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MSR 구조재료 개발 현황

용융염 원자로 구조재료 부식연구 (2017-2018)

U.S. Department of Energy

Bimetallic Composite (Incoloy 800H/Ni-201) Development and Compatibility in Flowing FLiBe as a Molten Salt Reactor (MSR) Structural Material

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ABSTRACT:

Much progress has recently been made on Molten Salt Reactor (MSR) conceptualization and technology development with the strategic support of the Department of Energy (DOE). However, detailed design, assessment of operational functionality, and evaluation of reliability and economics have been hampered by concerns regarding structural material compatibility with the flowing salt. Single alloy candidates may not be optimum choices for both chemical and mechanical reasons. Indeed, none of the commercially available structural alloys are considered to be entirely chemically compatible with hot flowing fluoride salts, because substantial amounts of alloying elements, particularly Cr, are susceptible to dissolution in liquid salts. Adherence to the use of a single alloy may result in unnecessarily restricting the functionality, reliability, and targeted lifetime of MSR systems. Therefore, it is imperative that a material system with the requisite high-temperature mechanical strength and chemical compatibility with flowing FLiBe be developed. The goal of this NEUP is to develop a bimetallic composite, Incoloy 800H/Ni-201, and test it under flowing FLiBe to investigate key high temperature mechanical behavior to support its ASME codification, and to quantify the performance gain of this bimetallic composite over single alloy candidates (Incoloy 800H, Hastelloy N, and SS 316).

The main goal of the proposed project is to develop a new bimetallic alloy (Incoloy 800H/Ni-201) structural material for the MSR, and compare its post-exposure mechanical performance in flowing FLiBe with single alloys SS 316, Hastelloy N, and Incoloy 800H, in the context of ASME codification. The specific objectives of the proposed research are to: (1) fabricate Incoloy 800H/Ni-201 on an industrial scale; (2) evaluate key mechanical performance gains of Incoloy 800H/Ni-201, compared to single alloy candidates (SS 316 and Incoliy 800H), required for the ASME codification; (3) quantify and validate attainable performance gains by using Incoloy 800H/Ni-201 in place of the current single alloy candidates in the context of ASME BPVC codification; and (4) assess the service time extension of key power plant components (i.e., heat exchangers, or pressure vessel) through stress modeling and simulation. This research will establish the scientific foundation of the triad: 'flow affected alloying element dissolution-microstructure-mechanical behavior,' in the context of ASME codification.

The performance comparison between our proposed Incoloy 800H/Ni-201 bimetallic composite versus Incoloy 800H, Hastelloy N, and stainless steel (SS) 316 will provide a significantly advanced basis for the strategic selection of material. In addition, each component in the MSR system possesses different coolant velocities. Our investigation on the effect of velocity on the alloy element dissolution will advance material choices for key nuclear components. These findings will enable nuclear engineers to design more detailed power plant operation schemes and economic assessments.

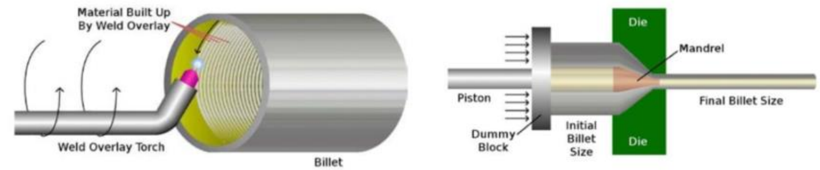
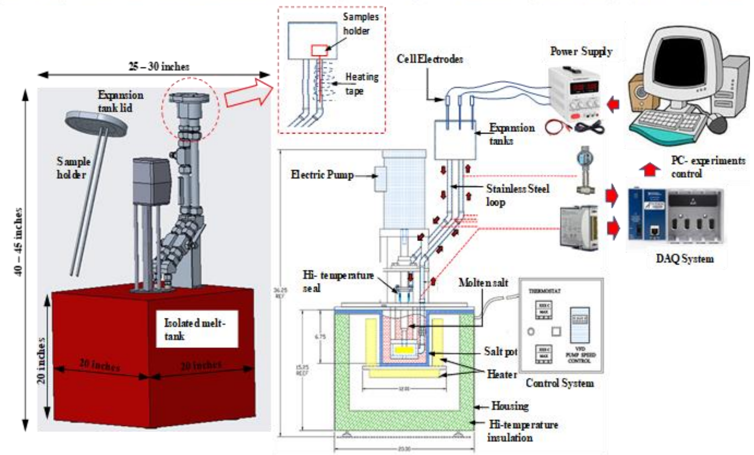


Figure 4: Proposed processing methods for the 800H/Nik-201 bimetallic composite, chosen to minimize interfacial layer stresses and maximize material yield. (Left) Weld-overlay and (Right) Co-extrusion.



Oxidizing and reduction (Redox) potential

Anodic reaction: $M \rightarrow M^{n+} + ne^{-}$

Cathodic reaction: $Ox^{n+} + ne^{-} \rightarrow Red$

Overall reaction: $M + Ox^{n+} \rightarrow M^{n+} + Red$

Redox Potential (Nearnst Equation)

$$E_{M^{n+}/M}\,(vs.\,Cl/Cl^{-}) = E^{o}_{M^{n+}/M} + \frac{RT}{nF}\ln\left(\frac{a_M^{n+}}{a_M}\right)$$

Standard electrode potential

Activity for relevant species

$$E^{o}_{M^{n+}/M}(vs.\,Cl/Cl^{-}) = \Delta G^{o}_{f}(MCl_n)/nF$$

Standard Gibbs free energy of formation

$$a_M = 1 \text{ for pure metals}$$

$$a_M^{n+} = \gamma_m^{n+} C_m^{n+} \approx x_0 \text{ (for comparison)}$$

Activity coefficient

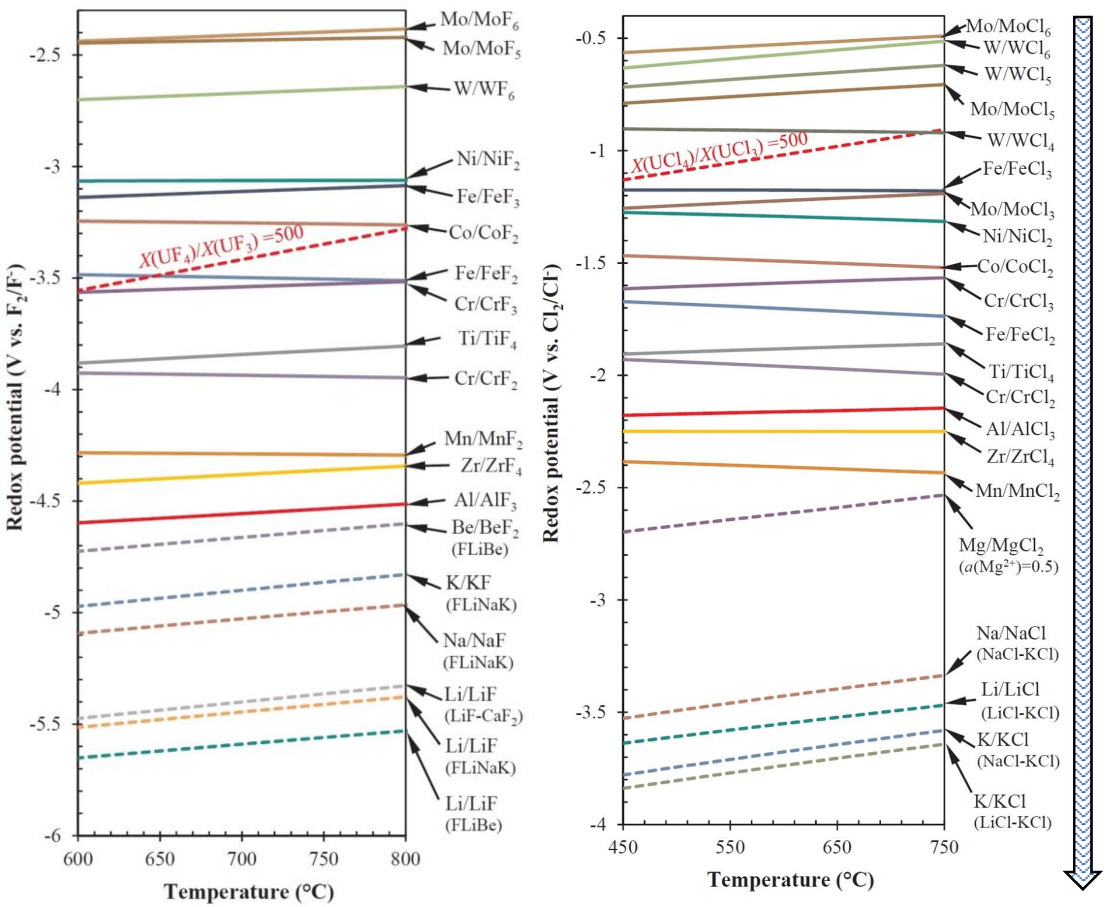
Redox potential with hydrogen as a reference

Half Reaction					potential
F_2	+	$2e^-$	⇌	$2F^-$	+2.87 V
Pb^{4+}	+	$2e^-$	⇌	Pb^{2+}	+1.67 V
Cl_2	+	$2e^-$	⇌	$2Cl^-$	+1.36 V
Ag^+	+	$1e^-$	⇌	Ag	+0.80 V
Fe^{3+}	+	$1e^-$	⇌	Fe^{2+}	+0.77 V
Cu^{2+}	+	$2e^-$	⇌	Cu	+0.34 V
$2H^+$	**+**	**$2e^-$**	**⇌**	**H_2**	**0.00 V**
Fe^{3+}	+	$3e^-$	⇌	Fe	−0.04 V
Pb^{2+}	+	$2e^-$	⇌	Pb	−0.13 V
Fe^{2+}	+	$2e^-$	⇌	Fe	−0.44 V
Zn^{2+}	+	$2e^-$	⇌	Zn	−0.76 V
Al^{3+}	+	$3e^-$	⇌	Al	−1.66 V
Mg^{2+}	+	$2e^-$	⇌	Mg	−2.36 V
Li^+	+	$1e^-$	⇌	Li	−3.05 V

increasing strength as an oxidizing agent

increasing strength as an reducing agent

Oxidizing and reduction (Redox) potential



Increasing strength as a reducing agent (less thermodynamically stable)

Redox potential of various redox couples as a function of temperature in fluoride and chloride salts. Solid line: metal dissolution at a_m^{n+} of 10^{-6}
[Guo et al., Progress in Material Science 97 (2018) 448-487]

What these figures mean:

1. Cr is most prone to oxidation among major alloying elements (Fe, Cr, Ni)

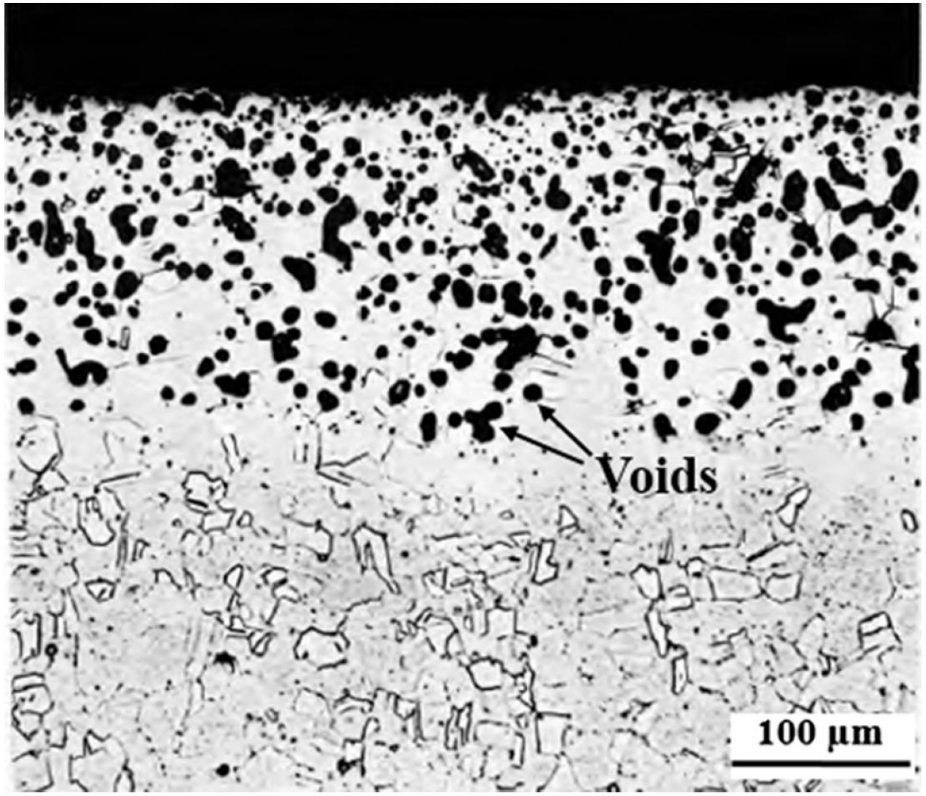
2. Ni is least prone to oxidation among major alloying elements (Fe, Cr, Ni) → Basis of our interest in Ni based alloy !

3. If an oxidant with its reduction potential above the solid line is present in the melt, the metal will be corroded until the concentration of dissolved M^{n+} elevates to the equilibrium level at which $E_{M^{n+}/M} = E_{Ox/Red}$

4. Major salt constituents (Li, K, Na, Mg) are far below the oxidation potentials of structural metals, indicating that cations of salt constituents are not expected to cause considerable corrosion of metals.

5. Dissolved Actinides and other impurities are the major cause of corrosion.
   i.e.: structural alloys can be corroded by the reduction of UCl_4 to UCl_3
   $\mathrm{U(IV)} + \mathrm{e}^- \rightarrow \mathrm{U(III)}$ is very oxidizing !

Selective corrosion of Cr: key concern for corrosion in MSR



Typical photomicrograph of Inconel 600 after exposure to molten fluorides
[Manly et al., ORNL, ORNL-2349, 1957]

Major oxidizing factors 1: Actinides and fission products

Actinides can act as oxidants to cause metal corrosion depending on their reduction potentials

$$E_{U(IV)/U(III)} = E^*_{U(IV)/U(III)} + \frac{RT}{nF} ln \frac{X_{U(IV)}}{X_{U(III)}}$$

Where formal potential $E^*_{U(IV)/U(III)} = E^o_{U(IV)/U(III)} + \frac{RT}{nF} ln \frac{\gamma_{U(IV)}}{\gamma_{U(III)}}$

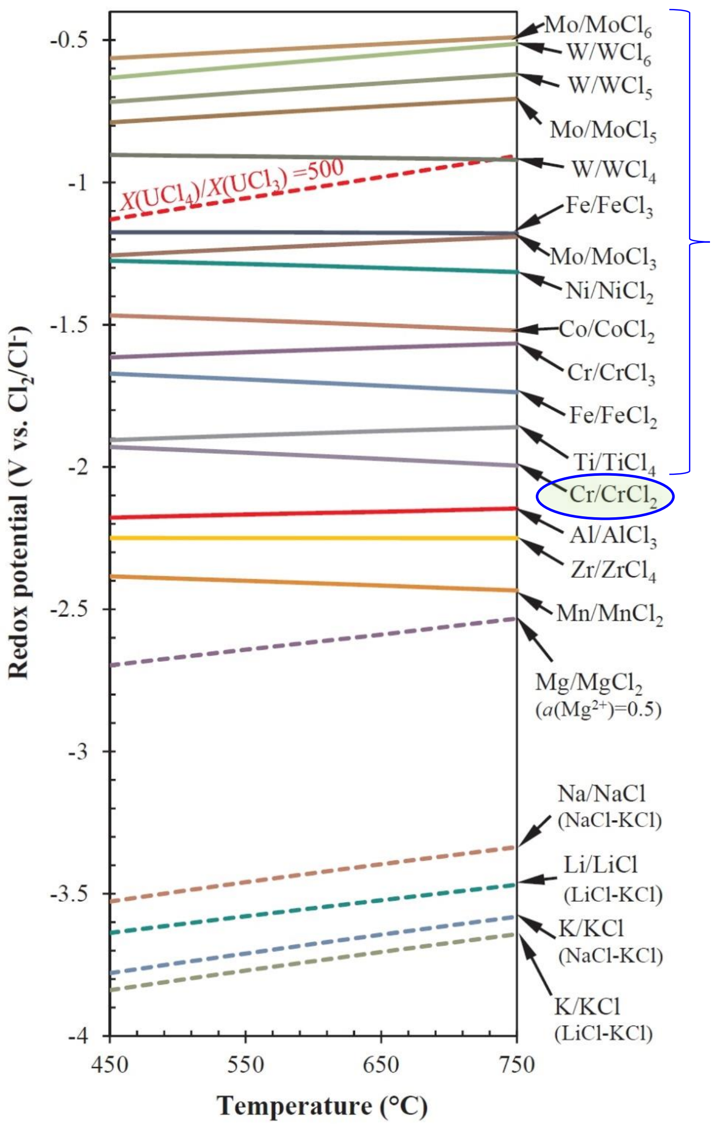
Formal potentials of actinides and fission products in molten chlorides and fluorides, mostly based on the work done for MSREs

	E^a [V vs. Cl_2/Cl^-] in LiCl-KCl	E^a [V vs. F_2/F^-] In FLiBe
U(IV)/U(III)	$-1.669 + 2.1 \times 10^{-4}T$ [59]	$-4.766 + 8.51 \times 10^{-4}T$ [50]
U(III)/U	$-2.943 + 5.87 \times 10^{-4}T$ [49]	$-4.955 + 6.74 \times 10^{-4}T$ [50]
Th(IV)/Th	$-2.985 + 5.56 \times 10^{-4}T$ [49]	$-5.413 + 7.64 \times 10^{-4}T$ [60,61]
Pu(III)/Pu	$-3.337 + 7.54 \times 10^{-4}T$ [49]	–
Pa(IV)/Pa	$-2.754 + 6.0 \times 10^{-4}T$ [60]	–
Np(IV)/Np(III)	$-1.250 + 6.64 \times 10^{-4}T$ [62]	–
Np(III)/Np	$-3.230 + 7.19 \times 10^{-4}T$ [49]	–
Y(III)/Y	$-3.603 + 6.88 \times 10^{-4}T$ [49]	–
Zr(IV)/Zr(II)	−2.118 at 723 K [63]	–
Zr(II)/Zr	$-2.298 + 4.12 \times 10^{-4}T$ [49]	–
Zr(IV)/Zr	−2.068 at 723 K [63]	$-4.986 + 7.99 \times 10^{-4}T$ [50]
La(III)/La	$-3.575 + 6.06 \times 10^{-4}T$ [49]	$-5.946 + 8.65 \times 10^{-4}T$ [50]
Ce(III)/Ce	$-3.534 + 5.92 \times 10^{-4}T$ [49]	$-5.872 + 8.61 \times 10^{-4}T$ [50]
Pr(III)/Pr	$-3.541 + 6.30 \times 10^{-4}T$ [49]	–
Nd(III)/Nd	$-3.567 + 6.28 \times 10^{-4}T$ [49]	–
Sm(III)/Sm(II)	$-2.618 + 7.76 \times 10^{-4}T$ [49]	~ −3.5 at 812 K [57]
Sm(II)/Sm	–	< Be(II)/Be [57]
Eu(III)/Eu(II)	$-1.356 + 7.2 \times 10^{-4}T$ [49]	$-4.741 + 1.040 \times 10^{-3}T$ [47][a]
Gd(III)/Gd	$-3.514 + 7.32 \times 10^{-4}T$ [64]	–

[Guo et al., Progress in Material Science 97 (2018) 448-487]

Obtaining relevant formal potentials in the relevant molten salt, with understanding of inter-species interaction constitutes the key required thermodynamic data base

Major oxidizing factors 2, 3, and 4: Structural metal impurities, moisture, and oxygen



② *Presence these structural metal impurities in molten salt will corrode : i.e., $Cr \rightarrow Cr^{2+} + 2e-$*

③ *Reduction of dissociated H^+*

$$H_2O(g) + 2Cl^- \leftrightarrow O^{2-} + 2HCl(g)$$

HCl is assumed to be fully dissociated in molten chloride salts as Cl^- is an exceedingly weak conjugate base .

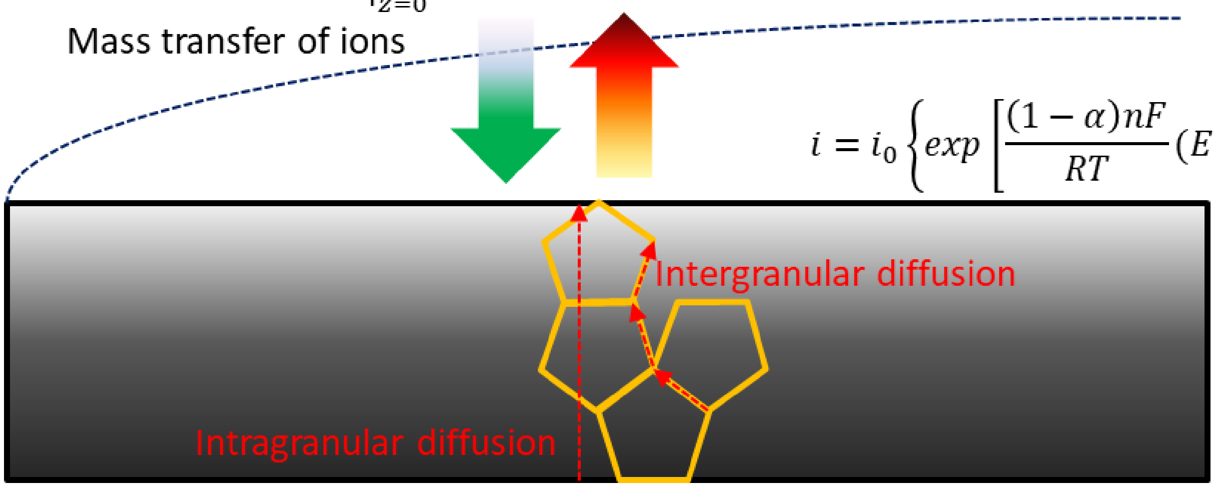
$$H^+ + e^- \rightarrow \frac{1}{2}H_2$$

④ *Oxygen gas is a strong oxidant in molten chloride salt*

$$O_2 + 2e^- \rightarrow O_2^{2-}$$
$$O_2^{2-} + 2e^- \rightarrow 2O^{2-}$$
$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Factor for kinetics of corrosion

$$J = -D\left.\frac{\partial C}{\partial z}\right|_{z=0} = K_m(C_s - C_{bulk}) \qquad K_m = \mathrm{f}(\mathrm{Re}, \mathrm{Sc}, x^*)$$



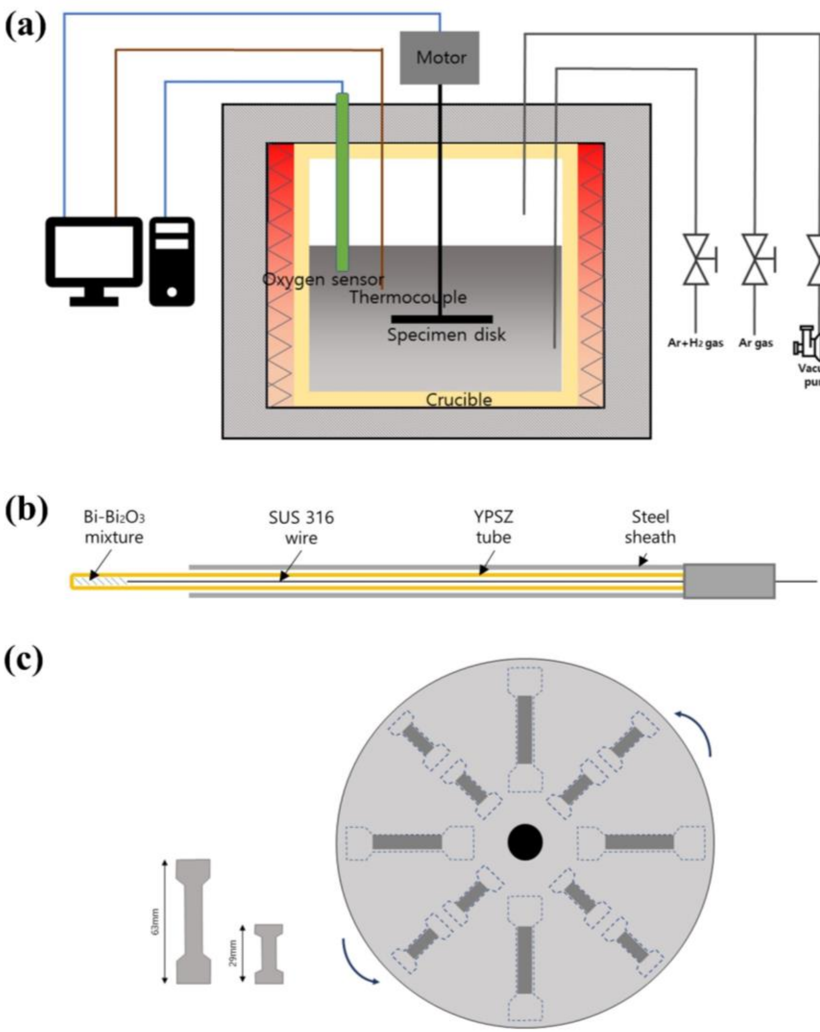
$$i = i_0\left\{exp\left[\frac{(1-\alpha)nF}{RT}(E - E_{eq})\right] - exp\left(-\frac{\alpha nF}{RT}(E - E_{eq})\right)\right\}$$

Current density for a given potential of an electrode reaction

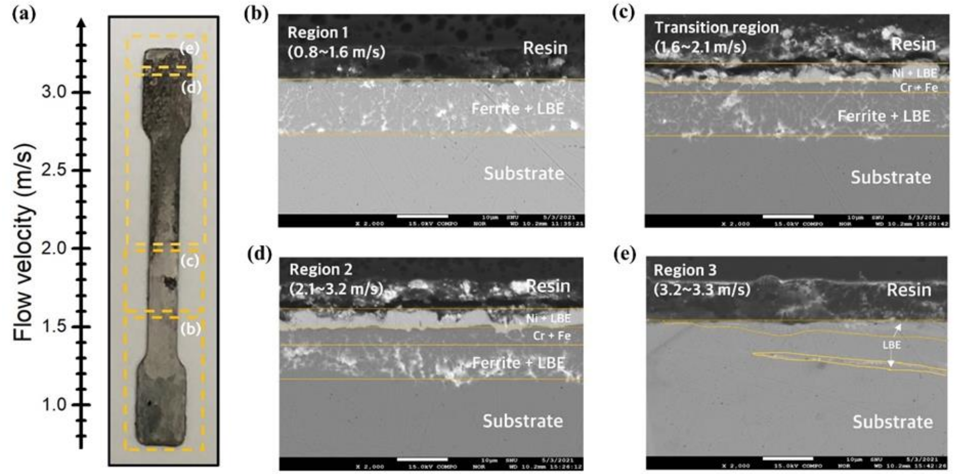
Corrosion rate is controlled by reaction rate, solid-diffusion, and mass transfer across the fluid boundary layer.

Because of its complexity, it is best addressed by experimental investigation.

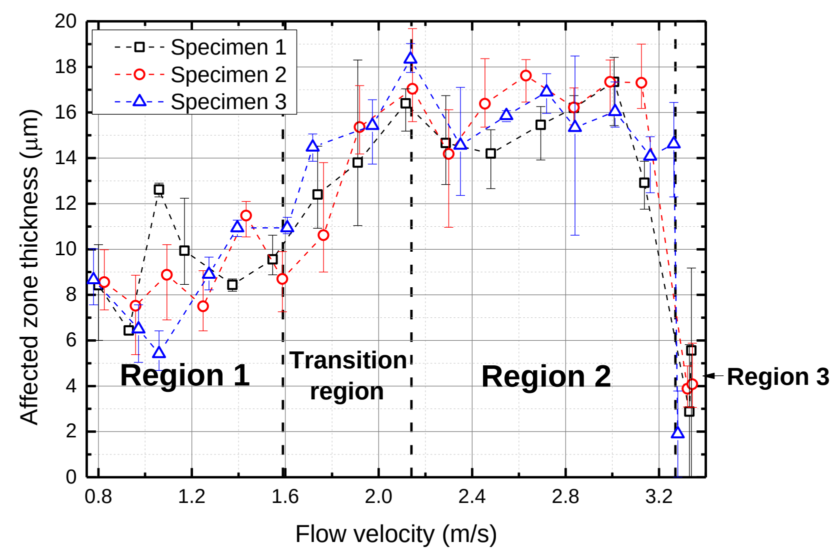
Flow accelerated corrosion in LBE at SNU Fuel Materials and Safety Lab



Schematic drawing of (a) whole experiment apparatus, (b) oxygen sensor, (c) specimens and specimen holder

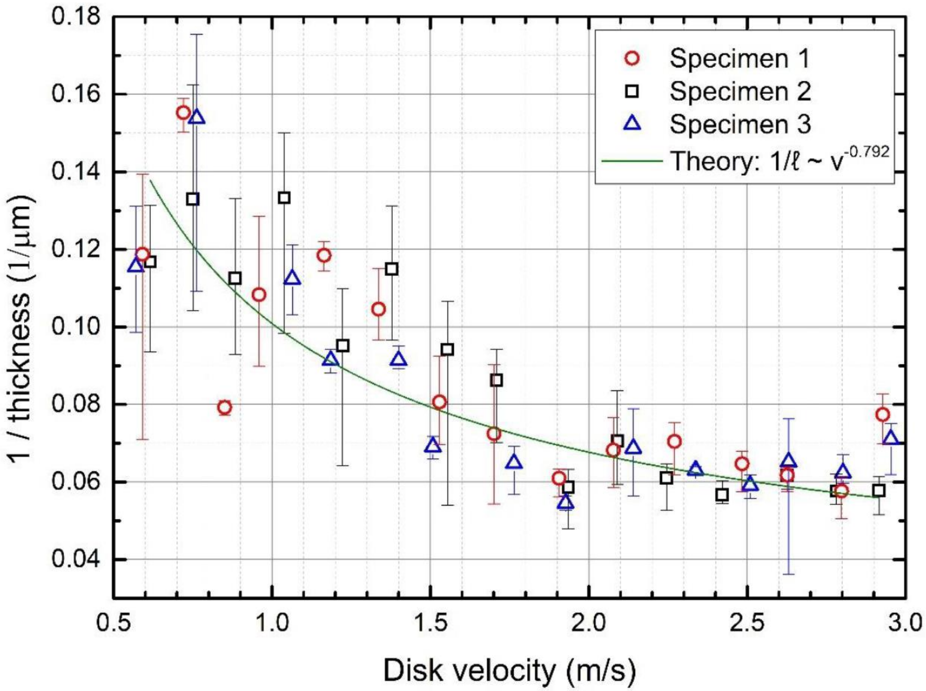


(a) Image of post-experiment specimen, and SEM images of (b) region 1, (c) transition region, (d) region 2, (e) region 3.



Affected zone thickness measured through EPMA line scan following flow velocity, and differentiation of corrosion regions according to thickness changes

Flow velocity dependent LBE corrosion



Reciprocal of affected zone thickness with respect to flow velocity ($\frac{1}{l} = a' + b'v^{-0.792}$, a' = 0.02223, b' = 0.07869, R-square = 0.69).

Flow-dependent corrosion rate modeling

$$J_{diss} = k_d(S_M - C_M^w)$$

$$J_{diff} = -D_M \frac{\partial C_M}{\partial y}\bigg|_{y=0\ (wall)} = K_m(C_M^w - C_M^b)$$

$$J_{diss} = \frac{1}{A}\frac{dm_M}{dt} = \frac{K_m k_d}{K_m + k_d}(S_M - C_M^b) = R\,(S_M - C_M^b)$$

$$Sh = \frac{K_m r}{D_M} = CRe_\omega^{0.896}\,Sc^{0.249}$$

$$\frac{1}{J_{diss}} = \frac{1}{\frac{K_m c_1}{K_m + c_1}c_2} = \frac{1}{\frac{c_4 v^{0.792} c_1}{c_4 v^{0.792} + c_1}c_2} = a + bv^{-0.792}$$

$$\mathrm{A}\int_0^t J_{diss}dt = \int_{m_{M,initial}}^{m_{M,final}} dm_M \approx \rho A \int_0^l dl$$

$$J_{diss}At = \Delta m_M \approx \rho A l$$

$$\frac{1}{l} \approx a' + b'v^{-0.792}$$

Historical development of corrosion resistant alloys for MSRs

Late 1940s: Aircraft Nuclear Propulsion (ANP) Program

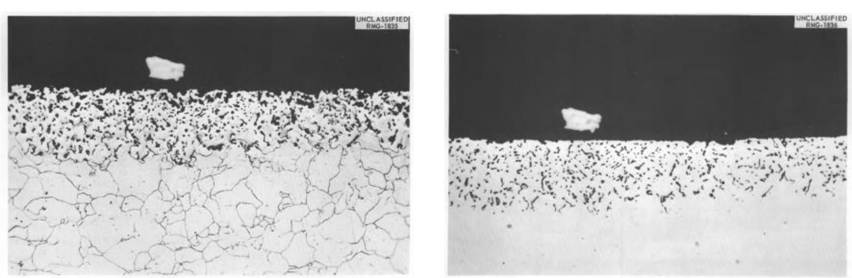
- Pure Mo-Ni: Outstanding corrosion performance. Poor physical properties and fabrication difficulties

- Hastelloy B (Ni-28Mo-5Fe) and Hastelloy W (Ni-25Mo-5Cr-5Fe) were satisfactory, but became brittle due to the formation of Ni-Mo intermetallic compounds.

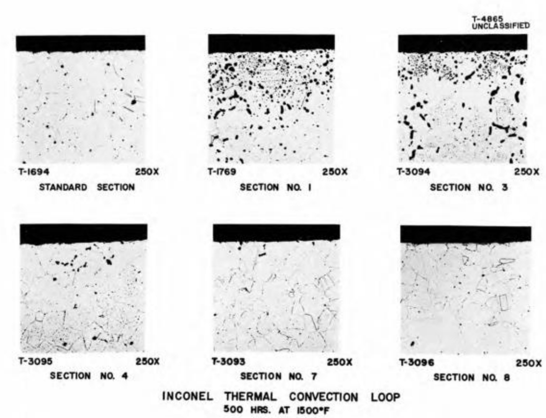
1954: Aircraft Reactor Experiment (ARE) – 2.5MW reactor with NaF–ZrF_4-UF_4

- Inconel 600 (Ni-15Cr-7Fe) operated successfully for nine days at ~900℃ without a problem. Post operative examination showed a depth of corrosion attack up to ~100μm

- ~120-180 μm at 1000h, ~350 μm at 3000h, ~630 μm at 8300h at ~870 ℃ in the subsequent loop experiments



Cottrell WB eta l.,. Disassembly and postoperative examination of the aircraft reactor experiment, ORNL-1868. Oak Ridge, TN, USA:Oak Ridge National Laboratory; 1958.

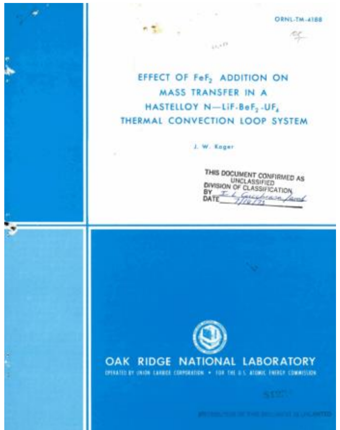


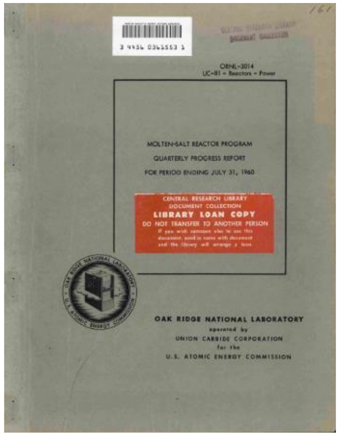
Manly WD,, et al. Aircraft reactor experiment – metallurgical aspects, ORNL-2349. Oak Ridge, TN, USA: Oak Ridge National Laboratory; 1957.

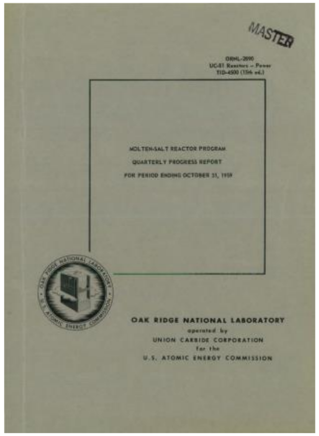
Historical development of corrosion resistant alloys for MSRs

Extensive loop tests during 1958-1964:

- Extensive tests conducted to examine the corrosion resistance of Hastelloy N (Ni-16Mo-7Cr-4.5Fe) and Incoloy 600 in flowing $^{7}LiF - BeF_2$ at ~700℃ up to one year.
- Velocity: 0.006 to 0.025 m/s (natural convection) and 2.3-5 m/s (forced convection)
- Hastelloy-N backgrounds: compared to Hastelloy B and W, the Mo content was reduced to 15-17 wt% to preclude the aging embrittlement. 6-8 wt% Cr is necessary to provide sufficient resistance to air oxidation.
- The corrosion resistance of Inconel 600 is found inadequate considering the 40 year service
- Hastelloy-N showed little corrosion attack with smaller corrosion depths ($\leq 51\mu m$)



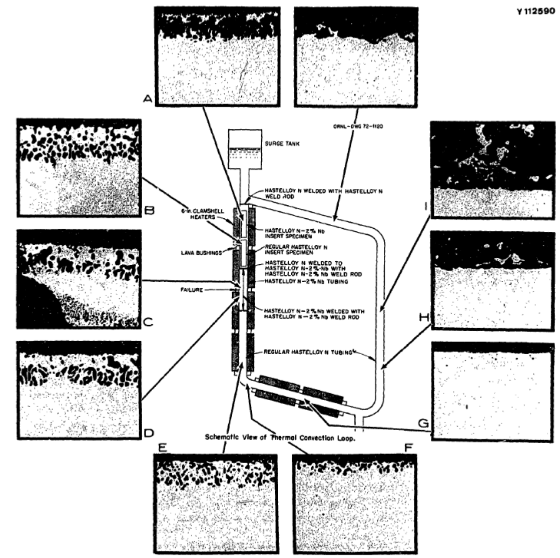




Historical development of corrosion resistant alloys for MSRs

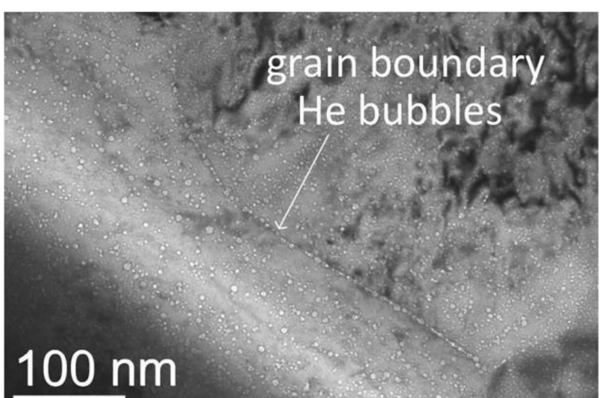
MSRE during 1965-1969: "Limitations of Hastelloy-N"

- All metal components exposed to the molten salt were made of Hastelloy N. Corrosion of Hastelloy N was found acceptable.
- Hastelloy-N thermal convection loop operated with MSRE fuel at maximum temperature of 704℃ for 9.2 years- corrosion depth less than 76 μm .
- Two main problems of Hastelloy N were discovered:
  ① Irradiation embrittlement,
  ② tellurium induced intergranular cracking

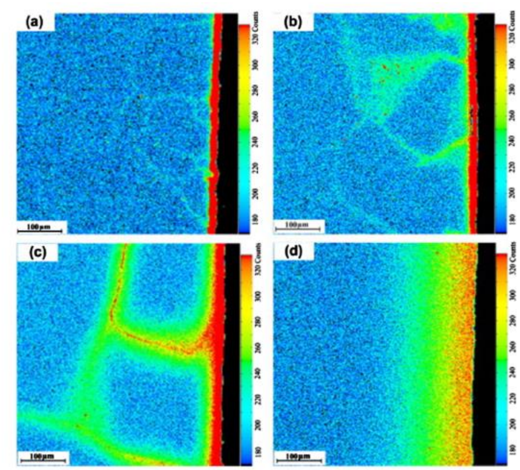


[ORNL-TM-4189.1972]

$$^{58}Ni + n \rightarrow {}^{59}Ni$$
$$^{59}Ni + n \rightarrow {}^{4}He + {}^{56}Fe$$



[Materials Science and Technology, 33,518-536, 2016]



Distribution of Te for the Ni sample annealed at (a) 700℃ (b) 800℃ (c) 900℃ (d) 1000℃
[Journal of Nuclear Materials,441,372-9, 2013]

Historical development of corrosion resistant alloys for MSRs

1970s: Modified Ni-based alloy development- Ti/Nb added Hastelloy-N

- Fine and dispersed carbides are formed within the grain matrix which trap the helium and prevented its migration to the grain boundaries.

- 1 to 2% Nb improved the resistance to Te-induced IGC.

- Understanding of the importance of the Cr and Fe contents :
  Stainless steels and nickel-based alloys with more than 20wt% Cr are considered inadequate for MSRs although they may exhibit improved resistance to Te-induced IGC

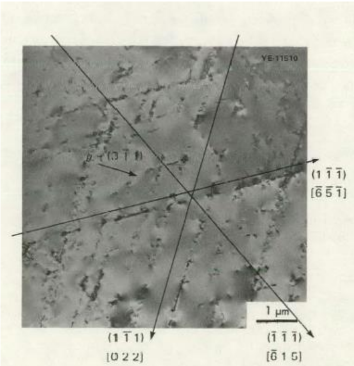


Fig. 18. Unstressed portion of 1%-Nb-modified Hastelloy N solution annealed at 650°C for 1175 hr. Original magnification: 25,000×.

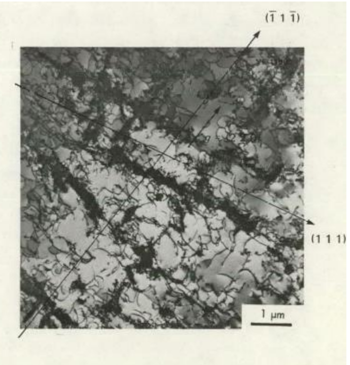


Fig. 19. Specimen of 1%-Nb-modified Hastelloy N solution annealed and stressed at 40,000 psi and 650°C for 1175 hr. Original magnification: 25,000×.

[ORNL/TM-5920, 1978]

Table 9. Compositions of test alloys

	Ni	Cr	Fe	Mo	Cu	Al	Nb	Mn
Monel	65				35			
Hastelloy N	~70	7	5	16				
Inconel 600	~75	15	7					
Inconel 606	~70	20	2				2	3
Inconel 601	~60	23	14			1		
Inconel 690	~50	30	15					
Incoloy 811E	~30	21	47					

Table 10. Weight changes of alloys exposed to LiF-BeF$_2$-ThF$_4$-UF$_4$ (68-20-11.7-0.3 mole %) at 690°C for 2776 hr

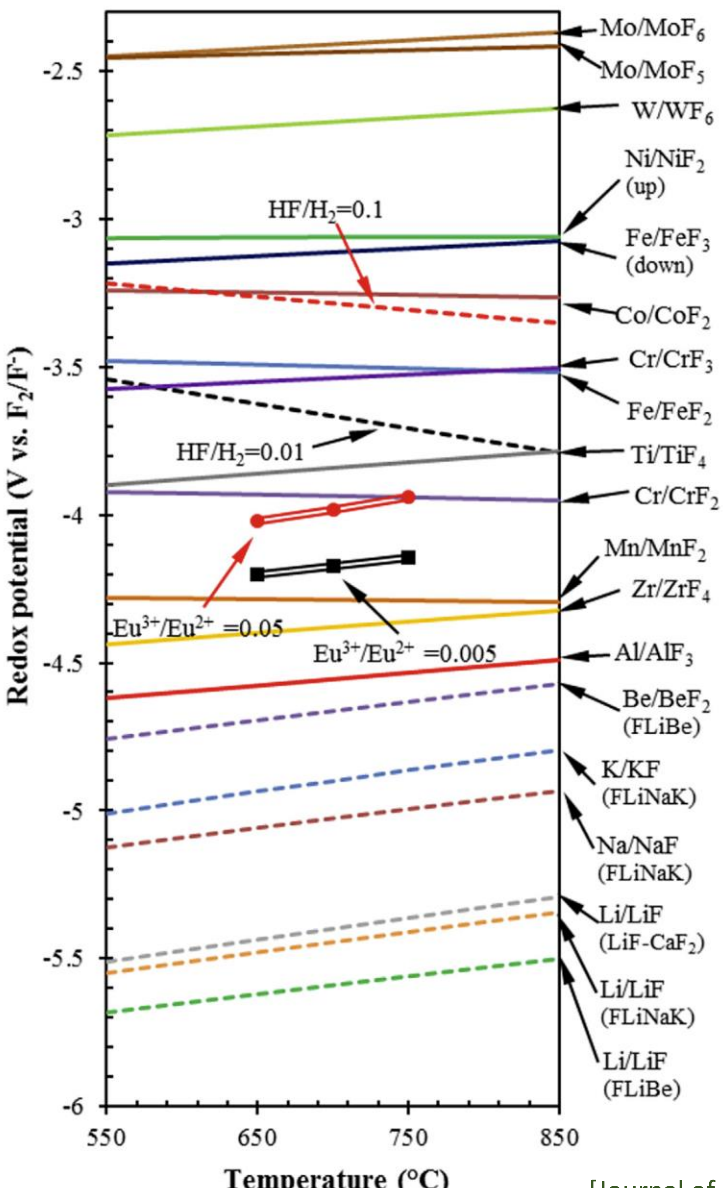
Alloy	Chromium content (%)	Iron content (%)	Total active alloying constituents[a] (%)	Weight change (mg/cm^2)
Monel	0	1	2	+0.78
Hastelloy N	7	5	14	−0.15
Inconel 600	15	7	25	−0.49
Inconel 606	20	2	27	−6.6
Inconel 601	23	14	38	−16.0
Inconel 690	30	15	45	−55.5
Incoloy 811E	21	47	70	−116.7

[a]Constituents that tend to form rather stable fluorides. All corrosion specimens were annealed 1 hr at 1121°C except Monel, which was annealed 1 hr at 800°C.

20wt% Cr is the limit

[ORNL/TM-4286, 1972]

Importance of redox control



[Journal of Nuclear Materials 496 (2017) 197-206]

Today's MSR materials

Rule of thumbs (key lessons learned from the past):

- ① Don't go above 20wt% Cr

  ② Add small Ti and Nb to avoid Te-IGC and Irradiation embrittlement

  ③ *Classic Hastelloy-N may need to be avoided*

Codified in AMSE section III Division 5 (Incoloy 800H, SS 316L)

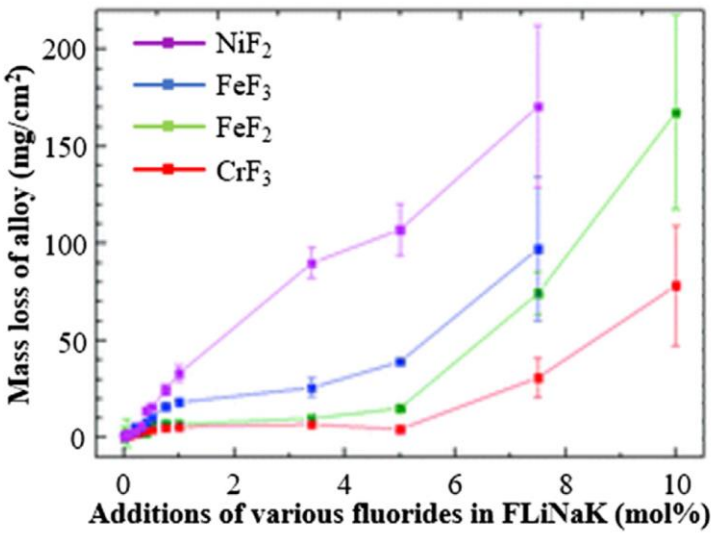
Base of MOSART (HN80MT)

	Hastelloy-N	Hastelloy N Ti-mod	Hastelloy N Nb-mod	HN80MT	HN80M-VI	HN80MTY	Incoloy 800H	SS 316L
Ni	Base	Base	Base	Base	Base	Base	30.0-35.0	10.0-14.0
Mo	16-17	11-14	11-13	12.1	12.2	13.2	-	2.0-3.0
Cr	7.1	6-8	6-8	7.02	7.61	6.81	19.3-23.0	16-18.0
Fe	4-5	0.1	0.1	<0.33	0.28	0.15	39.5 (Max)	Balance
Mn	0.55	0.15-0.25	0.15-0.25	<0.1	0.22	0.013	-	2.00
Ti	<0.01	0.5-2	-	1.72	0.001	0.93	0.15-0.60	-
Nb	-	0-2	1-2	-	1.48	0.01	-	-
Al	0.03	-	-	-	0.038	1.12	-	-
Si	0.57	0.1	0.1	<0.05	0.04	0.04	0.15-0.60	0.75
W	0.14	-	-	-	0.21	0.072	-	-
Co	0.03	-	-	-	0.003	0.003	-	-
Cu	-	-	-	<0.01	0.12	0.02	-	-
C	0.06	0.05	0.05	0.004	0.02	0.025	0.1	0.03

Today's MSR materials: performance of a codified materials- Incoloy 800H

Unacceptably poor performance of bare Incoloy 800H

- The high Cr content ($\geq 20wt\%$) *undesirably increases corrosion rate.*



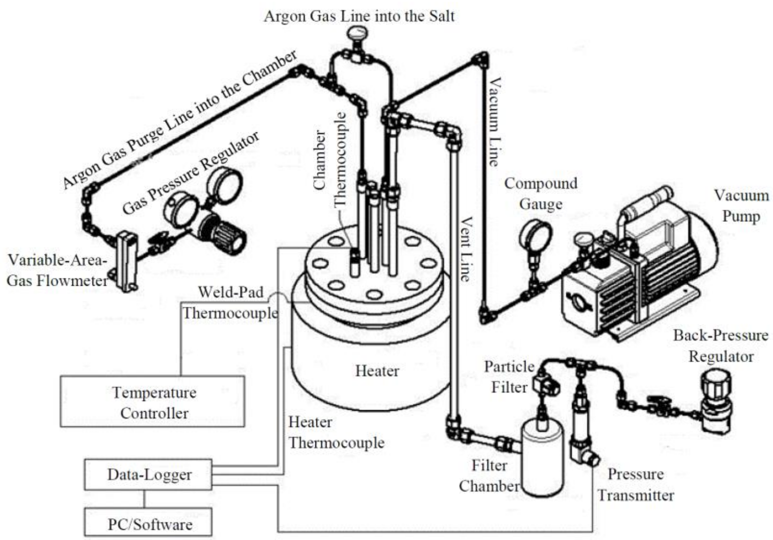
Mass loss of Incoloy 800H/HT in additions of various fluorides. Test duration: 8h; Temperature: 650℃
[Progress in Materials Science 97 448-487(2018)]

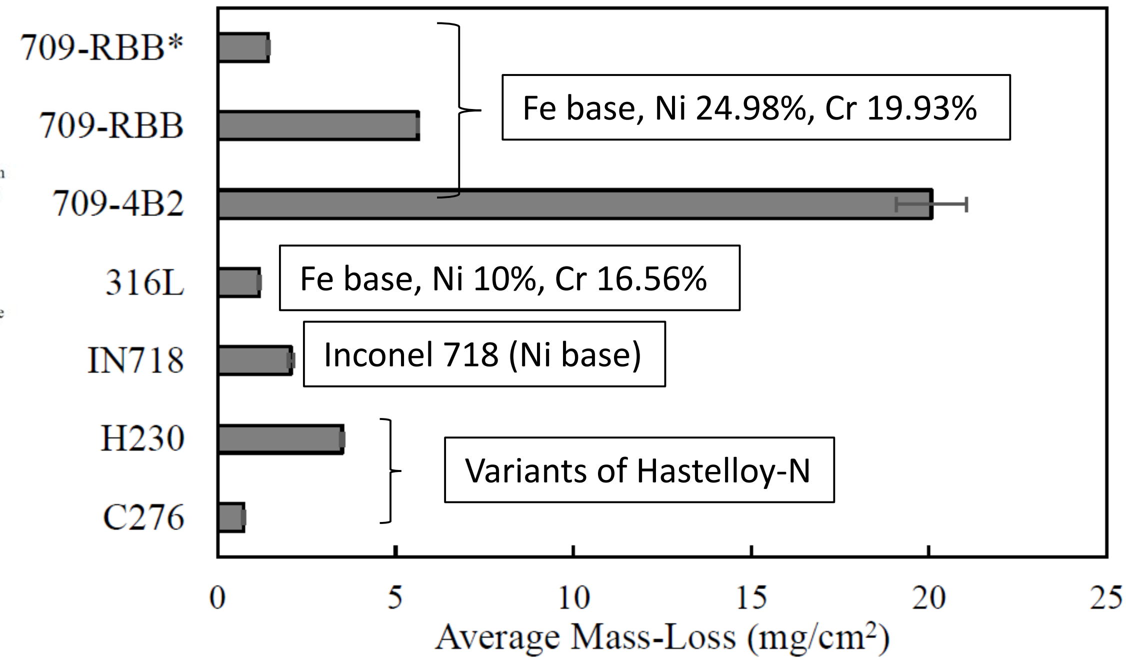
	Container	Temp (℃)	Time (h)	Corrosion rate ($\mu m/year$)
Incoloy 800H	Ni	850	500	727.2
Hastelloy N	Ni	850	500	15.8
Cr	Ni	700	500	1027.5$\pm$120.0

Corrosion of materials in contact with dissimilar materials in molten FLiNaK
[Progress in Materials Science 97 448-487(2018)]

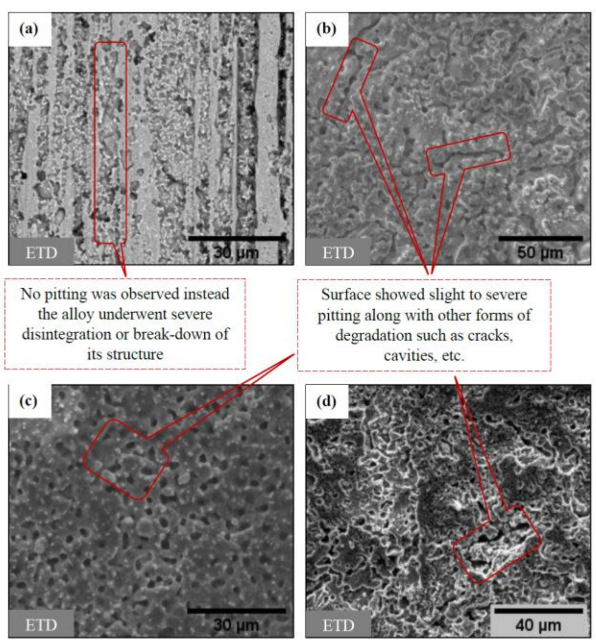
Today's MSR materials: performance of a codified materials- SS 316L

Recent movements to revisit the performance of 316L





Average mass-loss (mg/cm^2) in nickel and ferrous-based alloys after exposure to KCl-$MgCl_2$-NaCl salt at 800°C for 100 hours. [Brendan D'Souza, Ph.D thesis, Virginia Tech 2021]



Some MSR developers have selected SS316 as a construction material for their first-to-market strategy.

SEM characterization of (a) SS316L (b) 709-4B2 (c) 709-RBB, and (d) 709-RBB* after exposure to KCl-$MgCl_2$-NaCl salt at 800°C for 100 hours.

ASME codification status for Ni-based alloy

Qualification of a material for use in the ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Facility Components," Division 5, "High Temperature Reactors," will facilitate licensing with the Nuclear Regulatory Commission. Hastelloy N has not been qualified for use in nuclear construction, and significant additional characterization would be required for Code qualification. Given that this alloy is susceptible to He embrittlement and has limited high-temperature strength, it is not recommended that Code qualification be pursued. Instead, it is recommended that a systematic development program be initiated to develop new nickel alloys that contain a fine, stable dispersion of intermetallic particles to trap He at the interface between the matrix and particle and with increased solid solution strengthening from addition of refractory elements. Extensive screening of attractive alloy compositions for elevated temperature strength, microstructural stability, weldability, and resistance to He embrittlement (characterized using ion implantation) will lead to an alloy down-selection for commercialization and Code qualification.

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

MSR이 NRC의 인허가를 통과하기 위해서는 구조재료의 ASME Section 3 Division 5 (High Temperature Reactors)통과가 필요함.

기존의 Hastelloy N도 코드통과를 위해서는 상당량의 추가 실험이 필요한 상황임. 따라서 새로운 Nickel기반 합금개발을 추천함.

CONSIDERATIONS OF ALLOY N CODE EXTENSION FOR COMMERCIAL MOLTEN SALT REACTOR DEVELOPMENT AND DEPLOYMENT

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To achieve Code qualified design and construction of the MSR system, Alloy N is currently the most technically ready alloy for consideration. Its present Code qualification for non-nuclear applications provides a good foundation for an upgrade and extension to cover the desired nuclear applications. A considerable amount of materials property data for Alloy N already exist and can be leveraged for the Code upgrade and extension. In strategic planning, the existing data may be leveraged to satisfy the needs of near-term, first version MSR deployment before new alloys and Alloy N variants can be successfully developed, commercialized, and Code qualified.

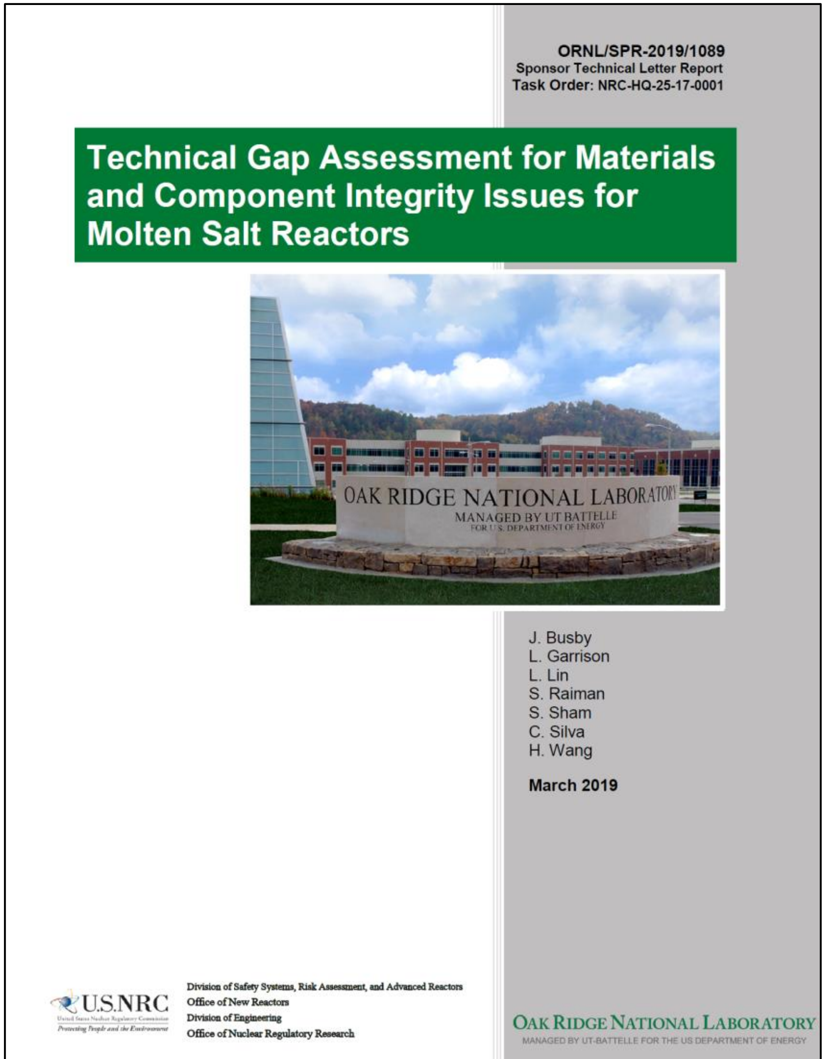
Collection and management of the historical data must be conducted following the established protocol for ASME Materials Properties Database that supports the ASME Codes and Standards development to ensure correct interpretation, understanding, and use of the information. Research should be conducted for gaps in the historical data to be identified and filled with generation of new data at earliest time possible.

Because Code qualification of an alloy for nuclear applications requires a large quantity of data that takes long time to generate, domestic and international collaboration may be pursued under the GIF umbrella to achieve cost- and time-efficiency.

기존의 실험 데이터를 활용하여 Hastelloy N의 빠른 코드통과를 지원하는 것을 주장함. 그러기 위해 부족한 데이터를 정확히 파악하는 연구가 중요하다 함. Hastelloy N의 경우도 10년은 족히 소요될 것으로 예상됨.

새로운 Ni 합금 및 Hastelloy N variant 개발을 위해서는 많은 시간이 필요한 만큼 GIF등을 통한 국제협력의 필요성을 언급함.

ASME codification status for Ni-based alloy



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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L. Garrison
L. Lin
S. Raiman
S. Sham
C. Silva
H. Wang

March 2019

U.S.NRC
Division of Safety Systems, Risk Assessment, and Advanced Reactors
Office of New Reactors
Division of Engineering
Office of Nuclear Regulatory Research

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

- MSRE showed acceptable compatibility of highly pure fluoride salts with Hastelloy-N, but data acquired under other conditions are scattered and not well controlled.
- Data on materials in chloride salts are especially limited.
- There is a need for rate modeling to predict lifetimes of salt-facing materials.
- There is a significant lack of quality irradiation data for many of the metals, including Hastelloy-N. The selection of any material for an MSR must consider the combined effects of irradiation and corrosion, for which there are very limited data for any of the materials under consideration.
- A strategy of cladding corrosion-resistant materials on salt-wetting surfaces of MSR components constructed of qualified materials is considered in nth-of-a-kind MSR systems. Yet, not much research has been conducted (Tensile strength, Creep, Fatigue, Corrosion, Weldments).

제 2장

결론 및 제언

MSR 구조재료 연구개발 동향

Codified Ferrous Alloy 연구
- SS316L과 같은 Codified된 재료가 쓰일 수 있는 MSR 환경 및 컴포넌트 연구
- 1차측의 특정 부분 (예: 저온, 저유속 구간) 에서는 SS 316L가 사용될 수 있을 것으로 사료됨. 최근의 SS 316L이 Chloride환경에서 괜찮은 부식저항성을 보고하는 연구결과가 발표되고 있음.

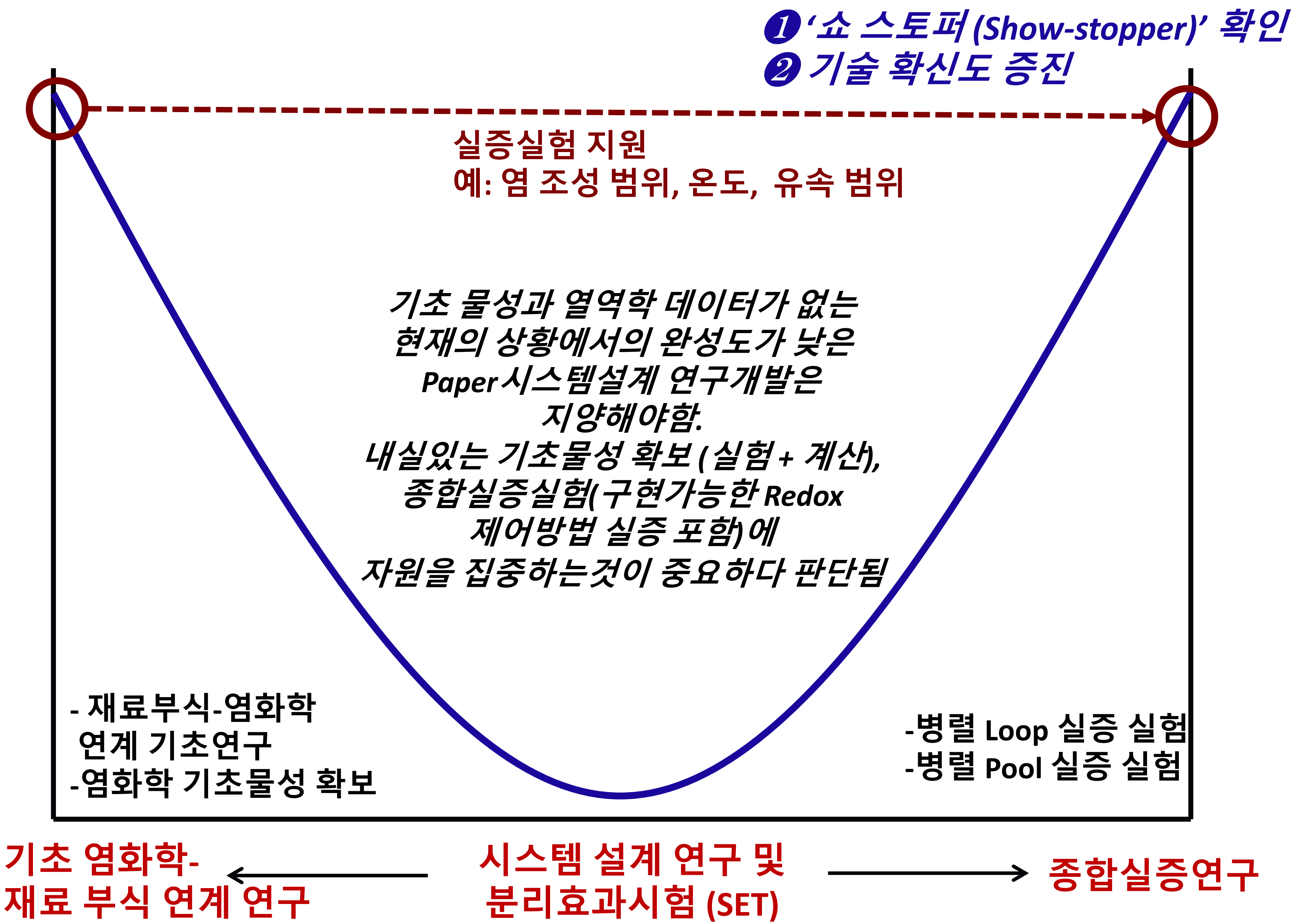
Codified Alloy + Corrosion resistant material weld-overlay 연구 (근시일 대안)

- Codified ferrous 및 Ni alloy에 표면에 코팅을 적용하는 연구
- ASME에서도 clad 합금의 평가 방법 및 설계기준 확립 필요를 언급
- SS316/Incoloy 800H, Ni-201/Incoloy 800H, Hastelloy-N/SS316 등을 아우르는 Bi-Metallic Alloy 연구를 추진해볼 필요가 있음

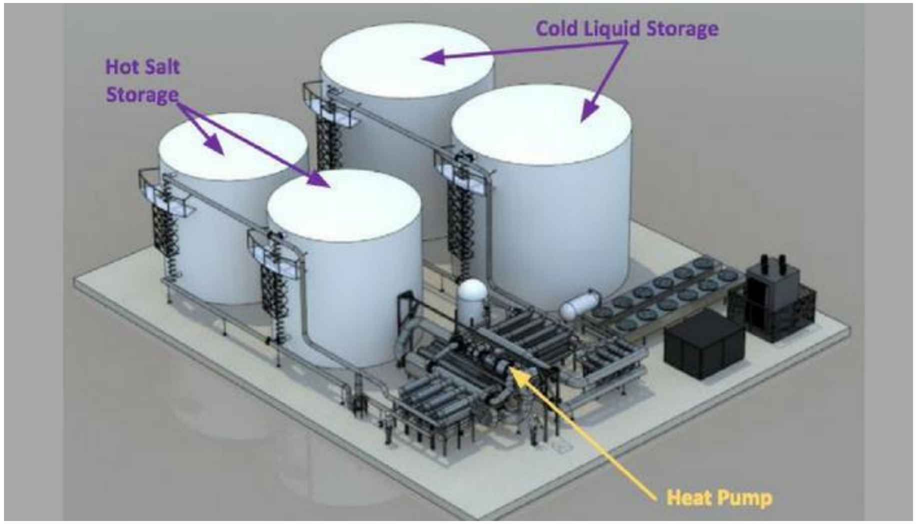
Ni-based Alloy ASME codification 연구 [국제협력]
- 국제 협력을 통해 진행하는것이 바람직 (The Generation 4 International Forum등)
- Hastelloy-N 방사선 조사가 상대적으로 덜 한 component등에는 선택적으로 활용될 가능성 있음 (T<700℃)
- 펌프의 임펠러, 노심 중앙 부분 컴포넌트등에는 신형 Ni-based alloy나 Hastelloy-N variant가 필요하다는 것이 중론

Redox potential 제어 연구
- MSR환경에서 Redox potential 기초 열역학 데이터 구축 연구
- 구현 가능한 Redox potential 제어시스템 설계 연구

제언: 기초 염화학-재료부식 연계 연구와 실증실험 중점 초기 연구



제언: 용융염 파생기술 개발 (용융염 열저장)



- 단기간의 기술개발을 통해 활용할 수 있는 용융염 열 저장 기술개발 등을 아우르는 과제를 기획하여 기업의 적극적 참여를 유도.
- 비원자력 분야의 국내외 용융염/구조재료부식 전문가 참여를 진작시켜 연구 기반확충.
- 경수로 시스템 – 용융염 열저장 연계 시스템 개념 설계 지원 등을 통하여 국내 원자력 연구인력 참여확대.

제언: 법 및 정책지원 [미국의 신형원전 삼법]

노형에 대한 기술뿐만이 아니라 핵심연구시설 및 제도적 기반을 마련하는 기회가 되었으면 함.

NEICA [2018] The Nuclear Energy Innovation Capabilities Act

- U.S NRC에 비용분담 (Cost-share)을 강제하여 민간 사업자의 규제신청비용 절감
- 고속로 개발을 위한 고속중성자 재료실험 장치 지원 (VTR)
- 신형원전 실증실험 지원
- 신형원전 컴퓨터 코드개발 지원

"기반 시설 구축 (Dream enabler)"

"차세대원자로 규제 지원"

"차세대원자로 고객 확보"

NEIMA [2019] The Nuclear Energy Innovation and Modernization Act

- 규제비용 투명성 및 예측가능성 제고
- 가동원전 규제비용 투입 제한
- 차세대 원자로 규제체계를 2027년까지 확립

NELA [2020] The Nuclear Energy Leadership Act

- 신형원자로에 관하여 미국 국방부 (DoD)가 첫번째 고객 (customer)가 되는것을 지원하는 법령
- 규제가 철폐된 에너지 시장에서 비록 가격경쟁력이 부족하여도 미국의 패권을 위해 신형원자로의 실증을 가능케하는 것을 주요 골자로 함
- 초소형 원자로를 주로 염두하고 있는 것으로 보여짐

경청해주셔 감사합니다.