MERCURIE CONSULTING

Targeted Design Solutions

Fusion Devices: Activation Product Licensing and Decommissioning

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Disclosures

- Consulting Services for Helion Energy

- This presentation is the result of an independent analysis. Statements and opinions expressed are those of the presenters individually and not those of Helion Energy.

Fusion Device Background

- Continuous collaboration between government & private industry[1]
  - DOE
  - NRC
  - Agreement States
- Agreement States have experience licensing fusion devices under 10 CFR Part 30

Purpose

- Discuss licensing // activation products & Radiation Safety Program
- Discuss waste & decommissioning // approaches for fusion & costs

Licensing Progression for Fusion System – Check Sources & Storage Device

Radioactive material	Form	Possession	Authorized Use
Californium 252	Sealed Source	___ mCi Total not to exceed ___ sources	Check detector operations; verify detector design & neutron activation foils; validate simulations
Radium 226	Disk Source / Capsule	___ nCi Total not to exceed ___ sources	Test & verify alpha particle detectors
Depleted Uranium	Getter Bed	___ kg	Capture & store hydrogen for R&D

Licensing Progression for Fusion System – Check Sources

Radioactive material	Form	Possession	Authorized Use
Barium 133	Sealed source	___ µCi	Sealed source contained within a detector
Cobalt 60	Sealed source	___ mCi	Check source (high count rate environments)
Americium 241 / Beryllium	Sealed source	___ Ci	Check source (neutrons)

Licensing Progression for Fusion System – Instrumentation

Radioactive material	Form	Possession	Authorized Use
Uranium 234	Fission chamber detector	___ g Total not to exceed ___ sources	Sensing component in instruments
Uranium 235	Fission chamber detector	___ g Total not to exceed ___ sources	Sensing component in instruments
Uranium 238	Fission chamber detector	___ g Total not to exceed ___ sources	Sensing component in instruments

Licensing Progression for Fusion System – Tritium

Radioactive material	Form	Possession	Authorized Use
Hydrogen 3	Sealed source	___ Ci	Sealed source contained in neutron generator
Hydrogen 3	Gas/Liquid	XX,XXX Ci	Energy & byproduct generation

Licensing Progression for Fusion System – Activation Products

Radioactive material	Form	Possession	Authorized Use
Any radioactive material with atomic numbers 3 to 83, inclusive; half-life *less than* or equal to 120 days except as otherwise specified	Activated byproduct material	As necessary*	Possession and storage incident to production activities; Performance testing of irradiated materials by external vendors.
Any radioactive material with atomic numbers 3 to 83, inclusive; half-life *greater than* or equal to 120 days except as otherwise specified	Activated byproduct material	As necessary*	Possession and storage incident to production activities; Performance testing of irradiated materials by external vendors.

*Expected to be changed to discrete limits over time with operational experience & better understanding of impurities

Radiation Safety Program

- Radiation Safety Committee
- Radiation Safety Program documentation: policy, procedures, & work instructions for the following:
  - Ordering, Receipt, & Handling
  - Inventory & Transfer
  - **ALARA // Radiation Dose Monitoring**
  - Radiation Surveys
  - Emergency Procedures
  - RAM Transport
  - Audits
  - **RAM Waste**
  - **Decommissioning & Financial Assurance**

Radiation Safety Program Considerations

ALARA

- Procedures address delay time for re-entry for short-lived activation products to decay
- Similar to procedures for particle accelerators
- Longer-term - consider background radiation from longer-lived activation products as experience is gained; utilize area and personnel monitoring

DOSE MONITORING TECHNOLOGY

- Dosimeters specific to neutrons

DECOMMISSIONING FUNDING PLAN

Decommissioning Waste

OPTIONS

- Reuse/ Recycling
- Onsite storage
- Plans to transfer LLRW – Class A

"Class A waste is waste that is usually segregated from other waste classes at the disposal site.

***Class A low level waste loses its radioactive hazard in less than 100 years*.**

The physical form and characteristics of Class A waste must meet the requirements set forth in 10CFR 61.56. Low-level waste includes items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation [NRC]"

NRC Waste Classifications

Radionuclide	Concentration (Ci/m^3)
C^{14}	8
C^{14} in activated metal	80
Ni^{59} in activated metal	220
Nb^{94} in activated metal	0.2
Tc^{99}	3
I^{129}	0.08
Alpha emitting transuranic nuclides with half-life greater than 5 years	[1]100
Pu^{241}	[1]3,500
Cm^{242}	[1]20,000

NRC Waste Classifications

Radionuclide	Concentration (Ci/m^3)		
	Col. 1	**Col. 2**	**Col. 3**
Total of all nuclides with less than 5 year half-life	700	([1])	([1])
H^3*	**40**	**([1])**	**([1])**
Co^{60}	**700**	**([1])**	**([1])**
Ni^{63}	**3.5**	**70**	**700**
Ni^{63} in activated metal	**35**	**700**	**7000**
Sr^{90}	0.04	150	7000
Cs^{137}	1	44	4600

[1]no limits established for these radionuclides in Class B or C wastes

*tritiated waste materials; not tritium itself, which is valuable to the fusion process

Notable Activation Products: C^{14}

- C^{14} produced from N^{14} reactions with neutrons
  - N^{14} present in vacuum (air) and as an impurity in vessel/components
  - Half life 5730 yrs
- Expected to have negligible effect on decommissioning
  - From literature, For a 3,000 MW fusion device: 90-430 Ci/yr
  - Limit 8-80 Ci/m^3
- Based on NRC limits, current fusion concepts under 1,000 MW: C^{14} will not be a concern
- C^{14} waste will be disposed as Class A waste

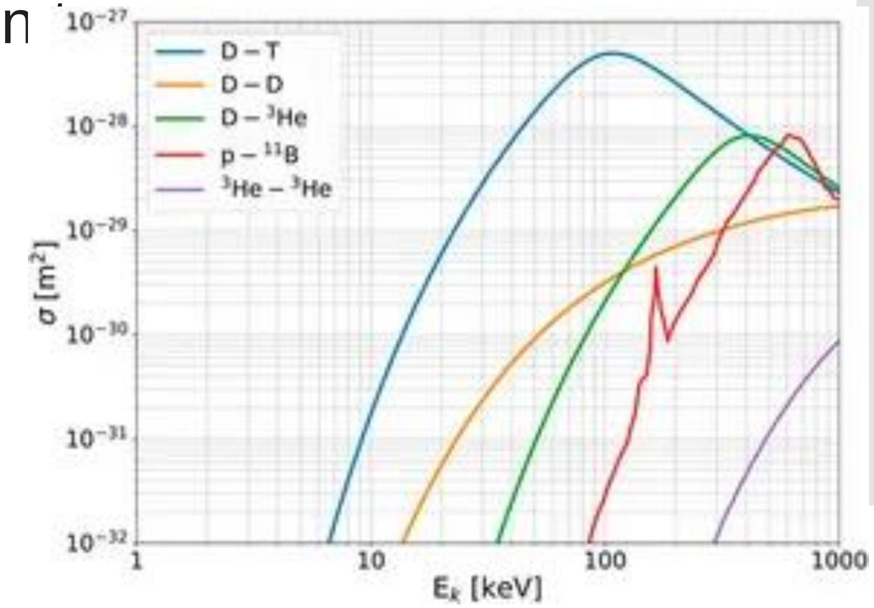
Notable Activation Products: Co^{60}

- Special caution when handling Co^{60} due to high energy gamma emissions
- 5.3 y half life
- Minimal waste volume : electrical cables & impurities in steel (Co^{59} and Cu^{63} activation)
- Waste expected to be Class A

H^3 Contaminated Waste

- Half life 12.3 y
- Minimal tritiated waste (D-He^3) :

  Side reactions:
  - D + D→T* (1.01 MeV) +p (3.02 MeV) makes tritium 50%
  - D + D → He^3 (0.82 MeV) + n (2.45 MeV) makes he (fuel for reaction) 50%
  - D-T ->He^4+ n (17.6 MeV) occurs depending on
- Expect some tritiated Class A waste management
  - Concrete structures
  - Shield and concrete shield



*Tritium decays to He^3 or reacts in D-T reaction

An Approach for D-He^3 Fusion Devices : Activation Products → Waste

Isotope	Half Life	Decay	Limit (Ci/m^3)	Expected Waste Class
Ni^{59}	76000 y	e-capture	Class A : 220 Class B: 22	Class A
Nb^{94}	2326 y	Beta with low energy gammas (keV)	Class A : 0.02 Class B: 0.2	Class A
Ni^{63}	100 y	Beta	Class A (metal) : 0.02 Class B (metal): 0.2 Class A (other materials) : 0.02 Class B (other materials): 0.2	Class A
H^3 (tritium)	12.5 y	Beta	Class A: 40 Class B: >40 Effects of external radiation and internal heat generation on transportation, handling, and disposal will limit concentrations for these wastes.	Class A
Co^{60}	5.3 y	Beta with gamma emission at 1.17 and 1.33 MeV	Class A: 700 Class B: >700 effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes.	Class A
C^{14}	5700 y	Beta	Class A (metal) : 8 Class C (metal): 80 Class A (other materials) : 0.8 Class C (other materials): 8	Class A

*All other waste is Class A; this includes long lived isotopes such as Mn^{54} (312 d), Zn^{65} (244 d) and Fe^{55} (2.7 y) and Ca^{45} (165 d)

Decommissioning & Financial Assurance

A licensee authorized to possess radioactive material in excess of the limits specified in 10 CFR 30.35 must submit a **decommissioning funding plan (DFP)** or provide a certification of financial assurance for decommissioning.

- DFP required for fusion devices given the quantities of tritium and activation products
- Historically fission reactors used as starting point for requirements

Fission Reactor vs Fusion Device vs Particle Accelerator Waste

FISSION REACTORS

- Fission waste includes **fission products, actinides**, activated components, concrete, and tritiated waste
  - **Not representative of fusion waste**
  - Nuclear facility waste *hazards* are not representative of fusion facilities

FUSION DEVICES

- 14 MeV (and other energy) neutrons activated materials
- Tritium is a reaction byproduct or reagent
- **Low-level waste consists of solid metallic activation products, activated concrete, and tritium; no transuranic elements**

PARTICLE ACCELERATORS

- Proton accelerator - protons above 10 MeV produce neutrons when striking most materials
- Electron accelerators - neutrons are produced when electron energy is above 17 MeV
- Neutron activation products and tritium contamination (e.g., in cooling water systems)
  - **Similar activation products and tritium concerns as fusion devices**

Current Decommissioning Strategies

DECON and SAFSTOR

- Commonly used for nuclear power plants
- Immediate and deferred dismantling
- Must be completed within 60 years

Historical Precedent for Fusion	
TFTR	worked from lower to higher activity/contamination
JET	vessel and main building placed in 30-year care and maintenance period then dismantle using operations and robotics; other activities to proceed in parallel
NIF	3 years of cool down for major components

Decommissioning Precedent: Tokamak Fusion Test Reactor (TFTR)

- D-T device, shut down 1997 decom started 1999, at the time 2nd largest fusion device in the world
- Focus on recycling & segregation of tritium contaminated & activated materials for cost reduction
- On time: **(3 years) and under budget 36.8 Million**
- Last item to be removed and decommissioned was the tokamak
  - Vacuum vessel filled with concrete and cut segments using diamond wire cutting (DWC)
  - Transported to Hanford for radwaste burial

- **Novel technologies significantly reduced cost and risk associated with the project:**
  - DWC of vacuum vessel allowed for shipping in Type A containers for shallow land burial disposal
  - Crimping ends of tritiated pipes and lines to safely dismantle tritiated components
  - Improvements in saw technology for cutting large irregular pieces of hard metals to reduce size of waste packages

Proposed Decommissioning for Fusion Devices

- Borrow from experimental and particle accelerators
- Design for Decommissioning:
  - Disposal, decontamination, recycling, and ease of dismantling
- Use low activation materials
- Use surface finishes that limit tritium sorption
- To identify risk:
  - Understand activation products: appropriate modelling
  - Classify components by hazard both rad and other
  - Follow ALARA principles, assign priority where needed; minimize dose to workers and limit contamination spread from high to lower contamination areas
- Sequester by activity and dispose only when needed (ideal is decay/decontamination)
- Use novel technologies: example diamond wire cutting TFTR
  - Look at examples in nuclear industry for waste compacting & remote handling strategies

An Approach for D-He3 Fusion Device Decommissioning

Activation products for He^3 fusion	Follow similar approach to TFTR: lowest activity first; 1 year of shutdown to plan and stage; After 1 year of decay, significant decrease in radioactive waste, reducing disposal costs and risk

Decommissioning Cost Estimates

Nuclear power plant	$500 million to $2 billion
Nuclear research reactor (10 MW)	<$20 million
Accelerators Class 1: 2-30 MeV medical linac Class 2:10-100 MeV (30 MeV) cyclotron/equip/vaults/hot cells/fume hoods 6,000 tons of low-level radioactive waste Class 3: 100-900 MeV (Triumf 520 MeV) accelerator/decontamination Class 4 : GeV-TeV Tevatron accelerator	$20k-30 million $20 000–40 000 $6.3 million $30 million (est.) $10 million (est.)
Neutrons source: European spallation source (most powerful long pulse neutron source)	$330 million
SRB leading Canadian producer of tritium light sources	$530k
Large fusion devices TFTR National ignition facility	 $36.8 million (2002); $64 million (2024) <$30 million (1998); $60 million (2024)
He3 fusion devices	**$10-20 million**

Summary

- Use experience from licensing particle accelerators
  - Step-wise approach: check sources and detectors → energy & byproduct materials, as well as activation products
- Expect standard radiation safety programs/policies with consideration for:
  - Delayed vault entry to keep doses ALARA, similar to particle accelerators
  - Dose monitoring & detection equipment for neutrons
  - Decommissioning plans
    - Similar to Tokamak Fusion Test Reactor (TFTR)
    - Fusion DFP $10+ M range << Fission Reactor DFP $100 M or billions