Overview of the safety and licensing aspects of future fusion power plants

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Overview

• Origin and magnitude of radioactive material production from fusion

• Aspects of radioactive material confinement
  – Decay heat management

• Regulatory limits on radiation dose

• Mobilizable radionuclides: activation products and tritium

• Release mechanisms: coolants, dust, permeation

• Characteristics of fusion waste; regulation
## Utility perspectives on fusion

<table>
<thead>
<tr>
<th>US Utility Requirements (1994)</th>
<th>Example Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost advantage over other available options</td>
<td>High thermal conversion efficiency and component efficiencies, compact (high beta), low recirculating power (e.g. high I&lt;sub&gt;BS&lt;/sub&gt;), high availability, low cost of fabrication.</td>
</tr>
<tr>
<td>Eased licensing process</td>
<td>Plant standardization, low activation materials, low energy release potential, low tritium inventory.</td>
</tr>
<tr>
<td>No need for evacuation plan</td>
<td>Low activation materials, low energy release potential, passive safety, reliable containment, low tritium inventory</td>
</tr>
<tr>
<td>Produce no high-level waste</td>
<td>Materials choices, waste management</td>
</tr>
<tr>
<td>Reliable, available, and stable</td>
<td>Ample design margins, uncomplicated designs, rapid maintenance</td>
</tr>
<tr>
<td>No local or global atmospheric impact</td>
<td>Low CO&lt;sub&gt;2&lt;/sub&gt; emissions, low tritium emissions</td>
</tr>
<tr>
<td>Fuel cycle is closed and on-site, High fuel availability</td>
<td>Fuel cycle is closed and on-site, High fuel availability</td>
</tr>
<tr>
<td>Capable of partial load operation, Available in a range of unit sizes</td>
<td>500 MW – 1 GW</td>
</tr>
</tbody>
</table>

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

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

  – 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:

\[ D + ^3\text{He} \rightarrow ^4\text{He} (3.6 \text{ MeV}) + H (14.7 \text{ MeV}) \quad \quad H + ^{11}\text{B} \rightarrow 3 \, ^4\text{He} (8.7 \text{ MeV}) \]

  – Side reactions (D+D, ^4\text{He}+^{11}\text{B}) release some of the power in neutrons
  – Substantially reduced radiological hazards relative to D-T, but harder to achieve

• The rest of this talk is focused on issues related to D-T fusion
Neutron activation

- The D-T fusion reaction produces neutrons: \( \text{D} + \text{T} \rightarrow ^{4}\text{He} \ (3.5 \text{ MeV}) + n \ (14.1 \text{ MeV}) \)
- The blanket re-produces tritium via reactions with lithium:
  \[ n + ^{6}\text{Li} \rightarrow ^{4}\text{He} + \text{T} + 4.8 \text{ MeV} \quad \text{n} + ^{7}\text{Li} \rightarrow ^{4}\text{He} + \text{T} + n' - 2.5 \text{ MeV} \]
- So, the “products” of fusion are only stable helium isotopes:
  - \( \text{D} + ^{6}\text{Li} \rightarrow ^{4}\text{He} \)
- Contrast this with fission, which produces a distribution of radioactive materials (some very long-lived) according to the yield curve:
- But, unfortunately the D-T fusion fuel cycle is not entirely free of radioactive materials and waste
- Any other elements present in breeding or structural materials can be transmuted by incident neutrons, with volumetric activation rate:
  \[ A = N\sigma\phi \quad N = \text{number density}, \ \sigma = \text{cross section}, \ \phi = \text{neutron flux} \]
- Many of the resultant activation products are radioactive, and therefore a hazard to human health

Some basics on radiation dose

• As radiation passes through the body, the imparted energy per unit mass is the *absorbed dose*, $D$:
  - $1 \text{ rad} = 0.01 \text{ J/kg} = 0.01 \text{ Gray (Gy)}$

• The dose equivalent, $H$, is modified by a weighting factor, $Q$:
  - $H = D \times Q$
  - Units of $H$: 1 rem = 0.01 sievert (Sv)

• The quality factor accounts for differing biological effect depending on the linear energy transfer due to collisions (energy/length), and increases with mass and charge of the particle

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray, gamma, or beta radiation</td>
<td>1</td>
</tr>
<tr>
<td>Alpha particles, multiple-charged particles, fission fragments and heavy particles of unknown charge</td>
<td>20</td>
</tr>
<tr>
<td>Neutrons of unknown energy</td>
<td>10</td>
</tr>
<tr>
<td>High-energy protons</td>
<td>10</td>
</tr>
</tbody>
</table>

• Radiation damages cells, and high doses (> 50 rem) are linked to various cancers
• There are no data to establish a firm link between cancer and doses < 10 rem
• A lethal dose is ~ 400 rem
• The average person is exposed to ~0.62 rem/year from natural and medical sources:

https://www.nrc.gov/docs/ML0333/ML033390088.pdf
How much activated material?

- Because the radioactive byproducts of fusion come entirely from activation, this depends on what materials comprise the reactor
- But, it’s not trivial
- Converted to (ingestion) dose and normalized to the operating power, it’s more than from a fission reactor at short (10+ year) times
- Use of low-activation materials can make it dramatically lower at longer times
Radioactive Material Concerns

- Significant radionuclide inventories imply a need to manage:
  - Radiation Exposure
    - Radiation exposures can be avoided by adequately confining mobilizable inventories of radioactive materials
  - 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
Confinement of Radioactive Material

- Fusion reactors do not experience reactivity transients 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.
    - Mitigation of disruptions and runaway electrons critical to avoid loss of coolant in tokamaks.
    - 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).

Disruptions in JET

E.M. Hollmann, JNM 415 (2011) S27–S34
Decay Heat generation in the elements

Low-activation materials

• Most future reactor designs plan to use a structural material that is a modified version of grade 91 steel, iron alloyed with:

<table>
<thead>
<tr>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Si</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0-9.5</td>
<td>0.85-1.05</td>
<td>0.18-0.25</td>
<td>0.06-0.1</td>
<td>0.2-0.5</td>
<td>0.08-0.12</td>
</tr>
</tbody>
</table>

• Activation of Molybdenum and Niobium creates long-lived waste:
  
  \[ ^{99}\text{Tc} \colon t_{1/2} = 211,100 \text{ y}, \quad ^{93}\text{Mo} \colon t_{1/2} = 4,000 \text{ y}, \quad ^{94}\text{Nb} \colon t_{1/2} = 20,300 \text{ y} \]

• Molybdenum replaced with tungsten, niobium replaced with tantalum\(^1\) to create Reduced Activation Ferritic/Martensitic (RAFM) steels, e.g.:

  - EUROFER-97 (Fe-9Cr-1W-0.2V-0.12Ta), developed in Europe
  - F82H (Fe-8Cr-2W-0.2V-0.04Ta), developed in Japan
  - Similar alloys developed in Korea, China

• Other low-activation materials (e.g. \(\text{V-4Cr-4Ti}^2\), \(\text{SiC}^3\)) are not yet sufficiently developed for fusion applications

\(^1\)H. Tanigawa et al., *Nuclear Fusion* 57 (2017) 092004.
Decay heat in fission reactors

- Decay heat comes principally from fission products, and so scales with reactor power
  - ~7% at shutdown
- Its presence after full shutdown requires emergency cooling
- Inability to remove it in off-normal scenarios ultimately resulted in core melt at Three Mile Island and Fukushima
Decay Heat in FusionReactors

- The amount of decay heat depends in principle on many choices:
  - Structural Materials
  - Blanket Concepts
    - Liquids: PbLi (Dual-coolant lead-lithium), FLiBe
    - Solids: Li$_2$TiO$_3$, Li$_4$SiO$_4$, Li$_2$ZrO$_3$, LiAlO$_2$, with Be$_{12}$Ti Multiplier
  - Fusion Power
  - Device size
  - Etc.

- To assess the amount decay heat expected from a D-T fusion device, we have conducted a series of neutronic and activation analyses looking at the influence of these design choices

- Models are parametrically constructed using Cubit python API
- Neutronic analysis with DAG-MCNP 6.2 with FENDL-3.2b nuclear data
- Activation analysis with FISPACT-II and TENDL-2017 nuclear data
- Many possibilities considered in fusion program history...

- Activation (short-term decay heat or long-term waste) was a significant driver in eliminating many from consideration
Model

- Base case: FNSF, $R_0 = 4.8\text{m}$, $P_{\text{fus}} = 518\text{ MW}$
- First Wall: 34% RAFM steel, 66% He
  - 2mm W armor
- Blankets: Dual-coolant PbLi (DCLL)
  - 7.5% RAFM, 15% He, 3.9% SiC, balance PbLi
- Vertical Stabilizing Shell: 100% W
- Back wall: 80% RAFM, 20% He
- Structural Ring
  - IB: 28% RAFM, 20% He 52% WC
  - OB/top/bottom: 28% RAFM, 20% He, 52% Borated RAFM
- Divertors: 41% W-1.1TiC, 12% RAFM, 47% He

Two year operation (irradiation) assumed
$R_0 = 3.0\ m$

$R_0 = 4.8\ m\ (\text{FNSF})$

$R_0 = 5.9\ m$
Baseline (FNSF/DCLL) results

- Total decay heat is 7.4 MW 1 s after shutdown (~1.5% of full power)
- About half of this is from the blankets
- 20-25% is from tungsten structures: FW armor, divertors, vertical stabilizing shell, and IB shielding (WC)
  - This amount of decay heat is common to all subsequent analyses; these materials have not been varied
Decay heat dependence on structural material

- FNSF design with RAFM replaced by different structural materials:

![Graph showing decay heat generation over time for different structural materials.]

- 7-12 MW at 1 s

- SiC case dominated by tungsten components, not blankets
Decay heat dependence on structural material

- Blankets/FW/BW/OB SR only:

![Graph showing decay heat generation over time after irradiation for different materials.]

- Cobalt isotopes dominate (Ni activation products)
- 54 Mn dominates
- Pb activation, not SiC!
Decay heat dependence on blanket concept

- FNSF with PbLi replaced with other breeder/multiplier materials:

  7-18 MW at 1 s
  Dominated by $^{16}\text{N}$ in FLiBe

$^{95}\text{Zr}, \, ^{95}\text{Nb}$ add significantly in $\text{Li}_2\text{ZrO}_3$ breeder

$^{46}\text{Sc}$ (from Ti in multiplier) adds significantly in solid breeders
Decay heat dependence on fusion power

• For a given geometry and materials, decay heat scales linearly with fusion power, i.e. the decay heat fraction is the same:
Decay heat dependence on reactor size (major radius)

• For a given geometry, fusion power, and materials, total decay heat is nearly independent of the reactor size
  – Surface area is decreased, but flux increases proportionally
Decay heat density

- Component volumes decrease as major radius decreases
- This implies larger decay heat densities in compact devices
- Armor decay heat density is high, but this component is thin (2mm)
- Combinations of high activation materials can result in similar decay heat densities to advanced fission reactor concepts like HTGR

Decay Heat takeaways

• D-T fusion reactors will produce a non-trivial amount of decay heat; depending on material choices, this might be ~1.5-3.5% of the fusion power just after shutdown

• It remains lower than a comparable fission reactor if low activation materials are used
  – Decay heat density is lower than fission

• Total decay heat in a tokamak scales linearly with fusion power and is independent of reactor size (major radius)
  – More compact devices will increase decay heat density, and decrease surface area available to remove it

• Passive decay heat removal is essential to the attractiveness of fusion as an energy source, and should be a primary consideration in reactor design and material selection
How is radioactive material mobilized?

• While melting of structures should be avoidable in a fusion reactor accident, radioactive materials can be mobilized in a few other ways

• Plasma-surface interactions create dust that will accumulate inside the vacuum vessel; this dust can potentially be transported outside the vacuum vessel in the event of a breach

• Coolant leaks can transport radioactive material outside confinement boundaries, e.g. dissolved tritium or activation products in the coolant
  – Most breeder materials are relatively low-activation compared to structural materials: Li, F, Be, O, Si (less so Ti) have primarily very short-lived activation products or don’t activate significantly
  – Pb activation products in PbLi breeders are probably the most significant concern
  – Isotopes of particular concern include $^{203}$Hg and $^{210}$Po:
    
    $^{206}\text{Pb} \xrightarrow{n,\alpha} ^{203}\text{Hg}$  
    $^{208}\text{Pb} \xrightarrow{n,\gamma} ^{209}\text{Pb} \xrightarrow{\beta^-} ^{209}\text{Bi} \xrightarrow{n,\gamma} ^{210}\text{Bi} \xrightarrow{\beta^-} ^{210}\text{Po}$
  – $^{210}$Po decays by emission of a 5.4 MeV alpha particle and is extremely radiotoxic
  – It is also rather volatile, and evaporates from free surfaces in the form of PbPo
  – Chemical reactions can also mobilize material in the form of aerosols

• Tritium is highly mobile, and can permeate through solid structures
NRC licensing status

- The US Nuclear Regulatory Commission has authority over commercial fusion devices in the US
- They are presently evaluating whether to license fusion reactors under 10 CFR parts 20 and 30 ("byproduct material," accelerators) or 10 CFR part 50/53 ("utilization facility," fission reactors); white paper\(^1\) released in September
- Presented to the Advisory Committee on Reactor Safeguards (ACRS) in October; their response\(^2\):
  - Endorsed part 30 for devices with < 10g tritium and < 0.01 MW/m\(^2\) (< 0.1 dpa)
  - But criticized this approach generally, citing fission-like decay heat and other hazards, and noting factual inaccuracies in white paper
- Hybrid approach was recommended (decide whether a given design fits under 20/30 or 53 depending on magnitude of hazards)

\(^1\)https://www.nrc.gov/docs/ML2225/ML22252A192.pdf
\(^2\)https://www.nrc.gov/docs/ML2230/ML22306A260.pdf
Safety requires that tritium releases must be kept low

- DOE standard\(^1\) limits on routine airborne and liquid releases:
  - National Emission Standards for Hazardous Air Pollutants (40 CFR 61): 0.1 mSv/yr (10 mrem/yr)
  - National Primary Drinking Water Regulations (40 CFR 141.16): 0.04 mSv/yr (4 mrem/yr)
  - All sources (10 CFR 20.1301): 1 mSv/yr (100 mrem/yr)

- Adherence to off-normal limits needs to be demonstrated by accident analysis

- Tritium releases may challenge normal/AOO limits; for “generic site” considered for FNSF analysis, 0.1 mSv/yr (10 mrem/yr) \(\rightarrow\) 0.29 g T/yr
  - \(0.29\) g T/yr = \(10^{-5}\) FNSF fusion/breeding rate


Quantities of Tritium in Fusion Devices

• Fusion reactors consume tritium at rate of 152 g/GW-d, and must breed it the same rate or higher

• This is about $10^3 \times$ the rate of production in a MSR, $10^6 \times$ of a LWR

• The plasma burns only a small fraction each pass, so fueling rate must be 20-200x larger

• Future reactors will produce tritium in a breeding blanket at the same rate it is consumed or higher to fuel other devices

• Safety concerns include:
  – Permeation of tritium through high temperature blanket and HX structures (pipes, vessel walls, etc.)
  – Large tritium inventories in components
Tritium flows and loss paths

Safety analyses seek to quantify the rate of tritium loss through all systems, in both normal and off-normal operating scenarios.

The Tritium Migration and Permeation (TMAP) code was originally developed at INL for this purpose.
**Diffusion/Permeation**

- The fundamental driver of tritium migration is its ability to diffuse through metals, with permeation flux \( J = -D(\partial C/\partial x) \)

- At moderate to high pressures, the partial pressure and solid concentration at gas/solid interfaces are related by Sieverts' Law: \( C_i = K_S \sqrt{P_i} \)

- The resultant “permeation” flux is given by \( J = \frac{DK_S(C_1 - C_2)}{x} \)

- The constant of proportionality \( \Phi = DK_S \) is the permeability

M. Shimada in Comprehensive Nuclear Materials
https://doi.org/10.1016/B978-0-12-803581-8.11754-0
Trapping

• Tritium is subject to **trapping** at defect sites in structural materials

• The density of trap sites increases with radiation damage; irradiation increases the density of higher energy traps

\[
\frac{\partial C_t}{\partial t} = \alpha_t f_t C_m - \alpha_r C_t
\]

- \(C_t\) – Trapped concentration (m\(^{-3}\))
- \(\alpha_t\) – Trapping rate coefficient (s\(^{-1}\))
- \(f_t\) – Probability of landing in a trap site (\(\cdot\))
- \(C_m\) – Mobile concentration (m\(^{-3}\))
- \(\alpha_r\) – Release rate coefficient (s\(^{-1}\))

\[
\alpha_t = \frac{D}{\lambda^2} \quad f_t = \frac{c_t^0 - C_t}{N} \quad \alpha_r = v_o \exp\left(-\frac{E_t}{kT}\right)
\]

- \(D\) – Tritium diffusion coefficient (m\(^2\)-s\(^{-1}\))
- \(\lambda\) – Jump distance or lattice constant (m)
- \(c_t^0\) – Trap site concentration (m\(^{-3}\))
- \(N\) – Bulk material atom density (m\(^{-3}\))
- \(v_o\) – Debye frequency (s\(^{-1}\))
- \(E_t\) – Trap energy (eV)


https://doi.org/10.1088/0031-8949/2011/T145/014051
Tritium transport analysis of the FNSF

- The Fusion Nuclear Science Facility (FNSF) is a 518 MW US design featuring a DCLL blanket
- Tritium permeation and the influence of design features was systematically analyzed
- The base design had tritium permeation losses of $6.18 \text{ g/yr}$, larger than $0.29 \text{ g/yr}$ target
  - Partly a result of conservative parameter choices (e.g. lowest measured T solubility in PbLi)
    - More optimistic choices (within measured ranges) give as low as $0.05 \text{ g/yr}$
    - Driven primarily by PbLi pipe losses
- Quantitative effect of design features systematically evaluated...

Tritium transport analysis of the FNSF (cont’d)

- Significant design features and impacts:
  - DCLL Blanket
    - High flow rates reduce residence times
    - SiC flow channel inserts act as a permeation barrier
  - High efficiency (95%) vacuum permeator for T extraction from PbLi
    - A relatively compact design based on tantalum permeator tubes (764,15m long) provided, but needs engineering demonstration
    - Permeation increases significantly as efficiency is reduced
  - Concentric hot/cold leg piping
    - Single most effective mitigation!
    - Permeation increases to 115 g/yr without it

Permeation barrier coatings

• The FNSF design did not take credit for any permeation barriers

• Ceramic (e.g. Al$_2$O$_3$, Er$_2$O$_3$) coatings have shown significant promise in laboratory settings, but significantly degraded performance in reactor environments

• The reasons are not completely understood, but may result from a combination of:
  – Degredation of the coating (e.g. cracks)$^1$
  – Radiation-enhanced diffusion$^2$
  – Radiation damage to microstructure$^3$

• Remains an ongoing area of research

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Guard pipes

- Permeation barriers may be effective in less demanding environments that target permeation loss paths, e.g. on the outside of ex-vessel piping
- Other engineered barriers may be effective here as well
- In the FNSF design, guard pipes swept with low pressure He significantly reduced permeation with no significant heat loss

<table>
<thead>
<tr>
<th>He purge velocity (m/s)</th>
<th>Outer pipe temp (°C)</th>
<th>Inner pipe temp (°C)</th>
<th>Heat loss (W)</th>
<th>Tritium loss (g/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>-</td>
<td>417</td>
<td>-</td>
<td>4.21</td>
</tr>
<tr>
<td>0.1</td>
<td>94</td>
<td>416</td>
<td>65</td>
<td>0.014</td>
</tr>
<tr>
<td>1.0</td>
<td>353</td>
<td>414</td>
<td>2,083</td>
<td>1.19</td>
</tr>
<tr>
<td>10.0</td>
<td>350</td>
<td>414</td>
<td>21,350</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Tritium Takeaways

• Tritium is highly mobile in high-temperature systems and this migration poses a significant safety & environmental issue for future fusion reactors

• Solution, diffusion, surface effects, mass transport, and trapping all play a role in tritium transport predictions
  – Parameter uncertainties are a significant hindrance to predictive models
  – Trapped inventories are uncertain
  – Integral test data needed for validation

• Permeation barriers are needed to help limit tritium permeation
  – Barriers could take many forms
Waste from Fusion

- The volume of radioactive material produced by a fusion reactor is large relative to a fission reactor.

- But since radionuclides are produced by neutron activation rather than fission, reduced-activation materials can ensure waste is not long-lived.

- 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): everything else, classified based on hazard:

<table>
<thead>
<tr>
<th>Nuclear waste classification under 10 CFR 61 rules</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waste class</strong></td>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td>Class A</td>
<td>Decays to acceptable levels during side occupancy</td>
</tr>
<tr>
<td>Segregated waste</td>
<td>Segregated, minimum requirements</td>
</tr>
<tr>
<td>Class B</td>
<td>Stabilized and decays to levels that do not pose a danger to public health and safety in 100 years</td>
</tr>
<tr>
<td>Stable waste</td>
<td>Covered to reduce surface radiation to a few percent of natural background</td>
</tr>
<tr>
<td>Class C</td>
<td>Does not decay to safe levels in 100 y. Decays to acceptable safe levels in 500 y *</td>
</tr>
<tr>
<td>Intruder waste</td>
<td>Five meters below surface with natural or engineered barrier</td>
</tr>
<tr>
<td>Waste that does not meet Class C definition</td>
<td>Does not qualify for near-surface disposal. Proposed disposal methods are considered on a case-by-case basis</td>
</tr>
<tr>
<td></td>
<td>Geologic</td>
</tr>
</tbody>
</table>

* 10 CFR 61 defines “acceptably safe levels” to mean that the inadvertent entry into the waste would result in a whole-body dose of less than 0.5 rem/y. Natural background radiation gives an average yearly dose of about 0.1 rem/y.
Waste classification as per 10 CFR 61

- As with our safety analyses, the philosophy behind classification and disposal of LLW is based on quantitative limits on radiation dose to members of the public.

- Class C waste disposed of in shallow land burial results in only "acceptably safe" doses (500 mrem/yr) in the following scenario:
  - "Institutional control" prevents any access to the site for 100 years.
  - It is assumed to be "stable" (i.e. recognizable as radioactive waste) for 500 years.
    - Maybe after 100 years, somebody starts to build a house on the site...
      - Construction workers will recognize radioactive waste as such and cease operations within 6 hours.

  - After 500 years, it’s no longer recognizable. The house is built (in 500 hours) and the inhabitants grow half of their food on site. They receive dose (<500 mrem/yr) from inhalation, ingestion, and direct exposure.
Specific Activity Limits

- Under the preceding scenario, one can calculate corresponding specific activity limits (SAL) for a given radioisotope.

- The waste disposal rating (WDR) is the sum of the fractional contributions of each isotope to the overall limit; for Class C waste, WDR < 1

\[
WDR = \sum_i \frac{a_i \text{[Ci/m}^3\text{]}}{SAL_i \text{[Ci/m}^3\text{]}}
\]

- NRC (in 10 CFR 61) only specified SALs for a handful of isotopes though.

- In the late 1980s, Fetter\(^1\) employed a similar logic to determine SALs for a comprehensive set of potential fusion activation products.

- **Whether these or other limits are to be adopted as regulation has not been addressed.**

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Class C SAL, Ci/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-129</td>
<td>0.08</td>
</tr>
<tr>
<td>Sr-90</td>
<td>7000</td>
</tr>
<tr>
<td>Cs-137</td>
<td>4600</td>
</tr>
<tr>
<td>Pu-241</td>
<td>3,500</td>
</tr>
<tr>
<td>Cm-242</td>
<td>20,000</td>
</tr>
<tr>
<td>(\alpha)-emitting transuranics with (t_\frac{1}{2} &gt; 5) yr</td>
<td>100</td>
</tr>
<tr>
<td>C-14</td>
<td>8</td>
</tr>
<tr>
<td>C-14 in activated metal</td>
<td>80</td>
</tr>
<tr>
<td>Ni-59 in activated metal</td>
<td>220</td>
</tr>
<tr>
<td>Ni-63</td>
<td>700</td>
</tr>
<tr>
<td>Ni-63 in activated metal</td>
<td>7000</td>
</tr>
<tr>
<td>Nb-94 in activated metal</td>
<td>0.2</td>
</tr>
<tr>
<td>Tc-99</td>
<td>3</td>
</tr>
</tbody>
</table>

Alloy concentrations to meet Class C disposal

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
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Assumes 5 MW/m² for 4 years; and E. T. Cheng, “Concentration Limits of Natural Elements in Low Activation Materials”, presented at ICFRM-8, Sendai, Japan, October 1997
Summary

• D-T fusion will produce a significant amount of radioactive material via neutron activation of surrounding components

• Use of low activation materials can reduce decay heat produced by this material to lower levels than fission reactors
  – Likely not trivial levels though; passive decay heat removal is a critical aspect of facility design

• Designers need to verify that release of mobilizable inventories (activated coolant & dust, tritium) does not exceed regulatory dose limits (under normal operation and accident conditions)

• Use of low activation materials can also potentially eliminate the need for long-term/deep geologic waste disposal