

ARIES-AT Nuclear Parameters, Radial Build, and Activation Analysis

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With inputs from:

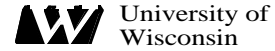
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Web address:

<http://fti.neep.wisc.edu/FTI/ARIES/DEC99/lae.pdf>

ARIES Project Meeting
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UCSD

Design Parameters



| | |
|--|-----------------------------|
| 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 |
| Γ : Peak OB , IB | 6.1 , 4 MW/m ² |
| Average OB , IB | 5.2 , 2.8 MW/m ² |
| FW poloidal length * – OB , IB | ~5.5 , 4.5 m |
| SiC burnup limit | 3% |
| FS dpa limit | 200 dpa |
| Machine lifetime | 40 FPY |
| HT magnet/cryostat composition from L. Bromberg | |
| ARIES-RS' vacuum vessel configuration (to be modified based on Clearance considerations) | |

* Between X points

Nuclear Parameters

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

- Self-cooled LiPb/SiC FW/blanket
- Constant-flow, integral FW design (3.3 cm thick; 40% SiC, 60% LiPb)
- IB and OB blankets only (no blanket behind divertor)
- 90% enriched LiPb
- 30 cm thick IB FW/blanket
- 65 cm thick OB FW/blanket segmented into:
 - 30 cm FW/Blanket -I
 - 35 cm Blanket-II
- 6 cm thick vertical stabilizing shell (90% W, 10% LiPb) at top/bottom:
 - Between blanket segments on OB
 - Between blanket and shield on IB
- Penetrations:
 - 1.5 m² on OB for CD and plasma control, per TK
 - 2 cm radial gaps between 16 blanket modules

- **Reference nuclear parameters:**

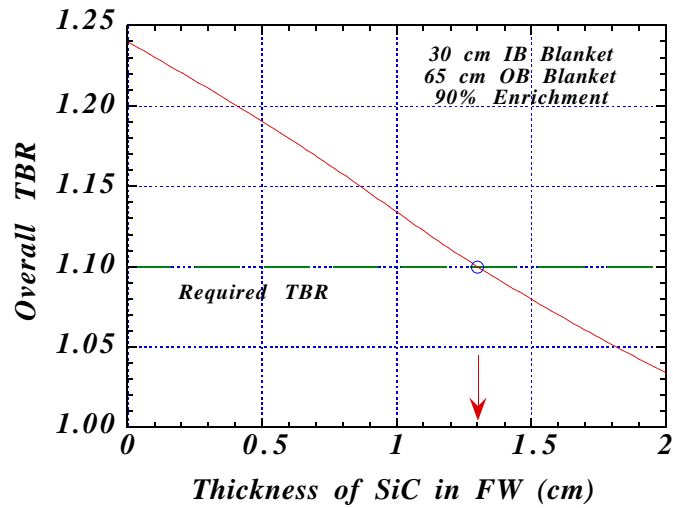
| | |
|------------------------|-------------------------|
| Overall TBR | 1.1 |
| Overall Mn | 1.1 |
| SiC Burnup rate | 1% per FPY* |
| FW EOL Fluence | 18.5 MWy/m ² |
| FW Lifetime | 3 FPY |

- **Comments:**

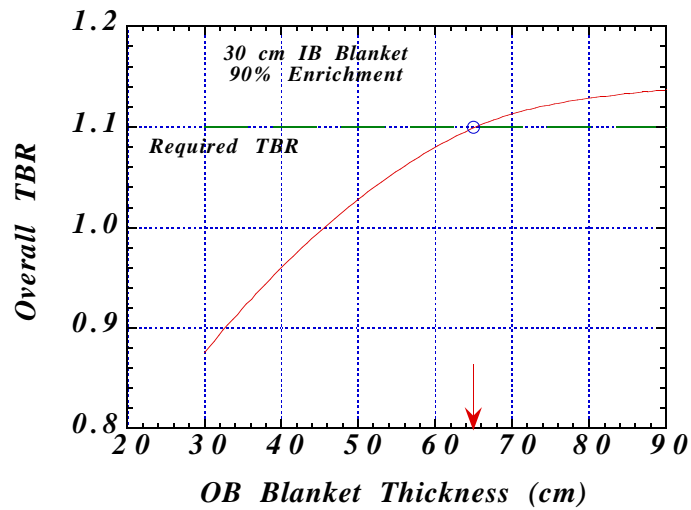
- Breeding is marginal
- More SiC content in FW will degrade breeding
- Thicker blanket will increase breeding
- Higher enrichment (> 90%) is expensive and has insignificant impact on breeding

* 0.7% Si, 0.3% C

TBR vs. FW SiC Content and Blanket Thickness

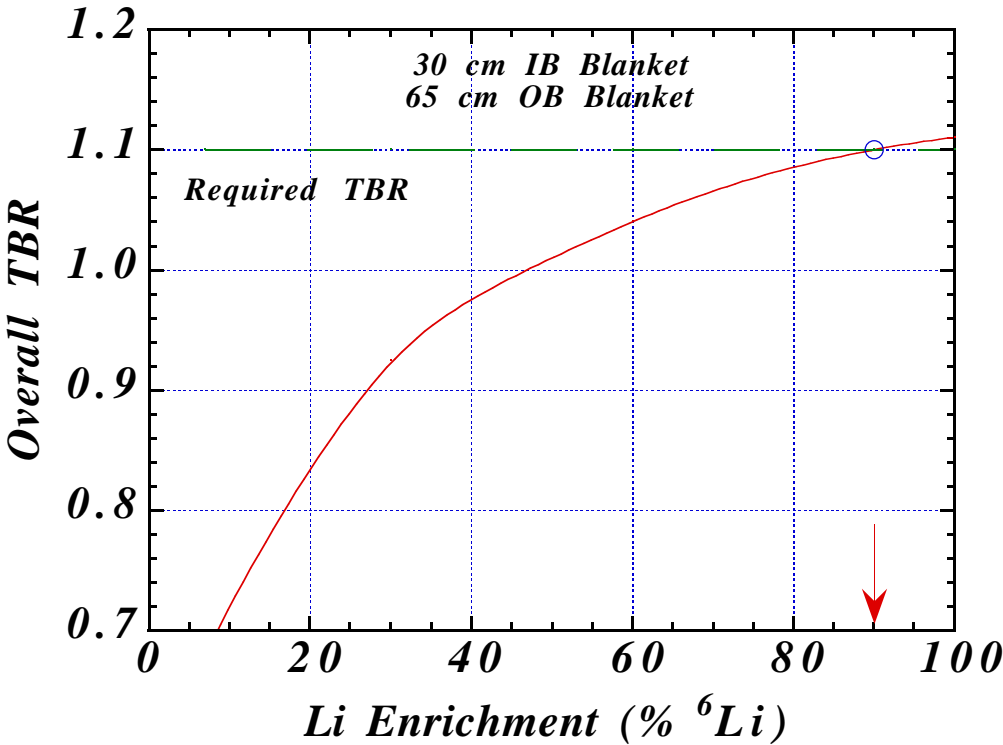


SiC content in FW has significant impact on breeding



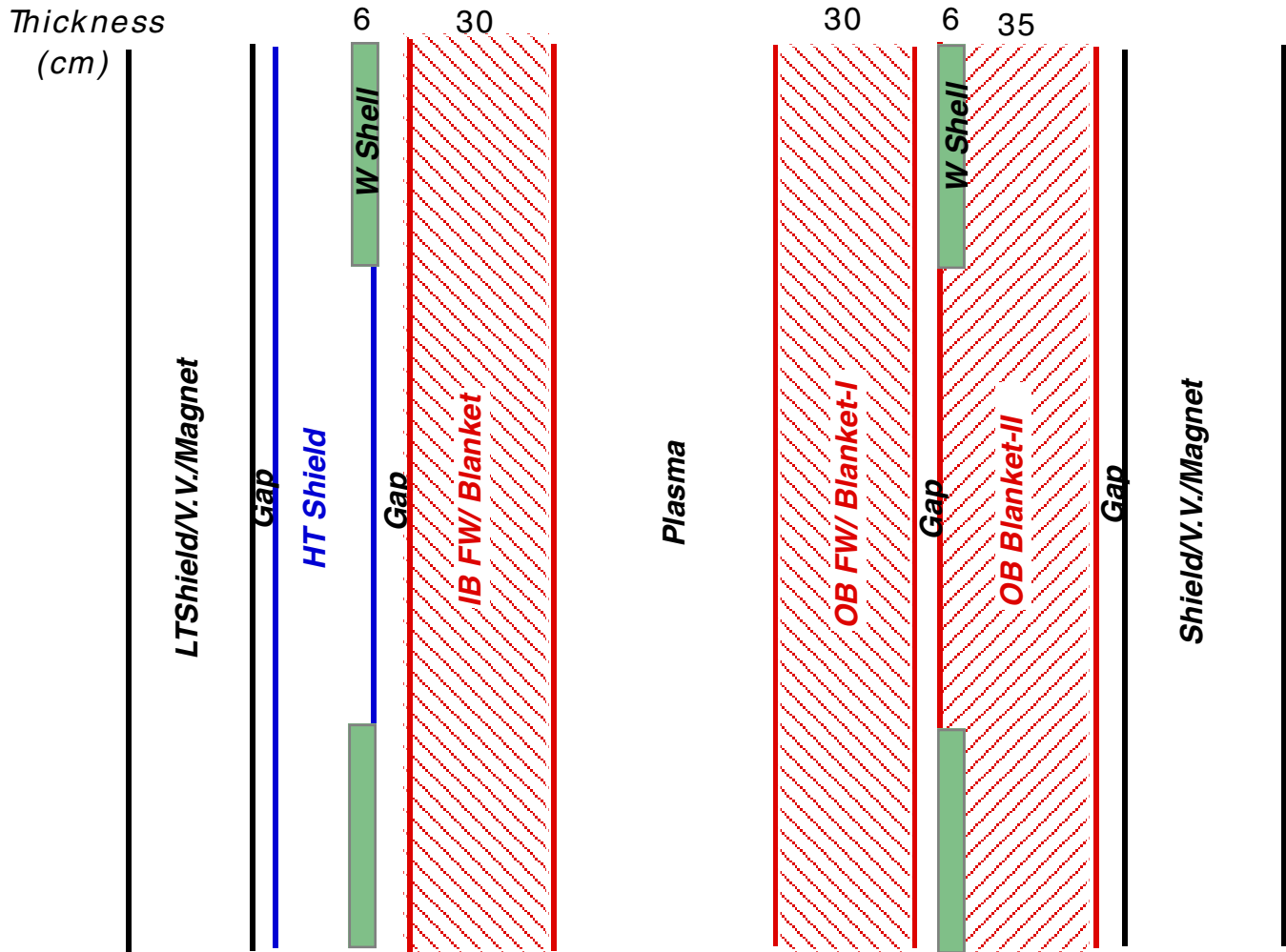
Thicker OB blanket increases breeding slightly (~3%)

TBR vs. Li Enrichment



Blanket will not breed if enrichment drops below 90%

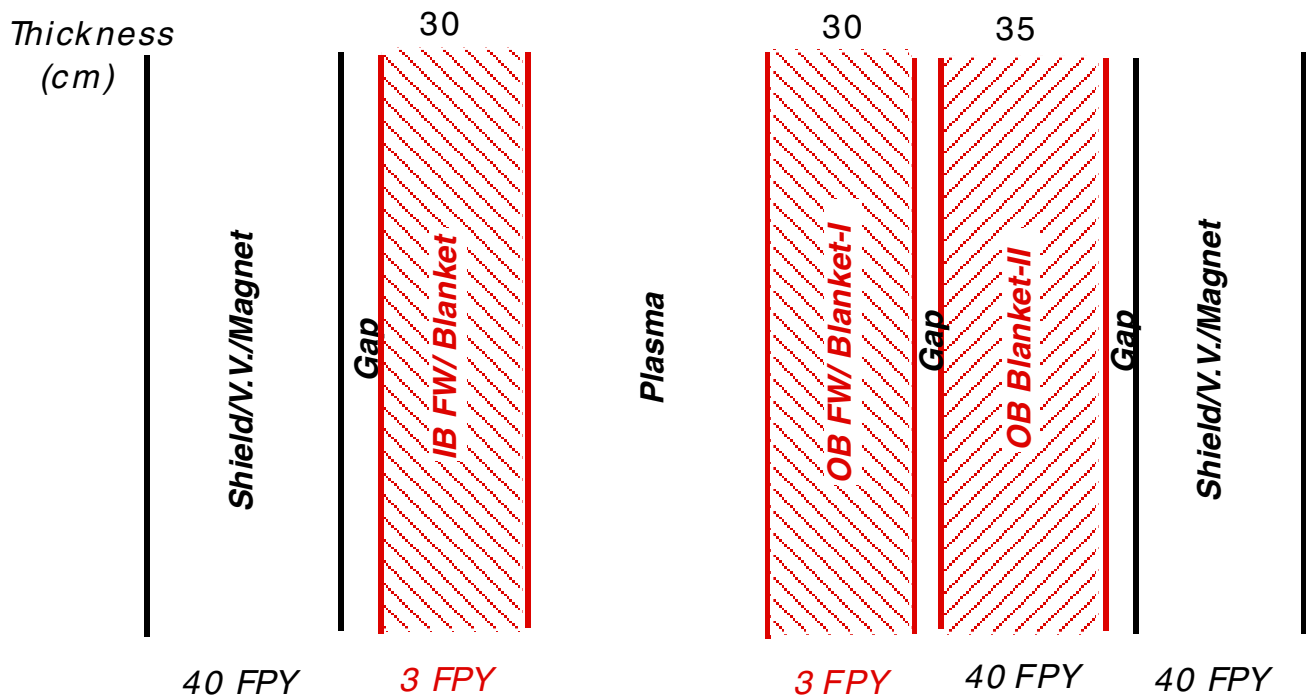
Impact of W Shell on Breeding



- Two separate shells placed at top/bottom of IB and OB sides
- OB shells cover 50% of poloidal length
- Shell has no significant impact on breeding of FW/B-I
- 6 cm thick shell **reduces breeding behind it by 50%**
- Based on 3-D calculations, regions behind shells contribute 10% to TBR
 - ⇒ Shell reduces breeding by ~ 0.05 , resulting in overall TBR of 1.1

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.



- **Back wall of B-I is lifetime component.** BW could be reused to reduce radwaste stream
- Ratio of replaceable component volume to total radwaste volume is 20-30% and drops to 10-20% if B-I back wall is reused

Nuclear Heat Load to In-vessel Components*

($P_n = 1390$ MW)

| Nuclear Heating (MW) | <u>Inboard</u> | <u>Outboard</u> | <u>Divertor</u> | <u>Total</u> | |
|----------------------|------------------------|---------------------|---------------------|--------------|-------|
| FW or DP | 90 | 212 | 36** | 338 | (22%) |
| Blanket | 230 | 708 [#] | --- | 938 | (61%) |
| HT Shield | <u>60^{##}</u> | <u>20</u> | <u>174</u> | 254 | (17%) |
| Total | 380 (25%) | 940 (61%) | 210 (14%) | 1530 | |

Overall neutron energy multiplication is 1.1

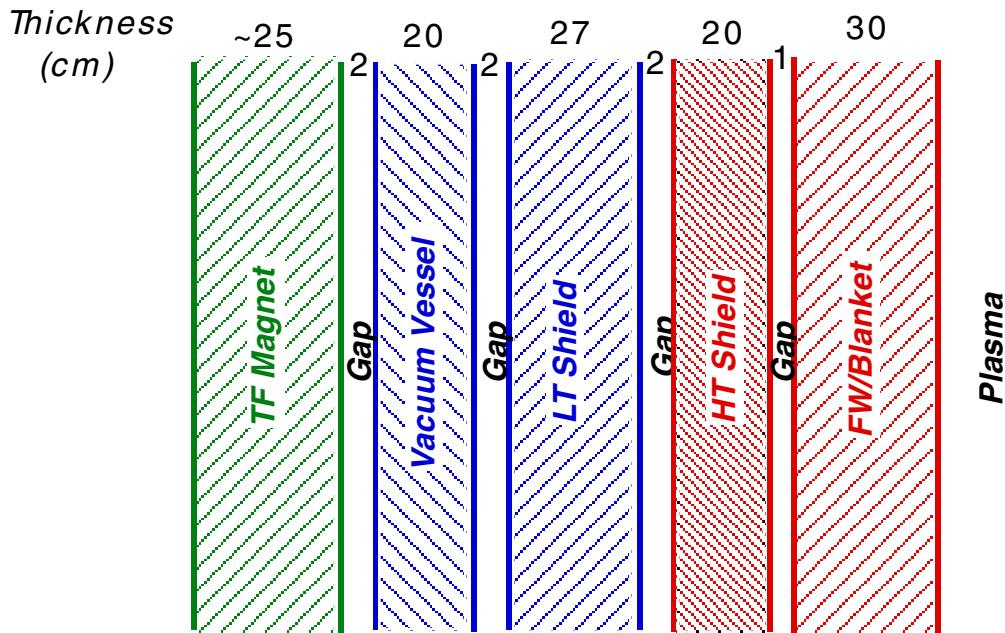
* To be confirmed by 3-D analysis

** Assumed 5 cm thick SiC/LiPb (40/60) divertor plates

[#] 560 MW in B-I, 36 MW in W shells, 112 MW in B-11

^{##} 15 MW in W shells, 45 MW in shield

Inboard Radial Build



Component

Composition[#]

FW (3.3 cm)

40% SiC , 60% LiPb (90% Li-6)

Blanket (26.7 cm)

7% SiC , 93% LiPb (90% Li-6)

HT Shield

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

LT Shield

15% FS , 5% H₂O , 80% WC

Vacuum Vessel

35% FS , 40% H₂O , 25% WC

HT Magnet

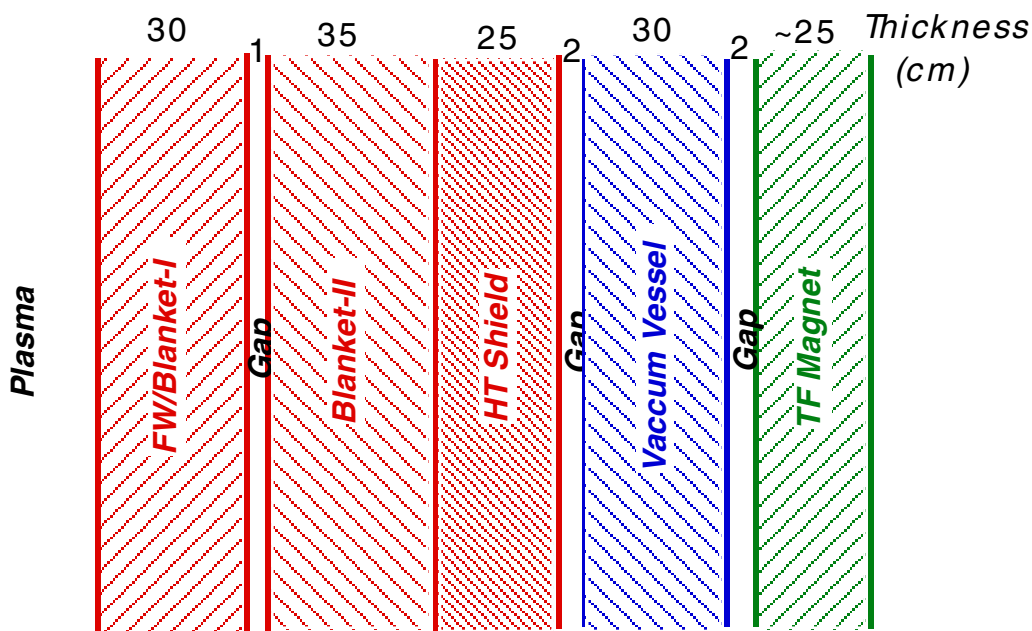
87% SS, 10% LN, 2.5% Y₁Ba₂Cu₃O₅, 0.5% Ag

- V.V. and TF magnet **radiation limits are all met^{*}** for peak $\Gamma = 4 \text{ MW/m}^2$ (1 He appm at V.V and 10^{19} n/cm^2 at magnet @ EOL)

[#] SiC and WC are 95% dense

^{*} Safety factor of 3 considered in all shielding calculations

Outboard Radial Build



Component

Composition[#]

FW/Blanket-I:

FW (3.3 cm)

40% SiC , 60% LiPb (90% Li-6)

B-I (26.7 cm)

7% SiC , 93% LiPb (90% Li-6)

Blanket-II

8% SiC , 92% LiPb

HT Shield

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

Vacuum Vessel

25% FS , 60% H₂O, 15% B-FS

HT Magnet

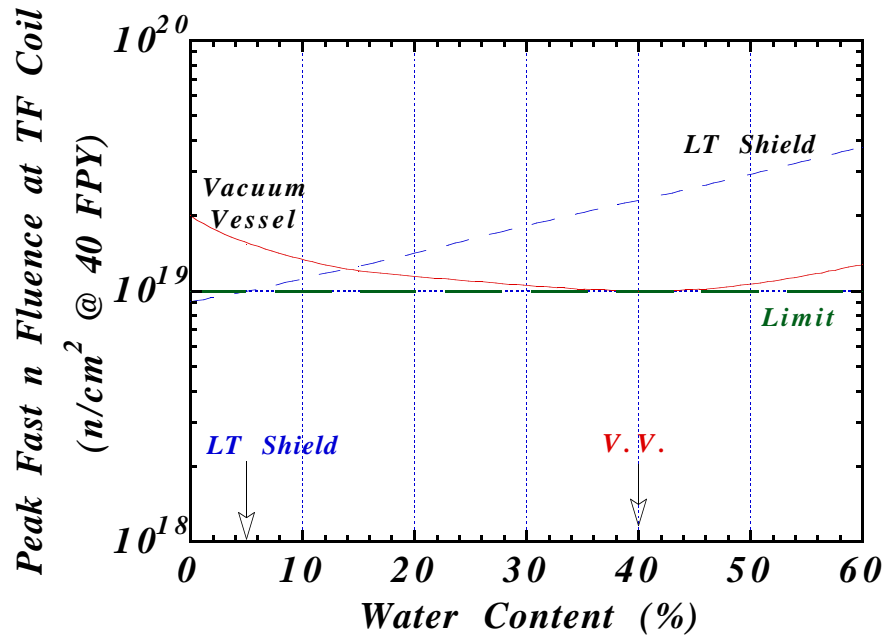
87% SS, 10% LN, 2.5% Y₁Ba₂Cu₃O₅, 0.5% Ag

- Blanket-II and HT shield could be combined in a single lifetime component
- V.V. and TF magnet radiation limits are all met* for peak $\Gamma = 6 \text{ MW/m}^2$
(1 He appm at V.V and 10^{19} n/cm^2 at magnet @ EOL)
- No need for separate LT shielding component

[#] SiC and WC are 95% dense

* Safety factor of 3 considered in all shielding calculations

Optimum Water Content in IB LT Shield and V.V.



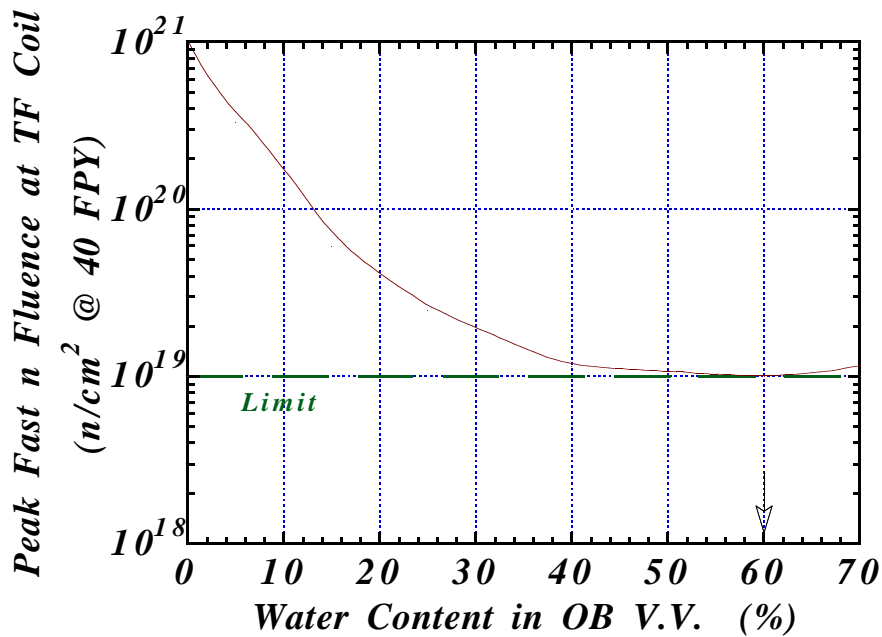
- Trading WC filler for water, optimum compositions are:

IB LT shield: 15% FS structure , 5% H₂O, 80% WC filler

IB V.V.: 35% FS structure , 40% H₂O, 25% WC filler

- Thinner V.V. could be cleared (to be confirmed by activation analysis)

Optimum Water Content in OB V.V.



- Trading B-FS filler for water, optimum V.V. composition is:

25% FS structure , 60% H₂O, 15% B-FS filler

- Thinner V.V. could be cleared (to be confirmed by activation analysis)

Impact of WC filler on IB Shield Size

- Low-cost manufacturing technique could only be applicable to metallic structural components (without filler)
- **WC filler** of both IB LT shield and V.V. was **replaced by FS** structure
- **FS shield/V.V. will increase radial build by 15 cm**
- Thicker IB components result in **larger machine**
- **Impact on COE of thicker but cheaper IB shield/V.V. needs to be assessed by ASC**

Comparison Between ARIES-AT and ARIES-RS Radial Builds



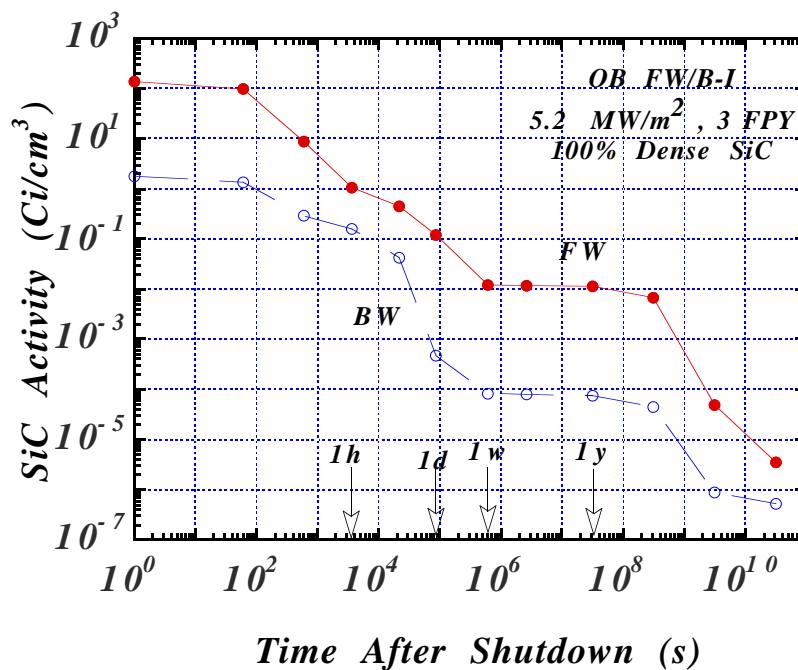
| ARIES design | <u>Inboard</u> | | <u>Outboard</u> | |
|---------------------------------------|----------------|------------|-----------------|------------|
| | <u>AT</u> | <u>RS</u> | <u>AT</u> | <u>RS</u> |
| Thickness (cm): | | | | |
| FW/Blanket-I | 30 | 20 | 30 | 20 |
| Blanket-II | --- | --- | 35 | 30 |
| Replaceable Shield | --- | 20 | --- | 7 |
| HT shield | 20 | 26 | 25 | 28 |
| LT shield | 27 | 28 | --- | 40 |
| Vacuum vessel | <u>20</u> | <u>20</u> | <u>30</u> | <u>30</u> |
| Subtotal | 97 | 114 | 120 | 155 |
| Magnet & cryostat | <u>25</u> | <u>55</u> | <u>25</u> | <u>55</u> |
| Total | 122 | 169 | 145 | 210 |
| Net reduction in thickness | 47 | 0 | 65 | 0 |

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

Activation Analysis

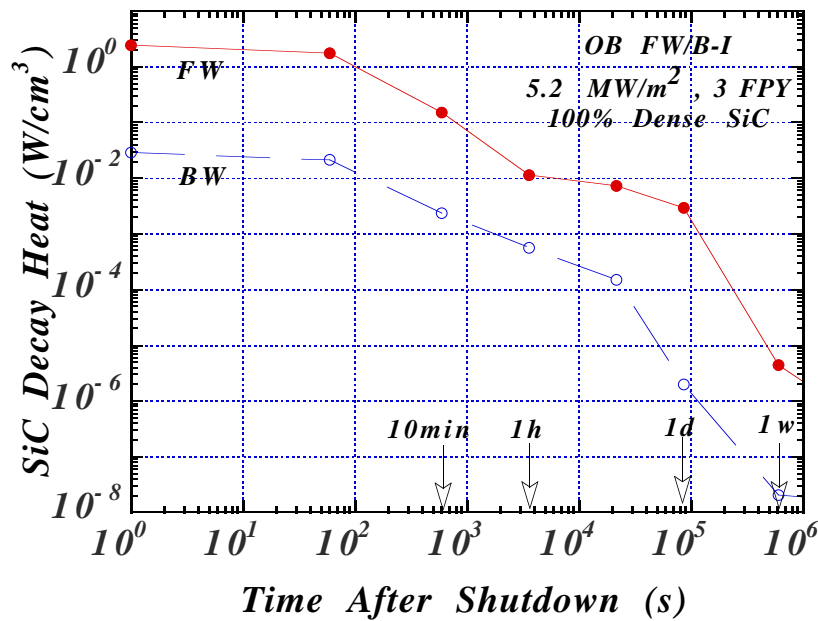
- **Codes and model:**
 - Activation: **ALARA** code; **FENDL-2** activation library
 - Flux: 1-D **DANTSYS** code; FENDL-1 Xn data
 - 175 n and 42 g group structure
 - **3-D neutron flux** used to re-normalize 1-D flux for all components
 - Average OB and IB Γ are 5.2 and 2.8 MW/m², respectively
 - **Operation time:** 3 FPY for FW/B-I, 40 FPY for all other components
- Activity, decay heat, WDR, and clearance index **depend strongly on** material, flux level, neutron spectrum, operation time, and cooling period
- **Results reported here are for:**
 - **OB side only**, as defined by OB radial build.
(IB side exhibits similar behavior at reduced level)
 - SiC and FS materials with **impurities**
 - 100% dense **compact waste** (coolants and void excluded)
- **Results include:**
 - **Activity and decay heat** as function of time after shutdown
 - Fetter's and NRC (10CFR61) **waste disposal ratings** for individual components at end of service lifetime
 - **Dominant radionuclides** at various times after shutdown
- **Clearance** calculations are underway
- **Benchmarking of ALARA** (activity, decay heat, and WDR) with DKR-Pulsar code showed excellent agreement

Activity OB FW/Blanket-I (3 FPY)



- OB FW contains highest activity among all SiC structures
- Compared to FW, activity generated in back wall (BW) is lower by factor of 10 or more
- Radial SiC structural ribs of B-I contain intermediate activity

Decay Heat OB FW/Blanket-I (3 FPY)



- OB FW contains highest decay heat among all SiC structures
- **LiPb may contain higher decay heat than SiC.** Coolant activation will be assessed for LOFA analysis

Class C Waste Disposal Rating OB FW/Blanket-I (3 FPY)

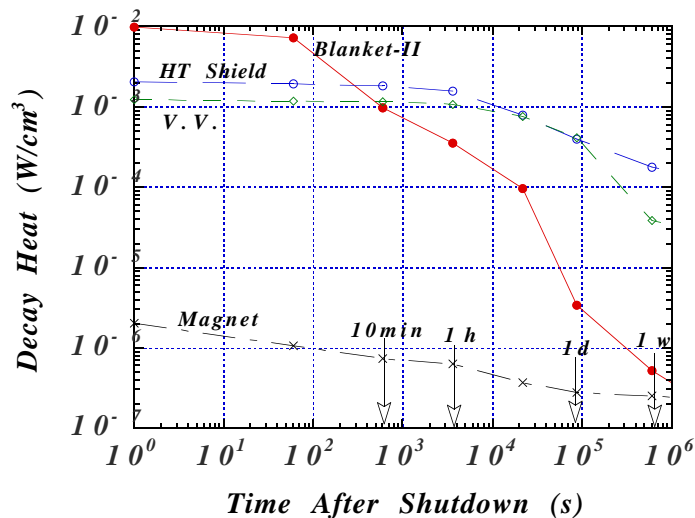
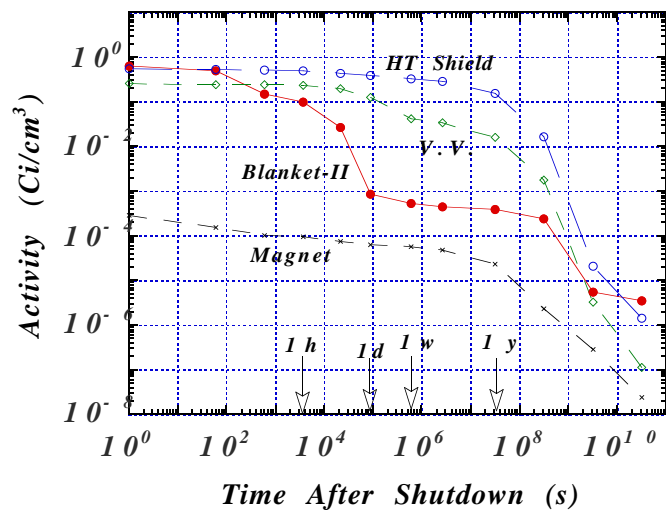


| | Fetter's WDR | NRC WDR |
|----------------|-------------------------|--------------------|
| FW | 0.3 | 0.04 |
| Cell | 0.006 | 0.01 |
| BW | <u>0.0002</u> | <u>0.007</u> |
| Average | 0.1 | 0.02 |

- WDR is for compact waste (void excluded)
- WDR < 1 means component qualifies as Class C low level waste
- **Al²⁶** is dominant nuclide for **Fetter's WDR**
Si²⁸ (n , np) Al²⁷ (n , 2n) Al²⁶
- **C¹⁴** is dominant nuclide for **NRC WDR**
C¹² (n , γ) C¹³ (n, γ) C¹⁴
- **BW could last for 40 FPY** and qualifies as Class C LLW
(Fetter's and NRC WDR_{BW} are 0.01 and 0.1 @ 40 FPY, respectively)

OB FW/Blanket-I qualify easily as Class C LLW after 3 FPY

Activity and Decay Heat OB Blanket-II, HT Shield, V.V., and Magnet (40 FPY, 5.2 MW/m², 100% Dense Composition)



Class C Waste Disposal Rating
OB Blanket-II, HT Shield, V.V., and Magnet
(40 FPY, 5.2 MW/m², Compact Waste)



| | Fetter's WDR | NRC WDR |
|-------------------|---|--|
| Blanket-II | 0.002 (Al ²⁶) | 0.05 (C ¹⁴) |
| HT Shield | 0.17 (Nb ⁹⁴ , Tc ⁹⁹ , Ho ^{166m}) | 0.1 (Nb ⁹⁴ , Ni ^{63,59}) |
| V.V. | 0.05 (Nb ⁹⁴ , Ho ^{166m}) | 0.03 (Nb ⁹⁴) |
| Magnet | 0.01 (Ag ^{108m} , Nb ⁹⁴) | 0.004 (Nb ⁹⁴) |

All OB permanent components qualify as Class C LLW after 40 FPY

Dominant Radionuclides for OB Components @ Various Time After Shutdown (in descending order)



Activity:

| | <u>SiC FW</u> | <u>HT Shield</u> | <u>V.V.</u> | <u>Magnet</u> |
|---------------------------|-------------------------------------|---|---|--|
| Shutdown | Al ^{28,29,30} | Fe ⁵⁵ ,W ^{185,187} , Mn ⁵⁶ ,Cr ⁵¹ ,Re ¹⁸⁶ | W ¹⁸⁷ ,Re ¹⁸⁸ ,Mn ⁵⁶ , Cr ⁵¹ ,Fe ⁵⁵ | Ag ¹¹⁰ ,Mn ⁵⁶ , Ag ¹⁰⁸ ,Fe ⁵⁵ |
| t < 1 d | Na ²⁴ ,Si ³¹ | Fe ⁵⁵ ,W ^{185,187} , Mn ⁵⁶ ,Cr ⁵¹ ,Re ¹⁸⁶ | W ¹⁸⁷ ,Fe ⁵⁵ , W ¹⁸⁵ ,Cr ⁵¹ ,Re ¹⁸⁸ | Mn ⁵⁵ ,Fe ⁵⁵ ,Co ⁵⁸ , Ag ¹¹⁰ ,Cr ⁵¹ |
| 1d < t > 1w | Na ²⁴ ,T,P ³² | Fe ⁵⁵ ,W ¹⁸⁵ ,Cr ⁵¹ , Fe ⁵⁹ ,Mn ⁵⁴ ,Re ¹⁸⁶ | Fe ⁵⁵ ,W ¹⁸⁵ ,Cr ⁵¹ , Re ¹⁸⁶ ,W ¹⁸⁷ ,Fe ⁵⁹ | Fe ⁵⁵ ,Co ⁵⁸ , Ag ¹¹⁰ ,Cr ⁵¹ ,Mn ⁵⁴ |
| 1w < t > 1y | T | Fe ⁵⁵ ,W ¹⁸⁵ ,Mn ⁵⁴ | Fe ⁵⁵ ,W ¹⁸⁵ ,Co ⁶⁰ | Fe ⁵⁵ ,Co ⁵⁸ ,Ag ^{110m} , Mn ⁵⁴ |
| 1y < t > 10y | T,C ¹⁴ | Fe ⁵⁵ ,T,Co ⁶⁰ | Fe ⁵⁵ ,Co ⁶⁰ ,T | Fe ⁵⁵ ,Ni ⁶³ ,Co ⁶⁰ |
| > 10 y | C ¹⁴ ,Be ¹⁰ | Ni ⁶³ ,T,Mo ⁹³ , Nb ^{93m} ,Ni ⁵⁹ | Ni ⁶³ ,T,Ni ⁵⁹ , Mo ⁹³ ,Nb ^{93m} | Ni ⁶³ ,Ag ^{108m} ,Ni ⁵⁹ , C ¹⁴ ,Mo ⁹³ ,Nb ^{93m} |

Decay Heat:

| | <u>SiC FW</u> | <u>HT Shield</u> | <u>V.V.</u> | <u>Magnet</u> |
|--------------------------|---|--|--|--|
| Shutdown | Al ^{28,29,30} | Mn ⁵⁶ ,W ^{187,185} | W ¹⁸⁷ ,Mn ⁵⁶ ,Re ¹⁸⁸ | Ag ¹¹⁰ ,Mn ⁵⁶ |
| t < 1 d | Na ²⁴ ,Si ³¹ | Mn ⁵⁶ ,W ^{187,185} | W ¹⁸⁷ ,Mn ⁵⁶ ,Re ¹⁸⁸ | Mn ⁵⁵ ,Ag ¹¹⁰ ,Co ⁵⁸ |
| 1d < t > 1w | Na ²⁴ ,Si ³¹ ,P ³² | W ¹⁸⁵ ,Fe ⁵⁹ , Mn ⁵⁴ | Co ⁶⁰ ,Fe ⁵⁹ ,W ^{185,187} | Ag ^{110m} ,Co ⁵⁸ , Mn ⁵⁴ |