U.S. DEPARTMENT OF ENERGY | Office of Nuclear Energy

Nuclear Energy University Programs (NEUP) Fiscal Year 2018 Annual Planning Webinar Advanced Reactor Components (Subtopics RC-1.1 & 1.2)

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U.S. Department of Energy

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Office of Nuclear Energy Mission Areas

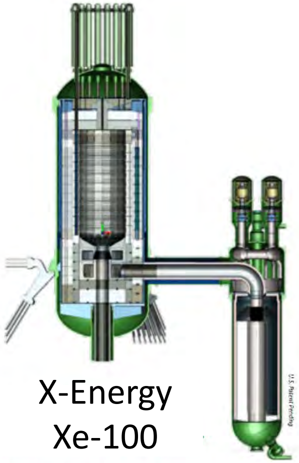
- Sustaining the Current Fleet of Light Water Reactors
- Deploying Small Modular Reactors
- **Demonstrating Advanced Reactors**
- Nuclear Waste Management
- Nuclear Science User Facilities and Enabling Capabilities

Advanced Reactor Vision and Strategy

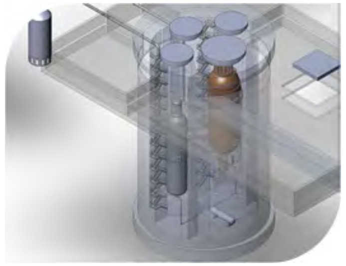
- By 2050, advanced Rx will provide significant component of nuclear energy
- By early 2030s, two non-LWRs will be technically mature enough to complete NRC licensing reviews and allow construction
- **ART will identify & resolve technical challenges to support detailed design, regulatory review, and deployment**

Several Advanced Reactor Designs Are Being Developed By Industry

Gas-Cooled Reactors



X-Energy
Xe-100

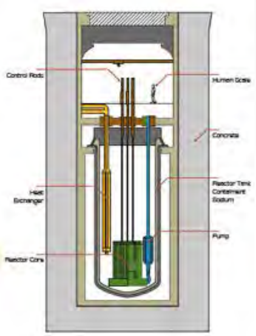


Areva USA
SC-HTGR

Fast Reactors

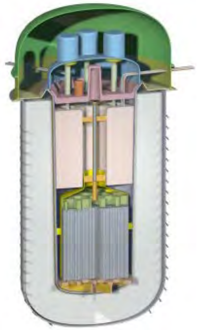
GE Hitachi
PRISM

TerraPower
TWR

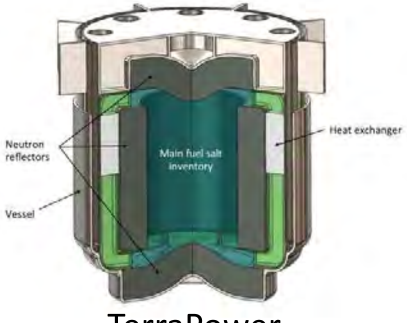


Advanced Reactor
Concepts LLC
ARC-100

Molten Salt Reactors



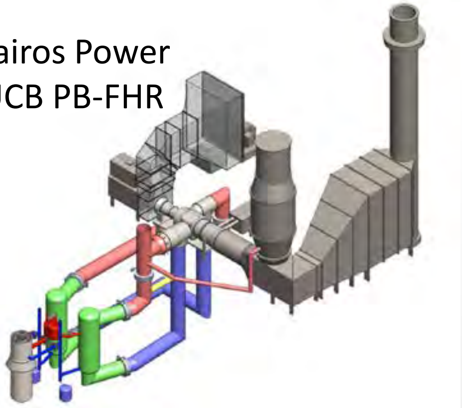
Terrestrial Energy USA
IMSR



TerraPower
MCFR

Elysium USA
MCSFR

Kairos Power
UCB PB-FHR



Structural Materials Are Critical for Advanced Nuclear Reactors

- Development and qualification of advanced structural materials are critical to the <u>design</u> and <u>deployment</u> of the advanced non-LWR reactor systems
  - Fast Reactors (FRs)
  - Gas-cooled Reactors (GCRs)
  - Molten Salt Reactors (MSRs)
- Structural materials must perform over design lifetimes at high temperatures for coolant boundaries and components (vessels, piping, internals, heat exchangers, steam generators, etc.)
- In addition to the operating temperature range, selection of construction materials for an advanced reactor is critically dependent on the coolant and its chemistry
  - Material compatibility and mass transfer of alloy constituents are major issues
- Different construction materials are typically required for different advanced reactor systems

MSR Systems Have Many Different Design Characteristics Leading to Different Materials Challenges

Vs

Different salt chemistries and their reactions with metals

Chloride salts

Vs

Fluoride salts

Liquid fuel

Fuel salt, fission products

Vs

Coolant salt

Vs

Solid fuel

Primary coolant salts

Vs

Secondary coolant salts

Drastically different design lives

4 yrs

Vs

30 to 60 yrs

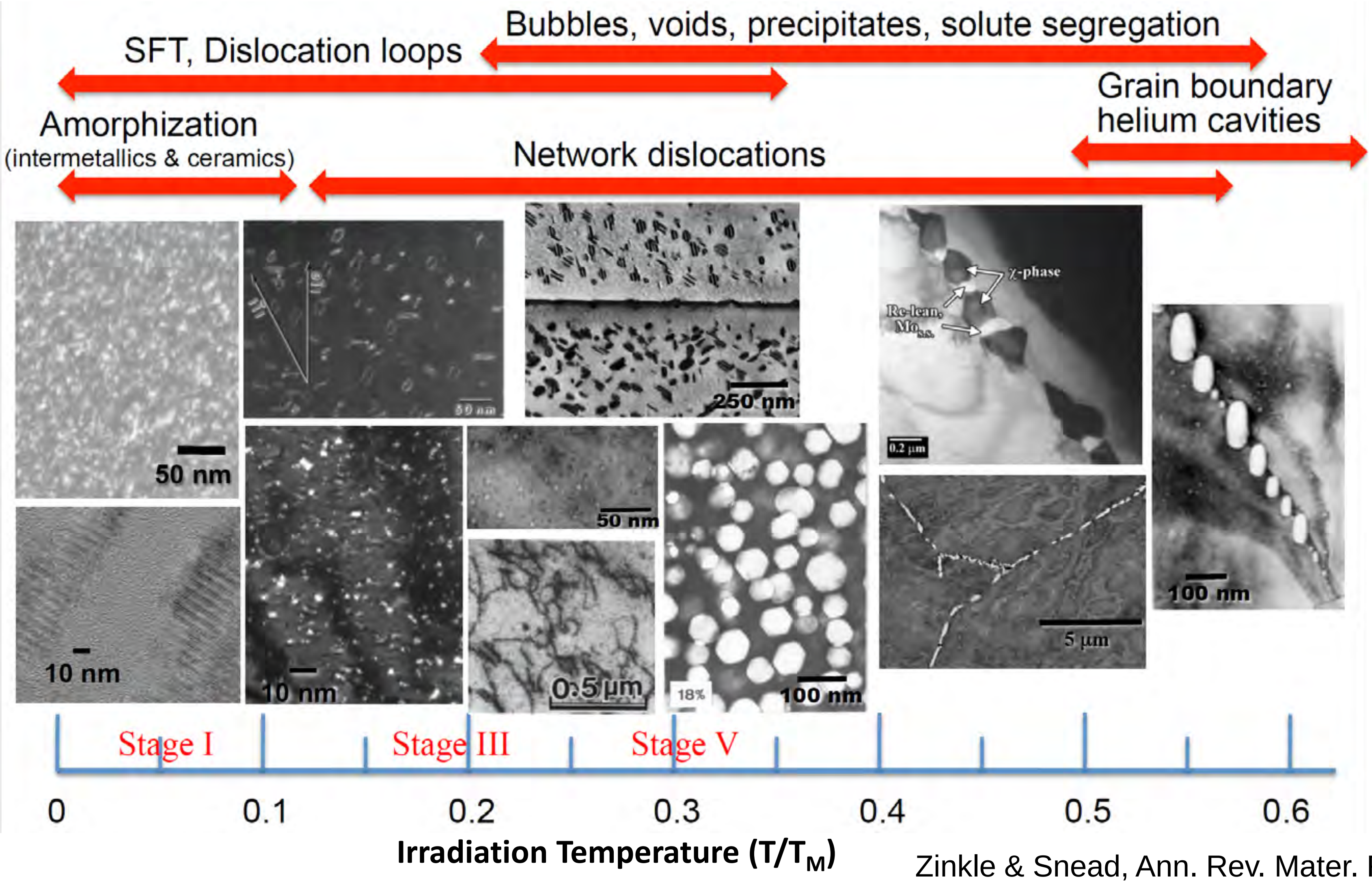
Limited Code-Approved Materials Are Available for MSRs

- **304H and 316H (stainless steels, 300,000 h)**
- **Alloy 800H (high alloy, 300,000 h)**
- **2.25Cr-1Mo (ferritic, 300,000 h)**
- **Modified 9Cr-1Mo (ferritic-martensitic, 300,000 h)**
  - **Extensions of these 5 materials to 500,000 h design lives being finalized by ASME code committees**
  - **ASME has all needed data, will complete in 2 to 3 years**
- **Alloy 617 (Ni-based alloy, Code Case in ballot for 100,000 h)**
- **These Class A materials not optimum for MSR structural applications due to the extreme environments of high temperatures, corrosive salts, and neutron irradiation (including fission products)**

Corrosion of Structural Materials in Molten Salts Differs from Other Coolants

- Molten Fluoride Salts
  - Fluorides remove oxide layers from metals
  - Mass transfer due to thermal & activity gradient in MSR circuits
  - Selective dissolution of Cr near alloy surface and along grain boundaries in Cr-bearing alloys
  - Intergranular cracking in Hastelloy N due to tellurium corrosion from fission product
  - Corrosion accelerated by presence of impurities
- Molten Chloride Salts
  - Oxide layers can form on metal surface in molten chloride salts but mostly porous and non-protective
  - Formation of a stable passivating oxide layer is much more challenging
  - Corrosion is due to depletion of Cr in alloy matrix underneath oxide layer and the intergranular corrosion
  - Generally, nickel-based alloys have better corrosion resistance than stainless steels
  - Very few studies on effects of actinides and fission products on the materials corrosion

MSR Component Doses Can Range from <1 to 25 dpa



Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Potential for irradiation damage of MSR materials must be assessed

ART NEUP Structural Materials Research Supports Near-Term and Long-Term Needs for MSR Structural Materials in FY18

- **RC-1.1. Down-Selection of Cladding Materials for Structural Components in Liquid-Fueled Molten Salt Reactors**
  - **Supports near-term MSR deployment**
- **RC-1.2. Innovative New Alloys for Molten Salt Reactor Structural Applications**
  - **Supports longer term MSR deployment**

Cladded Component Concept Supports Near-Term MSR Deployment

- Overall Plans
  - Conduct R&D to develop new design rules and analysis methods for integrity of cladding, its corrosion protective functions, and of cladded structural components for the anticipated service lifetime and conditions in MSRs
    - Initially focus on weld overlay (may extend to other possible fabrication methods)
  - Develop and incorporate construction rules (acceptance, materials, design, fabrication, examination) for cladded components in ASME Section III Division 5 and in-service inspection procedures in Section XI
- Support near-term MSR deployment
  - Enable MSR designers to deploy ASME Code-compliant cladding/base metal combinations, including non-Code qualified cladding materials, for Class A components that could be licensed for vendor-specific MSR designs, without the need of very long term data generation

Required Considerations for Cladded Components

Clad — Salt-wetted surfaces

- Salt compatibility
- Irradiation resistance and embrittlement due to fission products (e.g., tellurium)
- Weldability on Division 5 Class A materials
- Ability to maintain good ductility and low strength for design lifetime

Clad/Base Metal — Fusion zone

- Weldability
- Mechanical interactions (creep, creep-fatigue, stress relaxation, compliance, etc.)
- Metallurgical interactions (formation of brittle phases, diffusion due to composition gradient, etc.)

Base Metal — Division 5 Class A materials

- High temperature strength for design lifetime
- Irradiation resistance

RC-1.1 focuses on issues for clads that are exposed to fuel salts, neutron irradiation, fission products and high temperatures

RC-1.1. Down-selection of Cladding Materials for Structural Components in Liquid-Fueled Molten Salt Reactors

- **Proposal are sought to down-select a collection of existing alloys, or to develop new classes of alloys, that can be applied as integral clads using weld overlay for structural components in thermal and fast spectrum MSRs using liquid fuels**
- **Characteristics of the welded clad materials to be considered include, but not limited to, ductility, compatibility with different fuel salts, irradiation damage resistance, fission product embrittlement resistance, and weldability on Division 5 Class A base metals**
- **Use of innovative scoping test techniques with integrated computation materials engineering to accelerate the down-selection process is encouraged**
- **As part of the deliverables, plans should be developed for future intermediate-term testing to confirm the favorable characteristics observed during the relatively short time frame of the NEUP project, and to close any gaps that might exist, e.g., confirmatory neutron irradiation testing**
- **While not required, interaction with MSR designers on their system requirements is highly encouraged**

Development of Innovative Alloys to Support Long-Term MSR Deployment

- The cladded component concept supports near-term deployment of MSRs by removing the significant long-lead efforts in developing and Code-qualifying new structural materials
- The use of ASME Code-qualified materials as base metals in the cladded component concept may not be optimum and may have lifetime restrictions
- Construction of components without cladding may be preferable from engineering perspective
- Using a cladded component concept to support near-term deployment opens up an window of opportunity to develop and Code-qualify new structural materials that would meet the corrosion and irradiation requirements of MSRs for nth-of-a-kind insertion

RC-1.2. Innovative New Alloys for Molten Salt Reactor Structural Applications

- Proposals are sought to develop new metallic alloy(s) that can be used for welded construction of structural components of thermal or fast spectrum MSR designs that use liquid fuel
- Characteristics of new metallic alloy(s) include, but are not limited to, high temperature strength, fuel salt compatibility, irradiation damage resistance, fission products embrittlement, and weldability, for the desired life times of the components
- Novel application of high-value experiments with integrated computation materials engineering for the development and testing of new metallic alloy(s) is highly encouraged
- Non-traditional alloys such as high entropy alloys that would meet the requirements could also be considered
- While not specifically a part of this activity, the long-term goal of alloys developed under this effort would be their qualification for nuclear service under ASME Section III, Division 5, hence the long-term stability, fabricability, and potential capability for commercialization of any alloys developed are important
- While not required, interaction with MSR designers on their system requirements is highly encouraged

Points of Contact for RC-1.1 & 1.2

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