Nuclear and Activation Issues for SiC/SiC Composites

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http://fti.neep.wisc.edu/FTI/POSTERS/lae_ornl.pdf

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Objectives

- Address key nuclear and activation issues for latest SiC-based ARIES design (ARIES-AT):
  - Breeding capability of blanket
  - Lifetime of structural components
  - Activation and decay heat levels
  - Waste disposal rating (WDR)

- Assess impact of nuclear and activation parameters on design choices:

Parameters	Issues
TBR	Breeder type Blanket thickness Li enrichment
Radiation damage	Service lifetime Radial build
WDR	Service lifetime

- Shielding capability of SiC:
  - Limitations
  - Optimal shield design

Key Design Parameters for ARIES-AT

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 , 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

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[*] Between X points

[#] Impact of 3% burnup on SiC properties needs to be assessed by R&D program

Computational Tools: Codes and Data Library Used in Analysis

- 3-D transport code: MCNP – version 4.A
  - Continuous energy
  - Pointwise Xn data

- Discrete ordinate transport code: DANTSYS
  - 1-D and 2-D geometry
  - 175 neutron and 42 gamma group structure
  - P_3-S_8 approximation

- Activation code: ALARA[*] (developed recently @ UW)
  - 175 neutron and 42 gamma group structure
  - Pulsed activation capability

- Most recent FENDL-2 Xn data library

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[*] Analytic and Laplacian Adaptive Radioactivity Analysis

Blanket Neutronics

- Key blanket features:
  - Self-cooled FW/blanket
  - IB and OB blankets only (no blanket behind divertor):
    - 30 cm thick IB FW/blanket
    - 65 cm thick OB FW/blanket
  - 90% enriched breeder
  - 6 cm thick W vertical stabilizing shell
  - CD Penetrations and assembly gaps

- Three candidate breeders (compatible with SiC):

	- $Li_{17}Pb_{83}$	- $Li_{25}Sn_{75}$	- $F_4Li_2Be^{\#}$
TBR	1.1	0.9	0.85

⇒ LiPb is preferred breeder
$Li_{25}Sn_{75}$ and F_4Li_2Be will not meet breeding requirement

- 3-D nuclear parameters for SiC/LiPb design:

Overall TBR	1.1^*
Overall Mn	1.1
SiC Burnup rate	1% per FPY
FW EOL Fluence	18 MWy/m^2
FW Lifetime	3 FPY

- Comments:
  - SiC content in FW has significant impact on breeding level
  - Thicker blanket increases breeding slighltly (~3%)
  - Blanket will not breed with lower enrichment (< 90%) unless Al or Cu shell replaces W shell

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[#] natural Li
[*] a requirement

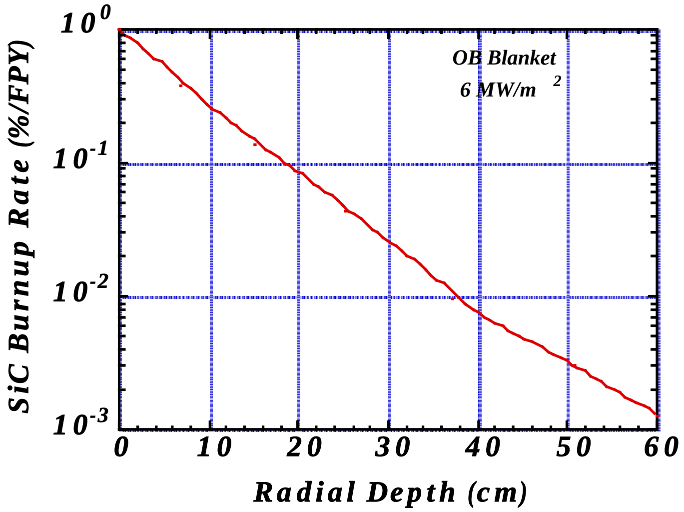
Peak Radiation Damage to SiC FW

	Inboard	Outboard
He appm/FPY	4,800	5,300
H appm/FPY	1,900	2,100
dpa/FPY	60	70
Nuclear Heating (W/cm^3)	25	30

- (n,He) and (n,H) high energy reactions ($E_n > 3$ MeV) transmute Si and C into Al, Mg, Li, and Be
- He production in SiC is excessive (8-10 times that of FS). Impact of He and other transmutations on SiC properties needs to be assessed
- Burnup rate calculations:
  - Each (n,He) or (n,H) reaction with either Si or C atom burns a SiC molecule
- Results: 1% SiC burnup rate per FPY @ 6 MW/m^2:
  - Si burns faster than C (0.7% Si and 0.3% C)

  $\Rightarrow$ More free C atoms than free Si atoms in SiC/SiC composites
  Impact on SiC properties !?

Blanket Segmentation



- Burnup rate drops fast within blanket

- To reduce radwaste stream and replacement cost, segment OB blanket into:
  - 30 cm thick replaceable FW/Blanket-I
  - 35 cm thick permanent Blanket-II*

- Based on 3% burnup limit and peak OB Γ of 6 MW/m^2, components' lifetimes are:

OB FW/B-I	3	FPY
OB B-II	40	FPY
HT shield	40	FPY

- IB blanket will be replaced with OB blanket on same time basis to enhance availability

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* Boundary between replaceable and permanent blankets will be confirmed by 3-D

SiC Shielding Capability

- From the shielding viewpoint, metals are superior to SiC

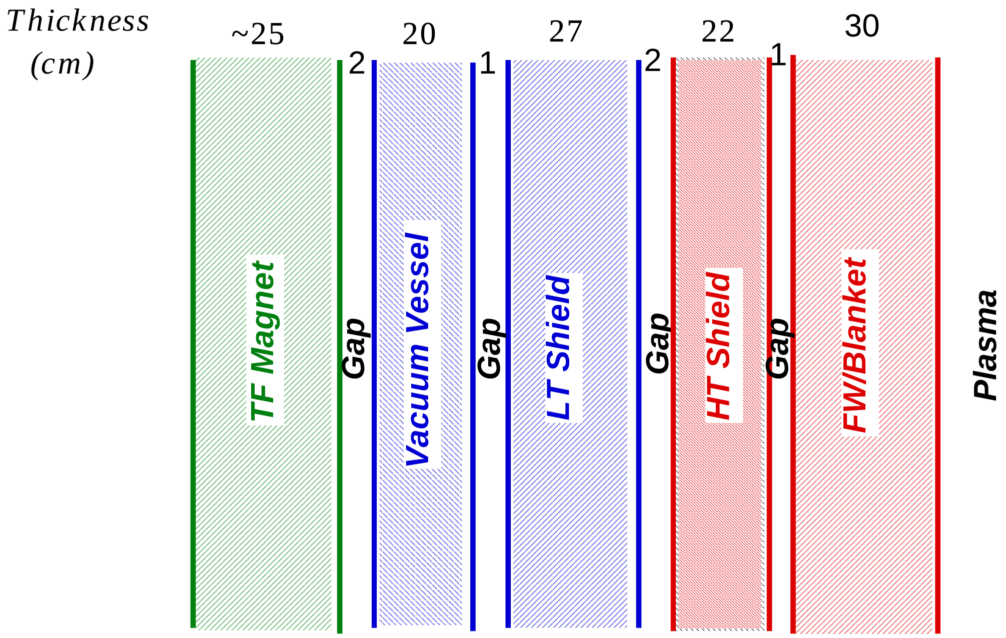
- Shield made entirely out of SiC/SiC composites (400 \$/kg) is extremely expensive

- Shield contains 15-20% of nuclear heating that must be recovered at high temperature (HT) to improve power balance. This means SiC structure should be used in shield

- Recommendations:
  - Divide the shield into HT and LT components (the latter could contain few % of heating)
  - Limit use of SiC structure to HT components
  - Use steel filler with SiC structure for better shielding
  - Employ more efficient, expensive WC and/or B_4C filler for IB shield /V.V. to reduce machine size (monitor decay heat of WC components)
  - Use water to cool LT shield and V.V. to improve shielding performance
  - Optimize composition of shield and V.V.; trade filler for water
  - Size blanket to protect shield for plant life to reduce radwaste stream

- If implemented correctly, design will have attractive features:
  - Compact machine
  - Competitive cost
  - Low radwaste volume/mass

Inboard Radial Build



Component	**Composition**[#]	**Lifetime (FPY)**
FW (1.9 cm)	51% SiC , 49% LiPb	3
Blanket (28.1 cm)	12% SiC , 88% LiPb	3
HT Shield	15% SiC , 10% LiPb , 75% B-FS	40
LT Shield	15% FS , 10% H_2O , 75% WC	40
Vacuum Vessel	35% FS , 65% H_2O	40
HT Magnet	87% SS, 10% LN, 2.5% $Y_1Ba_2Cu_3O_5$, 0.5% Ag	40

- V.V. and TF magnet radiation limits are all met[*] for peak Γ= 4 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

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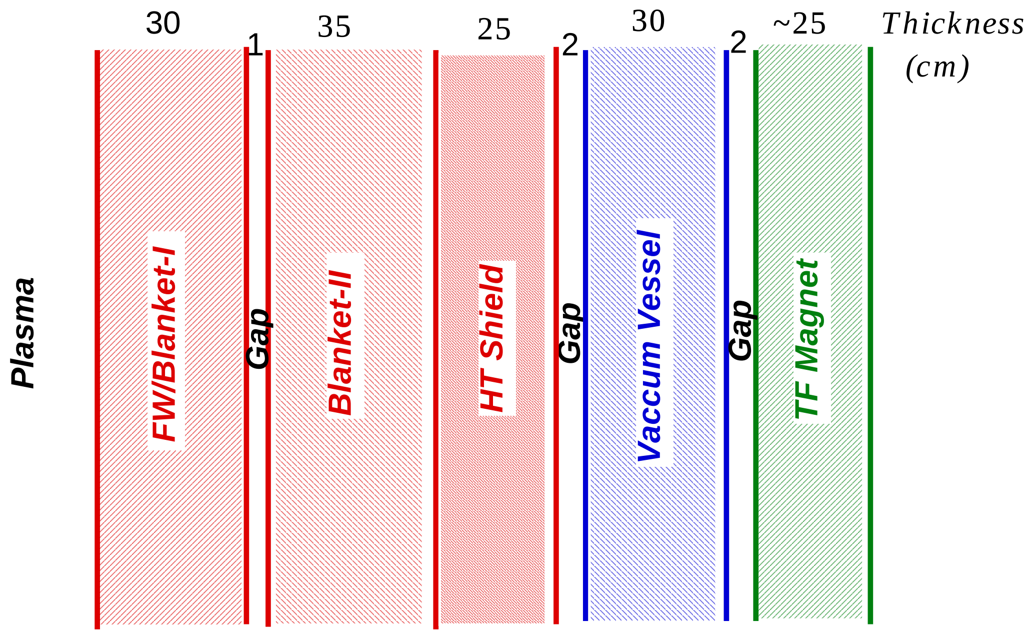

Component	Composition[#]	Lifetime (FPY)
FW/Blanket-I:		3
FW (1.9 cm)	51% SiC , 49% LiPb	
B-I (28.1 cm)	12% SiC , 88% LiPb	
Blanket-II	14% SiC , 86% LiPb	40
HT Shield	15% SiC , 10% LiPb , 75% B-FS	40
Vacuum Vessel	25% FS , 75% H_2O	40
HT Magnet	87% SS, 10% LN, 2.5% $Y_1Ba_2Cu_3O_5$, 0.5% Ag	40

- V.V. and TF magnet radiation limits are all met[*] for peak $\Gamma = 6$ 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

Activation Issues

- SiC has attractive safety features

- Activation 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 with impurities
  - 100% dense compacted 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 @ EOL of individual components

- Clearance and LOCA/LOFA results are not available yet. Analyses are underway

Impurity Levels Considered in SiC-Based ARIES Designs

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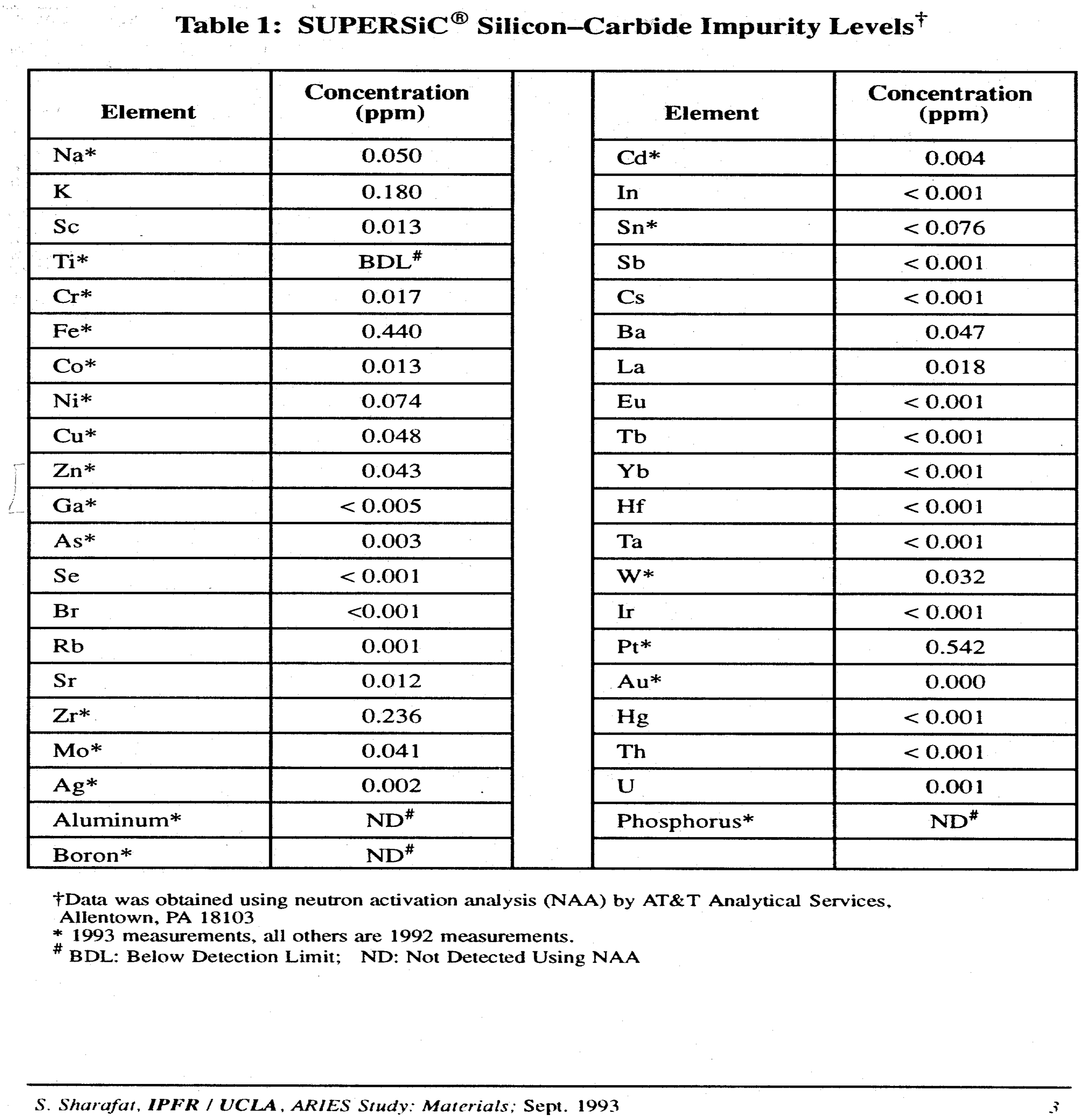


Table 1: SUPERSiC® Silicon–Carbide Impurity Levels[†]

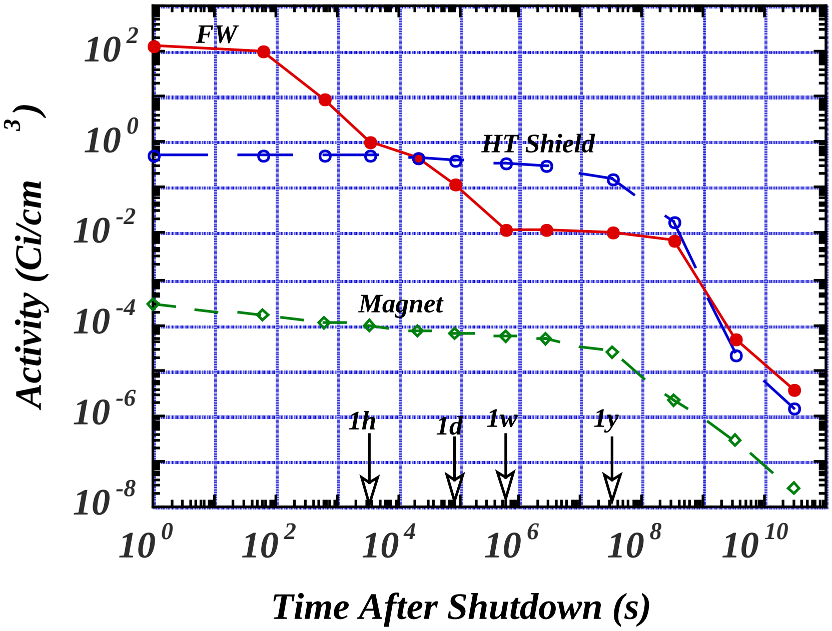
Element	Concentration (ppm)		Element	Concentration (ppm)
Na*	0.050		Cd*	0.004
K	0.180		In	< 0.001
Sc	0.013		Sn*	< 0.076
Ti*	BDL[#]		Sb	< 0.001
Cr*	0.017		Cs	< 0.001
Fe*	0.440		Ba	0.047
Co*	0.013		La	0.018
Ni*	0.074		Eu	< 0.001
Cu*	0.048		Tb	< 0.001
Zn*	0.043		Yb	< 0.001
Ga*	< 0.005		Hf	< 0.001
As*	0.003		Ta	< 0.001
Se	< 0.001		W*	0.032
Br	<0.001		Ir	< 0.001
Rb	0.001		Pt*	0.542
Sr	0.012		Au*	0.000
Zr*	0.236		Hg	< 0.001
Mo*	0.041		Th	< 0.001
Ag*	0.002		U	0.001
Aluminum*	ND[#]		Phosphorus*	ND[#]
Boron*	ND[#]			

[†] Data was obtained using neutron activation analysis (NAA) by AT&T Analytical Services, Allentown, PA 18103

* 1993 measurements, all others are 1992 measurements.

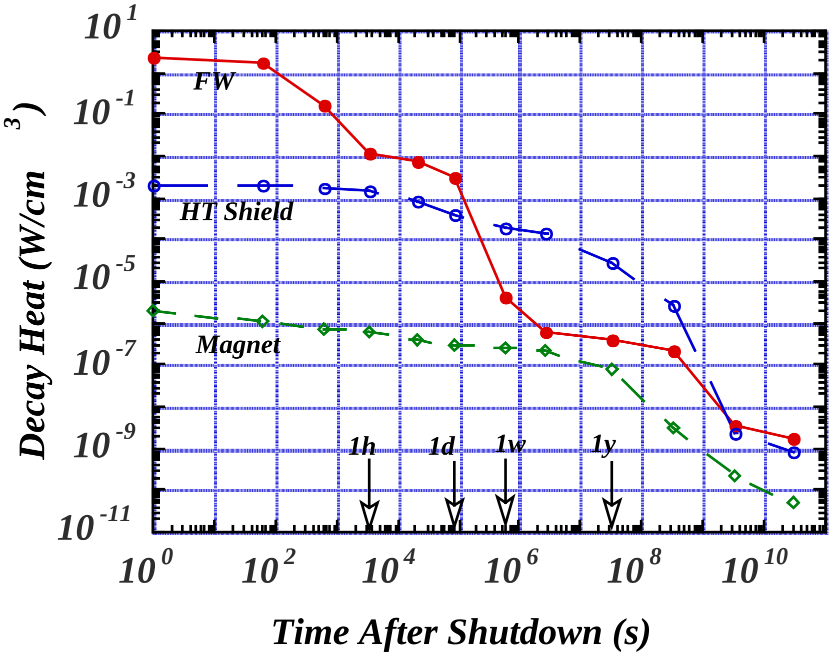
[#] BDL: Below Detection Limit; ND: Not Detected Using NAA

Activity



- FW contains higher activity than B-I and B-II
- SiC activity decays rapidly shortly after shutdown
- Highly irradiated SiC FW generates lower intermediate activity (1d-5y) than well protected FS shield

Decay Heat



- Unlike metals, SiC decay heat drops fast after one minute, meaning slight increase in SiC temperature during LOCA/LOFA events

- In blanket, LiPb breeder may contain higher decay heat than SiC structure
  ⇒ LOFA could be more critical than LOCA

Dominant Radionuclides
@ Various Times After Shutdown
(in descending order)

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Activity:

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

Decay Heat:

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

Class C Waste Disposal Rating

	Fetter's WDR	**NRC WDR**
FW/Blanket-I	0.1 (Al^{26})*	0.02 (C^{14})
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})

- WDR < 1 means component qualifies as Class C low level waste
- Al^{26} is dominant nuclide for Fetter's WDR of SiC components:
  Si^{28} (n , np) Al^{27} (n , 2n) Al^{26}
- C^{14} is dominant nuclide for NRC WDR of SiC components:
  C^{12} (n , γ) C^{13} (n, γ) C^{14}

Highly irradiated SiC blanket qualifies easily as Class C LLW after 3 FPY

For SiC, radiation damage limit is more restrictive life limiting factor than waste disposal limit

Impact of brazing materials on SiC WDR will be assessed

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* Dominant radionuclides in descending order

Conclusions

- SiC blanket with LiPb breeder provides adequate breeding (TBR=1.1). Other $Li_{25}Sn_{75}$ and F_4Li_2Be breeders will not meet breeding requirement unless Be is incorporated in blanket

- 3% burnup limit results in EOL fluence of 18 MWy/m^2 and service lifetime of 3 FPY for SiC components opertating at 6 MW/m^2

- Activation analysis performed so far identified no safety concerns for SiC components:
  - Unlike metals, SiC activity and decay heat drop rapidly by 3 orders of magnitude in one day, meaning slight increase in SiC temperature during LOCA/LOFA events
  - SiC radwaste qualifies easily as Class C LLW, meaning simplified waste management