U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Nuclear Energy University Program (NEUP) Fiscal Year 2020 Annual Planning Webinar Molten Salt Reactor Materials (Subtopic RC-1)

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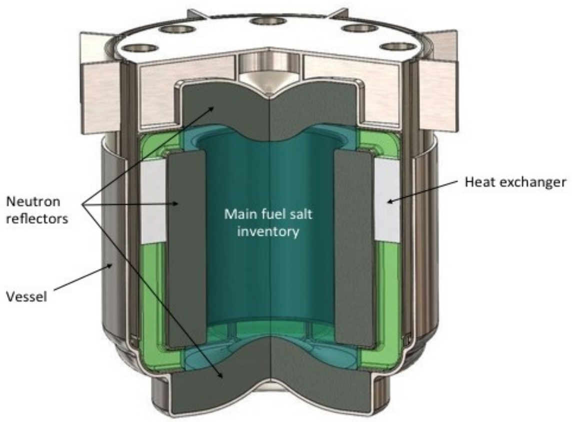
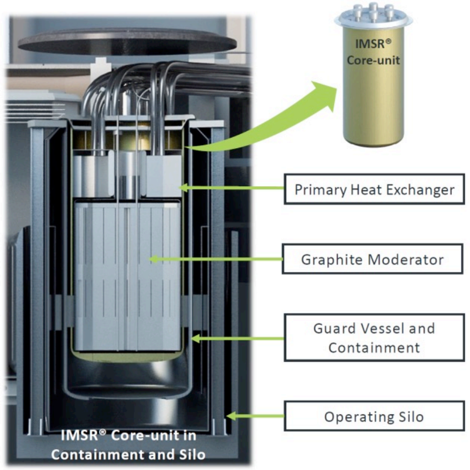
U.S. Department of Energy
August 7, 2019

Examples of Molten Salt Reactor (MSR) Designs being Developed by Industry

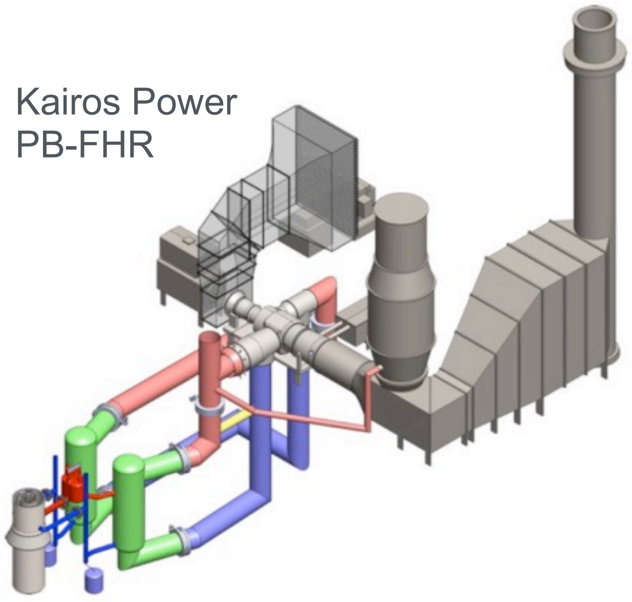


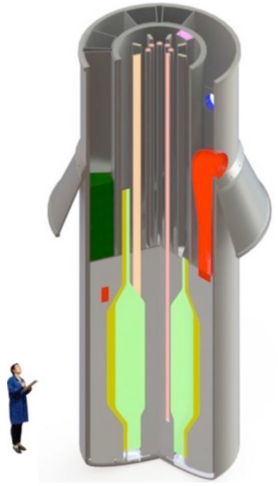
TerraPower
MCFR



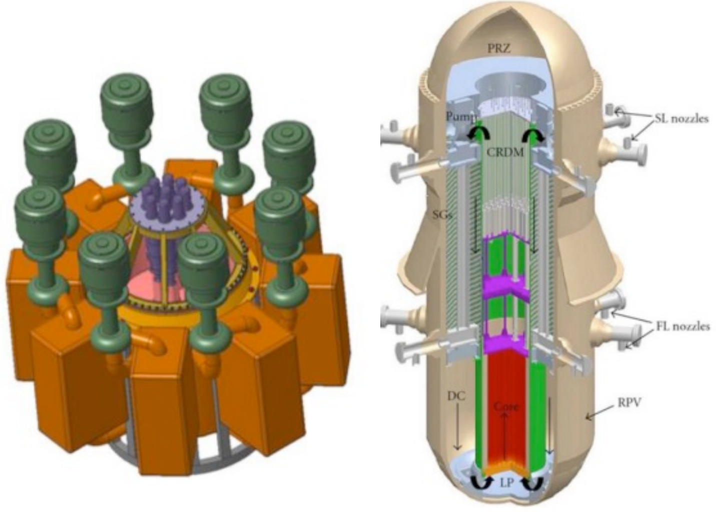
Terrestrial Energy
IMSR

Kairos Power
PB-FHR

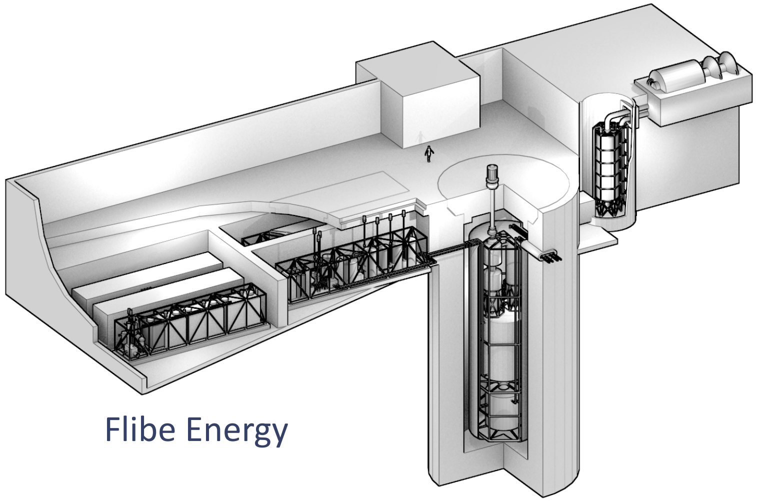




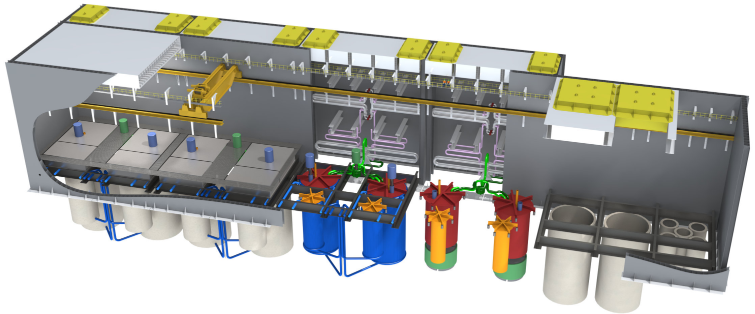
Reactor Vessel
Cross Section



Elysium USA, MCSFR



Flibe Energy



ThorCon Power

MSR Operating Conditions

- Relative to PWR, MSR's operate at lower pressure, higher temperature, and in very different coolant (Max dose is approximate)

Fuel	Coolants			Pressure (MPa)	Estimated Max. Dose (dpa)	Estimated Lifetime (years)	Example
	Primary or Fuel Salt	Secondary Salt	Tertiary Salt				
Solid	FLiBe	Nitrate	---	0.1	<10	>10	Kairos FHR
Liquid In assembly (not pumped)	Fuel UCl_3~760°C Primary (Hf?)ZrF_4 based (650-525°C)	595-450°C	565-270°C-				Moltex
Liquid	U-Zr-FLiBe (685-635°C)	FLiBe (595-550°C)		0.1	200		MSRE (~1.5 years full power)
Liquid	U/Th-FLiBe (704-564°C)	(621-454°C)	$NaNO_3$ / KNO_3 (598-344°C)				ThorCon
Liquid	U-Cl	*		0.1	200		TerraPower
Solid	Water	Water		16	100	60+	Commercial PWR

* To be determined, KF-ZrF_4, FLiNaK, KCl-$MgCl_2$, etc.

(Allen, Busby et al. 2010, Robertson 1965, ThorConUSA 2018, Andreades, Cisneros et al. 2014, MoltexEnergy 2018, Latkowski 2015)

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

Fast Spectrum Vs **Thermal Spectrum**

- Fast Spectrum: Higher point defect generation rate
- Thermal Spectrum: Lower point defect generation rate

Different salt chemistries and their reactions with metals

- Chloride salts
- Vs
- Fluoride salts

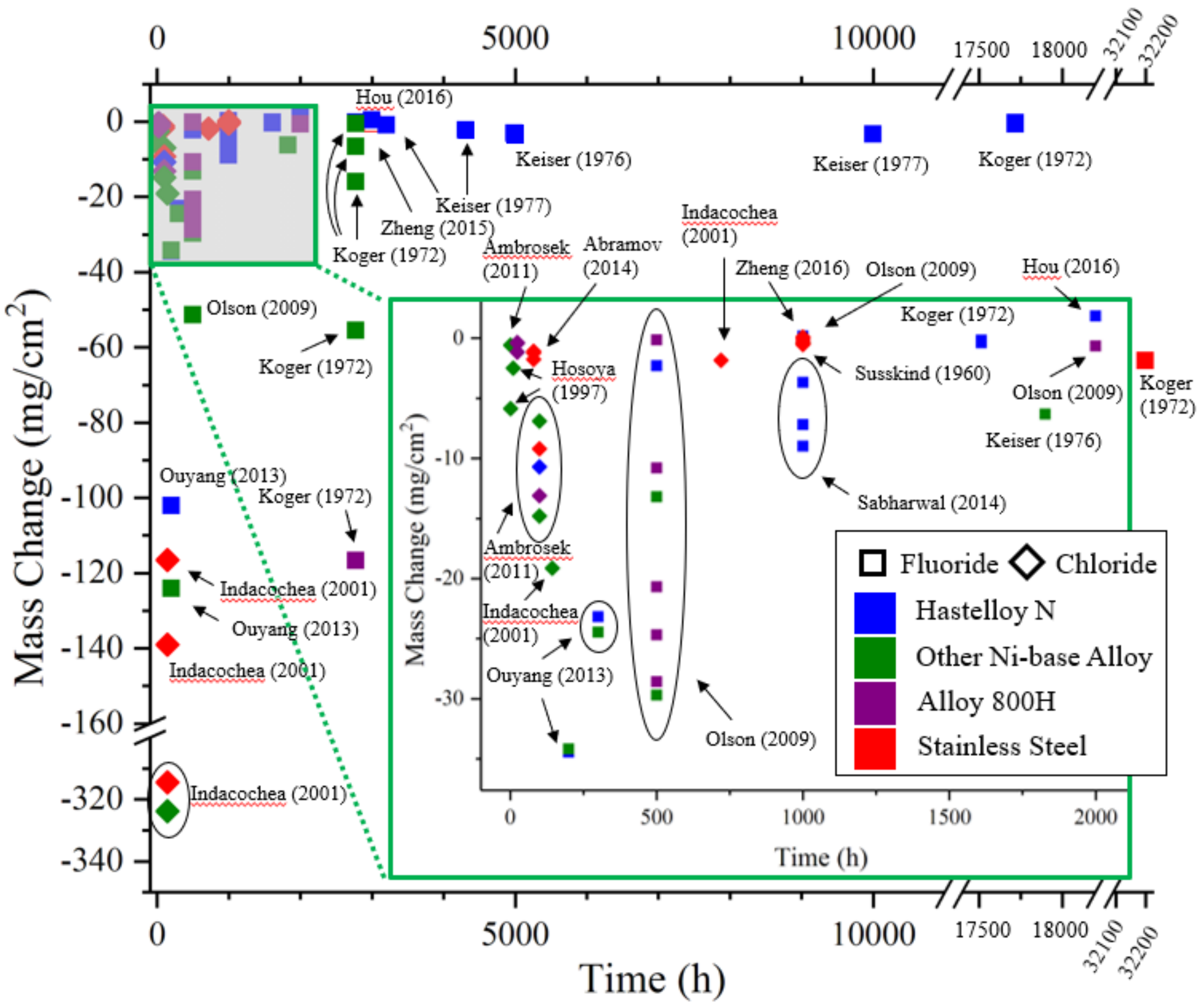
Liquid fuel Vs **Solid fuel**

- Liquid fuel:
  - Fuel salt, fission products
  - Vs
  - Coolant salt
- Solid fuel:
  - Primary coolant salts
  - Vs
  - Secondary coolant salts

Drastically different design lives

- 5 yrs
- Vs
- 30 to 60 yrs

Results of Corrosion Experiments in Molten Fluoride and Chloride Salts

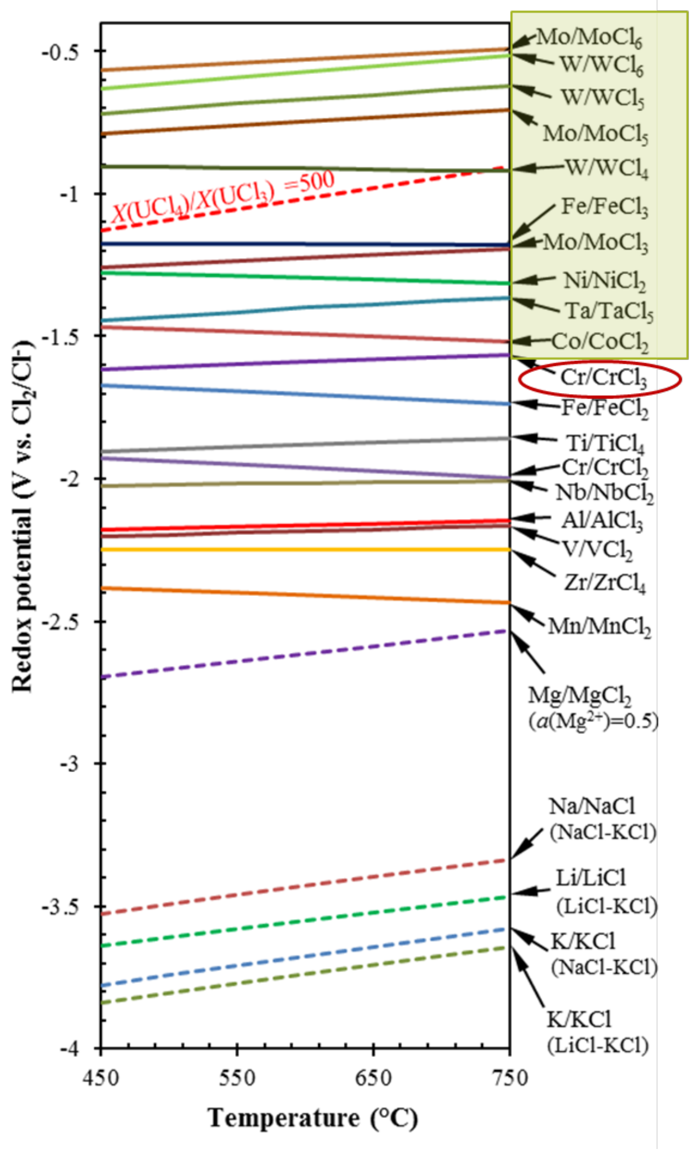


Raiman, Lee, J. Nucl. Mater. (2018)

Corrosion rates are highly varying because of the variety of conditions, methods, and salt chemistries used

Corrosion in Molten Chloride Salts Differs from Other Reactor Coolants

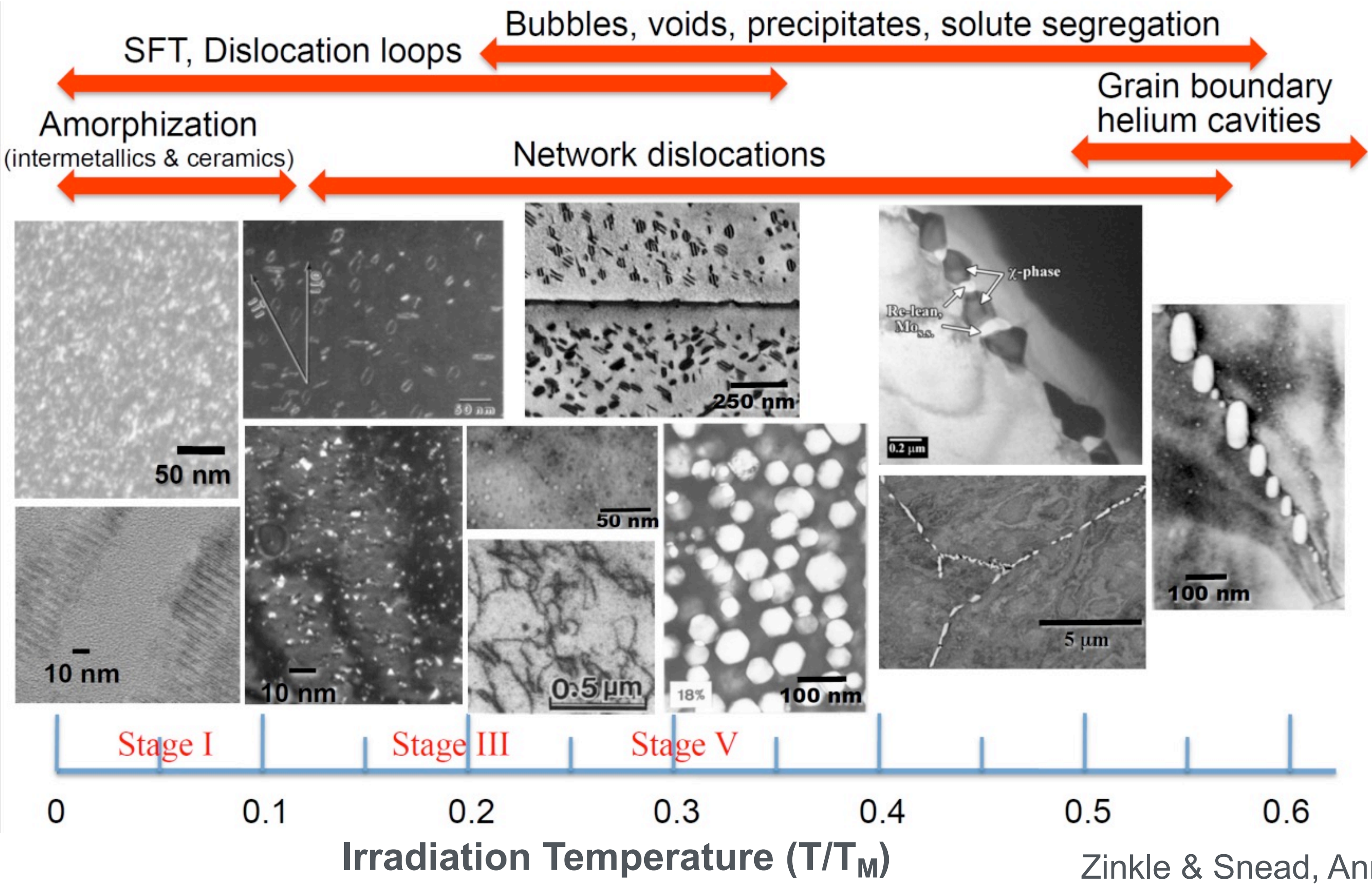
- Oxide layers can form on metal surface in molten chloride salts but mostly porous and non-protective
- Formation of a stable passivating oxide layer is much more challenging
- Corrosion is due to depletion of Cr in alloy matrix underneath oxide layer and the intergranular corrosion
- Need to control potential below Cr/$CrCl_2$ to mitigate corrosion
- Oxidizing impurities must be minimized
- Want materials noble to Cr corrosion potential
- 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



Increasing Nobility

(Guo, Zhang et al. 2018) updated by the Authors to include Nb, Ta, and V

MSR Component Doses Can Range From Less Than One to 25 DPA

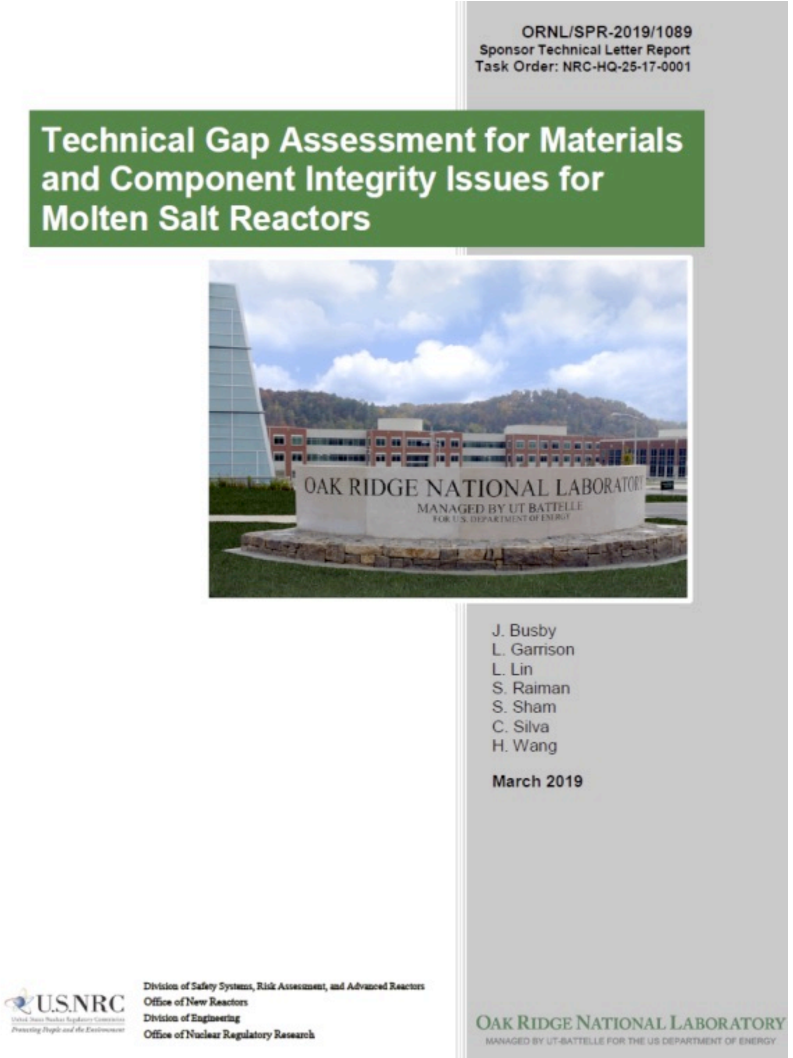


Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Potential for irradiation damage of MSR materials must be assessed

Limited ASME Nuclear Code Approved Materials for MSRs

- ASME Section III, Division 5, Class A structural materials
  - 304H and 316H (stainless steels, 815C, 300,000 h)
  - Alloy 800H (high alloy, 760C, 300,000 h)
  - 2.25Cr-1Mo (ferritic, 300,000 h)
  - Modified 9Cr-1Mo (ferritic-martensitic, 650C, 300,000 h)
- Extensions of these 5 materials to 500,000-hour design lives are being pursued by ASME code committees
  - One to two years to complete
- New Division 5, Class A Code Case for Alloy 617 (954C, 100,000 h)
- These Class A materials are not optimum for MSR structural applications due to the extreme environments of high temperatures, corrosive salts, and neutron irradiation (including fission products)


ORNL/SPR-2019/1089
Sponsor Technical Letter Report
Task Order: NRC-HQ-25-17-0001

Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Technical Gap Assessment For Materials And Component Integrity Issues For Molten Salt Reactors

US NRC ADAMS Public Documents

Accession Number: ML19077A137

NEUP Structural Materials Research

- **Supports long-term needs for MSR structural materials**
- **Awards on developing the next generation MSR structural materials for applications in fluoride-based MSRs were made in FY18 and FY19**

FY20 Call: Innovative New Structural Materials for Molten Chloride Salt Fast Reactor Applications

- **Proposals are sought to develop high performance new metallic alloy(s) that can be used for welded construction of structural components of molten chloride salt fast reactors using liquid fuel**
- **Non-metallic materials are not within the scope of this call**
- **Characteristics of the new metallic alloy(s) to be considered include, but are not limited to:**
  - **High temperature strength up to 900 to 950C**
  - **Long-term thermal stability**
  - **Chloride-based salt/fuel salt compatibility**
  - **Irradiation damage resistance**
  - **Resistance to possible fission or transmutation product embrittlement**
  - **Tensile and creep ductility**
  - **Fabricability and weldability**

Project Scope (Cont'd)

- **Innovative concepts are highly encouraged, for example,**
  - **Exploiting nano-scale interfaces within the alloy to trap defects and possible transmutation products**
  - **Applying novel, high-value experiments with integrated computation materials engineering (ICME) for the development and testing of new metallic alloy(s)**
- **While not required, interaction with MSR designers on their system requirements is highly encouraged**

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