Development of Engineering Grade FeCrAl Alloys for Clad

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Advanced Fuels Campaign

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

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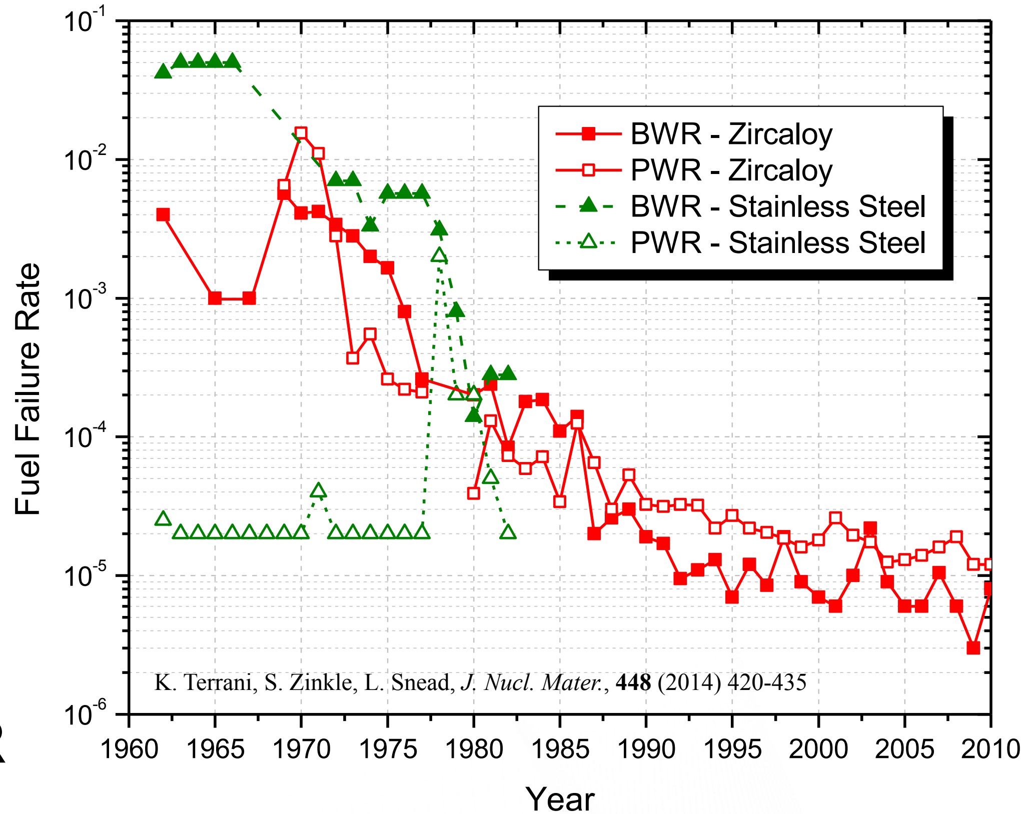
Fe-Based Alloys as LWR Fuel Cladding

- Austenitic stainless steels were used into the 1980s as B/PWR fuel cladding
- The higher neutron absorption in the cladding was accommodated with thinner wall and occasionally higher fuel stack height.
- While the austenitic variants suffered from corrosion in BWR environments, they exhibited superior performance in PWRs



"Since fuel experience was so good, almost a negligible failure rate, it may be that design margins were much too great and it may still be economic to use thin collapsed steel cladding?"

D. H. Locke, *Nuclear Engineering and Design*, **33** (1975) 94-124

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Pathway to Develop Nuclear Grade ATF Cladding FeCrAl Alloy

Phase I: Effect of Major Alloying Elements

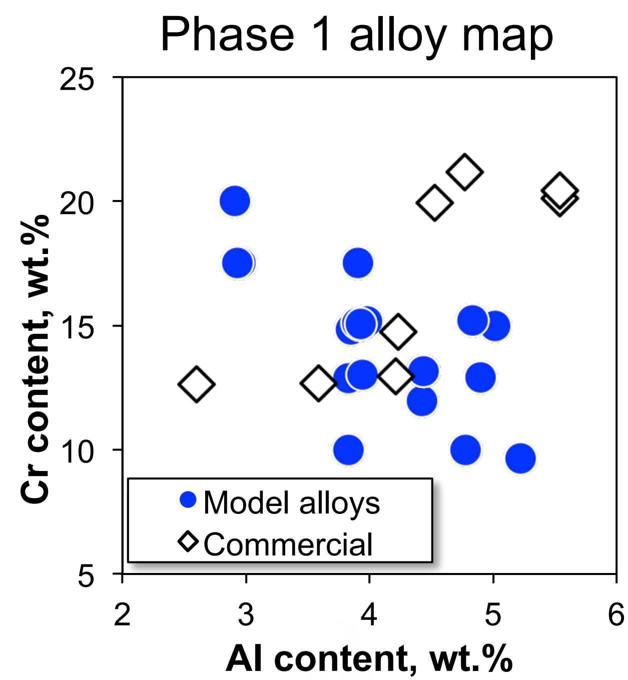
Focus on Basic Alloy Properties f(Cr-Al)

- *Processibility*
- *Tensile properties*
- *Steam oxidation*
- *Environmental corrosion*
- *Aging effects*
- *Weldability*
- *Neutron irradiation*
- *Thin tube drawing*
- *Burst testing*
- *Tritium transport*

Phase II: Effect of Minor Alloying Elements

Focus on Strengthening Mechanisms

- *CALPHAD to study various strengthening strategies*
- *Various systems of minor element additions*
- *Thermo-mechanical treatment (TMT)*
- *Verification of optimized basic properties*
- *Translation into thin tube production*



At least 20 alloys processed in each phase

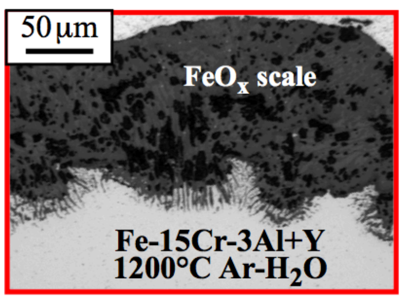
Arc Melt + Drop Cast → Hot Forge → Hot Roll → Annealing — ***Sheet Production***

Arc Melt + Drop Cast → Hot Extrusion → Drawing → Annealing — ***Tube Production***

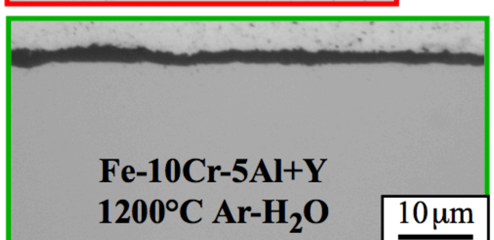
Selected Phase-I Alloy Development Activities

Phase I: Cr and Al Content Effects on Steam Oxidation

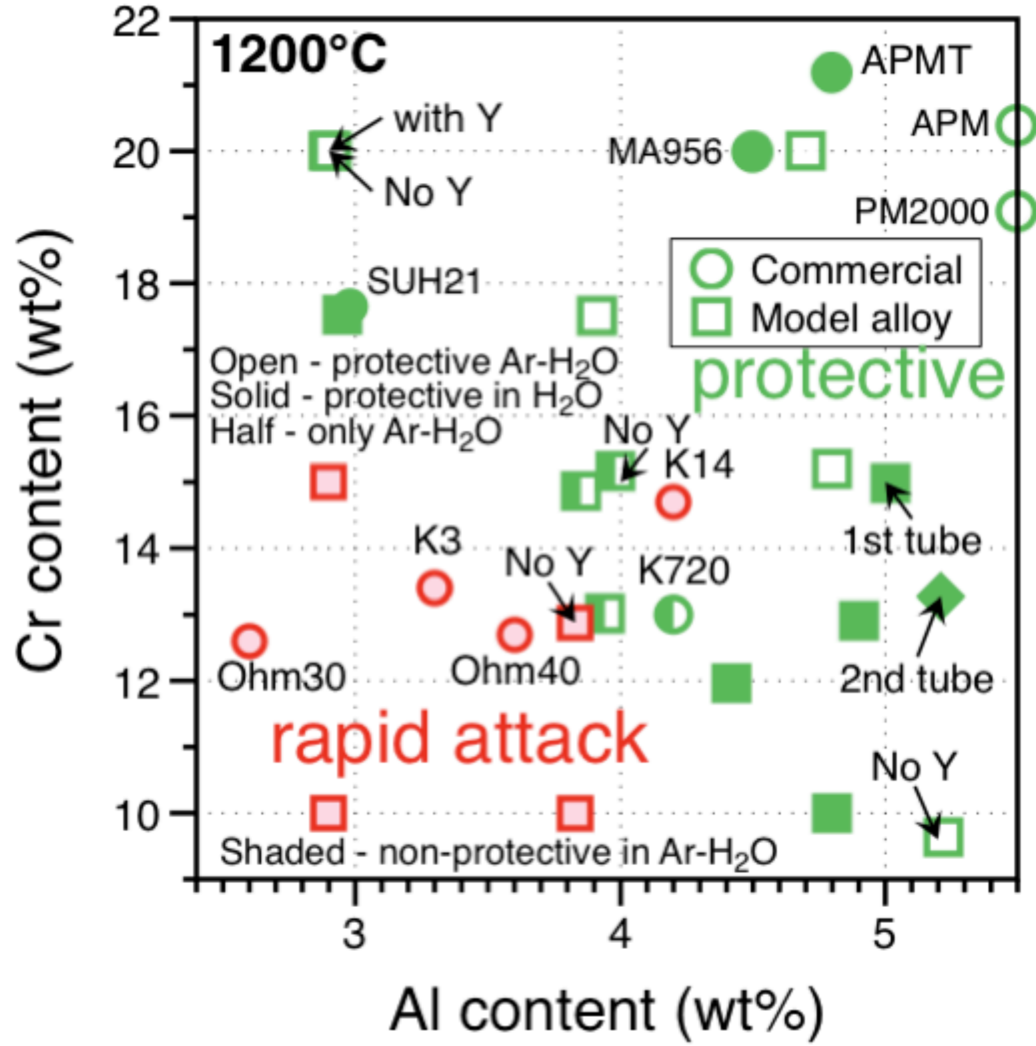
- In FeCrAl alloys, a critical combination of Cr and Al contents is necessary to produce a protective alumina layer on the surface upon steam exposure.



4h



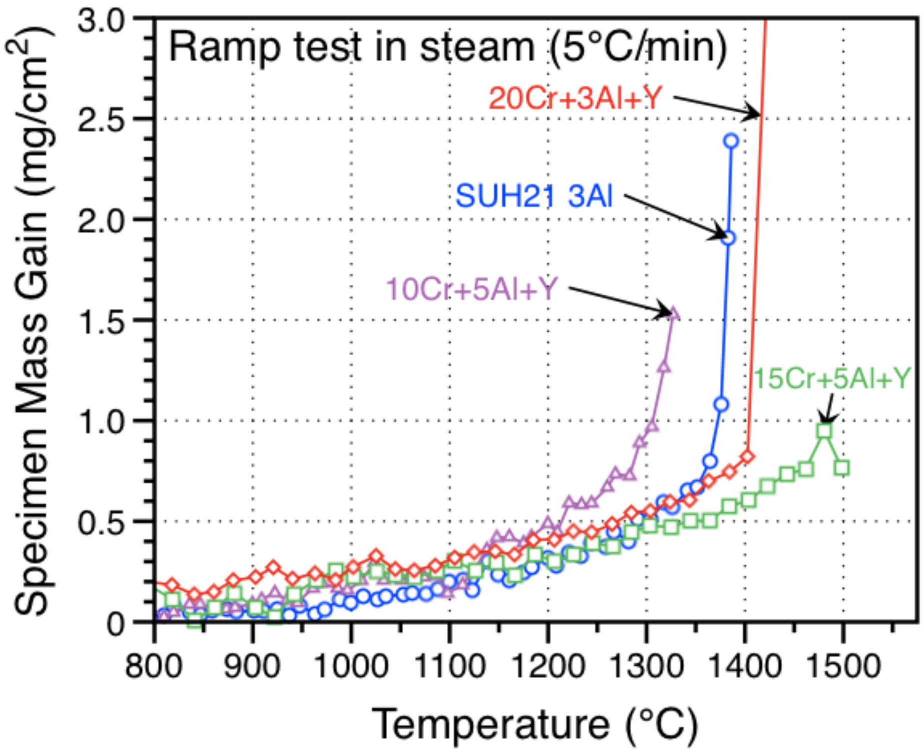
24h

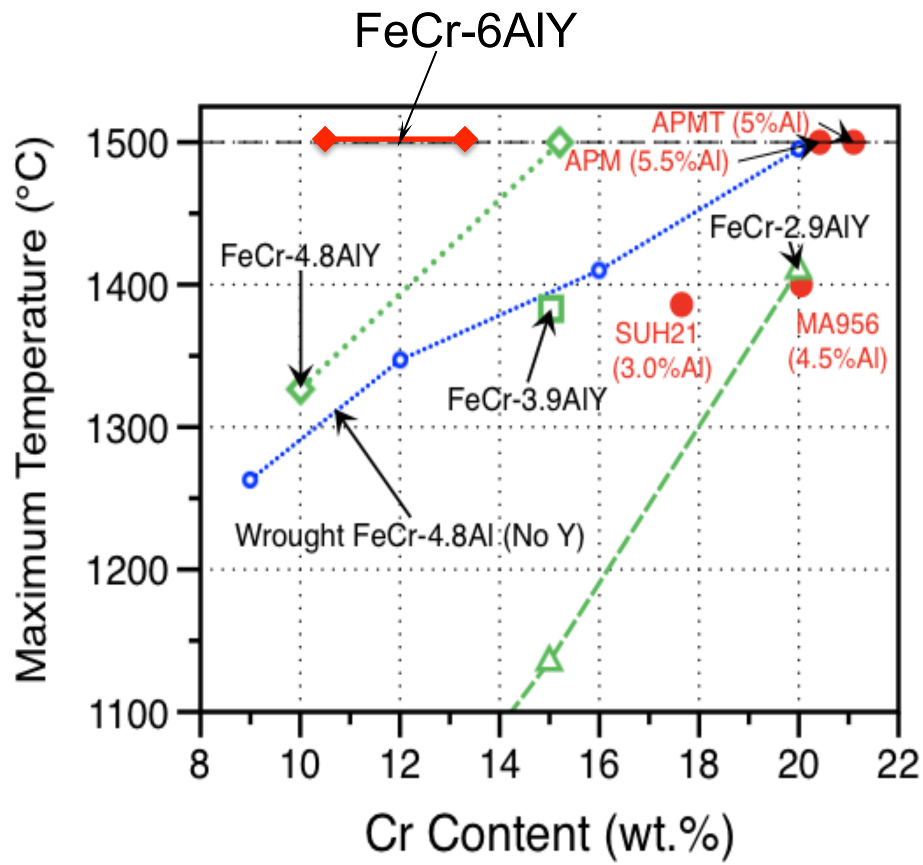


B. Pint et al., *Metallurgical and Materials Transactions E*, submitted, 2014

Phase I: Cr and Al Content Effects on Steam Oxidation

- Max Use Temperature determined via ramp testing starting at 600°C

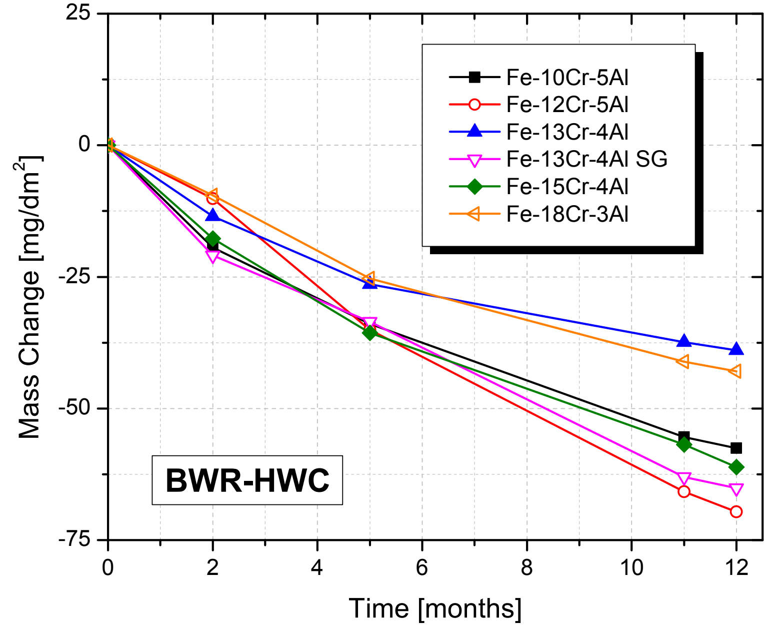


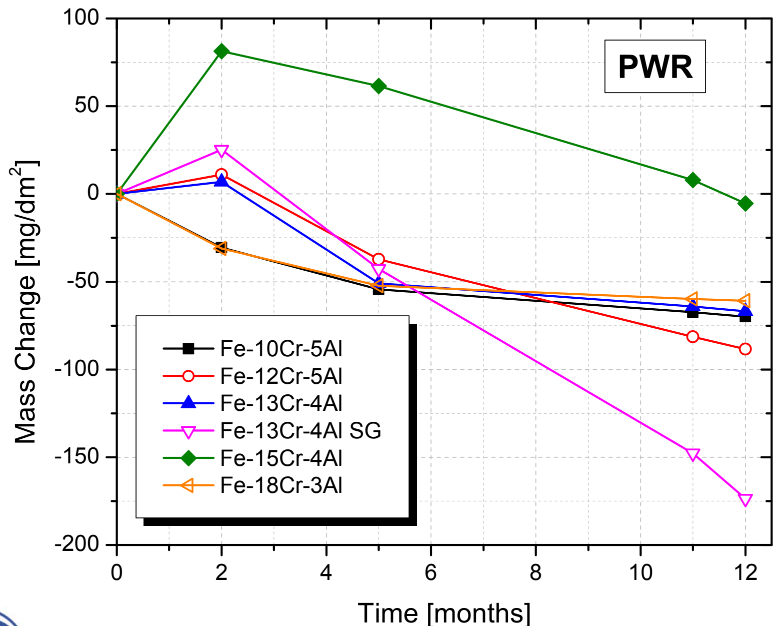


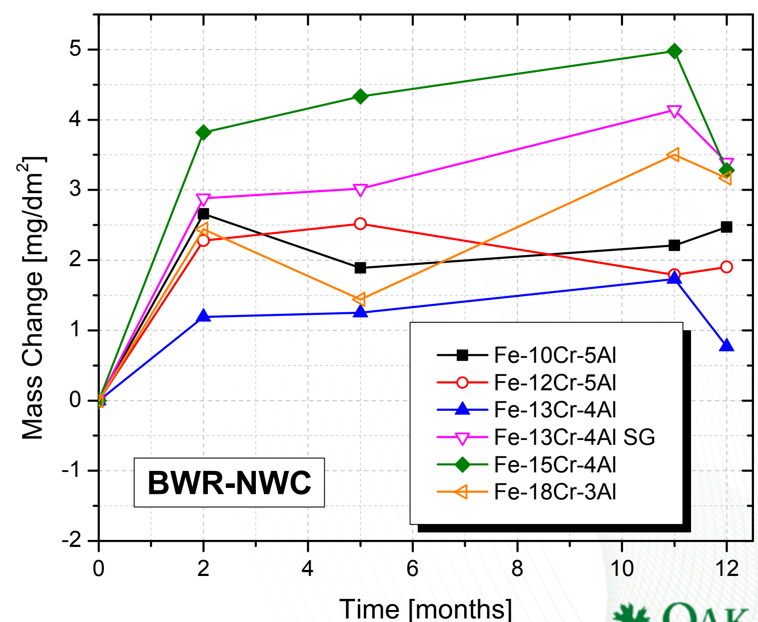
B. Pint et al., *Manuscript for Microscopy of Oxidation 9,* April 2014
B. Pint et al., *Metallurgical and Materials Transactions E*, submitted, 2014

Phase I: Cr and Al Content Effects on Hydrothermal Corrosion

- Minimal corrosion is observed after 1 year
- 100 mg/dm^2: 1.3 µm of metal loss (mass loss) or 6.3 µm of oxide formation (mass gain)
- No distinct Cr and Al effects.
- BWR-HWC and PWR: oxide films are M_3O_4 type with M a mixture of Fe and Cr. BWR-NWC, high oxygen activity, results in M_2O_3 type oxides.







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Phase I: Commercial Tube Fabrication

- Thin tube fabrication has been pursued by three labs with good results (LANL, ORNL, GE).

Cast (VIM)

Extruded

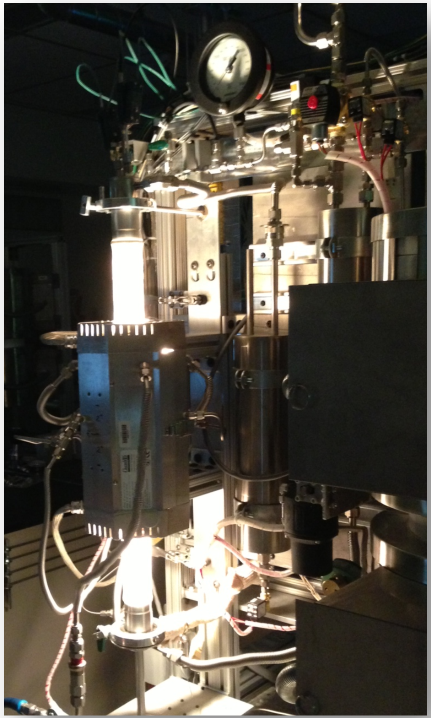
Machined

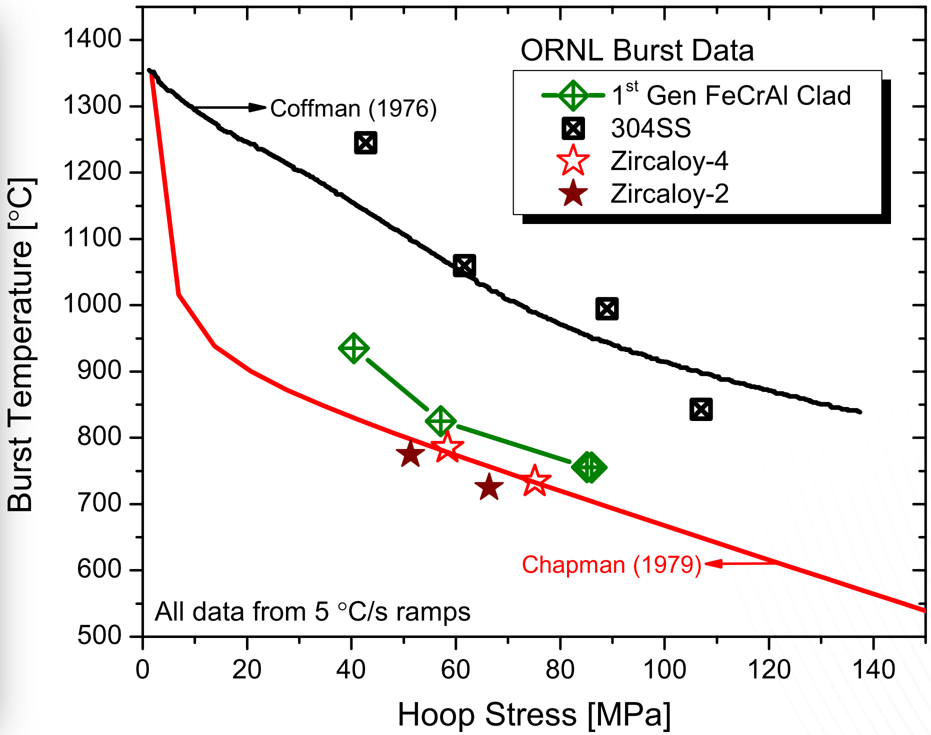
Tube-drawn

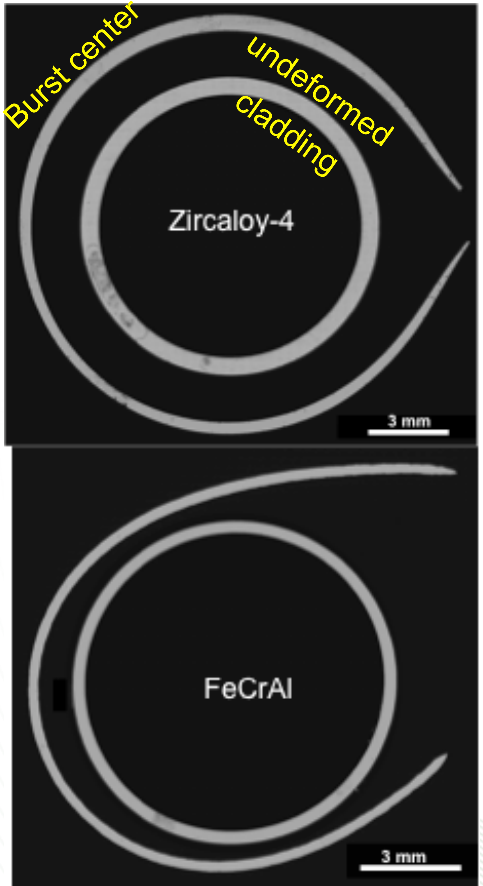
Phase I: LOCA Burst Testing of FeCrAl alloys

- modest improvement in burst behavior was observed for 1st Gen FeCrAl alloys while the extent of ballooning was much less, indicating that the magnitude of creep is negligible in these alloys.

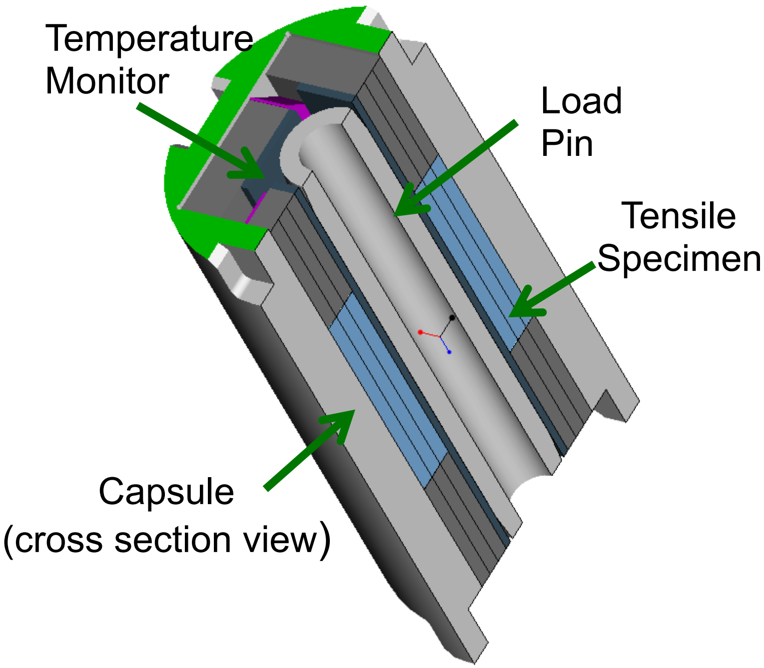
- Internally pressurized
- Steam outside
- 5°C/s heating
- To 1200°C
- 3°C/s cooling

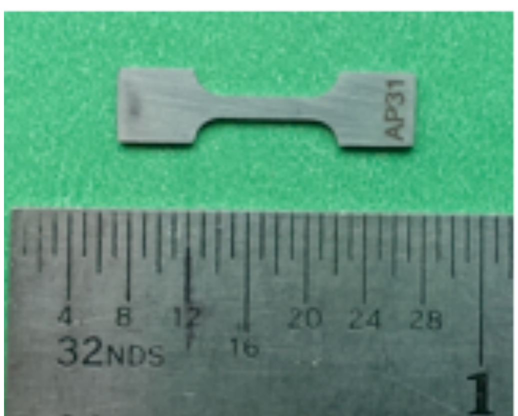






ORNL Phase-I FeCrAl HFIR Irradiation





HFIR Studies:

- 5 drop-in capsules (non-instrumented) containing 36 sub-sized tensile specimens (SS-J2) of the model Fe-Cr-Al alloys and 12 passive SiC thermometry, inserted into target bundle in flux trap; inserted Oct. 2013
  - Dose/fluence = 0.3 dpa ($3.7x10^{20}$ n/cm^2 E>0.1 MeV) 0.8 dpa ($9.3x10^{20}$ n/cm^2 E>0.1 MeV) 1.6 dpa ($1.8x10^{21}$ n/cm^2 E>0.1 MeV) 8.6 dpa ($9.6x10^{21}$ n/cm^2 E>0.1 MeV) target: 16 dpa (TBD)
  - Dose rate = $7.2x10^{-7}$ dpa/s
  - Target temperature: ~320 °C, nominal: ~340-390 °C
- All irradiations completed before Feb. 2015 (in 8 HFIR cycles)
- PIE completed using IMET and LAMDA facilities at ORNL
  - Three 'can' design (one shown above-left) used to facilitate quick disassembly

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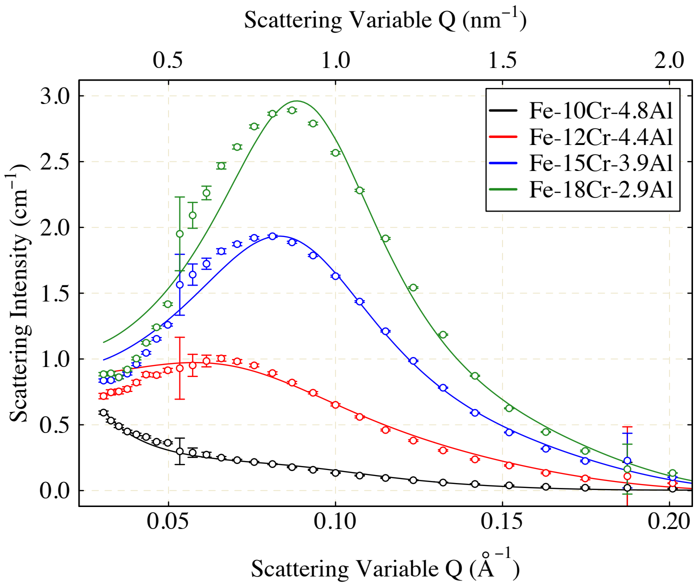
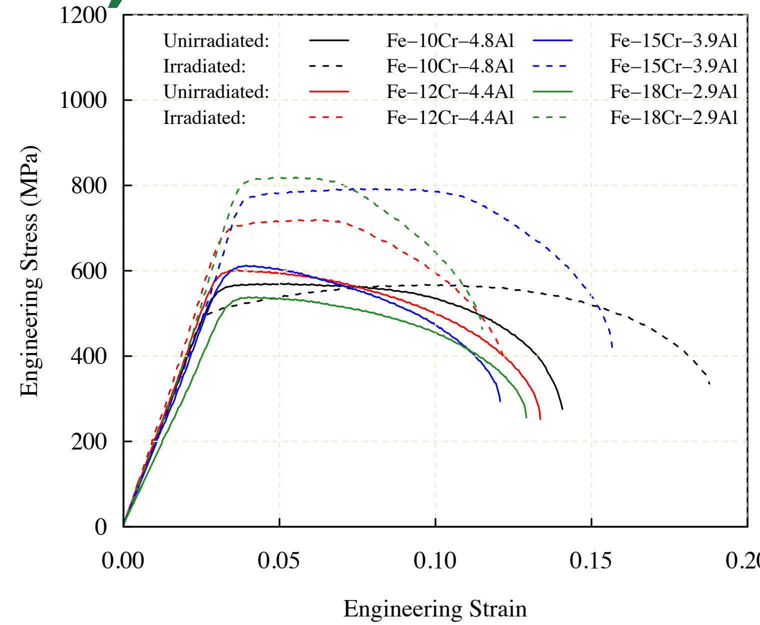
Summary of PIE Efforts of Neutron Phase-I FeCrAl Alloys (1.6 dpa, 387°C)

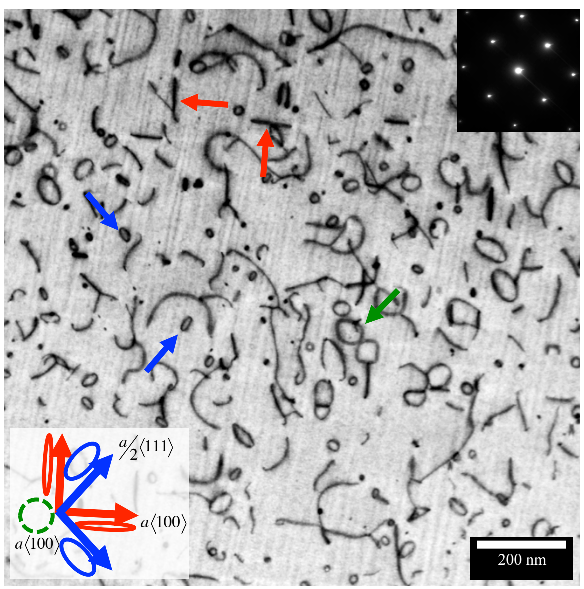
Phase Stability



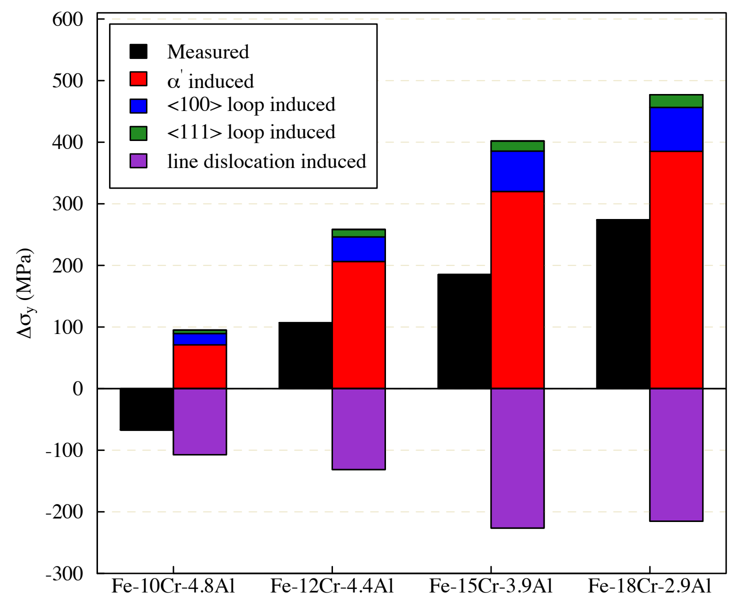
Tensile Properties



Dislocation Loop Formation



Structure-Property Relationship



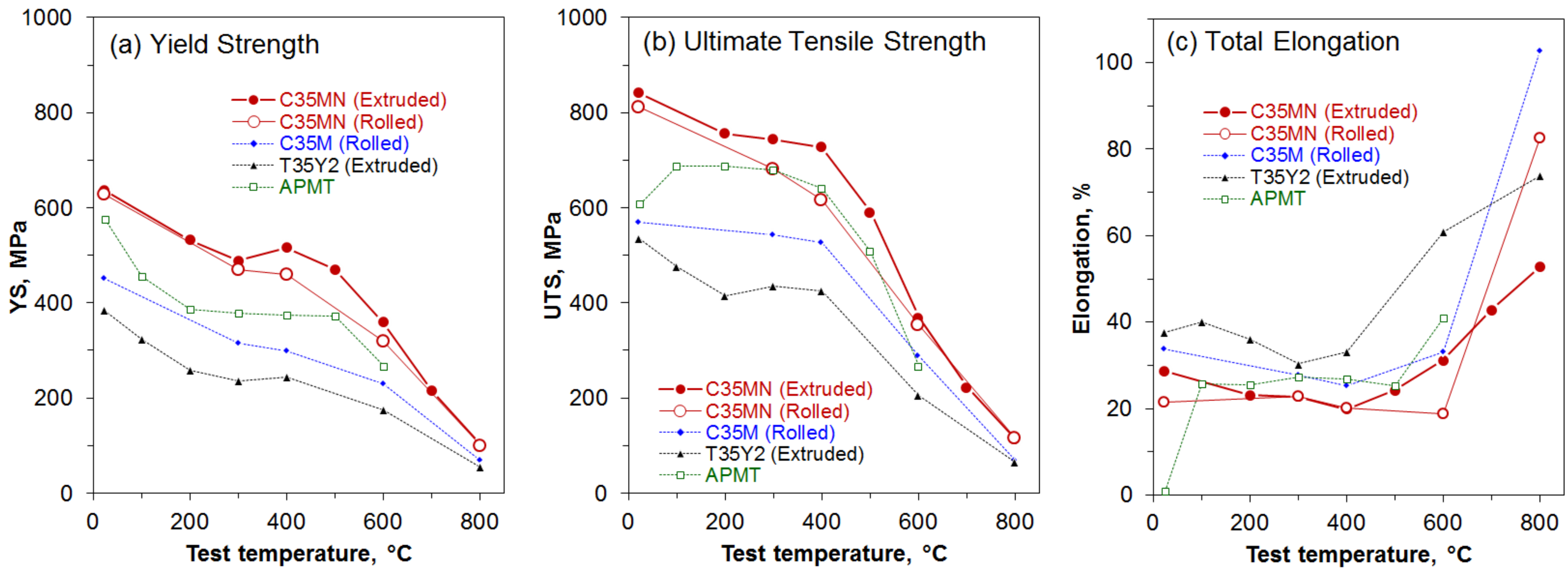
K. G. Field, X. Hu, K. C. Littrell, Y. Yamamoto, L. L. Snead, Radiation tolerance of neutron- irradiated model Fe-Cr-Al alloys, Under review in *Journal of Nuclear Materials*, 2015.

Selected Phase-II Alloy Development Activities

Phase-II Alloys: Optimization of Mechanical Properties

- Informed alloy development aided by computational thermodynamics

- High strength alloys with good ductility and formability have been produced



Y. Yamamoto, B. Pint, K. Terrani., K. Field, Y. Yang, L. L. Snead, Development and Property Evaluation of Nuclear Grade Wrought FeCrAl Fuel Cladding for Light Water Reactors, Under review in *Journal of Nuclear Materials*, 2015.

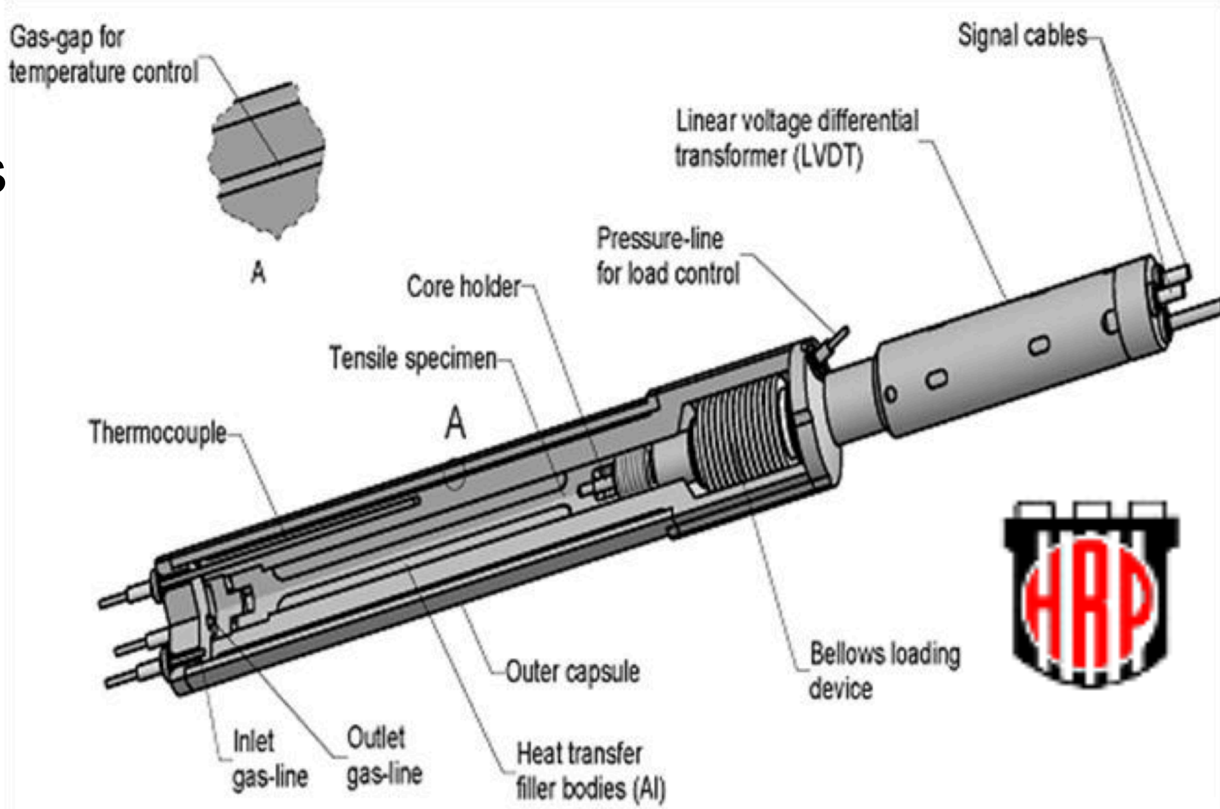
Phase II Alloys: In-pile Creep Testing

- To produce applicable and reliable irradiation creep data that can then be input to fuel performance analysis tools to predict ATF cladding behavior

- Tests started March 2015 with 4 capsules (2 alloys).

- Temperature 350°C, Max stress is 325 MPa (~2/3 YS).

- Results will be open to the community as they become available



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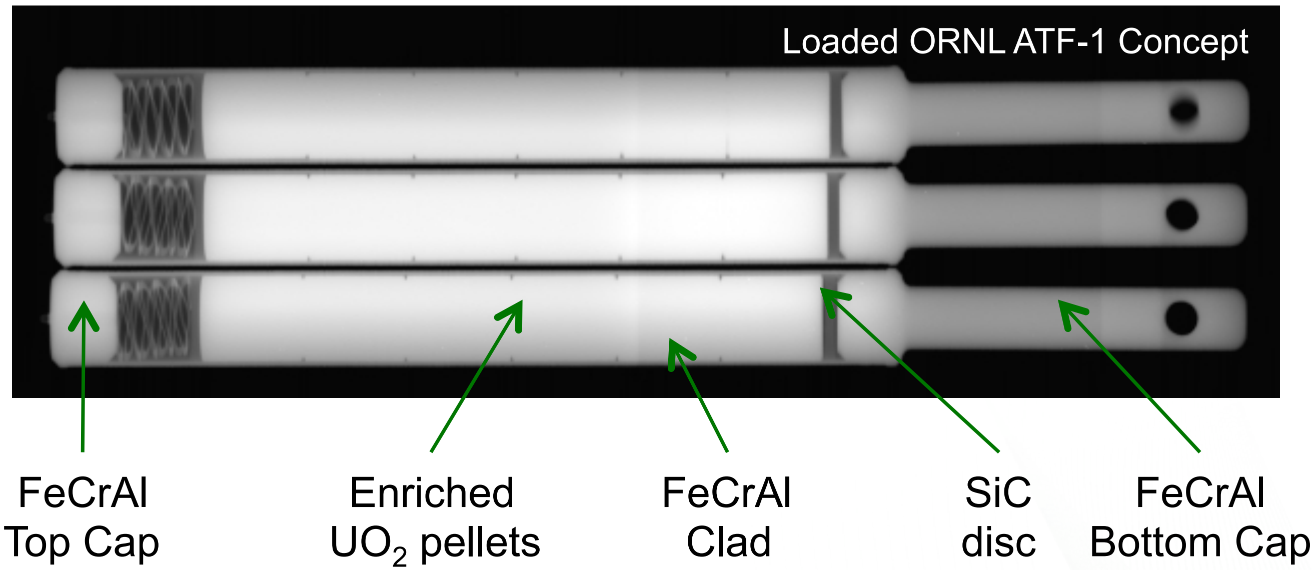
Fueled Irradiation Tests with Phase-II FeCrAl Thin Tubes (<400 μm)

- 3 rodlets containing UO_2 fuel pellets are being irradiated to 10, 30, and 50 GWd/MT in INL's Advanced Test Reactor
- Fe-13Cr-5.2Al-2Mo-0.2Si-1Nb-0.05Y cladding and end caps (C35MN)



- Instrumented tests at Halden ATF cladding rig in 2016. ORNL (representing US DOE) initiated the ATF rig under the joint program in the first.

Summary

- An extensive database (both engineering and scientific) in support of development and qualification of nuclear-grade FeCrAl alloys is being generated.
- This dataset will support introduction of a LTR in the coming years.
- ORNL is focused in identifying and optimizing a nuclear-grade wrought FeCrAl alloy for ATF cladding application, rather then examination of available commercial alloys optimized for other applications.
- Under Phase-II of US DOE program, close collaboration with GE and GNF will enable an effective transition toward field development of the engineered cladding.