Developing a Regulatory Framework for Fusion Energy Systems

NRC Public Meeting
June 7, 2022

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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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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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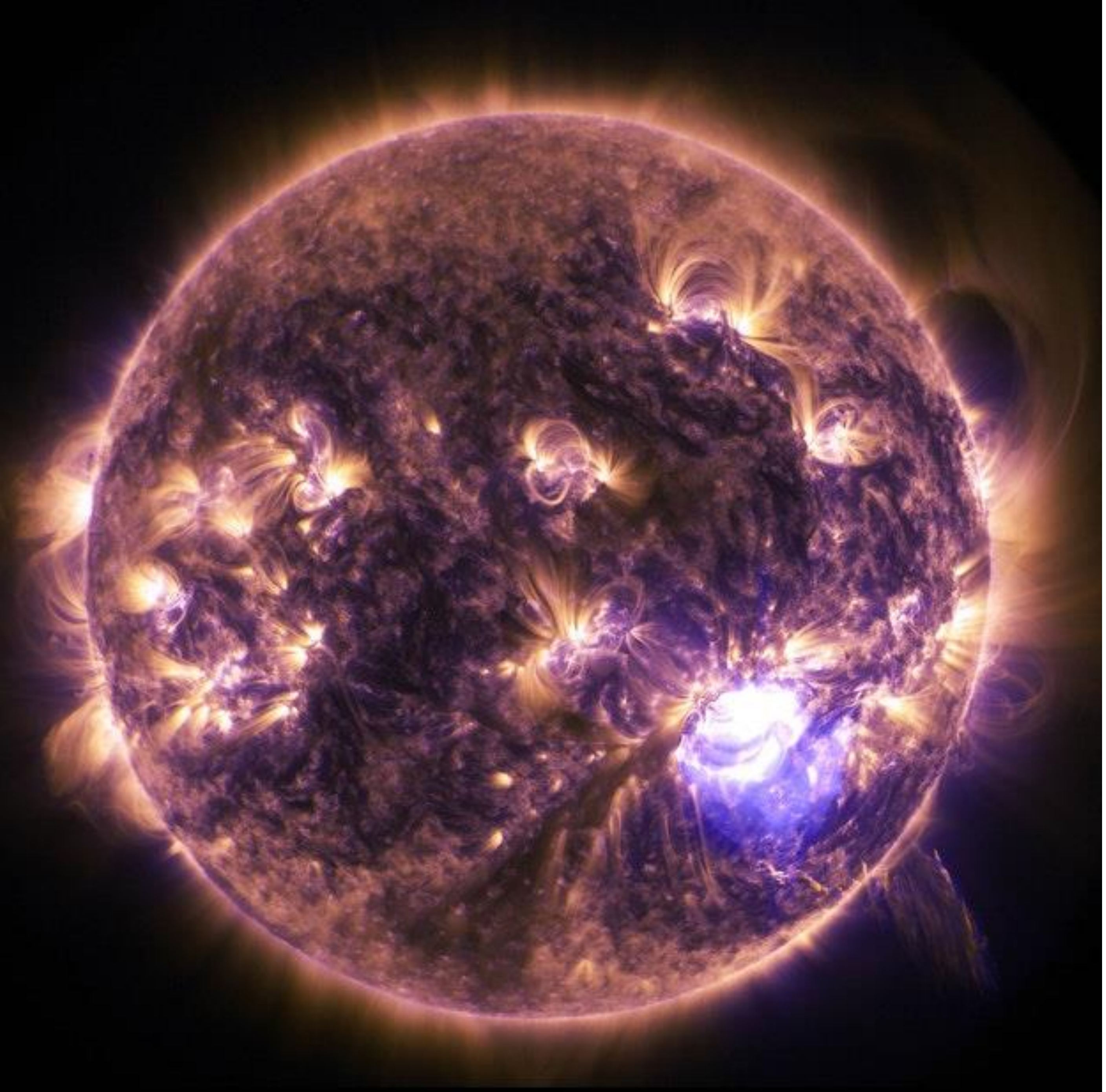


OVERSIGHT OF RESEARCH AND DEVELOPMENT ACTIVITIES

REGULATING CURRENT ACTIVITIES WITH EXISTING FRAMEWORK

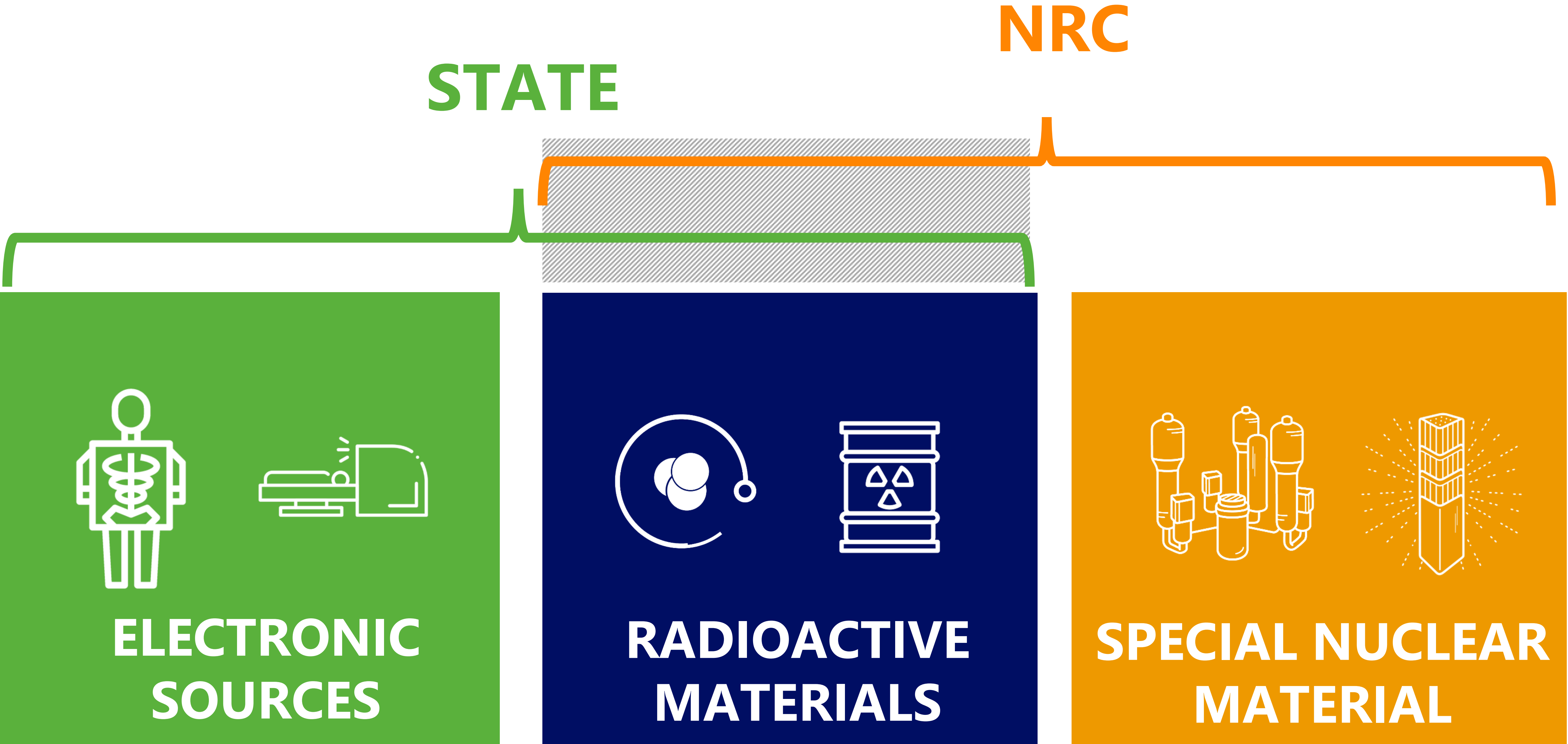
Agreement State Representative to Fusion Energy Systems Working Group

DIEGO SAENZ
Nuclear Engineer
diego.saenz@wi.gov

TODAY'S AGENDA

- Current Regulations
- Currently Licensed
- Near-term Licensing
- Long-term Licensing
- Questions

CURRENT FRAMEWORK



NRC

STATE

ELECTRONIC SOURCES

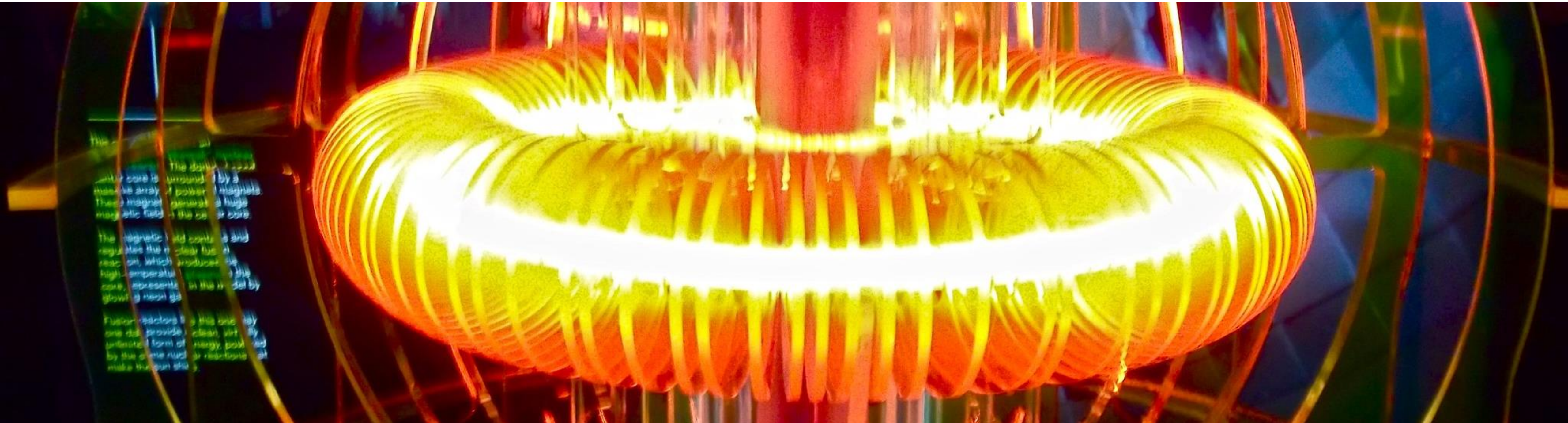
RADIOACTIVE MATERIALS

SPECIAL NUCLEAR MATERIAL

CURRENTLY LICENSED

Fusion Devices (non-energy)

Radioactive Materials (tritium and activation products)



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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ASSOCIATION

The Voice of a new Industry

The Fusion Industry Association is an international coalition of companies working to electrify the world with fusion - the unparalleled power of the stars. Energy from fusion will provide clean power for everyone that's safe, affordable, and limitless.

FIA Membership

FUSION
INDUSTRY
ASSOCIATION

Commonwealth
Fusion Systems

generalfusion®

tae TECHNOLOGIES

first light

tokamak
energy
a faster way to fusion

ZAP ENERGY™

HELION

HB11
ENERGY
LASER BORON FUSION

AVALANCHE

TYPE ONE
ENERGY

LPP FUSION

FOCUSED
ENERGY

MIFTI

SHINE™

MarvelFusion

Xcimer
Energy
Company

CTFusion
As Brilliant as the Sun

Electric
Fusion
Systems

RENAISSANCE
FUSION

HelicitySpace

HYPERJET
FUSION CORP

Helical Fusion

HORNE
TECHNOLOGIES

NK

PrincetonSATELLITE
SYSTEMS

nearstar
FUSION

EX-Fusion

Key Scoping Questions

1) What is the scope of commercial fusion energy systems being considered, including common and unique operating characteristics and hazards?
2) How should we define commercial fusion energy systems? How does this relate to treatment of accelerators?
3) What are the research and development plans for commercial fusion energy systems?
4) What do commercial fusion energy stakeholders consider to be most appropriate regulatory framework?

1. Scope of Commercial Fusion Plants in the US

FIA Members will be the first – and likely only – to market.

Among FIA Members, there is no “generic” fusion power plant, but some common features

- Fusion fuel inventory in all fusion systems at any time is very small, and cannot be arbitrarily increased without system shutting off.
- **Zero** usage of special nuclear materials (i.e. uranium, plutonium) in fusion energy systems.
- New fusion fuel must be added and fusion products removed to maintain power production, otherwise fusion power shuts off
- All fusion approaches can only fuse a small amount of fusion fuel in the plasma at any time, otherwise fusion power shuts off
- All plans are for smaller than existing nuclear fission fleet (~1GWe) and smaller than international government plans for DEMO. No FIA member plans for devices greater than about 350 Mwe – some much smaller.
- None will require active cooling after shutdown

From a risk-informed perspective, all of the conceived fusion reaction types or fuel choices present risks that can be appropriately regulated under Part 30 regulations

1a. Scope of Hazards for Commercial Fusion Energy

- Fusion systems have zero usage of special nuclear materials, and fusion is not a nuclear chain reaction
- Normal fusion operations can produce neutrons and gamma rays, which can be effectively shielded using currently in-use materials including concrete, water, and metal hydrides
- Off-normal events result in automatic shutdown of fusion reactions, and cannot lead to a meltdown
- Tritium releases in credible fusion device accidents are below the annual dose limit to the public of 100 mrem, and in all scenarios are below emergency planning threshold of 1000 mrem
- Refined dust analyses are underway by FIA members, but contribution to offsite impact is expected to be low compared to tritium
- The offsite impacts are akin to those of byproduct materials licensees, not of fission reactors that use special nuclear materials and are based on nuclear chain reactions
- Offsite impact risk for fusion is low relative to utilization facilities and do not support a design basis/beyond design basis construction

See FIA Presentation to NRC Meeting, March 23, 2022:
https://www.nrc.gov/docs/ML2208/ML22081A057.pdf

2. How should we define commercial fusion energy systems?

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- **Technical case leads the way**
- **Fusion MUST BE defined separately from fission**
  - Even though both technologies are intended to produce electricity, fusion devices and fission reactors **share no common risks** or radiological hazards
  - Fusion devices do not use or produce special nuclear material, high level waste, or spent nuclear fuel, and cannot have a criticality event
  - Fusion devices fundamentally are not utilization facilities
- **Materials Framework (Part 30) is the appropriate regulatory framework for fusion devices**
  - Fusion devices have much more in common with devices such as accelerators and cyclotrons, which are appropriately regulated under Part 30
  - Although no developers are planning large facilities, even very large fusion facilities would be most appropriately managed under Part 30, rather than being subject to utilization facility requirements
  - Part 30 already contains risk-informed “grades” of regulation that can be applied to specific facilities based on a variety of factors

3. What are the research and development plans for commercial fusion energy systems?

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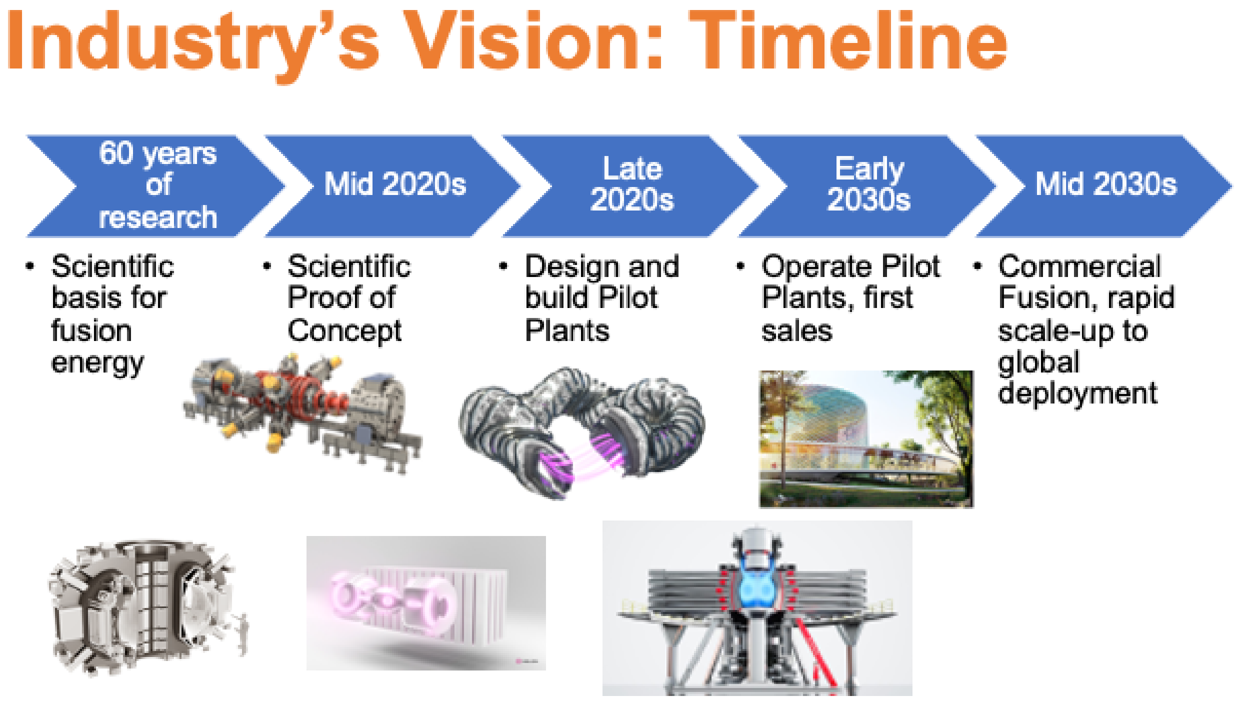
There is a common development timeline, defined by acceleration.

FIA Members are moving into fusion pilot plants by the late 2020s, and commercial pilot plants in a decade.

- FIA members are moving at an accelerated rate, relevant to the "Bold Decadal Vision to Accelerate Fusion Energy" announced at a White House summit on March 17.
- FIA members anticipate applying for a commercial operation license as early as 2026, with more coming 2027-2030



Industry's Vision: Timeline

60 years of research	Mid 2020s	Late 2020s	Early 2030s	Mid 2030s
Scientific basis for fusion energy	Scientific Proof of Concept	Design and build Pilot Plants	Operate Pilot Plants, first sales	Commercial Fusion, rapid scale-up to global deployment

4. Legal Considerations for Fusion Regulation

Credit:

The Honorable Jeffrey S. Merrifield & Sidney L. Fowler,

Pillsbury Winthrop Shaw Pittman LLP

Overview

- Legal framework for fusion regulation will significantly impact the US fusion industry and the NRC

- Technical case must lead the way
  - FIA and fusion developers want fusion to be safe
    - Safety is one the biggest reasons people are excited about fusion!
  - A regulatory framework should ensure public trust and confidence

- Regulatory certainty paves the way for investment and development.

Overview

Framework for fusion should fit the NRC’s existing legal authority

- How does the Atomic Energy Act (AEA) play a role in fusion regulation and what restrictions does the AEA impose on the NRC’s choice of regulatory structure?
    - AEA does not provide clear guidance (fusion never mentioned in statute)
    - Any legislative history predates the commercial fusion industry by decades
- **AEA provides sufficient authority to allow the Commission discretion for how it chooses to regulate fusion**
    - The Commission has very broad discretion to interpret the AEA to ensure adequate protection of public health and safety
    - The Commission is the sole authority to determine when a facility that does not use Special Nuclear Materials is classified as a utilization facility
- **Statutory clarifications could be helpful but are not needed**

Background

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- **Two legal frameworks:** Materials (Part 30) versus Utilization Facility
  - Key differences: criticality, special nuclear material

- **Materials by far, is the larger of the two frameworks**
  - 10,000 licensees
  - Most flexible
  - Focuses on material inventory and radiation itself as source of concerns

- **Utilization facility is targeted to one type of system, where high risk is based on unique nature of controlled criticality and/or usage of special nuclear material**

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Background

- **Three options have been discussed**: Utilization Facility, “Hybrid”, Part 30/Materials
- **FIA supports a Part 30 approach**
    - Most appropriate for fusion hazards
    - Fully protective of public health, safety and the environment
    - Maintains US competitiveness
    - Best way to provide near-term regulatory certainty
- There is a global race to commercialize fusion energy
- Other countries are exploring regulatory frameworks similar to existing materials facilities

FIA Concerns with Utilization Facility Framework

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- Technically unsuitable
    - Focused on unique risks of fission and special nuclear material
    - Uncontrolled criticality, creation and release of additional radionuclides during meltdown, long-term and high-level waste, proliferation risk
    - Imposes licensing, construction, operational, and financial requirements that are not proportionate to fusion hazards
- Overregulation that presents existential risk to US fusion
    - Timeline, exports, licensing, construction and operational costs
    - Limits on investment and imposition of Price Anderson costs
    - These impacts are not commensurate with the risks and are wholly unnecessary to ensure reasonable assurance of adequate protection
- These concerns extend beyond licensing and operational oversight
    - International deployment potentially hampered, particularly to developing nations that most need fusion
    - Restrictions on foreign investment and ownership

FIA Concerns with “Hybrid” Framework

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- **Option is not led by technical considerations**
  - The framework should be chosen to match the technology and hazards
  - The “hybrid” concept is not defined, and therefore unclear how it could be suited to fusion
- **Lack of a technical or pragmatic basis**
  - “Hybrid” framework would require extensive rulemaking
  - Without a clear purpose driving the “hybrid” approach, any rulemaking is likely to be needlessly complex
- **Unclear legislative basis** - could require legislative changes
- **Likely to result in lengthy rulemaking and create significant near-term regulatory uncertainty**
- **Could adversely and unnecessarily affect investment environment and could result in focus on non-U.S. deployment**

FIA Concerns with “Hybrid” Framework

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- **A “fission-lite” hybrid approach would still impose unnecessary and burdensome requirements**
  - An approach that labels fusion devices as utilization facilities but “scales back” certain fission-reactor requirements would still result in the imposition of many unnecessary AEA requirements (e.g., foreign investment)
- **Fuel fab model not technically suited**
  - Fusion facilities do not involve Special Nuclear Material or criticality concerns
- **A “materials-plus” hybrid approach is duplicative**
  - Part 30 already allows the NRC to require design and operation necessary to ensure safety
- **Likely to result in lengthy rulemaking and create significant near-term regulatory uncertainty**

FIA Concerns with New Part 30 Regulations

- **Too soon/lack of licensing and operating experience**
    - Should build experience before establishing generally applicable regulations
    - Example: The NRC created Part 36 framework for irradiators in the early 1990s—after decades of experience licensing and operating this technology
- **Diversity of designs**
    - Large number of commercial fusion developers with differing technologies
    - Many designs in early stages
    - Could result in significant rulemaking effort to address ultimately irrelevant design issues and broad application required would be overly conservative
- **Given diversity plus lack of initial licensing and operating experience, unclear how rulemaking at this stage would benefit the industry or the NRC**
- **The FIA opposes this approach at this time**

FIA Concerns with New Part 30 Regulations

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Regulatory Uncertainty & Delay

- Fusion cannot wait on rulemaking to begin designing commercial-scale devices
- **If the Commission ultimately chooses to issue additional Part 30 regulations:**
  - Wait until several commercial-scale facilities have been licensed and brought online to provide industry and agency experience
    - *(Similar to Commission's history with irradiators and well-logging devices)*
  - **Ensure that developers may proceed under a Part 30 specific-license**
    - Allows developers to proceed with commercial designs now with regulatory confidence
    - Mirrors the Commission's approach to Part 53, where advanced reactor developers may still choose to proceed under Parts 50 or 52

Practical Basis for Existing Part 30

- **Fusion facilities have corresponding hazards to current Part 30 technologies**
  - E.g., irradiators, particle accelerators
  - Hazards based on fixed material inventories and radiation produced by operation

- **Part 30 regulation is inherently “technology-inclusive”**
  - Risk-informed, performance-based approach
  - Long history of showing its ability to license and regulate extremely broad range of technologies

- **Inherently scalable**

Precedent for Part 30 Regulation

- Precedent shows discretion to regulate fusion under Part 30
  - Fusion resembles technologies already regulated under Part 30
    - i.e., particle accelerators
  - Current fusion devices all regulated under Part 30 framework
  - No apparent reason this should change
- Fusion hazards traditionally regulated under Part 30
  - Tritium processing and handling facilities
  - Activated materials and low-level waste
    - E.g., materials produced by accelerators are regulated under Part 30
  - Radiation produced from use of radionuclides other than special nuclear material
    - E.g., shielding requirements for irradiators or accelerators
- Most efficient way for the Agency to meet NEIMA requirement of 2027 for fusion regulatory framework

Atomic Energy Act

Definition of Byproduct Material

- "any material that—(i) has been made radioactive by use of a particle accelerator and (ii) is produced, extracted, or converted after extraction ... for use for a commercial, medical, or research activity."
- **The current definition of byproduct material is sufficient for all fusion hazards**
    - Within the Commission's discretion to extend this definition to material used in or produced by a fusion device

Tritium	Activated materials	Radiation
• Main hazard of most DT fusion devices • Produced by blanket for further energy production • Already regulated under Part 30	• Produced as result of energy production • Precedent shows materials produced as incident to commercial activity qualify as byproduct material • i.e., NRC already regulates activated materials produced by use of an accelerator as byproduct material	• Materials framework already gives the NRC ability to regulate radiation produced by use of materials-based devices • E.g., regulations governing shielding and dose requirements for irradiators, accelerators, nuclear medicine

Note that this framework still gives NRC oversight of device.

- The Commission has authority to regulate device to ensure there is no materials release or radiological exposure
- This gives NRC the right to oversee those aspects of design that pertain to accidents and ensure the design and operation of the device will provide reasonable assurance of adequate protection

Does the Atomic Energy Act Require the Commission to Classify Fusion Facilities as Utilization Facilities?

- AEA Definition Utilization Facility:

  "(1) any equipment or device, except an atomic weapon, determined by rule of the Commission to be capable of making use of special nuclear material . . . or peculiarly adapted for making use of atomic energy in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public"

- **Very broad discretion – "determination by rule of the Commission."**
  - Only the Commission has authority to determine a non-SNM-based technology is a utilization facility
  - Commission has incredible latitude to only act when it determines the safety case truly warrants it.

> "In the Presidential Message recommending the legislation which culminated in the Atomic Energy Act of 1954, it was said that flexibility was a peculiar desideratum and that, absent an accumulation of experience with the new civilian industry hopefully to be brought into being, 'it would be unwise to try to anticipate by law all of the many problems that are certain to arise.' Congress agreed by enacting a regulatory scheme which is virtually unique in the degree to which broad responsibility is reposed in the administering agency, free of close prescription in its charter as to how it shall proceed in achieving the statutory objectives." Siegel v. Atomic Energy Comm'n, 400 F.2d 778, 783 (D.C. Cir. 1968) (citations omitted)

  - Siegel has been cited for this proposition as recently as 2021

Does the Atomic Energy Act Require the Commission to Classify Fusion Facilities as Utilization Facilities?

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- “capable of making use of special nuclear material . . . or peculiarly adapted for making use of atomic energy in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public”
    - First prong inapplicable - No proposed fusion energy technology uses SNM
- **“Making use of atomic energy” is not a dispositive test**
    - AEA Definition of Atomic Energy: “The term ‘atomic energy’ means all forms of energy released in the course of nuclear fission or nuclear transformation.”
- **Many materials facilities use atomic energy**
    - irradiators – use gamma energy produced from radioactive decay
    - radioisotope thermoelectric generators – produce electricity with heat energy from radioactive decay
    - accelerators – use energy from accelerated particles to transmute elements

Does the Atomic Energy Act Require the Commission to Classify Fusion Facilities as Utilization Facilities?

- Addressed in another presentation, but note that defense impacts or environmental impacts not dispositive to establish that a technology is a utilization facility
- Materials based technologies often subject to export controls
  - e.g. certain technologies may be subject to EAR or ITAR and have “dual use” classification or military uses
- Materials facilities present certain health, safety, and environmental risks
  - Some facilities like irradiators have very large quantities of radionuclides
  - **Commercial fusion presents lower defense, health, safety, and environmental impacts than many materials facilities**
- Use of atomic energy, defense/national security uses, or environmental/health impact does not require the Commission regulate fusion devices as utilization facilities
  - Must be of such significance and dependent on Commission determination and discretion
- Production of electricity not mentioned in AEA but also not dispositive (e.g. RTGs)

Nuclear Energy Innovation and Modernization Act

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- NEIMA Definition: “In this Act . . . The term ‘advanced nuclear reactor’ means a nuclear fission or fusion reactor, including a prototype plant . . . .”
- NEIMA definition does not impose utilization facility classification
  - “advanced reactor” isn’t defined term in AEA, so **NEIMA does not implicate existing AEA provisions**
    - NEIMA definition of “Advanced Reactor” only relevant within context of NEIMA – i.e., “in this act”
  - **NEIMA does not require the NRC to impose any particular framework**
    - Requirement that advanced **fission** reactors are utilization facilities dictated by AEA, not NEIMA
- 42 USC 16271(b)(1) – “The term ‘advanced nuclear reactor’ means . . . . a radioisotope power system that utilizes heat from radioactive decay to generate energy”
  - Added by the Infrastructure Investment and Jobs Act
  - No suggestion that radioisotope power systems like RTGs now be regulated as utilization facilities

Minor Edits Could Clarify AEA

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- Commission already has discretion to regulate fusion under either framework
  - No revisions to the AEA are strictly needed
  - The Commission's history of regulation of particle accelerators provides sufficient precedent for regulation under the materials framework
- AEA written decades before good understanding of fusion so minor additional language could help clarify fusion regulatory regime

Add category to definition of byproduct material	Add definition of fusion energy device
AEA Sec. 11(c): "(5) any material that has been made radioactive by use of a fusion energy device." • This would provide sufficient clarification to NRC jurisdiction of fusion-produced materials • Would adequately cover regulation of radiation produced by operation of the fusion device.	AEA Sec. 11(kk): "The term 'fusion energy device' means any equipment or device, except an atomic weapon, capable of producing energy from the nuclear transformation of atoms into heavier elements for commercial or industrial purposes." • The definition would support added category for byproduct material

Conclusion

- **The FIA supports a Part 30 approach**
  - Technical considerations should guide the Commission’s process
    - **The technical case supports a Part 30 approach**
    - There is no technical basis for a utilization facility or hybrid approach
  - **A utilization facility or hybrid approach could significantly undermine the competitiveness of the US commercial fusion industry**
    - Impose unnecessary costs that are unrelated to increases in safety
    - Result in a rulemaking timeline that would force pilot plants to be built elsewhere
    - **Likely to make the US non-viable for development of commercial fusion**
- **AEA gives the Commission discretion to regulate fusion under Part 30**
  - Precedent of regulation of similar technologies and hazards under Part 30
  - Broad discretion given to the Commission in the AEA
  - Nothing in AEA or NEIMA dictates the Commission choose any particular framework

THANK YOU

Questions? Comments?
https://www.fusionindustryassociation.org/contact-3

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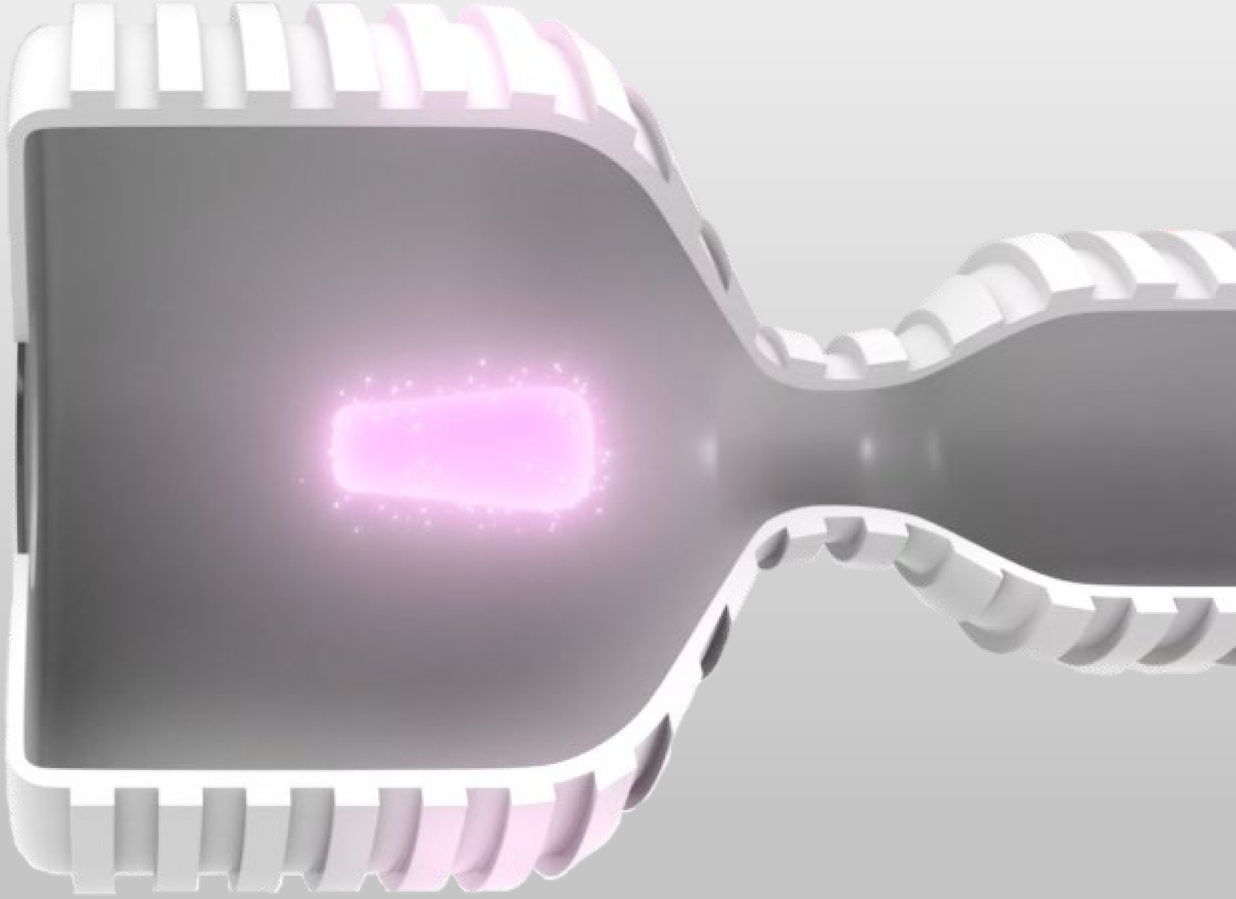
Evaluating Common Defense & Security Use of Part 30 Tools for Fusion



07 June 2022

Sachin Desai, Helion Energy
Michael Hua, Helion Energy

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)

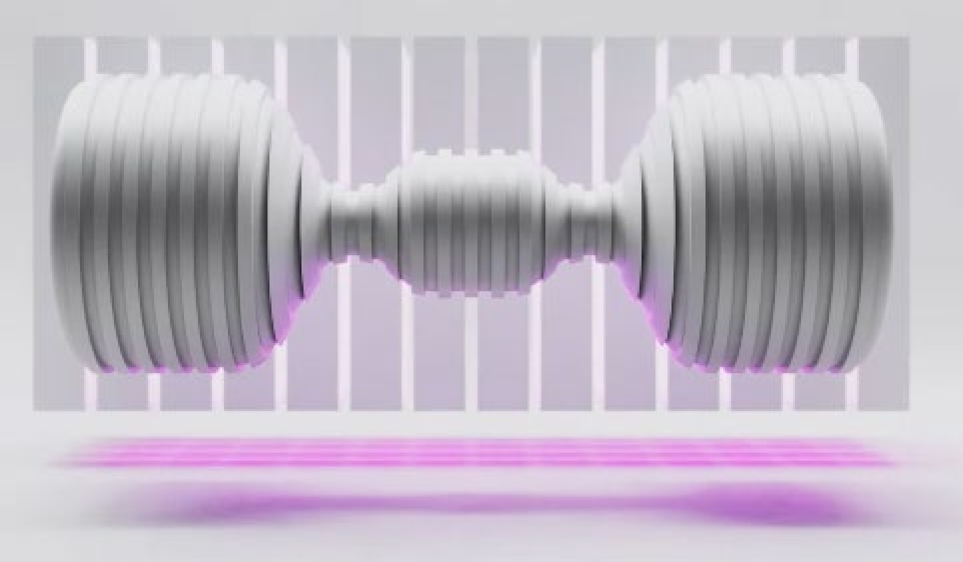
- Trigger Lists focus on SNM/fuel cycle, to this day exclude fusion devices and tritium
  - Note on nuclear reactor in Trigger Lists: "This entry does not control fusion reactors"

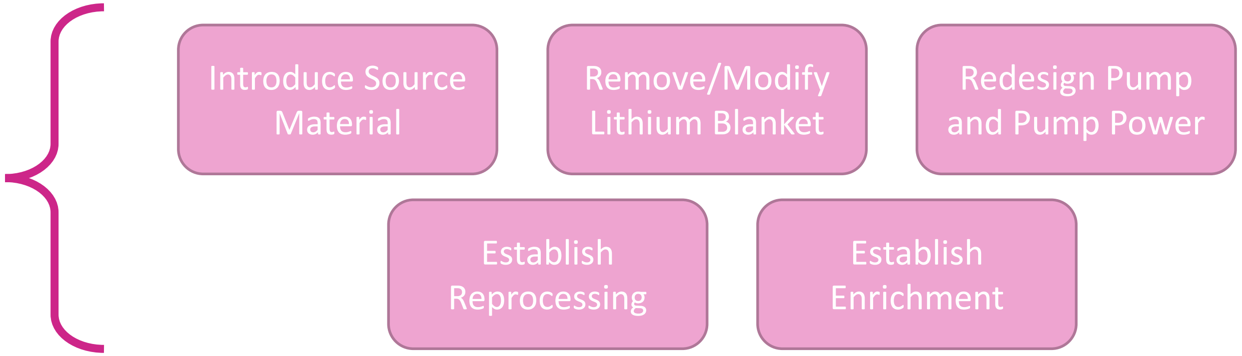
Focus on SNM proliferation algins with NPT & NRC practice

- 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

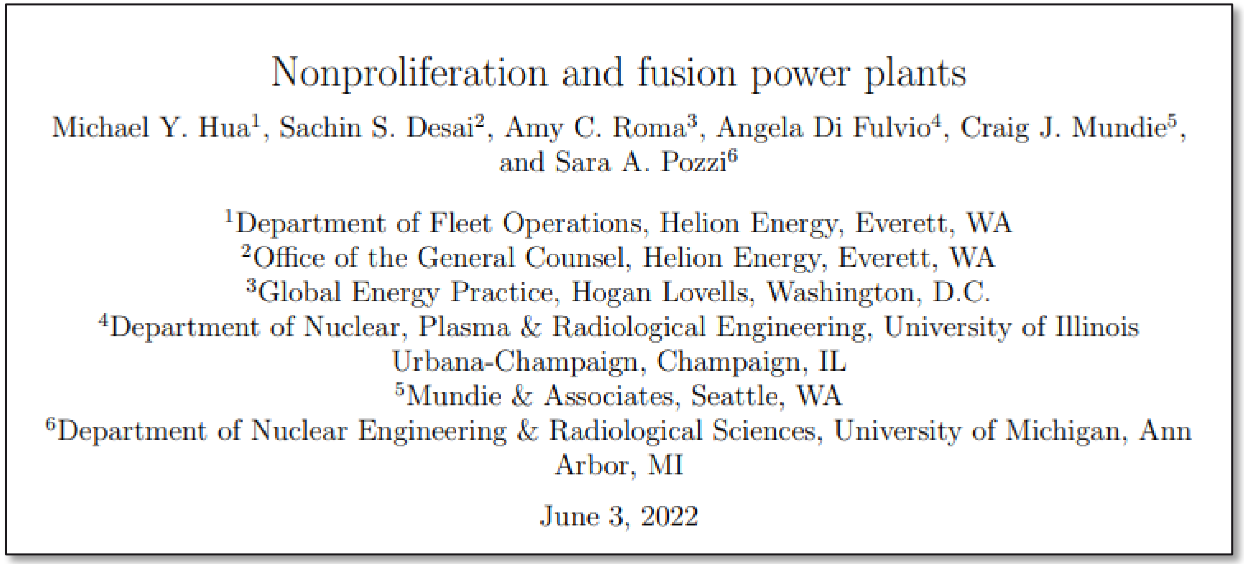
- The primary risk involving fusion is abuse of the technology or materials outside the US
  - Tritium & tritium management systems already covered by export controls, such as:
    - 10 CFR 110.9; ECCN 1C235 and 1A231
  - Fusion technology and materials (e.g., Li-6) also already covered in large part, 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

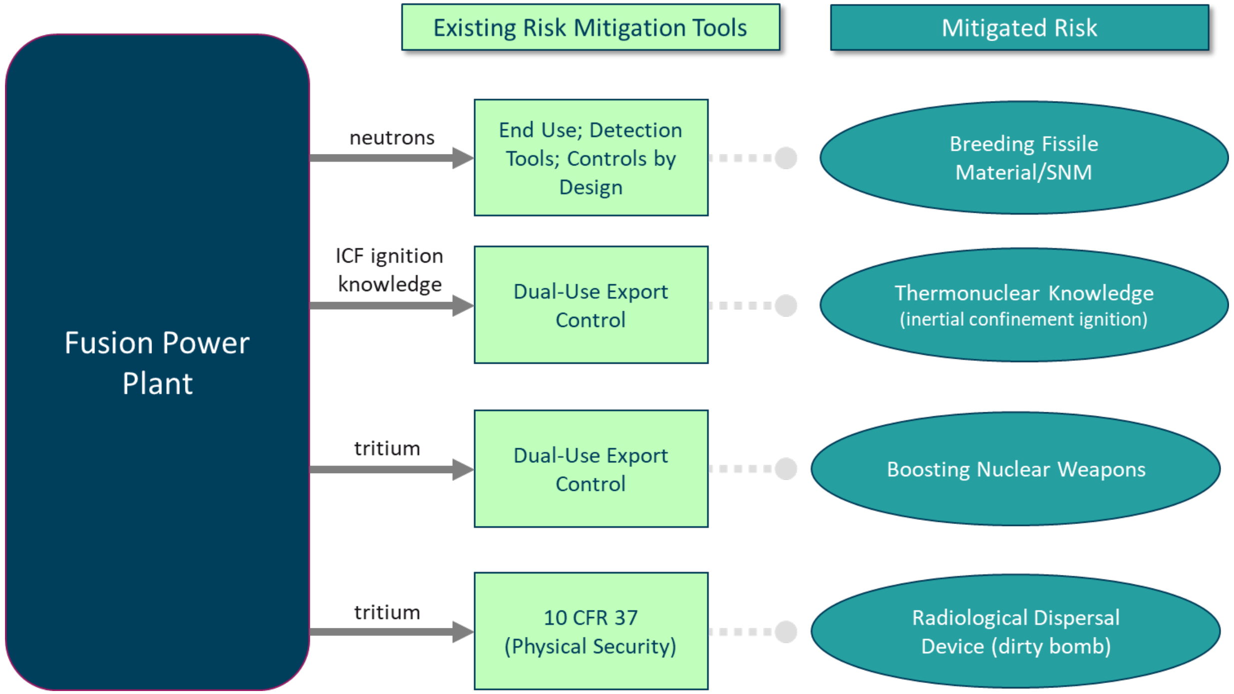


Nonproliferation and fusion power plants

Michael Y. Hua[1], Sachin S. Desai[2], Amy C. Roma[3], Angela Di Fulvio[4], Craig J. Mundie[5], and Sara A. Pozzi[6]

[1]Department of Fleet Operations, Helion Energy, Everett, WA
[2]Office of the General Counsel, Helion Energy, Everett, WA
[3]Global Energy Practice, Hogan Lovells, Washington, D.C.
[4]Department of Nuclear, Plasma & Radiological Engineering, University of Illinois Urbana-Champaign, Champaign, IL
[5]Mundie & Associates, Seattle, WA
[6]Department of Nuclear Engineering & Radiological Sciences, University of Michigan, Ann Arbor, MI

June 3, 2022



Existing Risk Mitigation Tools

Mitigated Risk

Fusion Power Plant

neutrons → End Use; Detection Tools; Controls by Design → Breeding Fissile Material/SNM

ICF ignition knowledge → Dual-Use Export Control → Thermonuclear Knowledge (inertial confinement ignition)

tritium → Dual-Use Export Control → Boosting Nuclear Weapons

tritium → 10 CFR 37 (Physical Security) → Radiological Dispersal Device (dirty bomb)

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

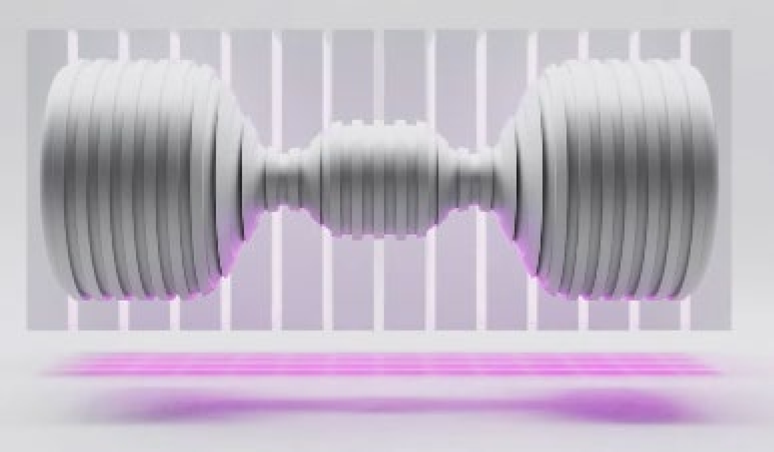
- SNM not used and not present in fusion facilities

Use of Part 30 Tools for Fusion

Fusion during operation

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

Fusion Device



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

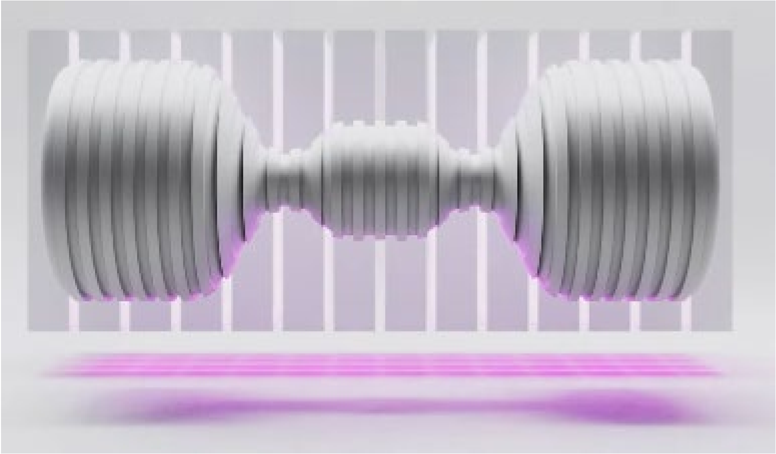
Accelerator (e.g., cyclotron)

- 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?

Technical

- *Access*
- *Shielding*
- *Fire*
- *Monitoring*
- *Device Control*
- *Vault Integrity*

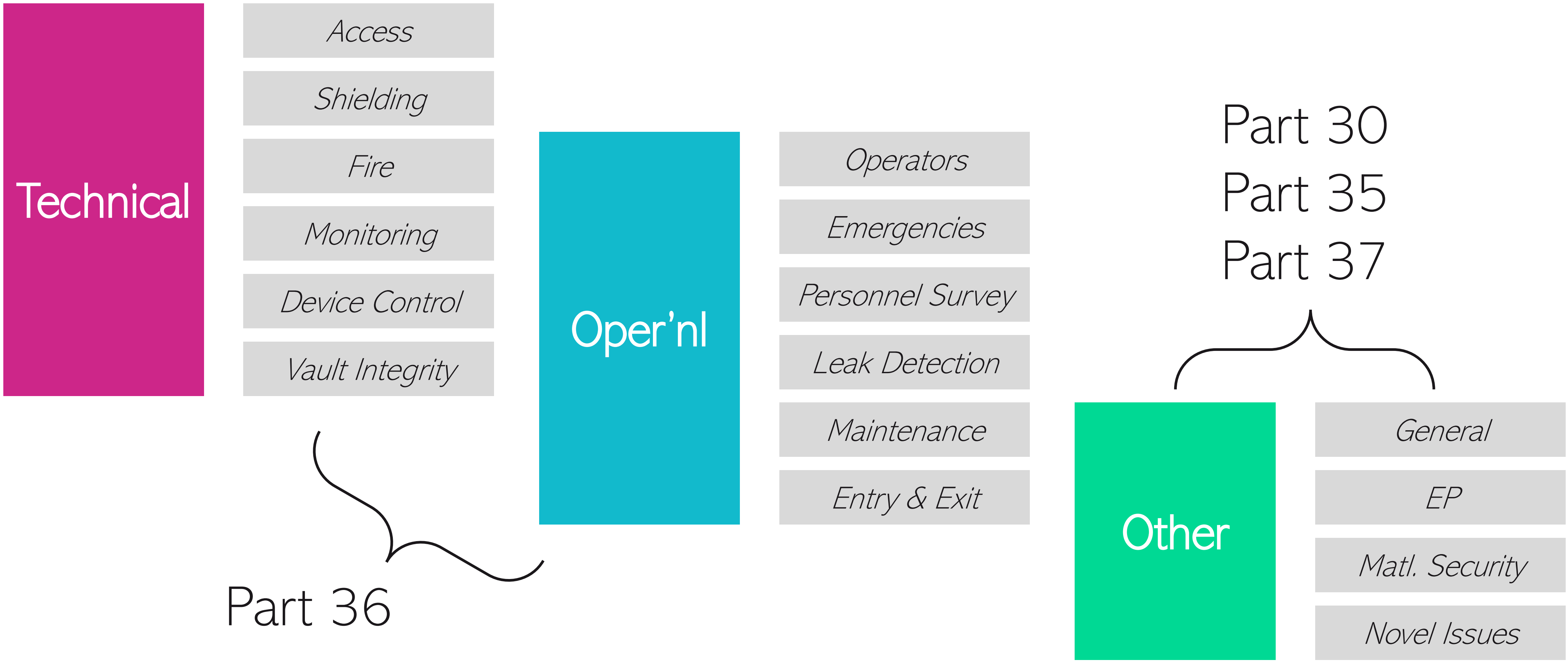
Oper'nl

- *Operators*
- *Emergencies*
- *Personnel Survey*
- *Leak Detection*
- *Maintenance*
- *Entry & Exit*

Other

- *General*
- *EP*
- *Matl. Security*
- *Novel Issues*

What could the NRC look to?



Technical

- Access
- Shielding
- Fire
- Monitoring
- Device Control
- Vault Integrity

Part 36

Oper'nl

- Operators
- Emergencies
- Personnel Survey
- Leak Detection
- Maintenance
- Entry & Exit

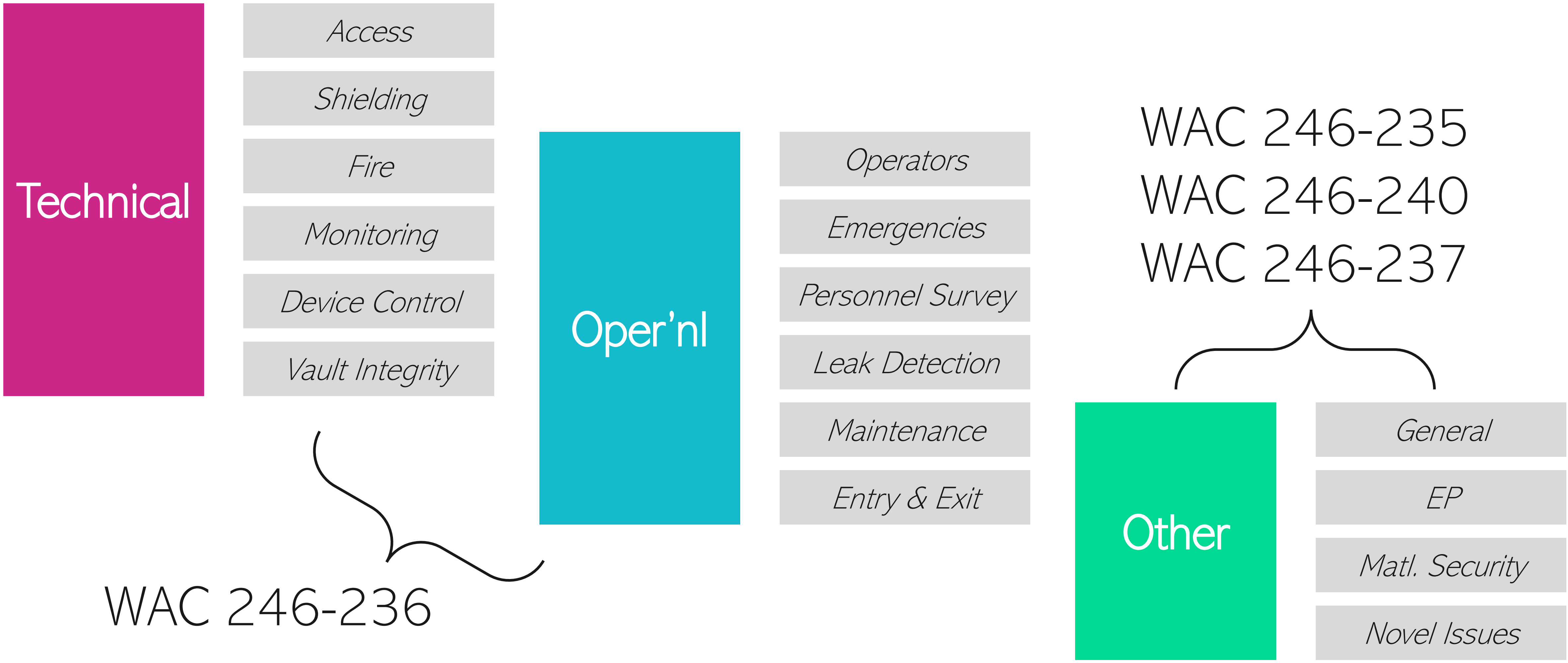
Part 30
Part 35
Part 37

Other

- General
- EP
- Matl. Security
- Novel Issues

What could the States look to?

In the state of Washington, for example:



Technical

- *Access*
- *Shielding*
- *Fire*
- *Monitoring*
- *Device Control*
- *Vault Integrity*

Oper'nl

- *Operators*
- *Emergencies*
- *Personnel Survey*
- *Leak Detection*
- *Maintenance*
- *Entry & Exit*

WAC 246-236

WAC 246-235
WAC 246-240
WAC 246-237

Other

- *General*
- *EP*
- *Matl. Security*
- *Novel Issues*

Sample design requirements usable from Part 36

Section (Based on Part 36)	Title	Key Regulatory Concepts
36.23	Access Control	• 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	• Dose rates cannot exceed 2 millirem per hour outside of shielded areas
36.27	Fire Protection	• Heat and smoke detectors • Automated fire extinguishing when required
36.29	Radiation Monitors	• Airborne material detection • Neutron detection • Entry and exit detection
36.31	Device Control	• Indication of on/off as well as safety system status/output • Ability to turn off easily (manual and automated)
36.33	Shielding Pools	• Metallurgical and leak/purity requirements • Dose limits
36.37	Power Failures	• Automatic stop of commercial operations
36.39	Design Requirements	• Sets forth performance requirements for above systems, as well as e.g., foundations, liquid handling, seismic, computers, wiring…
36.41	Construction monitoring	• 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	- Operator training, testing, safety review, and related requirements (relatively simple requirements; reliance on guidance)
36.53	Operating and Emergency Procedures	- 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	- Standard dosimetry requirements
36.57	Radiation Surveys	- Surveys with startup and over time - Survey requirements and consequences of failure
36.59	Leak Detection	- 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	- 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	- Basic requirements for maintaining purity of shielding pools
36.65	Attendance During Operation	- Staffing requirements for operator and additional individual(s)
36.67	Entry and Exit	- 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

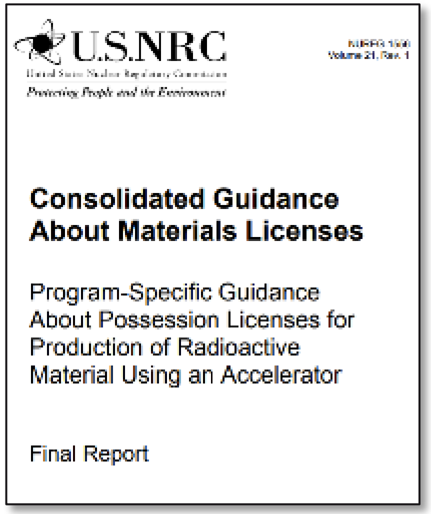
- Horizontal scaling can address different design themes and subsystems

- 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



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-1556
Volume 21, Rev. 1

Consolidated Guidance About Materials Licenses

Program-Specific Guidance About Possession Licenses for Production of Radioactive Material Using an Accelerator

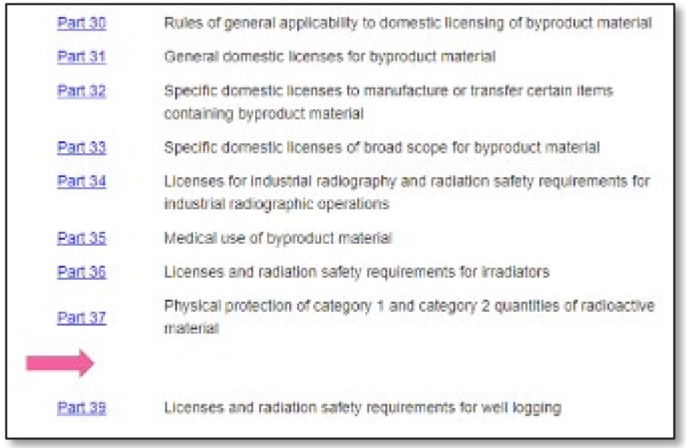
Final Report

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 39	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

Conclusions

- 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

Questions?

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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Public Comment on Fusion Safety & Licensing

B.A. Grierson
Director, FPP Design Hub

GENERAL ATOMICS

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

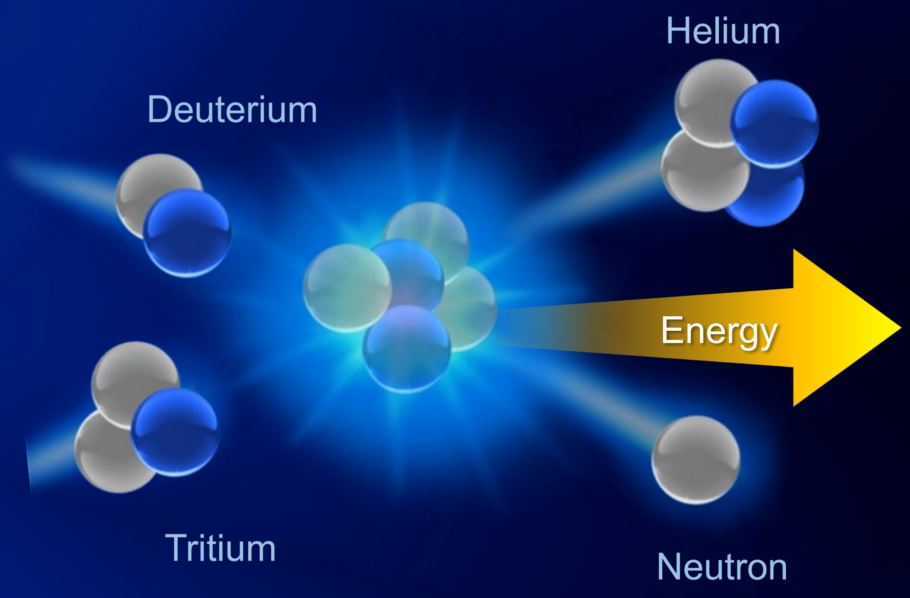
- **General Atomics is pursuing a FPP concept and is focused on safety, licensing, and social impact**
  - Appropriate regulations to ensure public and worker safety
  - Inclusion of safety, licensing, and byproduct disposal in FPP requirements
  - Embracing the need for a *social license*
  - Offering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

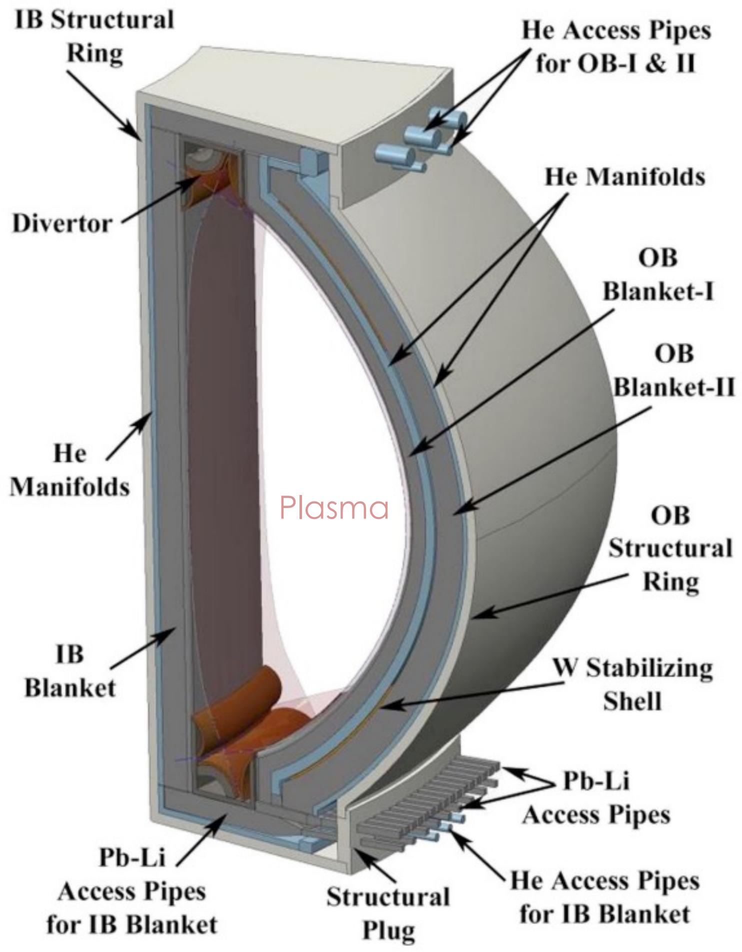
A Community Plan for Fusion Energy and Discovery Plasma Sciences

Report of the 2019–2020 American Physical Society Division of Plasma Physics Community Planning Process

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



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

- **Lithium in the blanket provides source of tritium**

  $^6Li + n \rightarrow {}^4He + T$

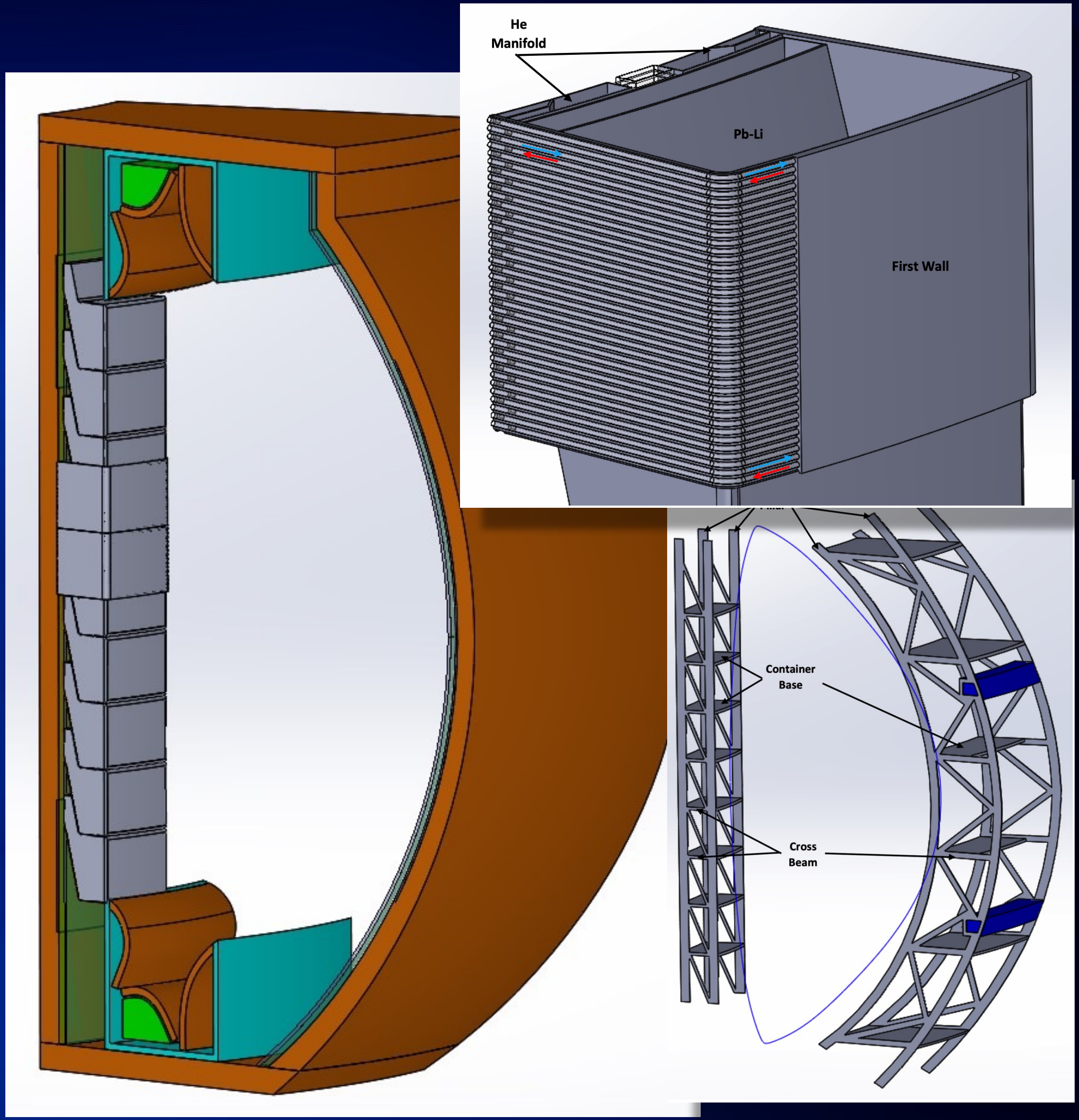
- **One neutron is produced from D-T**
  - Can only get one T back
  - Must add neutron multiplier (Be, Pb) to increase tritium breeding
- **Choices of materials affects safety assessment**
  - Breeding material: solid, liquid
  - Coolant: water, helium
  - Structural & functional material: Steel, alloy, ceramic

← Example investigated in detail: PbLi breeder with dual helium/PbLi cooling, reduced activation steel w/silicon carbide insulator

Utilizing Silicon Carbide in a Compact Tokamak FPP

- **RAFM steels superior to conventional steel due to lower Ni and better thermal properties[1]**

- **SiC offers further advantages[2]**
  - 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



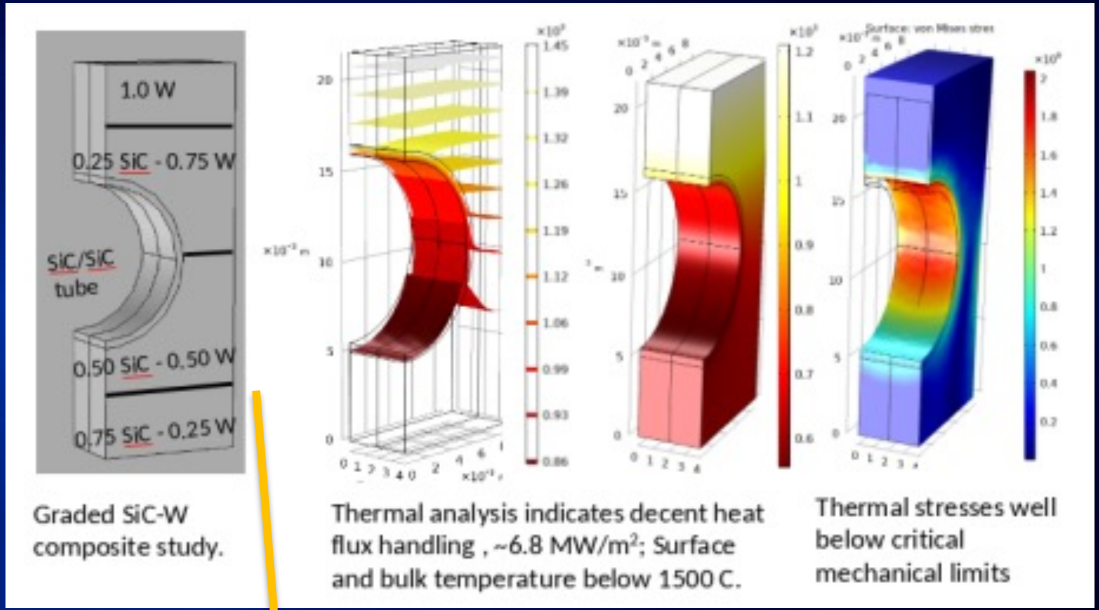
[1] H. Tanigawa *et. al.*, Nucl. Fusion **57** 092004 (2017)
[2] M. Tillack, *et. al.*, Fus. Eng. and Design **180**, 113155 (2022)

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**

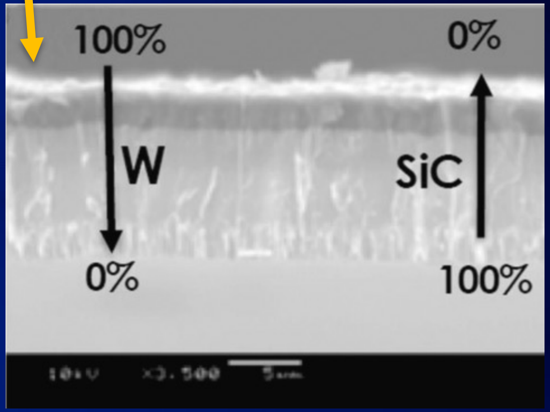
- **Engineered SiC/Tungsten (W) materials have superior heat removal capabilities and resistance to plasma-induced damage**



Graded SiC-W composite study.

Thermal analysis indicates decent heat flux handling , ~6.8 MW/m^2; Surface and bulk temperature below 1500 C.

Thermal stresses well below critical mechanical limits



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

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***

[1] D. Petti *et. al.*, Fus. Eng. and Des. **80** 111–137 (2006)
[2] Humrickhouse & Merrill, Fus. Sci. & Tech. **67** 167-178 (2015)
[3] Humrickhouse & Merrill, Fus. End. & Design. **135** 302-303 (2018)

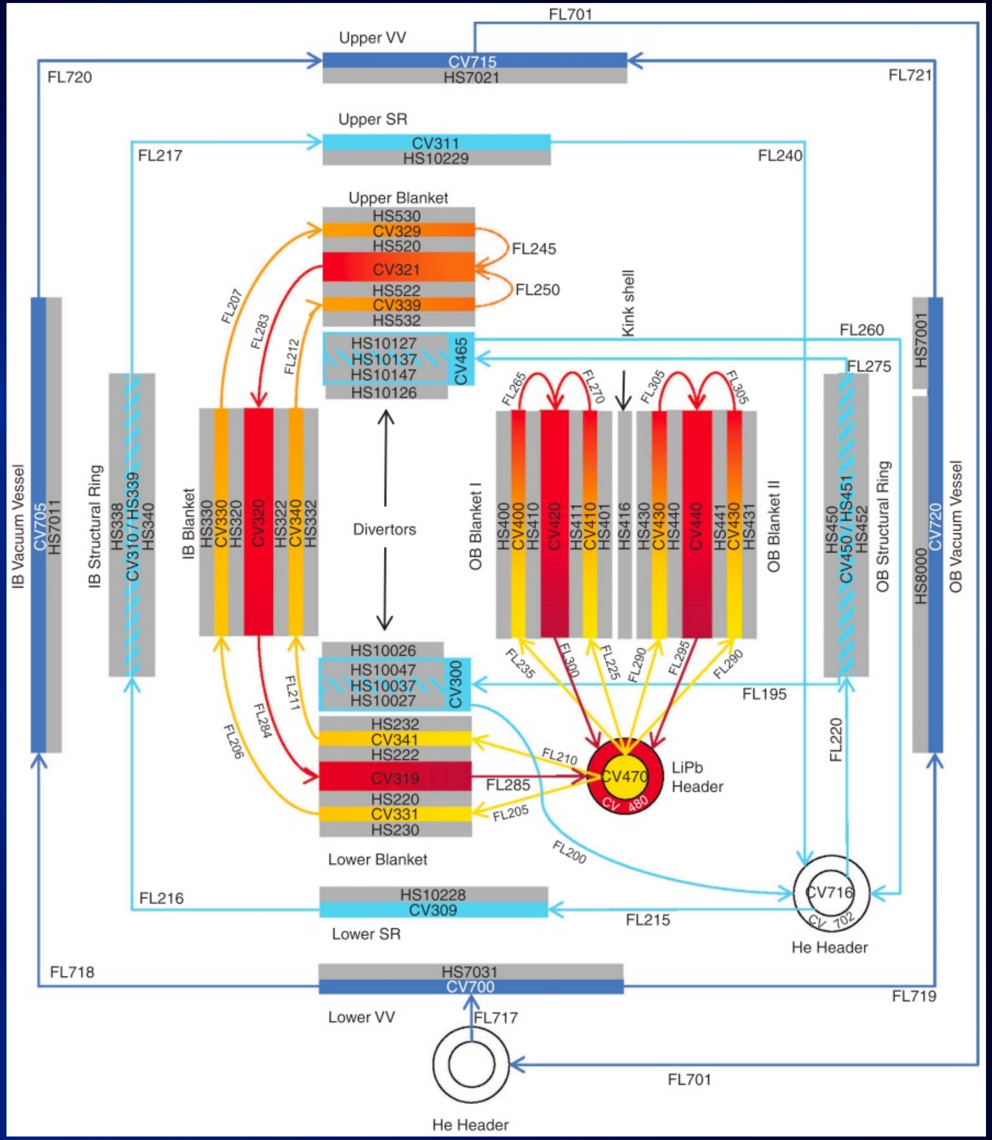
Previously Studied Scenarios Remain Highly Relevant

- **Long term station blackout (LTSBO) can initiate two primary scenarios requiring decay heat removal:**
    1. Loss of flow accident (LOFA)
    2. Loss of coolant accident (LOCA)

- **Maintenance cycle inclusion of decay heat**

- **In-vessel off-normal events**
    - Mobilization of tritium from co-deposits

- **Loss of vacuum or pumping**
    - Release of tritium into cryostat
    - Release of tritium into stack



MELCOR (Originally SNL) modified for fusion by INL

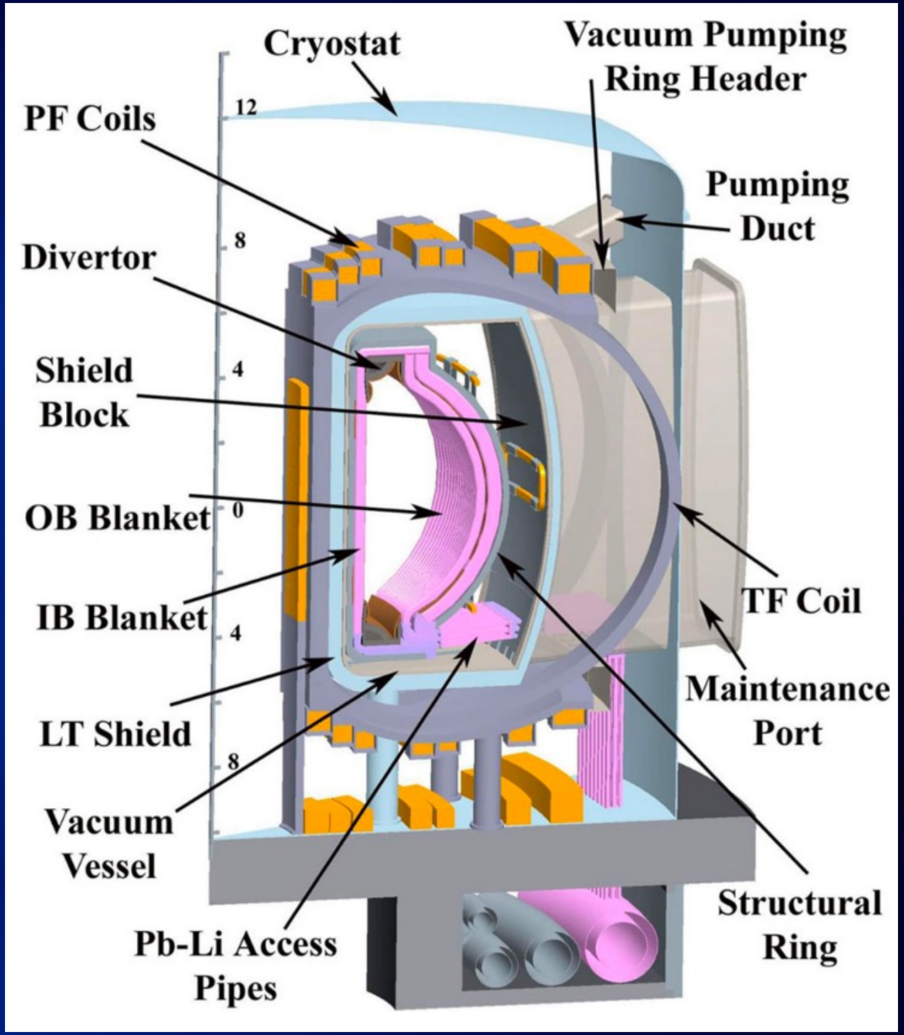
Humrickhouse & Merrill, Fus. Sci. & Tech. **67** 167-178 (2015)

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

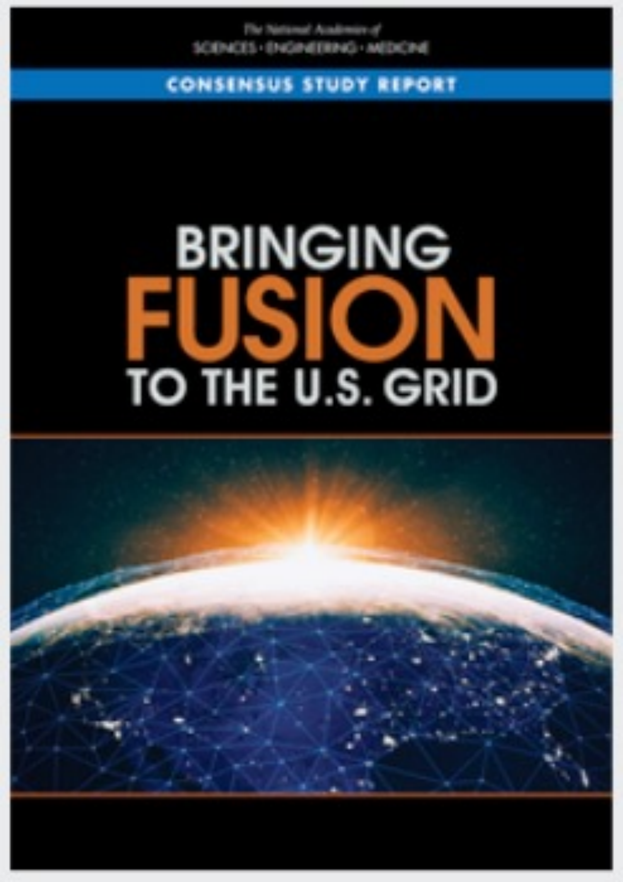
"The analyses show that none of these accidents are expected to breach confinement boundaries or lead to large releases of radioactive material from the ARIES-ACT1 power core."



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

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



The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

BRINGING FUSION TO THE U.S. GRID

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
  - Inclusion of safety, licensing, and byproduct disposal in FPP requirements
  - Embracing the need for a *social license*
  - 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

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	

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

CFS Regulatory Presentation

Tyler Ellis, Ph.D.

Commonwealth Fusion Systems

CFS path to commercial fusion energy

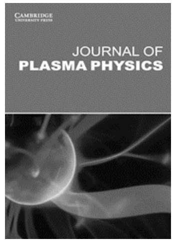
COMPLETED
Proven science
Alcator C-Mod

COMPLETED
October 2020
Published peer-reviewed SPARC physics basis in Journal of Plasma Physics

COMPLETED
September 2021
Demonstrate groundbreaking magnets

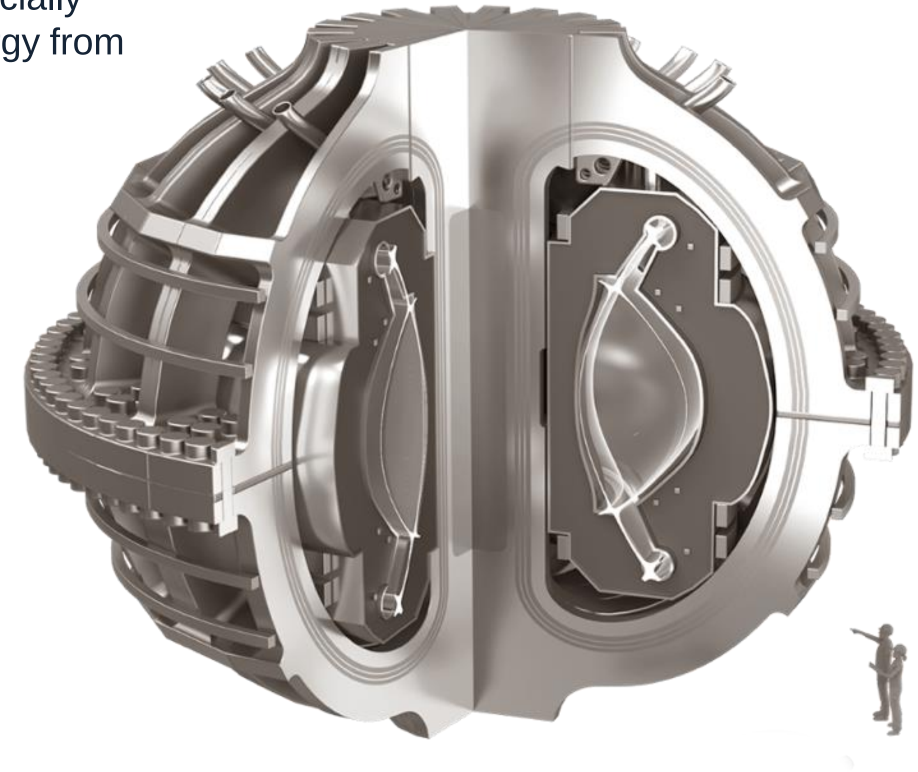
CONSTRUCTION UNDERWAY
Operational in 2025
Achieve commercially relevant net energy from fusion

Early 2030s
Fusion power on the grid $P_{electric}$~200MW


CAMBRIDGE UNIVERSITY PRESS
JOURNAL OF PLASMA PHYSICS

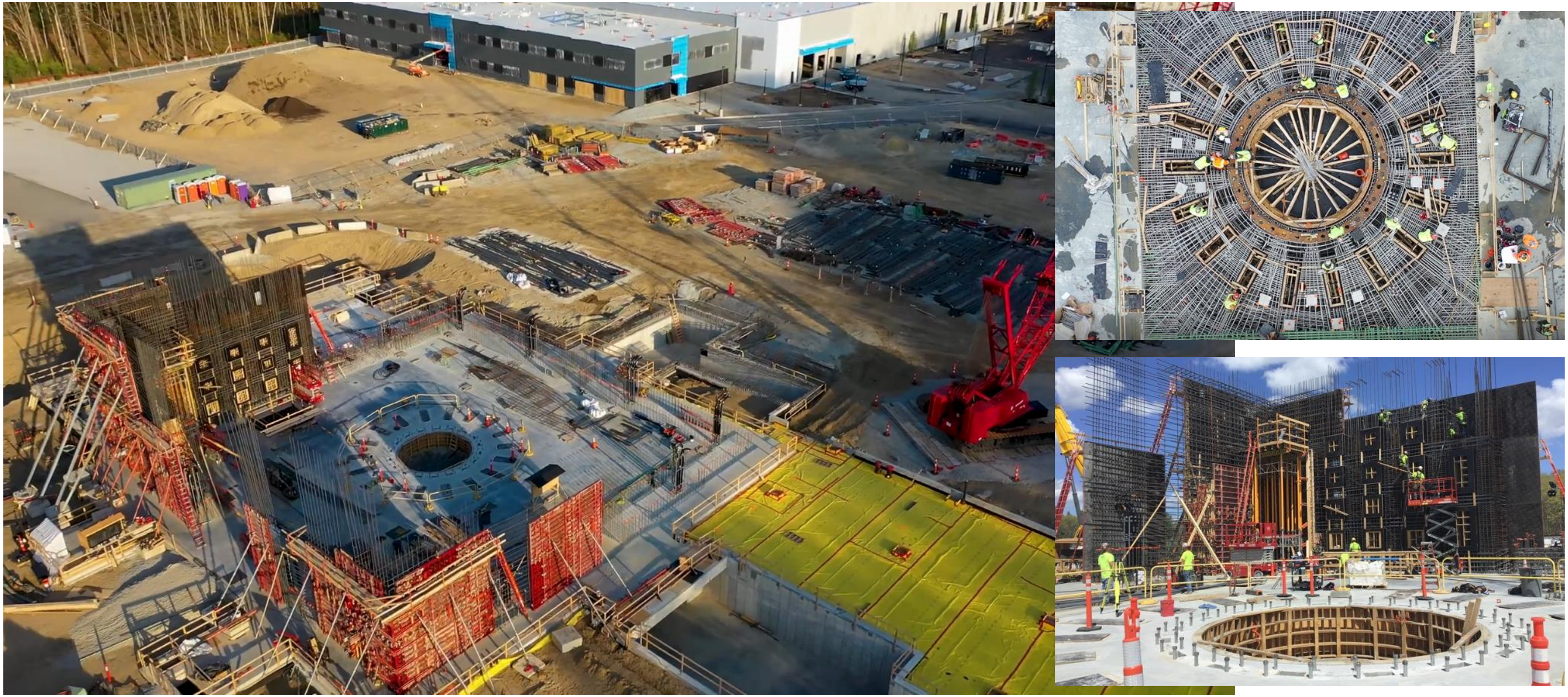

HTS Magnets


SPARC


ARC

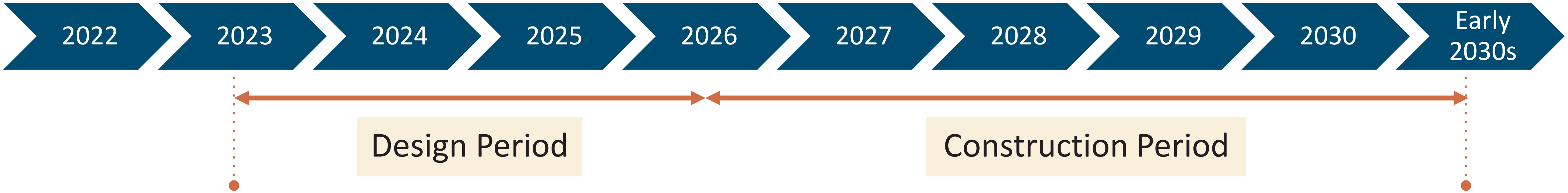
CFS Magnet Factory and SPARC

- 47-acre site located at Devens, MA includes CFS headquarters, magnet manufacturing, and SPARC building



Decadal Timeline for Fusion

- Most private fusion companies, including CFS, have targeted the early 2030s to have commercial fusion power plants on the grid consistent with the DOE decadal vision and strategy for commercial fusion
- CFS has already started a global siting search for the first ARC
- Assuming a ~5-year construction period and ~3-year design period, private companies need regulatory certainty by 2023 to support this timeframe and keep the U.S. as a viable location for ARC and other first fusion power plants



2022

2023

2024

2025

2026

2027

2028

2029

2030

Early 2030s

Design Period

Construction Period

Regulatory certainty needed

Commercial fusion on the grid

CFS's Goals for US Regulatory Process

- Regulatory clarity for fusion energy
  - *As quickly as reasonable (with white paper schedule) by minimizing changes to formal regulations*
  - *Align with the current licensing of materials used in or created by particle accelerators*
- Use existing specific licensing (with conditions addressing machine-specific issues) and NUREGs processes
- No legislative changes to the Atomic Energy Act or completely new parts of the Code of Federal Regulations (CFR) are necessary to establish a framework for fusion
  - *CFS is not opposed to updating the AEA to keep pace with fusion energy's maturation*
  - *But waiting on legislative action would unnecessarily delay the regulatory certainty needed for first generation fusion machines to be built in the United States*
- Leverage expertise across Agreement States and inherent flexibility of existing materials licensing approach to build operational experience with fusion
- Maintain compatibility with global trends in fusion regulation such as the United Kingdom's materials licensing approach for commercial fusion

CFS's Recommendations

- **Recommend regulating fusion energy systems under a Part 30 materials focused framework using existing NUREG-1556 Volume 21 for guidance**
- If modifications are needed as the industry develops operational experience, an appendix can be added to NUREG-1556 Volume 21 or a new NUREG based on NUREG-1556 Vol 21 can be written
- This process of regulating new technologies under Part 30 and updating guidance as needed after sufficient operational experience has been learned is how the NRC treated several technologies previously
- These options require no legislative changes and can be implemented within the NRC
- Preserve flexibility and administrative efficiency to develop a regulatory framework based on which fusion technologies actually apply for a license
- If NRC is concerned about legal ambiguities in applying its materials licensing approach to fusion, NRC could add a definition of "fusion energy machine" that explicitly brings fusion-activated materials within the domain of particle accelerators

Flexibility via Materials Licensing Approach

- **Materials licensing is inherently graduated to calibrate regulatory scrutiny with risks involved with the byproduct materials**
  - The differences between utilization facility licensing in Parts 50 and 52 and the materials licensing program in Part 30 are **not** “gaps”
    - *They are reasonable policy choices by Congress and the Commission reflecting understandings of the risks involved*
  - For non-DT fusion technologies, the materials licensing approach also contains exemption amounts below which materials licensing requirements would not apply (these exemptions would also apply to produced byproduct and activated material)
    - *States should still have full authority to regulate these machines*

Flexibility via a Materials Licensing Approach

- **Flexibility makes clear that there is no need to differentiate between “large” or “small” scale fusion facilities**
  - ITER was never intended to be commercial scale and new technology has rendered it to be one of a kind
    - *CFS’s 2021 HTS magnet demonstration unlocks ~40x smaller tokamak designs*
    - *ARC will be an order of magnitude smaller than ITER and slightly smaller than JET*
  - Differentiating regulatory treatment based on the “scale” of a facility doesn’t further any NRC health, safety, security, or environmental objective
  - The sole determinant for regulatory treatment is the nature of the hazard presented and risk that the hazard (following mitigation) might present to people or the environment
    - *Part 30 materials licensing provides adequate flexibility and coverage to meet this standard*

Materials License Enables an Evolution

- **Optionality: NUREG process can evolve with the commercial fusion industry**
  - Maintain current approach where fusion fits into NUREG 1556 Vol. 21 (production of radioactive material using an accelerator) for first generation of commercial fusion machines and limitations/controls can be added by conditions to specific licenses
  - As technology evolves and industry learns, Vol. 21 could be supplemented with an appendix to address issues that arise which build on lessons learned and standardized conditions to specific licenses
  - A fusion-specific NUREG guidance document based on Vol 21 may be considered as the industry matures, likely after several commercial devices are operating and completed multiple full operational and maintenance cycles

Defining “Fusion Energy Machine” in Parts 20/30 NRC regulations

- If NRC is concerned about ambiguity within its material licensing program, it can address possible jurisdictional questions by exercising its discretion to define “particle accelerators” as follows
- “**Fusion energy machine** means a machine in which charged particles are accelerated in order to create conditions conducive to fusion reactions and in which the products of such reactions (including heat or other electromagnetic radiation) are captured for the purpose of generating energy. Fusion energy machines are deemed to be particle accelerators.”
- By deeming fusion energy machines as particle accelerators, NRC would resolve potential confusion in oversight of byproduct material, like tritium, that is produced and consumed on site (essentially catalyzing the D-Li fuel reaction)[1]
- This definition clarifies the agency’s intent as evidenced by its statement in the 2007 final rulemaking for byproduct material that DT neutron generators fit within the particle accelerator paradigm established by Congress and implemented by NRC

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[1] David R. Lewis, Jeffrey S. Merrifield, and Sidney L. Fowler, Considerations in the Regulation of Fusion-Based Power Generation Devices at 3 (Nov. 19, 2020), https://www.pillsburylaw.com/images/content/1/4/v8/144195/Article-Licensing-Fusion-Power-Nov2020.pdf.

Defining “Fusion Energy Machine” in Parts 20/30 NRC regulations

- **Congress has granted NRC broad discretion around the definition of “particle accelerator,” and NRC has exercised this discretion in Parts 20 and 30 of its regulations**
  - *The AEA does not define “particle accelerator” and Congress has not defined the term in any statute*
  - *NRC defined “particle accelerator” for Parts 20/30 as “any machine capable of accelerating electrons, protons, deuterons, or other charged particles in a vacuum and of discharging the resultant particulate or other radiation into a medium at energies usually in excess of 1 megaelectron volt. For purposes of this definition, "accelerator" is an equivalent term.”*
    - Given the voltages and capture of particles or radiation into a medium for useful work in a fusion machine (e.g., heat and neutrons), fusion energy machines fit well within the definition of particle accelerator

Defining “Fusion Energy Machine” in Parts 20/30 NRC regulations

- **In establishing its definition of “particle accelerators,” NRC intended to cover byproduct material produced by neutron generators that are very similar fusion energy machines**
- NRC explained that “[i]f a neutron generated by the accelerator is used to produce radioactive material via neutron activation, and the resulting radioactive material is used for a commercial, medical, or research activity, the radioactive material (and any incidentally produced radioactive material) would be regulated as byproduct material under Section 11e.(3) of the AEA as amended by the EPAct.”[2]
- On the basis of this reasoning, <u>this definition should capture all byproduct material produced fusion energy machines currently envisioned by the fusion industry</u>

[2] 72 Fed. Reg. 55,896 (Oct. 1, 2007).

NRC has exercised this discretion before: Cyclotrons

- **NRC incorporated a category of devices, cyclotron, which was not mentioned in Congress's mandate in EPAct 2005, to the "particle accelerator" construct.**
- The Commission has defined "cyclotron" as "a particle accelerator in which the charged particles travel in an outward spiral or circular path. A cyclotron accelerates charged particles at energies usually in excess of 10 megaelectron volts and is commonly used for production of short half-life radionuclides for medical use."
  - Cyclotrons are an apparatus in which charged atomic and subatomic particles are accelerated by an alternating electric field while following an outward spiral or circular path in a magnetic field
  - Sources are varied as to whether cyclotrons are technically a category of particle accelerators
- Tokamaks and other fusion machines appear to share a lot of similarities with this description of cyclotrons with comparable energies involved, but some cyclotrons are far larger than any commercial fusion system on the drawing board employing far higher energies[3]
- *With a similar exercise of discretion, NRC could likewise place fusion energy machines within the category of particle accelerators for the purposes of Parts 20 and 30*

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[3] Largest cyclotron in the world is TRIUMF in Canada with an 18-meter diameter and accelerating protons up to 520 MeV (compared with deuterium-tritium fusion reactions releasing 17.6 MeV of energy with a far smaller sized machine).

Why a new CFR part (e.g. 38) now is inappropriate for fusion

- **Additional regulatory treatment might become relevant after sufficient commercial operation, but that is not the case for fusion today**
- Part 36 for irradiators was developed after decades of operation of irradiators around the world and it took over two years to finalize
  - *Irradiators were initially licensed under Part 30*
  - *NRC developed separate regulatory treatment to standardize rules in one place, streamline licensing approvals, clarify inspection requirements and incorporate operating lessons*
- Part 37 on category 1/2 sources was first introduced as additional license conditions for radioactive materials quantities of concern in 2004 and finalized as Part 37 in 2013
- Similarly, Part 39 for well loggers was also created in 1987 after significant operational experience was gained from some 90,000 well logging operations at the time
- Although there are more than 100 tokamaks globally (many safely operating in the US under Part 30 licenses), no commercial fusion energy machines exist, so there is no operating history to base a new regulatory approach upon

Why a new CFR part (e.g. 38) now is inappropriate for fusion

- **Using the specific licensing process with development or revision of existing NUREGs lets Agreement States, the NRC, and the regulated community proceed down a well understood regulatory pathway with a flexible set of regulatory tools like license-specific conditions and up-to-date regulatory guidance**
  - *At this stage, the NUREG guidance process will be sufficient to support fusion machine licensing and provide adequate protection for public health and safety as the fusion sector evolves*
  - *Preserve flexibility and administrative efficiency to develop a regulatory framework based on which fusion technologies apply for a license and their actual risks, attempting to write a complete set of new regulations now could result in arbitrary regulatory obligations that don’t support the NRC mission to protect public health, safety and the environment and constrain the emerging fusion industry*
  - *Establishment of a new CFR part for fusion would introduce regulatory uncertainty for a long period of time, thus making the U.S. a far less competitive country for locating new fusion power plants*

Environmental Justice and Compliance

- Fusion energy has enormous environmental benefits and addresses environmental justice
  - Fusion technologies will be baseload without any air, water, or other emissions that have traditionally affected environmental justice communities disproportionately
  - No reason to expect that fusion machines would be sited disproportionately in environmental justice communities, and may in fact be a positive addition
  - Staying within the Part 30 materials licensing framework ensures that the regulatory treatment for fusion will evolve as NRC's environmental justice processes evolve and improve
- NUREG 1748 describes the NEPA compliance and environmental review processes for materials licensing
  - Provides flexibility for categorical exclusions, environmental assessments, or environmental impact statements (EIS)
  - Given the relatively small footprints and negligible offsite environmental impacts from the operation of fusion energy machines, it is unlikely that licensing of fusion energy machines would significantly affect the quality of the human environment, so no EIS would be required
    - *Therefore, a categorical exclusion or environmental assessment would be the most relevant processes for licensing future fusion machines*
- Agreement states have comparable processes that are flexible to meet state environmental review goals
- CFS believes that NUREG 1748 is appropriate for the fusion energy sector at this time

No substantive connection to common defense and security

- **Commercial fusion devices do not use special nuclear material or source material as the NRC defines these terms**
- Fusion energy machines as designed will not be capable of producing fissionable materials
  - *Using any neutrons released in fusion reactions to produce fissionable materials would be an extraordinarily challenging way to create weapons material*
  - *Manufacturing weapons materials would require a complete re-design of a fusion machine*
    - *First, one needs to have access to either special nuclear material or source material in violation of the safeguard regime*
    - *Moderation of neutrons would be needed since the fission cross-section is higher than capture for both uranium/thorium*
    - *Fission fragment isotopes necessitate a separate reprocessing step done in a separate facility which would require transportation of highly radioactive material off-site*
    - *Fission fragment isotopes would likely also cause operational issues since the blanket systems are not designed for this and they would take neutrons away from re-generating tritium which is needed for fusion power operation*
- Consumable inputs for fusion energy machines, such as tritium to assist in the start up of a deuterium-lithium fueled facility like future ARCs, are all available on the commercial market so there is no diversion of materials like tritium from national defense or other security uses
  - *Lithium-6 is not the only isotope required to generate tritium, other isotopes of lithium can also be used*
  - *CFS is working with MIT on an ARPA-E funded project to demonstrate the key technology to demonstrate that all forms of lithium, not only lithium-6, can be used to produce the tritium catalyst on a commercial basis*
  - *If the tritium market tightens in the future, CFS plans to be fully self sufficient on tritium supplies for future fleet growth*

No substantive connection to common defense and security

- **Although each private company has intellectual property they want to protect, the vast majority of fusion energy technology is not secret and is not limited to the United States.**
  - The public fusion experiment, ITER, is an international collaboration involving many countries around the world
    - *The US has been working with these global partners, and sharing technical information and components, for decades*
    - *Classification of fusion as a utilization facility has the potential to create challenges for subsequent US ITER collaboration*
  - There is no reason to anticipate that any US Government interest would prompt a restriction on controlling access to this widely available technology
- Once commercialized, fusion energy machines will contribute to an integrated electricity grid with many sources of electric generation (thermal energy, renewable energy, existing or advanced fission energy, or energy storage)
    - *It is highly unlikely that any critical defense/security activity will be reliant solely on fusion energy in the foreseeable future*
    - *Bear in mind that many fusion technologies, including CFS's, is simply a more efficient way to boil water for a steam turbine*

Summary

- CFS believes regulating fusion energy systems under a Part 30 materials focused framework using existing NUREG-1556 Volume 21 for guidance is sufficient to ensure a safe fusion energy industry

- If modifications are needed as the industry develops operational experience, an appendix can be added to NUREG-1556 Volume 21 or a new NUREG volume can be added based on NUREG-1556 Vol 21

- Minor updates to the existing regulations in Parts 20 and 30 can resolve any residual confusion in NRC's materials licensing program

- This process of regulating new technologies under Part 30 and updating guidance as needed after sufficient operational experience has been gained is how the NRC treated several previous technologies such as irradiators and well-loggers

The fastest path to limitless, clean energy

Commonwealth
Fusion Systems

Agenda

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1:00 pm	Welcome, Introductions, and Overview	NRC
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5:00 pm	Opportunity for Public Comment	
5:30 pm	Adjourn	

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

Confinement Methods

Fusion Reactions

Fusion Fuel Cycles

Power Conversion Cycle

Facility Size

Commonwealth Fusion Systems

first light

tae TECHNOLOGIES

tokamak energy

generalfusion®

ZAP ENERGY™

HELION

CTFusion

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.

Public

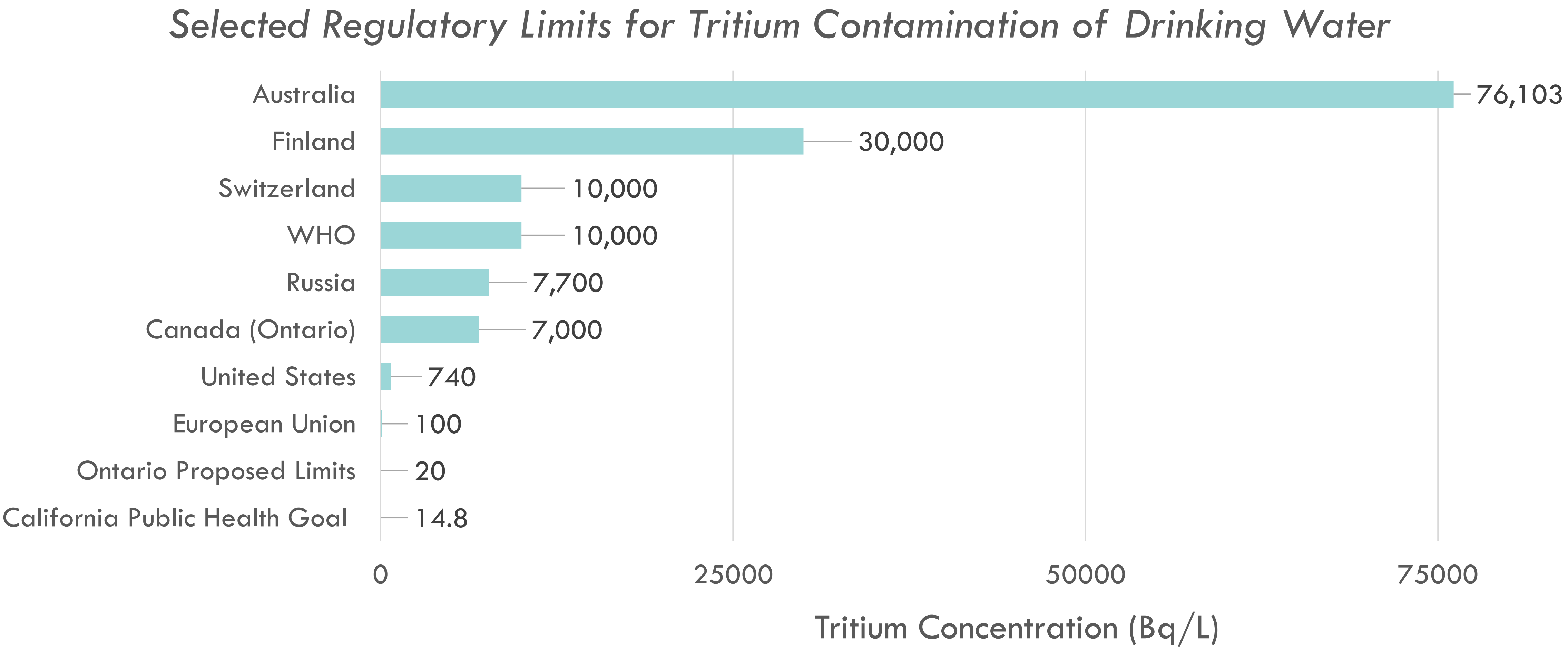
Workers

Environment

Setting acceptable limits on:

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

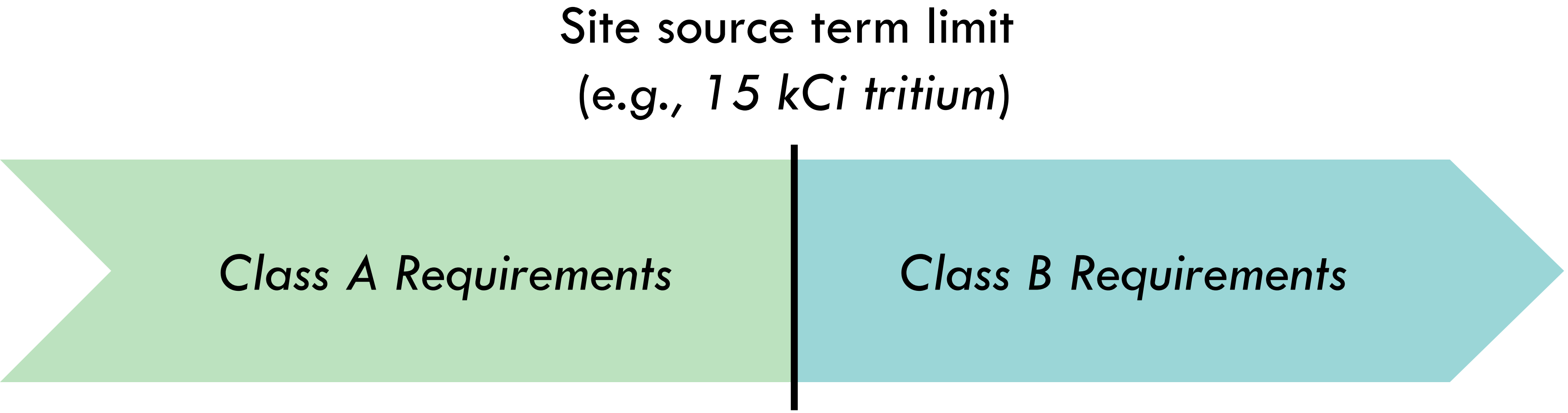
Development of regulatory requirements can be arbitrary and reflect a variety of competing stakeholder interests, assumptions



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

	Benefits	Drawbacks
Prescriptive regulation	• Predictable • Consistent	• Inflexible • Hard to codify
Performance-based regulation	• Versatile • Simple to develop	• Harder to review • Inherent variability

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



Site source term limit
(e.g., *15 kCi tritium*)

Class A Requirements

Class B Requirements

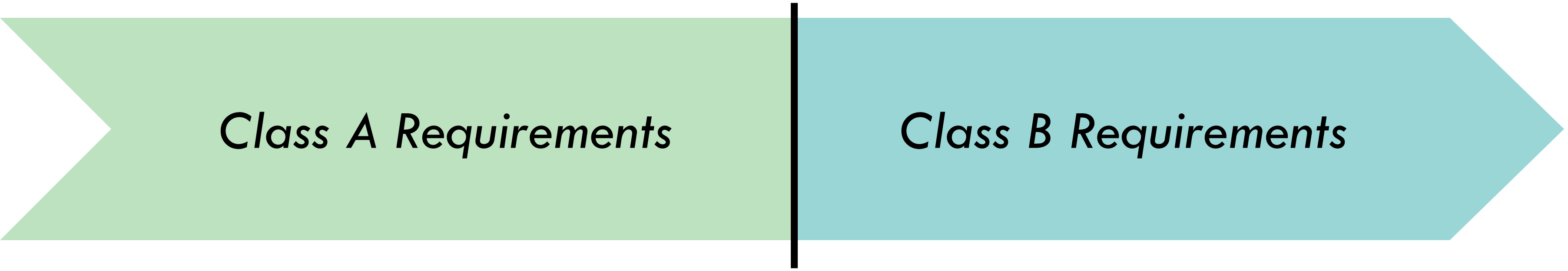
Consequence relevant parameters

- 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



Offsite dose limit
(e.g., *1 rem TEDE*)

Class A Requirements

Class B 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

Unform performance-based regulatory requirements

Scalable regulatory treatment based on applicant safety case for compliance with requirements

Define consistent regulatory requirements

Develop applicant specific safety case

Scale regulatory reviews based on safety case

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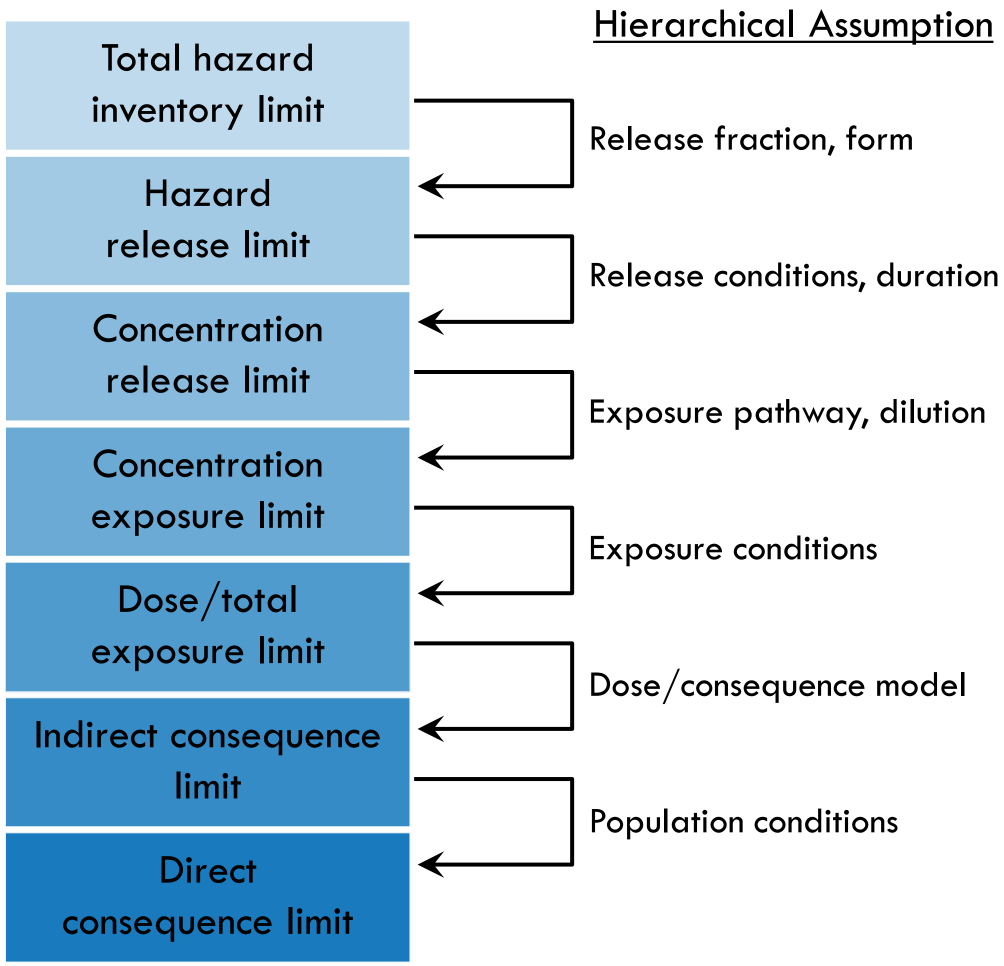
Comparison of regulatory limits and goals is be challenging based on technology and hazard differences

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 μCi/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 Assumption

Total hazard inventory limit

Release fraction, form

Hazard release limit

Release conditions, duration

Concentration release limit

Exposure pathway, dilution

Concentration exposure limit

Exposure conditions

Dose/total exposure limit

Dose/consequence model

Indirect consequence limit

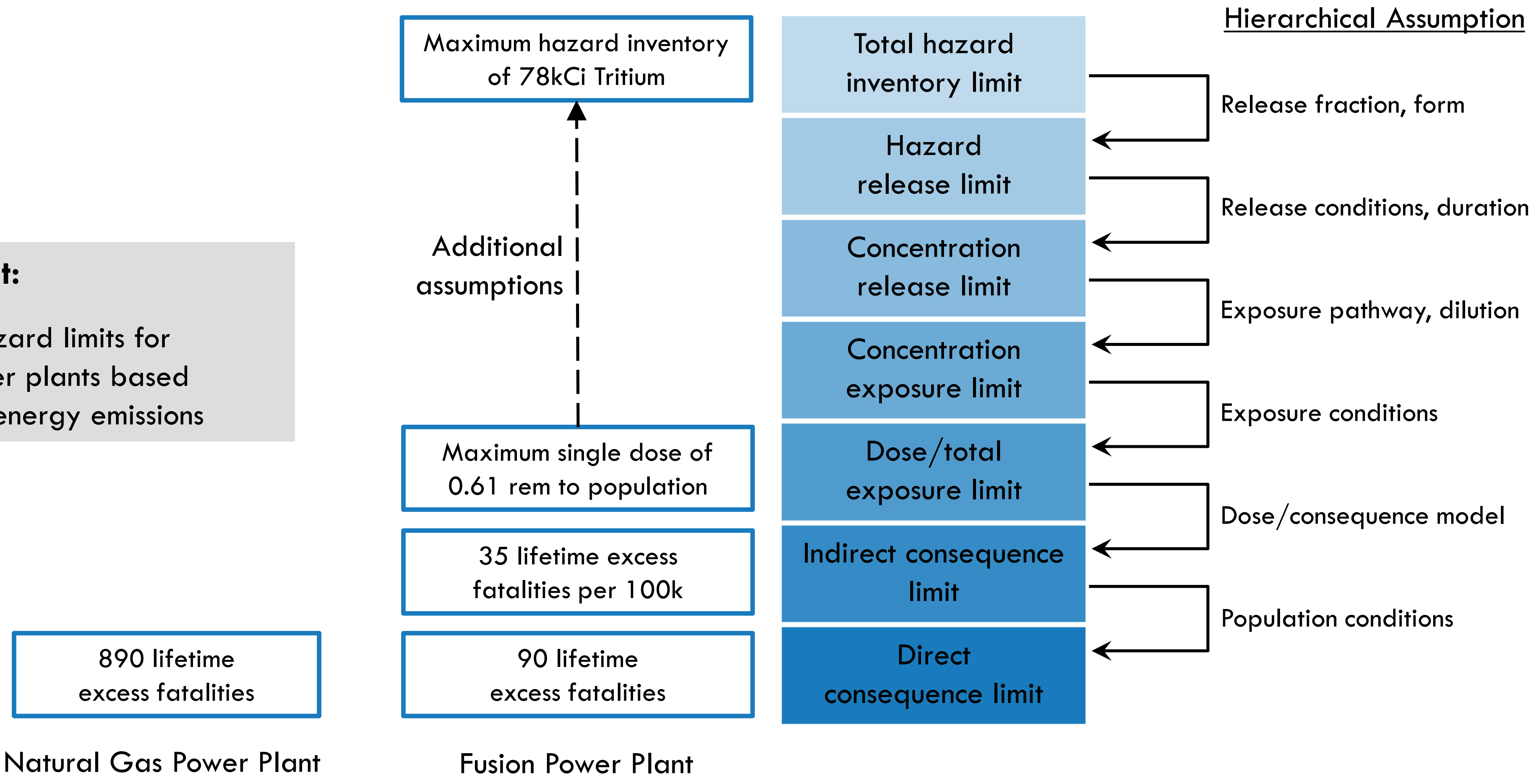
Population conditions

Direct consequence limit

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



Maximum hazard inventory of 78kCi Tritium

Additional assumptions

Maximum single dose of 0.61 rem to population

35 lifetime excess fatalities per 100k

890 lifetime excess fatalities

90 lifetime excess fatalities

Natural Gas Power Plant

Fusion Power Plant

Total hazard inventory limit

Hazard release limit

Concentration release limit

Concentration exposure limit

Dose/total exposure limit

Indirect consequence limit

Direct consequence limit

Hierarchical Assumption

Release fraction, form

Release conditions, duration

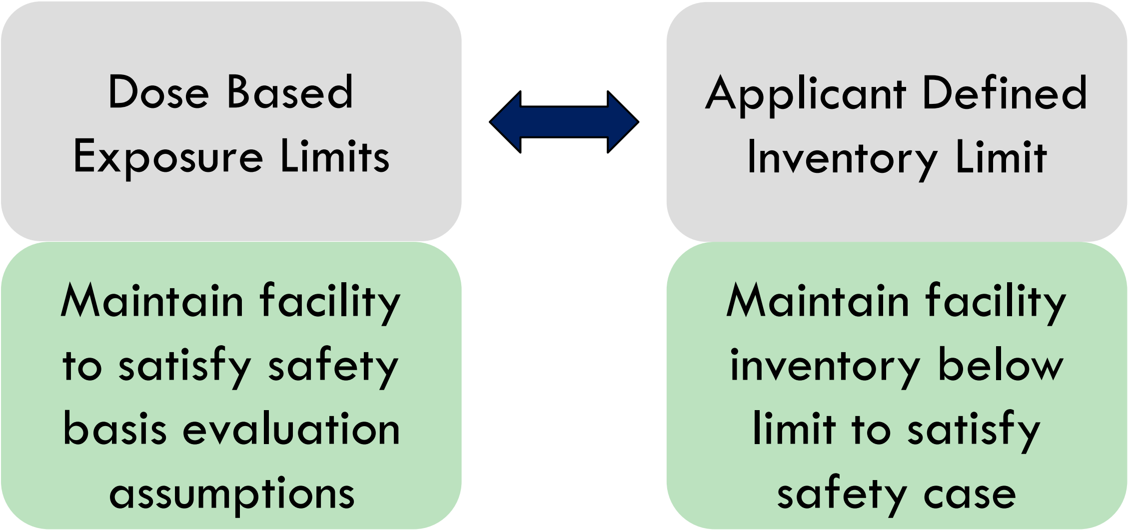
Exposure pathway, dilution

Exposure conditions

Dose/consequence model

Population conditions

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

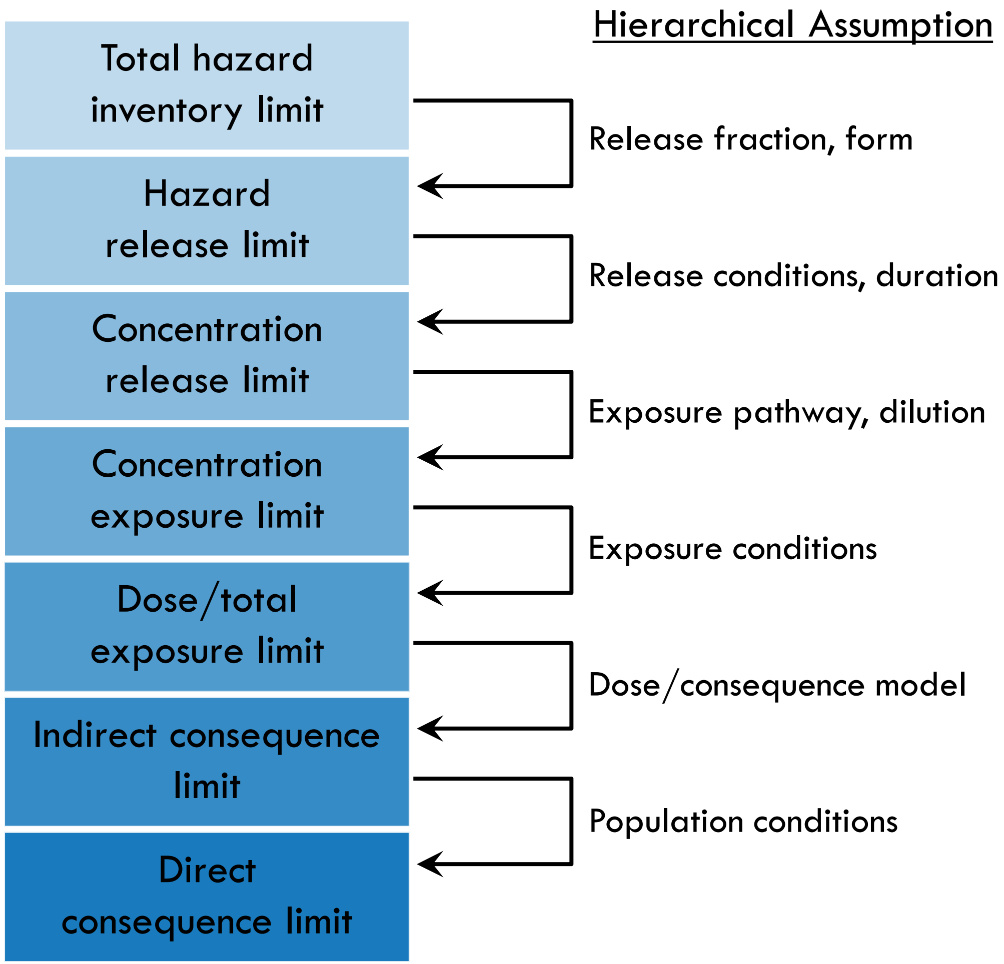


Dose Based Exposure Limits

Maintain facility to satisfy safety basis evaluation assumptions

Applicant Defined Inventory Limit

Maintain facility inventory below limit to satisfy safety case



Hierarchical Assumption

Total hazard inventory limit

Release fraction, form

Hazard release limit

Release conditions, duration

Concentration release limit

Exposure pathway, dilution

Concentration exposure limit

Exposure conditions

Dose/total exposure limit

Dose/consequence model

Indirect consequence limit

Population conditions

Direct consequence limit

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

Unform performance-based regulatory requirements

Scalable regulatory treatment based on applicant safety case for compliance with requirements

Define consistent regulatory requirements

Develop applicant specific safety case

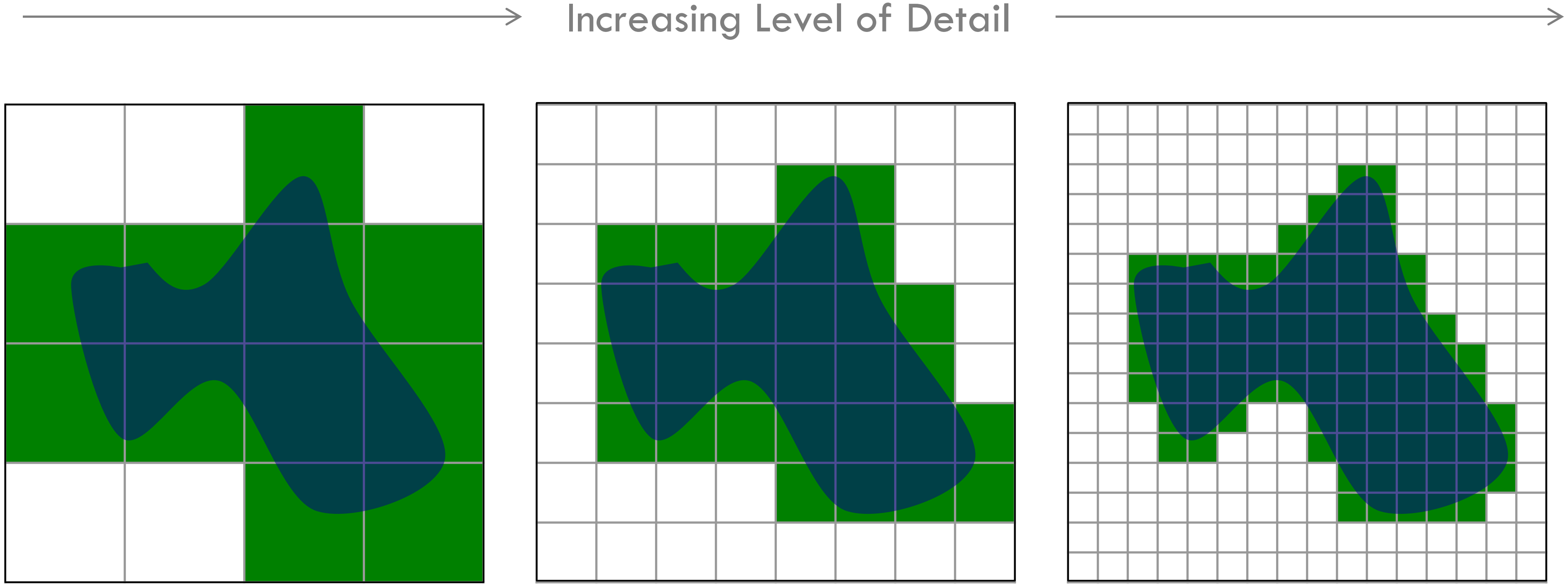
Scale regulatory reviews based on safety case

Method

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

Example Limit:

Shape must occupy less than 50% of total box area



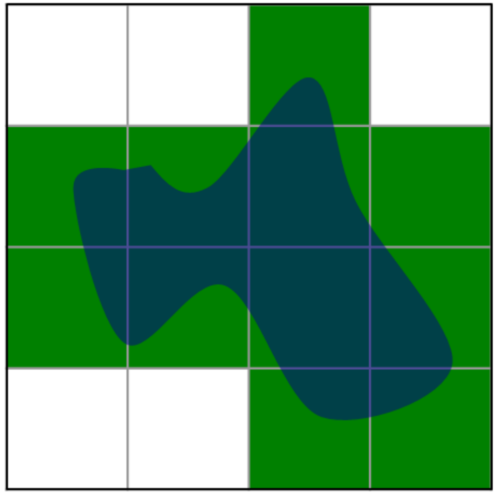
11/16 = 69%
Fails Regulatory Limit

30/64 = 47%
Passes Regulatory Limit

84/256= 33%
Passes Regulatory Limit

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

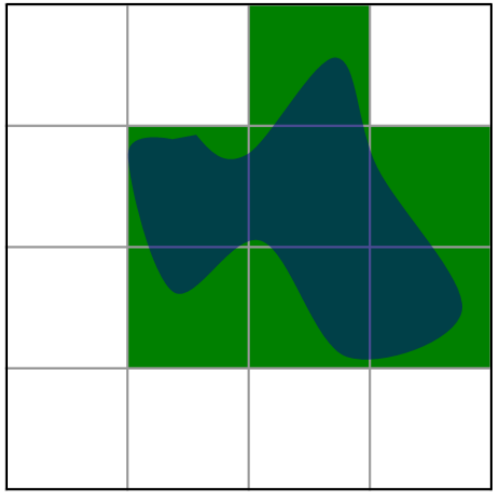
Original



11/16 = 69%

Fails Regulatory Limit

Change design to meet limit

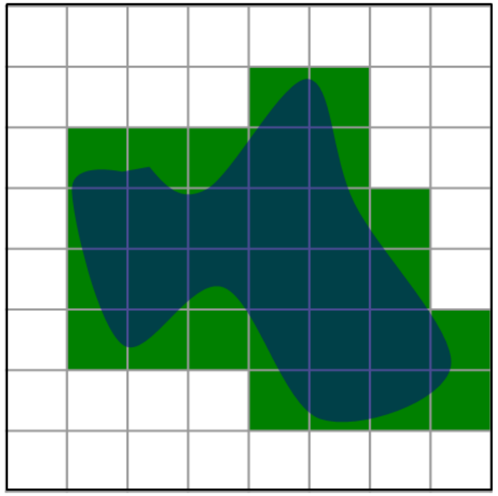


7/16 = 44%

Passes Hazard Limit

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

Change evaluation to meet limit



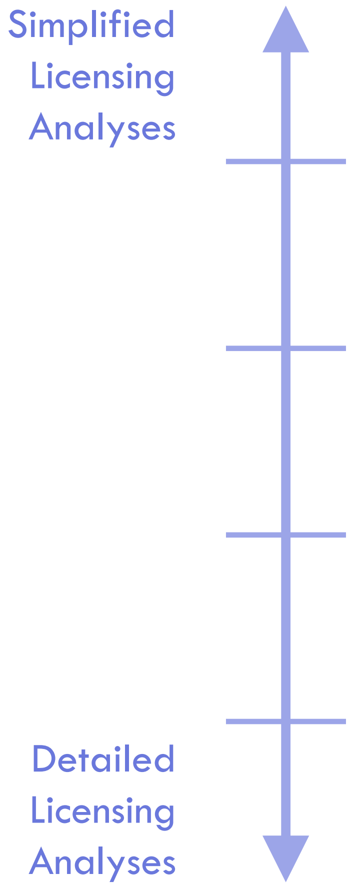
30/64 = 47%

Passes Hazard Limit

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

Method

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



Worst Case Release Evaluation

“What’s the worst that could happen?”

Maximum Credible Release Evaluation

“What’s the worst that could *really* happen?”

Deterministic Design Basis Analysis

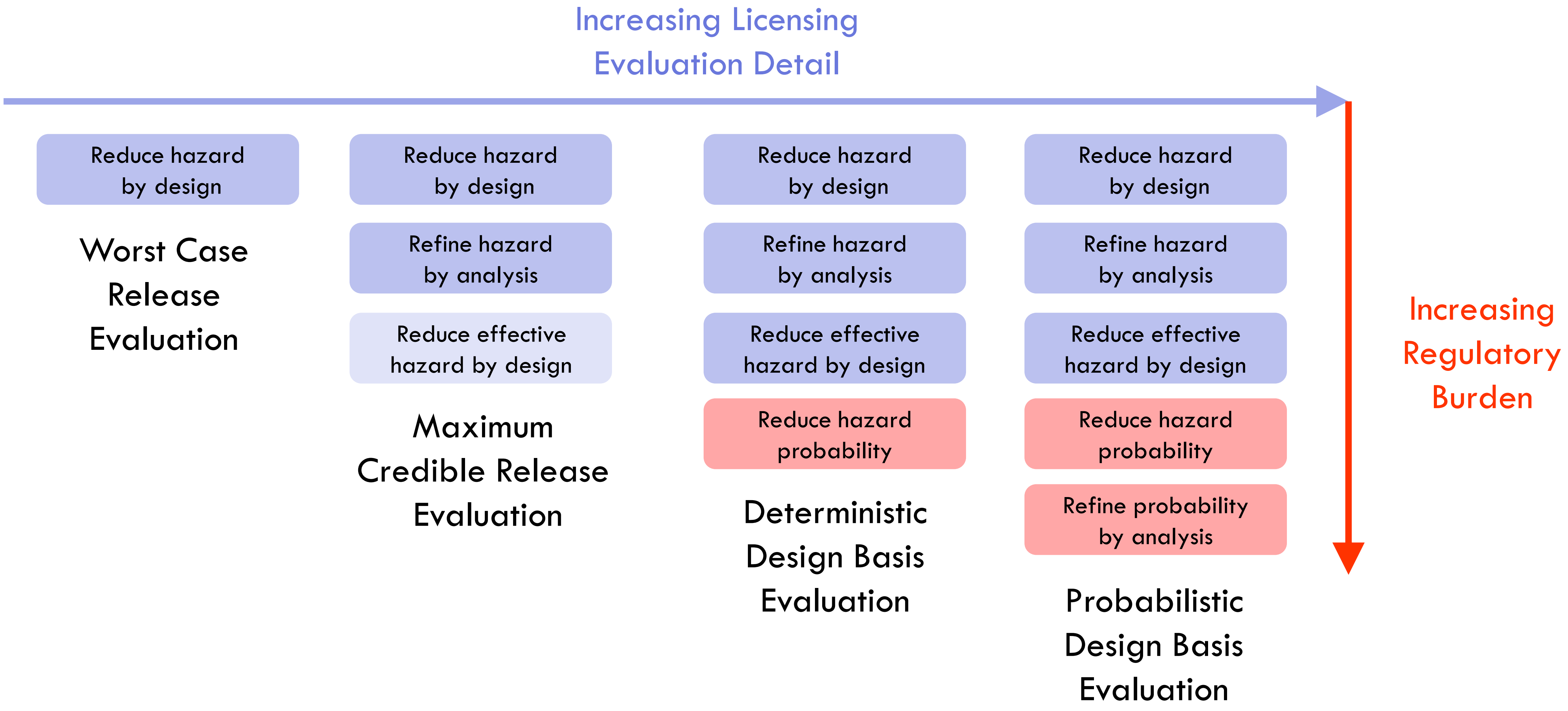
“What would happen if…?”

Probabilistic Design Basis Analysis

“How likely is it and what would happen if…?”

Method

Selecting licensing evaluations requires characterization of regulatory and design tradeoffs



Increasing Licensing Evaluation Detail

Increasing Regulatory Burden

Reduce hazard by design

Worst Case Release Evaluation

Reduce hazard by design

Refine hazard by analysis

Reduce effective hazard by design

Maximum Credible Release Evaluation

Reduce hazard by design

Refine hazard by analysis

Reduce effective hazard by design

Reduce hazard probability

Deterministic Design Basis Evaluation

Reduce hazard by design

Refine hazard by analysis

Reduce effective hazard by design

Reduce hazard probability

Refine probability by analysis

Probabilistic Design Basis Evaluation

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

Unform performance-based regulatory requirements

Scalable regulatory treatment based on applicant safety case for compliance with requirements

Define consistent regulatory requirements

Develop applicant specific safety case

Scale regulatory reviews based on safety case

Review

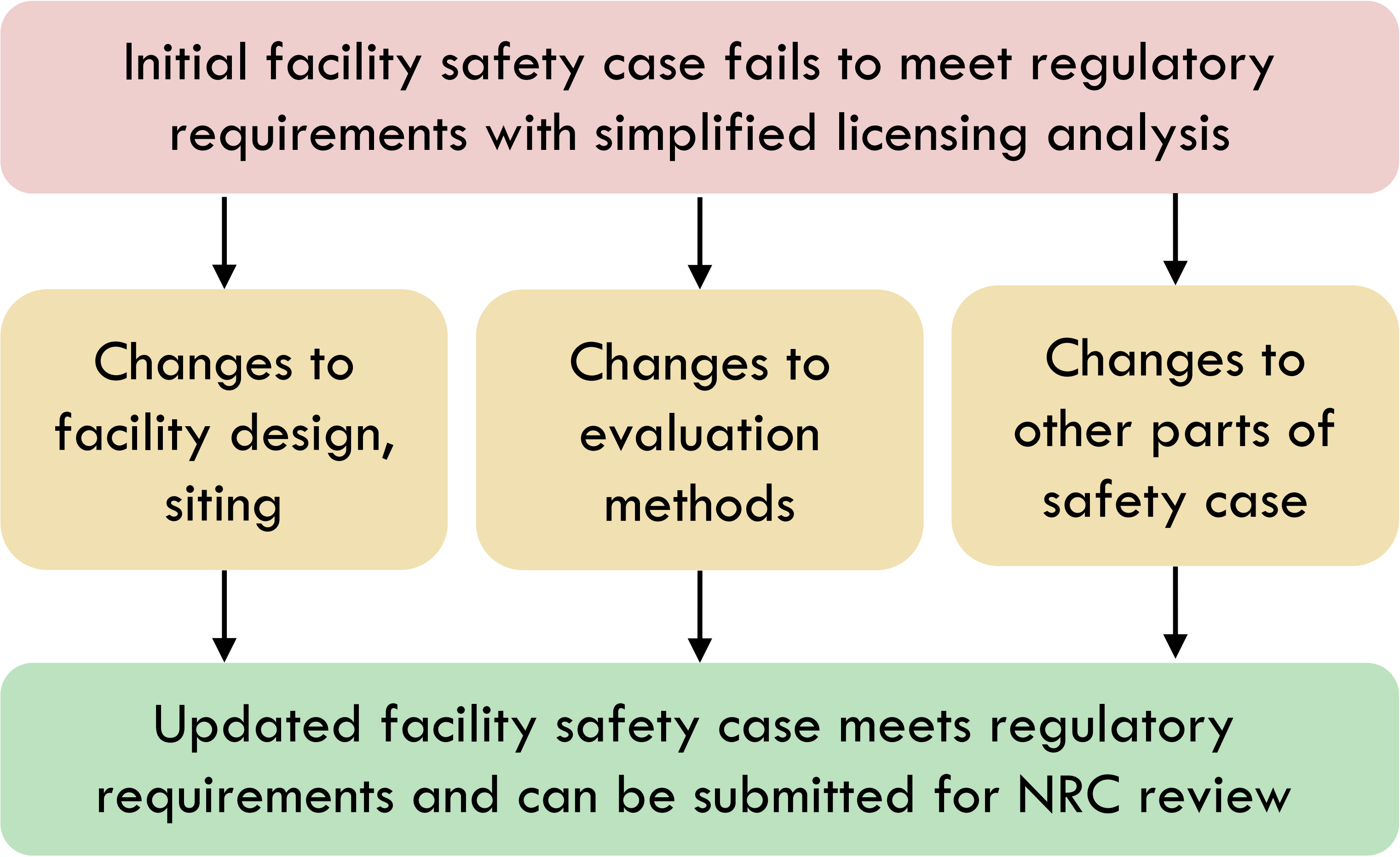
Facilities using simpler safety case to meet performance-based regulation should have lower regulatory burden

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

Increasing Regulatory Burden

Review

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



Initial facility safety case fails to meet regulatory requirements with simplified licensing analysis

Changes to facility design, siting

Changes to evaluation methods

Changes to other parts of safety case

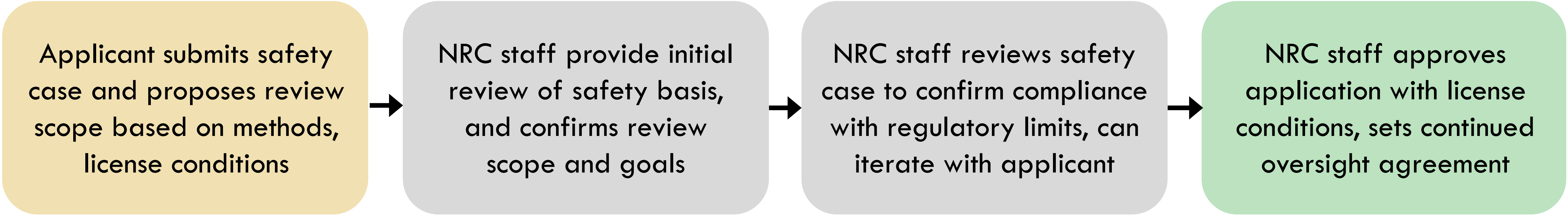
Updated facility safety case meets regulatory requirements and can be submitted for NRC review

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

Review

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



Applicant submits safety case and proposes review scope based on methods, license conditions

→

NRC staff provide initial review of safety basis, and confirms review scope and goals

→

NRC staff reviews safety case to confirm compliance with regulatory limits, can iterate with applicant

→

NRC staff approves application with license conditions, sets continued oversight agreement

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

	Example Safety Basis	*Example Scaled Review*
Fusion Facility A	• Site-wide tritium < 10 g • 300 m to site boundary • Maximum credible evaluation	• 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

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

Unform performance-based regulatory requirements

Scalable regulatory treatment based on applicant safety case for compliance with requirements

Define consistent regulatory requirements

Develop applicant specific safety case

Scale regulatory reviews based on safety case

Agenda

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1:20 pm	Agreement States Current Oversight of Fusion R&D Activities	Diego Saenz
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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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Savannah River National Laboratory

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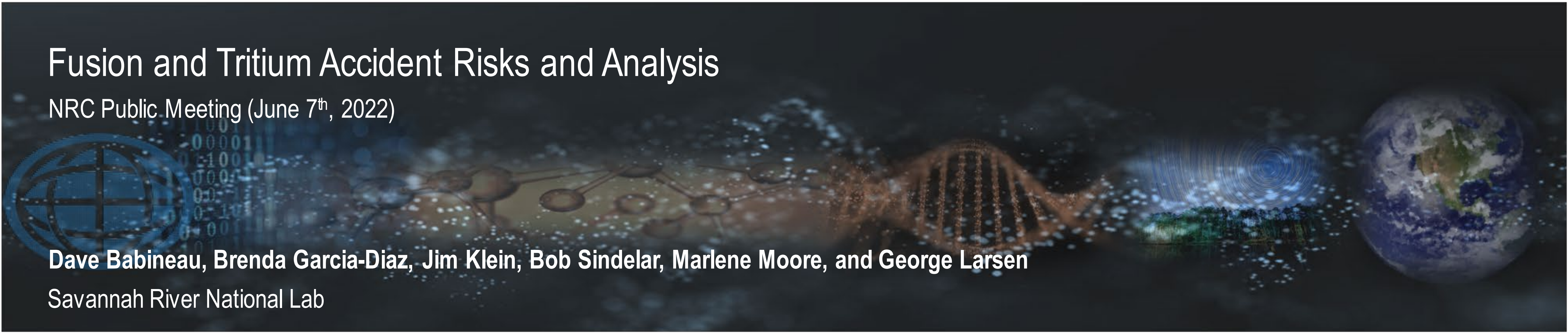

Fusion and Tritium Accident Risks and Analysis

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

U.S. DEPARTMENT OF ENERGY

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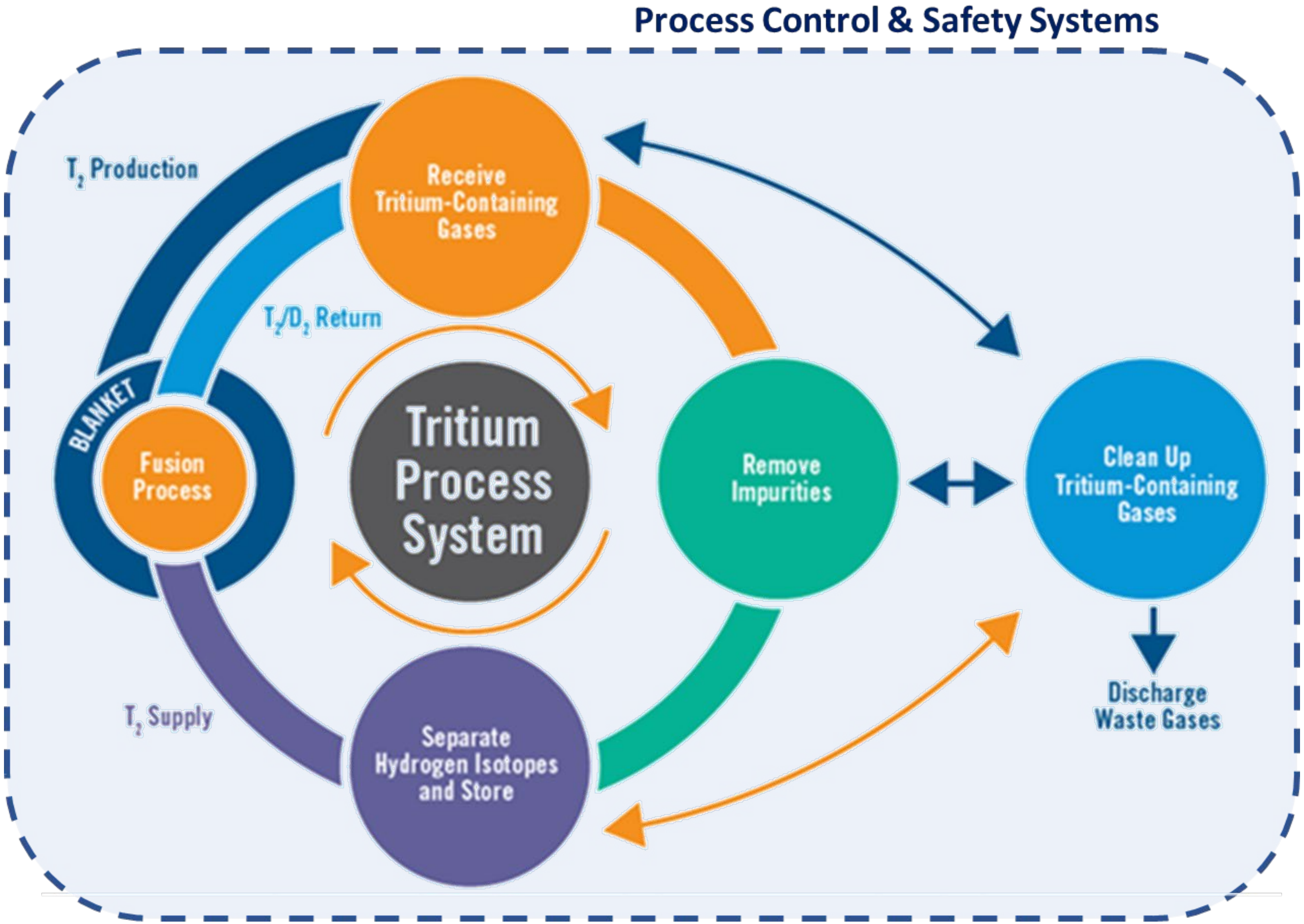
Tritium Fuel Cycle: Similar Core for All Applications with Blanket Integration for Fusion

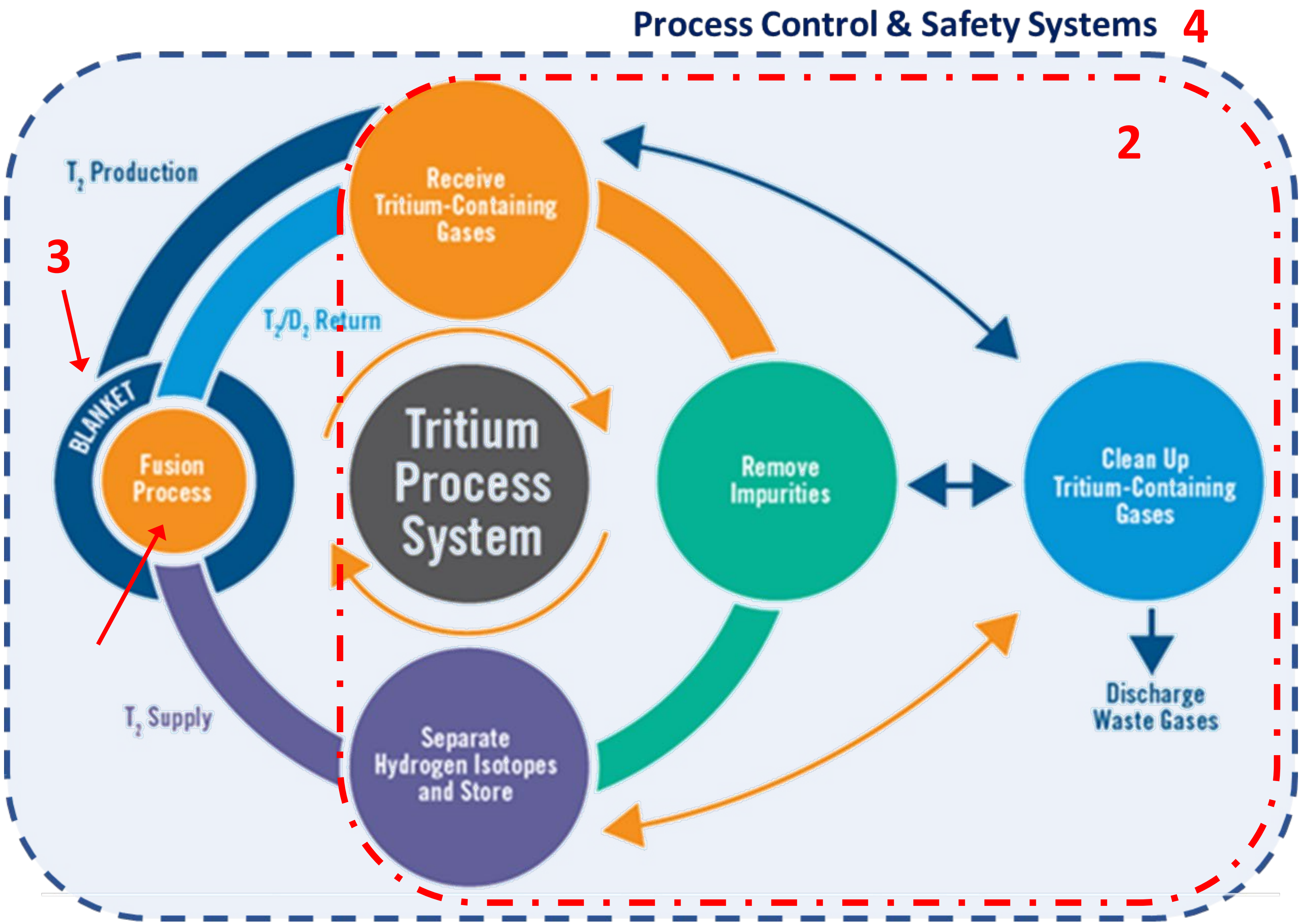


- Bulk separation of hydrogen isotopes from other gases
- Remove impurities that enter process (e.g. HTO, nitrogen, etc.)
- Store and account for isotopes
- Clean exhaust gas and ensure it is suitable for release

- Proposed blanket technologies vary significantly and are at low TRL levels
- Need caution with SF_6 used for high voltage electronics and tritiated ammonia generated from N_2 used in divertor

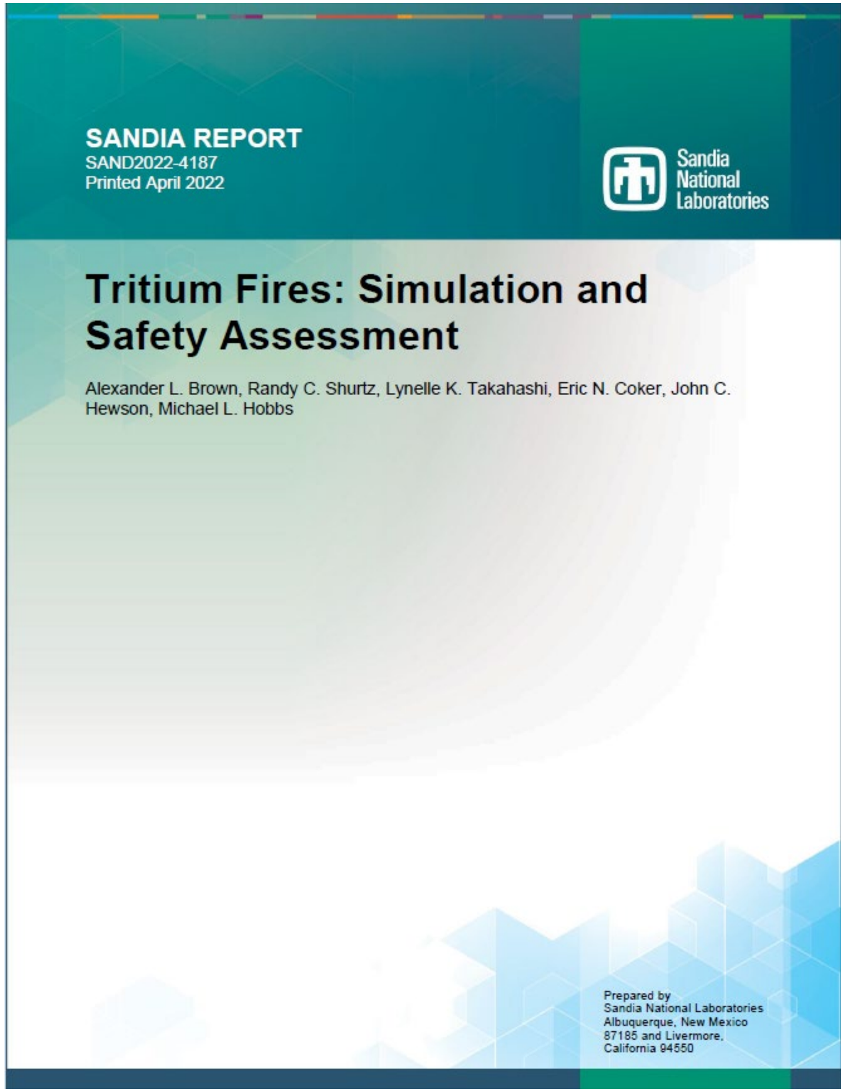
Key Fuel Cycle Areas for Regulation and Safeguards

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 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
- 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 T_2 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]*



SANDIA REPORT
SAND2022-4187
Printed April 2022

Sandia National Laboratories

Tritium Fires: Simulation and Safety Assessment

Alexander L. Brown, Randy C. Shurtz, Lynelle K. Takahashi, Eric N. Coker, John C. Hewson, Michael L. Hobbs

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Fires, Tritium, and Conversion of Tritium to HTO

- 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)

- 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*

  - *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)

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

- 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 breech 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

- 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)

- 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

- 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

- 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

- 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

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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
  Stellarators
  Spherical tokamak (ST)
  Field-reversed configurations (FRC)
  Reversed-field pinches (RFP)
  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

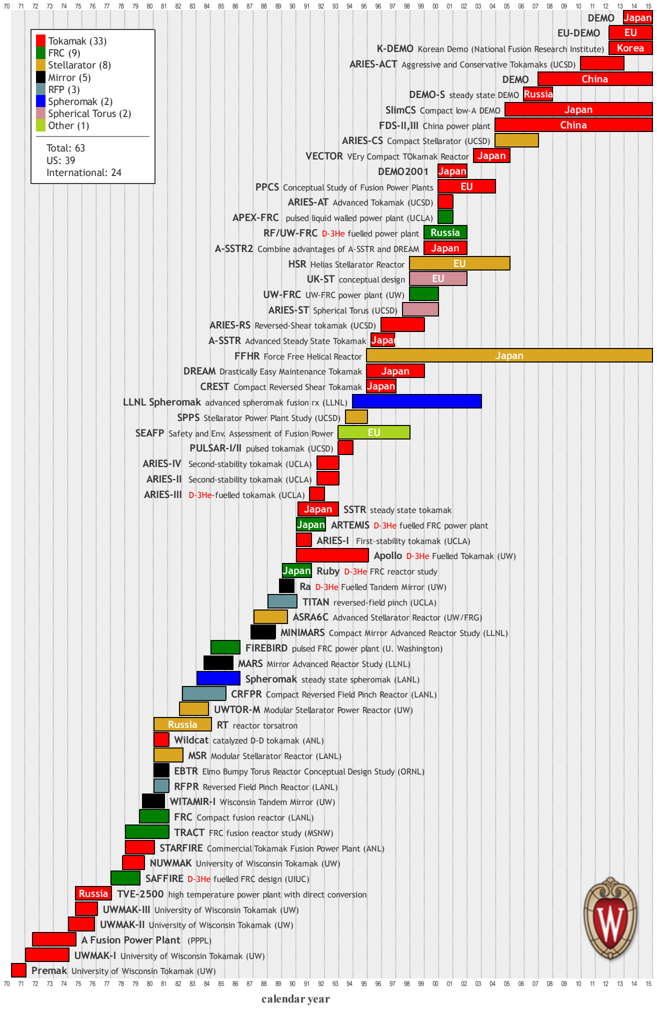
(under strict alloying element and impurity control),

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.

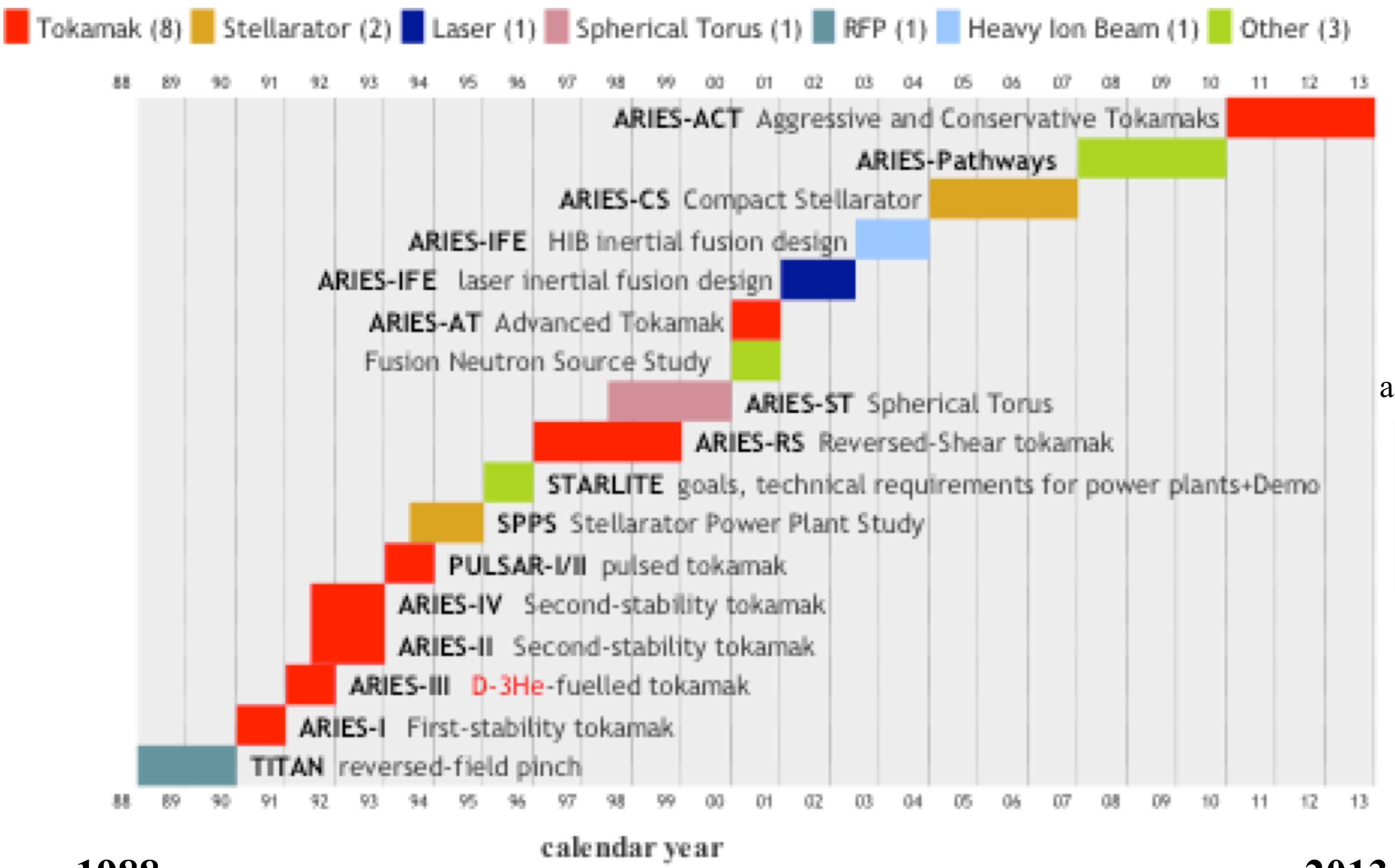
Most studies and experiments are currently devoted to **D-T fuel cycle** – least demanding to reach ignition.

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

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

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

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

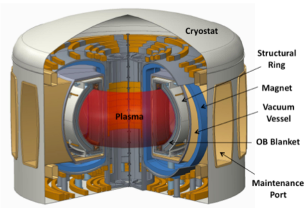


1988 **2013**

ARIES-ACT

Tokamak

(with reduced activation structure)

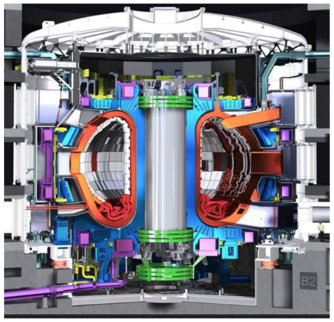


http://qedfusion.org/aries.shtml

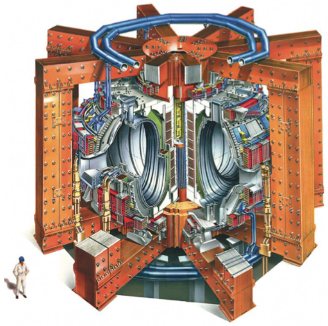
The ARIES project focused mainly on the device. Less attention was given to the BOP.

Worldwide Pathways to Fusion Energy

ITER

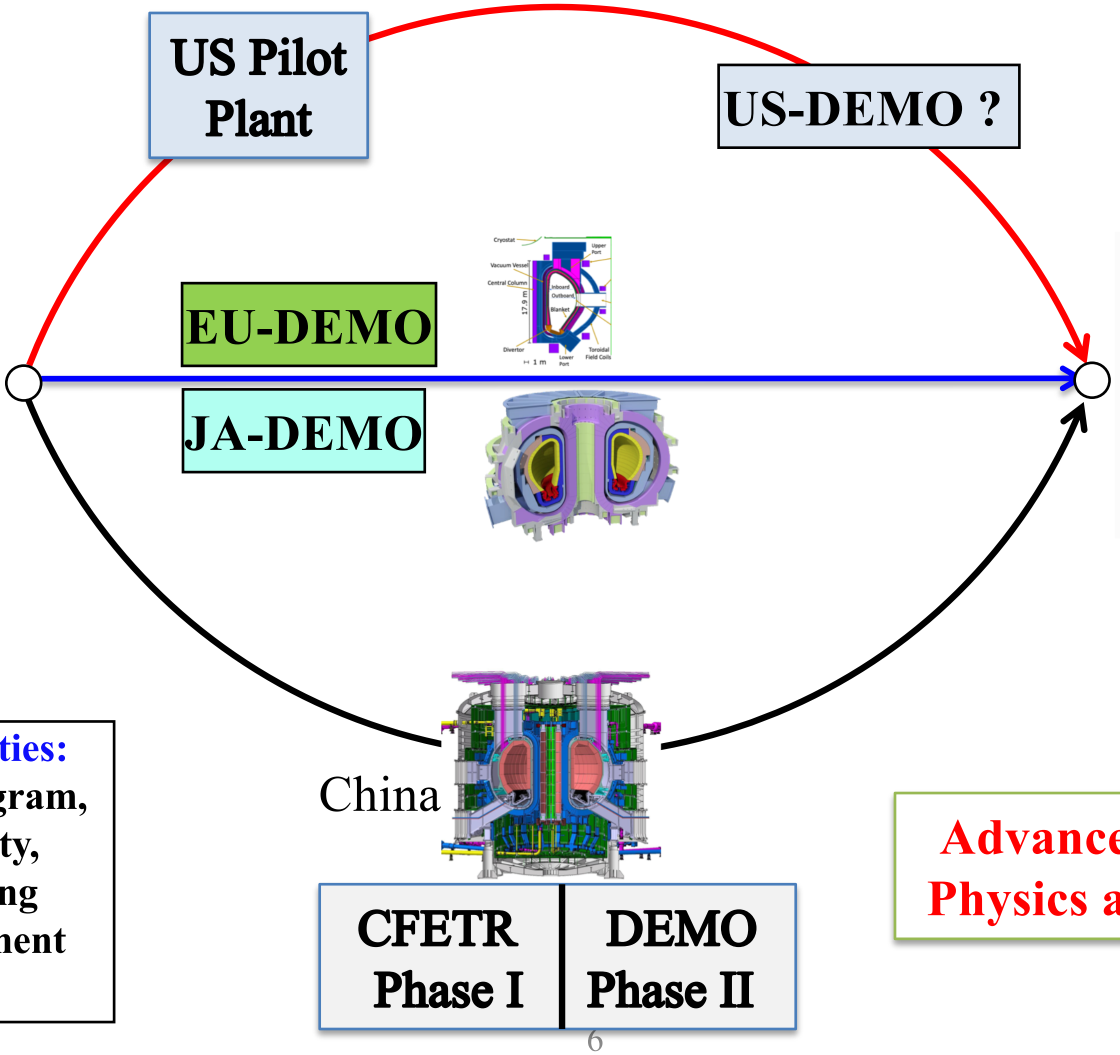


JET



+ 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 ?

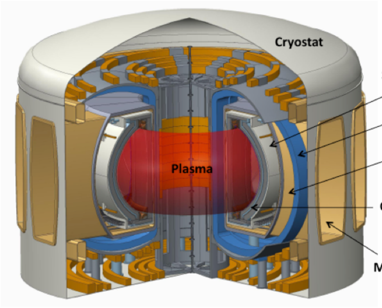
EU-DEMO

JA-DEMO

China

CFETR Phase I | **DEMO Phase II**

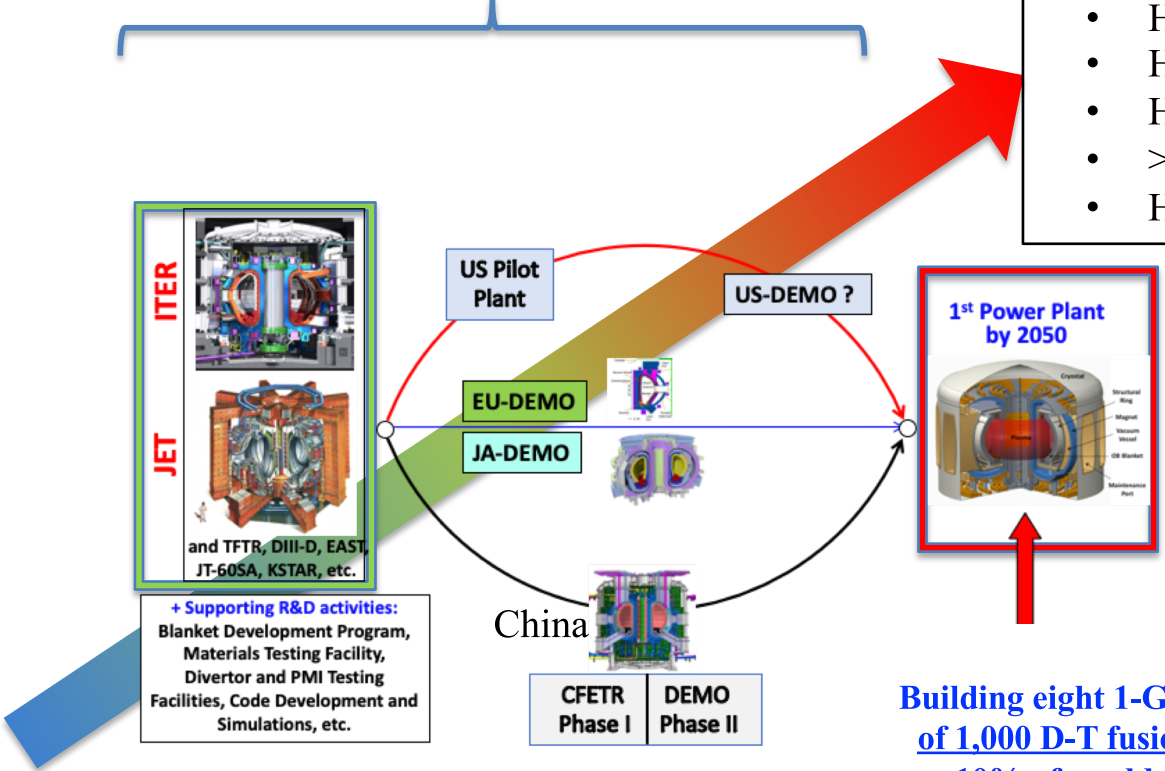
1st Power Plant by 2050



Advanced or Conservative Physics and/or Technology?

Radioactivity Level Varies Widely with Designs

One-of-a-kind Devices



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

High Radioactivity **(Power Plant):**

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

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

Low Radioactivity **(ITER):**

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

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

Resources Will Eventually be Limited

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

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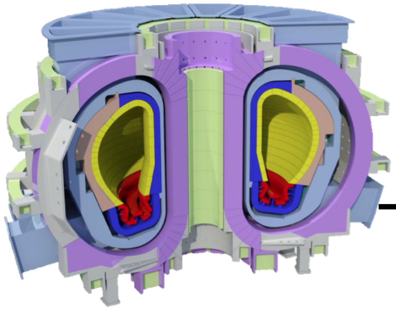
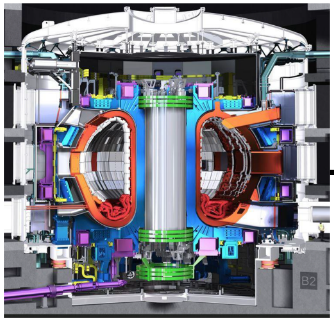
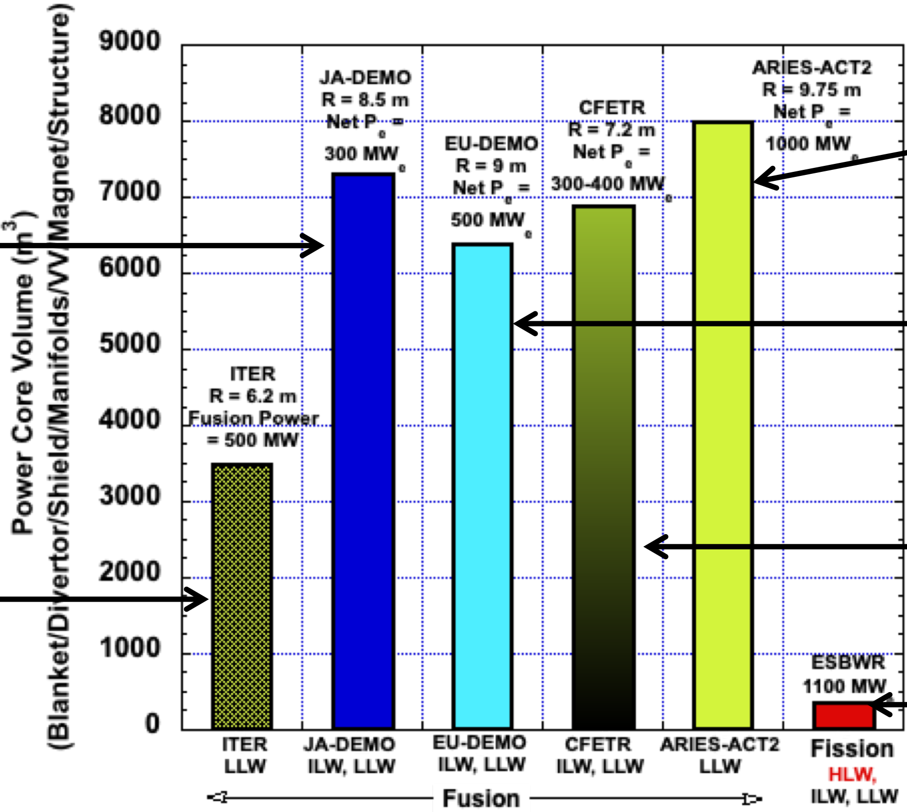
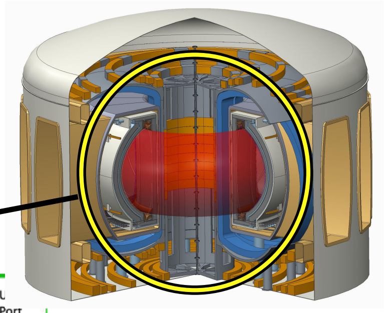
* Radioactive waste (radwaste) management

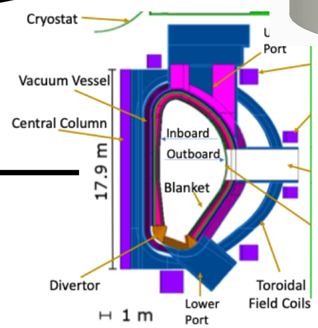
Fusion Designs Employing Reduced-Activation Materials Could Generate Only LLW$^{\#}$, but in Large Quantity Compared to Fission

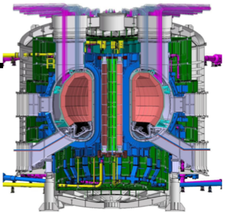


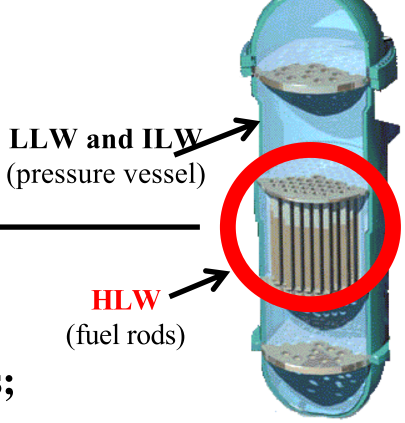












Actual volume of fusion power components in ITER, JA, EU, China, and US ARIES designs; not compacted, no replacements; no plasma chamber; no cryostat/bioshield.

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

Others came and mostly disappeared

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

Activated materials – not counted as radwaste

Each option faces its own set of challenges

The Disposal Option

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

Environmental Concerns and Facts

- **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.nr c.gov/waste/llw-disposal/llw-pa/gtcc-transuranic-waste-disposal.html*

Waste Disposal Rating – Metric for Waste Classification

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

- **WDR < 1** means Class C LLW (using Class C limits)
- **WDR < 0.1** means waste may qualify as Class A LLW (to be re-evaluated using Class A limits)
- **WDR > 1** means GTCC.

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

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

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* *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

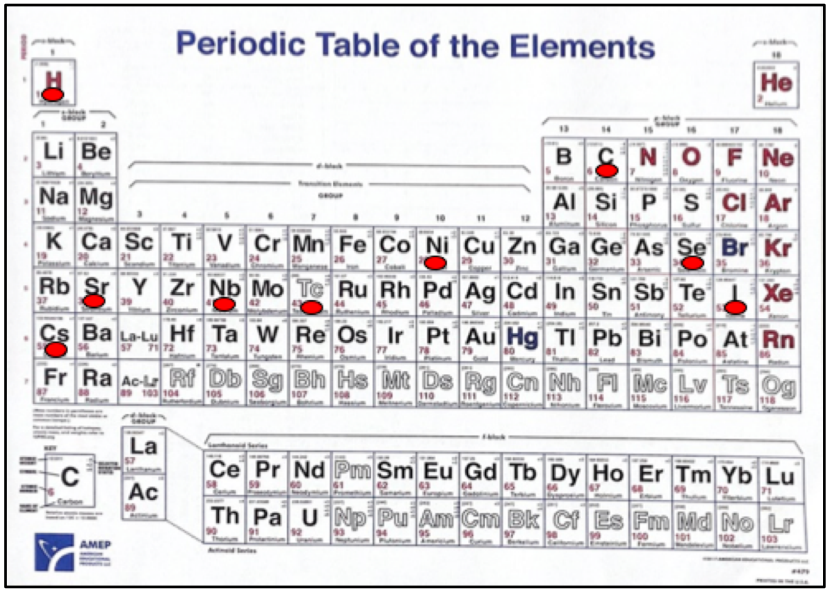
Fetter et al.* expanded the NRC 10CFR61 list considerably and performed analyses to determine the Class C specific activity limits for many radionuclides of interest to fusion using a methodology similar to that of NRC. Although Fetter's calculations carry no regulatory endorsement by NRC, they are useful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

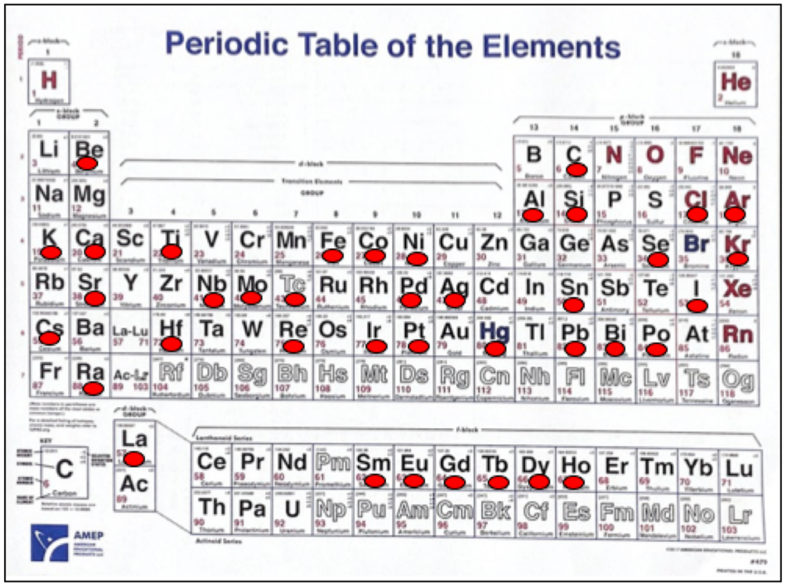
- **Not** in regulation form yet
- Approved by U.S. Fusion Safety Standing Committee[#]
- Class C limits for **53** radionuclides of interest to fusion
- **No** limits available for Class A LLW.

- *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).*

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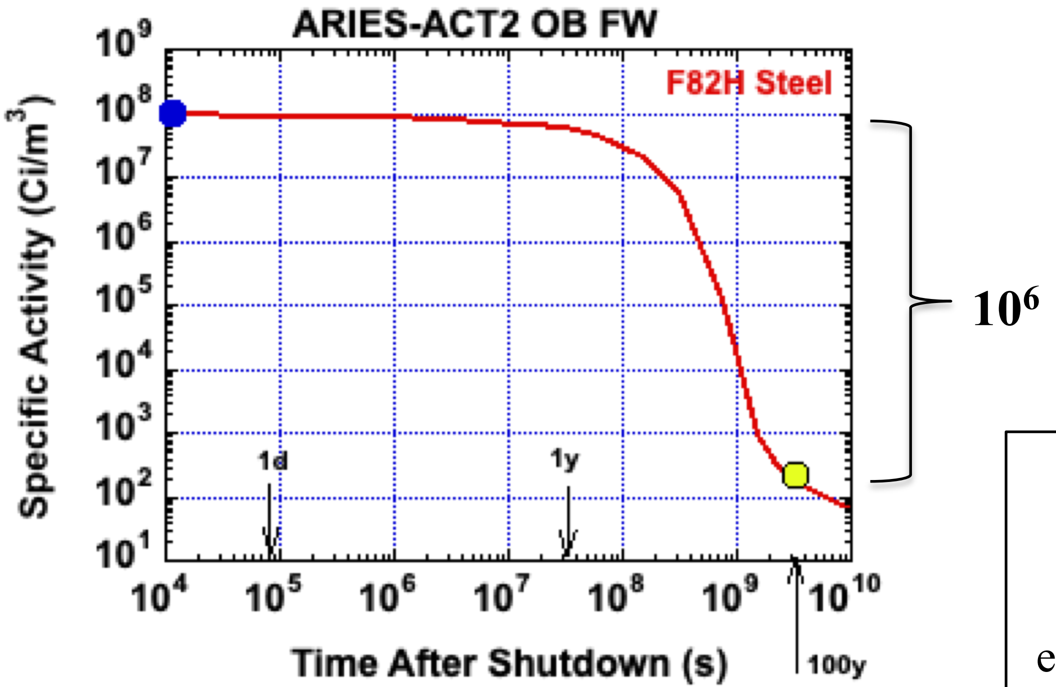
* Excluding actinides and fission products.

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?

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* 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

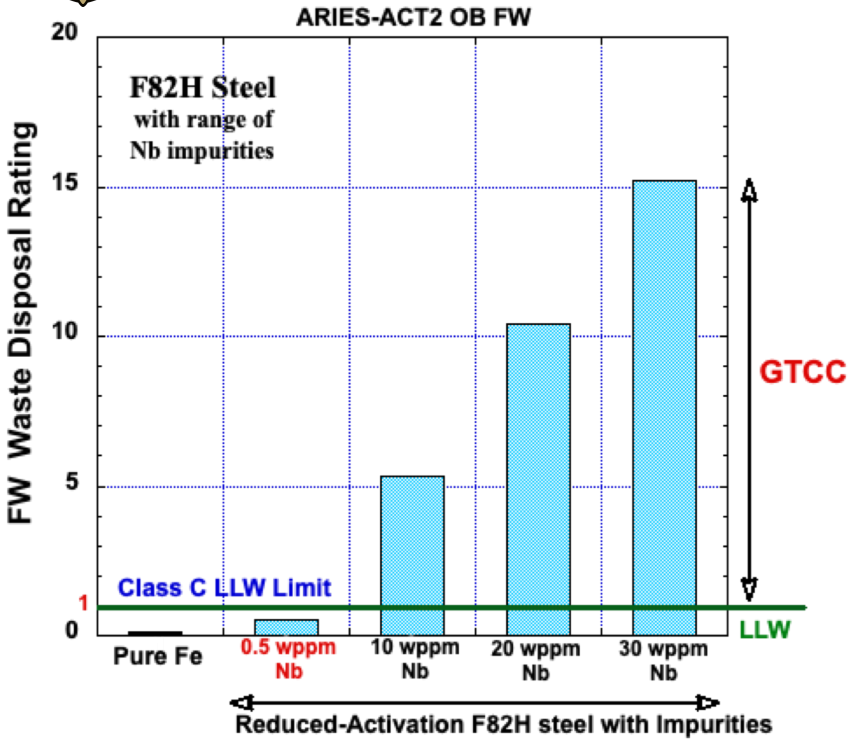
Compositional limitations for fusion designs:

- 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.

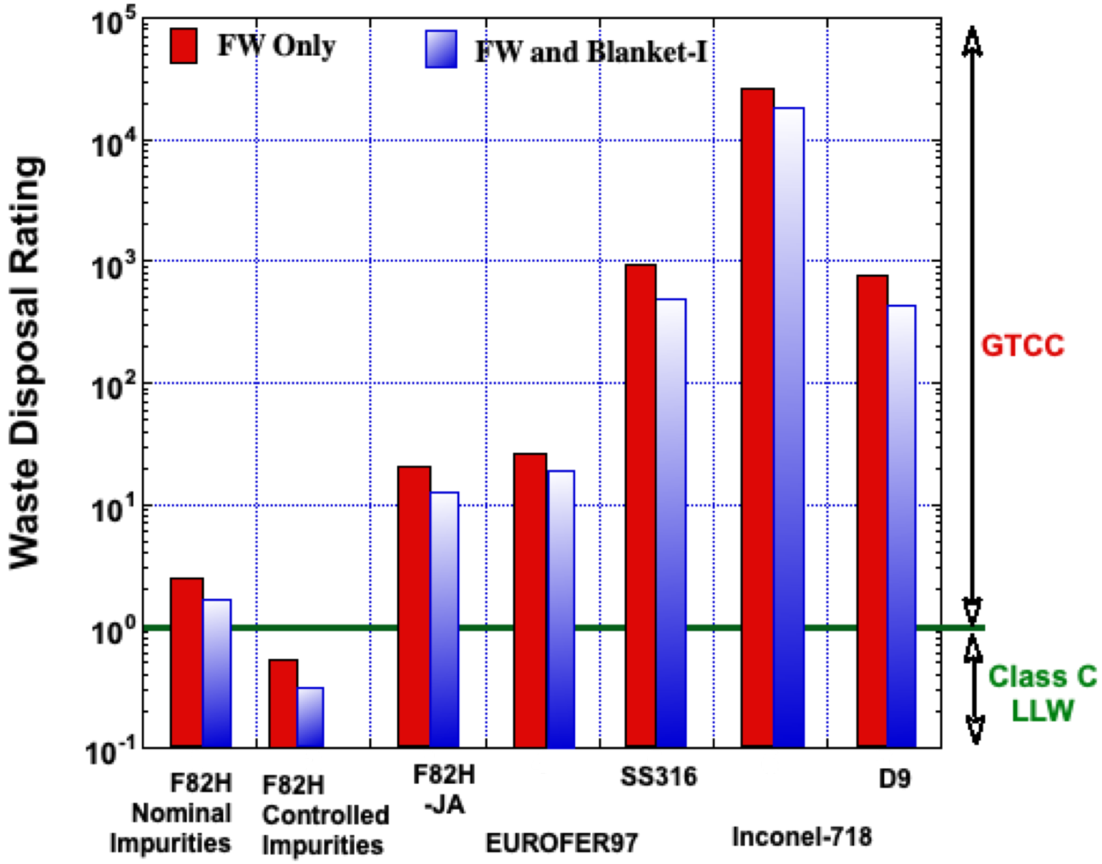
- Nb impurity impacts WDR greatly and should be kept below 1 wppm.

- 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



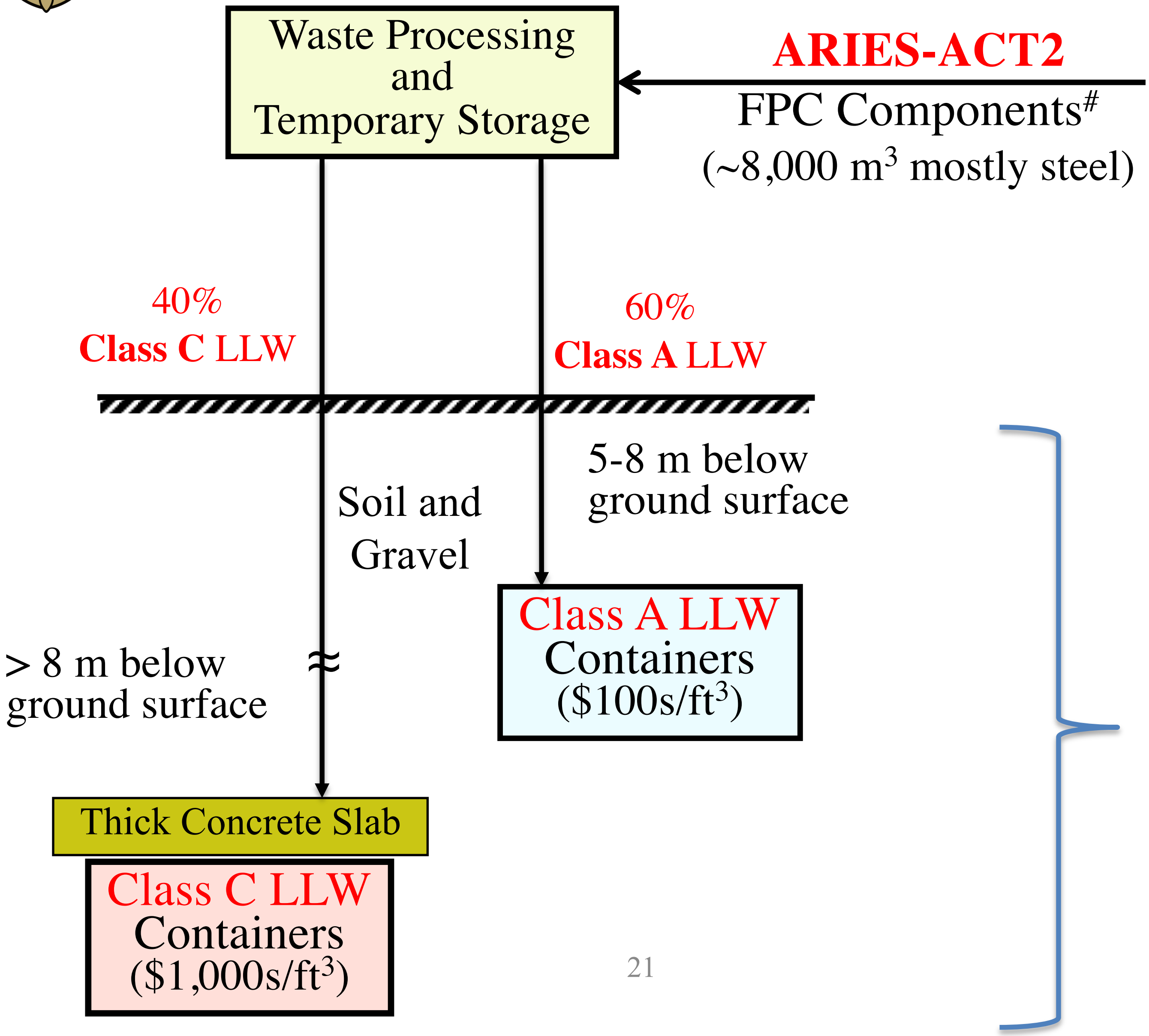
Nb impurity has major impact on WDR



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

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

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

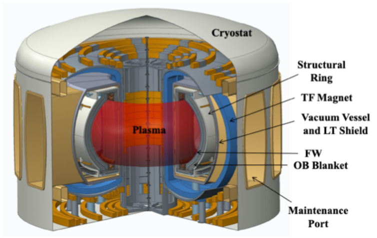


Waste Processing and Temporary Storage

ARIES-ACT2

FPC Components#

(~8,000 m^3 mostly steel)



40%

Class C LLW

60%

Class A LLW

Soil and Gravel

5-8 m below ground surface

> 8 m below ground surface

≈

Class A LLW Containers (\$100s/ft^3)

Thick Concrete Slab

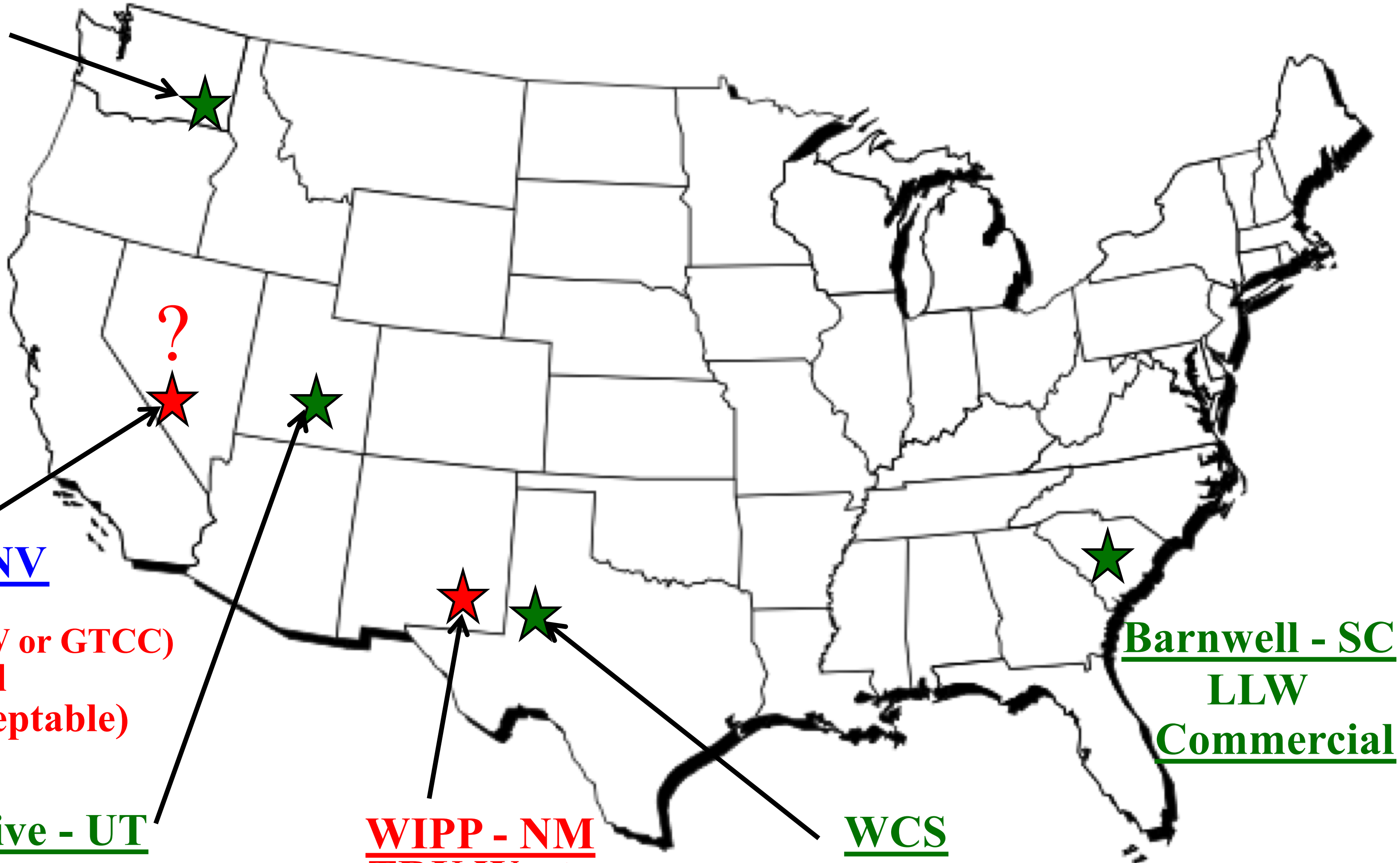
Class C LLW Containers (\$1,000s/ft^3)

Will be disposed of in commercial LLW repositories.

Where?

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

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



Richland - WA
LLW
Commercial

Yucca Mountain - NV
HLW
(Spent fuel only; no LLW or GTCC)
Commercial
(not politically acceptable)

Clive - UT
LLW
Commercial

WIPP - NM
TRU Waste
For Defense Program only

WCS
LLW
Commercial
and Government

Barnwell - SC
LLW
Commercial

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

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

- Barnwell facility in SC:
  - 1971 – 2038
  - Receives Class A, B, C LLW
  - Supports east-coast reactors and hospitals
  - 870,000 m^3 capacity
  - 90% Full
  - In July 2008, Barnwell facility closed to all LLW received from outside 3 Compact States: CT, NJ, SC
  - 36 states lost access to Barnwell, having no place to dispose 91% of their Class B & C LLW
  - NRC now allows storing LLW onsite for extended period.
- Clive facility in Utah:
  - Receives nationwide Class A LLW only
  - Disposes 98% of US Class A waste volume, but does not accept sealed sources or biological tissue waste – a great concern for biotech industry
  - 4,571,000 m^3 capacity
  - Closure by 2024.
- Richland facility in WA:
  - Class A, B, C LLW
  - Supports 11 northwest states
  - 1,700,000 m^3 capacity
  - Closure by 2056.
- WCS (Waste Control Specialists) in TX:
  - Newest facility for disposal, storage and treatment of LLW from all 50 states.
  - Class A, B, C LLW.

Limited option for disposal will drive disposal cost high

Key Issues and Needs for Disposal

Some issues/needs are related to activation areas inside FPC (that could be addressed by fusion designers), while others are related to areas outside FPC, requiring industrial, national lab, and fission experiences, DOE-OFES and NRC involvements.

Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclides, radiation level, component size, weight, etc.).

Issues:

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

Needs:

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

Key Takeaways:

Existing U.S. LLW sites cannot handle 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 μSv/y (< 1% of background radiation).

Decommissioning Goal for 21st Century

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

U.S.:

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

- *Related references:*

Hrncir, T., et al., (2013). "The impact of radioactive steel recycling on the public and professionals," Journal of Hazardous Materials, 254-255, 98-106.

US Department of Energy, "Recycle of Scrap Metals Originating from Radiological Areas," DOE/EA-1919 (2012). https://www.energy.gov/nepa/ea-1919-recycle-scrap-metals-originating-radiological-areas.

Radiological Assessments for Clearance of Equipment and Materials from Nuclear Facilities, Draft NUREG-1640, Nuclear Regulatory Commission, Washington, D.C. (1998).

ANIGSTEIN, R. et al., "Radiological Assessments for Clearance of Materials from Nuclear Facilities," volume 1, NUREG-1640, US Nuclear Regulatory Commission (2003). http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/.

U.S. Department of Energy, "Clearance And Release Of Personal Property From Accelerator Facilities," DOE-STD-6004-2016 (2016). https://www.standards.doe.gov/standards-documents/6000/6004-astd-2016.

Decommissioning Goal for 21st Century (Cont.)

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

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* 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.

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* 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:

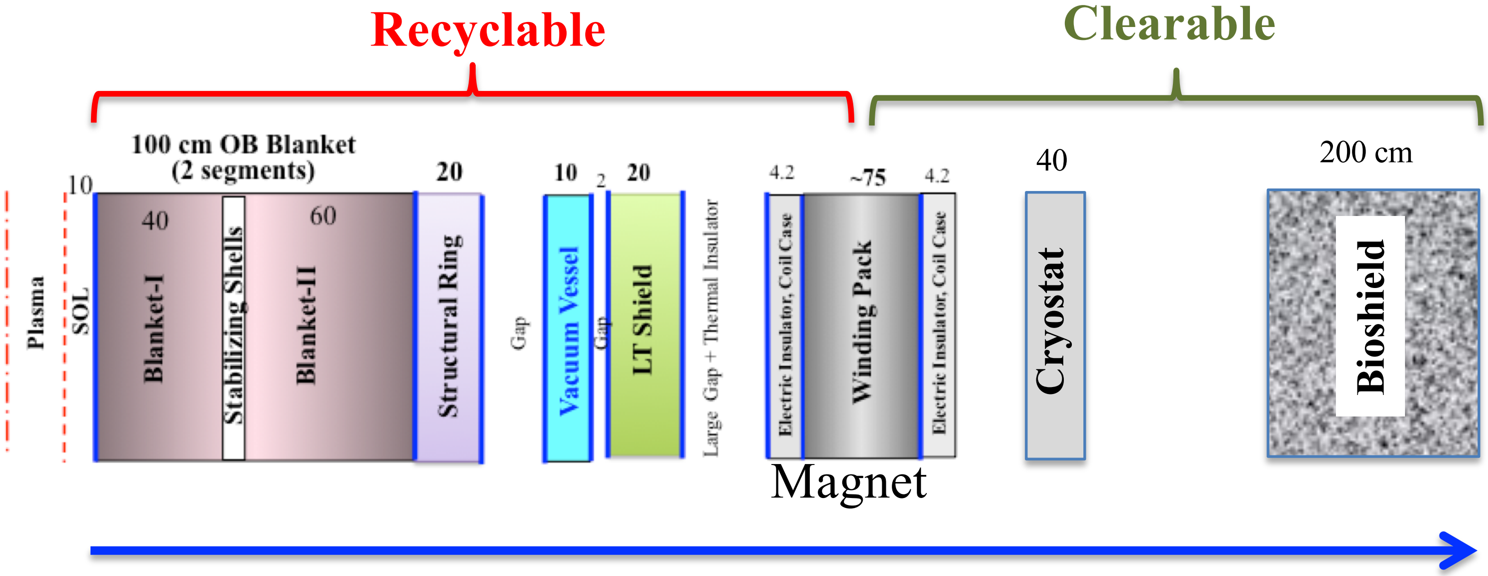
Clearance Levels for Radionuclides in Solid Materials – Application of Exemption Principles, Interim Report IAEA-TECDOC-855, International Atomic Energy Agency, Vienna (1996).

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

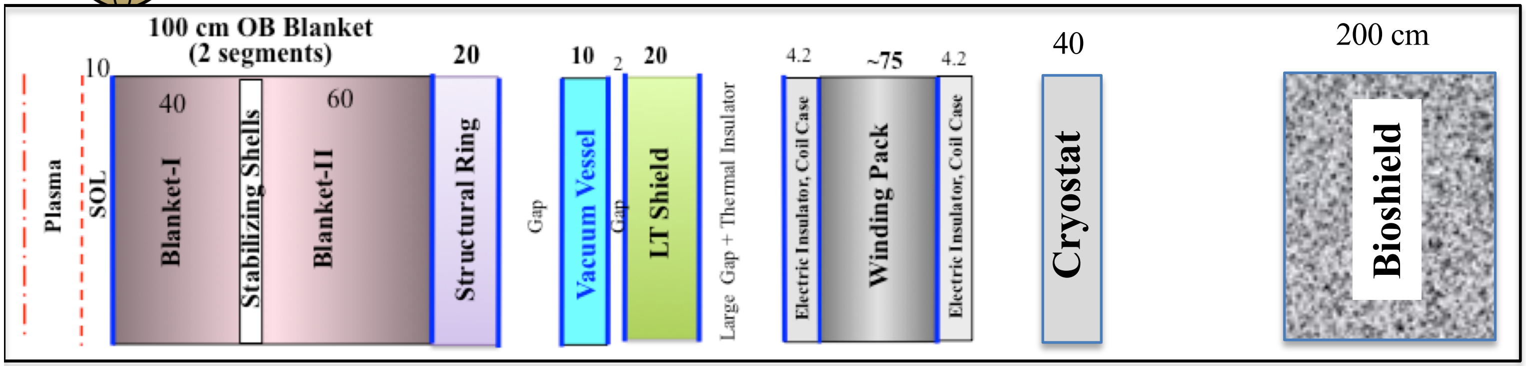


Increasing Clearance Potential

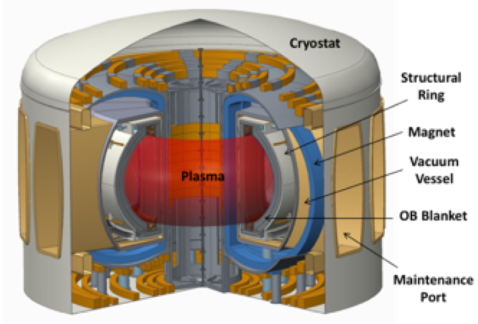
The Recycling Option

- 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)



ARIES-ACT2



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

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

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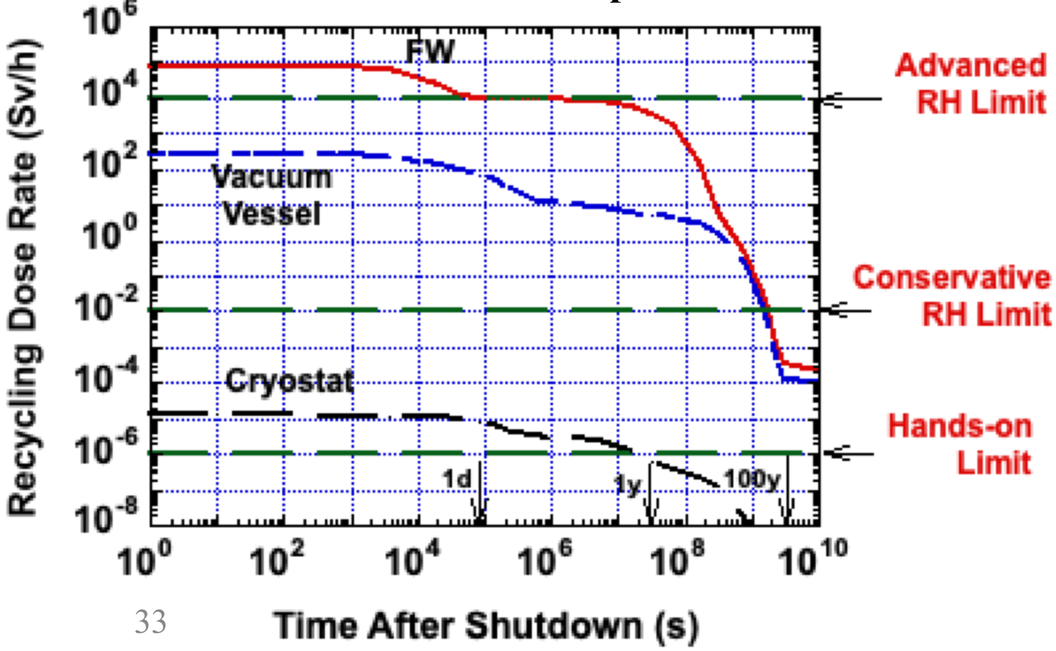
* Other recycling criteria may apply.

ARIES-ACT2 OB Components



Key Issues and Needs for Recycling

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

Issues:

- Separation of various activated materials from complex components
- Radiochemical or isotopic separation processes for some materials, if needed
- Treatment and remote re-fabrication of radioactive materials. Any residual He that affects rewelding?
- Radiotoxicity and radioisotope buildup and release by subsequent reuse
- Properties of recycled materials? Any structural role? Reuse as filler?
- Handling of tritiated materials during recycling
- Management of secondary waste. Any materials for disposal? Volume? Radwaste level?
- Energy demand for recycling process
- Cost of recycled materials
- Recycling plant capacity and support ratio

Needs:

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

Fusion-Related Recycling Developments

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

  E. Perry, J. Chrzanowski, C. Gentile, R. Parsells, K. Rule, R. Strykowsky, M. Viola, "Decommissioning of the Tokamak Fusion Test Reactor". Princeton Plasma Physics Laboratory report PPPL-3896 (October 2003). https://digital.library.unt.edu/ark:/67531/metadc735658/.

  - 200 tons of lead was removed for re-use. Lead bricks were painted (to mitigate lead health issues) and re-used 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 m^3) either recyclable or suitable for clearance
  - ~1,000 m^3 of LLW and ILW will be managed, treated, disposed and/or transferred for long-term storage.

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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).*
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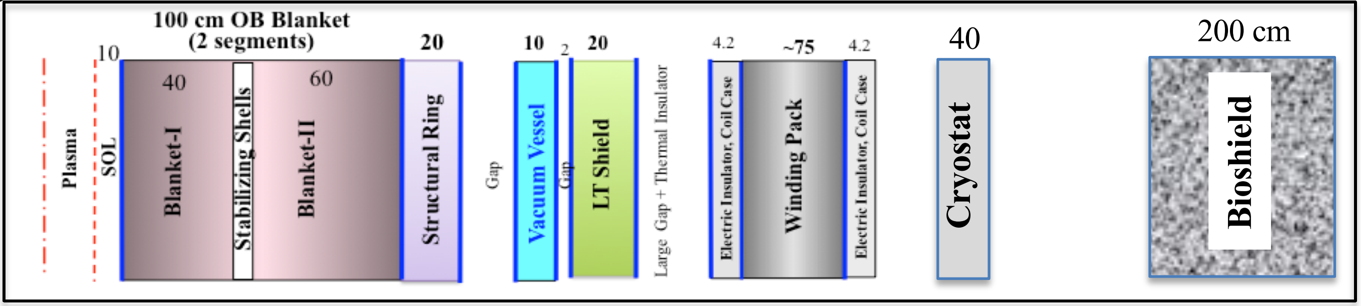
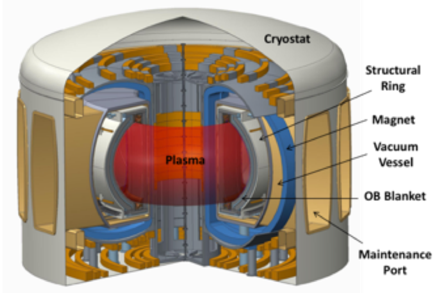
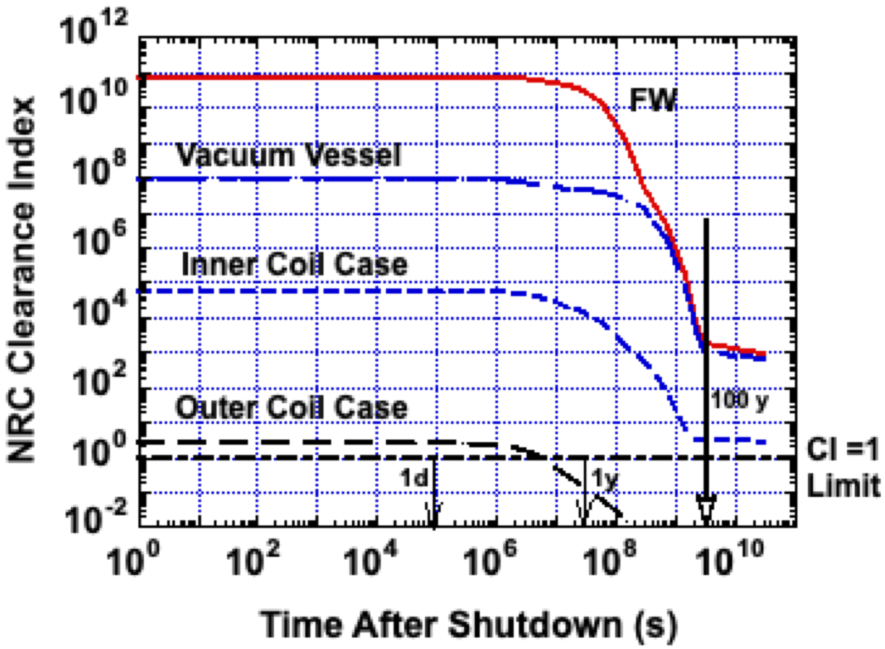
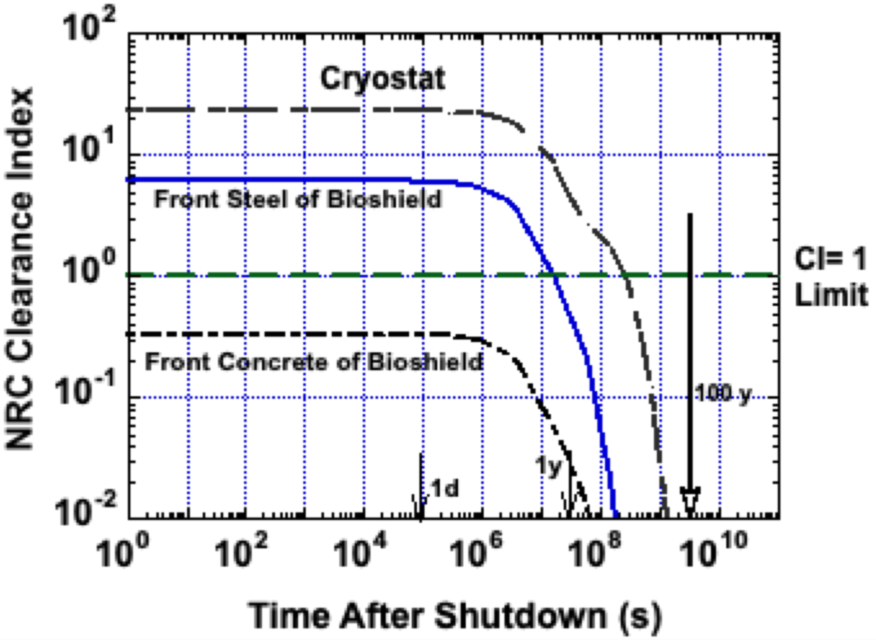
Clearance Example: ARIES-ACT2 Outboard Components









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

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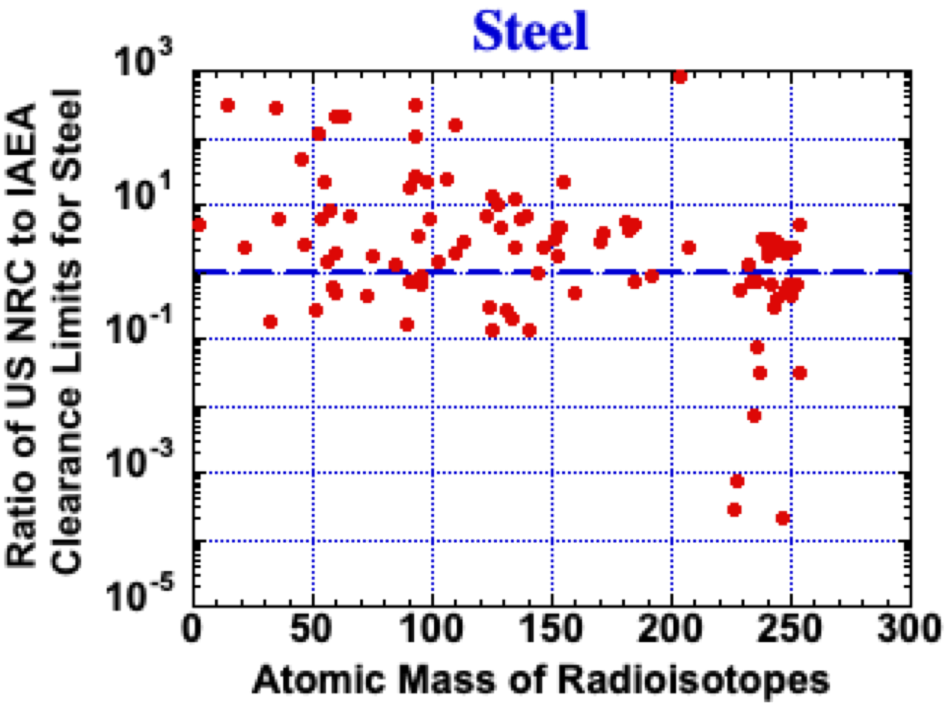
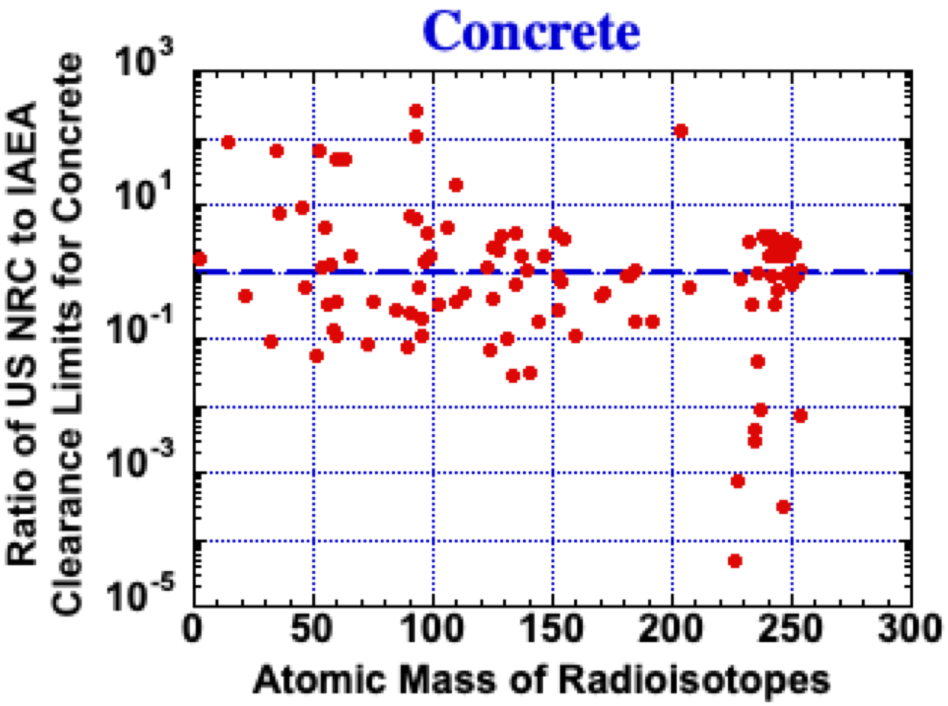
L. El-Guebaly and M. Zucchetti, "Progress and Challenges of Handling Fusion Radioactive Materials," Fusion Science and Technology, Vol. 68, No. 3 (2015) 484-491.
L. El-Guebaly, L. Mynsberge, A. Davis, C. D'Angelo, A. Rowcliffe, B. Pint, "Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant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

Clearance Concerns

- 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}Nb, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, ^{157,158}Tb, ^{163,166m}Ho, ^{178n}Hf, ^{186m,187}Re,^{193}Pt, ^{208,210m,212}Bi, and ^{209}Po)
- Radioisotope buildup and release by subsequent reuse.

Needs:

- NRC clearance limits for fusion activated materials
- Accurate measurements and reduction of impurities that deter clearance of some components
- International effort to harmonize standards and regulations of clearance
- Reversible assembling process of components and constituents
- Large capacity and low-cost interim storage facility
- Clearance infrastructure
- Clearance market.

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[*] *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 m^3 of LLW due to its minimization of waste volumes and recycling.

Big Rock Point in Michigan*:

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

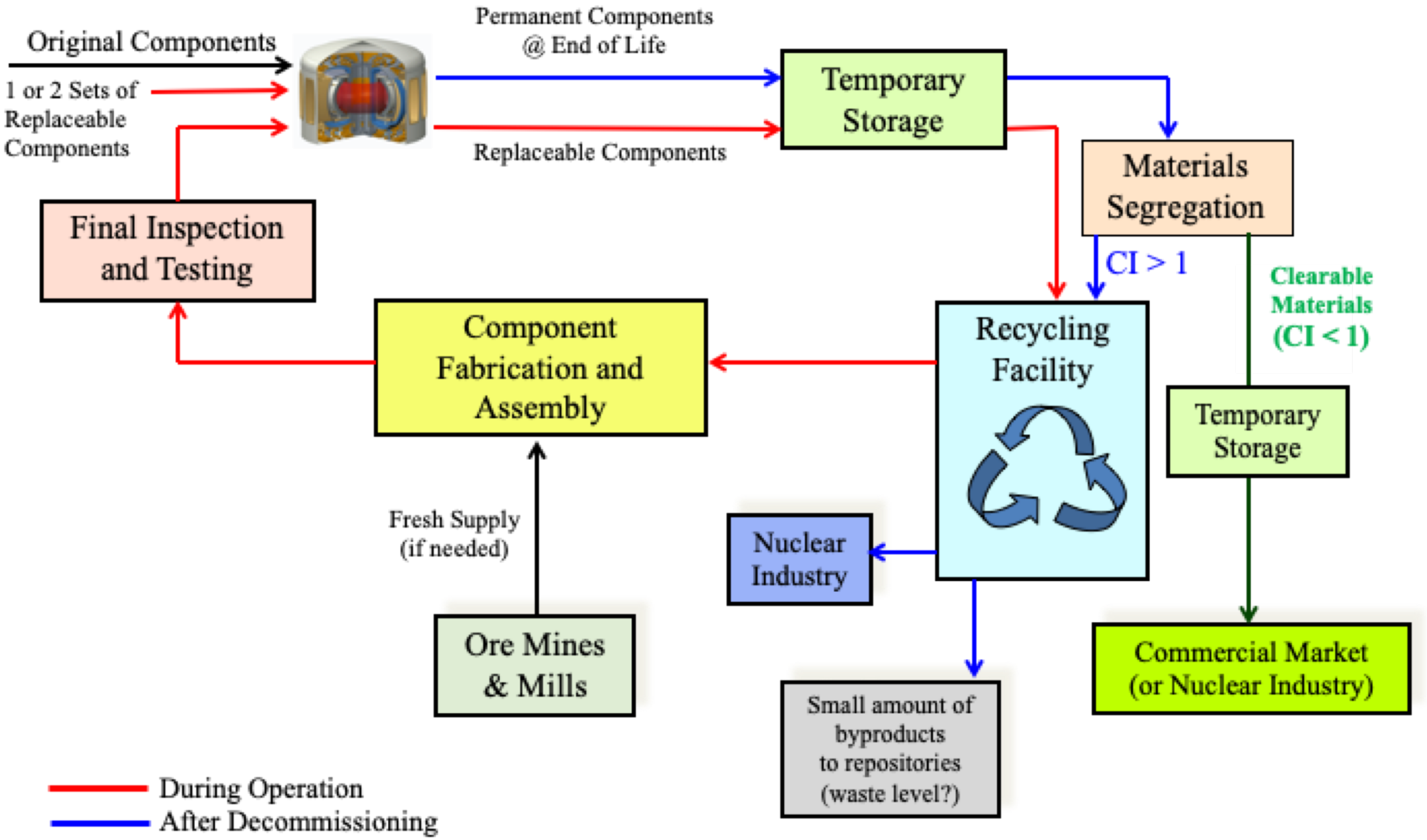
** Banovac, K. et al., "Power Reactor Decommissioning – Regulatory Experiences from Trojan to Rancho Seco and Plants In-Between," Proceedings of the ANS Topical Meeting on Decommissioning, Decontamination, and Reutilization (DD&R 2010), Idaho Falls, Idaho, August 29-September 2, 2010, American Nuclear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

Conclusions

- It is just a matter of time to develop the fusion recycling and clearance technologies and their official regulations.
- Possibility of material recycling/clearance could be demonstrated by directed R&D programs. *Many of the identified issues/needs overlap with fission industries, but adaptation to fusion is necessary (radionuclide profile, radiation level, component size, weight, etc.).*
- **NRC** could 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



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  - 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 202Luigi Di Pace et al., “Suitable Recycling Techniques for DEMO Activated Metals.” IAEA TECDOC on Fusion RWM. To be published. .
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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	

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Opportunity for Public Comment

Thank You!