Fuel Cycle Research and Development

Severe Accident Test Station (SATS) and alloy developments

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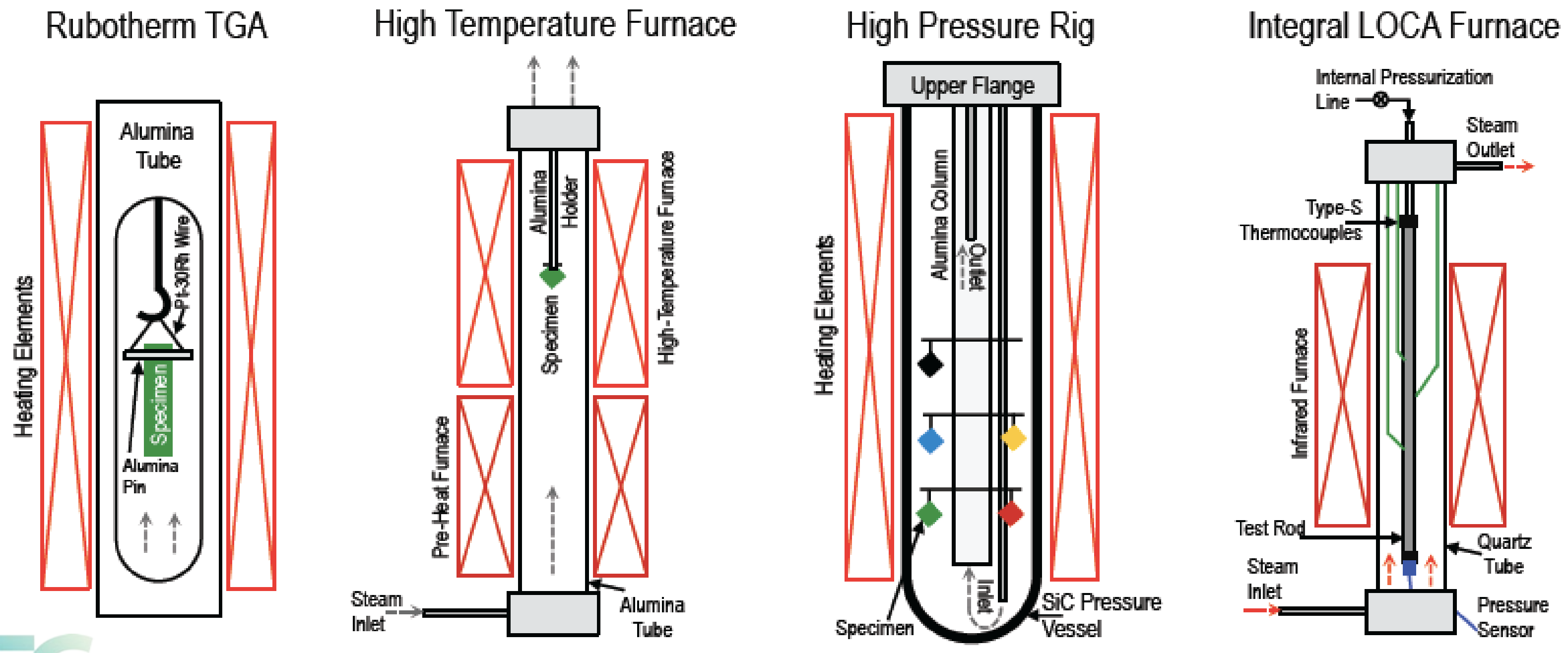
Oak Ridge National Laboratory

Severe Accident Test Station at ORNL

- **National facility for evaluating new cladding concepts**
  - Four modules with different capabilities
  - Steam to 1700°C and 1-30 bar



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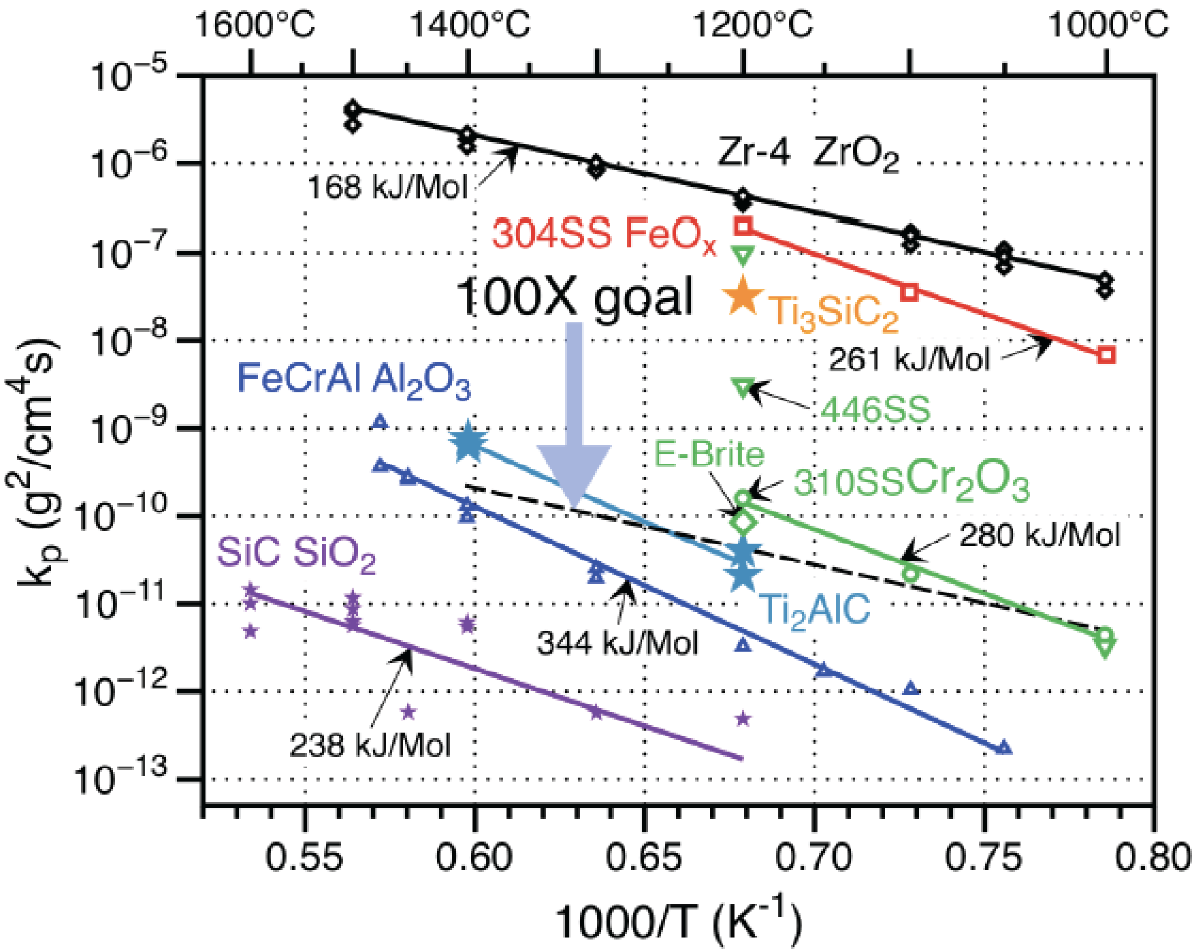
Several candidates meet >100X lower steam oxidation kinetics

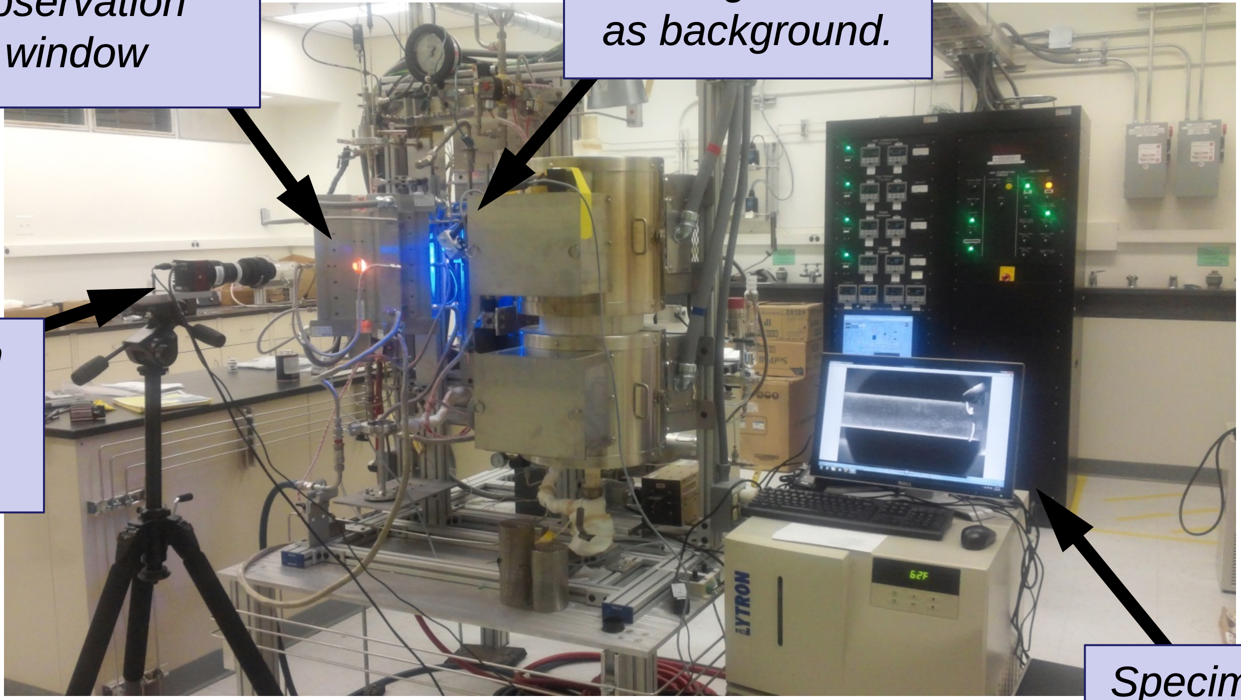


B.A. Pint et al., Met. Mater. Trans. E, in press

Several different experiments available in SATS modules

- **Rubotherm TGA (thermogravimetric analysis)**
  - Isothermal (4h) experiments → parabolic rate constant
  - Ramp (5°C/min) test in steam to 1500°C → maximum use Temp.
- **High Temperature Furnace Module**
  - Isothermal (~4h) experiments → mass change/microstructure
  - 1700°C maximum
- **Integral LOCA Furnace Module**
  - Burst test of pressurized tubes in steam → burst T vs. pressure
  - 305mm (12”) long, 9.5mm diameter tubing (not coupons, high TRL)
- **High Pressure/Temperature “Keiser” Rig**
  - 2012: minimal pressure effect on steam oxidation

Upgrade of LOCA furnace: View port for burst test



Trial run with optical imaging using port in IR furnace

Images obtained during the trial burst test from RT to 1100℃ (gif-animation)

- 304SS tube specimen heated to 1100°C.
  - No steam
- ~450 psi at burst
  - Internal tube pressure
- Images taken during test
  - In-situ measurements possible
- Development in progress
  - air convection issue
  - Incorporate quartz tube

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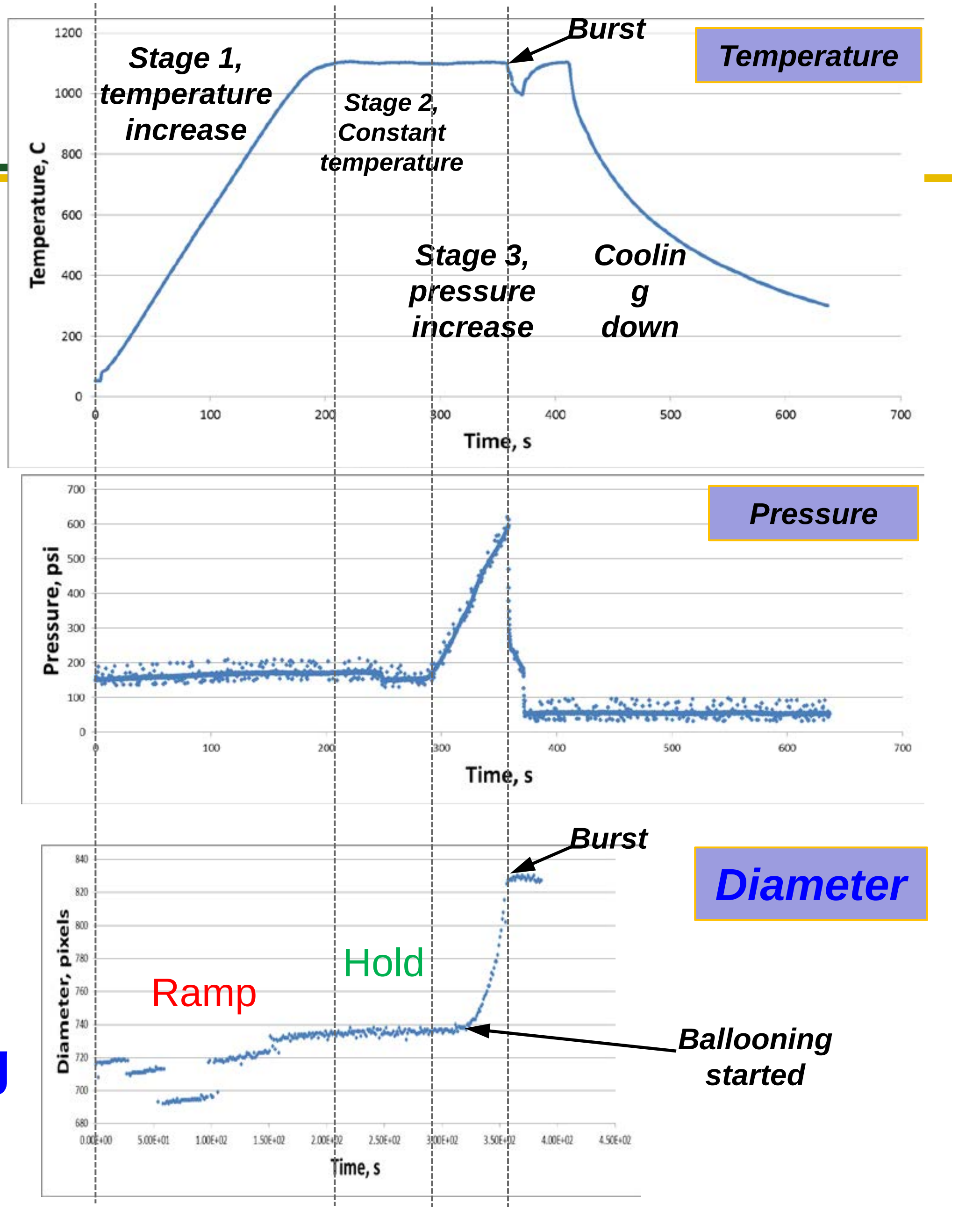
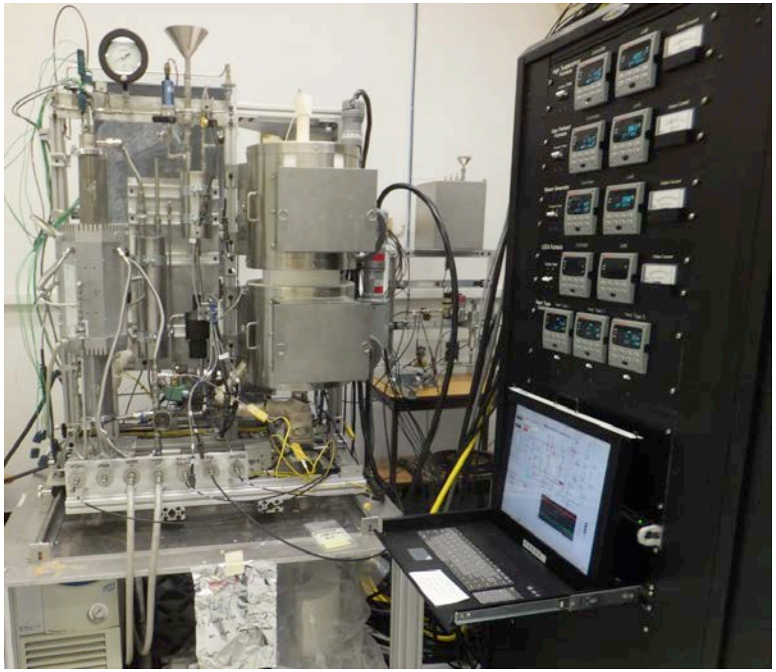
- **Data from trial run**
  - Tube pressurized
  - Heated in air
  - Heating to 1100°C
  - Plastic strain -> burst
  - Burst T, P identified
  - Image: diameter vs. time
- **Accuracy**
  - Current ±0.7%
    - Air convection issue
  - Possible ±0.2%
- **Future upgrade**
  - Incorporate quartz tube
  - Burst in steam
- **Unique Data for Modeling**
  - 2D strain data for BISON



In-cell SATS ready to deploy in hot cell

- High temperature and Integral LOCA modules
- FY15: Worked with hot cell staff to correct minor issues
- Hot cell space has been prepared to receive SATS and plugs ready to install
- Operating procedure complete and reviewed
- Awaiting insertion and demonstration funding
  - Demo on commercial fuel rod



Community Testing

- General Electric – work now covered under FOA
- Westinghouse – SiC/SiC steam testing 1300°-1500°C
- Halden Project – CrN coatings on Zircaloy

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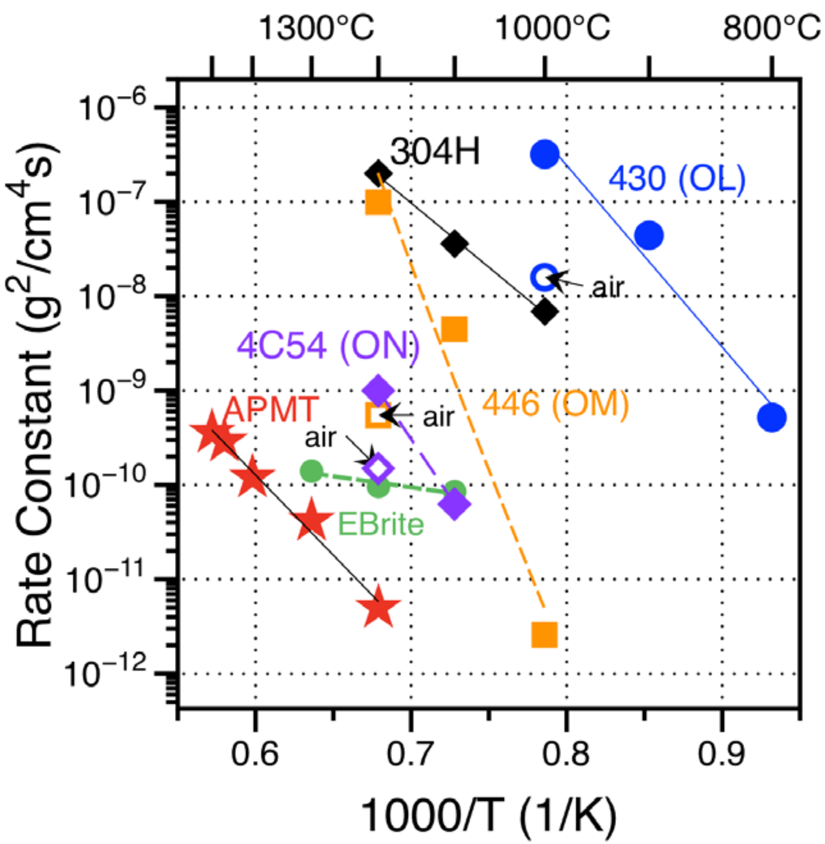
GE evaluating FeCrAl and FeCr alloys

- **Initial results on steam oxidation of FeCr alloys**
  - Plan "B" (FeCrAl is plan A)
- **Surprising that few were protective at 1200°C**
- **Further work will examine the effect of minor elements on oxidation resistance**
  - Mn, Si, Ti, Y, etc.
  - Model Fe-Cr-X alloys



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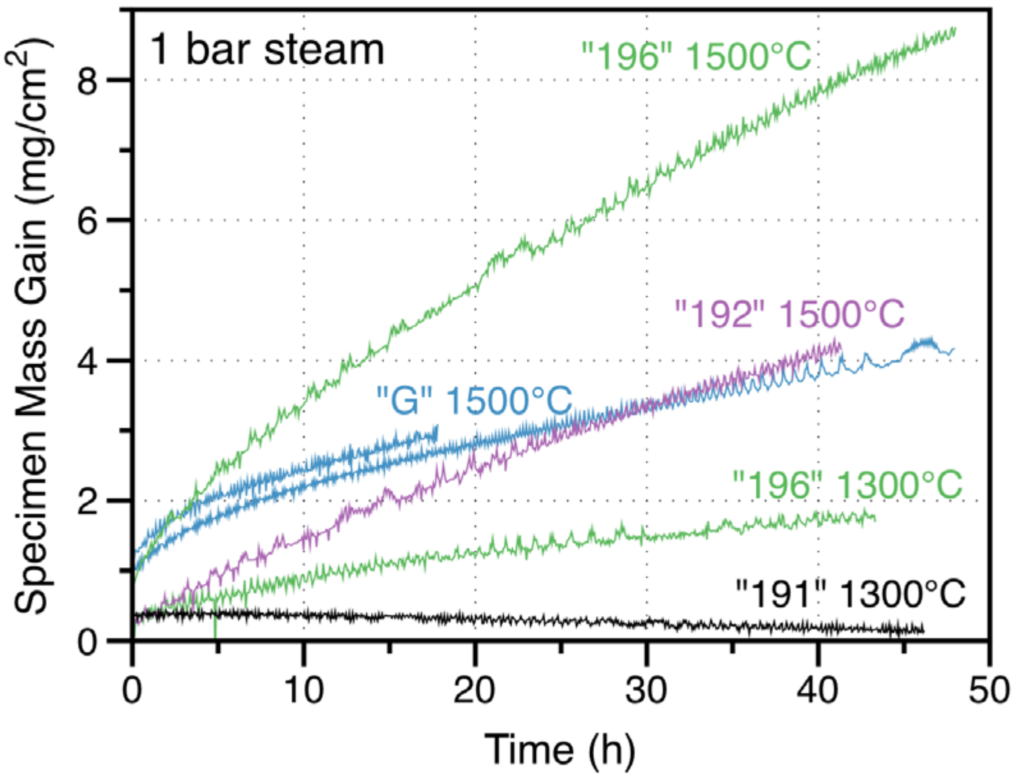
ICP analysis of Fe-Cr alloys

Alloy	Cr	Mn	Si	Al	N	S	Other
Gr.91	9.1	0.39	0.24	<	0.052	0.0122	0.86 Mo
405	12.9	0.48	0.37	0.26	0.023	<3	0.003 Ti
430	16.7	0.49	0.26	0.004	0.031	0.0009	0.002 Ti
446	24.9	0.76	0.19	<	0.108	0.0098	0.003 Ti
4C54	25.4	0.71	0.49	<	**0.167**	0.0036	0.004 Ti
E-Brite	25.8	<	0.22		0.008	0.0100	1.0 Mo
Model	25.0	0.67	0.25	0.01	0.001	0.0030	**0.002 Y**

Inductively coupled plasma analysis –
optical emission and mass spectroscopy

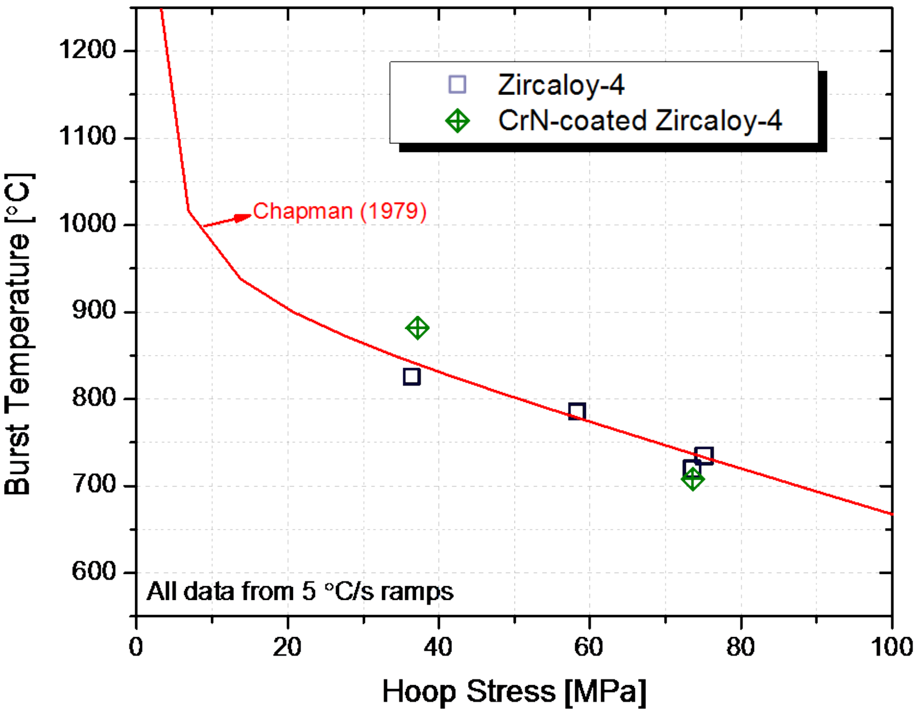
Westinghouse: SiC/SiC composite specimens at 1300°-1500°C



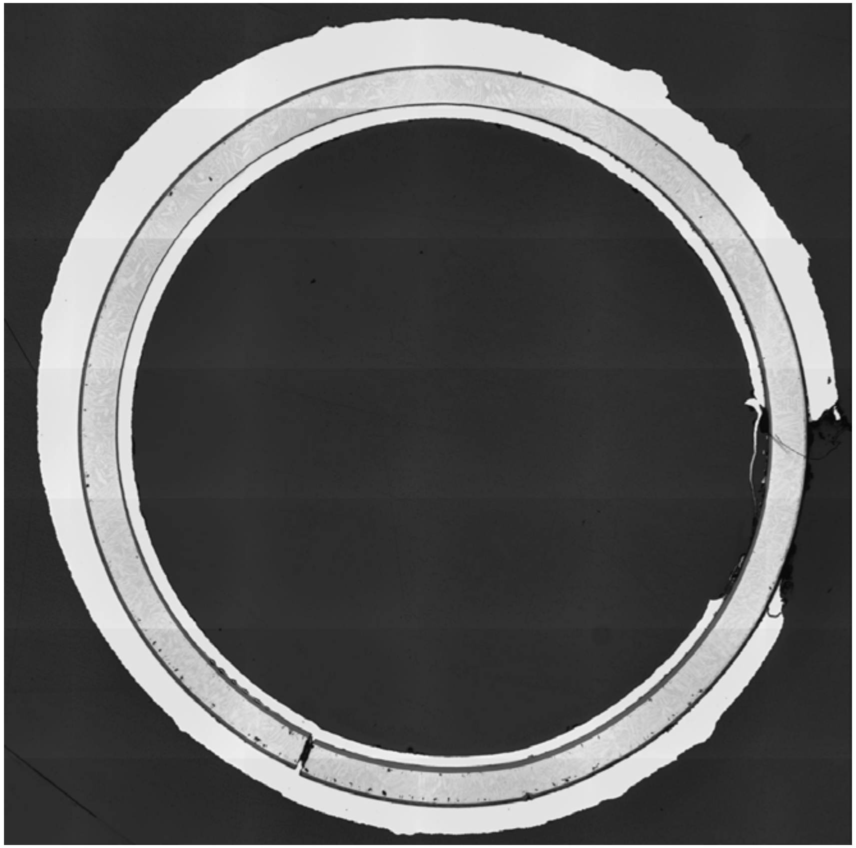
- **Very long exposures**
  - Normally 4h tests
  - Several furnace failures
- **Several SiC/SiC compositions**
- **Much higher mass gains than for CVD SiC**

Burst-testing: CrN coated Zircaloy

- **Coated tubes received from Halden Project**
- **Proprietary, wear-resistant CrN coating**
  - Not an ATF concept
  - Resistant to fretting wear
  - Completed in-pile testing with fuel
- **Similar burst temperatures as uncoated Zircaloy-4 tubes**



Metallography of burst tubes



Zircaloy-4

CrN coated Zr-4

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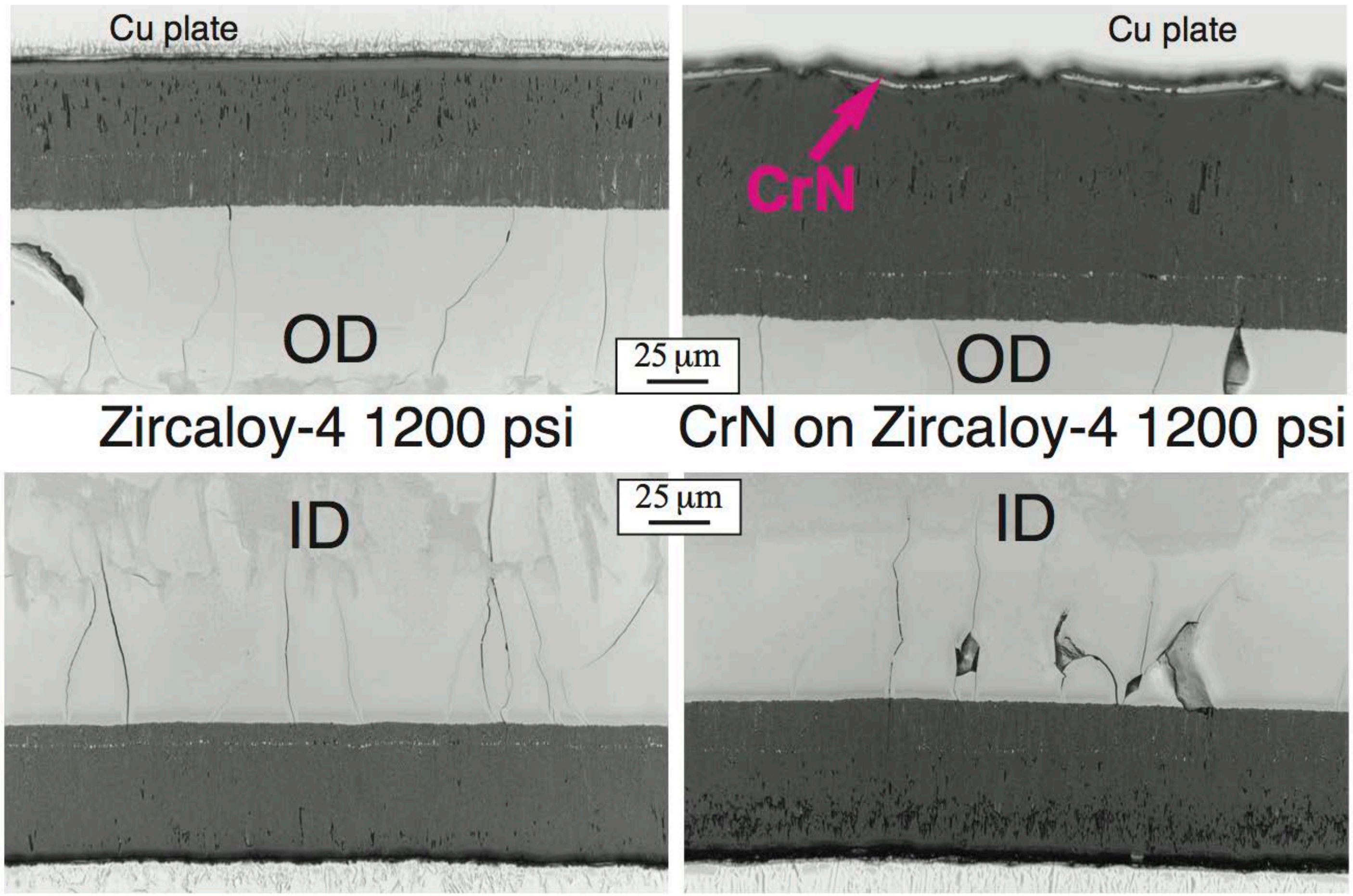
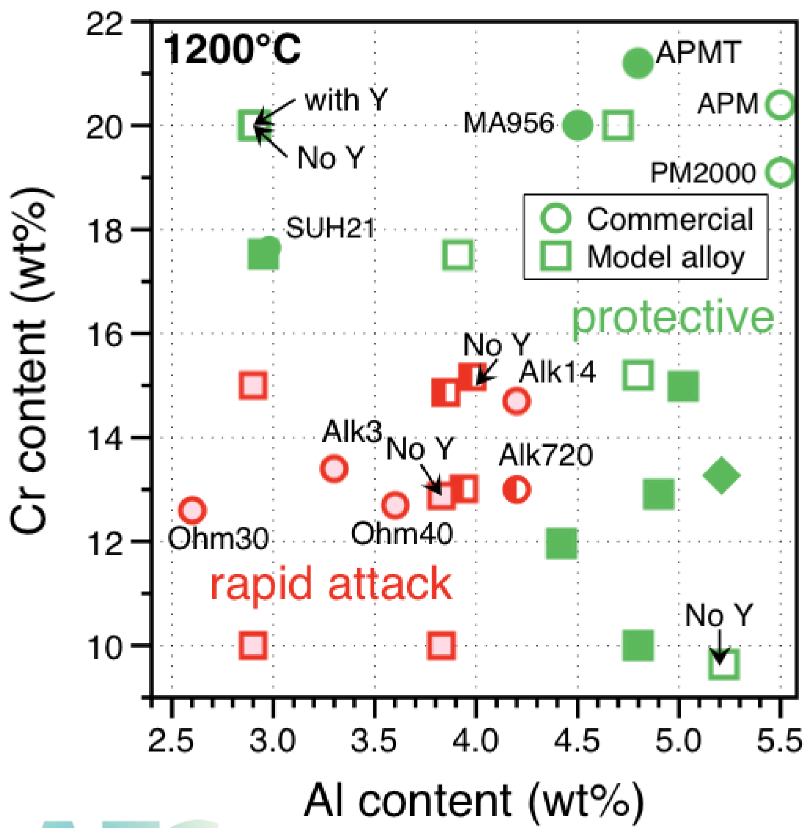
Similar oxide scale formed with and without the CrN coating

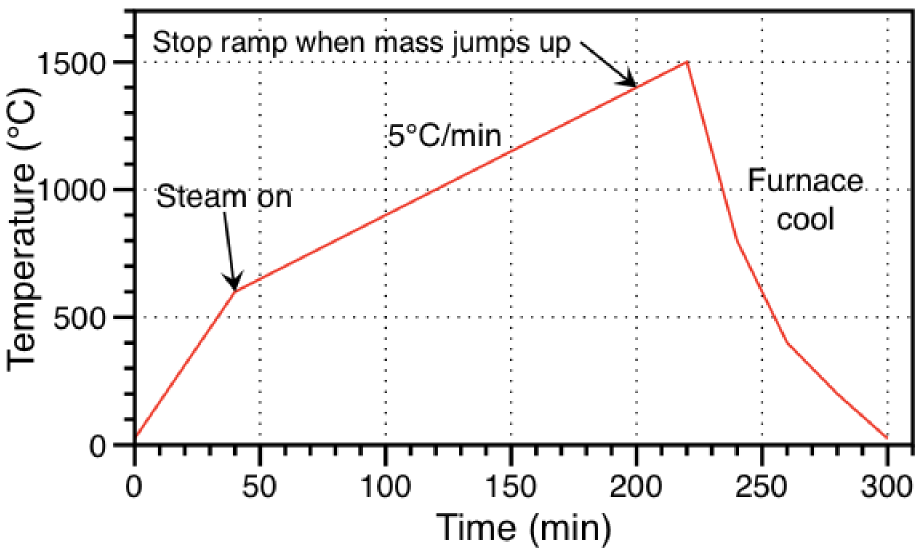


FeCrAl oxidation: Ramp testing followed 1200°C screening

2012-2013 testing



~2014 testing



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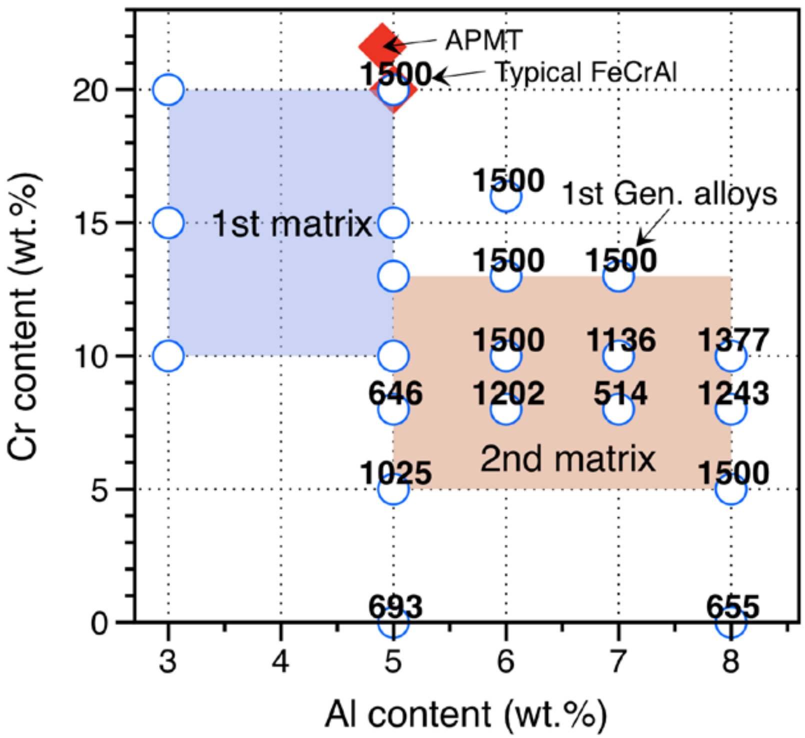
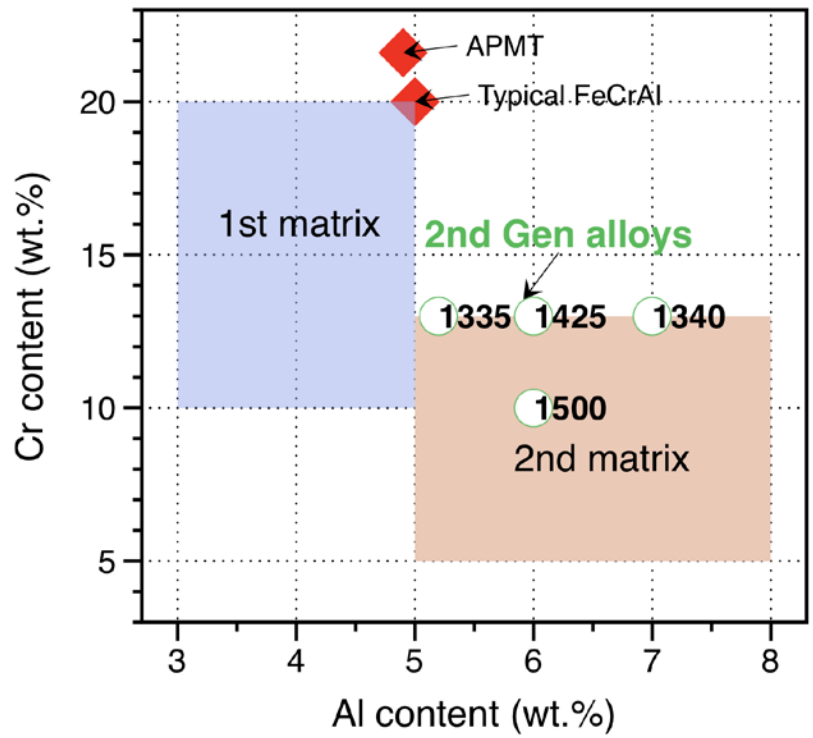
Ramp testing of new FeCrAl compositions

1st Gen. FeCrAl alloys



2nd Gen. FeCrAl alloys



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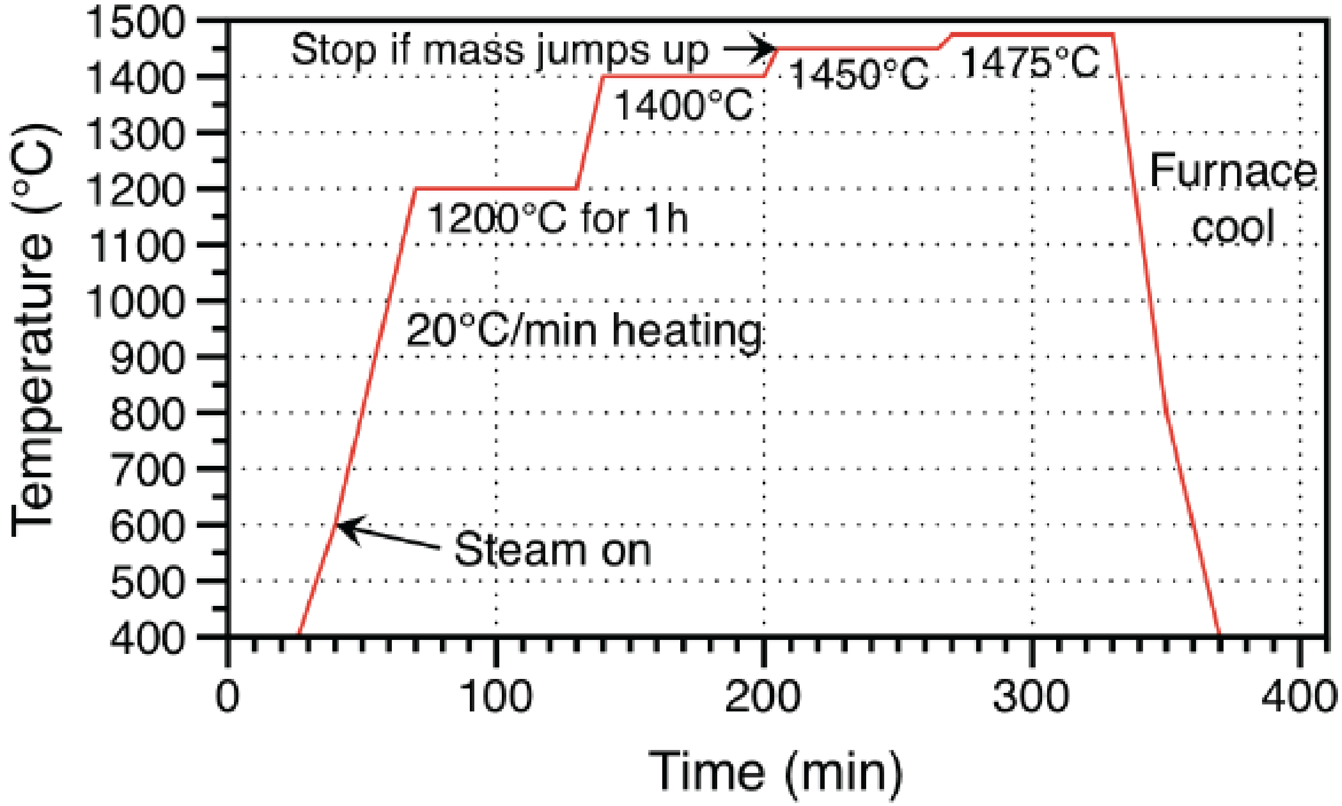
Inconsistent behavior between ramp and 1400°C isothermal tests

Alloy	Ramp T_{max}	1400°C isothermal
B 20Cr 5Al	1500	✔
B 10Cr 6Al	1500	✖
B 10Cr 7Al	1136	–
B 10Cr 8Al	1377	✔
B 13Cr 6Al	1500	✖
B 13Cr 7Al	1500	✖
B 16Cr 6Al	1500	✖
C 10Cr 6Al	1500	✖
C 13Cr 6Al	1425	✖

Hypothesis: 1400°C steam too severe for bare, low-Cr FeCrAl

"Step" test at 1200°-1475°C developed to test hypothesis



Rubotherm TGA: stop testing if rapid oxidation

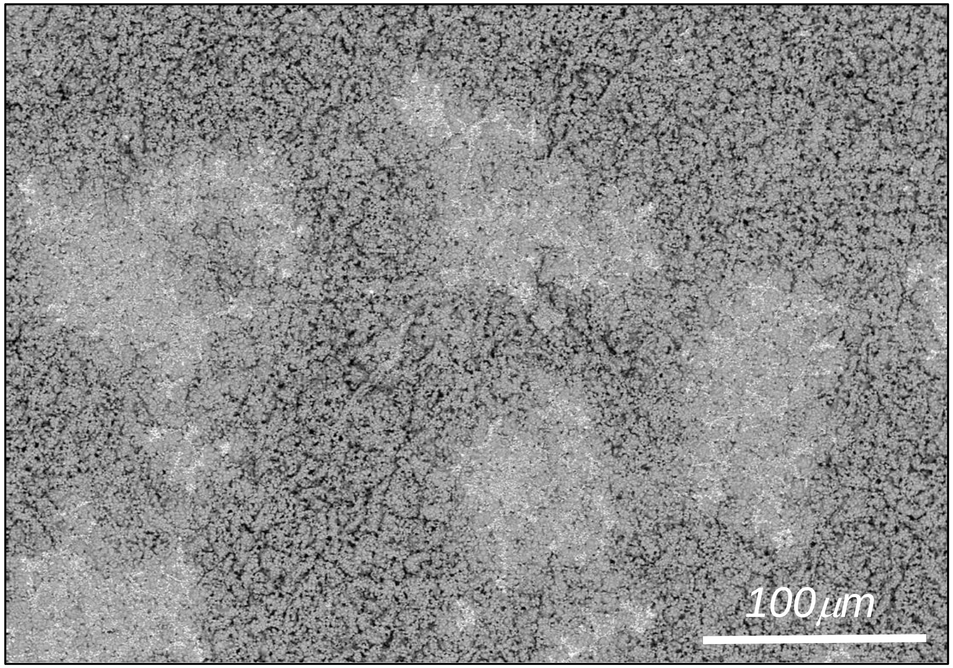
Step test results more consistent with ramp test results

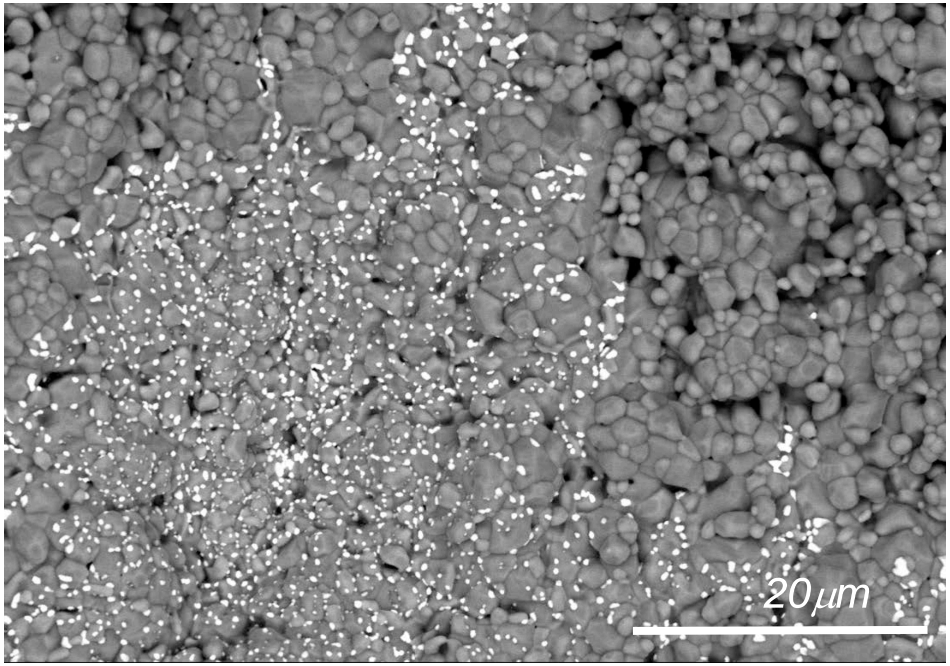
Alloy	Ramp T_{max}	1400°C steam	Step to 1475°C
B 20Cr 5Al	1500	✔	
B 10Cr 6Al	1500	✖	✔
B 10Cr 7Al	1136	–	✔
B 10Cr 8Al	1377	✔	✔
B 13Cr 6Al	1500	✖	
B 13Cr 7Al	1500	✖	
B 16Cr 6Al	1500	✖	
C 10Cr 6Al	1500	✖	✔
C 13Cr 6Al	1425	✖	✔

- Final "step": 1h steam oxidation at 1475°C
- Solidus temperature: ~1520°C
- Pre-oxidation important to ≥1400°C steam resistance
- Initiated study of flow rate effect on oxidation

Top view Fe-10Cr-8Al-Y after 4h at 1400ºC

Dense Yttria-rich alumina area + Areas with alumina grain clusters





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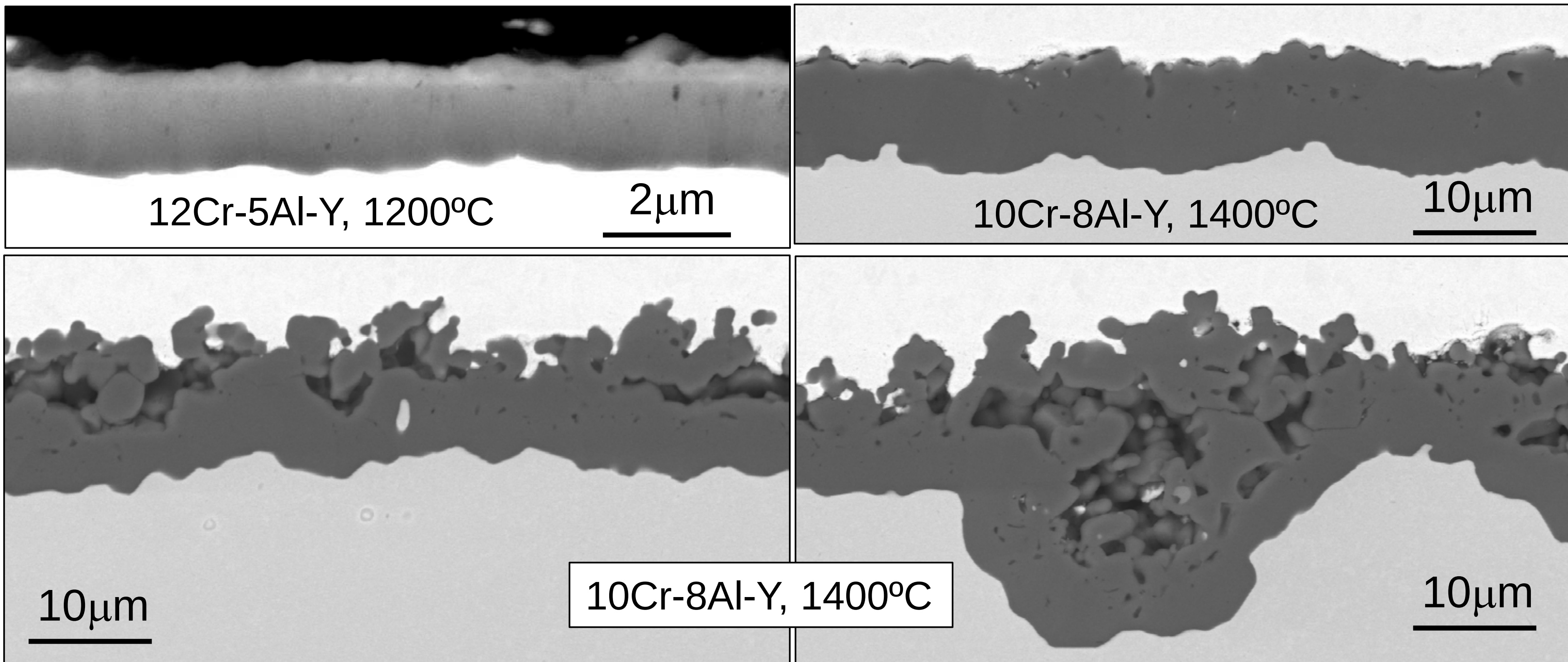
New alumina degradation mechanisms at 1400ºC in steam?

Degradation mechanisms not observed at 1350ºC in Air
Could affect early formation of alumina scale



4h steam testing

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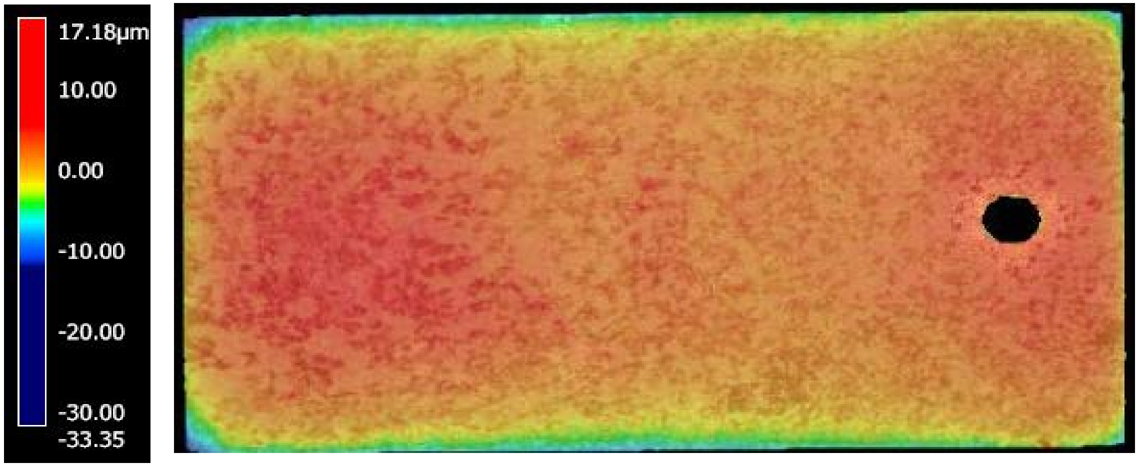
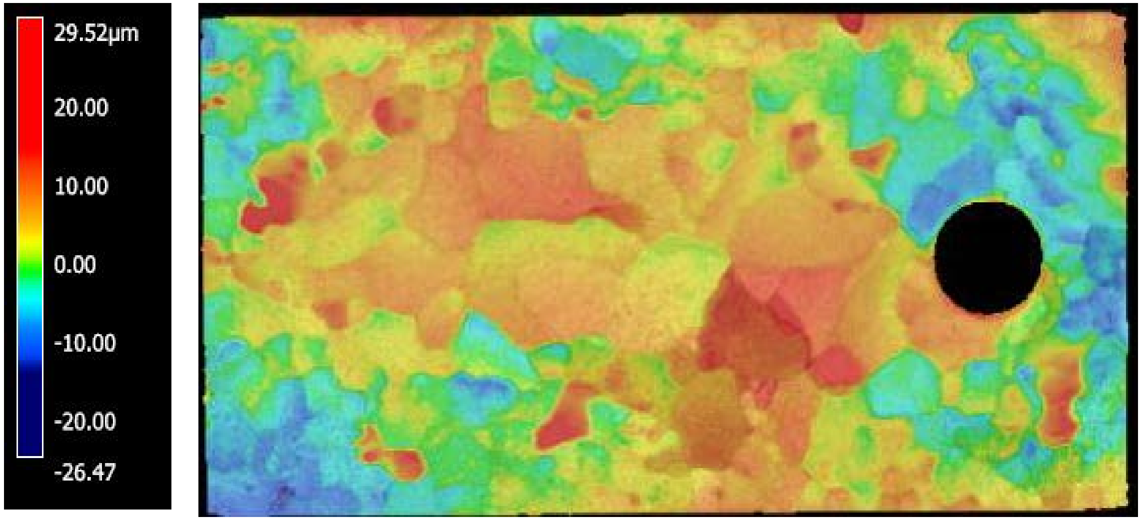
3D macroscopic height maps show grain deformation



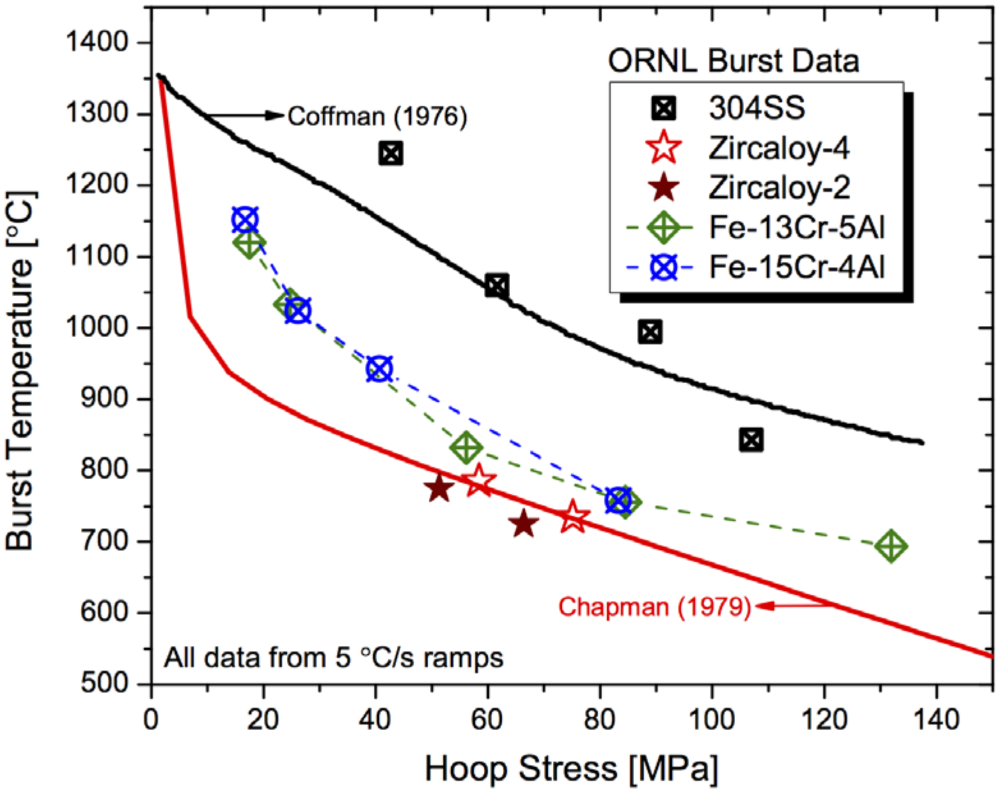
Fe-10Cr-6Al
4h at 1200°C



Fe-10Cr-6Al
4h at 1400°C

Burst testing of 1st generation FeCrAl alloys

- **Additional tubing made by LANL**
  - 1st generation alloys
  - Fe-13Cr-5Al+Y
  - Fe-15Cr-4Al+Y
- **Awaiting commercial tubing to test 2nd generation FeCrAl alloys**



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Summary

- **Severe Accident Test Station is deployed and actively operating**
  - Four modules with different capabilities for high temperature steam testing
  - ~240 specimens so far in FY15
  - New imaging capability to assist model development
- **In-cell version is awaiting deployment in hot cell**
  - Re-establishing US capability for LOCA testing of commercial fuel rods
- **SATS used to support FCRD community**
  - GE work supported under FOA
  - SiC/SiC exposures for Westinghouse
  - Halden Project: Burst test CrN coatings
- **ORNL focus on FeCrAl oxidation**
  - Expanded composition matrix to 8%Al and 0-13%Cr
  - "ramp" and "step" tests confirm alumina formation to 1475°C
  - Current interest in 6%Al and 10-13%Cr alloys