

Nuclear damage Parameters for SiC/SiC Composite in Fusion Systems

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He/dpa ratio is significantly higher than in a fission reactor nuclear environment (~10 vs. ~0.3 for FS)
Effect more pronounced for SiC (~90 vs. ~1 for SiC)

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Application of SiC/SiC WISCONSIN Composites in Fusion Systems

- SiC/SiC composites have been considered for use in fusion systems
- Because of their low induced radioactivity and high temperature operation they represent an attractive candidate for structural material
- They have been proposed as structural material for FW and blanket in several MFE and IFE designs
- SiC/SiC composite is the preferred structural material for FW and blanket of the HAPL IFE design with magnetic intervention
- SiC/SiC composites are considered for use as flow channel inserts (FCI) in dual coolant lithium lead blanket (DCLL). They provide electrical insulation to mitigate MHD effects and thermally isolate the high temperature LiPb from the low temperature helium cooled FS
- Lifetime of SiC/SiC composites in fusion radiation environment is a major critical issue
- Radiation effects in fiber, matrix, and interface components represent important input for lifetime assessment
- Impact of radiation on insulating properties of FCI is also a critical issue

High Average power Laser (HAPL) Conceptual Design



- Direct drive targets
- Dry wall chamber
- 40 KrF laser beams
- 367.1 MJ target yield
- 5 Hz Rep Rate
- 6 MW/m² peak NWL

- Dry wall must accommodate ion and photon threat spectra from target
- Extreme flux of intermediate energy ions pose a significant issue of extremely high pulsed temperatures and erosion/ablation of FW
- Magnetic intervention used to steer ions away from chamber wall
- Large fraction of magnetic energy can be dissipated in chamber walls if an electrically resistive structural material is used (SiC/SiC)
- LiPb or Flibe self-cooled blankets used
- 1 cm Be insert used in FW coolant channel with Flibe for tritium selfsufficiency

Nuclear Analysis for SiC/SiC in WISCONSIN Fusion Environment

- Radiation parameters determined for SiC/SiC composites for MFE and IFE systems
- Configurations of ARIES-AT advanced tokamak and HAPL laser fusion conceptual designs were used



ARIES-AT

HAPL



Calculation of damage Parameters

- Rates of dpa, He production, H production, and % burnup calculated for both sublattices of SiC fiber/matrix and interface material
- The cross section library includes all partial reaction cross sections required to determine gas production and transmutations
- The library includes the damage energy cross sections needed to determine the atomic displacements
- Used recommended displacement energies for SiC, namely 20 and 40 eV for the C and Si sublattices, respectively
- Leading interface material candidates are graphite and multilayer SiC
- Damage parameters for the SiC interface material are identical to those for the SiC fiber/matrix
- Damage parameters for the graphite interface material are same as those for C sublattice of SiC except for dpa due to the higher (30 eV) displacement energy

Peak Damage Parameters in WISCONSIN OB SIC/SIC FW of MFE System

LiPb Blanket

	C Sublattico	Si Sublattico	SiC	Graphite
	Sublattice	Sublattice		Interlace
dpa/FPY	112	97	105	75
He appm/FPY	15858	4001	9930	15858
H appm/FPY	3	7309	3656	3
% Burnup/FPY	0.64	1.13	1.77	0.64

Flibe Blanket

	С	Si	SiC	Graphite
	Sublattice	Sublattice		Interface
dpa/FPY	52	66	59	35
He appm/FPY	16633	4473	10553	16633
H appm/FPY	3	8064	4033	3
% Burnup/FPY	0.68	1.25	1.93	0.68

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Observations on Peak Damage WISCONSIN Parameters in MFE System

- Idpa rates in C and Si sublattices of the SiC fiber/matrix are comparable
- Idpa rate in graphite interface is 33% lower than in C sublattice of SiC
- He production rate in C sublattice of SiC and graphite interface is about a factor of 4 higher than in Si sublattice of SiC and is dominated by the (n,n³α) reaction
- He production rate in graphite interface is 60% higher than average He production rate in the SiC fiber/matrix
- Significant hydrogen production occurs in Si with a negligible amount produced in C
- Burnup rate of Si sublattice is twice that for C sublattice of SiC fiber/matrix and graphite interface



Comments on Burnup of SiC

- Burnup of Si sublattice is about a factor of 2 more than that for C sublattice
- The burnup is equivalent to introducing impurities in the sublattices of the SiC
- Property degradation depends on the kind of impurities introduced
- Transmutation of Si produces primarily Mg and Al with smaller amount of P and main transmutation product for C is Be with smaller amount of B and Li
- Nonstoichiometric burnup of Si and C is expected to be worse than stoichiometric burnups and could be an important issue for SiC

Impact of Breeder/Coolant on SiC/SiC Damage Parameters



- Peak dpa values with Flibe are about half those with LiPb
- Peak gas production and burnup rates with Flibe are higher by 3-10% than with LiPb
- Idpa values with Flibe have steeper radial drop compared to that in LiPb blanket while gas production and burnup rates have slightly less steep radial drop
- Flibe is more effective attenuating intermediate energy neutrons while LiPb is more effective attenuating high-energy neutrons

Neutron Energy Spectra at FW WISCONSIN for LiPb and Flibe Blankets



	LiPb	Flibe
	Blanket	Blanket
Total Neutron	4.3×10^{15}	3x10 ¹⁵
Flux (n/cm ² s)		
Average Energy	2.67	3.76
(MeV)		

- Harder spectrum with Flibe
- Larger total neutron flux with LiPb due to increased secondary neutron production from Pb that are mostly in the 10 keV to 2 MeV range
- These intermediate energy neutrons result in higher dpa with LiPb
- High energy flux (E>2 MeV) is much smaller with LiPb resulting in lower gas production and burnup rates

Different Features of IFE Systems

Significant geometrical, spectral and temporal differences between IFE and MFE systems affect radiation damage levels with impact on lifetime assessment

Geometrical differences:

Point source in IFE \Rightarrow Source neutrons in IFE chambers impinge on the FW/blanket in a perpendicular direction \Rightarrow For same NWL, lower radiation effects at FW with smaller radial gradient in blanket



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Different Features of IFE Systems

Spectral differences:

- Fusion neutron interactions in compressed IFE target result in considerable softening of neutron spectrum incident on the FW/ blanket in IFE chambers
- Softened source neutron spectrum with 10-13 MeV average energy depending on target ρR with some neutron multiplication (~1.05)



- Combined geometrical and spectral differences impact time-integrated radiation damage parameters
- Simple scaling of radiation effects with neutron wall loading between IFE and MFE systems is inappropriate

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Peak Damage Parameters in WISCONSIN SIC/SIC FW of HAPL

LiPb Blanket

	С	Si	SiC	Graphite
	Sublattice	Sublattice		Interface
dpa/FPY	111	82	96	73
He appm/FPY	7718	2106	4912	7718
H appm/FPY	5	3783	1894	5
% Burnup/FPY	0.32	0.59	0.91	0.32

Flibe Blanket

	С	Si	SiC	Graphite
	Sublattice	Sublattice		Interface
dpa/FPY	45	47	46	30
He appm/FPY	8096	2388	5242	8096
H appm/FPY	5	4252	2129	5
% Burnup/FPY	0.35	0.66	1.01	0.35

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Comparison between FW Neutron Spectra in IFE and MFE



- Calculated total neutron flux values at FW are nearly identical in both systems for the same NWL
- Spectrum is softer in IFE system with average energy of 1.66 MeV compared to 2.67 MeV in MFE system

Comparison between FW Damage Parameters in IFE and MFE

- Peak values for the same neutron wall loading are significantly different
- Gas production and burnup rates are about a factor of 2 lower in IFE system compared to that in MFE system with the same NWL
- The peak dpa rate in IFE is lower than that in the OB region of MFE by ~7% for LiPb blanket and ~20% for Flibe blanket
- These differences are due to geometrical and spectral differences between IFE and MFE systems



Pulsed Effects in IFE Systems

- In IFE chamber neutron source has a pulsed nature
- Energy spectrum of neutrons from target results in time of flight spread and backscattering from blanket extends period over which a particular radiation effect takes place
- Time spread is larger for radiation effects produced by lower energy neutrons (time spread of dpa larger than that for gas production and transmutation)



Pulsed Effects in IFE Systems (Cont'd)

- Peak instantaneous damage rates in IFE FW/blanket are ~5 to 8 orders of magnitude higher than steady state damage rates produced in MFE systems
- Difference in time spread results in higher instantaneous He/dpa ratios in IFE systems compared to MFE systems
- Time dependent neutronics analysis is necessary for subsequent microstructure evolution analysis
- Analysis is underway to determine pulsed instantaneous damage parameters in SiC/SiC FW of HAPL and couple results with microstructure evolution analysis

Pulsed Damage parameters in WISCONSIN HAPL SIC/SIC FW



Temporal peaking factor is significantly higher for He production than for atomic displacement (8.7x10⁷ vs. 1.1x10⁷)

Peak instantaneous He/dpa ratio is much higher than that determined from the temporal average (cumulative) values (368 vs. 47)

Use of SiC FCI as Insulator in WISCONSIN DCLL Blanket

- The Dual Coolant Lithium Lead (DCLL) blanket concept is the preferred US blanket concept for commercial fusion plants
- It provides a pathway to high outlet temperature with current generation structural materials
- A key element is use of SiC (foam or composite) flow channel inserts (FCI) for electrical and thermal insulation



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Peak Damage Parameters in WISCONSIN Sic FCI of DCLL Blanket

Neutronics calculations for the DCLL concept in OB region of MFE system with a NWL of 6 MW/m^2

	С	Si	SiC	Graphite
	Sublattice	Sublattice		Interface
dpa/FPY	76	65	70	51
He appm/FPY	9500	2462	5977	9500
H appm/FPY	2	4485	2238	2
% Burnup/FPY	0.38	0.69	1.07	0.38

- Relative values for different constituents are similar to those obtained for the SiC/SiC FW of self-cooled LiPb blanket
- Damage parameter values are lower by ~40% due to attenuation in the 3 cm thick He-cooled ferritic steel FW



Metallic Transmutation Products in SiC FCI

- FCI is not a structural element and main concern is degradation in its primary role as electrical and thermal insulator
- Degradation in resistivity results from introduction of metallic transmutation products
- Transmutation calculations using the ALARA code determined rate of build-up of different metallic transmutation products



 Dominant metallic transmutation product is Mg that builds up to ~0.43 at% concentration at the expected lifetime of a DCLL blanket in a fusion power plant
It is essential to assess impact of these levels on electrical and thermal conductivities of FCI to determine if it will restrict lifetime of the DCLL to less than that determined by radiation damage to ferritic steel FW

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- Radiation damage parameters in SiC/ SiC composite have strong dependence on the blanket design (coolant, breeder) and plasma confinement approach (MFE, IFE)
- Input needed from materials community regarding appropriate lifetime criterion