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

L. El-Guebaly, D. Henderson, A. Abdou
Fusion Technology Institute
University of Wisconsin - Madison

With inputs from:
I. Sviatoslavsky, P. Wilson, M. Sawan (UW), R. Raffray, R. Miller (UCSD),
D.K. Sze (ANL), C. Kessel (PPPL), and S. Malang (FZK)

Web address:
http://fti.neep.wisc.edu/FTI/ARIES/MAR2000/nucl_lae.pdf

ARIES Project Meeting
20-21 March 2000
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 , div.	6.1 , 4 , 2 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% (1.5 atom% He)
FS dpa limit	200 dpa
Machine lifetime	40 FPY
HT magnet	

ARIES-RS' vacuum vessel configuration

[#] 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^2 for ICRF, 1.1 m^2 for NBI, 1 m^2 for LH on OB, per TK
    - 2 cm radial gaps between 16 blanket modules

- Reference nuclear parameters:

Overall TBR	1.16
Overall M_n	1.1
SiC Burnup rate	1% per FPY[#]
FW EOL Fluence	18.5 MWy/m^2
FW Lifetime	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

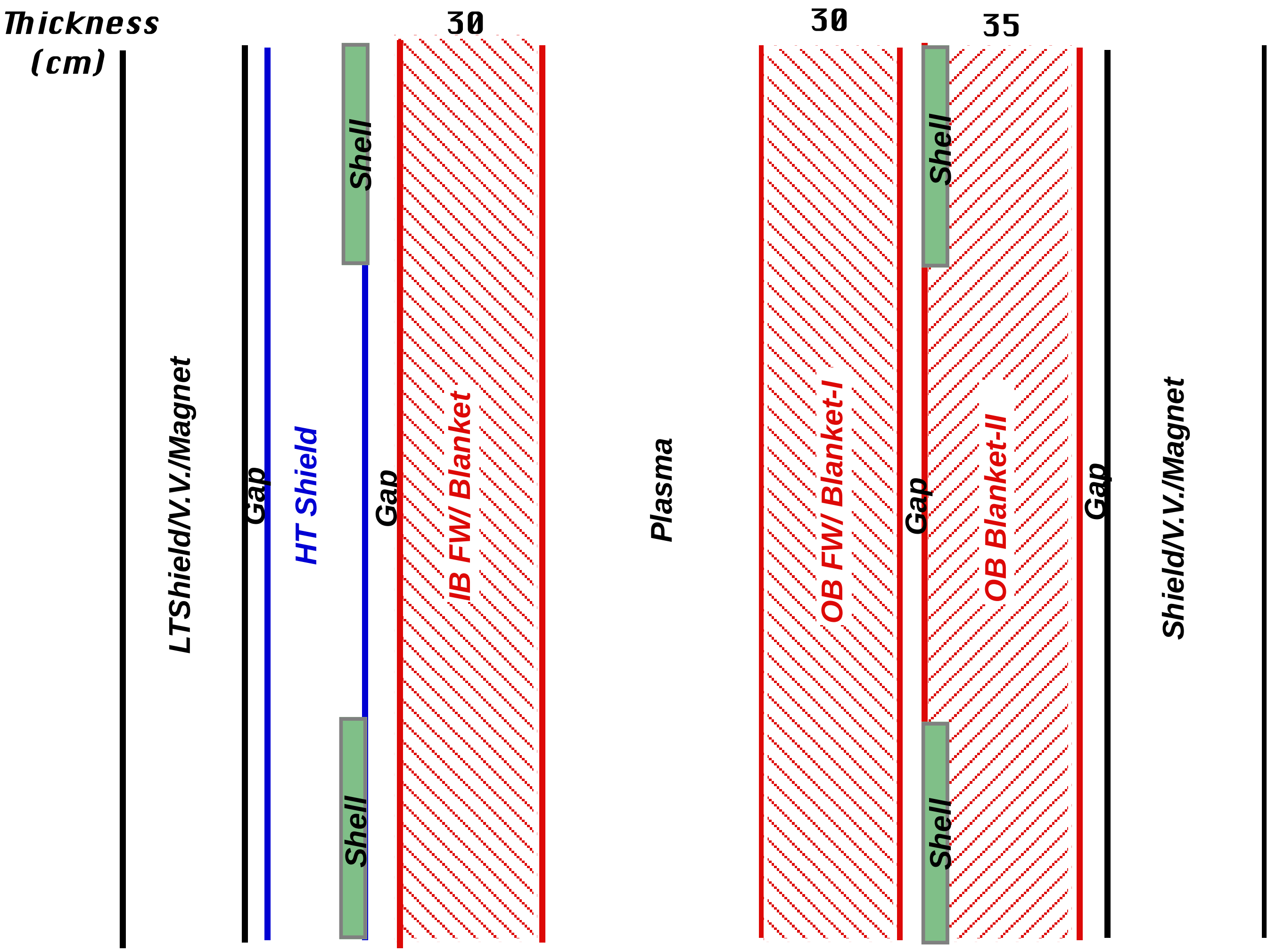
---

[*] Using FENDL-2 cross section data library

[#] 0.7% Si , 0.3% C

Impact of Stabilizing Shell on TBR

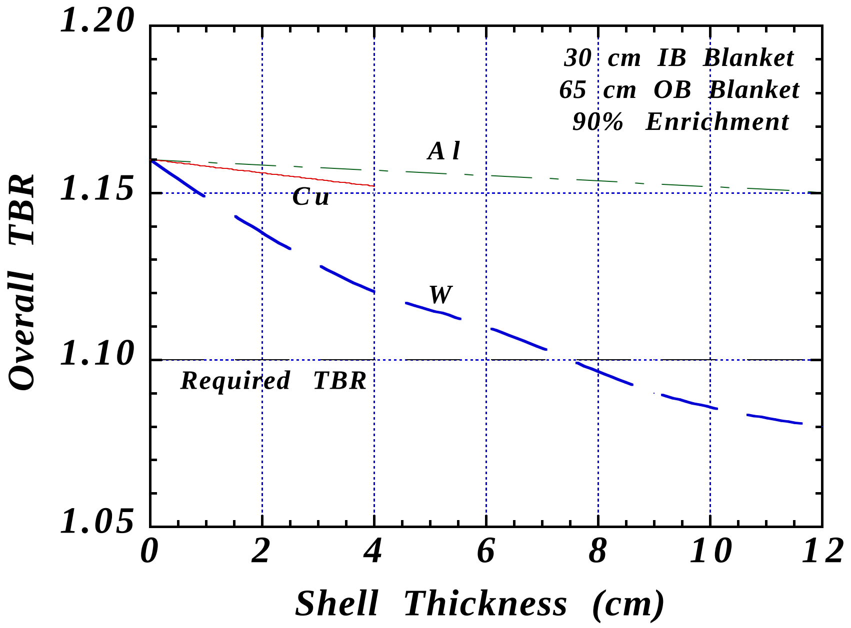
University of
Wisconsin



- 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.)

University of Wisconsin



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	400 °C	1000 °C
W Shells	6 cm	12 cm
	36 MW[*]	57 MW
Al Shells	4 cm	11 cm
	5 MW	13 MW
Cu Shells	2 cm	4 cm
	7 MW	16 MW

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

---

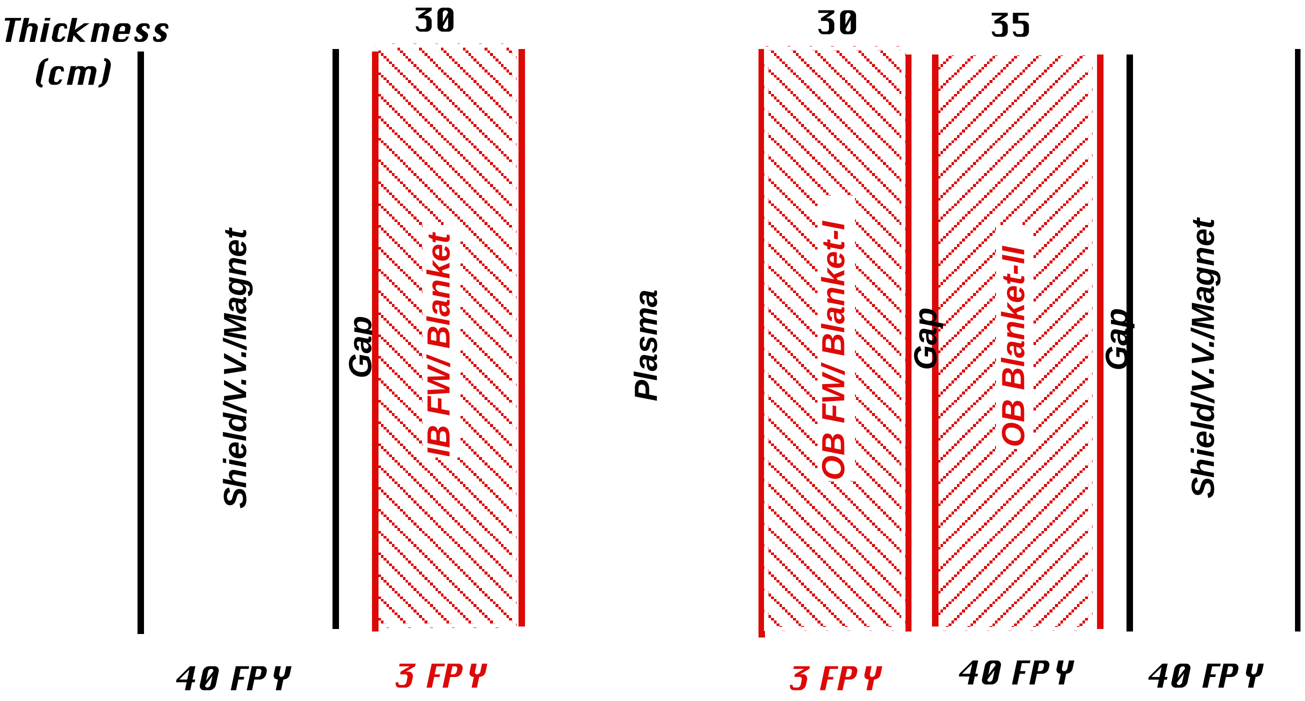
[*] Heating in both upper and lower shells

Observations on Stabilizing Shell Design

- 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 embrittlment. 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

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

10^{19} n/cm^2	Peak fast n fluence[#] to HT S/C
---	Radiation resistant thermal insulator

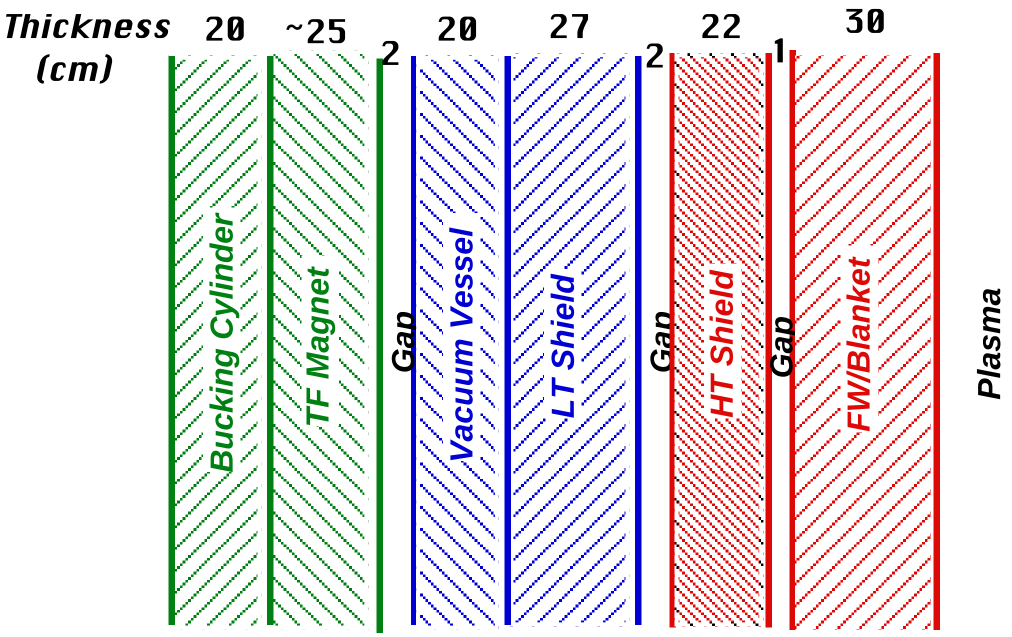
- ARIES-RS LT S/C magnet radiation limits:

10^{19} n/cm^2	Peak fast n fluence to Nb_3Sn S/C
2 mW/cm^3	Peak nuclear heating
6x10^{-3} dpa	Peak atomic displacement to Cu stabilizer[*]
10^{11} rad	Peak dose to GFF polyimide
---	Radiation resistant thermal insulator

[#] $E_n > 0.1$ MeV

[*] 85% of dpa can be annealed out by warming up magnets during maintenance

Inboard Radial Build



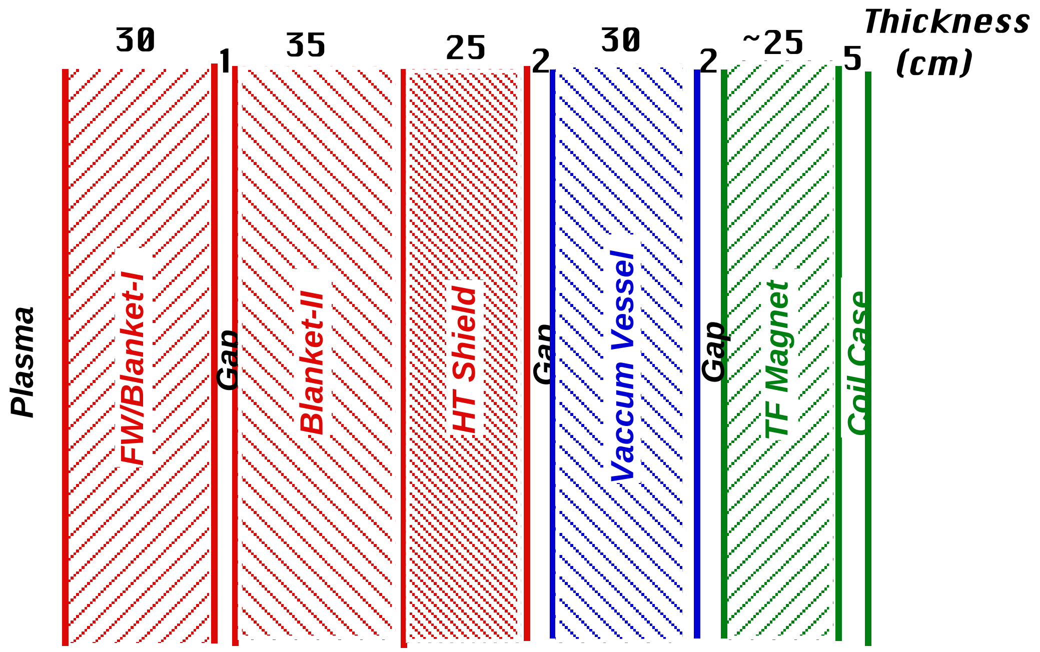
Component	**Composition**[#]
FW (1.9 cm)	51% SiC , 49% LiPb
Blanket (28.1 cm)	12% SiC , 88% LiPb
HT Shield	15% SiC, 10% LiPb , 75% B-FS
LT Shield	15% FS , 10% H_2O , 75% WC
Vacuum Vessel	35% FS , 65% H_2O
HT Magnet	87% SS, 10% LN, 2.5% $Y_1Ba_2Cu_3O_5$, 0.5% Ag
Bucking cylinder	95% SS, 5% LN

- 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[*] for peak $\Gamma = 4$ MW/m^2 (200 dpa at LT shield 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



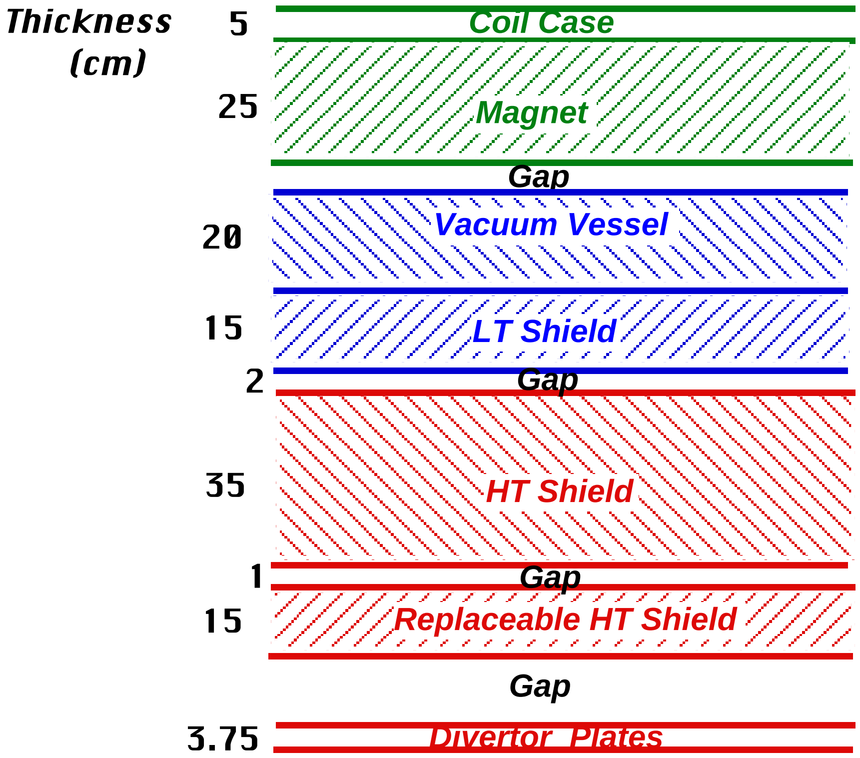
Component	**Composition**[#]
FW/Blanket-I:	
FW (1.9 cm)	51% SiC , 49% LiPb
B-I (28.1 cm)	12% SiC , 88% LiPb
Blanket-II	14% SiC , 86% LiPb
HT Shield	15% SiC , 10% LiPb , 75% B-FS
Vacuum Vessel	25% FS , 75% H_2O
HT Magnet	87% SS, 10% LN, 2.5% $Y_1Ba_2Cu_3O_5$, 0.5% Ag
Coil Case	95% SS, 5% LN

- 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 $\Gamma = 6$ MW/m^2 (200 dpa for FS,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

Vertical Build



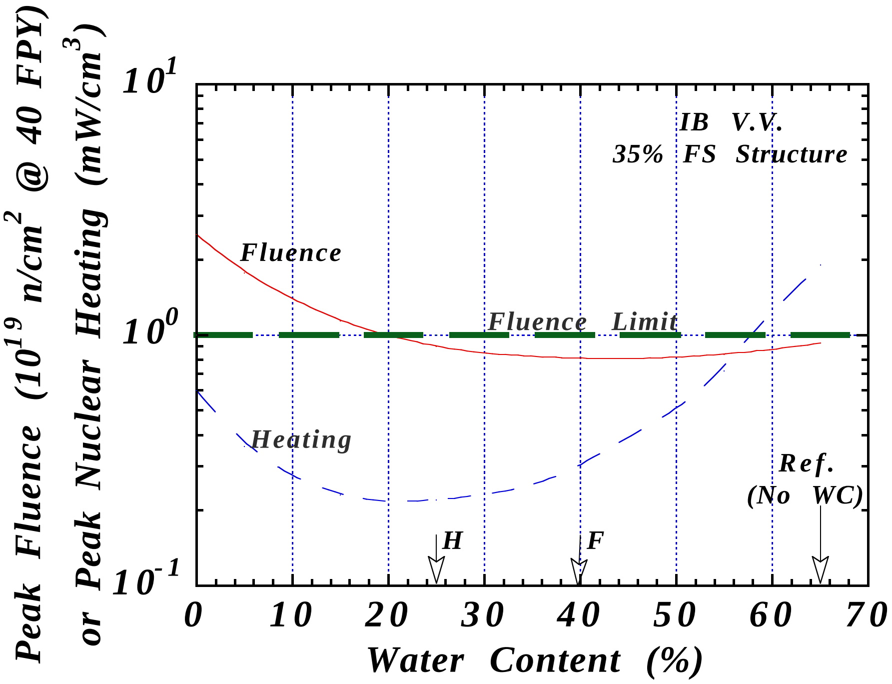
Component	**Composition**[#]
Divertor Plates	19% W , 5% SiC , 76% LiPb
Replaceable HT Shield	15% SiC , 10% LiPb, 75% FS
HT Shield	15% SiC , 10% LiPb , 75% B-FS
LT Shield	15% FS , 10% H_2O , 75% B-FS
Vacuum Vessel	35% FS , 65% H_2O
HT Magnet	87% SS, 10% LN, 2.5% $Y_1Ba_2Cu_3O_5$, 0.5% Ag

- 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 $\Gamma = 2$ MW/m^2 (200 dpa at LT shield and 10^{19} n/cm^2 at magnet @ EOL)
- Shielding behind inner divertor plates will be assessed

[#] 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

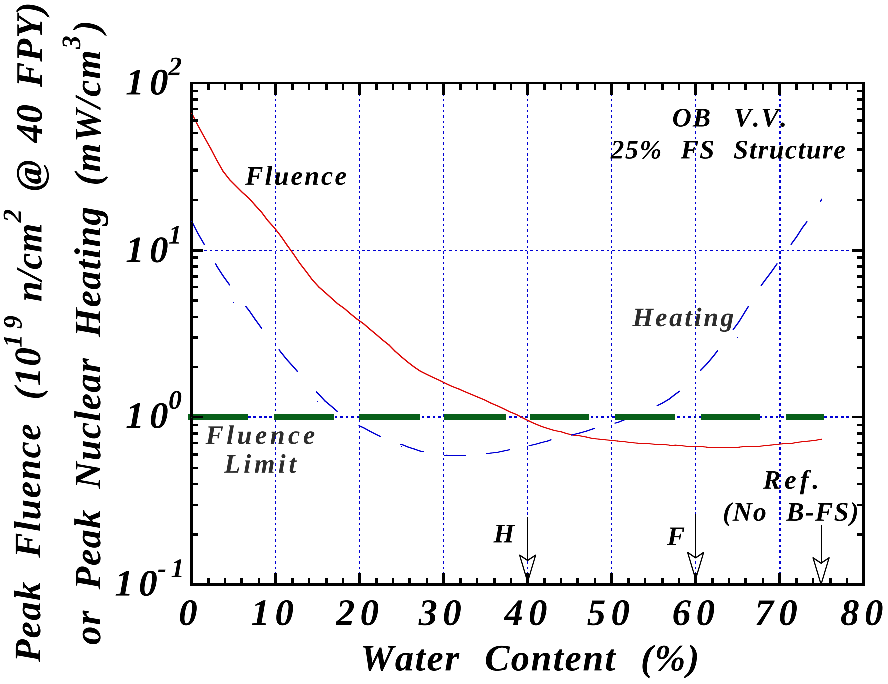
- Eliminating WC filler simplifies V.V. design but results in high magnet heating, high thermal neutron flux, and high activity at V.V.

- Optimum VV composition for fluence:
  35% FS structure , 40% H_2O, 25% WC filler

- Optimum VV composition for heating:
  35% FS structure , 25% H_2O, 40% WC filler

Optimum Composition of OB V.V.

University of Wisconsin



- 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_2O, 15% B-FS filler
- Near optimum VV composition for heating that meets fluence limit:
  25% FS structure , 40% H_2O, 35% B-FS filler

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

University of Wisconsin

	Inboard		**Outboard**		**Divertor**	
ARIES-	**AT**	**RS**	**AT**	**RS**	**AT**	**RS**
Thickness (cm):						
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	20	20	30	30	20	20
Subtotal	**99**	**114**	**120**	**155**	**89**	**125**
Reduction in thickness	**15**	**0**	**35**	**0**	**36**	**0**
Magnet & cryostat	25	55	25	55	25	55
Total	**124**	**169**	**145**	**210**	**114**	**180**
Net reduction in thickness	**45**	**0**	**65**	**0**	**66**	**0**

- 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 Γ are 5.2 and 2.8 MW/m^2, respectively
  - Operation time: 3 FPY for FW/B-I, 40 FPY for all other components
  - Continuous operation, unless indicated (this overestimates radioactivity of intermediate $T_{1/2}$ 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

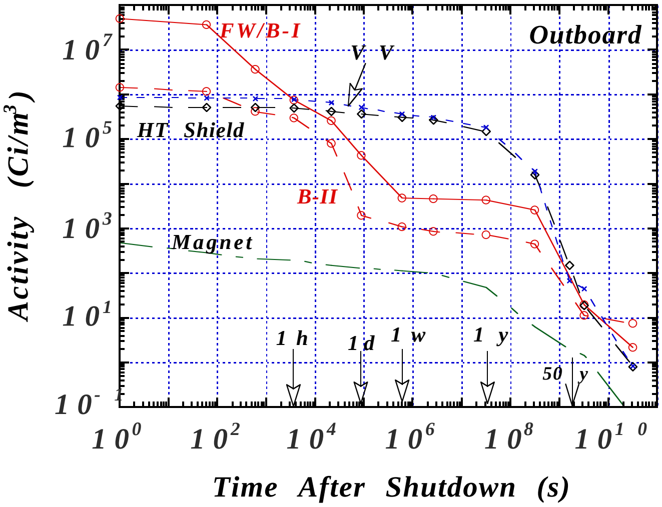
- Results reported here are for:
  - 100% dense compacted waste (coolants and void excluded)
  - IB and OB sides as defined by radial builds
  - SiC, WC, and LiPb compositions with impurities.
  - FS with impurity control (IC) to qualify as Class C waste

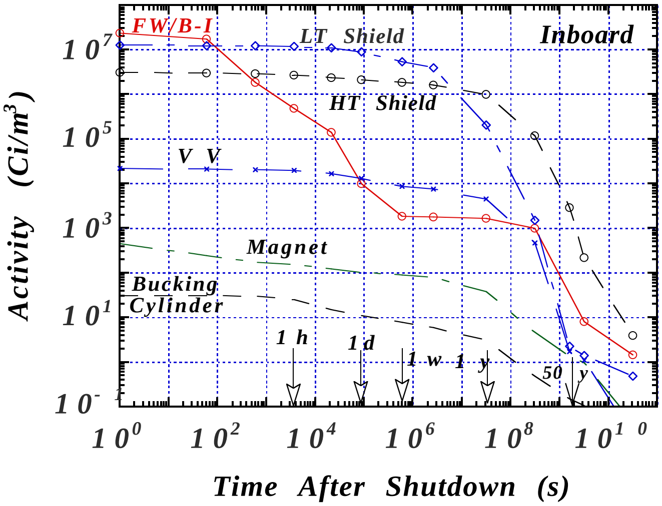
Elements	Original FS wppm	FS w/ IC wppm
Nb	4	1
Mo	70	20

  - 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

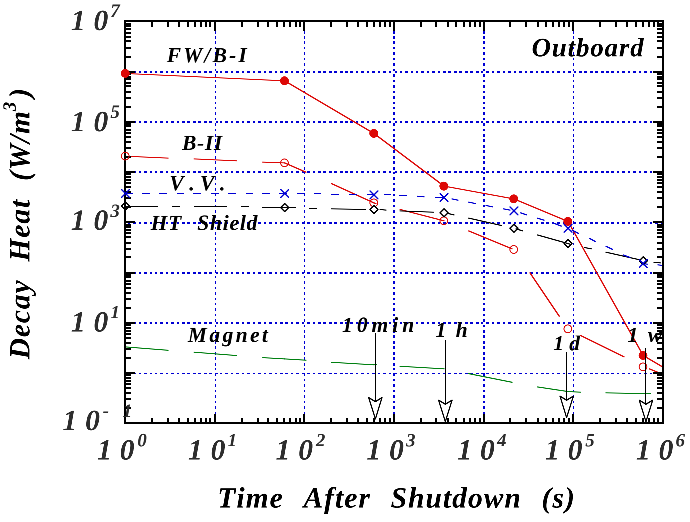


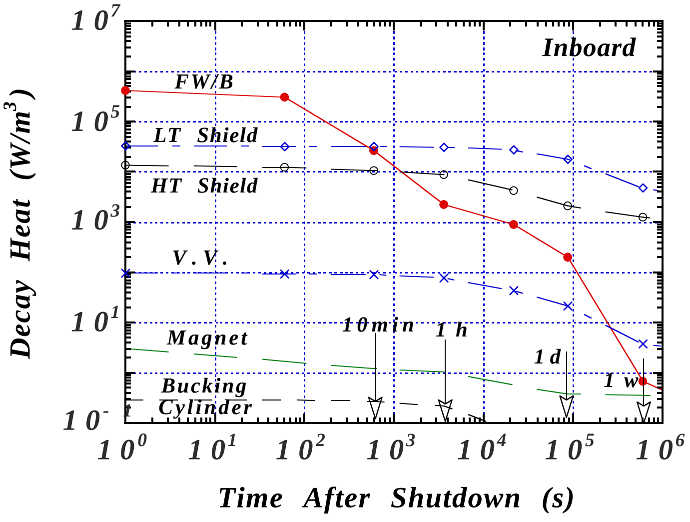


- Unlike metals, SiC activity drops by several orders of magnitude shortly after shutdown
- Highly irradiated SiC components generate lower intermediate activity (1d-5y) than well protected FS and WC components

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

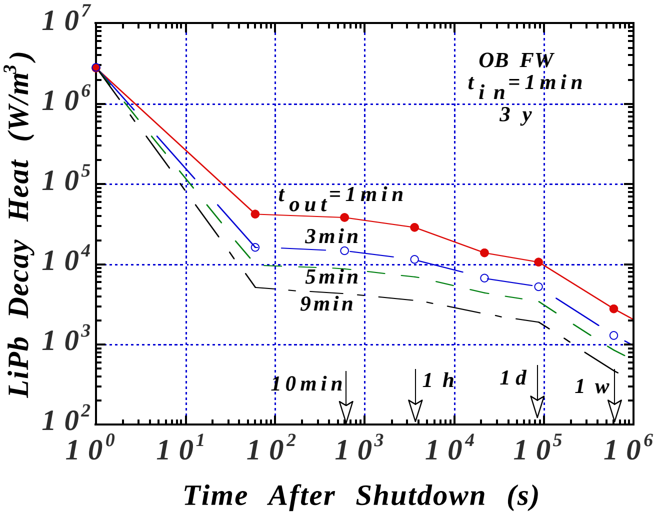
LiPb Decay Heat for LOFA Analysis

- 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} ~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)

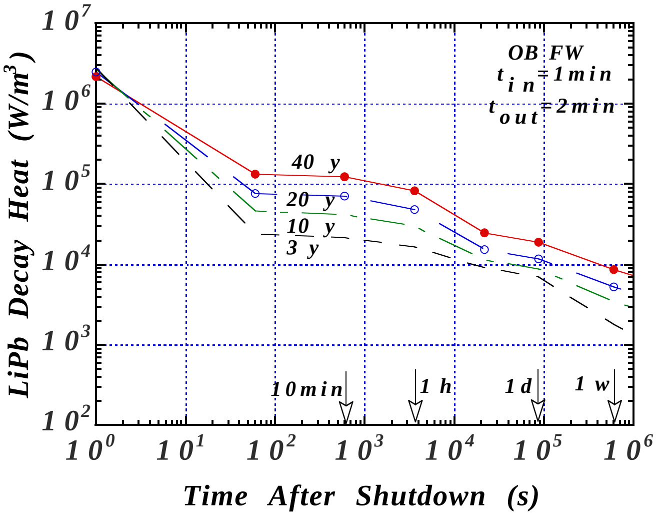
- Pulsed analysis performed to determine:
    - Sensitivity of LiPb decay heat to t_{out}
    - Variation of LiPb decay heat with operation time (3,10,20,40 y)

- 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 Dacay Heat Decreases with t_{out}



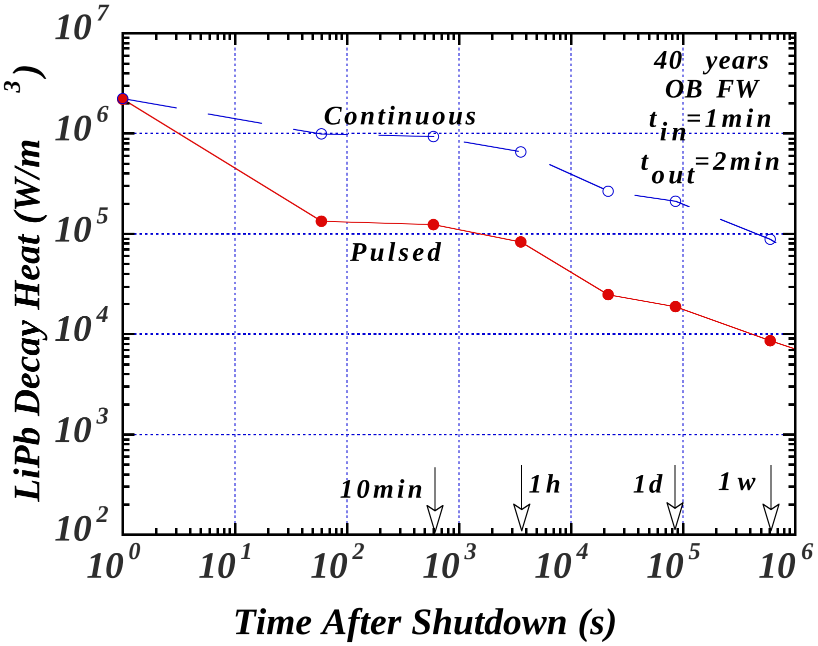
LiPb Decay Heat Increases with Operation Time

- Selected parameters for LOFA analysis:

  t_{in} = 1 min for B-I and 3.4 min for B-II
  t_{out} = 2 min
  Irradiation time = 40 y (7x10^6 irradiation periods for B-I and 4x10^6 for B-II)

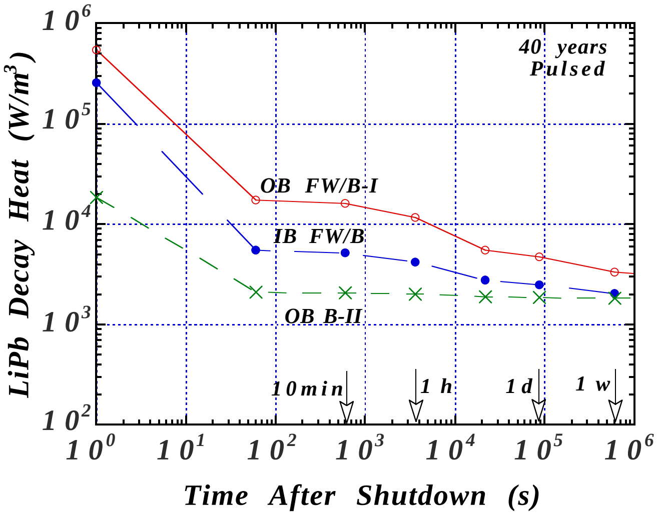
LiPb Decay Heat for LOFA Analysis (cont.)

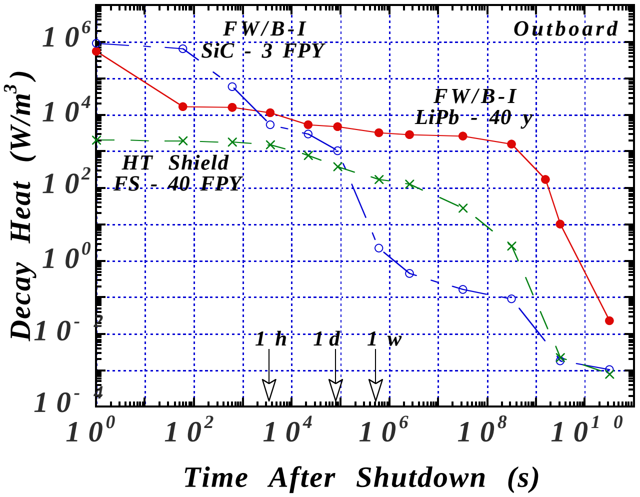
University of Wisconsin



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

- 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^{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 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

Class C Waste:	**Fetter-H**	**Fetter-L**
Outboard Components:		
FW/B-I	0.092	0.095
B-II	0.004	0.02
HT Shield	0.2	0.3
V.V.	0.05	0.055
Magnet	0.016	0.023
Inboard Components:		
FW/B	0.019	0.021
HT Shield	0.7	**1.0**[*]
LT Shield	0.030	0.046
V.V.	0.0014	0.0017
Magnet	0.015	0.022
Bucking Cylinder	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
Outboard Components:		
FW/B-I	12*	0.03
B-II	3*	0.1
HT Shield	8	0.2
V.V.	3*	0.03
Magnet	0.1	0.005
Inboard Components:		
FW/B	5*	0.02
HT Shield	128	0.6
LT Shield	0.3	0.02
V.V.	0.08	0.001
Magnet	0.1	0.005
Bucking Cylinder	0.04	0.003

- For SiC components, T and C^{14} are dominant nuclides for NRC-A WDR and C^{14} is dominant nuclide for NRC-C WDR

  $C^{12}\ (n, \gamma)\ C^{13}\ (n, \gamma)\ C^{14}$
- Some components qualify as Class A LLW

All components qualify as Class C LLW @ EOL

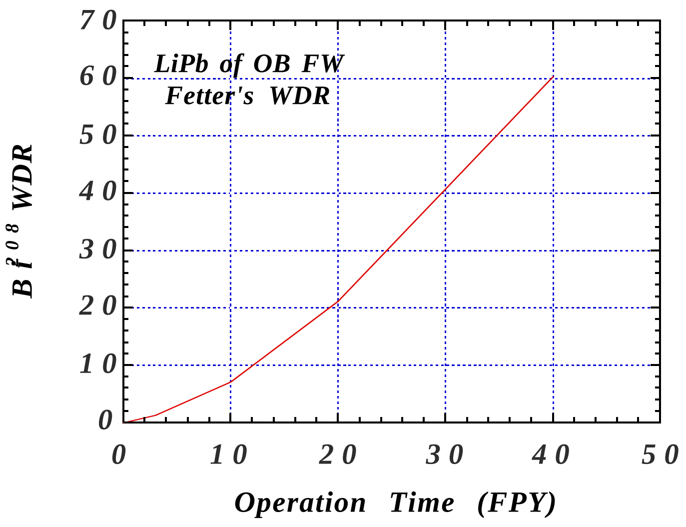
---

* 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
- Bi^{208} is dominant nuclide for Fetter’s WDR (95%)
- Pb and Bi impurity (43 wppm) generate 90% and 10% of Bi^{208}, respectively, via the following reactions:
  Pb^{208} (n,γ) Pb^{209} (β^- decay) Bi^{209} (n,2n) Bi^{208}
  Bi^{209} (n,2n) Bi^{208}
- Also, Bi generates Po^{210} which raises safety concerns:
  Bi^{209} (n,2n) Bi^{208} (n,γ) B^{i209} (n,γ) Bi^{210} (β^- decay) Po^{210}
- Bi production continues to rise during operation



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

Conclusions

- Neutronics:
  - Blanket meets breeding requirement (TBR ≥ 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