Nuclear Issues and Analysis for ARIES Spherical and Advanced Tokamaks

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http://fti.neep.wisc.edu/FTI/uwfdm.html

Objectives

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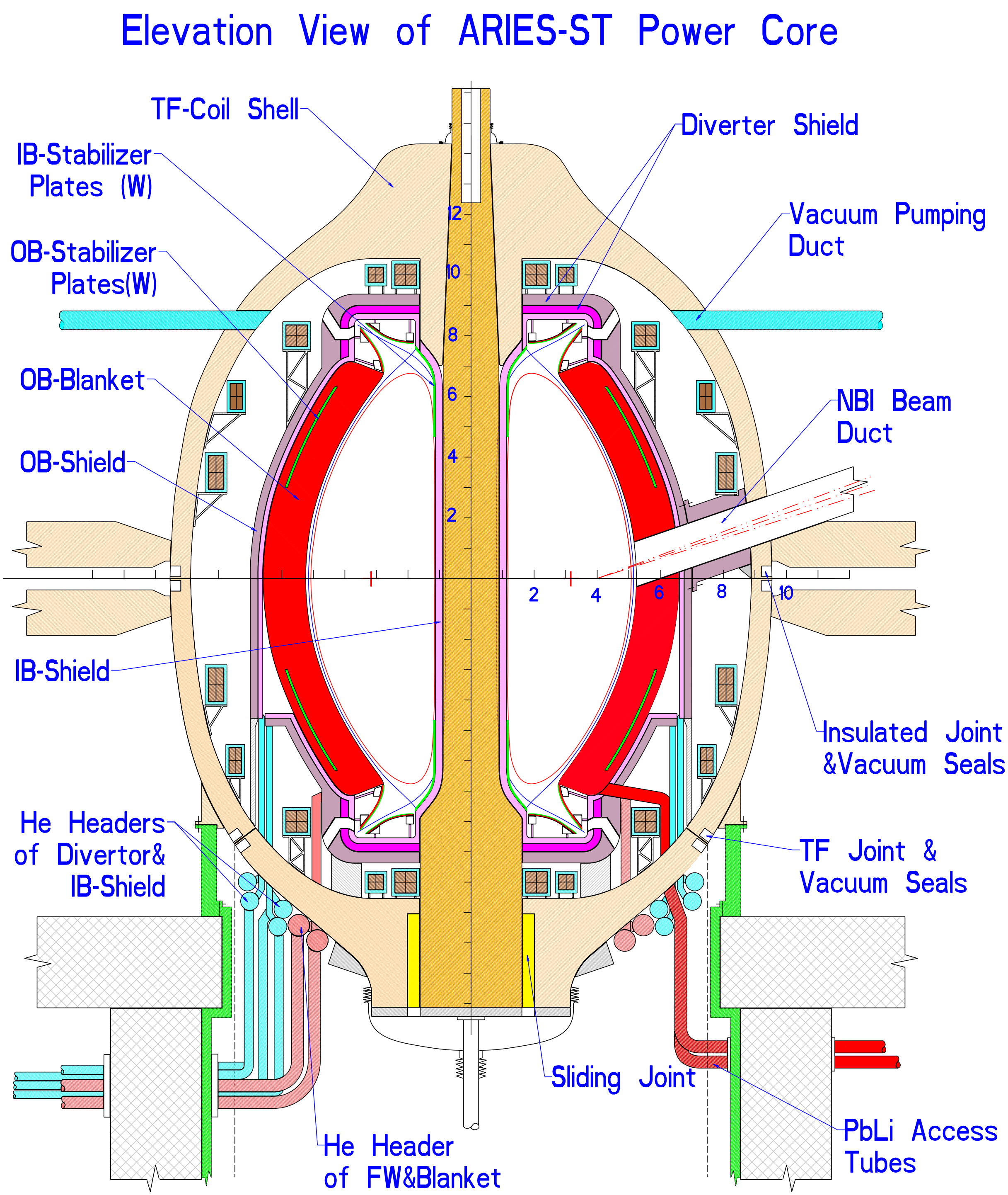
- Address key nuclear issues for Spherical and Advanced tokamaks:
  - Protection of center post
  - Breeding capability of blanket options
  - Lifetime of structural components

- Assess impact of nuclear parameters on design choices:

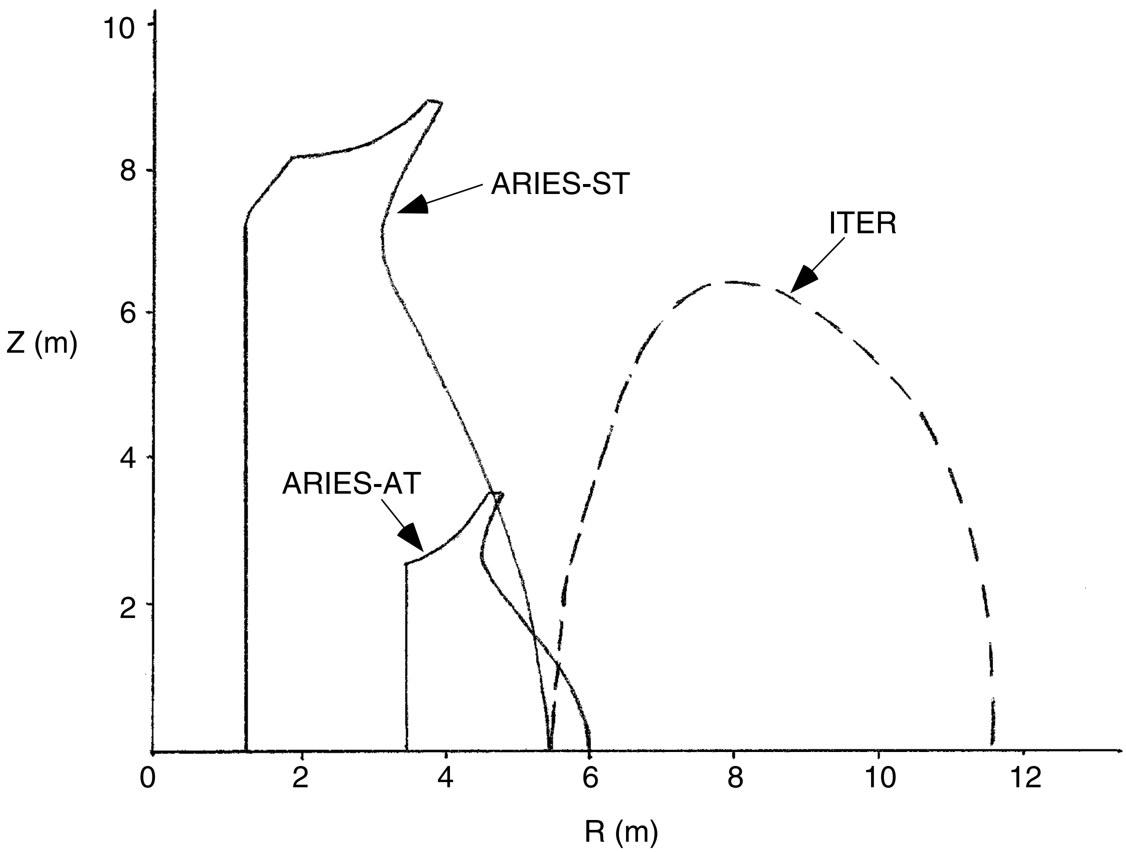
Parameters	Issues
TBR	Breeder type
	Blanket thickness/composition
	Li enrichment
Mn	HT and LT components
Radiation damage	Service lifetime
	Radial build

- Shielding assessment:
  - Requirements
  - Need for IB shield to protect center post
  - Optimal shield design

- Comparison between 1-D and 3-D neutronics results



Elevation View of ARIES-ST



FW Location

First Wall Location

Tritium Breeding Requirement

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- 3-D overall TBR should be ≥ 1.1

  10% breeding margin accounts for:
  - Uncertainties in Xn data of Li and Pb (7%)
  - Uncertainties in calculations and modeling (2%)
  - T losses [hold-ups and decay] (< 1%)
  - T supply for new power plants (< 1%)

- Actual net TBR after plant operation may range between 1.01 and 1.2

- Blanket design should be flexible to adjust net TBR to 1.01

- In case of overbreeding (net TBR > 1.01), reduce TBR by:
  - Lowering enrichment
  - Replacing back cell(s) by steel shield

- In case of underbreeding (net TBR < 1.01), major changes will be needed to adjust TBR:
  - Increase enrichment to 90%
  - Thicken blanket
  - Install blanket on inboard (⇒ higher P_{Ω})
  - Add Be to Cell 1 of LiPb blanket (safety!)
  - Reduce A of ARIES-ST (economics !)
  - Change blanket design (⇒ exclude water from CP)

ARIES-ST Blanket Neutronics

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- Four blanket options proposed for ARIES-ST:
  - LiPb/FS/SiC/He
  - Li/V
  - Li_2TiO_3/FS/SiC
  - Li_2O/SiC

  LiPb/FS/SiC/He is preferred option:
  - Compatible with water-cooled center post
  - Withstand high wall loadings
  - Avoid safety problems associated with other options

- FW/blanket main features:
  - 3.1 cm thick FW (25% FS, 75% He)
  - 1 m thick outboard-only blanket (76% LiPb, 6% FS, 6% He, 12% SiC)
  - 60% enriched Li^6

- 3-D results:

Overall TBR	1.1
Overall Mn	1.1

- Energy recovered from all components except water-cooled CP

Peak Radiation Damage to FW per Unit Wall Loading

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	ARIES-ST		ARIES-AT	
	1-D	3-D	1-D	3-D
Inboard:				
dpa/FPY	25	13	28	15
He appm/FPY	210	120	1730	1200
H appm/FPY	830	510	1220	480
Nuclear Heating (W/cm^3)	16	7	12	6
Outboard:				
dpa/FPY	15	11	18	11
⇒ FW/B EOL Fluence (MWy/m^2)		18		
He appm/FPY	170	110	1410	870
H appm/FPY	660	470	990	350
⇒ FW/B EOL Fluence (MWy/m^2)				18.5
Nuclear Heating (W/cm^3)	10	6	9	5

- 1-D model overestimates FW damage and underestimates damage to back components
- 3-D results should be used to re-normalize 1-D n source for individual components

Differences Between 3-D and 1-D Analyses

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	3-D	1-D
Model	actual	toroidal cylindrical
Angular distribution of incident 14 MeV n's on FW	mostly perpendicular ⇒ lower front damage higher back damage	perpendicular and tangential components
Plasma shape	actual	cylindrical
n source distribution	actual	uniform, shifted outward
Reflection from i/b, o/b, div.	actual	no div. effect
Vertical variation of n wall loading	non-uniform ⇒ less reflection from parts off midplane	uniform ⇒ more reflection
Cross section data	pointwise	multi-group

Subsystem Requirements for Inboard Shield of ARIES-ST

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	Shield Size
• **Design requirements:**	
- Protect CP against radiation for > 3 FPY (Cu embrittlement, resistivity change, activation, coolant radiolysis)	↑
- Enhance outboard breeding	↑
- Reduce heat load and thermal stress to CP	↑
• **Safety requirements:**	
- Compatible with CP and blanket	
• **Economic requirements:**	
- Prolong CP lifetime (replacement cost, availability, radwaste stream)	↑
- Maximize Mn (⇒ recover i/b heating)	↑
- Reduce Joule losses (⇒ minimize shield size)	↓

Unshielded CP does not offer attractive design

Inboard shield competes with CP for valuable space

Contradicting requirements mean inboard shield design is a compromise between several constraints

Shielding parameters should be chosen to optimize overall design, not only to minimize Joule losses in CP

20 cm Thick He-Cooled Inboard Shield is Optimal for ARIES-ST

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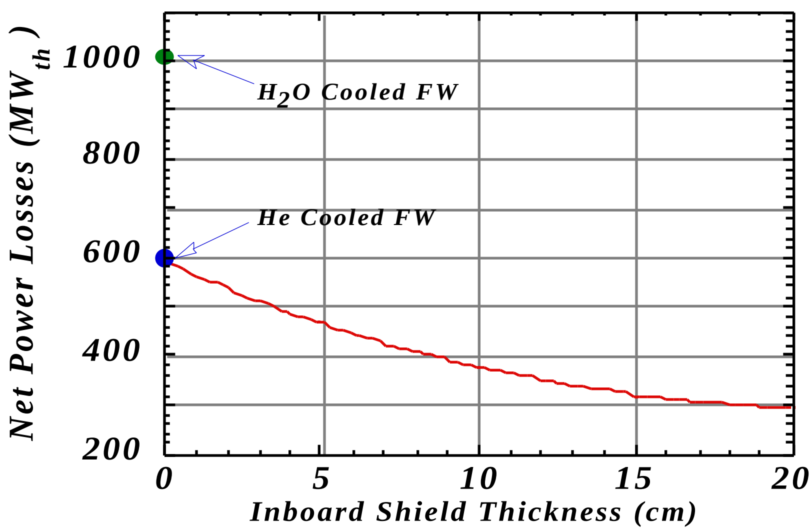
- Inboard power losses (and thus COE) minimize near 20 cm thick shield
- Net i/b power losses (in MW_{th})=

$$P_\Omega/\eta + NH_{CP} + PP/\eta - [(SH + NH)_{FW/shld} + 0.9\, PP]$$

where P_Ω is CP Joule losses,
η is thermal conversion efficiency,
SH is Surface Heating,
NH is Nuclear Heating,
PP is He Pumping Power (90% of PP is recovered as thermal heat)



- Designs with i/b shields thinner than 20 cm will have higher COE, lower breeding, higher CP damage, shorter CP lifetime, higher Cu radwaste stream, and higher CP decay heat

Key Design Parameters

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	ARIES-ST	ARIES-AT
Fusion Power (MW)	3000	2200
Net Electric Power (MW_e)	1000	1000
Aspect ratio	1.6	4
Elongation	3.4	1.9
Major radius (m)	3.2	4.8
Minor radius (m)	2	1.2
Neutron wall loading (MW/m^2)		
Peak outboard	6.4	6.6
Peak inboard	3.7	5.1
Structural material	FS	SiC/SiC
Radiation damage limit	200 dpa	3% burnup
Plant lifetime (FPY)	40	40

ARIES-AT
Inboard Radial Build

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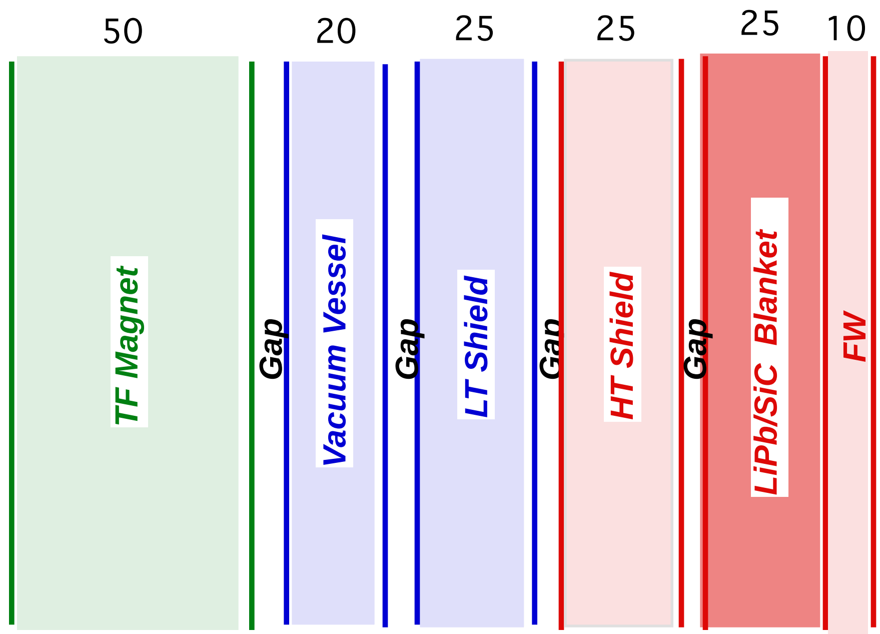

Components	Composition
FW	17% SiC , 26% LiPb, 57% void
Blanket	8% SiC , 92% LiPb
HT Shield	15% SiC, 10% LiPb , 75% B-FS
LT Shield	15% FS , 5% H_2O , 80% WC
Vacuum Vessel	35% FS , 40% H_2O , 25% WC

ARIES-AT
Outboard Radial Build

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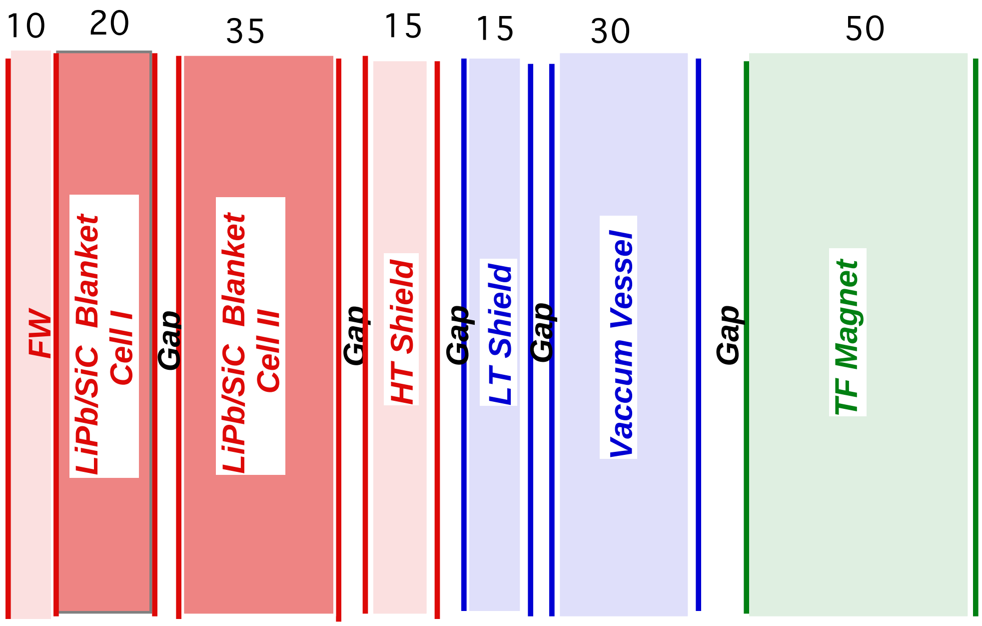

Components	Composition
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HT Shield	15% SiC, 10% LiPb , 75% B-FS
LT Shield	15% FS , 5% H_2O , 80% B-FS
Vacuum Vessel	25% FS , 60% H_2O, 15% B-FS

ARIES-AT Blanket Neutronics

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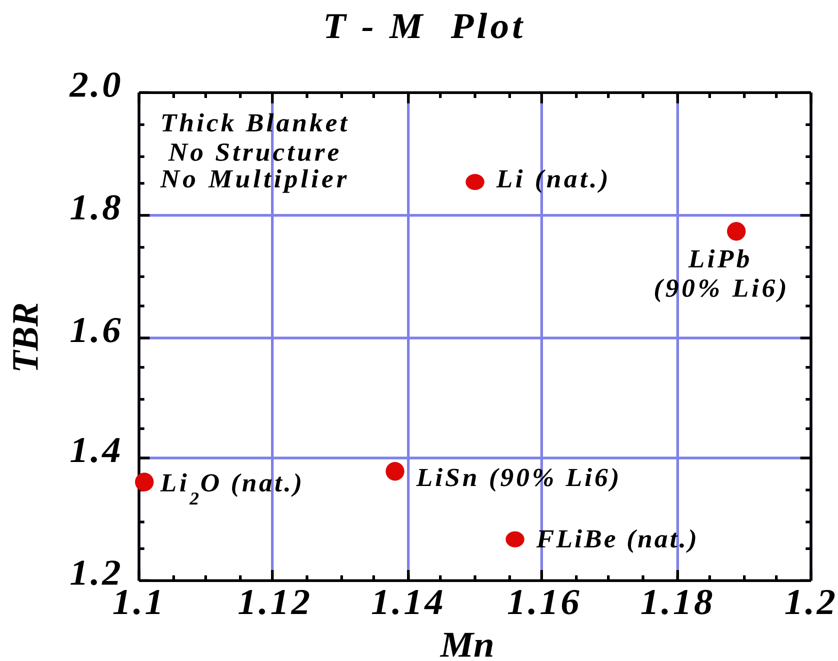
- Three candidate breeders:
  - $Li_{17}Pb_{83}$ - $Li_{25}Sn_{75}$ - F_4Li_2Be



- $Li_{25}Sn_{75}$ and F_4Li_2Be have lower breeding potential than $Li_{17}Pb_{83}$
- Other enrichments yield lower TBR
- Structure, penetrations, and geometry degrade overall TBR to 1.1 or less

ARIES-AT Blanket Neutronics (cont.)

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- Actual designs:

	LiPb/SiC	LiSn/SiC	FLiBe/SiC
Overall TBR	1.1	0.92	0.87

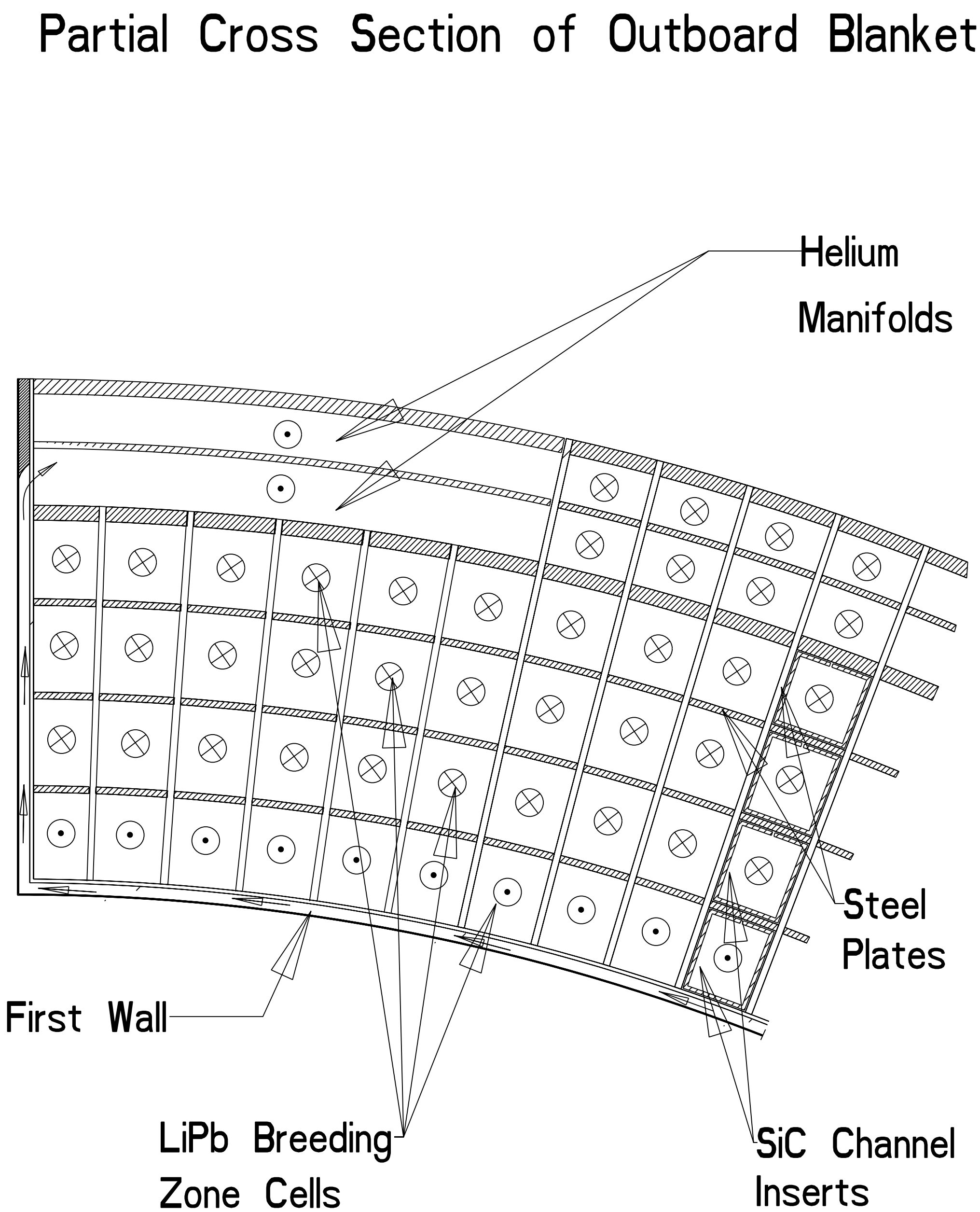
  - For SiC system, LiPb provides highest breeding among ALL breeders
  - Overall TBR of thick LiSn/SiC and FliBe/SiC blankets will not exceed 1.0
  - Need to use Be with LiSn/SiC and FliBe/SiC blankets to achieve TBR of 1.1

- Main features of LiPb/SiC Blanket:
  - 5 cm thick FW (40% SiC, 60% LiPb)
  - 25 cm thick IB blanket (8% SiC, 92% LiPb)
  - 55 cm thick OB blanket (8% SiC, 92% LiPb)
  - 90% enriched Li^6

- 3-D results for LiPb/SiC blanket:

Overall TBR	1.1
Overall Mn	1.1

- Energy recovered from all components except water-cooled LT shield



Cross Section of ARIES-ST Blanket

Shielding Requirements

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- Provide lifetime protection for S/C magnets — $< 10^{19}$ n/cm^2
- Provide lifetime protection for V.V. — < 1 He appm
- Protect workers/personnel — < 2.5 mRem/h
- Power production component
  (< 1% nuclear heating in LT shield)
- OB shield is lifetime component — < 200 dpa for FS; < 3% burnup for SiC
- Reasonable cost
- Attractive safety & environmental characteristics:
  – Compatible with FPC components
  – Low level waste (Class C)
  – No hazardous materials
  – No damage in case of LOCA/LOFA
- Clear as many components as design allows for reasonable cost
- Meet stress and temperature limits
- Reliable, maintainable, replaceable, recyclable

Inboard Shielding Options for ARIES-ST

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- Candidate materials:

Structure	Coolant**	Filler
FS	He	FS
	H_2O	W
	D_2O	WC
	LiPb	WB

- W-based shields are not attractive options:
  - – generates high decay heat
  - – degrades outboard breeding

- Features of candidate inboard shields:

I- Helium cooled FS FW/shield:

+ 20 cm thick shield
+ 400 MW i/b heating recovered
+ high Mn (1.1)
+ acceptable outboard breeding for FS/He shield only
+ safety barrier between CP and blanket
– 25 MW higher Joule losses in CP
– 40 MW_e He pumping power (~90% recovered as thermal heat)

II- Water cooled FS FW/shield:

+ 12 cm thick shield
+ 25 MW lower Joule losses in CP
– marginal outboard breeding
– 400 MW i/b heating dumped as low grade heat
– low Mn (1.0)
– water radiolysis and corrosion problems
– need T removal system for water loop
– larger CP and higher magnet cost

** 20% He or 10% water in shield

Conclusions

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- Nuclear issues that raised most concern are protection of center post and breeding potential of candidate breeders
- Unshielded CP does not offer an attractive design
- LiPb blanket provides adequate breeding with 5% excess breeding capability
- LiSn and FLiBe will not meet breeding requirements unless Be is used in blanket
- Key neutronics results:

Overall TBR	1.1
Overall M_n	1.1
PFC and CP lifetimes	3 FPY
Shield and magnet lifetimes	40 FPY
FW/B EOL Fluence	18 MWy/m^2

- Good agreement obtained between 1-D and 3-D analyses for global values: overall TBR and M_n
- 1-D analysis overestimates local radiation damage to PFCs and underestimates damage at back of blanket/shield