared or recycled for re-use
    - To minimize activated materials in a fusion plant that cannot be cleared or recycled.

* https://fire.pppl.gov/snowmass02.html#Snowmass99Section.

Decommissioning Goal for 21st Century (Cont.)

- **2007 FESAC Fusion 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 required for the expected quantities of power plant relevant materials.

* 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. https://burningplasma.org/web/ReNeW/FESAC_Greenwald_final_report.pdf.

Decommissioning Goal for 21st Century (Cont.)

IAEA

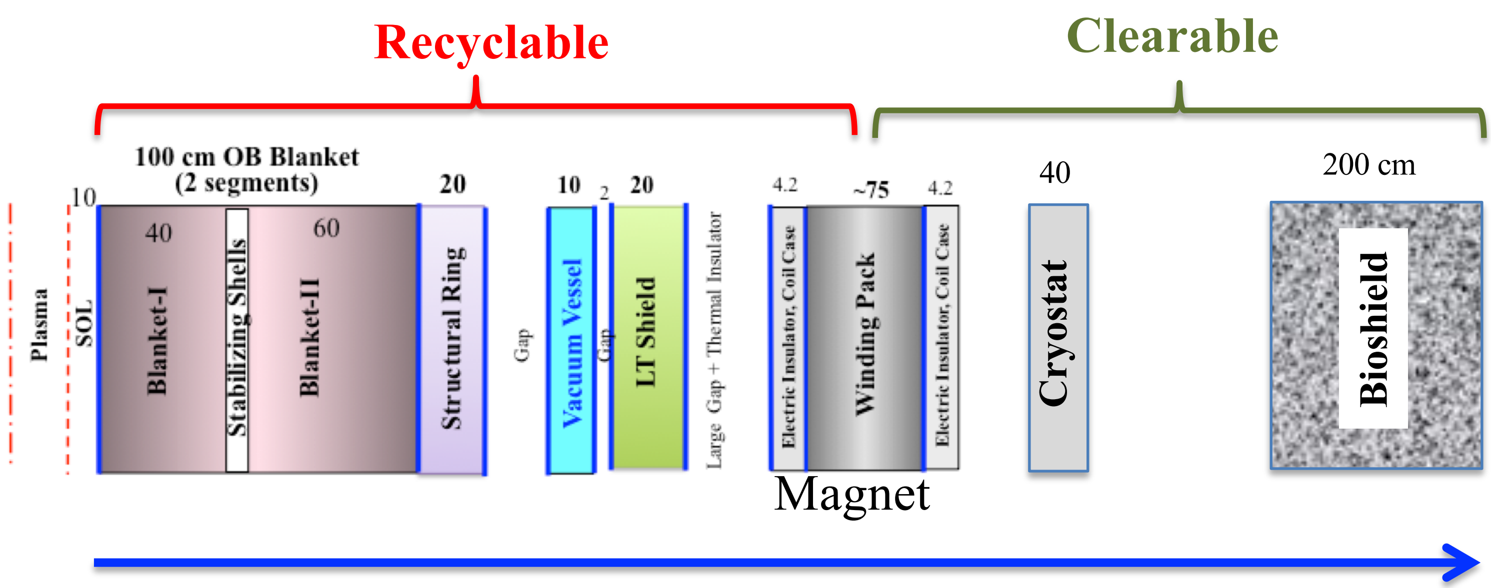
- The 2008 IAEA report*:

  "The IAEA should expand its efforts to help states establish safe and sustainable approaches to managing spent fuel and nuclear waste, including recycling and waste minimization, and to build public and international support for implementing these approaches."

- *https://www.belfercenter.org/sites/default/files/files/publication/gov2008-22gc52inf-4.pdf.*

What should be done to embrace recycling/clearance as prime option for fusion radwaste management?

Typical Radial Build



The Recycling Option

Recycling Criteria

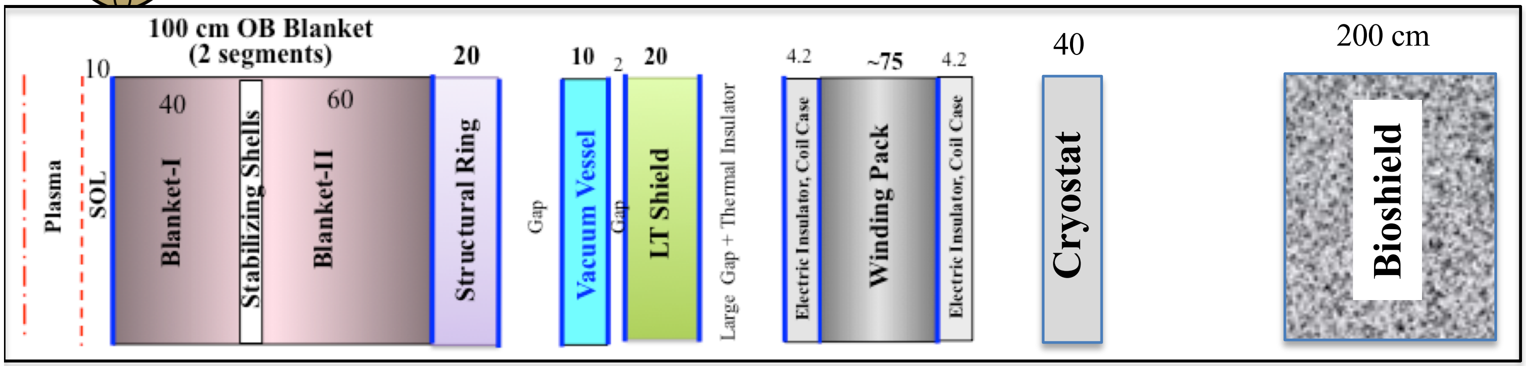
Recycling: reuse of materials within nuclear industry

Important criteria:

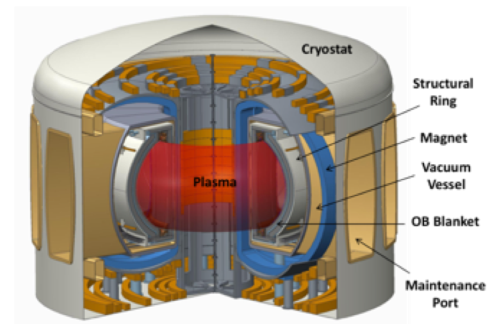
- Dose to remote handling (RH) equipment
- Decay heat level during reprocessing (controlled by active cooling)
- Economics of fabricating complex shapes remotely
- Physical properties of recycled products
- Efficiency of detritiation system.

The most restrictive criterion (dose to RH equipment) has been used for ARIES designs to determine RH technology and interim storage period

Recycling Example: ARIES-ACT2 OB Components (FW - Bioshield)



ARIES-ACT2

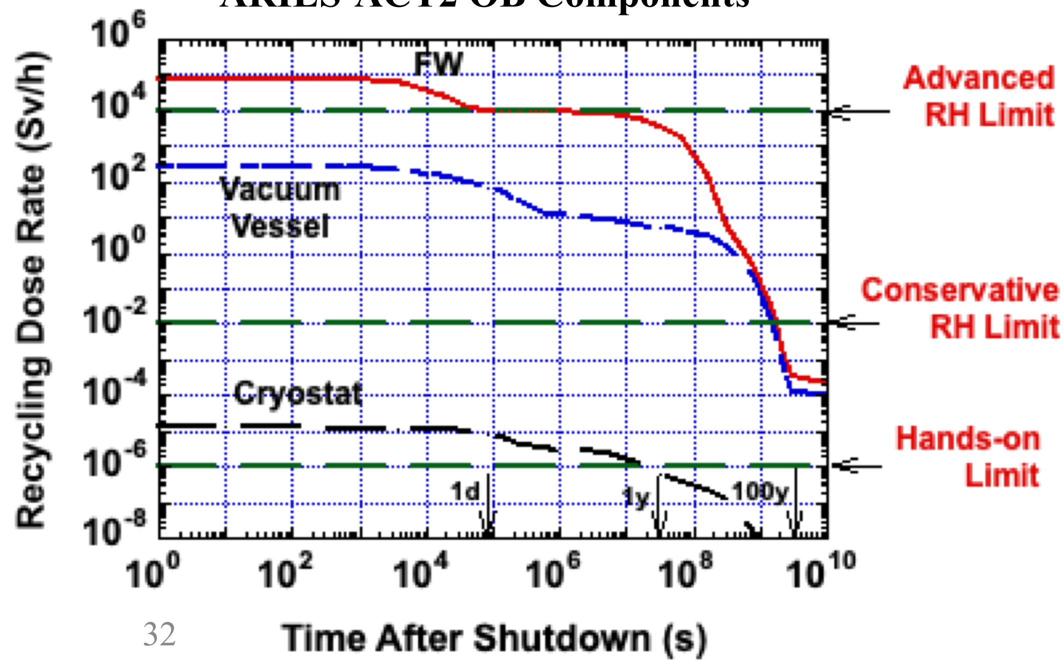


All FPC components can potentially be recycled in < 1y with advanced RH equipment*.

Cryostat (and bioshield) could be recycled with hands-on shortly after shutdown.

* Other recycling criteria may apply.

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 tritiated 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

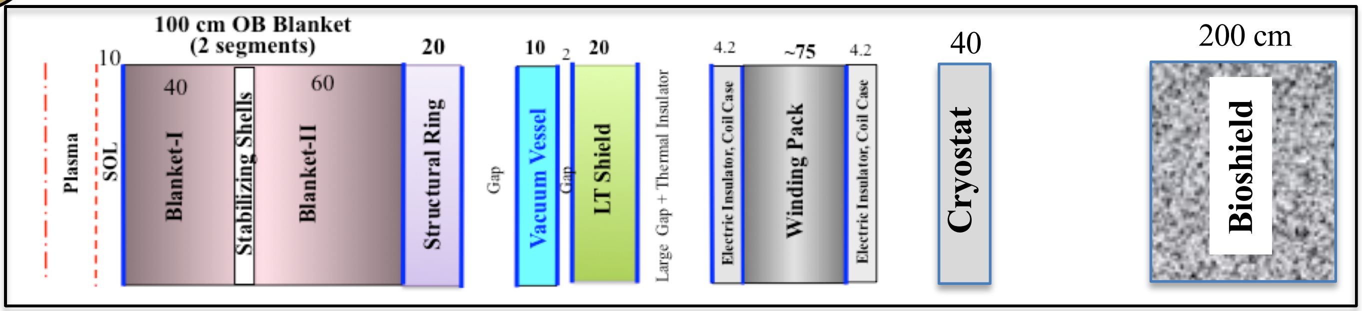
Needs:
- NRC to regulate the use of recycled materials from nuclear facilities
- R&D program to address recycling issues
- Radiation-resistant remote handling equipment
- Rigorous time-dependent radiotoxicity of recycled liquid breeders
- Reversible assembling process of components and constituents (to ease separation of materials after use)
- Efficient detritiation system to remove > 95% of tritium before recycling
- Large capacity and low-cost interim storage facility with decay heat removal capability
- Nuclear industry should accept recycled materials
- Recycling infrastructure.

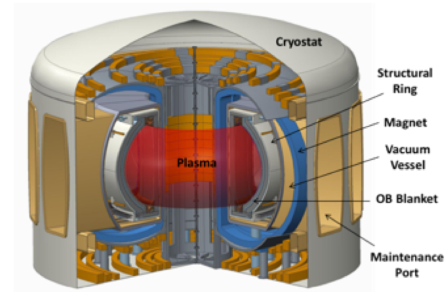
The Clearance Option

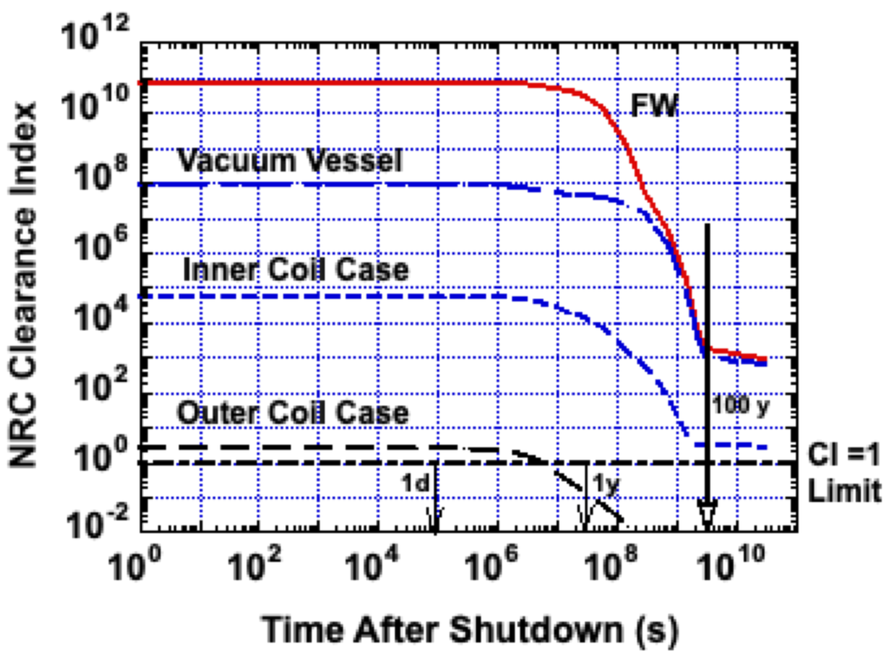
- Relatively easy to apply from science perspectives
- NRC **and** IAEA guidelines/regulations/standards* exist
- Clearance from DOE facilities has been ongoing since 1990s on a case-by-case basis
- Key issues and needs for fusion.

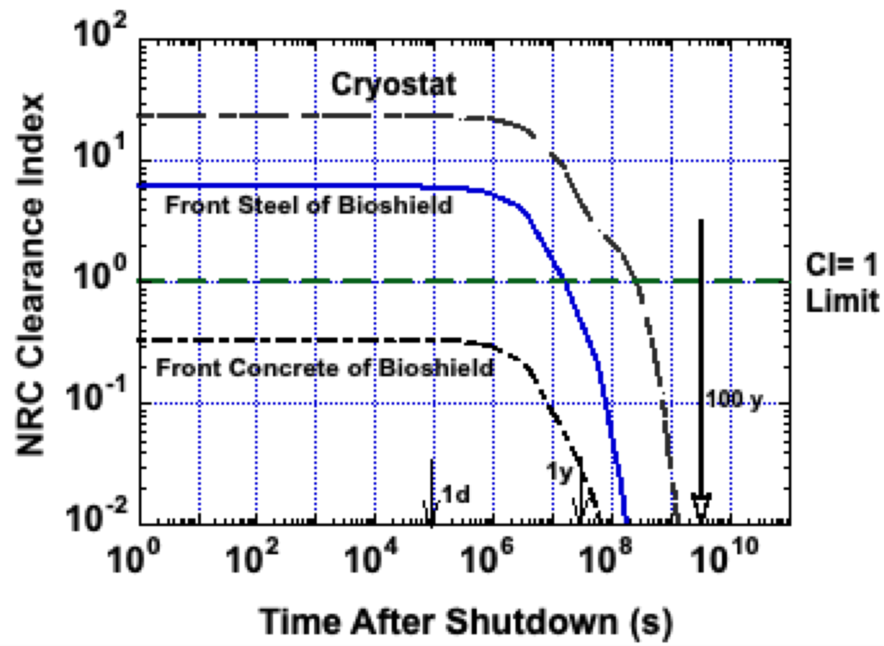
- *Anigstein, R. et al., "Radiological Assessments for Clearance of Materials from Nuclear Facilities," volume 1, NUREG-1640, US Nuclear Regulatory Commission, June 2003. Available at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/.*
- *U.S. Department of Energy, "Clearance And Release 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.*
- *Clearance Levels for Radionuclides in Solid Materials – Application of Exemption Principles, Interim Report IAEA-TECDOC-855, International Atomic Energy Agency, Vienna (1996).*
- *International Atomic Energy Agency, "Application of the concepts of exclusion, exemption and clearance". IAEA Safety Standards Series, No. RS-G-1.7 (2004). http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf.*
- *Safety Report Series [IAEA-SRS44] (2005) "Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance", Safety Report Series N.44 International Atomic Energy Agency (2005). https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1213_web.pdf.*

Clearance Example: ARIES-ACT2 Outboard Components







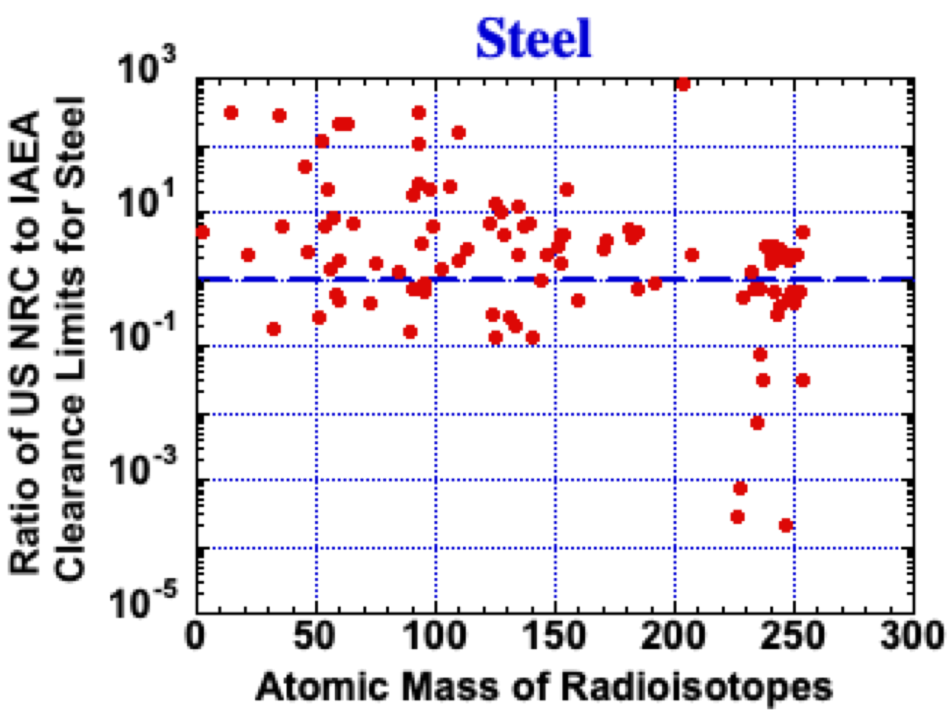


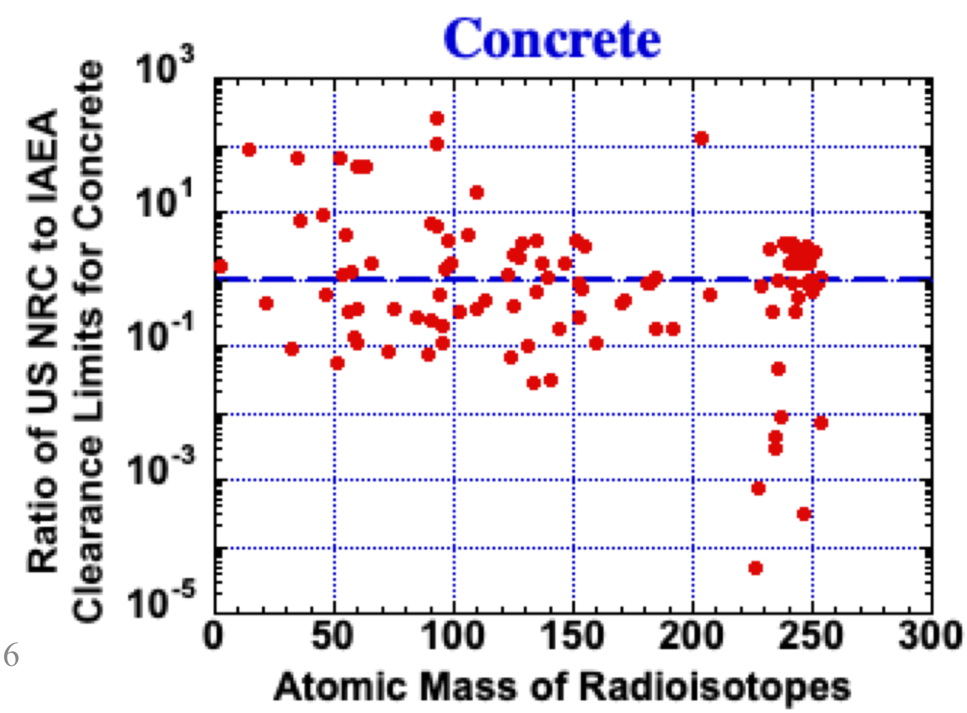
Cryostat, Bioshield, and some magnet constituents are clearable in ~20 y after decommissioning

L. El-Guebaly and M. Zucchetti, "Progress and Challenges of Handling Fusion Radioactive Materials," Fusion Science and Technology, Vol. 68, No. 3 (2015) 484-491.
L. El-Guebaly, L. Mynsberge, A. Davis, C. D'Angelo, A. Rowcliffe, B. Pint, "Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket," Fusion Science and Technology, 72, Issue 1 (2017) 17-40.

Clearance Concerns

- <u>All CI evaluations lack numerous fusion-relevant radioisotopes</u> that introduce uncertainties in CI prediction of fusion components.
- <u>Discrepancies between clearance standards</u> that could impact CI evaluation and storage period.
- Future efforts by NRC, IAEA and others to <u>harmonize the clearance standards</u> and reduce the differences are essential as steel products and scraps are routinely sold internationally and clearable materials may penetrate the worldwide commercial market.





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}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)
- 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 some components
- International effort to harmonize standards and regulations of clearance
- 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.*

Examples of Recycling and Clearance Developments

Fusion-Related Recycling Developments

- **U.S. ORNL Y-12 Team** [1,2] is investigating possibility of recycling ~10 Tons of Be metal (from U.S. weapons program) to reuse as tiles for ITER FW (to avoid the disposal cost) and launched testing program to qualify Be for ITER.
- **TFTR experimental facility** (decommissioned in 1999-2002):

  E. Perry, J. Chrzanowski, C. Gentile, R. Parsells, K. Rule, R. Strykowsky, M. Viola, "Decommissioning of the Tokamak Fusion Test Reactor". Princeton Plasma Physics Laboratory report PPPL-3896 (October 2003). https://digital.library.unt.edu/ark:/67531/metadc735658/.
  - 200 tons of lead was removed for re-use. Lead bricks were painted (to mitigate lead health issues) and re-used as shield for diagnostics on NSTX-U.
  - ~54 thousand cubic feet of radwaste was disposed of at Hanford site
  - 400 tons of concrete shielding was stored at different locations on-site. Clearable?
- **JET experimental facility** (to be decommissioned in 2020s):

  V. McKay and D. Coombs, "Management of Radioactive Waste from Fusion – The JET Experience." IAEA TECDOC on Fusion RWM. To be published in 2023.
  - Majority of solids (> 100,000 m^3) either recyclable or suitable for clearance
  - ~1,000 m^3 of LLW and ILW will be managed, treated, disposed and/or transferred for long-term storage.

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).

Example of Decommissioning Projects – Fission Reactors

Plum Brook reactor in Ohio:

Smith, K. "Mission complete," Construction & Demolition Recycling, volume 15, number 1, January/February 2013, pages 14-18. Available at: http://www.cdrecycler.com/digital//20130102/index.html

– ~95% of all demolished materials (concrete and metals) were reused or recycled.
– Concrete stayed on site as backfill into the void of the reactor.
– Scrap steel was scanned for radiation before being sent to scrap metal yards.
– Contaminated material was placed in boxes for disposal at the Clive facility in Utah.

Trojan plant in Oregon*:

– All concrete structures were decontaminated and released for unrestricted use.
– D&D activity only disposed of 12,375 m^3 of LLW due to its minimization of waste volumes and recycling.

Big Rock Point in Michigan*:

– Half of the concrete was non-impacted so it was reused (never had the potential for neutron activation or exposure to licensed radioactive material).
– Other half of the demolition debris (19.16 Mkg of predominantly concrete and some metals) was mildly contaminated or activated and the licensee requested disposal in a State of Michigan Type II landfill.

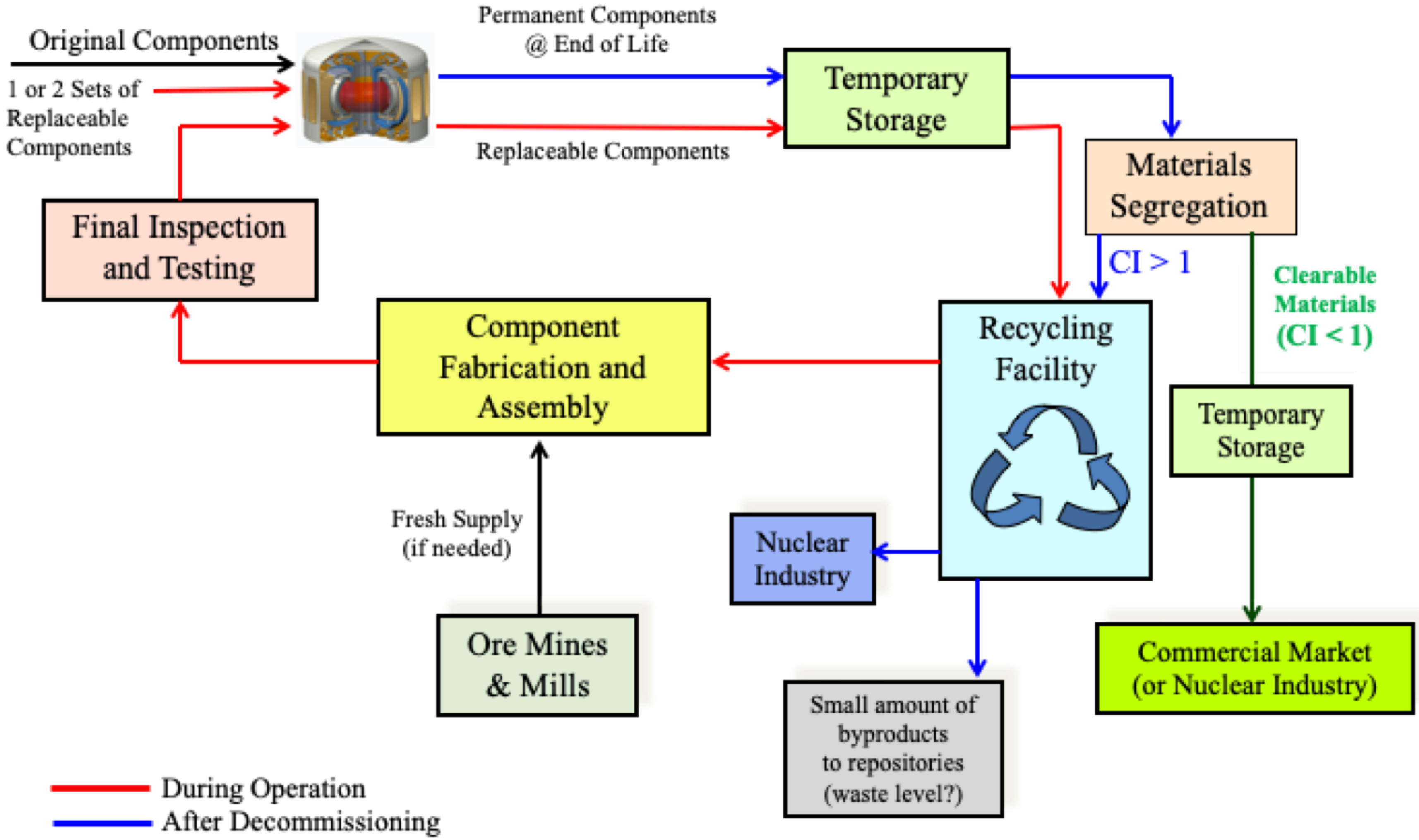
** Banovac, K. et al., "Power Reactor Decommissioning – Regulatory Experiences from Trojan to Rancho Seco and Plants In-Between," Proceedings of the ANS Topical Meeting on Decommissioning, Decontamination, and Reutilization (DD&R 2010), Idaho Falls, Idaho, August 29-September 2, 2010, American Nuclear Society.*

Conclusions

- It is just a matter of time to develop the fusion recycling and clearance technologies and their official regulations.
- Possibility of material recycling/clearance could be demonstrated by directed R&D programs. *Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclide profile, radiation level, component size, weight, etc.).*
- **NRC** could issue recycling/clearance standards that include all radioisotopes encountered in fusion and develop fusion-specific category for the LLW and GTCC remaining waste after recycling.
- **Fusion designers should**:
  - Integrate the recycling/clearance approache at early stages of fusion designs
  - Involve industries and address issues/needs for recycling/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.
  - **NRC** reached out to the fusion community to regulate fusion. Fusion designers engaged with NRC on several fusion challenges and presented the integral radwaste management strategy that promotes recycling/clearance and avoids disposal.

Flow Diagram for Fusion Decommissioning



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).

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- D. Henderson, L. El-Guebaly, P. Wilson, and A. Abdou, "Activation, Decay Heat, and Waste Disposal Analysis for ARIES-AT Power Plant," Fusion Technology, 39, No. 2, 444 (2001).
- L. El-Guebaly, P. Wilson, and D. Paige, "Initial Activation Assessment of ARIES Compact Stellarator Power Plant," Fusion Science and Technology, 47, No. 3, 440-444 (2005).
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- L. El-Guebaly, V. Massaut, K. Tobita, and L. Cadwallader, "Goals, Challenges, and Successes of Managing Fusion Active Materials." Fusion Engineering and Design 83, Issues 7-9 (2008) 928-935.
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- 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). https://www.novapublishers.com/catalog/product_info.php?products_id=51057.
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- L. El-Guebaly, L. Mynsberge, C. Martin, D. Henderson, "Activation and Environmental Aspects of ARIES-ACT1 Power Plant," Fusion Science and Technology, 67, No. 1, 179-192 (Jan 2015). ISSN: 1536-1055.
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First IAEA Fusion-Related RWM Publication

Just published:
(May 30, 2022)

IAEA nuclear fusion

SPECIAL TOPIC • OPEN ACCESS

Overview on the management of radioactive waste from fusion facilities: ITER, demonstration machines and power plants

Sehila M. Gonzalez de Vicente[12,1], Nicholas A. Smith[2], Laila El-Guebaly[3], Sergio Ciattaglia[4], Luigi Di Pace[5], Mark Gilbert[6], Robert Mandoki[7], Sandrine Rosanvallon[8], Youji Someya[9], Kenji Tobita[10] and David Torcy[11] – Hide full author list

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- Technical Program Chair: L. El-Guebaly (UW).
- 40 attendees representing 11 countries.
- 26 papers will be published in IAEA TECDOC (2023).