Structural Materials Research within the Gen IV International Forum

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Advanced Non-Light Water Reactors –
Materials and Component Integrity Workshop
U.S. NRC Headquarters, Rockville, MD
December 9-11, 2019

Generation IV Concept

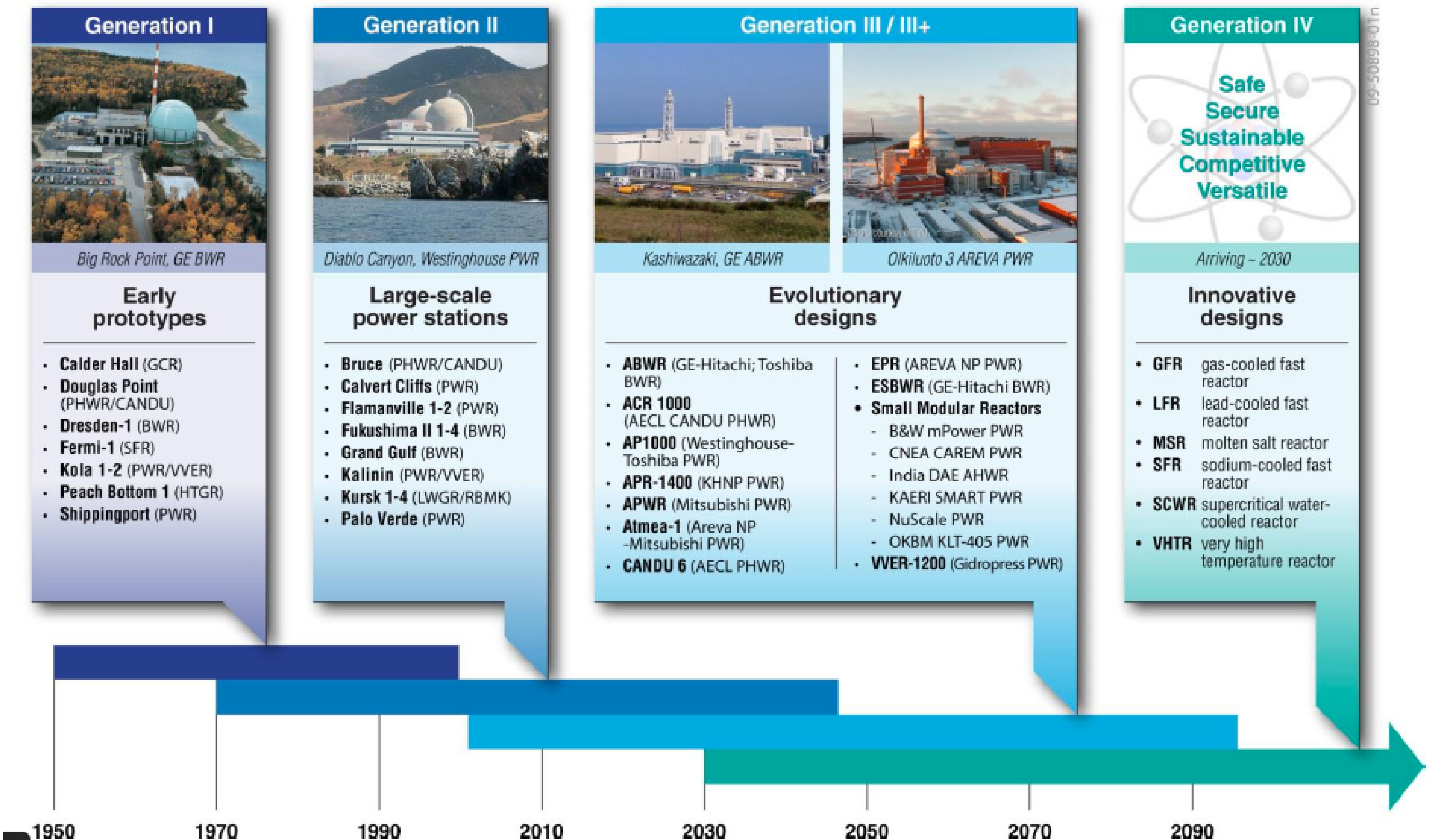
- GIF Framework Agreement implemented 2005
- Goals – Sustainability, Safety & Reliability, and Proliferation Resistance & Physical Protection
- Nearly 100 reactor designs were evaluated and down selected to 6 most promising concepts
  - Sodium Fast Reactor
  - Gas-Cooled Fast Reactor
  - Lead Fast Reactor
  - Very High Temperature Reactor
  - Supercritical Water Cooled Reactor
  - Molten Salt Reactor
- System Steering Committee for each reactor concept
  - Plan and integrate R&D Projects
  - Project Arrangements are technology-specific

Fourteen Current Members of Generation IV International Forum

Argentina*	Japan
Australia	Republic of Korea
Brazil*	Russian Federation
Canada	Republic of South Africa
People's Republic of China	Switzerland
Euratom	United Kingdom
France	United States

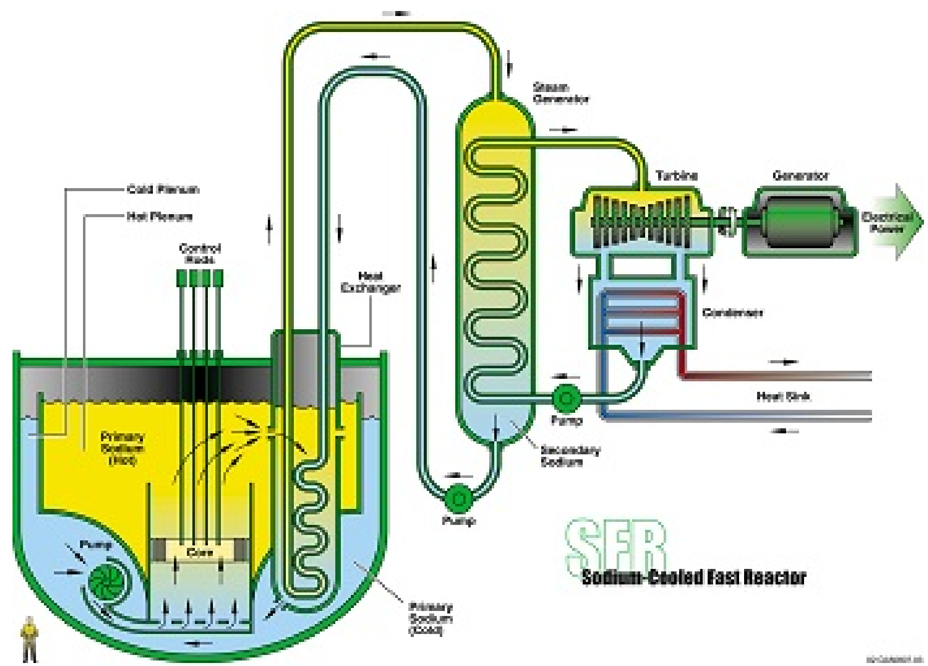
**Inactive members*

Generation IV Evolution

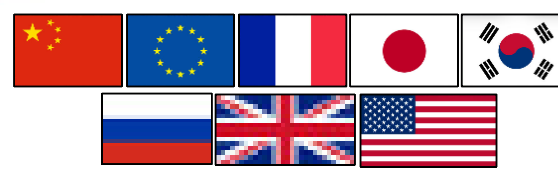


Sodium Fast Reactor

- Integral part of the closed fuel cycle
  - Can either burn actinides or breed fissile material
- R&D focus
  - Analyses and experiments to demonstrate safety approaches
  - High burn-up minor actinide bearing fuels development
  - Develop advanced components and energy conversion systems
- BN-800 operating in Russia & CEFR in China
- No specific materials R&D projects active, but extensive work on high-dose-tolerant fuel claddings

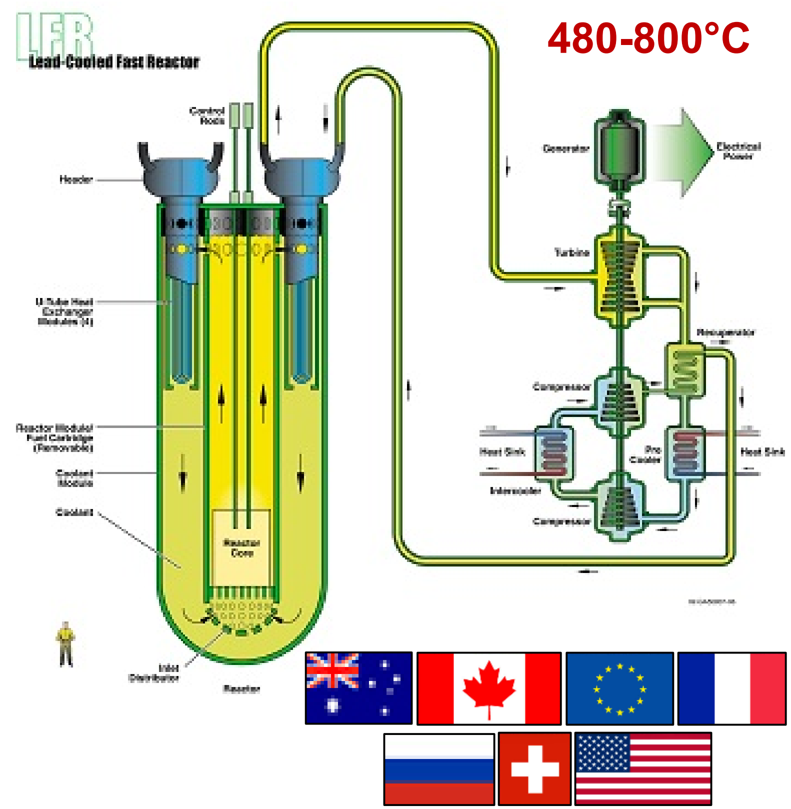


500-550°C



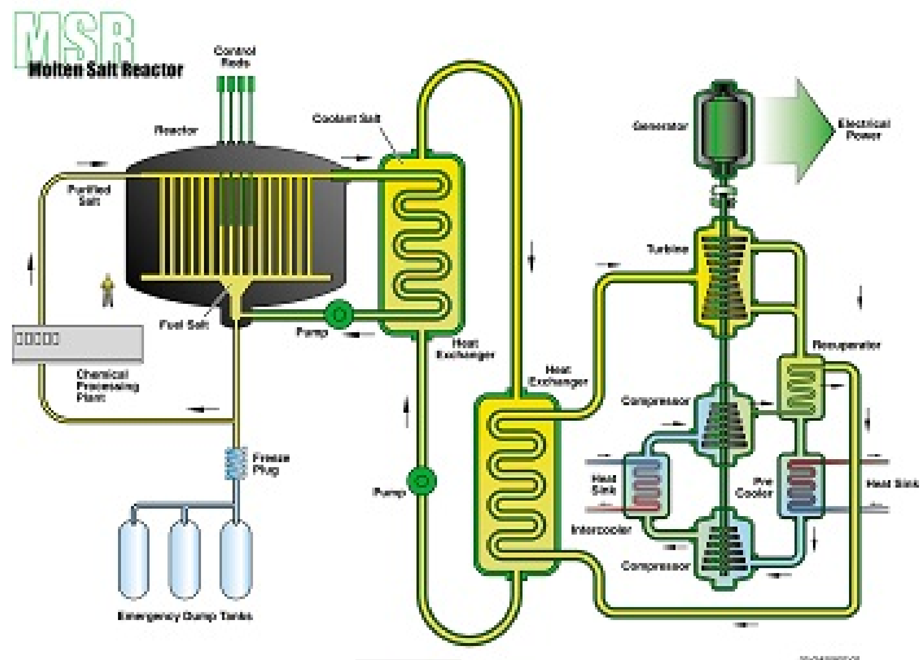
Lead Fast Reactor

- Lead is not chemically reactive with air or water and has lower coolant void reactivity
- Variants include both lead and lead-bismuth cooled systems
- LFR MOU working towards SteeringCom & technical projects
- Principal materials issue is materials compatibility with lead or lead-bismuth coolant
  - Precise oxygen-chemistry control or protective cladding layers needed
- Europe’s ELFR lead-cooled system, Russia’s BREST-OD-300 and the U.S. SSTAR system are actively being developed



Molten Salt Reactor

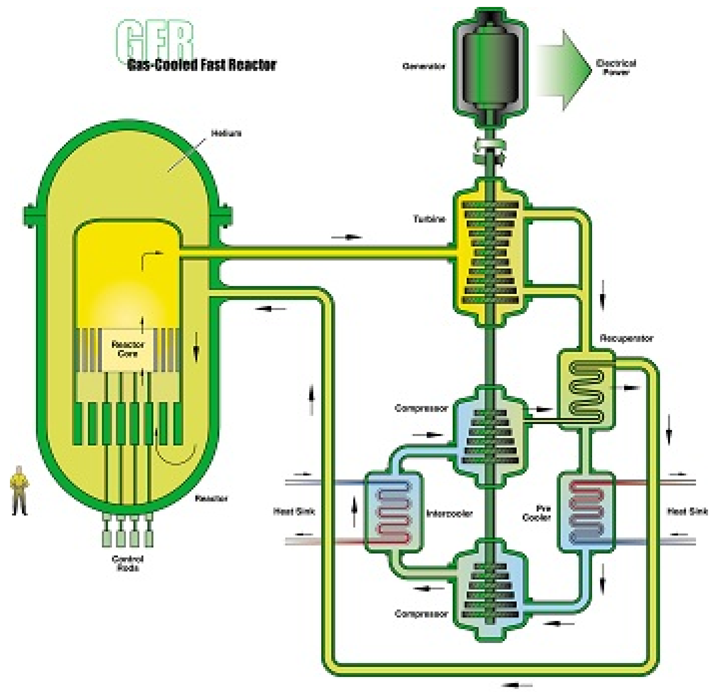
- Two design options: fuel dissolved in MS coolant, solid fuel with MS coolant
- Variants include both thermal & fast designs, with fluoride or chloride salts
- Key technical focus
  - Neutronics
  - Materials and components
  - Safety and safety systems
  - Liquid salt chemistry and properties
  - Salt processing
- MOU working towards SteeringCom & technical projects
- Materials compatibility with MS
  - Salt chemistry controls
  - Stable alloys w/o oxide layers
  - High-dose-tolerant, fine-grained graphites that avoid salt intrusion



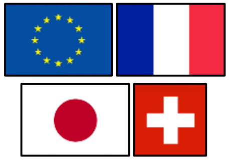
700-800°C

Gas Fast Reactor

- High temperature, inert coolant and fast neutrons for a closed fuel cycle
- Fast spectrum enables extension of uranium resources and waste minimization
- High temperature enables non-electric applications
- Very advanced system
- Passive safety challenges
- Requires advanced materials and fuels
  - Key technical focus: SiC-clad carbide fuel
  - Lack of graphite will impact helium chemistry
- High temperature materials issues include in VHTR Materials Project

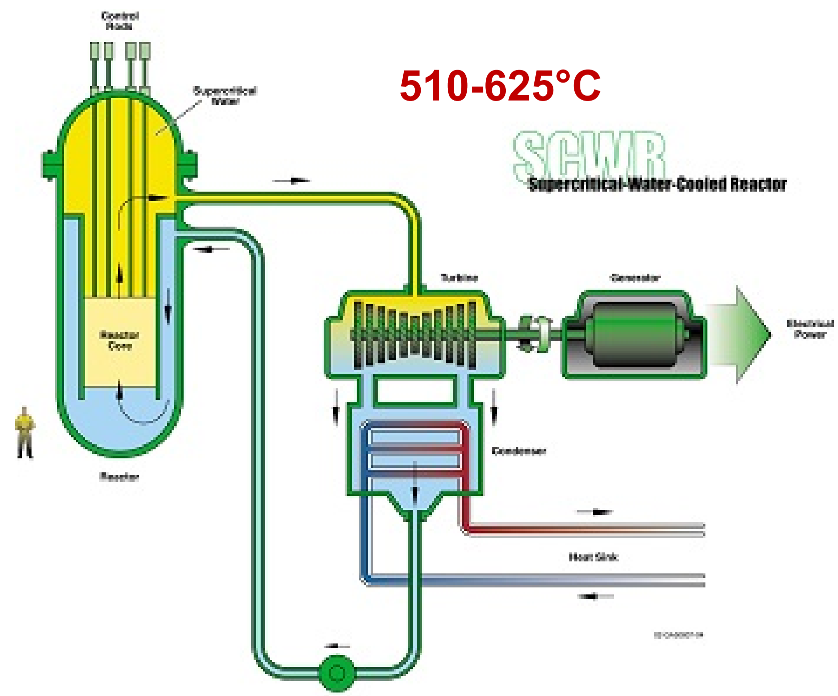


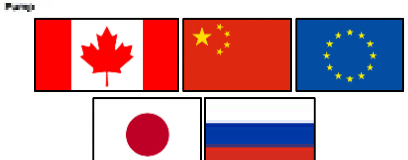
≈850°C



Supercritical Water Cooled Reactor

- Merges GEN-III+ reactor technology with advanced supercritical water technology used in coal plants
  - Operates above the thermodynamic critical point (374°C, 22.1 MPa) of water
  - Fast and thermal spectrum options
- Includes pressure vessel and pressure tube variants
- Key technology issues:
  - Materials, water chemistry, and radiolysis
  - Thermal hydraulics and safety to address gaps in SCWR heat transfer and critical flow databases
  - Fuel qualification
- Materials and Chemistry R&D project focused on corrosion and SCC of alloys in SCWR conditions





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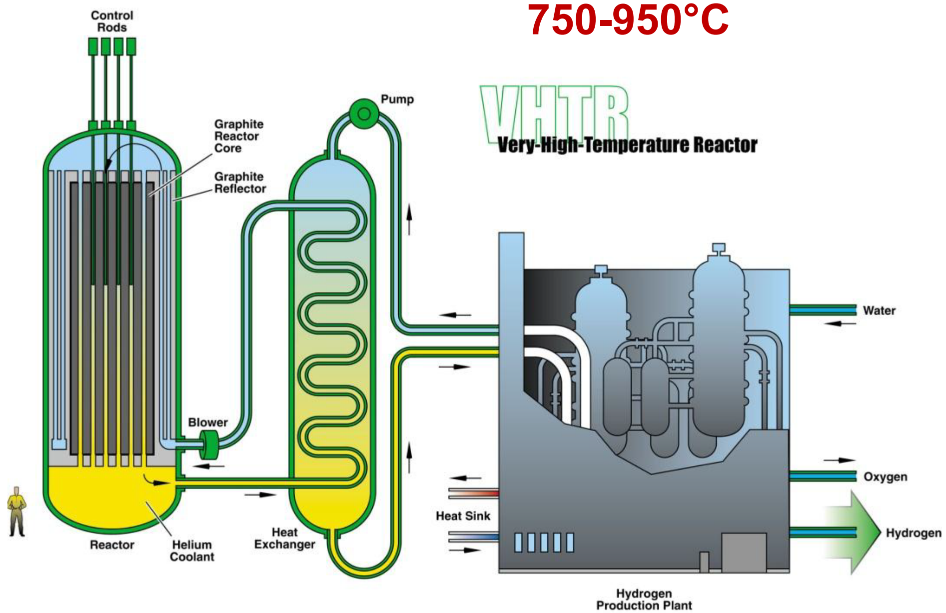
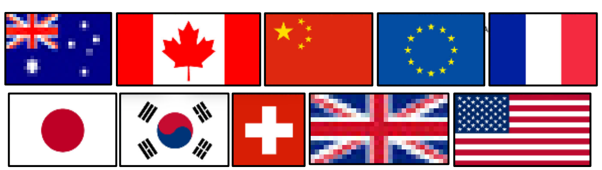
Very High Temperature Reactor

- High temperature He-cooled reactor enables both electrical generation and process heat applications
- Goal – VHTR outlet temperature of 950-1000°C, with near term (HTGR) focus on 750-850°C
- Reference configurations: prismatic & pebble bed cores
- Japan HTTR & China HTR-10 in operation; China HTR-PM demo plant nearing completion
- Includes strong materials R&D focus
  - Graphite
  - Metals & Design Methods
  - Ceramics & Composites
  - Contributions shared via Gen IV Materials Handbook

750-950°C



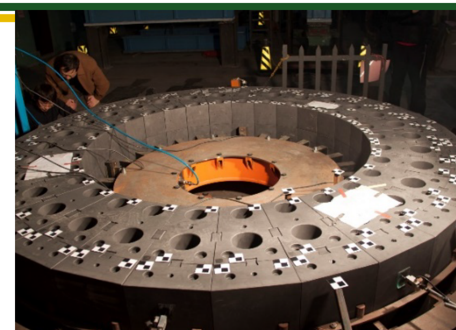


Advanced Reactors Need Additional Limited Options for Approved Alloys for Elevated Temperature Construction

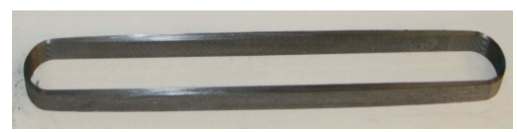
- **Only six alloys are qualified in ASME Sec III Division 5 for service in inelastic temperature range**
  - **Two ferritic steels: 2 ¼Cr-1Mo and 9Cr-1Mo steels**
  - **Two stainless steels: 304 and 316**
  - **Two high-temperature alloys: Alloy 800H and Alloy 617**
- **Hastelloy N (and similar foreign alloys, GH3535) are not yet approved for liquid salt service**
- **Advanced alloys (e.g., high-entropy, ODS, TMT, Ni, etc.) need development and qualification**
- **Corrosion resistant alloys for lead and SCW compatibility (Modified 310 SS, high Si F/M steels, FeCrAl alloys, new Ti & Zr alloys) need development and qualification**
- **Beryllium for compact reactor reflectors**

Graphites, Ceramics, and Composites Need Qualification and Code Coverage for Advanced Reactors

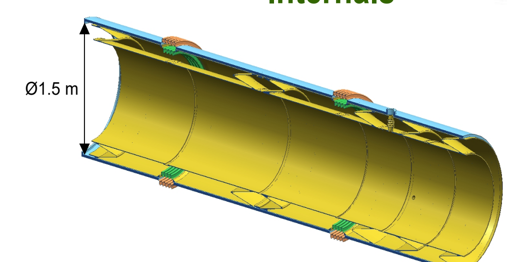
- Graphite used for core supports in HTGRs, VHTRs & MSRs
- Ceramics & composites used as specialized reactor internals
- Special issues
  - Insufficient material standards
  - Lack of ductility
  - Need for statistically set load limits
  - Coupled irradiation and environmental effects
- Now included in ASME Code Section III Division 5
- Additional qualification required



Graphite Core Supports



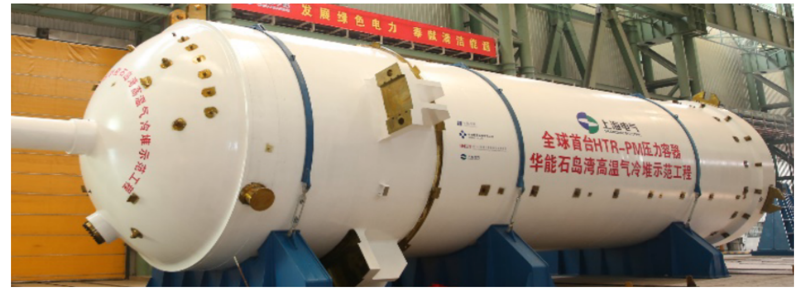
Composite Reactor Internals



Hot Gas Ducts

Very High Temperature Alloys (800H, 617, Hast X(R) & Hast N) for IHXs and SGs Are of Greatest Concern for HTRs

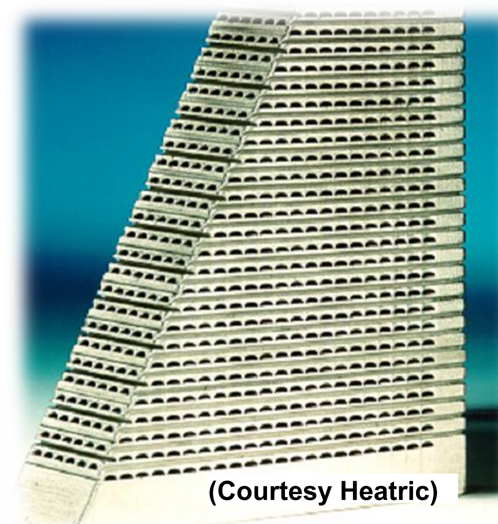
- Temperatures 700 up to 950°C
- Corrosion and creep-fatigue damage
- 800H & 617 are ASME Code qualified to 762°C & 950°C
- Alloys X & X(R) suitable but not yet Code qualified
- 2 1/4Cr-1Mo Code-qualified for lower SG temperatures
- Improved high temperature design methodology essential



HTR PM Heat Exchanger

THTR-300 Steam Generator

Printed Circuit Board Heat Exchanger



(Courtesy Heatric)

High Temperature Design Methodologies Need Updating

- **Weldments**
  - Weldment evaluation methods, metallurgical & mechanical discontinuities, transition joints, tube sheets, validated design methodology
- **Aging & environmental issues**
  - Materials aging, irradiation & corrosion damage, short-time over-temperature/load effects
- **Creep and fatigue**
  - Creep-fatigue (C-F), negligible creep, racheting, thermal striping, buckling, elastic follow-up, constitutive models, simplified & overly conservative analysis methods
- **Multi-axial loading**
  - Multi-axial stresses, load combinations, plastic strain concentrations

High Temperature Code Materials and HTDM Need Updating *(cont)*

- **Materials allowables**
  - Elevated temperature data base & acceptance criteria, min vs ave props, effects of melt & fab processes, 60-year allowables
- **Failure criteria**
  - Flaw assessment and LBB procedures
- **Analysis methods and criteria**
  - Strain & deformation limits, fracture toughness, seismic response, core support, simplified fatigue methods, inelastic piping design, thermal stratification design procedures
- **Rules for design/use of clad structures for high temperature service, including efficacy and reliability of coatings or cladding for corrosion prevention**
- **Construction rules for CHEs for high temperature service**

SiC/SiC Composites Are Potentially Applicable to Many Advanced Reactor Concepts

Reactor Concept	Application	Operating Condition	Project / Design Examples	Possible Deployment
Fusion	• Blanket structures • Various functions	• He, Pb-Li • 400-900°C • >50 dpa	• ARIES • EU-PPCS • DREAM	• Long-term
HTGR VHTR	• Reaction control systems • Core support	• He • 600-1100°C • Up to ~40 dpa	• SC-HTGR • GT-HTR300C	• Near-term
LWR	• Channel box • Grid spacer • Fuel cladding	• Water • 300-500°C • ~10 dpa	• PWR (WHC) • BWR (EPRI)	• Mid-term? (ATF)
FHR AHTR	• Core structures • RCS	• Liquid salt • ~700°C • >10 dpa	• AHTR • SMR's	• Long-term
SFR	• Core structures • Fuel cladding/support	• Liquid sodium • 500-700°C • >100 dpa	• CEA	• Long-term
GFR	• Core structures • Fuel cladding/support	• He • 700-1200°C • >100 dpa	• CEA • GA EM^2	• Long-term

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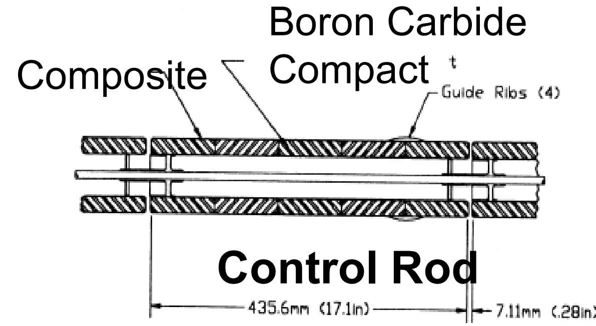
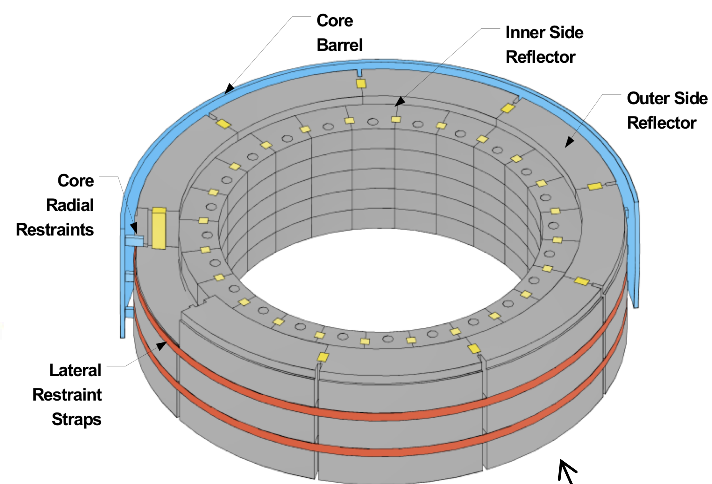
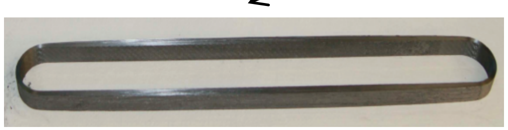
Structural Composites Are Being Developed & Qualified for Advanced Reactors

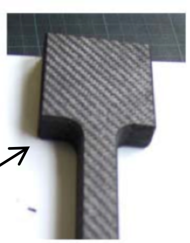
- **SiC-SiC and C-C are best candidates for non-metallic control rods**
- **C-C composites also evaluated for structural reactor internals applications at lower doses**
- **Irradiation, corrosion, architecture, manufacture & testing standard development all needed**



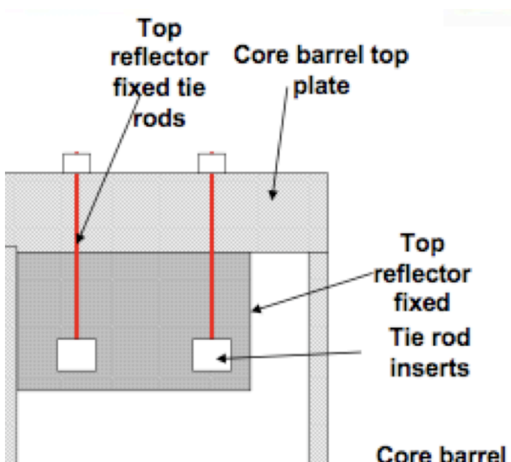


Lateral Core Restraint Rings



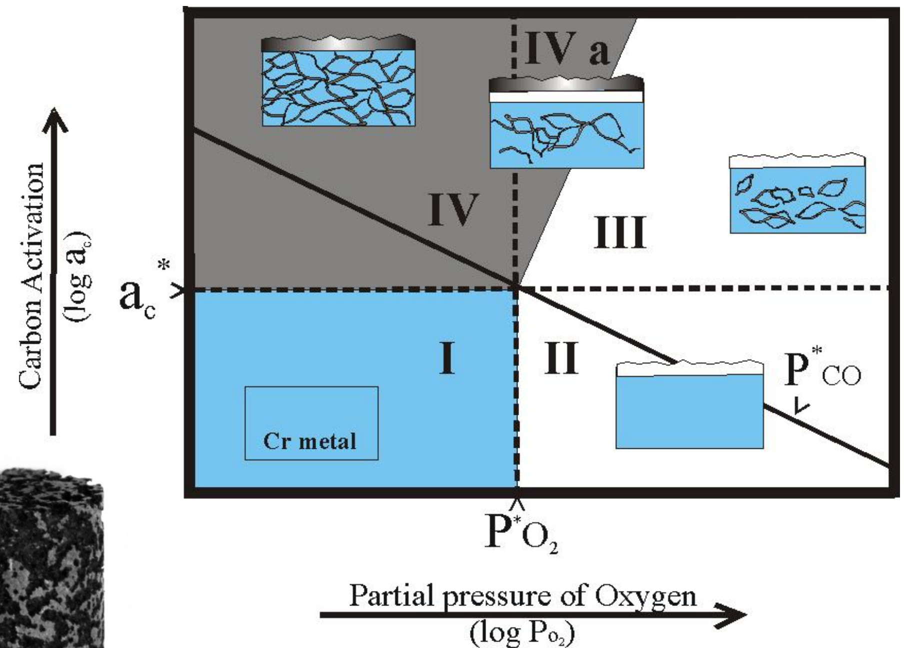


Core Tie Rod

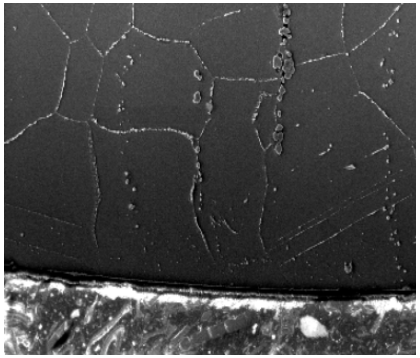


Alloys & Graphite in High Temperature Coolant Environments Must Be Qualified

- Oxidation, carburization, and decarburization of metallic components
- SCC and LME effect
- Microstructural stability & strength impacts during long-term aging
- Mass and strength loss in graphite and composites
- Impact of coolants on metallic tribology
- High temperature strength, environmental compatibility & corrosion in Hi Temp coolants



Chronic graphite oxidation



Alloy 617 Aged 100 Hours at 1000°C in air

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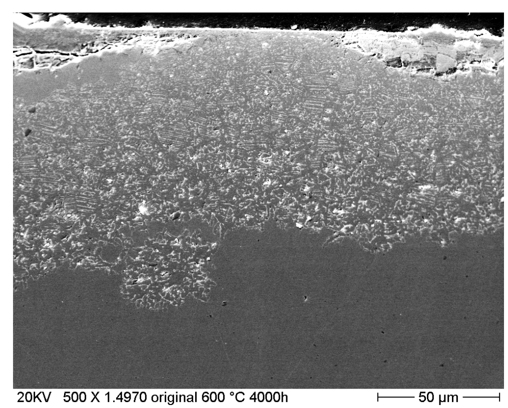
Environmental Compatibility Is Especially Challenging for MSRs, LFRs, and SCWRs

- Protective oxide films not formed in molten salts
- Lead coolants require very tight oxygen control & may cause liquid metal embrittlement
- Enhanced stress corrosion cracking in supercritical water plus impact of irradiation-induced free radicals
- Development of coatings, claddings & associated design methods needed
- Qualification of new materials may be required
  - Modified 310 SS, high Si F/M steels, FeCrAl alloys, advanced hi temp nickel alloys, new Ti & Zr alloys

GIF SCWR ROUND ROBIN EXERCISE #2 *Canadian Nuclear Laboratories Reference # 900-511300-STD-001*

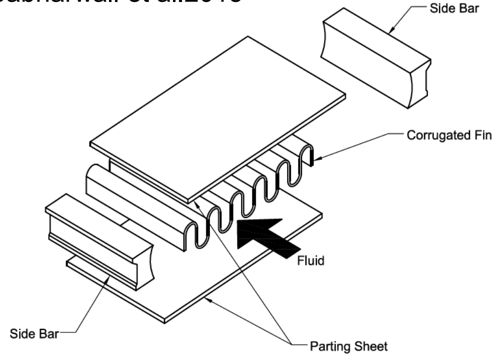


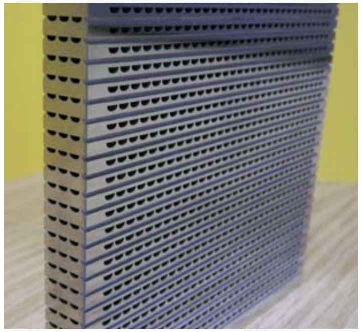
1.4970 steel exposed to LBE at 600°C *A. Weisenburger et. al. IAEA Tech Mtg on structural materials for heavy liquid metal cooled fast reactors, Vienna, 15-17 October*

Compact Heat Exchanger Usage in HTRs Requires Qualified Design and Construction Rules

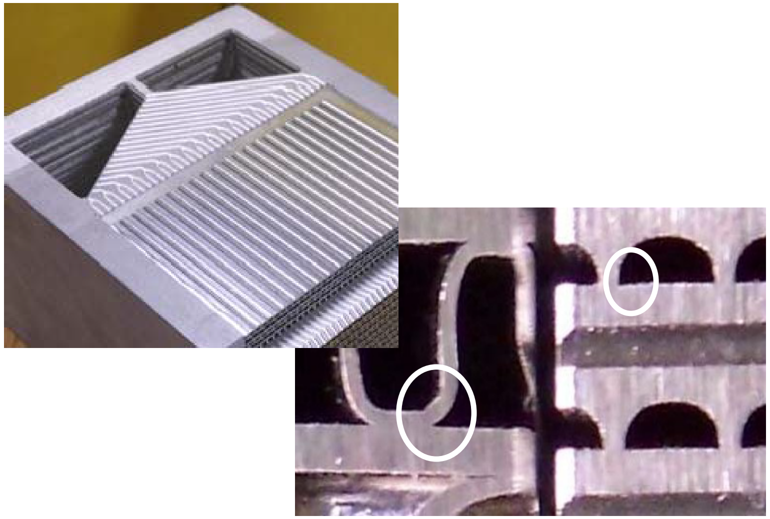
- **Complex channels & corners result in stress concentrations**
  - Transfer external boundary conditions transfer to internals
  - Significant pressure & thermal stress redistribution

Sabharwall et al.2013





Southall et al., ICAPP ‘08



Southall et al., ICAPP ‘09

- **MicroChannel**
  - Chemically etched integral flow channels
  - Good for high pressure
- **PlateFin**
  - Corrugated plate fin sandwiched between two flat plates or shims
  - More efficient use of materials and larger flow passages

Each Advanced Reactor Requires Materials for Its Own Temperature, Dose & Coolant Compatibility Needs

Primary Circuit Materials (classic-*future*)										
Reactor	ROT °C	Dose-dpa		RPV	Piping	Internals	HX	SG	Cladding
		RPV	Internals						
LWR	288	<<1	10-20	508/533 (clad w/ss)	low alloy or SS	304/316/ *NF-709*	N/A	508/533/ 600/690	Zirc/ *SiC-SiC*
Helium cooled	750-800/ *850-950*	<<1	1-5	508/533/ *Gr 91*	508/533/ *Gr 91*	graphite/ 304/316/ 800H */SiC-SiC*	800H/*617*	2.25Cr-1Mo/ 800H/*617*	SiC TRISO
Sodium cooled fast	500-550	<1	10-20/ *80-150*	304/316/ *NF-709*	2.25Cr-1Mo/ 316/*Gr 91/Gr 92/NF-709*	304/316/ *NF-709/ SiC-SiC*	304/316/ *NF-709*	2.25Cr-1Mo/ 800H/ *Gr 91/Gr 92*	HT-9/ *Gr 92 ODS*
Molten Salt cooled	700/ *750-900*	<<1	1-25	Hast N/ *316SS or 800H-clad/ new Ni alloy*	Hast N/ *316SS or 800H-clad/ new Ni alloy*	Hast N/*C-C or SiC-SiC/new Ni alloy*	Hast N/ *316SS, 800H or 617 w Ni clad/ new Ni alloy/ SiC-SiC*	Hast N/ *316SS, 800H or 617 w Ni clad/ new Ni alloy/ SiC-SiC*	SiC TRISO
Pb/ Pb-Bi cooled fast	500-550	<30	100-200	HT-9/Gr 91/ *Si mod steel*	HT-9/Gr 91/ *Si mod steel*	HT-9/Gr 91/ *Si mod steel/ SiC-SiC*	HT-9/Gr 91/ *Si mod steel*	HT-9/Gr 91/ *Si mod steel*	HT-9/ *Gr92/ ODS*
SCWR	510-625	<<1	20-30	508/533 (clad w/ss)	low alloy/ SS/ *new SS*	304/316/*new SS/ 800H/NF-709*	N/A	508/533/ 600/690/*625/ new SS*	Zirc/*TI-alloys/ SiC-SiC*

Materials R&D in the Gen IV International Forum Is Generated and Shared

- Some Project Arrangements for Materials R&D are in place
  - Very High Temperature Reactor
  - Gas-Cooled Fast Reactor
  - Supercritical Water Cooled Reactor
- Other reactor systems have identified R&D needs
  - Lead Fast Reactor
  - Molten Salt Reactor
  - Sodium Fast Reactor
- R&D needs for metals, graphite, ceramics, composites, and high temperature design methods span multiple systems
- Environmental challenges related to coolant compatibility, irradiation doses, and service temperatures are reactor specific