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

Clean. Reliable. Nuclear.

Nuclear Energy University Program (NEUP) Fiscal Year 2019 Annual Planning Webinar Molten Salt Reactor Materials (Subtopic RC-1)

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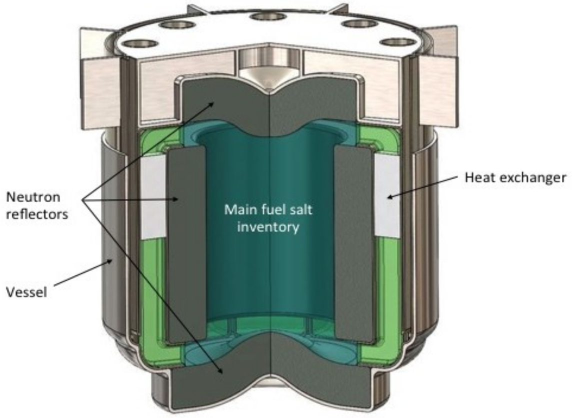
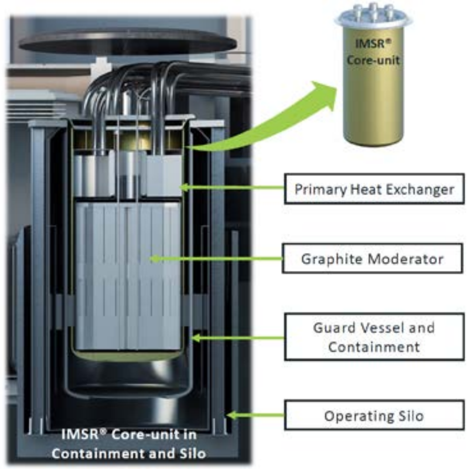
U.S. Department of Energy

August 8, 2018

Examples of MSR Designs being Developed by Industry

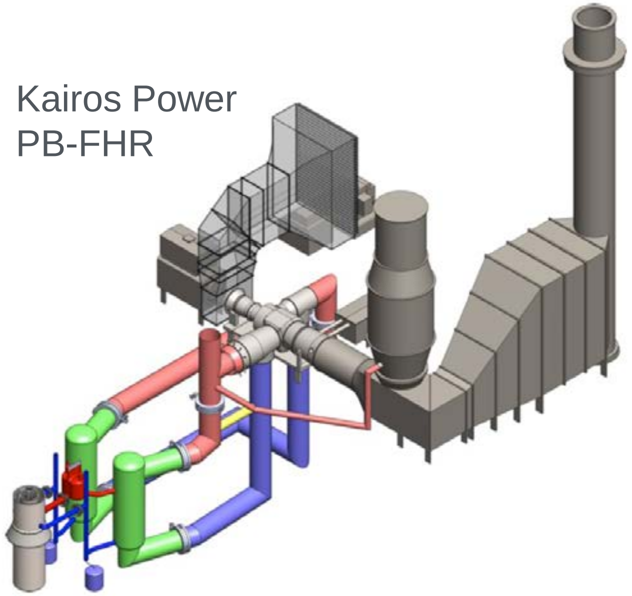


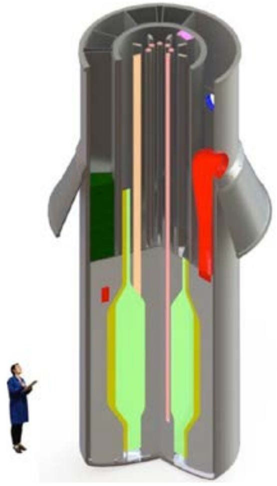
TerraPower
MCFR



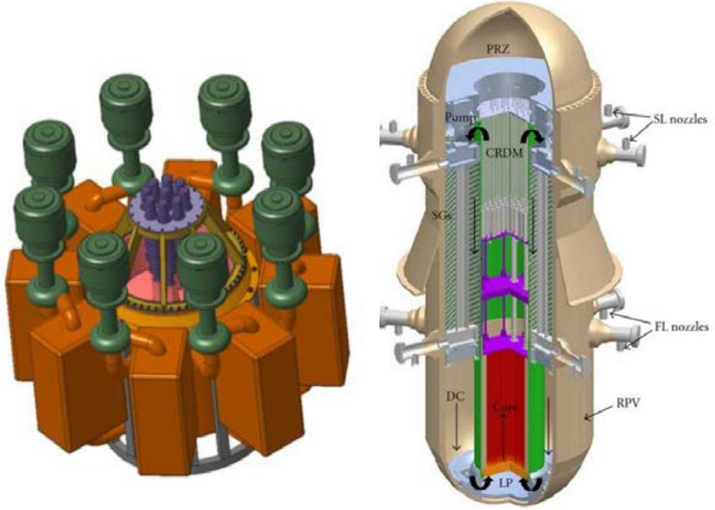
Terrestrial Energy
IMSR

Kairos Power
PB-FHR

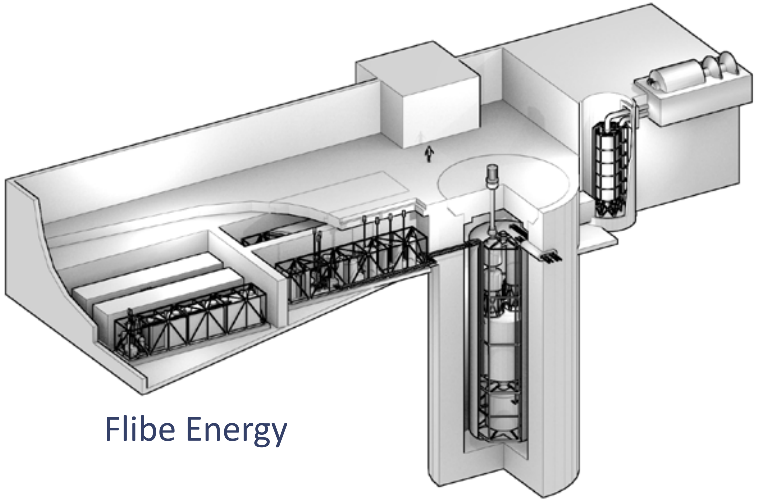




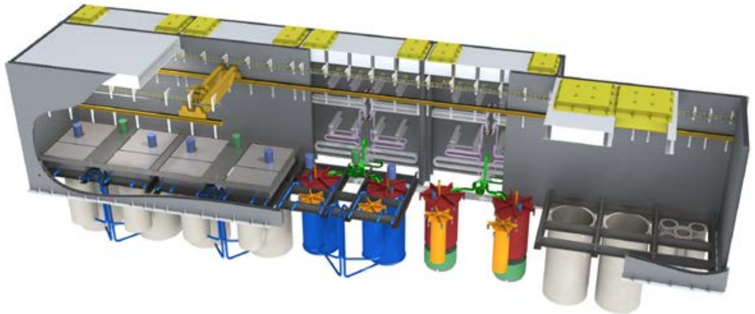
Reactor Vessel
Cross Section



Elysium USA, MCSFR



Flibe Energy



ThorCon Power

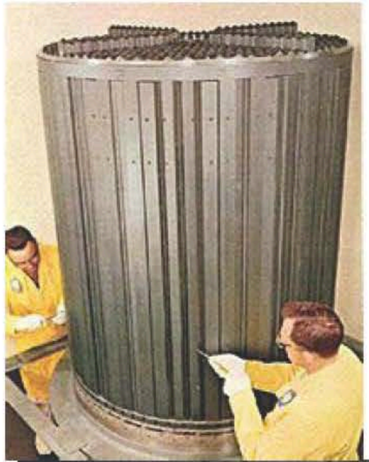
Limited ASME Nuclear Code Approved Materials for MSRs

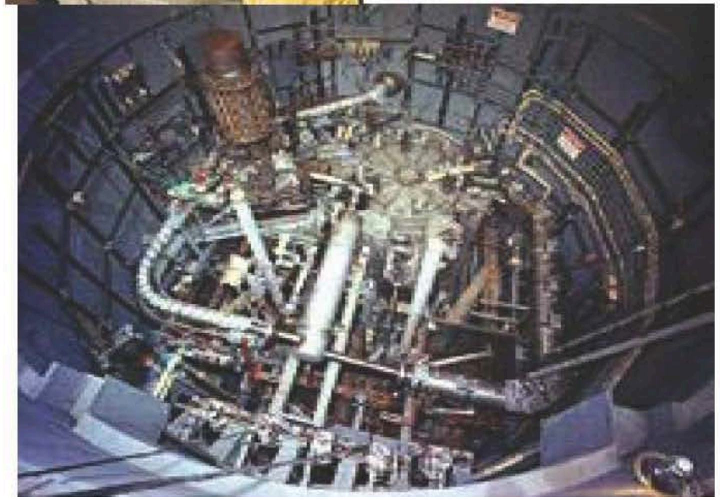
- 304H and 316H (stainless steels, 300,000 h)
- Alloy 800H (high alloy, 300,000 h)
- 2.25Cr-1Mo (ferritic, 300,000 h)
- Modified 9Cr-1Mo (ferritic-martensitic, 300,000 h)
  - Extensions of these 5 materials to 500,000 h design lives being finalized by ASME code committees
  - ASME has all needed data,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

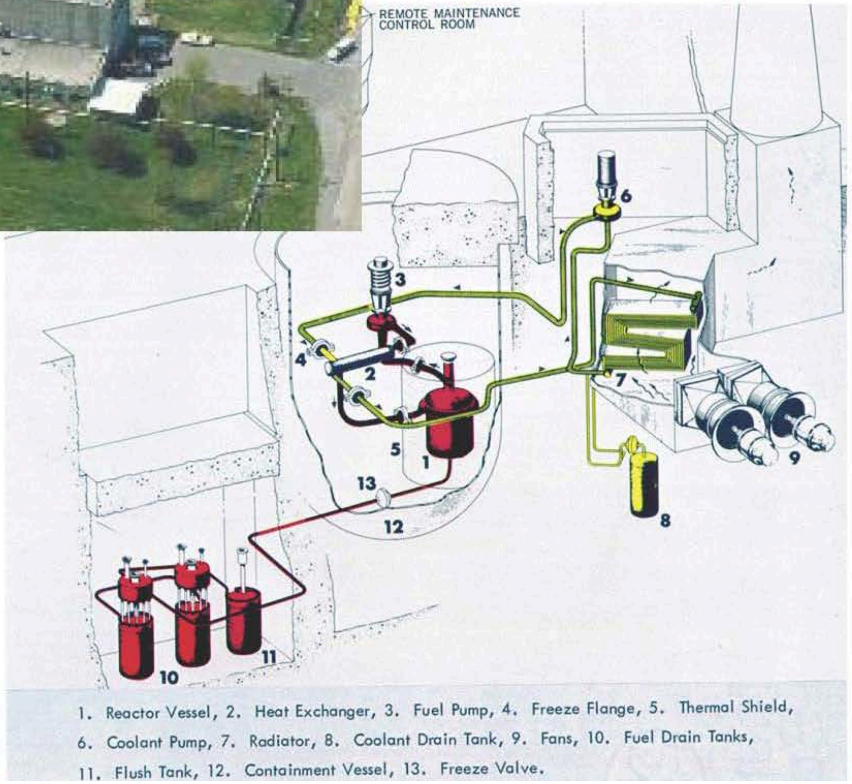
Molten Salt Reactor Experiment (MSRE)

Operated at Oak Ridge National Laboratory from 1965 to 1969

The Primary Reactor-Based Experience with Molten Salts

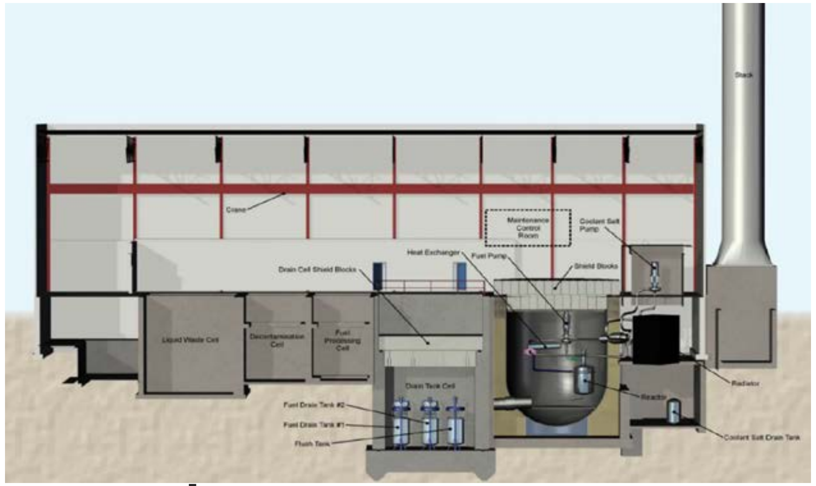






Molten Salt Reactor Experiment (MSRE)

- Fuel (^{235}U, ^{233}U and ^{239}Pu) dissolved in a fluoride salt
  - Liquid-fuel reactor
  - Thermal-spectrum limited breeder reactor
  - 7.34 MWt
  - 1225^{o}F (662 C) outlet temperature
  - ^{7}Lithium-beryllium fluoride salt
    - 65% Li7F - 29.1% BeF2 - 5% ZrF4 - 0.9% UF4
  - Program cancelled when the liquid metal fast breeder reactor chosen



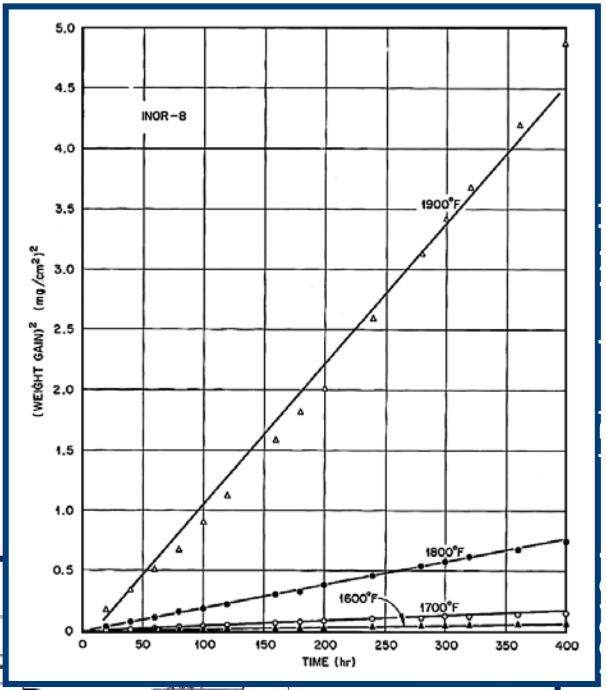
- New interest in MSR
  - Fast spectrum or thermal spectrum
  - Liquid fuel or solid fuel
  - Target diverse markets – base load electricity generation, process heat applications, desalination, water purification, remote locations

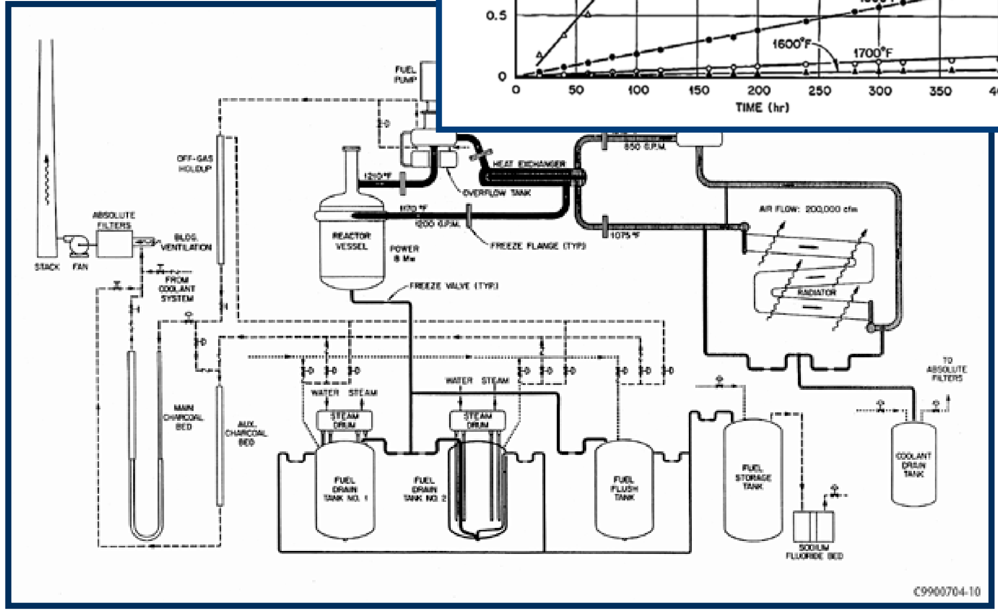
For the Relatively Low-Temp MSRE, INOR-8 (Hastelloy N) Was Developed

- Designed for compatibility with molten fluoride salts
- Minimum Cr but sufficient to provide oxidation resistance (6-8%)
- Does not embrittle on aging
- Limited aluminum, titanium, and carbon contents minimize fabrication and corrosion problems
- Carbides are stable
- Qualified in ASME Non-Nuclear Code (Sec VIII) to 1300F (700C)

Element	Percentage[a]
Nickel	Balance
Molybdenum	15.00---18.00
Chromium	6.00---8.00
Iron	5.00
Carbon	0.04---0.08
Manganese	1.00
Silicon	1.00
Tungsten	0.50
Aluminum + titanium	0.50
Copper	0.35
Cobalt	0.20
Phosphorus	0.015
Sulfur	0.020
Boron	0.010
Others, total	0.50

[a]Single values are maximum percentages



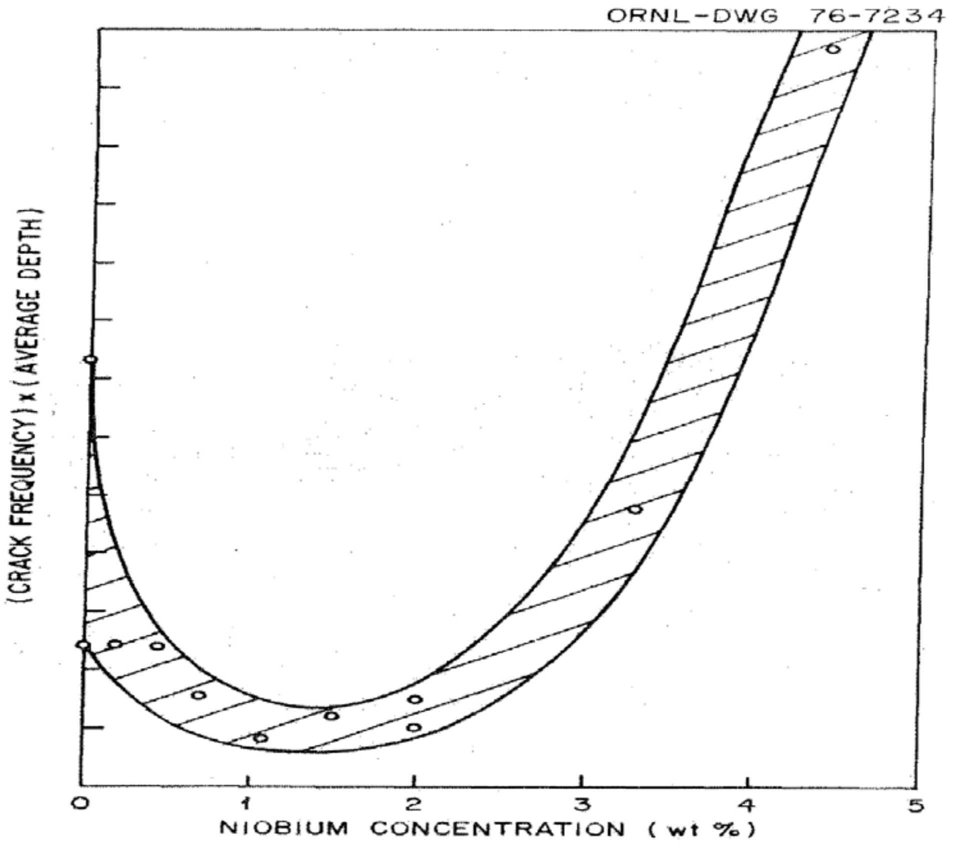


Several Post-Operation Issues Identified

- DeVan and Evans demonstrated that the temperature dependent solubility of CrF_2 in fluoride salts resulted in removal of Cr from the hottest metal surfaces and deposition of Cr on the coolest surfaces
- INOR-8 suffered radiation-induced embrittlement primarily attributed to helium produced by interaction of thermal neutrons with ^{10}B which is an impurity in the alloy
- Fission product tellurium caused shallow intergranular cracking in INOR-8 exposed to the fuel salt

The Effect of Niobium Addition on Tellurium Cracking of Hastelloy N Was Determined

- **Effect of Niobium additions to Hastelloy N on grain boundary cracking after exposure to salt containing Cr_3Te_4 + Cr_5Te_6 for 250 hours at 700C**
- **Shows 1-2 wt % Niobium provides most improvement**

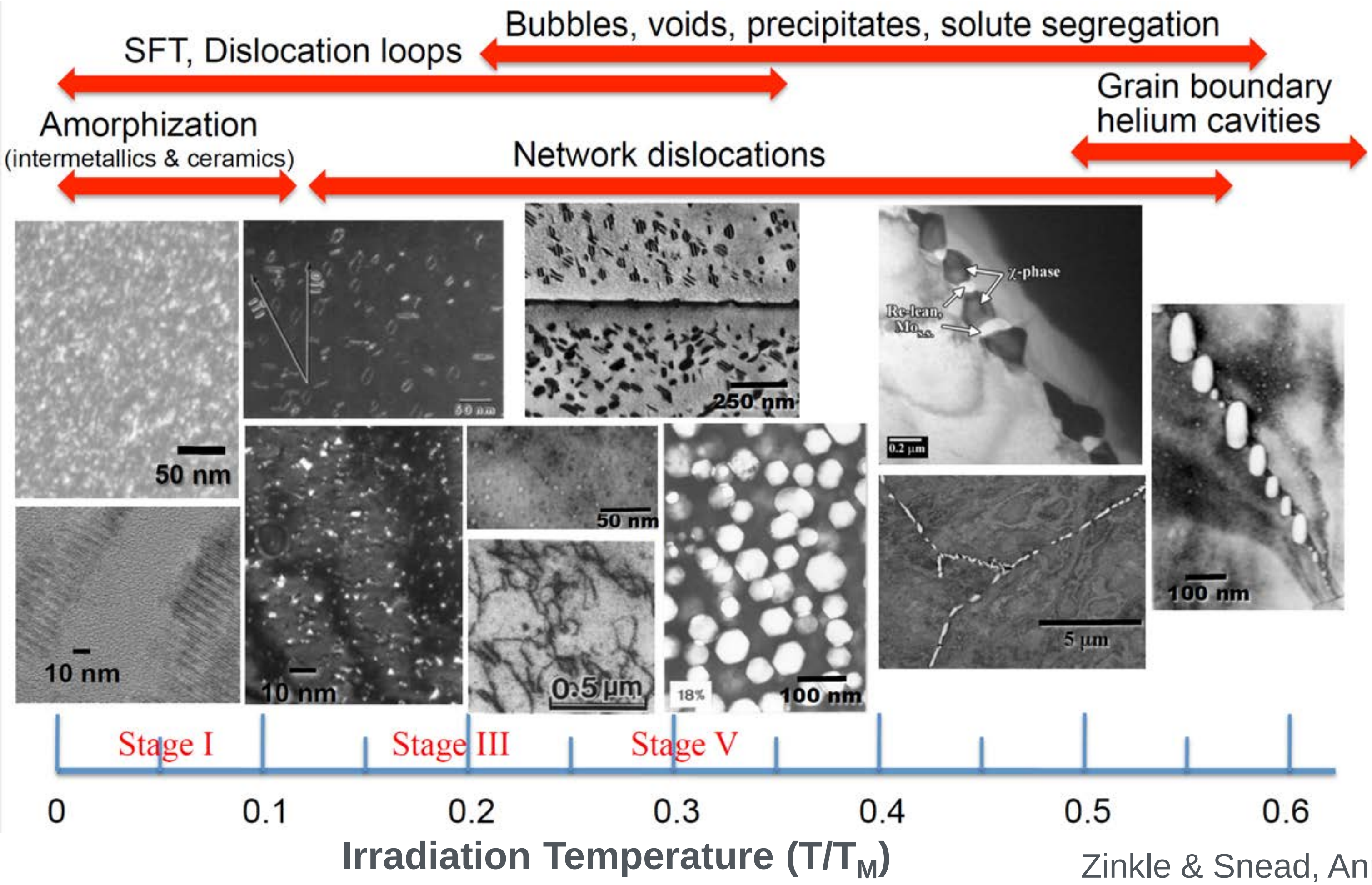


From J.R. Keiser "Status of Tellurium-Hastelloy N Studies in Molten Fluoride Salts", ORNL/TM-6002, Oct 1977

Various Nickel Alloy Developments for MSR Applications

Element	Hasteloy N US	Hasteloy NM US	HN80M-VI Russia	HN80MTY Russia	HN80MTW Russia	MONICR Czech Rep	GH3535 China	EM-721 France
Ni	base	base	82	82	77	base	base	68.8
Cr	7.52	7.3	7.61	6,81	7	6,85	6.88	5.7
Mo	16.28	13.6	12.2	13,2	10	15,8	15.9	0.07
Ti	0.26	0.5–2.0	0.001	0,93	1.7	0,026		0.13
Fe	3.97	< 0.1	0.28	0,15		2,27	4.1	0.05
Mn	0.52	0.14	0.22	0,013		0,037	0.49	0.086
Nb	-	-	1.48	0,01		< 0,01	0.01	-
Si	0.5	< 0.01	0.040	0,040		0,13	1.01	0.065
Al	0.26	-	0.038	1,12		0,02	0.88	0.08
W	0.06	-	0.21	0,072	6	0,16		25.2

MSR Component Doses Can Range from <1 to 25 dpa



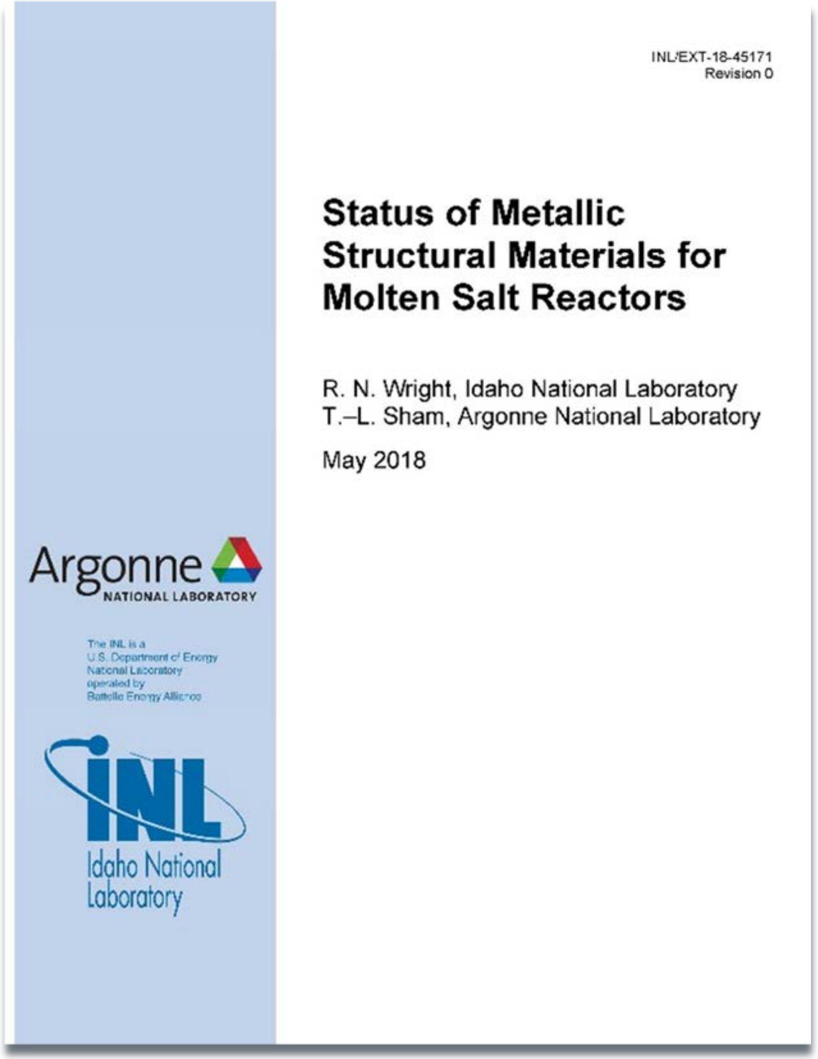
Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Potential for irradiation damage of MSR materials must be assessed

Assessment of Available Alloys

In May 2018, an assessment of available materials for MSR was completed. The recommendation is to develop advanced nickel-based alloys for use in MSRs.

https://art.inl.gov/ART Document Library/High Temperature Materials/45171 Status of Metallic Structural.pdf



INL/EXT-18-45171
Revision 0

Status of Metallic Structural Materials for Molten Salt Reactors

R. N. Wright, Idaho National Laboratory
T.–L. Sham, Argonne National Laboratory

May 2018

Argonne NATIONAL LABORATORY

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

INL Idaho National Laboratory

NEUP Structural Materials Research Supports Long-Term Needs for MSR Structural Materials in FY19

RC-1. Innovative New Nickel Alloys for Molten Salt Reactor Structural Applications

- **Proposals are sought to identify existing or to develop new Nickel alloy(s) that can be used for welded construction of structural components of MSR designs that use either solid or liquid fuel**
- **Characteristics of the candidate Nickel alloy(s) to be considered include, but not limited to,**
  - **High temperature strength: 1400 – 1600F (760 – 870C) for long design lifetime (300,000 h) and up to 1800F (980C) for short term excursions**
  - **Salt compatibility**
  - **Irradiation damage resistance (including helium generation from n,α reactions with thermal neutrons)**
  - **Resistance to fission products embrittlement**
  - **Weldability, amenable to fabrication scale up**
  - **Long-term microstructural stability in the MSR environment**

RC-1 Project Scope (Cont'd)

- Innovative concepts such as exploiting nano-scale interfaces within the alloy to trap defects and helium, and novel application of high-valued experiments (implantation, ion irradiation, etc.) with integrated computation materials engineering are highly encouraged
- 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 candidate alloys are important
- While not required, interaction with MSR designers on their system requirements is highly encouraged

RC-1. Innovative New Nickel Alloys for Molten Salt Reactor Structural Applications

- Collaborations with the Engineering and Physical Sciences Research Council (EPSRC) in the UK are strongly encouraged as UK funding is available for UK institutions participating as collaborators for the scope of RC-1

Points of Contact for RC-1 MSR Materials

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