

Thorium Energy Alliance

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Advanced Space-based Nuclear Energy Platforms: the Pebble Bed Modular Reactor, Silicon Carbide and Molten-Salt Compatibility

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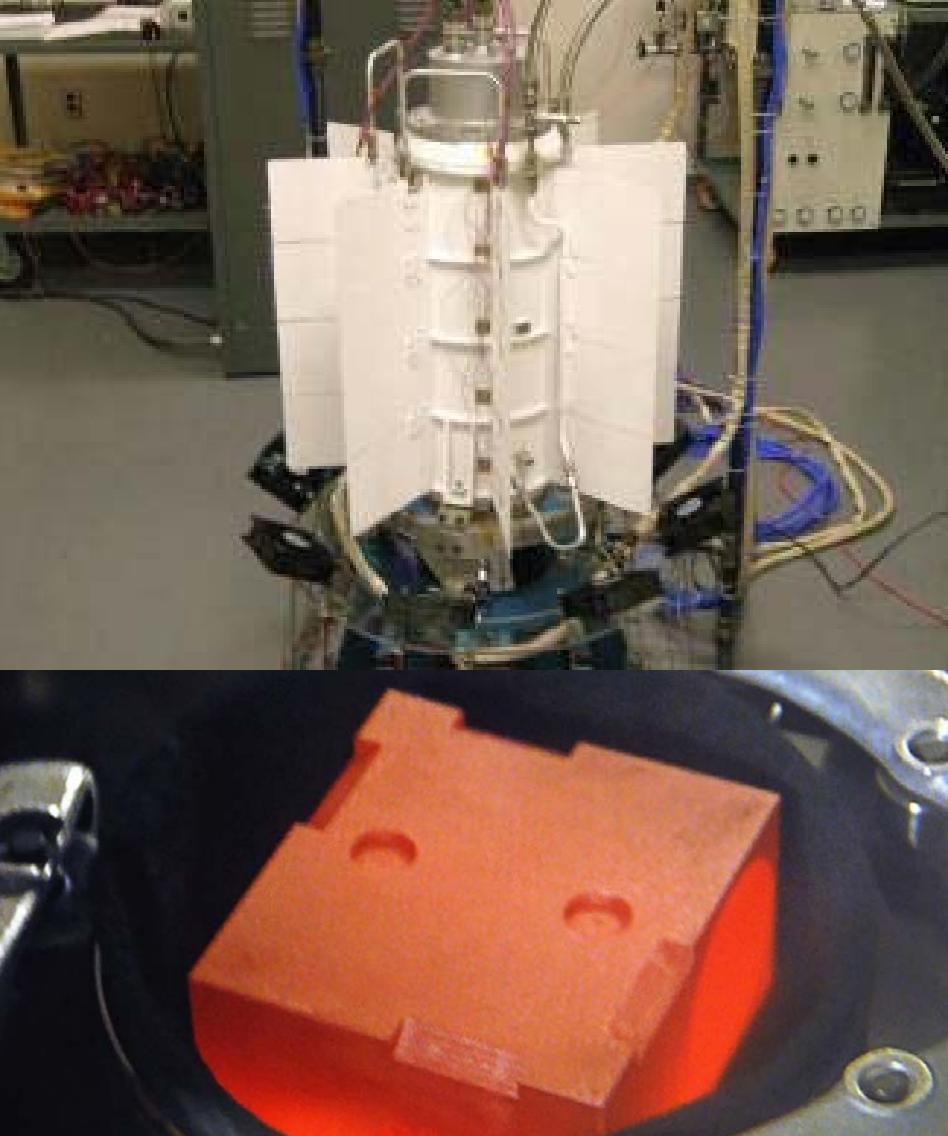
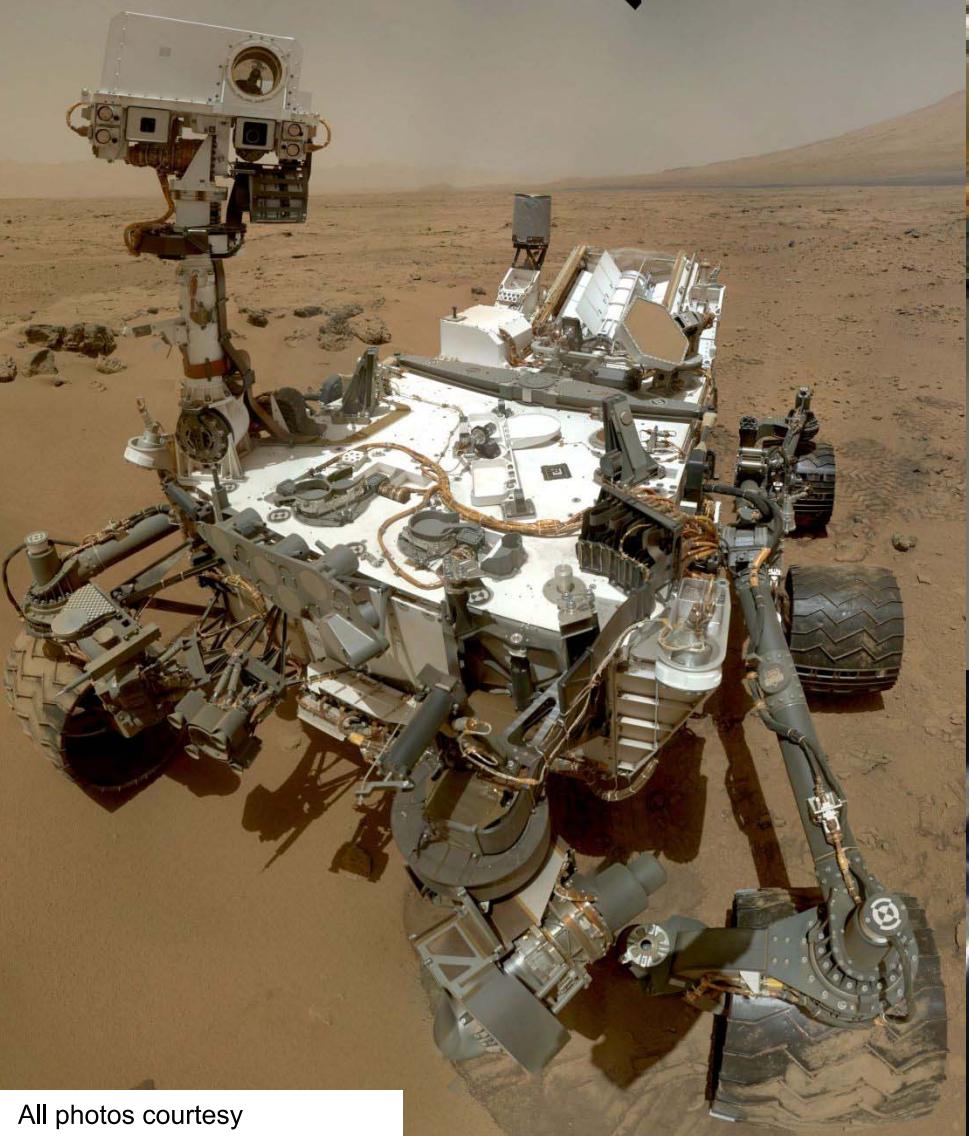
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Nuclear Power is Essential to Achieving Mars by 2030



Brief History of Nuclear Energy Sources for Space Applications

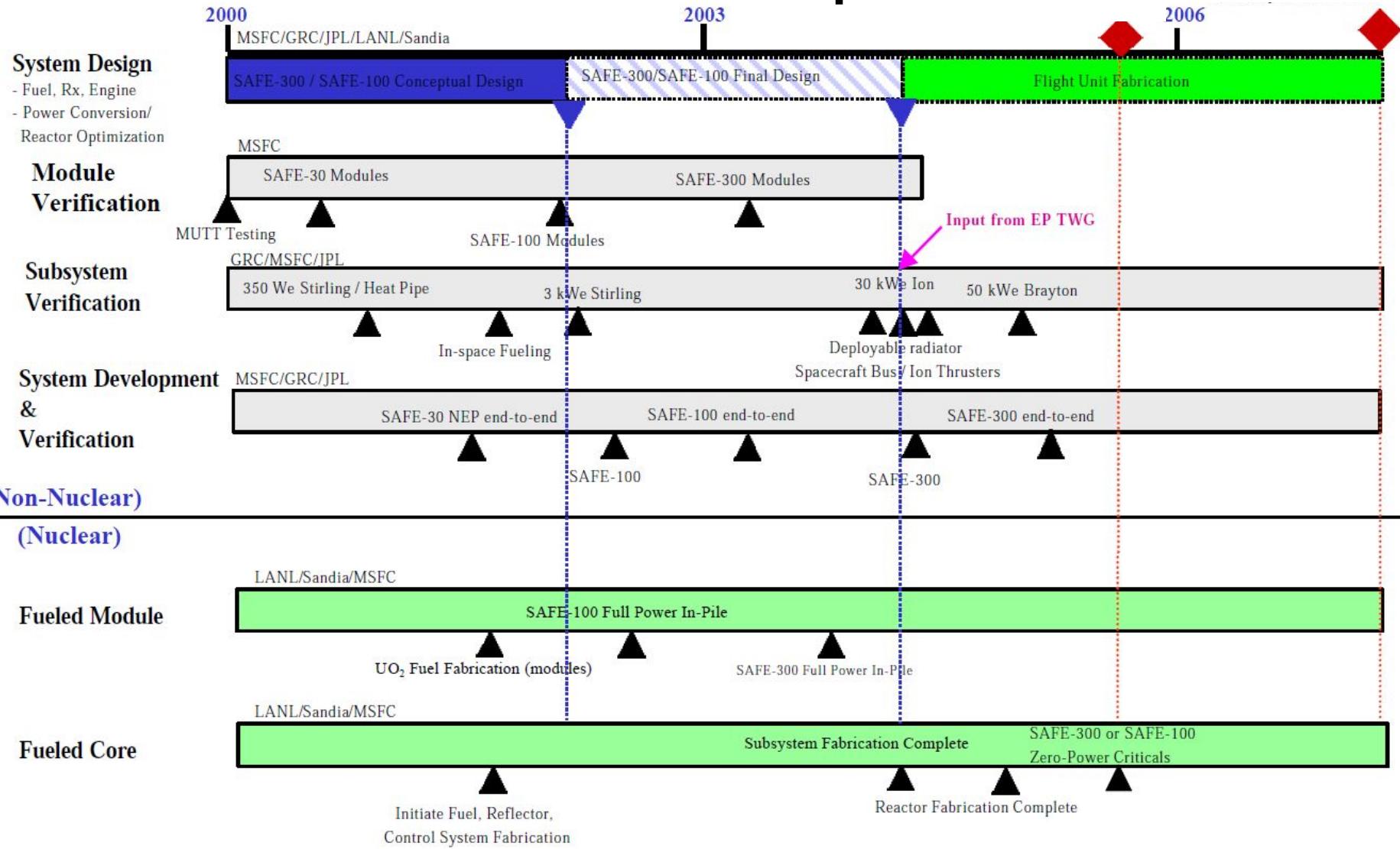
TABLE 1 Comparison of Specific Energy Density of Competing Space Power Sources

<u>System</u>	<u>Specific Energy Density (Watts (electric) per kilogram)^a</u>
<u>Solar/battery</u>	10-25
<u>Radioisotope thermal generators</u>	5-10
<u>Nuclear (100 kW(e) today's technology)</u>	25-50

^aEntire system, including power conversion and conditioning equipment, heat dispersal system, shielding, instrumentation, and structural components.

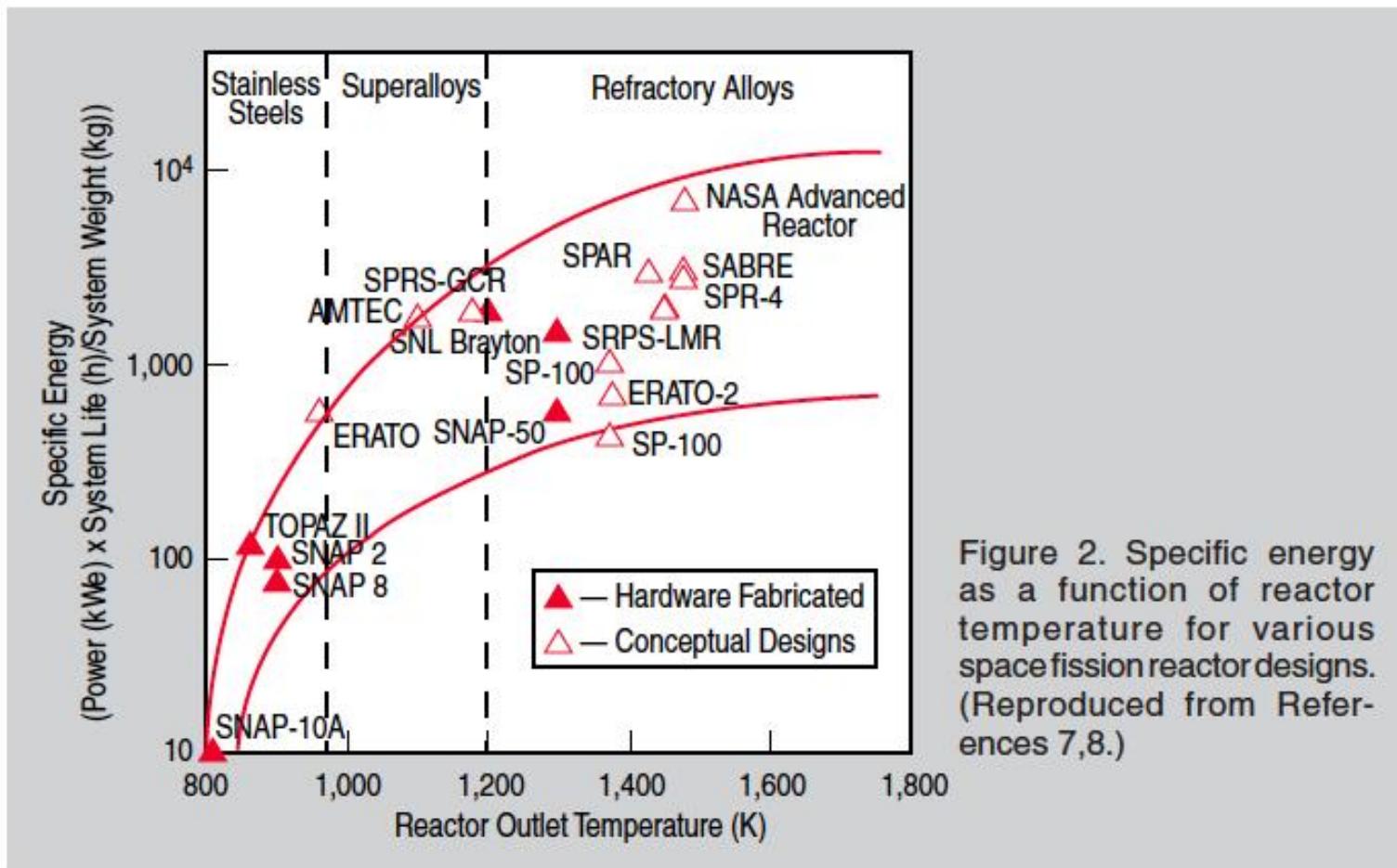
Deutch, J.M., Agnew, H.M., Avery, R. Goldstein, H., Grant, N.J., Rasmussen, N.C., Stone, H.E., Ward, D.A. Wertheim, R.H. Advanced Nuclear Systems for Portable Power in Space. National Academy Press, 1983.

Safe Affordable Fission Engine Roadmap



Van Dyke, M et al. (2001). *The Safe Affordable Fission Engine (SAFE) Test Series*.
NASA/JPL/MSFC/UAH 12th Annual

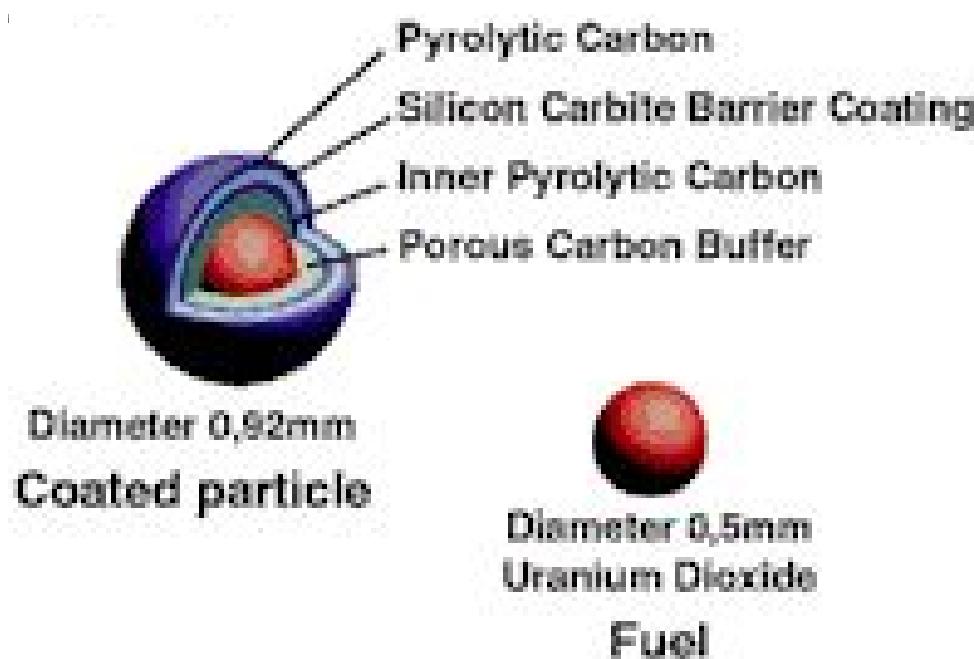
Brief History of Nuclear Energy Sources for Space Applications



Busby, J.T., Leonard, K.J. J. Miner. Met. Mater. Soc. (JOM). 59(4), 2007; 20-26

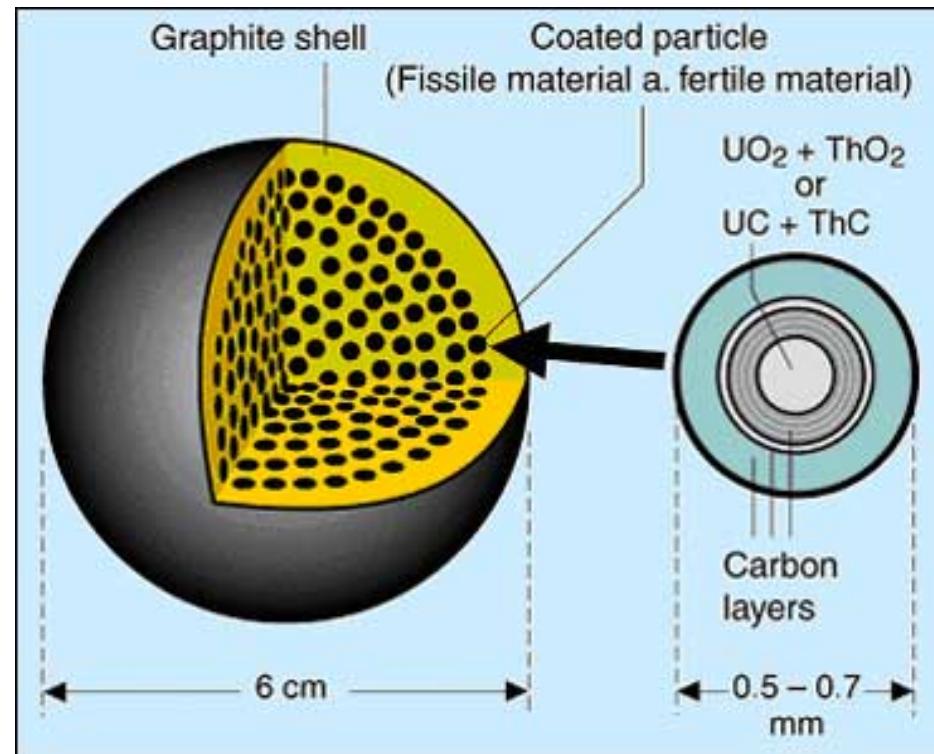
Pebble-bed Modular Reactors (PBMR): The TRISO Fuel Unit

- Coated particle PBMR fuel showing structure of the fuel pebble (cutaway)
- SiC has a complex structure



SiC and Tri-isotropic Fuels (TRISO) and the Pebble Bed Modular Reactor (PBMR)

- SiC as a structural barrier to contain fission products
- Provides tensile support to the metal-oxide core
- Structural considerations of SiC partially responsible for failure of SiC?



http://daryanenergyblog.wordpress.com/ca/part-6_htgr/

Overview of the Properties of SiC

- High refractory index
- Low neutron-capture cross section
- Ability to bind to composite materials
- High tensile strength
- Chemical resistance

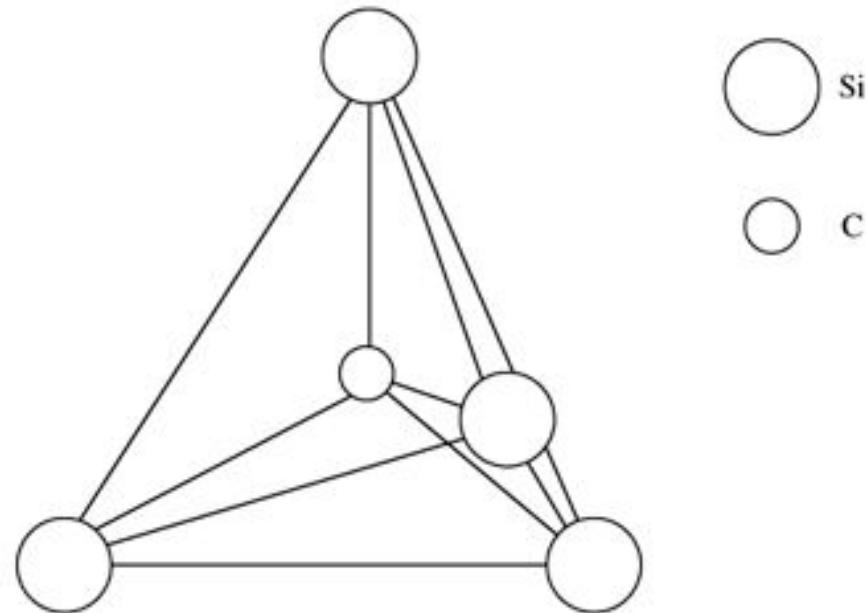
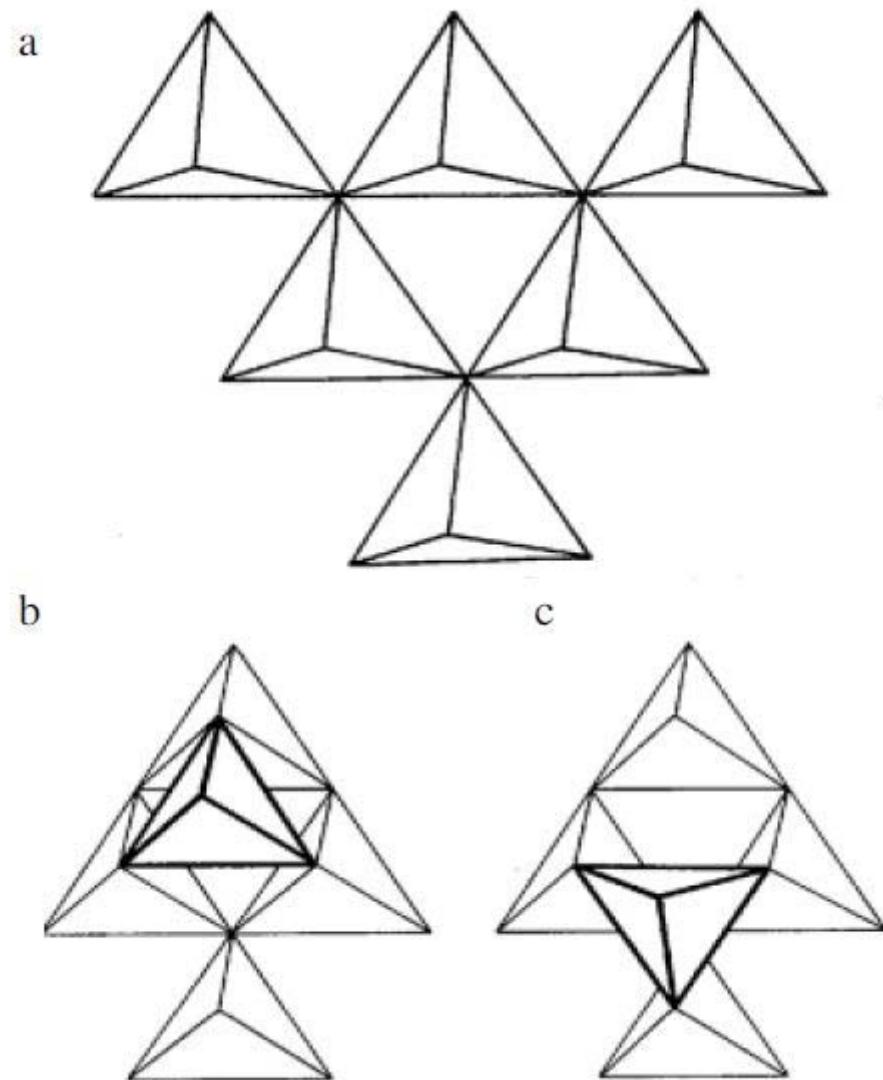


Figure 1. Representation of basic silicon carbide tetrahedra.

SiC: Crystallographic Views

- High refractory index
- Low neutron-capture cross section
- Ability to bind to composite materials
- High tensile strength
- Chemical resistance

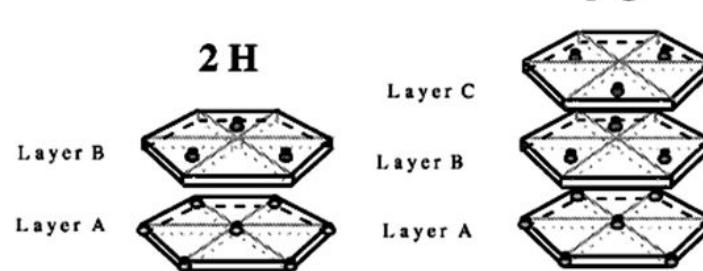


Shaffer, P.T.B. Acta Cryst. B25 (1969) 477-488

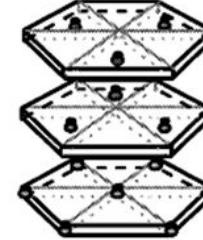
Structural Considerations of SiC

- Alternating tetrahedra of SiC_4 (or CSi_4) units
- Different stacking of SiC_4 units in the crystallographic “c” direction give rise to “polytypism”
- Different polytypes have different properties
- Control of formation of polytypes difficult to control

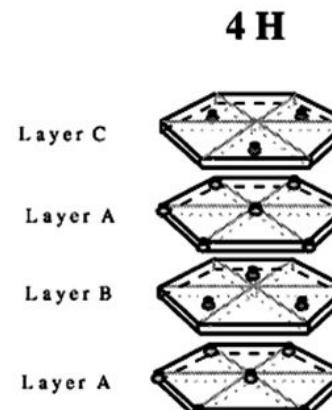
S i C



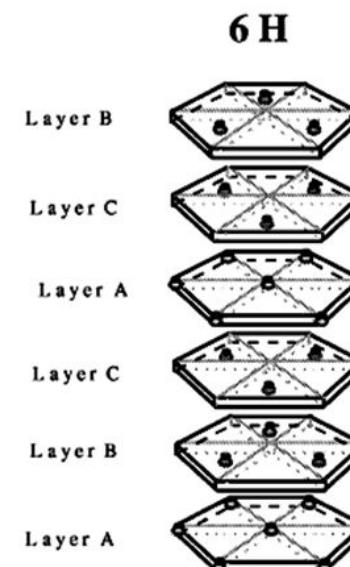
3 C



4 H

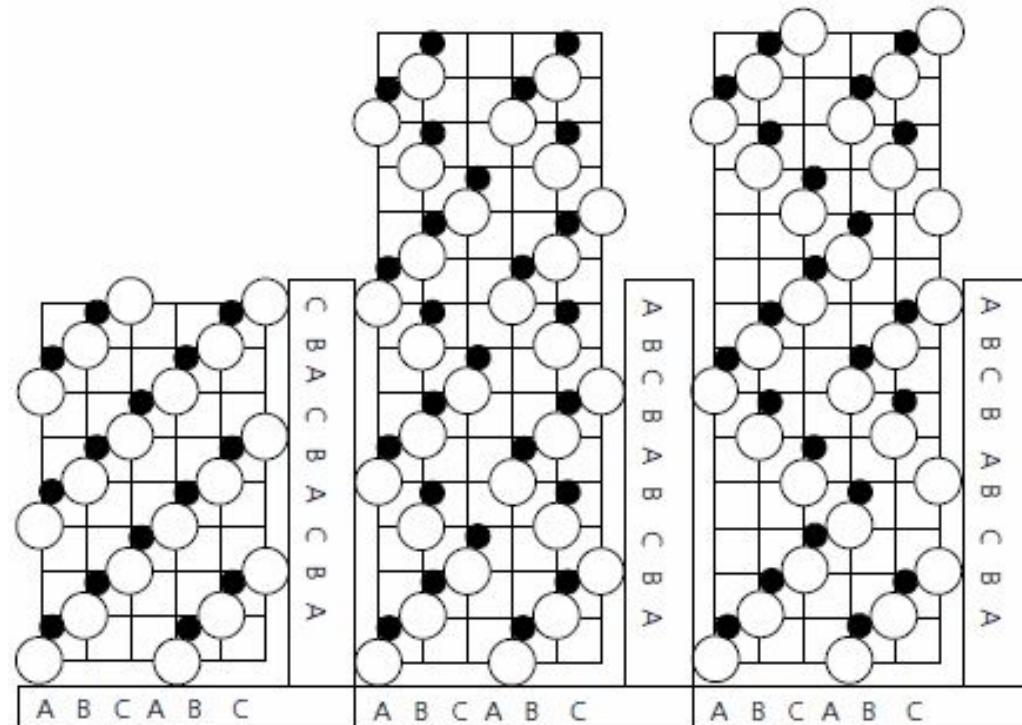


4 H



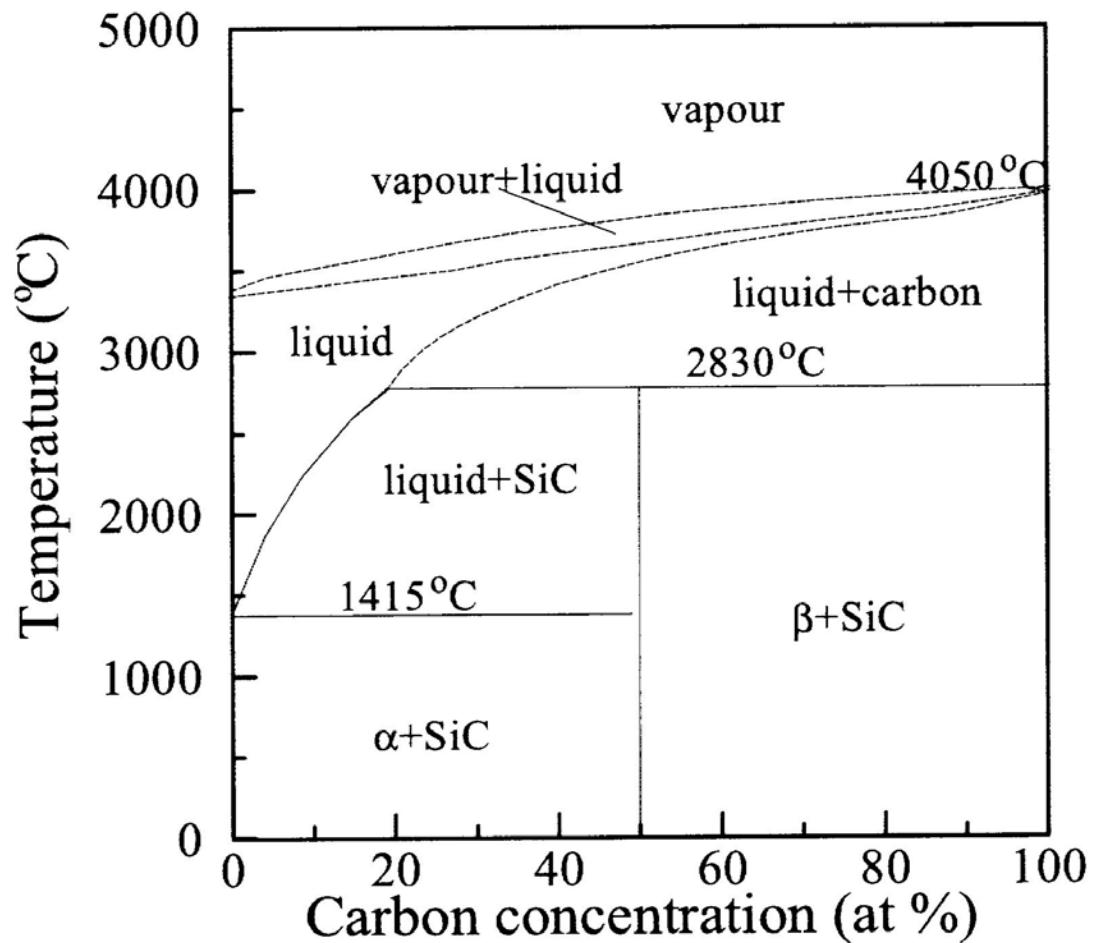
Syntactic Coalescence of SiC

- In addition to polytypism, SiC is capable of forming structures with *alternating* layers of each polytype
- This phenomenon is known as syntactic coalescence.
- Syntactic coalescence further complicates the structure of SiC and its predictable properties



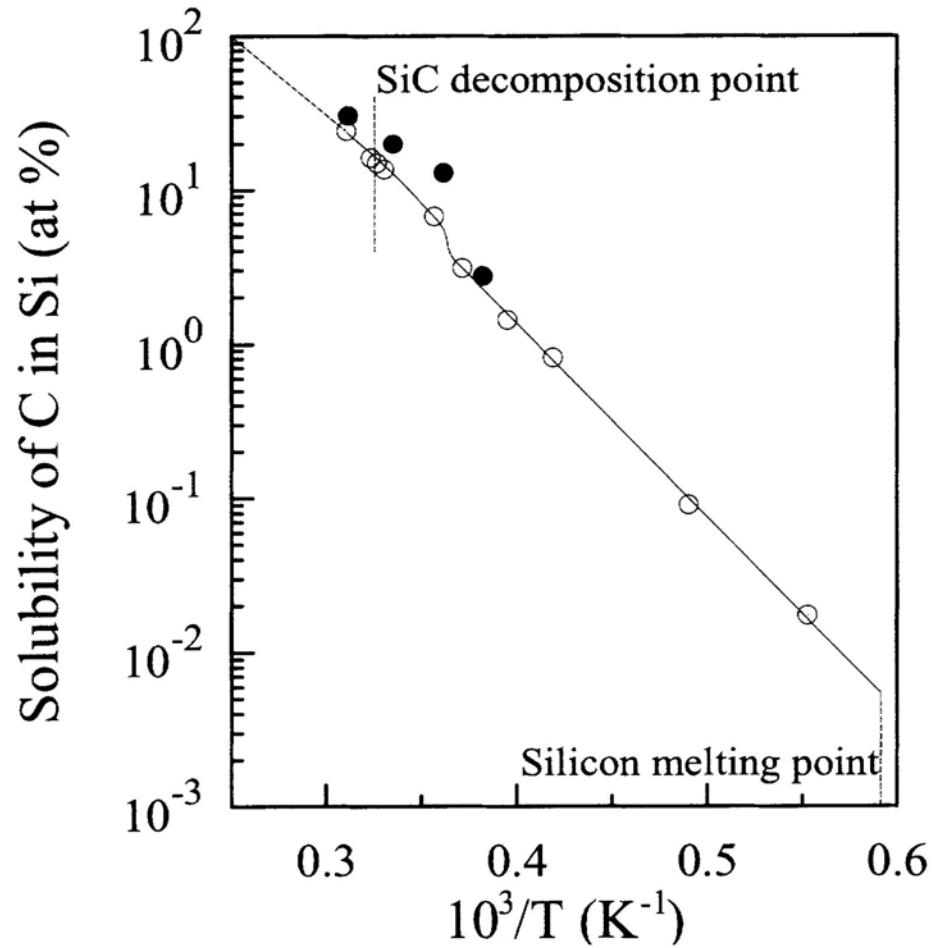
Shaffer, P.T.B. *Acta Cryst.* **1969**, *B25*, 477.

Structure of SiC



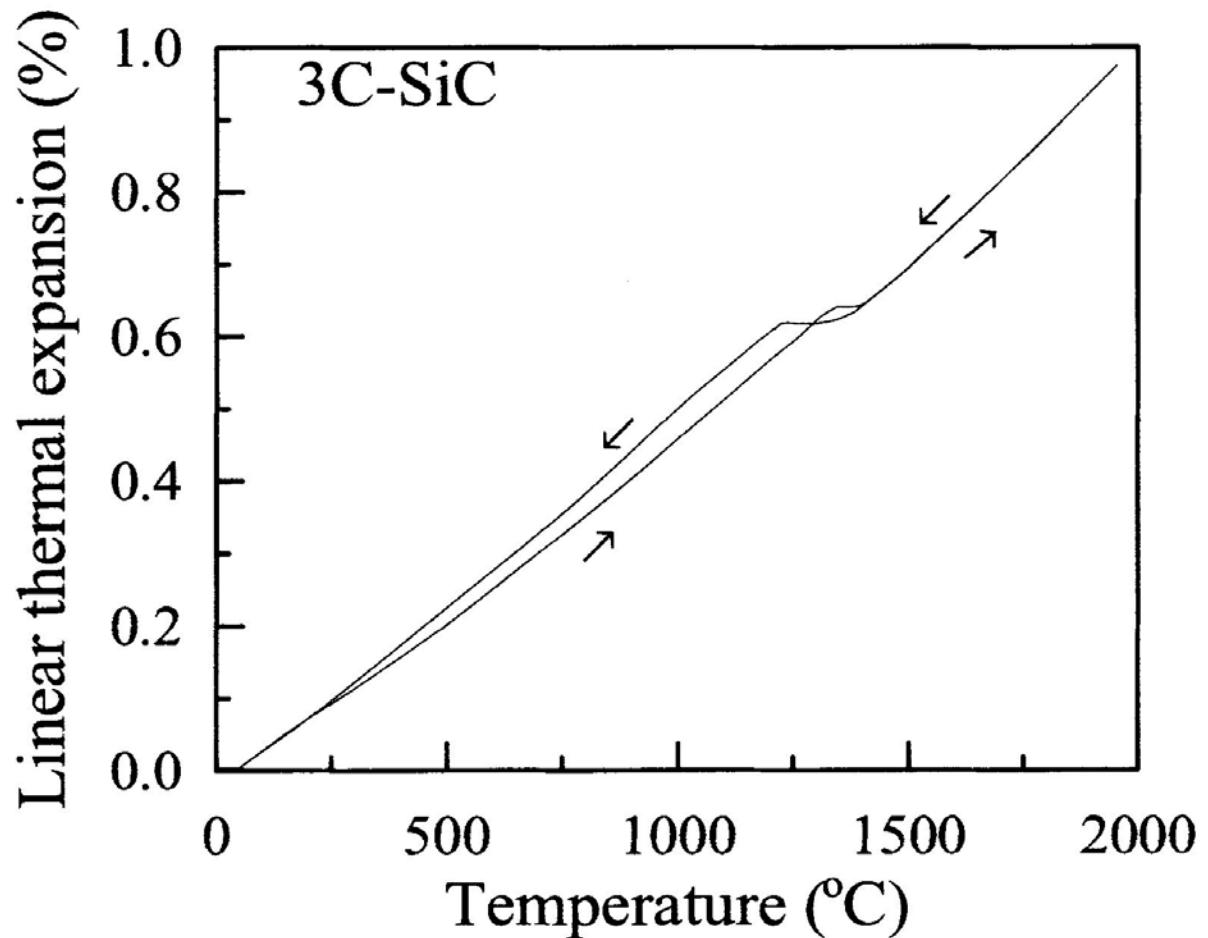
Tairov, Yu.M., V.F. Tsvetkov, in Handbook on Electrotechnical Materials Eds. Koritskii, Yu.V., V.V. Pasynkov, B.M. Tareev, Vol.3, Sec.19, "Semiconductor Compounds AlV BIV", Energomashizdat, Leningrad, 1988, 446-471.

Structure of SiC



Marshall, R., Mater. Res. Bull., Special Issue 4 (1969), S73-S84. Proceedings of the International Conference on Silicon Carbide, University Park, Pennsylvania, October 20-23, 1968.

Structure of SiC



Kern, E.L, Hamill, D.W., Deem, H.W., Sheets, H.D. *Mater. Res. Bull.* **4** (1969) 25.

Structure of SiC

- Rearrangement of SiC layers
- May occur as a vaporization re-crystallization
- May occur as a solid-state reaction
- A diffusional rearrangement requires nucleation and expansion of stacking faults of the basal plane^{2,3}

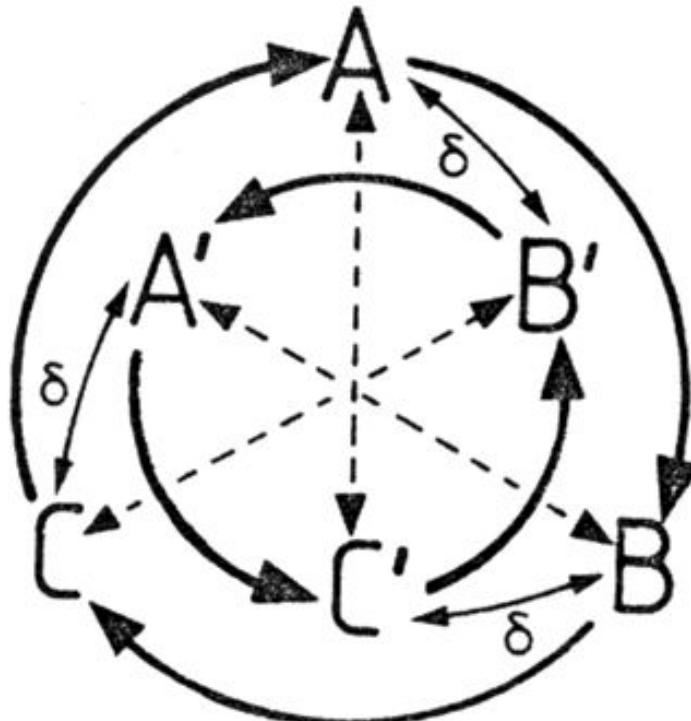


Figure 2 shows a useful nomogram for visualising this and indeed may be used for correctly specifying the stacking sequence of any SiC polytype.

1- (Figure) T. F. Page, The Physics and Chemistry of Carbides, Nitrides and Borides. Edited by R. Freer, Kluwer Acad. Publishers, Netherlands, (1990) 197-214 pg 206

2 - Werheit H. (1979) J. Less-Common Met. 67, 143

3 - Franz R. (1989), Thesis, University of Duisburg

Structure of SiC

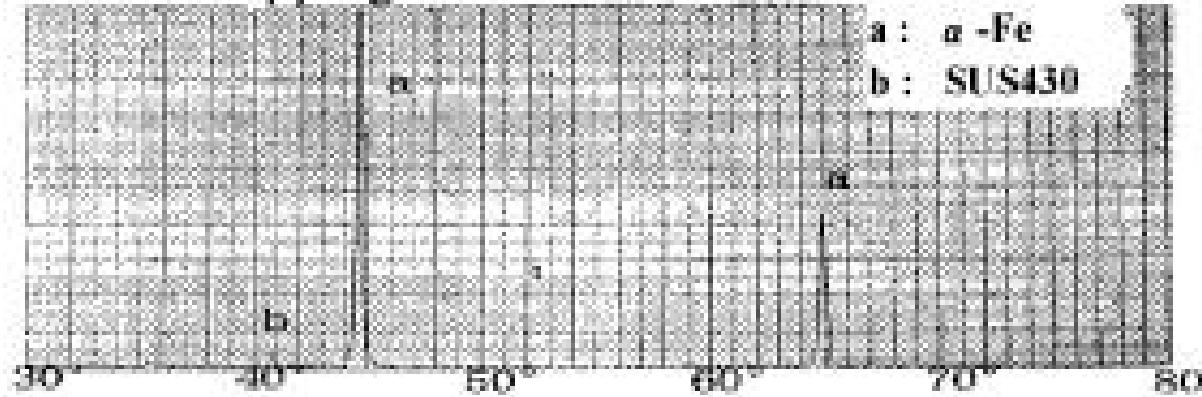
- Rearrangement of SiC layers
- Dramatic difference in band gap energies
- Changes in reactivity

Polytype	Band gap [14] eV	Lattice constants [10]		
		a	c	c/na
2H (11)	3.300	3.076	5.048	0.8205
4H (22)	3.263			
6H (33)	3.023	3.0806	15.1173	0.8179
3C (∞)	2.390	3.0827	7.5510	0.8165

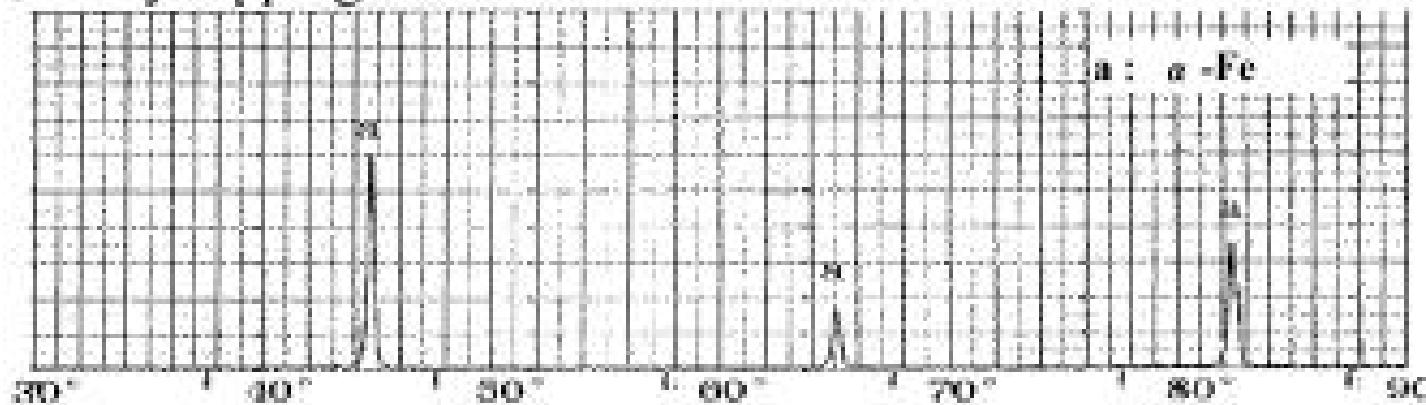
T. F. Page, The Physics and Chemistry of Carbides, Nitrides and Borides. Edited by R. Freer, Kluwer Acad. Publishers, Netherlands, (1990) 197-214 pg 206

Brief exposure to Molten Salt Environments

○ Before dipping



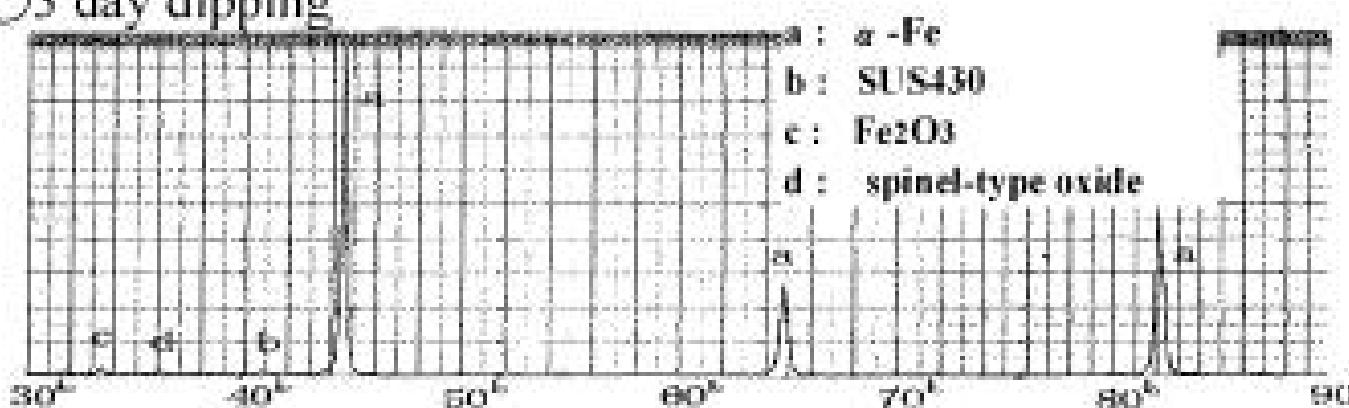
○ 1 day dipping



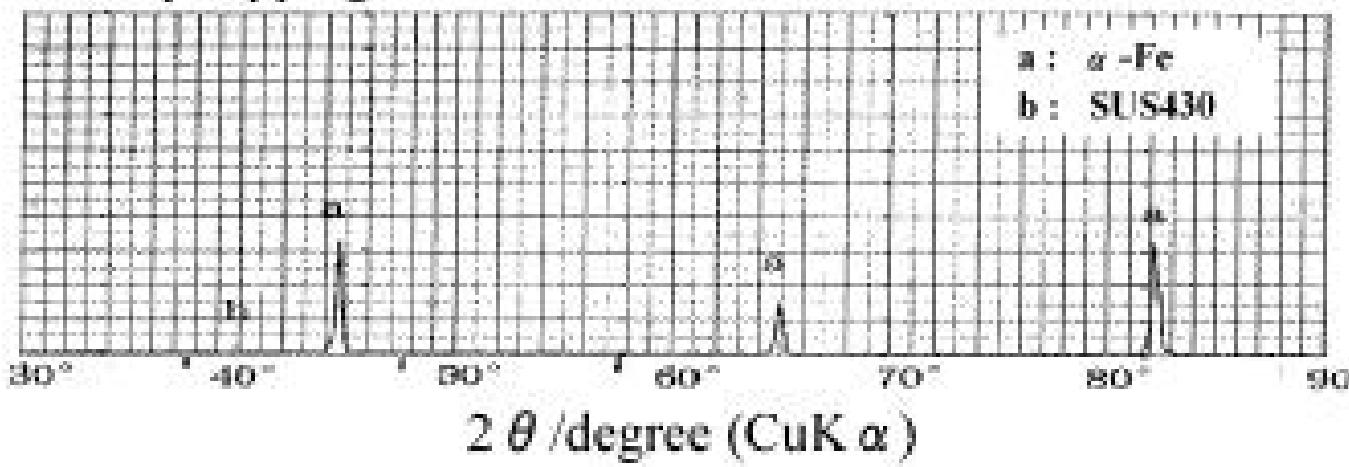
Nishimura, H., Terai, T., Yoneoka, T., Tanaka, S., Sagara, A., Motojima, O. J. Nucl. Mater. 283-287
(2000) 1326-1331

Brief exposure to Molten Salt Environments

○ 3 day dipping



○ 10 day dipping



Nishimura, H., Terai, T., Yoneoka, T., Tanaka, S., Sagara, A., Motojima, O. J. Nucl. Mater. 283-287
(2000) 1326-1331

Conclusions

- Inherent polytypism/syntactic coalescence promote stacking faults, particularly at elevated temperatures
- Even cursory exposure to fluorinating molten salts deleterious to SiC integrity, with polytypic symmetry proportional to chemical reactivity
- Space-based or Terrestrial Nuclear Reactor design must consider alternatives to SiC should be seriously considered for PBMR fuel units, Molten-salt Reactor refractory materials.

Future Work

- DFT modeling of SiC and polytypes to discover the chemico-physical sources of such material dynamics
- Modeling, experimentation with alternative materials such as TiC, carbon-carbon composites (TKM, etc.) and M-C/composite hybrids, functionalized carbon scaffolding.
- Space-based or Terrestrial Nuclear Reactor design must consider alternatives to SiC should be seriously considered for PBMR fuel units, Molten-salt Reactor refractory materials.