Ceramic Composites for Next Step Nuclear Power Systems

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Generation IV
The Next Generation Nuclear Power Reactors

- **Generation IV is a multinational collaboration for the research, development, and construction next generation pilot nuclear power plant by 2015.**

- **Several Options Being Studied Internationally:**

  Very High Temperature Gas-Cooled Reactor
  Gas-Fast Reactor
  Molten Salt Reactor
  Super Critical Water Reactor
  Lead Fast Reactor
  Sodium Fast Reactor

The Competitors for VHTR in the United States

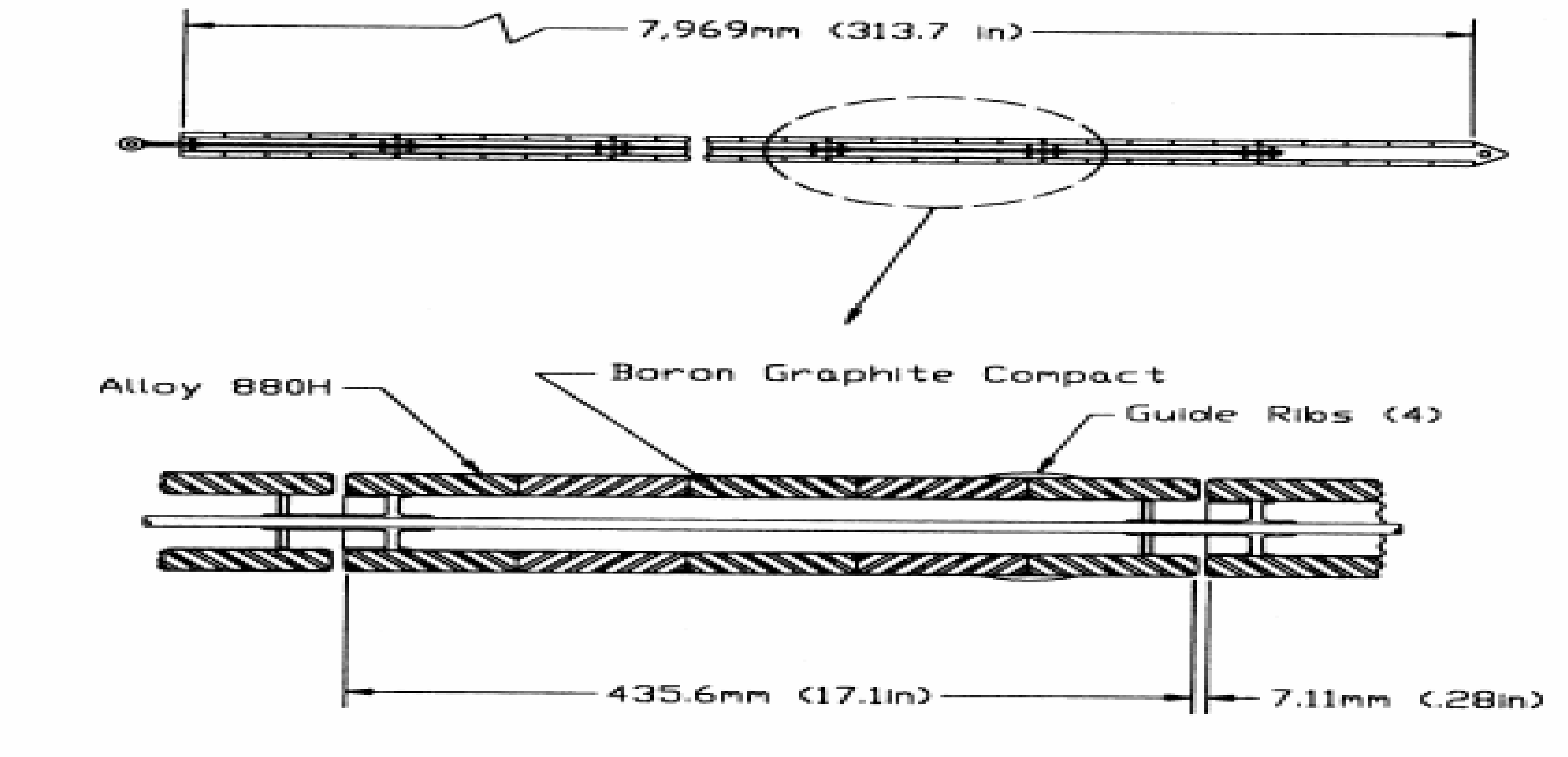
- The Gas Turbine, Modular High-Temperature Reactor (GT-MHR)
- The Pebble Bed Modular Reactor (PBMR)

Comparison of Example VHTR Operating Conditions and Features with GT-MHR and Fort St. Vrain

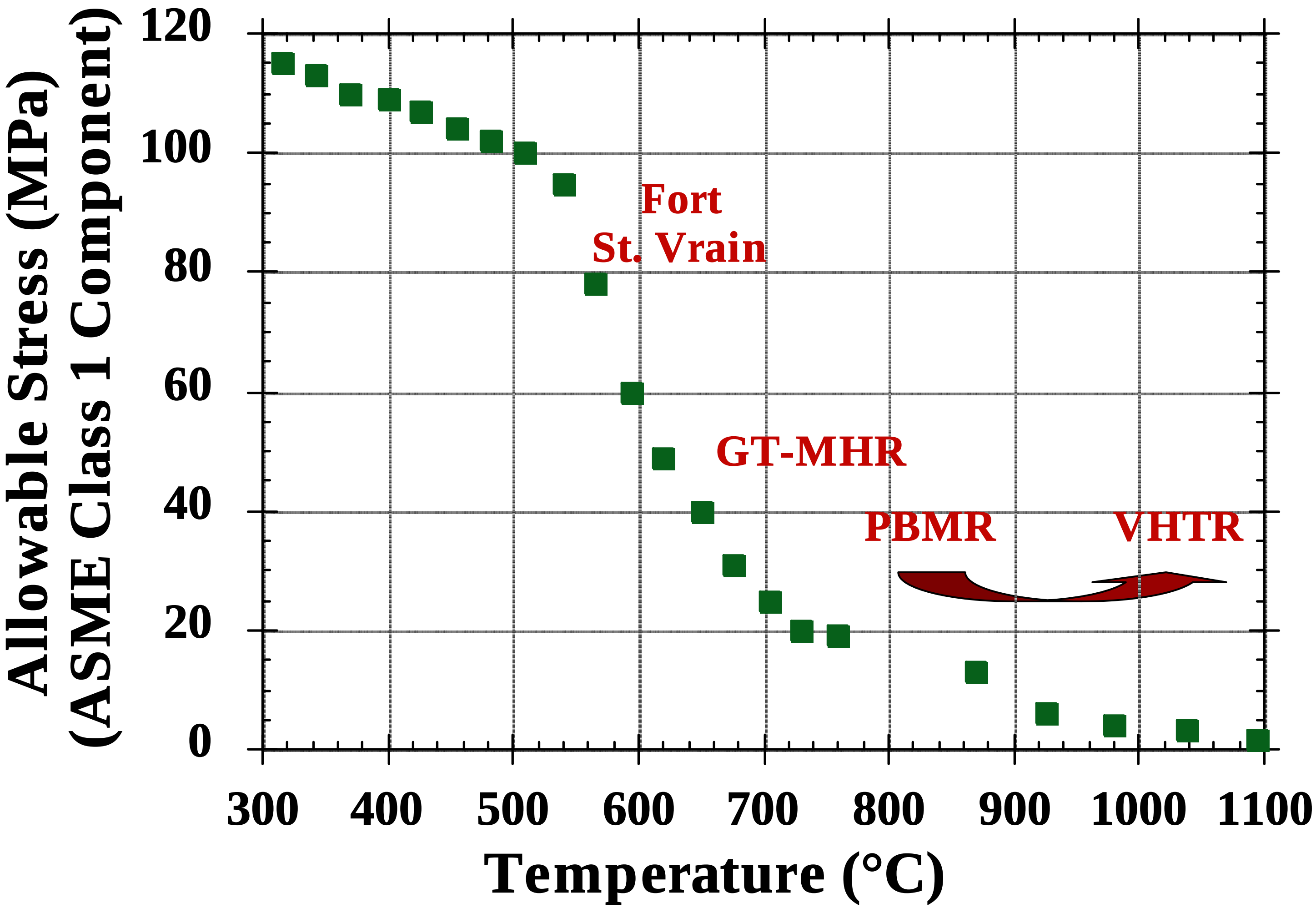
Condition or Feature	Fort St. Vrain HTGR	GT-MHR	VHTR
Power Output (MWt)	841	600	600 - 900 (Depends on core heigh
Average power density (w/cm^3)	6.3	6.5	4 - 6.5
Coolant and Pressure (MPa / psia)	Helium @ 4.83 / 700	Helium @ 7.12 / 1032	Helium @ 7.12 / 1032
Moderator	Graphite	Graphite	Graphite
Core Geometry	Cylindrical	Annular	Annular
Safety Design Philosophy	Active Safety Sys	Passive	Passive
Plant Design Life (yrs)	30	60	60
Core outlet temp. (°C)	785	850	1000
Core inlet temp. (°C)	406	488	490 (Needs to be optimized
Fuel – Coated Particle	HEU-PyC/SiC Th/ 93% ^{235}U	LEU-PyC/SiC	a) LEU-PyC/SiC b) LEU-PyC/ZrC
Fuel Max Temp – Normal Operation (°C)	1260	1250	a) ~1250 b) ~ 1400

GT-MHR Control Rod Concept

(Courtesy of General Atomics)

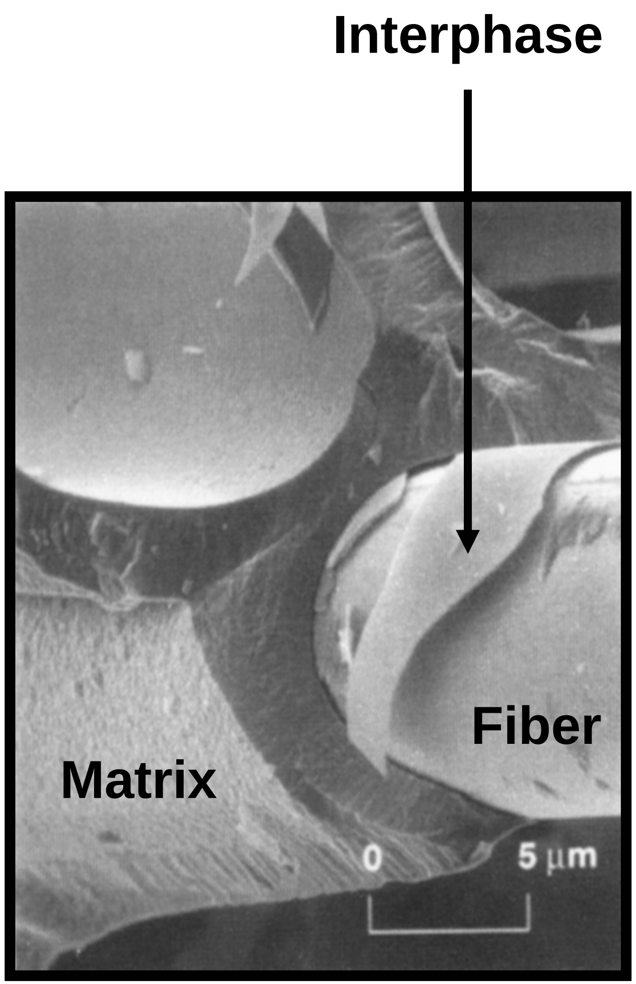


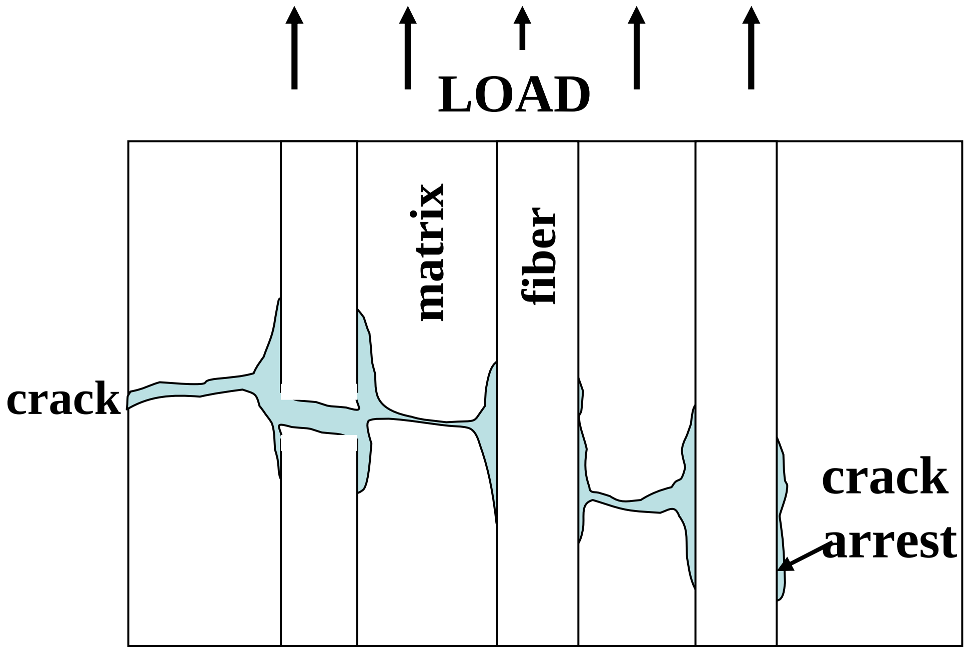
Incoloy 800 H for Nuclear Use



- Workhorse alloy: steam generator, control rod and plenum application
- Incoloy 800 : Ni30-35, Cr(19-23), Fe(39.5 min), C(0.1max.),Ti+Al(0.3-1.2)

Composite -v- Monolithic Ceramics

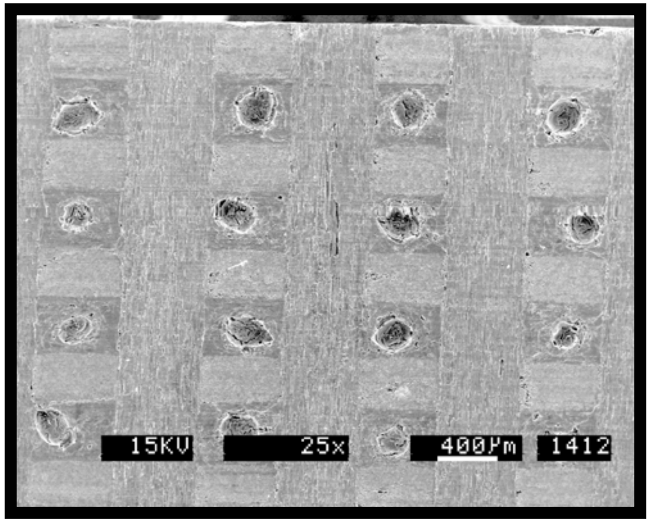


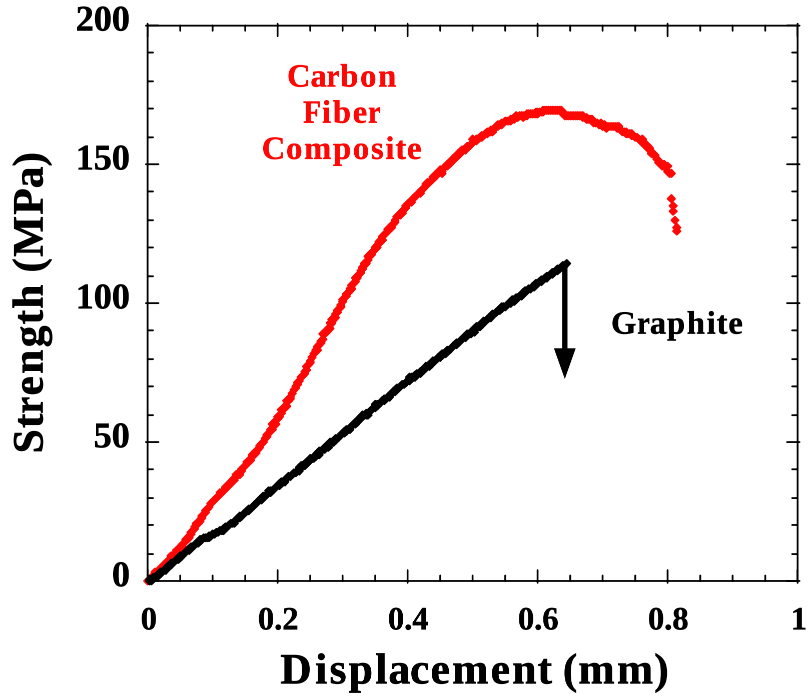


Composite materials, whether platelet, chopped fiber, or continuous fiber reinforced are superior "engineering"materials to monolithics:

- **generally higher strength, especially in tension**
- **higher Weibull modulus (more uniform failure)**
- **much higher damage tolerance (fracture toughness)**

Composite -v- Monolithic Ceramics

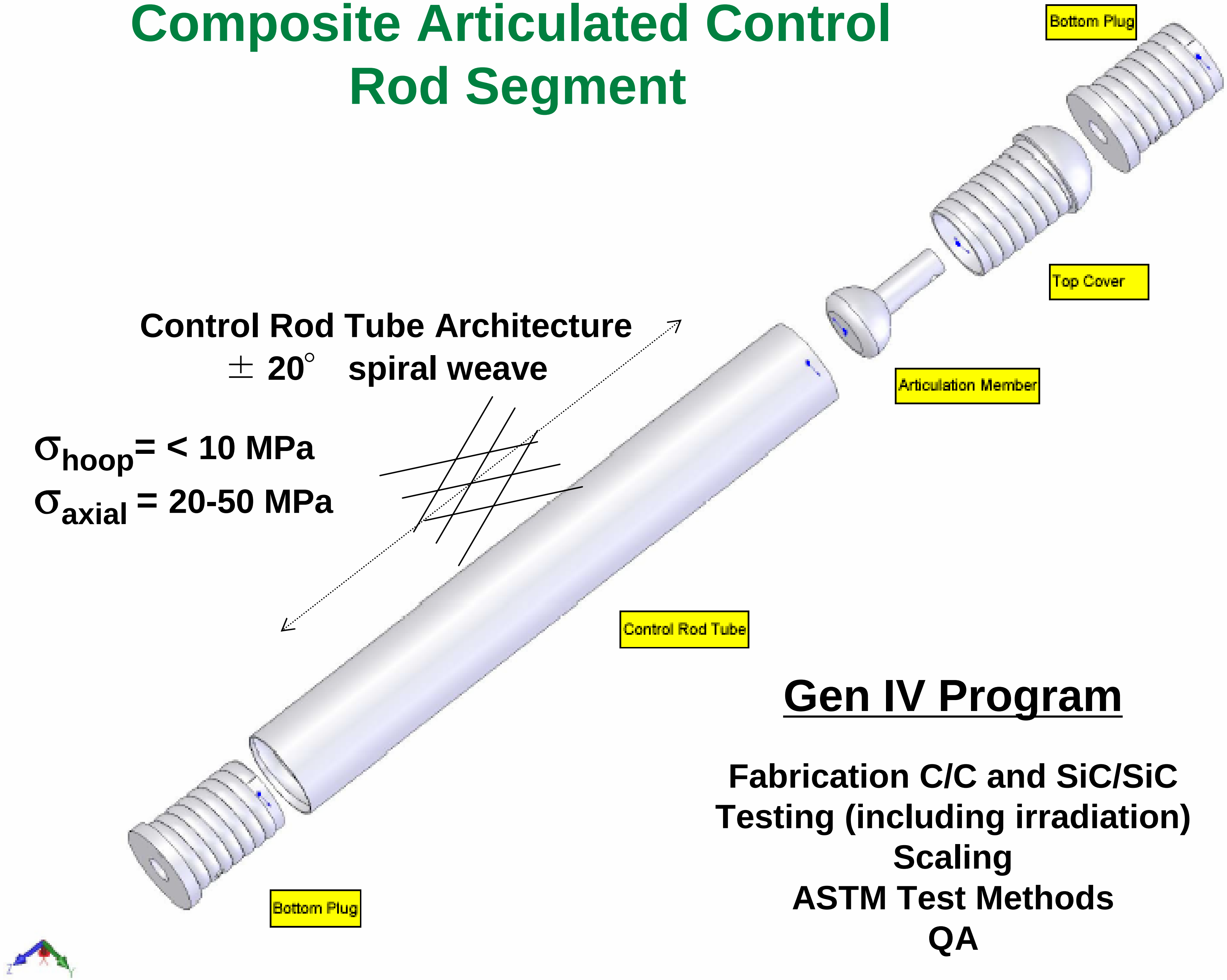




	Toughness MPa/m$^{1/2}$
Steel	> 50
Tungsten	< 20
Monolithic Ceramic	3
Platelet Reinforced Ceramic	6
Chopped Fiber Reinforced	10
Continuous Fiber Reinforced Ceramic	25-30

	Monolithic Strength (MPa)	Composite Strength (MPa)
SiC	100 ± 50	220 ± 20
Graphite	107 ± 20	176 ± 20

Composite Articulated Control Rod Segment



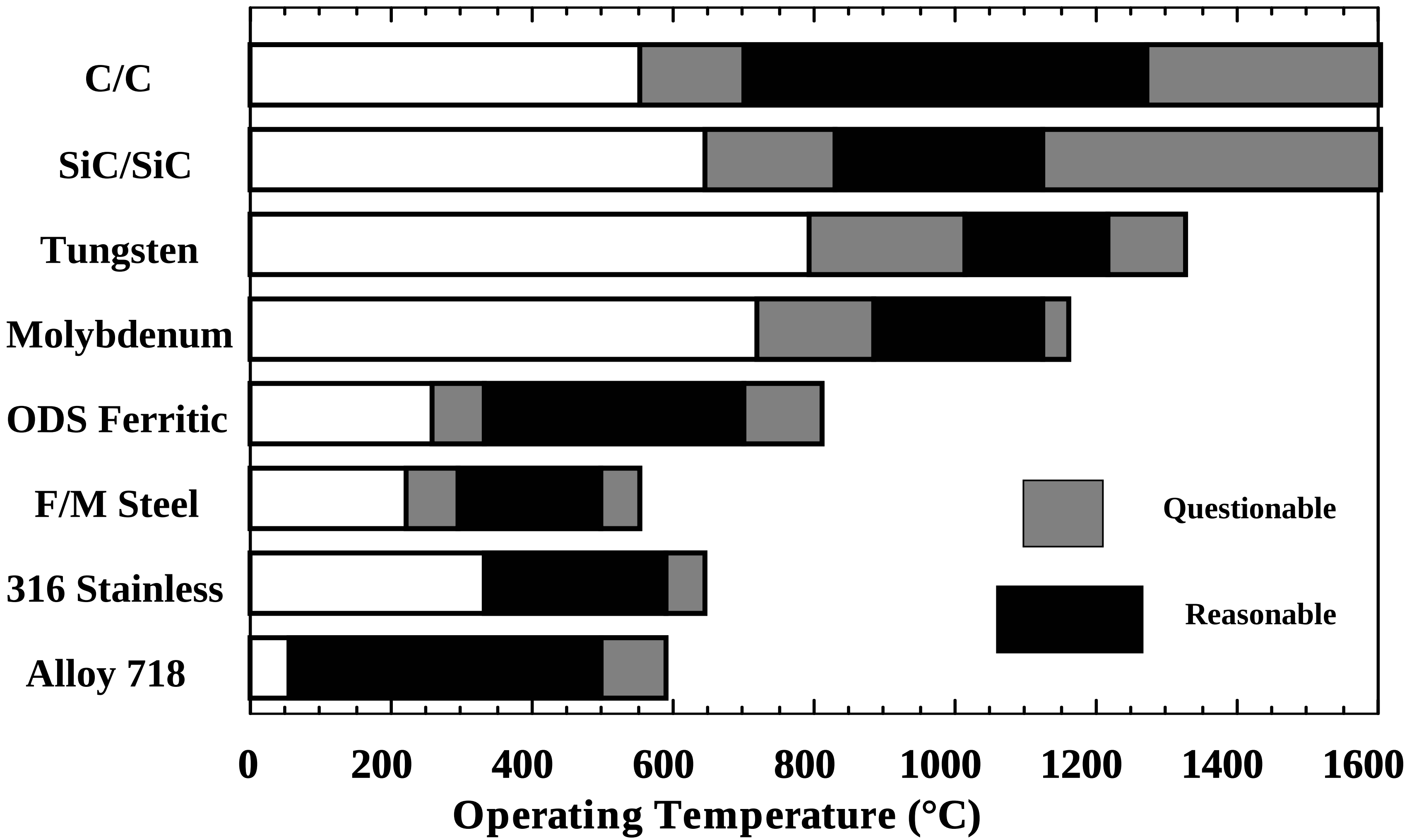
Control Rod Tube Architecture
$\pm$ 20° spiral weave

σ_{hoop} = < 10 MPa
σ_{axial} = 20-50 MPa

Gen IV Program

Fabrication C/C and SiC/SiC
Testing (including irradiation)
Scaling
ASTM Test Methods
QA

Operating Range, Highly Irradiated Structural Materials

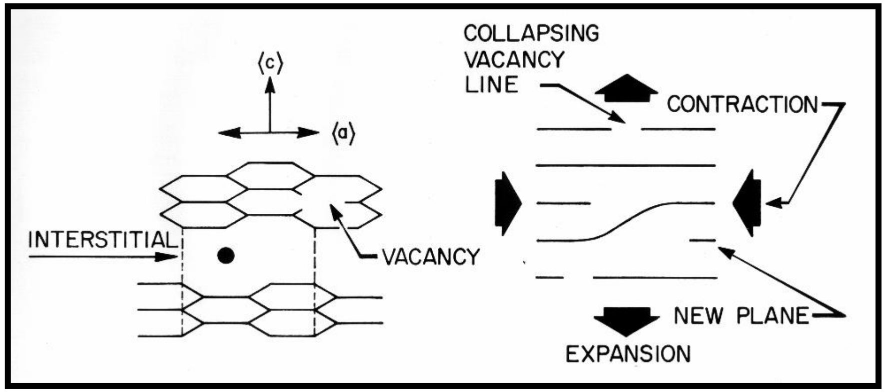


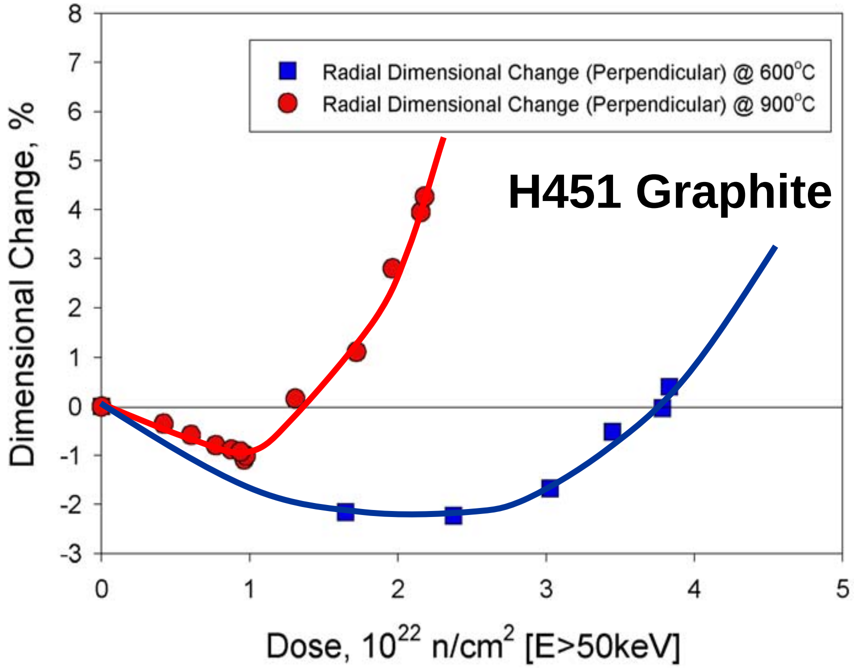
Ceramic Structural Composites For Nuclear Application

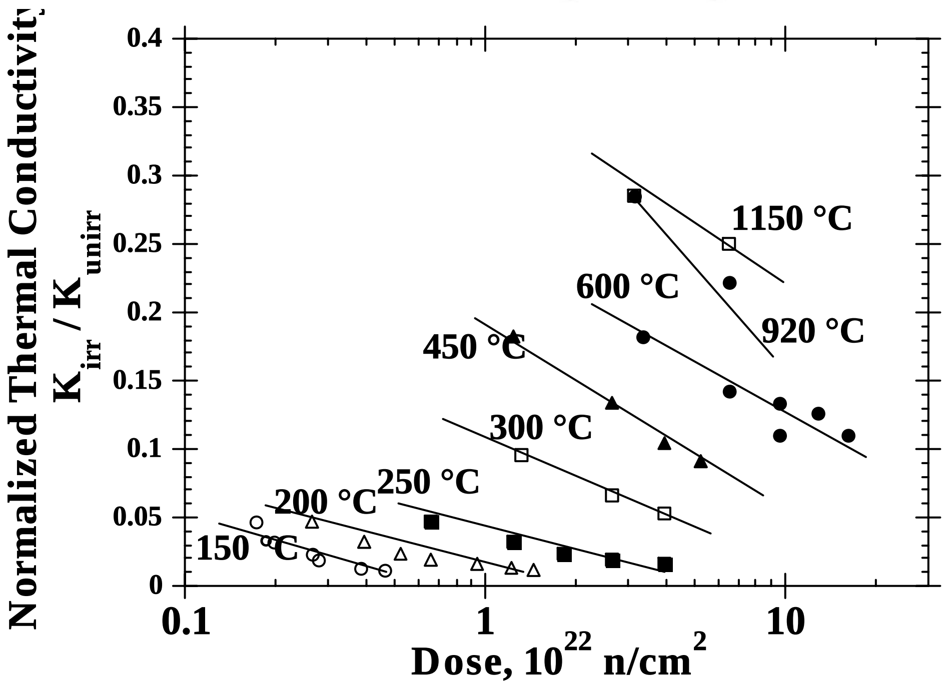
Carbon/Carbon Composites

- *In widespread structural use*
- *Manufacturing and design methods understood*
- *Expensive…*

Graphite Under Irradiation

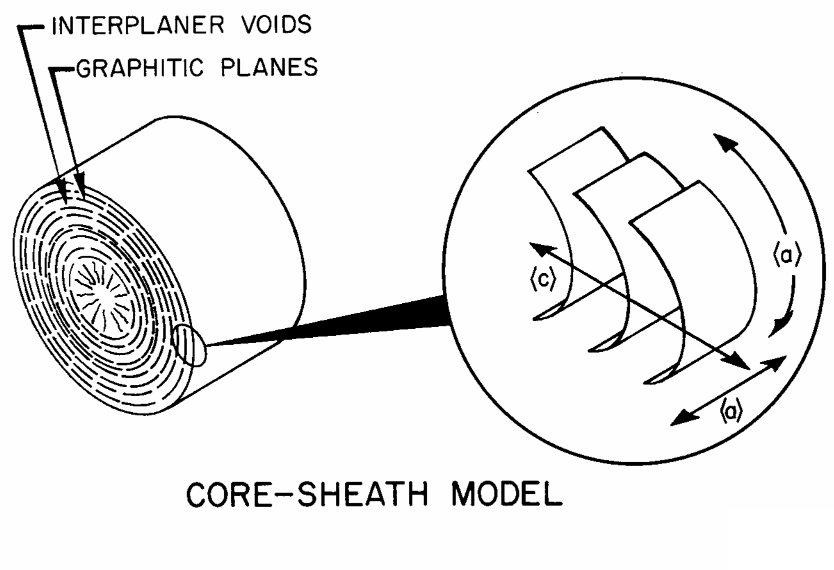


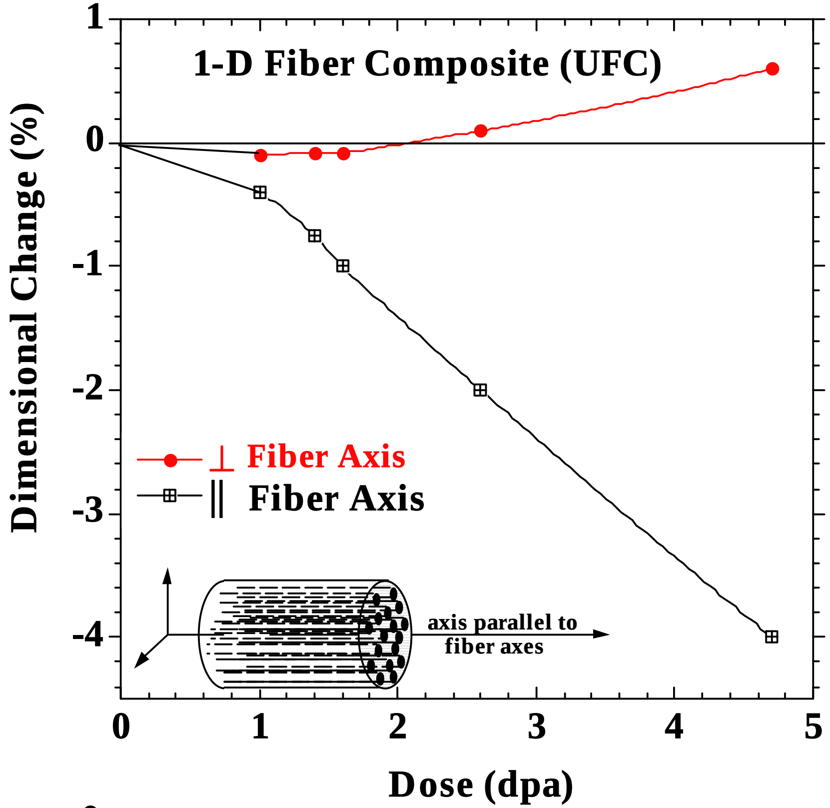


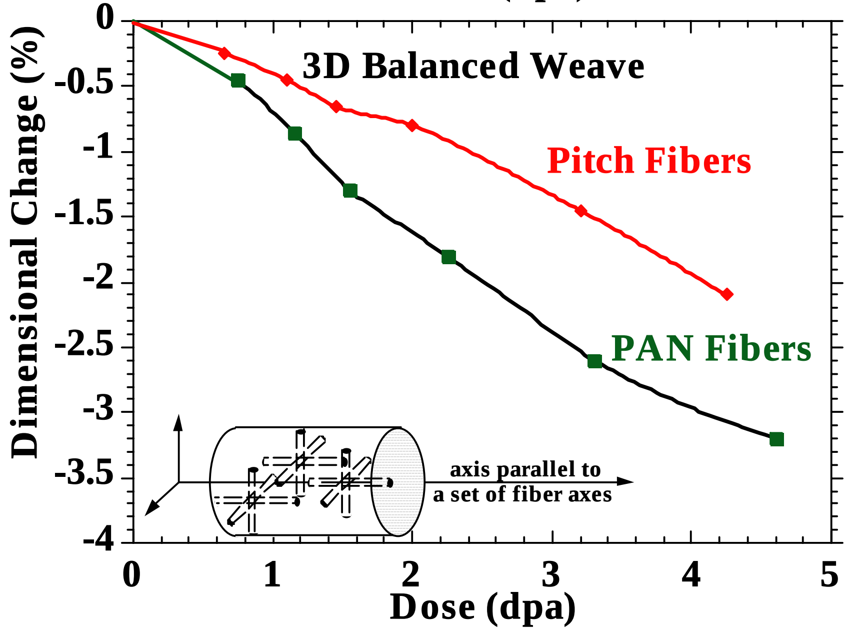


CFC's Under Irradiation

(HFIR , 600° C)

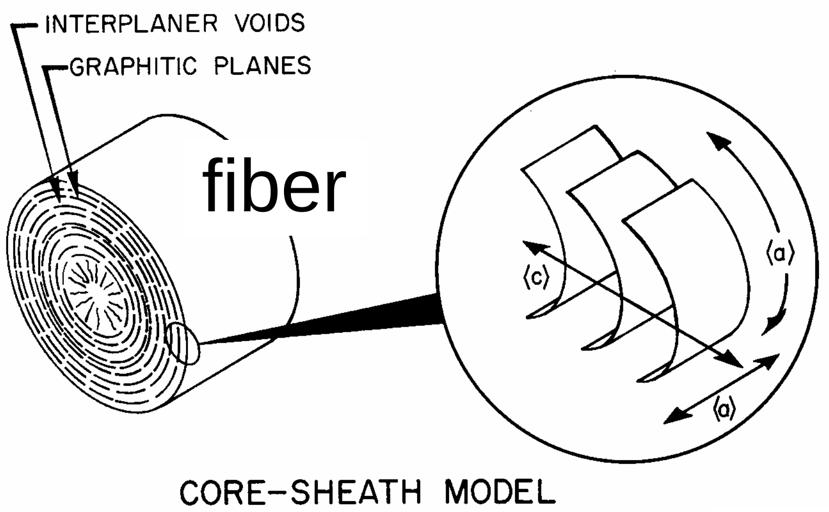






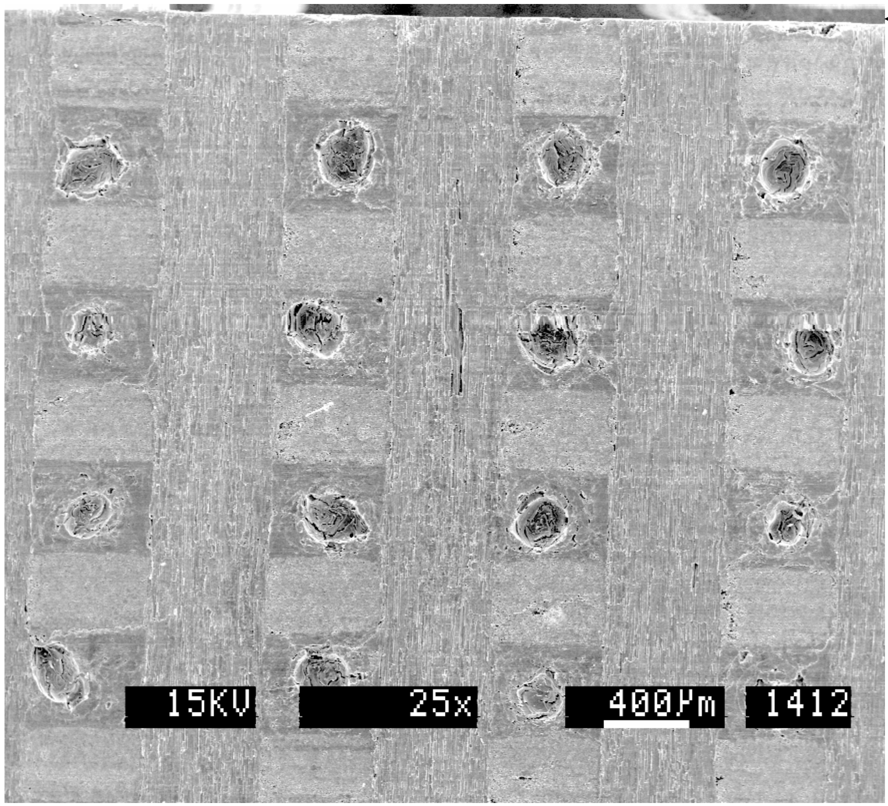
CFC's Under Irradiation

Composite allows "engineering" of properties such as dimensional change



~ 10 dpa (1 FP year)

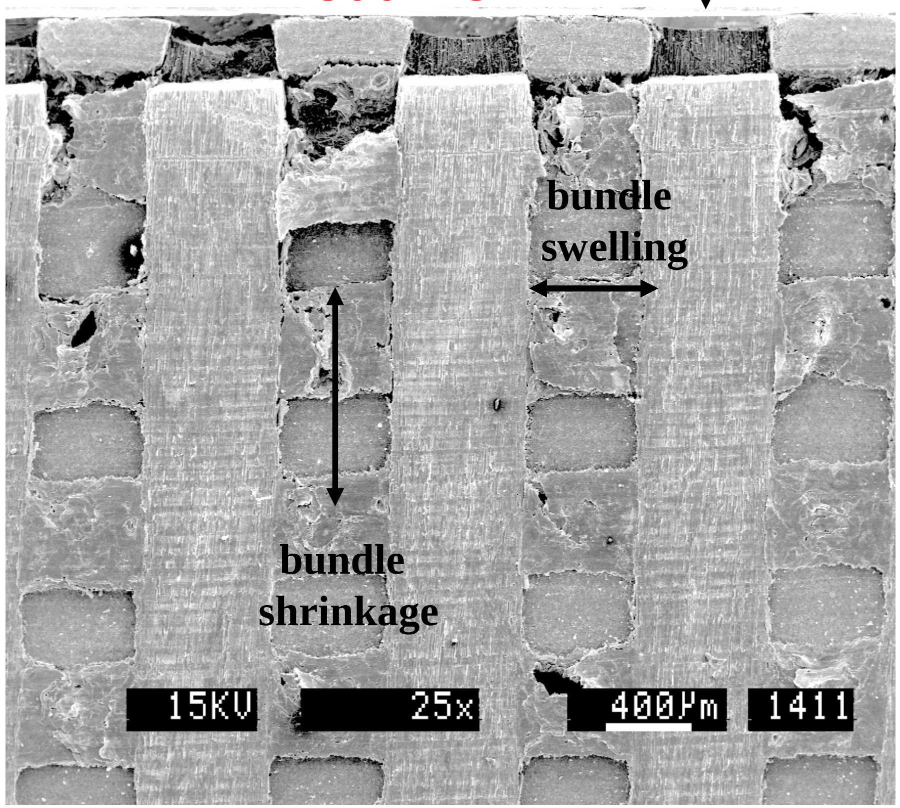
500° C

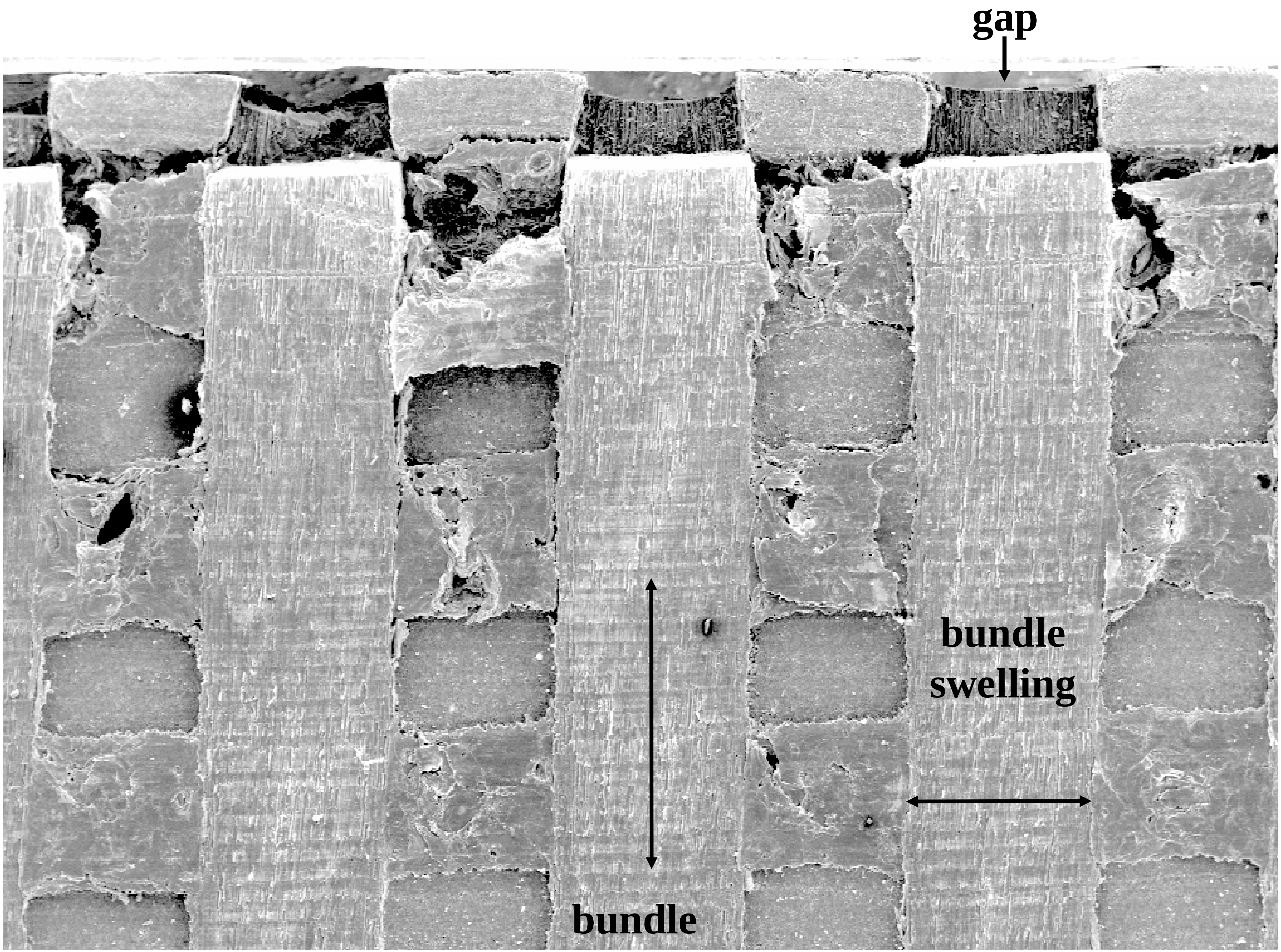


sample surface

800° C

gap




gap
bundle
swelling
bundle

Ceramic Structural Composites

SiC/SiC Composites

- *Essentially no current structural application*
- *Manufacturing and design methods immature*

Ceramic Structural Composites

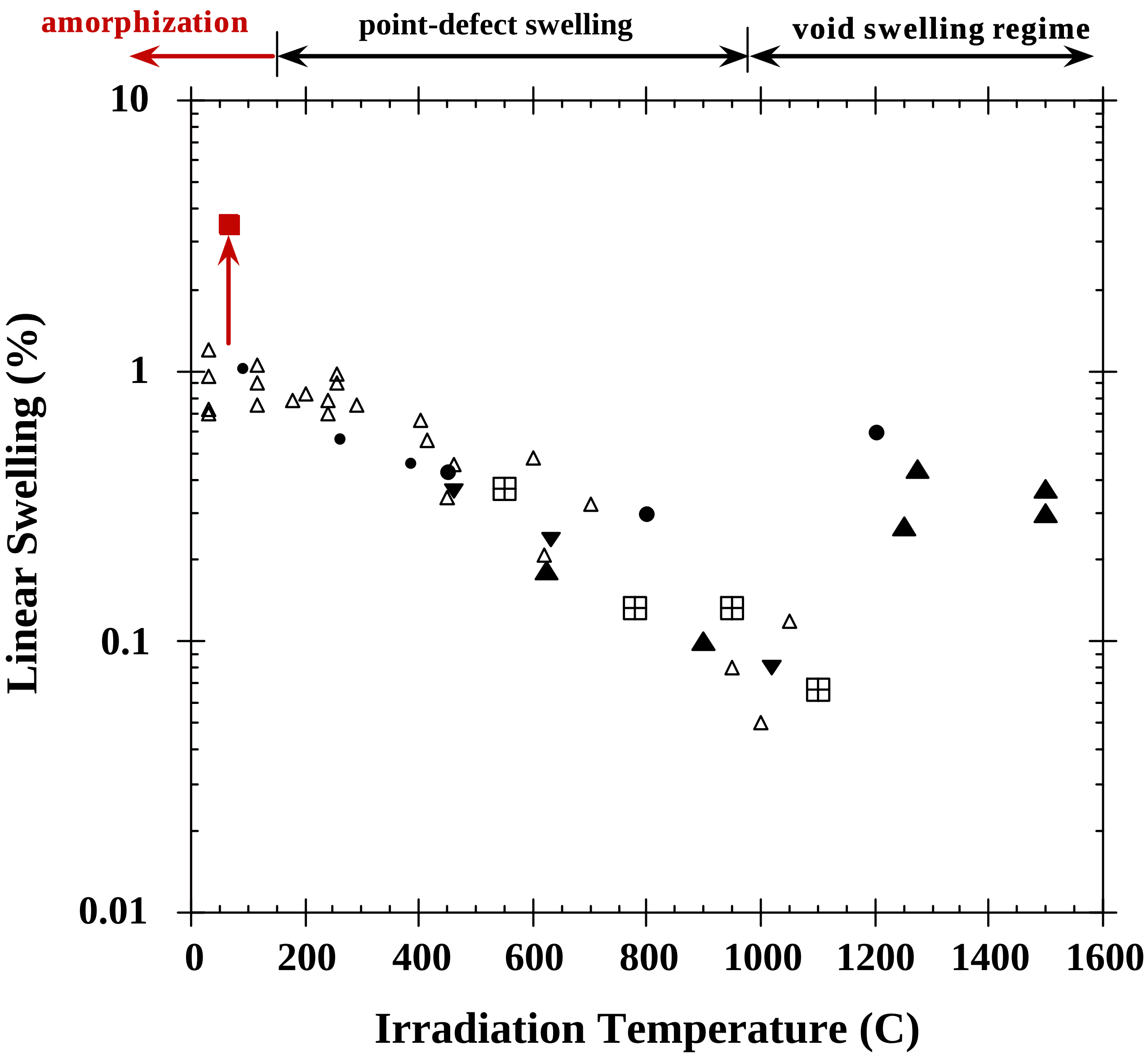
SiC/SiC Composites Under Irradiation

- *May survive for life of machine*
- *Thermal conductivity is likely less than assumed*
- *Electrical conductivity appears not to be a problem*

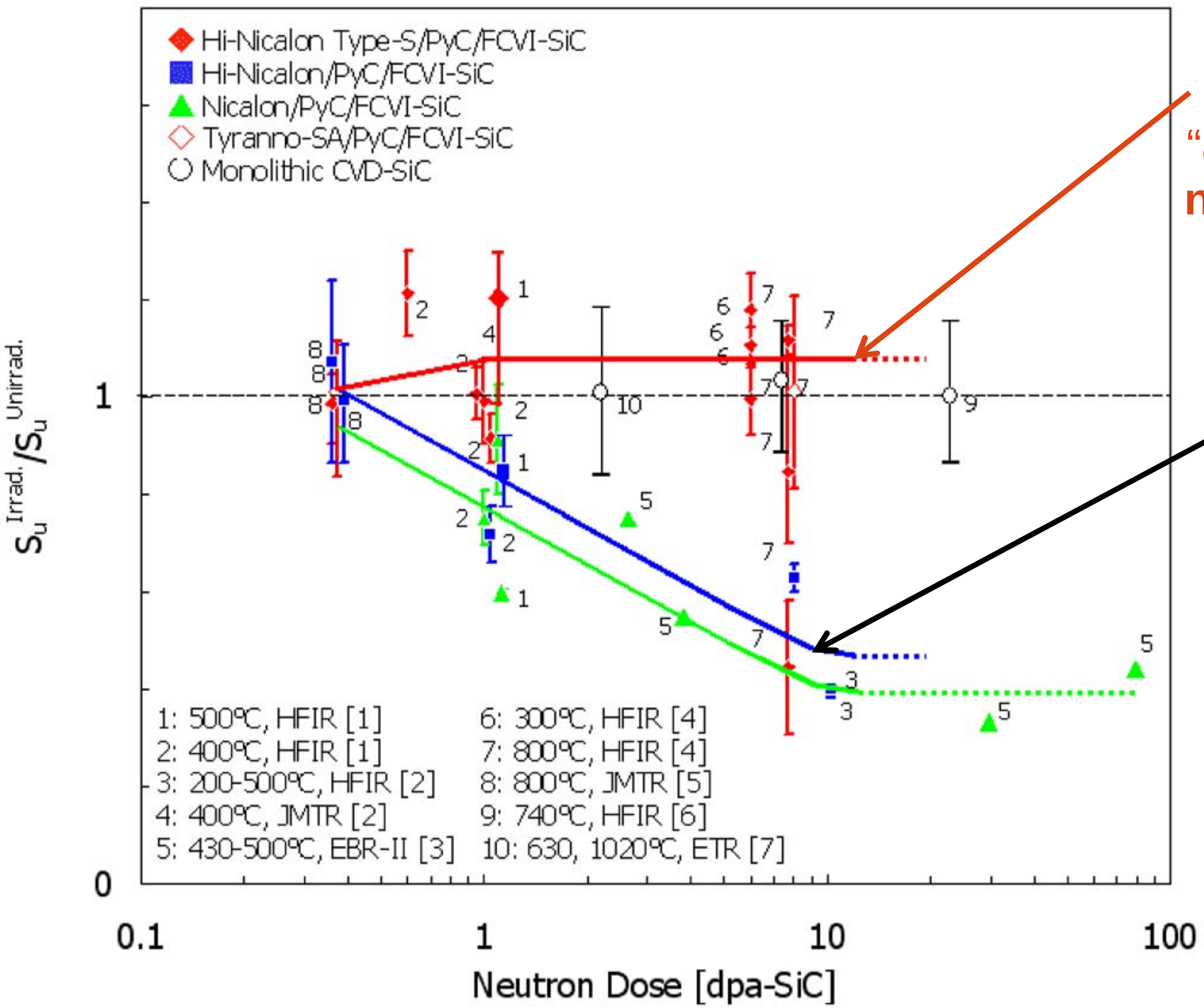
Silicon Carbide Under Irradiation

- **Irradiation-induced thermo-physical property changes (swelling, thermal conductivity, strength) saturate by a few dpa for T< 1000° C. Driven by simple defect clusters.**

- **Irradiation performance for T>1000° C is not well understood.**



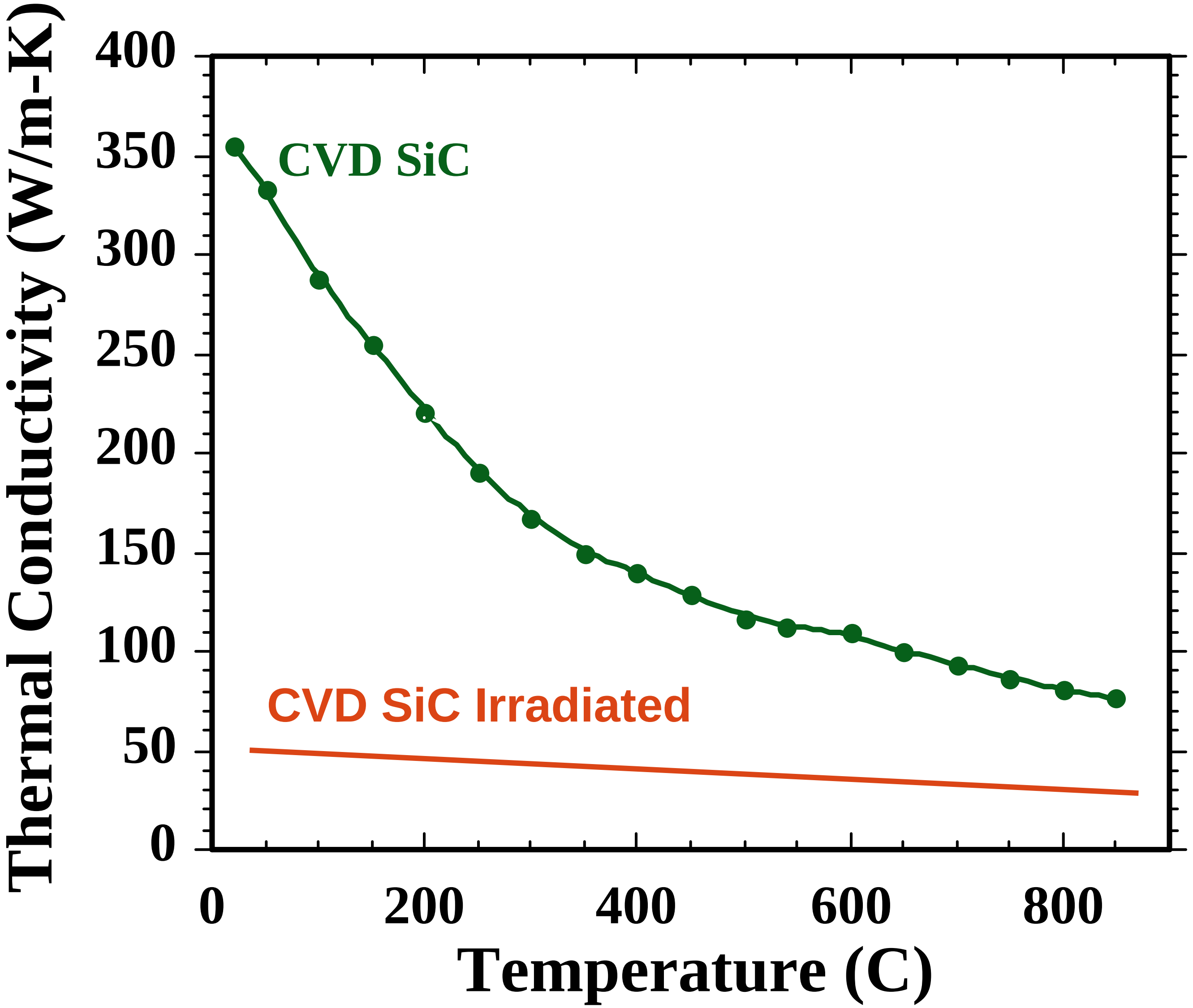
SiC/SiC Composites : Strength and Stability



Bend strength of irradiated "advanced" composites show **no degradation** up to 10 dpa

1st- and 2nd generation irradiated SiC/SiC composites show **large strength loss** after doses >1 dpa

SiC/SiC Composites : Thermal Conductivity



Materials Comparison at 1000° C

Material	Cost $/Kg	Life (dpa)	Irradiation-Induced Property Change @ 1000°C			
			Volume	Strength (MPa)	Modulus	Thermal Conductivity W/m-K
Superalloy	25	~5	-	-	-	-
CFC*	~200	10-15	-5%	150→250	+20%	250→180
SiC/SiC*	~400	>50?	+1%	75→75	-10%	50→20

*** does not include prototyping or NDE evaluation.**

NGNP	Operating Temp	Maximum Temp	Lifetime Dose
Control Rods & Guide Tubes	1200° C	1600° C	25 dpa
Upper Plenum Shroud/Core Restraint	650° C	1300° C	0.05 dpa
Floor Blocks	600° C	600° C	<0.05 dpa
Hot Duct Inner Shell	1000° C	1200° C	0.005 dpa

Concluding Remarks

- **Both GFR and NGNP concepts will require composite materials to achieve design goals, most importantly core internal temperature.**

- **Presently, there are only two viable candidate composites are C/C and SiC/SiC.**

- **C/C composite are more mature and have clear advantages in cost, manufacturability and some thermomechanical properties (eg thermal conductivity.)**

- **SiC/SiC has a clear advantage on irradiation stability, specifically a lower level of swelling and retention of mechanical properties. Offers possibility lifetime component for control rod application to NGNP (C/C would require 2-3 replacements over life.)**

- **Ceramic composite will require substantial investment in ASTM development, NDE development, and must be handled by prototyping and proof testing. Substantial additional costs compared to more conventional alloys.**


Questions ???

Yield Strength of Various Structural Materials