Waste Issues and Radiological Inventory in LiPb

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Web address:
http://fti.neep.wisc.edu/FTI/ARIES/SEP2000/waste_lae.pdf

ARIES Project Meeting
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PPPL

Inboard Radial Build*

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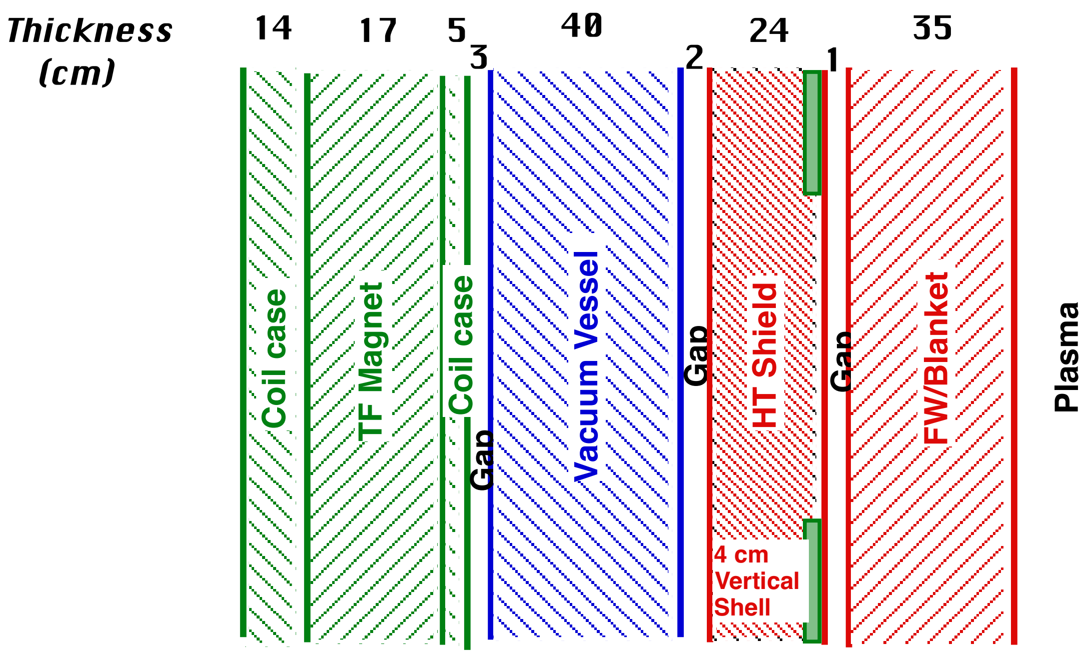

Component	Composition#
FW (1.4 cm)	73% SiC , 27% LiPb
Blanket (33.6 cm)	17% SiC , 83% LiPb
HT Shield	15% SiC, 10% LiPb , 70.3% B-FS, 4.7% W
Vacuum Vessel	13% FS, 22% H_2O, 65% WC
Coil Case	95% 304SS, 5% LN
Winding Pack	72% Inconel, 7% $Y_1Ba_2Cu_3O_5$, 7% CeO_2, 0.5% Ag, 13.5% GFF Polyimide

- VV/case gap contains 15% superinsulation

* Safety factor of 3 considered in all shielding calculations
# SiC and WC are 95% dense

Outboard Radial Build[*]

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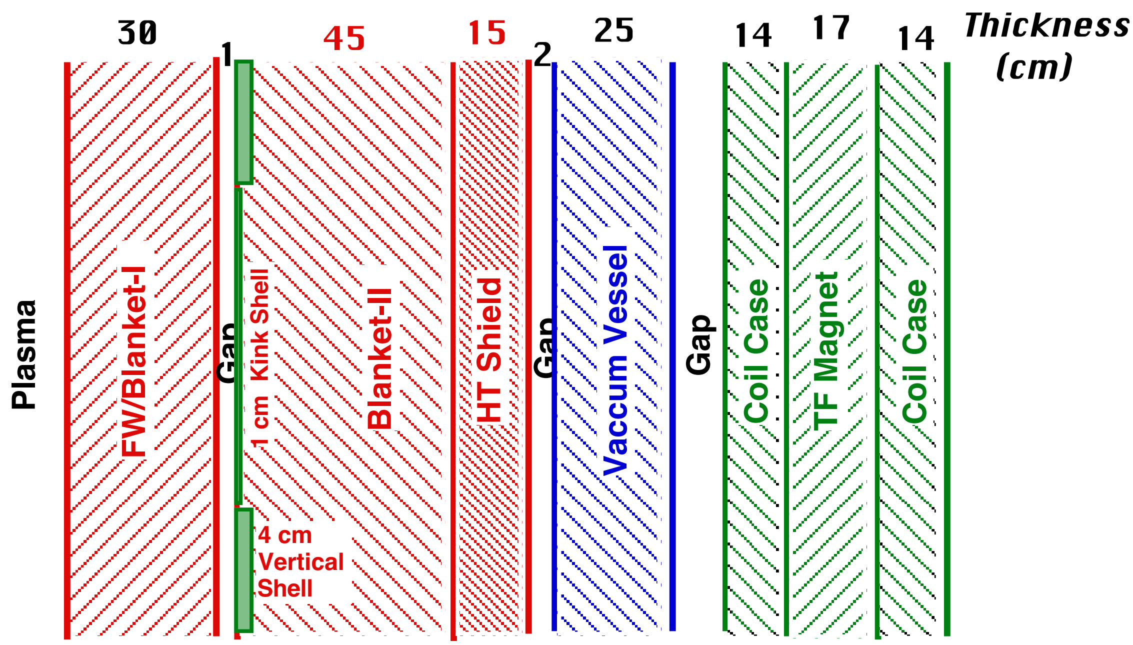

Component	Composition[#]
FW/Blanket-I:	
FW (1.4 cm)	73% SiC , 27% LiPb
B-I (28.6 cm)	17% SiC , 83% LiPb
Blanket-II	19.3% SiC , 77.3% LiPb , 3.4% W
HT Shield	15% SiC , 10% LiPb , 75% B-FS
Vacuum Vessel[**]	30% FS , 70% H_2O
Coil Case	95% 304SS, 5% LN
Winding Pack	72% Inconel, 7% $Y_1Ba_2Cu_3O_5$, 7% CeO_2, 0.5% Ag, 13.5% GFF Polyimide

- Along with blanket/shield/V.V., 5 cm thick port enclosures and 5 cm side coil case provide shielding for sides of winding pack

- Wedge underneath magnet is composed of B-II, HT shield, and V.V.

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[*] Safety factor of 3 considered in all shielding calculations
[#] SiC and WC are 95% dense
[**] Composition is slightly of-optimum to simplify V.V. design

Vertical Build*

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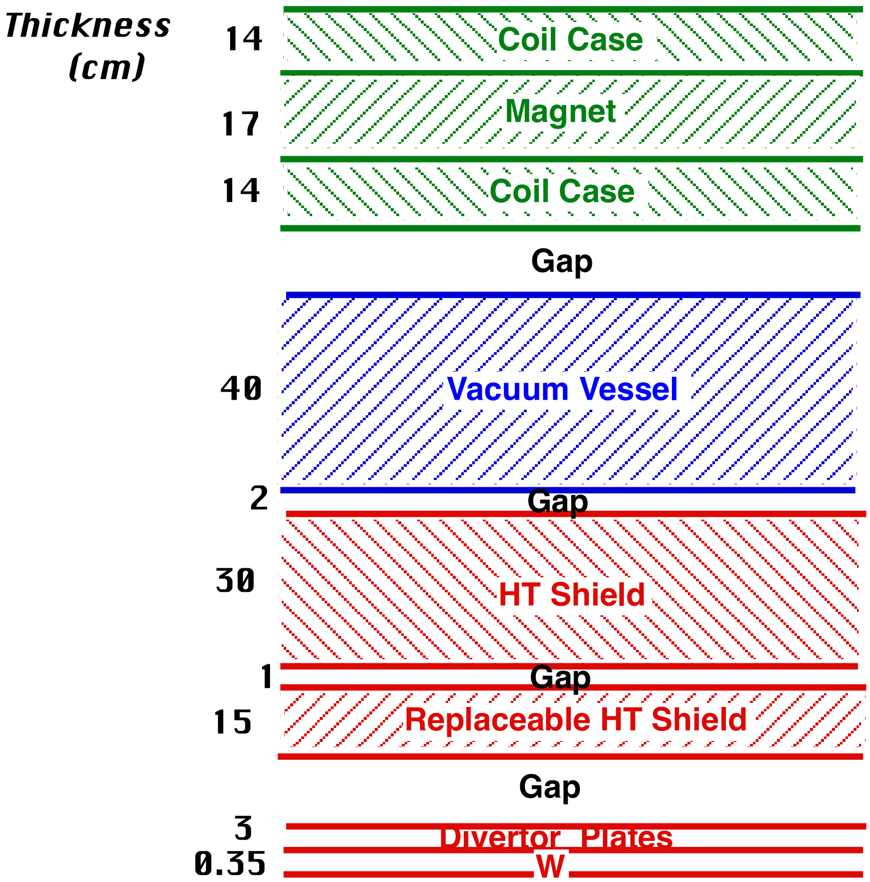

Component	**Composition#**
W coating	100% W-0.2%TiC alloy
Divertor Plates	46% SiC , 54% LiPb
Replaceable HT Shield	15% SiC , 10% LiPb, 75% FS
HT Shield	15% SiC , 10% LiPb , 75% B-FS
Vacuum Vessel	13% FS, 22% H_2O, 65% B-FS
Coil Case	95% 304SS, 5% LN
Winding Pack	72% Inconel, 7% $Y_1Ba_2Cu_3O_5$, 7% CeO_2, 0.5% Ag, 13.5% GFF Polyimide

- No info available on size of pumping ducts to design penetration shield

* Safety factor of 3 considered in all shielding calculations
\# SiC and WC are 95% dense

Inconel-625 Contains Higher Nb Fraction Compared to Other SS

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Composition of SS (in wt%) for ARIES-AT Magnet:

(Phil Heitzenroeder - PPPL – 6/30/2000)

Element	Inconel-625 for winding pack	316 SS-LN*
C	0.1 max	0.01
Mn	0.5 max	1.48
Si	0.5 max	0.1
P	0.15	0.003
S	0.015	0.0014
Cr	20-23	17.17
Nb	1.72	0.055
Ta	1.72	
Co	1.0 max	
Mo	8-10	2.03
Fe	5.0 max	66.82
Al	0.4 max	
Ti	0.4 max	
Ni	58 min	12.14
N	0.19	

Inconel-625 contains 30 times Nb of 316 SS-LN

Element	304 SS for coil case (no Nb)
C	0.08
Mn	2.00
P	0.045
S	0.03
Si	0.75
Cr	18-20
Ni	8-10.5
N	0.10
Fe	Balance

* used in ARIES-AT magnet developed before 6/30/00

Waste Disposal Rating

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- WDR reported for compacted waste (void excluded)
- WDR < 1 means component qualifies as LLW
- WDR remains constant for 100's of years after shutdown, unless indicated
- All components should meet BOTH Fetter's and NRC-10CFR61 WD limits for Class A or C LLW
- Waste disposal limits:
  - NRC (10CFR61):
    - **Official** U.S. WD limits
    - NRC has developed Class A and Class C WD limits for 9-10 isotopes beside actinides.
    - NRC limits not available for ~90 isotopes of interest to fusion
    - Class A has low limit for tritium ($T_{1/2}$~12.3 y)
  - Fetter's:
    - **Not** in regulations form
    - Approved by U.S. Fusion Safety Standing Committee
    - NRC has not endorsed Fetter's limits
    - No limits available for Class A LLW
    - Fetter developed Class C WD limits for 101 isotopes of interest to fusion. 19 isotopes have range of limits rather than single value due to uncertainties in corrosion assumptions. Those beta emitters are: C^{14}, Si^{32}, Cl^{36}, Ca^{41}, Ni^{63}, Se^{79}, Sr^{90}, Tc^{97}, Tc^{98}, Tc^{99}, Pd^{107}, I^{129}, Sm^{151}, Gd^{148}, Gd^{150}, Dy^{154}, Pb^{210}, Ra^{226}, Ac^{227}
    - Fetter-L and Fetter-H WDRs are calculated using Fetter's low and high limits, respectively.
    - Fetter-L limits were not considered in previous ARIES designs
    - Fetter-L is more conservative

Fetter's Waste Disposal Rating

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	Fetter-H Class C Limits w/o Shells	Fetter-H Class C Limits with W Shells*	Fetter-L Class C Limits w/o Shells	Fetter-L Class C Limits with W Shells
Inboard Components:				
FW/B	0.017		0.019	
HT Shield	0.45	0.47	0.7	0.73
V.V.	0.03		0.08	
Magnet:	**0.07**		**0.09**	
Inner coil case	9e-6		1.5e-5	
Winding pack	0.15		0.18	
Outer coil case	2e-6		3e-6	
Outboard Components:				
FW/B-I	0.09		0.092	
B-II	0.001	0.3	0.01	0.6
HT Shield	0.15		0.22	
V.V.	0.06		0.07	
Magnet:	**0.1**		**0.12**	
Inner coil case	2e-4		3e-4	
W.P.	0.24		0.29	
Outer coil case	2e-6		3e-6	

- Use of Inconel-625 structure increased W.P. WDR by factor of > 10
- Dominant nuclides for W.P. WDR are Nb^{94} (78-94%) and Tc^{99} (3-19%)

Based on Fetter's limits, all components qualify as Class C LLW @ EOL

* 4 cm thick vertical stabilizing shells on both IB and OB. 1 cm thick kink shell on OB only.

NRC Waste Disposal Rating

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	NRC Class A Limits w/o Shells	NRC Class A Limits with W Shells	NRC Class C Limits w/o Shells	NRC Class C Limits with W Shells
Inboard Components:				
FW/B	4		0.017	
HT Shield	56	54	0.39	0.41
V.V.	0.1		0.008	
Magnet:	**0.7**		**0.07**	
Inner coil case	0.017		4e-5	
Winding pack	1.42		0.14	
Outer coil case	0.004		2e-4	
Outboard Components:				
FW/B-I	11		0.03	
B-II	1.3	4.7	0.07	0.37
HT Shield	4.3		0.1	
V.V.	3.6		0.04	
Magnet:	**1.1 @ SD** **0.98 @ 100y**		**0.09**	
Inner coil case	0.44		4e-3	
Winding pack	2.4		0.23	
Outer coil case	0.003		3e-5	

- NRC-A WDR reported at shutdown (unless indicated) and drops with time after shutdown
- Use of Inconel-625 structure increased W.P. WDR by factor > 10
- Dominant nuclide for W.P. WDR is Nb^{94} (> 95%)
- Dispose W.P. and coil cases as single unit to qualify as Class A LLW after 100 y storage period

Based on NRC limits, all components qualify as **Class C LLW @ EOL**

Radiological Inventory in LiPb

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- There are safety concerns for both Po^{210} (138.4 d $T_{1/2}$) and Hg^{203} (46.6 d $T_{1/2}$) radioisotopes
- Activation analysis determines:
  - Build up of radioactive inventory with operation time
  - Time to reach activity limit and start purification system
- **Polonium production path:**
  - Po^{210} produced from Bi and Pb
  - Bi^{209} impurity (43 wppm) in LiPb generates Po^{210} and dominates Po^{210} production at early years of operation
  - Pb produces Bi^{209} that generates Po^{210}. Primary production path is:

    Pb^{208} (n,γ) Pb^{209} (β^- decay) Bi^{209} (n,γ) Bi^{210} (β^- decay) Po^{210}
  - Po^{210} activity limit is very low (25 Ci or 0.001 wppb), per Petti
  - Choice between removing Bi or Po depends on simplicity of purification technique

If easier to separate, on-line removal of Bi is recommended as a method to control Po^{210}

- **Mercury production path:**
  - Pb generates 9 Hg isotopes* through many multiple capture production paths
  - Hg^{203} activity limit is 25 kCi, per Petti

* Hg^{198} – Hg^{206}

LiPb Flow Patterns

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- Five LiPb flow paths* for in-vessel components with various residence times:
  - Lower divertor & IB Blanket
  - Upper divertor and 1/2 OB Blanket-I
  - 1/2 OB blanket-I
  - IB shield & 1/2 OB Blanket-II
  - OB shield and 1/2 OB Blanket-II

- LiPb residence times*:
  - 1 s in IB FW
  - 2 s in OB FW
  - 8-12 s in side and back walls
  - 3 s in divertor tubes and 7 s in return channels
  - 35 s in channel of IB Blanket
  - 70 s in channel of OB Blanket-I
  - 240 s in channel of OB Blanket-II
  - 60 s in shield

- *Effective* residence time should consider flow path, actual residence time, and wall loading effect. For example, ~10 s in divertor then 2 s in OB FW means > 2 s *Effective* residence time for OB FW

- LiPb spends ~2 min in outer loop for heat removal, T extraction, and Po/Bi/Hg purification

- Assume LiPb returns to same location inside torus. Real system offers ex-vessel mixing of LiPb from all in-vessel flow paths that cannot be modeled by existing modern codes

- Same LiPb will be used for 40 FPY (Li can be refurbished if needed)

- 600 m^3 of LiPb (8.8 g/cm^3) in all loops
- 80% system availability

* per Raffaray

Po, Bi, and Hg Inventories in LiPb Estimated Using Three Approximate Methods

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- European Approximation (crude; limited by EU activation code capability):
  - Calculate OB FW inventory at end-of-life with 100% availability
  - Divide results by 10 to account for:
    - Radial profile of n flux and spectrum
    - In-vessel and ex-vessel flow history
    - Ex-vessel mixing
    - Availability

- UW Approximation-I (simple):
  - Calculate all inventories in all components with SAME flow history using 80 s residence time for in-vessel and 2 min for ex-vessel*
  - Include effect of:
    - Radial profile of n flux and spectrum
    - Approximate in-vessel flow history (based on educated guess)
    - Ex-vessel flow history
    - Results averaged based on coolant volume of individual components
    - Variation with operation lifetime at increment of 4 FPY
    - Availability
  - Neglect effects of:
    - Variation of flow history by component
    - Flow sequence within flow path
    - Ex-vessel mixing, meaning LiPb returns to same in-vessel component

- UW Approximation-II (more accurate but time consuming):
  - Calculate all inventories in all components with actual residence times considering 2 min for ex-vessel
  - Include effect of:
    - Radial profile of n flux and spectrum
    - Variation of flow history by component
    - Flow sequence within flow path
    - *Effective* residence times
    - Ex-vessel flow history
    - Results averaged based on coolant volume of individual components
    - Variation with operation lifetime at increment of 4 FPY
    - Availability
  - Neglect effects of:
    - Ex-vessel mixing, meaning LiPb returns to same in-vessel component

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* ratio of times equals roughly to ratio of in-vessel to ex-vessel LiPb volumes

Bi and Po Inventories in LiPb

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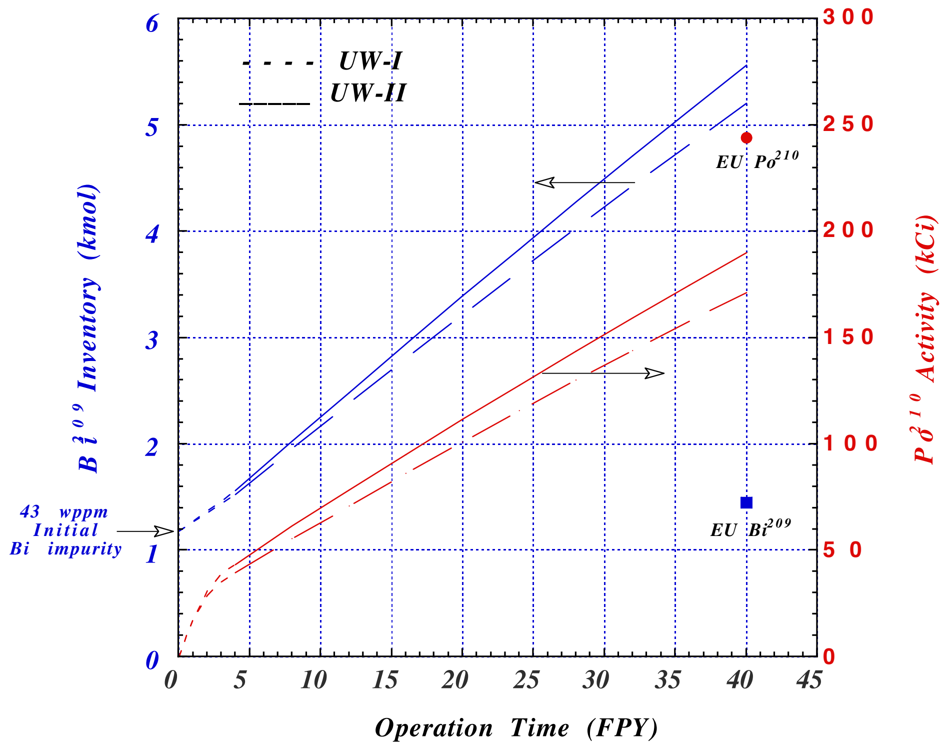

- Results of UW approximations-I and –II agree within 10%

- At end-of-life, EU approximation overestimates Po^{210} activity by 40% and underestimates Bi^{209} inventory by factor of 4*

- Bi and Po inventories vary non-linearly with operation time

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* OB FW flux and spectrum are not representative. High FW flux accentuates double capture leading to high Po^{210} production. Bulk of LiPb has Bi^{209} inventory > 10% of OB FW's

Bi and Po Inventories in LiPb (cont.)

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- Bi impurity (43 wppm) dominates Po^{210} production at early years of operation:

Operating time	% of Po^{210} generated from Bi impurity	% of Po^{210} generated from Pb
4 FPY	60%	40 %
40 FPY	15%	85%

- Extrapolation of UW results indicates the following:

Inventory / activity:	Bi^{209}		Po^{210}		
@ 1 FPY	390 mol	81 kg	18 kCi*	4 g	0.72 wppb
@ 1 second	1.2×10^{-5} mol	3 mg	$>6\times10^{-4}$ Ci	$>1.3\times10^{-7}$g	$>2\times10^{-8}$ wppb

- Po^{210} activity reaches 25 Ci limit at < 12 h of operation

⇒ Po^{210} purification system should start at any time before 12 hours

- Highly pure LiPb (w/ Bi impurity < 43 wppm) will prolong time before start of Po purification system. If longer time is needed, impact on LiPb unit cost should be assessed. In ASC, 5300 tonnes of LiPb currently costs 50 M$ @ 16 $/kg.

* 25 Ci of Po^{210} = 5.6 mg = 0.001 wppb

Hg Inventory in LiPb

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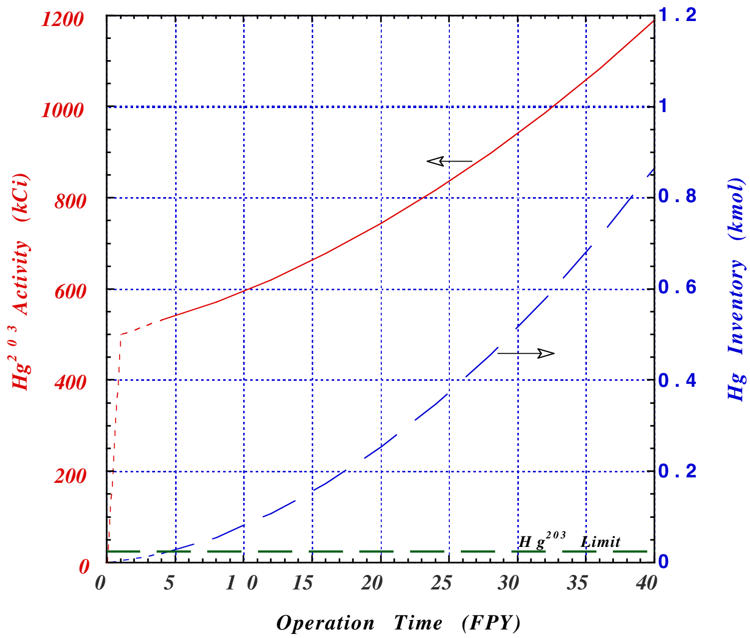

- Reported results are for UW approximations-I
- Hg inventory includes all 9 isotopes
- EU approximation overestimates Hg and Hg^{203} inventories @ EOL by factors of 25 and 32, respectively[#]
- Hg inventory varies non-linearly with operation time
- UW results indicate the following:

Inventory / activity*:	**Hg**		**Hg^{203}**	
@ 40 FPY	0.87 kmol	174 kg	1.2 MCi	87 g[##]
@ 1 FPY	5 mol	1 kg	~500 kCi	37 g
@ 1 second	1.6×10^{-7} mol	3×10^{-5} g	0.09 Ci	6×10^{-6} g

- Hg^{203} activity reaches 25 kCi limit after 3.5 days of operation

⇒ Hg^{203} purification system should start at any time before 3.5 days

[#] High FW flux and hard spectrum accentuate double capture and threshold reactions leading to high Hg production
[*] 1 kmol of Hg = 200 kg. 1 kCi of Hg^{203} = 0.073 g .
[##] Real production rate (w/o decay) is 15×10^{-6} g/s

Conclusions

Magnet radwaste:

- Inconel-625 contains high Nb fraction. Winding pack WDR is high (> 0.1) compared to previous ARIES designs
- Use of alternative SS (with lower Nb content) will reduce W.P. WDR by factor of 10 and allow separate burial of W.P. and coil case for Class A waste

LiPb radiological inventory:

- EU approximation is poor predictor (⇒ **do not use**)
- Bi, Po, and Hg inventories vary non-linearly with operation time
- Po^{210} activity reaches safety limit (25 Ci) at < 12 hours of operation
- Purification of initial LiPb to Bi concentration of ~ 1 wppm slows down Po^{210} generation at early days of operation, offering longer time (> 12 h) before reaching Po^{210} limit (25 Ci)
- Hg^{203} activity reaches safety limit (25 kCi) after 3.5 days of operation
- ARIES-AT design requires on-line removal of Bi or Po^{210} and Hg^{203} radioisotopes shortly after operation
- We recommend UW approximation-I with slightly higher in-vessel residence time (~90 s) for future analysis of ARIES-AT type designs