

# Updated Nuclear Parameters, Radial/Vertical Build, and Activation Analysis for ARIES-AT

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Web address:

[http://fti.neep.wisc.edu/FTI/ARIES/MAR2000/nucl\\_lae.pdf](http://fti.neep.wisc.edu/FTI/ARIES/MAR2000/nucl_lae.pdf)

ARIES Project Meeting  
20-21 March 2000  
UCSD

# Design Parameters<sup>#</sup>

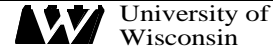


Fusion power	1737 MW
FW location at midplane – OB , IB	6.05 , 3.55 m
at top/bottom – OB , IB	~4.5 , 3.55 m
$\Gamma$ : Peak OB , IB , div.	6.1 , 4 , 2 MW/m <sup>2</sup>
Average OB , IB	5.2 , 2.8 MW/m <sup>2</sup>
FW poloidal length* – OB , IB	~5.5 , 4.5 m
SiC burnup limit	3% (1.5 atom% He)
FS dpa limit	200 dpa
Machine lifetime	40 FPY
HT magnet	
ARIES-RS' vacuum vessel configuration	

<sup>#</sup> 10/14/99 Strawman

\* Between X points

# Updated Nuclear Parameters\*



- **Key features of FW/Blanket:**

- 1/2000 FW/blanket design
- 1.9 cm thick FW: 51% SiC, 49% LiPb
- IB and OB blankets only (no blanket behind divertor):
  - 30 cm thick IB FW/blanket
  - 65 cm thick OB FW/blanket segmented into:
    - 30 cm FW/Blanket -I
    - 35 cm Blanket-II
- 90% enriched LiPb
- Vertical stabilizing shell not included
- Penetrations:
  - 0.6 m<sup>2</sup> for ICRF, 1.1 m<sup>2</sup> for NBI, 1 m<sup>2</sup> for LH on OB, per TK
  - 2 cm radial gaps between 16 blanket modules

- **Reference nuclear parameters:**

Overall <b>TBR</b>	1.16
Overall <b>M<sub>n</sub></b>	1.1
SiC <b>Burnup rate</b>	1% per FPY <sup>#</sup>
FW EOL <b>Fluence</b>	18.5 MWy/m <sup>2</sup>
FW <b>Lifetime</b>	3 FPY

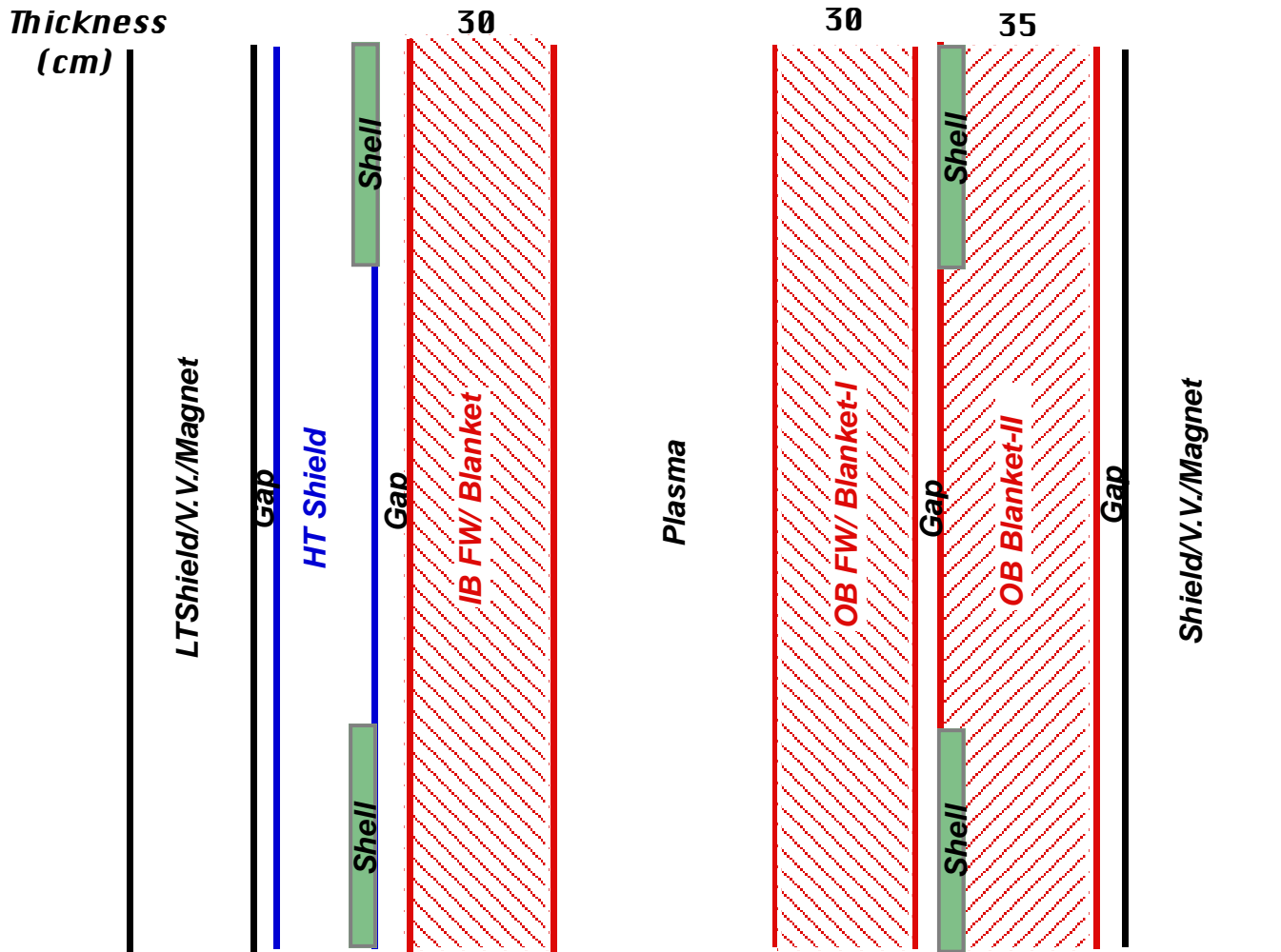
- **Comments:**

- More **SiC** content in FW degrades breeding
- **Thicker blanket** increases breeding slightly (~ 3%)
- Higher **enrichment** (> 90%) is expensive and has insignificant impact on breeding
- More **penetrations/gaps** reduce breeding
- **Vertical stabilizing shells** degrade breeding
- **Blanket thickness** and/or enrichment **will be adjusted** to meet breeding requirement of 1.1 after including stabilizing shell

\* Using FENDL-2 cross section data library

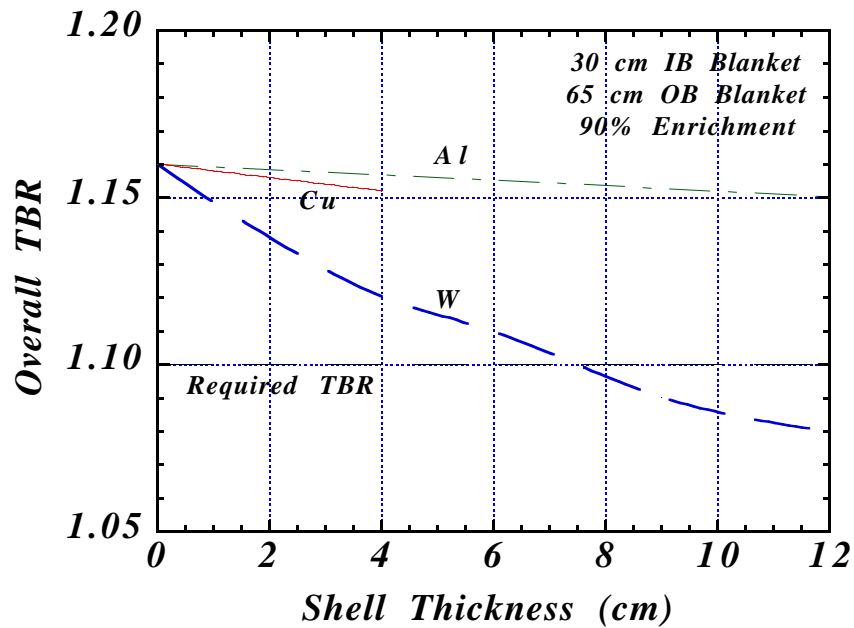
<sup>#</sup> 0.7% Si , 0.3% C

# Impact of Stabilizing Shell on TBR



- **Two continuously toroidal shells** placed at top/bottom of IB and OB sides
- **IB shells** embedded in HT shield
- **OB shells** embedded in B-II and cover 50% of poloidal length
- Shells have insignificant impact on breeding of FW/B-I
- Shells degrade **breeding** of upper/lower parts of B-II behind shells
- Based on 3-D calculations, B-II parts behind shells contribute ~10% to TBR

# Impact of Stabilizing Shell on TBR (cont.)



Al and Cu shells have < 1% impact on breeding

W shells could reduce breeding by 5-8%, depending on thickness

# Nuclear Heating Deposited in OB Stabilizing Shells

Operating Temperature	<u>400 °C</u>	<u>1000 °C</u>
W Shells	6 cm 36 MW*	12 cm 57 MW
Al Shells	4 cm 5 MW	11 cm 13 MW
Cu Shells	2 cm 7 MW	4 cm 16 MW

W shells contain 4-7 X nuclear heating deposited in Al or Cu shells

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\* Heating in both upper and lower shells

# Observations on Stabilizing Shell Design

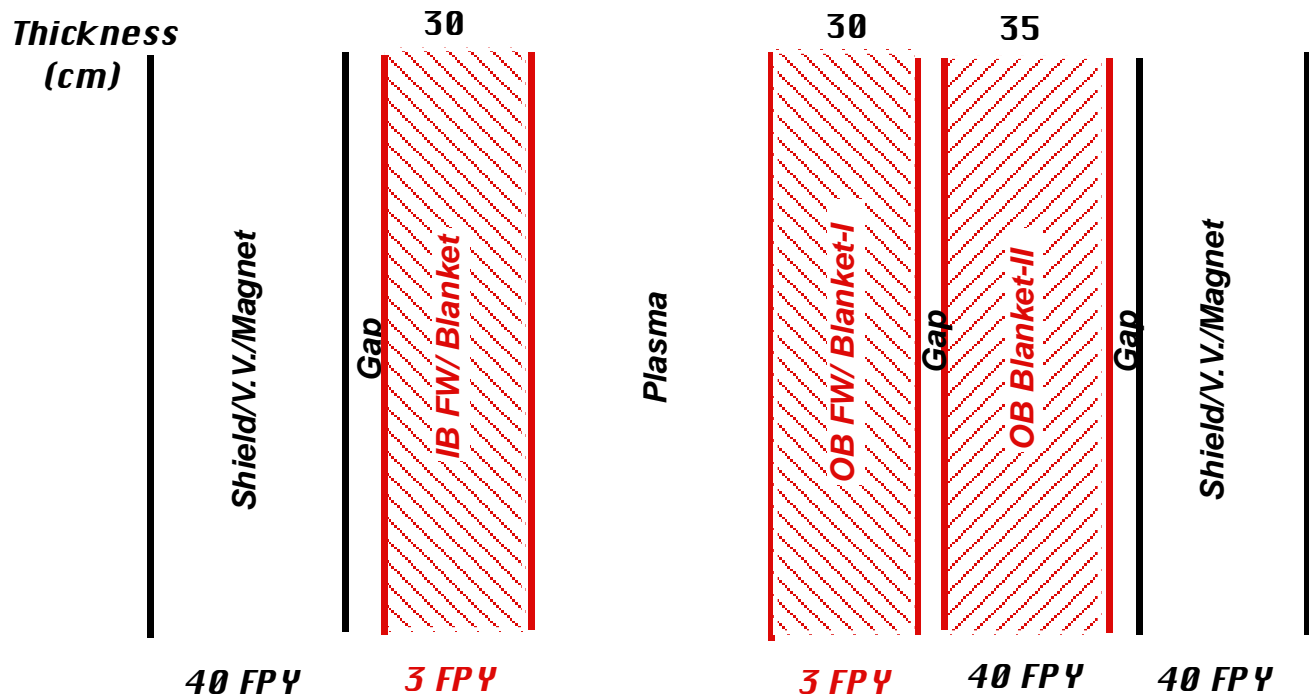
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- Passive cooling of all shells is not feasible. **Shells should be actively cooled, preferably with He**, per Rene and Malang,
- Recommended **operating temperature** for Al and Cu shells is **< 700 °C**.
- **W shell** should operate above 800 °C to avoid embrittlement. W shells will be ~10 cm thick and heavy
- Al shell (~5 cm thick) need W or TZM cladding (compatible below 700 °C)
- **3-4 cm thick Cu shell is recommended**. It is thin, light, and has negligible impact on breeding
- **Effect of disruption forces** on structural integrity of Cu should be assessed (may need to support Cu by steel cables or provide strong casing)
- Will **transmutations** increase Cu resistivity significantly? TBD
- Impact of Cu shells on decay heat, LOCA/LOFA temperature, and WDR will be assessed

# Components' Lifetimes

- Service lifetimes are based on:
  - 3% burnup limit for SiC structure of FW, blanket, HT shield
  - 200 dpa limit for FS structure of LT shield and V.V.



- Lifetime of stabilizing shell is unknown. TBD



# S/C Magnet Radiation Limits

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- ARIES-AT HT S/C magnet radiation limits:

$10^{19}$  n/cm<sup>2</sup>

Peak fast n **fluence**<sup>#</sup> to HT S/C

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Radiation resistant thermal insulator

- ARIES-RS LT S/C magnet radiation limits:

$10^{19}$  n/cm<sup>2</sup>

Peak fast n **fluence** to Nb<sub>3</sub>Sn S/C

2 mW/cm<sup>3</sup>

Peak nuclear **heating**

$6 \times 10^{-3}$  dpa

Peak atomic **displacement** to Cu stabilizer<sup>\*</sup>

$10^{11}$  rad

Peak **dose** to GFF polyimide

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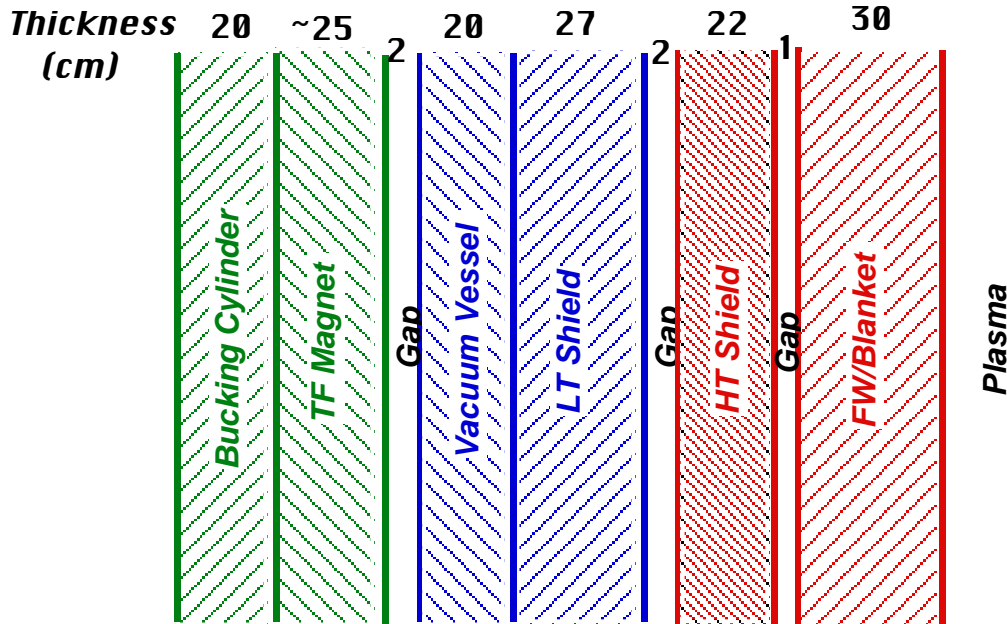
Radiation resistant thermal insulator

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<sup>#</sup>  $E_n > 0.1$  MeV

<sup>\*</sup> 85% of dpa can be annealed out by warming up magnets during maintenance

# Inboard Radial Build



## Component

## Composition<sup>#</sup>

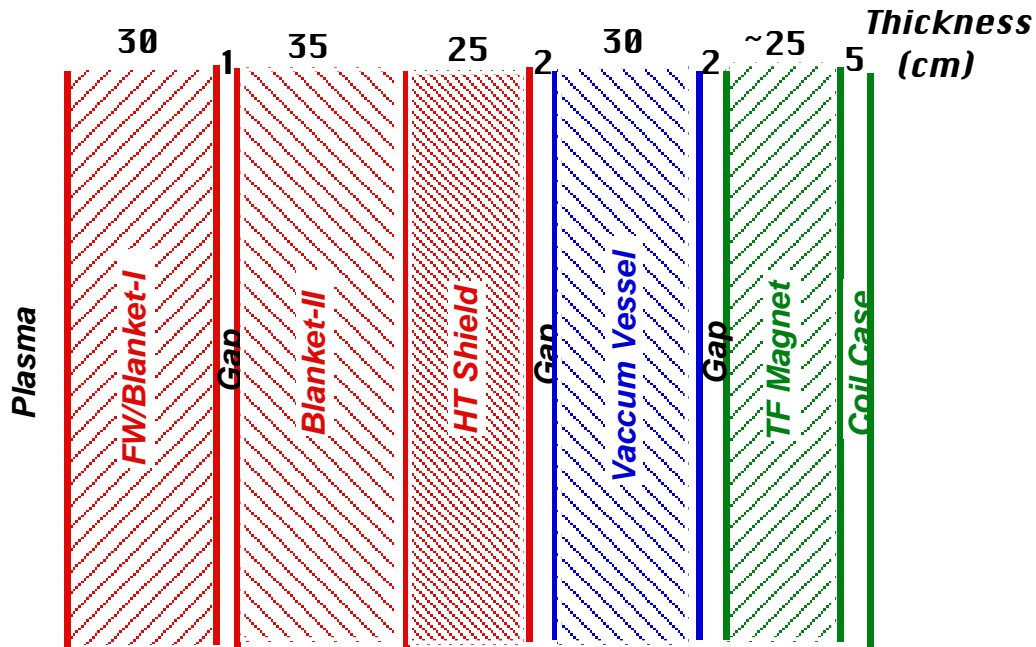
FW (1.9 cm)	51% SiC , 49% LiPb
Blanket (28.1 cm)	12% SiC , 88% LiPb
HT Shield	15% SiC, 10% LiPb , 75% B-FS
LT Shield	15% FS , 10% H <sub>2</sub> O , 75% WC
Vacuum Vessel	35% FS , 65% H <sub>2</sub> O
HT Magnet	87% SS, 10% LN, 2.5% Y <sub>1</sub> Ba <sub>2</sub> Cu <sub>3</sub> O <sub>5</sub> , 0.5% Ag
Bucking cylinder	95% SS, 5% LN

- LT shield and V.V. are combined in a single component. Reweldability limit (1 He appm) for FS is not met at front of LT shield  
 ⇒ Locate cut/weld areas away from high radiation zones
- LT shield and TF magnet **radiation limits are all met<sup>\*</sup>** for peak  $\Gamma = 4$  MW/m<sup>2</sup> (200 dpa at LT shield and 10<sup>19</sup> n/cm<sup>2</sup> at magnet @ EOL)

<sup>#</sup> SiC and WC are 95% dense

<sup>\*</sup> Safety factor of 3 considered in all shielding calculations

# Outboard Radial Build



## Component

## Composition<sup>#</sup>

### FW/Blanket-I:

FW (1.9 cm) 51% SiC , 49% LiPb

B-I (28.1 cm) 12% SiC , 88% LiPb

Blanket-II 14% SiC , 86% LiPb

HT Shield 15% SiC , 10% LiPb , 75% B-FS

Vacuum Vessel 25% FS , 75% H<sub>2</sub>O

HT Magnet 87% SS, 10% LN, 2.5% Y<sub>1</sub>Ba<sub>2</sub>Cu<sub>3</sub>O<sub>5</sub>, 0.5% Ag

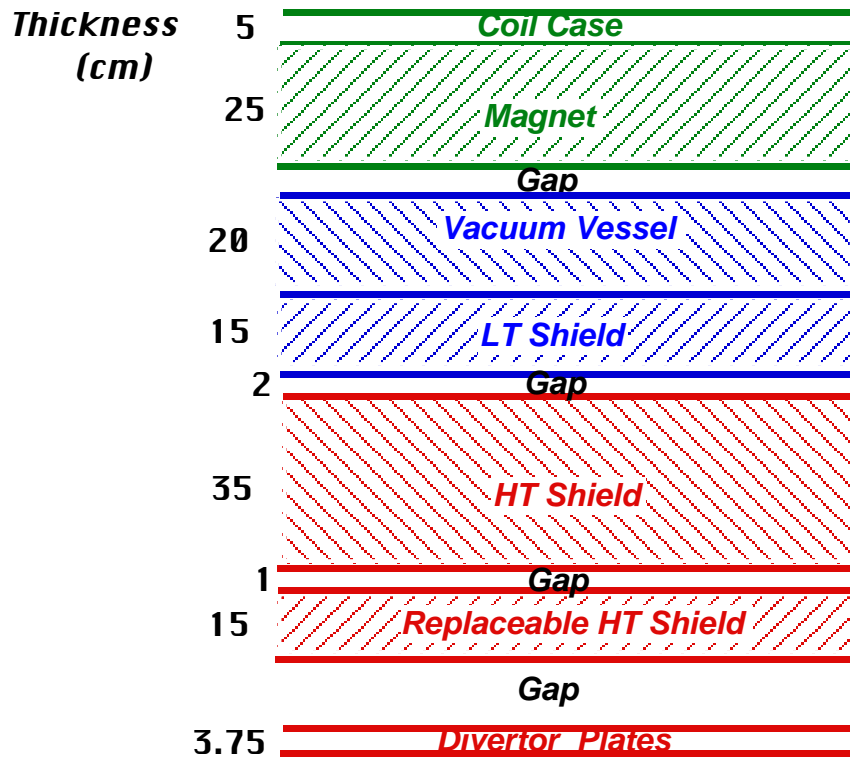
Coil Case 95% SS, 5% LN

- Blanket-II and HT shield could be combined in a single lifetime component
- FS, V.V., and TF magnet radiation limits are all met\* for peak  $\Gamma = 6 \text{ MW/m}^2$  (200 dpa for FS, 1 He appm at V.V., and  $10^{19} \text{ n/cm}^2$  at magnet @ EOL)

<sup>#</sup> SiC and WC are 95% dense

\* Safety factor of 3 considered in all shielding calculations

# Vertical Build



## Component

## Composition<sup>#</sup>

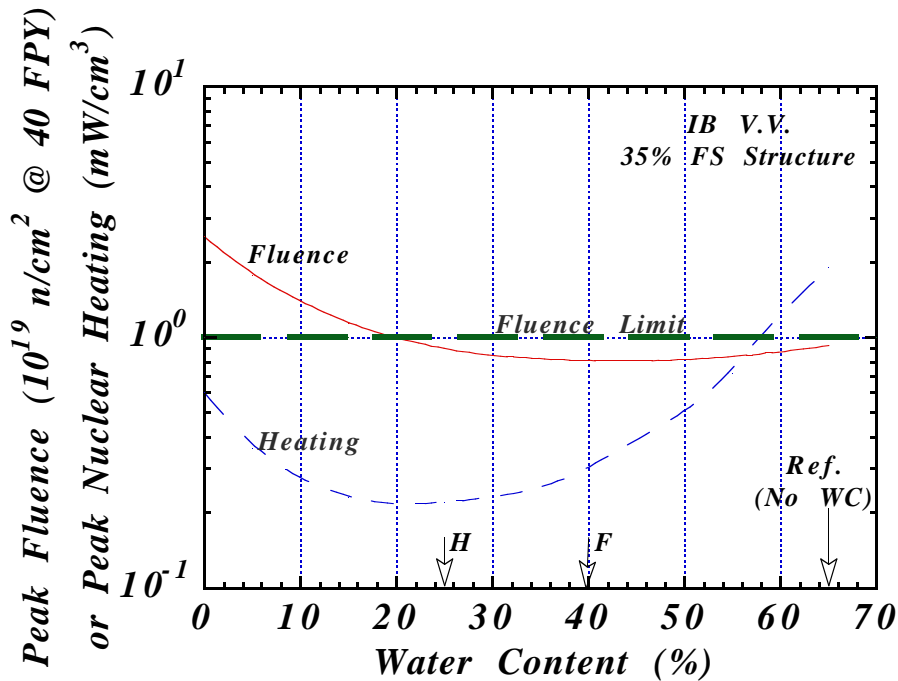
Divertor Plates	19% W , 5% SiC , 76% LiPb
Replaceable HT Shield	15% SiC , 10% LiPb, 75% FS
HT Shield	15% SiC , 10% LiPb , 75% B-FS
LT Shield	15% FS , 10% H <sub>2</sub> O , 75% B-FS
Vacuum Vessel	35% FS , 65% H <sub>2</sub> O
HT Magnet	87% SS, 10% LN, 2.5% Y <sub>1</sub> Ba <sub>2</sub> Cu <sub>3</sub> O <sub>5</sub> , 0.5% Ag

- LT shield and V.V. are combined in a single component. Reweldability limit (1 He appm) for FS is not met at front of LT shield
  - ⇒ Locate cut/weld areas away from high radiation zones
- LT shield and TF magnet **radiation limits are all met\*** for peak  $\Gamma = 2 \text{ MW/m}^2$  (200 dpa at LT shield and  $10^{19} \text{ n/cm}^2$  at magnet @ EOL)
- Shielding behind inner divertor plates will be assessed

<sup>#</sup> SiC and WC are 95% dense

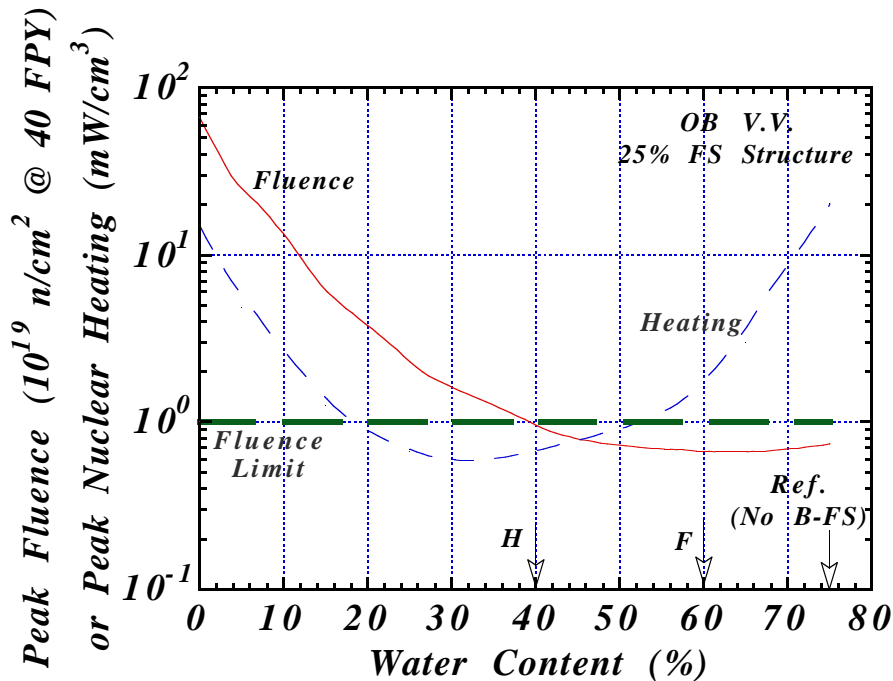
\* Safety factor of 3 considered in all shielding calculations

# Optimum Composition of IB V.V.



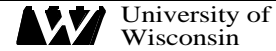
- V.V. composition **optimized by trading WC filler for water**
- **Eliminating WC filler** simplifies V.V. design but **results in high magnet heating, high thermal neutron flux, and high activity at V.V.**
- Optimum VV composition for fluence:  
35% FS structure , 40%  $\text{H}_2\text{O}$ , 25% WC filler
- Optimum VV composition for heating:  
35% FS structure , 25%  $\text{H}_2\text{O}$ , 40% WC filler

# Optimum Composition of OB V.V.



- V.V. composition **optimized by trading B-FS filler for water**
- **Eliminating B-FS filler simplifies V.V. design but results in high magnet heating, high thermal neutron flux, and high activity at V.V.**
- Optimum VV composition for fluence:  
25% FS structure , **60% H<sub>2</sub>O**, 15% B-FS filler
- Near optimum VV composition for heating that meets fluence limit:  
25% FS structure , **40% H<sub>2</sub>O**, 35% B-FS filler

# Comparison Between ARIES-AT and ARIES-RS Radial/Vertical Builds



ARIES-	<u>Inboard</u>		<u>Outboard</u>		<u>Divertor</u>	
	<u>AT</u>	<u>RS</u>	<u>AT</u>	<u>RS</u>	<u>AT</u>	<u>RS</u>
<b>Thickness (cm):</b>						
DP	---	---	---	---	4	5
FW/Blanket-I	30	20	30	20	---	---
Blanket-II	---	---	35	30	---	---
Replaceable shld	---	20	---	7	15	20
HT shield	22	26	25	28	35	35
LT shield	27	28	---	40	15	45
Vacuum vessel	<u>20</u>	<u>20</u>	<u>30</u>	<u>30</u>	<u>20</u>	<u>20</u>
<b>Subtotal</b>	<b>99</b>	<b>114</b>	<b>120</b>	<b>155</b>	<b>89</b>	<b>125</b>
<b>Reduction in thickness</b>	<b>15</b>	<b>0</b>	<b>35</b>	<b>0</b>	<b>36</b>	<b>0</b>
Magnet & cryostat	<u>25</u>	<u>55</u>	<u>25</u>	<u>55</u>	<u>25</u>	<u>55</u>
<b>Total</b>	<b>124</b>	<b>169</b>	<b>145</b>	<b>210</b>	<b>114</b>	<b>180</b>
<b>Net reduction in thickness</b>	<b>45</b>	<b>0</b>	<b>65</b>	<b>0</b>	<b>66</b>	<b>0</b>

- Thinner ARIES-AT radial/vertical builds are due to:
  - Superior shielding
    - better **LiPb** shielding performance compared to Li
    - use of **water** in LT shield and V.V. instead of He
  - thin HT **magnet**

# Activation Analysis

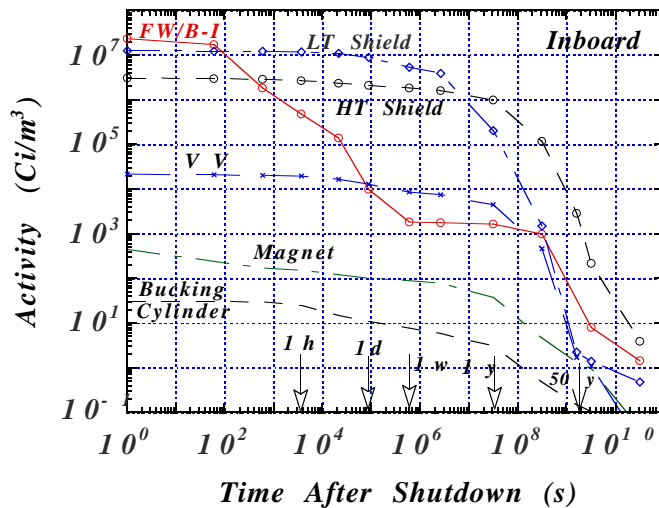
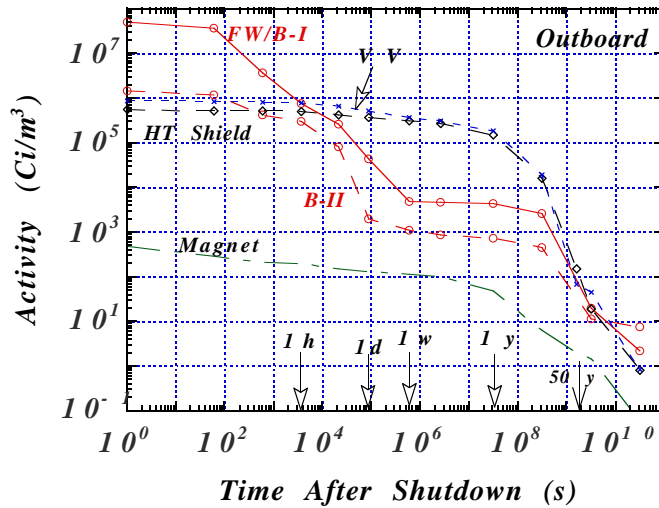
- Codes and model:
  - Activation: **ALARA** code; **FENDL-2** activation library
  - Flux: 1-D **DANTSYS** code; **FENDL-2** Xn data
  - 175 n and 42 g group structure
  - **3-D neutron flux** used to re-normalize 1-D flux for all components
  - Average OB and IB  $\Gamma$  are 5.2 and 2.8 MW/m<sup>2</sup>, respectively
  - **Operation time**: 3 FPY for FW/B-I, 40 FPY for all other components
  - **Continuous operation**, unless indicated (this overestimates radioactivity of intermediate T<sub>1/2</sub> nuclides by inverse of availability [10-25%])
- Activity, decay heat, WDR, and clearance index **depend strongly on** materials, flux level, neutron spectrum, operation time, and cooling period
- Results reported here are for:
  - 100% dense **compacted waste** (coolants and void excluded)
  - **IB and OB sides** as defined by radial builds
  - **SiC, WC, and LiPb** compositions with **impurities**.
  - **FS with impurity control (IC)** to qualify as Class C waste

Elements	Original FS wppm	FS w/ IC wppm
Nb	4	1
Mo	70	20

  - **Impurities for magnet constituents are not available yet**. Will be included in future calculations
- Results include:
  - **Activity**
  - **Decay heat**
  - **Fetter-L and Fetter-H waste disposal ratings** for Class C waste
  - **NRC (10CFR61) waste disposal ratings** for **Class C and A** waste

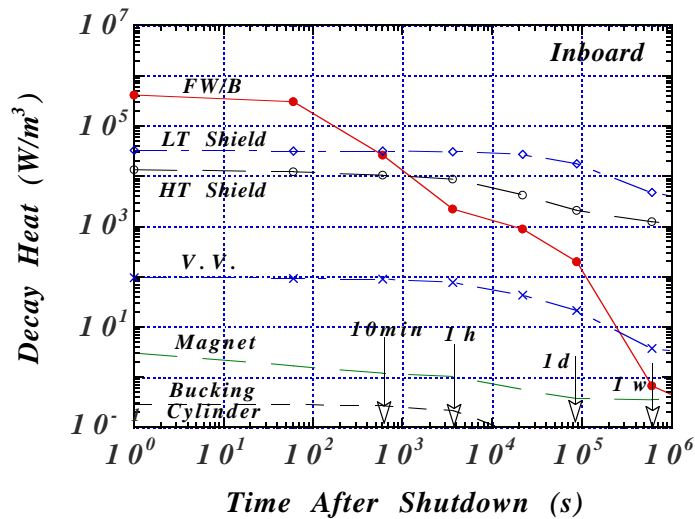
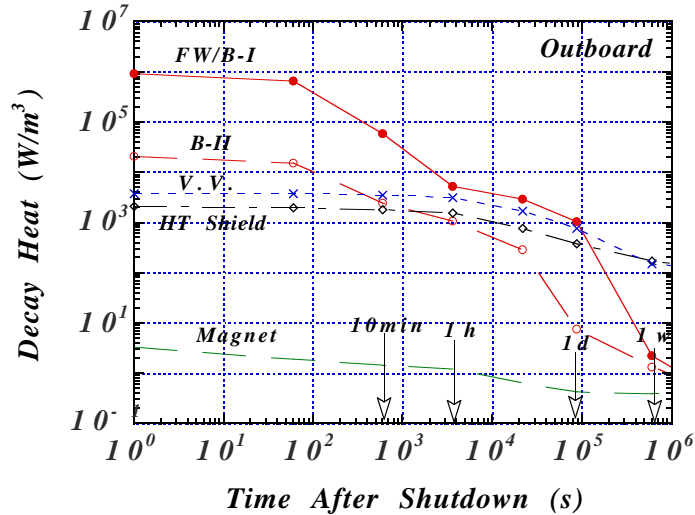


# Activity



- Unlike metals, **SiC activity drops by several orders of magnitude shortly after shutdown**
- Highly irradiated SiC components generate lower intermediate activity (1d-5y) than well protected FS and WC components

# Decay Heat (Coolants Excluded)



- Unlike metals, SiC **decay heat drops fast after one minute**, meaning slight increase in temperature of SiC components during LOCA/LOFA
- Detailed decay heat for individual constituents of all components (including coolants) provided for LOCA/LOFA analysis

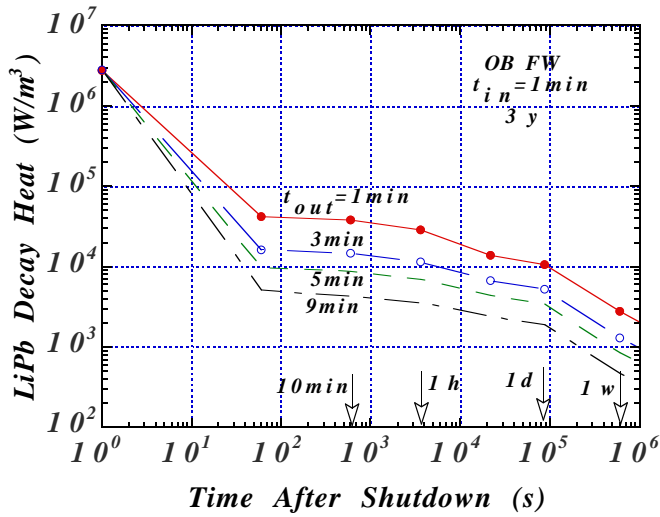
# LiPb Decay Heat for LOFA Analysis

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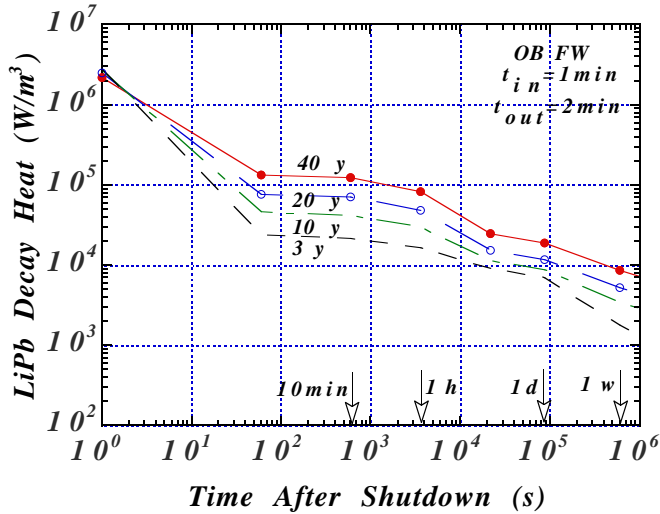
- **Assumptions:**
  - Same LiPb is used for 40 FPY (Li can be refurbished if needed)
  - LiPb spends 1 min in both divertor and FW/B-I and 3.4 min in both OB B-II and HT shield, per Rene
  - LiPb spends  $t_{out} \sim 2$  min in outer loop for heat recovery, T extraction, and Po/Bi/Hg purification
  - LiPb returns to same location inside torus (conservative)
  - 100% system availability (conservative)
  
- **Pulsed analysis** performed to determine:
  - Sensitivity of LiPb decay heat to  $t_{out}$
  - Variation of LiPb decay heat with operation time (3,10,20,40 y)
  
- Among all LiPb cooled components, highest LiPb decay heat is generated in LiPb of OB FW considered for sensitivity analysis

# LiPb Decay Heat for LOFA Analysis (cont.)

*LiPb Decay Heat Decreases with  $t_{out}$*



*LiPb Decay Heat Increases with Operation Time*



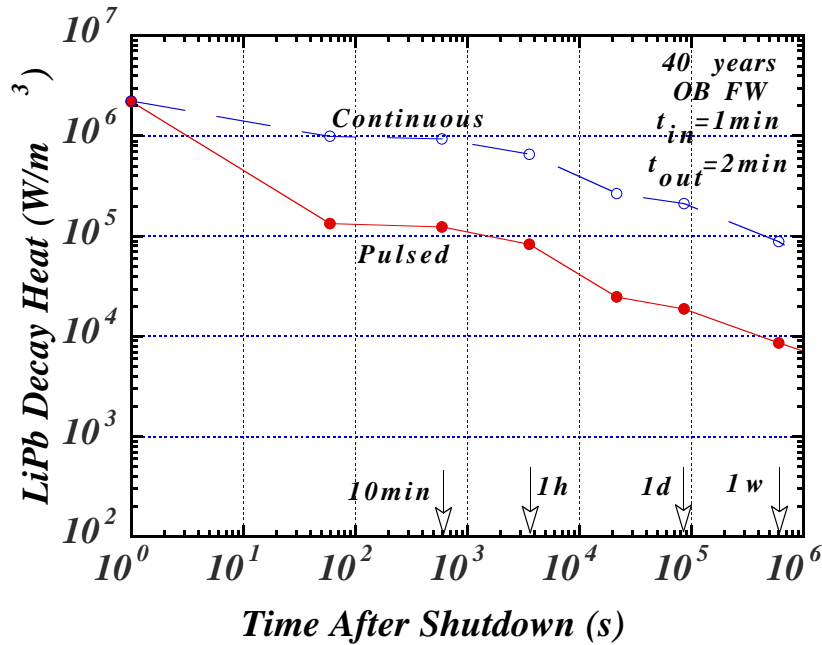
- Selected parameters for LOFA analysis:

$t_{in} = 1 \text{ min}$  for B-I and 3.4 min for B-II

$t_{out} = 2 \text{ min}$

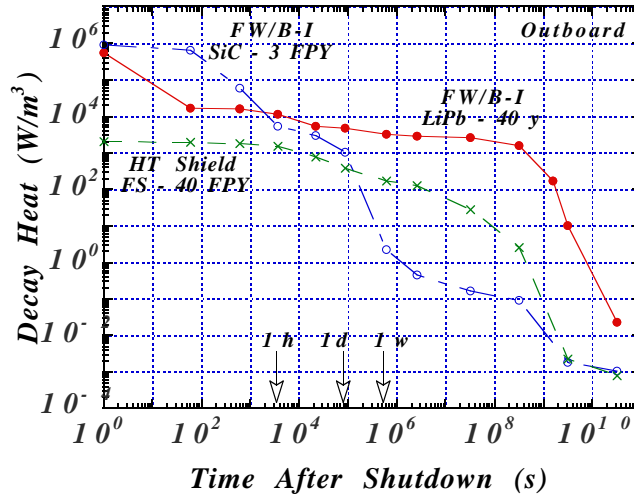
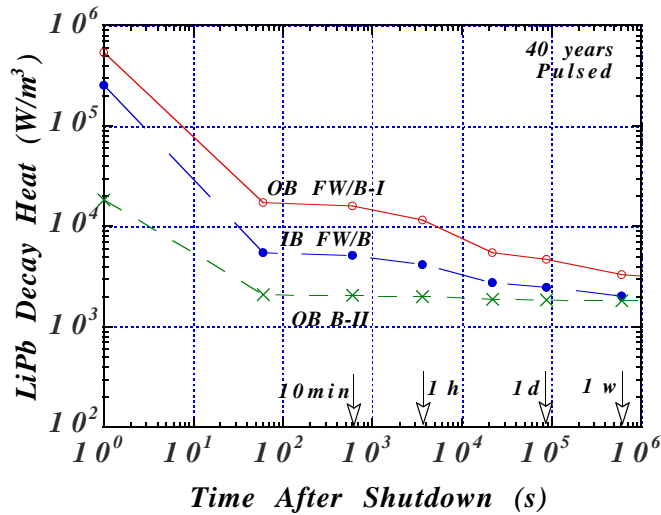
Irradiation time = 40 y ( $7 \times 10^6$  irradiation periods for B-I and  $4 \times 10^6$  for B-II)

# LiPb Decay Heat for LOFA Analysis (cont.)



Continuous irradiation overestimates decay heat of flowing LiPb by factor of 10

# LiPb Decay Heat for LOFA Analysis (cont.)



- LiPb of OB FW/B-I contains highest decay heat compared to other blankets
- 1 h after shutdown, LiPb generates higher decay heat than SiC  
 ⇒ LOFA is more critical than LOCA
- Less conservative assumptions reduce decay heat by 10-30%

# Waste Disposal Rating

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- WDR reported for **compacted waste** (void excluded)
- WDR < 1 means component qualifies as low level waste (LLW)
- WDR remains constant for 100's of years after shutdown, unless indicated
- **All components should meet BOTH Fetter's and NRC WD limits**
- **Fetter developed limits for 101 isotopes. 19 isotopes have range of limits rather than single value. Those (beta emitters) are: C<sup>14</sup>, Si<sup>32</sup>, Cl<sup>36</sup>, Ca<sup>41</sup>, Ni<sup>63</sup>, Se<sup>79</sup>, Sr<sup>90</sup>, Tc<sup>97</sup>, Tc<sup>98</sup>, Tc<sup>99</sup>, Pd<sup>107</sup>, I<sup>129</sup>, Sm<sup>151</sup>, Gd<sup>148</sup>, Gd<sup>150</sup>, Dy<sup>154</sup>, Pb<sup>210</sup>, Ra<sup>226</sup>, Ac<sup>227</sup>**
- **Fetter-L** and **Fetter-H** WDRs are evaluated for low and high limits, respectively, for Class C LLW. Fetter-L limits were not considered in previous ARIES designs.
- **NRC** has **Class C** and **Class A** WD limits for 9-10 isotopes. Class A has low limit for tritium

# Fetter's Waste Disposal Rating

<b>Class C Waste:</b>	<b>Fetter-H</b>	<b>Fetter-L</b>
<b>Outboard Components:</b>		
<b>FW/B-I</b>	0.092	0.095
<b>B-II</b>	0.004	0.02
<b>HT Shield</b>	0.2	0.3
<b>V.V.</b>	0.05	0.055
<b>Magnet</b>	0.016	0.023
<b>Inboard Components:</b>		
<b>FW/B</b>	0.019	0.021
<b>HT Shield</b>	0.7	<b>1.0*</b>
<b>LT Shield</b>	0.030	0.046
<b>V.V.</b>	0.0014	0.0017
<b>Magnet</b>	0.015	0.022
<b>Bucking Cylinder</b>	0.003	0.008

- $Al^{26}$  is dominant nuclide for Fetter's WDR of SiC components  
 $Si^{28} (n, np) Al^{27} (n, 2n) Al^{26}$

**All components qualify as Class C LLW @ EOL**

\* Dictated impurity control for FS. Value was 2 without impurity control

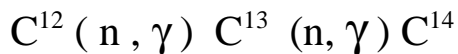


# NRC Waste Disposal Rating



	NRC Class A	NRC Class C
<b>Outboard Components:</b>		
<b>FW/B-I</b>	12*	0.03
<b>B-II</b>	3*	0.1
<b>HT Shield</b>	8	0.2
<b>V.V.</b>	3*	0.03
<b>Magnet</b>	0.1	0.005
<b>Inboard Components:</b>		
<b>FW/B</b>	5*	0.02
<b>HT Shield</b>	128	0.6
<b>LT Shield</b>	0.3	0.02
<b>V.V.</b>	0.08	0.001
<b>Magnet</b>	0.1	0.005
<b>Bucking Cylinder</b>	0.04	0.003

- For SiC components, **T** and **C<sup>14</sup>** are dominant nuclides for **NRC-A WDR** and **C<sup>14</sup>** is dominant nuclide for **NRC-C WDR**



- Some components qualify as Class A LLW

**All components qualify as Class C LLW @ EOL**

\* Could qualify as Class A LLW after 100 y of storage period

# LiPb Waste Disposal Rating

## Class C

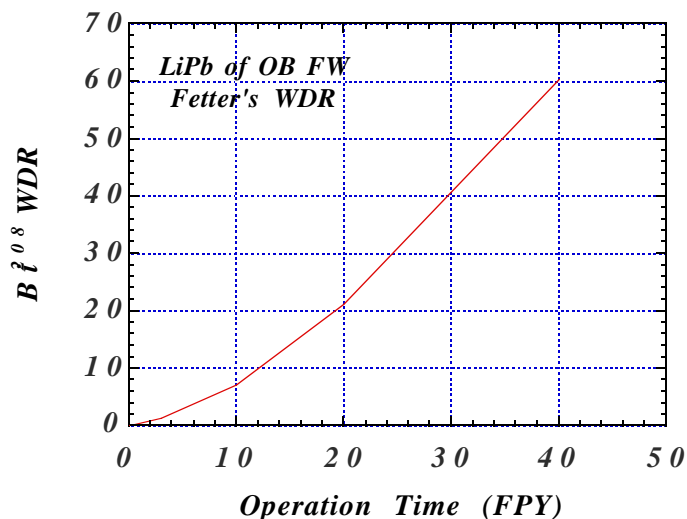
**Fetter-H,L**

5.5

**NRC**

0.0002

- LiPb does not qualify as Class C waste unless Bi is controlled during operation
- $\text{Bi}^{208}$  is dominant nuclide for **Fetter's WDR** (95%)
- Pb and Bi impurity (43 wppm) generate 90% and 10% of  $\text{Bi}^{208}$ , respectively, via the following reactions:  
 $\text{Pb}^{208} (n,\gamma) \text{Pb}^{209} (\beta^- \text{ decay}) \text{Bi}^{209} (n,2n) \text{Bi}^{208}$   
 $\text{Bi}^{209} (n,2n) \text{Bi}^{208}$
- Also, Bi generates  $\text{Po}^{210}$  which raises safety concerns:  
 $\text{Bi}^{209} (n,2n) \text{Bi}^{208} (n,\gamma) \text{Bi}^{209} (n,\gamma) \text{Bi}^{210} (\beta^- \text{ decay}) \text{Po}^{210}$
- Bi production continues to rise during operation



- **Purification system** should be designed to keep average  $\text{Bi}^{208}$  and  $\text{Po}^{210}$  inventories below permissible level

# Conclusions

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- **Neutronics:**
  - Blanket meets **breeding** requirement ( $TBR \geq 1.1$ ) with adequate margin
  - 3% burnup limit (1.5 atom% He) results in **lifetime of 3 FPY** for SiC components. If 2 atom% He is acceptable, burnup limit could be raised to 4%
- **Shielding:**
  - **Radial builds** are well optimized for the design constraints
  - May need to incorporate **WC/B-FS in V.V.** to reduce V.V. activation
- **Activation:**
  - Unlike metals, **SiC activity and decay heat drop rapidly by 3 orders of magnitude in one day**
  - LOFA is more critical than LOCA
  - **All components qualify easily as Class C LLW**
  - LiPb does not qualify as Class C waste unless **purification system** removes  $Bi^{208}$  during operation
  - **Nb and Mo impurity control** is needed for FS
  - Less conservative assumptions will result in lower activation
- **Stabilizing shells** will be included in future analysis