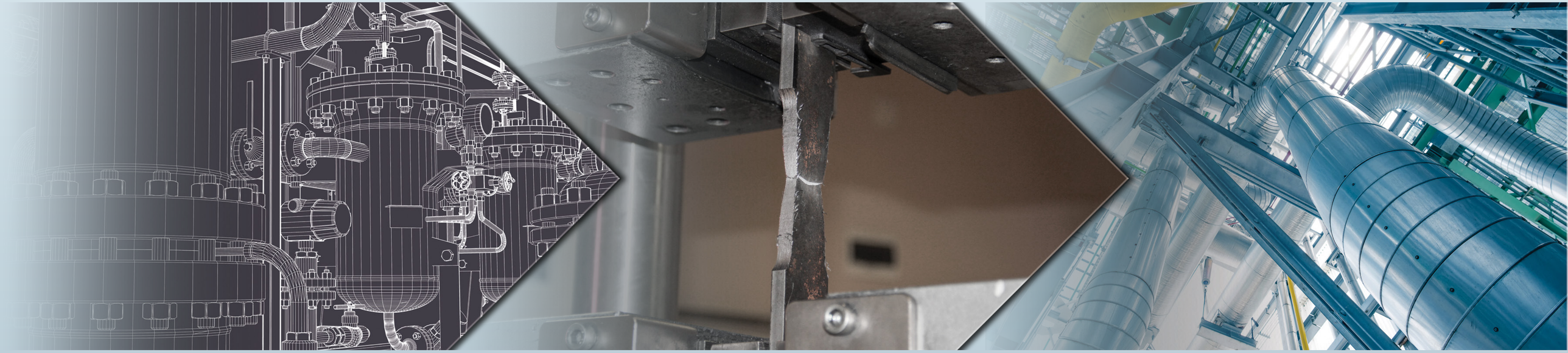
ADVANCED NUCLEAR TECHNOLOGY PROGRAM

ADVANCED REACTOR MATERIALS DEVELOPMENT ROADMAP



This Advanced Reactor Materials Development Roadmap provides for a planned coordination of materials development and validation programs to directly address gaps in order to support the near term deployment and progress advanced non-light water reactor designs.

EPRI RESOURCES

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Revision 0

OVERVIEW

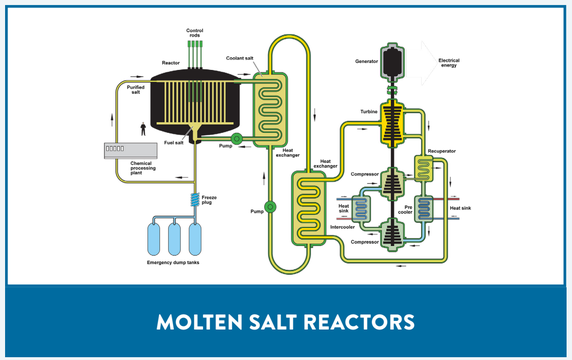
Advanced non-light water reactors (ANLWRs or ARs) operate at much higher temperatures than traditional nuclear power plants. Within this new operating regime, design practices now need to account for “time-dependent” behavior in material and component properties and in various coolants.

Materials of construction for ARs need to endure mechanical loads and often extreme environmental conditions for prolonged times while withstanding effects of temperature transients, effects of irradiation damage to material properties, and irradiation-induced swelling. To develop this roadmap, EPRI first conducted a series of four AR Materials Gap Analyses, one for each of the major reactor type based on coolant (report numbers and links to free downloads are included below):

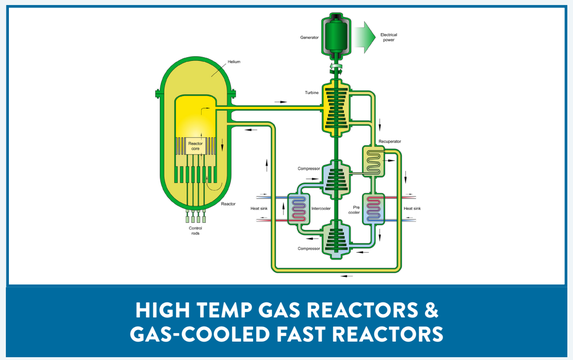
- 3002010726: Materials Properties Assessment and Gap Analysis for Molten Salt Reactors | https://www.epri.com/research/products/000000030020107260
- 3002016949: Materials Properties Assessment and Gap Analysis for Sodium-Cooled Fast Reactors | https://www.epri.com/research/products/000000003002016949
- 3002015815: Materials Properties Assessment and Gap Analysis for Very High Temperature Reactors and Gas-Cooled Fast Reactors | https://www.epri.com/research/products/000000003002015815
- 3002016950: Materials Properties Assessment and Gap Analysis for Lead-cooled Fast Reactors | https://www.epri.com/research/products/000000003002016950

The four reports identify key material property gaps that must be filled to support AR designs through literature reviews and industry survey on material science related knowledge. Providing a summary table of material gaps for each reactor type, these four crucial reports led to the first revision of this roadmap. It should be noted this roadmap is intended to be a living document; updated and prioritized based on the needs of the nuclear industry as advancements in material development, material science knowledge and data compilation are made.

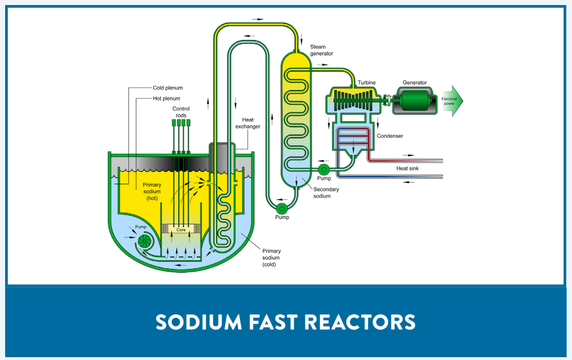
MAJOR REACTOR TYPES



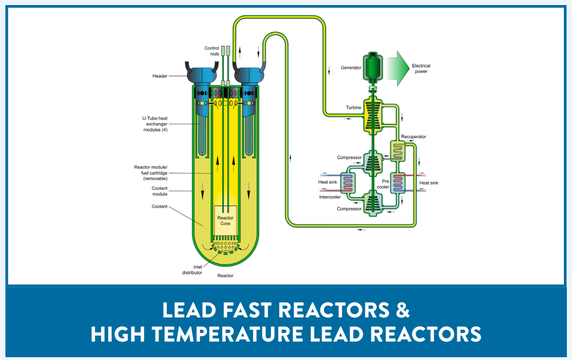
MOLTEN SALT REACTORS



HIGH TEMP GAS REACTORS & GAS-COOLED FAST REACTORS



SODIUM FAST REACTORS



LEAD FAST REACTORS & HIGH TEMPERATURE LEAD REACTORS

Above images courtesy US Department of Energy Nuclear Energy Research Advisory Committee, Generation IV Roadmap.

IMPLEMENTATION

EPRI's AR Materials Development Initiative is focused on addressing the gaps and closure activities laid out within this roadmap. This roadmap was established to help align efforts to more efficiently address the key obstacles that the nuclear power industry must address to facilitate widespread and timely deployment of ARs. Initial focus is on development of code required material properties to support initial deployment followed closely by capture of longer term response to neutron irradiation and in prototypic environments.

EPRI, AR developers, research organizations and government entities can use this work to help prioritize essential projects and establish new material development and qualification methods. This roadmap is intended to be a living document updated based on industry feedback as roadmap tasks are completed, material advancements are achieved, and improved designs are developed.

LAYOUT AND INSTRUCTIONS

This Advanced Reactor Materials Development Roadmap is an interactive PDF document with internal links to specific sections and pages of this document. The AR Material data gaps are organized by both reactor type and material type, as some materials and tasks will address needs for multiple reactor types. The gaps are also arranged and sorted in a visual roadmap timeline for addressing each need. To quickly jump to a specific section, material, or gap, use the navigation buttons at the top of each page. Within each page, additional details or granularity can be found by clicking or hovering over specific gaps or materials.

MOLTEN SALT REACTORS | Material R&D Gaps

COMPONENT	MATERIAL	NEEDED R&D
Core Support / Structural Materials	316 and Austenitic Alloys	• Proof of resistance to long-term corrosion in properly controlled salt environment • Time dependent properties for ASME code Sec III Div 5 qualification • Demonstration of performance —resistance to EAC (Environmentally Assisted Cracking) —in salt under loading • Development and demonstration of cladding (Mo rich) for protection
	Hastelloy N and variants	• Demonstration of radiation tolerance of Hast N variants (Proper understanding of chemistry -> microstructure -> properties • Development of properties for ASME code Sec III Div 5 qualification
Coolant	Salt	• Development of salt chemistry (and impurity) control. Demonstration of Te control
Moderator	Graphite	• Development of long-term properties in salt

HIGH TEMP GAS & GAS FAST REACTORS | Material R&D Gaps

COMPONENT	MATERIAL	NEEDED R&D
HIGH TEMP GAS REACTOR Core Support/ Structural Materials	316 and Austenitic Alloys	• Code approval of time dependent properties – creep, creep-fatigue
	316FR	• Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties
	800H	• Summary Document of Properties • Support ASME code extension of properties • Develop and qualify improved weld filler metal(s)
HIGH TEMP GAS REACTOR Vessel	Low Alloy Steels (LAS)	• Time dependent and fatigue properties for ASME code Sec III Div 5
HIGH TEMP GAS REACTOR Moderator	Graphite	• Development of long-term properties in reactor environment for the specific type of graphite to be employed
GAS FAST REACTOR Core support	Ferritic-Martensitics	• Demonstration of adequate resistance to swelling at high dpa. • Time dependent properties for ASME code Sec III Div 5. (including development of fabrication technologies – and demonstrate properties of joints
GAS FAST REACTOR Cladding and reflector	Ceramics	• For advanced GFR – SiC-SiC, Zr_3Si need materials endurance data for these materials

SODIUM FAST REACTORS | Material R&D Gaps

COMPONENT	MATERIAL	NEEDED R&D
Vessel and Core Support Structure	316 Stainless Steel	• Extend code properties to include time dependent behavior (Creep and Creep-Fatigue)
	Alloy 709 SS	• Summary Document of Properties • Demonstration of radiation tolerance (Proper understanding of chemistry -> microstructure -> properties • Development of properties for ASME Code Sec III Div 5 qualification
	D9 Stainless Steel	• Development of for ASME code Sec III Div 5 properties (including time dependent properties) for D9 • Development of swelling behavior at long times under realistic conditions – demonstrate adequacy
Core Support Structure and Cladding	Ferritic-Martensitics	• Prove adequacy of swelling resistance at high fluence • Development of fabrication technology and proof of performance of welds

LEAD-COOLED REACTORS | Material R&D Gaps

COMPONENT	MATERIAL	NEEDED R&D
LEAD FAST REACTOR Structural Materials/ Vessel	316	• (code qualified already) but need creep and creep-fatigue data to be added into code. • Need corrosion data/demonstration of resistance to lead corrosion
	Type 15-15Ti stainless	• Verification of swelling resistance • Development of code properties for 15-15Ti material design
LEAD FAST REACTOR Near core structures and cladding	Ferritic-Martensitics	• Demonstration of adequate resistance to swelling at high dpa. • Time dependent properties for ASME code Sec III Div 5. (including demonstrating properties of joints) • Demonstration of resistance to lead corrosion/development of corrosion data • Development of fabrication and effective joining methods
HIGH TEMP LEAD REACTOR Structural Materials/ Vessel	Alumina Forming Austenitic Stainless Steels	• Demonstration of resistance to lead corrosion • Demonstration of adequate resistance to irradiation/swelling at expected high dpa • Development of processing and joining of alumina forming austenitic stainless steels
HIGH TEMP LEAD REACTOR Cladding	SiC-SiC	• Development of SiC-SiC structures • Demonstration of resistance to lead corrosion • Development of properties and support to code qualification

AUSTENITIC STAINLESS STEELS | Material R&D Gaps

MATERIAL	NEEDED R&D
316H SS	• Extend BPV-III Div 5 Code properties to include time dependent behavior (Creep and Creep-fatigue) • Development and demonstration of cladding (Mo rich) for protection
316FR SS	• Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties • Demonstration of resistance to lead corrosion
Type 15-15Ti SS	• Verification of swelling resistance • Development of code properties for 15-15Ti material design
Alloy 709 SS	• Demonstration of radiation tolerance (Proper understanding of chemistry -> microstructure -> properties • Development of properties for ASME Code Sec III Div 5 qualification
Alumina Forming SS	• Demonstration of adequate resistance to irradiation/swelling at expected high dpa • Development of processing and joining of alumina forming austenitic stainless steels
D9 Stainless Steel	• Development of for ASME Code Sec III Div 5 properties (including time dependent properties) for D9 • Development of swelling behavior at long times under realistic conditions – demonstrate adequacy
CF8C-Plus	• Development of properties for ASME Code Sec III Div 5 qualification • Demonstration of radiation tolerance (Proper understanding of chemistry -> microstructure -> properties

FERRITIC-MARTENSITIC & LOW ALLOYS STEELS | Material R&D Gaps

MATERIAL	NEEDED R&D
Ferritic-Martensitic--9Cr	• Demonstration of adequate resistance to swelling at high fluence range • Time dependent properties for ASME Code Sec III Div 5 • Development of fabrication and effective joining methods
Ferritic-Marensitic--12Cr	• Demonstration of adequate resistance to swelling at high fluence range • Time dependent properties for ASME Code Sec III Div 5 • Development of fabrication and effective joining methods
Ferritic-Martensitic	• Validation of commercial reliability – properties sensitivity to heat treatment / local microstructures • Responds to fabrication processes – welding practices
Low Alloys Steels	• Time dependent and fatigue properties for ASME code Sec III Div 5

NICKEL-BASED ALLOYS | Material R&D Gaps

MATERIAL	NEEDED R&D
Hastelloy N	• Demonstration of radiation tolerance of Hastelloy N variants (Proper understanding of chemistry -> microstructure -> properties • Development of properties for ASME Code Sec III Div 5 qualification
617	• Summary Document of Properties
800H	• Support ASME code extension of properties • Development & qualification of improved weld filler metal(s)

GRAPHITE & CERAMICS | Material R&D Gaps

MATERIAL	NEEDED R&D
Graphite	• Development of long-term properties in salt, etc. ***for the specific type of graphite to be employed*** • Qualification process – standard graphite doesn't exist; vendor/manufacturer specific qualification
Ceramics	• For advanced GFR – SiC-SiC, Zr_3Si need materials endurance data

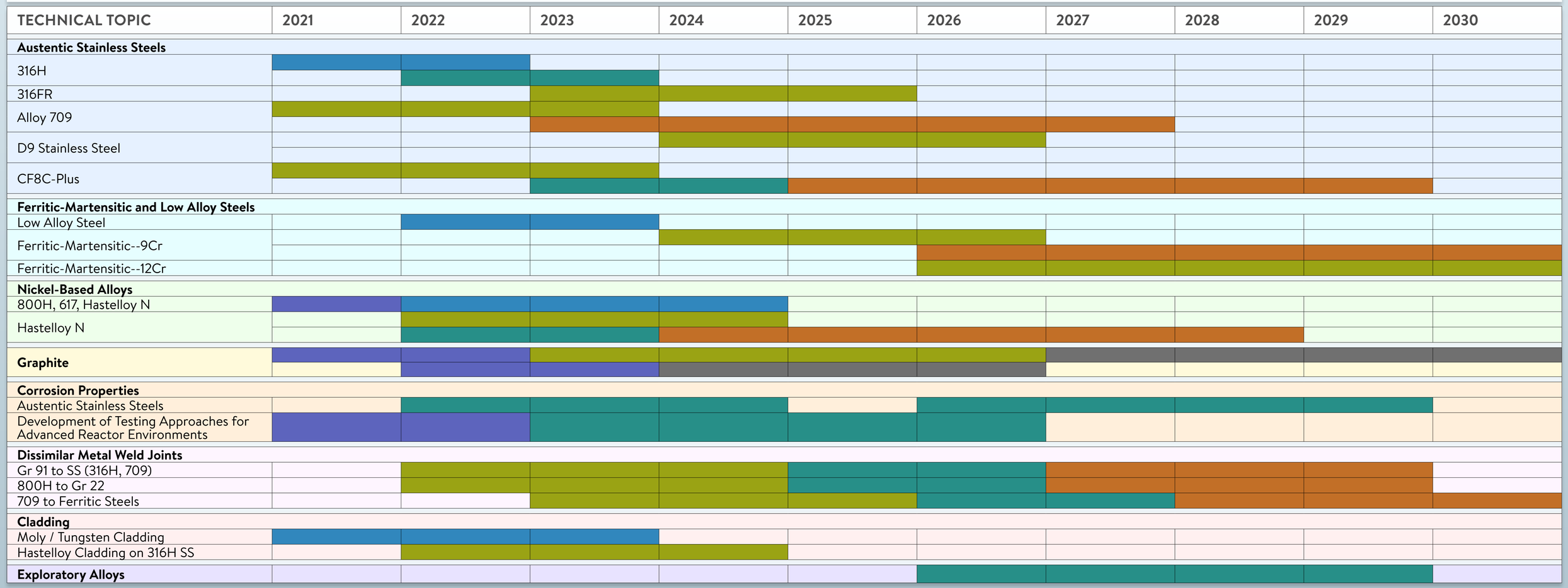
CORROSION | Material R&D Gaps

MATERIAL	NEEDED R&D
316FR	• Demonstration of resistance to lead corrosion
316H	• Proof of resistance to long time corrosion in properly controlled salt environment • Demonstration of performance (resistance to EAC) in salt under loading
Alumina Forming Austenitic Stainless Steels	• Demonstration of resistance to Lead corrosion
Ferritic-Martensitics--9Cr	• Demonstration of resistance to Lead corrosion/development of corrosion data
Ferritic-Martensitics--12Cr	• Demonstration of resistance to Lead corrosion/development of corrosion data
Salt	• Development of salt chemistry (and impurity) control. Demonstration of Te control
Graphite	• Development of long-time properties in salt, etc.
SiC-SiC	• Demonstration of resistance to lead corrosion

CLADDING | Material R&D Gaps

MATERIAL	NEEDED R&D
SiC-SiC	• Development of SiC-SiC structures • Demonstration of resistance to lead corrosion • Development of properties and support to code qualification
Low Alloy Steel	• Molybdenum Application methods

ROADMAP | Overview



Extend Code Properties | Mechanical / Code Properties | Corrosion Properties | Irradiation Properties | Near-Term Data Capture | Other

ROADMAP | Austenitic Stainless Steels

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
316H SS	Extend BPV-III Div 5. Code properties to include time dependent behavior									
		Corrosion behavior in salts								
316FR			Code qualification properties for ASME code Sec III Div 5 for 316FR including time dependent properties							
Alloy 709	Code qualification properties for ASME code Sec III Div 5 for 709 including time dependent properties (In Progress)									
			Evaluate resistance to irradiation/swelling at high dpa for 709							
D9 Stainless Steel				Code qualification properties for ASME code Sec III Div 5 for D9 including time dependent propertie						
						Evaluate resistance to irradiation/swelling at high dpa for D9 SS				
CF8C-Plus	Code qualification properties for ASME code Sec III Div 5 for CF8C-Plus cast & wrought forms including time dependent properties									
			Corrosion behavior of CF8C-Plus		Evaluate resistance to irradiation/swelling at high dpa for CF8C-Plus					

In Progress

Extend Code Properties | **Mechanical / Code Properties** | **Corrosion Properties** | **Irradiation Properties** | **Near-Term Data Capture** | **Other**

ROADMAP | Ferritic-Martensitic and Low Alloy Steels

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low Alloy Steel		Extend BPV-III Div 5. Code properties to include time dependent behavior (creep and creep-fatigue)--Grade 22 & 508 Properties								
Ferritic-Martensitic--9Cr				Code qualification properties for ASME code Sec III Div 5 for F/M-9Cr including time dependent properties						
						Evaluate resistance to irradiation/swelling at high dpa (9Cr and 12Cr)				
Ferritic-Martensitic--12Cr						Code qualification properties for ASME code Sec III Div 5 for F/M-12Cr including time dependent properties			Proof-of-Performance of Welds	
						Evaluate resistance to irradiation/swelling at high dpa (9Cr and 12Cr)				

Extend Code Properties | Mechanical / Code Properties | Corrosion Properties | Irradiation Properties | Near-Term Data Capture | Other

ROADMAP | Nickel-Based Alloys

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
800H, 617, Hastelloy N	Summary Document for 800H, 617, 709SS, and Hastalloy N	Support ASME Code Data for 617 and 800H								
800H	Develop and qualify improved weld filler metal(s)									
Hastelloy N		Code qualification properties for ASME code Sec III Div 5 for Hastelloy N (or derivants) including time dependent properties								
		Corrosion Behavior of Hast N in Molten salt		Evaluate resistance to irradiation/swelling at high dpa for Hastalloy N						

In Progress

Extend Code Properties | Mechanical / Code Properties | Corrosion Properties | Irradiation Properties | Near-Term Data Capture | Other

ROADMAP | Graphite & Ceramics

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Graphite & Ceramics	Evaluate UK Graphite Experience		Evaluate new Graphite alloys & move into ASME Code				Evaluate SiC-SiC structures			
		Technical Basis and Approach for Qualification of Graphite		Topical Report on Graphite						

Extend Code Properties | **Mechanical / Code Properties** | **Corrosion Properties** | **Irradiation Properties** | **Near-Term Data Capture** | **Other**

ROADMAP | Corrosion Properties

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Austentic Stainless Steels		Corrosion Behavior of Austenitic Stainless and in Molten salt				Prioritize resistance of Austenitic SS in Lead Environment				
Development of Testing Approaches for Advanced Reactor Environments	Participation in DOE VTR Test Vehicle		Follow on Materials Selection and (Corrosion + Mechanical effects)							

In Progress

Extend Code Properties | Mechanical / Code Properties | Corrosion Properties | Irradiation Properties | Near-Term Data Capture | Other

ROADMAP | Cladding

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Moly Cladding	Development and demonstration of cladding (Mo rich on LAS and 316H SS)									
Hastelloy Cladding on 316H SS		Development and demonstration of Hastelloy Cladding on 316H SS								

In Progress

Extend Code Properties | Mechanical / Code Properties | Corrosion Properties | Irradiation Properties | Near-Term Data Capture | Other

ROADMAP | Dissimilar Metal Weld Joints

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Gr 91 to SS (316H, 709)		Mechanical properties, including time dependent behavior (creep and creep-fatigue)			Corrosion Resistence in AR Environments		Evaluate resistance to irradiation/swelling at high dpa			
800H to Gr 22		Mechanical properties, including time dependent behavior (creep and creep-fatigue)			Corrosion Resistence in AR Environments		Evaluate resistance to irradiation/swelling at high dpa			
709 to Ferritic Steels			Mechanical properties, including time dependent behavior (creep and creep-fatigue)			Corrosion Resistence in AR Environments		Evaluate resistance to irradiation/swelling at high dpa		

Extend Code Properties | **Mechanical / Code Properties** | **Corrosion Properties** | **Irradiation Properties** | **Near-Term Data Capture** | **Other**

ROADMAP | Exploratory Alloys

TECHNICAL TOPIC	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Exploratory Alloys						Prioritize resistance of Exploratory Alloys in various environments				

BPV-III Div. 5

ASME Boiler & Pressure Vessel Code Section III - Division 5, which provides design, construction, certification, and quality assurance rules for the construction of vessels, piping, pumps, valves, supports, core support structures and nonmetallic components for use in high temperature reactor systems and their supporting systems.

dpa

Displacements per atom - a damage-based exposure unit

EAC

Environmentally assisted cracking

F/M

Ferritic-martensitic steels

Mo or Moly

Molybdenum

VTR

Versatile Test Reactor

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