

Materials for Microreactors

GAIN-EPRI-NEI-USNIC
Microreactor Workshop
Idaho National Laboratory – EIL Meeting Center
June 18-19, 2019

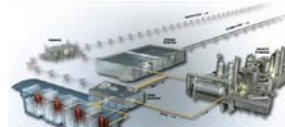
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ART Advanced Materials, Technology Area Lead
Argonne National Laboratory

Structural Materials for Microreactors

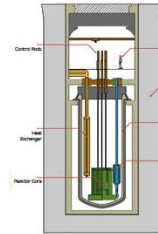
Westinghouse AP-1000



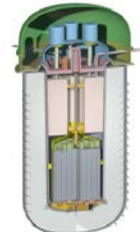
GA Gas-cooled Fast Reactor



Framatome- HTGR

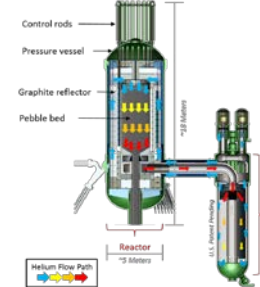


Advanced Reactor Concepts LLC ARC-100



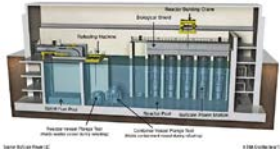
Terrestrial Energy IMSR

Xe-100 Pebble-Bed Reactor (200 MWth)



Gen IV Advanced Reactors

NuScale SMR, 12 X 50 MWe



Light Water Reactors

Heat Pipe Reactors

Microreactors

NuScale

Micro-Scale Nuclear Battery, U-Battery, Holos, Hydromine, General Atomics, NuGen, Ultra Safe Nuclear, X-energy

eVinci, Oklo, NuScale

- Microreactors

- Smaller size, lower power, component functionalities can be more easily integrated, can be fabricated in the shop
- Microreactor structural materials share many similar characteristics (temperature limits, corrosion, etc.) as the larger size light water reactors or Gen IV advanced reactors
- Heat pipe reactors are more unique

Considerations for Structural Materials Selection

- ASME design rules are developed to guard against structural failure modes
 - Ductile rupture, buckling, creep rupture, ratcheting, creep-fatigue interaction, creep buckling
- Materials selection considerations for replaceable or non-replaceable components include:
 - Core outlet temperature, operating transients (e.g., load-following), design lifetime, reactor coolant(s) and dose (if applicable)
- Factors affecting structural failure modes:
 - Temperature and stress effects - addressed by ASME Code
 - Environmental effects (coolant, irradiation) and materials degradation - responsibility of owner/operator

What Design Rules to Use Depends on How a Component is Classified

Performance-Based, Risk-Informed Component Classification	Applicable Codes and Standards Design Rules
Safety-related	ASME Section III Division 5 Class A
Non-safety related with special treatment	ASME Section III Division 5 Class B
Non-safety related	Commercial Codes

Permissible Section III Division 5 Class A Materials	Permissible Section III Division 5 Class B Materials (In the Creep Regime)	
<ul style="list-style-type: none"> • Type 304H and 316H stainless steels • Alloy 800H • 2¼ Cr - 1 Mo • Mod 9Cr – 1 Mo (Grade 91) • Alloy 617 (to be approved, December 2019) 	Ferritic steel	Carbon steels, low alloy steels, 2.25Cr-1Mo, 9Cr-1Mo
	Austenitic steel	CF8, 304, 304N, CF8M, 316L, 316, 316N, 321
	High-nickel alloy	A800, A800H, A600, Alloy X

NRC Endorsement of Section III Division 5

- DOE, ASME and industry Technology Working Groups have had many interactions with NRC on the need for the endorsement of ASME Section III Division 5
 - NRC review of this standard prior to licensing actions for advanced reactors would result in a substantial cost savings to applicants
 - Will reduce regulatory risk in the deployment of advanced reactors by US developers
- Two ASME Liaison Task Groups, one on metals and one on graphite, were formed to champion the endorsement effort
- The Division 5 Endorsement effort by NRC will be announced at the NRC Advanced Reactor Stakeholder meeting on June 27, 2019
- Plan to have the draft regulatory guide on ASME Section III Division 5 ready for public review by December 2020

Staged Approach to Code Qualify New Class A Materials for Microreactors

Stage	Implementation	Testing Time (Yr)			
A	<ul style="list-style-type: none"> Develop Conceptual Design Guide, 500,000 h life time Develop Division 5 Material Code Case for Class B construction 	1.5			
B	<ul style="list-style-type: none"> Develop Division 5 material Code Case for 100,000 h life time Project approximate, 500,000 h allowable stress values 		3		
C	<ul style="list-style-type: none"> Develop Division 5 material Code Case for 300,000 h life time Refine the approximate, 500,000 h allowable stress values 			7	
D	<ul style="list-style-type: none"> Extend material life time to 500,000 h in Division 5 Subsection HB, Subpart B 				11.5

- Leverage modeling and simulation of materials failure mechanisms to reduce testing effort and to shorten qualification time
- Materials surveillance program (stress, temperature, coolant, irradiation) can be implemented to mitigate risk when new materials are deployed at the early stages of qualification

Qualification of High Temperature Time Dependent Properties Specific to Components from Advanced Manufacturing Methods

Powder Metallurgy (PM) HIP Components

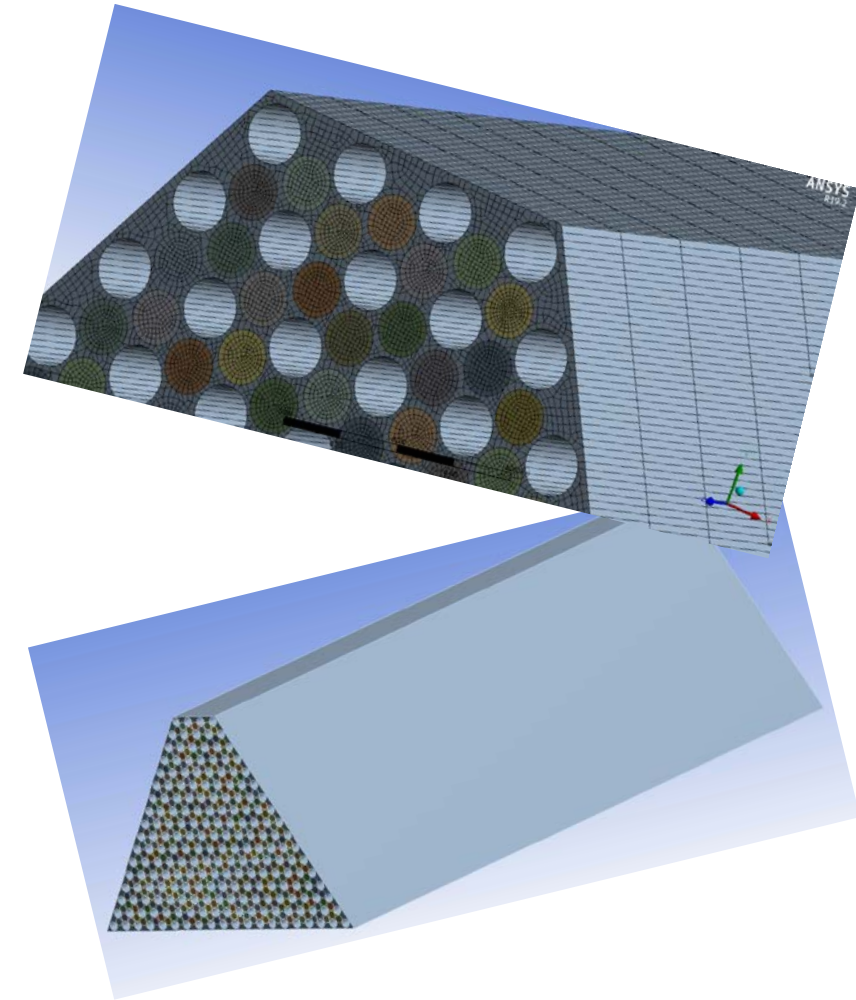
- **PM-HIP materials are Code qualified for Section III Subsection NB components (LWRs)**
 - A more mature technology
 - Tensile and creep properties have been shown to be equivalent to wrought material for Type 316 stainless steel and Grade 91 steel
 - They are allowed for use in the non-nuclear sections of the ASME Code for pressure vessels and piping
- **Properties of PM-HIP materials for high temperature cyclic loading have not been determined**
 - Scope of testing for Code qualification could be significantly reduced compared to a new material because only very limited amount of time consuming creep testing would be required
 - Testing of fatigue and creep-fatigue behavior could be reduced if it can be demonstrated that the properties are comparable to wrought material

Additively Manufactured Components

- The microstructure of as-deposited additively manufactured material typically appears similar to a welded microstructure
- Property characterization is typically limited to tensile characterization
 - It is not clear if post-deposition processing such as HIP consolidation or solution treatment will be required to develop conventional grain structure
- Qualification issues on long term high temperature properties of additively manufactured components must be resolved
- ASME acceptance criteria must be established before they can be deployed in high temperature microreactors

ASME Grade 91 Core Block Code Case - Microreactor Campaign

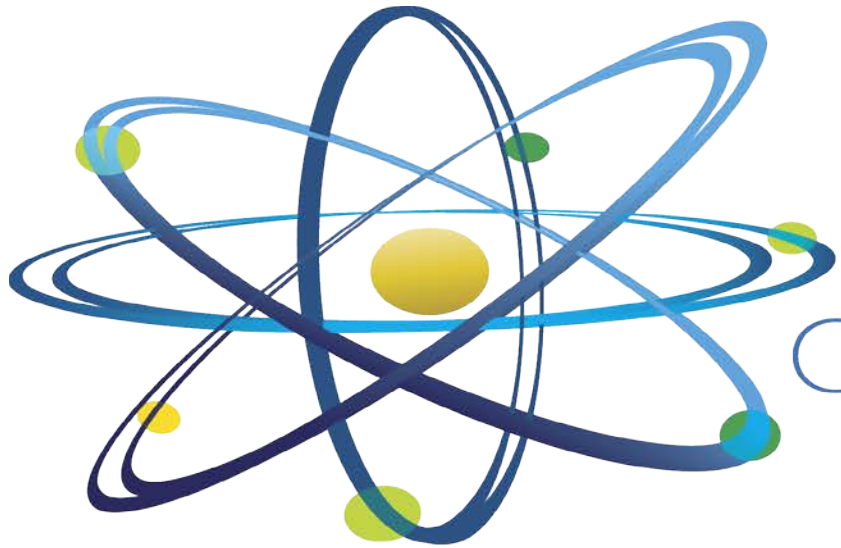
- The core block is a key component of the heat pipe microreactor design
- It integrates the functions of reactor vessel, core structural components and fuel cladding of traditional Gen IV advanced reactor designs into one single structure
- Type 316 stainless steel is the reference material for the core block construction
- Grade 91 steel is identified as additional candidate material for the core block construction to expand the design envelope
 - Lower thermal expansion coefficient and higher heat conductivity result in lower thermal stresses during reactor operations
 - Has higher resistance to radiation induced swelling
 - Less challenging machining issues due to low strain hardening
- ANL and ORNL are developing an ASME Grade 91 Code Case for the core block design, and an inelastic analysis method to support design evaluations



Contact Information

LMR, MSR, MicroRx Materials	GCR Materials	Graphite
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Questions?



Clean. **Reliable. Nuclear.**

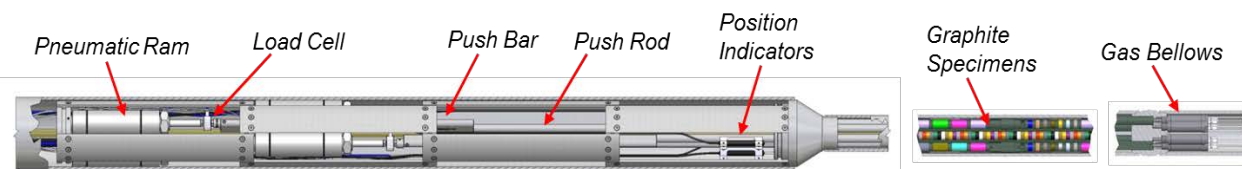
Backup Slides

National Laboratories Materials Capabilities

- High temperature designs (ANL, INL, ORNL)
 - Expertise in applying ASME high temperature rules, qualifying new materials and developing innovative solutions to material challenges in support of design
- High temperature mechanical properties testing (ANL, INL, ORNL)
 - Creep, fatigue, creep-fatigue, special key-feature test articles
 - Well established protocol for very long term creep tests (> 10 years)
- Coolant compatibility testing
 - Sodium loops (ANL, materials test loops; Mechanisms Engineering Test Loop, METL, to test small or intermediate scale advanced liquid metal components and instrumentation)
 - Gas loop (INL, helium, CO₂, nitrogen, etc., with precise impurities control)
 - Salt loops (ORNL, fluoride salt, chloride salt)
- Irradiated and un-irradiated graphite properties (INL, ORNL)
 - ATR, HFIR to support irradiation, hot cells to support PIE and testing



METL



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

Primary Circuit Materials (Classic/**Future**)

Reactor	Rx Outlet Temp (C)	Dose (dpa)		RPV	Piping	Internals	Heat Exchanger	Steam Generator	Fuel Cladding
		RPV	Internals						
Water cooled SMR thermal	288	<< 1	10 - 20	508/533 (cladded w/ SS)	low alloy or SS	<ul style="list-style-type: none"> • 304/316 • A709 	N/A	508/533/600/690	<ul style="list-style-type: none"> • Zirc • SiC-SiC
Helium cooled thermal	750 850-900	<< 1	1 - 5	<ul style="list-style-type: none"> • 508/533 • Gr 91 	<ul style="list-style-type: none"> • 508/533 • Gr 91 	<ul style="list-style-type: none"> • Graphite • 304/316/800H • SiC-SiC 	<ul style="list-style-type: none"> • 800H • 617 	<ul style="list-style-type: none"> • 2.25Cr-1Mo/800H • 617 	SiC TRISO
Sodium cooled fast	500 - 550	< 1	10 - 20 80 - 150	<ul style="list-style-type: none"> • 304/316 • A709 	<ul style="list-style-type: none"> • 2.25Cr-1Mo/ 316 • Gr 91/Gr 92 	<ul style="list-style-type: none"> • 304/316 • A709 • SiC-SiC 	<ul style="list-style-type: none"> • 304/316 • A709 • Gr 91 	<ul style="list-style-type: none"> • 2.25Cr-1Mo/800H • Gr 91/Gr 92 	<ul style="list-style-type: none"> • HT-9 • Gr 92 • ODS
Salt-cooled thermal	650 700-900	<< 1	1 - 25	<ul style="list-style-type: none"> • 316/Hast N • Cladded 316/800H • Insulated steel • New Ni alloy 	<ul style="list-style-type: none"> • 316/Hast N • Cladded 316/800H • Insulated steel • New Ni alloy 	<ul style="list-style-type: none"> • Hast N • C-C or SiC-SiC • New Ni alloy 	<ul style="list-style-type: none"> • 316/Hast N • Cladded 316/800H/617 • New Ni alloy • SiC-SiC 	<ul style="list-style-type: none"> • 316/Hast N • Cladded 316/800H/617 • New Ni alloy • SiC-SiC 	SiC TRISO
Lead/ Lead-Bismuth cooled fast	500-550	< 30	100 - 200	<ul style="list-style-type: none"> • HT-9/Gr 91 • Si mod steel • Alumina forming austenitic steel (AFA) 	<ul style="list-style-type: none"> • HT-9/Gr 91 • Si mod steel • AFA 	<ul style="list-style-type: none"> • HT-9/Gr 91 • Si mod steel • AFA • SiC-SiC 	<ul style="list-style-type: none"> • HT-9/Gr 91 • Si mod steel • AFA 	<ul style="list-style-type: none"> • HT-9/Gr 91 • Si mod steel • AFA 	<ul style="list-style-type: none"> • HT-9 • Gr 92 • ODS