Accident Tolerant Fuel: FeCrAl Cladding Development

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Fuel Cycle Research and Development

Core Degradation Phenomena

Dominated by System Response

Behavior of Fuel/Core Materials Affects Accident Progression

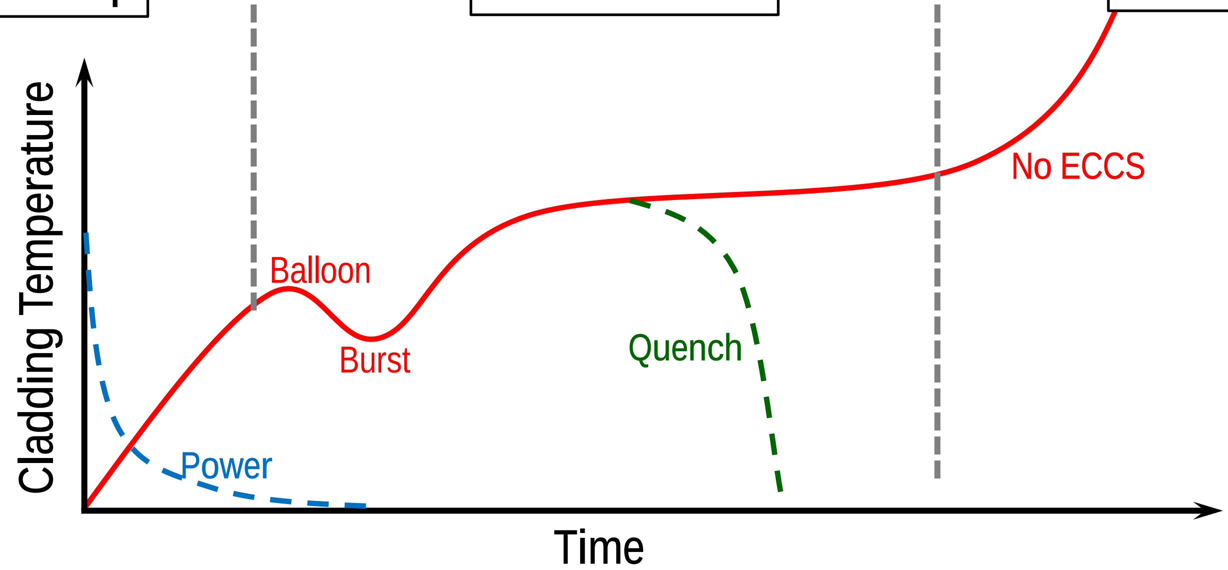
Focus on Radionuclide Retention

- *Decay heat drives decline in core water level*

- *Onset of core degradation processes and fission product release*
- *Degradation in fuel and core components that lead to further enthalpy production and hydrogen generation*

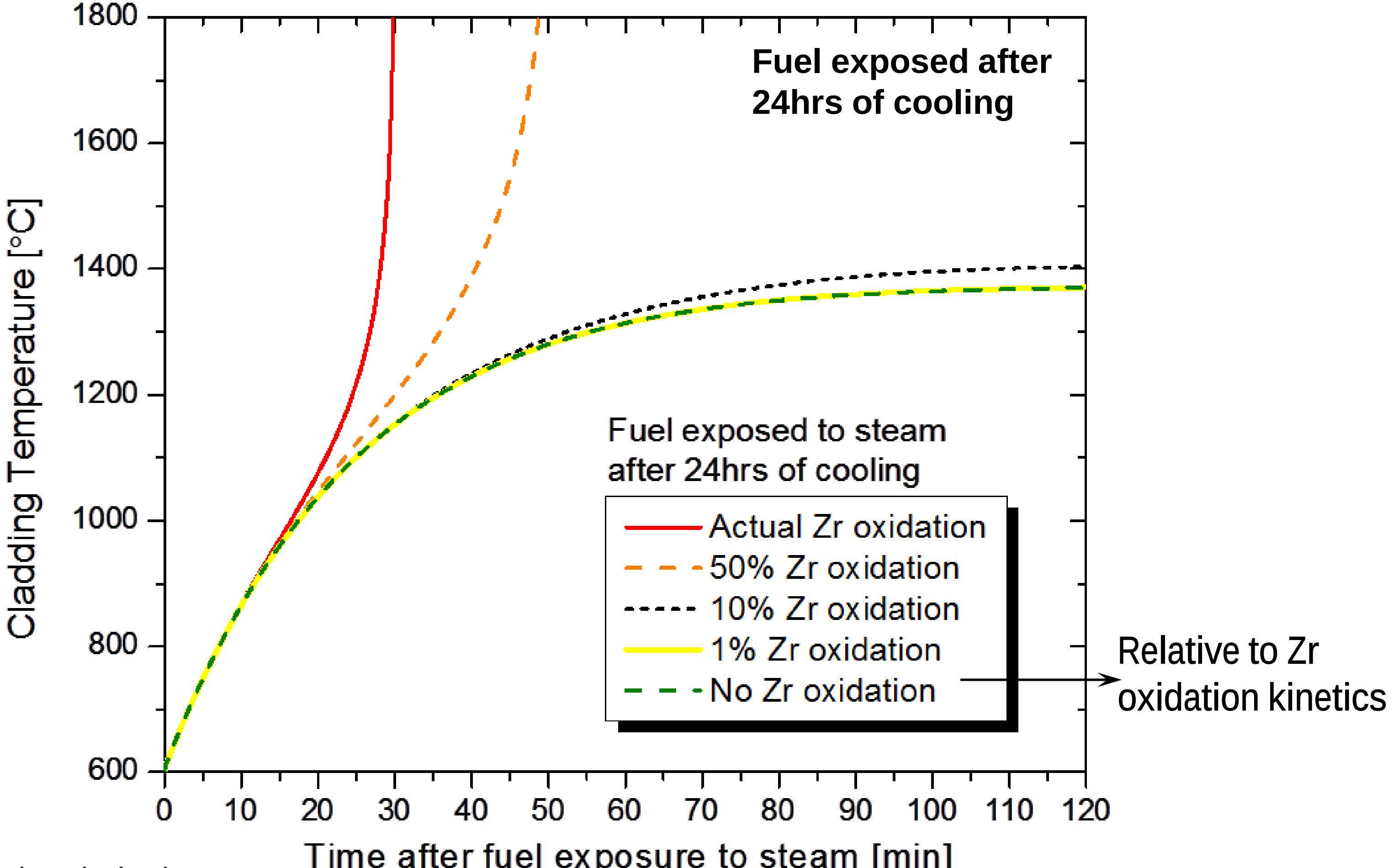
- *significant core relocation and melting leading to release of fission products*

300ºC — Lead Up — 800ºC — Mid-Phase — 1500ºC — Late-Phase



ATF: Materials With Slower Oxidation Kinetics Offer Larger Margins of Safety

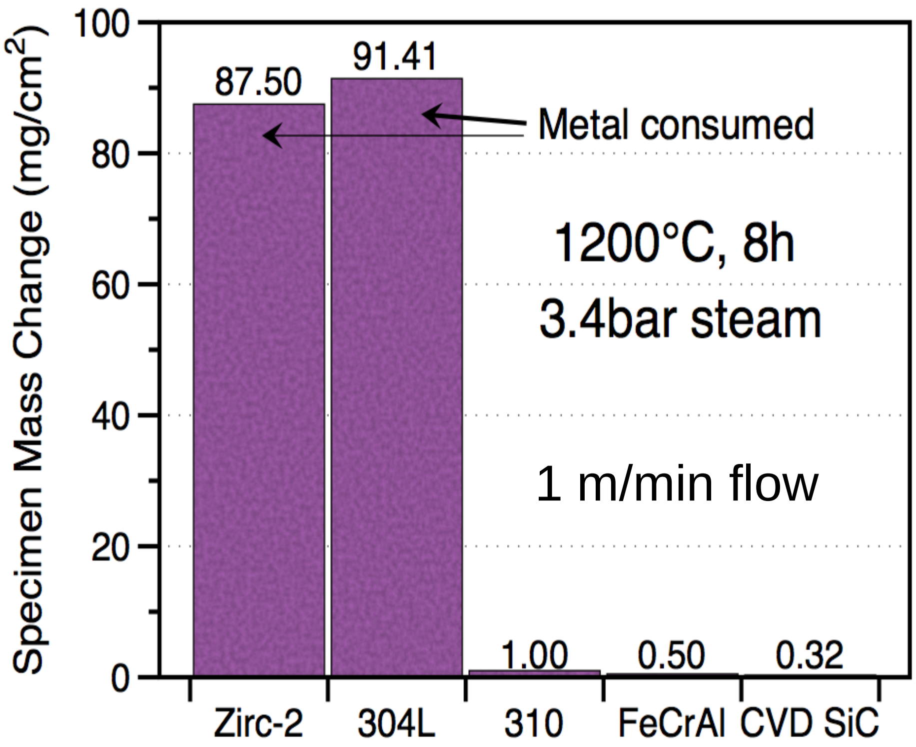
- Materials with slower oxidation kinetics in steam (~ 2 orders of magnitude or less) delay rapid cladding degradation



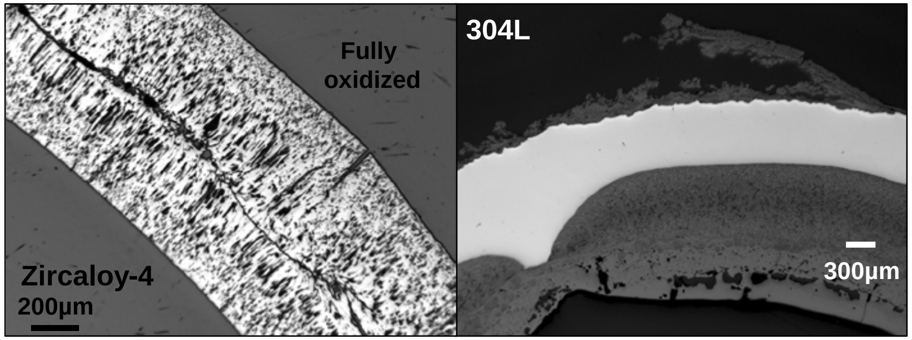
K. A. Terrani, et al., to be submitted

Oxidation Behavior in Steam

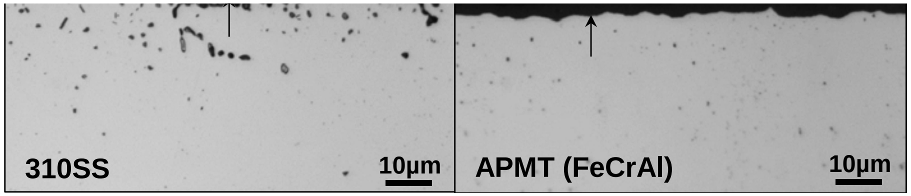
- Advanced Fe-based alloys and SiC materials offer significant improvements over Zr alloys and conventional stainless steels



1200C – 8 hours – 3.4 bar Steam

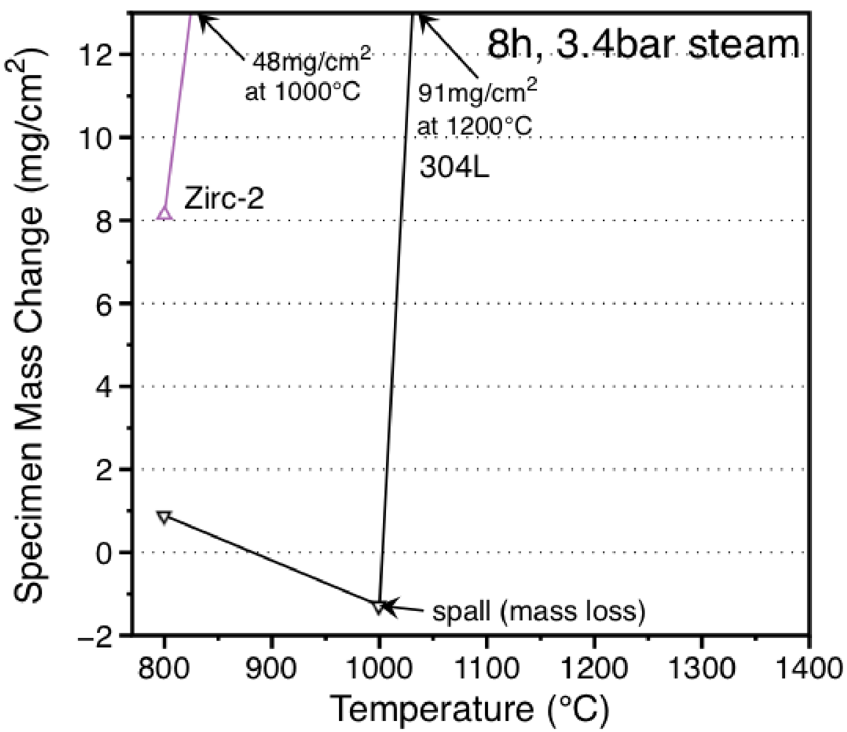


Conventional Alloys: Full or Near Full Consumption



Advanced Fe-Alloys: Minimal Reaction

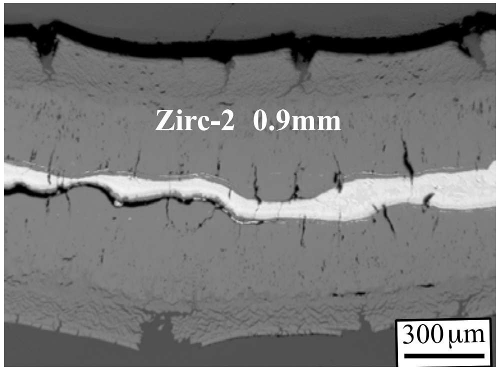
Baseline: steam oxidation
8h exposures, 3.4bar (50 psig) steam



- Initial test matrix
  - 800°, 1000°, 1200° C
  - 100% H_2O, H_2-50% H_2O
  - 50-300 psi (3.4-20.4bar)
- Zircaloy-2, 304L tubing
- High mass gain = thick oxide

Conventional choices: poor at 1200°C

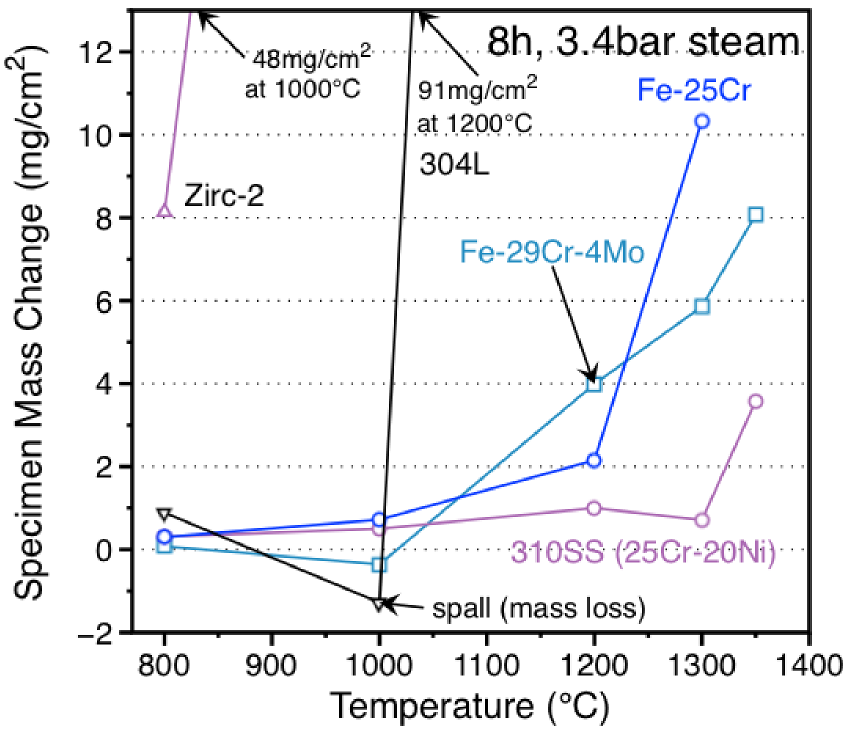
Only 2h in 10.3 bar (150 psig) steam



Typical fuel cladding ~600µm wall thickness

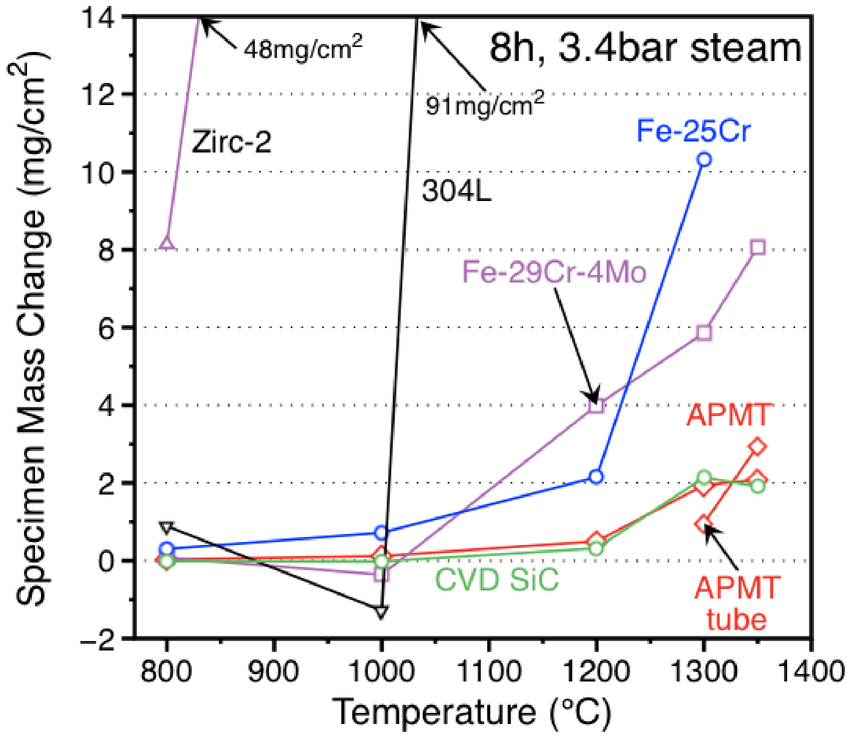
These alloys would provide no benefit in a severe accident

Screening Fe-Cr alloys: T effect
8h exposures, 3.4bar (50 psig) steam



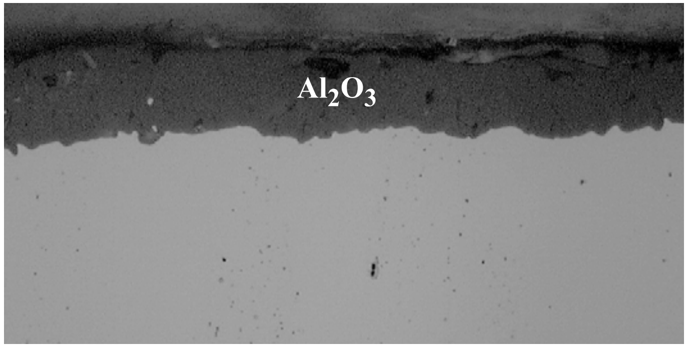
- Expanded matrix to 1350° C
- More Cr = more protection
- Spallation lowers 310 mass

Screening: best candidates 8h exposures, 3.4bar (50 psig) steam



- FeCrAl and CVD SiC
- Low 1350° C mass gains
- Kanthal APMT: forms protective Al_2O_3 scale

Al_2O_3 and SiO_2 are protective
3.4 bar steam exposures

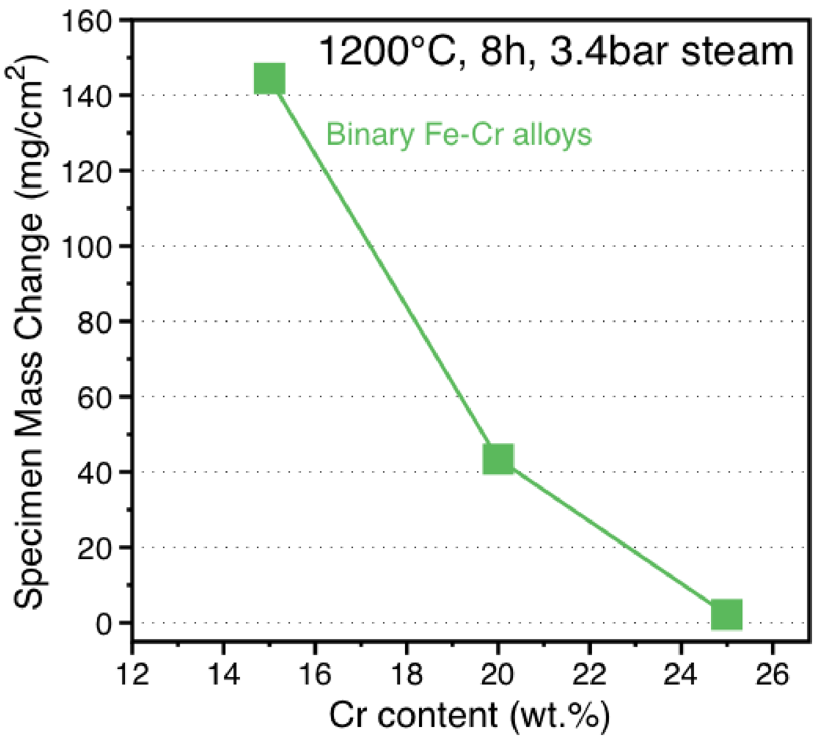


Obvious benefits for FeCrAl

SiC widely considered for fuel and support roles

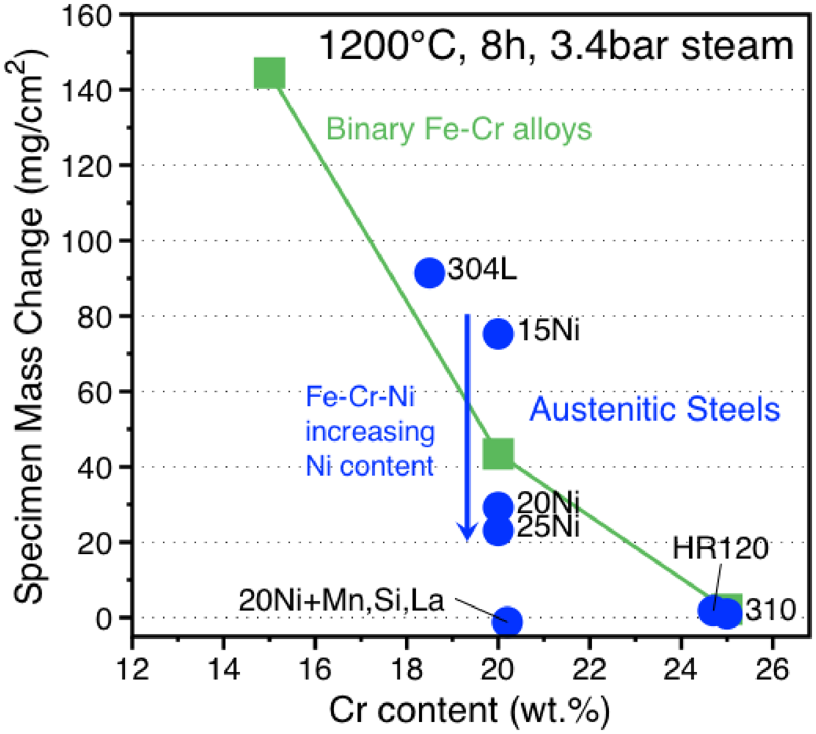
- SiO_2 water vapor problem: less relevant at 8h

Screening: Composition effects
8h exposures, 1200° C, 3.4bar steam



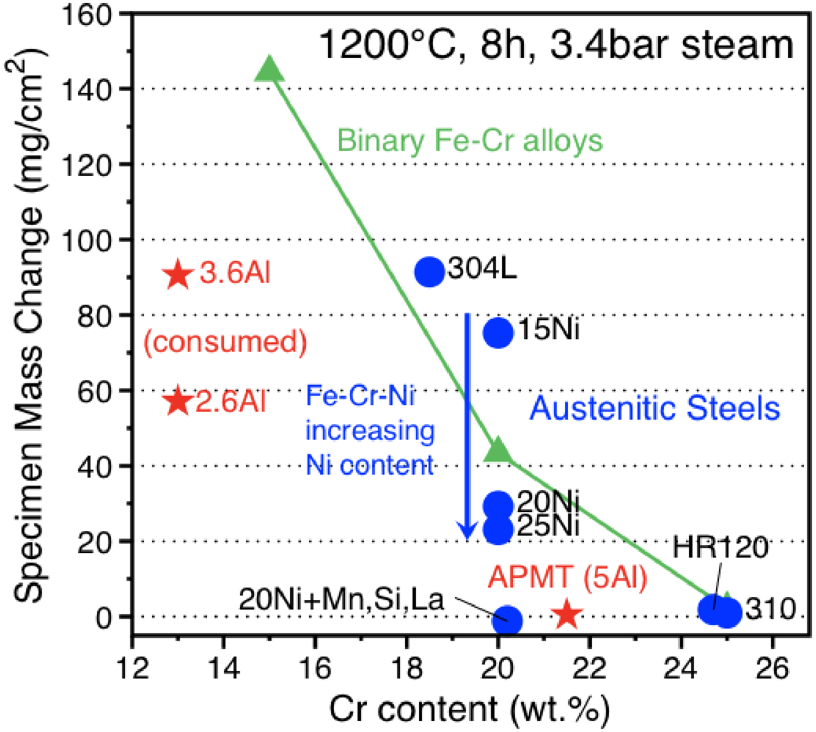
- Fe-Cr binary alloys
- Oxidation 101: more Cr makes it easier to form protective Cr_2O_3 layer

Screening: Composition effects 8h exposures, 1200° C, 3.4bar steam



- Fe-Cr-Ni alloys
- Commercial and model
- Cr+Ni beneficial
- Ni not desirable for cladding

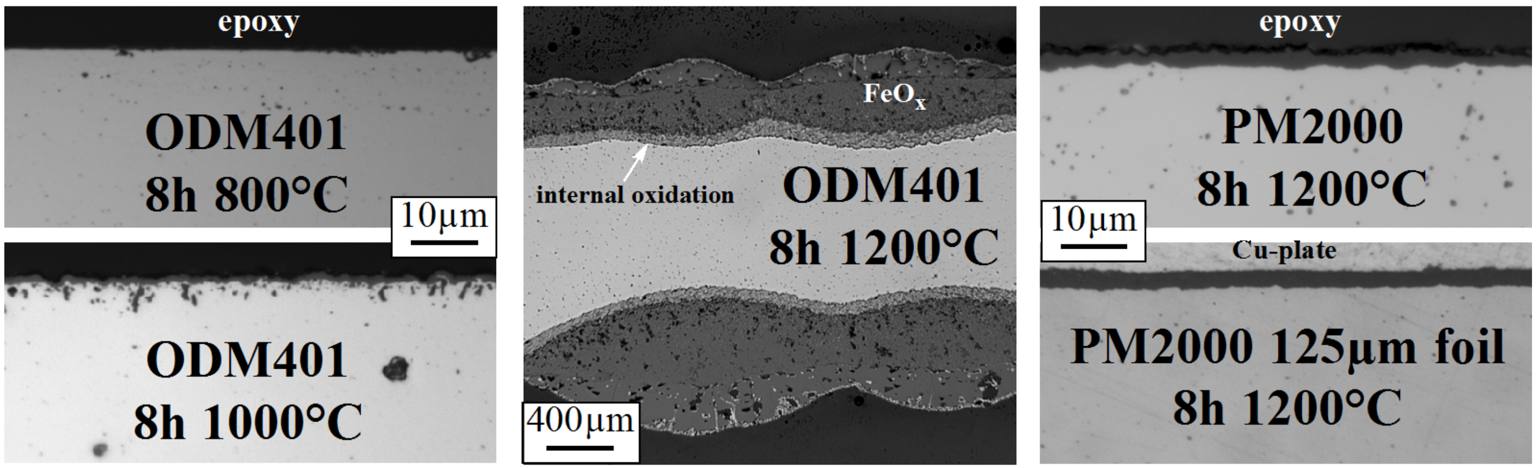
Screening: obvious Al benefit
8h exposures, 1200° C, 3.4bar steam



- APMT chosen initially
- Commercial tube alloy
- Surprisingly, leaner FeCrAl alloys did poorly

ODS alloys benefit from Al too

8h exposures in 10.3 bar of H_2-50%H_2O

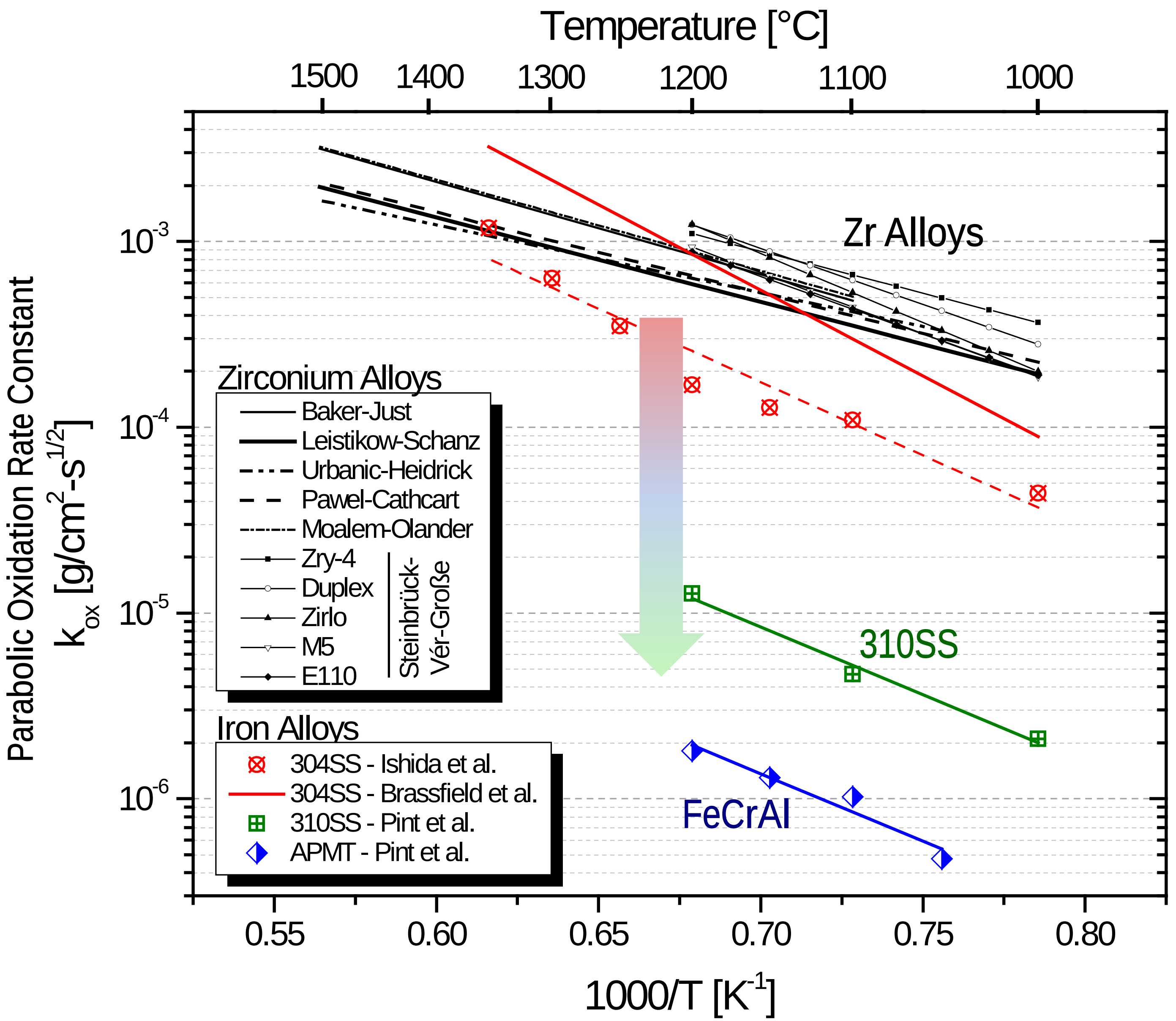


ODS Fe-15Cr **ODS FeCrAl**

ODS alloys very resistant to irradiation

Most work focuses on Fe-(9-13)Cr ODS alloys

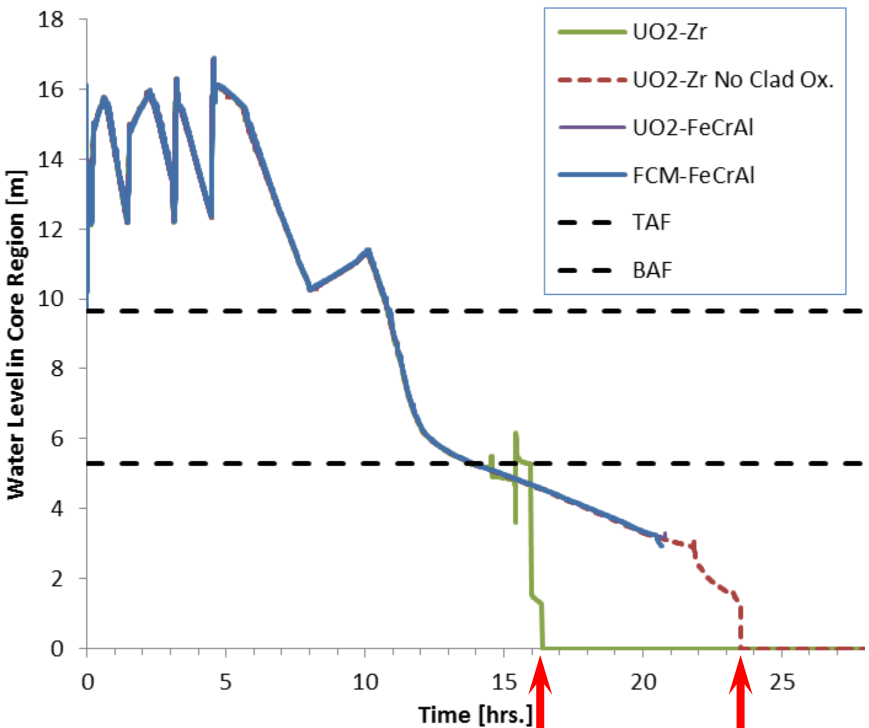
Fundamentals of Steam Oxidation Kinetics



2-3 orders of magnitude reduction in oxidation kinetics

MELCOR: Long-Term Station Blackout

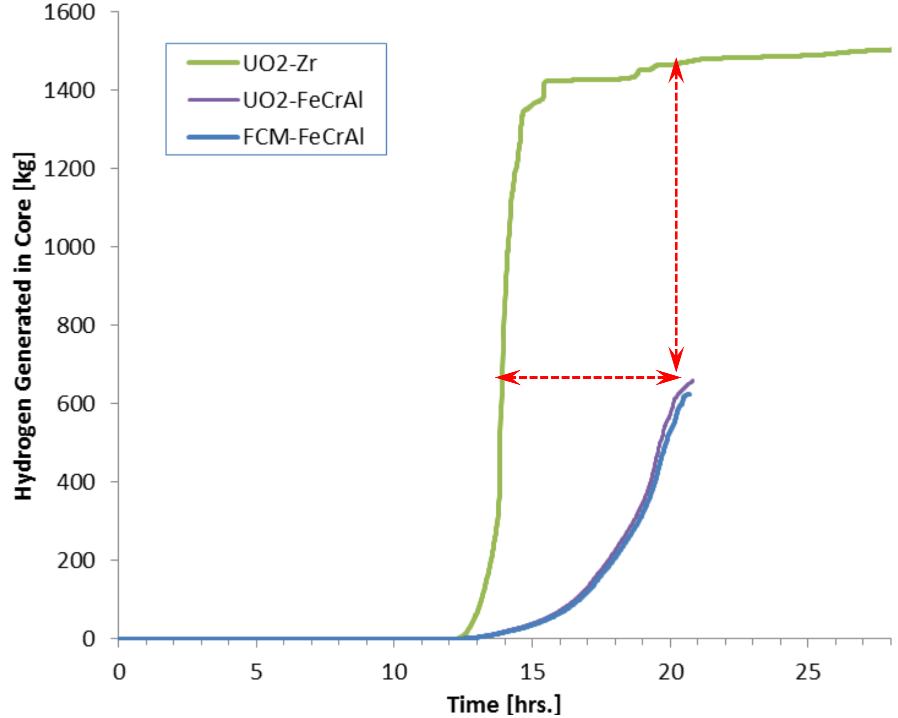
Delayed Lower Head Dryout



UO$_2$ – Zircaloy
16 h

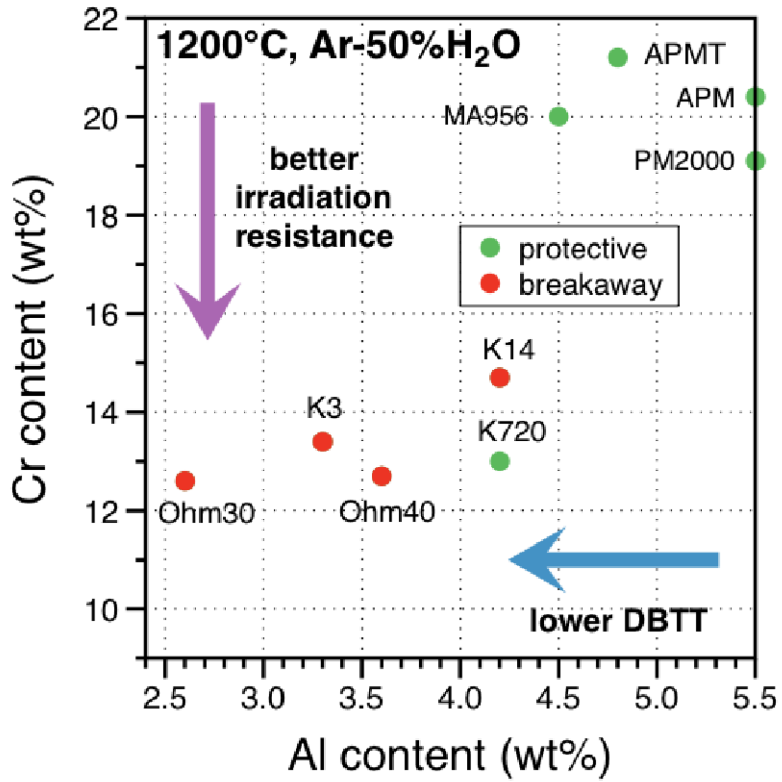
UO$_2$ – FeCrAl
23 h

Delayed and Reduced H_2 Generation



*Degradation in the UO$_2$ FeCrAl core dominated by Zr channelbox oxidation

Commercial FeCrAl alloys
TGA exposures at 1200°C in Ar-50%H_2O



Hard to explain results

Need for more model alloys to clarify boundary

Hot-rolled FeCrAlY model alloy plate

- No technical difficulty to hot-roll the alloys (0.032” thickness).

13-0412-06 B155Y 93%HR700˚C + AC 200X 20μm

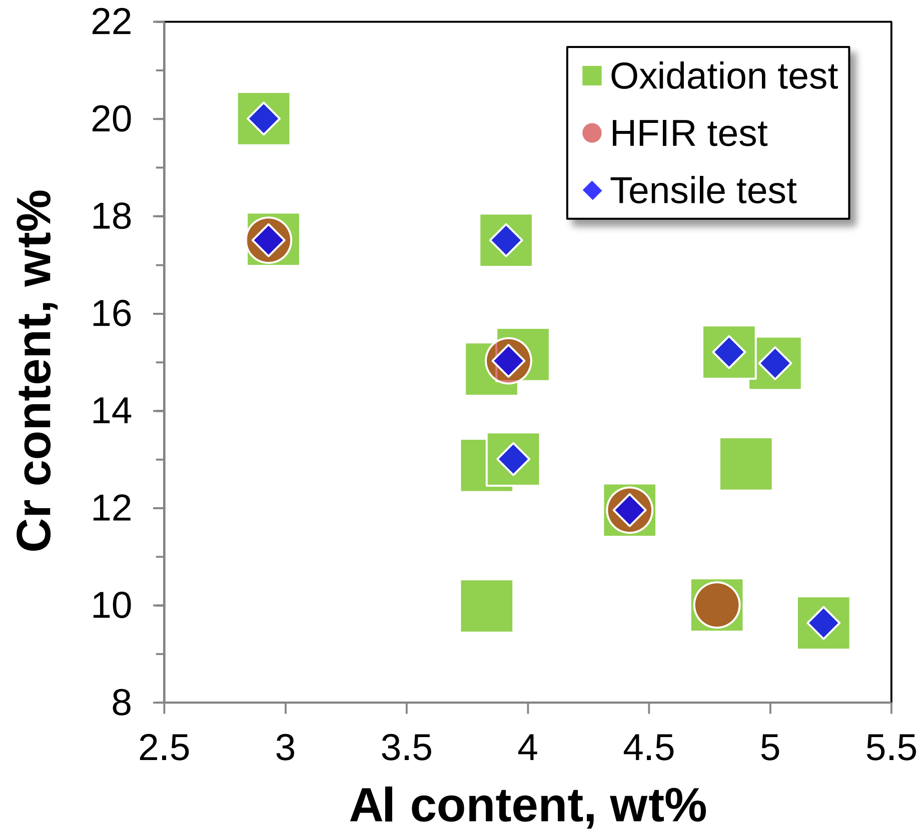
- Cold-roll can also be done at RT after GS control
  - No intermediate annealing required
  - Up to 2mil thickness

Chemistry of the Alloys Studied

Table: Chemistry of the alloys

ID	Composition, wt%			
	Fe	Cr	Al	Y
B105N	85.12	9.64	5.22	<0.001
B104Y	86.12	9.99	3.83	0.040
B154Y	81.18	14.86	3.85	0.012
B184Y	78.39	17.51	3.91	0.043
B183Y	79.27	17.53	2.95	0.019
B203N	77.05	20.01	2.91	<0.001
B155Y	79.87	14.98	5.02	0.033
B125Y	83.56	11.96	4.42	0.027
B134N	83.27	12.88	3.83	<0.0003
B134Y	83.02	13.01	3.94	0.007
B135Y	82.10	12.91	4.90	0.031
B154Y-2	80.99	15.03	3.92	0.035
B183Y-2	79.52	17.51	2.93	0.017
F1C5AY	85.15	10.01	4.78	0.038
F5C5AY	79.88	15.21	4.83	0.063
B154N	80.84	15.16	3.98	<0.0003

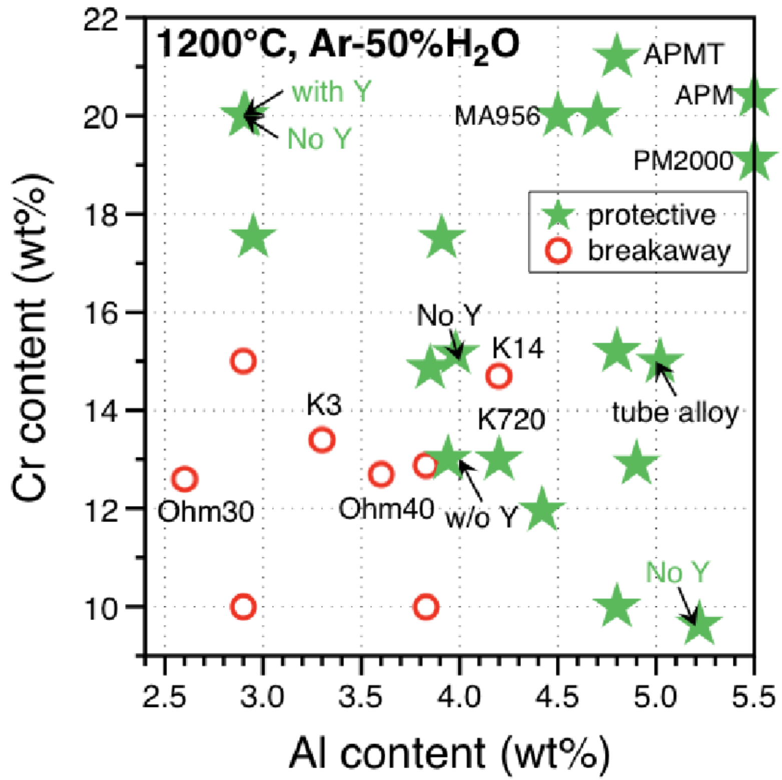
Cr vs. Al map of the alloys

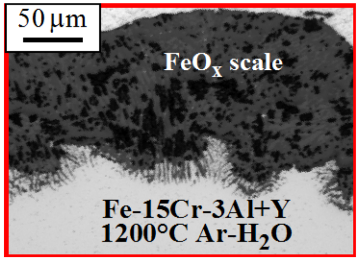


- Compared with commercially available FeCrAl alloys
  - APMT (Fe-22Cr-5Al + Y_2O_3 base, ODS)
  - Alkrothal 14 (Fe-15Cr-4Al + Zr base)

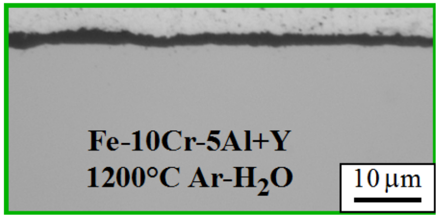
Model FeCrAl alloys

TGA exposures at 1200°C in Ar-50%H_2O





4h

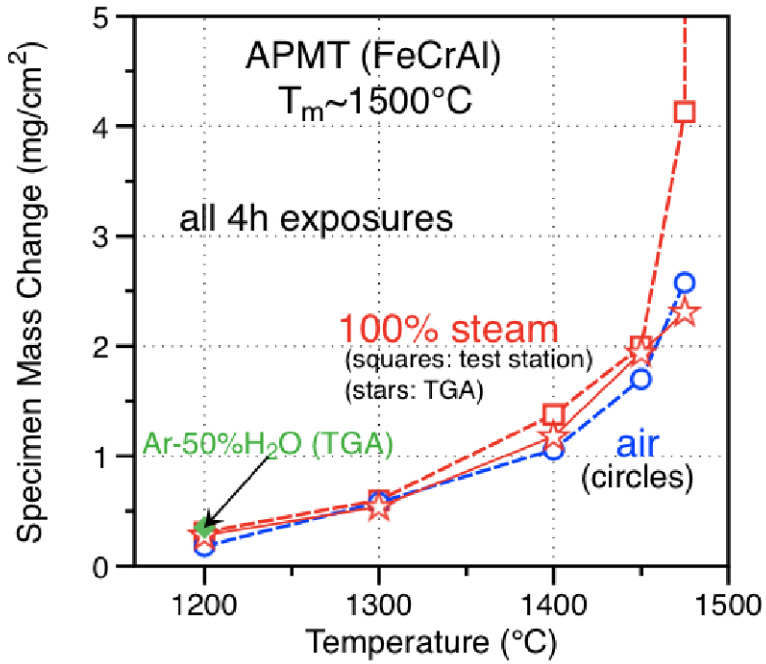


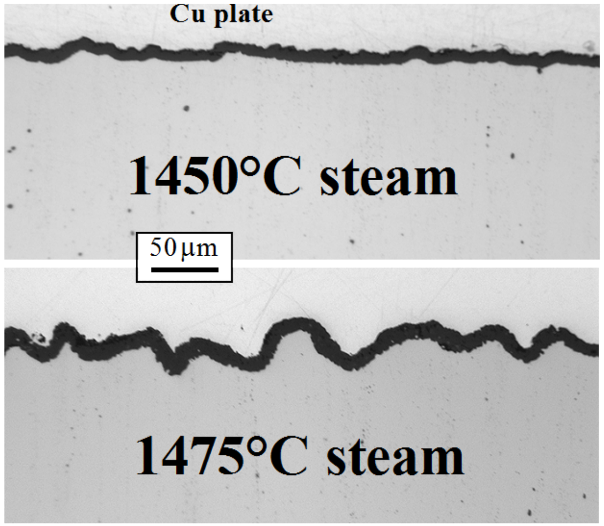
24h

Established kinetic boundary for protective alumina
Exception may be few additions in K14 (no Y)

Effect of steam on APMT oxidation

4h test in 100% steam in High T module





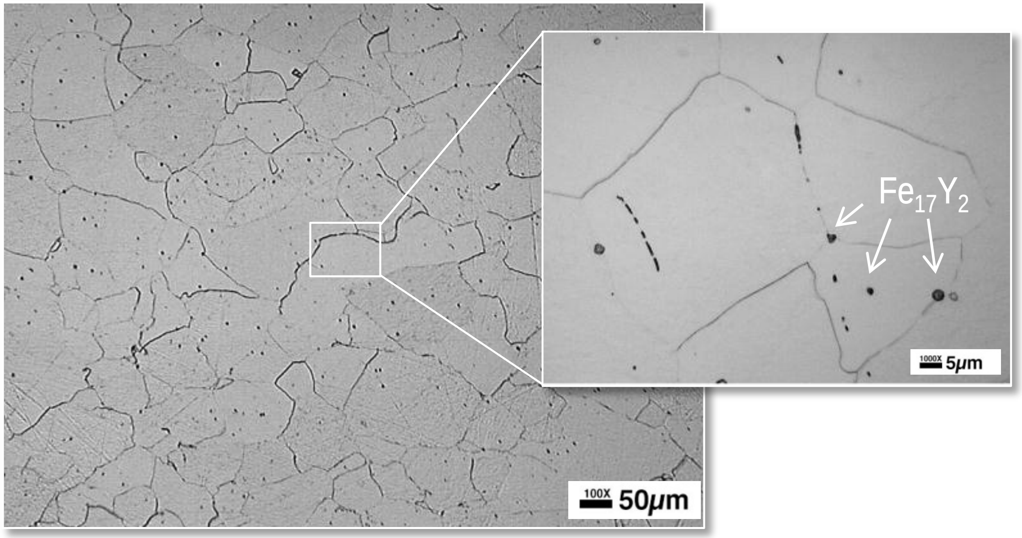
Similar results in both test modules

circles (high T module); stars (Rubotherm TGA)

Surface roughness due to weak substrate?

Quality of Trial FeCrAlY Tube (B155Y)

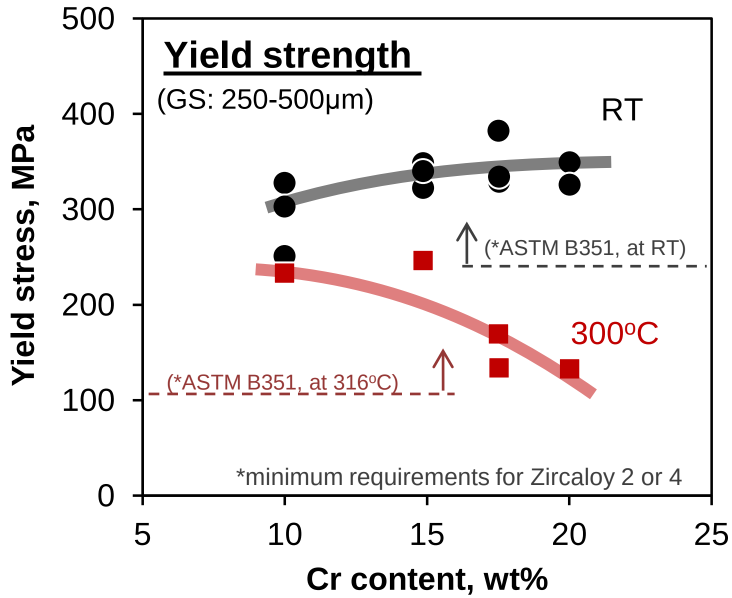
OM micrographs (cross-sectional view)

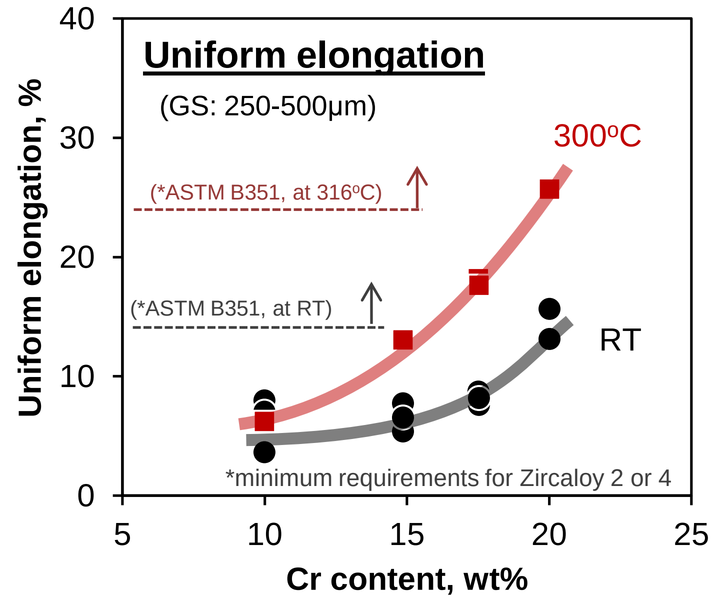


Machined tube (OD 9.5mm x WT0.6mm x L51mm)

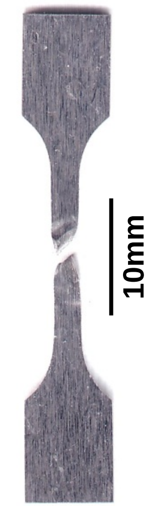
- Uniform grain structure with spherical $Fe_{17}Y_2$ particles.
- Average grain size: ~69μm
- Forging resulted in slightly deformed grain morphology, not recrystallization.
- Successfully machined tube form with 2” length.
- It was drilled at the center, EDMed inside and outside, and then ground/polished for making final size/surface.

Preliminary Tensile Test Results of ORNL ATF FeCrAl Alloys (1st Gen.)



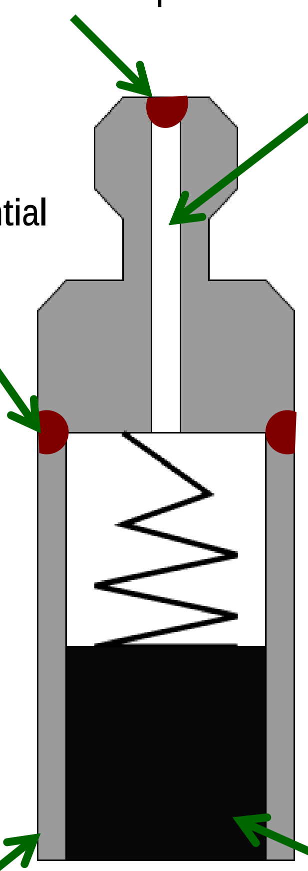


Sub-sized specimen (after testing at RT)



- First attempt was made with non-controlled grain size specimens (~250-500 μm).
    - o YS exceeded min. requirement of Zircaloy 2 or 4, at both RT and 300°C.
    - o Higher Cr is good for ductility, but lowers YS at 300°C.
- Optimization of the grain size (~30-50 μm) is currently in progress.
- Further property improvement via solution/precipitate strengthening is planned, as the 2nd generation ORNL ATF FeCrAl alloys.

Welding trials



Top Cap Assembly

- Understand the mechanical properties of weldments made in model FeCrAlY alloys
  - 3 alloys selected with varying Cr and Al content
  - 2 welding types tested
    - E-beam: initial screening
    - Laser: in-depth investigation
  - Demonstrate weld of top and bottom caps for cladding

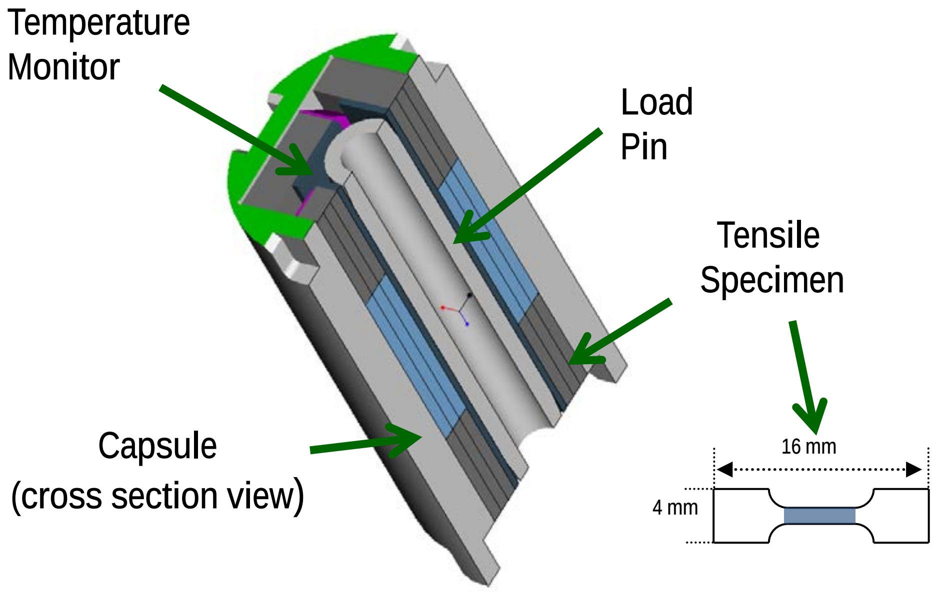
	Nominal, wt%		
	Cr	Al	Y
B125Y	**12**	**4.5**	**0.15**
B154Y-2	**15**	**4**	**0.15**
B183Y-2	**17.5**	**3**	**0.15**

Summary of FeCrAlY Welding Trials

1. E-beam welding of FeCrAlY alloys resulted in defect free welds
2. Laser welding lead to decreased strength levels and increased ductility levels
   - Neck and fracture occurred in fusion zone
   - No evidence of welding-caused embrittlement
   - B125Y alloy has the best strength level after welding compared to other alloys
3. FeCrAlY alloys are suitable for complex geometry weldments

Good weldability of unirradiated FeCrAlY model alloys

HFIR Irradiation Design and PIE



- 4 ORNL ATF candidate + 2 commercial alloys to be inserted to HFIR
  - Varying Cr content across selected alloys
- Planned PIE:
  - Tensile tests at RT, 320 °C, & accident temperature to determine mechanical performance
  - **SANS to determine α' volume fraction**
  - Analytical electron microscopy from non-gauge section of tensile specimens

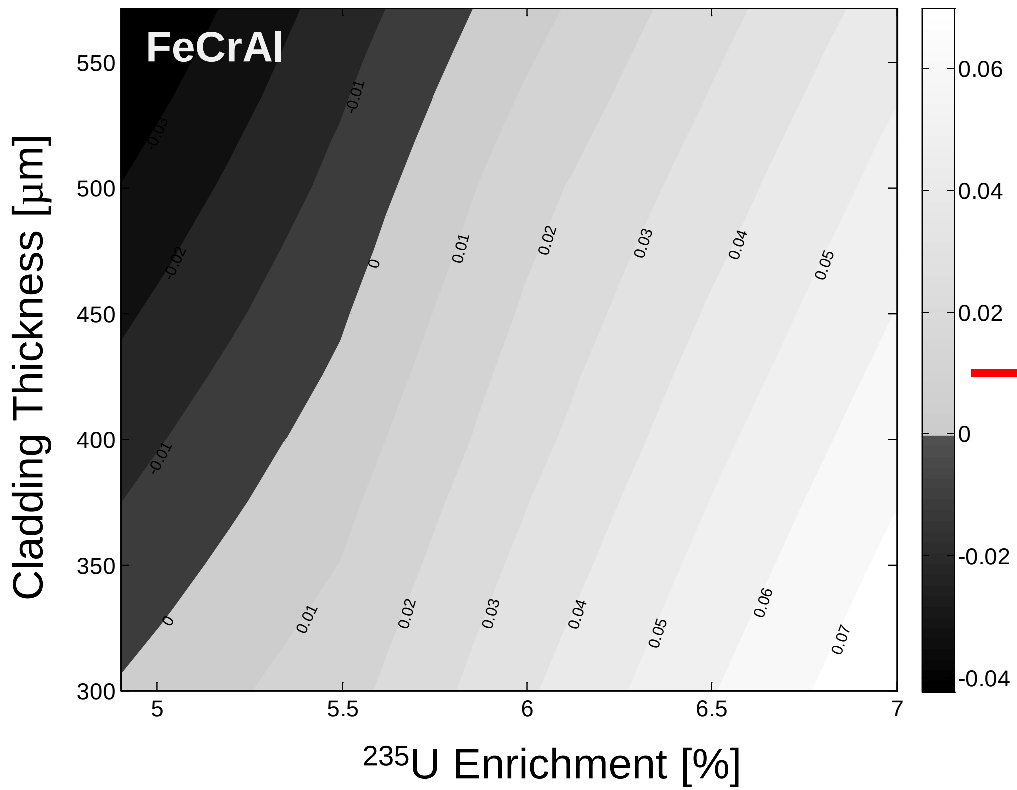
FY2013

Low Dose: FY2014
High Dose: FY2015

Neutronics and Economics of Steel Clad

Two strategies to make up for neutron absorption in the cladding and maintain identical cycle lengths to Zr clad:

- **Reduce clad thickness** (steel is stronger and more oxidation resistant)
- Increase ^{235}U enrichment



Difference In End Of Life Reactivity SS Clad Vs Zr Clad

Results in 15-25% Increase in Fuel Cost

Summary/Future Work

- Current ORNL focus on optimizing FeCrAl for cladding
  - Welding and tensile properties acceptable
  - Initial Cr/Al selected based on accident conditions
  - Need ~300° C water corrosion data
  - Irradiation data coming
  - Kanthal AF tubing made by LANL: burst test
  - Fe-15Cr-15Al+Y ready for ATR irradiation
- Other teams developing ATF candidates
  - Range of properties need to be compared/ranked

backups

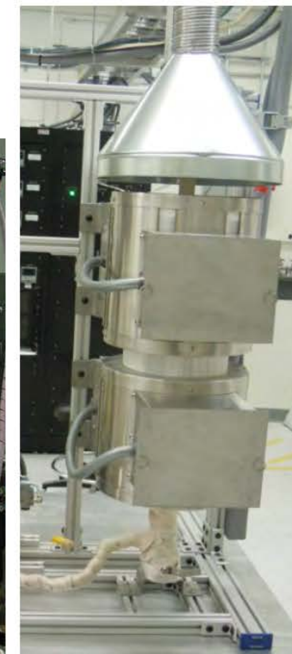
Severe accident test station

National facility for testing new cladding concepts
- multiple "modules"
- steam to 1700°C, typically 1-10 cm/s
- pressure to 30 bar

Rubotherm TGA

"Keiser rig"
high P/T ~1500°C

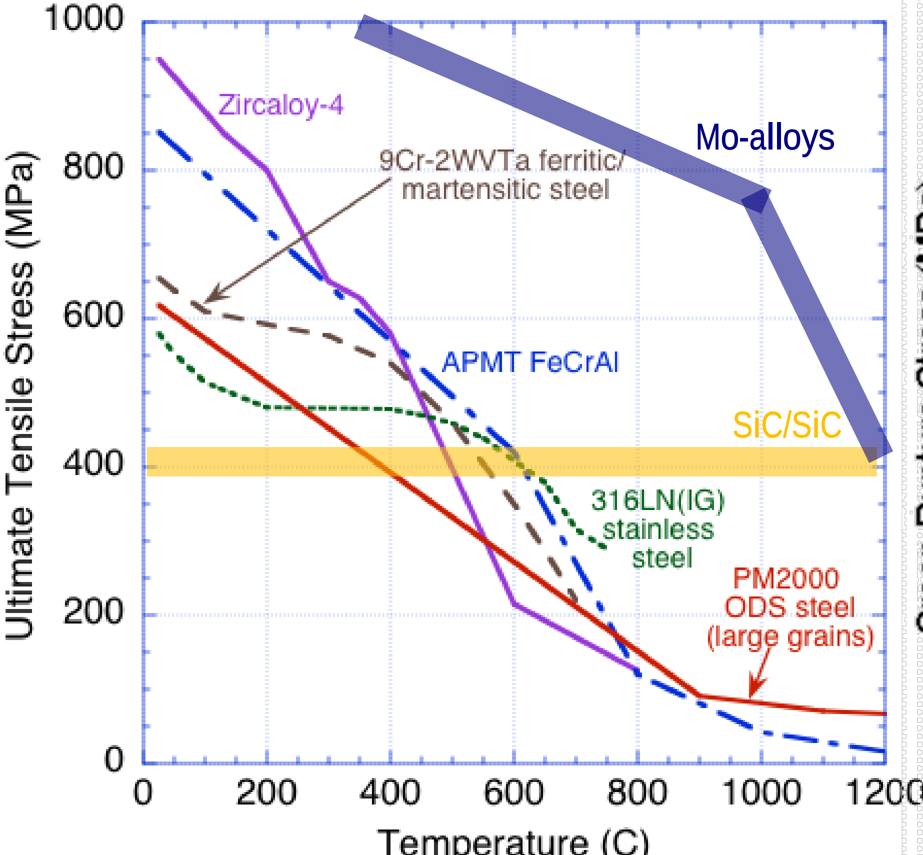
standard LOCA

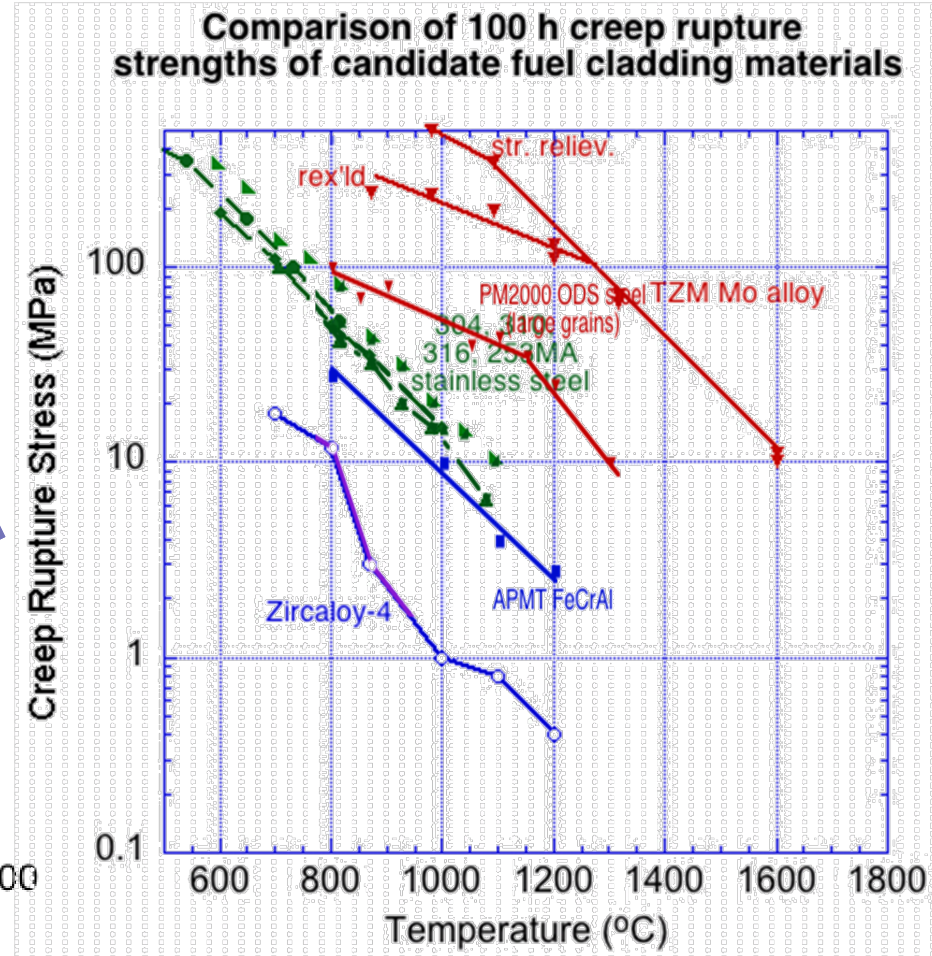


high T ~1700°C

in- & ex-cell units

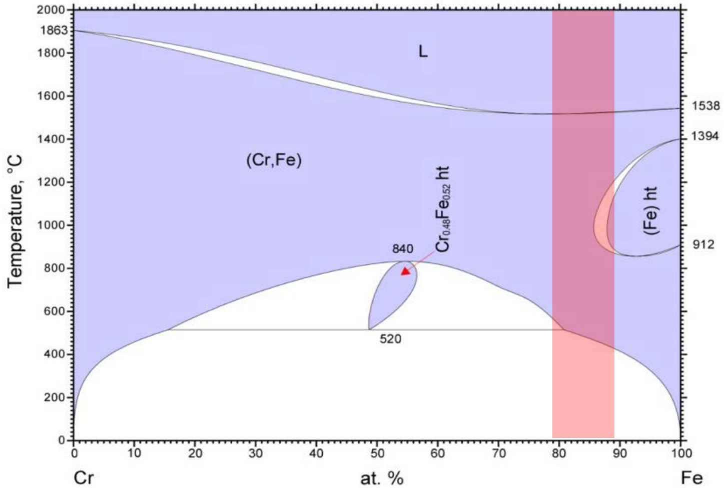
Strength and Creep Behavior of Some Candidate Cladding Materials





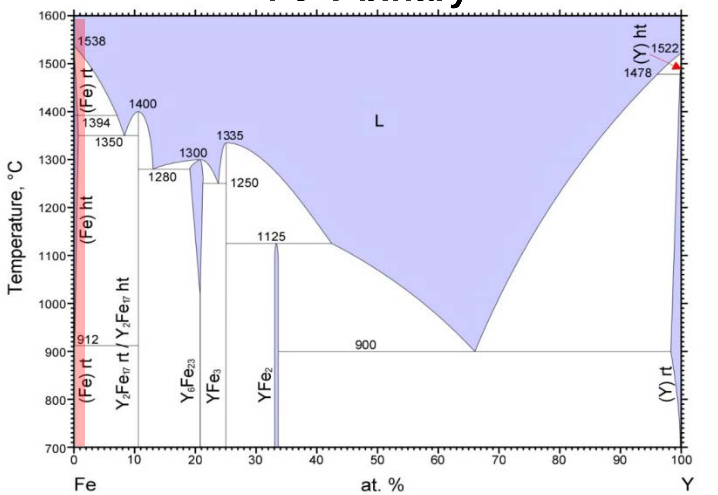
Consideration from Phase Diagrams

Fe-Cr binary



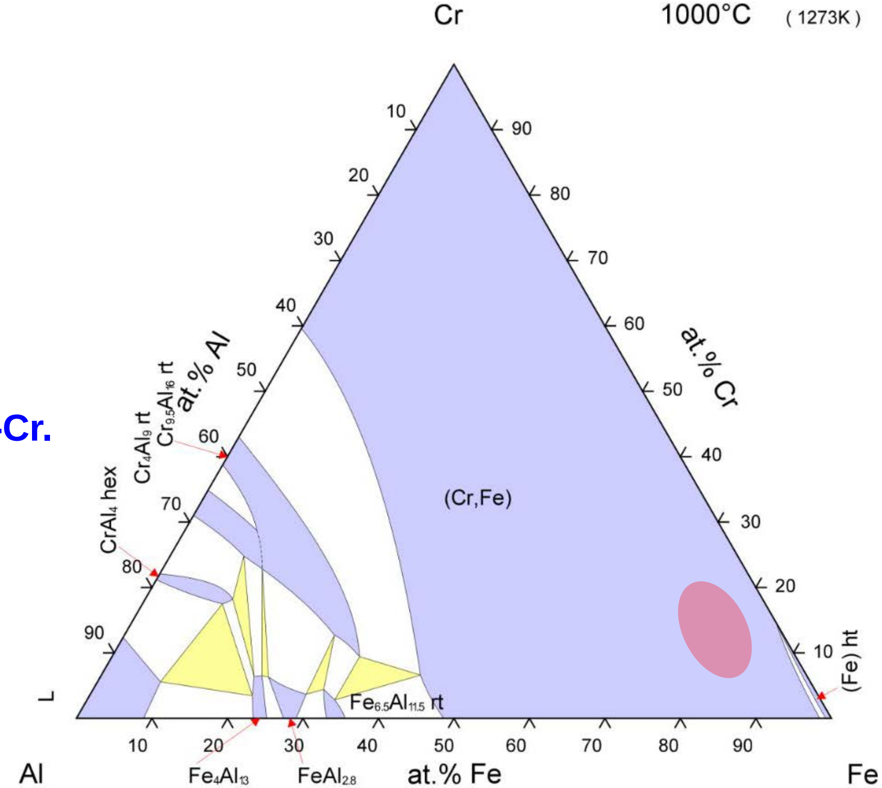
- **No sigma formation between 10-20Cr, but α-Cr.**

Fe-Y binary



- **Little Y solubility in Fe, $Fe_{17}Y_2$ may form (but very little).**

Fe-Cr-Al ternary



- **Ferrite single-phase at around 1000°C (hot-rolling temperature).**