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

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U.S. DEPARTMENT OF ENERGY

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

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.

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:

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

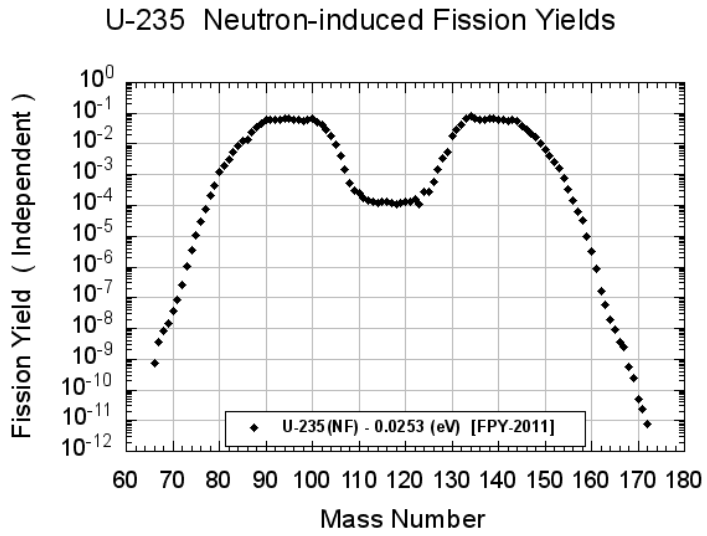
  - Side reactions (D+D, $^{4}He+^{11}B$) release some of the power in neutrons
  - Substantially reduced radiological hazards relative to D-T, but harder to achieve

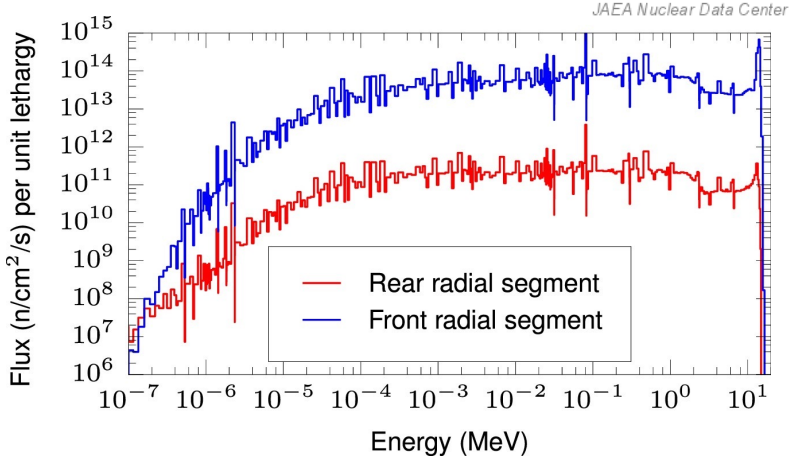
- The rest of this talk is focused on issues related to D-T fusion

Neutron activation

- The D-T fusion reaction produces neutrons: 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





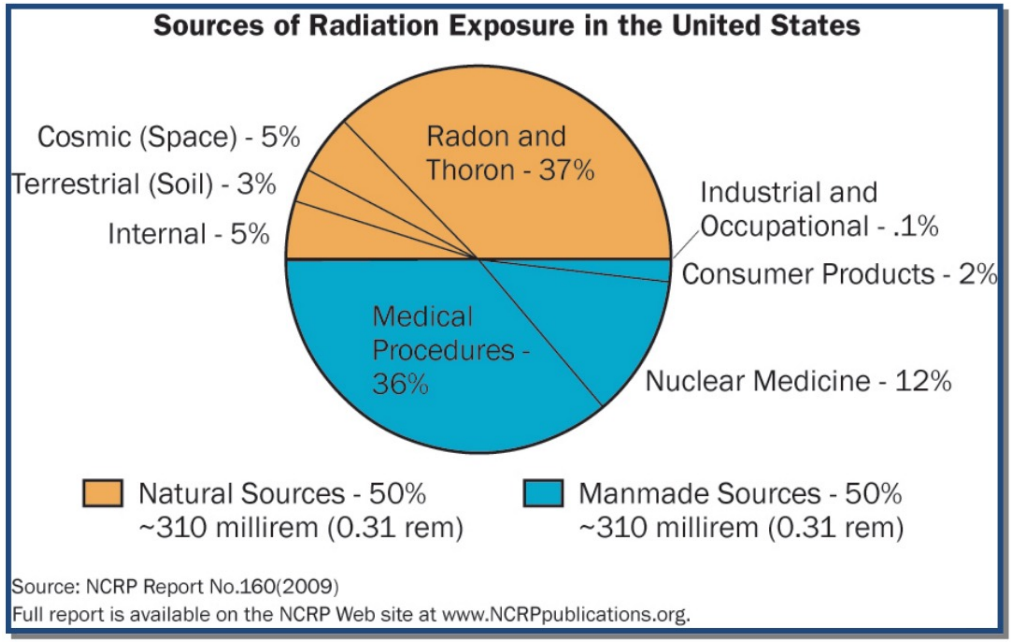
J. Shimwell, *Fusion Engineering and Design* **98-99** (2015) 1868-1871.

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:

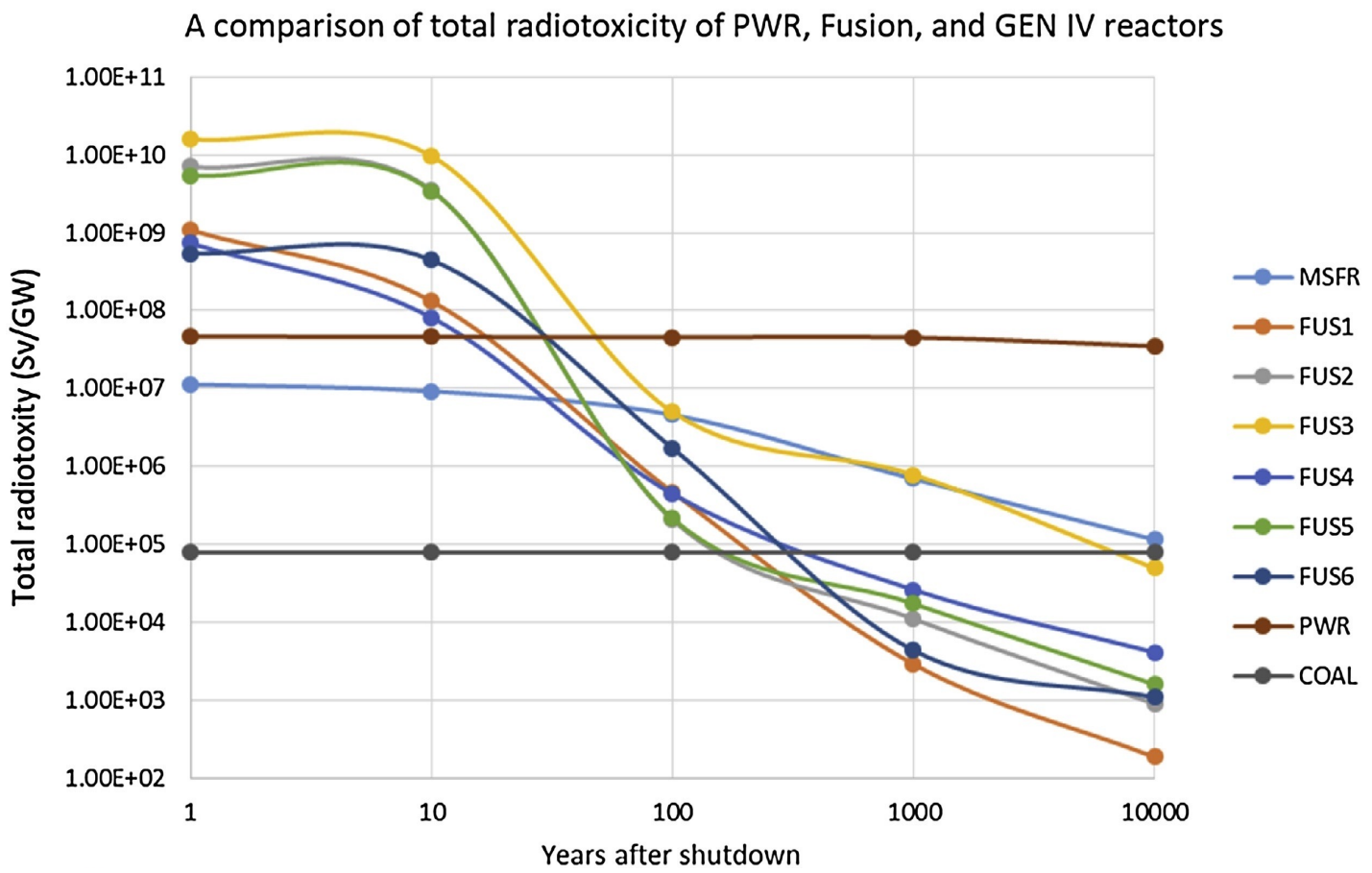


https://www.nrc.gov/docs/ML0333/ML033390088.pdf

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

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



FUS1 = V alloy, Li_2O
FUS2 = RAFM steel, PbLi
FUS3 = RAFM steel, Li_4SiO_4
FUS4 = SiC composite, PbLi
FUS5 = RAFM steel, PbLi
FUS6 = SiC composite, Li_4SiO_4

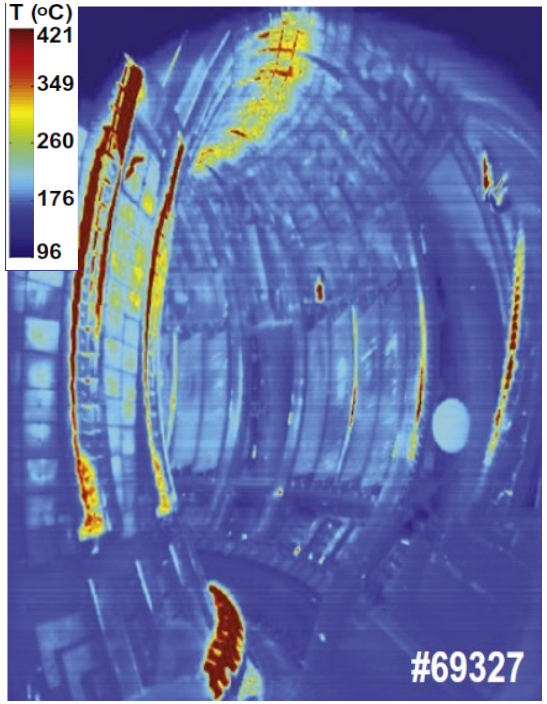
Radioactive Material Concerns

- 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

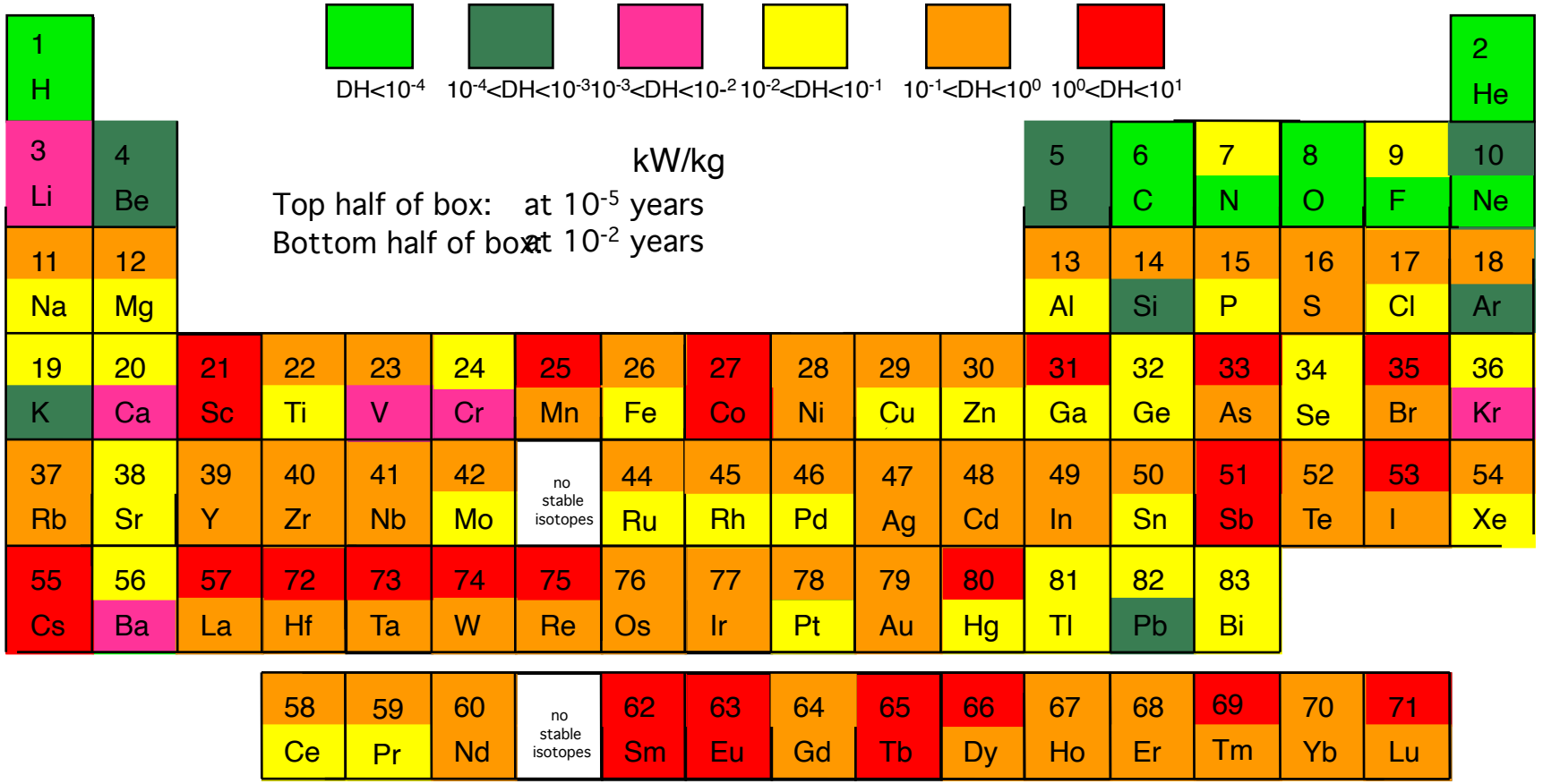
- Fusion reactors do not experience *reactivity* transients that can occur in a fission reactor
- But they do have some large stored energies; these need to be dissipated safely in off-normal scenarios (avoid rapid/local deposition)
- Challenges to confinement of radioactive material include:
  - Ensuring 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



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

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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:

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:
- ^{99}Tc: $t_{1/2}$ = 211,100 y, ^{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

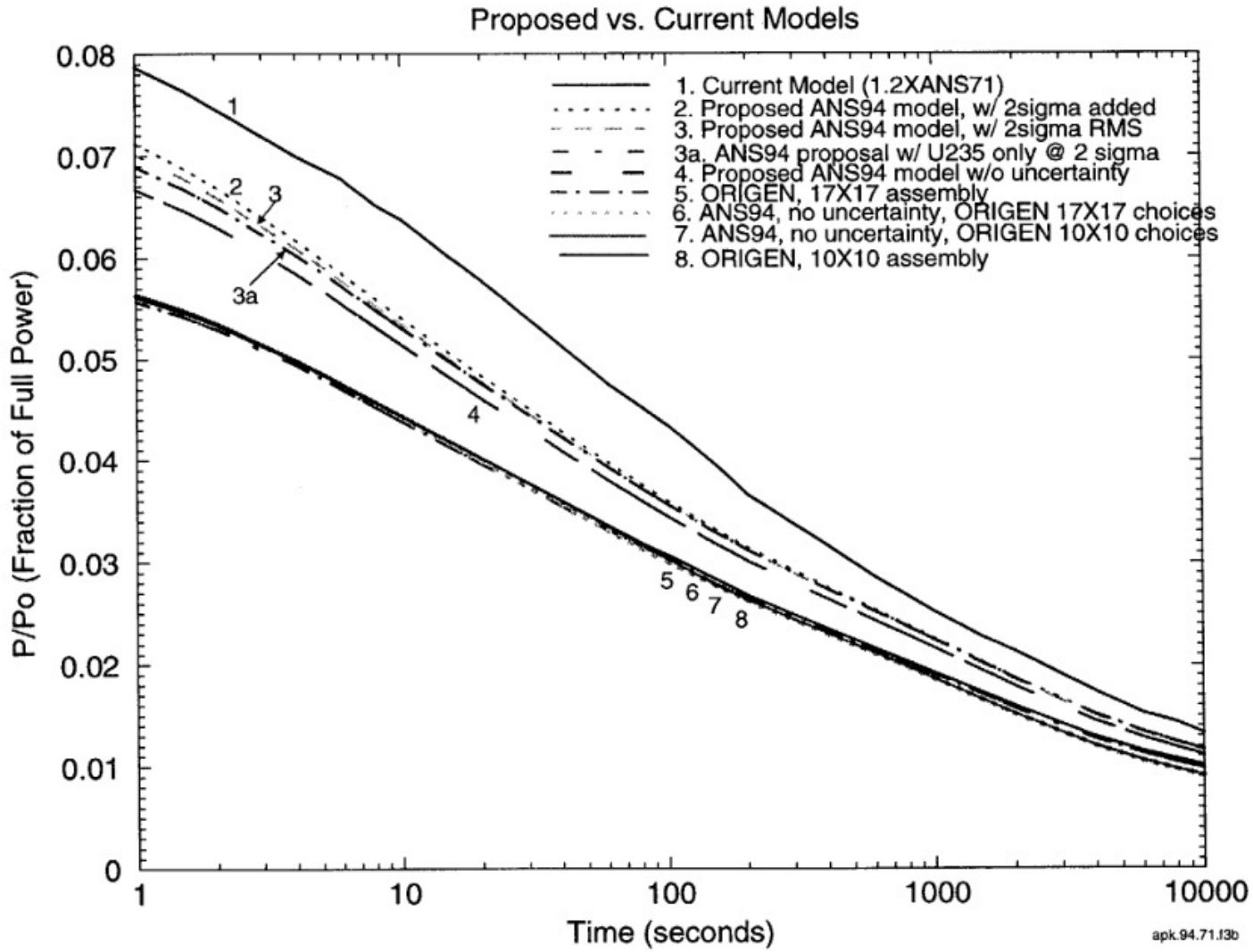
[1]H. Tanigawa et al., *Nuclear Fusion* **57** (2017) 092004.
[2]R. Kurtz et al., *Journal of Nuclear Materials* **283-287** (2000) 70-78.
[3]L. Snead et al., *Journal of Nuclear Materials* **417** (2011) 330-339.

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 shut down requires emergency cooling
- Inability to remove it in off-normal scenarios ultimately resulted in core melt at Three Mile Island and Fukushima

10 CFR 50, Appendix K

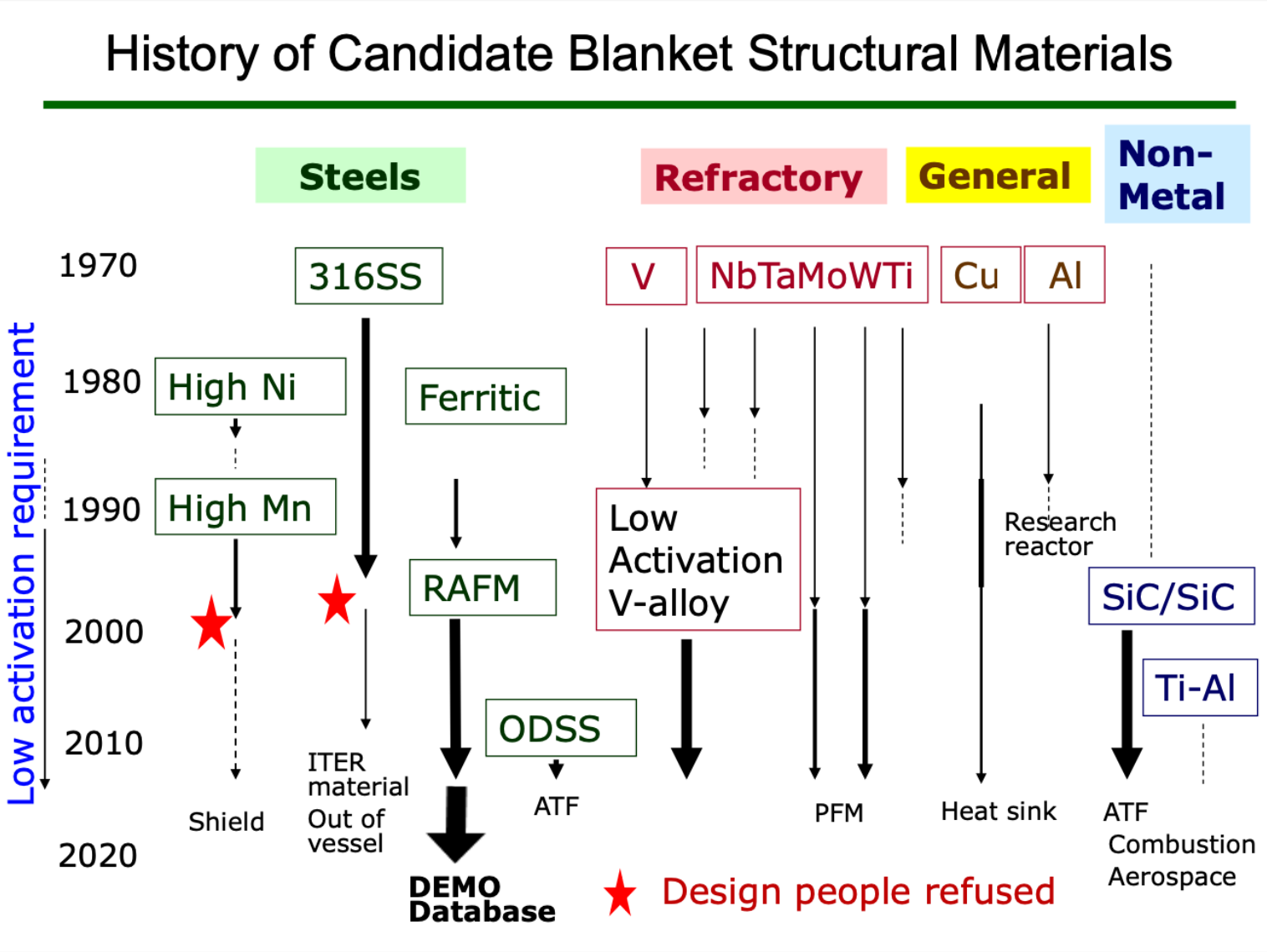
Figure 1. Appendix K Decay Heat Comparison



Decay Heat in Fusion Reactors

- The amount of decay heat depends in principle on many choices:
  - Structural Materials
  - Blanket Concepts
    - Liquids: PbLi (Dual-coolant lead-lithium), FLiBe
    - Solids: Li_2TiO_3, Li_4SiO_4, Li_2ZrO_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

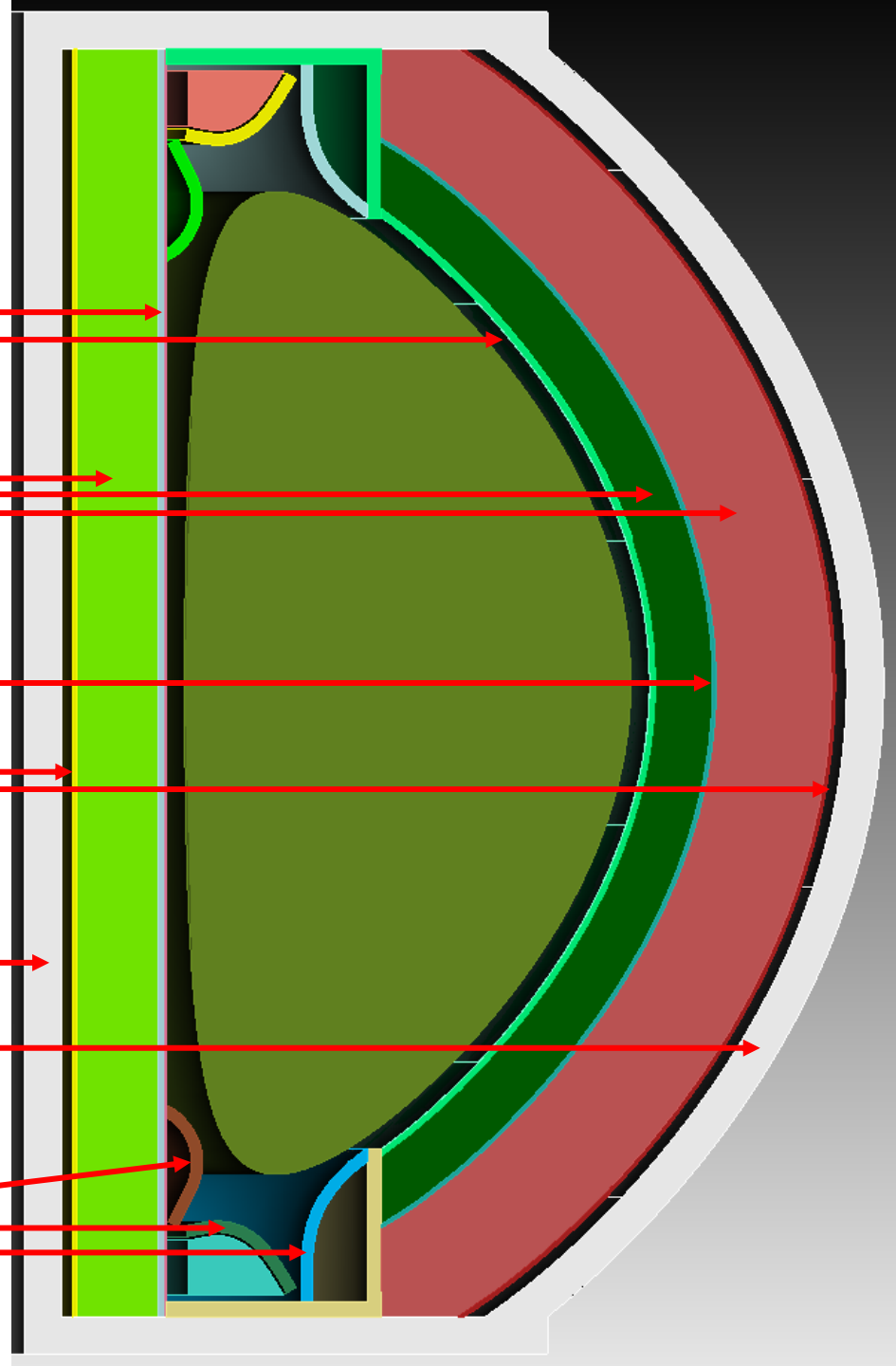
Structural Materials: T. Muroga, 3/29/2022



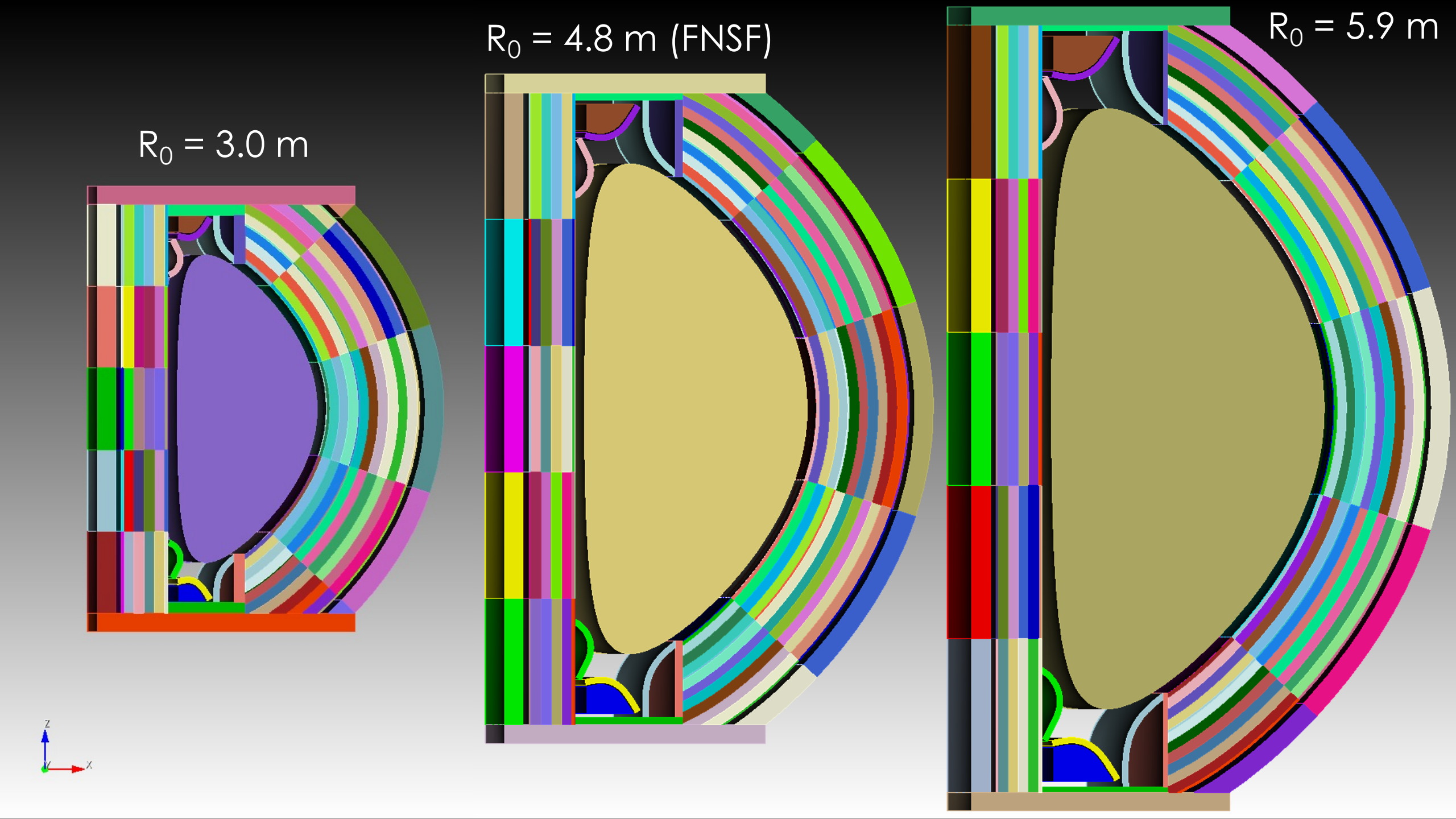
- Many possibilities considered in fusion program history…
- Activation (short-term decay heat or long-term waste) was a significant driver in eliminating many from consideration

Model

- Base case: FNSF, R_0 = 4.8m, P_{fus} = 518 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

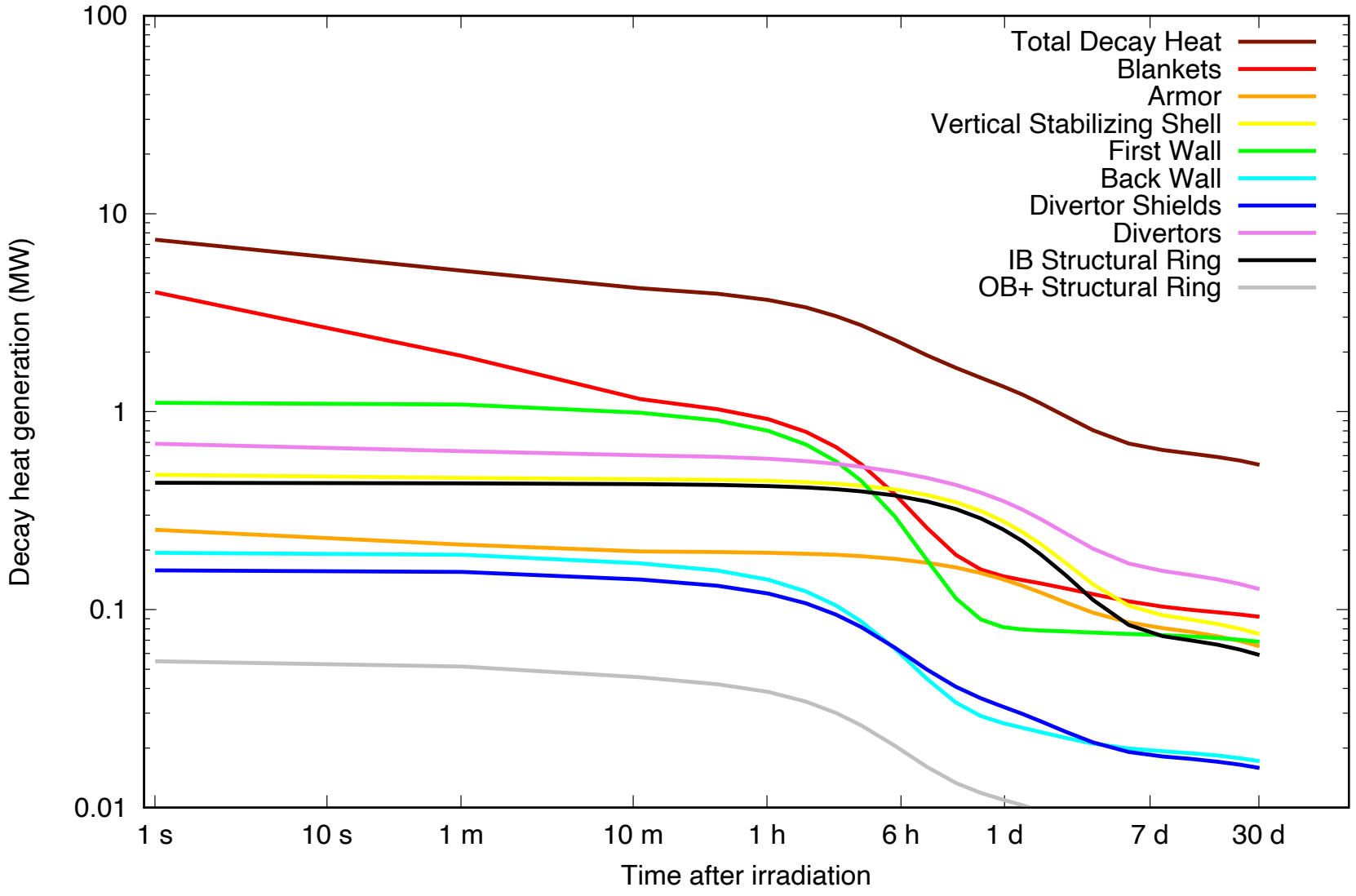


Two year operation (irradiation) assumed


R_0 = 3.0 m
R_0 = 4.8 m (FNSF)
R_0 = 5.9 m
Z
Y
X

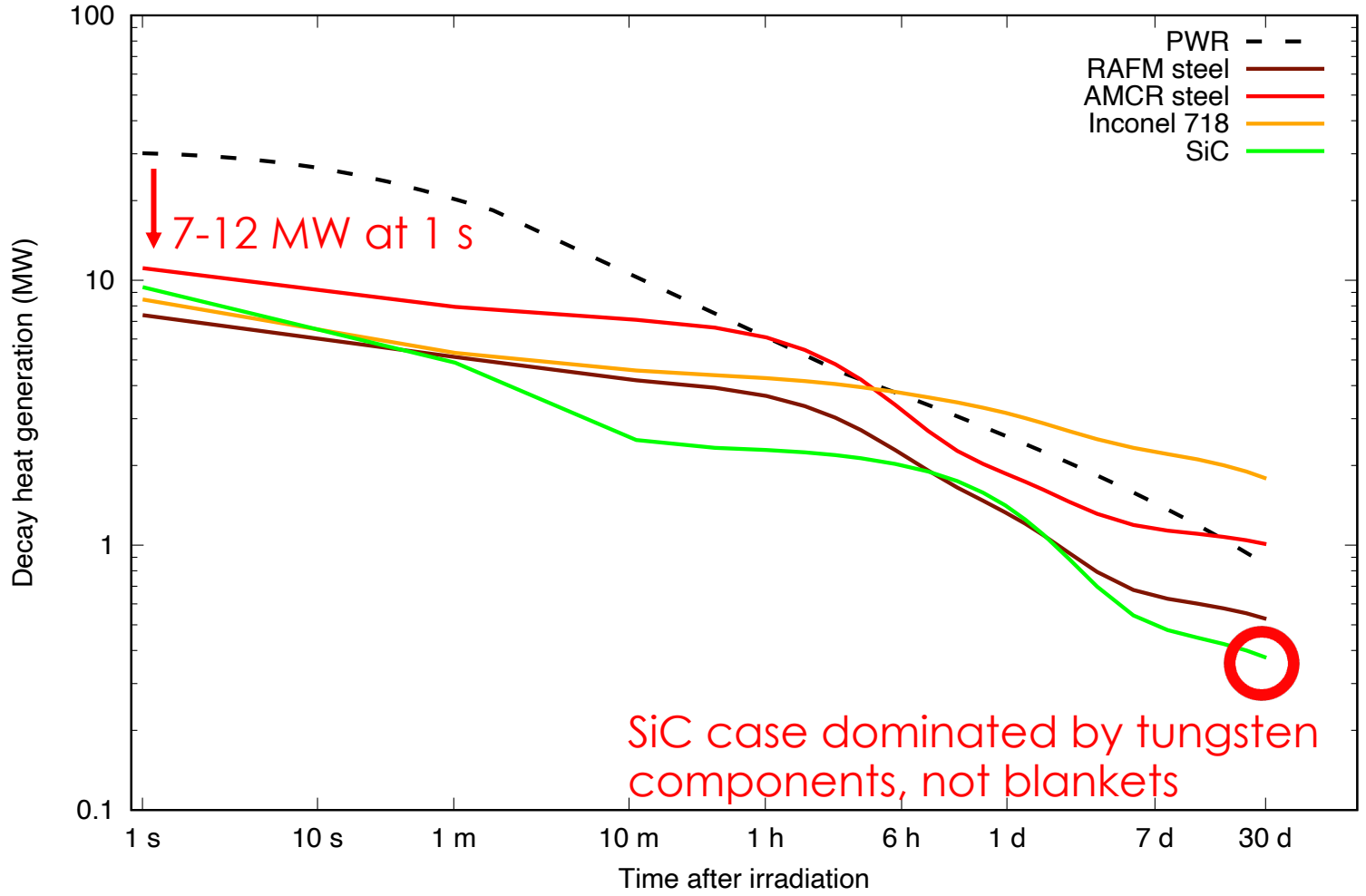
Baseline (FNSF/DCLL) results

- 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:



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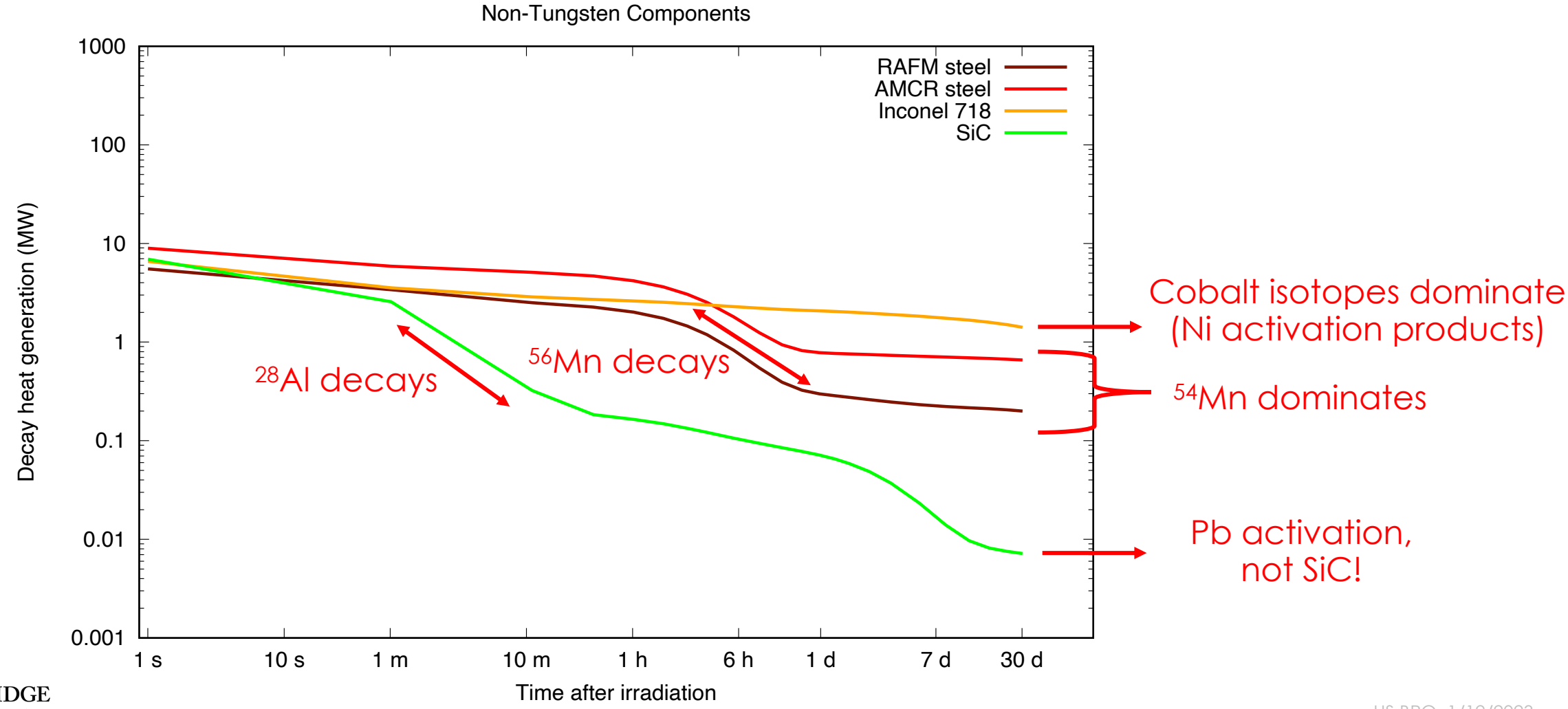
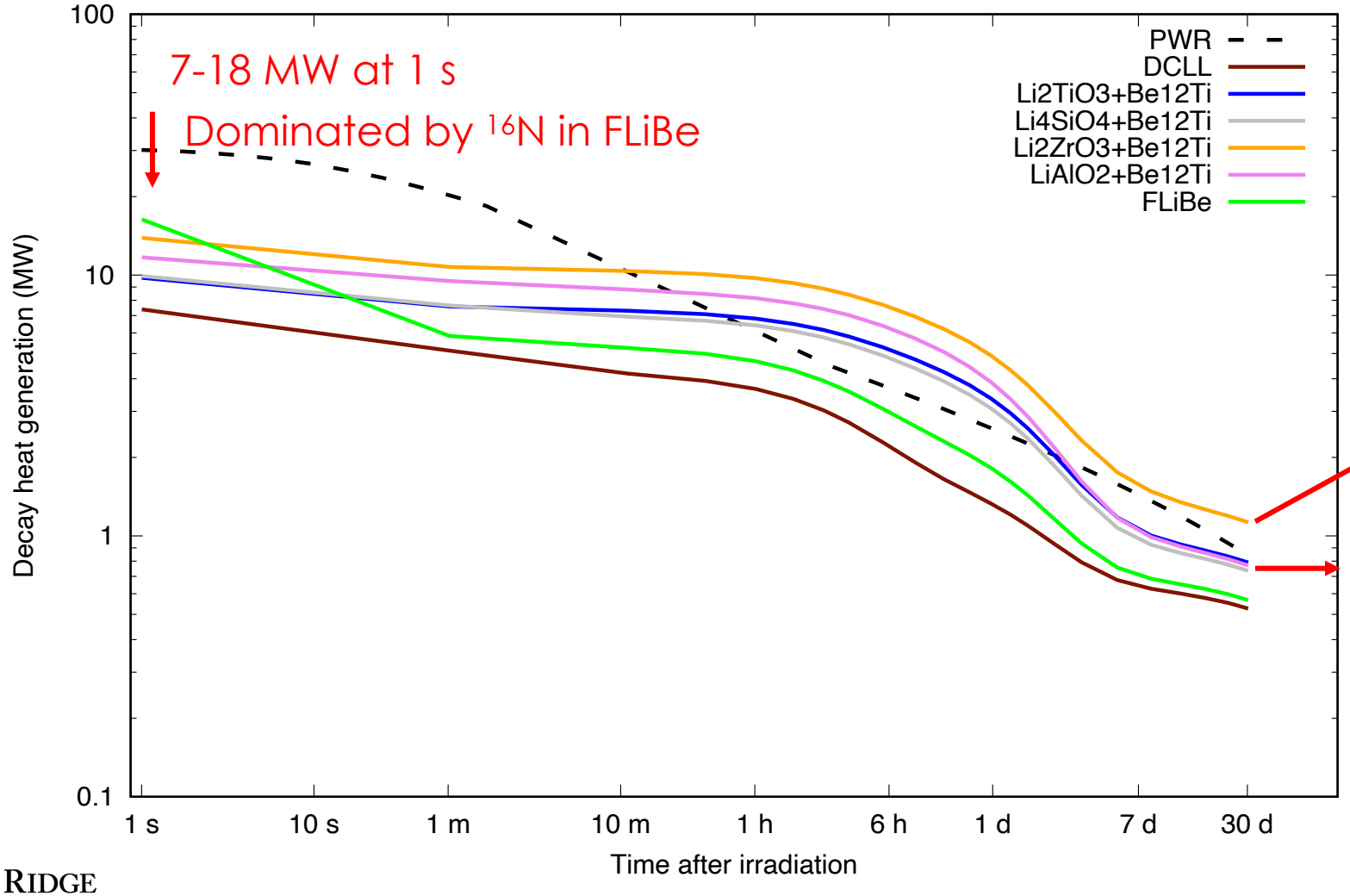
Decay heat dependence on structural material

- Blankets/FW/BW/OB SR only:



Decay heat dependence on blanket concept

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

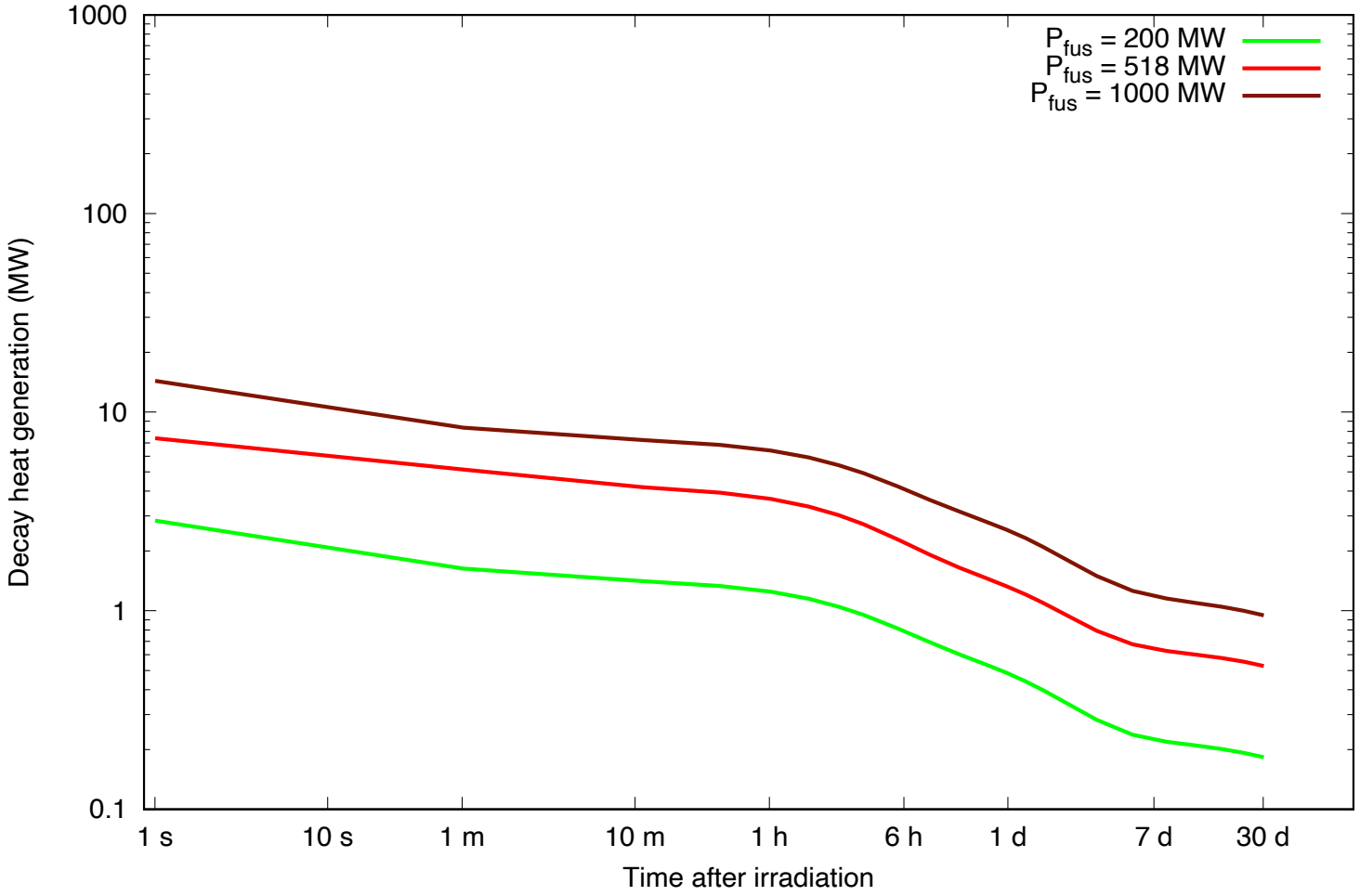


^{95}Zr, ^{95}Nb add significantly in Li_2ZrO_3 breeder

^{46}Sc (from Ti in multiplier) adds significantly in solid breeders

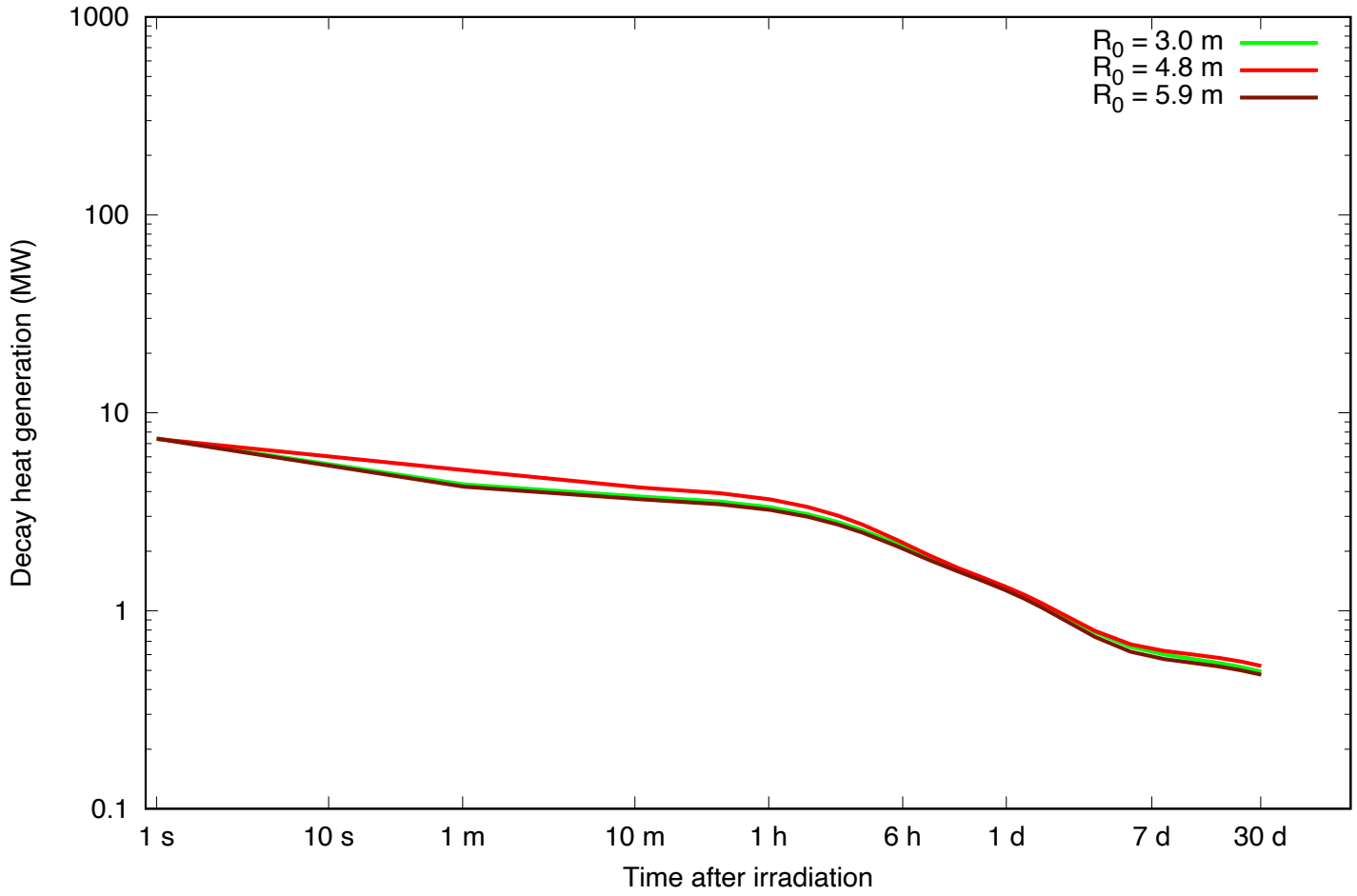
Decay heat dependence on fusion power

- For a given geometry and materials, decay heat scales linearly with fusion power, i.e. the decay heat fraction is the same:



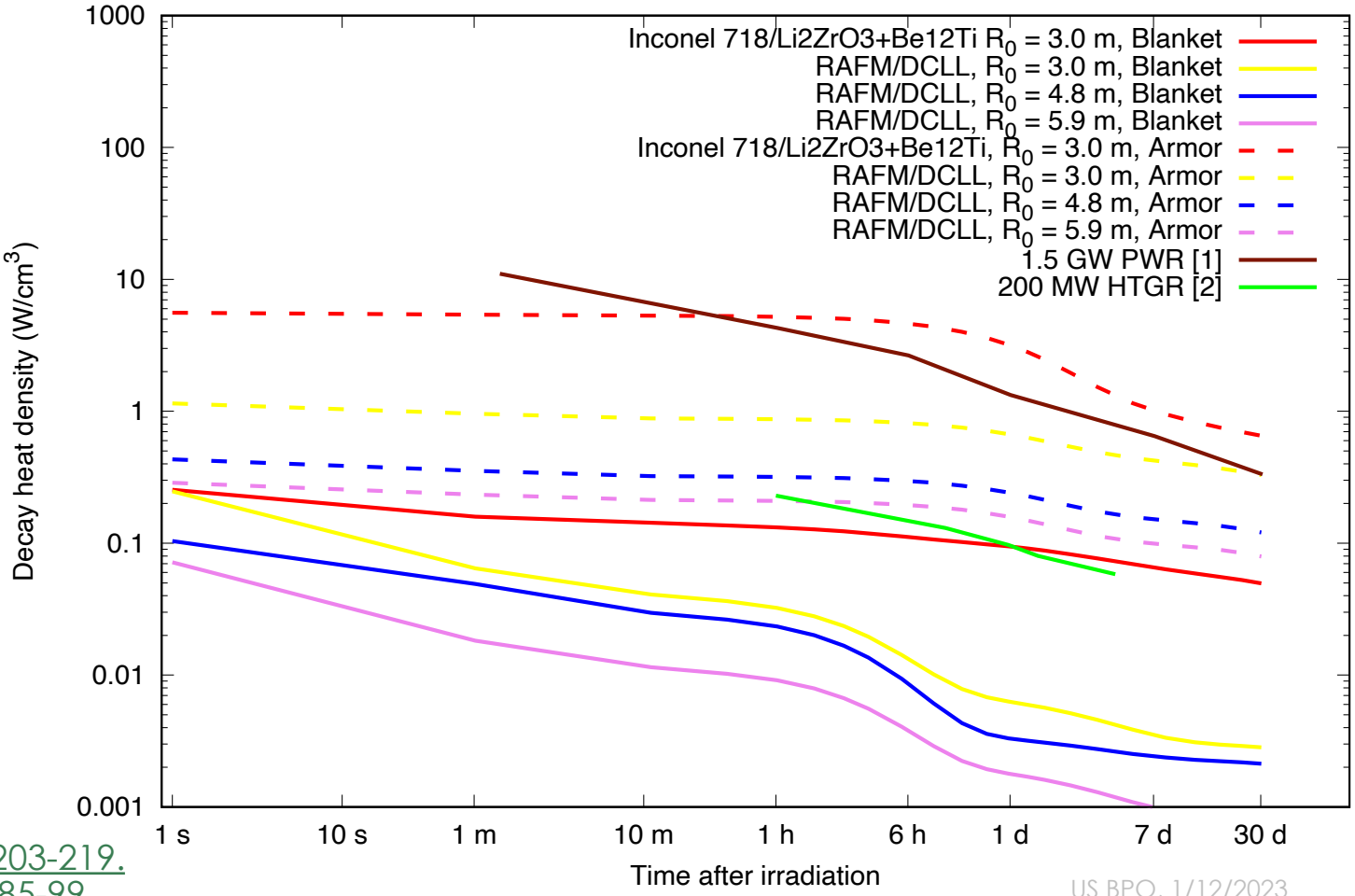
Decay heat dependence on reactor size (major radius)

- 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



[1] H.-W. Bartels, *Fus. Eng. Des.* **31** (1996) 203-219.
[2] L. P. Hong, IAEA TECDOC-1210 (2001) 85-99.

Decay Heat takeaways

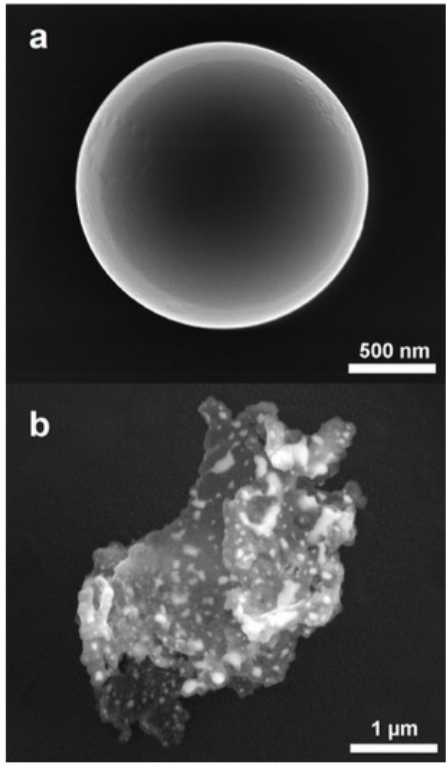
- D-T fusion reactors will produce a non-trivial amount of decay heat; depending on material choices, this might be ~1.5-3.5% of the fusion power just after shutdown
- It remains lower than a comparable fission reactor *if* low activation materials are used
  - Decay heat density is lower than fission
- 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:

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

  - ^{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
- Tritium is highly mobile, and can permeate through solid structures



Tungsten dust from ASDEX-Upgrade

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)

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)

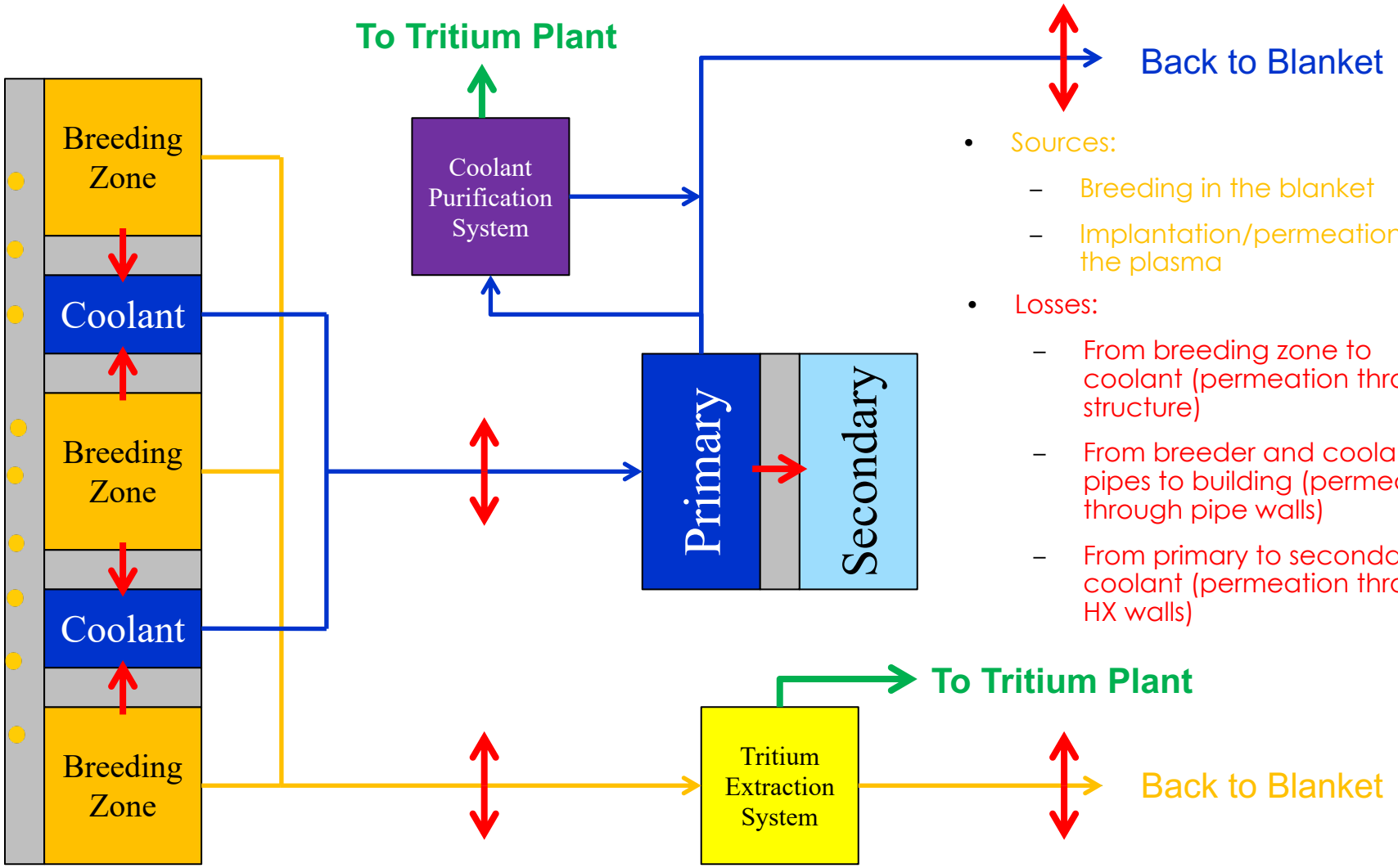
- Adherence to off-normal limits needs to be demonstrated by accident analysis
- Tritium releases may challenge normal/AOO limits; for "generic site" considered for FNSF analysis, 0.1 mSv/yr (10 mrem/yr) -> 0.29 g T/yr
  - 0.29 g T/yr = 10^{-5} FNSF fusion/breeding rate

[1]DOE-STD-6002-96, "Safety of Magnetic Fusion Facilities: Requirements" https://www.standards.doe.gov/standards-documents/6000/6002-astd-1996
[2]P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

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 10^3x the rate of production in a MSR, 10^6x 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

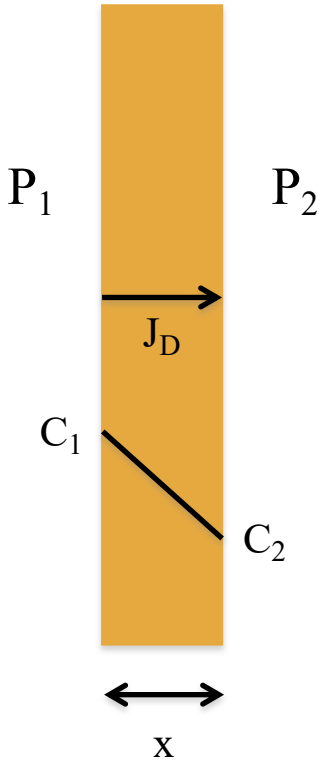


- Sources:
  - Breeding in the blanket
  - Implantation/permeation from the plasma
- Losses:
  - From breeding zone to coolant (permeation through structure)
  - From breeder and coolant pipes to building (permeation through pipe walls)
  - From primary to secondary coolant (permeation through HX walls)

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

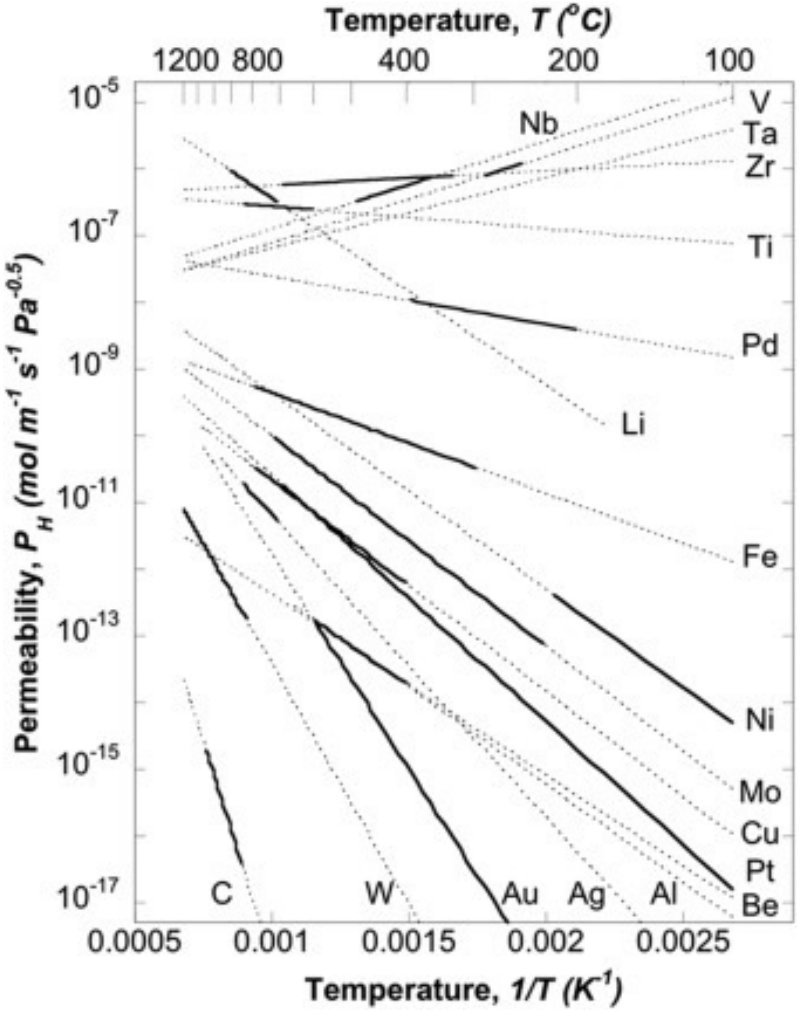
Diffusion/Permeation



- 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

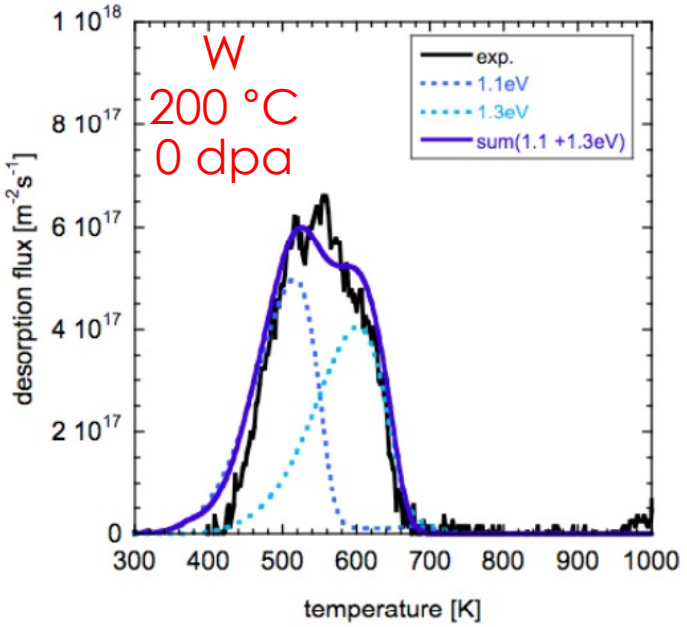
- Tritium is subject to ***trapping*** at defect sites in structural materials
- The density of trap sites increases with radiation damage; irradiation increases the density of higher energy traps

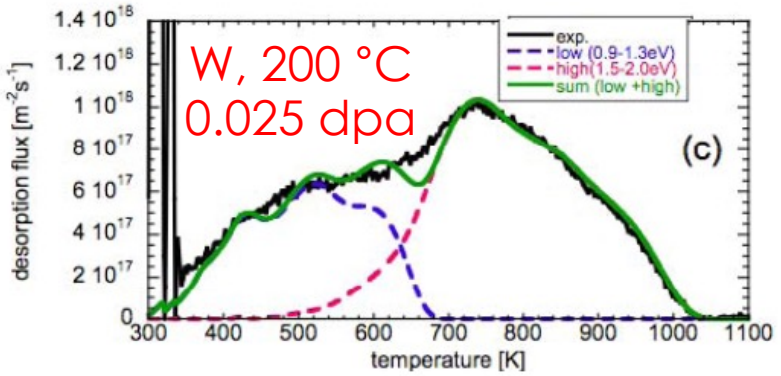
$$\frac{\partial C_t}{\partial t} = \alpha_t f_t C_m - \alpha_r C_t$$

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

$$\alpha_t = \frac{D}{\lambda^2};\ f_t = \frac{c_t^o - C_t}{N};\ \alpha_r = \nu_o \exp\left(-\frac{E_t}{kT}\right)$$

D – Tritium diffusion coefficient (m^2-s^{-1})
λ – jump distance or lattice constant (m)
c_t^o – Trap site concentration (m^{-3})
N – Bulk material atom density (m^{-3})
ν_o – Debye frequency (s^{-1})
E_t – Trap energy (eV)

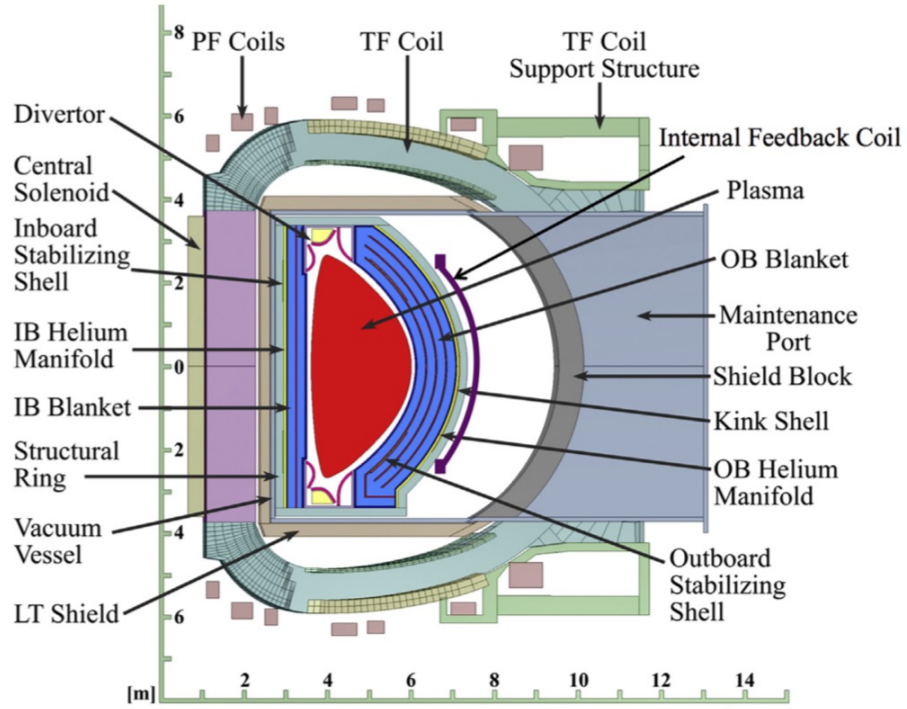


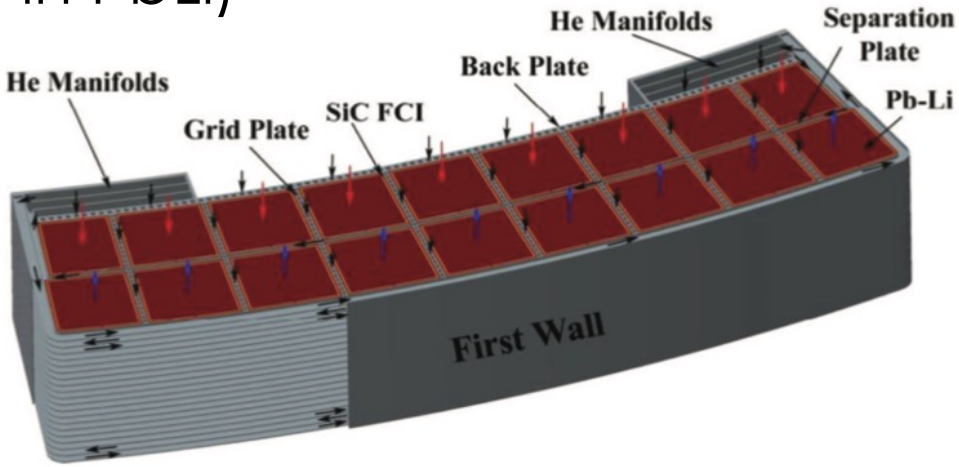


M. Shimada, *Phys. Scr. T.* **T145** (2011) 014051.
https://doi.org/10.1088/0031-8949/2011/T145/014051

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 g/yr**, larger than **0.29 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 g/yr
  - Driven primarily by PbLi pipe losses
- Quantitative effect of design features systematically evaluated…





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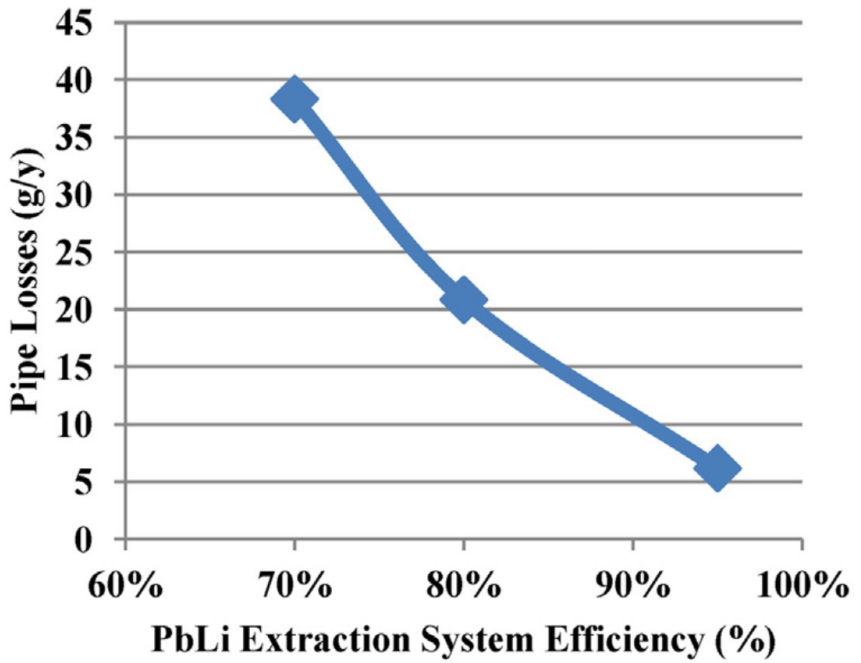
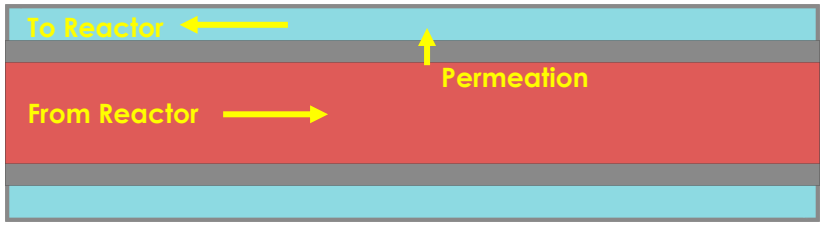
P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

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



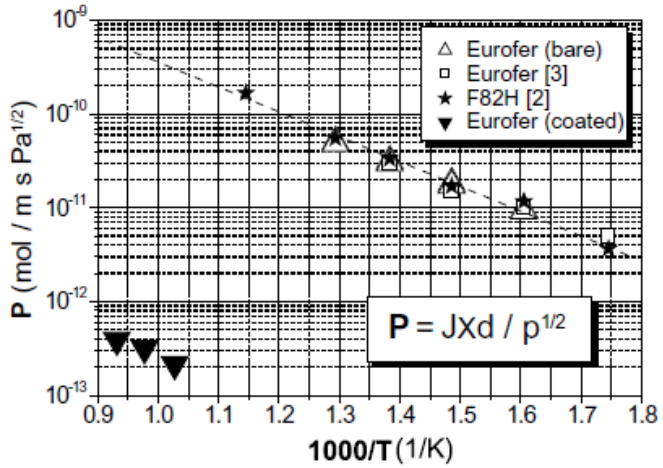


P. W. Humrickhouse, *Fus. Eng. Des.* **135** (2018) 302-313; https://doi.org/10.1016/j.fusengdes.2017.04.099

Permeation barrier coatings

- The FNSF design did not take credit for any permeation barriers
- Ceramic (e.g. Al_2O_3, Er_2O_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

D. Levchuck, *J. Nucl. Mater.* **328** (2004) 103.
https://doi.org/10.1016/j.jnucmat.2004.03.008



Irradiation testing of tritium/hydrogen barriers

Test	Barrier system[a]	Effective PRF
LIBRETTO-2	Alum/316L	<80
LIBRETTO-3	316L/TiC	3
	Al_2O_3/316L	3
	316L/alum/Al_2O_3	15
TREXMAN	Cr_2O_3/SS316	10
	SS316/Cr_2O_3	100
Loop-1	Alum/SS316/alum	150
WC-1	Alum/SS316/alum	150

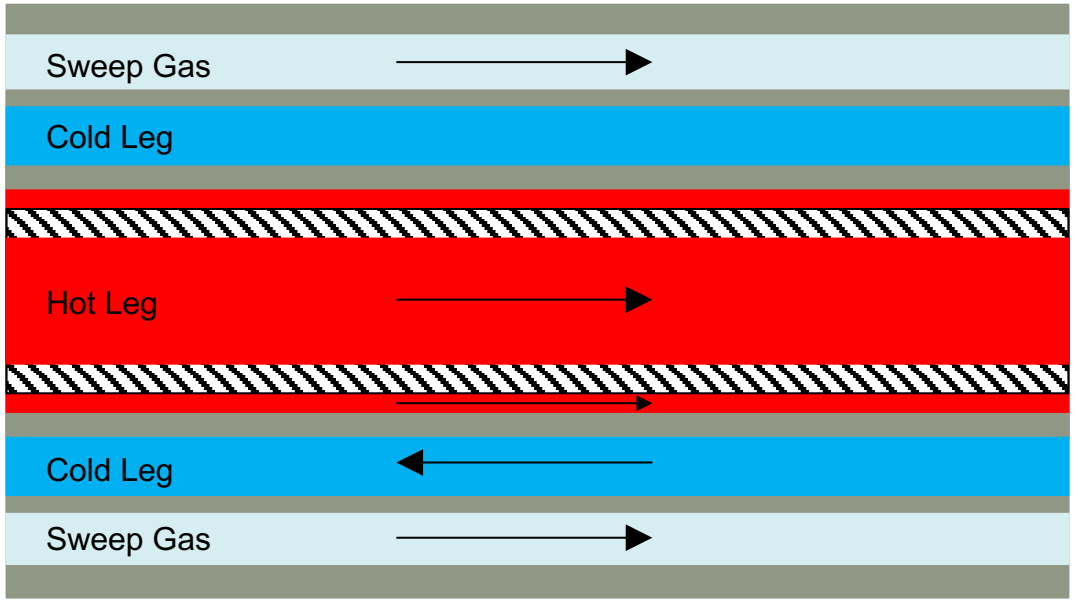
G. W. Hollenberg, *Fus. Eng. Des.* **28** (1995) 190.
https://doi.org/10.1016/0920-3796(95)90039-X

[1]R. Causey, in *Comprehensive Nuclear Materials*, 2012.
[2]W. Luscher, J. Nucl. Mater. **437** (2013) 373.
[3]X.-D. Pan, Nucl. Fusion 61 (2021) 036004.

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

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



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

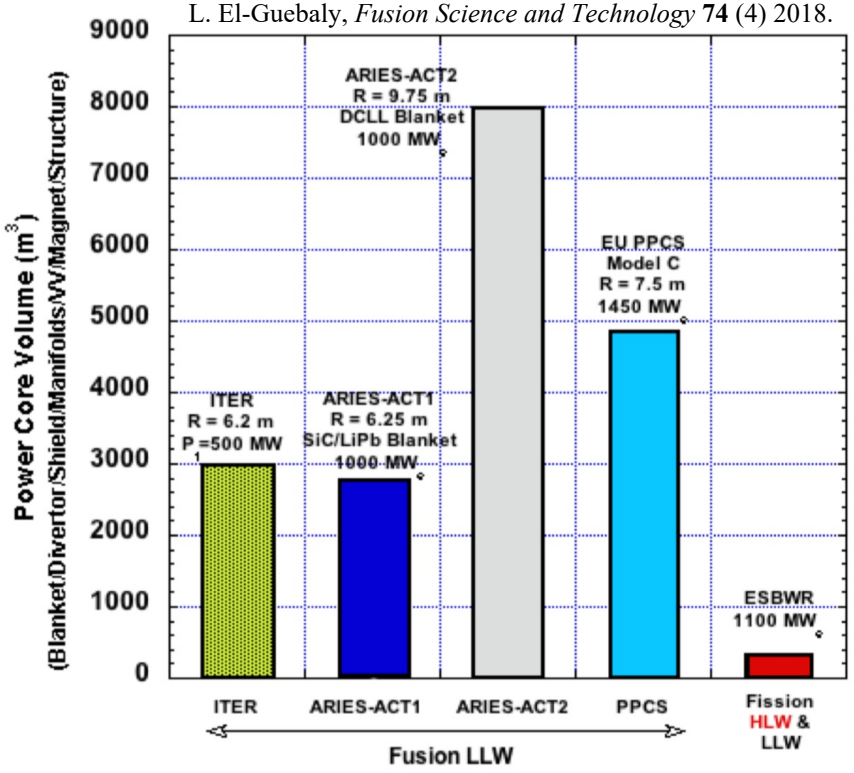
- The volume of radioactive material produced by a fusion reactor is large relative to a fission reactor
- But since radionuclides are produced by neutron activation rather than fission, reduced-activation materials can ensure waste is not long-lived
- High Level Waste (HLW):
  - Spent fuel and materials 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:

Nuclear waste classification under 10 CFR 61 rules

Waste class	Definition	Disposal
Class A Segregated waste	Decays to acceptable levels during side occupancy	Segregated, minimum requirements
Class B Stable waste	Stabilized and decays to levels that do not pose a danger to public health and safety in 100 years	Covered to reduce surface radiation to a few percent of natural background
Class C Intruder waste	Does not decay to safe levels in 100 y. Decays to acceptable safe levels in 500 y [a]	Five meters below surface with natural or engineered barrier
Waste that does not meet Class C definition	Does not qualify for near-surface disposal. Proposed disposal methods are considered on a case-by-case basis	Geologic

[a] 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.

L. El-Guebaly, *Fusion Science and Technology* **74** (4) 2018.



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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

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

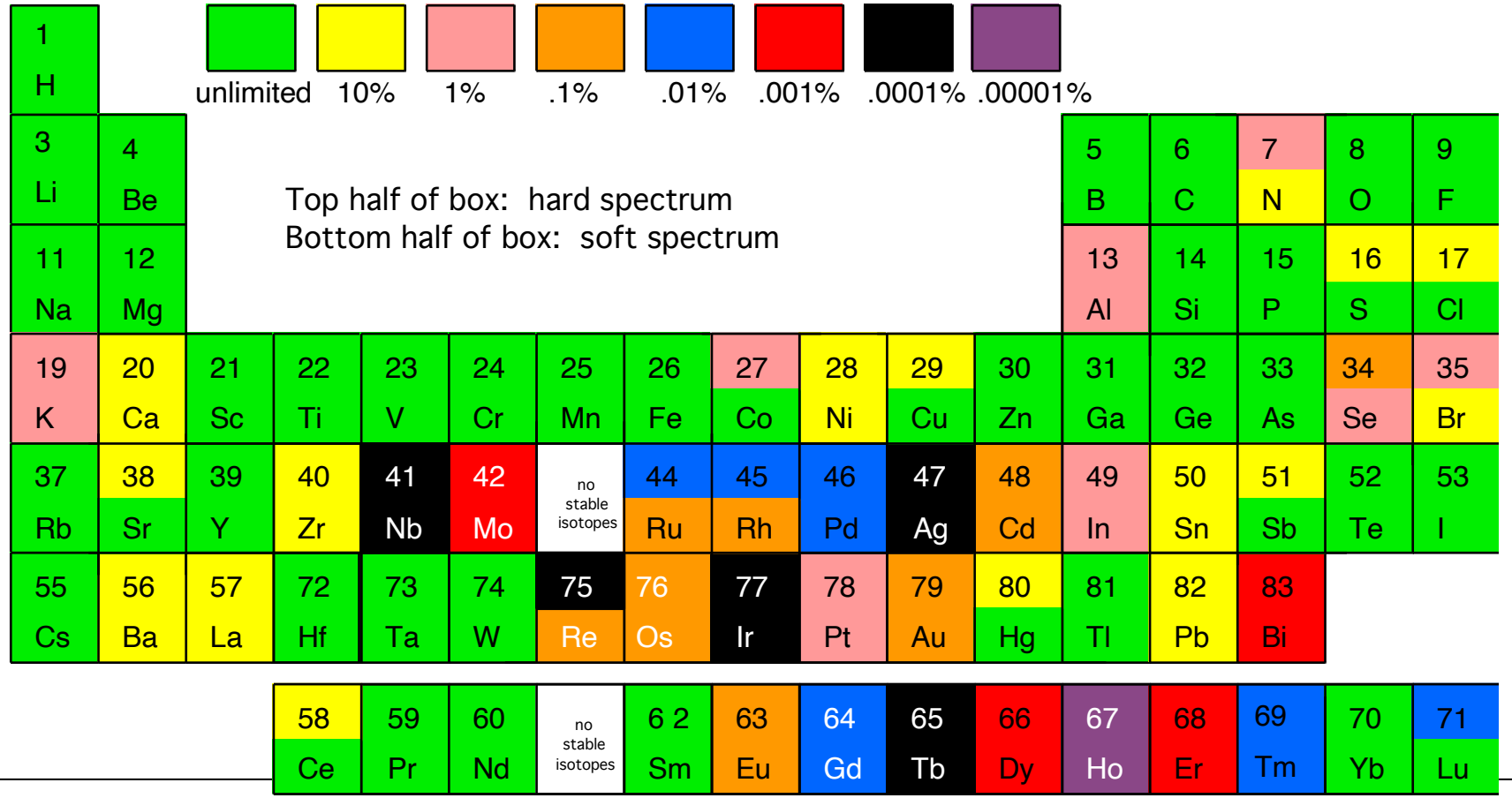
- NRC (in 10 CFR 61) only specified SALs for a handful of isotopes though
- In the late 1980s, Fetter[1] employed a similar logic to determine SALs for a comprehensive set of potential fusion activation products
- ***Whether these or other limits are to be adopted as regulation has not been addressed***

10 CFR 61 Class C
Specific Activity Limits

Radionuclide	Class C SAL, Ci/m^3
I-129	0.08
Sr-90	7000
Cs-137	4600
Pu-241	3,500
Cm-242	20,000
α-emitting transuranics with $t_{1/2}$ > 5 yr	100
C-14	8
C-14 in activated metal	80
Ni-59 in activated metal	220
Ni-63	700
Ni-63 in activated metal	7000
Nb-94 in activated metal	0.2
Tc-99	3

[1]S. Fetter et al., *Fusion Engineering and Design* **6** (1988) 123-130; S. Fetter et al., *Fusion Engineering and Design* **13** (1990) 239-246.

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**

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