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Shielding of Transportable Fission Batteries

Issues and Potential Solutions

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INL is managed by Battelle Energy Alliance
for the US Department of Energy

Idaho National Laboratory

Outline

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- Microreactor Shielding Issues
- Types of Shielding Materials
  - Casks
  - Reactors
- More (Or Less) favorable geometries
- Possible Solutions

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    - Third level
      - Fourth level
        - Fifth level

Microreactor Shielding Issues

- Why we cannot shield microreactors like casks
  - Reactors have significantly greater radiation intensities compared to casks, thus requiring thicker shields
  - Reactors have voluminous structures within the shield:
    - Reactor vessels, reflectors, core-support structure
    - Some have built-in: Intermediate heat exchangers (IHX), steam Generators, or heat pipes
- How to make a better shield
  - More atoms in less space stops more radiation but also increases density, so the better the shield, the heavier the shield
- How to provide greater safety of the primary coolant boundary
  - Increase vessel wall thickness
  - Increase coolant volume (e.g., tank-type construction)

Microreactor Shielding Issues Cont.

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- γ-ray shields
  - Attenuated by interactions with electrons of the atom
  - Higher Z-number and greater atomic packing makes more dense but not less massive
- ^{1}n shields
  - Attenuated by interactions with the nucleus
  - Lower Z-number slows ^{1}n leading to greater interaction cross section - *<u>Note</u>: $^{1}H(n,\gamma)^{2}H$ produces a 2.23 MeV γ-ray*
  - Certain atoms (B-10, Li-6, W, Gd) have a high neutron absorption cross section.
    - Capture reaction typically emit prompt secondary γ-rays
      - B-10 (478 keV), Li-6 (n/a), W (4-7.5 MeV)
      - Gd (γ-cascade with very few >1 MeV photons)
  - Certain atoms have a large inelastic scattering cross-section
    - Useful for slowing down fast ^{1}n: U-238, Fe-56, Ni-58, Pb-208, W

Shielding Materials Used in Casks

- Neutron absorbers placed between fuel assemblies
  - Borated metals and CERMETs, carbon nanotubes (CNT), hex-BN, boric acid, Cd, Gd_2O_3, Sm_2O_3, etc.
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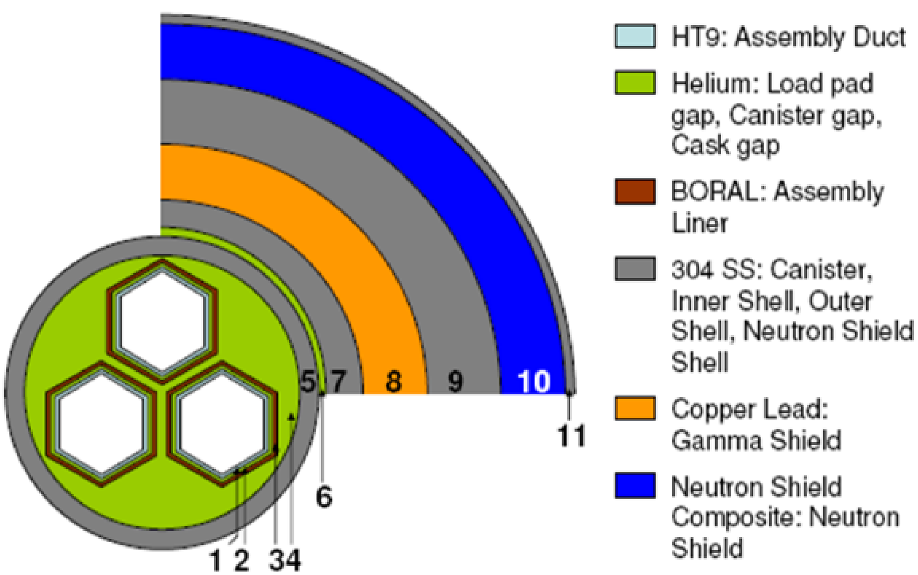

D_{limit}<10 mrem @ 2m

	Analysis Program	Dose Rate @ 2 meters	Shield Thickness
Gamma Dose	MicroShield 7.01	1.6 mrem/hr	7 cm Lead
Neutron Dose	SCALE 5.1 SAS4	6.7 mrem/hr	20 cm NS-4-FR
	Total	8.3 mrem/hr	

- Neutron shield:
  - B_4C, BN, LiF, Gd_2O_3
  - Paraffin, polymers, epoxy, polyimides
  - Borated concrete
- γ-ray shield:
  - Lead, uranium, Gd_2O_3
  - W, WC, WB, W_2B_5, WB_4
  - Stainless steel (ss304)
  - Ferrous concrete

Shielding Materials Used in Reactors

- Shielding to minimize:
  - Structural damage
  - Activation
  - Dose to people
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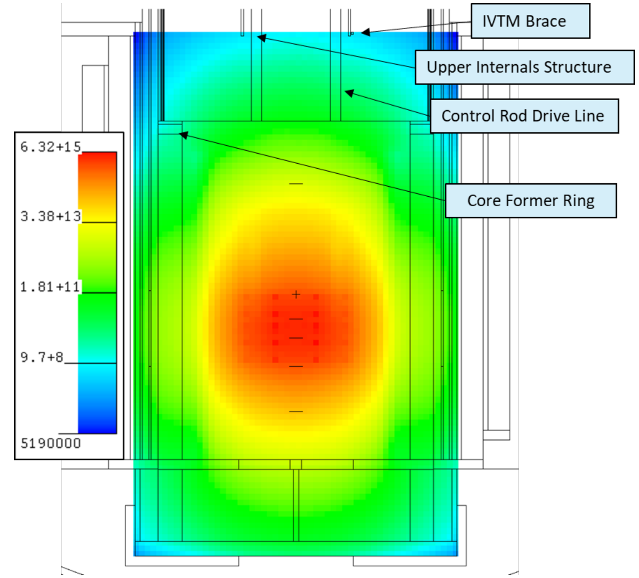
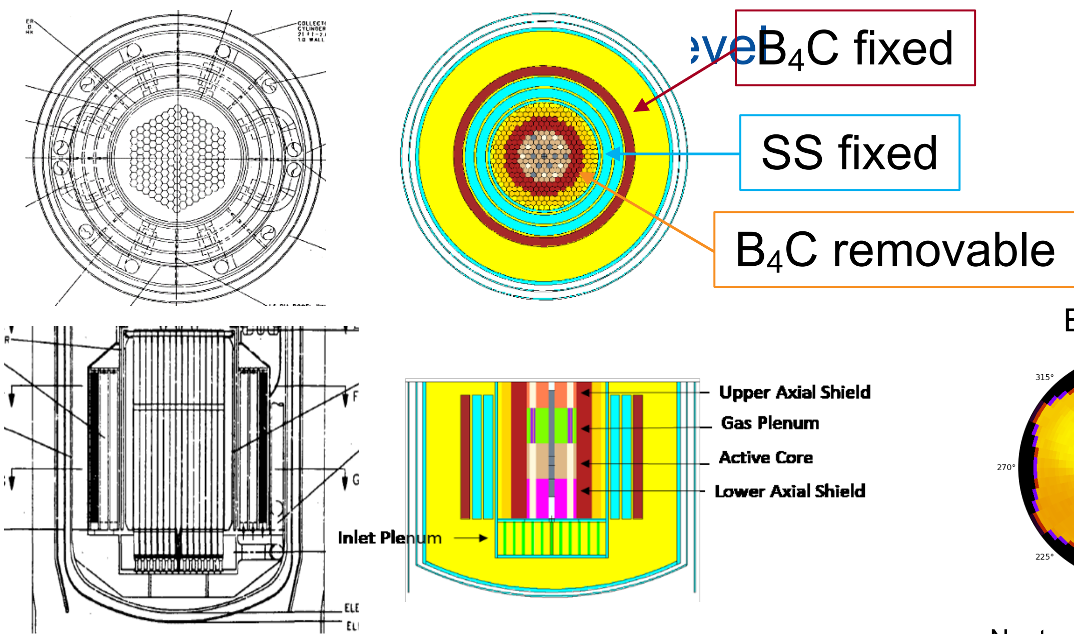
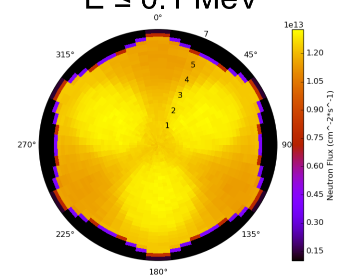


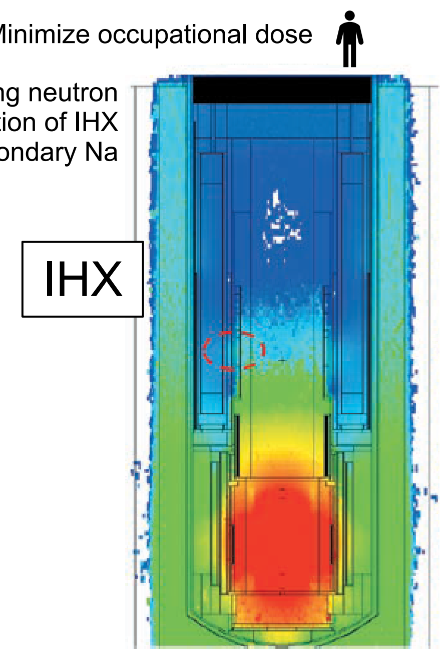
Fast flux exposure to core support structures



Versatile Test Reactor (VTR) in-vessel core structures modeled in Monte Carlo Nth Particle (MCNP6)



Neutron streaming through coolant channels of lower reflector block



More (Obese) favorable geometries

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- For an annular shield, the volume is inversely proportional to the shield's mean radius
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  - Highest density materials are usually placed the farthest from core center
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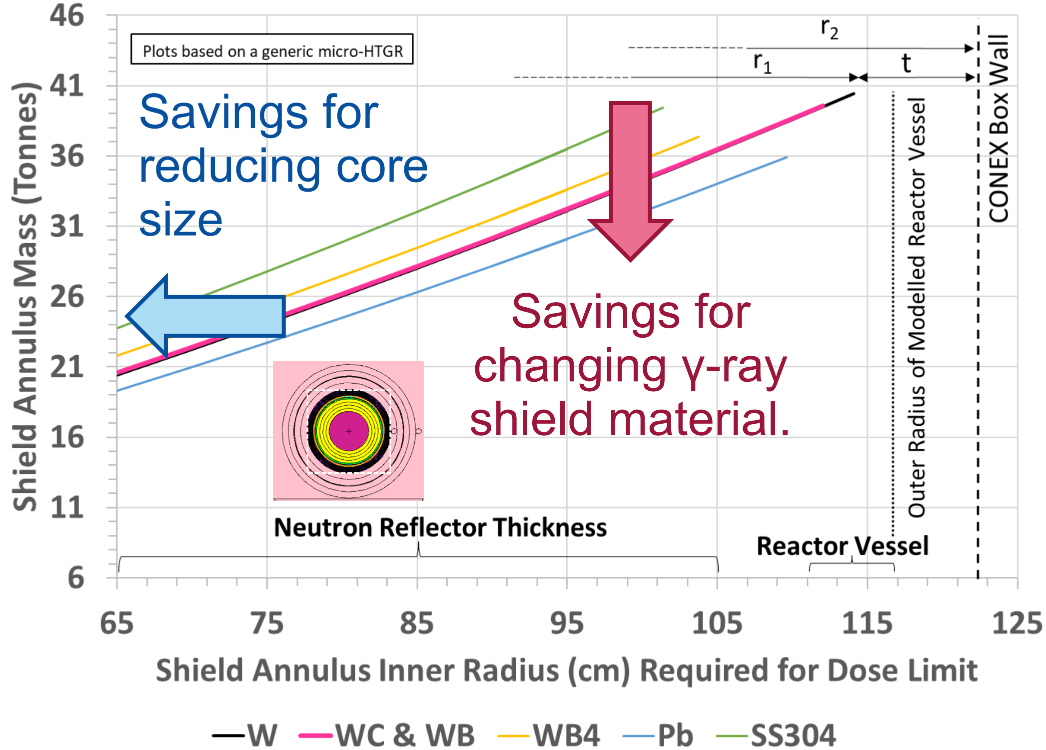
Annulus Top/Bot



- Assume:
  - High Temperature Gas Reactor (micro-HTGR)
  - 7 MWth for 3 years
  - 1 week of decay
  - Transport dose limit is: 10 mrem at 2 m
  - W shield barely fit within the CONEX
- Shield mass is more sensitive to geometry than to density

Types of Radiation Sources

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- Operation (prompt radiation)
  - γ-ray and ^{1}n from fission
  - (n,2n) and (γ,n) from threshold reactions
  - Secondary γ-ray from (n,γ), (n,n'), and $^{10}B(n,\alpha)^{7}Li$

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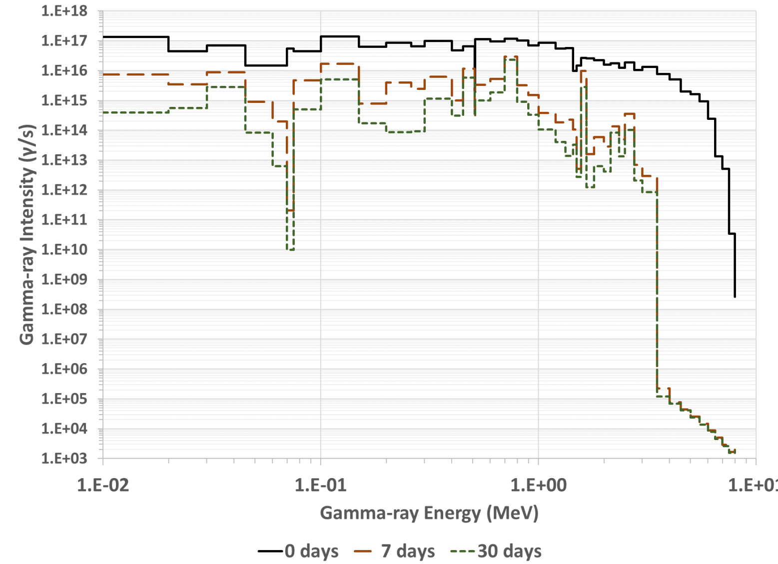
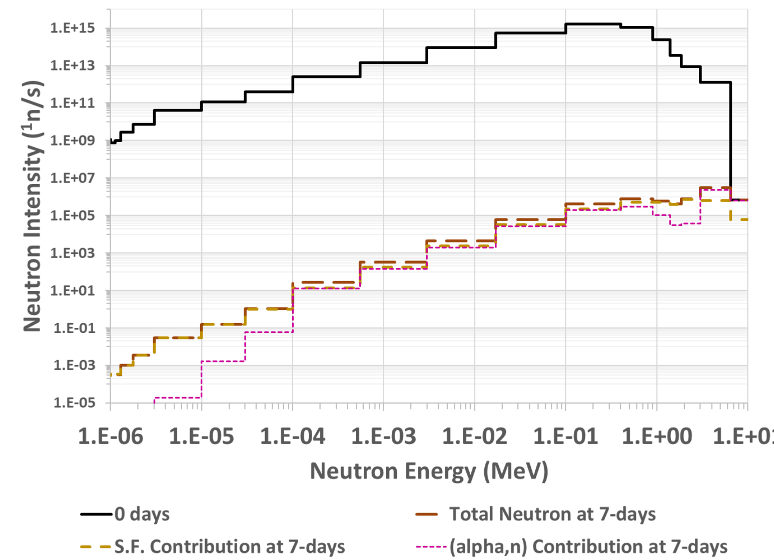
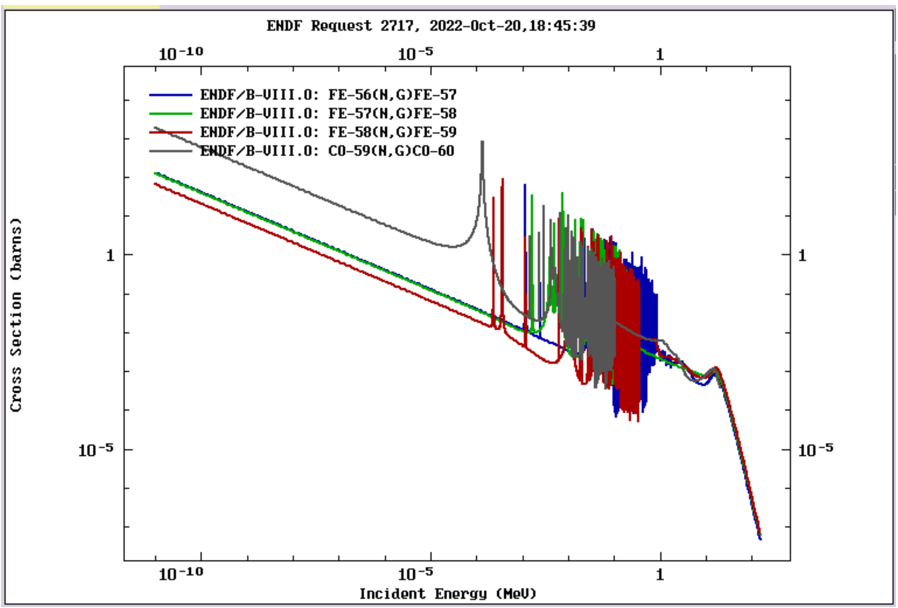
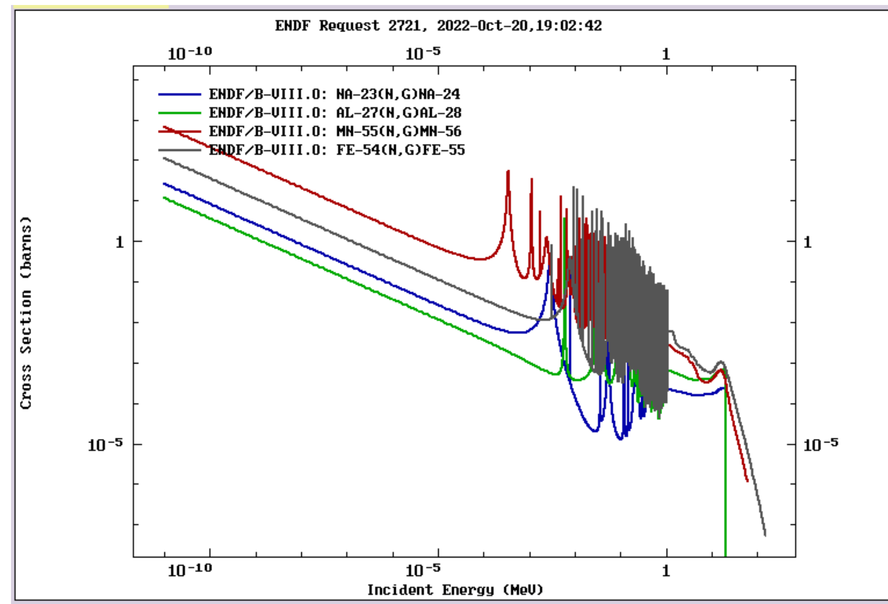
- Transportation (delayed radiation)
  - Fission product decay
    - γ-ray for seconds to centuries
    - ^{1}n for seconds
  - Actinide decay
    - γ-ray for centuries to millennia
    - ^{1}n from spontaneous fission
    - (α,^{1}n) from interaction with light nuclide (e.g., oxygen during decay)





Relevant Cross Sections Leading to Activation





$$^{56}Fe \rightarrow {}^{57}Fe \rightarrow {}^{58}Fe \rightarrow {}^{59}Fe \xrightarrow{\beta^-} {}^{59}Co \rightarrow {}^{60}Fe$$

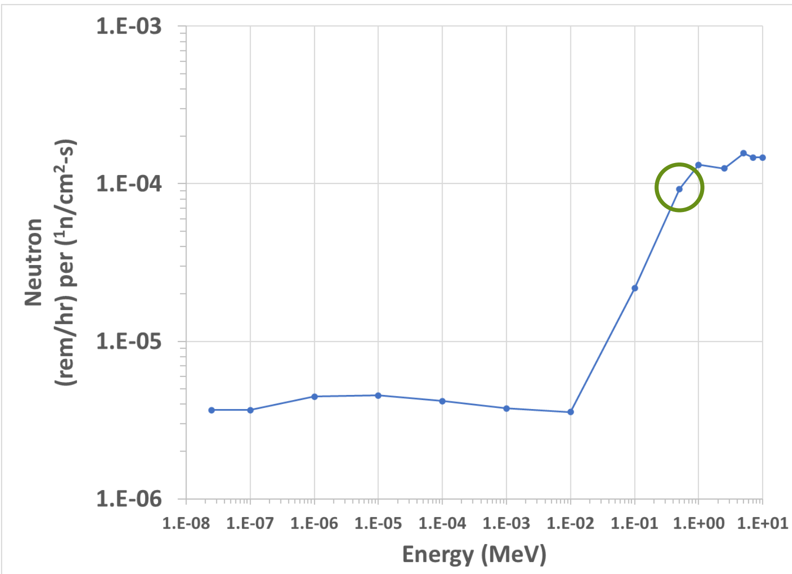
Cobalt activation from Fe-56 and/or Co-59

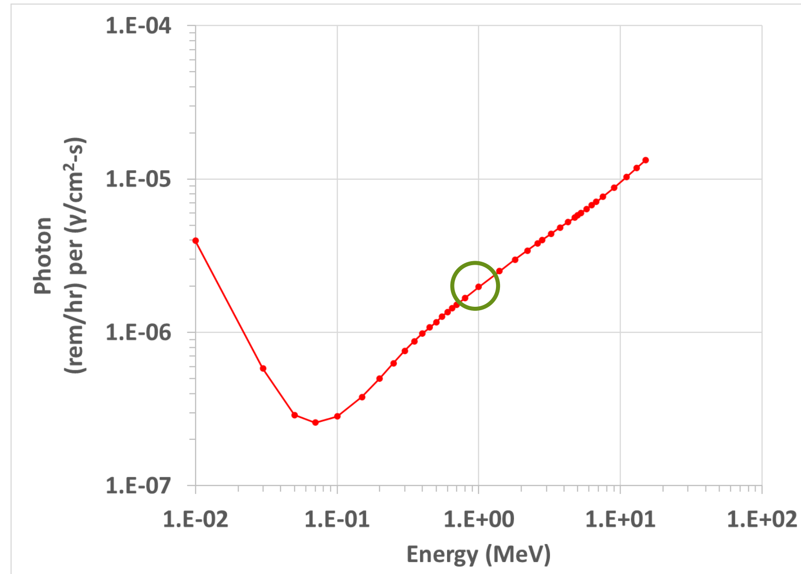
- Most relevant isotopes for soil activation
- Dose contribution varies based on elemental composition

Relevant Dose Limits

Regulation	Description	Dose	Distance
10 CFR 71.47	Transportation	200 mrem/hr	Surface
10 CFR 71.47	Transportation	10 mrem/hr	2 m from Surface
10 CFR 71.47	Transportation	2 mrem/hr	Occupational Spaces
10 CFR 835.1002	Occupational	0.5 mrem/hr	Occupational Spaces
10 CFR 835, Appendix D	Fixed + Removable Contamination (β^-/γ)	5,000 DPM/100 cm^2	Surface
10 CFR 835.202	Occupational TEDE (external/internal)	5 rem/yr	Occupational Spaces
10 CFR 835.2	Radiation Area	5 mrem/hr	30 cm from Surface
10 CFR 835.2	High Radiation Area	0.1 rem/hr	30 cm from Surface
10 CFR 835.2	Very High Radiation Area	500 rads/hr	1 m from Surface
10 CFR 20.1301, Subpart D	Public Individual	2 mrem/hr	Unrestricted Area
10 CFR 20.1301, Subpart D	Public Individual	0.1 rem/year	Site Boundary

Flux-to-Dose Conversion Factors ANSI/ANS-6.1.1-1977





- Minimum flux outside reactor at steady state
  - <u>Not</u> radiation area < 5 mrem/hr
  - 0.1 mrem/hr per one ¹n/cm²-s → **<u>5 mrem/hr per 50 ¹n/cm²-s (E>100 keV)</u>**
  - *2 micro-rem/hr per one γ/cm²-s → 5 mrem/hr per 2,500 γ/cm²-s*

Possible Shields—Order of Operation

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- In-vessel shielding—mass & dose constrained
  - Shields against ^{1}n (E<1 keV)—Steel activation, (i.e., Co-60 buildup)
  - Shields against ^{1}n (E>1 MeV)—struct. displacement-per-atom (dpa)
- Fixed transportable shield—mass & volume & dose constrained
  - Shields against delayed γ-ray and ^{1}n
  - Made of high-z and high density
  - Must fit within conveyance
  - Optimized by $\downarrow$ core radius & $\downarrow$ reflector thickness and $\uparrow$ attenuation
- Attachable biological shield (prompt and primary)—activation and dose constrained
  - Shields against ^{1}n (E>100 keV)—dose to humans
  - Shields against ^{1}n (E<100 keV)—soil & concrete activation
- Exterior shielding
  - Shields against prompt γ-ray created within biological shield
  - Earthen berms, water tanks, concrete t-barriers

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Sketch of Shield Buildup

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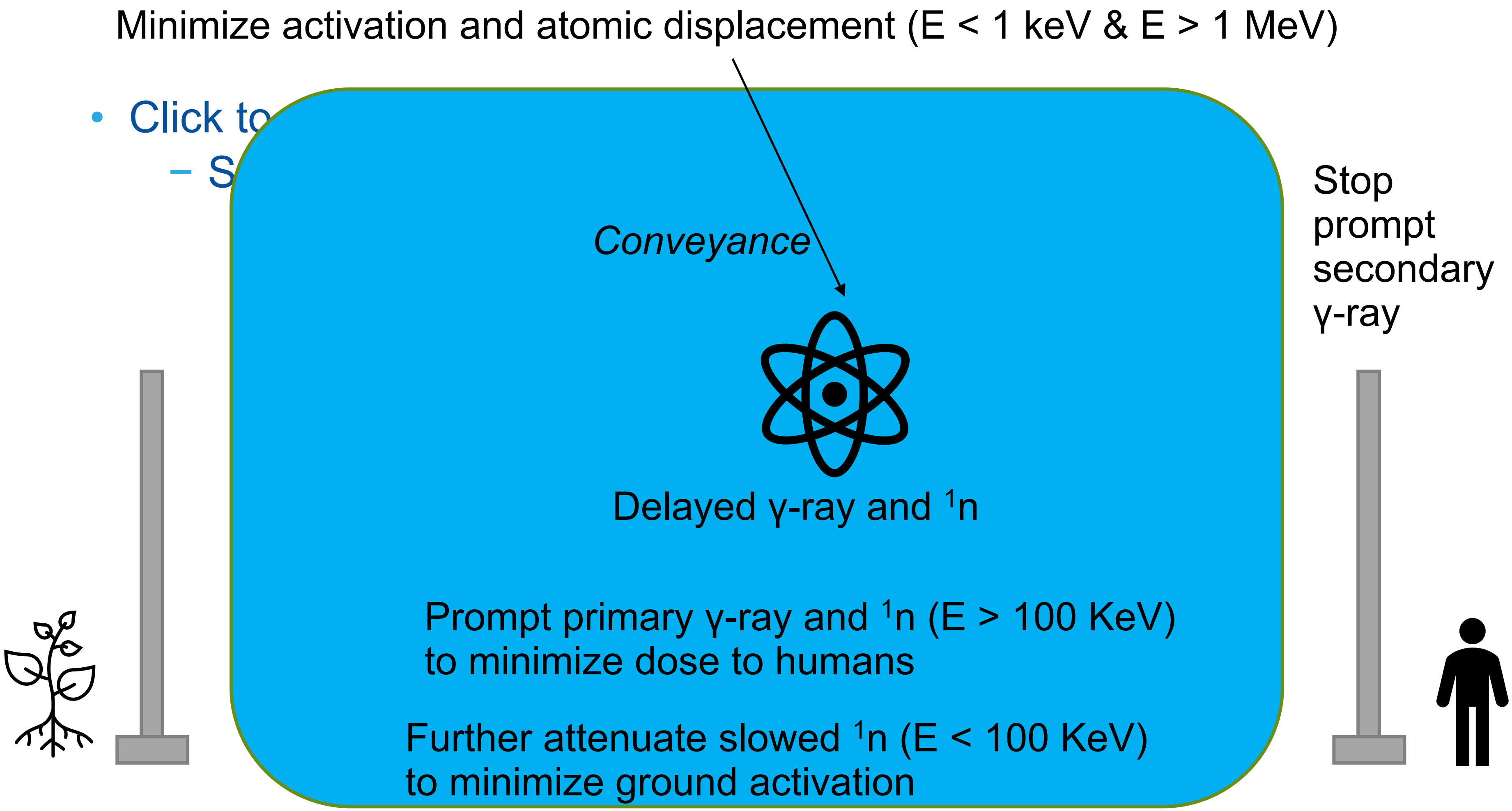

Sketch of Shield Buildup

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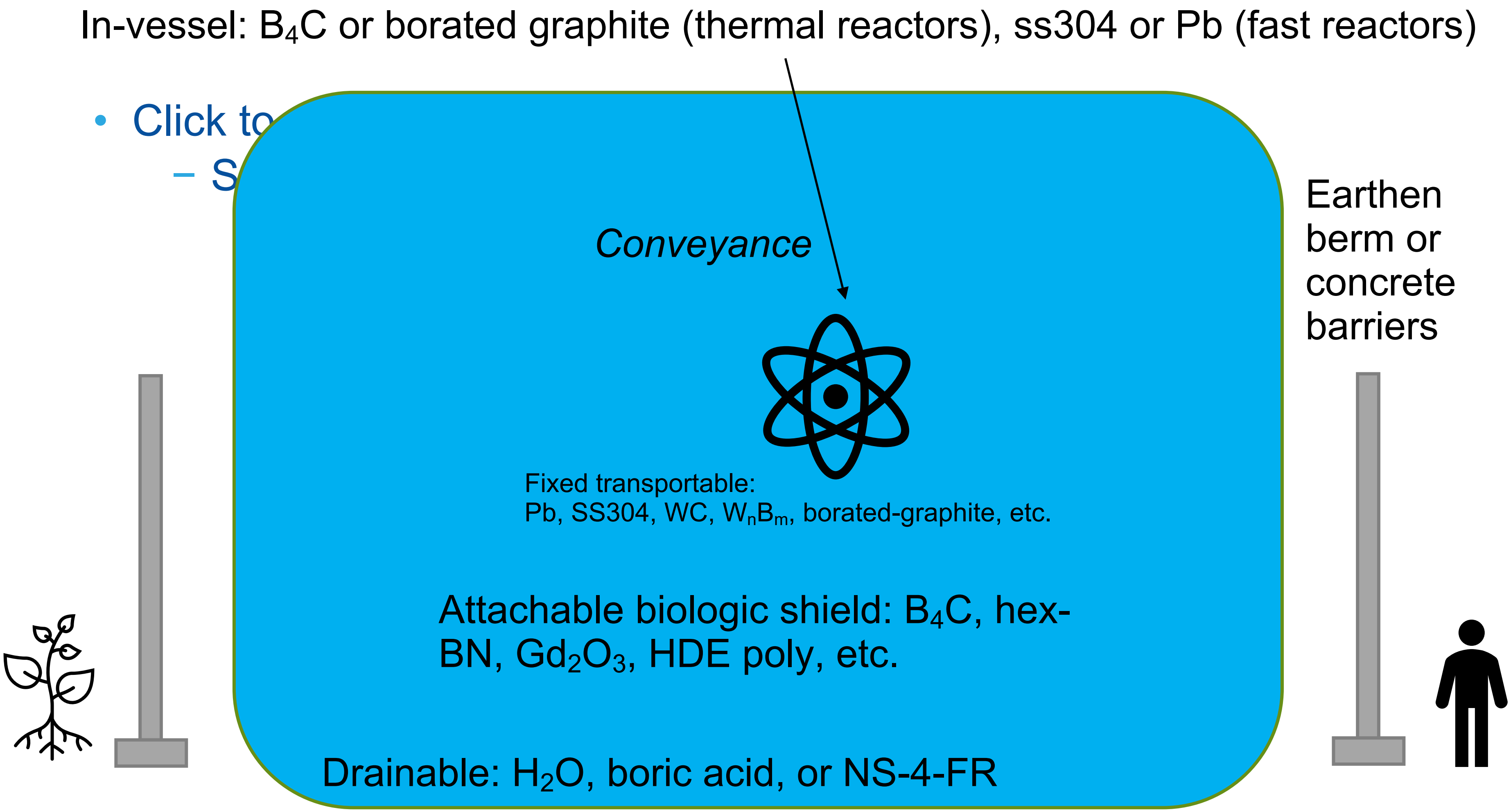

Summary

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- Shield thickness is not affected by "micro-"
  - Same incident flux intensity
  - Same orders of attenuation to get to dose limit
  - Shield mass is more affected by geometry (or nearness to core center) than attenuating material selection

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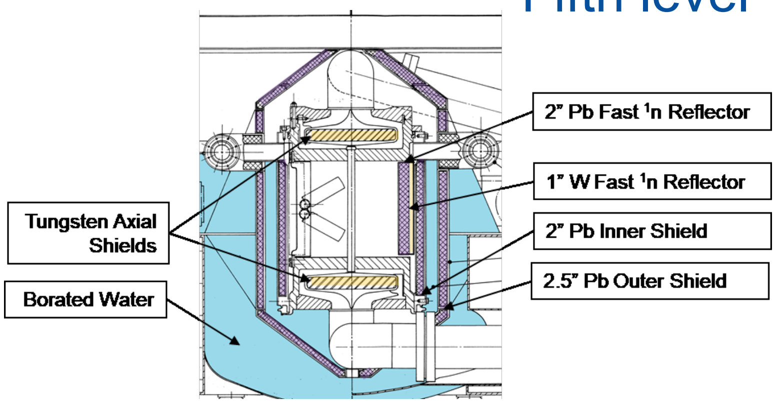
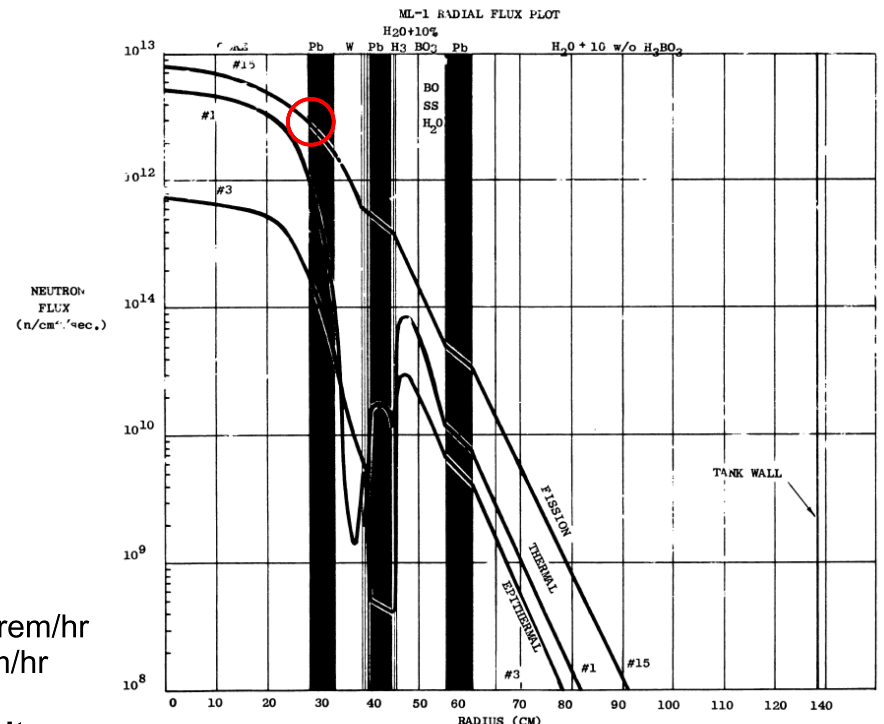
ML-1 shielding configuration





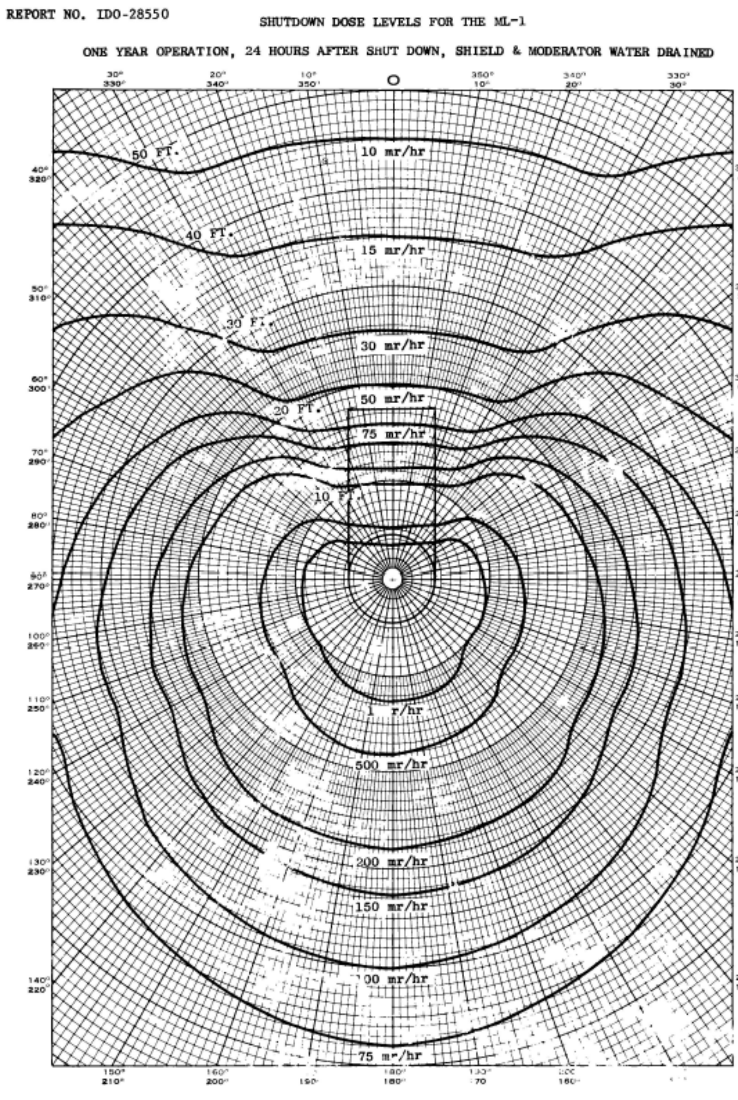
Steady state operation

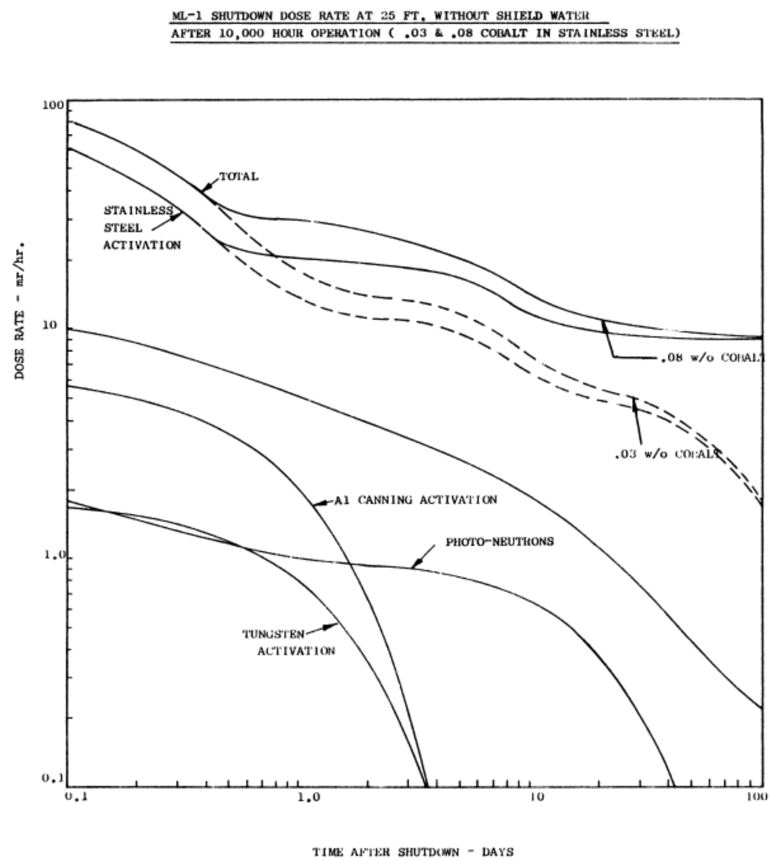
- Dose rate to control cab (500 feet away) limited to 5 mrem/hr
- Dose rate near reactor 25 feet away limited to 25 mrem/hr
- Fast flux entering the shields ~10^{12} ^{1}n/cm^{2}-s
  - **11 orders reduction needed to meet dose limits**

Summary

- The design constraints of volume, mass, attenuation, and cost dictate the arrangement of material placement
  - Shields inside the reactor vessel minimizes activation (i.e., Co-60) and neutron damage (i.e., dpa) to core structures
  - Delayed γ-ray and photo-neutron shields are fixed and transported with conveyance
    - They “assist” with prompt γ-ray and ^{1}n attenuation in the biologic shielding
  - Prompt γ-ray and ^{1}n shields are attached to the conveyance during operation and constitute the biologic shield – attenuate the fast flux most harmful to humans
  - The less costly ^{1}n shields go outside the biologic shield to reduce the ^{1}n flux to the point of nil soil and concrete activation
  - The least costly shields, earthen berms, concrete t-barriers, or ferrous-concrete walls go beyond the reactor and external shield components
    - This shields against prompt secondary γ-ray

Shutdown Dose Map from ML-1 Design Report (3 MWth for 1 Year)





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