Damage Production and Accumulation in SiC Structures in Inertial and magnetic Fusion Systems

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Application of SiC/SiC Composites in Fusion

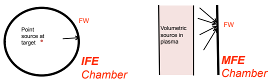
- SiC/SiC composites have been proposed as structural material for FW and blanket in several MFE) and IFE power plants because of their low induced radioactivity and high temperature operation
- SiC/SiC composite is preferred structural material for High Average Power Laser (HAPL) design with magnetic intervention due to its large electrical resistivity that allows dissipating magnetic energy resistively
- Radiation effects on fiber, matrix, and interphase must be properly assessed for determination of component lifetime and performance under irradiation
- We determine the key radiation damage parameters and highlight the significant geometrical, spectral and temporal differences that exist between IFE and MFE systems
- Self-cooled blanket concepts with LiPb and Flibe were analyzed

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

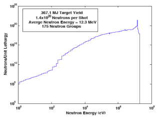
Geometrical differences:

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



Spectral differences:

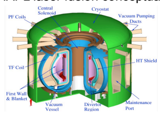
- Fusion neutron interactions in compressed IFE target result in considerable softening of neutron spectrum incident on the FW/blanket in IFE chambers
- Softened source neutron spectrum with 10-13 MeV average energy depending on target ρR with some neutron multiplication (~1.05)



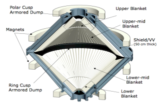
- Combined geometrical and spectral differences impact time-integrated radiation damage parameters
- Simple scaling of radiation effects with neutron wall loading between IFE and MFE systems is inappropriate

Nuclear Analysis for SiC/SiC in Fusion

- 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



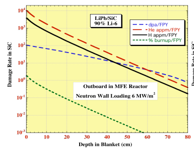
ARIES-AT



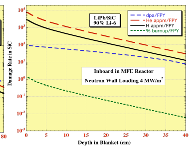
HAPL

		dpa/ FPY	He appm/ FPY	H appm/ FPY	% Burnup/ FPY
MFE System					
C	LiPb	112	15858	3	0.64
	Flibe	52	16633	3	0.68
Si	LiPb	97	4001	7309	1.13
	Flibe	66	4473	8064	1.25
SiC	LiPb	105	9930	3656	1.77
	Flibe	59	10553	4033	1.93
Graphite	LiPb	75	15858	3	0.64
	Flibe	35	16633	3	0.68
IFE System					
C	LiPb	111	7718	5	0.32
	Flibe	45	8096	5	0.35
Si	LiPb	82	2106	3783	0.59
	Flibe	47	2388	4252	0.66
SiC	LiPb	96	4912	1894	0.91
	Flibe	46	5242	2129	1.01
Graphite	LiPb	73	7718	5	0.32
	Flibe	30	8096	5	0.35

Radial Variation of Damage Parameters in OB and IB MFE LiPb Blankets

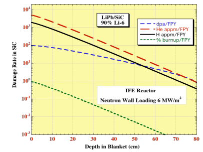


OB LiPb Blanket

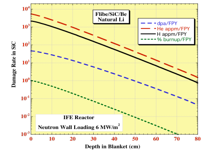


IB LiPb Blanket

Radial Variation of Damage Parameters in IFE Blanket



LiPb Blanket



Flibe Blanket

Observations on Peak Damage Parameters

- dpa rates in C and Si sublattices of the SiC fiber/matrix are comparable
- dpa rate in graphite interface is 33% lower than in C sublattice of SiC
- He production rate in C sublattice of SiC and graphite interphase is about a factor of 4 higher than in Si sublattice of SiC and is dominated by the (n,n´3α) reaction
- He production rate in graphite interphase 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 interphase
- Gas production and burnup drop faster as one moves deeper in blanket

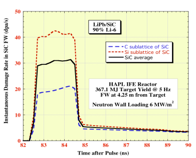
Comments on SiC Burnup

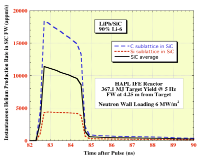
- Burnup of Si sublattice is about a factor of 2 more than that for C
- The burnup is equivalent to introducing impurities in the sublattices of the SiC
- Property degradation depends on the kind of impurities introduced
- Transmutation of Si produces primarily Mg and Al with smaller amount of P and 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

Comparison between 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
- Gradient of damage profile as one moves away from FW is smaller in IFE than in MFE

Pulsed Damage parameters in HAPL SiC/SiC FW





		Temporal Peak	Time Average	Peak/ Average
dpa/s				
C	LiPb	21.25	3.24×10^{-6}	6.6×10^{6}
	Flibe	20.56	1.23×10^{-6}	1.7×10^{7}
Si	LiPb	42.58	2.35×10^{-6}	1.8×10^{7}
	Flibe	42.50	1.27×10^{-6}	3.4×10^{7}
SiC	LiPb	31.39	2.80×10^{-6}	1.1×10^{7}
	Flibe	30.96	1.25×10^{-6}	2.5×10^{7}
He appm/s				
C	LiPb	18410	2.02×10^{-4}	9.1×10^{7}
	Flibe	18410	2.05×10^{-4}	9.0×10^{7}
Si	LiPb	4404	5.96×10^{-5}	7.4×10^{7}
	Flibe	4410	6.48×10^{-5}	6.8×10^{7}
SiC	LiPb	11407	1.31×10^{-4}	8.7×10^{7}
	Flibe	11410	1.35×10^{-4}	8.5×10^{7}

- Temporal peaking factor is significantly higher for He production than for atomic displacement (8.7×10^7 vs. 1.1×10^7)
- Peak instantaneous He/dpa ratio is much higher than that determined from the temporal average (cumulative) values (368 vs. 47)

Defect Production in SiC/SiC Composites

- Production of lattice defects in SiC results in non-stoichiometric displacements of Si and C atoms, which in turn can result in changes in local chemistry and a wide variety of lattice defects
- Point defects form on the sub-lattices of C and Si independently. Additionally, Si and C atoms can switch positions forming anti-site defects
- The strong directional bonding and mass difference between Si and C atoms render the crystalline form of β-SiC exceptional radiation resistance characteristics
- Molecular dynamics (MD) studies show that replacement collision sequences (RCSs) are improbable, and that the displacement of C atoms is much easier than Si
- Approximately 80% of displacement atoms were shown to be of the carbon-type
- The presence of helium results in further increases in the swelling rate by the gas-driven swelling mechanism

Lifetime Considerations

- The useful lifetime of SiC/SiC composites in a fusion neutron environment presently is only speculated
- Development work to date has determined that the most radiation resistant SiC composites are manufactured from essentially stoichiometric fiber, matrix, and interphase and these constituents behave under irradiation essentially as pure SiC
- Transmutations will likely produce an unbalanced stoichiometry, and depending on the irradiation temperature, this may result in significant microstructural changes
- Loss of strength is expected due to helium bubble formation at the grain boundaries or the presence of low-melting metallic transmutation products
- The extremely high instantaneous damage rates present in IFE can lead to significant microstructure changes
- The high instantaneous dpa rates could result in higher recombination rates with the void growth being inhibited and swelling decreased as compared to the equivalent continuous irradiation case

Conclusions

- Radiation damage parameters in SiC/SiC composite have strong dependence on the blanket design (coolant, breeder) and plasma confinement approach (MFE, IFE)
- Lifetime depends primarily on effect of He and metallic transmutants such as Mg, Al, and Be
- As facilities are not currently available to experimentally simulate the fusion neutron environment, active modeling and experimental activities in this area will provide significant insight into the physics of damage production and accumulation in SiC/SiC composites