SALT COMPOSITION, CORROSION, AND TRITIUM CONTROL IN THE KP-FHR

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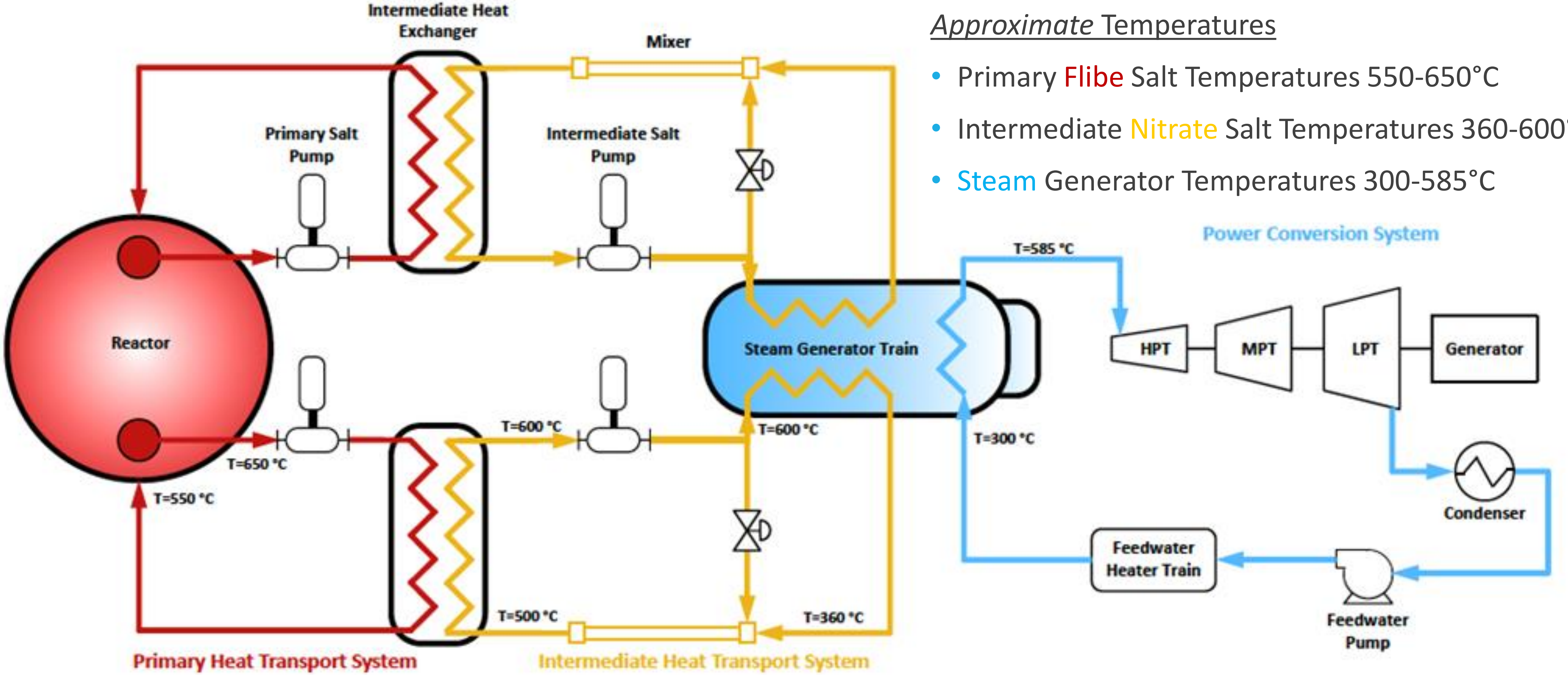
Kairos Power's mission is to enable the world's transition to clean energy, with the ultimate goal of dramatically improving people's quality of life while protecting the environment.

Outline

- Salt chemistry: Flibe
- Impurity effects on materials performance
- Corrosion Testing & Analysis Strategy
- Redox Control
- Materials for Tritium Management
- Summary

Kairos Power High Temperature Fluoride Cooled Reactor (KP-FHR)



Approximate Temperatures

- Primary Flibe Salt Temperatures 550-650°C
- Intermediate Nitrate Salt Temperatures 360-600°C
- Steam Generator Temperatures 300-585°C

Flibe Composition Guidelines

Allowable Impurities in Flibe

Impurity	MSRE General Specification Allowable Concentration[1] (wt.%)	Expected Kairos Power
Oxygen (Water)	0.1	≤
Cu	0.005	≤
Fe	0.01	≤
Ni	0.0025	≤
S	0.025	≤
Cr	0.0025	≈
Al	0.015	≤
Si	0.01	≤
B	0.0005	≤
Na	0.05	≈
Ca	0.01	≈
Mg	0.01	≈
K	0.01	≈
Li (natural)	0.005	≈
Zr (natural)	0.0025	≤
Cd	0.001	≤

[1]Shaffer, J.H. (1971). Preparation and Handling of Salt Mixtures for the Molten Salt Reactor Experiment, Oak Ridge National Laboratory.

Allowable Impurities in Flibe

- It may preferable to set an integrated limit on impurities
- Kairos Power is assessing controlling several corrosive impurities (table to the right) in total, i.e. $\Sigma_{\text{impurities}} < \#\#\#$ wt. ppm
- Many of these are dissolved fluorides that can result in chromium oxidation via:

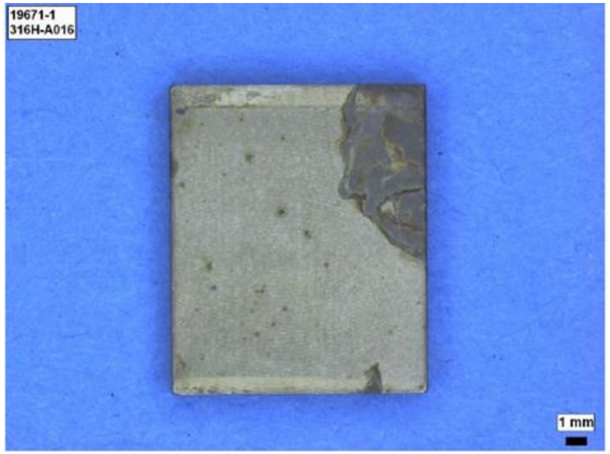
$$Cr + \frac{2}{x} MF_x \rightarrow CrF_2 + \frac{2}{x} M$$

Ag	Ge	P	Se
As	Hg*	Pb	Si
Au	I	Pd	Sn
B*	In	Po	Ta
	Ir	Pt	Tc
Cd*	Mo	Re	Te
Co	Nb	Rh	Tl
Cu	Ni	Ru	V
Fe		S	W
Ga	Os*	Sb	Zn
*These elements further limited by neutronics			

Corrosion & Redox Control

Initial Corrosion Testing (University of Wisconsin, FCL-0)

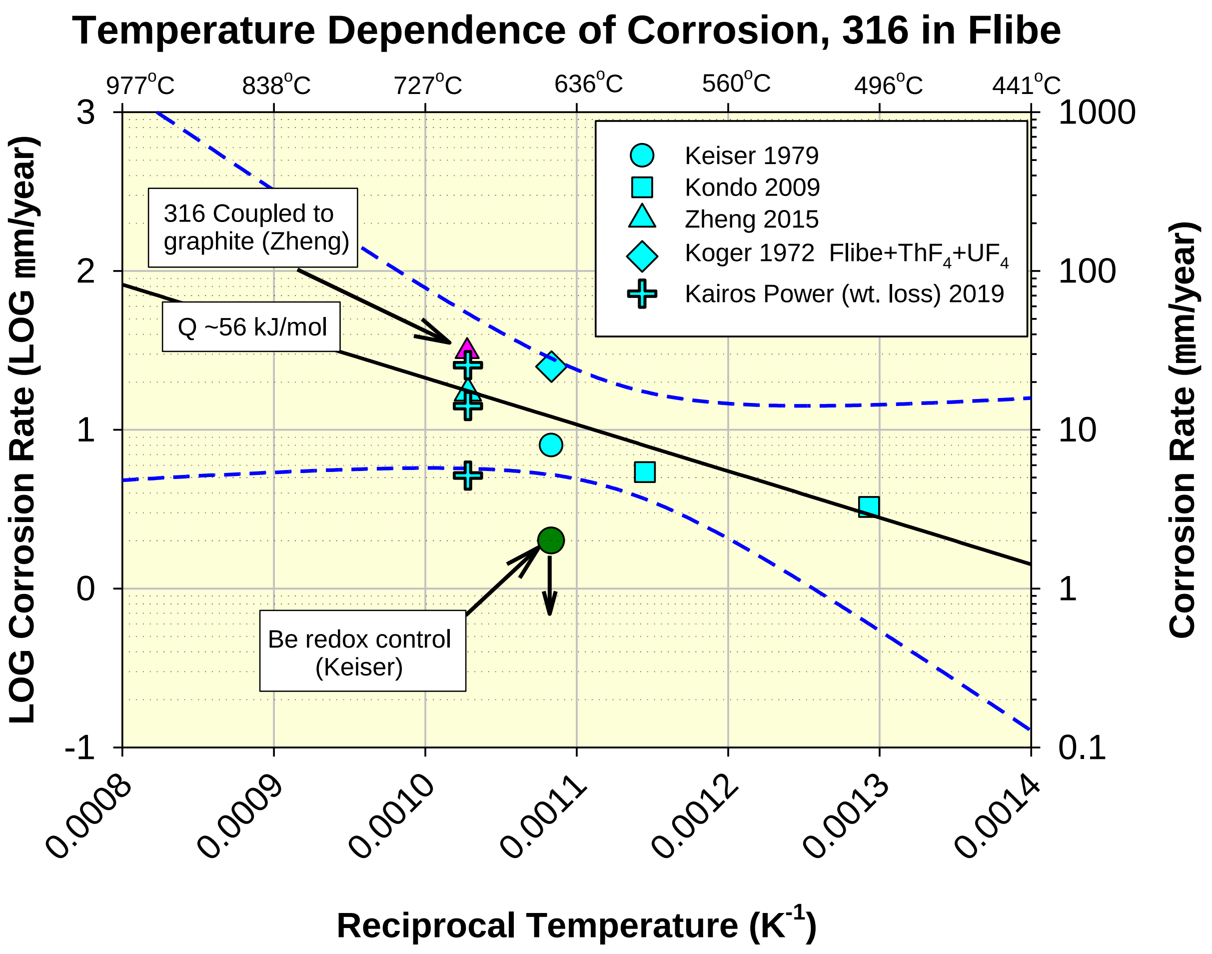
- Material: 0.5” thick, hot rolled 316H Plate (ASTM)
- Condition: Annealed at 1052°C (1925°F) min. and water quenched
- Machined coupons (0.58”x0.48”x0.0625”)
- Coupon orientation L-T
- Exposed 1000 hours / T = 700°C (hot), 650°C (cold), Flow = 2m/s



Initial Corrosion Data: 316, 700°C, Flibe, Flowing Loop (FCL-0)

- Sample shows Cr depletion rates consistent with the literature
  - Relatively impure salt
  - Not steady state corrosion rate
  - Rates based on weight change consistent with literature →

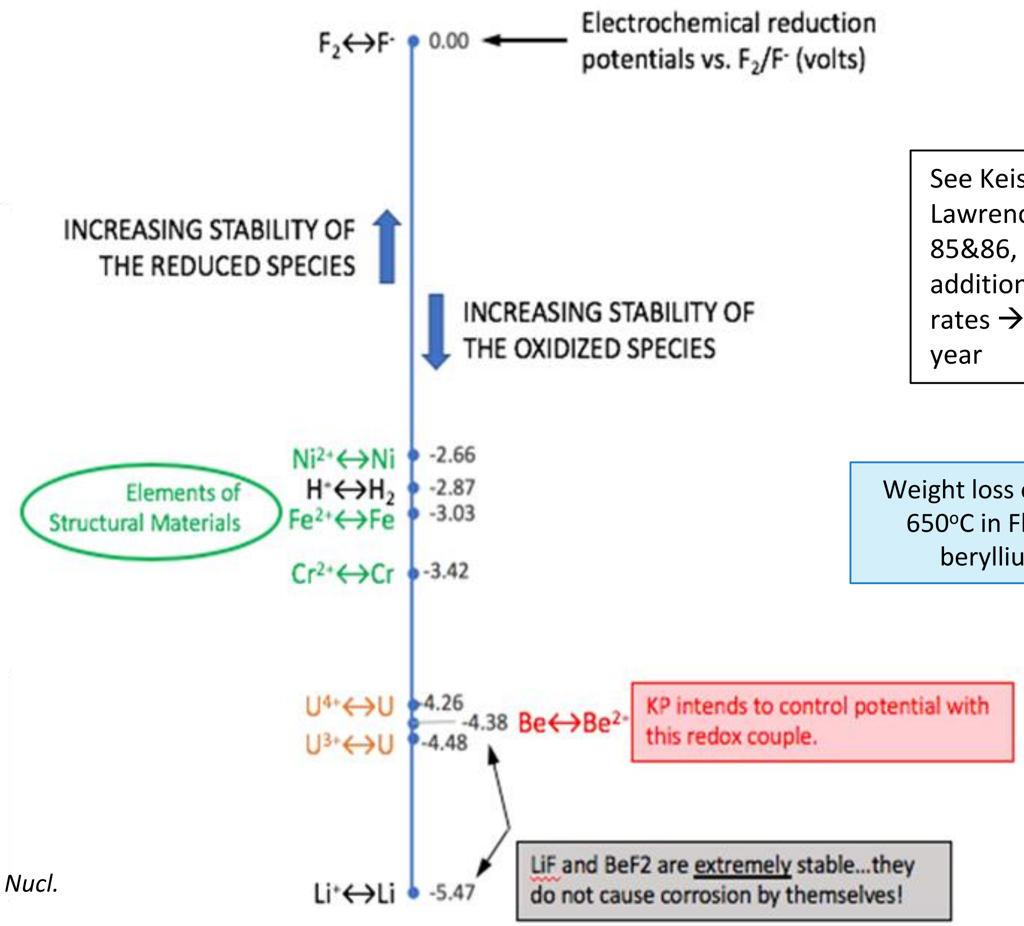
See Data of Zheng et al., JNM 2015, testing in 700°C Flibe – The Kairos data Are consistent with this study



Conceptual Overview – Flibe Chemistry Control

- The Flibe in KP-1 will be buffered by dissolved Be metal. The this method of corrosion protection was demonstrated in the MSRE program
- Beryllium will react with oxidants and impurities to protect structural alloys
  - $Be + oxidant = Be^{2+} + inert$
  - Ex: $Be + 2HF = BeF_2 + H_2$
- The concentration of Be in the Flibe will be controlled the KP-FHR chemistry control system, monitored by an electrochemical probe
- Maintaining a controlled concentration of dissolved Be will fix the redox potential of the Flibe and control the chemistry of radionuclides (tritium, activation products, etc.)

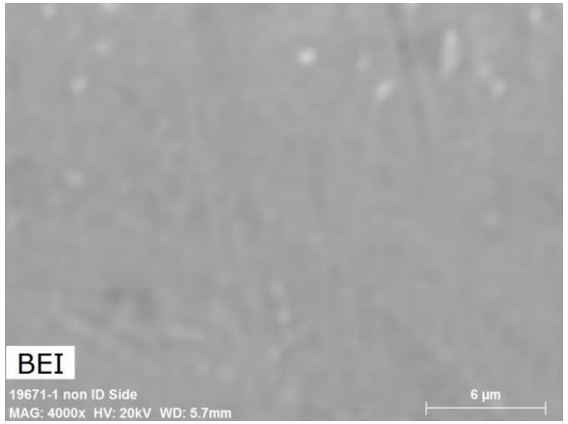
J.R. Kaiser, J.H. DeVan, E.J. Lawrence, “Compatibility of molten salts with type 316 stainless steel”, *J. Nucl. Mat.*, 85/86, 295-298.



See Keiser, DeVan, and Lawrence, JNM Vol. 85&86, 1979. With Be addition, 316 corrosion rates → < 2 microns per year

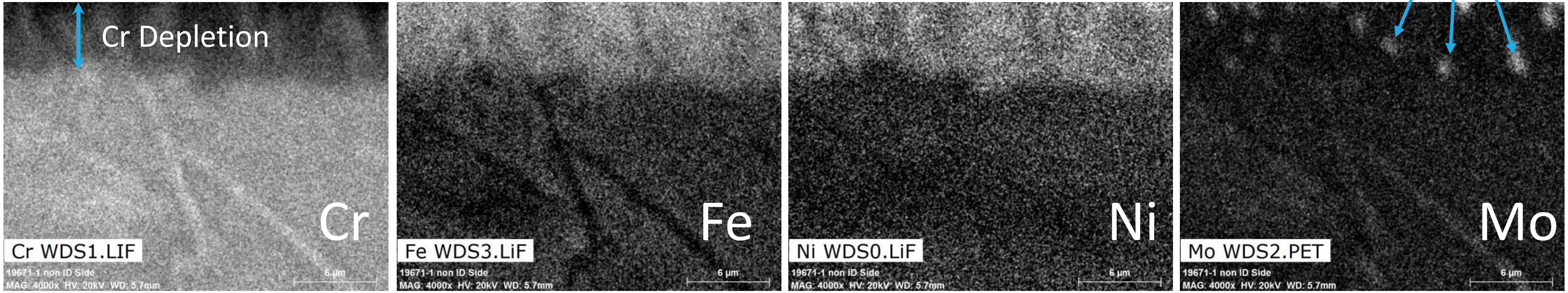
Weight loss of 316 stainless steel at 650^{o}C in Flibe with and without beryllium metal additions

Corrosion Coupon Characterization – WDS Mapping

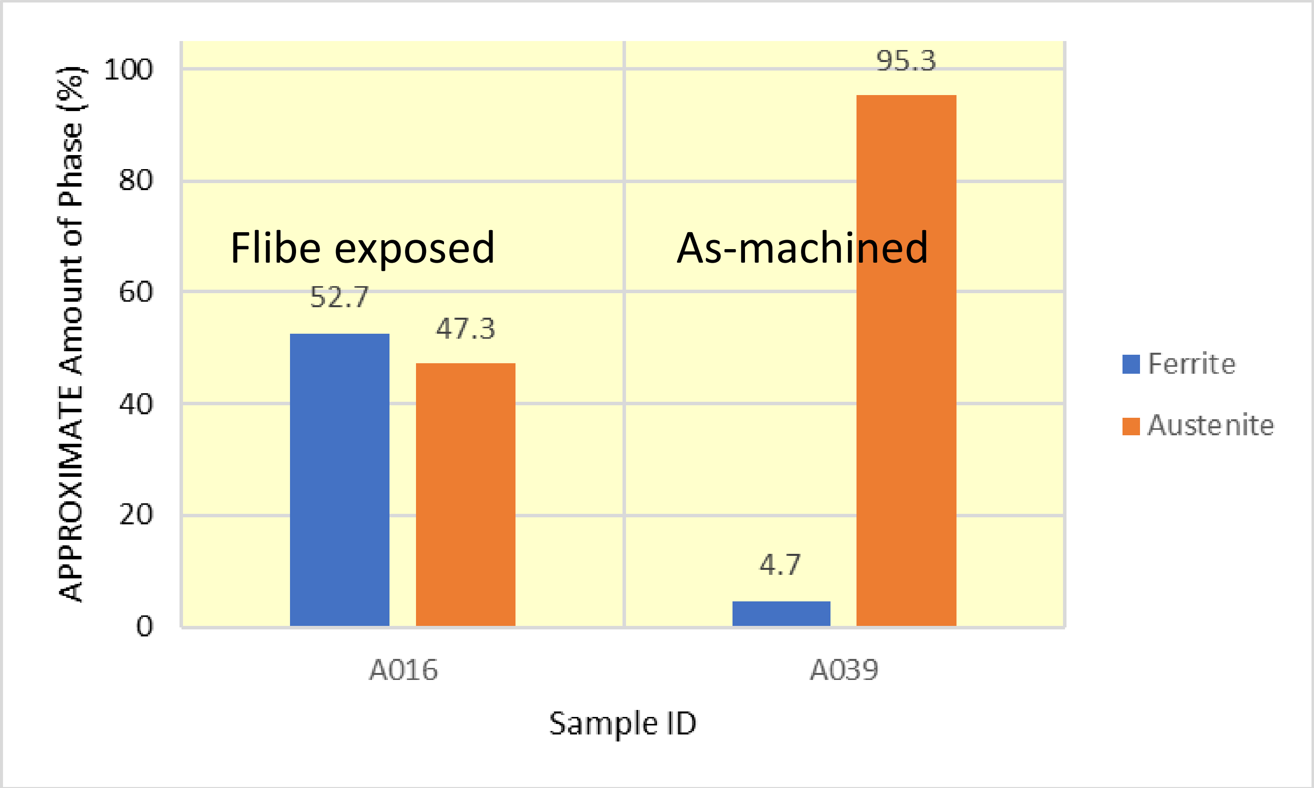


- Cr loss as expected
- But, uniform attack at 1000 hours, no IG penetration
- Mo rich phase present in corroded layer
- Cr loss likely a conservative corrosion metric

Mo rich Laves



Corrosion Analysis

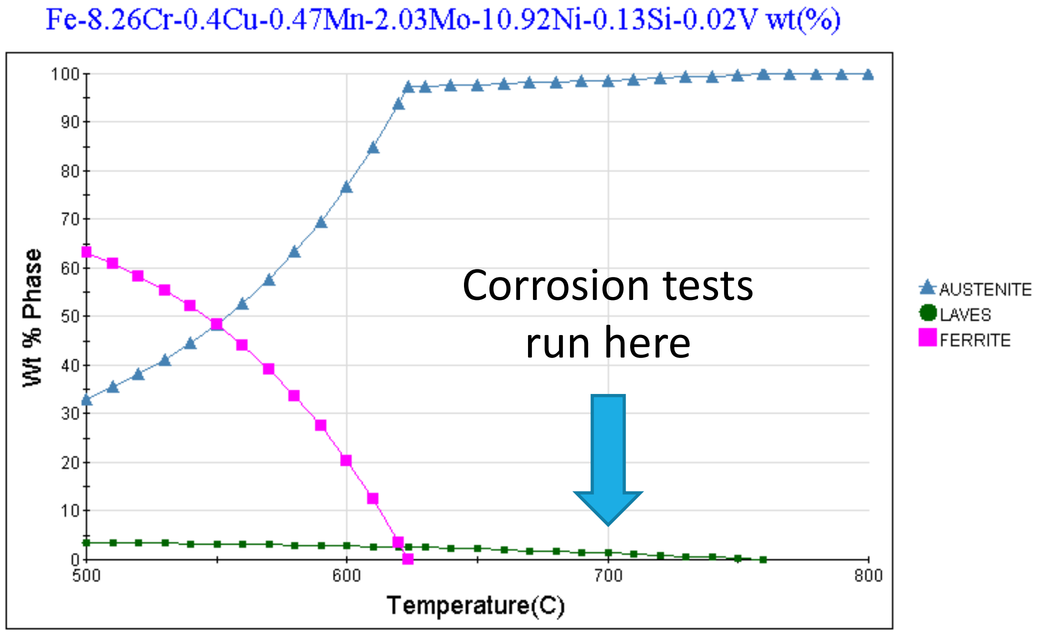


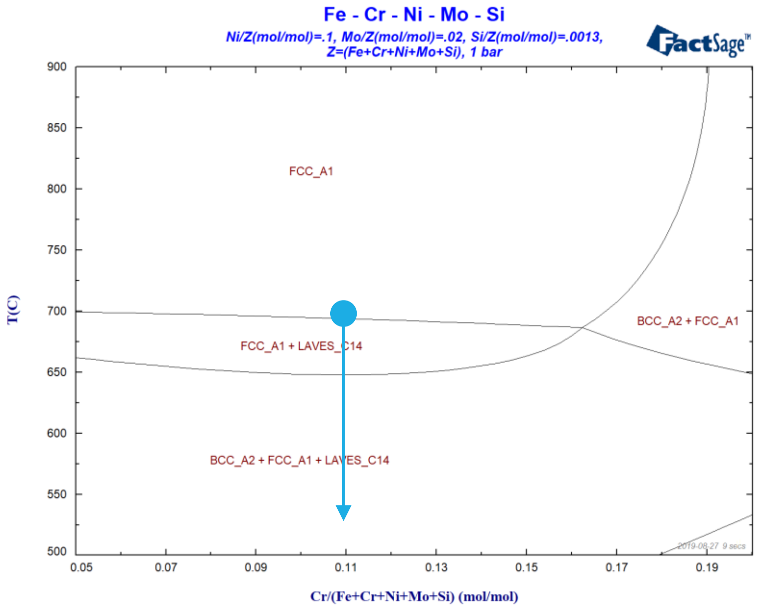
Zheng, G., et al. (2015). "Corrosion of 316 Stainless Steel in High Temperature Molten Li2BeF4 (FLiBe) Salt." Journal of Nuclear Materials 461: 143-150.

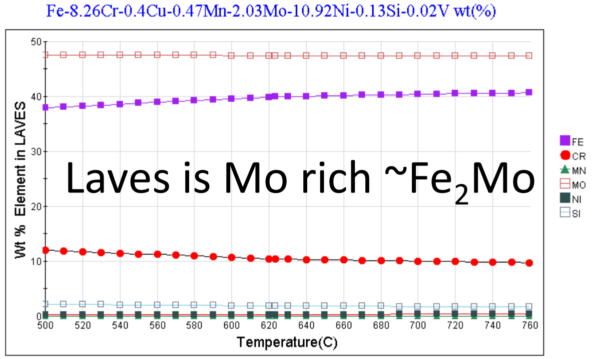
- XRD shows notably higher ferrite on the Flibe exposed corrosion surface
- Zheng et al. (Wisconsin) also reported high ferrite in 316 exposed to Flibe (700°C/3000 hours), attributed to the 'corrosion environment'
- How do you lose a ferrite stabilizer (Cr) and form more ferrite? → computational thermodynamics

Phase Predictions from Corroded Layer

- Thermodynamic modelling of corrosion layer composition via JMatPro and FactSage Fe-10.92Ni-8.26Cr-2.03Mo-0.47Mn-0.40Cu-0.13Si-0.02V
- Key points
  - At 700°C, austenite is stable, ferrite likely forms on cooling
  - 2 phase region below about

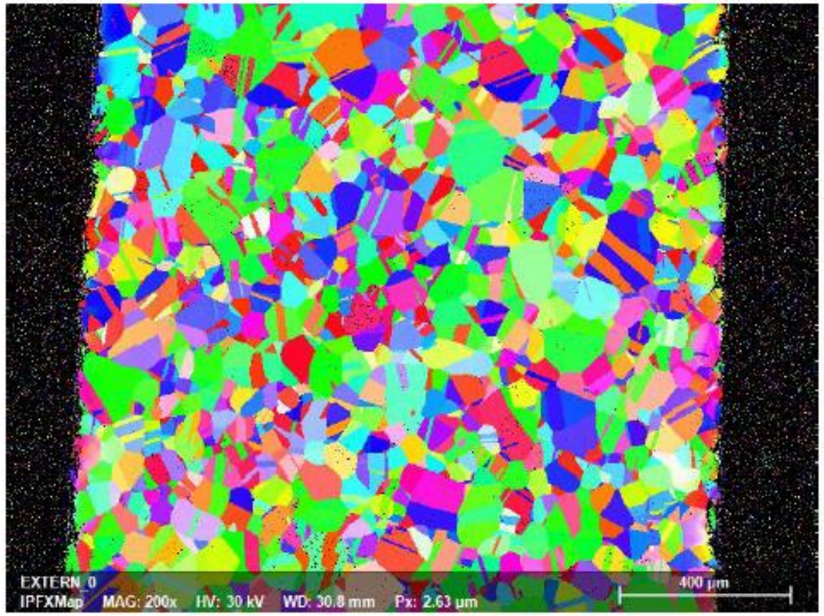


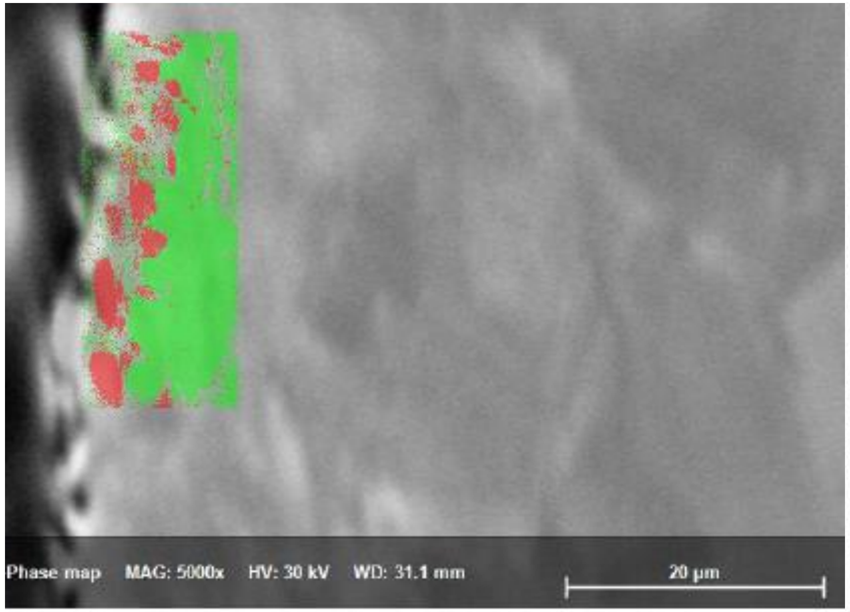


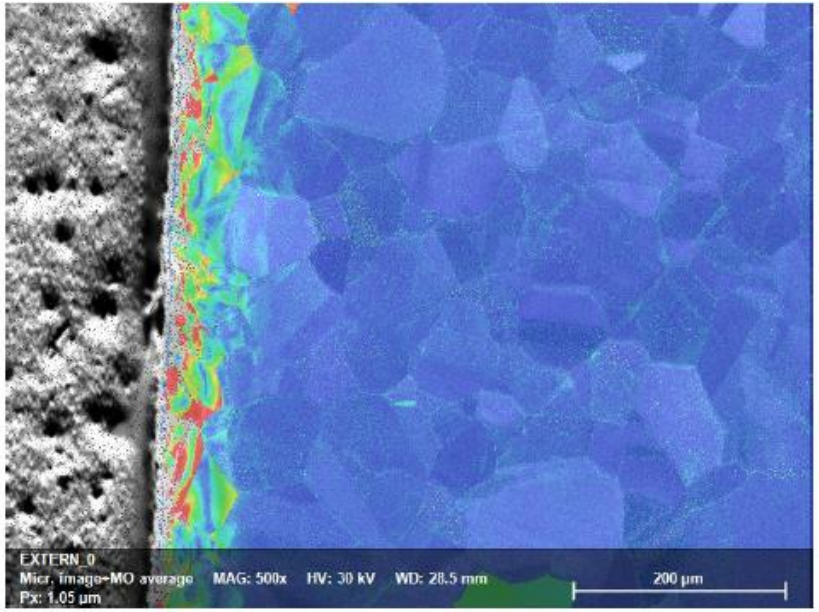


Electron Backscatter Diffraction of Corroded Layer

- Annealed, equiaxed 316H sample
- EBSD Confirms ~50% ferrite (red) in the corroded layer
- Corroded layer has significant plastic strain (machining damage?)







Materials for Tritium Management

Tritium Generation in KP-FHR

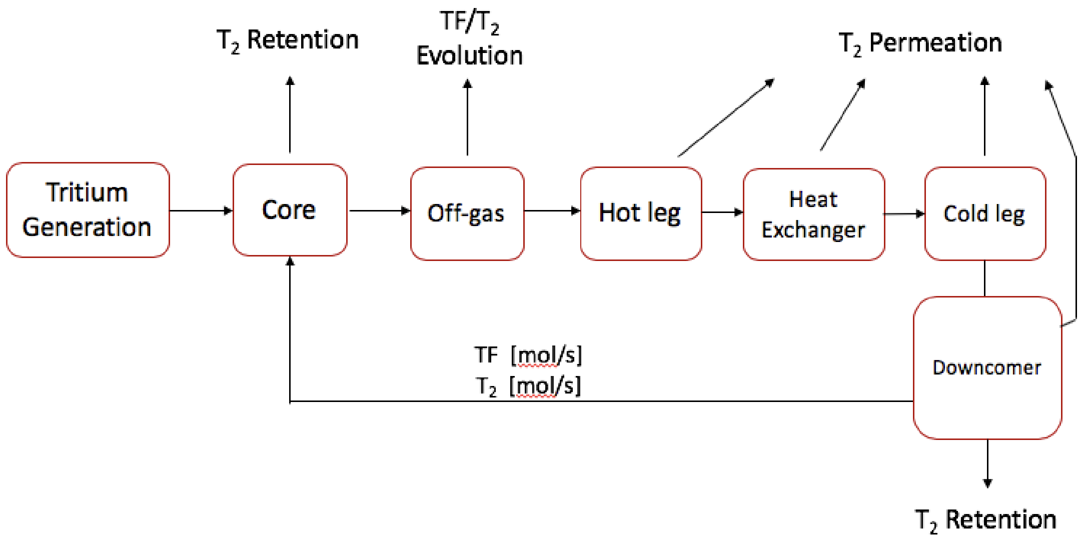
- Tritium will be generated due to neutron reaction with Flibe
- KP-FHR's Tritium Management Strategy is to assure that all environmental releases are monitored and comply with licensed pathways and limits
- The chemistry control system in the KP-FHR will keep the tritium in a reduced state as T^0 or T_2
  - The formation of tritium fluoride will be mitigated through reactions with beryllium metal to avoid corrosion
- Kairos Power is developing several methods by which tritium transport will be controlled, e.g. low permeability cladding
- Kairos Power is working with MIT to model tritium production, diffusion pathways and release via the TRIDENT code

$$ {}^{6}_{3}LiF + n \rightarrow He + TF $$

$$ {}^{7}_{3}LiF + n \rightarrow He + TF + n' $$

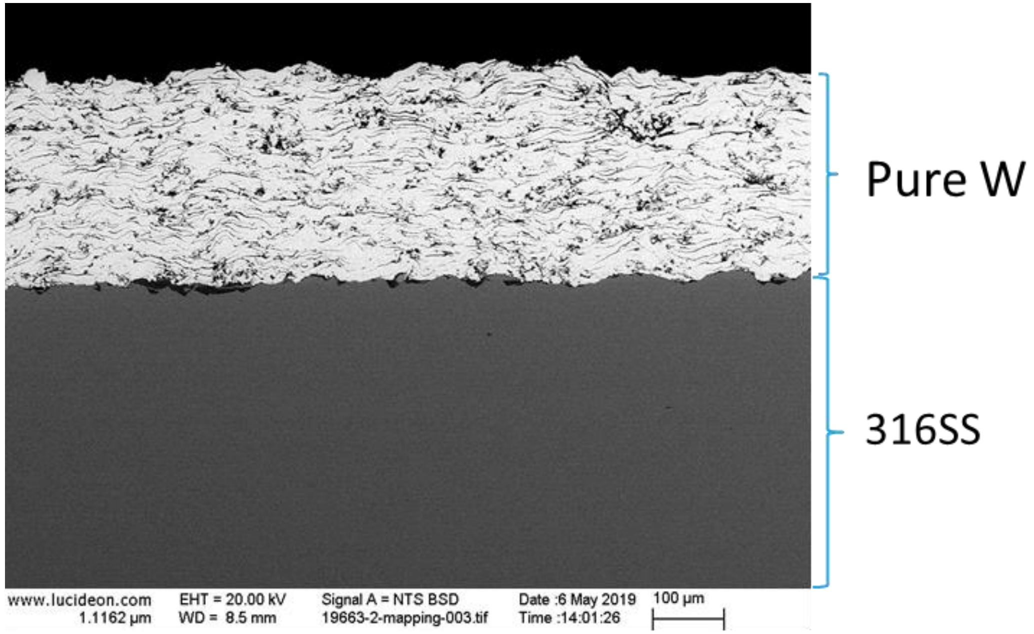
$$ BeF_2 + n \rightarrow {}^{4}_{2}He + {}^{6}_{2}He + 2F^- $$

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^+ + \overline{\nu}_e \; (t_{\frac{1}{2}} = 0.8\,s) $$

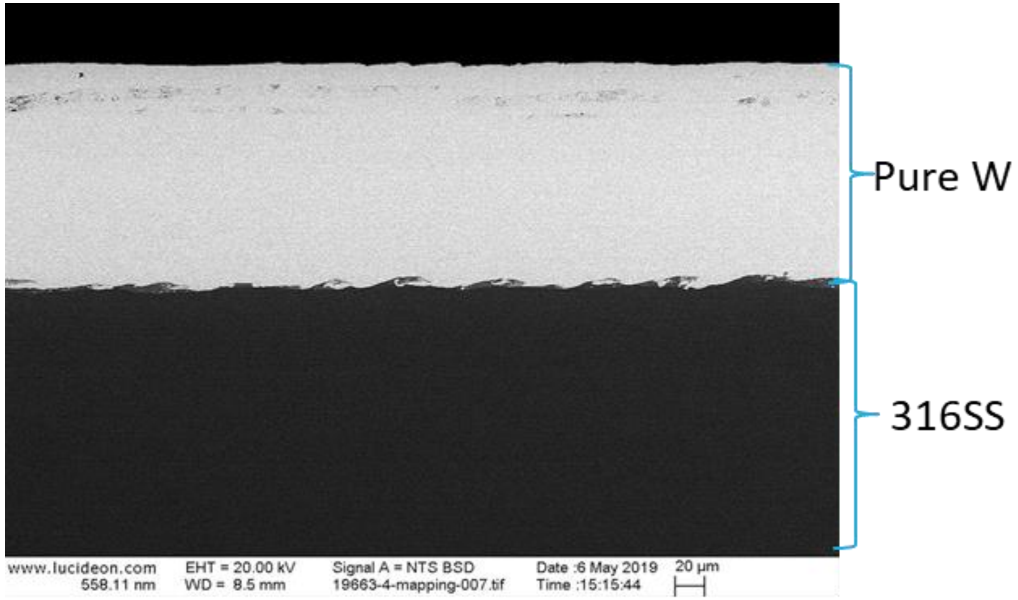


Materials Development: Cladding

- W coatings are desirable for both corrosion resistance and low tritium permeability
- Currently evaluating several coatings (carbide, oxide, metallic) and methods (thermal spray, cold spray, explosion bonding, etc.)
- Note Kairos / ANL (Messner & Sham) GAIN to develop ASME rules for corrosion resistant cladding



Thermal Sprayed W



Explosion Bonded W

Summary

- Kairos Power has understanding and experience with impurity control for Flibe
  - Ability to meet or exceed historic composition guidelines
  - Currently purifying salt for upcoming corrosion and stress corrosion testing programs
- Scoping corrosion testing indicates 316 SS rates comparable with literature data
  - Note rates in ‘nominal’ Flibe, conservative definition of corrosion rate via Cr loss
  - Redox control of the salt provides additional benefit
  - Aware of potential metallurgical complications to testing
- Materials for Tritium Management
  - Developing several methods of mitigation (trapping, permeation, recovery, etc.)
  - Working with ANL to develop ASME rules to use corrosion resistance cladding
  - Working with MIT to model tritium production and release
  - Goal is to achieve comparable release (or less) relative to conventional PWR’s