



Developing a Regulatory Framework for Fusion Energy Systems

NRC Public Meeting
1 of 152
June 7, 2022

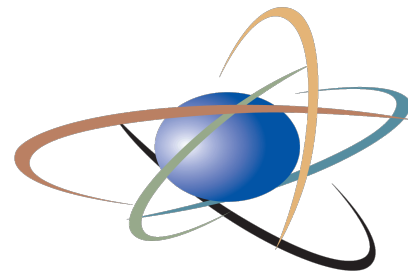


Agenda

Time	Topic	Speaker
1:00 pm	Welcome, Introductions, and Overview	NRC
1:10 pm	NEPA Overview	Don Palmrose
1:20 pm	Agreement States Current Oversight of Fusion R&D Activities	Diego Saenz
1:45 pm	FIA Presentation	Andrew Holland
2:15 pm	Helion Presentation: AEA Common Defense and Security and Application of Materials Framework Tools for Fusion	Michael Hua and Sachin Desai
2:55 pm	Break	
3:10 pm	General Atomics Perspectives	Brian Grierson
3:30 pm	CFS Presentation	Tyler Ellis
3:50 pm	Right-sizing Regulation based on Scale of Fusion Facility Hazards	Patrick White
4:20 pm	Fusion and Tritium Accident Risks and Analysis	Dave Babineau
4:40 pm	Development of Integral Management Scheme for Fusion Radioactive Materials	Laila El-Guebaly
5:00 pm	Opportunity for Public Comment	
5:30 pm	Adjourn	

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U.S. NRC

UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

NEPA Overview

Donald Palmrose

Office of Nuclear Material Safety and Safeguards

NEPA Overview

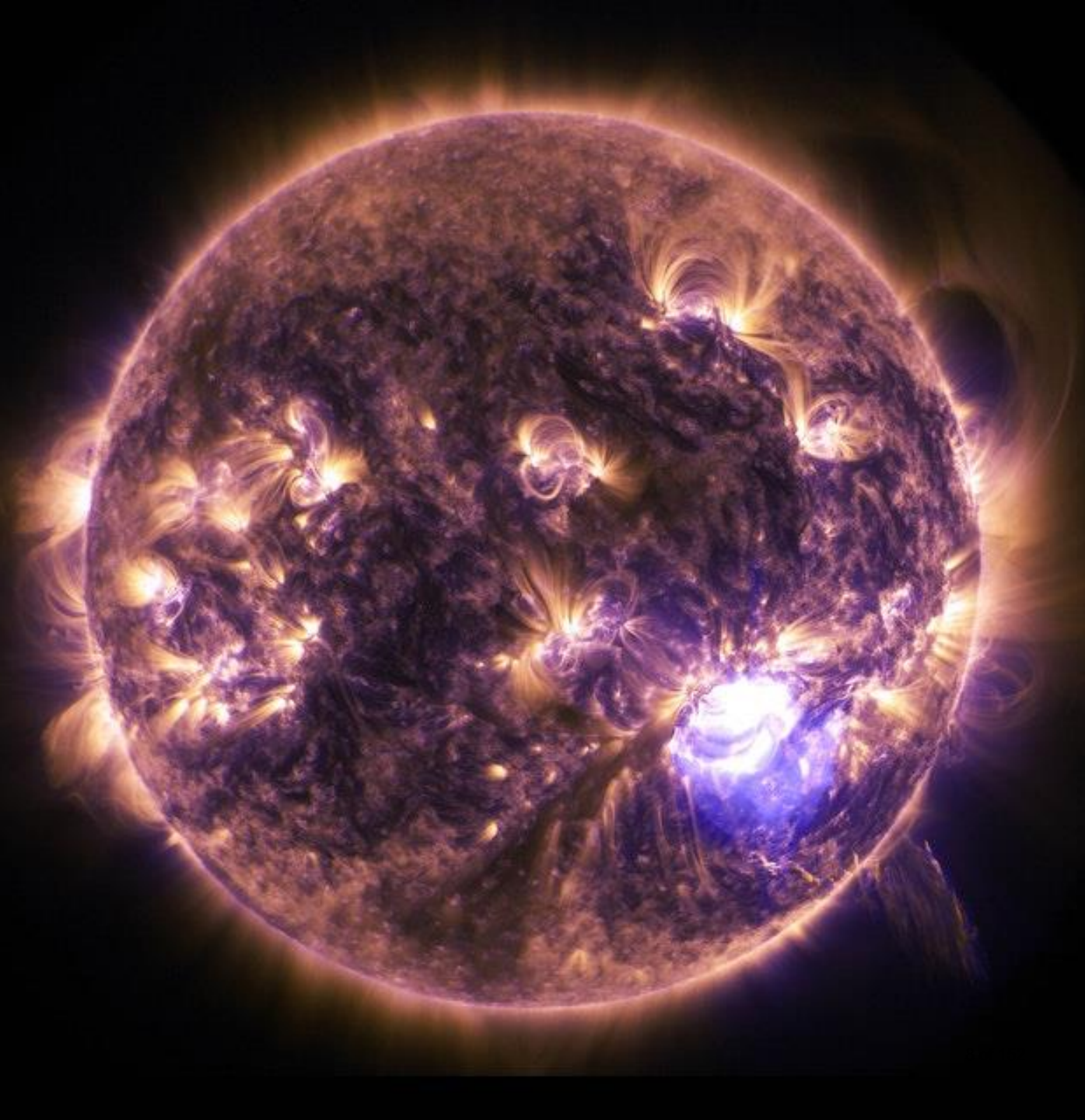
- National Environmental Policy Act of 1969 (NEPA), as amended 42 U.S.C. § 4321 et seq. is a national policy for the government to consider environmental issues in the conduct of Federal activities
 - ⊕ There are also other laws, regulations, and rules that the NRC implements through its NEPA activities (e.g. ESA, NHPA)
- NEPA Section 102(2)(C) and the NRC's implementing regulations (10 CFR Part 51) require an environmental impact statement (EIS) for major Federal actions significantly affecting the quality of the human environment
 - ⊕ Or the Commission determines the proposed action should be covered by an EIS
- The NRC prepared EISs for nuclear electrical generation stations and significant material-licensed facilities such as enrichment facilities and fuel fabrication facilities.

NEPA Considerations

- Nuclear Energy Innovation and Modernization Act of 2019 (NEIMA) includes fusion in the definition of an advanced nuclear reactor
- The draft Advanced Nuclear Reactor Generic EIS (ML21222A055) before the Commission also would apply to a fusion power plant
- Staff anticipates several environmental impacts would be due to the size/footprint/location
 - ✦ Examples are Ecology, Land Use, & Socioeconomic
- Applicants are encouraged to discuss the environmental review process during pre-application meetings

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OVERSIGHT OF RESEARCH AND DEVELOPMENT ACTIVITIES

**REGULATING CURRENT
ACTIVITIES WITH EXISTING
FRAMEWORK**

Agreement State Representative to Fusion Energy
Systems Working Group

DIEGO SAENZ

Nuclear Engineer

diego.saenz@wi.gov

TODAY'S AGENDA



**Current
Regulations**



**Currently
Licensed**



**Near-term
Licensing**



**Long-term
Licensing**

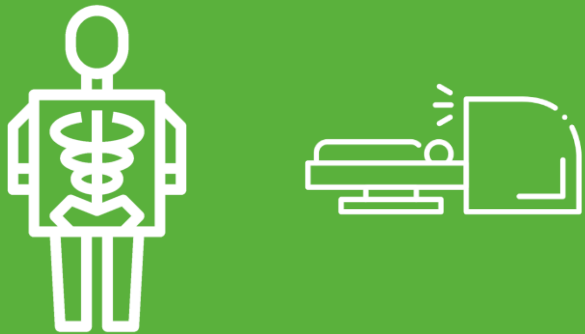


Questions

CURRENT FRAMEWORK

STATE

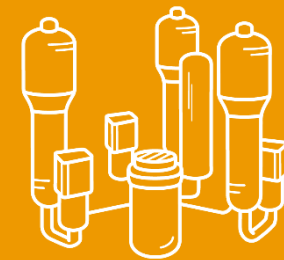
NRC



**ELECTRONIC
SOURCES**



**RADIOACTIVE
MATERIALS**

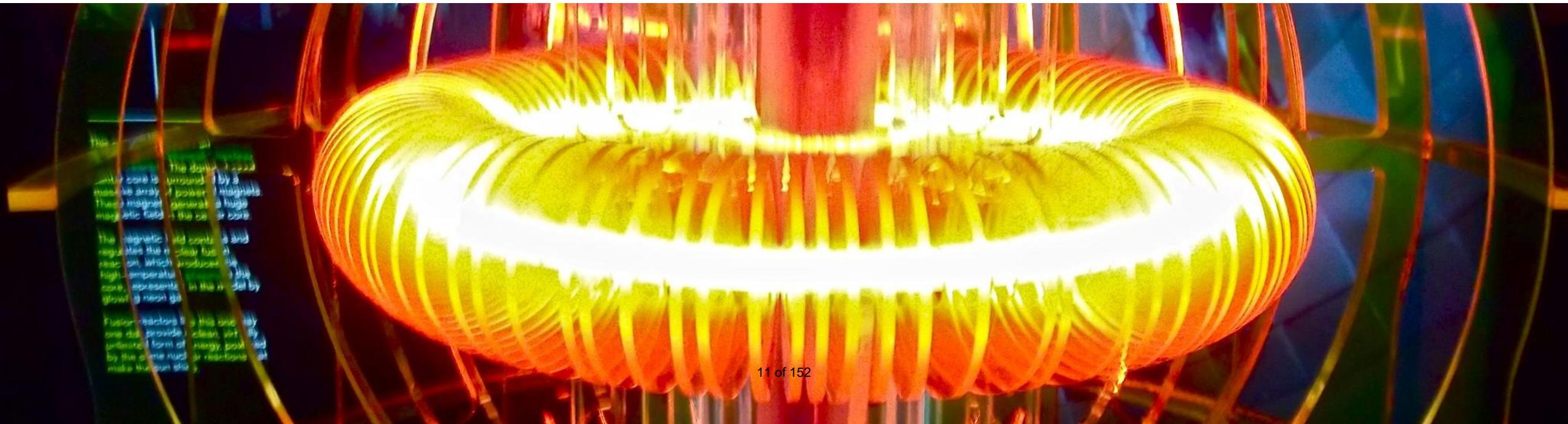


**SPECIAL NUCLEAR
MATERIAL**

CURRENTLY LICENSED

**Fusion Devices
(non-energy)**

**Radioactive Materials
(tritium and
activation products)**



The tokamak is a donut-shaped fusion reactor core is surrounded by a massive array of powerful magnets. These magnets generate a huge magnetic field in the central core. The magnetic field contains and regulates the nuclear fusion reaction, which produces the high-temperature plasma. The core represents the model by glow of neon gas.

Fusion reactors are the only way we can provide clean, virtually unlimited form of energy, powered by the same nuclear reactions that make the sun shine.

NEAR-TERM LICENSING

**Fusion Devices
(non-energy)**

**Radioactive Materials
(tritium and
activation products)**



LONG-TERM LICENSING

- **Fusion Devices (non-energy)**
- **Radioactive Materials**
- **Fusion Energy**



QUESTIONS?



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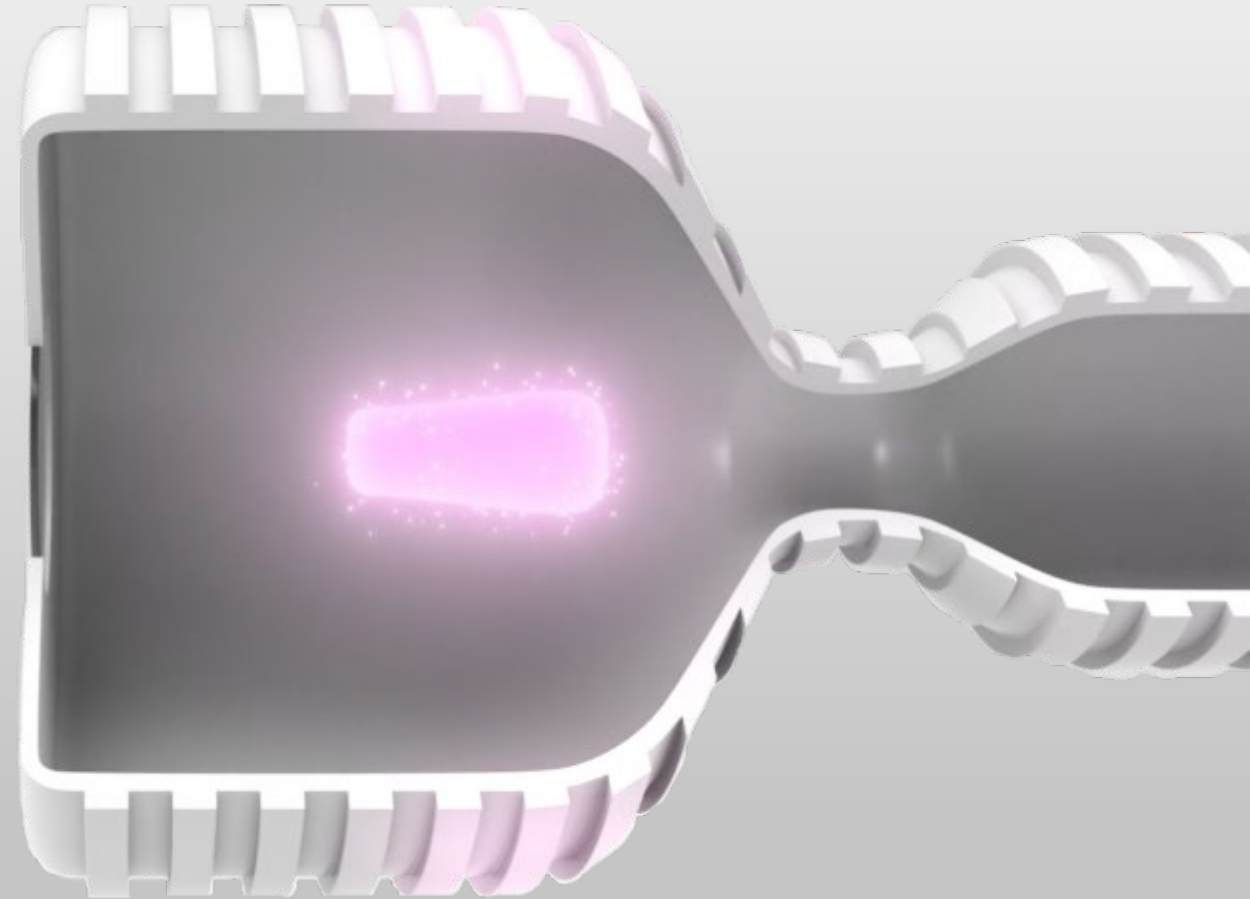
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Evaluating Common Defense & Security Use of Part 30 Tools for Fusion

07 June 2022

Sachin Desai, Helion Energy
Michael Hua, Helion Energy



The background image shows the interior of a tokamak fusion reactor. It features a complex arrangement of metallic structures, including the toroidal field coils and the central solenoid. A bright, glowing plasma is visible in the center, surrounded by a dense network of cables and support structures. The lighting is a mix of cool blues and warm oranges, highlighting the intricate engineering of the facility.

Outline

- Evaluating Common Defense and Security
- Use of Part 30 Tools for Fusion

Evaluating Common Defense and Security

Summary

- Common defense and security primarily concerns the diversion of special nuclear material (SNM)
- Commercial fusion devices are not of significance to common defense and security – because they are not designed to handle or create SNM
- Security for fusion materials, when needed, can be appropriately controlled via the materials framework (Part 37), not the SNM framework (Part 73)

Context: Common Defense & Security (“Common Defense”)

- AEA tasks the NRC to help prevent bad actors from developing nuclear weapons
- “Common Defense” woven conceptually throughout the AEA
 - “The processing and utilization of source, byproduct, and special nuclear material must be regulated in the national interest and in order to provide for the common defense and security and to protect the health and safety of the public.” (AEA § 2.d)
- Concerns “unacceptable likelihood of grave or exceptionally grave damage to United States” (CLI-04-17)
 - But what does this extend to? (see slide 7)

Context: Common Defense

- Helpful sources of legal interpretation:
 - Nuclear Non-Proliferation Act of 1978 (NNPA) & related rulemakings
 - Export controls case law (*e.g.*, 647 F.2d 1345; CLI-20-2)
 - Part 37 & 73 rulemaking context (*e.g.*, 78 Fed. Reg. 16,922; NUREG-0095)
- Affects Agreement State licensing authority (AEA § 274.m), but:
 - Presence of any Common Defense question does not mandate utilization facility licensing (Parts 37, 110)
 - Joint Public Health/Common Defense questions need not eliminate state involvement in licensing (*e.g.*, radiological dispersion devices (RDDs), 78 Fed. Reg. 16,927)

What is In Scope for Common Defense & Security?

- Key concern – SNM proliferation ⇒ Not Fusion
 - NPT & NNPA
 - NRC practice
- Additional concern – RDDs
 - Part 37 rulemaking
 - Joint public health & safety concern
- Not in Scope – Geo-political criteria (e.g., energy security)
 - Executive deference (seen in export licensing precedent)

Common Defense -- SNM Proliferation, Not Fusion

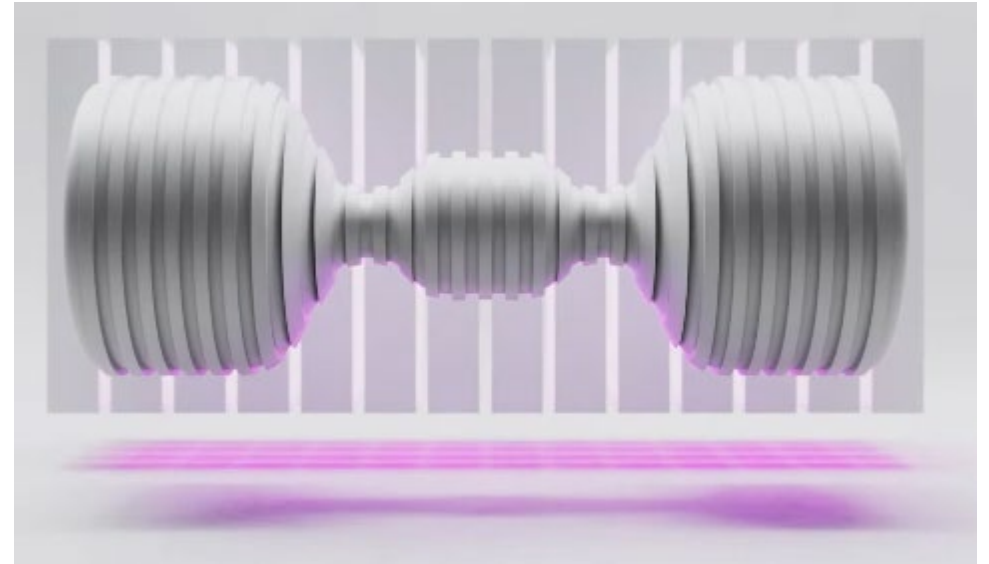
- NNPA connects Common Defense to nuclear explosive proliferation:
 - NNPA § 204 (creating AEA § 126): An export will not be “inimical to the common defense and security because it lacks *significance for nuclear explosive purposes*”
 - NRC decisions cement link (*e.g.*, CLI-20-2; CLI-17-3; CLI-04-17)
- NRC explicitly links nuclear explosive proliferation to Trigger Lists (INFCIRCs 209/254)
 - Part 110 Final Rule Considerations: “The components, items and substances chosen [for Part 110] are essentially those on the Nuclear Suppliers’ Group and IAEA Zangger Committee trigger lists, *thus reflecting an international consensus on items considered to be significant for nuclear explosive uses*” (43 Fed. Reg. 21,641, at 21,642)
- Trigger Lists focus on SNM/fuel cycle, to this day *exclude fusion devices and tritium*
 - Note on nuclear reactor in Trigger Lists: “This entry does not control fusion reactors”

Focus on SNM proliferation aligns with NPT & NRC practice

- NPT is focused on SNM proliferation
 - NPT scope: “(a) source or special fissionable material, or (b) equipment or material especially designed or prepared for the processing, use or production of special fissionable material”
 - Trigger Lists clarify “especially designed” prong, and focus on SNM/fuel cycle, excluding fusion/tritium
 - Model Additional Protocol (INFCIRC/540) re-examined safeguards but still leaves out fusion/tritium
 - Recognition that fusion doesn't need safeguards—changing this will require amending int'l agreements
- NRC practice likewise is focused on SNM risk
 - NRC definition of “significance” tied to SNM quantities (*e.g.*, Parts 73/74)
 - NRC inimicality reviews have looked to compliance with Part 73 (SNM-focused) (SECY-16-0056)
 - NRC licenses tritium as byproduct material, even in large quantities

Commercial fusion does not use or produce SNM

- Commercial fusion devices are not “especially designed” (or “peculiarly adapted”) to produce SNM, nor even handle it
- Fusion-fission hybrids are fundamentally distinct from commercial fusion



Example Modifications

Introduce Source Material

Remove/Modify Lithium Blanket

Redesign Pump and Pump Power

Establish Reprocessing

Establish Enrichment

What is not Common Defense & Security

- Does not include geopolitical considerations, such as:
 - Energy security
 - Economic competition
- AEA points to Executive & Congress on general national security, *e.g.*:
 - [CLI-20-02](#): AEA export licensing criteria—which look to common defense and security—do not consider “economic or market-based interests”
 - [CLI-04-17](#): Executive Branch has key role to make “strategic judgements,” and NRC role is complementary

Fusion risks appropriately addressed by export controls

- The primary risk involving fusion is **abuse of the technology or materials outside the US**
 - Tritium & tritium management systems already covered by export controls, such as:
 - 10 CFR 110.9; ECCN 1C235 and 1A231
 - Fusion technology and materials (e.g., Li-6) also already covered in large part, such as:
 - ECCN 0D999 and 1C233, and ECCNs for other components/parts | End-use prohibitions
- USG export controls agencies already have sole jurisdiction
- Treatment of fusion by export controls aligns with current nonproliferation regime
 - E.g., Fusion and tritium excluded from Trigger Lists (which clarify NPT & concern safeguards), **but tritium and tritium systems are on the NSG “dual use” list (which concerns export controls)**

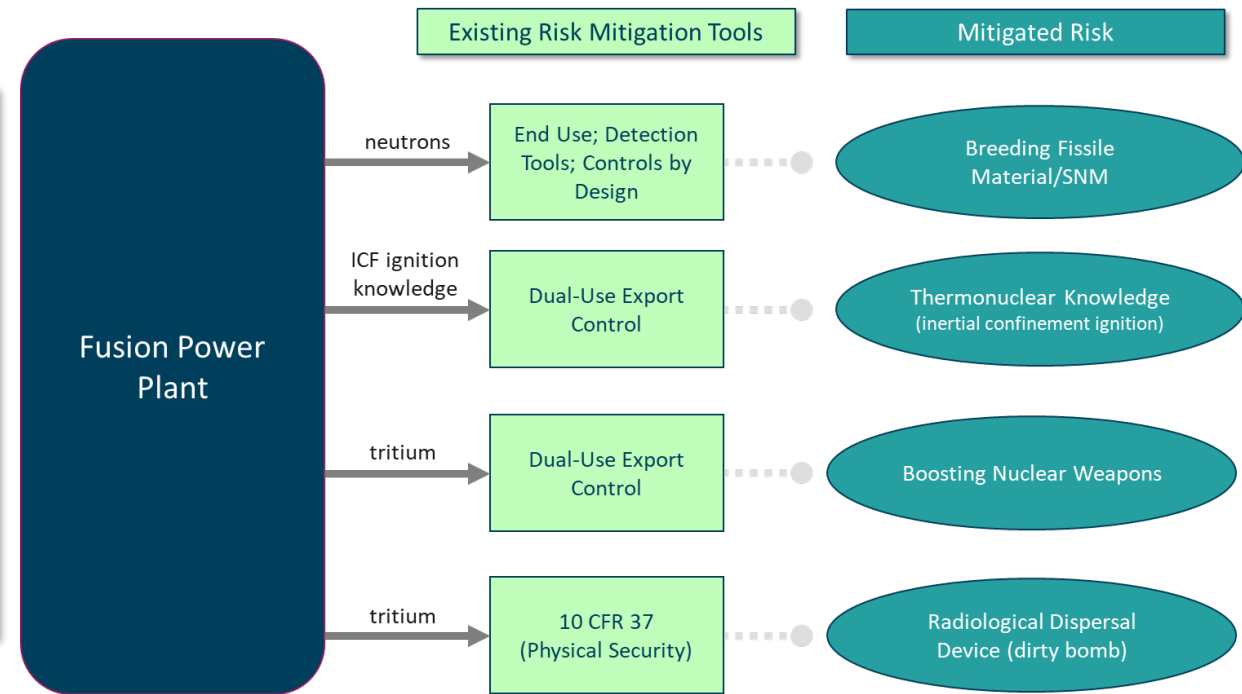
See our paper: “Nonproliferation and fusion power plants”

To be published in an academic journal; preprint can be made available

Nonproliferation and fusion power plants
Michael Y. Hua¹, Sachin S. Desai², Amy C. Roma³, Angela Di Fulvio⁴, Craig J. Mundie⁵,
and Sara A. Pozzi⁶

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⁴Department of Nuclear, Plasma & Radiological Engineering, University of Illinois
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⁶Department of Nuclear Engineering & Radiological Sciences, University of Michigan, Ann
Arbor, MI

June 3, 2022



Security for materials facilities is handled in Part 37

- Risk of material diversion RDDs (“dirty bombs”) is addressed with physical security: Part 37 – Phys. Protection of Category 1 and Category 2 Quantities of Rad. Mat.
 - Category 1: typically used in radiothermal generators, irradiators, and radiation teletherapy.
 - Category 2: typically used in industrial gamma radiography, high- and medium-dose rate brachytherapy, and radiography.
- Category threshold values come from IAEA TECDOC-1344, IAEA Code of Conduct, and International Conference on Security of Radioactive Sources 2003 (the Hofburg Conference)
- Using the same threshold calculations for categories one and two, the tritium thresholds are:
 - Category 1 (H-3): ~5.6 kg
 - Category 2 (H-3): ~56 g

Part 37 ≠ Part 73

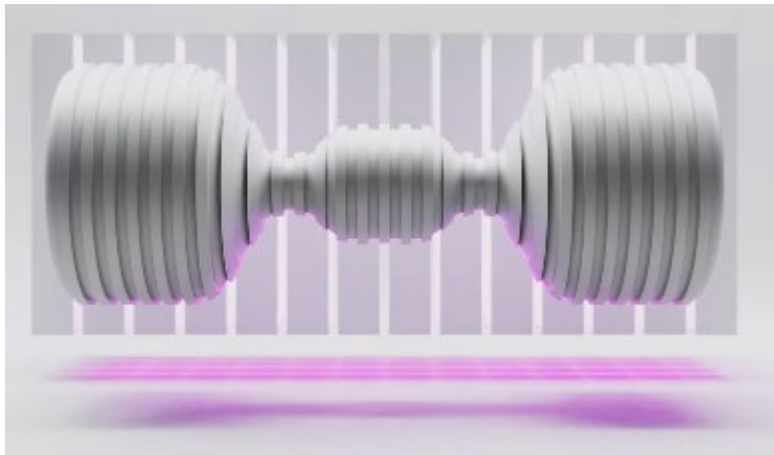
- Part 73 Purpose: “This part prescribes requirements for the establishment and maintenance of a physical protection system which will have capabilities for the protection of **special nuclear material** at fixed sites and in transit and of plants in which **special nuclear material** is used”
- Part 73 presumes the presence of special nuclear material; focuses on physical protection of this already existing material
- SNM not used and not present in fusion facilities

Use of Part 30 Tools for Fusion

Fusion during operation

Key Concept: Fusion's operational impacts are fundamentally similar to those of a particle accelerator

Fusion Device



- Neutron and photon radiation
- In-process fuel/accelerated particles and exhaust
- Activated shielding

Accelerator (e.g., cyclotron)

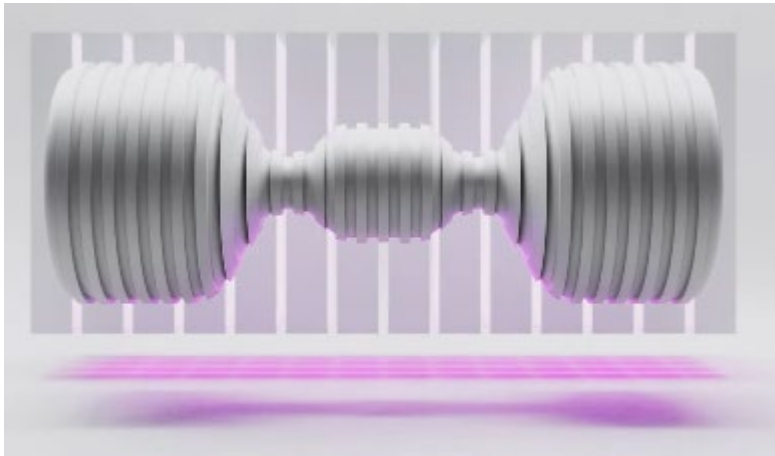


- Neutron and photon radiation
- In-process fuel/accelerated particles and exhaust
- Activated shielding

Fusion during accidents

Key Concept: Fusion impacts are fundamentally akin to those of industrial facilities

Fusion Device



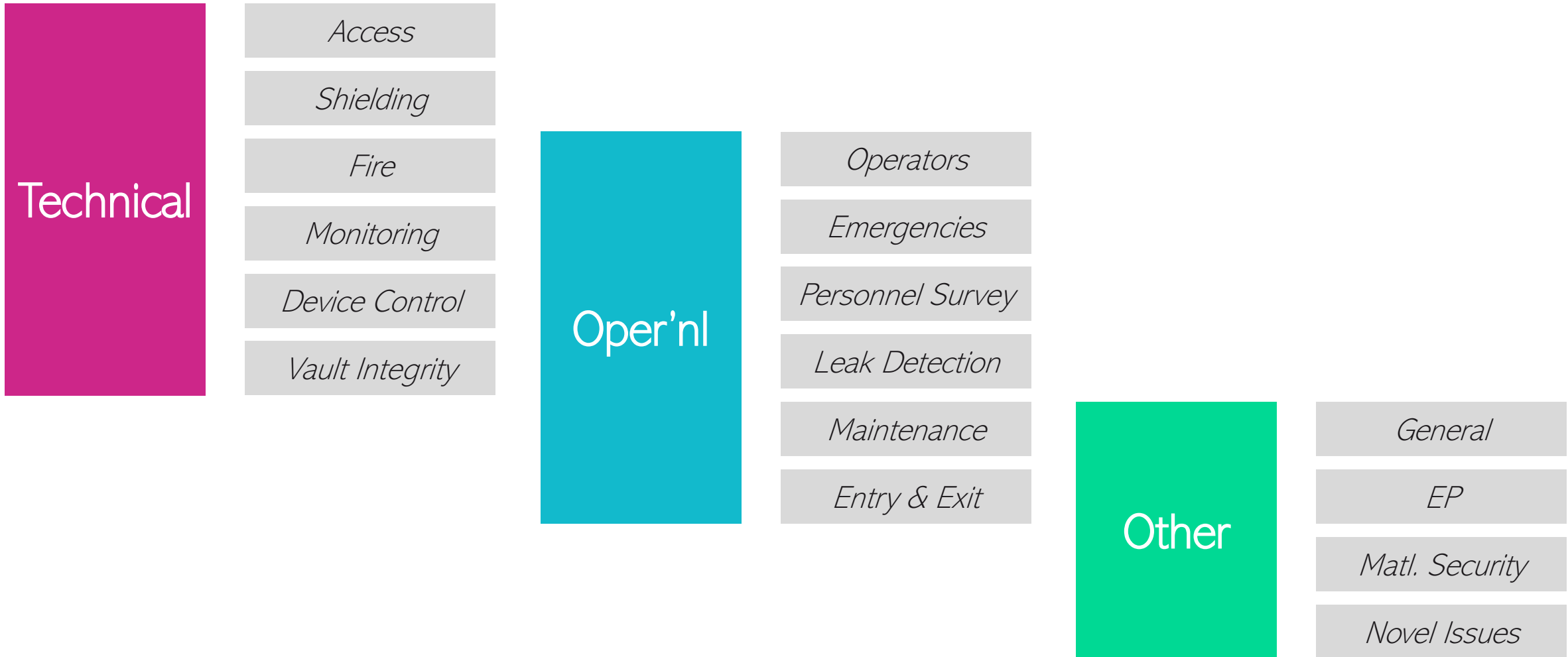
- Reactions (fusion) immediately cease
- Device has very limited releasable inventory
- No need for active cooling (may have pools)
- Tritium handling is complex *materials* issue

Industrial Facility

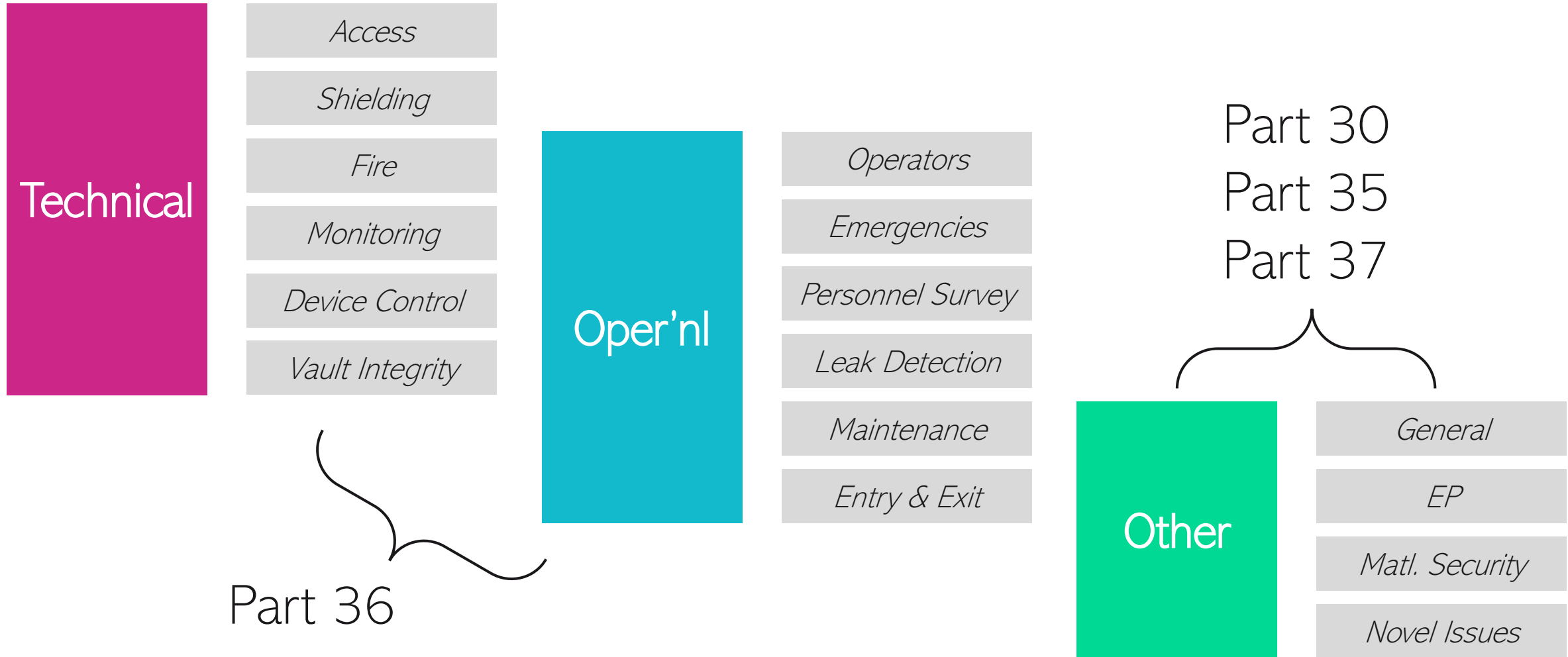


- Reactions (decay) continue – may need to close shielding
- Devices have small-to-large releasable inventory
- Usually, no need for complex active cooling (pools instead)
- Diversity of issues to evaluate

What could the NRC need to control for?

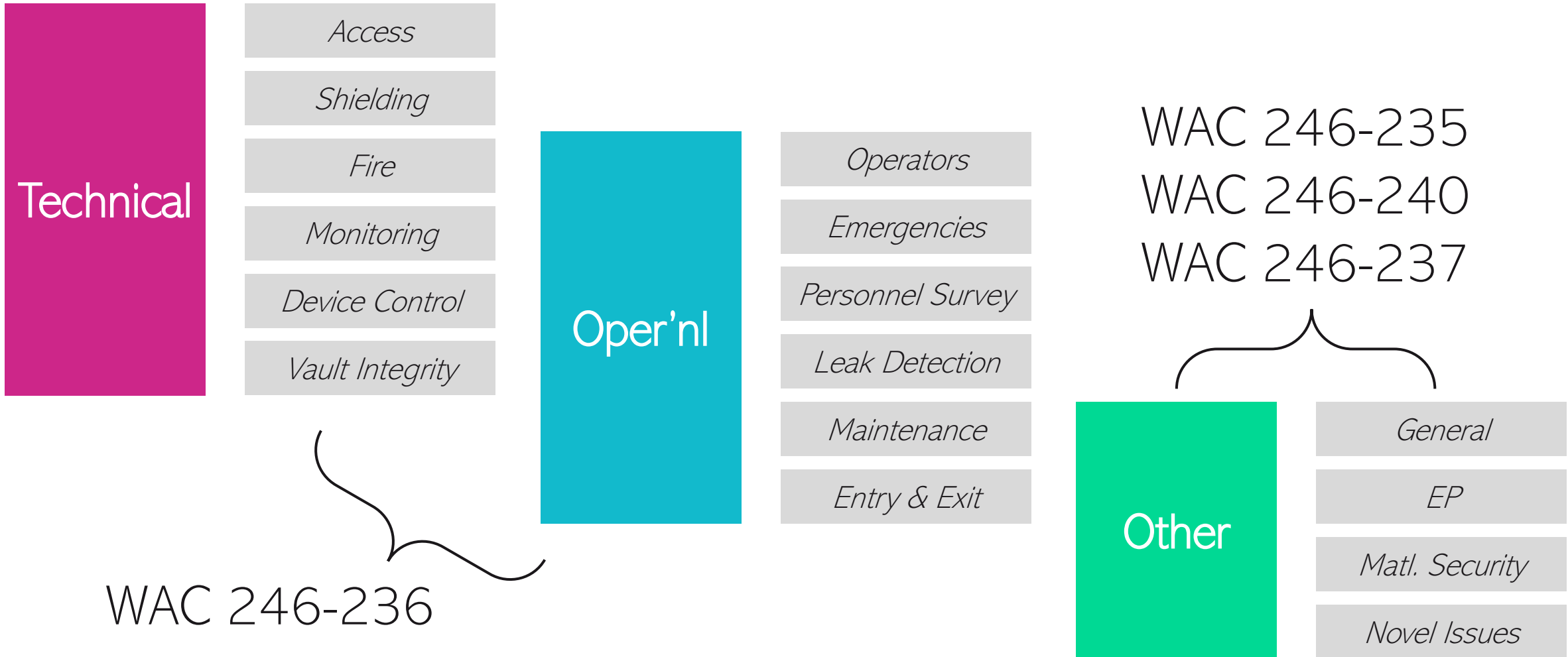


What could the NRC look to?



What could the States look to?

In the state of Washington, for example:



Sample **design** requirements usable from Part 36

Section (Based on Part 36)	Title	Key Regulatory Concepts
36.23	Access Control	<ul style="list-style-type: none"> • Barring entrance to rooms containing fusion device/ancillary system during ops. (essentially covering all potential high-radiation areas) • Opening of door triggers alarms/shutdown (w/ backup intruder detection) • Alerts prior to start of operations
36.25	Shielding	<ul style="list-style-type: none"> • Dose rates cannot exceed 2 millirem per hour outside of shielded areas
36.27	Fire Protection	<ul style="list-style-type: none"> • Heat and smoke detectors • Automated fire extinguishing when required
36.29	Radiation Monitors	<ul style="list-style-type: none"> • Airborne material detection • Neutron detection • Entry and exit detection
36.31	Device Control	<ul style="list-style-type: none"> • Indication of on/off as well as safety system status/output • Ability to turn off easily (manual and automated)
36.33	Shielding Pools	<ul style="list-style-type: none"> • Metallurgical and leak/purity requirements • Dose limits
36.37	Power Failures	<ul style="list-style-type: none"> • Automatic stop of commercial operations
36.39	Design Requirements	<ul style="list-style-type: none"> • Sets forth performance requirements for above systems, as well as e.g., foundations, liquid handling, seismic, computers, wiring...
36.41	Construction monitoring	<ul style="list-style-type: none"> • Sets forth requirement to ensure construction meets design requirements

Sample **operating** requirements usable from Part 36

Section (Based on Part 36)	Title	Key Regulatory Concepts
36.51	Training	<ul style="list-style-type: none"> Operator training, testing, safety review, and related requirements (relatively simple requirements; reliance on guidance)
36.53	Operating and Emergency Procedures	<ul style="list-style-type: none"> Safety procedures for operators (e.g., entry/leaving, dosimeters, leak testing, maintenance checks) On-site emergency procedure requirements (e.g., personnel overexposure, alarms, equipment failures, loss of shielding pool liquid) Revision requirements (Off-site emergency requirement threshold set in Part 30/under review)
36.55	Personnel Monitoring	<ul style="list-style-type: none"> Standard dosimetry requirements
36.57	Radiation Surveys	<ul style="list-style-type: none"> Surveys with startup and over time Survey requirements and consequences of failure
36.59	Leak Detection	<ul style="list-style-type: none"> Detection of leaks from vacuum vessels (as opposed to sealed sources) Checks for equipment before entry into shielding pools Decontamination of leaks
36.61	Inspection and Maintenance	<ul style="list-style-type: none"> Inspections of key active systems (e.g., access control, monitors, wiring for safety systems, shielding pool systems) Requirement to repair faults
36.63	Pool Liquid Purity	<ul style="list-style-type: none"> Basic requirements for maintaining purity of shielding pools
36.65	Attendance During Operation	<ul style="list-style-type: none"> Staffing requirements for operator and additional individual(s)
36.67	Entry and Exit	<ul style="list-style-type: none"> Radiation checks prior to entry and exit of fusion device/ancillary system rooms

Example: § 36.25 Shielding

The following mark-ups are meant to be illustrative, not complete and comprehensive

- a. The radiation dose rate in areas that are normally occupied during operation of a ~~panoramic irradiator~~-fusion device may not exceed 0.02 millisievert (2 millirems) per hour at any location 30 centimeters or more from the wall of the room when the sources are exposed. The dose rate must be averaged over an area not to exceed 100 square centimeters having no linear dimension greater than 20 cm. Areas where the radiation dose rate exceeds 0.02 millisievert (2 millirems) per hour must be locked, roped off, or posted.
- b. The radiation dose at 30 centimeters over the edge of the pool of a ~~pool irradiator~~-fusion device may not exceed 0.02 millisievert (2 millirems) per hour when the ~~sources are in the fully shielded position~~-device is on.
- c. The radiation dose rate at 1 meter from the shield of a ~~dry-source-storage panoramic irradiator~~-fusion device when the ~~source is shielded~~-device is off may not exceed 0.02 millisievert (2 millirems) per hour and at 5 centimeters from the shield may not exceed 0.2 millisievert (20 millirems) per hour.

Example: § 36.37 Power failures (shutdown)

- a. If electrical power at a ~~panoramic irradiator~~-fusion device is lost for longer than 10 seconds, the ~~sources~~-device must automatically ~~return to the shielded position~~-shutdown.
- b. The lock on the door of the radiation room of a ~~panoramic irradiator~~-fusion device may not be deactivated by a power failure.
- c. During a power failure, the area of any ~~irradiator~~-fusion device where sources are located may be entered only when using an operable and calibrated radiation survey meter.

Example: § 36.41 Construction monitoring and acceptance testing

- a. *Shielding.* For ~~panoramic irradiators~~ fusion devices, the licensee shall monitor the construction of the shielding to verify that its construction meets design specifications and generally accepted building code requirements for reinforced concrete.
- b. *Foundations.* For ~~panoramic irradiators~~ fusion devices, the licensee shall monitor the construction of the foundations to verify that their construction meets design specifications.
- c.

Example: § 36.23 Access control

- a. **[Physical Barrier]** Each entrance to a radiation room at a ~~panoramic irradiator-fusion device~~ must have a door or other physical barrier to prevent inadvertent entry of personnel if the ~~sources are not in the shielded position-device is on~~. ... [cannot turn device on when door is open, opening the door must cause shutdown, ..., the door cannot prevent anyone inside the room from leaving].
- b. **[Alarms]** In addition, each entrance to a radiation room at a ~~panoramic irradiator-fusion device~~ must have an independent backup access control to detect personnel entry while the ~~sources are exposed-device is on~~. Detection of entry ... must also activate a visible and audible alarm to make the individual entering the room aware of the hazard. The alarm must also alert at least one other individual who is onsite of the entry. That individual shall be trained on how to respond to the alarm and prepared to promptly render or summon assistance.
- c. **[Detectors]** A radiation monitor must be provided to detect the presence of high radiation levels in the radiation room of a ~~panoramic irradiator-fusion device~~ before personnel entry. The monitor must be integrated with personnel access door locks to prevent room access when radiation levels are high. Attempted personnel entry while the monitor measures high radiation levels, must activate the alarm described in paragraph (b) of this section. The monitor may be located in the entrance (normally referred to as the maze) but not in the direct radiation beam.

35.1000 can help manage technology innovation

- 35.1000 establishes dynamic program to address emerging medical technologies
 - NRC-led team evaluates new medical technology
 - Guidance developed by NRC & partners, flowed down to Agreement States
- Concept can be applied to new fusion technologies as they emerge, such as:
 - New fusion approaches
 - New fusion fuels
 - New approaches to shielding or fuel breeding
 - New tritium management technologies

The Part 30 framework can scale to the diversity of fusion

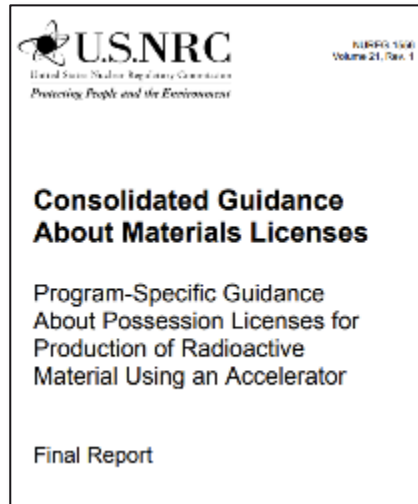
- **Horizontal scaling** can address different design themes and subsystems
-

- In Part 35, for example:
 - Subpart F – Manual Brachytherapy
 - Subpart G – Sealed Sources for Diagnosis
 - Subpart H – Photon Emitting Remote Afterloader Units, Teletherapy Units, and Gamma Stereotactic Radiosurgery Units
 - Subpart K – other uses (35.1000)

- **Vertical scaling** can address different sizes of device (pertaining to radiological impact)
-

- Examples:
 - Part 37 scales with onsite inventory with thresholds
 - Part 30: emergency plan required if offsite dose consequence is above 1 rem/5 rem to thyroid
 - Part 30: exempt quantities

Implementation of materials framework tools for fusion




Available Vehicles

Guidance
(e.g., NUREG rev.)



New Part
(e.g., Part 38)

Part 30	Rules of general applicability to domestic licensing of byproduct material
Part 31	General domestic licenses for byproduct material
Part 32	Specific domestic licenses to manufacture or transfer certain items containing byproduct material
Part 33	Specific domestic licenses of broad scope for byproduct material
Part 34	Licenses for industrial radiography and radiation safety requirements for industrial radiographic operations
Part 35	Medical use of byproduct material
Part 36	Licenses and radiation safety requirements for irradiators
Part 37	Physical protection of category 1 and category 2 quantities of radioactive material
	
Part 38	Licenses and radiation safety requirements for well logging

NRC Considerations

- Legal permissibility (role of guidance vs. rules to incorporate desired controls)
- Ability to support Agreement State implementation
- Ease of resolution (simplest path often best path)

Initial devices can be licensed under the current Part 30 framework as needed, as longer-term solution developed

- Fusion devices are not of significance to the common defense and security
- Potential material security risks can be adequately handled by Part 37
- The Part 30 framework has many regulatory tools suitable to handle fusion
- There are options on how to implement these existing tools

Conclusions

Questions?



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Public Comment on Fusion Safety & Licensing

B.A. Grierson
Director, FPP Design Hub

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GA's Approach to a Fusion Pilot Plant (FPP)

- **General Atomics is pursuing a FPP concept and is focused on safety, licensing, and social impact**
 - Appropriate regulations to ensure public and worker safety
 - Inclusion of safety, licensing, and byproduct disposal in FPP requirements
 - Embracing the need for a *social license*
 - Offering our voice

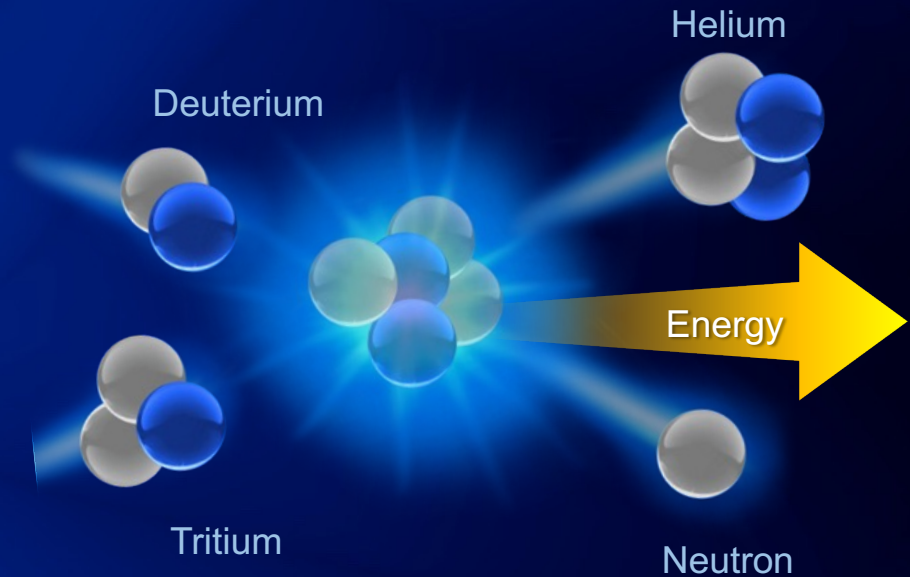


What is Fusion?

- Fusion is the process that powers the stars, and occurs when two light elements (such as hydrogen) combine into a heavier element (such as helium) under extremely high temperatures and pressures

Key differences from fission:

- **Fusion** requires energy input to combine elements
 - Cannot create a runaway nuclear reaction
- **Fusion** is fueled by hydrogen (deuterium and tritium)
 - Extracted from seawater and created with lithium
- **Fusion** requires a vacuum
 - A leak in the vessel instantly stops the process
- **Fusion** emits only helium
 - Does not produce high-level long-lived radioactive waste or byproducts for proliferation

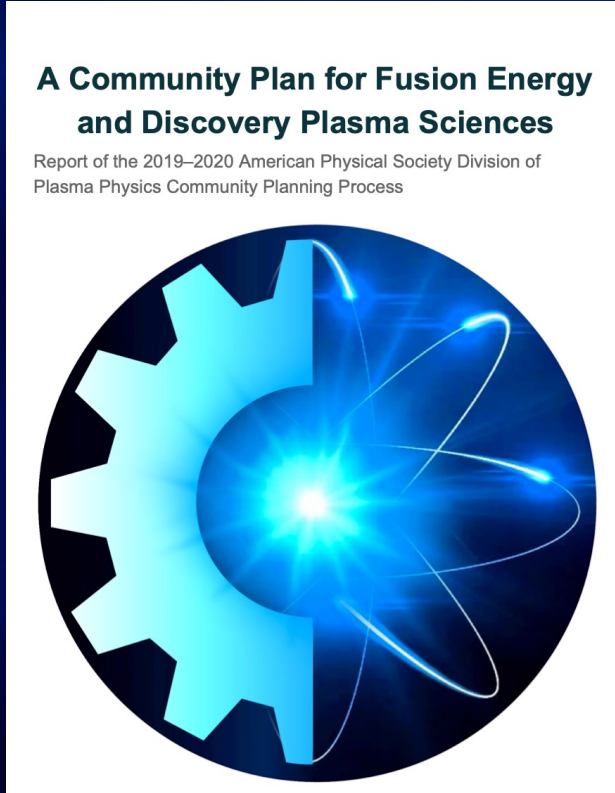


Safety is Essential in the Fusion Community

- **Safety & licensing**
 - Strategic objective of Community Planning Process
 - Pilot plant safety case should pave the way for commercial electricity
- **Safety assessments have been performed for multiple devices**
 - Larger ($R > 6$ m, 1 GWe) device: ARIES, DEMO, K-DEMO
 - Smaller ($R < 5$ m) devices: FNSF
- **More compact & higher confinement devices at lower fusion power offer safety advantages**
 - **Smaller** → Reduced volume for tritium inventory and byproduct materials
 - **Lower fusion power** → smaller tritium processing capacity needed

Community Plan Safety Recommendations

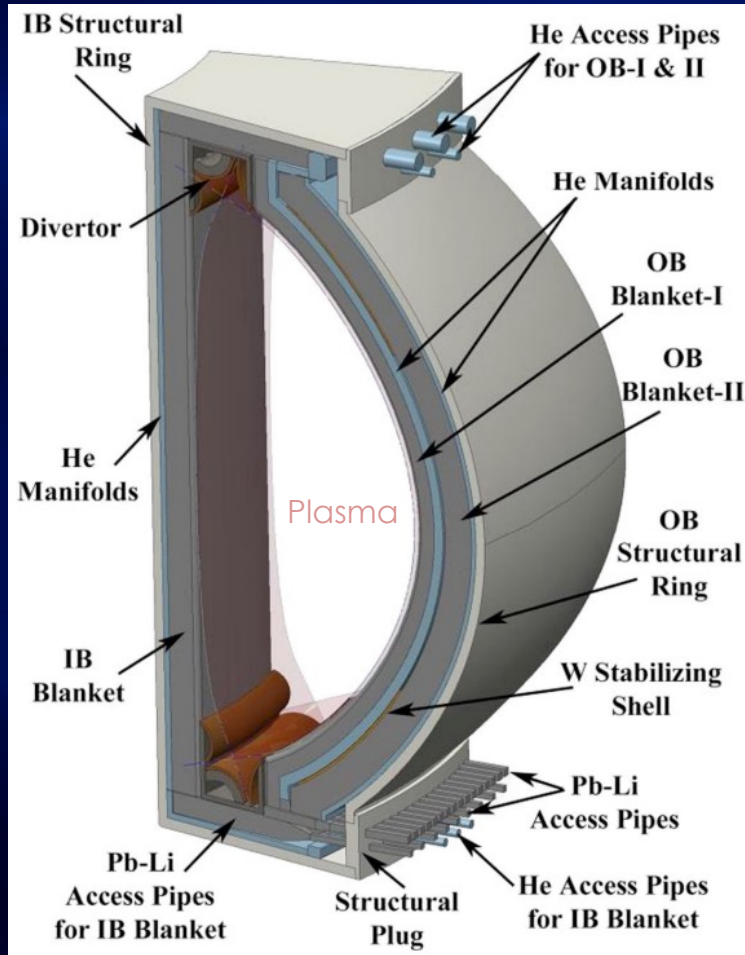
Develop the balance of plant technology, remote handling, maintenance approach, and licensing framework necessary to ensure safe and reliable operation of the fusion pilot plant



- **Establish working group to develop licensing approach**
- **Establish technical basis for safety and licensing**
- **Develop sensors and diagnostics for survey**
- **Establish strategies for remote calibration, alignment, maintenance, and replacement of components**
- **Carry out conceptual design and small-scale tests of balance of plant equipment**

The Fusion Blanket

A Key Component for Fusion Safety and Waste Assessment

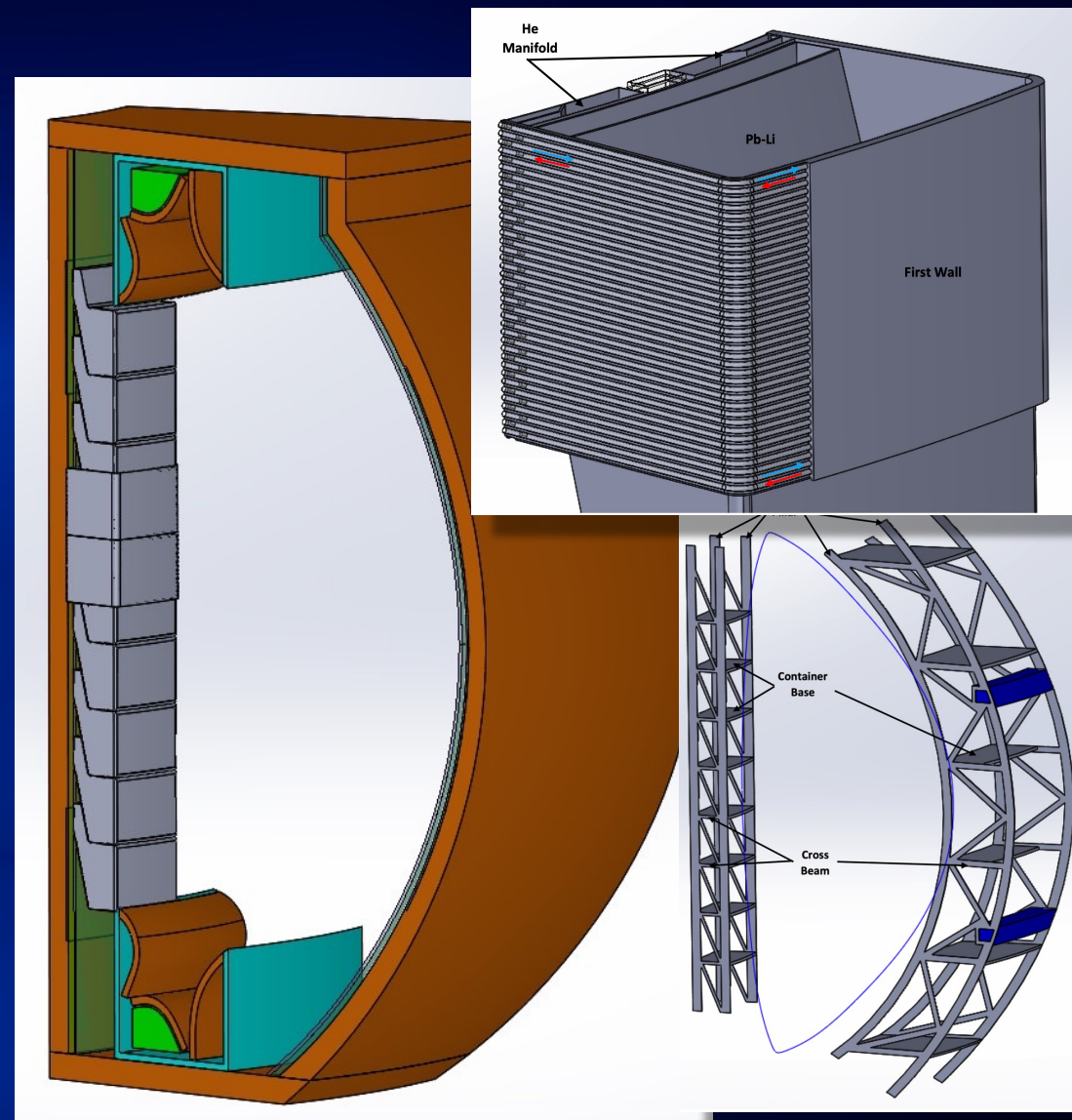


- Lithium in the blanket provides source of tritium
$${}^6\text{Li} + n \rightarrow {}^4\text{He} + \text{T}$$
 - One neutron is produced from D-T
 - Can only get one T back
 - Must add neutron multiplier (Be, Pb) to increase tritium breeding
 - Choices of materials affects safety assessment
 - Breeding material: solid, liquid
 - Coolant: water, helium
 - Structural & functional material: Steel, alloy, ceramic
- ← Example investigated in detail: PbLi breeder with dual helium/PbLi cooling, reduced activation steel w/silicon carbide insulator

X. Wang, et. al., Fus. Sci. & Tech. 67 193-219 (2015)

Utilizing Silicon Carbide in a Compact Tokamak FPP

- RAFM steels superior to conventional steel due to lower Ni and better thermal properties¹
- SiC offers further advantages²
 - Lower activation than RAFM steel
 - Reduced waste and decay heat challenge for maintenance
 - High temperature strength superior to steel for high thermal efficiency
 - Material compatibility with PbLi with low corrosion

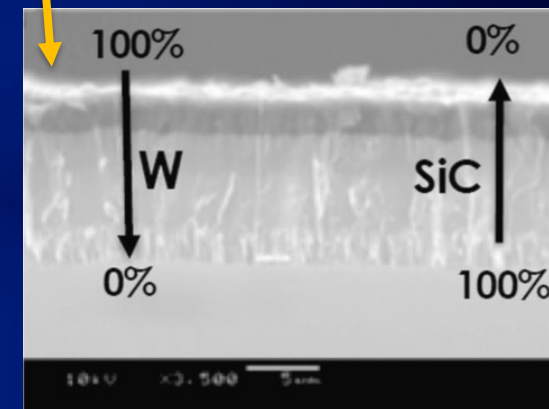
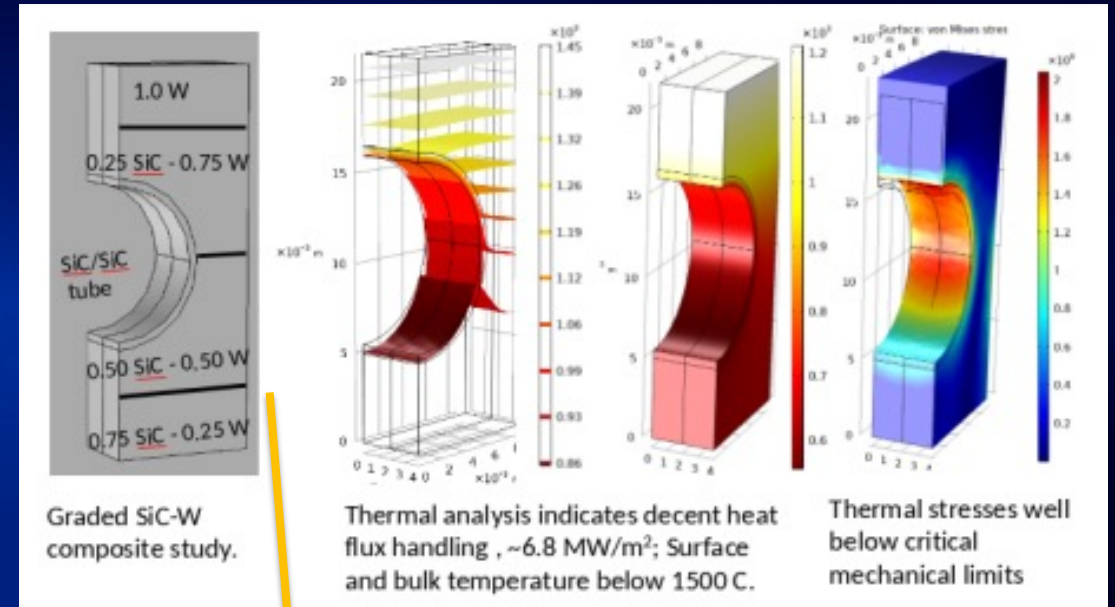


¹H. Tanigawa *et. al.*, Nucl. Fusion **57** 092004 (2017)

²M. Tillack, *et. al.*, Fus. Eng. and Design **180**, 113155 (2022)

Recent Advances in Silicon Carbide (SiC) Address Previous Challenges

- GA's Nuclear Technologies and Materials Division demonstrated SiC in accident tolerant fuels for fission reactors in conditions relevant to fusion
- Acceptably low He permeation at internal pressures far beyond those needed to cool a fusion first wall
- Engineered SiC/Tungsten (W) materials have superior heat removal capabilities and resistance to plasma-induced damage



Past and Current Studies Rely on ALARA Safety Policy Principle

As Low As Reasonably Achievable

ARIES-AT [1], ARIES-ACT1 [2], FNSF[3] studies guided by DOE-STD-6002-96

- *The public shall be protected such that no individual bears significant additional risk to health and safety from the operation of those facilities above the risks to which members of the general population are normally exposed*
- *Fusion facility workers shall be protected such that the risks to which they are exposed at a fusion facility are no greater than those to which they would be exposed at a comparable industrial facility*
- *Risks both to the public and to workers shall be maintained as low as reasonably achievable (ALARA)*
- *The need for an off-site evacuation plan shall be avoided*
- *Wastes, especially high-level radioactive wastes, shall be minimized*

¹D. Petti et. al., Fus. Eng. and Des. **80** 111–137 (2006)

²Humrickhouse & Merrill, Fus. Sci. & Tech. **67** 167-178 (2015)

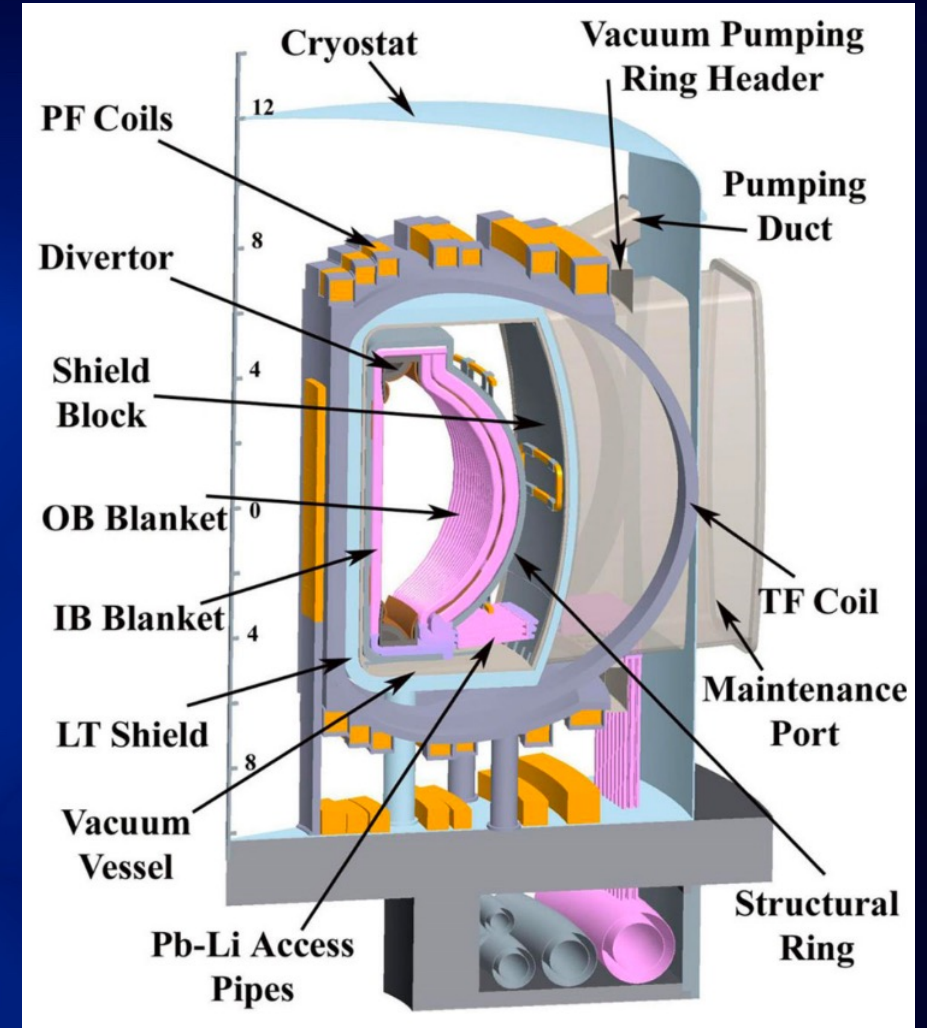
³Humrickhouse & Merrill, Fus. End. & Design. **135** 302-303 (2018)

Unique Safety Considerations

- **Fusion has unique safety considerations distinct from fission power plants**
 - Tritium as a fuel is the primary component of fusion systems for radiation protection
 - Low-level waste byproduct materials are unique to fusion components
- **Tools are available for performing safety assessments for fusion devices**
 - MELCOR, TMAP, HOTSPOT
- **Key design features and recommendations that limit tritium permeation and losses identified**
 - i.e. reduced lengths of cooling pipes

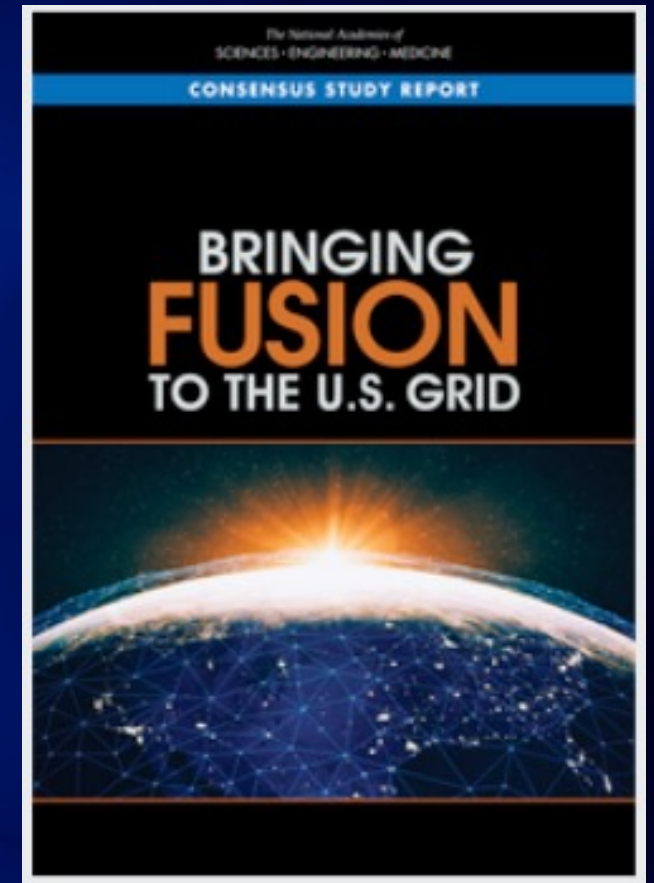
Tokamak Fusion Pilot Plants and Power Plant Safety

“The analyses show that none of these accidents are expected to breach confinement boundaries or lead to large releases of radioactive material from the ARIES-ACT1 power core.”



The National Academies '21 Report Made a Recommendation Consistent with Studies Reviewed: 10 CFR Part 20/30

- Finding: A regulatory process that minimizes unnecessary regulatory burden is a critical element of the nation's development of the most cost-effective fusion pilot plant
- Finding: Because existing nuclear regulatory requirements for utilization facilities (**10 CFR Part 50**) is tailored to fission power reactors, it **is not well suited to fusion technology**
- Finding: The current regulatory framework used for radiation protection and byproduct material provided under **10 CFR Parts 20 and 30** is well suited to fusion technology



GA's Approach to a Fusion Pilot Plant (FPP)

- **General Atomics is pursuing a FPP concept focused on safety, licensing, and social impact**
 - Appropriate regulations to ensure public and worker safety
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 - Offering our voice

We agree with the recommendation of the National Academies that fusion byproducts be classified as accelerator byproducts under Part 30 Regulation



Thank you to the NRC for the opportunity to present

Thank you for your attention

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Right-sizing Regulation based on Scale of Fusion Facility Hazards

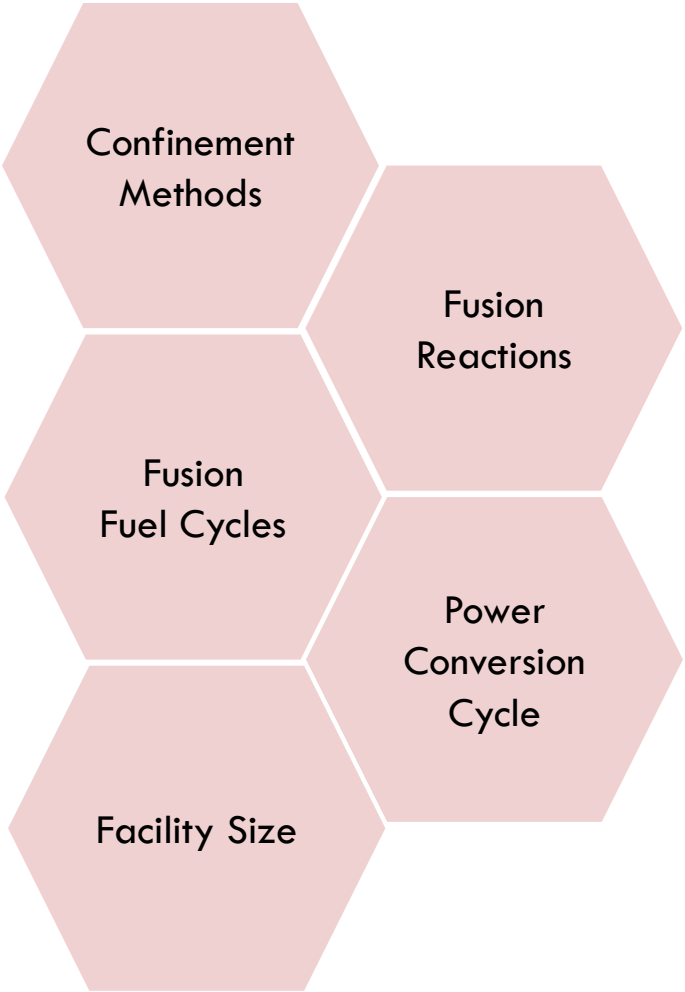
Patrick White (r.patrick.white@gmail.com)

Project Manager, Nuclear Innovation Alliance (pwhite@nuclearinnovationalliance.org)

Nuclear Regulatory Commission Public Meeting – June 7, 2022

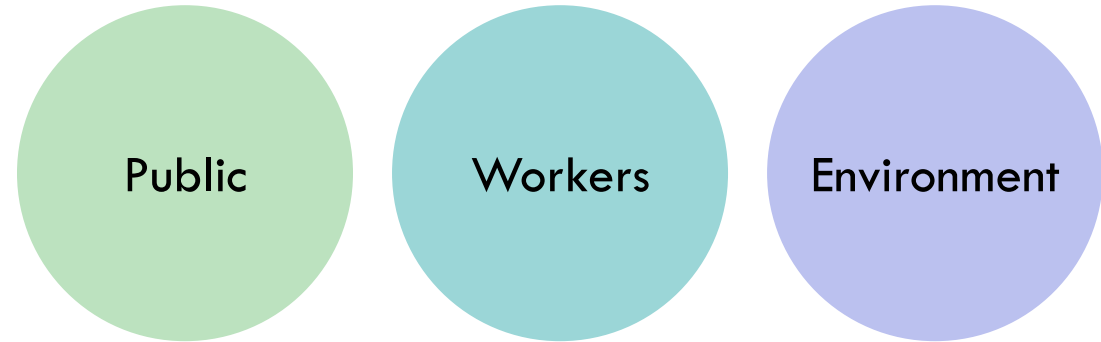
Meeting Topic: Developing Options for a Regulatory Framework for Commercial Fusion Energy Systems

Development of regulation for fusion is challenging due to technology diversity and early stage of design



Regulatory requirements are the translation of social and political constraints to the technical constraints on an activity

The NRC licenses and regulates the Nation's civilian use of radioactive materials to provide reasonable assurance of adequate protection of public health and safety and to promote the common defense and security and to protect the environment.

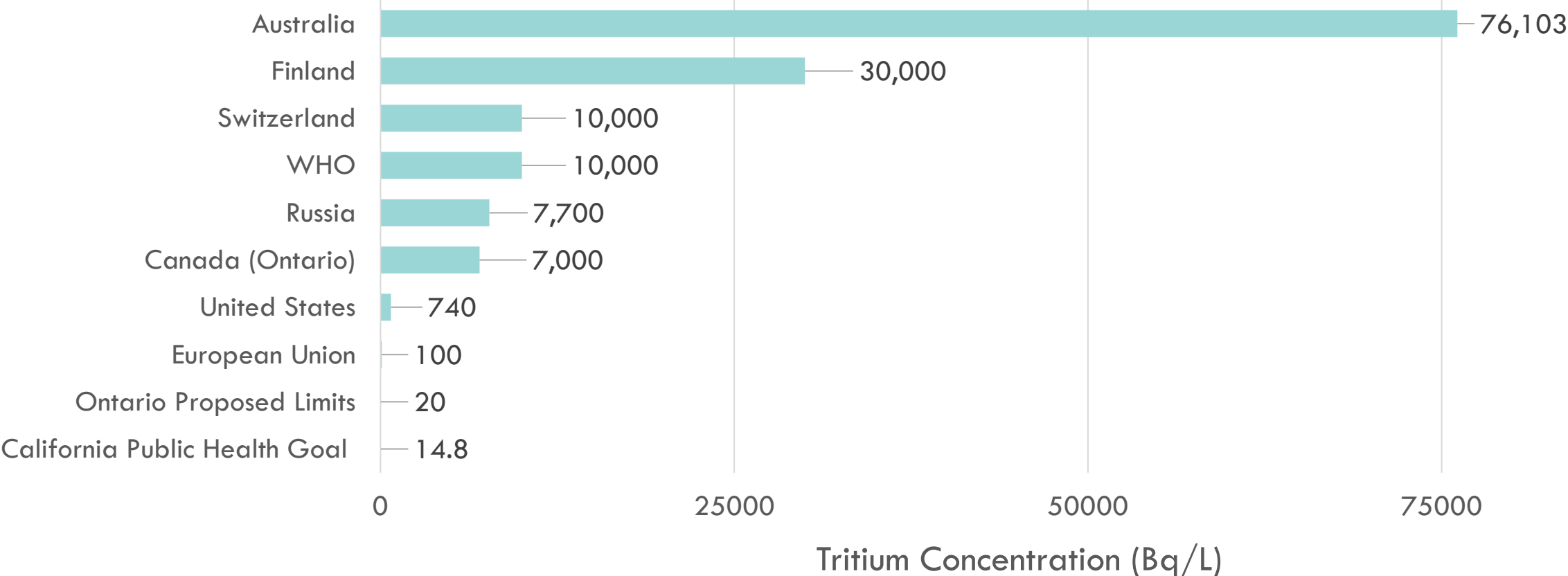


Setting acceptable limits on:

- Acute consequences
- Latent consequences
- Infrequent consequences
- Cumulative consequences
- Societally prioritized consequences

Development of regulatory requirements can be arbitrary and reflect a variety of competing stakeholder interests, assumptions

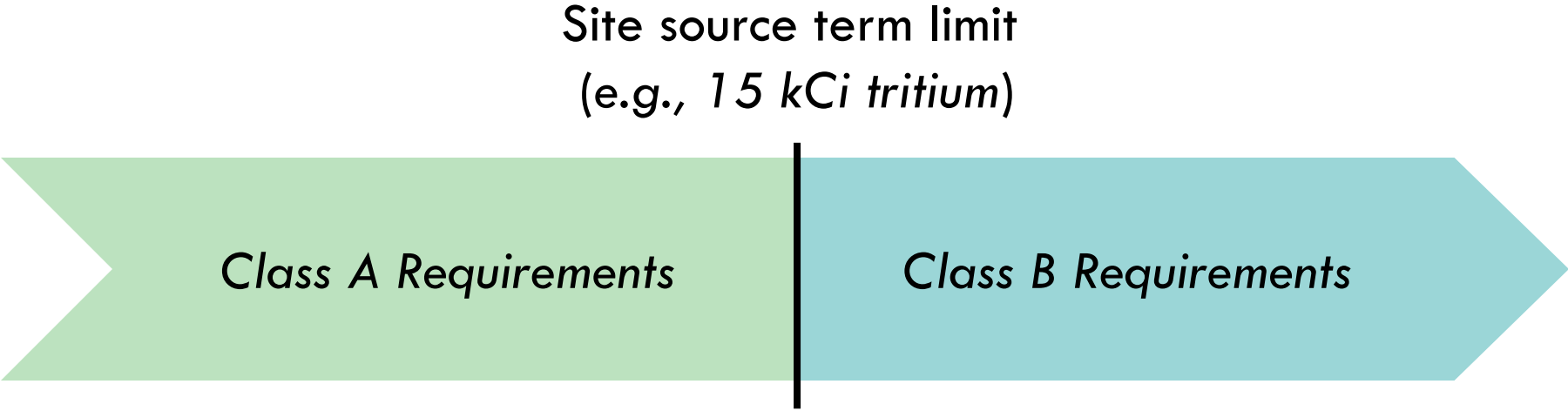
Selected Regulatory Limits for Tritium Contamination of Drinking Water



Definition of regulatory requirements requires selection of prescriptive or performance-based regulatory regimes

	Benefits	Drawbacks
Prescriptive regulation	<ul style="list-style-type: none">• Predictable• Consistent	<ul style="list-style-type: none">• Inflexible• Hard to codify
Performance-based regulation	<ul style="list-style-type: none">• Versatile• Simple to develop	<ul style="list-style-type: none">• Harder to review• Inherent variability

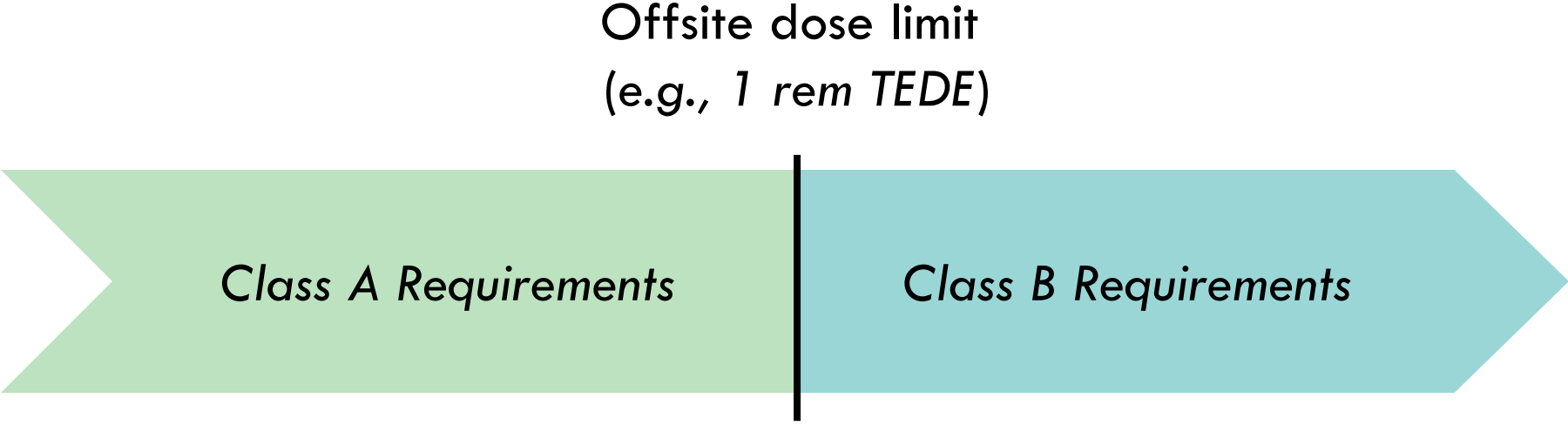
Prescriptive tiered regulatory frameworks can result in inconsistent, inadequate, or inappropriate regulatory requirements



Consequence relevant parameters

- Radiological inventory
- Radionuclide form
- Release fractions
- Other radionuclides
- Fusion facility siting
- Release conditions
- Meteorological conditions
- Surrounding populations
- Dose health effects
- Dose conversion
- Emergency protective actions post-release

Performance-based tiered regulatory frameworks can result in overly burdensome regulatory requirements



Evaluation relevant parameters

- Evaluation complexity
- Methodological assumptions
- Implicit or explicit treatment of probability, uncertainty, risk
- Evaluation conservatism
- Reliance on engineered safeguards, systems, structures, components to meet regulatory limits

Uniform performance-based regulatory requirements and scalable reviews enable consistent regulation of diverse fusion technologies



Define consistent regulatory requirements

Develop applicant specific safety case

Scale regulatory reviews based on safety case

Uniform performance-based regulatory requirements and scalable reviews enable consistent regulation of diverse fusion technologies



Define consistent regulatory requirements

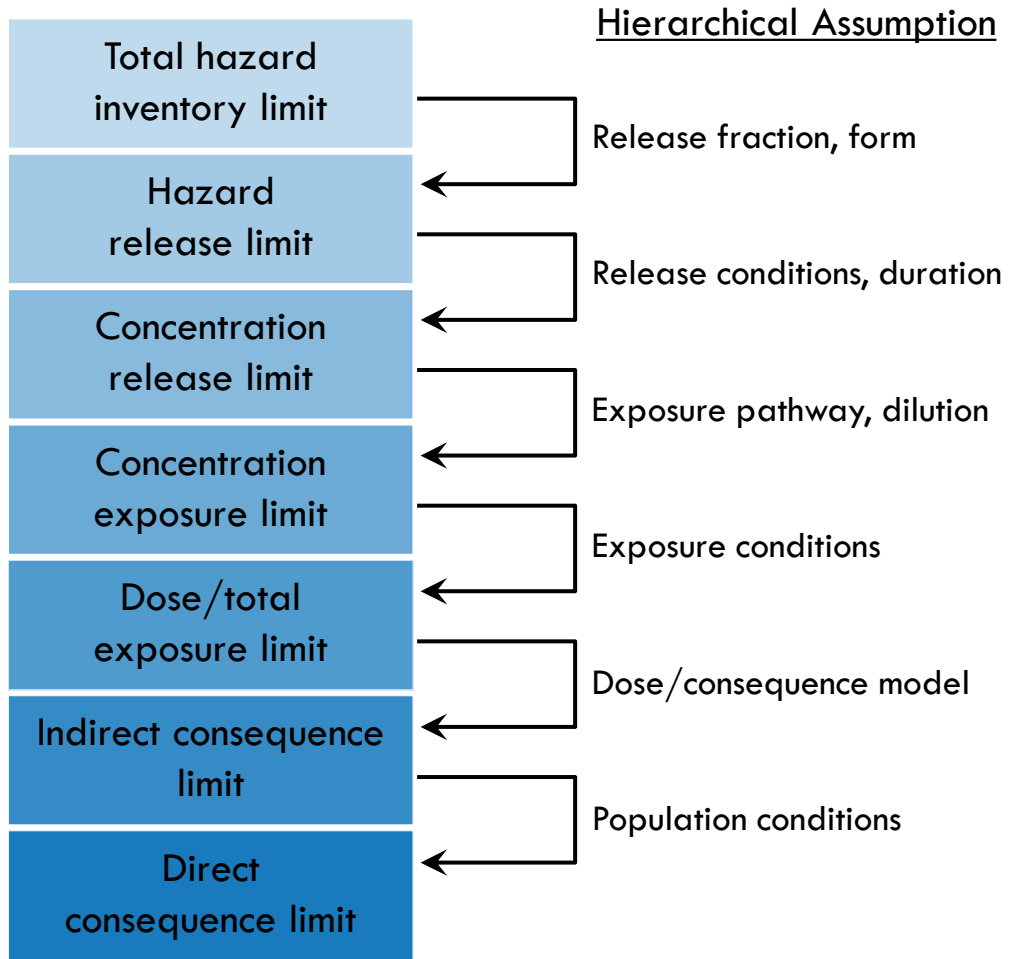
Develop applicant specific safety case

Scale regulatory reviews based on safety case

Comparison of regulatory limits and goals is be challenging based on technology and hazard differences

10 CFR 30.72 Material Threshold for Emergency Planning	Tritium Inventory > 20,000 Ci
10 CFR 20 Appendix B Effluent Release Limits	Tritium Release to Air < $10e-7 \mu\text{Ci}/\text{ml}$
10 CFR 20 Annual Dose Limit for Members of the Public	Total public dose < 0.1 rem per year
EPA Protective Action Limit for Public Evacuation	Maximum public dose equivalent > 1 rem
10 CFR 50.32 Reactor Siting Evaluation Limits	Public exposed dose equivalent < 25 rem
NRC Policy Statement on Latent Quantitative Health Objective	Total excess cancer fatalities < 0.1% all other causes
NRC Policy Statement on Acute Quantitative Health Objective	Total excess early fatalities < 0.1% all other causes

Hierarchical hazard limits facilitate development of societally consistent regulatory limits across technologies



Hierarchical hazard limits facilitate development of societally consistent regulatory limits across technologies

Example Limit:
Fusion acute hazard limits for 500 MW_e power plants based on natural gas energy emissions

890 lifetime excess fatalities

Natural Gas Power Plant

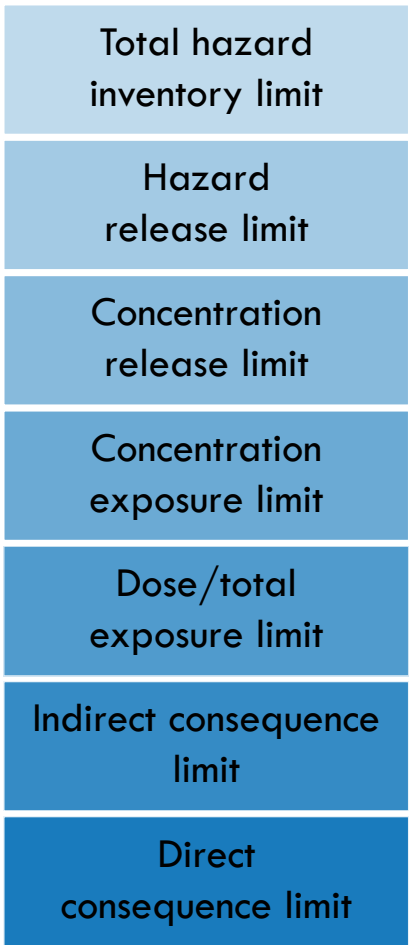
Maximum hazard inventory of 78kCi Tritium

Maximum single dose of 0.61 rem to population

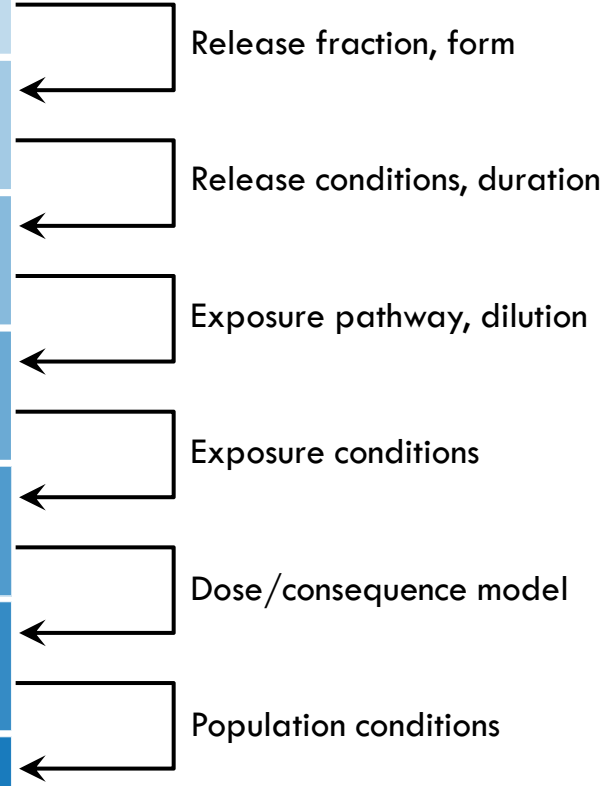
35 lifetime excess fatalities per 100k

90 lifetime excess fatalities

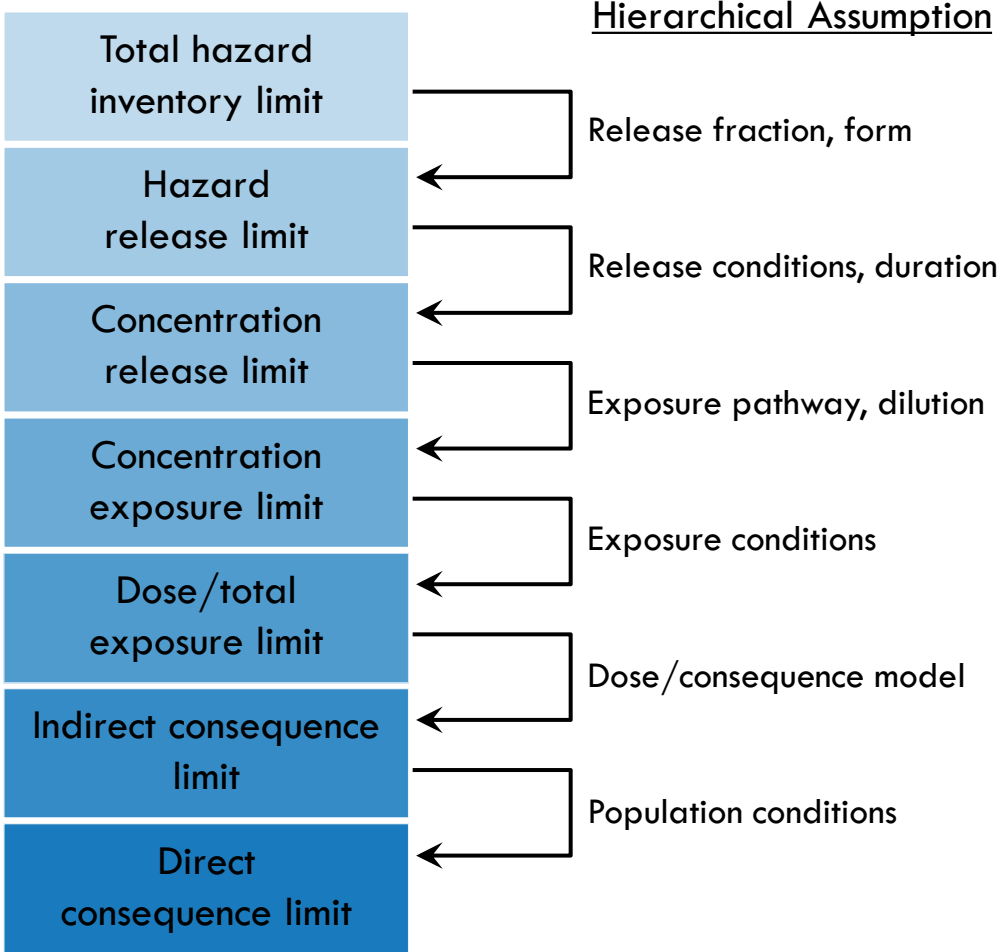
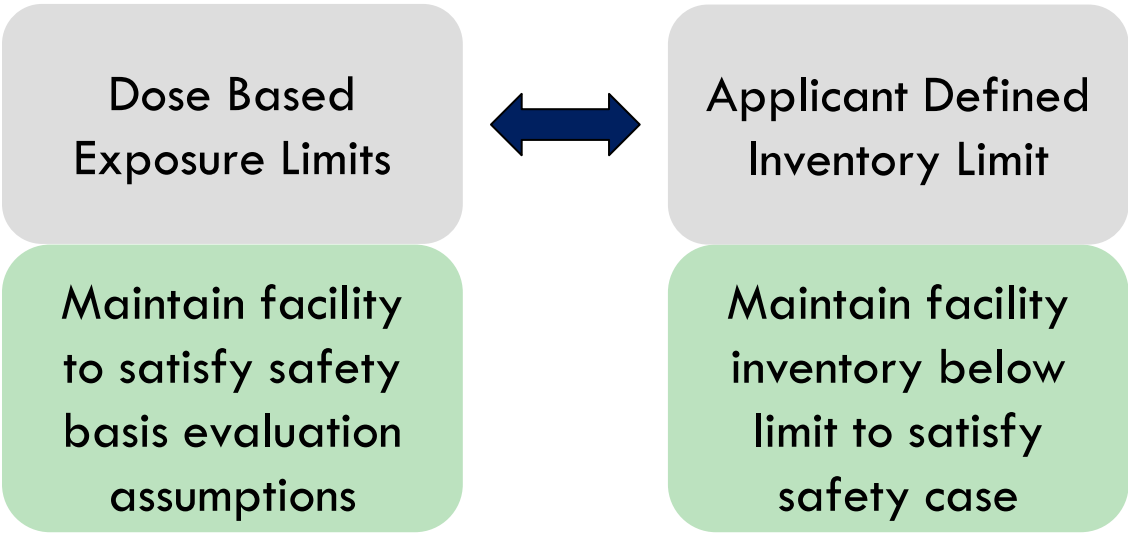
Fusion Power Plant



Hierarchical Assumption



Hierarchical hazard limits also enable applicants to define simplified regulatory requirements for operation



Uniform performance-based regulatory requirements and scalable reviews enable consistent regulation of diverse fusion technologies



Define consistent regulatory requirements

Develop applicant specific safety case

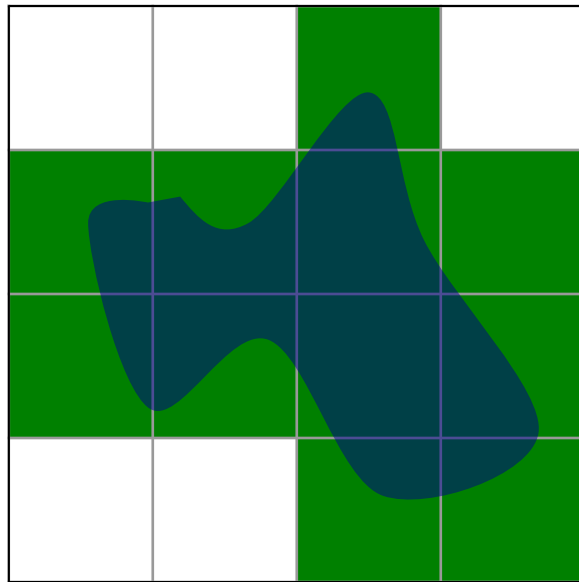
Scale regulatory reviews based on safety case

Licensing evaluation methods do not determine safety – they demonstrate compliance with limits

→ Increasing Level of Detail →

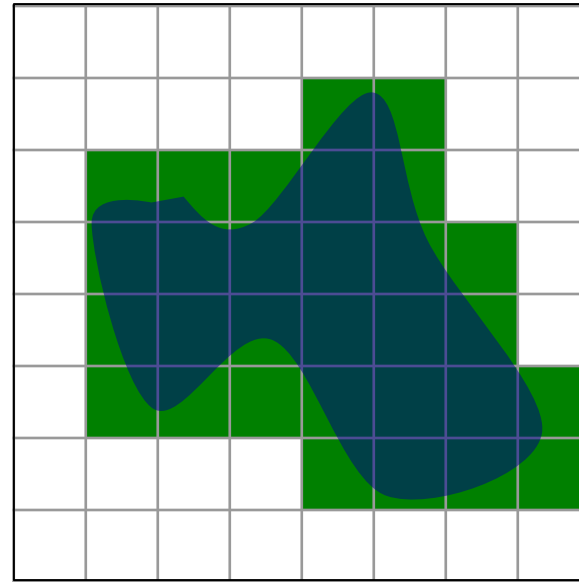
Example Limit:

Shape must occupy less than 50% of total box area



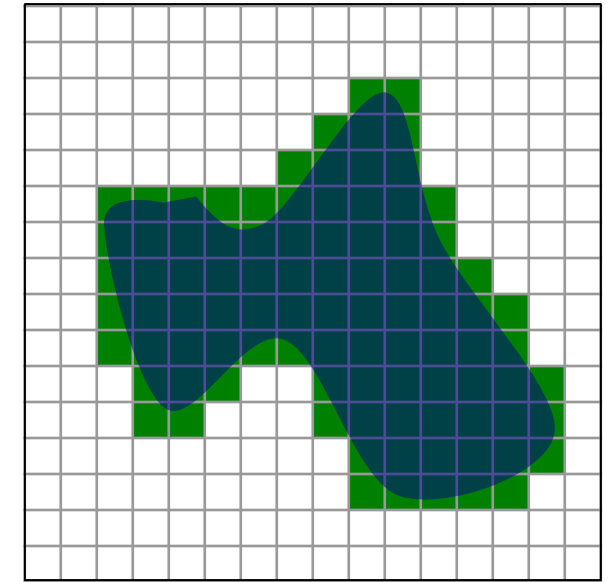
$$11/16 = 69\%$$

Fails Regulatory Limit



$$30/64 = 47\%$$

Passes Regulatory Limit

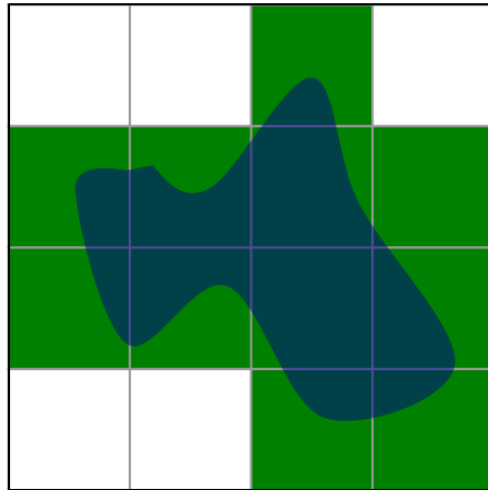


$$84/256 = 33\%$$

Passes Regulatory Limit

Licensing evaluation assumptions and conservatism are balanced with design changes to meet limits

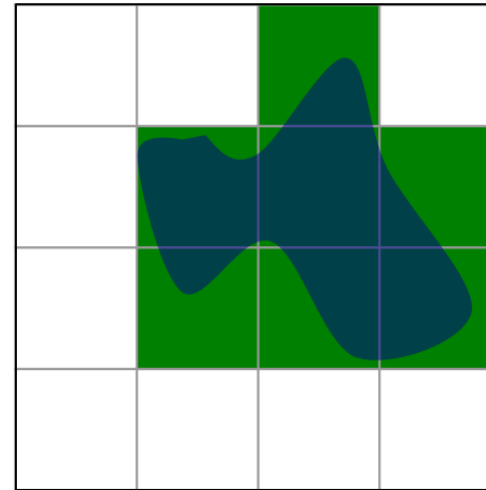
Original



$$11/16 = 69\%$$

Fails Regulatory Limit

Change design
to meet limit



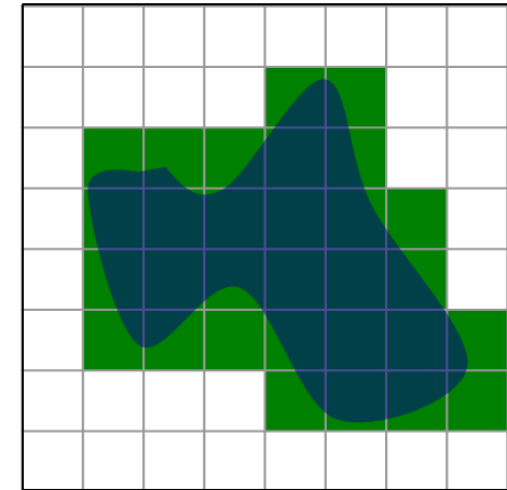
$$7/16 = 44\%$$

Passes Hazard Limit

- Greater safety margin
- New design, constraints
- Simpler safety case

83 of 152

Change evaluation
to meet limit



$$30/64 = 47\%$$

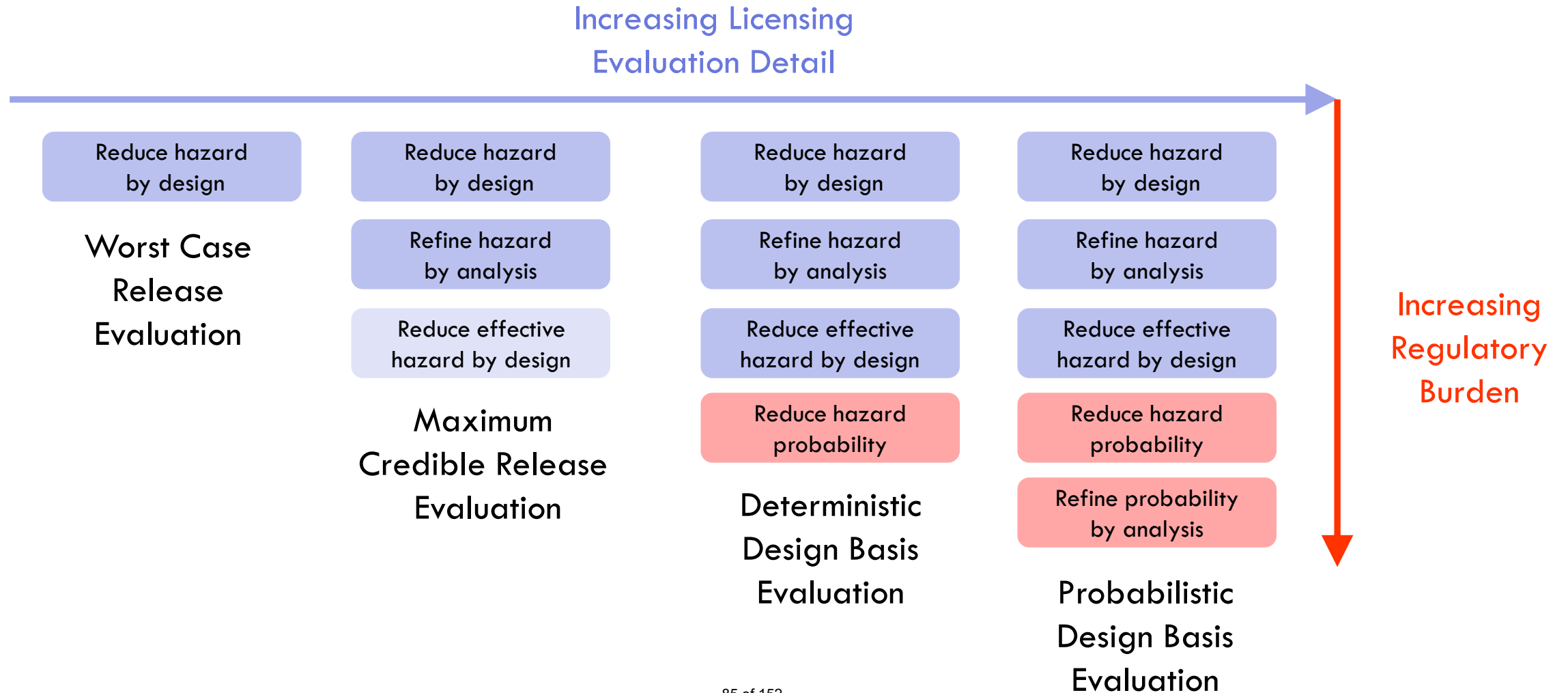
Passes Hazard Limit

- Same safety margin
- No design constraints
- More complex safety case

Licensing evaluation methods vary in their detail and inherent conservatisms when evaluating regulatory compliance



Selecting licensing evaluations requires characterization of regulatory and design tradeoffs



Uniform performance-based regulatory requirements and scalable reviews enable consistent regulation of diverse fusion technologies



Define consistent regulatory requirements

Develop applicant specific safety case

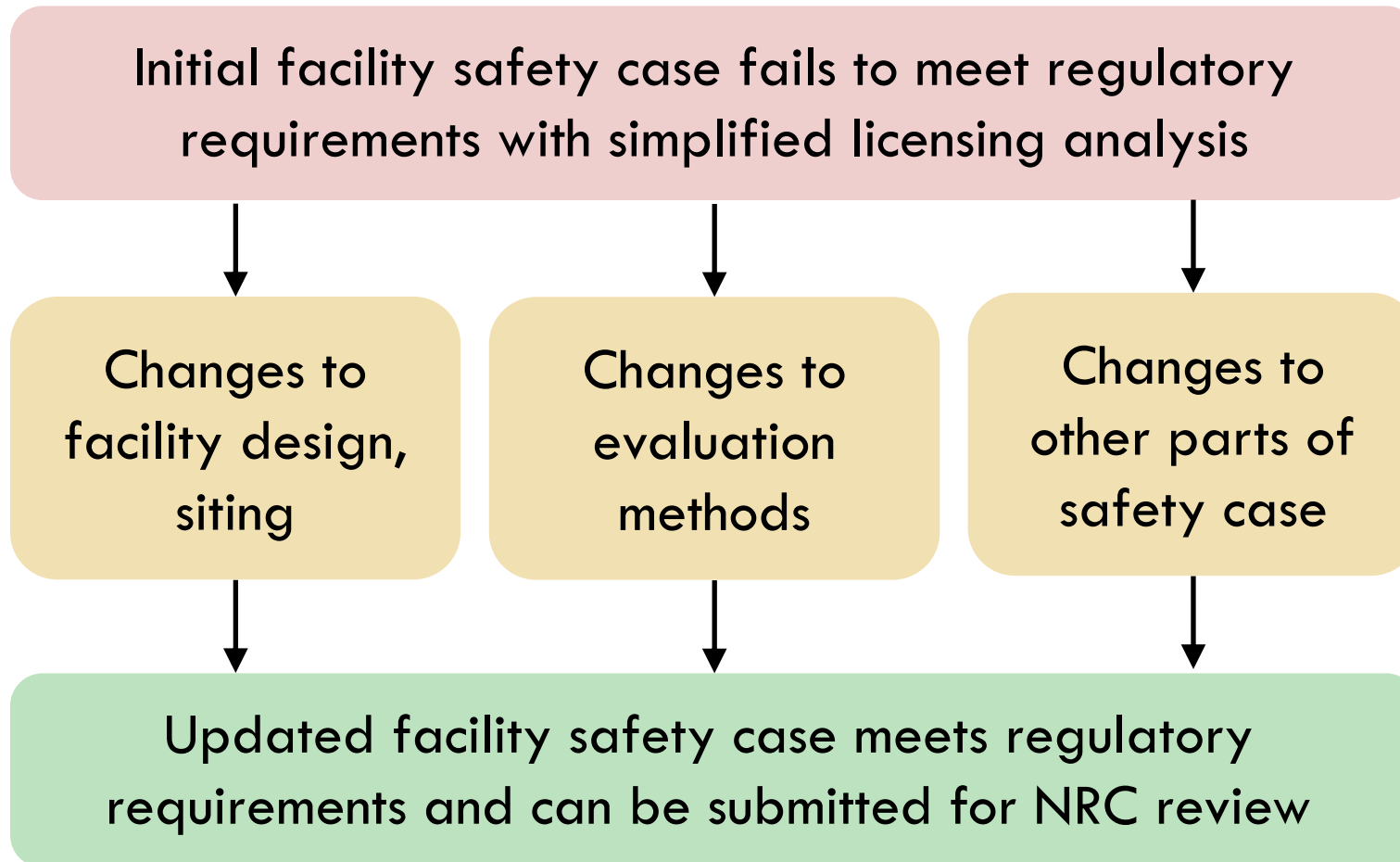
Scale regulatory reviews based on safety case

Facilities using simpler safety case to meet performance-based regulation should have lower regulatory burden

Safety Case Basis	Example Regulatory Oversight
Inherent safety by technology (hazards not present)	Review hazard identification
Inherent safety by design (hazards limited)	Review and validate hazard limitation by design, licensing evaluation methods
Passive safety by design (limited reliance on SSCs)	Validate SSC performance, limiting conditions, licensing evaluation methods
Active safety by design (reliance on SSCs)	Validate SSC performance, supporting systems, limiting conditions, licensing evaluation methods
Active safety by operations (reliance on human action)	Validate human performance, all operations, limiting conditions, licensing evaluation methods
Consequence mitigation by design or operation	Validate bounding events, facility performance, operator action, licensing evaluation methods



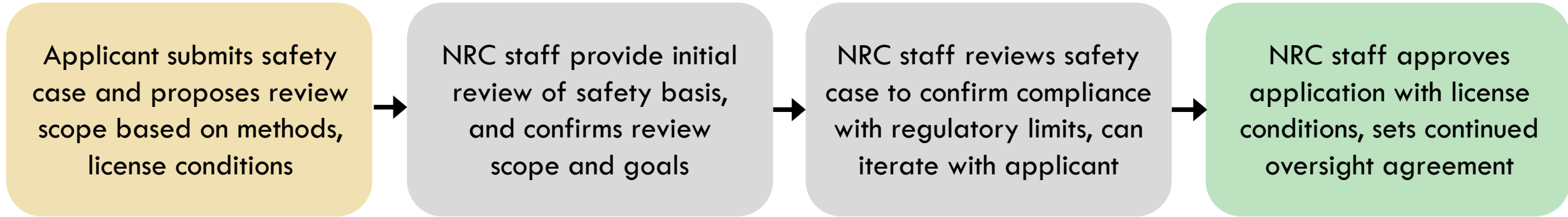
Applicants can develop facility-specific safety case with consideration of technical, business, and economic factors



Consideration factors include:

- Technical feasibility of design changes
- Economic impact of changes on design or analysis
- Schedule impacts of revised design or analysis methods
- Regulatory uncertainty or duration of review
- Public opinion/business risk of new safety case

Regulatory frameworks can reflect the independent oversight needed to ensure compliance with regulatory limits



Factors critical to regulatory success

- Clear, concise regulatory rule language
- Adequate regulatory guidance and reports
- Regulatory precedent and Commission direction
- Effective applicant and NRC project management
- Keeping review focused on safety basis factors

Regulatory requirements on radiation exposure could serve as uniform performance-based requirements for scaled review

Fusion
Facility A

Example Safety Basis

- Site-wide tritium < 10 g
- 300 m to site boundary
- Maximum credible evaluation

Example Scaled Review

- Limited NRC review to validate site-wide inventory, evaluation
- Conditions on site inventory

Fusion
Facility B

- Site-wide tritium > 150 g
- Safety systems credited with mitigating accident release
- Design basis safety evaluation

- Detailed NRC review on design, evaluations, licensing events
- Conditions on facility operation and maintenance

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Define consistent regulatory requirements

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Savannah River National Laboratory

We put science to work.™

Fusion and Tritium Accident Risks and Analysis

NRC Public Meeting (June 7th, 2022)

Dave Babineau, Brenda Garcia-Diaz, Jim Klein, Bob Sindelar, Marlene Moore, and George Larsen

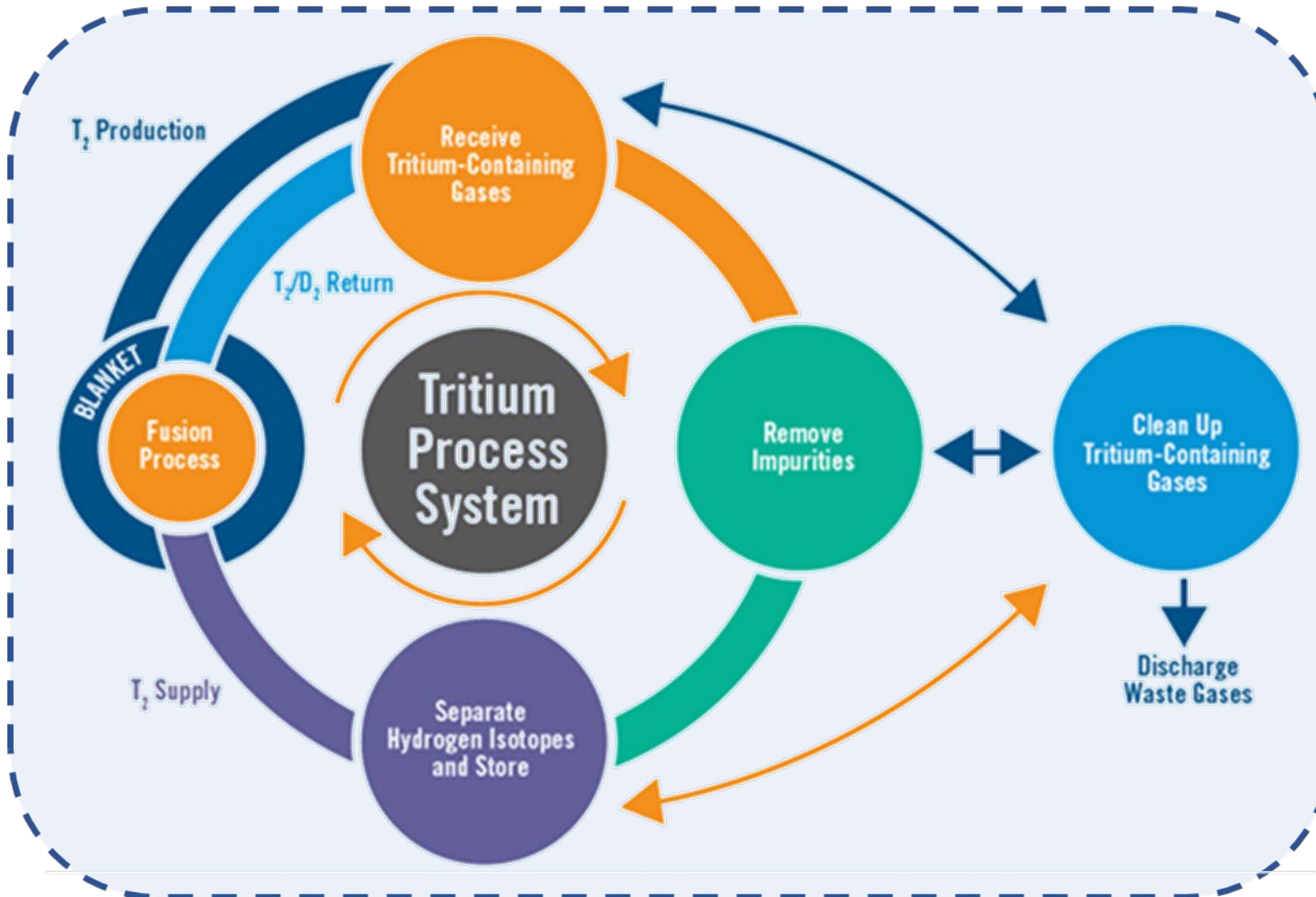
Savannah River National Lab

SRNL-STI-2022-00263

6/7/2022

Tritium Fuel Cycle: Similar Core for All Applications with Blanket Integration for Fusion

Process Control & Safety Systems



- **Main Fuel Cycle Processes are Similar to Other Tritium Cycles**
 - Bulk separation of hydrogen isotopes from other gases
 - Remove impurities that enter process (e.g. HTO, nitrogen, etc.)
 - Store and account for isotopes
 - Clean exhaust gas and ensure it is suitable for release
- **Blanket Tritium Extraction & DIR Unique to Fusion**
 - Proposed blanket technologies vary significantly and are at low TRL levels
 - Need caution with SF₆ used for high voltage electronics and tritiated ammonia generated from N₂ used in divertor

Key Fuel Cycle Areas for Regulation and Safeguards

1. Fusion Device

- Primarily a radiation hazard due to activation of materials (similar to accelerator)
- Minor amounts of tritium in the device compared to the tritium processing systems (however tritium uptake needs to be considered)

2. Tritium Processing

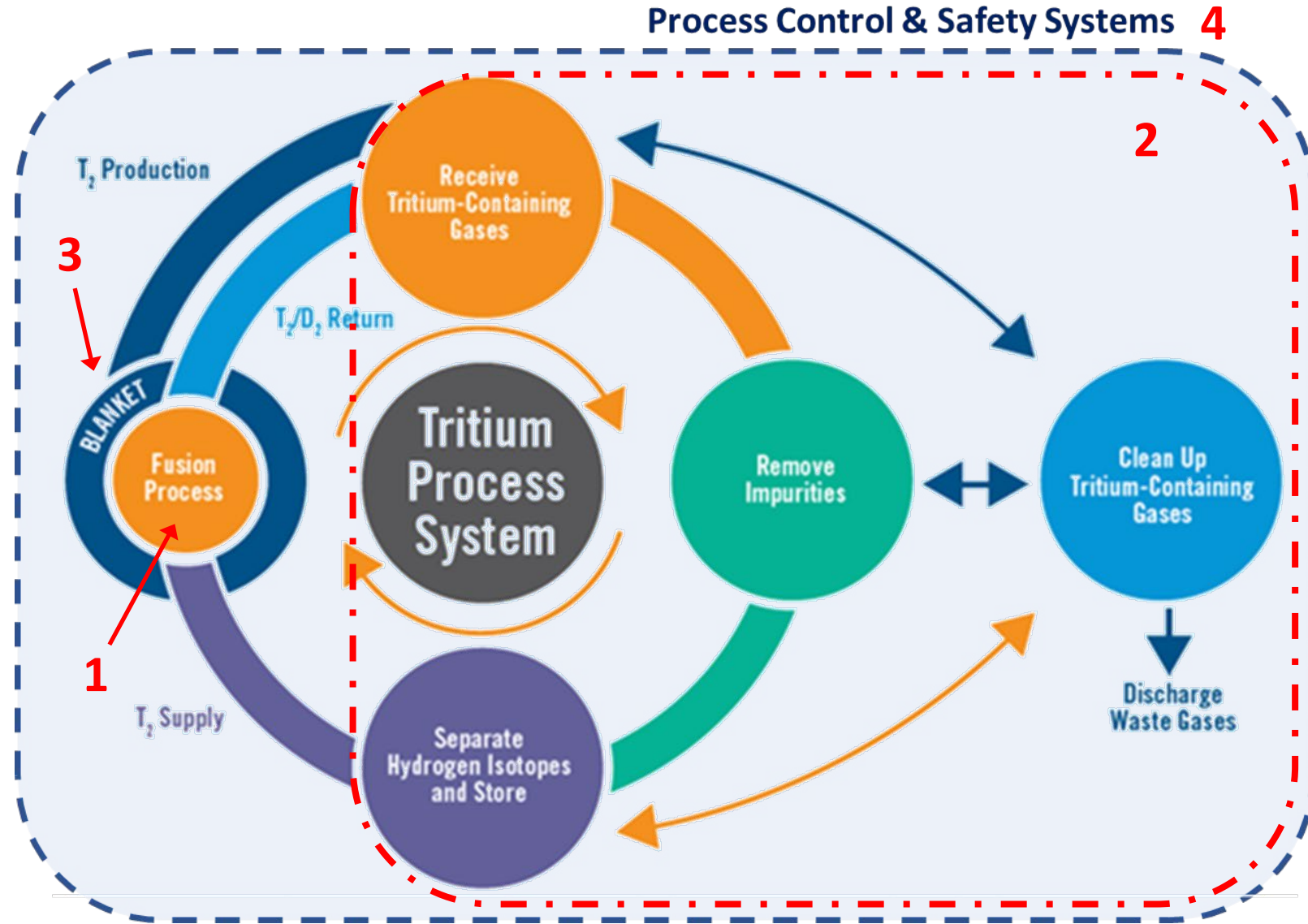
- Chemical plant with transferable radiological contamination hazard due to presence of tritium
- Significant experience at SRS and with NNSA on regulation/operation

3. Breeding Blanket

- High temperatures with potential for air-sensitive materials (e.g. Pb-Li, LiT) and also TF or beryllium / beryllium salts

4. Process Control & Safety Systems

- Tritium accountancy and/or tritium inventory needs
- Limit tritium releases due to permeation, operation and maintenance activities



Tritium Processing Regulation Considerations

- **Tritium is Unique among Radionuclides**

- Tritium is an exception to DOE-STD-1027 in terms of regulation

- *“At the recommendation of the Tritium Focus Group, the [hazard facility class] tritium threshold values were provided by the Tritium Focus Group (TFG) and are not calculated using the methodology in this Standard.” [Brown et al., Sandia2022-4187]*

- Tritium has many unique properties

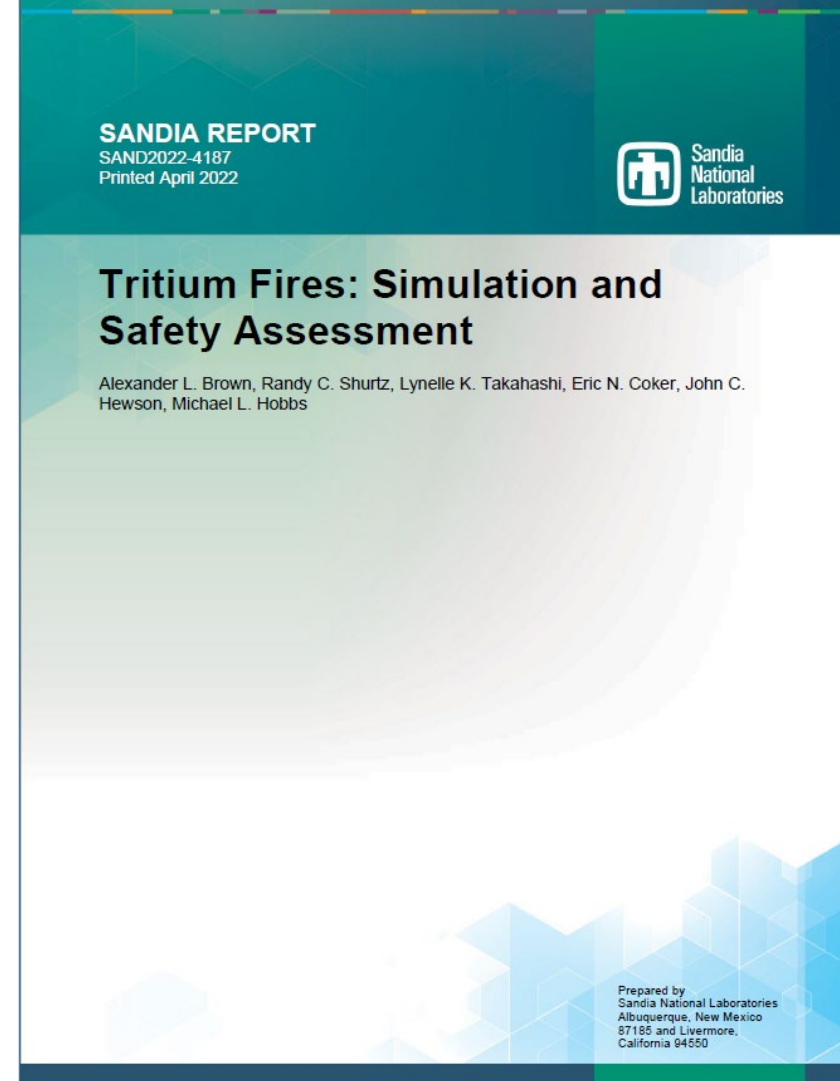
- Permeates solid metals
- Isotopically exchanges with protium or deuterium atoms in other materials
- Can be present as a gas (elemental or oxide), liquid (oxide or organic), or solid (hydride or organic) within the same facility
- Autocatalytic – spontaneously, but not necessarily quickly, reacts with other species

- **Form of Tritium in Accident Scenarios is Critical**

- Dose Coefficient (DC) for tritiated water (HTO) 10,000 times higher than the DC for tritium gas (HT) and the DC for an insoluble tritiated particle can be about ~14x that of HTO per DOE-STD-1129 (depends on particle size)

- Accident scenarios involving fires near tritium sources are often the limiting cases in accident analysis

- *“Since the DC for tritiated water vapor is much greater than for T₂ gas, facility-wide accidents involving fires or explosions are generally the default scenarios of greatest concern for overall facility hazard categorization.” [Brown et al., Sandia2022-4187]*



Fires, Tritium, and Conversion of Tritium to HTO

- **Oxidation Kinetics of Tritium are Not Well Studied or Understood**
 - There are limited literature sources that provide the chemical reaction kinetics of the tritium oxidation process available to use to address the spectrum of events. There are several references in the LA-UR-01-1825 report and kinetics data are inconsistent.
 - DOE/NNSA does not have any reports that have studied the kinetics of the combustion of actual tritium in open spaces but have only used surrogates (i.e. – deuterium or protium)
 - All available tritium oxidation rates / conversion percentages borrow from limited studies of tritium oxidation with and without catalysts in controlled spaces, or use experiential data from actual hydrogen deflagrations to attempt to develop a bounding value for the percent of tritium oxide that results in certain events
 - SRNL/SRS personnel have proposed needed fundamental studies with partners, because more studies are-needed with actual tritium (none have been funded as of now)
- **Many Tritium Oxidation / Combustion Scenarios are Based on Unconfined Spaces and Not Facilities**
 - LA-UR-01-1825, cited by presenters in the March 23rd meeting (ML22081A057), references unconfined space studies-when analyzing hazards for a large facility
 - *The HTO conversion percentage of 10% that was mentioned in that report was not intended as a bounding value according to the report authors*
 - *The 10% HTO conversion percentage assumption is not standard in DOE/NNSA analysis of hazards at tritium facilities*
 - *Tritium conversion of elemental to oxide and MAR dispersion is very dependent on space geometry and environmental conditions at the time of the release*
- **Hazard Analyses for Facilities are More Comprehensive than Using Bounding Tritium Conversion Values (e.g. - 10%)**
 - *Regulatory Frameworks and Detailed Licensing Evaluation following methods outlined in “Regulatory Frameworks and Evaluation Methodologies for the Licensing of Commercial Fusion Reactors” [White PhD Thesis, 2021] are much more common*
 - *Analysis of fire scenarios where the fire is confined such as a process vessel breach or adjacent fire to a tritium release are much more common scenarios used in accident analysis*

Regulatory Framework Should Allow Accident Analysis Approaches that can Best Handle Potential Bounding Accident Scenarios

Tritium Processing Accident Scenarios from the Tritium Extraction Facility (TEF)

Fire

Fire in one or more rooms resulting in the release of radioactive material (DU, HTO)

Full facility fire results in release of radioactive material (total Material-at-Risk (MAR) released as HTO)

Explosion

Explosion in Primary confinement (piping, tanks) results in release of tritium

Explosion in Secondary confinement results in release of tritium

Deflagration in transfer line results in release of tritium

Loss of Containment/Confinement

Loss of primary confinement outside glovebox (i.e. in transfer lines) results in release of tritium

Loss of primary confinement and secondary confinement from piping, tanks, and beds (including process piping and stripper beds) results in release of tritium

Breach of underground transfer line results in release of tritium

Tritium Processing Accident Scenarios from the Tritium Extraction Facility (TEF) at SRS

External Events

Vehicle crash results in the release of tritium, with and without fire

Natural Disasters

Seismic event involving all buildings causes a fire that results in release of radioactive material (bounding MAR released as HTO)

Tornado involving all buildings causes a fire that results in release of radioactive material (bounding MAR released as HTO)

- Defining a relevant set of accident scenarios and comparing them with how similar events are evaluated within the DOE/NNSA framework could be helpful in determining the regulation framework
- Fusion bounding tritium processing accidents will need to take into account hazards from other parts of the plant
- Pilot Plant inventory >30 g tritium would make the tritium processing portion of a fusion pilot plant be Hazard Category 2 in the DOE/ NNSA framework

Potential Accident Scenarios for Fusion Device Operation, Tritium Breeding, and Balance-of-Plant

- **Tritium Release During Fusion Machine Operation**

- Tritium inventory in the plasma is likely to be small (<0.1 g of tritium), but Material at Risk (MAR) in that section of the facility is more likely due to inventory of cryogenic pellets or gas used for fueling; tritiated dust (e.g. - W or Be) from the first wall; or other areas of tritium uptake
- For example, an accident scenario for this section could be breach of containment and tritium oxidation ignited by high temperatures in the fusion machine
 - *Unclear if this would be a limiting accident scenario for the overall plant – more evaluation would be needed on a case-by-case basis*
- In the DOE/NNSA framework, a facility containing only the fusion machine would likely be categorized as a radiological facility (<1.6 g tritium), but presence of additional fuel or other tritium containing materials could exceed this limit

- **Tritium Release from the Breeding Blanket**

- Blankets vary in composition (e.g. - molten Pb-Li, ceramics, molten FLiBe) and typically will be at high temperatures
- Blankets will contain tritium derivatives based on their chemistry due to conversion of Li to tritium (e.g. - LiT in Pb-Li or TF in FLiBe)
- Breach of containment of the blanket can lead to:
 - *Release of tritium and conversion to HTO due to high temperatures and presence of moisture/air*
 - *Potential worker hazards due to Pb, Be, fluorides*
- Tritium inventory in the blanket is desired to be maintained low but is likely to be higher than in the fusion machine.
- In the DOE/NNSA framework, a blanket for a 50 MW pilot plant would likely be a Hazard Category 3 facility with respect to tritium (1.6 – 30 g tritium)

- **Tritium Release from Power Cycle or other Tritium Recovery Systems**

- The heat exchanger to the power cycle will likely permeate tritium and can lead to tritium in the power cycle or other parts of the plant where it could be released. (secondary or tertiary loops could mitigate this)

Tritium Form and Handling Hazards to Workers and the Environment

- **DOE/NNSA Framework Incorporates Hazards to Workers and Environment in Addition to Hazards to Public**
 - Tritium fires caused by tritium stored on hydride beds are assumed to have higher impact to workers because of the potential inhalation of metal particles in addition to exposure to tritium
 - DOE-HDBK-1184-2004 and DOE-HDBK-1129 are used in the DOE/NNSA framework to determine doses from insoluble tritium particles
 - DOE-STD-1196-2011 is used for calculating Be dose effects to lungs if applicable from (BeOT or BeT_x) or other applicable Be forms
 - Tritium transport and deposition into the environment is also considered
- **Hazards to Workers in a Commercial Fusion Plant**
 - Tritium transport and permeation is significantly different than movement of solid nuclear materials in a fission plant where releases during maintenance or with permeation, etc. have higher potential to impact workers
 - Toxic components (e.g. - Pb, Be, and F) mixed with tritium from a breach of the blanket and/or neutron multiplier material would likely increase the hazard from the tritium similar to hydride beds
 - Regulation around worker safety should consider both toxic hazards as well as radiological hazards from tritium and other radionuclides
- **Hazards to Environment in a Commercial Fusion Plant**
 - Tritium emissions to the environment can be minimized, but they will not be eliminated.
 - Regulation should consider effects from both the release of tritium (all forms) and toxic materials to the environment

Summary

- Tritium hazards for fusion should be evaluated for: 1) the fusion device, 2) tritium processing, 3) the breeding blanket, and 4) cybersecurity and process control risks as well as tritium safeguards (if deemed necessary)
- Tritium has unique properties when compared with radioisotopes of other elements
- Tritium oxide (HTO) and insoluble tritiated particles have health risks that are 10,000 and ~144,000 times higher than the molecular form (HT), respectively
- Risks from tritiated water make fires where tritium can be oxidized very important accident scenarios that are very often limiting cases
- The regulatory framework for fusion will need to be able to incorporate potential accident scenarios from all parts of the plant
- How regulations are approached for worker protection and environmental protection with OSHA and the EPA should be considered especially with hydride materials and breeding blanket materials
- NNSA/DOE and SRNL/SRS have extensive experience handling tritium at the quantities required for fusion machines and balance of plant systems and can be a resource to the fusion community and NRC

Agenda

Time	Topic	Speaker
1:00 pm	Welcome, Introductions, and Overview	NRC
1:10 pm	NEPA Overview	Don Palmrose
1:20 pm	Agreement States Current Oversight of Fusion R&D Activities	Diego Saenz
1:45 pm	FIA Presentation	Andrew Holland
2:15 pm	Helion Presentation: AEA Common Defense and Security and Application of Materials Framework Tools for Fusion	Michael Hua and Sachin Desai
2:55 pm	Break	
3:10 pm	General Atomics Perspectives	Brian Grierson
3:30 pm	CFS Presentation	Tyler Ellis
3:50 pm	Right-sizing Regulation based on Scale of Fusion Facility Hazards	Patrick White
4:20 pm	Fusion and Tritium Accident Risks and Analysis	Dave Babineau
4:40 pm	Development of Integral Management Scheme for Fusion Radioactive Materials	Laila El-Guebaly
5:00 pm	Opportunity for Public Comment	
5:30 pm	Adjourn	



Development of Integral Management
Scheme for Fusion Radioactive Materials:
Recycling and Clearance, Avoiding Disposal

Laila El-Guebaly

Fusion Technology Institute

University of Wisconsin-Madison

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

**NRC Virtual Public Meeting:
“Developing Options for a Regulatory Framework
for Fusion Energy Systems”**

June 7, 2022



Worldwide Effort to Develop Fusion for Next Generation in 20-40 y

- 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 industries will develop several fusion concepts by 2030 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.)
 - What **other facilities** will be needed between ITER and 1st power plant?

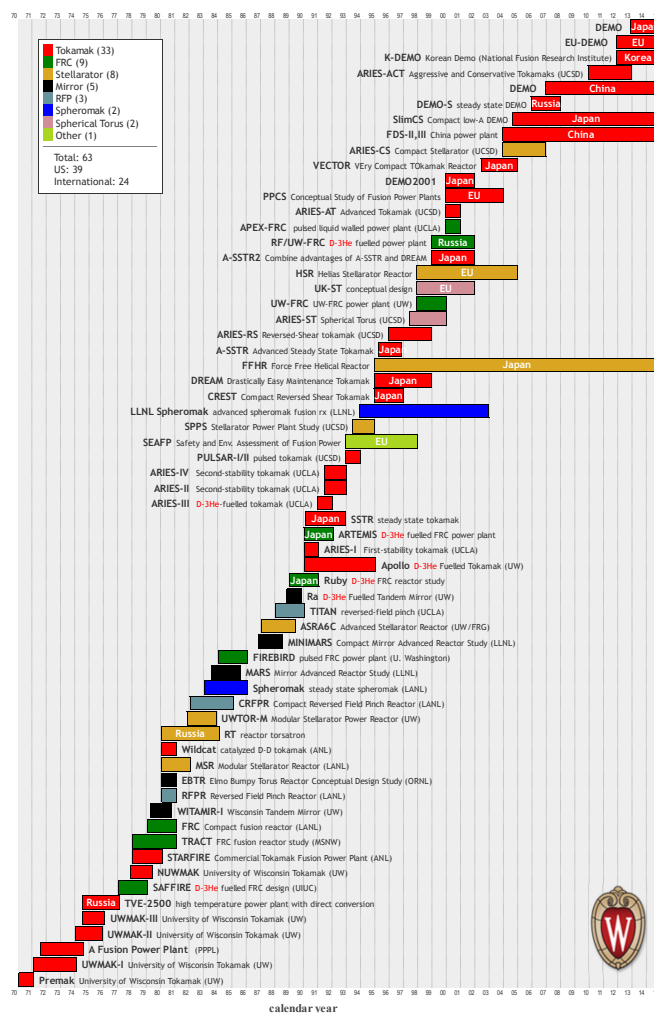
Majority of Fusion designs employing Reduced-activation materials generate low-level waste (under strict alloying element and impurity control), but in large quantity compared to fission.

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



Worldwide Interest in Building Fusion Power Plants by 2050

MFE Power Plant Studies, Worldwide



> 60 conceptual magnetic fusion 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.

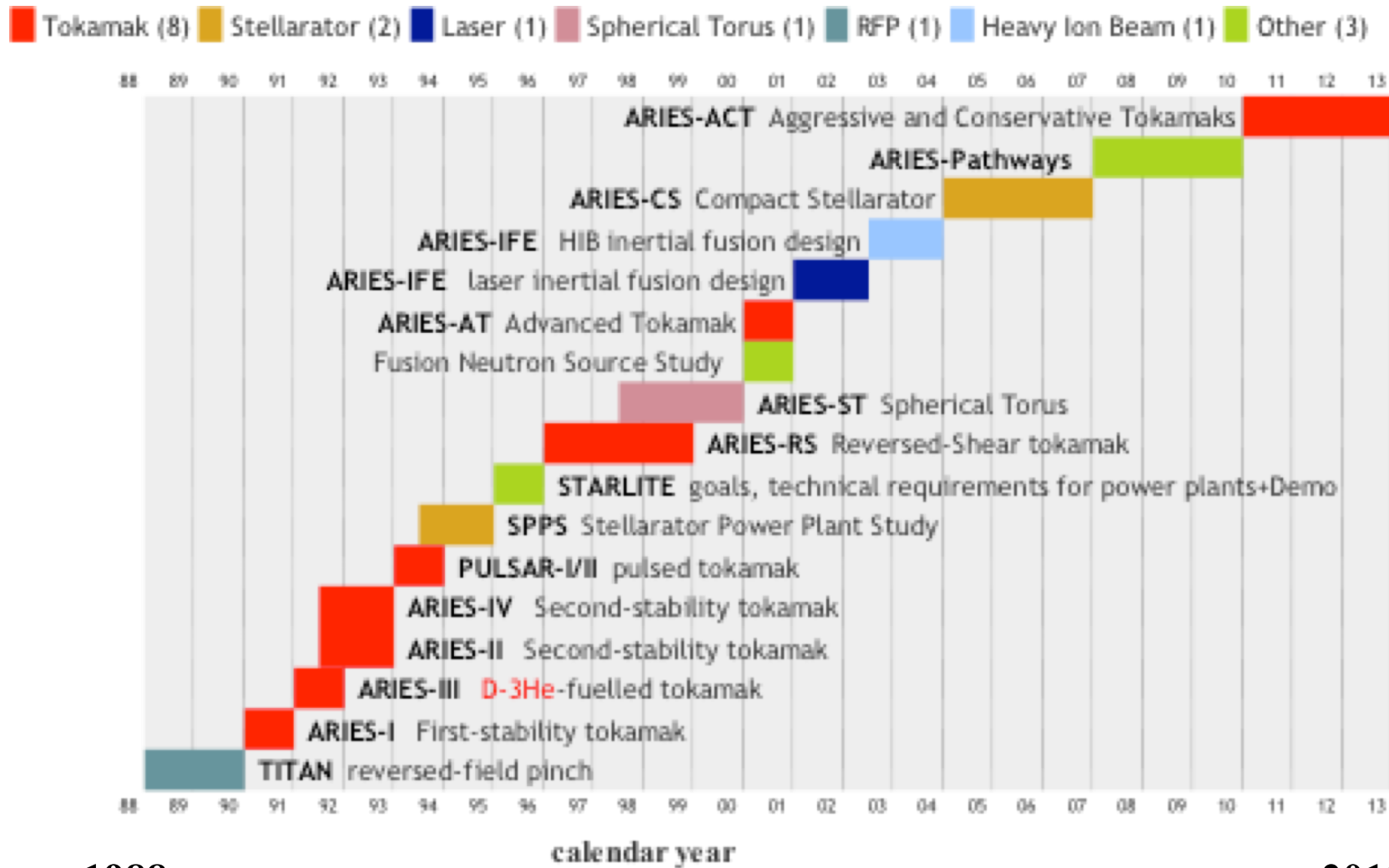
Stress on fusion safety stimulated research on fuel cycles other than D-T, based on ‘advanced’ reactions, such as D-D, D-³He, P-¹¹B, and ³He-³He.

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

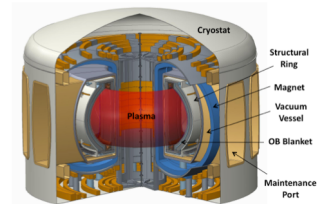
- Without going much into great details, these conceptual designs assess viability of new concepts as economically competitive energy sources, critically evaluate strengths and limitations, and ultimately guide national science and technology R&D programs.



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



ARIES-ACT
Tokamak
(with reduced activation structure)



1988

2013

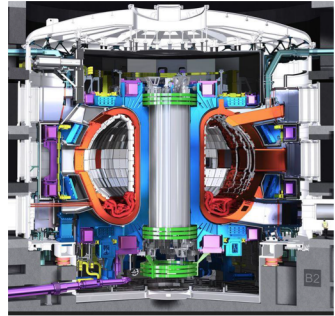
<http://qedfusion.org/aries.shtml>

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

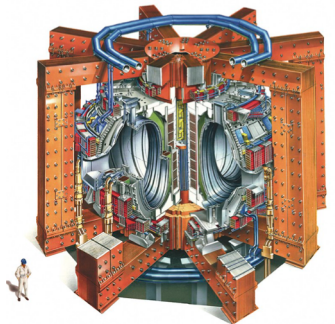


Worldwide Pathways to Fusion Energy

ITER



JET



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

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

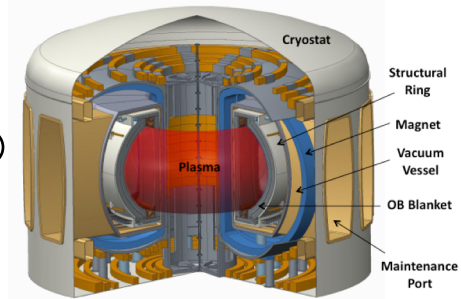
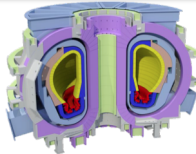
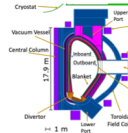
US Pilot
Plant

US-DEMO ?

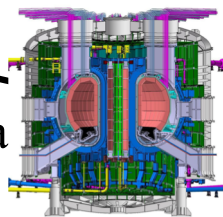
1st Power Plant
by 2050

EU-DEMO

JA-DEMO



China



CFETR
Phase I

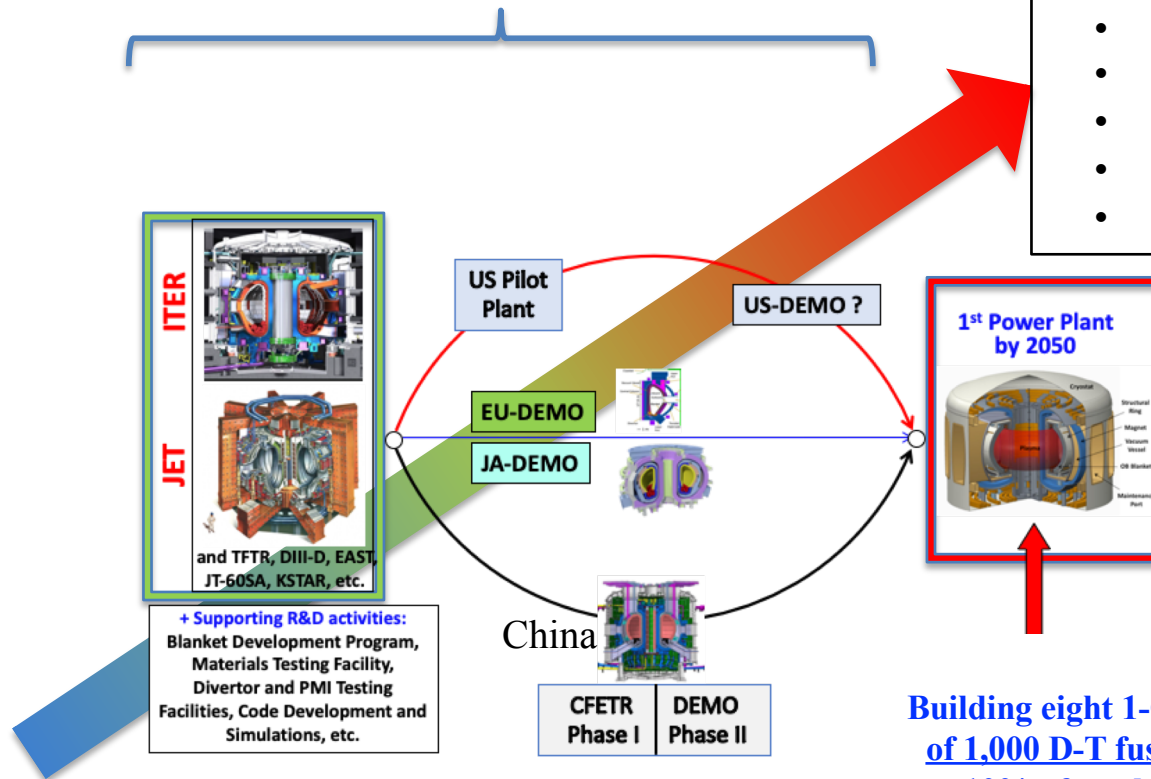
DEMO
Phase II

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 ($\geq 1 \text{ MW/m}^2$)
 - High availability (85%)
 - $> 50 \text{ y}$ lifetime
 - High n fluence ($\geq 20 \text{ MWy/m}^2$)

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)

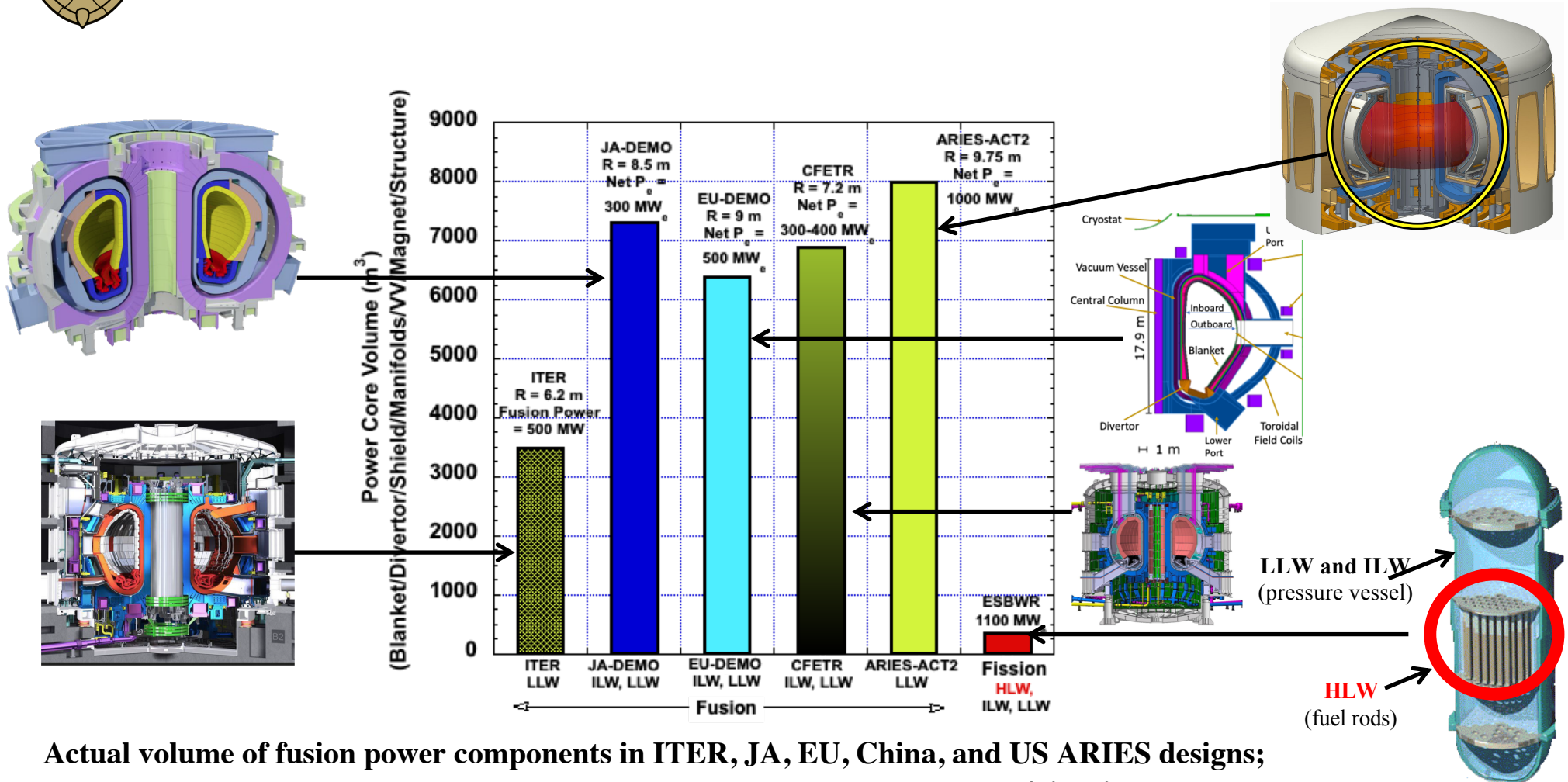
Building eight 1-GW_e fusion plants annually, fleet of 1,000 D-T fusion power plants could provide ~10% of world electricity demand by ~2200. Resources Will Eventually be Limited

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?



Nine Essential Criteria for Attractive Fusion Power Plants Reflect Safety and Environmental Attributes

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 clever design, recycling, and clearance**
 2. **No high-level waste; only Class C low-level waste or better (Class A).**

- Report for National Academy of Sciences (NAS): L. El-Guebaly et al., "Principles, Values, Metrics and Criteria for the Development of Magnetic Fusion Energy," Working Group-1 Report, March 14, 2018.

- 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).



Options for Managing Radioactive Materials

- **Geological “land based” disposal** – default option for fission waste for many nations.
- **Transmutation of long-lived radionuclides**
(\Rightarrow 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).
- **Recycling / reprocessing** (reuse within nuclear industry).
- **Clearance** (release to commercial market if materials are slightly radioactive, containing $10 \mu\text{Sv/y}$ ($< 1\%$ of background radiation)).

Others came and mostly disappeared

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

- **Concerns:**
 - For LLW fusion, 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.
- Land-based disposal has been the preferred U.S. option for LLW from commercial nuclear facilities since 1960s.
- 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.



NRC Classifications of Radwaste

- Radwaste sources: nuclear industries, utilities (from 104 US commercial fission reactors), university research laboratories, manufacturing and food irradiation facilities, hospitals, healthcare companies, and Department of Energy (DOE) facilities.
- Nuclear Regulatory Commission (NRC) 10 C.F.R. Part 61^{*} has specific disposal requirement for each type of waste.
- LLW classified into three classes:
 - Class A is the least hazardous type of waste
 - Class B is more radioactive than Class A
 - Class C waste must meet more rigorous requirements. Intrusion barrier, such as thick concrete slab, is added to waste trenches placed > 8 m deep in ground.

**Most fusion radwaste qualify as Class A or Class C LLW.
Some may qualify as GTCC[#]**

• 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.nrc.gov/waste/llw-disposal/llw-pa/gtcc-transuranic-waste-disposal.html>



Waste Disposal Rating – Metric for Waste Classification

NRC 10 CFR Part 61* classifies the waste at 100 years after shutdown according to its waste disposal rating (WDR), which is the ratio of specific activity (in Ci/m³) 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.

In few fusion designs, there are components with WDR >> 1

Many radionuclides of interest to fusion are not in NRC 10 CFR Part 61

* 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>.



In Early 1990s, Fetter Defined Specific Activity Limits for Majority of Fusion Radionuclides

Fetter's waste disposal limits

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:

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

* 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 fusion-relevant isotopes **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.

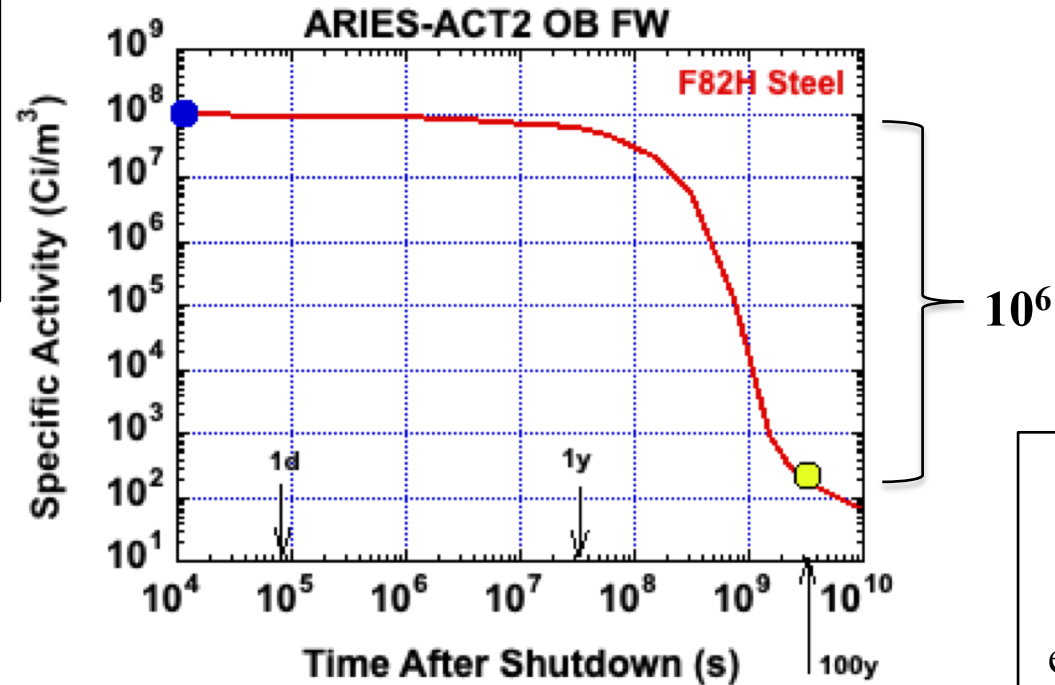


Fusion Radionuclide Profile

@ 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

Interim measures:

All fusion components should meet both NRC and Fetter's limits until NRC develops official guidelines for fusion radwaste.



Missing Fusion Radioisotopes in Both Limits Introduce Uncertainties in WDR Evaluation

	Elements / Radioisotopes @ 100 y after shutdown
Typical RAFM FW of Fusion Designs	38 / 71
NRC 10CFR61 Limits	9 / 11*
Fetter's Limits	39 / 53*

What would be the impact on WDR prediction
of missing fusion radioisotopes in both NRC and Fetter's limit?

* excluding actinides and fission products.



Worldwide Materials Program Developed Reduced-Activation Materials for Fusion Applications

Why?

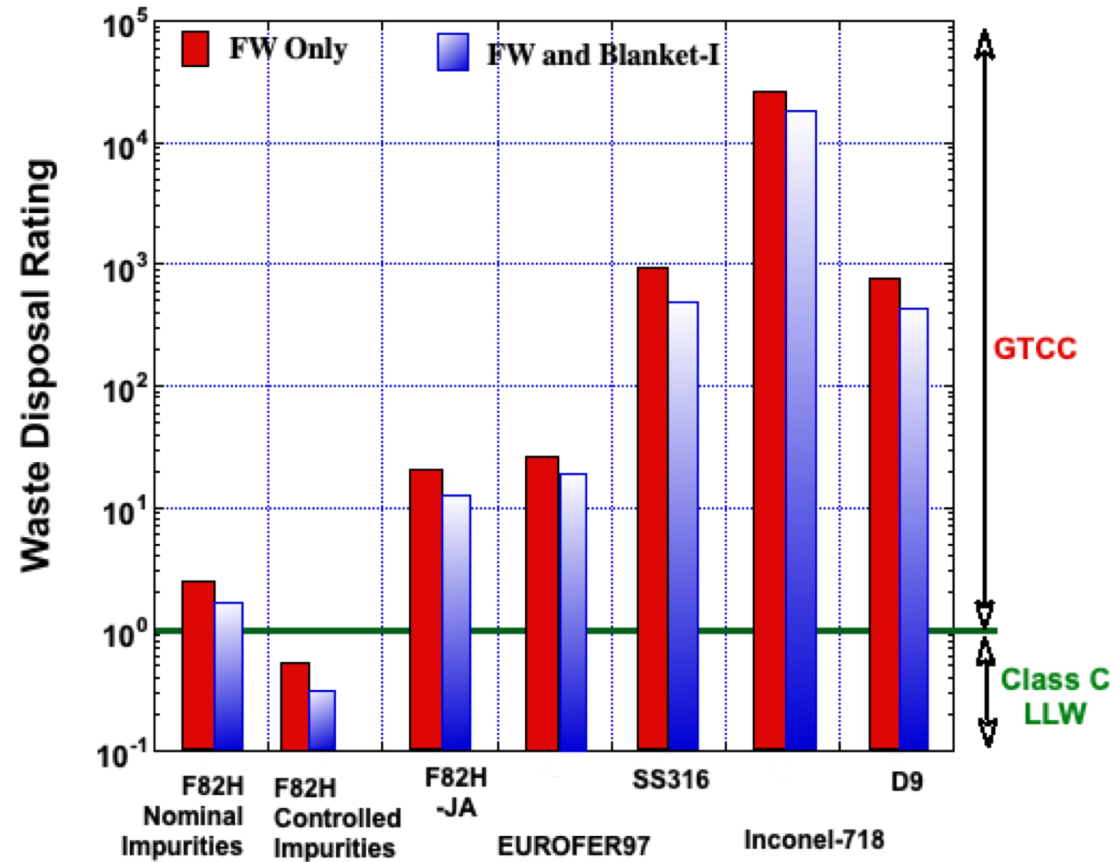
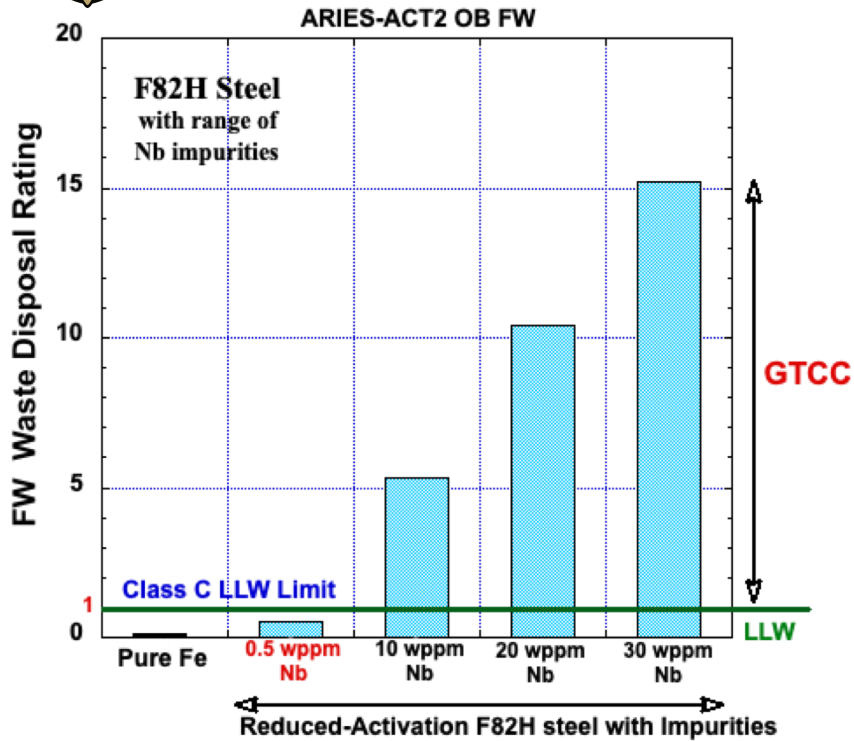
- To qualify fusion radwaste as LLW (with WDR < 1)
- Minimize hazard and release risk
- Allow multiple recycling of radioactive materials before reaching dose limit

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 avoid generating HLW.
- 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



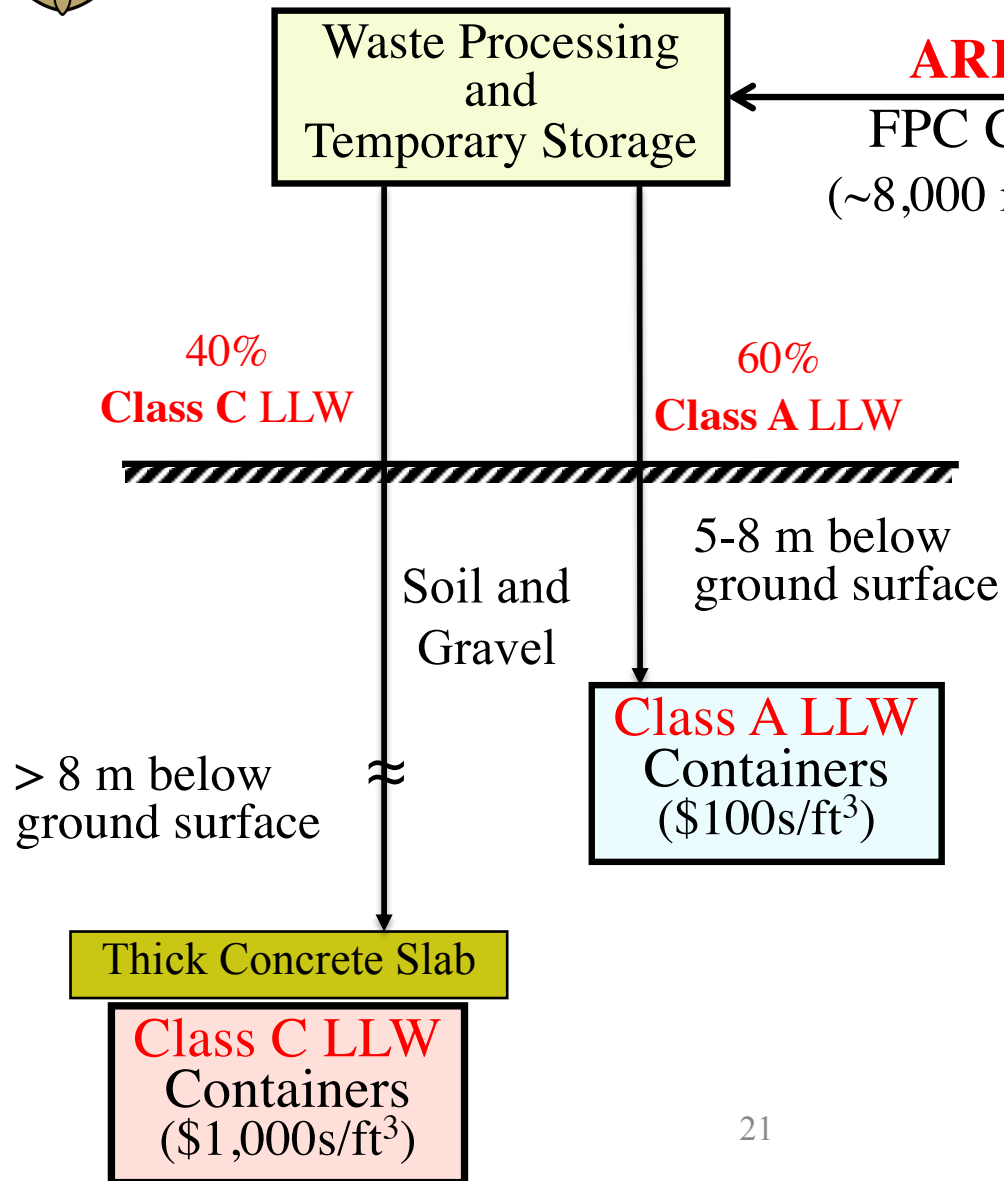
Nb impurity has major impact on WDR

To meet U.S. LLW design requirements:

- 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).

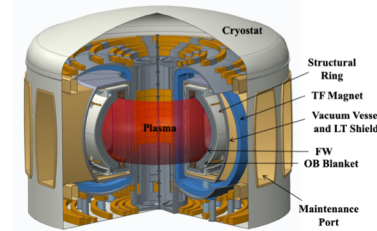


Radwaste of All ARIES Designs Classifies as LLW with Strict Alloying Elements and Impurity Control



ARIES-ACT2

FPC Components#
(~8,000 m³ mostly steel)



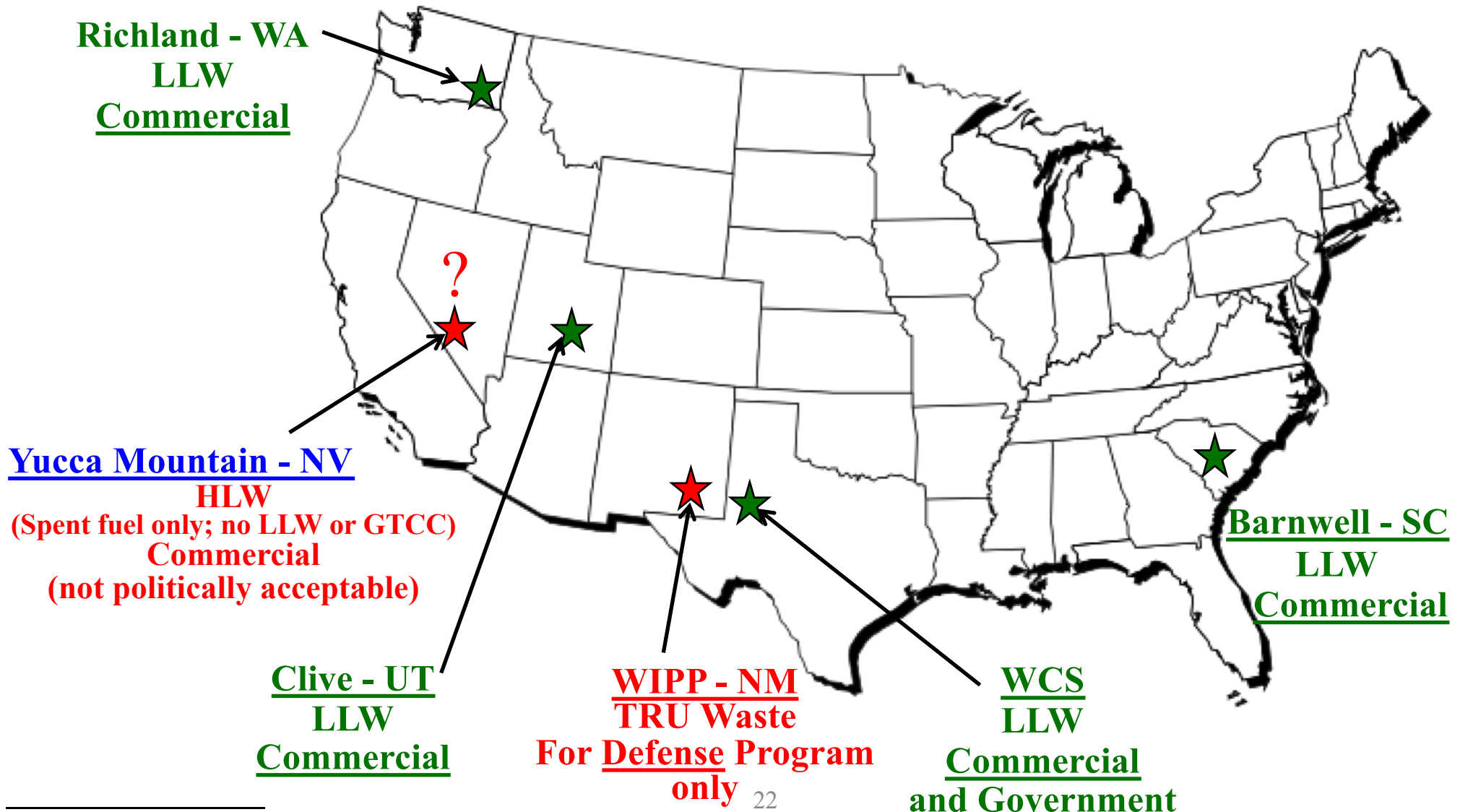
Excluding bioshield and cryostat, balance-of-plant equipment, and external components (e.g., HX, turbines, cooling towers, etc.).

Will be disposed of in commercial LLW repositories.

Where?



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





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 m³ 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 m³ capacity
 - Closure by 2024.
- **Richland facility** in WA:
 - Class A, B, C LLW
 - Supports 11 northwest states
 - 1,700,000 m³ 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 tritiated fusion radwaste

Disposing sizable 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.
 - Develop fusion-specific disposal class and regulations 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 μ Sv/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:*

Hrcir, 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 Chamber Science and Technology*](#)**
 - A waste management strategy focused solely on low activation materials does not address the entirety 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 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* recommends recycling and waste minimization of nuclear waste, stating: “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>

Related references:

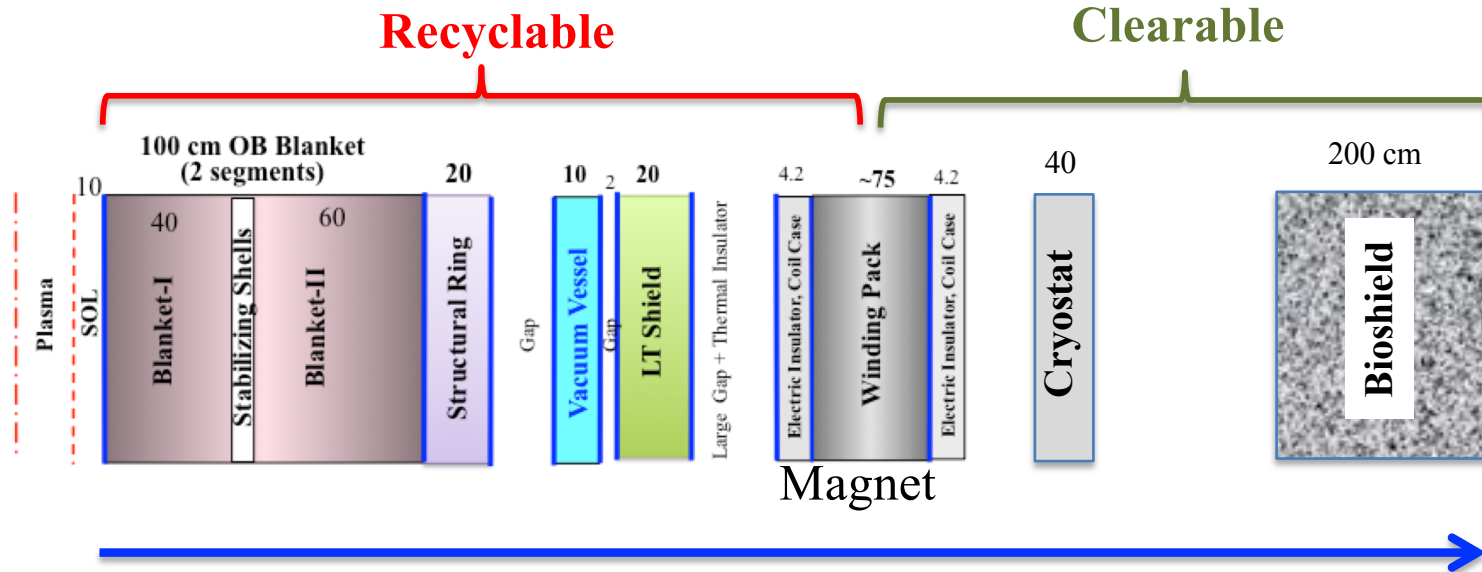
Clearance Levels for Radionuclides in Solid Materials – Application of Exemption Principles, Interim Report IAEA-TECDOC-855, International Atomic Energy Agency, Vienna (1996).

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.

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

Typical Radial Build



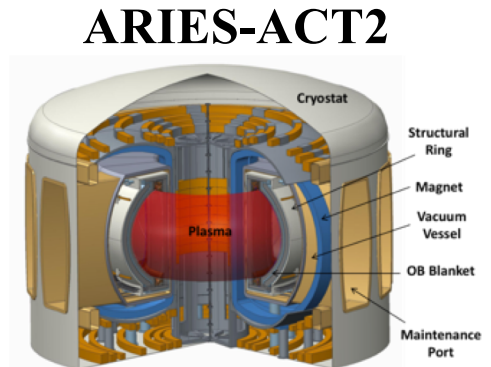
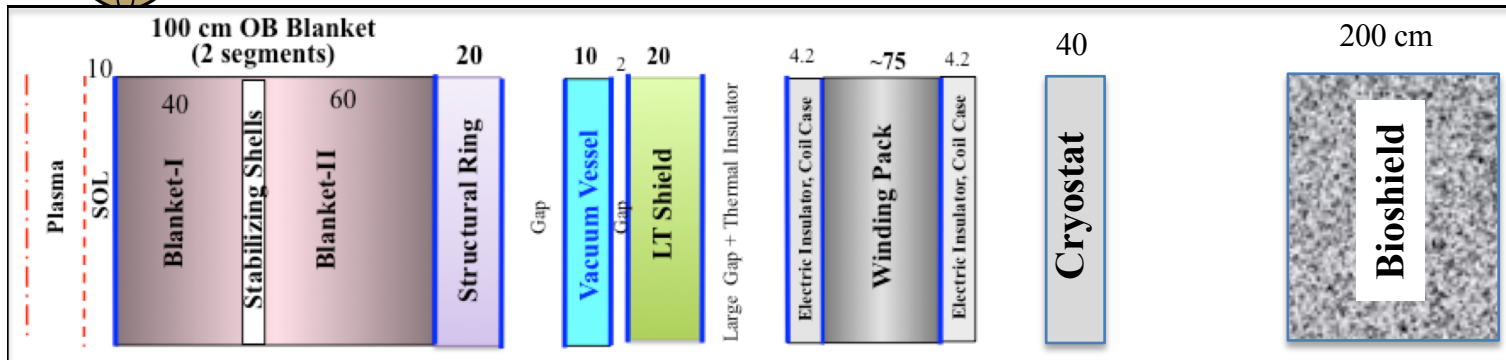
Increasing Clearance Potential

The Recycling Option

- Relatively easy to apply from science perspectives
- DOE guidelines exist
- Applied successfully to decommissioning projects since 2000
- Key issues and needs for fusion.



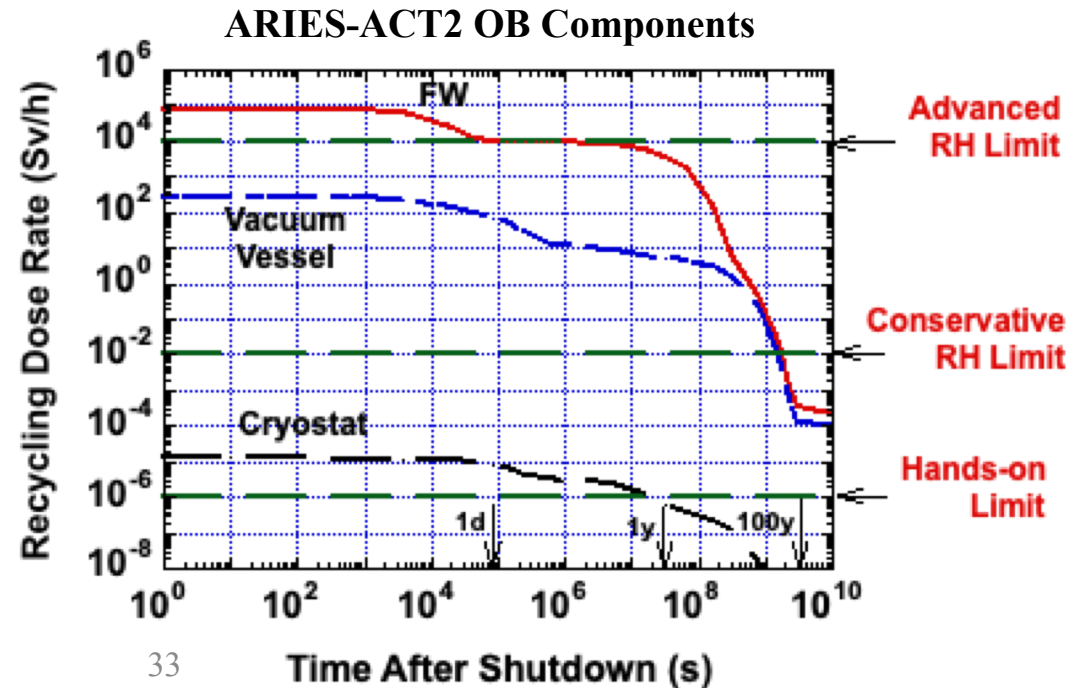
Recycling Example: ARIES-ACT2 OB Components (FW - Bioshield)



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.





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.



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. Strykowski, 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 them as shield for diagnostics used on NSTXU.
 - ~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 m³) either recyclable or suitable for clearance
 - ~1,000 m³ 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).

The Clearance Option

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

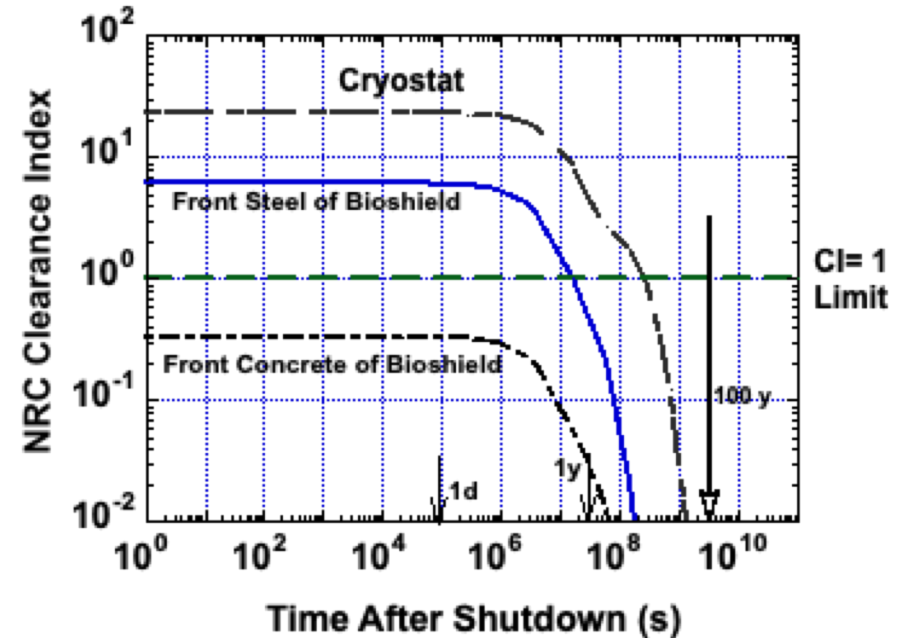
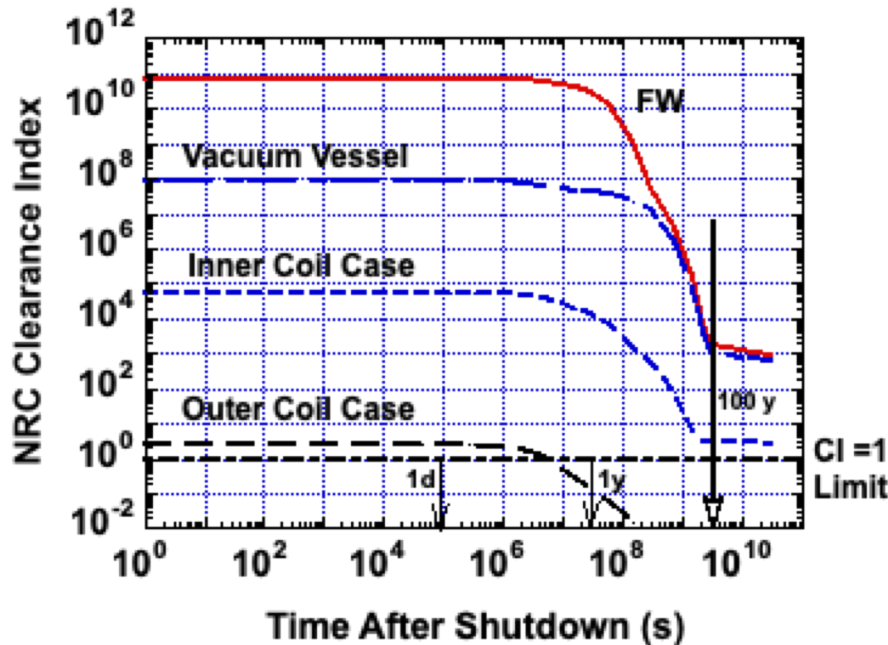
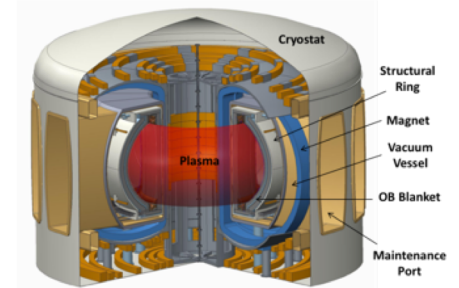
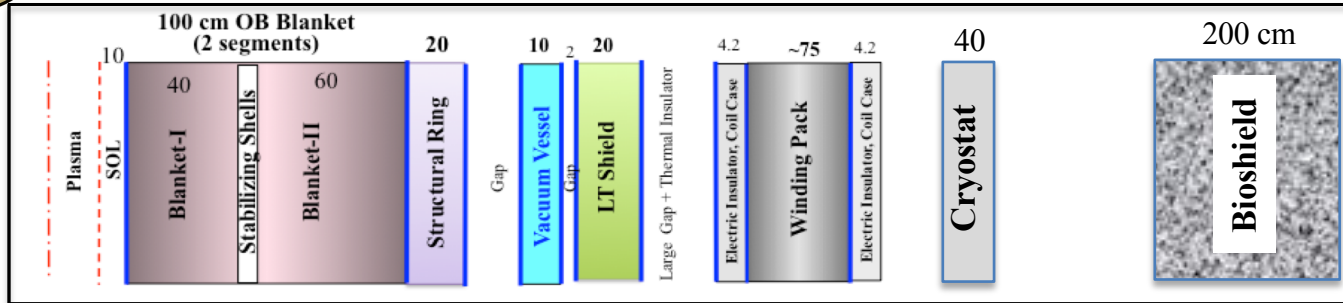
• Anigstein, R. et al., “Radiological Assessments for Clearance of Materials from Nuclear Facilities,” volume 1, NUREG-1640, US Nuclear Regulatory Commission, June 2003. Available at: <http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/>.

• # 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 Example: ARIES-ACT2 Outboard Components

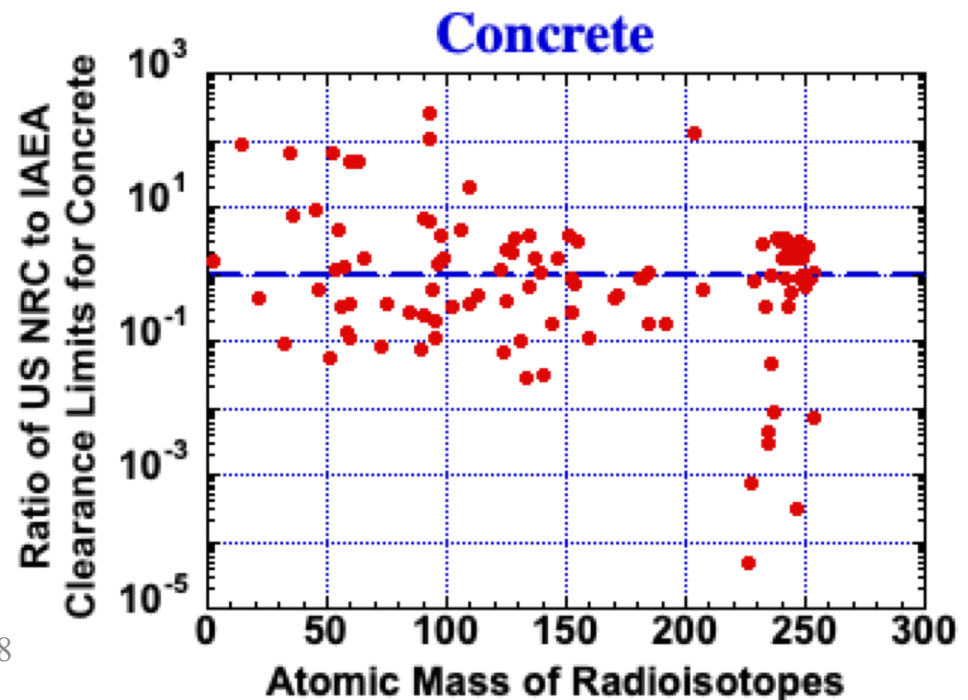
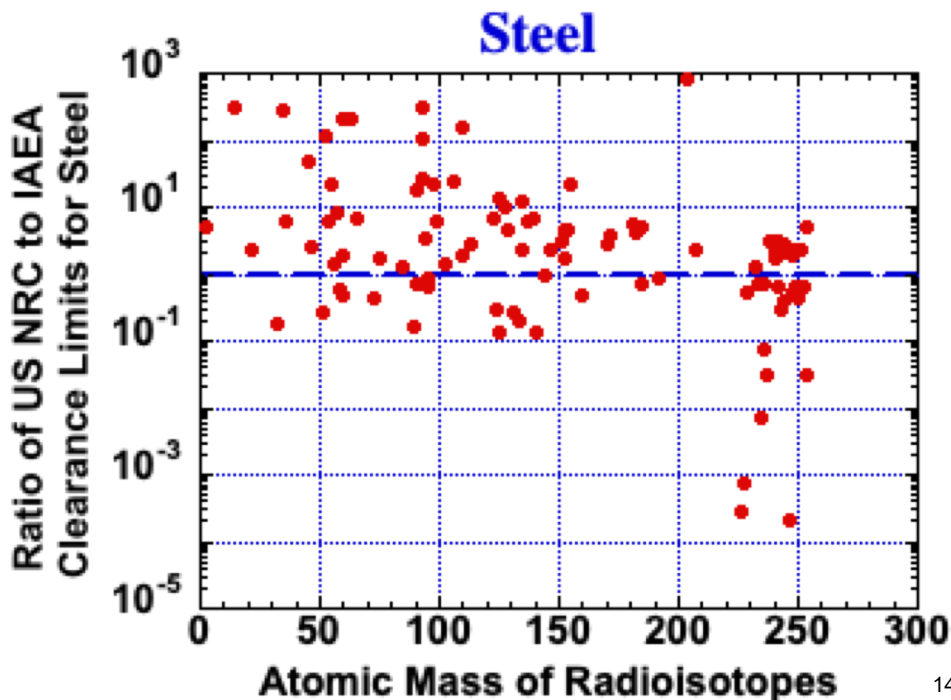


Cryostat, Bioshield, and some magnet constituents are clearable in ~20 y after decommissioning



Clearance Concerns

- All CI evaluations lack numerous fusion-relevant radioisotopes that introduce uncertainties in CI prediction of fusion components.
- Discrepancies between clearance standards that could impact CI evaluation and storage period.
- Future efforts by NRC, IAEA and others to harmonize the clearance standards 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 , $^{91,92}\text{Nb}$, ^{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 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.



Example of Integral 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 m³ 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 (D&R 2010), Idaho Falls, Idaho, August 29-September 2, 2010, American Nuclear Society.*

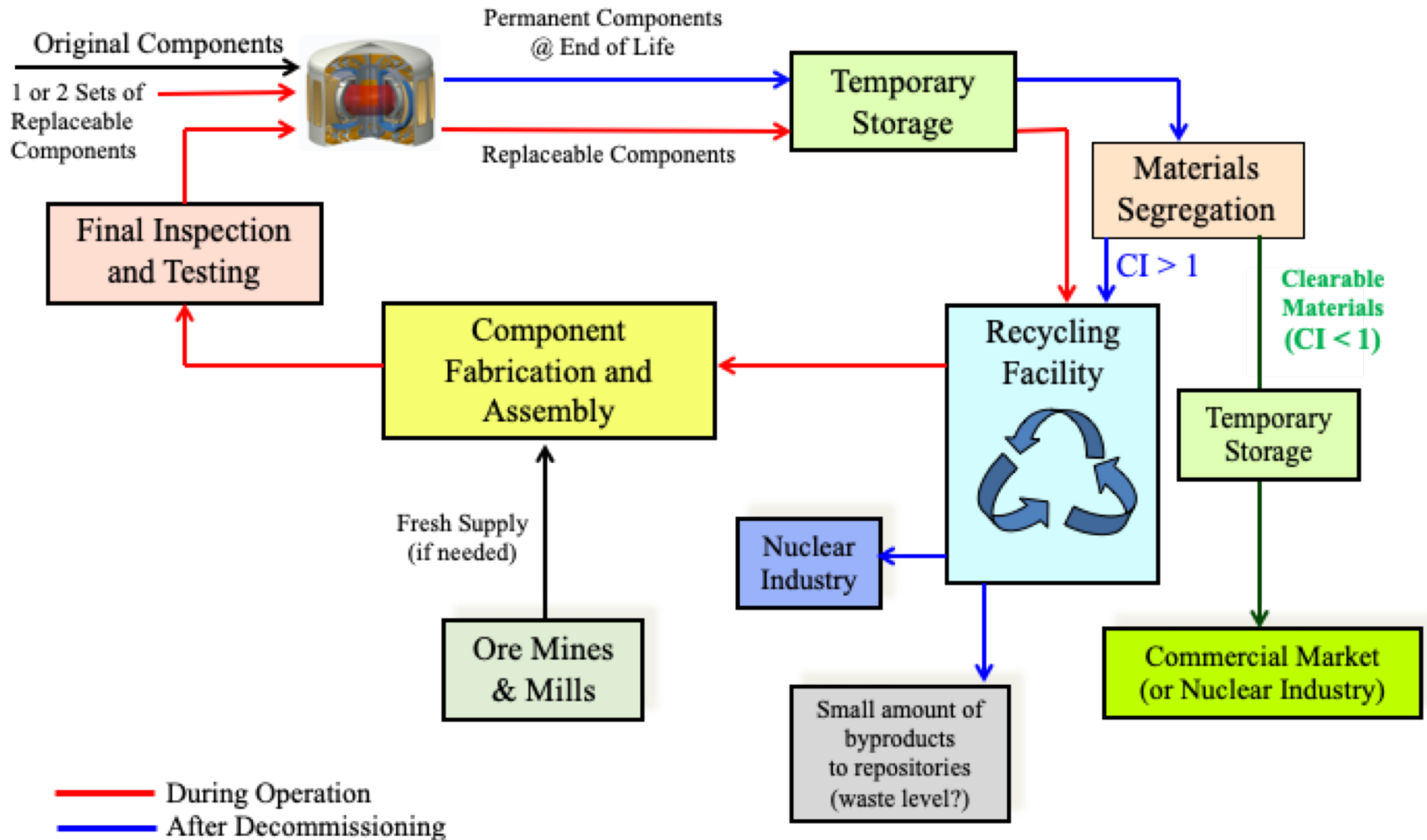


Conclusions

- 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 develop fusion-specific category for LLW and GTCC remaining waste after recycling/clearance.
- **Fusion designers should:**
 - Integrate the recycling and clearance approaches at early stages of fusion designs
 - Involve industries and address issues/needs for recycling and 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.



Flow Diagram for Fusion Decommissioning



Publications



ARIES Fusion-Related RWM Publications

- L. El-Guebaly, D. Henderson, A. Abdou, and P. Wilson, “Clearance Issues for Advanced Fusion Power Plants”, *Fusion Technology*, 39, No. 2, 986-990 (2001).
- 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).
- L. El-Guebaly, P. Wilson, and D. Paige, “Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants,” *Fusion Science and Technology*, 49, 62-73 (2006).
- L. El-Guebaly, “Environmental Aspects of Recent Trend in Managing Fusion Radwaste: Recycling and Clearance, Avoiding Disposal.” *Proceedings of 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology*, June 20 - 22, 2007, Vienna, Austria, IAEA-TM-32812. Published by IAEA on CD - ISBN: 978-92-0-159508-9.
- L. El-Guebaly, P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky, T. Tautges et al., “Designing ARIES-CS Compact Radial Build and Nuclear System: Neutronics, Shielding, and Activation,” *Fusion Science and Technology* 54, No. 3 (2008) 747-770.
- 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.
- L. El-Guebaly, R. Kurtz, M. Rieth, H. Kurishita, A. Robinson, “W-Based Alloys for Advanced Divertor Designs: Options and Environmental Impact of State-of-the-Art Alloys.” *Fusion Science and Technology* 60, Number 1 (2011) 185-189.
- L. El-Guebaly, T. Huhn, A. Rowcliffe, S. Malang, and the ARIES-ACT Team, “Design Challenges and Activation Concerns for ARIES Vacuum Vessel,” *Fusion Science and Technology* 64, no. 3 (2013) 449-454.
- 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.
- Laila El-Guebaly, “Overview of ARIES Nuclear Assessments: Neutronics, Shielding, and Activation,” *Progress in Nuclear Science and Technology* 4, 118-121 (2014). DOI: 10.15669
- 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.
- 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.
- 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 (Nov 2018).



IEA Fusion-Related RWM Publications

(U.S., EU, RF, China, S. Korea)

- L. El-Guebaly, R. Pampin, and M. Zucchetti, “Clearance Considerations for Slightly-Irradiated Components of Fusion Power Plants.” *Nuclear Fusion* 47 (2007) 480-484.
- M. Zucchetti, L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, and K. Tobita, “The Feasibility of Recycling and Clearance of Active Materials from a Fusion Power Plant,” *Journal of Nuclear Materials* 367-370 (August 2007) 1355-1360.
- M. Zucchetti, L. Di Pace, L. El-Guebaly, B.N. Kolbasov, V. Massaut, R. Pampin, and P. Wilson, “An Integrated Approach to the Back-end of the Fusion Materials Cycle.” *Fusion Engineering and Design* 83, Issues 10-12 (2008) 1706-1709.
- 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.
- M. Zucchetti, L. Di Pace, L. El-Guebaly, B.N. Kolbasov, V. Massaut, R. Pampin, and P. Wilson, “The Back End of the Fusion Materials Cycle.” *Fusion Science and Technology* 52, No. 2 (2009) 109-139.
- M. Zucchetti, L. Di Pace, L. El-Guebaly, B.N. Kolbasov, V. Massaut, R. Pampin, and P. Wilson, “The Back-End of Fusion Materials Cycle: Recycling and Clearance, Avoiding Disposal.” *Fusion Science and Technology* 56, Number 2 (2009) 781-788.
- Luigi Di Pace, Laila El-Guebaly, Boris Kolbasov, Vincent Massaut and Massimo Zucchetti, “Radioactive Waste Management of Fusion Power Plants,” Chapter 14 in Book: *Radioactive Waste*. Dr. Rehab Abdel Rahman (Ed.). InTech Open Access Publisher, Rijeka, Croatia. ISBN: 978-953-51-0551-0, InTech (April 2012). Available at <http://www.intechopen.com/books/radioactive-waste/radioactive-waste-management-of-fusion-power-plants>
- M. Zucchetti, L. Di Pace, L. El-Guebaly, J.-H. Han, B. N. Kolbasov, V. Massaut, Y. Someya, K. Tobita, and M. Desecures, “Recent Advances in Fusion Radioactive Material Studies,” *Fusion Engineering and Design*, 88, Issues 6-8 (2013) 652-656.
- Boris Kolbasov, Laila El-Guebaly, Vladimir Khripunov, Youji Someya, Kenji Tobita, Massimo Zucchetti, “Some Technological Problems of Fusion Materials Management,” *Fusion Engineering and Design*, 89 (2014) 2013-2017.
- 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.
- M. Zucchetti, Z. Chang, L. El-Guebaly, J.-H. Han, B. Kolbasov, V. Khripunov, M. Riva, Y. Someya, R. Testoni, K. Tobita, “Radioactive Waste Studies in the Frame of the IEA Cooperative Program on the Environmental, Safety and Economic Aspects of Fusion Power.” *Fusion Science and Technology*, 72 (4) (2017) 609-615.
- M. Zucchetti, Z. Chen, L. El-Guebaly, V. Khripunov, B. Kolbasov, D. Maisonnier, Y. Someya, M. Subbotin, R. Testoni, and K. Tobita, “Progress in International Radioactive Fusion Waste Studies,” *Fusion Science and Technology*, Vol 75, #5, 391-398 (2019).



EU, UK, China, RF Fusion-Related RWM Publications

• UK and Europe:

- L. Di Pace, A. Natalizio, Preliminary analysis of waste recycling scenarios for future fusion power plants, Fusion Engineering and Design, Vol. 69, pp. 775 – 779 (2003).
- 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.
- Luigi Di Pace, Teresa Beone, Antonello Di Donato, Patrizia Miceli, Franco Macci, Roberto Piancaldini, Egidio Zanin, “Feasibility Studies of DEMO Potential Waste Recycling by Proven Existing Industrial-Scale Processes,” Fusion Engineering and Design 146 (2019) 107-110.
- Luigi Di Pace, Teresa Beone, Antonello Di Donato, Alessandro Astri, Alessandro Colaneri, Angelo Cea, Daphne Mirabile, Ali Gökhan Demir, “DEMO radioactive wastes: decarburization, recycling and reuse by additive manufacturing,” Fusion Engineering and Design, Volume 168, July 2022 Luigi Di Pace et al., “Suitable Recycling Techniques for DEMO Activated Metals.” IAEA TECDOC on Fusion RWM. To be published. .
- Teresa Beone et al., “Application of Powder Metallurgy and Additive Manufacturing to Refabrication of DEMO Components/structures.” IAEA TECDOC on Fusion RWM. To be published in 2023.
- Luigi Di Pace, Teresa Beone, Patrizia Miceli, Antonello Di Donato, Franco Macci, Egidio Zanin, “Fusion specific approach and critical aspects in suitable industrial-scale processes and techniques for radioactive waste management of nuclear fusion power activated materials.” Presented at 9th European Commission conference on Euratom research and training in radioactive waste management FISA 2019 - EURADWASTE '19, Pitesti, Romania. Conference proceedings: <https://op.europa.eu/en/publication-detail/-/publication/fe1b968b-cbc8-11ea-adf7-01aa75ed71a1/language-en/format-PDF/source-140505052>

• China:

- Q. Cao et al., “Preliminary Radwaste Assessment, Classification and Management Strategy for CFETR.” IAEA TECDOC on Fusion RWM. To be published in 2023.
- X. Zhang et al., “Activation Analysis and Radwaste Assessment of CFETR,” submitted for publication in Fusion Engineering and Design.

• Russian Federation:

- 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.
- S.A. Bartenev, B.N. Kolbasov, E.N. Li, P.V. Romanov, V.N. Romanovskij, N.G. Firsin. “An improved procedure for radiochemical processing of activated fusion-reactor-relevant V-Cr-Ti alloy.” Fusion Engineering and Design, v. 84, issues 2-6 (2009) 427-429.



IAEA Fusion-Related RWM Publications

Just published:

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

Sehila M. Gonzalez de Vicente, Nicholas A. Smith, Laila El-Guebaly et al.

Nuclear Fusion **62** 085001 (2022) <https://doi.org/10.1088/1741-4326/ac62f7>

To be published in 2023:

IAEA TECDOC: Radioactive Waste Management for Fusion Facilities (tentative title).

40 attendees from 11 countries submitted 26 Papers at “First IAEA Workshop on Radioactive Waste Management for Fusion Facilities.” October 6-8, 2021, Vienna, AT.

Agenda

Time	Topic	Speaker
1:00 pm	Welcome, Introductions, and Overview	NRC
1:10 pm	NEPA Overview	Don Palmrose
1:20 pm	Agreement States Current Oversight of Fusion R&D Activities	Diego Saenz
1:45 pm	FIA Presentation	Andrew Holland
2:15 pm	Helion Presentation: AEA Common Defense and Security and Application of Materials Framework Tools for Fusion	Michael Hua and Sachin Desai
2:55 pm	Break	
3:10 pm	General Atomics Perspectives	Brian Grierson
3:30 pm	CFS Presentation	Tyler Ellis
3:50 pm	Right-sizing Regulation based on Scale of Fusion Facility Hazards	Patrick White
4:20 pm	Fusion and Tritium Accident Risks and Analysis	Dave Babineau
4:40 pm	Development of Integral Management Scheme for Fusion Radioactive Materials	Laila El-Guebaly
5:00 pm	Opportunity for Public Comment	
5:30 pm	Adjourn	

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Opportunity for Public Comment

A blurred background image showing several people in a meeting room. One person in the center is pointing towards a screen or whiteboard. The scene is brightly lit, possibly by a window on the right side.

Thank You!