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Overview of the US Fusion Safety Program

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Overview

- Source of radioactive material from fusion
- Confinement of radioactive material and unique aspects of fusion
- Radiological hazards: activation products and tritium
- Release mechanisms: dust, permeation
- Safety analysis
- Waste
- DOE Fusion Safety Standard

Radioactive materials from fusion

- Fusion of deuterium and tritium is the easiest reaction to achieve, but every reaction produces a high energy neutron and these carry 80% of the total fusion energy

$$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1\ MeV)$$

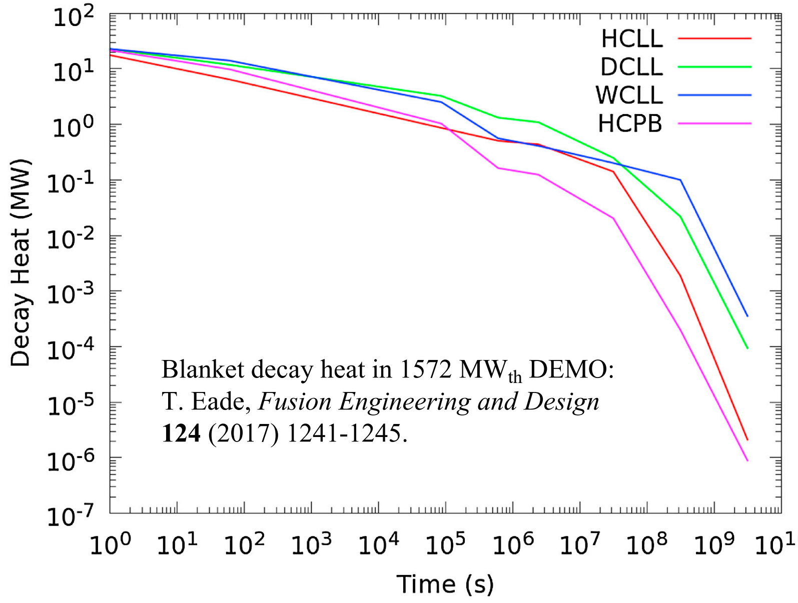
  - Tritium is itself radioactive, and its management has some unique challenges
  - Radioactive materials will be produced by neutron activation of structures, coolants, etc. surrounding the plasma
- Other fusion reactions are ostensibly aneutronic:

$$D + {}^{3}He \rightarrow {}^{4}He\ (3.6\ MeV) + H\ (14.7\ MeV) \qquad H + {}^{11}B \rightarrow 3\ {}^{4}He\ (8.7\ MeV)$$

  - Side reactions (D+D, ${}^{4}He+{}^{11}B$) release a small fraction of power in neutrons
  - Substantially reduced radiological hazards relative to D-T, but harder to achieve
- DOE program, reactor design studies, and Fusion Safety Program focused on issues related to D-T fusion

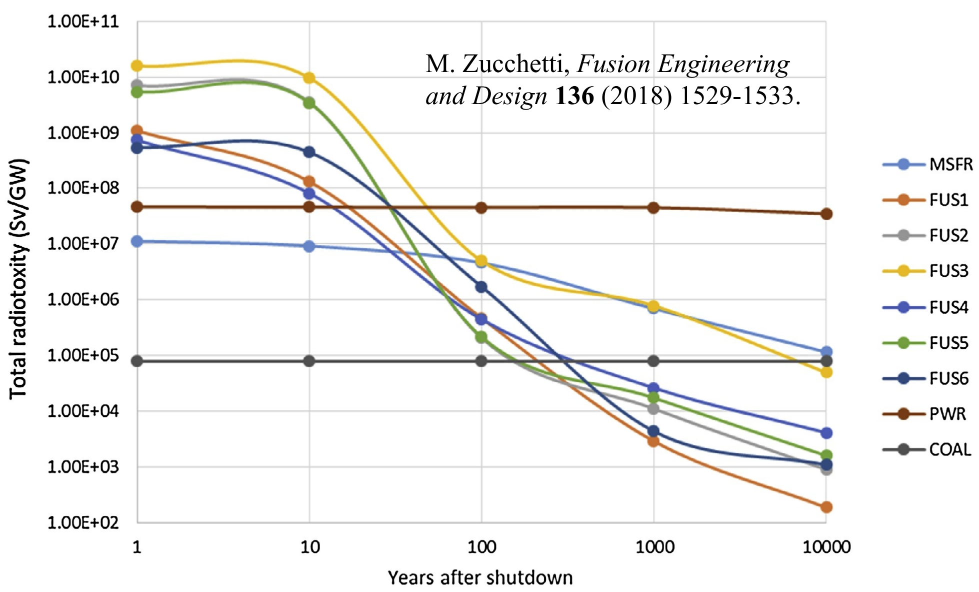
Radioactive Material Concerns

- In fusion, radioactive inventories will depend on material selection and design/operation characteristics (e.g., irradiation time). Both will impact:
- Decay Heat
  - Radioactive decay of activation products generates heat even after the reactor is shut down; this has to be managed safely
- Radioactive Waste
  - Use of low-activation structural materials and coolants can avoid creation of long-lived waste
- Radiation Exposure
  - Radiation exposures can be avoided by adequately confining mobilizable inventories of radioactive materials



Blanket decay heat in 1572 MW_{th} DEMO: T. Eade, *Fusion Engineering and Design* **124** (2017) 1241-1245.

A comparison of total radiotoxicity of PWR, Fusion, and GEN IV reactors

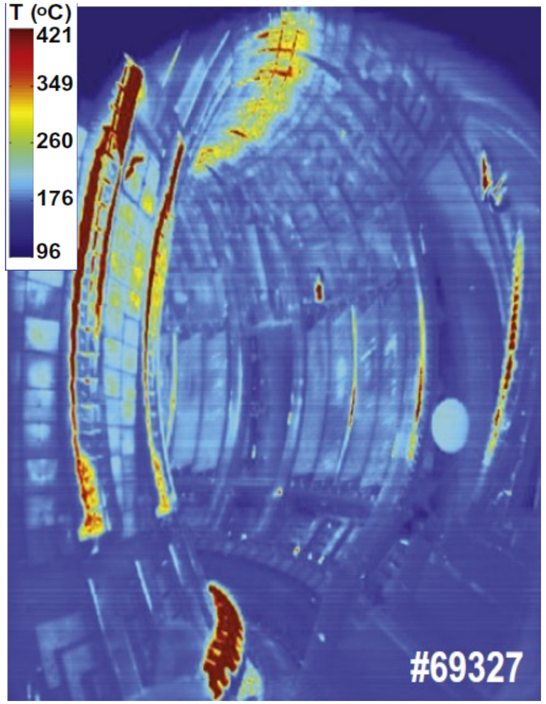


M. Zucchetti, *Fusion Engineering and Design* **136** (2018) 1529-1533.

Confinement of Radioactive Material

- Fusion reactors do not experience reactivity transients (power excursions) that can occur in a fission reactor
- But they do have some large stored energies; these need to be dissipated safely in off-normal scenarios (avoid rapid/local deposition)
- Challenges to confinement of radioactive material include:
  - Ensuring decay heat removal when required
  - Providing rapid controlled reduction in plasma energy when required
    - 0.5 GJ stored energy in ITER plasma[1]
  - Controlling coolant energy (e.g., pressurized water, cryogens)
  - Controlling chemical energy sources
    - E.g., air or steam reactions with lithium or beryllium
  - Controlling magnetic energy (e.g., stored in toroidal and poloidal field coils)
    - 51 GJ of stored energy in ITER magnets[2]

Disruptions in JET



E.M. Hollmann, *JNM* **415** (2011) S27–S34

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[1] ITER EDA Final Design Report Summary, IAEA, Vienna, 2001

[2] https://www.iter.org/mach/Magnets

Radioactive inventories and release paths

- Activated Materials
  - Activated structural materials should be mostly immobile
  - Dust created by plasma-surface interactions will be present in the plasma chamber; can be resuspended and transported
  - Activation products in coolants or other fluids can be released directly in the event of leaks
- Tritium
  - Tritium can permeate through materials at high temperature, a potential release even during normal operations
  - Stored inventories can be released during accidents, especially if temperatures increase
- Fusion Safety Program is primarily devoted to:
  - Understanding tritium and activation product transport phenomena
  - Development of radionuclide transport and accident simulation tools
  - R&D of technologies (e.g. tritium extraction and exhaust systems) that will minimize or eliminate hazards in future plants

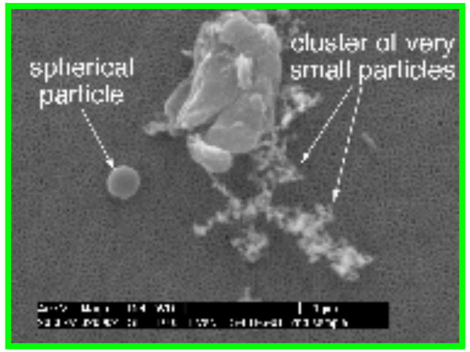
Tritium

- Tritium has a 12.3 year half-life and undergoes a weak β decay (18.6 keV max)
- As an isotope of hydrogen, it is readily incorporated into water and organic molecules
- Fusion reactors consume tritium at rate of 55.6 kg/GW-y, and must breed it the same rate or higher
- This is about 10^3x the rate of production in a MSR, 10^6x of a LWR
- The plasma burns only ~1% each pass, so fueling rate must be 100x larger
- Future reactors will produce tritium in a breeding blanket at the same rate it is consumed or higher to fuel other devices
- Concerns include:
  - Permeation of tritium through high temperature structures (pipes, vessel walls, etc.)
  - Large tritium inventories in components (e.g. cryopumps), tritium plant (~multiple kg)
- Program focused on obtaining data on tritium interactions with (irradiated) materials to inform predictive models of tritium transport in fusion plants (TMAP code)

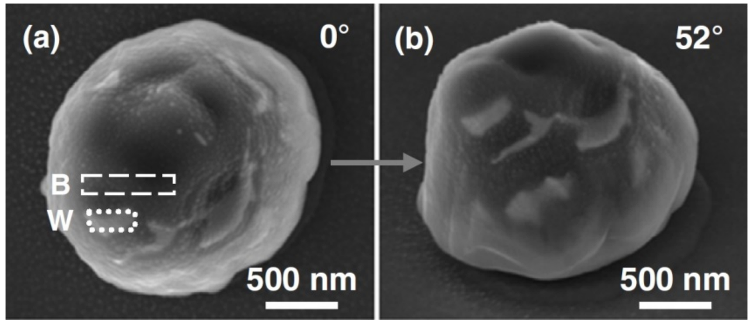
Tritium retention in irradiated materials in the Tritium Plasma Experiment

Dust

- A variety of plasma surface interactions (sputtering, arcs, melting, disruptions, etc.) create dust that will accumulate in the vacuum vessel
- This material is radioactive and mobilizable (e.g. in loss-of-vacuum)
- Quantity to be generated is uncertain; ITER adheres to administrative limit of 1000 kg
- Dust sampled from numerous operating tokamaks in an effort to understand size distribution, morphology, etc. and inform transport models
- Large quantities of resuspended dust could could have other impacts, e.g. large surface area for chemical reactions



Particle Size Distribution, Specific Surface Area, Surface Mass Density, Composition, Shape, and Tritium Content



Recent ASDEX Upgrade dust characterization: Balden, Humrickhouse, et al , *Nuclear Fusion* **54** (2014) 073010.

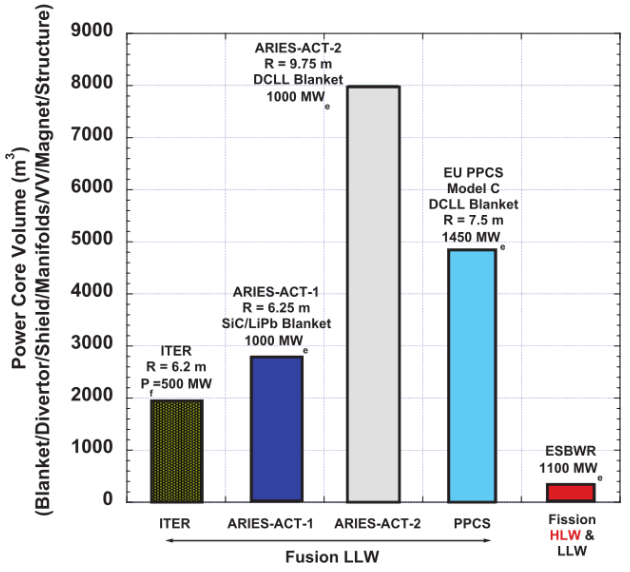
Accident Analysis with MELCOR

- MELCOR (developed by Sandia for the NRC) is an engineering-scale computer code for modeling the progression of severe accidents in nuclear power plants
  - Models thermal hydraulics, heat transfer, radionuclide transport (aerosols)
- Originally for LWRs, but now developed for advanced reactors (Sandia) and fusion (INL)
- INL modifications for fusion applications included:
  - Alternate fluids such as Li, PbLi, FLiBe, cryogens, models for freeze layer formation
  - Oxidation models for C, Be, W, informed by INL experiments
  - Additional aerosol transport phenomena: resuspension, turbulent and inertial deposition
  - Enclosure radiation models
  - Tritium permeation and transport models from TMAP
  - Lithium fire models
- An earlier version of the code (containing some of the above models) was pedigreed for use in ITER safety analysis, and was used in ITER licensing (NSSR 1&2, GSSR, RPrS)

Radioactive Waste

- NRC waste classifications (10 CFR 61.55):
  - High Level Waste (HLW)
    - Spent fuel and materials resulting from reprocessing of spent fuel
    - “Other highly radioactive materials that the Commission may determine require permanent isolation”
    - Requires deep geologic repository
  - Low Level Waste (LLW)
    - Class A (lowest hazard), B, and C
    - Class C can be disposed of by shallow land burial (5m below surface with natural or engineered barrier)
      - Class C criterion: “intruder dose” < 500 mrem/yr after 500 years[1]
    - Objective for fusion is structural materials that meet class C
      - Reference below outlines concentration limits for fusion materials
      - Reduced-Activation Ferritic Martensitic (RAFM) steel developed to meet class C disposal requirements

L. El-Guebaly, *Fusion Science and Technology* **67** (1) 2015.



Waste from fusion may be low level, but the volume may be large

Recycling/reuse of this material may reduce disposal burden

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[1] S. Fetter et al., *Fusion Engineering and Design* **6** (1988) 123-130.

DOE Fusion Safety Standard

- The DOE standard[1] safety policy for fusion:
  - 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.

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[1] DOE-STD-6002-96, "Safety of Magnetic Fusion Facilities: Requirements" (under revision)

DOE Fusion Safety Standard

- Radioactive and hazardous material confinement barriers of sufficient number, strength, leak tightness, and reliability shall be incorporated in the design of fusion facilities to prevent releases of radioactive and/or hazardous materials from exceeding evaluation guidelines during normal operation or during off-normal conditions:

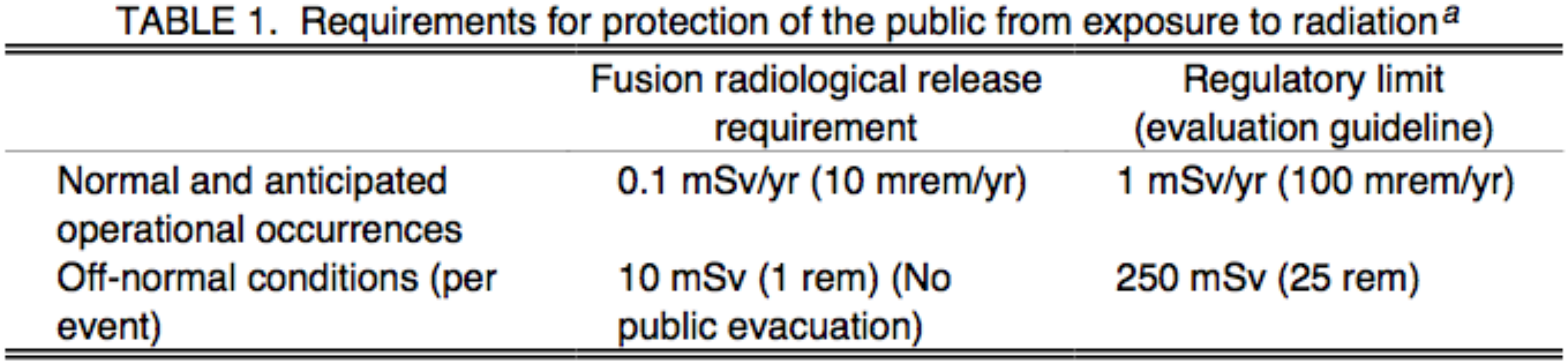

TABLE 1. Requirements for protection of the public from exposure to radiation[a]

	Fusion radiological release requirement	Regulatory limit (evaluation guideline)
Normal and anticipated operational occurrences	0.1 mSv/yr (10 mrem/yr)	1 mSv/yr (100 mrem/yr)
Off-normal conditions (per event)	10 mSv (1 rem) (No public evacuation)	250 mSv (25 rem)

- DOE standard limits on routine airborne and liquid releases:
  - National Emission Standards for Hazardous Air Pollutants (40 CFR 61): 10 mrem/yr
  - National Primary Drinking Water Regulations (40 CFR 141.16): 4 mrem/yr
  - All sources (10 CFR 20.1301): 100 mrem/yr

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[1] DOE-STD-6002-96, "Safety of Magnetic Fusion Facilities: Requirements" (under revision)

Summary

- D-T fusion reactors use radioactive fuel (tritium) and produce radioactive materials and waste via neutron activation
- Radiological hazards will depend on reactor design (materials), operation (irradiation time)
- Fusion has some unique stored energy sources (magnets, plasma) that have to be managed
- Tritium, activation products in coolants and dust are primary release vectors
- The Fusion Safety Program is actively engaged in understanding radionuclide retention and transport phenomena through experiments and modeling
- High level/long-lived waste can be largely avoided if low activation materials are used
- DOE has a fusion safety standard that can help inform licensing efforts

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