Activation Issues for Candidate Coating/Hohlraum Materials

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Key Design Issues for Target Coating/Hohlraum Materials

- Target performance (instability, gain, …) NRL,LLNL
- Target fabrication (cryo-layering, …) GA,LANL
- Target injection GA,LANL
- Target heating (emissivity, …) GA,UCSD
- Tritium retention/inventory/permeation ANL,LANL,GA
- Beam energy losses (driver cost; COE) LLNL,UCSD
- Safety: INEEL,UW,LLNL
  - Radioactive waste:
    - **WDR** (high or low level waste)
    - Volume (recycle hohlraum materials; economics !; repository capacity)
  - Off-site dose during accident

Candidate Coating/Hohlraum Materials

Laser

(NRL Target)

Gold	$_{79}\mathrm{Au}$
Tungsten	$_{74}\mathrm{W}$
Lead	$_{82}\mathrm{Pb}$
Platinum	$_{78}\mathrm{Pt}$
Palladium	$_{46}\mathrm{Pd}$
Silver	$_{47}\mathrm{Ag}$

HIB

Gold/Gadolinium	$_{79}\mathrm{Au}/_{64}\mathrm{Gd}$
Gold	$_{79}\mathrm{Au}$
Tungsten	$_{74}\mathrm{W}$
Lead	$_{82}\mathrm{Pb}$
Mercury	$_{80}\mathrm{Hg}$
Tantalum	$_{73}\mathrm{Ta}$
$\mathrm{Pb/Ta}/_{55}\mathrm{Cs}$	
Hg/W/Cs	
$\mathrm{Pb}/_{72}\mathrm{Hf}$	

Periodic Table of Elements

1 **H** Hydrogen																	2 **He** Helium
3 **Li** Lithium	4 **Be** Beryllium											5 **B** Boron	6 **C** Carbon		8 **O** Oxygen	9 **Fl** Flourine	10 **Ne** Neon
11 **Na** Sodium	12 **Mg** Magnesium											13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorous	16 **S** Sulphur	17 **Cl** Chlorine	18 **Ar** Argon
19 **K** Potassium	20 **Ca** Calcium	21 **Sc** Scandium	22 **Ti** Titanium	23 **V** Vanadium	24 **Cr** Chromium	25 **Mn** Manganese	26 **Fe** Iron		28 **Ni** Nickel	29 **Cu** Copper	30 **Zn** Zinc		32 **Ge** Germanium	33 **As** Arsenic	34 **Se** Selenium	35 **Br** Bromine	36 **Kr** Krypton
37 **Rb** Rubidium	38 **Sr** Strontium	39 **Y** Yttrium	40 **Zr** Zirconium	41 **Nb** Niobium	42 **Mo** Molybdenum	43 **Tc** Technecium	44 **Ru** Ruthenium	45 **Rh** Rhodium	46 **Pd** Palladium	47 **Ag** Silver	48 **Cd** Cadmium	49 **In** Indium	50 **Sn** Tin		52 **Te** Tellurium	53 **I** Iodine	
55 **Cs** Cesium	56 **Ba** Barium	57 **La** Lanthanum	72 **Hf** Hafnium	73 **Ta** Tantalum	74 **W** Tungsten	75 **Re** Rhenium	76 **Os** Osmium	77 **Ir** Iridium	78 **Pt** Platinum	79 **Au** Gold	80 **Hg** Mercury	81 **Tl** Thallium	82 **Pb** Lead	83 **Bi** Bismuth	84 **Po** Polonium	87 **At** Astatine	86 **Rn** Radon
87 **Fr** Francium	88 **Ra** Radium	89 **Ac** Actinium	104 **Rf** Rutherfordium	105 **Db** Dubnium	106 **Sg** Seaborgium	107 **Bh** Bohrium	108 **Hs** Hassium	109 **Mt** Meitnerium									

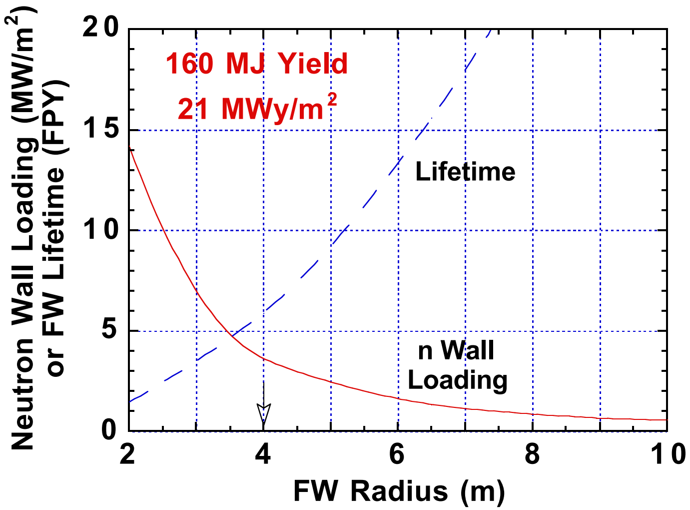
58 **Ce** Cerium	59 **Pr** Praseodynium	60 **Nd** Neodynium	61 **Pm** Promethium	62 **Sm** Samarium	63 **Eu** Europium	64 **Gd** Gadolinium	64 **Tb** Terbium	66 **Dy** Dysprosium	67 **Ho** Holmium	68 **Er** Erbium	69 **Tm** Thulium	70 **Yb** Ytterbium	71 **Lu** Lutetium
90 **Th** Thorium	91 **Pa** Protactinium	92 **U** Uranium	93 **Np** Neptunium	94 **Pu** Plutonium	95 **Am** Americium	96 **Cm** Curium	97 **Bk** Berkelium	98 **Cf** Californium	99 **Es** Einsteinium	100 **Fm** Germium	101 **Md** Menelevium	102 **No** Nobelium	103 **Lr** Lawrencium

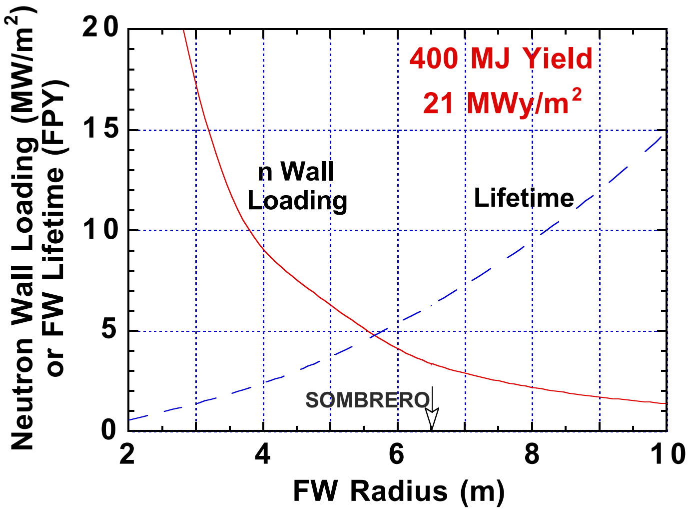
Main Parameters for WDR Analysis

Fusion Yield (MJ)	**160**	**400**
FW Radius (m)	4 ?	6.5 ?
Neutron Wall Loading (MW/m^2)	3.5	3.3
SiC/SiC FW Lifetime (FPY)	6	6.3
FW EOL Fluence (MWy/m^2)	**21**	
Rep Rate (Hz)	6	
# of Shots (million/y)	190	
Availability	85%	

- WDR depends strongly on EOL fluence
- 160 MJ case considered for activation analysis
- 400 MJ case will **not** alter conclusions

Variation of Neutron Wall Loading and Lifetime with FW Radius

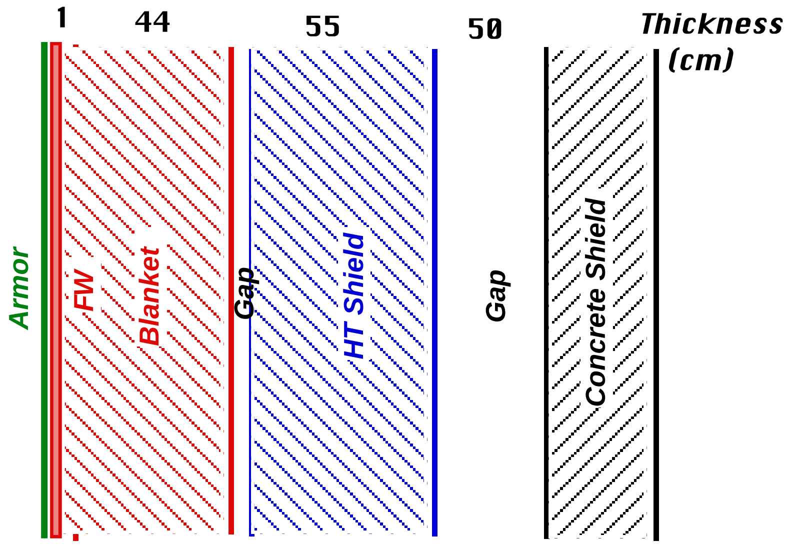




Larger FW radius ⇒ Lower Γ ⇒ Longer lifetime

Chamber Radial Build

Component	Composition
~0.2 cm Armor	C, W, or Au
1 cm FW#	SiC/SiC composites
44 cm Blanket#	20% SiC, 80% LiPb*
55 cm HT shield**	15% SiC, 10% LiPb, 75% B-FS
Concrete shield**	70% concrete, 20% steel, 10% He



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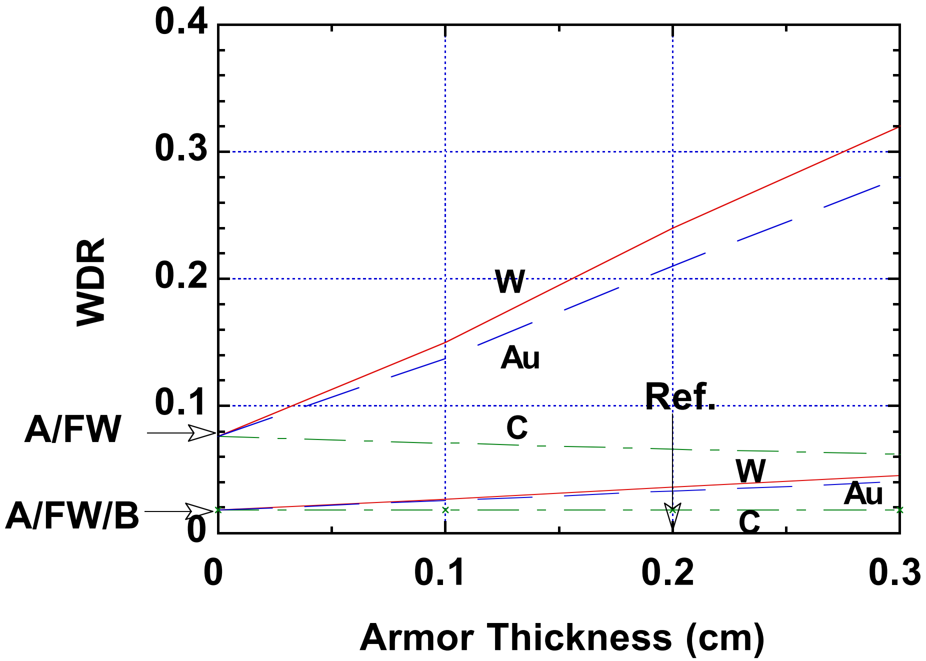
replaceable
* 90% enriched Li
** not optimized

Impact of Armor on WDR* of FW and Blanket



- Considerations other than waste disposal level will determine preferred armor material
- 0.2 cm W armor will be considered for further activation analysis

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* Evaluated with Fetter's limits for highly pure armors (no impurities)

Target Coating/Hohlraum

	Laser (~160 MJ)	**HIB** (~160 MJ)
Outer Radius	1.95 mm	6 mm
Equivalent Thickness	300 Å	60 µm
Mass per year	5 kg - Au[#]	70 tons - Au/Gd
Δ on FW armor @ EOL	8 µm	15 cm*
Δ Sticking on FW	**8 µm**	**~1 mm** (2.7 tons of Au/Gd)

- Could 2 mm armor support 2-4 tons of hohlraum materials?

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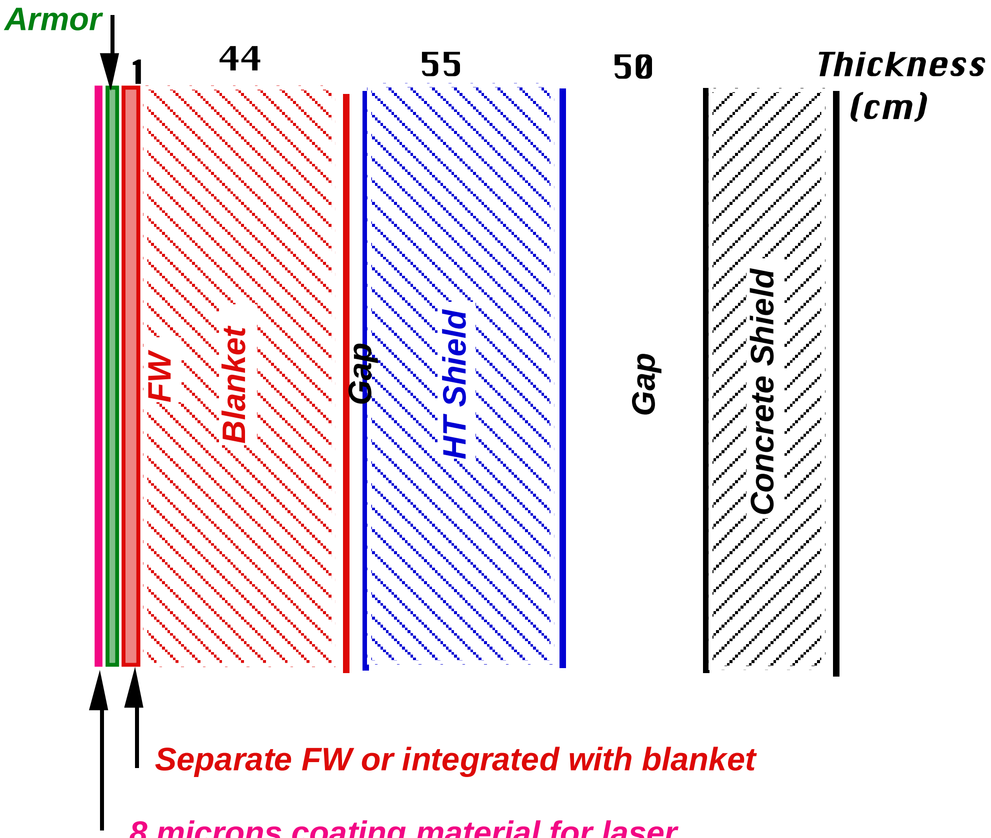
* Front layer will be melted by x-rays, per Peterson and Haynes

[#] Costs $50,000 per year @ $10/gm

FW Will be Plated with Coating/Hohlraum Materials



Separate FW or integrated with blanket

8 microns coating material for laser
1 mm hohlraum material for HIB

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Activation Process of Coating/Hohlraum Materials

Laser

- During burn, coating gets activated by source neutrons
- After burn, coating materials condense on FW armor and get reactivated during subsequent shots
- Coating materials could penetrate 10 μm into armor, per Haynes
- FW/B will be disposed at end of service lifetime
- Main activation concern is WDR of FW/B plated with coating materials

HIB

- During burn, hohlraum gets activated by source neutrons
- After burn, hohlraum materials condense on FW armor and get reactivated during subsequent shots
- In 2-3 wks, ~1 mm thick hohlraum materials accumulate on FW if T<1000 °C
- X-rays will melt additional layers
- Molten hohlraum materials run down (@ ~10 cm/s !), spending short time in chamber (minutes to days)
- Molten hohlraum materials will be collected at bottom of chamber for recycling after certain cooling period
- Main activation concerns are WDR of FW/B and recycling of collected hohlraum materials

Computational Tools and Model for Activation Analysis

- Spherical model
- Neutron and gamma transport analysis:
  - DANTSYS discrete ordinate code
  - 175 neutron and 42 gamma group structure
  - P_3-S_8 approximation
- Activation analysis:
  - ALARA code
  - Exact modeling of pulse sequence
  - 175 neutron group structure
- Nuclear Data:
  - FENDL-2 IAEA cross section library

Waste Disposal Criteria

- WDR < 1 means component qualifies as low level waste (LLW)
- All components should meet BOTH Fetter's and NRC-10CFR61 WD limits for Class C (or A) waste
- Reported WDR are for:
  - 160 MJ yield for laser and HIB targets
  - 21 MWy/m^2 EOL fluence
  - Highly pure coating/hohlraum/armor materials (no impurities)
  - Compacted solid waste (void excluded)
  - 100 years after shutdown (end of institutional control at disposal site)
  - Fetter's limit (more restrictive than NRC's for materials considered)
  - Volume average over :
    - Coating (or hohlraum) materials only
    - W armor and FW plated with Coating (or hohlraum) materials (C/A/FW)
    - W armor, FW, and blanket plated with Coating (or hohlraum) materials (C/A/FW/B)

Waste Disposal Rating
(Laser)

	Coating Material*		C/A/FW	C/A/FW/B
	---		0.24	0.04
Au	0.87	(^{194}Hg)	0.24	0.04
W	1.03	(^{186m}Re)	0.24	0.04
Pb	3.6	(^{208}Bi)	0.24	0.04
Pt	169	(^{192n}Ir)	0.35	0.05
Pd	4.6 x 10^3	(^{108m}Ag)	**3.3**	0.4
Ag	1.7 x 10^5	(^{108m}Ag)	**114**	**12.4**

FW and blanket should be disposed as single unit if palladium is preferred coating

Silver causes waste disposal problem if thickness on FW > 1 µm

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* 8 microns sticking on FW armor

Summary of Important Activation Pathways

Target Material: **Ag** Major WDR contributor: $^{\mathbf{108m}}\mathbf{Ag}$

Pathways:

$$\left.\begin{array}{l} {}^{109}\mathrm{Ag}\xrightarrow{(n,2n^*)} \\ {}^{107}\mathrm{Ag}\xrightarrow{(n,\gamma^*)} \end{array}\right\}{}^{\mathbf{108m}}\mathbf{Ag}$$

Target Material: **Pb** Major WDR contributor: $^{\mathbf{208}}\mathbf{Bi}$

Pathways:

$${}^{208}\mathrm{Pb}\xrightarrow{(n,\gamma)}{}^{209}\mathrm{Pb}\xrightarrow{\beta-}{}^{209}\mathrm{Bi}\left\{\begin{array}{l} \xrightarrow{(n,2n^*)}{}^{208m}\mathrm{Bi}\xrightarrow{IT}{}^{\mathbf{208}}\mathbf{Bi} \\ \xrightarrow{(n,2n^*)}{}^{\mathbf{208}}\mathbf{Bi} \end{array}\right.$$

Target Material: **Hg** Major WDR contributor: $^{\mathbf{194}}\mathbf{Hg}$

Pathways:

$${}^{196}\mathrm{Hg}\left\{\begin{array}{ccc} \xrightarrow{(n,2n^*)} & {}^{195\mathrm{m}}\mathrm{Hg} & \xrightarrow{(n,2n)} \\ & \downarrow \mathrm{IT} & \\ \xrightarrow{(n,2n)} & {}^{195}\mathrm{Hg} & \xrightarrow{(n,2n)} \end{array}\right\}{}^{\mathbf{194}}\mathbf{Hg}$$

Target Material: **Pd** Major WDR contributor: $^{\mathbf{108m}}\mathbf{Ag}$

Pathways:

$$\begin{array}{cccccc} {}^{110}\mathrm{Pd}\xrightarrow{(n,2n^*)} & {}^{109\mathrm{m}}\mathrm{Pd} & & {}^{109}\mathrm{Ag} & \xrightarrow{(n,2n^*)} & {}^{\mathbf{108m}}\mathbf{Ag} \\ & \downarrow \mathrm{IT} & & (n,n^*)\uparrow\downarrow IT & & \\ \left.\begin{array}{l} {}^{110}\mathrm{Pd}\xrightarrow{(n,2n)} \\ {}^{108}\mathrm{Pd}\xrightarrow{(n,\gamma)} \end{array}\right\} & {}^{109}\mathrm{Pd} & \xrightarrow{\beta-} & {}^{109\mathrm{m}}\mathrm{Ag} & & \end{array}$$

Target Material: **Ta** Major WDR contributor: $^{\mathbf{182}}\mathbf{Hf}$

Pathways:

$${}^{181}\mathrm{Ta}\left\{\begin{array}{l} \xrightarrow{(n,\gamma)}{}^{182}\mathrm{Ta}\left\{\begin{array}{lc} \xrightarrow{(n,p^*)} & {}^{182\mathrm{m}}\mathrm{Hf} \\ & \downarrow \mathrm{IT} \\ \xrightarrow{(n,p)} & {}^{\mathbf{182}}\mathbf{Hf} \end{array}\right. \\ \xrightarrow{(n,2n)}{}^{180}\mathrm{Ta}\xrightarrow{(n,p)\text{ or }\varepsilon}{}^{180}\mathrm{Hf}\xrightarrow{(n,\gamma)}{}^{181}\mathrm{Hf}\xrightarrow{(n,\gamma)}{}^{\mathbf{182}}\mathbf{Hf} \end{array}\right.$$

Target Material: **Pt** Major WDR contributor: $^{\mathbf{192n}}\mathbf{Ir}$

Pathways:

$${}^{194}\mathrm{Pt}\left\{\begin{array}{lcl} \xrightarrow{(n,2n^*)} & {}^{193\mathrm{m}}\mathrm{Pt} & \\ & \downarrow \mathrm{IT} & \\ \xrightarrow{(n,2n)} & {}^{193}\mathrm{Pt} & \xrightarrow{(n,p)\text{ or }\varepsilon}{}^{193}\mathrm{Ir}\xrightarrow{(n,2n^*)}{}^{\mathbf{192n}}\mathbf{Ir} \end{array}\right.$$

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Target Material: **W** Major WDR contributor: **^{186m}Re**

Pathways:

$$\begin{tikzcd}
{}^{186}\mathrm{W} \arrow[r, "(n,\gamma)"] & {}^{187}\mathrm{W} \arrow[r, "\beta-"] & {}^{187}\mathrm{Re} \arrow[dr, "(n,2n^{*})"] & \\
{}^{186}\mathrm{W} \arrow[r, "(n,2n^{*})"] & {}^{185m}\mathrm{W} \arrow[dd, "\mathrm{IT}"] & & \mathbf{{}^{186m}Re} \\
{}^{186}\mathrm{W} \arrow[dr, "(n,2n)"] & & & \\
 & {}^{185}\mathrm{W} \arrow[r, "\beta-"] & {}^{185}\mathrm{Re} \arrow[uur, "(n,\gamma^{*})"] & \\
{}^{184}\mathrm{W} \arrow[ur, "(n,\gamma)"] & & &
\end{tikzcd}$$

Target Material: **Gd** Major WDR Contributor: **^{158}Tb**

Pathways:

$$\begin{tikzcd}
{}^{157}\mathrm{Gd} \arrow[r, "(n,\gamma)"] & {}^{158}\mathrm{Gd} \arrow[dr, "(n,\gamma)"] & & & \\
 & {}^{158}\mathrm{Gd} \arrow[r, "(n,\gamma)"] & {}^{159}\mathrm{Gd} \arrow[r, "\beta-"] & {}^{159}\mathrm{Tb} \arrow[r, "(n,2n)"] & \mathbf{{}^{158}Tb} \\
 & {}^{160}\mathrm{Gd} \arrow[ur, "(n,2n)"] & & &
\end{tikzcd}$$

Target Material: **Au** Major WDR Contributor: **^{194}Hg**

Pathways:

$$\begin{tikzcd}
 & {}^{196m}\mathrm{Au} \arrow[dd, "\mathrm{IT}"] & & & \\
{}^{197}\mathrm{Au} \arrow[ur, "(n,2n^{*})"] \arrow[dr, "(n,2n)"] & & & & \\
 & {}^{196}\mathrm{Au} \arrow[r, "\beta-"] & {}^{196}\mathrm{Hg} \arrow[r, "(n,2n^{*})"] & {}^{195m}\mathrm{Hg} \arrow[r, "(n,2n)"] & \mathbf{{}^{194}Hg}
\end{tikzcd}$$

Waste Disposal Rating
(HIB)

Hohlraum Materials[#]			**H/A/FW**	**H/A/FW/B**
	---		0.24	0.04
Au/Gd (50:50)*	$1.2 \text{ x } 10^4$	(^{158}Tb)	**924**	**107**
Au	0.87	(^{194}Hg)	0.28	0.043
Pb	3.6	(^{208}Bi)	0.5	0.068
Hg	0.4	(^{194}Hg)	0.25	0.04
Ta	0.06	(^{182}Hf)	0.22	0.04
W	1.03	(^{186m}Re)	0.3	0.045
Pb/Ta/Cs (45:20:35)	1.5	(^{208}Bi)	0.34	0.05
Hg/W/Cs (45:20:35)	0.26	(^{194}Hg, ^{186m}Re)	0.24	0.04
Pb/Hf (70:30)	2.9	(^{208}Bi)	0.44	0.06

Gadolinium causes waste disposal problem if thickness on FW > 10 μm

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* atom %

[#] Assuming 1 mm sticking on FW armor

Energy Loss[#] and Economic Impact[*] of Hohlraum Materials Compared to Au/Gd

Hohlraum Materials	**$E/E_{Au/Gd}$**	**Driver Energy[**] (MJ)**	**Driver Cost ($B)**	**Δ DC ($B)**	**Δ COE (mills/kWh)**
Au/Gd	1	5.9/3.3	2.9/2.03	0	0
Pb/Ta/Cs	1.01	5.9/3.3			
Hg/W/Cs	1.04	6/3.4	2.93/2.06	0.03	0.4
Pb/Hf	1.04	6/3.4			
Au	1.25	6.7/3.7	3.16/2.16	0.26/0.13	3.7/1.8
Pb	1.28	6.7/3.7			
Hg	1.26	6.7/3.7			
Ta	1.25	6.7/3.7			
W	1.25	6.7/3.7			

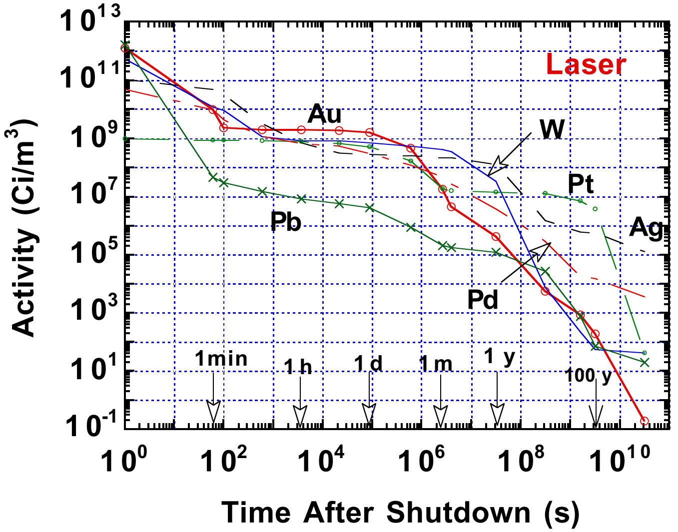
Exclude Gd, select best material(s) based on considerations other than WD, and take small hit on COE (< 5%)

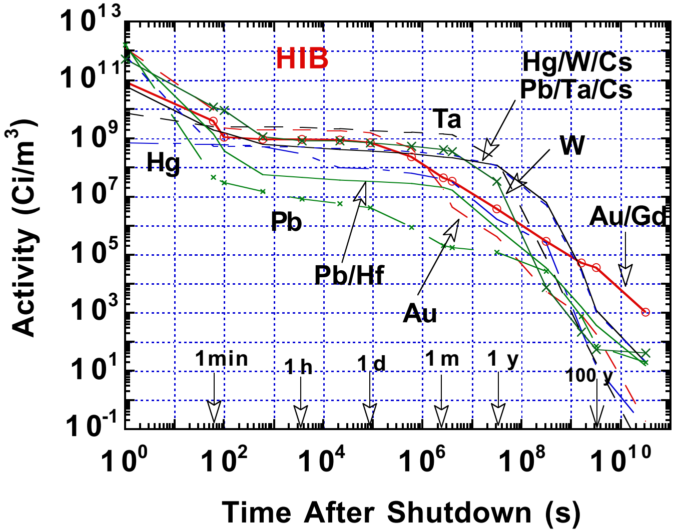
[#] Ref.: D. Callahan-Miller and M. Tabak, Phys of Plasmas (Vol 7, p 2083, May 2000)

[*] Preliminary results from W. Meier (2/26/01)

[**] conventional / close-coupled target

Activity of Coating/Hohlraum Materials Drops Rapidly After Shutdown





- Irradiation with **target flux** for tens of pico-seconds dominates early activity (< 1 min)
- After few minutes, almost all activities are due to reactivation with **FW flux**

Conclusions

- No waste disposal problem identified for:
  - Au, W, Pb, and Pt for **Laser** target coatings
  - Au, W, Pb, Hg, Ta, Hf, and Cs for **HIB** hohlraums
- **Palladium** coating can be used for laser target if FW and blanket are disposed as single unit
- **Silver** and **Gadolinium** generate high level waste considering realistic thickness on FW > 1 and 10 μm, respectively. This violates ARIES top-level requirements that call for only low-level waste
- Other considerations (fabrication, dose during accidents, etc.) may exclude material(s) from recommended list