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Northwestern Engineering

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

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Materials Science and Engineering 395-0

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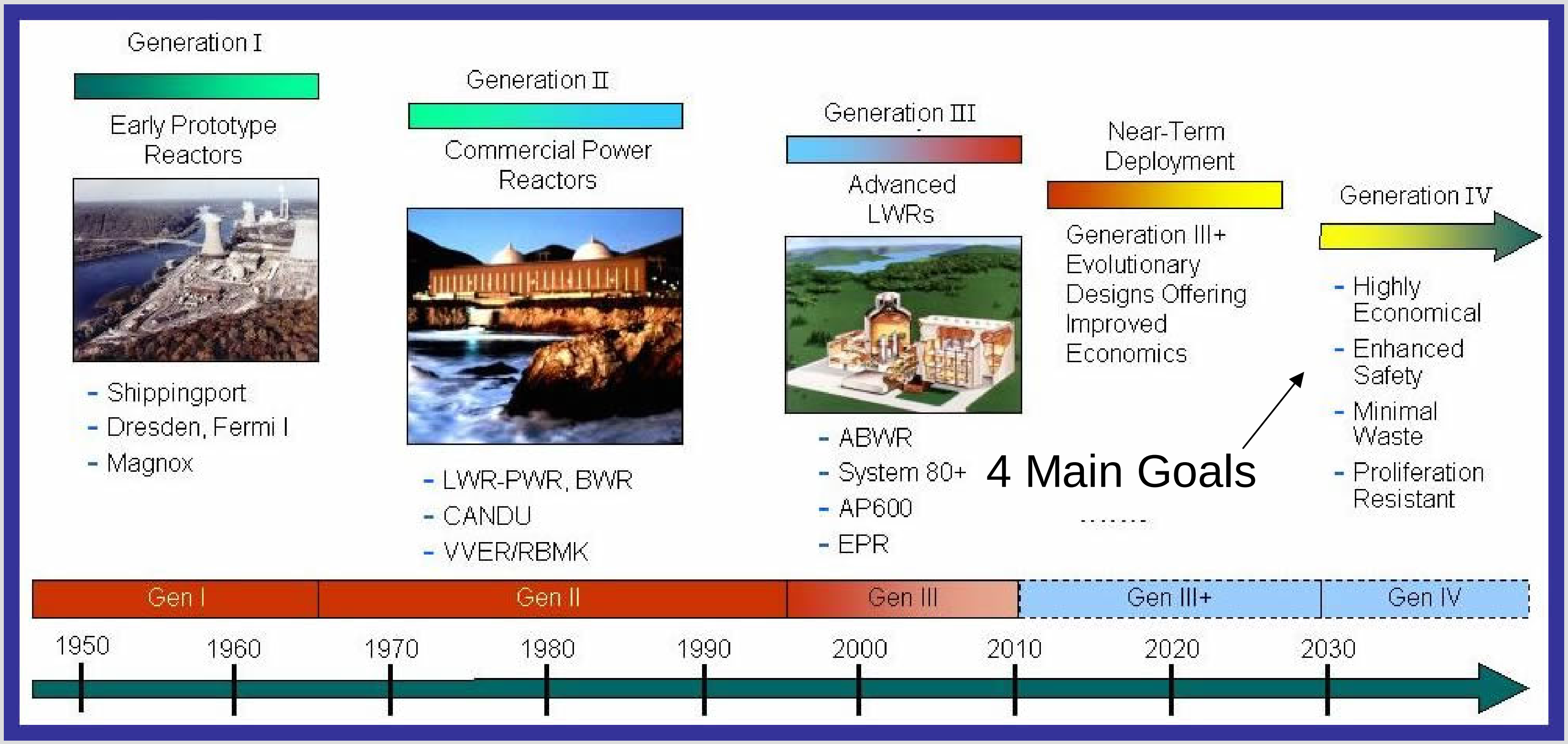
Review of Reactor Generations



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

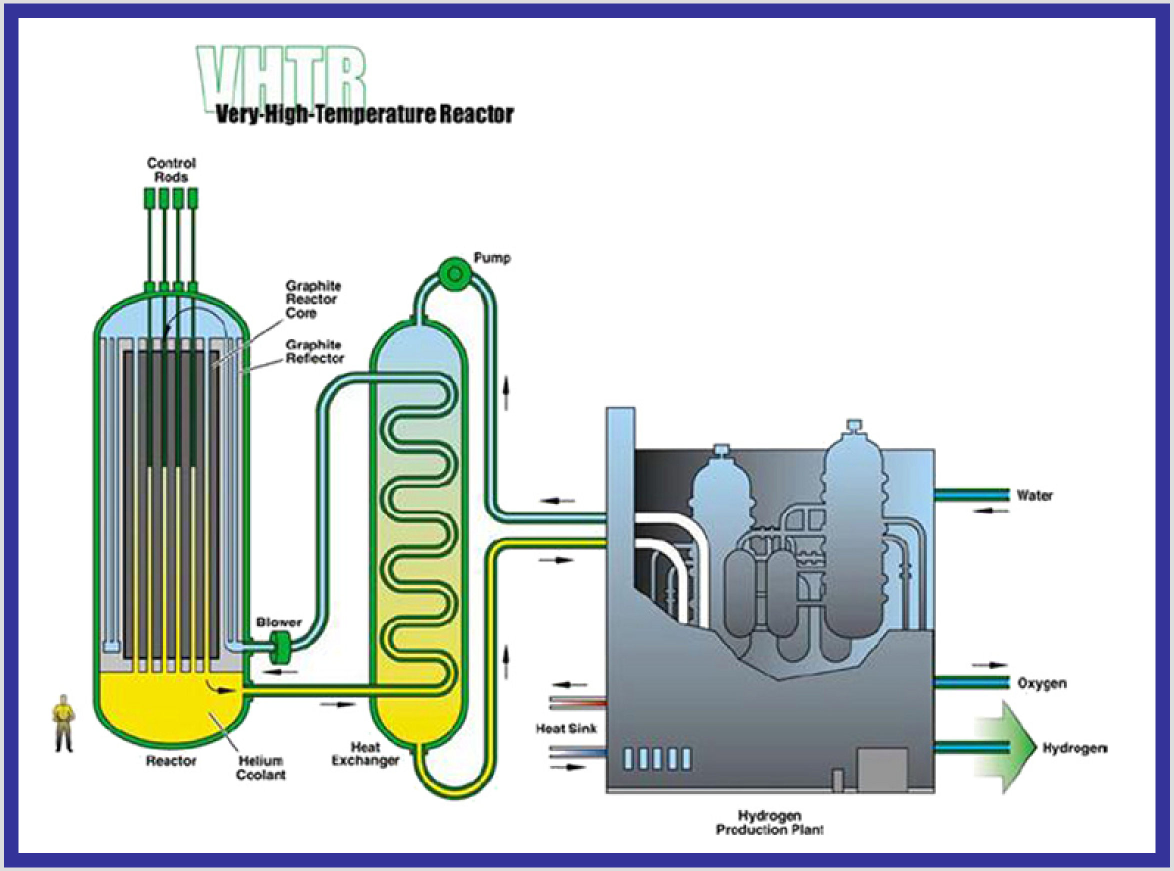
Generation-IV Types

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_2	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

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

Very High Temperature Reactor



Material Requirements – VHTR

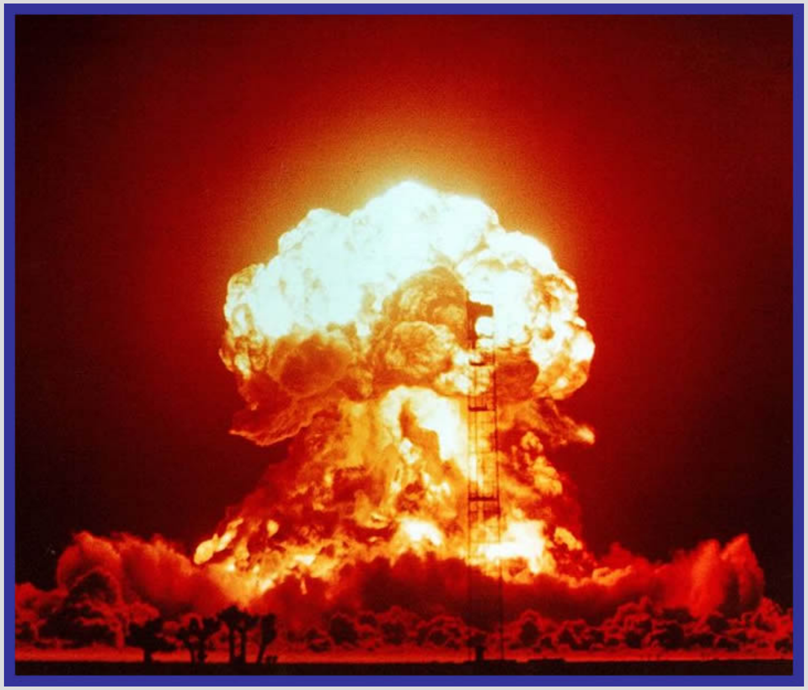
- Dimensional stability under irradiation and high temperatures
  - Under stress – irradiation creep or relaxation
  - Without stress – swelling or growth

- 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

Current Reactor Materials

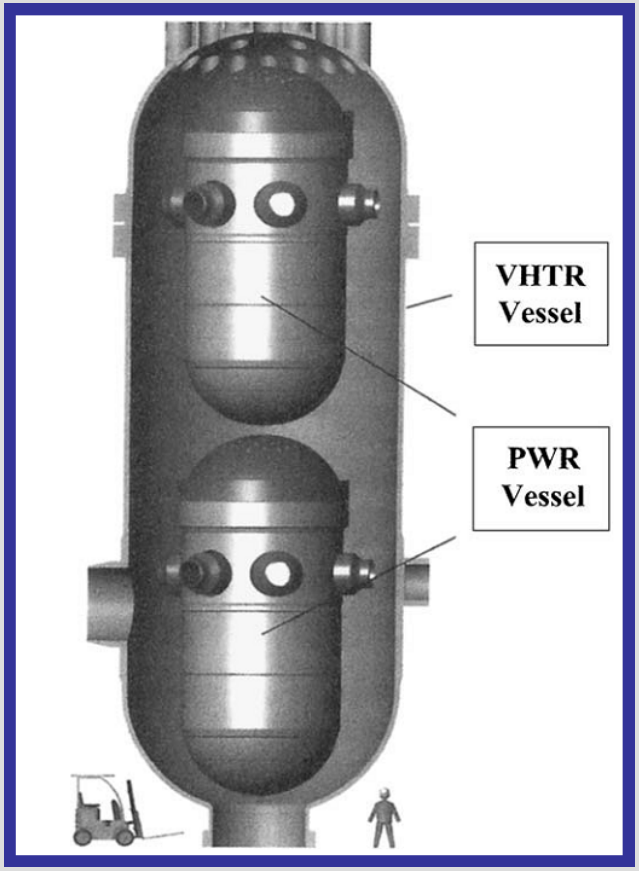
- Fuel cladding
  - Zirconium alloys:
  - Zircaloy-2, -4, and Zr-2.5Nb
- Moderators
  - Boron Carbide
  - Ag-In-CD (80-15-5) alloy
  - Gd_2O_3 with UO_2
- Outside the core
  - Low alloy ferritic steels
  - Stainless Steels (304)



http://en.wikipedia.org/wiki/File:Nuclear_fireball.jpg

VHTR Materials

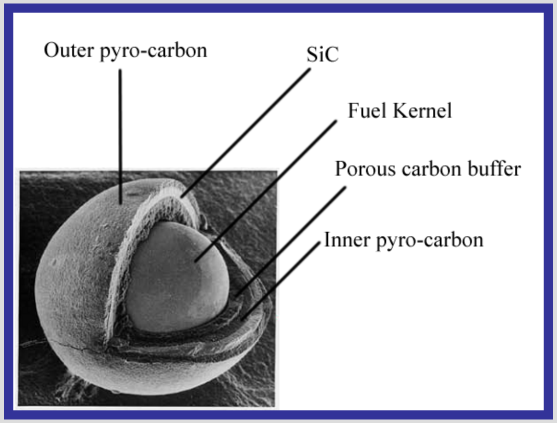
- Fuel
  - Tri-isotropic (TRISO)-layered particles
    - Pyrolytic carbon
    - Silicon carbide
    - Porous carbon
  - UO_2 and UC_2
- Moderator, central column, radial reflectors, etc
  - Graphite
    - i.e. H-451 – medium grain, near-isotropic, nuclear grade
- Outside the core
  - Ni-base Superalloys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



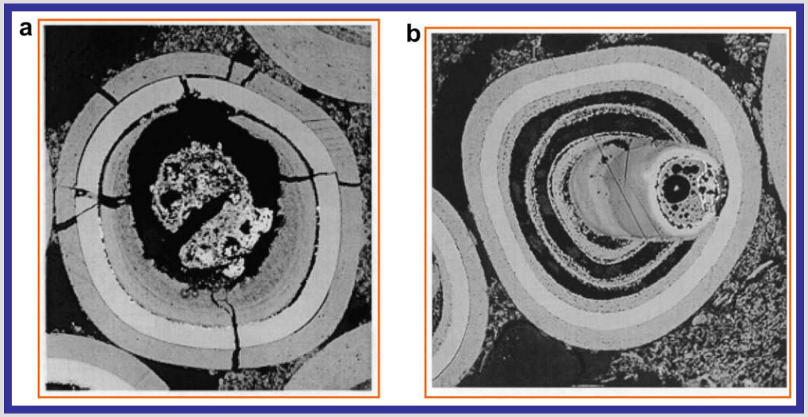
From ref [2]

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_2 and UC_2
  - UC_2 can reduce CO pressure



From ref [13]



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

Ni-Base Superalloys

- Corrosion resistance? Helium is not corrosive…
- H_2, H_2O, CO, CH_4, N_2, and CO_2 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:

$$xCH_{4(g)} + MO_{x(s)} \rightarrow xCO_{(g)} + 2xH_{2(s)} + M_{(s)}$$

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

References

[1] "15 Years of Progress." World Association of Nuclear Operators. 2006. http://www.wano.org.uk/PerformanceIndicators/PI_Trifold/WANO15yrsProgress.pdf

[2] T Abram and Sue Ion, Energy Policy **36** (2008) 4323–4330

[3] K. G. E. Brenner and L.W. Graham, Nuclear Technology **66** (1984) 404

[4] T. D. Burchell, J. Nucl. Mater. **381** (2008) 46–54

[5] C. Cabet and F. Rouillard, J. Nucl. Mater. (2009), doi:10.1016/j.jnucmat.2009.03.029

[6] D. D. DiJulio and A. I. Hawari, J. Nucl. Mater. (2009), doi:10.1016/j.jnucmat.2009.03.014

[7] "Executive Summary: Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" (PDF). National Renewable Energy Laboratory. Oct 2003. http://www.nrel.gov/csp/pdfs/35060.pdf

[8] C. Fazio, A. Alamo, A. Almazouzi, S. De Grandis, D. Gomez-Briceno, J. Henry, L. Malerba, and M. Rieth, J. Nucl. Mater. (2009), doi:10.1016/j.jnucmat.2009.03.020

[9] M. A. Fütterer, E. D'Agata, M. Laurie, A. Marmier, F. Scaffidi-Argentina, P. Raison, K. Bakker, S. de Groot, and F. Klaassen, J. Nucl. Mater. (2009), doi:10.1016/j.jnucmat.2009.03.030

[10] Y. Katoh, L. L. Snead, C. H. Henager Jr., A. Hasegawa, A. Kohyama, B. Riccardi, and H. Hegeman, J. Nucl. Mater. **367–370** (2007) 659–671

[11] K.L. Murty and I. Charit, J. Nucl. Mater. **383** (2008) 189–195

[12] R. K. Nanstad, D. A. McClintock, D. T. Hoelzer, L. Tan, and T. R. Allen, J. Nucl. Mater. (2009), doi:10.1016/j.jnucmat.2009.03.022

[13] D. Olander, J. Nucl. Mater. **389** (2009) 1–22

[14] K. Shimoda, A. Kohyama, and T. Hinoki, Compos Sci Technol (2009), doi:10.1016/j.compscitech.2009.03.011

[15] K. Shimoda, J.-S. Park, T. Hinoki, and A. Kohyama, Compos Sci and Technol **68** (2008) 98–105

[16] L. L. Snead, T. D. Burchell, and Y. Katoh J. Nucl. Mater. **381** (2008) 55–61

[17] "Wind Power: Capacity Factor, Intermittency, and what happens when the wind doesn't blow?" Renewable Energy Research Laboratory, University of Massachusetts at Amherst. http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_2a_Capacity_Factor.pdf

[18] P. Yvon and F. Carré, J. Nucl. Mater. **385** (2009) 217–222