Liquid Wall Radiological Assessment and Feasibility of Target Recycling

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With input from

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ARIES Meeting

January 10-11, 2002

UCSD

Objectives

- Identify radiological issues for candidate liquid wall (LW) materials:

  Pb
  LiPb
  Sn
  (will add Flibe)

- Address feasibility of recycling candidate hohlraum wall materials:

  Au/Gd
  Au
  W
  Pb
  Hg
  Ta
  Pb/Ta/Cs
  Hg/W/Cs
  Pb/Hf
  (will add Xe, Kr, and Hf at Moir's request)

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Radiological Assessment of LW Materials
(Pb, LiPb, and Sn)

- Assessment includes:
  - Activity
  - Decay heat
  - Waste disposal rating (WDR)
- LW in-chamber residence time is **unknown**. LW may survive thousands of pulses before being reprocessed and reused in chamber

  $\Rightarrow$ Parameterize number of pulses (1-10,000)
- Parameters and assumptions:
  - 458.7 MJ target yield*

    4 Hz rep rate (0.25 s between pulses)

    Perkins' neutron spectrum

    1 mm thick LW at 4 m radius#

    SiC/LiPb FW/Blanket system

    40 FPY plant life

    85% availability
  - LW materials spends 3 minutes outside chamber for reprocessing
  - Pb, LiPb, and Sn impurities included
  - LW materials only, no target debris

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* 6.4 MW/m^2 at LW; 21 MWy/m^2 for SiC

In-chamber LW amounts to 0.2 m^3

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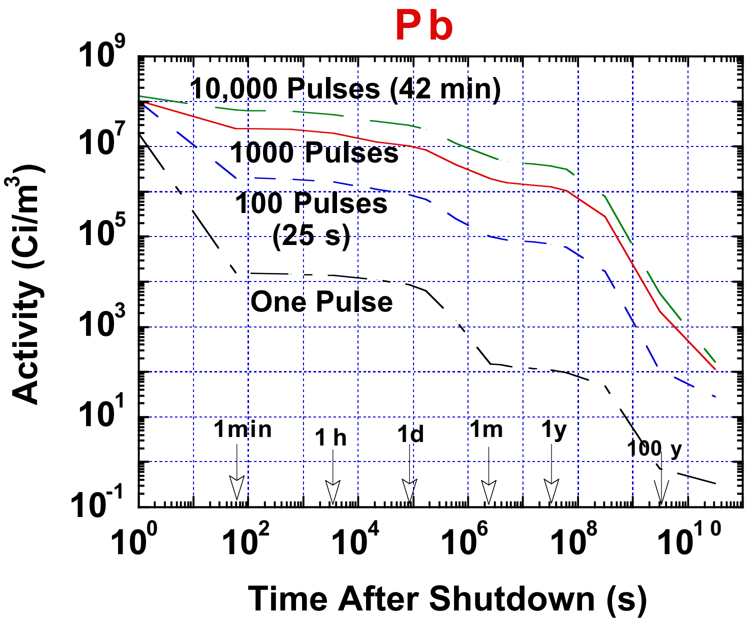
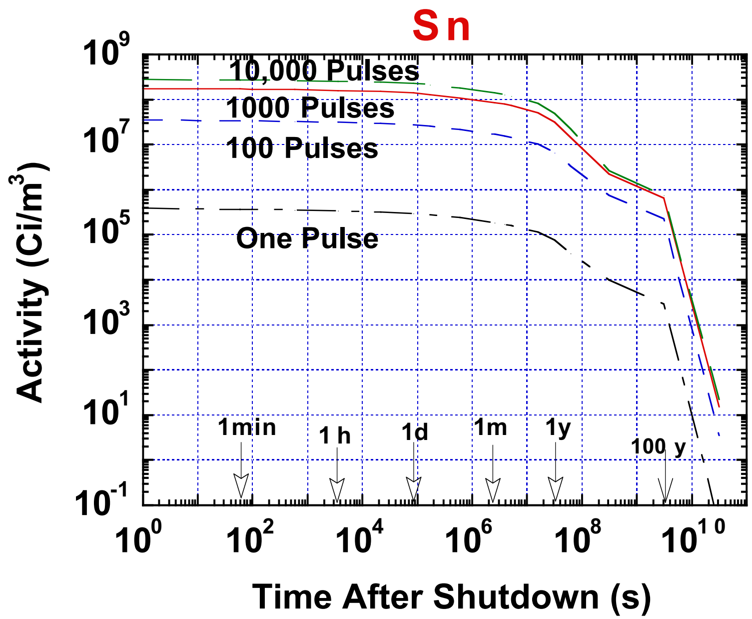
Activity





- 47 y of operation
- LiPb (w/o T) exhibits similar behavior to Pb
- Single shot produces very low activity
- Activity increases with residence time (= # of pulses x 0.25 s) and saturates after ~10,000 pulses
- Sn generates higher activity than Pb

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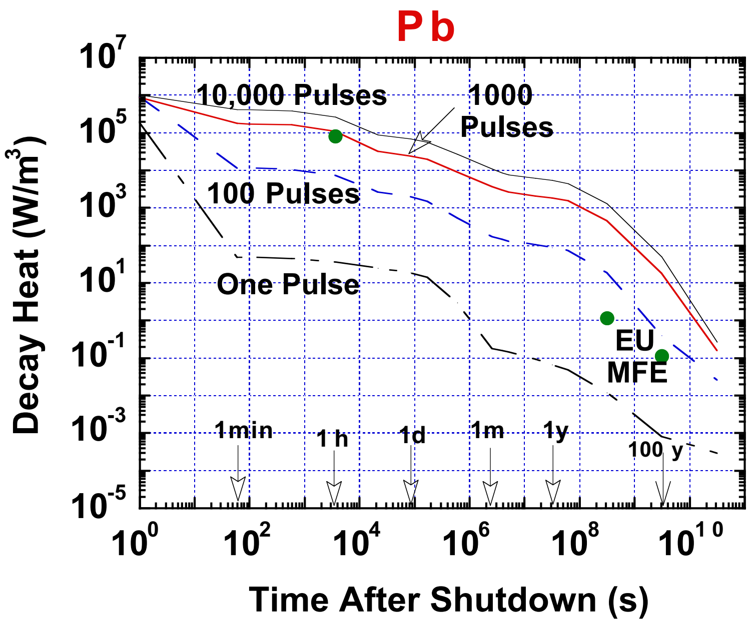
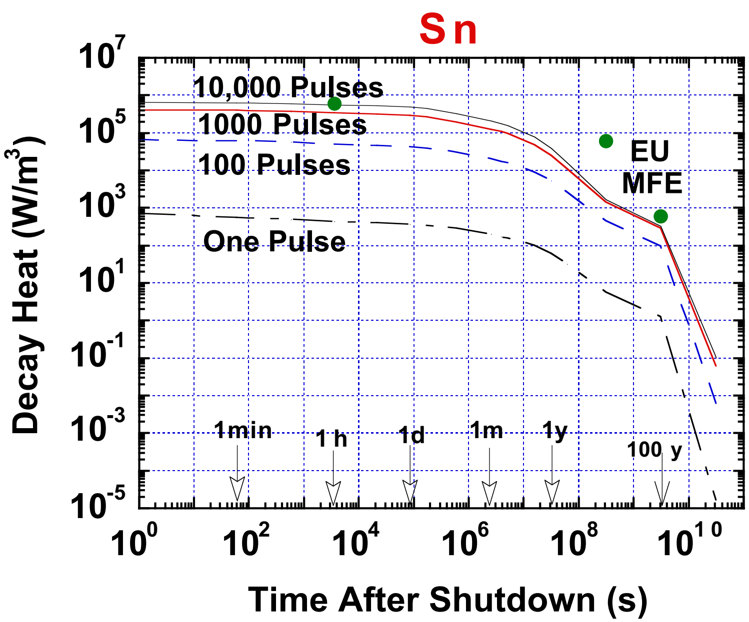
Decay Heat





- 47 y of operation
- LiPb (w/o T) exhibits similar behavior to Pb
- Pb decay heat drops rapidly after one hour
- Decay heat increases with LW residence time and saturates after ~10,000 pulses
- Sn generates higher decay heat than Pb
- Note differences between UW-IFE and EU-MFE* results

* C. Forty: Environmental/Economic/Fusion (EEF) study, tokamak FW spectrum, steady state calculations, 4 MW/m^2, 2.5 FPY, 100% availability, FISPACT code and 1990 data library.

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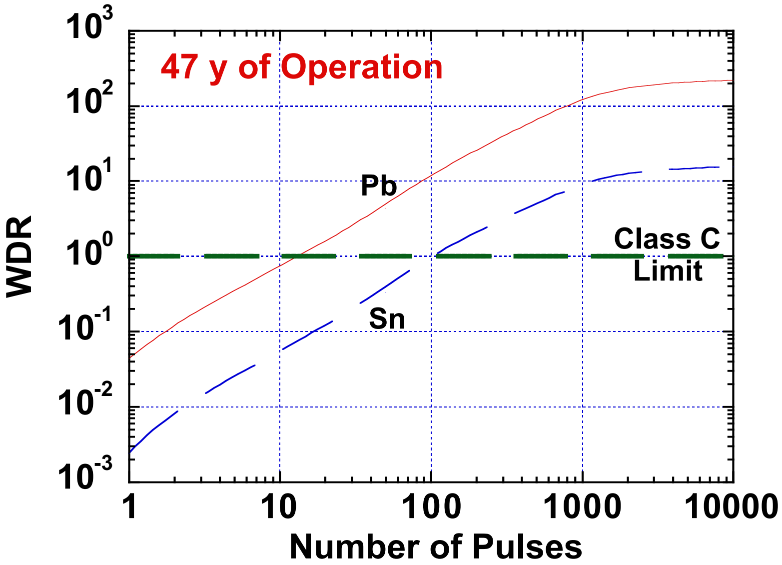
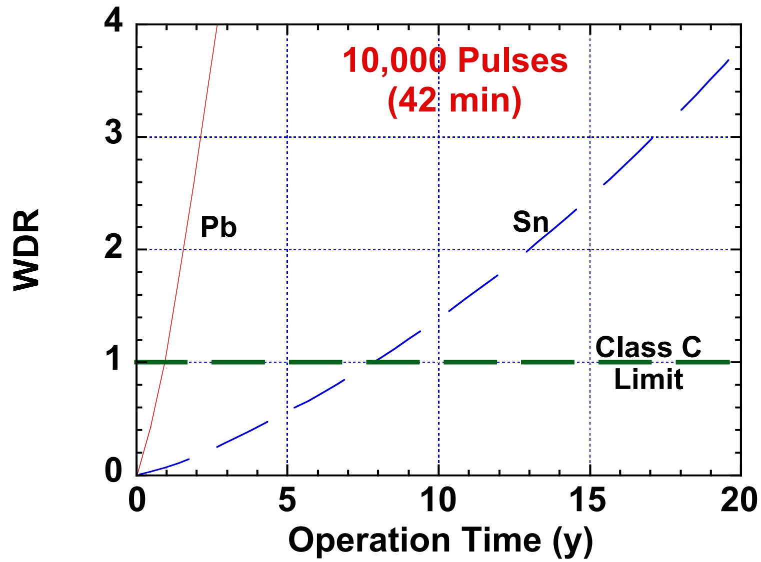
WDR*





- WDR increases with LW residence time and operation time
- Sn generates lower WDR than Pb
- To meet Class C waste requirement:
  - Filter out Bi and Ag transmutations on-line,
  - Use fresh Pb# after 1 y of operation and fresh Sn# after 8 y of operation, or
  - Limit in-chamber exposure of Pb to 12 pulses (3 s) and Sn to 100 pulses (25 s) and then remove from chamber to reprocess (unpractical)

* Evaluated at 100 y after operation
# ~0.5 m^3

Main Contributors to WDR of Liquid Wall Materials*

Pb	^{208}Bi
Sn	93% ^{108m}Ag, 4% ^{121m}Sn, 2% ^{126}Sn

* For 10,000 pulses and 47 y of operation

Conclusions of LW Radiological Assessment

- Sn generates higher activity and decay heat but lower WDR compared to Pb
- All activation responses increase with LW in-chamber residence time and saturates at ~ 40 min
- To meet Class C waste requirement, filter out Bi and Ag on-line and dispose of as HLW **or** limit reuse of Pb to 1 y and Sn to 8 y (⇒ higher inventory)

Target Recycling Study

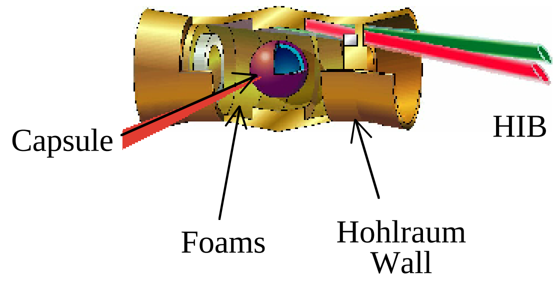
(work in progress)

Objectives of Target Recycling Study

- Answer two key questions:
  - How much waste is generated by target during operation?
  - Should any candidate hohlraum wall material be excluded for failing to meet recycling criteria?
- Estimate target inventory during plant life and compare it with nuclear island waste inventory
- Determine key elements for target recycling
- Develop recycling approach for ARIES-IFE-HIB to reduce target waste by 10 X or more
- Develop design solutions for materials with potential recycling problems
- Evaluate impacts of tradeoffs, such as target inventory, cooling period, waste level and volume, recycling cost, etc.

Background

- Each year, 10-20 tons of activated hohlraum materials will be disposed of in repositories, if not recycled



LLNL Close-Coupled Target Design

Capsule Radius*	2.34 mm
Hohlraum Wall Thickness*	15 µm
Target yield	458.7 MJ
Rep Rate	4 Hz
# of Shots	126 million shots/FPY
Plant Lifetime	40 FPY ; 47 y
Availability	85%
Volume of Hohlraum Wall	0.0085 cm^3/target
	1.1 m^3/FPY
	43 m^3/40 FPY
Mass of Hohlraum Materials	10-21 tons/FPY
	390-830 tons/40 FPY

* D. Callahan-Miller and M. Tabak, Phys of Plasmas, Vol 7, p 2083, May 2000

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Candidate Hohlraum Wall Materials*#

Materials		Composition (wt %)	Density (ton/m^3)	Mass/FPY (tons/FPY)
Gold/Gadolinium (ref.)	$_{79}Au/_{64}Gd$	50/50	13.5	15
Gold	$_{79}Au$		19.3	21
Tungsten	$_{74}W$		19.4	21
Lead	$_{82}Pb$		11.3	12
Mercury	$_{80}Hg$		13.6	15
Tantalum	$_{73}Ta$		16.6	18
Lead/Tantalum/Cesium	$Pb/Ta/_{55}Cs$	45/20/35	9.1	10
Mercury/Tungsten/Cesium	Hg/W/Cs	45/20/35	10.6	11
Lead/Hafnium	$Pb/_{72}Hf$	70/30	11.9	13

* D. Callahan-Miller and M. Tabak, Phys of Plasmas, Vol 7, p 2083, May 2000

Highly pure materials assumed for activation analysis

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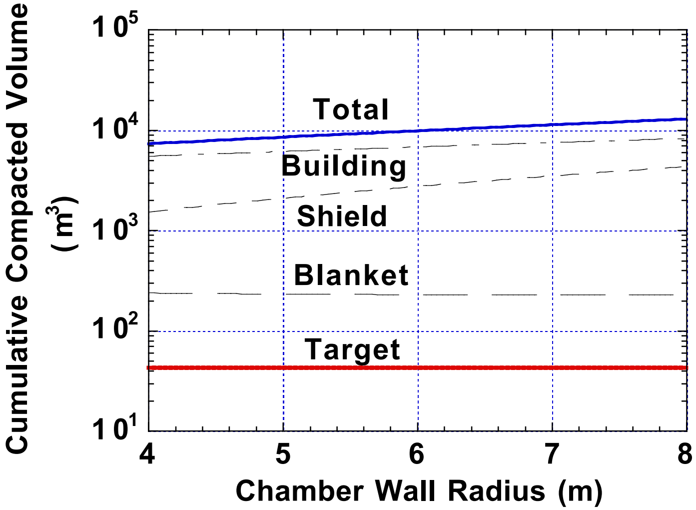
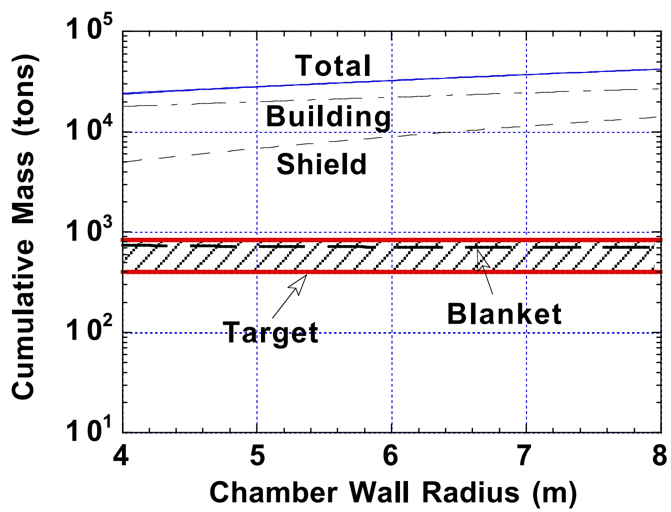
Hohlraum Wall Materials Represent Small Waste Stream for IFE





- **Typical dimensions**:

Component	Shape	Inner Radius	Thick.	Structure	Height
Chamber Wall	Sphere	R_w	1 cm	SiC	
Blanket	Sphere	R_w+0.01m	40 cm	20% SiC	
Bulk Shield	Cylinder	R_w+0.41+1* m	2 m	80%Conc.,10%SS	3 R_i
Building	Cylinder	R_w+3.41+10* m	1 m	85%Conc.,10%SS	2 R_i

Hohlraum walls constitute only 0.6% of cumulative volume and < 4% of cumulative waste mass

* Gap

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Hohlraum Wall Materials Represent Small Waste Stream for IFE (Cont.)

- Target recycling should be considered if recycling is a top-level requirement for ARIES-IFE-HIB
- One of ARIES' "**goals**" is to recycle all components

⇒ Develop target recycling approach for ARIES-IFE-HIB:

  - to reduce waste
  - to enhance repository capacity
  - to lower consumption of materials with limited resources
  - to save in direct cost of expensive materials (such as Au)

- Recycling introduces activation, decay heat, waste disposal, and radioactive material handling/processing problems

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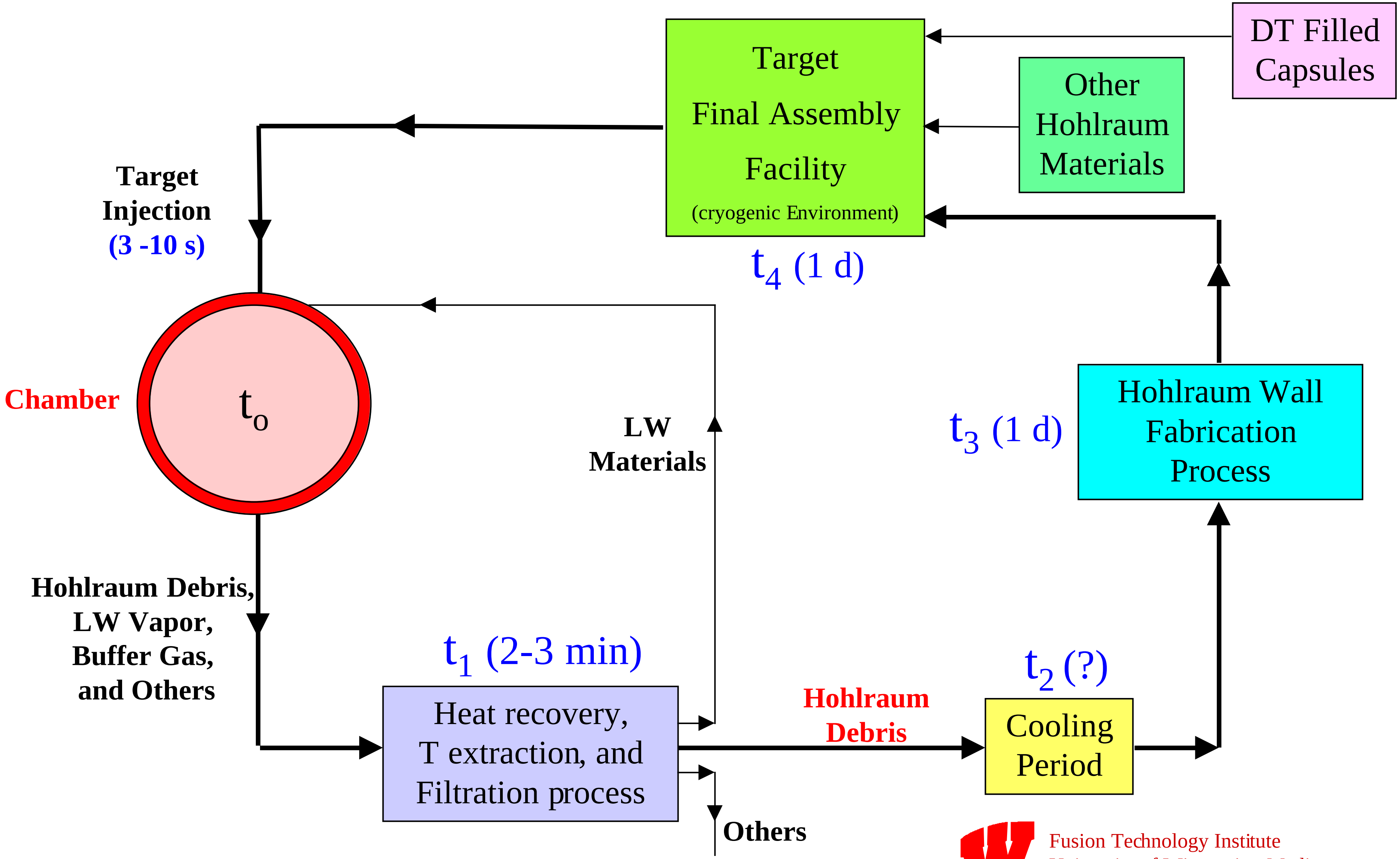
Hohlraum Recycling Process



Hohlraum Recycling Process (Cont.)

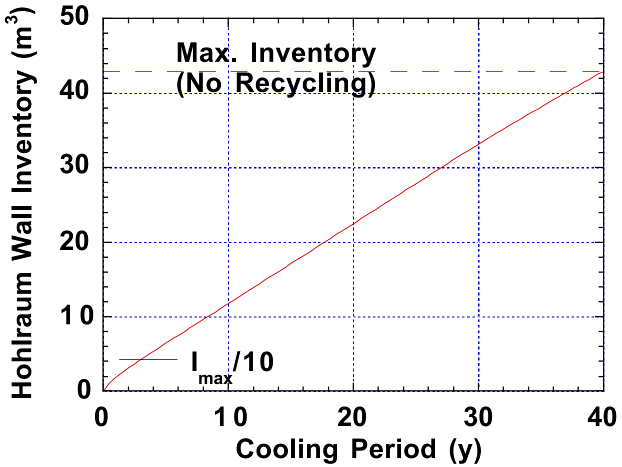
- Separation Process:
  - On-line separation of elements leaving chamber (LW materials, buffer gas, D, T, C, Fe, Al, Be, Br, etc) from hohlraum debris, except transmutations (conservative assumption). For example, Au/Gd transmutations include Os, Ir, Pt, Hg / Nd, Pm, Sm, Eu, Tb, Dy, Ho, Er.
  - Some elements will be disposed of
  - Radioactive hohlraum debris (containing transmutations) will be stored and sent in batches to Target Fabrication Facility for recycling
- Cooling Period:
  - Materials dependent
  - Time could range from zero to few years, depending on decay rate of activated hohlraum debris
  - Cooling periods ≤ 2 y reduce hohlraum inventory by 10 X or more
- Hohlraum Wall Fabrication Process:
  - Fabrication of recycled debris into radioactive hohlraum walls
  - Fabrication process takes ~ one day, per Nobile and Schwendt (LANL)
  - Capsule fabrication (DT filling, layering, holding, etc) and foam fabrication could be done in parallel with hohlraum wall fabrication
- Target Final Assembly Facility:
  - Assembly process of all components in cryogenic environment: capsule, organic and metal foams, and radioactive hohlraum wall
  - Assembly process takes ~ one day, per Nobile and Schwendt (LANL)

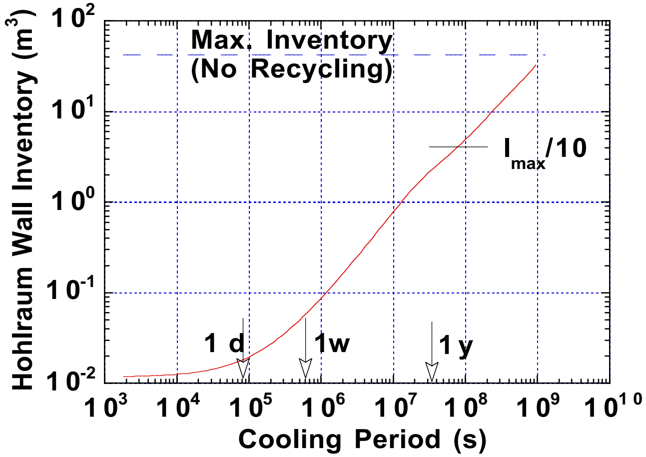
Hohlraum Recycling Process (Cont.)

- Hohlraum debris spend > two days outside chamber ($\Sigma_i\, t_i$, i=1- 4) for recycling, depending on cooling period
- Remote handling may be required during fabrication and assembly processes, depending on activation level at end of cooling period
  - ⇒ Limited personnel access to target fabrication facility
  - ⇒ More difficult and time consuming maintenance/repair of target fabrication equipment
- Target fabrication activities will be fully automated, per Schultz.
  - ⇒ Penalty of dealing with radioactive materials is not severe
- Storage space for radioactive materials is needed in ALL facilities
- Economics of recycling process should be addressed
- Losses during fabrication will be ignored

Cooling Periods ≤ 2 y Reduce Hohlraum Inventory by 10 X or more

- Inventory varies linearly with cooling period
- Steady-state inventory accounts for:
  - 2 d back-up
  - t_2+1
  - 2 d for recycling
  - Short time in chamber
- 2 d backup inventory is needed to account for repair of recycling system; e.g., 0.006 m^3 (80 kg of Au/Gd)
- Store irradiated materials in 1h, 1d, or 1y bins, depending on cooling period unit
- Start-up inventory !?
- More sophisticated approach could reduce inventory further





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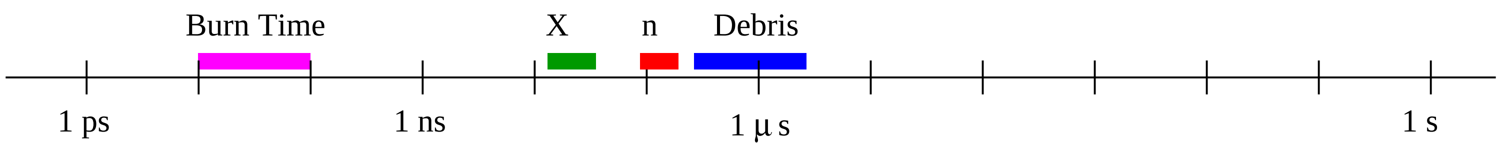
Several Factors May Prematurely Terminate Recycling Process Requiring Fresh Hohlraum Wall Materials

- Waste disposal rating of hohlraum debris violates Class C low level waste top-level requirement (most restrictive factor)
- Transmutation level in hohlraum debris reaches limit set by target designers to minimize beam losses to hohlraum walls. Alternative option is to separate transmutations on-line and address feasibility and economic issues
- Decay heat of radioactive hohlraum materials raises frozen DT temp above 1.8 K before target injection. Mogahed's preliminary analysis showed insignificant change in temperature for LLNL target design. Alternative option is to develop more forgiving target design!
- Accident dose at site boundary exceeds 1 rem following accidents in chamber and/or in Target Fabrication Facility

Species Arrival Time @ Chamber Wall

(5 m Radius Chamber, 4 Hz)

X-rays	**15-25 ns**
Neutrons	**90-150 ns**
Debris ions	**0.2-2 μs**



One Pulse (0.25 s)

Continuous Pump Out of Chamber*

* Amount of pumped materials varies during pulse, per Sviatoslavsky

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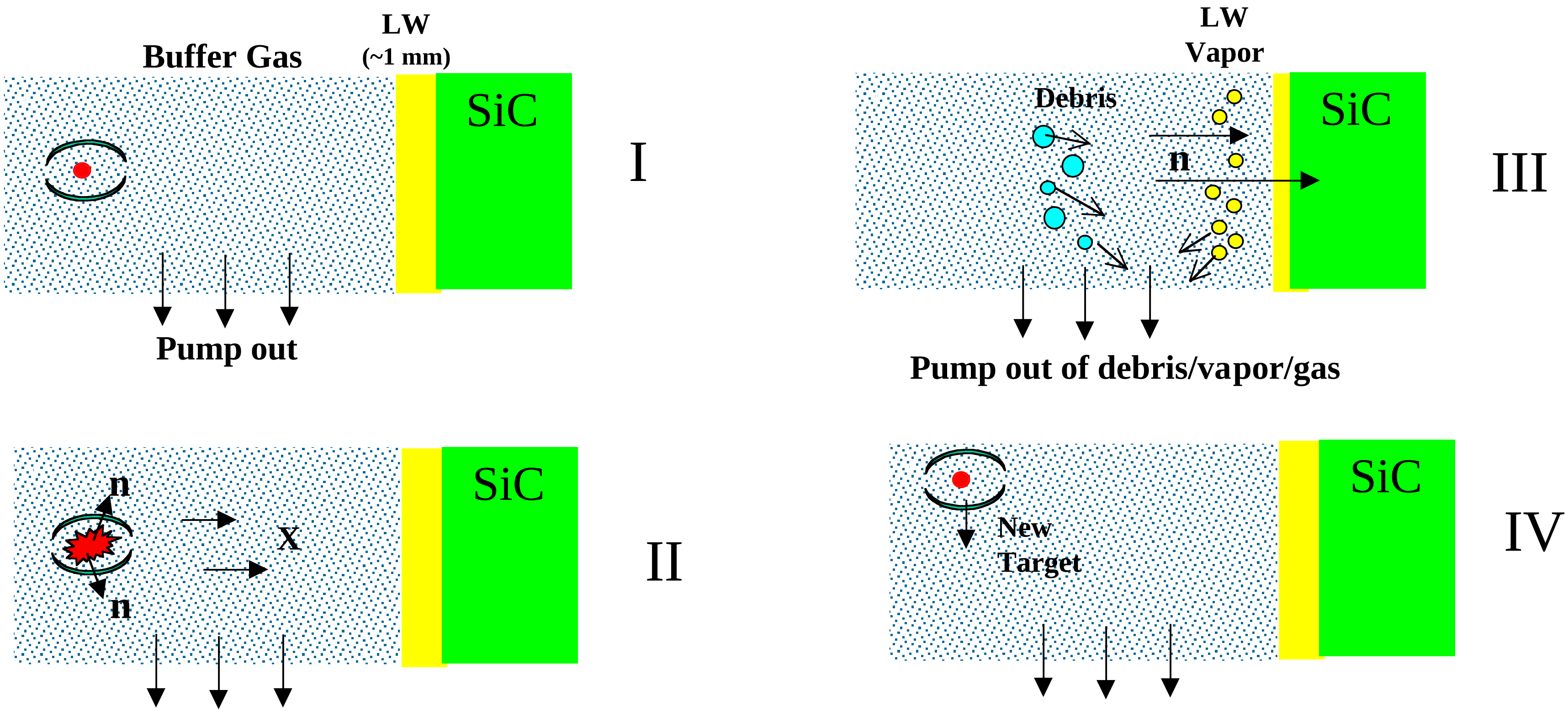
Sequence of Events - Option I

High Density Buffer Gas (~5 torr)



Dense gas stops x-rays and target debris

Hohlraum debris irradiated once per pulse with target flux at center of chamber

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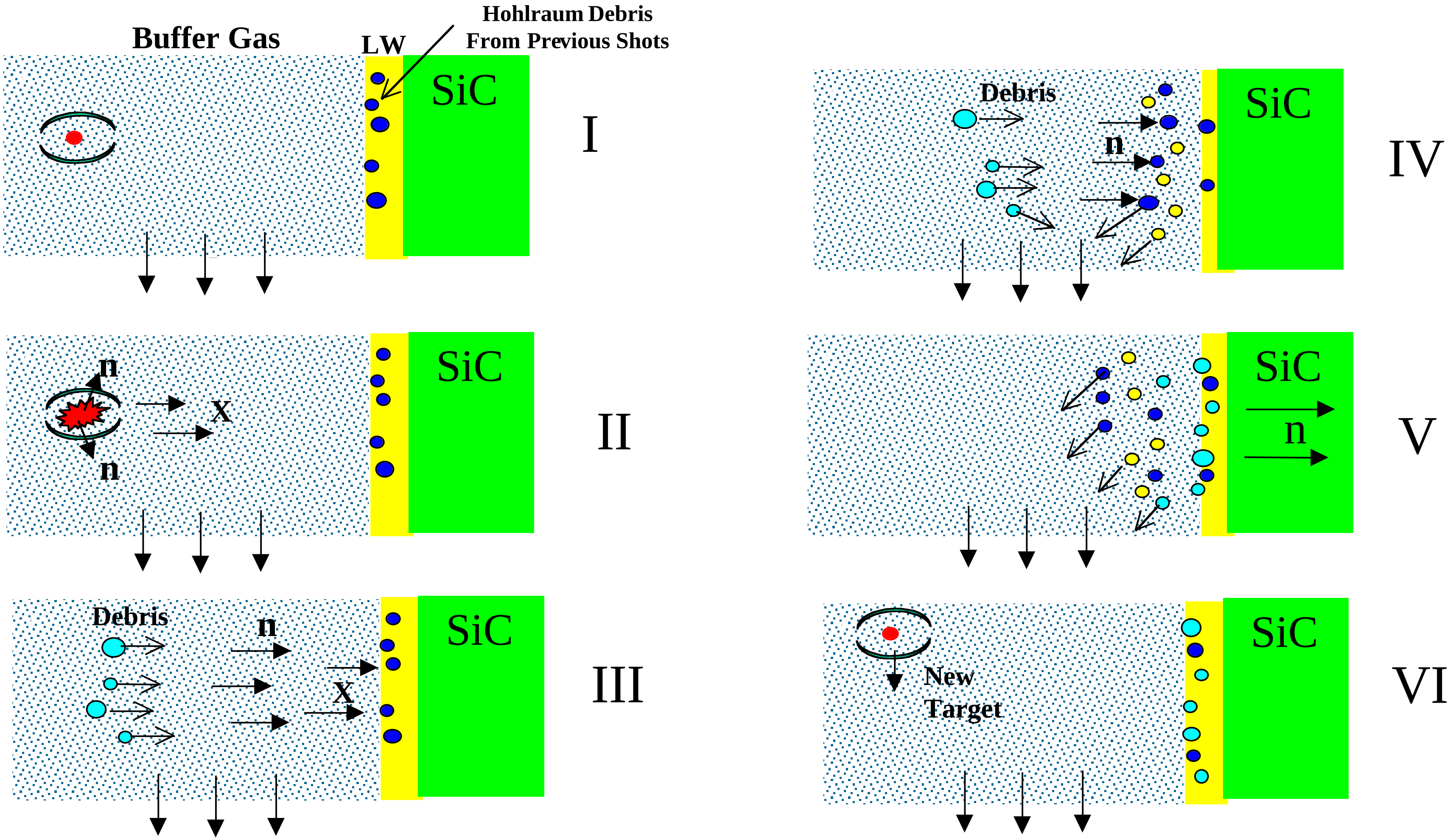
Sequence of Events - Option I (Cont.)

High Density Buffer Gas (~5 torr)

- LW will be needed only for small chambers (R_w < 4 m), per Peterson
- **During burn**, 14 MeV neutrons interact with and activate hohlraum walls
- **After burn,** dense buffer gas (~5 torr) stops x-rays and debris before reaching chamber wall
- LW vapor, buffer gas, and activated debris are continuously pumped out for recycling
- **Conservative assumptions:**
  - Hohlraum materials get irradiated once per shot with energetic 14 MeV source neutrons at chamber center
  - Transmutations continue to build up with time in hohlraum wall materials
  - On-line atomic separation of hohlraum debris for recycling
  - After specific cooling period, recycled radioactive hohlraum materials spend at least 2 days in Target Fabrication Facility before target injection

Sequence of Events - Option II

Low Density Buffer Gas (~10^{-3} torr)



Hohlraum debris get irradiated many times with target and wall fluxes before leaving chamber

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Sequence of Events - Option II (Cont.)

Low Density Buffer Gas (~10^{-3} torr)

- **During burn**, 14 MeV neutrons interact with and activate hohlraum walls
- **After burn:**
  - X-rays evaporate 10 µm of LW loaded with debris from previous shots
  - At vicinity of chamber wall, neutrons (av. E_n = 11.8 MeV) interact with evaporated debris and also with remaining debris in LW
  - Slow debris from this shot get pumped out with buffer gas. Fast debris reach LW and get embedded in seeped LW
- In-chamber residence time of debris depends on LW residence time
- LW vapor, buffer gas, and activated debris are continuously pumped out for recycling
- **Conservative assumptions:**
  - Buffer gas will not stop all hohlraum debris
  - Debris get irradiated several times before being pumped out:
    - With energetic 14 MeV source neutrons at chamber center
    - With softer, less intense n flux at vicinity of chamber wall during subsequent shots
  - Transmutations continue to build up with time in hohlraum wall materials
  - On-line atomic removal of LW materials* and gases before start of recycling process
  - After cooling period, radioactive hohlraum wall materials spend at least 2 days in Target Fabrication Facility before target injection

* up to 0.1 µm particles can be removed

No Major Change in Materials' WDR after One Shot

Hohlraum Wall Materials	WDR	EOL Inventory	
		m^3	Tons
Gold/Gadolinium (ref.)	2×10^{-8}	43	580
Gold	0	43	830
Tungsten	2×10^{-6}	43	830
Lead	2×10^{-5}	43	480
Mercury	5×10^{-4}	43	580
Tantalum	0	43	710
Lead/Tantalum/Cesium	1×10^{-5}	43	390
Mercury/Tungsten/Cesium	2×10^{-4}	43	450
Lead/Hafnium	8×10^{-5}	43	510

Without recycling, all materials qualify as Class C (or A) LLW after one shot

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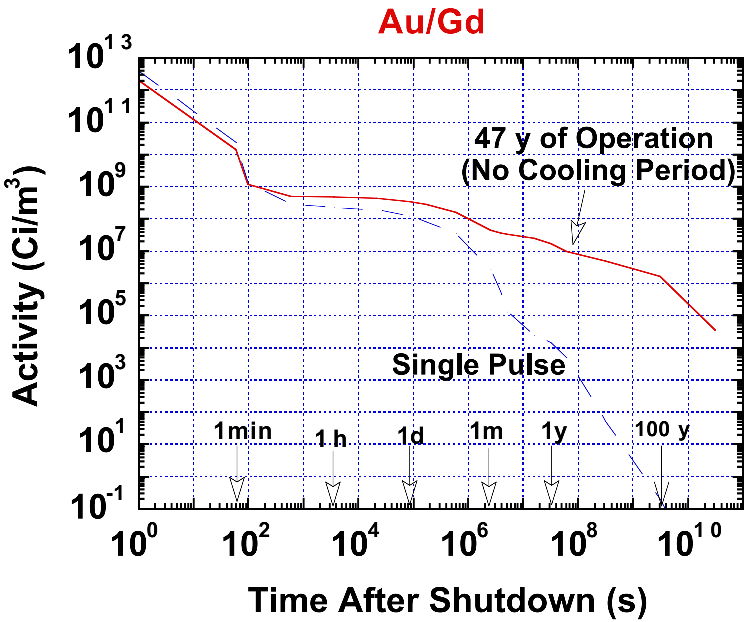
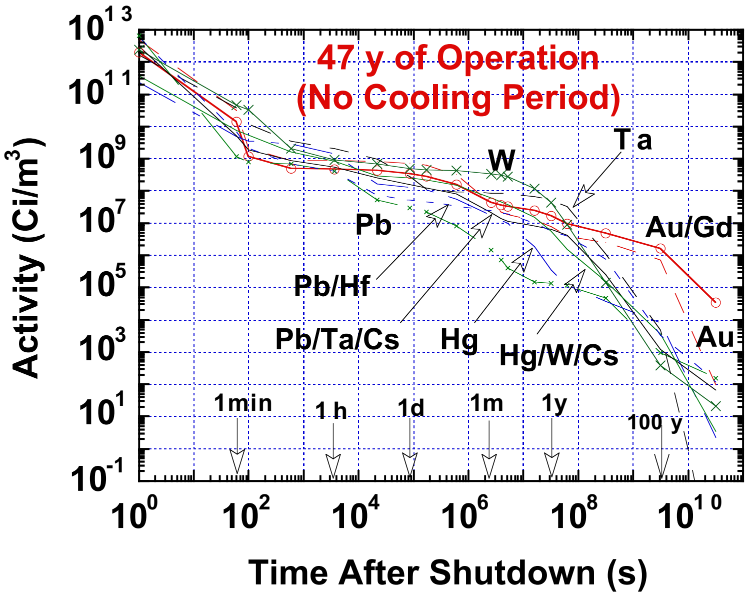
Recycling Increases Intermediate and Long-term Activity (Option-I)





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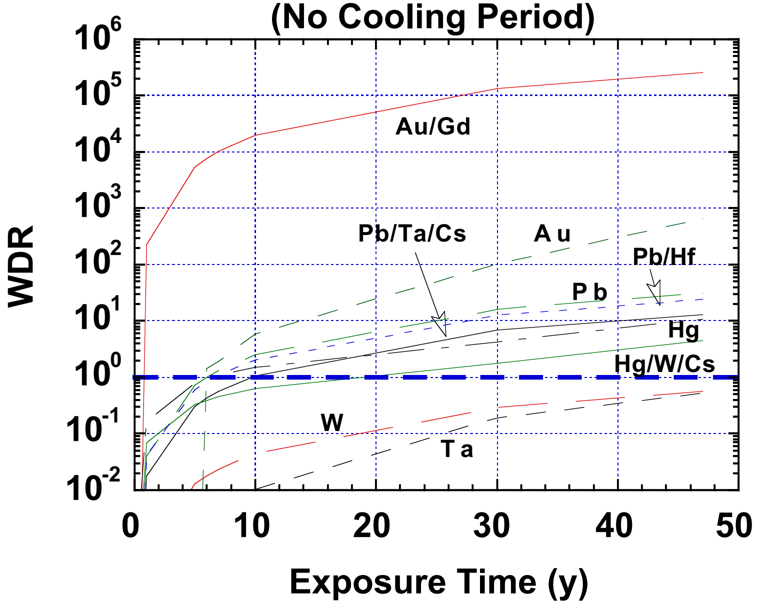
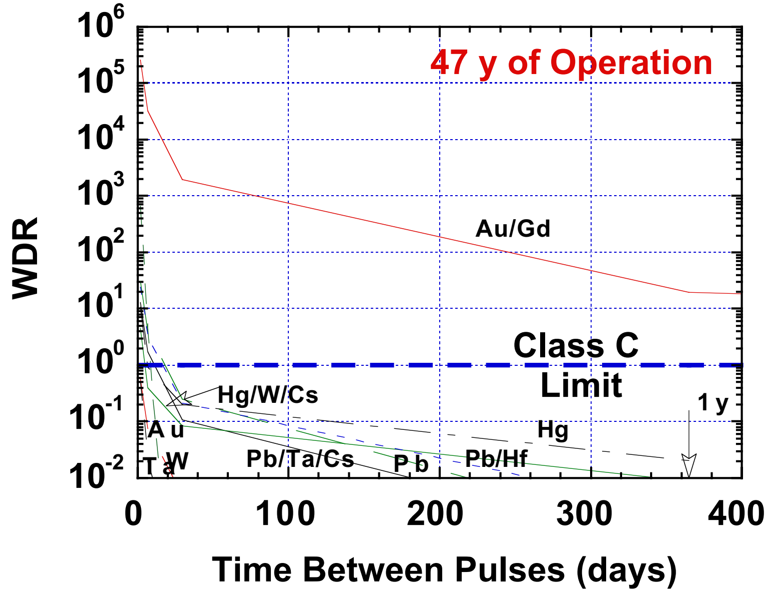
Recycling Impacts WDR (Option-I)





- Time between pulses = cooling period + fabrication/assembly time (2 d)
- WDR reported at 100 y after end of exposure
- **Recommendations:**
  - Do not recycle Au/Gd
  - W and Ta are Class C waste @ EOL even without cooling period
  - To meet Class C waste requirement for materials other than Gd,W, Ta:
    - limit exposure time to 5 - 20 years for no cooling period, or
    - extend cooling period to 3 - 16 days and recycle during 47 y of operation

Recommended Exposure/Cooling Time To Meet Class C LLW Requirement

	Maximum Exposure Time*	Total Inventory @ EOL (m^3)
Au/Gd	NA	43
Au	5.5 y	0.1
W	47 y	0.01
Pb	6 y	0.1
Hg	6 y	0.1
Ta	47 y	0.01
Pb/Ta/Cs	10 y	0.06
Hg/W/Cs	20 y	0.04
Pb/Hf	7 y	0.08

* No cooling period

	Minimum Cooling Period#	Total Inventory @ EOL (m^3)
Au/Gd	NA	43
Au	7 d	0.03
W	0	0.01
Pb	16 d	0.06
Hg	5 d	0.03
Ta	0	0.01
Pb/Ta/Cs	9 d	0.04
Hg/W/Cs	3 d	0.02
Pb/Hf	15 d	0.06

47 y operation

Main Contributors to WDR of Hohlraum Wall Materials*

Au/Gd (50:50)	^{158}Tb
Au	83% ^{192n}Ir, 16% ^{194}Hg
W	93% ^{186m}Re, 6% ^{178n}Hf
Pb	96% ^{208}Bi, 3% ^{202}Pb
Hg	50% ^{192n}Ir, 50% ^{194}Hg
Ta	^{178n}Hf
Pb/Ta/Cs (45:20:35)	96% ^{208}Bi, 3% ^{202}Pb
Hg/W/Cs (45:20:35)	50% ^{192n}Ir, 50% ^{194}Hg
Pb/Hf (70:30)	95% ^{208}Bi, 3% ^{202}Pb

* 47 y of operation with no cooling period

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Recycling Dose Limit

Hands-on limit*#:	
without ALARA principle	10 μSv/h
with ALARA principle	1 μSv/h
Remote handling limit*##	10 mSv/h (very conservative)
Advanced RH Equipment Limit+	3000 Sv/h

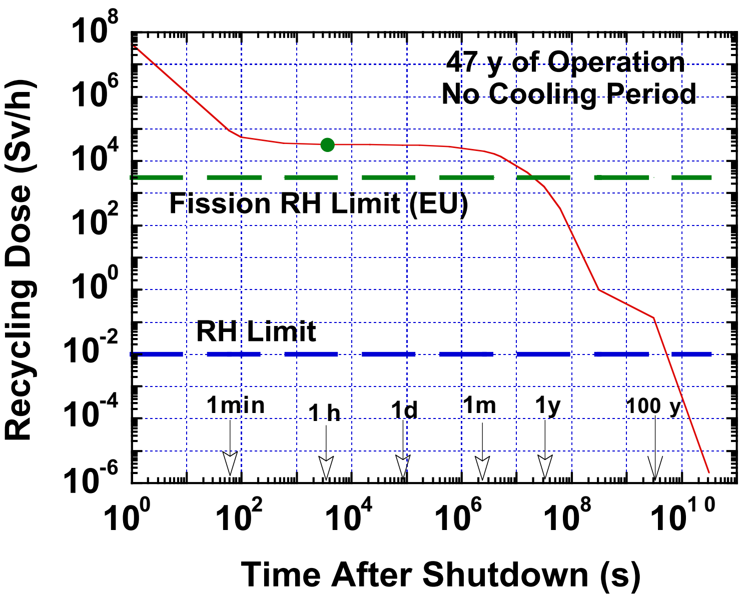
* Ref: D. Petti et al., "Safety Analysis of Initiating Events", ARIES E-meeting, Oct 17, 2001. Same as Japanese and European limits

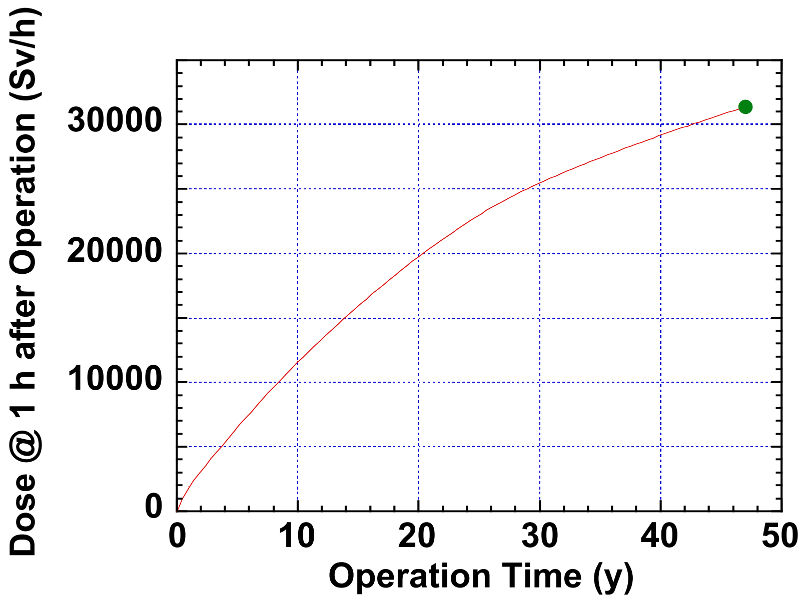
\# Based on 20 mSv annual limit for 2000 h/y worker

\## Based on arbitrary factor of 1000 above HO limit

\+ For fission waste, per N. Taylor. On-going EU recycling study will develop RH limit for fusion waste

Tungsten Recycling Dose





- W recycling dose exceeds "conservative" RH limit (0.01 Sv/h) by several orders of magnitude
- W could meet dose limit for advanced, radiation-resistant RH equipment (> 3000 Sv/h) with cooling period of 1 y or less (TBD)

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Conclusions of Target Recycling Study

- Target inventory (43 m^3, 400-800 tons) is small compared to total radwaste (10,000 m^3, 30,000 tons) of ARIES-IFE-HIB
- Low target inventory means recycling should not limit hohlraum wall material choices, unless recycling is a top-level requirement for ARIES-IFE
- WDR:
  - Without recycling (one-shot use), all candidate hohlraum wall materials qualify for low level waste
  - With recycling:
    - Gd generates high level waste after ~10 pulses $\Rightarrow$ do not recycle Gd
    - W and Ta meet Class C waste requirement for 47 y of operation with no cooling period
    - For others:
      - End recycling process after 5-20 y and use fresh materials, or
      - Store materials for 3-16 days before recycling
- Recycling dose:
  - Analysis is underway to determine cooling periods that meet both recycling limit and Class C waste requirement