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### Materials in Generation-IV Very High Temperature Reactors – Challenges and Opportunities

Kent Shirer Materials Science and Engineering 395-0 Prof. Dunand

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### **Review of Reactor Generations**



http://www.ne.anl.gov/images/activ/programs/geniv/picture1.jpg

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### **Generation-IV Types**

Generation-IV Reactor Systems (from ref [11] and [http://www.world-nuclear.org/info/inf77.html])							
System	Coolant	Neutron spectrum	Core outlet temp (°C)	Pressure (High = 7-15 MPa)	Fuel	Cycle	Use
Very high temperature reactor (VHTR)	Gas (i.e. helium)	Thermal	>900	High	$UO_2$ pebbles or prism	Open	Electricity & Hydrogen
Gas-cooled fast reactor (GFR)	Gas (i.e. helium)	Fast	~850	High	U-238 + U- 235 or Pu-239	Closed, on site	Electricity & Hydrogen
Sodium-cooled fast reactor (SFR)	Liquid Metal (i.e. Na)	Fast	~550	Low	U-238 & MOX	Closed	Electricity
Lead-cooled fast reactor (LFR)	Liquid Metal (i.e. Pb, Pb- Bi)	Fast	550-800	Low	U-238 + U- 235 or Pu-239	Closed, regional	Electricity & Hydrogen
Super critical water-cooled reactor (SCWR)	Water	Thermal/ fast	350-620	Very High	UO <sub>2</sub>	Open (Thermal) or Closed (Fast)	Electricity
Molten salt reactor (MSR)	Molten salt (fluoride salts)	Thermal/ fast*	700-800	Low	$UF_4$ in salt	Open or Closed*	Electricity & Hydrogen

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### **Generation-IV Potential**

Generation-IV Reactor System Potential (from ref [2])								
Generation-IV Goal	VHTR	GFR	SFR	LFR	SCWR	MSR		
Efficient electricity generation (Economics)	Very high	High	High	High	High	High		
Flexibility: availability of high- temperature process heat (Economics)	Very high	High	Low	Low	Low	Low		
Sustainability: creation of fissile material (Proliferation and Waste)	Medium/ low	High	High	High	Low	Medium/ low		
Sustainability: transmutation of waste (Waste and Proliferation)	Medium	Very high	Very high	Very high	Low	High		
Potential for 'passive' safety (Safety)	High	Very low	Medium/ low	Medium	Very low	Medium		
Current technical feasibility (Economics and Safety)	High	Medium/ low	High	Medium	Medium/ low	Low		

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### **Very High Temperature Reactor**



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## **Material Requirements – VHTR**

- Dimensional stability under irradiation and high temperatures
  - Under stress irradiation creep or relaxation
  - Without stress swelling or growth
- Mechanical properties must be acceptable after ageing
  - 50,000h operation target between major maintenance work compared to 15,000h for most current gas turbine plants
    - Tensile strength
    - Ductility
    - Creep Resistance
    - Fracture toughness
    - Resilience (shock)
- Corrosion resistance or chemical compatibility between structural materials and the coolant or process fluid

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## **Current Reactor Materials**

- Fuel cladding
  - Zirconium alloys:
  - Zircaloy-2, -4, and Zr-2.5Nb
- Moderators
  - Boron Carbide
  - Ag-In-CD (80-15-5) alloy
  - $Gd_2O_3$  with  $UO_2$
- Outside the core
  - Low alloy ferritic steels
  - Stainless Steels (304)



http://en.wikipedia.org/wiki/File:Nuclear\_fireball.jpg

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### **VHTR Materials**

- Fuel
  - Tri-isotropic (TRISO)-layered particles
    - Pyrolytic carbon
    - Silicon carbide
    - Porous carbon
  - $UO_2$  and  $UC_2$
- Moderator, central column, radial reflectors, etc
  - Graphite
    - i.e. H-451 medium grain, near-isotropic, nuclear grade
- Outside the core
  - Ni-base Superalloys
  - Silicon carbide fiber reinforced silicon carbide matrix composites (SiC/SiC)



From ref [2]

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### **TRISO** particles

- Pyro-carbon
  - Single cleavage planes → good thermal conductivity (for thermal neutrons)
  - Outer layer structural strength
  - Inner layer retain fission gasses
- SiC
  - Retain fission gases
- Porous Carbon
  - Space for fission gases and CO
- UO<sub>2</sub> and UC<sub>2</sub>
  - UC<sub>2</sub> can reduce CO pressure



From ref [13]



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# Graphite

- Polycrystalline
- High degree of graphitization
- High chemical purity
  - Minimize thermal neutron absorption in the moderator
- Random bulk
  orientation
  - Dimensional stability under high neutron fluxes
- Reduce irradiation doses to other parts

- Issues
  - Neutron irradiation induces
    dimensional changes
  - Local differences in neutron dose and temperature induce differential stress in the graphite
  - Stresses are relaxed by the creep strain due to neutron irradiation (no thermal creep at operation temps)
- These mechanisms are not well-understood

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## **Ni-Base Superalloys**

- Corrosion resistance? Helium is not corrosive...
- H<sub>2</sub>, H<sub>2</sub>O, CO, CH<sub>4</sub>, N<sub>2</sub>, and CO<sub>2</sub> impurities highly diluted in He
- Dilution causes single gas species interaction with metallic materials

Oxidation of a metal by water vapor:  $xH_2O_{(g)} + M_{(s)} = MO_{x(s)} + x/2H_{2(g)}$ 

Reaction of water vapor with carbon from an alloy:

 $H_2O_{(g)} + C_{(s)} \rightarrow CO_{(g)} + H_{2(g)}$ 

Decomposition of carbon monoxide:  $xCO_{(g)} + M_{(s)} \rightarrow MO_{x(s)} + xC_{(s)}$ 

Decomposition of methane on a metallic surface:

$$CH_{4(g)} = C_{(s)} + 2H_{2(g)}$$

Reduction by methane of a metallic oxide:  $xCH_{4(g)} + MO_{x(s)} \rightarrow xCO_{(g)} + 2xH_{2(s)} + M_{(s)}$ 

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# SiC/SiC

- Want benefits of ceramics without being as brittle:
- Can be engineered to have pseudo-ductile and predictable fracture modes
- Continuous fiber reinforcement of SiC/SiC
  - More tolerant to mechanical loading and thermal shock.
- SiC/SiC composites are capable of being used for larger and more complex components than monolithic silicon carbide

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### **Exciting Area of Research**

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	ARTICLEINFO ABST Available online xxxx Graphite	INFO ABSTRACT (raphite is of principal interest in Generation IV nuclear reactor concepts. In particular, graphite will be				RETRACT		
	the moderator for the Very High investigations that aim at unders tions, neutron powder diffraction sity PUSTAR reactor. The collec erflections, characteristic of tunbo combined with a Neuted-like ref parameters that aim at describing ties of a random and registered a the studied reactor grade graphite layer spacing for the specimens is the lattice constant is slightly less fitting the neutron diffraction pat		Temperature Reactor. In support of experimental and computational tanding the behavior of reactor grade graphite under operating condi- experiments have been performed at the North Carolina State Univer- ted diffraction patterns exhibit intense brazdening of several of the stratic stacking. In order to quantify this disorder structurally, a model finement approach was implemented which includes several refinable this type of structure. Stacking parameters representing the probabil- lishing between stacking packages were defined. The results indicate that specimens contain a small fraction of layer disorder. The inferred inter- signity layer than the theoretical value for graphite of 0.335 nm and than 0.246 nm. The developed methodology is found to be successful in terms of reactor grade graphite.		Available online xxxx It	has been internationally re-	cognized that materials science and materials development are key issues	
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					tt p	time to more than one type of innovative reactor systems. The present work has been prepared with a in of describing the rationale, the objectives, the work plan and the expected results of this research oject.		
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