Transmutation Effects on SiC/SiC Composites (Calculations)

L. El-Guebaly and M. Sawan
Fusion Technology Institute
University of Wisconsin-Madison
http://fti.neep.wisc.edu/UWNeutronicsCenterOfExcellence

Contributors:
Y. Katoh (ORNL), L. Snead (MIT), N. Ghoniem (UCLA), P. Wilson (UW)

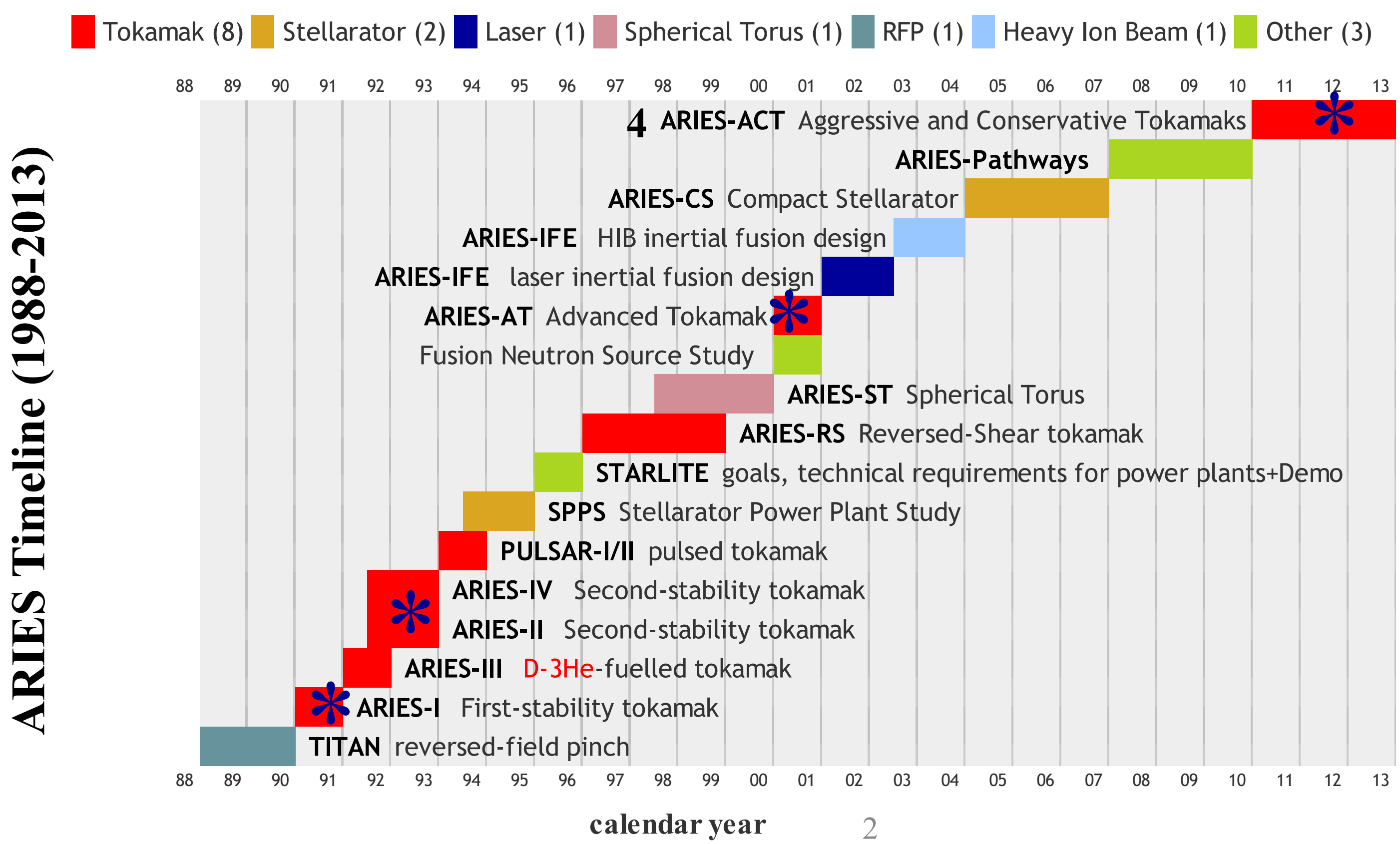
Fusion Materials Workshop
ORNL and University of Tennessee, Knoxville
July 25-29, 2016

SiC/SiC Composites Functionality in US Fusion Devices

- **SiC/SiC composite structural material in 4 ARIES power plants**:

1990 ARIES-I, 1992 ARIES-IV, 2000 ARIES-AT, 2013 ARIES-ACT1,4

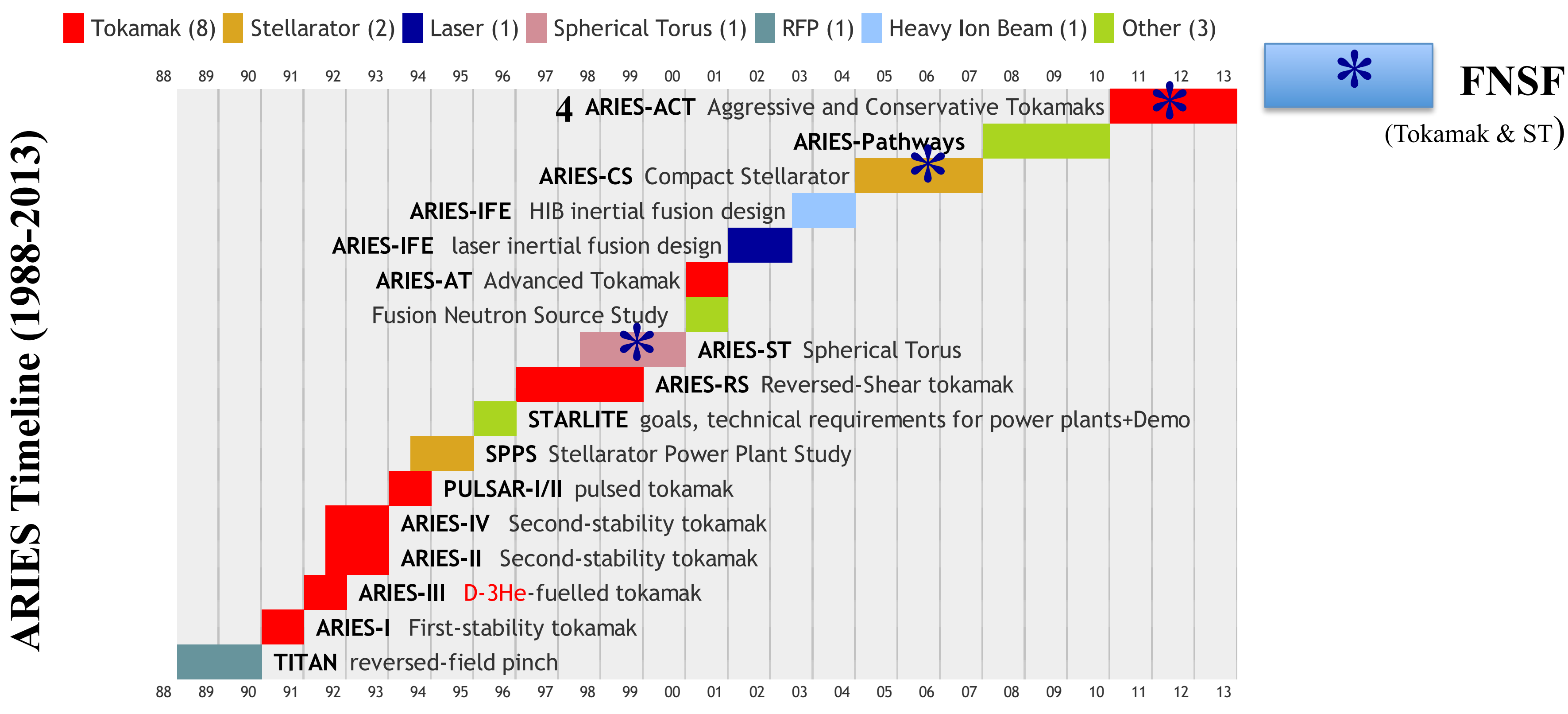
Ceramic Breeders — PbLi Breeder



SiC/SiC Composites Functionality in US Fusion Devices (Cont.)

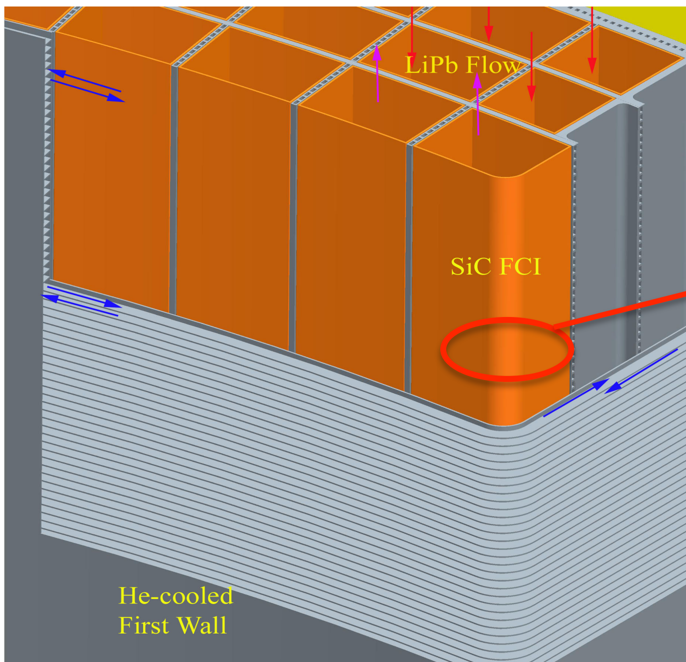
- **Flow Channel Insert (FCI) for dual-cooled PbLi (DCLL) blanket of 3 ARIES power plants and 2 Fusion Nuclear Science Facilities (FNSF):**

1998 ARIES-ST, 2004 ARIES-CS, 2013 ARIES-ACT2,3, 2016 FESS-FNSF (tokamak), 2016 ST-FNSF



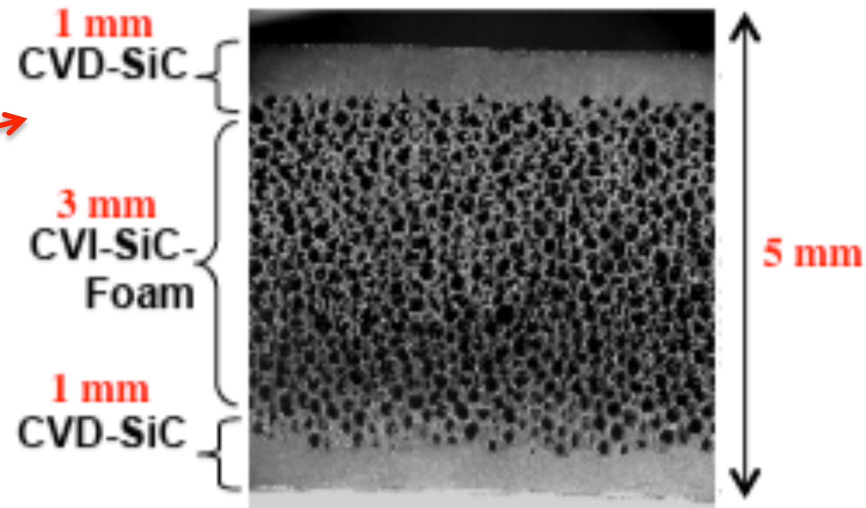
SiC FCI for DCLL Blankets

FCI serves as electric and thermal insulator between RAFM/ODS structure and hotter PbLi breeder/coolant.



Typical DCLL Blanket

0.5 cm Thick SiC FCI

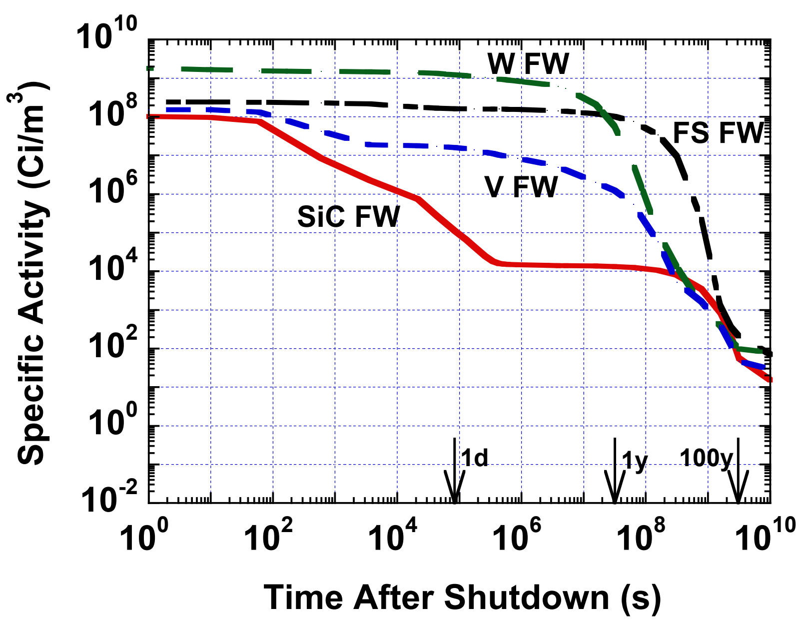


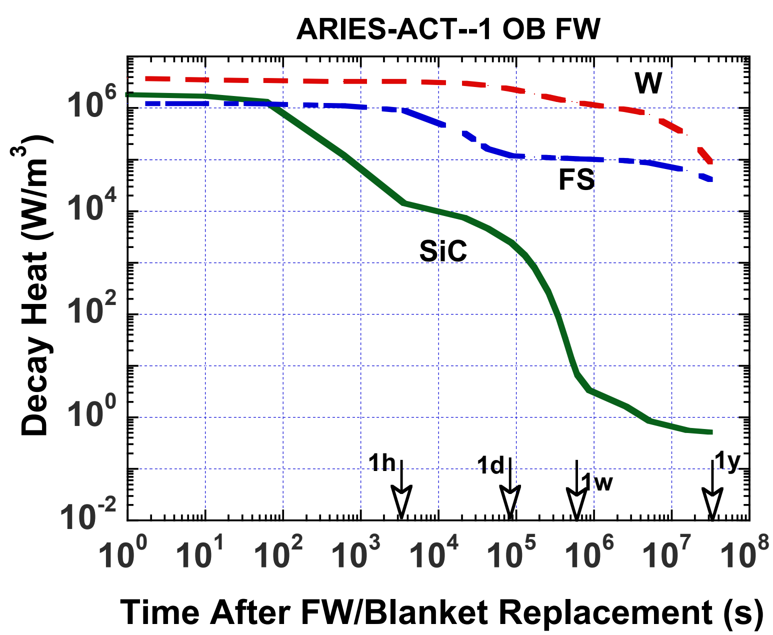
Ref.: S. Malang et al., "Development of the lead lithium (DCLL) blanket concept," Fusion Science and Technology, 60, 249 (2011).

Ref.: S. Sharafat et al., "Development status of a SiC-foam based flow channel insert for a U.S.-ITER DCLL TBM," Fusion Science and Technology, 56, 883 (2009).

SiC Advantages and Concerns

- **Advantages**:
  - High operating temperature (1000°C) ⇒ high thermal conversion efficiency (55-60%) and lower cost of electricity
  - Radioactivity and decay heat decrease rapidly after operation – remarkable safety advantage; Class A low-level waste (C-14 at > 100 y).





SiC Advantages and Concerns (Cont.)

- **Concerns**:
  - Fabrication of full banana-shaped sectors; joining technology; recycling of composites
  - Cost of composites with impurity control
  - Trouble holding vacuum; He leak tightness; PbLi infiltration
  - 14 MeV irradiation effects:
    - Excessive He production (compared to steel-based alloys), large transmutation products that could impact electric and thermal properties
    - Burnup of SiC and impact on structural integrity of composites
  - Life-limiting criterion; no firm guidelines yet. Criteria may include:
    - Burnup of Si and C atoms (3% in ARIES designs)
    - Thermal and mechanical stresses
    - Thermal creep
    - Atomic displacement (as for RAFM alloys).
  - Need 14 MeV neutron source to irradiate SiC and understand impact of high gas production and metallic transmutants on SiC properties. IFMIF/DONES could provide data in few decades.

Radiation Damage to SiC

Unique features:

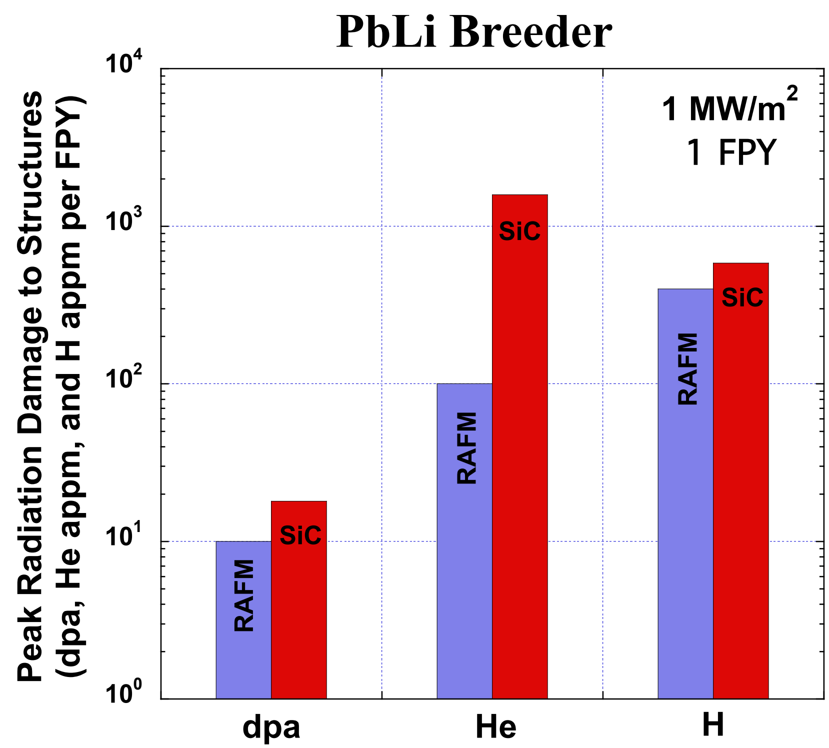
– High He/dpa ratio of ~90 (~10 for RAFM)

– H/dpa ratio of ~33 (~40 for RAFM)

– High He/H ratio of ~2.5 (~0.25 for RAFM)

– Si atoms burn faster than C atoms at 2:1 ratio

– Each gas production reaction with either Si or C atom could potentially burn SiC.



Refs.: – *L. El-Guebaly*, "Neutronics Aspects of ARIES-II and ARIES-IV Fusion Power Reactors," Fusion Technology, Vol. 21, No. 3, Part 2B, 2128 (1992).

– L. El-Guebaly, "Nuclear Performance Assessment of ARIES-AT," Fusion Eng. Des., 80, 99 (2006).

*– L. El-Guebaly and L Mynsberg, "Neutronics Characteristics and Shielding System for ARIES-ACT1 Power Plant," Fusion Science and Technology, **67**, No. 1, 107-124 (2015).*

– M. Sawan, "Damage Parameters of Structural Materials in Fusion Environment Compared to Fission Reactor Irradiation," Fusion Eng. Des., 87, 551 (2012).

– M.E. Sawan, N.M. Ghoniem, L. Snead, Y. Katoh, "Damage Production and Accumulation in SiC Structures in Inertial and Magnetic Fusion Systems," J. Nucl. Mater. 417 (2011) 445–450.

– M. Sawan, Y. Katoh, and L. L. Snead, "Transmutation of Silicon Carbide in Fusion Nuclear Environment," J. Nucl. Mater., 442, 1–3, S370 (2013).

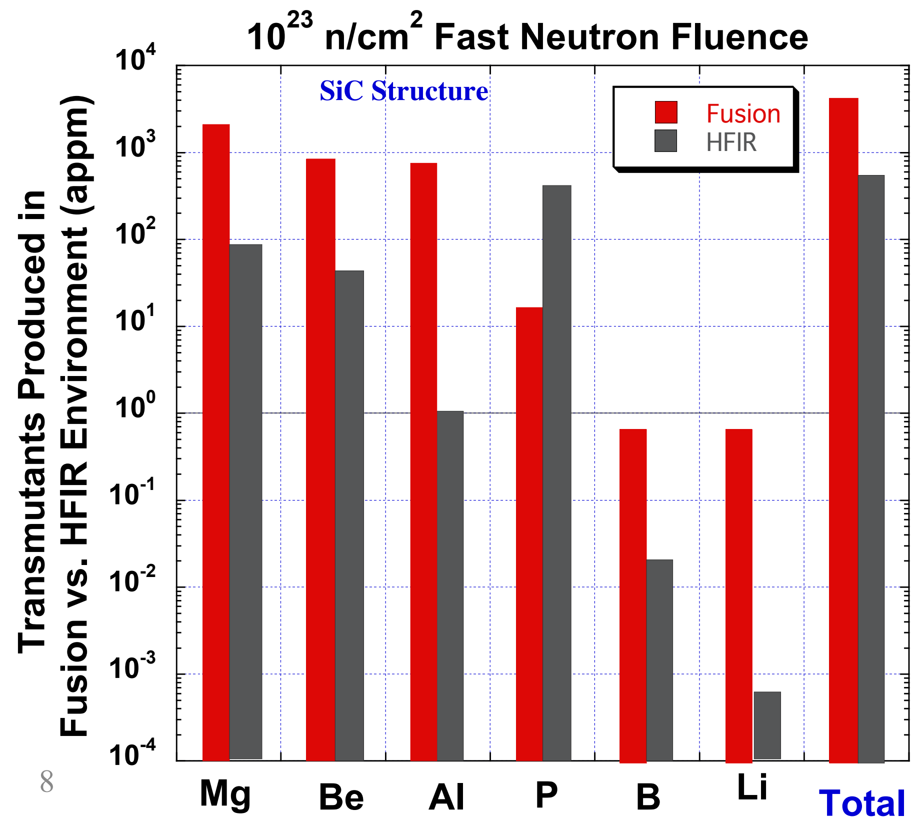
Transmutation of SiC

- Energetic fusion neutrons (with E > 3 MeV) transmute **1.3 at.%** of SiC into: Mg (~58%), Be (22%), Al (~20%), P (0.4%), B (~0.02%), and Li (0.01%).
- For same 10^{23} n/cm^2 fast neutron fluence, HFIR* transmutes **0.18 at.%** of SiC into: Mg (~16%), Be (8%), Al (~0.2%), P (~76%), B (~0.004%), and Li (0.0001%).

SiC Reactions producing transmutants:
- Mg and Al produced by high energy (n,α) and (n,d) reactions with Si
- Li, Be, and B produced by high energy reactions with C
- P produced by low energy (n,γ) reactions with Si followed by β decay (dominant in fission).

Fission system is inadequate to simulate level and mix of metallic transmutants produced in SiC of fusion systems

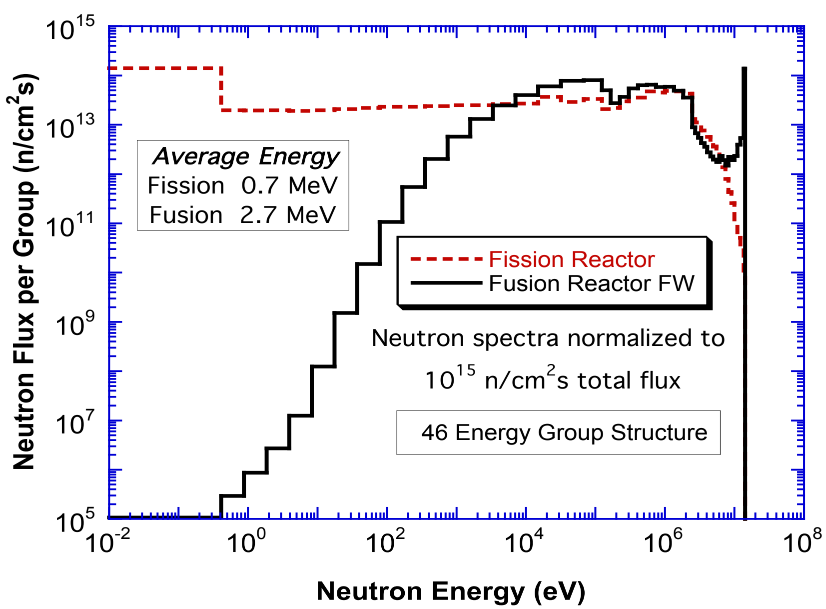
Ref.: M. Sawan, Y. Katoh, and L. L. Snead, "Transmutation of Silicon Carbide in Fusion Nuclear Environment," J. Nucl. Mater., 442, 1–3, S370 (2013).

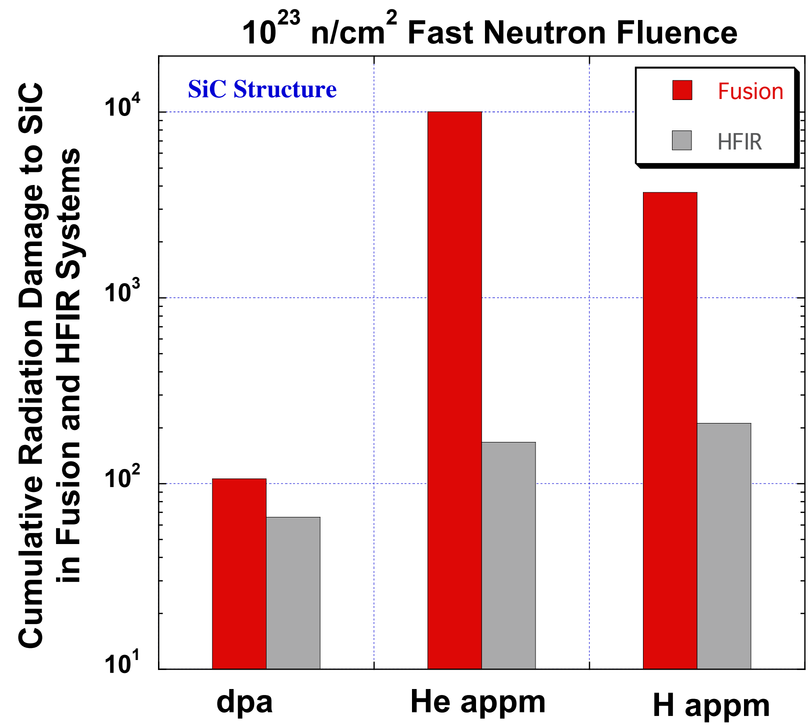


* Mostly thermal neutrons; No neutrons above 10 MeV.

Fission Reactor Underestimates Radiation Damage to SiC of Fusion Systems

Radiation damage and gas production are greatly influenced by neutron energy spectrum: significantly harder in fusion compared to fission.





SiC	Fusion (ARIES-AT geometry)	HFIR
He / dpa	95	2.5
H / dpa	35	3.2

Fission system is inadequate to simulate dpa and gad production in SiC of fusion systems

Impact of Transmutation Products and Atomic Displacement on SiC Properties

- Burnup of SiC atoms (through transmutations) could lead to substantial modifications in physical, chemical, and mechanical properties.

- Defects produced by atomic displacement could alter SiC electric properties.

- Few examples of expected effects:
  - Impact of **transmutation** products on SiC **electric conductivity**
  - Impact of **transmutation** products on **corrosion resistance** of SiC
  - Impact of **atomic displacement** on SiC **electrical properties**.

- **Such impacts have been explored only to very limited extent and still not fully understood**.

Ref.: M. Sawan, Y. Katoh, and L. L. Snead, "Transmutation of Silicon Carbide in Fusion Nuclear Environment," J. Nucl. Mater., 442, 1–3, S370 (2013).

Impact of Transmutation Products on SiC Electric Conductivity

- **Pure SiC is a semi-insulating material** at relatively low temperatures.
- Electrical conductivity of SiC is usually determined by **impurities** in the temperature range of interest.
- With N as the common primary impurity in CVI SiC matrix, SiC/SiC composite is often considered electronically an **n-type semiconductor**.
- Numerous reports on **very significant effects of small amount** of impurity doping on electronic properties of SiC*:
  - **P doping** to 0.1-1000 ppm used to alter electrical properties (16 appm in fusion)
  - **Al doping** to < 0.1 ppm used to alter electronic properties (762 appm in fusion).
- Individual effects of 2232 appm **Mg**, 851 appm **Be**, and 762 appm **Al** in fusion spectrum could be very significant. PNL will examine effect of Mg on electric conductivity (refer to Kurtz's presentation).
- Collective effect of all transmutants may be more complex.
- **Transmutation in fusion environment is anticipated to over-compensate the initially n-type SiC**. The evolution of electrical conductivity at given temperature could be very drastic during the semiconductor type transition.

* *T. Ohshima, A. Uedono, H. Itoh, M. Yoshikawa, K. Kojima, S. Okada, I. Nashiyama, K. Abe, S. Tanigawa, T. Frank, G. Pensl, "Relationship between Donor Activation and Defect Annealing in 6H-SiC Hot-Implanted with Phosphorus Ions," Mater. Sci. Forum 338–342 (2000) 857.*

Impact of Transmutation Products on SiC Corrosion Resistance

- Corrosion resistance is another property that may potentially be significantly influenced by chemical composition change resulting from transmutation.

- The outstanding **oxidation resistance of SiC** is enabled by presence of **silica scale** formation on its surface.

- Presence of **Al** in this silica scale is known to **promote corrosion** of SiC in the passive oxidation regime by **enabling transport of oxygen**[**].

- **Mg** (most abundantly produced metallic transmutant by fusion neutrons) is known to **react with silica** producing Mg_2Si and MgO, potentially altering oxidation behavior of SiC.

*** J.A. Costello, R.E. Tressler, "Oxygen Penetration into Silicon Carbide Ceramics during Oxidation," Ceram. Int. 11 (1985) 39–44.*

Impact of Atomic Displacement on SiC Electrical Properties

- **Atomic displacement produces Frenkel defects** that alter SiC electrical properties. (In fact, implantation-doped or nuclear transmutation doped SiC often has to be annealed to mitigate the Frenkel defects for the intended doping effect to be properly activated).

- Previous study[#] indicated all of carrier density, mobility, and **electronic level in polycrystalline 3C–SiC are significantly modified after irradiation in HFIR**.

- Effect of **fusion** spectrum **could be very significant**.

- **Synergistic effects** of defect production, nuclear transmutation, and dynamic annealing at elevated temperatures in fusion environment could be very complex.

 # Y. Katoh, S. Kondo, L.L. Snead, "DC Electrical Conductivity of Silicon Carbide Ceramics and Composites for Flow Channel Insert Applications," J. Nucl. Mater. 386 (2009) 639–642.

Concluding Remarks

- Up to **1.3 at.%** metallic transmutants are generated in SiC FW at ~ 20 MWy/m^2 – the expected lifetime of SiC/PbLi blanket for 3% burnup limit.
- Variety of nuclear reactions with different threshold energies ($E_n > 3$ MeV) produce **6 transmutants**: Mg (58%), Be (22%), Al (20%), P, B, Li.
- Irradiation in **HFIR** produces different levels of dpa and gas production and very different amount and mix of transmutants:
  - ~ an order of magnitude lower metallic transmutation products
  - Mg is only 16% of metallic transmutation products
  - P is dominant transmutant (76%).
- **Combined effect** of massive production of transmutants (Mg, Al, and Be) and atomic displacement in fusion is **unknown**, but expected to be significant on oxidation, transport properties (electrical and thermal), and elevated temperature mechanical properties.
- Since irradiation in fission reactors is not adequate, there is a need to perfom irradiation experiments using **14 MeV** neutron sources (IFMIF or DONES).
- As such facilities are not currently available to experimentally simulate the fusion neutron environment, **ion implantation and active modeling and simulation** in this area help understand the expected effects on electronic, physical, and mechanical properties (next presentation by C. Henager).