SiC Metallic Transmutant Production in Fusion Systems

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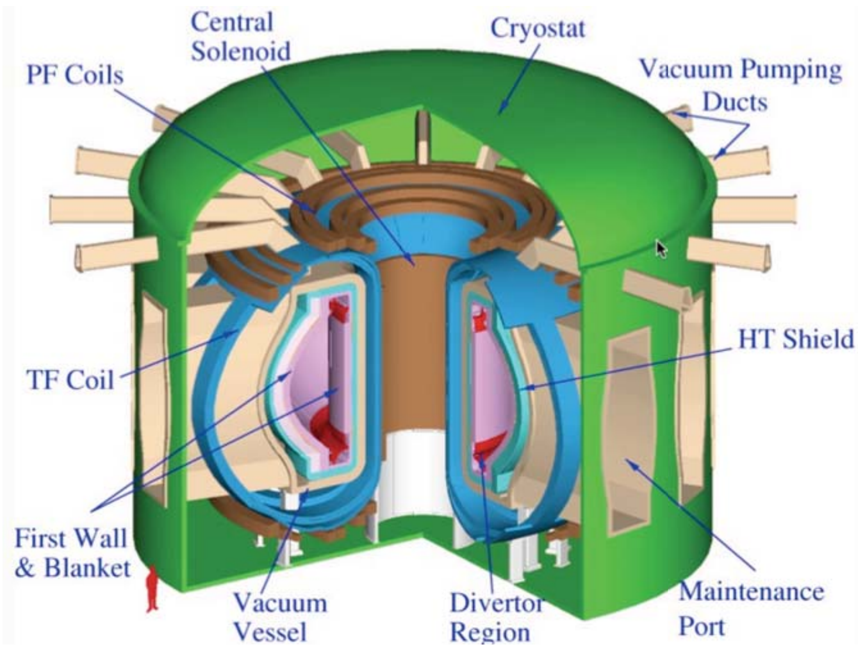
Application of SiC/SiC Composites in Fusion Systems

- 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 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 interphase components represent important input for lifetime assessment
- Neutron irradiation produces metallic transmutants that could change the properties and affect the performance of the SiC/SiC composite

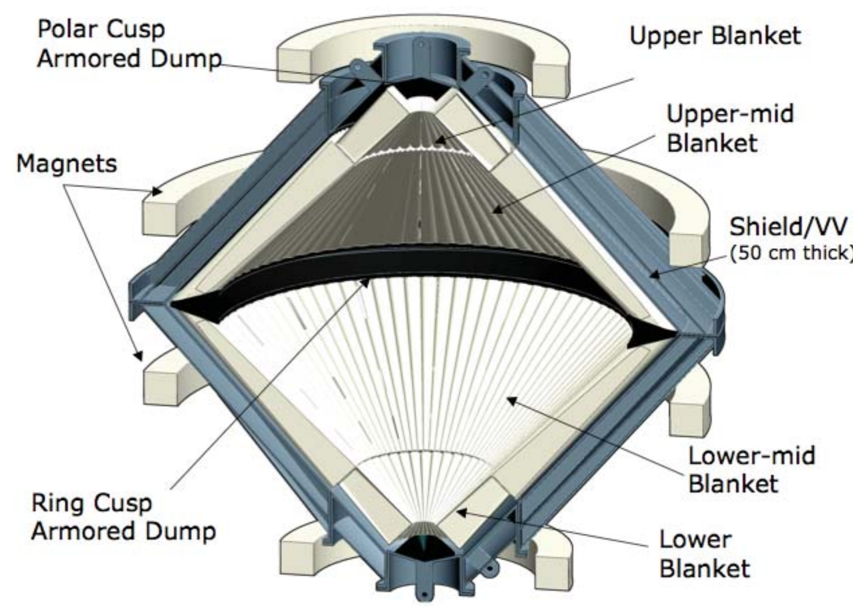
Nuclear Analysis for SiC/SiC in Fusion Environment

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



ARIES-AT

14 MeV source
Glancing incidence



HAPL

Soft source spectrum (11-13 MeV)
Perpendicular incidence

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FW/Blanket Systems Analyzed

- Self-cooled blanket concepts with LiPb and Flibe were analyzed
- Same blanket radial build used in MFE and IFE systems
- The model for LiPb blanket includes a 7-mm thick SiC/SiC composite FW followed by a breeding blanket (90% LiPb enriched to 90% ^{6}Li and 10% SiC/SiC composite structure)
- For the Flibe blanket option, a 7-mm thick FW is followed by 5-mm thick FW coolant channel and a 10-mm thick Be insert followed by the blanket with 90% Flibe (with natural Li) and 10% SiC/SiC composite
- Blanket thickness is 80 cm for IFE and OB region of MFE. 40 cm thick IB blanket used in MFE
- A water cooled steel shield is modeled behind the blanket

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Calculation Approach

- 1D calculations with PARTISN and ALARA codes and FENDL-2.1 data
- For MFE system
  - Cylindrical geometry with ARIES-AT radial build at mid-plane
  - 5.2 m major radius, IB FW radius 3.85 m, OB FW radius 6.55 m
  - Uniform 14.1 MeV source in plasma zone
- For IFE system
  - Spherical geometry with 4.25 m FW radius corresponding to location closest to target
  - Point isotropic neutron source used at center of chamber with softened target energy spectrum (12.3 MeV average)
- Neutron wall loading in IFE system and OB region of MFE system normalized to the same value of 6 MW/m^2. The corresponding value in IB side of MFE is 4 MW/m^2

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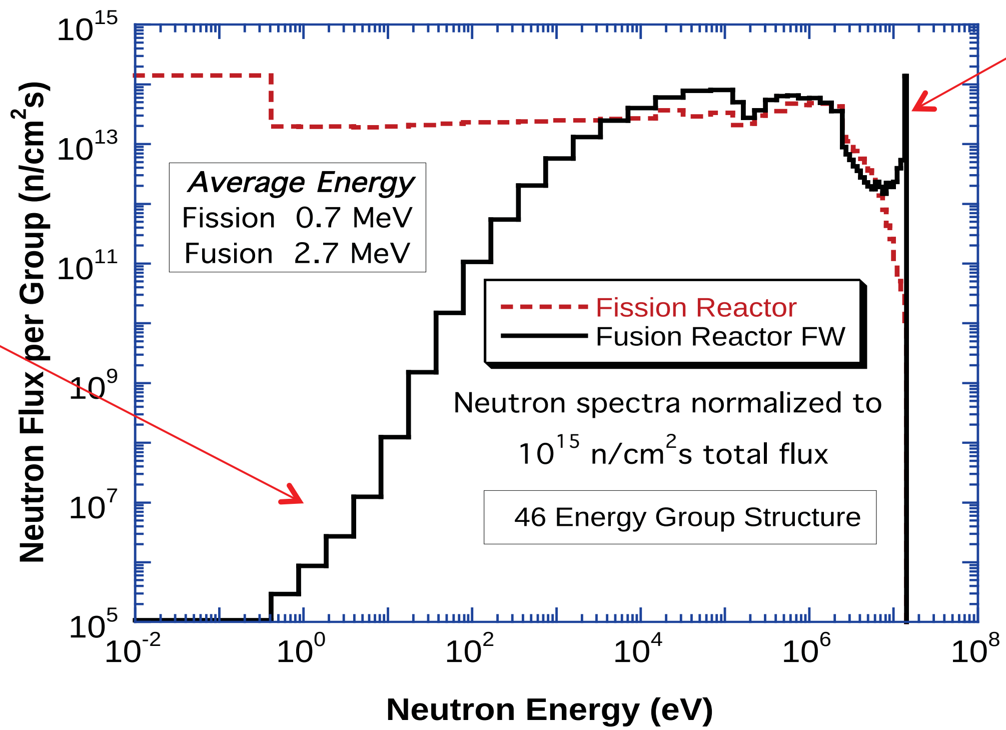
Much Harder Neutron Spectrum in Fusion Compared to Fission



- He/dpa ratio is significantly higher than in a fission reactor nuclear environment (~10 vs. ~0.3 for FS)
- Effect more pronounced for SiC
- Compared radiation parameters in fusion and fission systems

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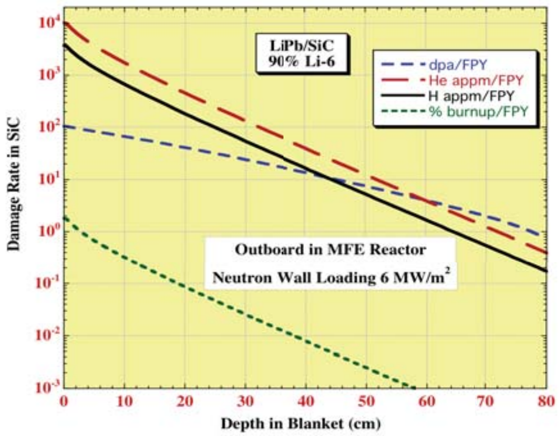
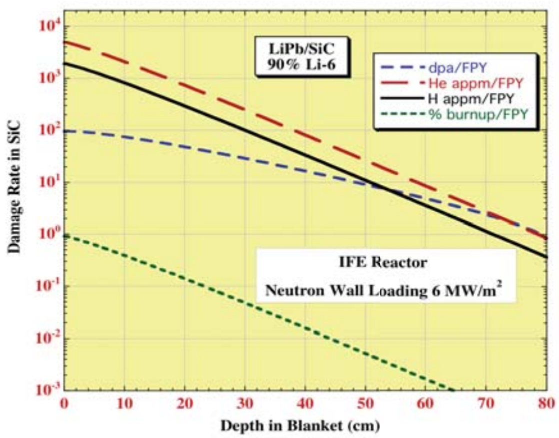
Damage Parameters in MFE and IFE Blankets



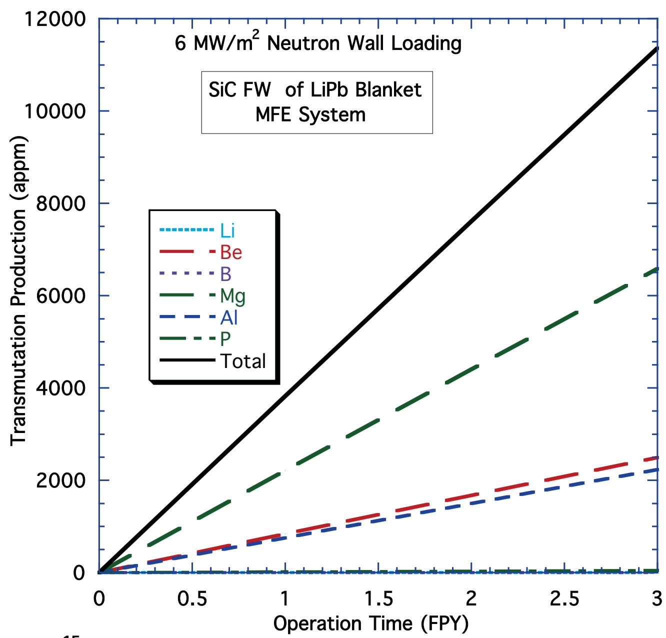


Peak Parameters

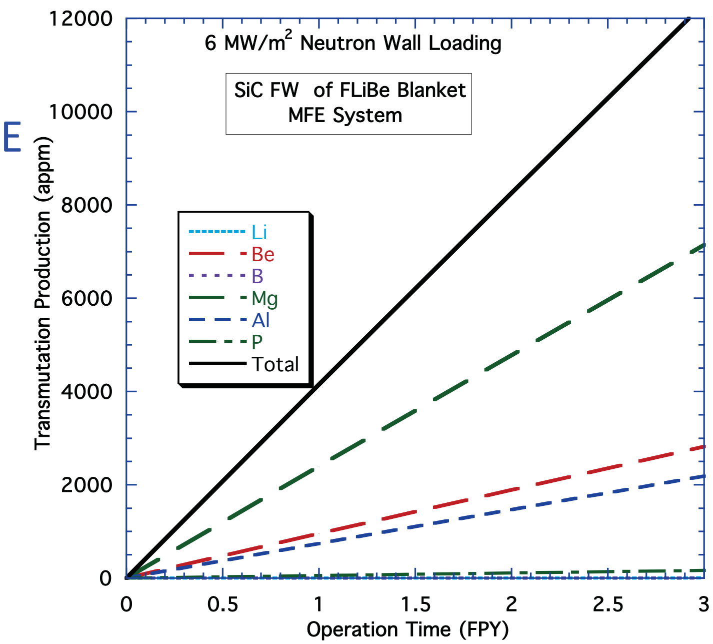
		dpa/ FPY	He appm/ FPY	H appm/ FPY	% Burnup/ FPY
		MFE System			
C	LiPb	112	15858	3	0.64
	Flibe	52	16633	3	0.68
Si	LiPb	97	4001	7309	1.13
	Flibe	66	4473	8064	1.25
SiC	LiPb	105	9930	3656	1.77
	Flibe	59	10553	4033	1.93
Graphite	LiPb	75	15858	3	0.64
	Flibe	35	16633	3	0.68
		IFE System			
C	LiPb	111	7718	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

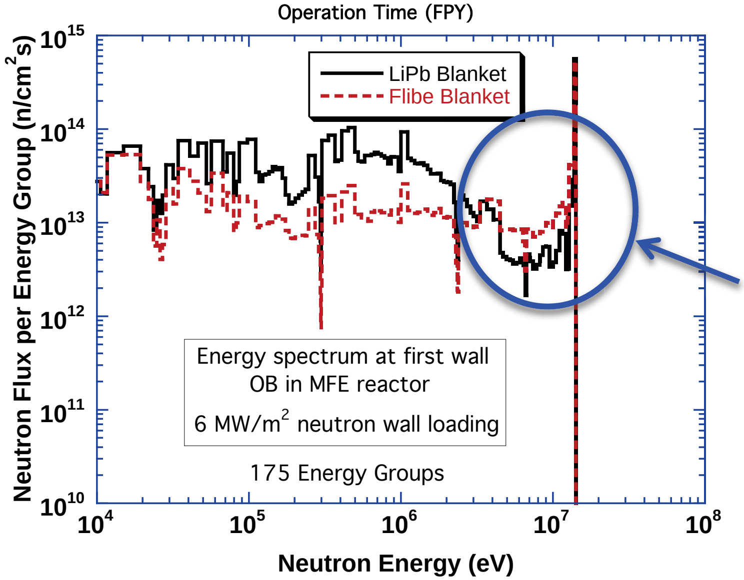
- dpa rates in C and Si sublattices of the SiC fiber/matrix are comparable
- dpa rate in graphite interphase is 33% lower than in C sublattice of SiC
- He production rate in C sublattice of SiC and graphite interphase is about a factor of 4 higher than in Si sublattice of SiC and is dominated by the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

Buildup of Metallic Transmutants Depends on Blanket Design



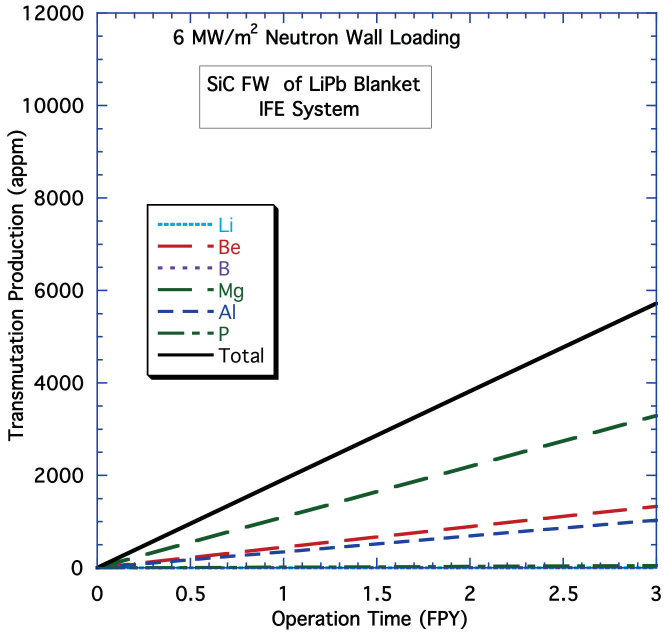
MFE



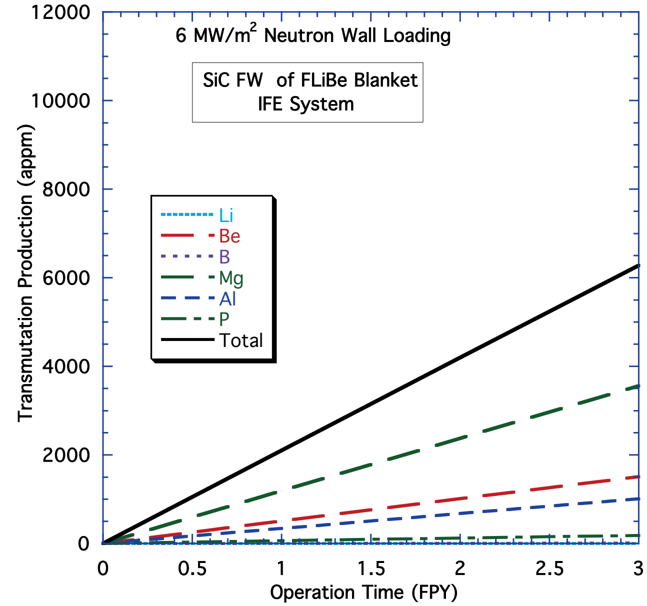


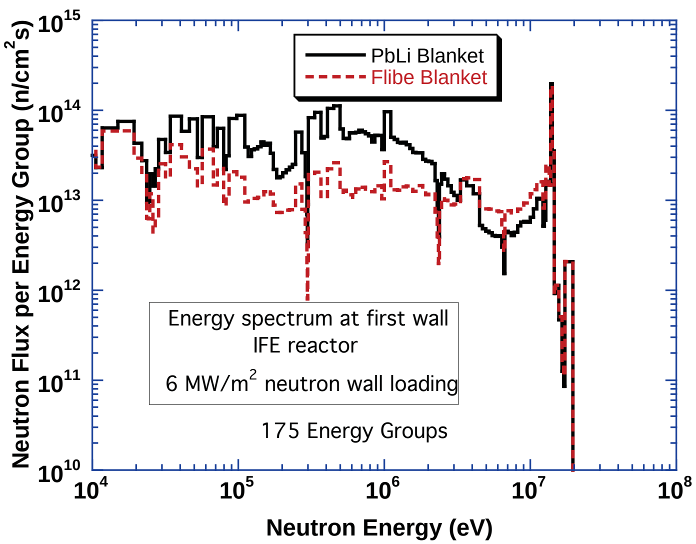
- Transmutation production is slightly higher in Flibe blanket compared to LiPb blanket
- This is due to harder spectrum
- Up to ~1.3% metallic transmutation products are generated in SiC/SiC FW after 20 MWy/m^2

Buildup of Metallic Transmutants Depends on Blanket Design



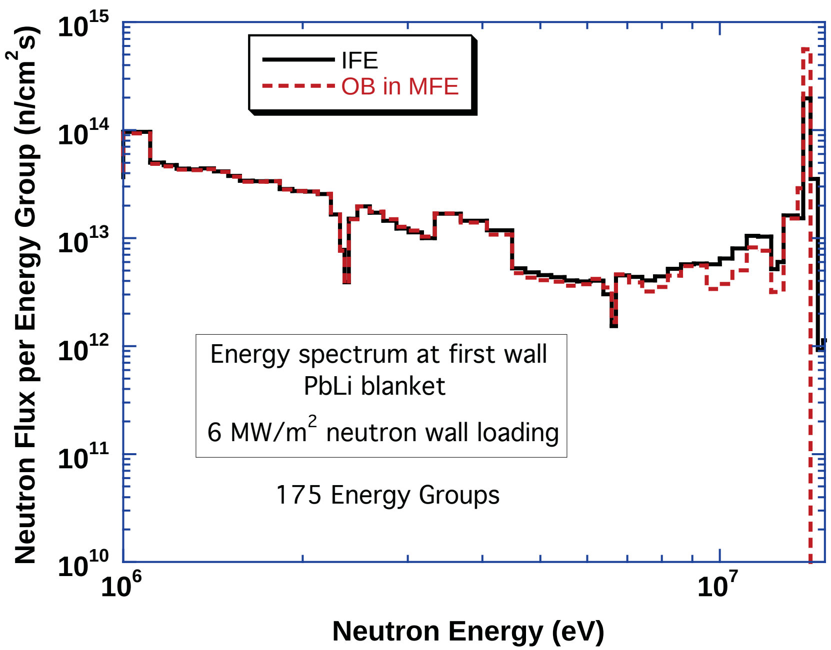
IFE

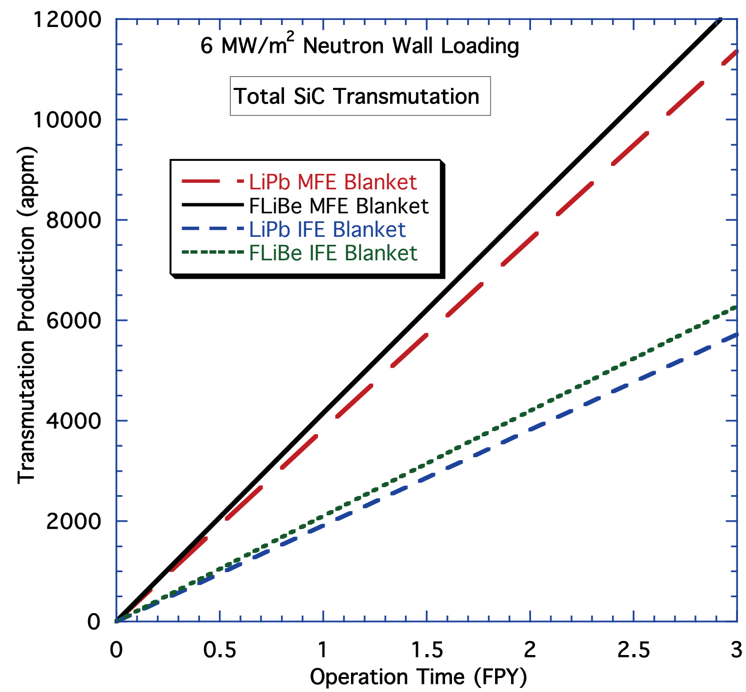




- Transmutation production is slightly higher in Flibe blanket compared to LiPb blanket
- This is due to harder spectrum
- Up to ~0.7% metallic transmutation products are generated in SiC/SiC FW after 20 MWy/m^2

Buildup of Metallic Transmutation Products Depends on Confinement Concept





- Metallic transmutation production in MFE is about twice that in the softer spectrum IFE
- Up to ~1.3% metallic transmutation products are generated in SiC/SiC FW after 20 MWy/m^2
- It is essential to assess impact of these levels on electrical and thermal conductivities and other properties

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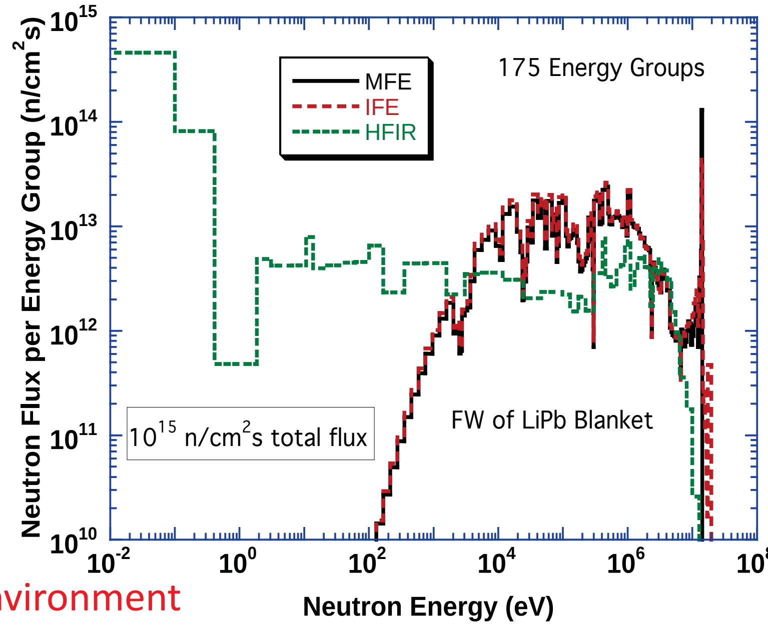
SiC Irradiation in Fission Reactors Produces Much Less He/dpa

- Neutron spectrum in fission reactors is much softer than in FW of fusion systems
- HFIR spectrum from S. Mahmood, et al., "Neutron Dosimetry of the HFIR Hydraulic Facility," ORNL/TM-12831, Feb. 1995



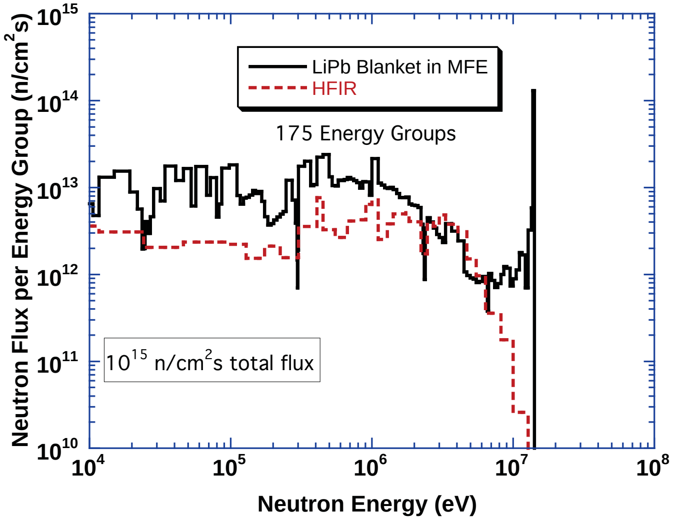
Composition of He/dpa ratio of SiC in Fusion Environment versus Fission (HFIR) Environment

Normalized to 10^{23} n/cm^2 fast neutron (E>0.1 MeV) Fluence

	LiPb-MFE	Flibe-MFE	LiPb-IFE	Flibe-IFE	HFIR
% neutrons at E>0.1 MeV	75.5%	53.7%	71.9%	45%	24.3%
dpa	106	123	104	127	66
He appm	10029	22056	5305	14416	167
He/dpa ratio (appm/dpa)	95	179	51	114	2.5

⇨ He/dpa is about two orders of magnitude lower in fission reactor irradiation

SiC Irradiation in Fission Reactors Produces Much Less Metallic Transmutants



Transmutation of SiC in Fusion Environment vs. Fission (HFIR) Environment

(appm results for a fast neutron fluence of 10^{23} n/cm^2)

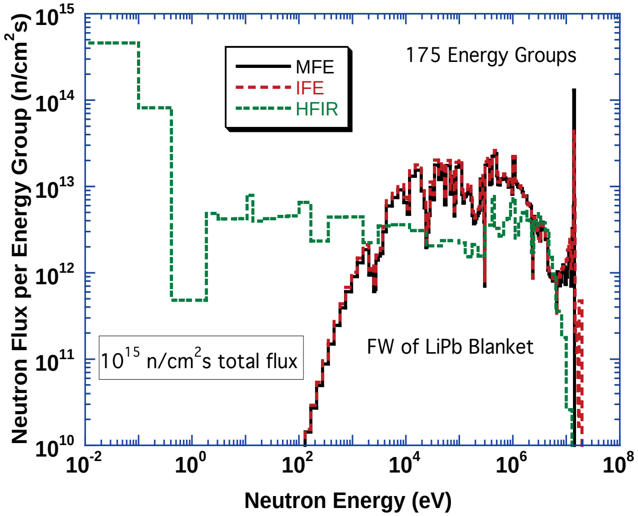
	LiPb-MFE	Flibe-MFE	LiPb-IFE	Flibe-IFE	HFIR
% neutrons at E>0.1 MeV	75.5%	53.7%	71.9%	45%	24.3%
Li	0.6	2.0	0.3	1.4	5.9×10^{-4}
Be	851	1970	482	1386	45
B	0.6	1.3	4.8	12	1.9×10^{-2}
Mg	2232	4973	1189	3263	87
Al	762	1527	374	927	1
P	16.4	116.2	19.6	168	413
Total	3862	8590	2070	5757	546

Transmutation production per dpa in HFIR comparable to previous results by Heinisch J. Nucl. Mat., 327 (2004) 175-181

	P	H	He	Mg	Be
This study	6.2	3.3	2.5	1.3	0.7
Heinisch, 2004	6.1	3.3	2.5	1.5	1.4

Irradiation in fission reactors to same fast neutron fluence yields about an order of magnitude lower transmutation products

SiC Irradiation in Fission Reactors Produces Significantly Different Mix of Metallic Transmutants



- Composition of transmutation products is significantly different in fission reactors compared to FW or deep in blanket of fusion systems
- While Mg is the dominant metallic transmutation product in fusion, P dominates in fission reactor irradiation

Composition of Transmutation Products of SiC in Fusion FW Environment versus Fission (HFIR) Environment

	LiPb-MFE	Flibe-MFE	LiPb-IFE	Flibe-IFE	HFIR
Li	0.014%	0.024%	0.013%	0.023%	0.0001%
Be	22.03%	22.94%	23.29%	24.07%	8.31%
B	0.016%	0.016%	0.237%	0.207%	0.0035%
Mg	57.79%	57.89%	57.45%	56.68%	15.88%
Al	19.73%	17.78%	18.07%	16.10%	0.15%
P	0.42%	1.35%	0.94%	2.92%	75.65%

Composition of Transmutation Products of SiC in FW and FLiBe Blanket IFE Fusion Environment versus Fission (HFIR) Environment

	Flibe-IFE-FW	Flibe-IFE-Blanket	HFIR
Li	0.023%	0.006%	0.0001%
Be	24.07%	25.3%	8.31%
B	0.207%	0.2%	0.0035%
Mg	56.68%	56.5%	15.88%
Al	16.10%	11.8%	0.15%
P	2.92%	6.2%	75.65%

- Mg and Al produced by high energy reactions with Si
- Li, Be, and B produced by high energy reactions with C
- P produced by low energy reactions with Si

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Effects of Transmutation on Electronic Properties May be Overwhelming

- In HFIR neutronic environment, no significant transmutation effect is anticipated.
- In doping treatment of SiC semiconductors,
  - P doping to 0.1-1000 ppm is used to alter electrical properties.
  - Methods of P doping include nuclear transmutation doping (NTD).
  - Al doping to <0.1 ppm is typically used to alter electronic properties.
- Collective effects of transmutation doping of various elements on electronic properties are unknown.

Ohshima et al, Mater. Sci. Forum, 2000

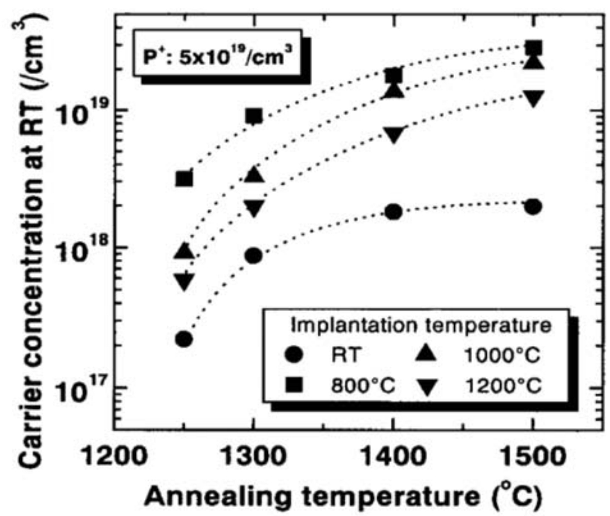

Fig. 1 Annealing temperature dependence of the carrier concentration at RT in 6H-SiC implanted with P^+ at RT, 800, 1000 and 1200 °C.

Effects of Metallic Impurities on Other Properties of SiC

- Al in SiC is known to enhance oxidation by carrying oxygen in silica scale which serves as an oxidation barrier without Al.
- Mg – SiC system is known to produce Mg_2Si at elevated temperatures.
  $4Mg + SiO_2 \rightarrow Mg_2Si + 2MgO$
  reaction is anticipated to alter oxidation behavior of SiC.

Costello and Tressler, Ceram. Int'l, 1985

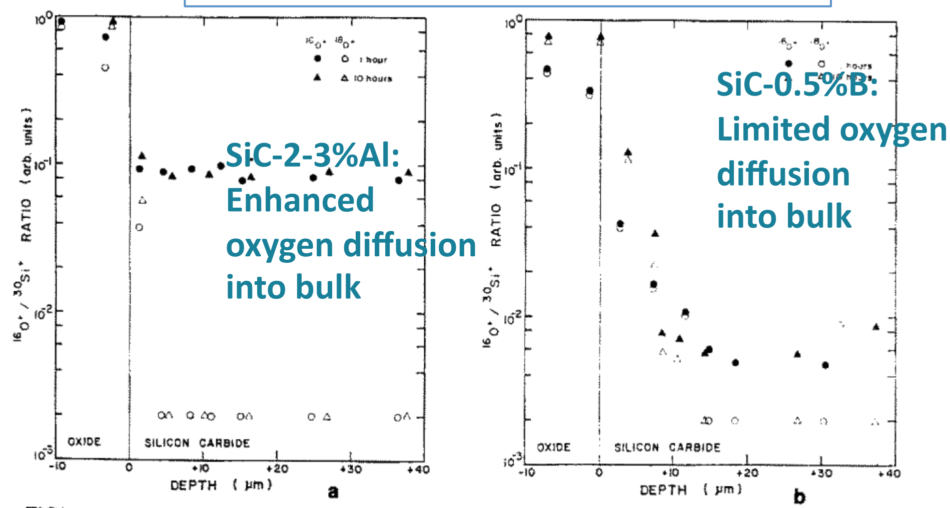

FIGURE 5 - Oxygen isotope profiles into (a) hot pressed silicon carbide, and (b) sintered alpha silicon carbide oxidized at 1300°C for 1 and 10 hours.

- Combined effects of massive production of transmutant Mg, Al, and Be is unknown but potentially significant on oxidation, transport properties (electrical and thermal), and elevated temperature mechanical properties of SiC.

Conclusions

- Radiation damage parameters in SiC/SiC composite have strong dependence on 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
- Metallic transmutation products of total amount ~1.3% are produced in fusion systems
- Amount and mix of transmutation products are very different from that in fission reactor irradiation
- Combined effects of massive production of transmutant Mg, Al, and Be is unknown but potentially significant on oxidation, transport properties (electrical and thermal), and elevated temperature mechanical properties
- Since irradiation in fission reactors is not adequate we need to do experiments using ion implantation and/or high energy neutron source
- As facilities are not currently available to experimentally simulate the fusion neutron environment, active modeling in this area will provide significant help understanding effects on properties