Safety Considerations of Building a Fusion Pilot Plant

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SULI – Introduction to Fusion Energy and Plasma Physics

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Why Fusion?

- Abundant fuel resources (D, Li)!
- No carbon emissions!
  - Fission reactors achieve this too…
  - Fusion reactor design should seek to improve upon the shortcomings of fission:
    - Passive safety
      - No potential for severe accidents requiring evacuation
    - Produces less and/or shorter-lived radioactive waste (environmentally benign)

Utility perspectives on fusion

Safety/Environmental Issues

US Utility Requirements (1994)	Example Attributes
Cost advantage over other available options	High thermal conversion efficiency and component efficiencies, compact (high beta), low recirculating power (e.g. high I_{BS}), high availability, low cost of fabrication.
Eased licensing process	Plant standardization, **low activation materials**, low energy release potential, **low tritium inventory**.
No need for evacuation plan	**Low activation materials**, low energy release potential, **passive safety**, **reliable containment**, **low tritium inventory**
Produce no high-level waste	**Materials choices**, waste management
Reliable, available, and stable	Ample design margins, uncomplicated designs, rapid maintenance
No local or global atmospheric impact	Low CO_2 emissions, **low tritium emissions**
Fuel cycle is closed and on-site, High fuel availability	Fuel cycle is closed and on-site, High fuel availability
Capable of partial load operation, Available in a range of unit sizes	500 MW – 1 GW

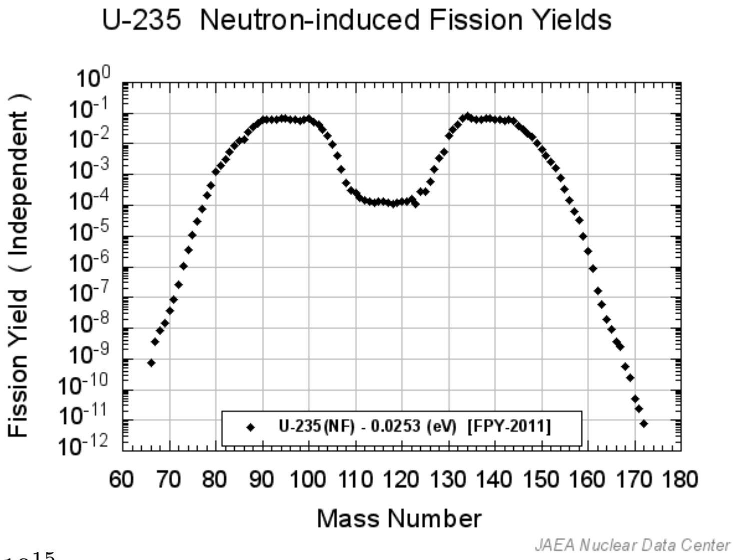
M. Tillack, 2014 TOFE, based on J. Kaslow et al., *Journal of Fusion Energy* **13** (2/3) 1994.

Neutron activation

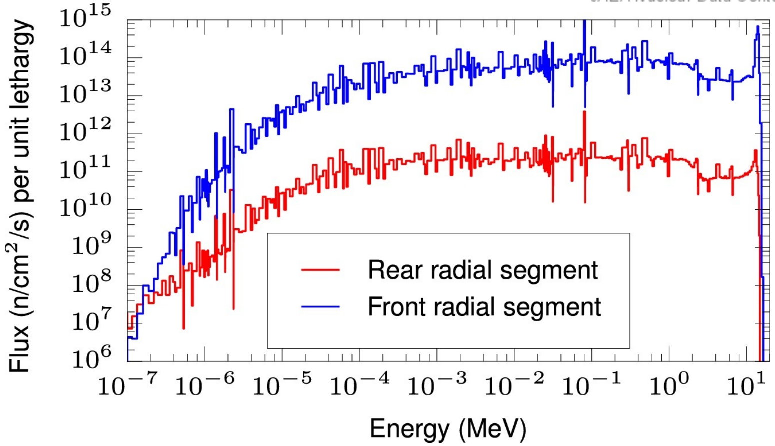
- The D-T fusion reaction produces neutrons: D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)
- The blanket re-produces tritium via reactions with lithium:

  n + ^{6}Li → ^{4}He + T + 4.8 MeV   n + ^{7}Li → ^{4}He + T + n' - 2.5 MeV

- So, the "products" of fusion are only stable helium isotopes:
  - D + ^{6}Li → 2 ^{4}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:
- $A = N\sigma\phi$ N = number density, σ = cross section, ϕ = neutron flux
- Many of the resultant activation products are radioactive, and therefore a hazard to human health



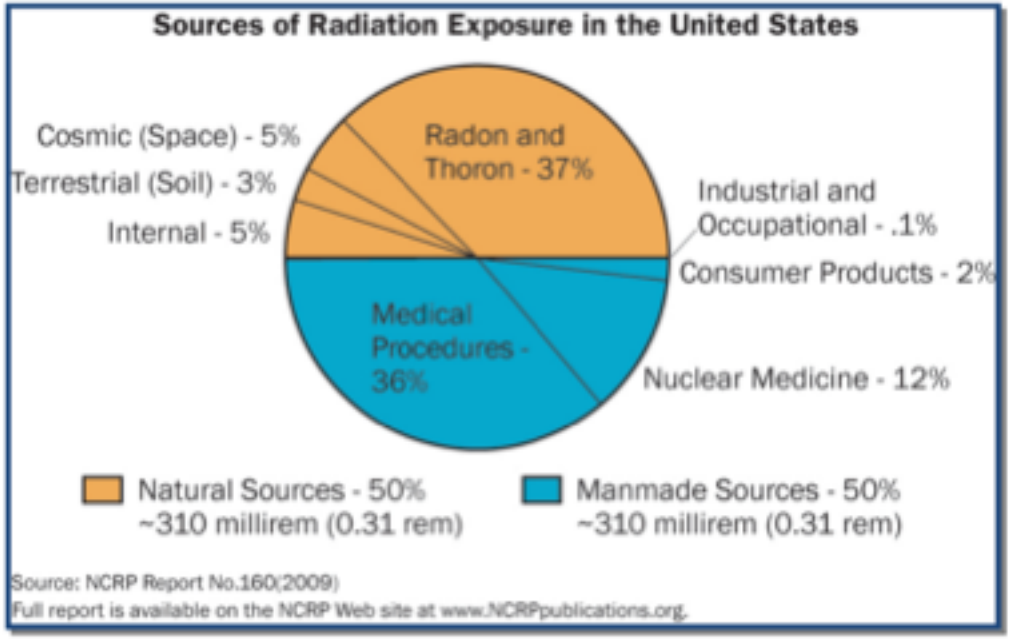
J. Shimwell, *Fusion Engineering and Design* **98-99** (2015) 1868-1871.

Some basics on radiation dose

- As radiation passes through the body, the imparted energy per unit mass is the *absorbed dose, D*:
  - 1 rad = 0.01 J/kg = 0.01 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

Type of radiation	Q
X-ray, gamma, or beta radiation	1
Alpha particles, multiple-charged particles, fission fragments and heavy particles of unknown charge	20
Neutrons of unknown energy	10
High-energy protons	10

- 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

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.

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

DOE Fusion Safety Standard

- Potential safety concerns:
  - Ensuring afterheat removal when required
  - Providing rapid controlled reduction in plasma energy when required
  - Controlling coolant energy (e.g., pressurized water, cryogens)
  - Controlling chemical energy sources
  - Controlling magnetic energy (e.g., toroidal and poloidal field stored energy)
  - Limiting airborne and liquid releases to the environment
- 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:

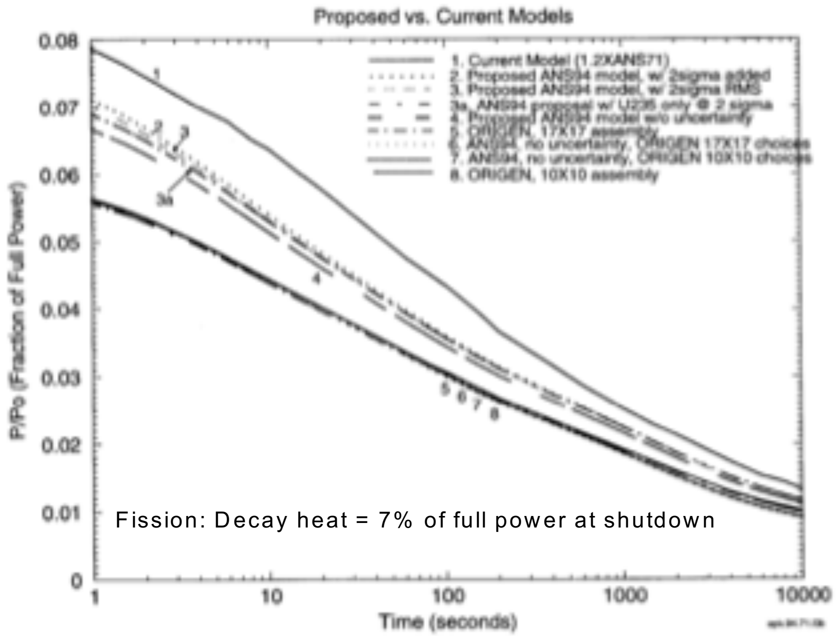
TABLE 1. Requirements for protection of the public from exposure to radiation[a]

	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)

Radioactive Material Concerns

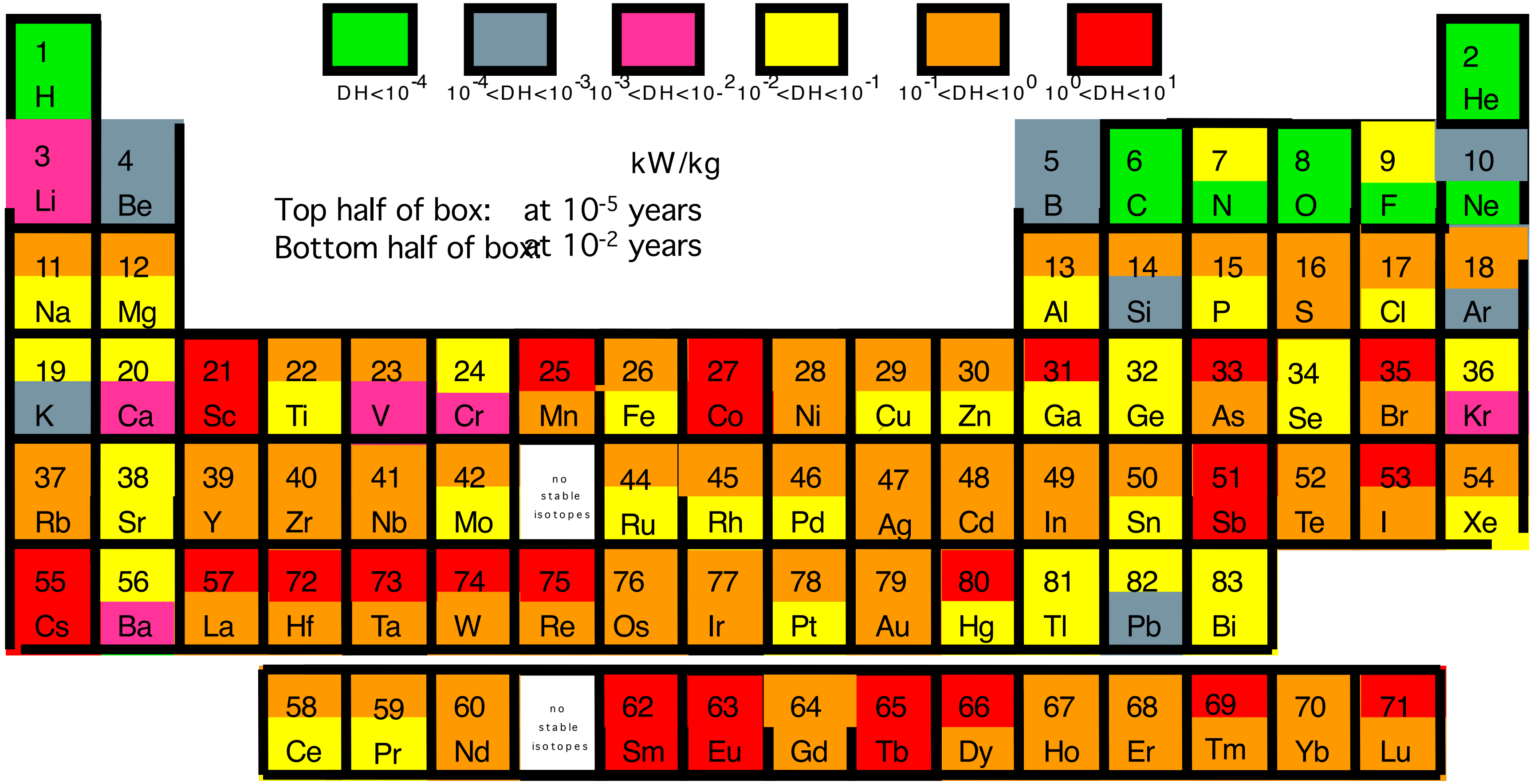
- Decay Heat
  - Radioactive decay of activation products generates heat even after the reactor is shut down; this has to be removed safely
- Radiation Exposure
  - Any radioactive materials released from a fusion reactor may result in exposure to individuals, e.g. via inhalation of gases or aerosols
- Radioactive Waste
  - If activation products of a fusion reactor have long half-lives, these require long-term disposal strategies similar to radioactive waste from fission
- In fusion, because the radioactive materials are the result of neutron activation, and these are dictated entirely by our choice of materials
- So, in principle we can reduce all of the above by selecting low-activation constituents from the periodic table…

Figure 1. Appendix K Decay Heat Comparison



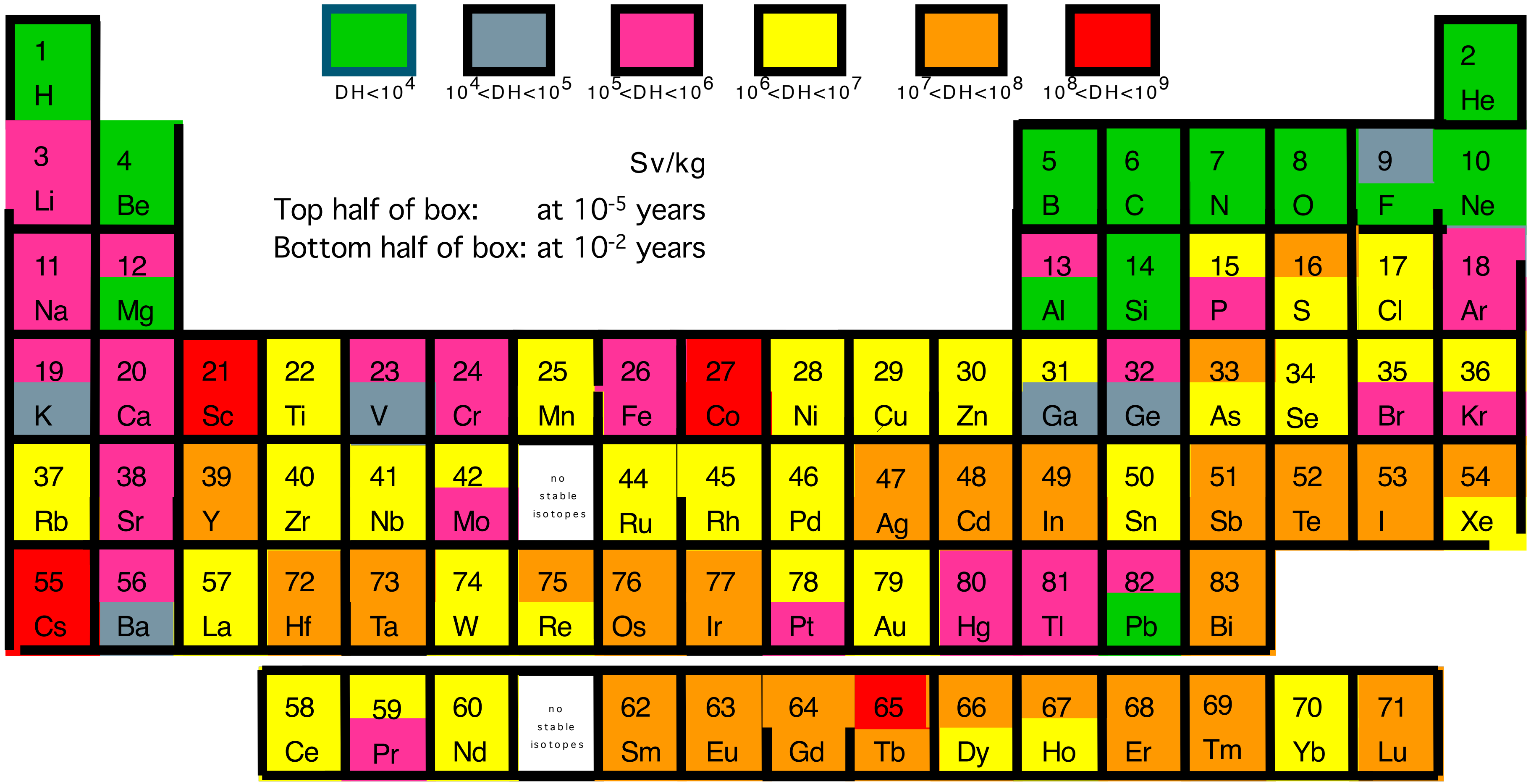
https://www.nrc.gov/docs/ML0217/ML021720702.pdf

Decay Heat



Based on C. B. A. Forty, et al., Handbook of Fusion Activation Data; Part 1. Elements Hydrogen to Zirconium, AEA FUS 180, May, 1992. Assumes 4.15 MW/m^2 for 25 years

Radiation Exposure



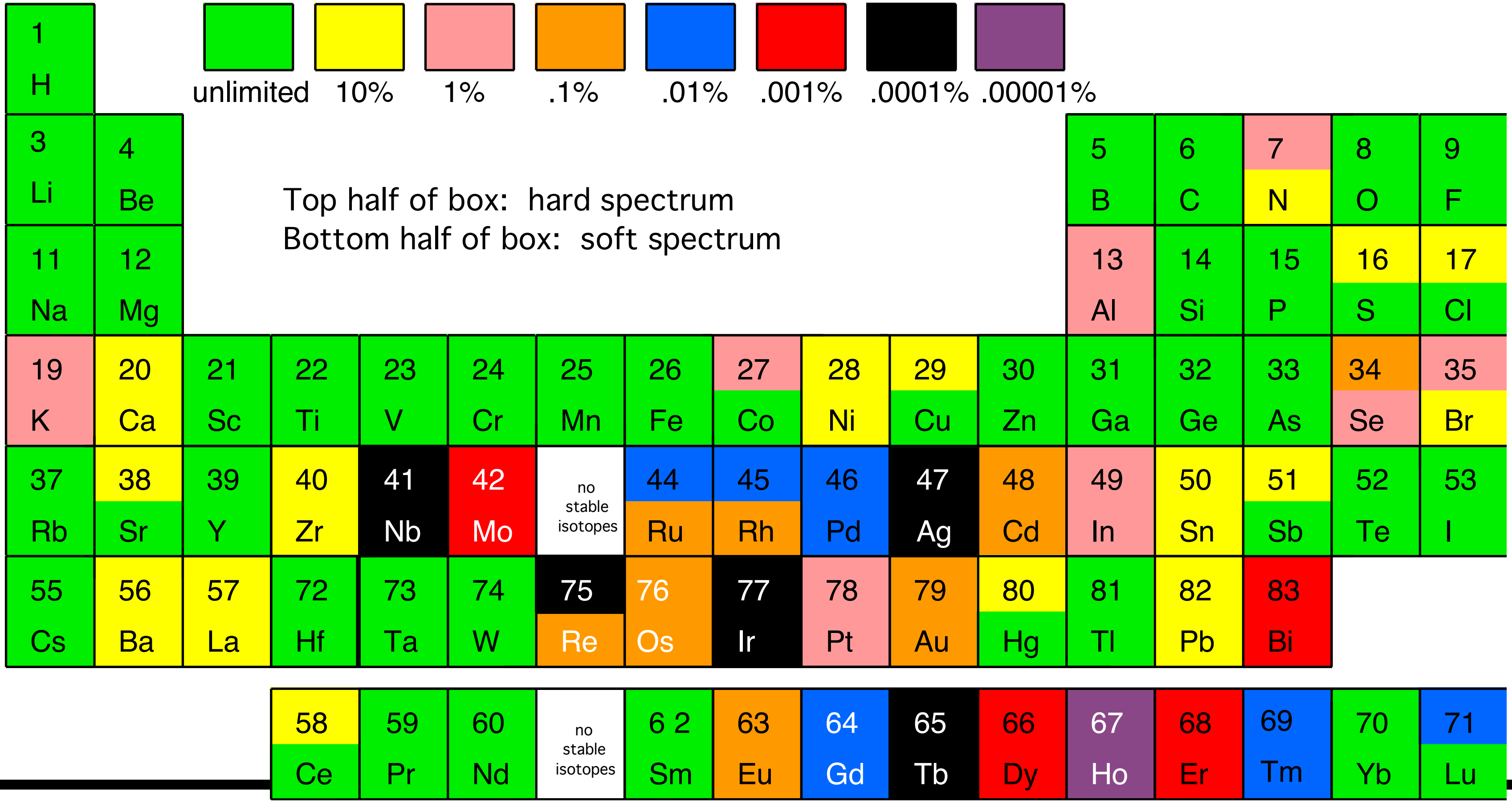
Based on C. B. A. Forty, et al., Handbook of Fusion Activation Data; Part 1. Elements Hydrogen to Zirconium, AEA FUS 180, May, 1992. Assumes 4.15 MW/m^2 for 25 years

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
    - Fusion can avoid high level waste!
  - 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
        - Scenario: someone builds a house on top of unrecognizable waste 500 years in the future, lives there, and grows half their food on the waste site[1]
    - Objective for fusion is structural materials that meet class C
      - Reference below outlines concentration limits for fusion materials

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

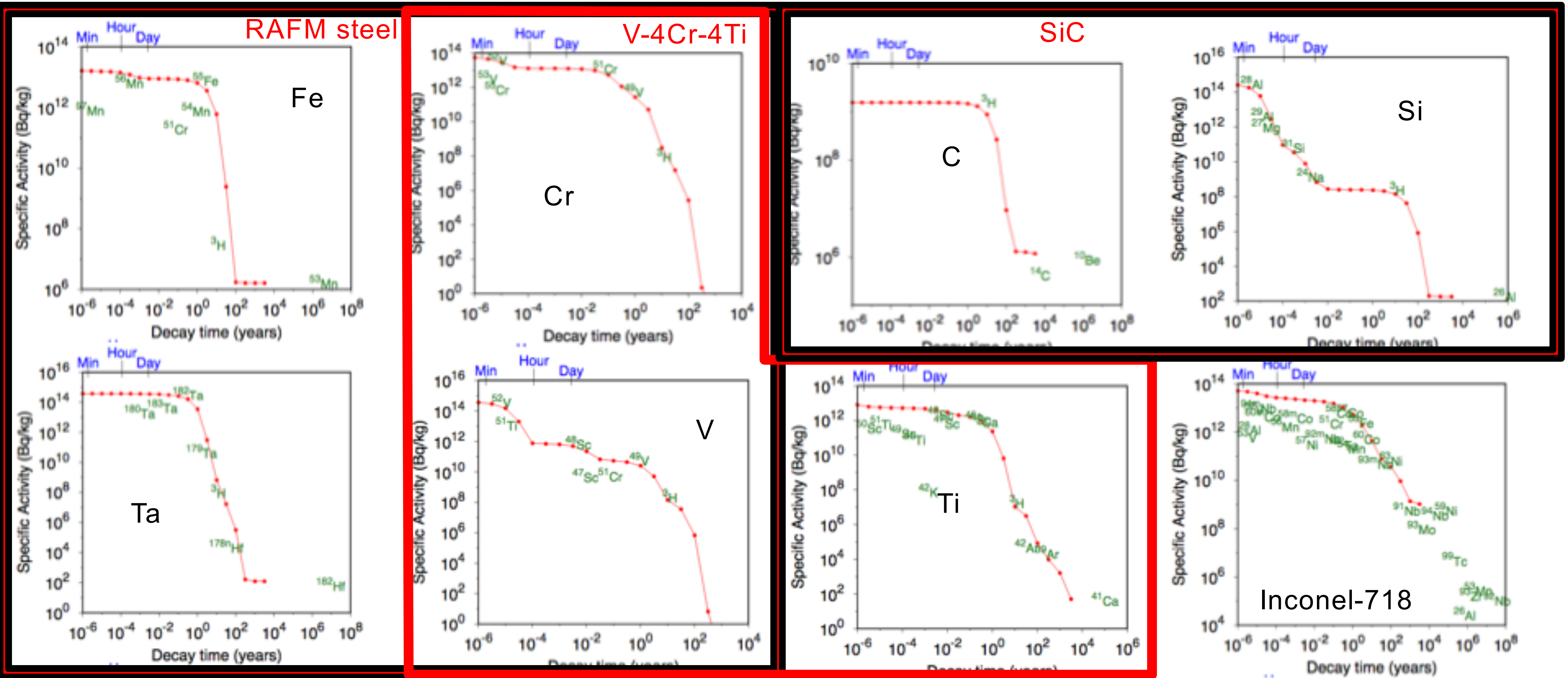
Alloy concentrations to meet Class C disposal



From: Piet, et al., “Initial Integration of Accident Safety, Waste Management, Recycling, Effluent, and Maintenance Considerations for Low-Activation Materials”, **Fusion Technology**, Vol. 19, Jan. 1991, pp. 146-161.
Assumes 5 MW/m^2 for 4 years; and E. T. Cheng, “Concentration Limits of Natural Elements in Low Activation Materials”, **presented at ICFRM-8, Sendai, Japan,October 1997**

Decay heat of elements over time

- At ITER FW flux and spectrum, following 14 year ITER operational scenario (from CCFE-R(16)37)



Low-activation materials

- Our “default” fusion reactor structural material is a modified version of grade 91 steel, iron alloyed with:

Cr	Mo	V	Nb	Si	C
8.0-9.5	0.85-1.05	0.18-0.25	0.06-0.1	0.2-0.5	0.08-0.12

- Activation of Molybdenum and Niobium creates long-lived waste:
- ^{93}Mo: $t_{1/2}$ = 4,000 y, ^{94}Nb: $t_{1/2}$ = 20,300 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. V-4Cr-4Ti[2], SiC[3]) are not yet sufficiently developed for fusion applications

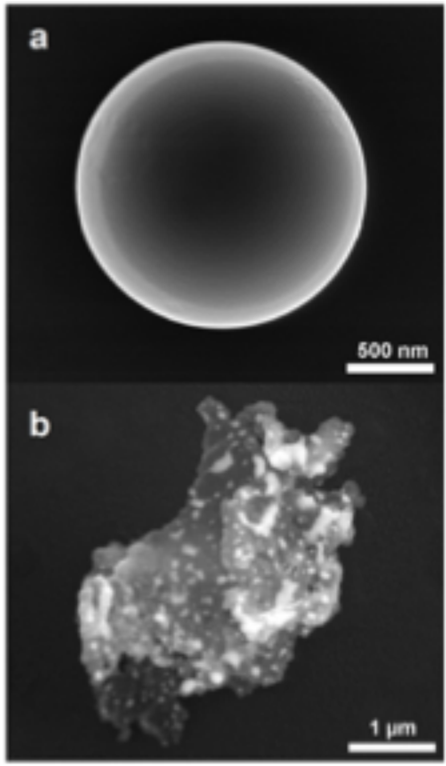
[1]H. Tanigawa et al., *Nuclear Fusion* **57** (2017) 092004.
[2]R. Kurtz et al., *Journal of Nuclear Materials* **283-287** (2000) 70-78.
[3]L. Snead et al., *Journal of Nuclear Materials* **417** (2011) 330-339.

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:

$$^{206}Pb \xrightarrow{n,\alpha} {}^{203}Hg \qquad {}^{208}Pb \xrightarrow{n,\gamma} {}^{209}Pb \xrightarrow{\beta-} {}^{209}Bi \xrightarrow{n,\gamma} {}^{210}Bi \xrightarrow{\beta-} {}^{210}Po$$

  - ^{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…



Tungsten dust from ASDEX-Upgrade

Lithium

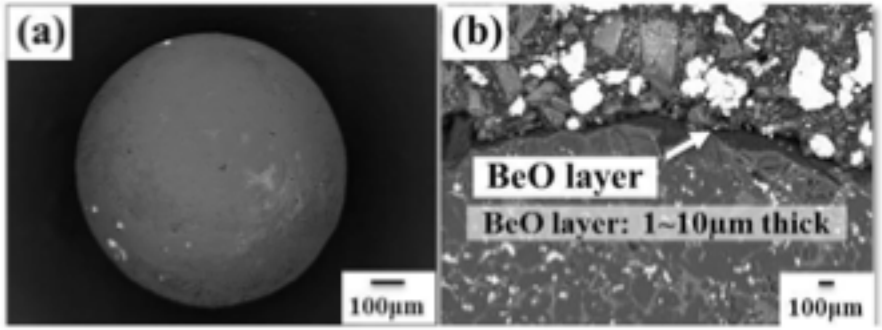
- Lithium is the only element capable of breeding sufficient tritium to keep a fusion reactor running:

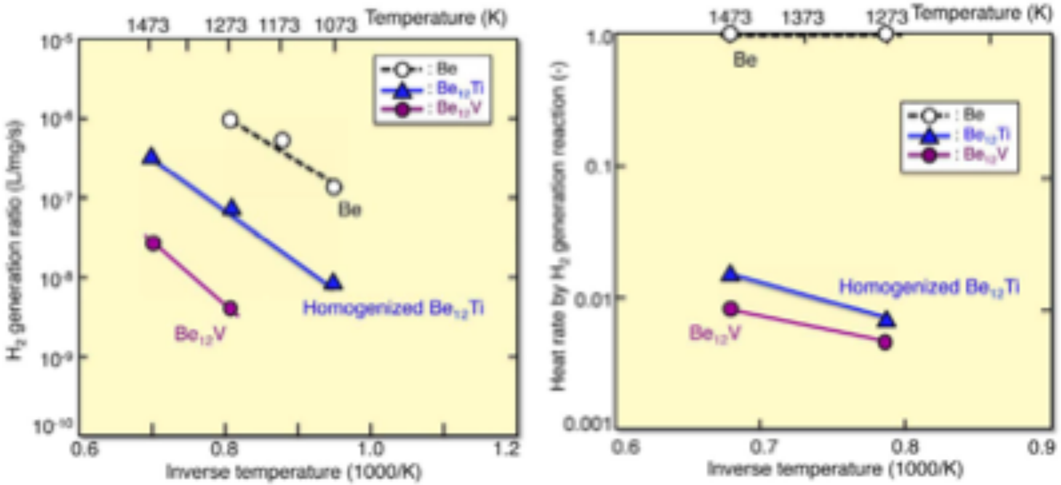
$$n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785\ MeV \qquad n + {}^{7}Li \rightarrow {}^{4}He + T + n' - 2.5\ MeV$$

- So, by definition, the blanket must contain a high density of lithium compounds, e.g.:
  - Liquid metals: pure Li (T_{melt} = 180.5 °C), $Pb_{83}Li_{17}$ (T_{melt} = 180.5 °C)
  - Solid ceramics Li_2TiO_3, and Li_4SiO_4
  - Molten salt FLiBe ($2LiF+BeF_2$, T_{melt} = 459 °C)
- Lithium metal is highly (and exothermically) chemically reactive with air (both oxygen and nitrogen) and water:
- $Li + H_2O \rightarrow LiOH + ½H_2$; $Li + ½\,H_2O \rightarrow ½\,Li_2O + ½H_2$; $4Li + O_2 \rightarrow 2Li_2O$; $6Li + N_2 \rightarrow 2Li_3N$
- Pure lithium also retains large amounts of tritium
- Chemical reactivity and tritium retention are greatly reduced in the eutectic alloy $Pb_{83}Li_{17}$, which is preferred as a liquid metal breeder
  - Adequate tritium breeding maintained by high cross section for (n,2n) reactions in Pb, one of only two elements that are effective neutron multipliers
- As a liquid metal plasma facing component, circulating lithium inventories should be minimized, and tritium extraction will be important

Beryllium

- Beryllium is used in ceramic breeder blankets as a neutron multiplier (via [n,2n] reactions); it is also a very effective neutron moderator/reflector
- It also has some unique safety challenges
- Inhalation of beryllium aerosols or particulates can provoke *chronic beryllium disease* in a subset of exposed individuals, in which an inflammatory immune response damages the lungs over time; it is chronic and sometimes fatal
  - Respiratory protection necessary (gloveboxes, respirators, etc.) when working with beryllium in the laboratory
- In a fusion reactor, beryllium is also subject to very exothermic oxidation at high temperature in air or water:
  - $Be + \frac{1}{2}O_2 \rightarrow BeO + 609$ kJ/mol
  - $Be + H_2O \rightarrow BeO + H_2 + 367$ kJ/mol
- Beryllide intermetallic compounds such as $Be_{12}Ti$ and $Be_{12}V$ are being investigated as alternatives for future reactors and have demonstrated increased oxidation resistance

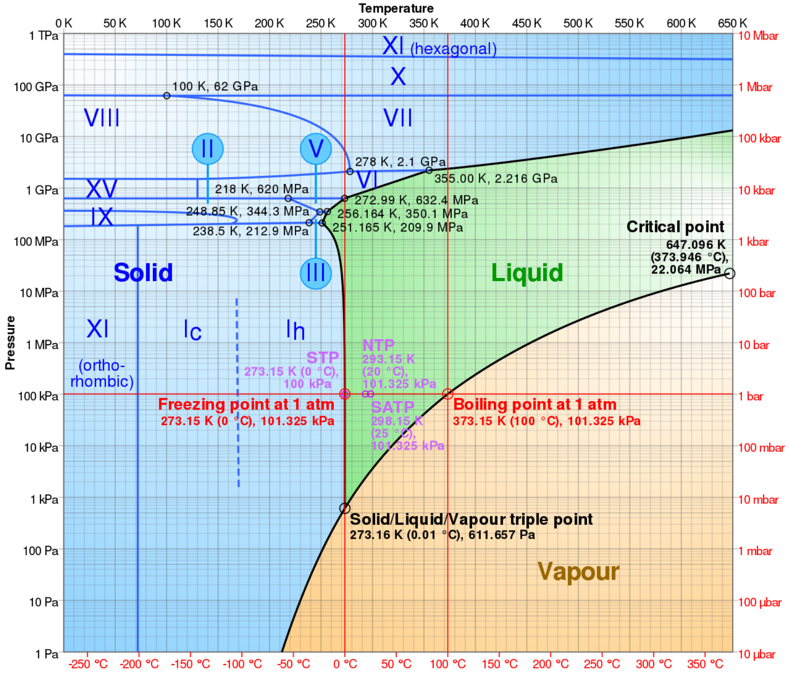




M. Nakamichi et al. *Nuclear Materials and Energy 15 (2018) 71–75*

Water

- Water is an excellent heat transfer medium, and a "balance of plant" (heat exchangers, etc.) based on water has a very high degree of technological maturity
- But it also creates some significant safety issues!
- High pressures (155 atm) are required to keep water liquid at high (~325 °C) temperature
  - Water-cooled systems will always be near a phase change
  - In an event involving loss of forced cooling (pumps cease to function, e.g. due to loss of power), some undesirable accident sequences become possible:
  - Loss of forced cooling
    - → Boiling due to decay heat
      - → Reduced heat transfer and overpressure
        - → Breach resulting in steam reaction with Be or Li
          - → More heat, pressure, and hydrogen generation
            - → Breach resulting in hydrogen release
              - → Hydrogen explosion
                - → Dispersal or radioactive materials



Regardless of the choice of coolants, ensuring passive removal of decay heat (e.g. by natural convection) should be an objective of the design!

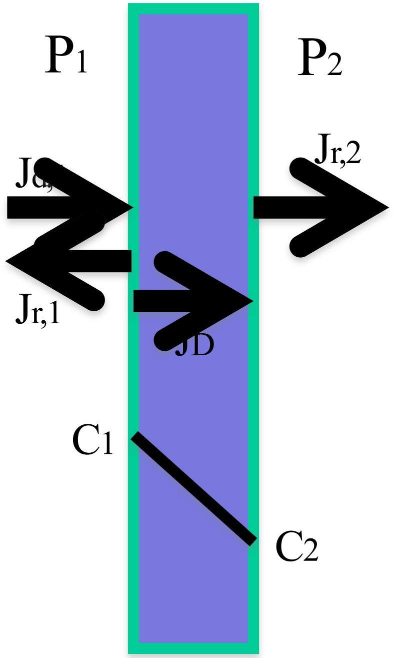
For these and other reasons, we've tried to avoid or minimize the use of water in fusion reactors

Tritium

- Tritium is itself radioactive, and decays via beta emission (18.6 keV) with a 12.3 year half life
- Tritium is a unique radiological hazard because:
  - It is chemically identical to hydrogren, and can take the place of hydrogen in substances readily absorbed by the human body (especially water, but also other organic compounds)
  - At high temperatures, it readily diffuses through solid metals, and is therefore difficult to completely confine within a fusion reactor and its ancillary systems

Tritium Permeation

- Consider a gas/solid interface. At each surface:
  - Molecules in the gas dissociate and adsorb as atoms on the surface, with flux $J_d = K_d P_{T_2}$
  - Atoms on the surface recombine to form molecules, and are released into the gas $J_r = K_r C^2$
  - Or, they begin to diffuse through the structure, with diffusion flux $J = \frac{-D(C_2 - C_1)}{x}$



- If surface dissociation/recombination are fast relative to diffusion (*diffusion limited*):

$$J_{d,i} = J_{r,i} \rightarrow C_i = K_s \sqrt{P_i}$$ Sieverts' Law,

where $K_s = \sqrt{K_d / K_r}$ is the *solubility*

- Say C_2 is small…
- If diffusion is fast relative to surface dissociation/recombination (*surface limited*):

$$C_i \approx C_0 \qquad J_D \approx 0 \qquad J_{r,2} \approx -J_{r,1} \approx \frac{1}{2} J_{d,1}$$

When performing tritium transport analyses, we model an entire reactor system (reactor, piping, heat exchangers, building, etc.) with a network of 1D structures like that shown, to try and estimate how much tritium permeates from our reactor to the environment

Tritium Permeation (2)

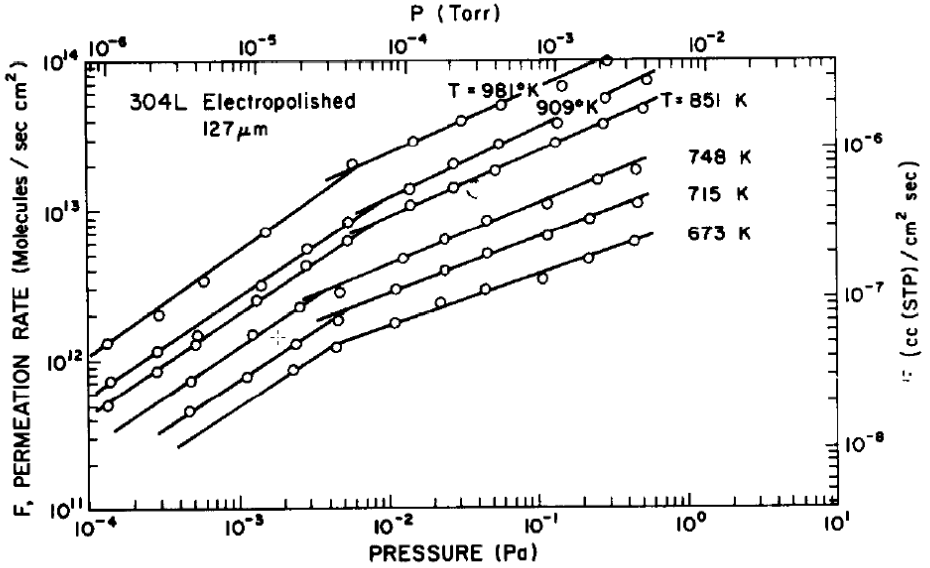
- When diffusion is rate limiting (W' >> 1): $J = \frac{DK_s\sqrt{P}}{x}$

- Define *permeability*: $\Phi \equiv DK_s \Rightarrow J = \frac{\Phi\sqrt{P}}{x}$

- When surface effects are rate limiting (W' << 1): $J = K_d P$
- A dimensionless number* tells us where the transition is:

$$W' = \frac{K_d x\sqrt{P}}{\Phi}$$

- Diffusion-limited (~√P) transport is usually assumed if parameters unknown

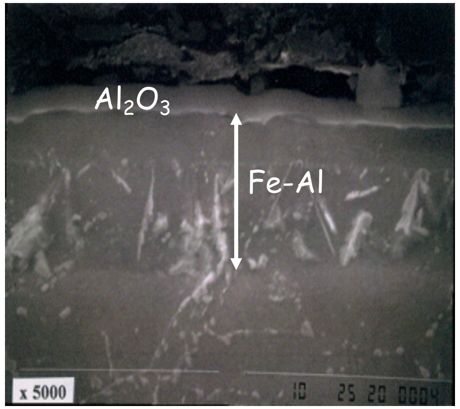


Perkins and Noda *JNM* **71** (1978) 349-364.

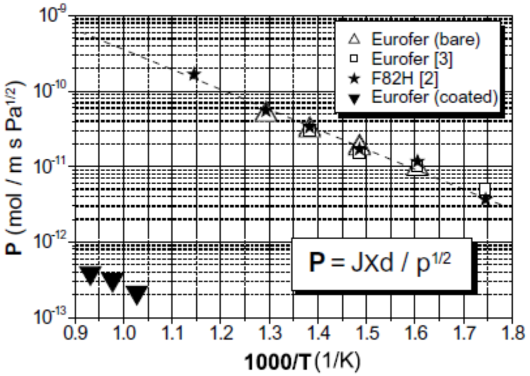
*Ali-Kahn et al *JNM* **76/77** (1978) 337-343.

Mitigating tritium permeation

- There are a variety of strategies for limiting tritium permeation; multiple of these will probably be employed simultaneously (defense in depth) in a real fusion reactor
- Bottle it up
  - Apply barriers with varying degrees of robustness that inhibit tritium transport
- Get it out
  - Deploy efficient tritium extraction systems near the outlet of the blanket

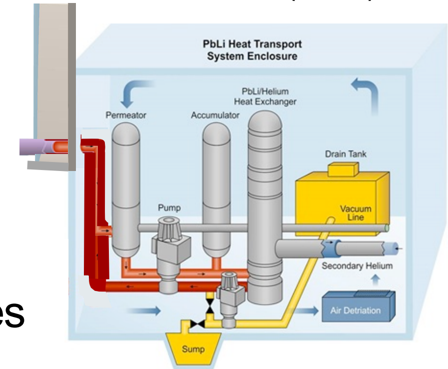


Al_2O_3 deposition by CVD - Jürgen Konys



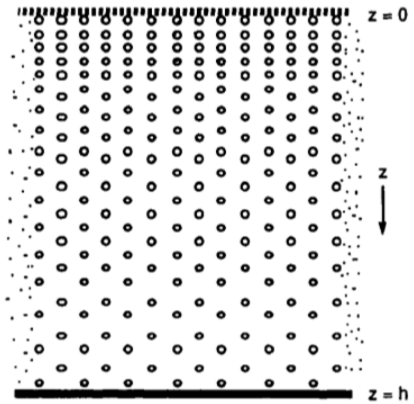
Levchuck et al *JNM* **328** (2004) 103

Permeation barrier coatings



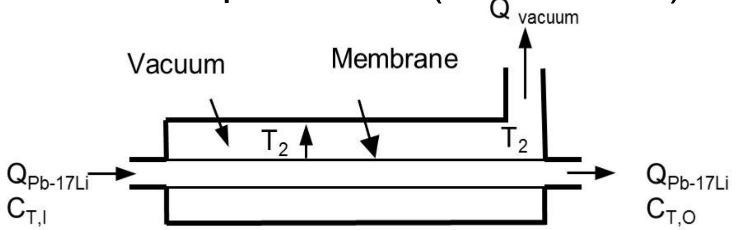
Vaults/enclosures

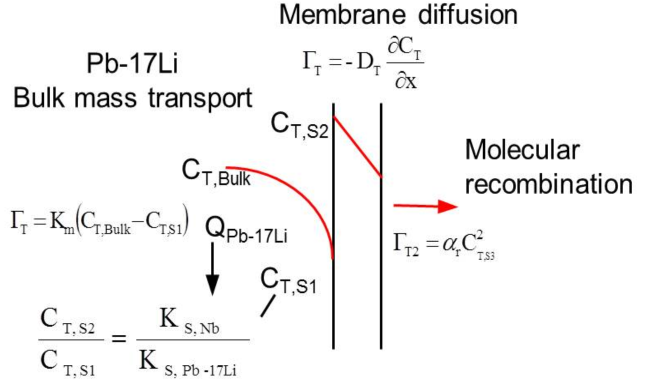
Extraction columns



Sprays (vacuum sieve tray)

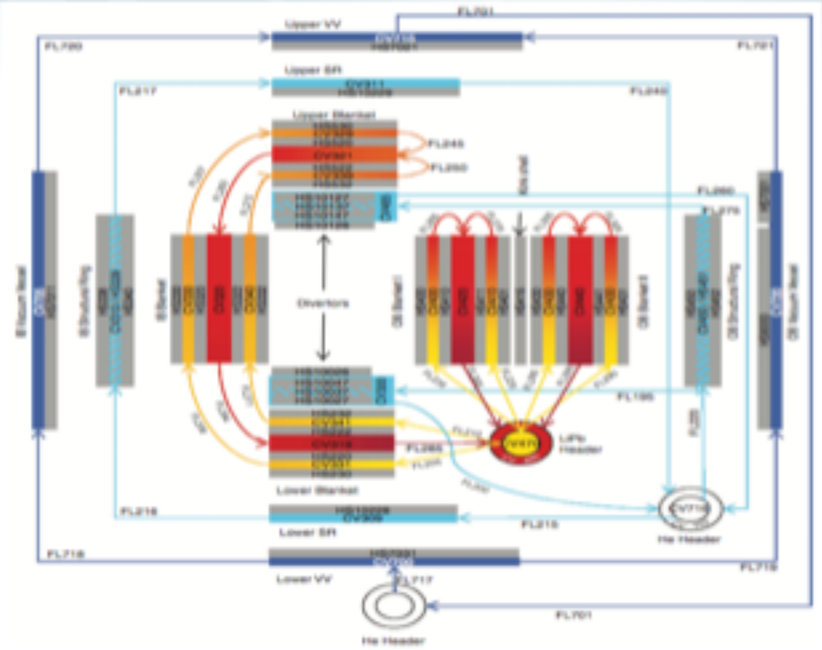
Vacuum permeator (membranes)

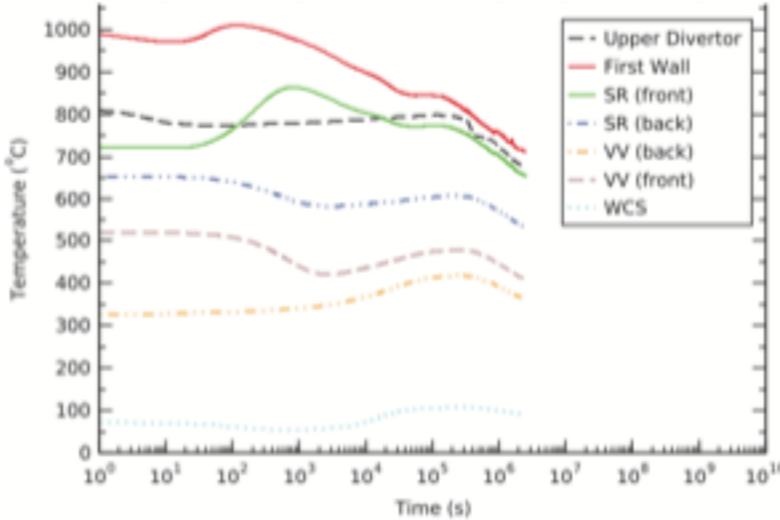




Accident Analysis

- After mitigating as many safety issues as possible *by design*, we demonstrate via safety analysis that a reactor concept is passively safe
- Integrated, plant-scale (coarsely nodalized) modeling includes:
  - Fluid flow (potentially multiphase), with well established empirical relations for friction and pressure drop
  - Heat transfer: 1D conduction through solids and convection heat transfer coefficients at fluid/solid interfaces
  - Aerosol transport: solution of the aerosol dynamic equations that govern the convective transport, and competing deposition and resuspension mechanisms, of particulates
  - Chemical reactions: capture any that consume solid structures, add heat, and produce aerosols
  - Tritium Transport: predict tritium transport as gas (HT) and water (HTO) in normal and off-normal conditions



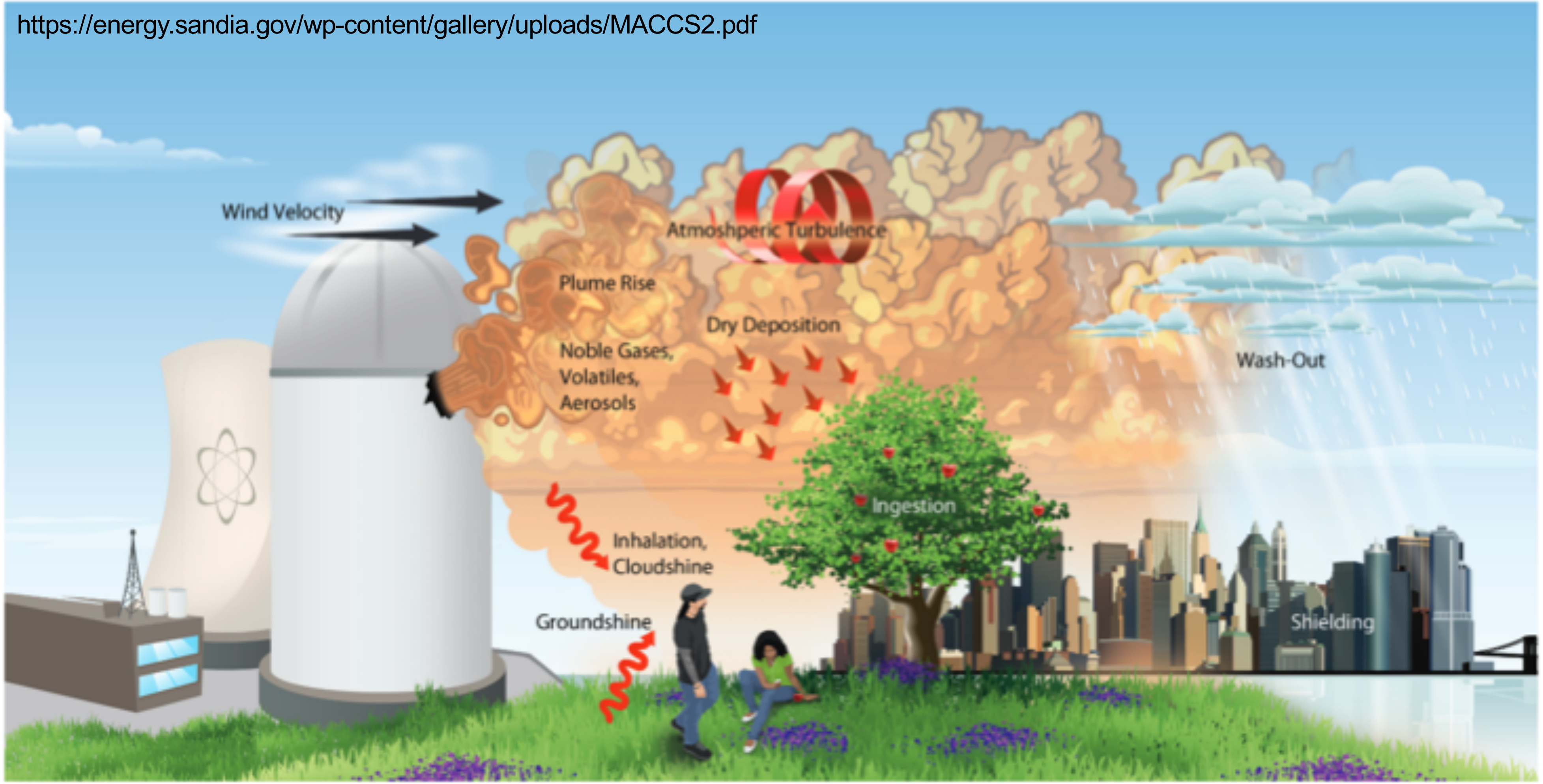


Component temperatures during ARIES-ACT1 LOFA

P. Humrickhouse, *Fusion Science and Technology* **67** (2015) 167-178

Transport in the environment

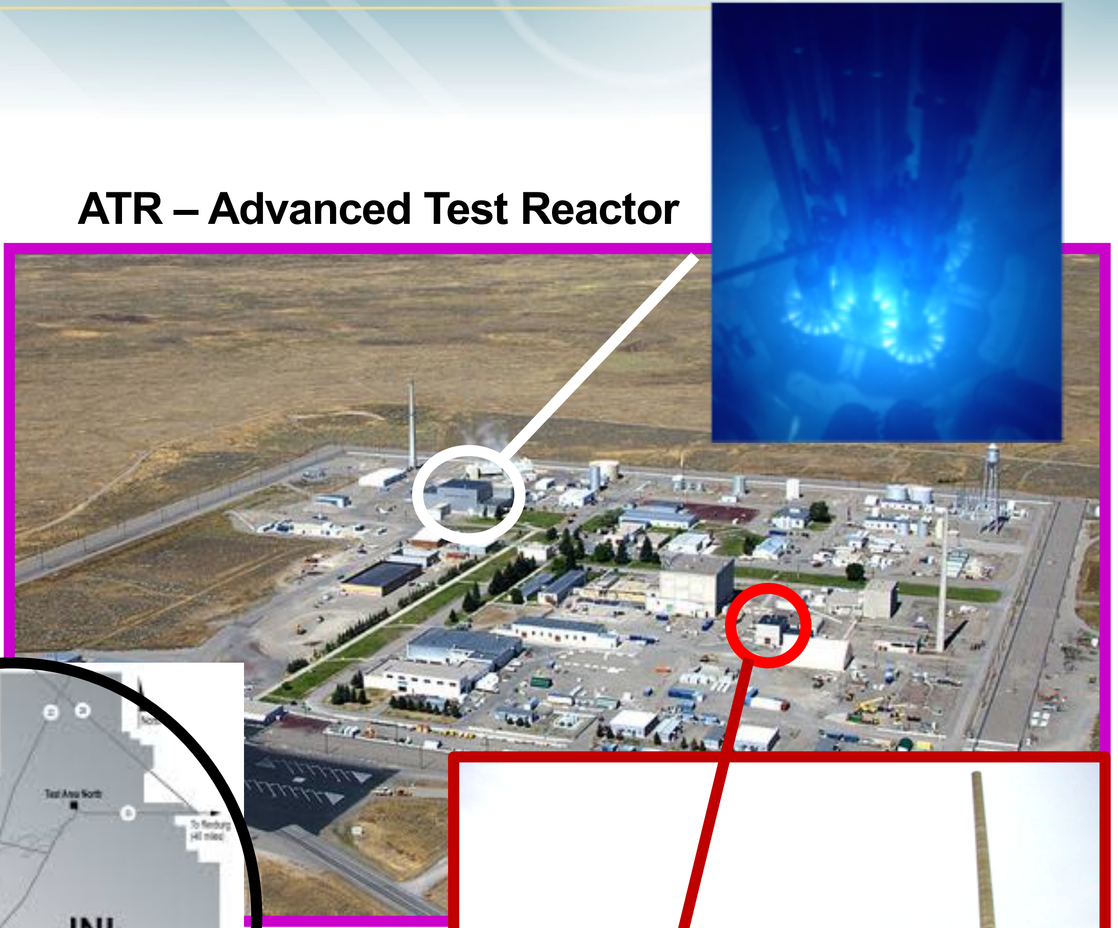
- Given a radionuclide release, codes such as MACCS2 (developed at Sandia) model transport phenomena in the environment that might lead to radiation exposures

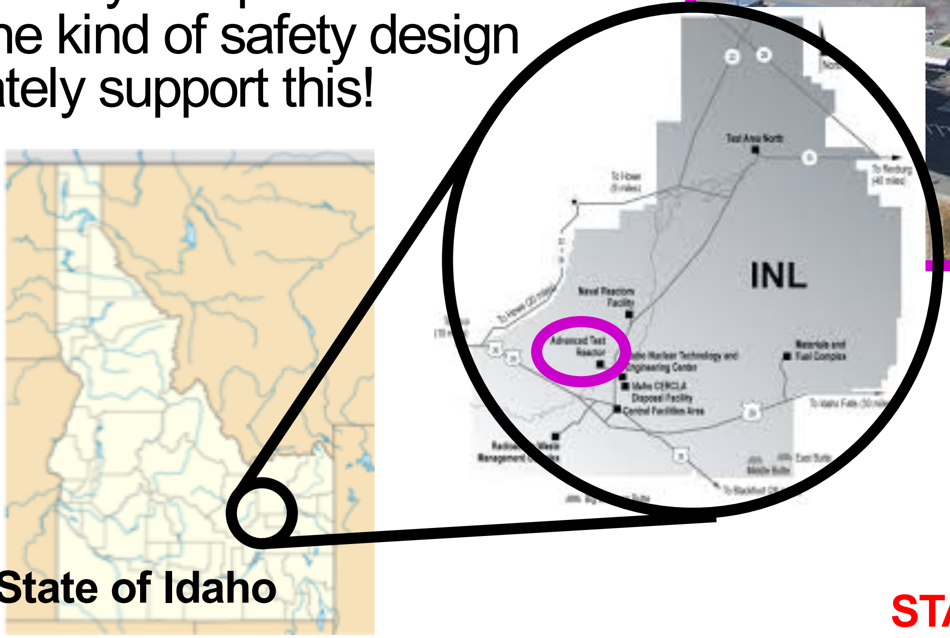


A simple solution…

- Have a big site! The 890 square mile Idaho National Laboratory (originally the National Reactor Testing Station) came to be with this in mind
- Much of the fusion safety research described in this presentation has been conducted in the INL fusion safety program, including at our Safety and Tritium Applied Research (STAR) facility
- Of course, we aim to site future commercial fusion reactors on small sites- hopefully this presentation has given you a flavor for the kind of safety design and analysis that will ultimately support this!

ATR – Advanced Test Reactor





State of Idaho

STAR – Safety and Tritium Applied Research


INL
Idaho National Laboratory