Oxidation of Alloys Targeted for Advanced Steam Turbines

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Abstract

Ultra supercritical (USC) power plants offer the promise of higher efficiencies and lower emissions. Current goals of the U.S. Department of Energy's Advanced Power Systems Initiatives include coal generation at 60% efficiency, which would require steam temperatures of up to 760°C. This research examines the steamside oxidation of alloys for use in USC systems, with emphasis placed on applications in high- and intermediate-pressure turbines.

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Office of Fossil Energy

Outline

- Introduction and Background
- Research Approach
- Results of Research in Progress
- Summary

Introduction

- **Project funded out of the Advanced Research (AR) Program of Fossil Energy (FE) of DOE**
- **In support of DOE Advanced Power System goals of 60% efficiency from coal generation that require USC steam turbine conditions of:**
  - 760°C (1400°F)
  - 37.9 MPa (5500 psi)

Efficiency Improvement over a Subcritical 16.5 MPa/538°C/ 538°C Plant

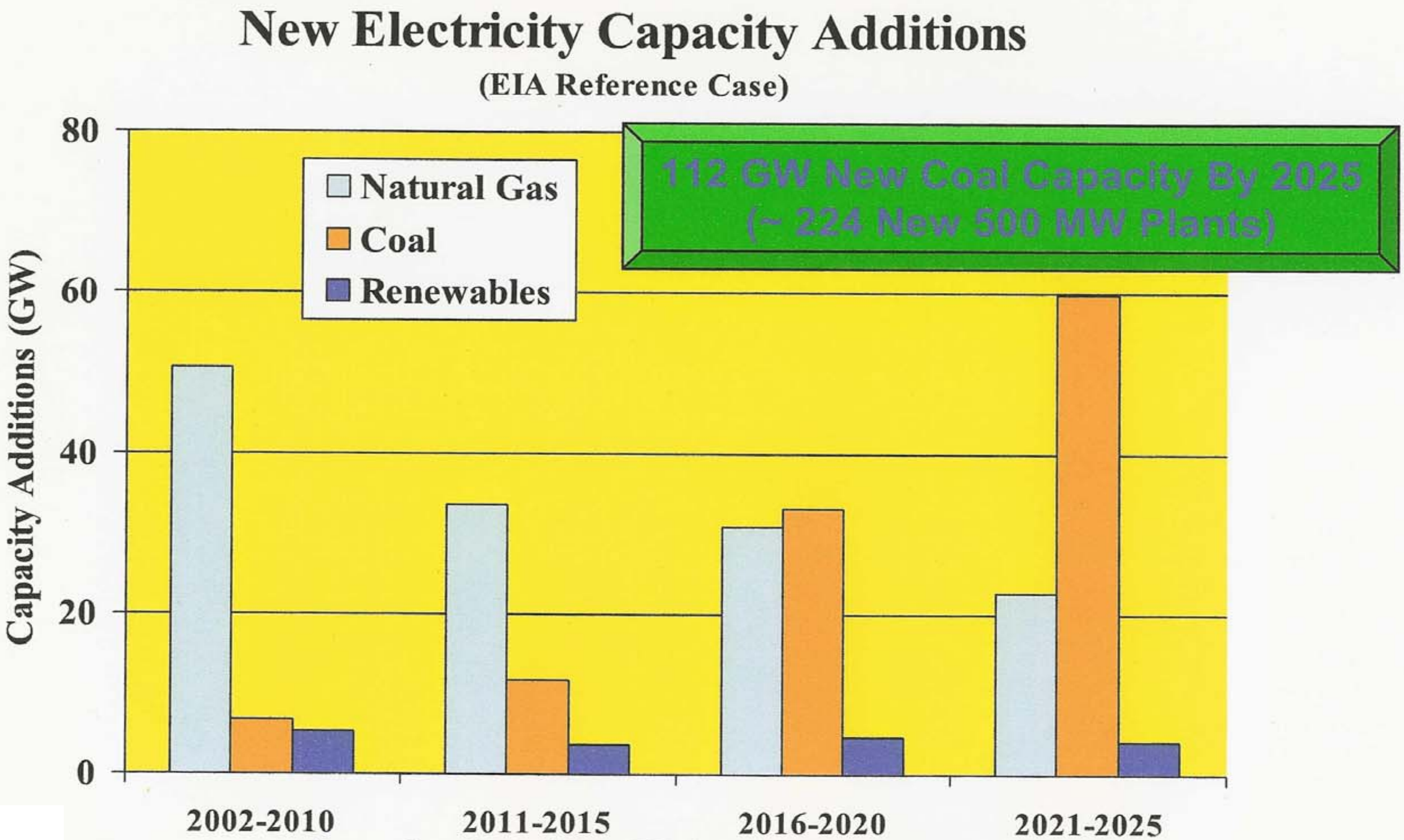
Steam Conditions	Recent Power Plant Examples	Net Percentage Point Increase in Efficiency	Net Plant Efficiency, %
28.4 MPa/538/566°C	Schwarze – 1998	2.9	39.9
		4.0	41.0
		4.5	41.5
		4.9	41.9
31.0 MPa/593/621°C	Alvedore 1 – 2000 Westfalen – 2004	5.2	42.2
31.0 MPa/593/593/593°C	Nordjylland - 1998	6.5	43.5

Each 1% increase in efficiency eliminates ~1,000,000 tons of CO_2 emissions over the lifetime of an 800-MW plant

Swanekamp, 2002

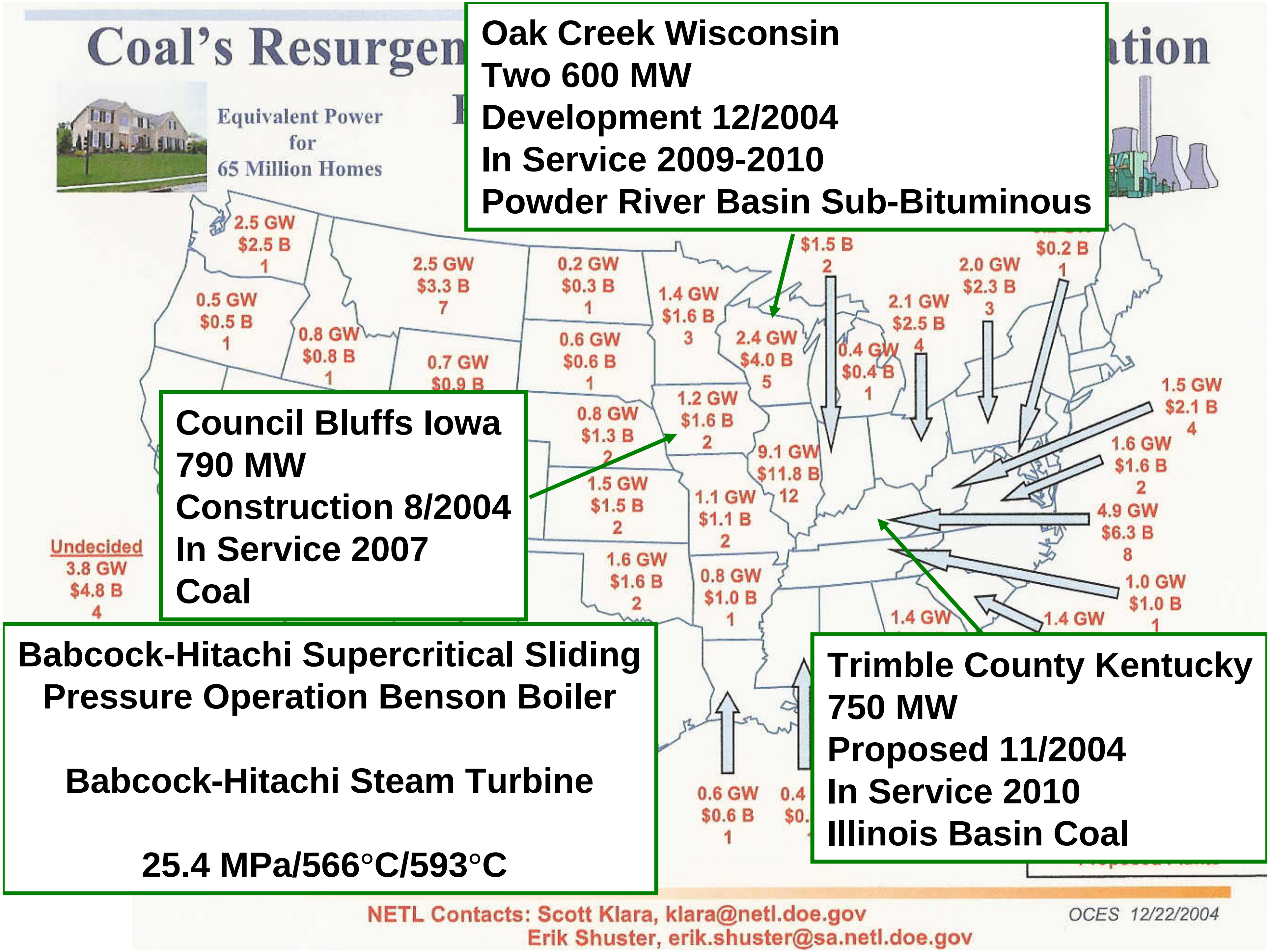
112 GW New Coal Capacity By 2025

(Accounts for 42% of New Capacity Additions)



Source: Data Derived From EIA Annual Energy Outlook 2004

NETL Contacts: Scott Klara, klara@netl.doe.gov
Erik Shuster, erik.shuster@sa.netl.doe.gov



Coal's Resurgen
ation
Equivalent Power
for
65 Million Homes
Oak Creek Wisconsin
Two 600 MW
Development 12/2004
In Service 2009-2010
Powder River Basin Sub-Bituminous
Council Bluffs Iowa
790 MW
Construction 8/2004
In Service 2007
Coal
Babcock-Hitachi Supercritical Sliding Pressure Operation Benson Boiler
Babcock-Hitachi Steam Turbine
25.4 MPa/566°C/593°C
Trimble County Kentucky
750 MW
Proposed 11/2004
In Service 2010
Illinois Basin Coal
2.5 GW $2.5 B 1
0.5 GW $0.5 B 1
0.8 GW $0.8 B 1
2.5 GW $3.3 B 7
0.7 GW $0.9 B
0.2 GW $0.3 B 1
0.6 GW $0.6 B 1
0.8 GW $1.3 B 2
1.5 GW $1.5 B 2
1.6 GW $1.6 B 2
1.4 GW $1.6 B 3
1.2 GW $1.6 B 2
1.1 GW $1.1 B 2
0.8 GW $1.0 B 1
2.4 GW $4.0 B 5
9.1 GW $11.8 B 12
$1.5 B 2
0.4 GW $0.4 B 1
2.1 GW $2.5 B 4
2.0 GW $2.3 B 3
$0.2 B 1
1.5 GW $2.1 B 4
1.6 GW $1.6 B 2
4.9 GW $6.3 B 8
1.0 GW $1.0 B 1
1.4 GW
1.4 GW
0.6 GW $0.6 B 1
0.4
Undecided 3.8 GW $4.8 B 4
NETL Contacts: Scott Klara, klara@netl.doe.gov
Erik Shuster, erik.shuster@sa.netl.doe.gov
OCES 12/22/2004

Research Goals

- Determine the steamside oxidation behavior of target alloys for use in USC turbines
- Determine the role of pressure on oxidation mechanisms
- Examine curvature effects on spallation

High Pressure (HP) Turbine

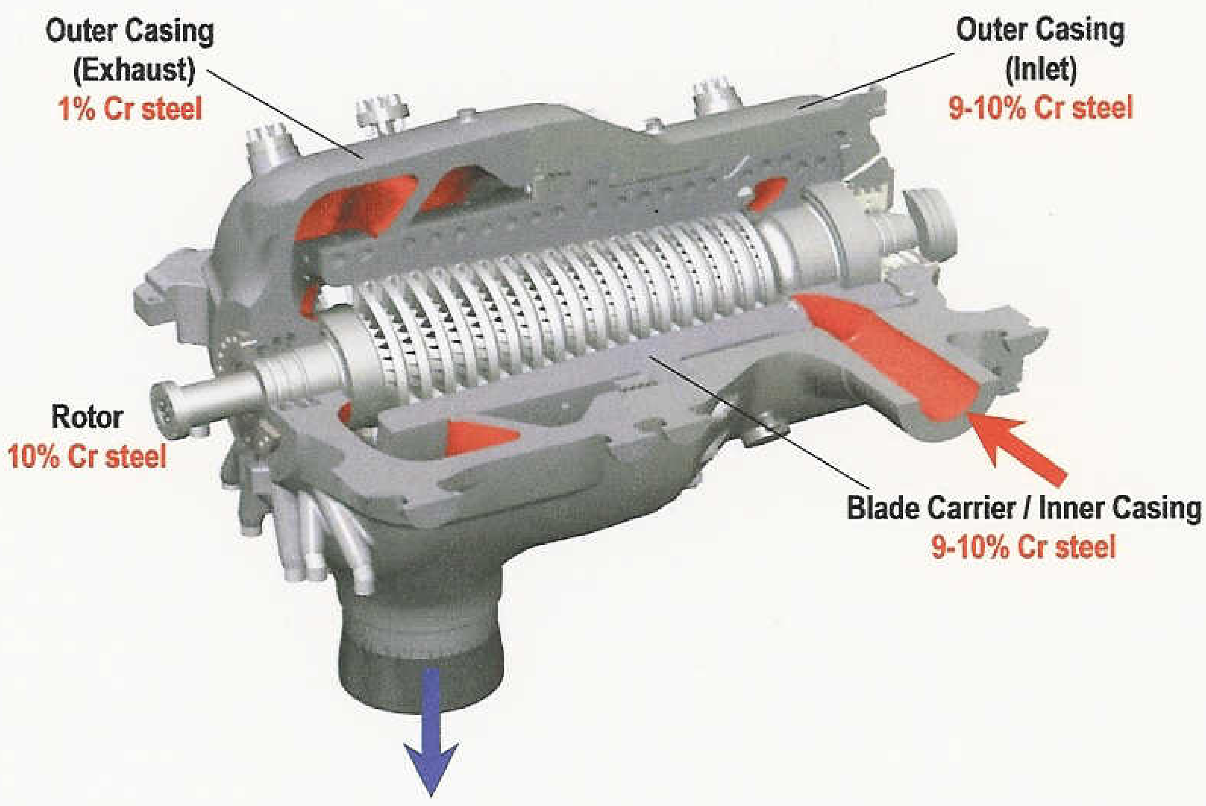


Figure 5. HP Turbine with Axial Divided Barrel Design for Steam Conditions 300bar/600°C (4350psia/1112°F)

Kern et al., 2004

Steam Cooled IP Turbine

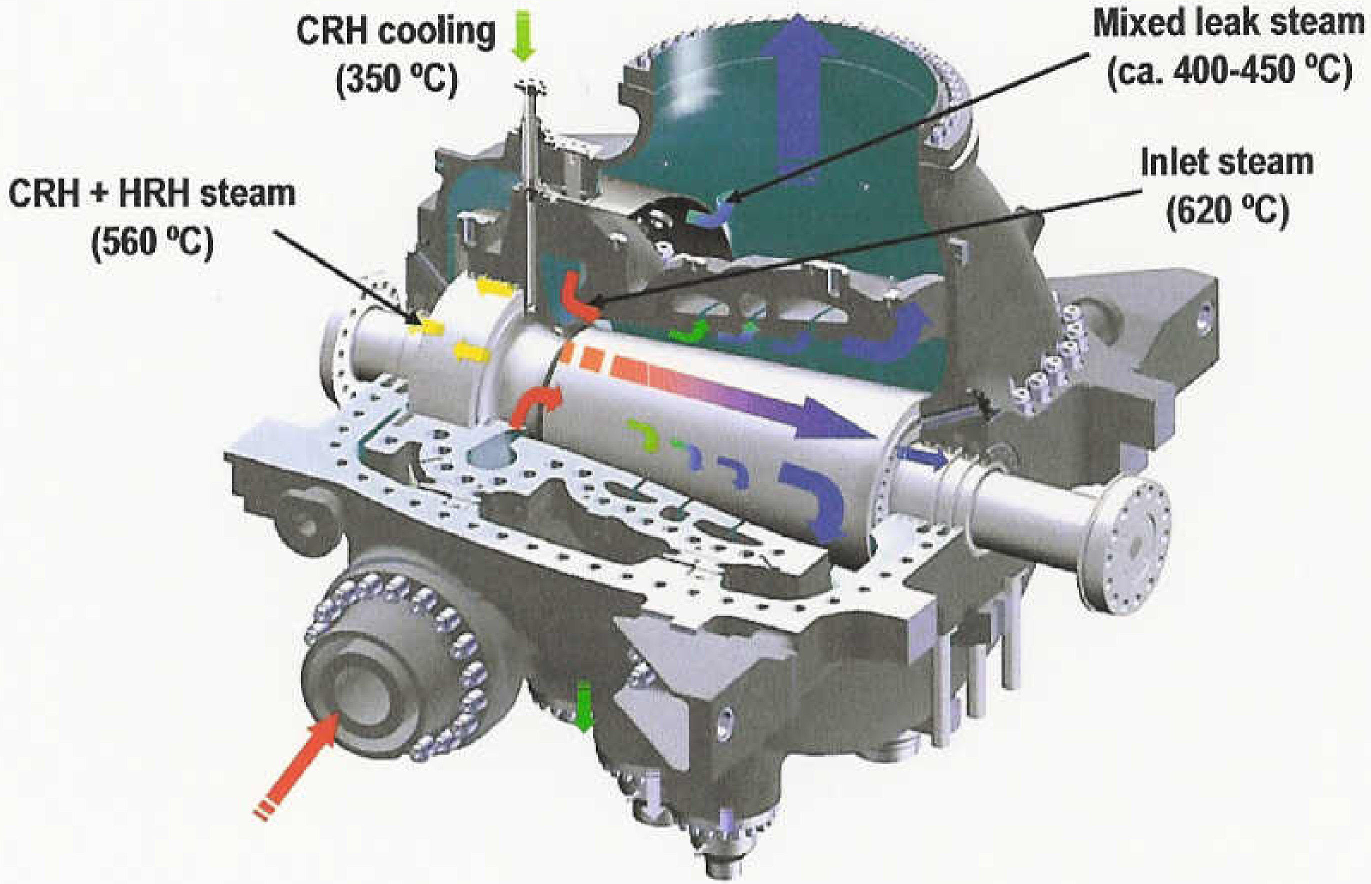


Figure 7. IP Turbine in Single Flow Design with External Cooling for 620°C Application

Kern et al., 2004

Engineering Options

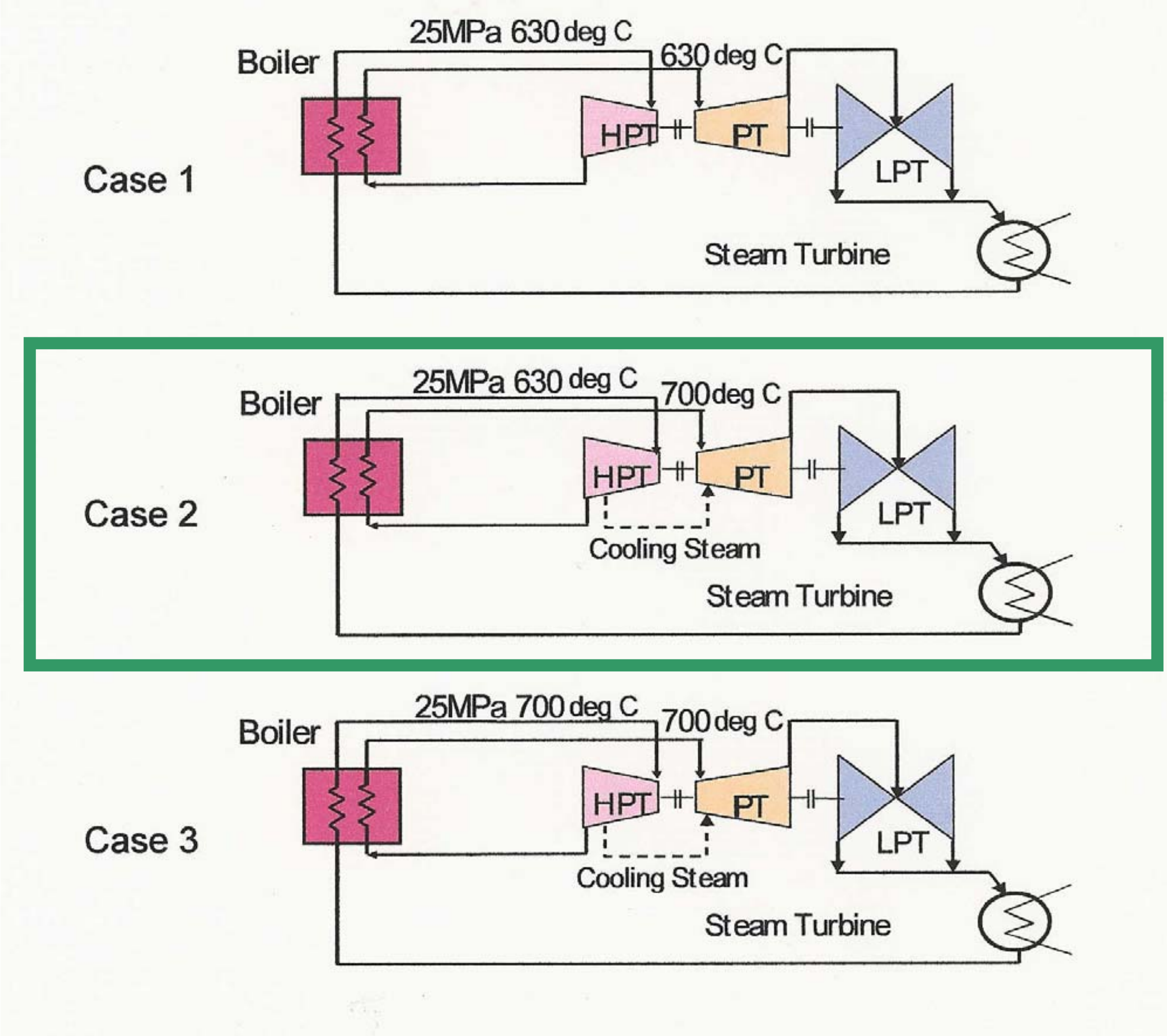


Figure 3-2 Flow Diagrams

Fukuda et al., 2004

Closer to usage are **steam-cooled, high temperature, intermediate pressure** turbine sections

Cost vs Temperature

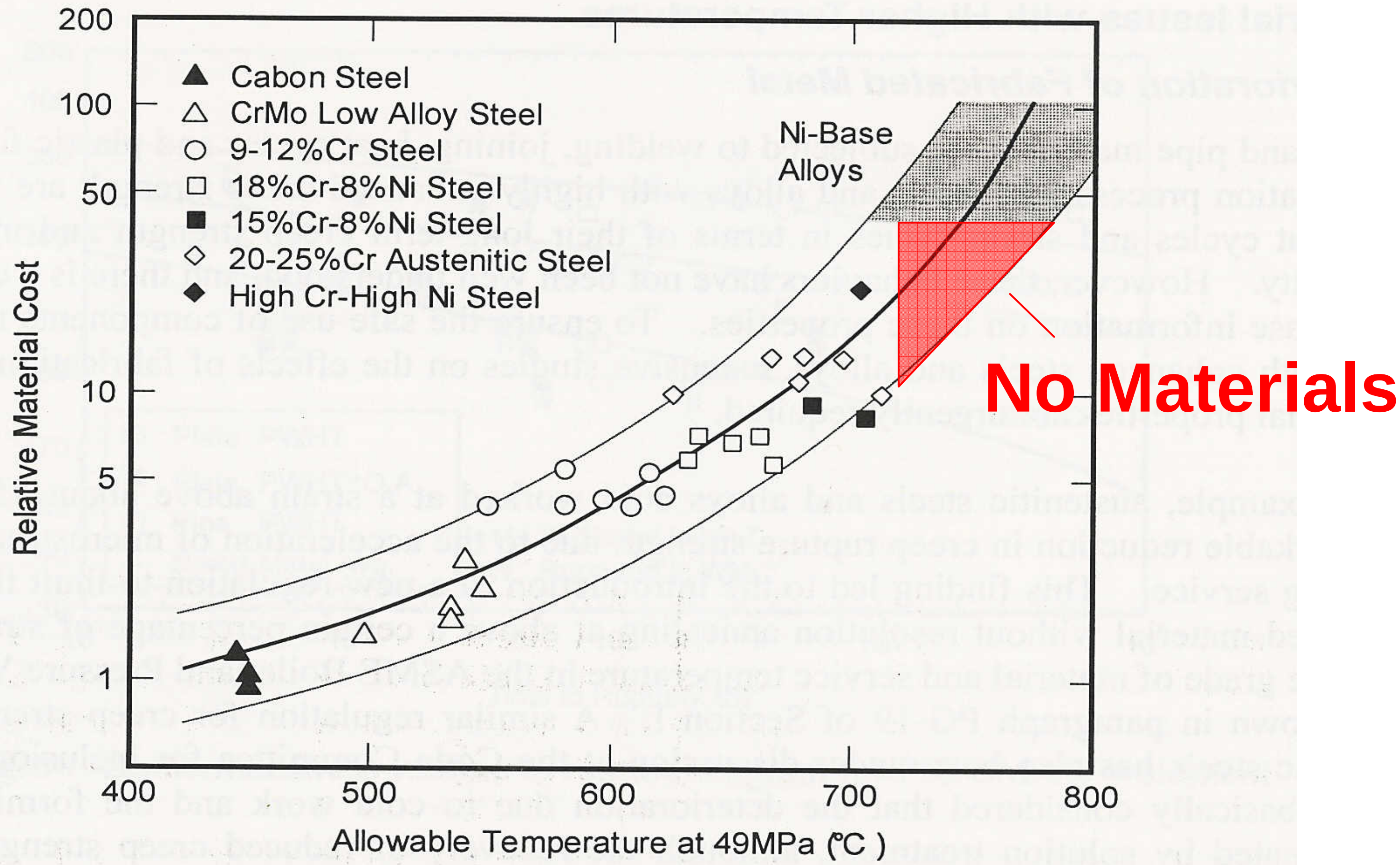


Fig. 7 Relation between allowable metal temperature at the allowable stress of 49MPa and the relative material cost

Masuyama, 2004

Research Approach

- **Ultra Supercritical Steam Exposures**
  - Temperatures 593 to 760°C (1112-1400°F)
  - Pressures of 2400 to 5500 psi (16.5-37.9 MPa)
- **Cyclical Oxidation in Moist Air**
  - Hourly cycles to examine adhesion and spallation behavior of protective oxides
- **TGA in Steam+Argon**
  - Determine oxidation mechanisms, kinetics, activation energies
- **Furnace Exposures in Moist Air**
  - Economical long-term tests

Alloy Compositions

Nominal compositions of alloys of interest for USC turbine applications.

Alloy	Fe	Cr	Ni	Co	Mo	Nb	C	Si	Mn	Ti	Al	Other
12	Bal	11		3		0.07	0.1	0.3	0.2			3 W 0.2 V 0.04 Nd 0.04 N
6W		23	43			0.18	0.08	0.4	1.2	0.08		6 W 0.003 B
617 UNS N06617		22	55	12.5	9		0.07				1	
230 UNS N06230	<3	22	55	<5	2		0.1				0.35	14 W <0.015B 0.02 La
740	1	24	49	20	0.5	1.8		0.5		1.6	0.75	
90 UNS N07090	1.5	19.5	55.5	18			0.06			2.4	1.4	
718 UNS N07718	18.5	19.0	52.5		3	5.1	0.08 max			0.9	0.5	0.15 Cu max
J1		12.1	Bal		18					1	0.8	
J5		12.5	Bal		22				0.5	1		0.04 Y

Candidate alloys for USC turbine applications

- High Strength Alloys
  - **12** -- **230**
  - -- **617**
  - **6W** -- **740**

Highest Strength in Alloy Category

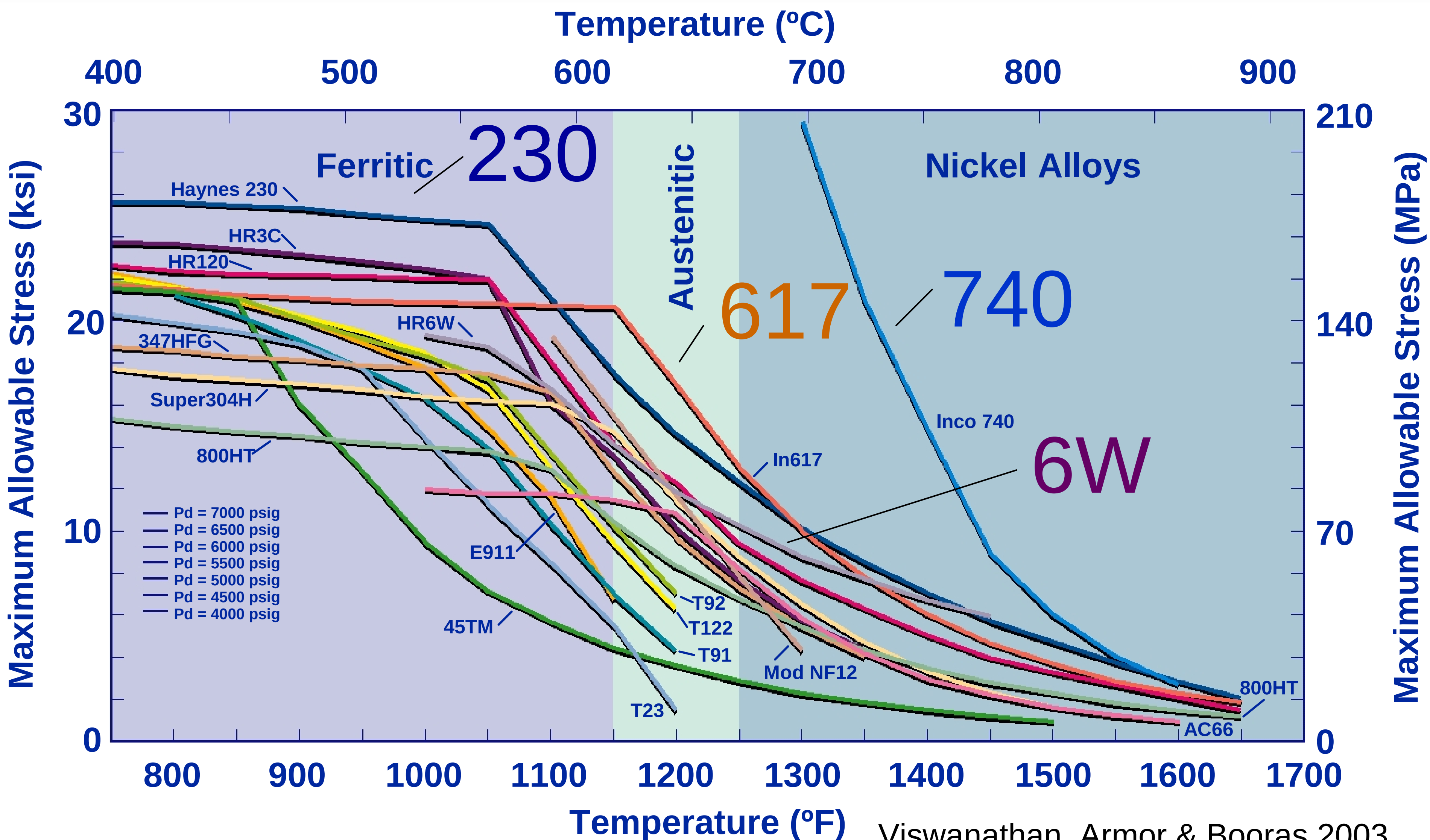
- Additional Ni-base superalloys
  - **90** -- **718**

Candidate Blade Materials (EPRI)

- Also
  - -- **J1** -- **J5**

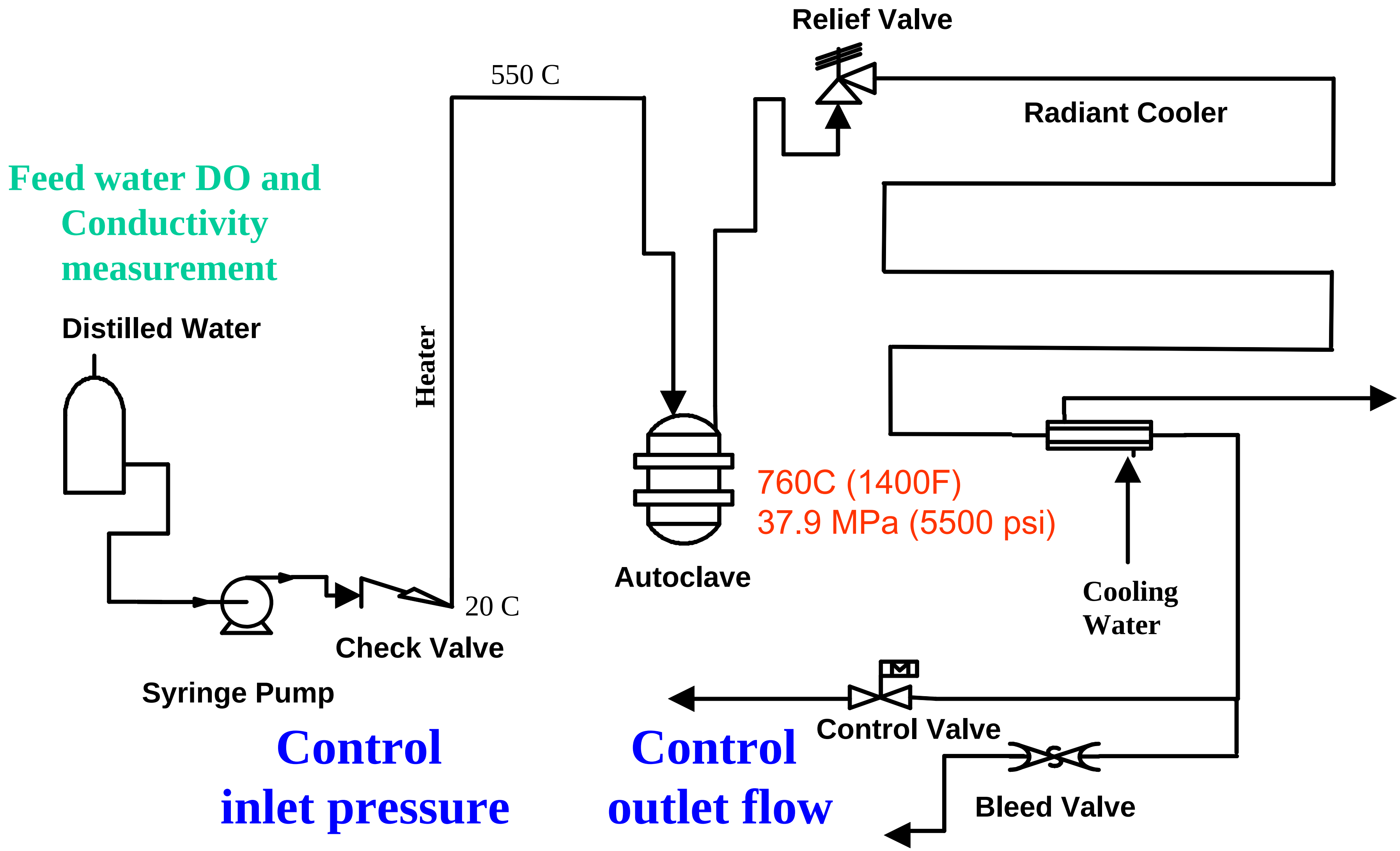
Low CTE Nickel Alloys

Alloy Strength

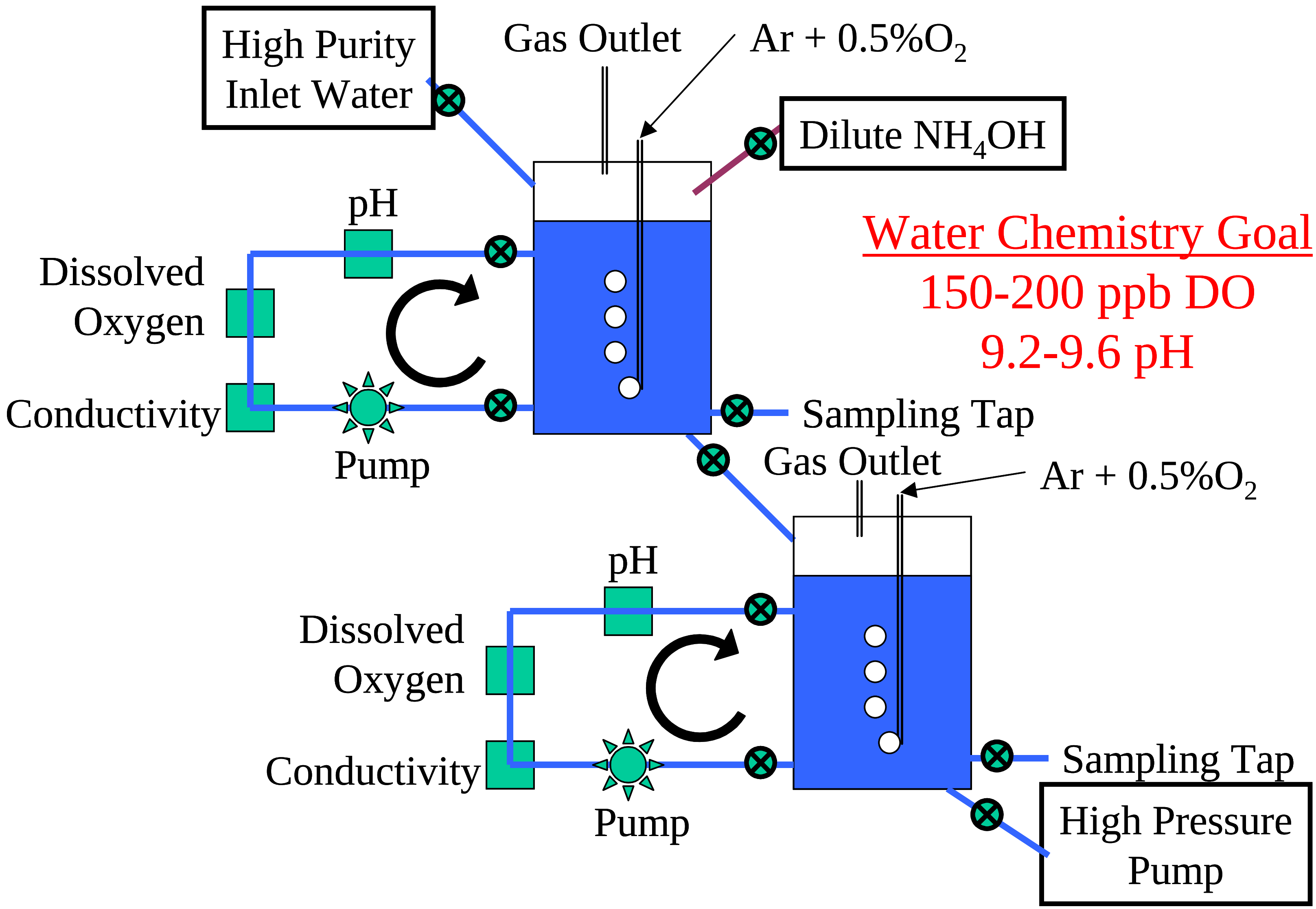


Viswanathan, Armor & Booras 2003

USC Test Loop



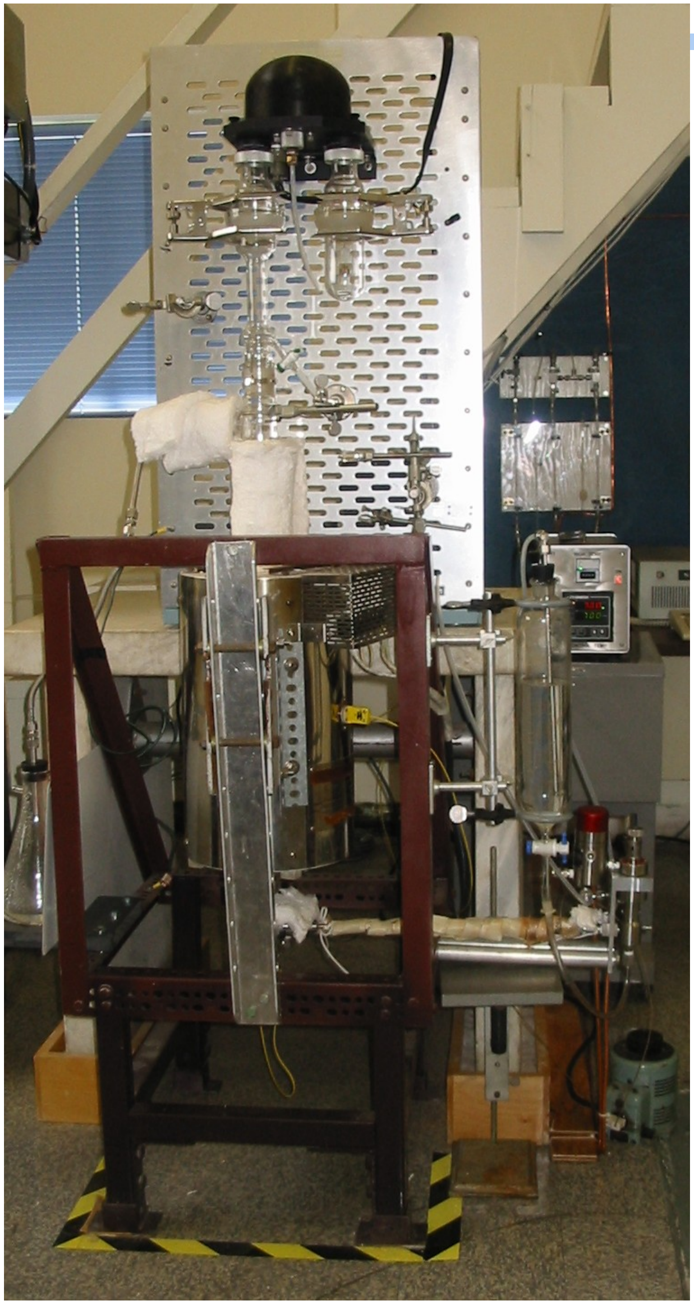
USC Feed Water System



<u>Water Chemistry Goal</u>

150-200 ppb DO

9.2-9.6 pH



TGA Testing in Steam

Thermogravimetric analysis to give kinetics and corrosion mechanism information.

Temperatures up to 800°C
Flowing steam plus Ar
Atmospheric pressure

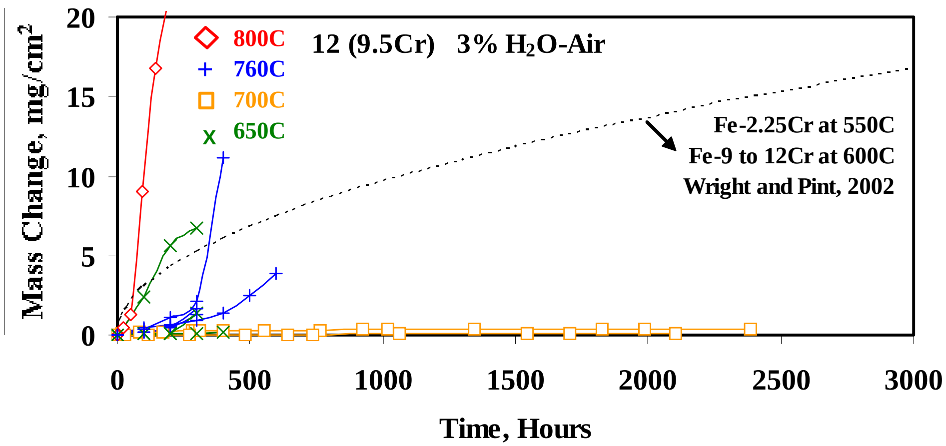
Feed water is oxygen saturated

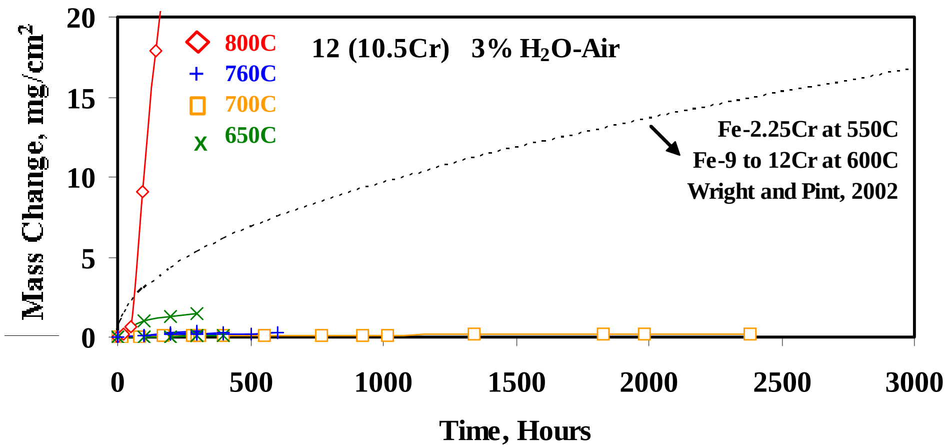
TGA Results

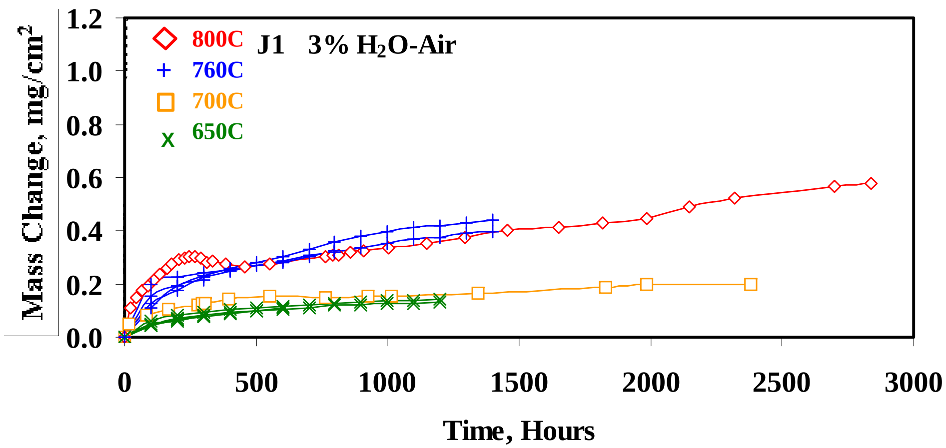
Thermogravimetric analysis (TGA) for 300 hr tests in O_2-saturated steam plus 60%Ar at 800°C

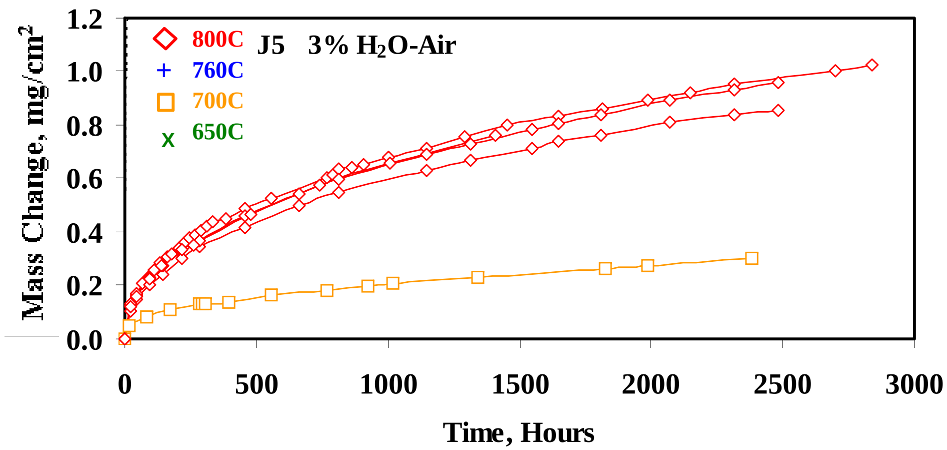
Alloy	%Cr	Reaction Order, n	Parabolic R^2	Parabolic Rate Constant, k_p $mg^2cm^{-4}s^{-1}$
12 (9.5Cr)	9.5	1.78	1.000	1.2×10^{-3}
12 (9.5Cr)	9.5	1.90	1.000	1.4×10^{-3}
12 (10.5Cr)	10.5	1.70	1.000	1.6×10^{-3}
12 (10.5Cr)	10.5	1.76	0.995	1.7×10^{-3}
J1	12.1	1.73	0.990	3.5×10^{-7}
J5	12.5	1.91	0.990	1.5×10^{-7}
617	22	1.62	0.960	1.4×10^{-7}
617	22	2.63	0.585	3.9×10^{-8}
230	22	1.78	0.878	6.9×10^{-8}
230	22	1.79	0.645	3.7×10^{-8}
6W	23	1.87	0.524	3.3×10^{-8}
740	24	2.20	0.527	7.2×10^{-7}

Furnace Exposures

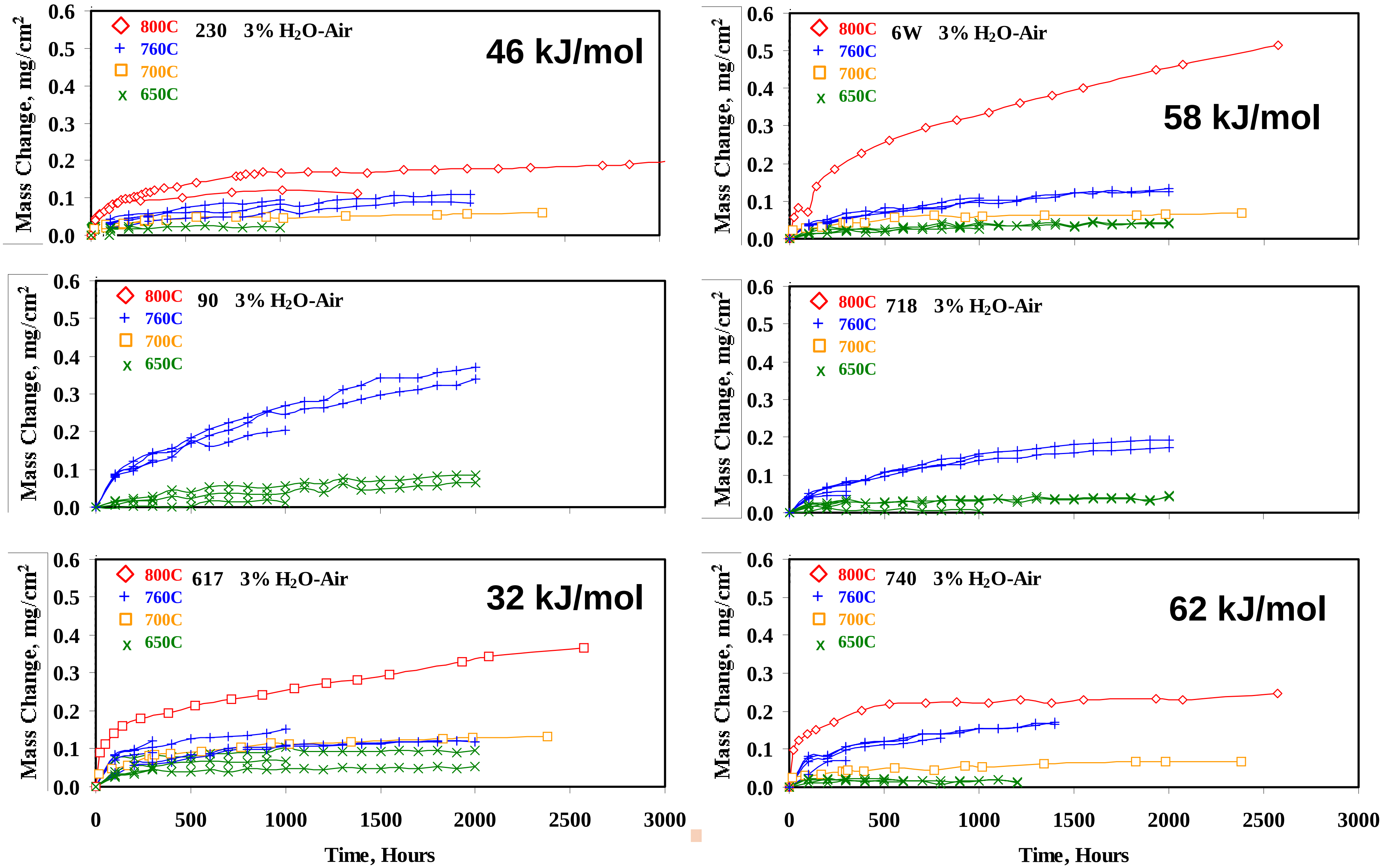








Furnace Exposures



Cyclic Oxidation

Scale adhesion information during thermal cycles

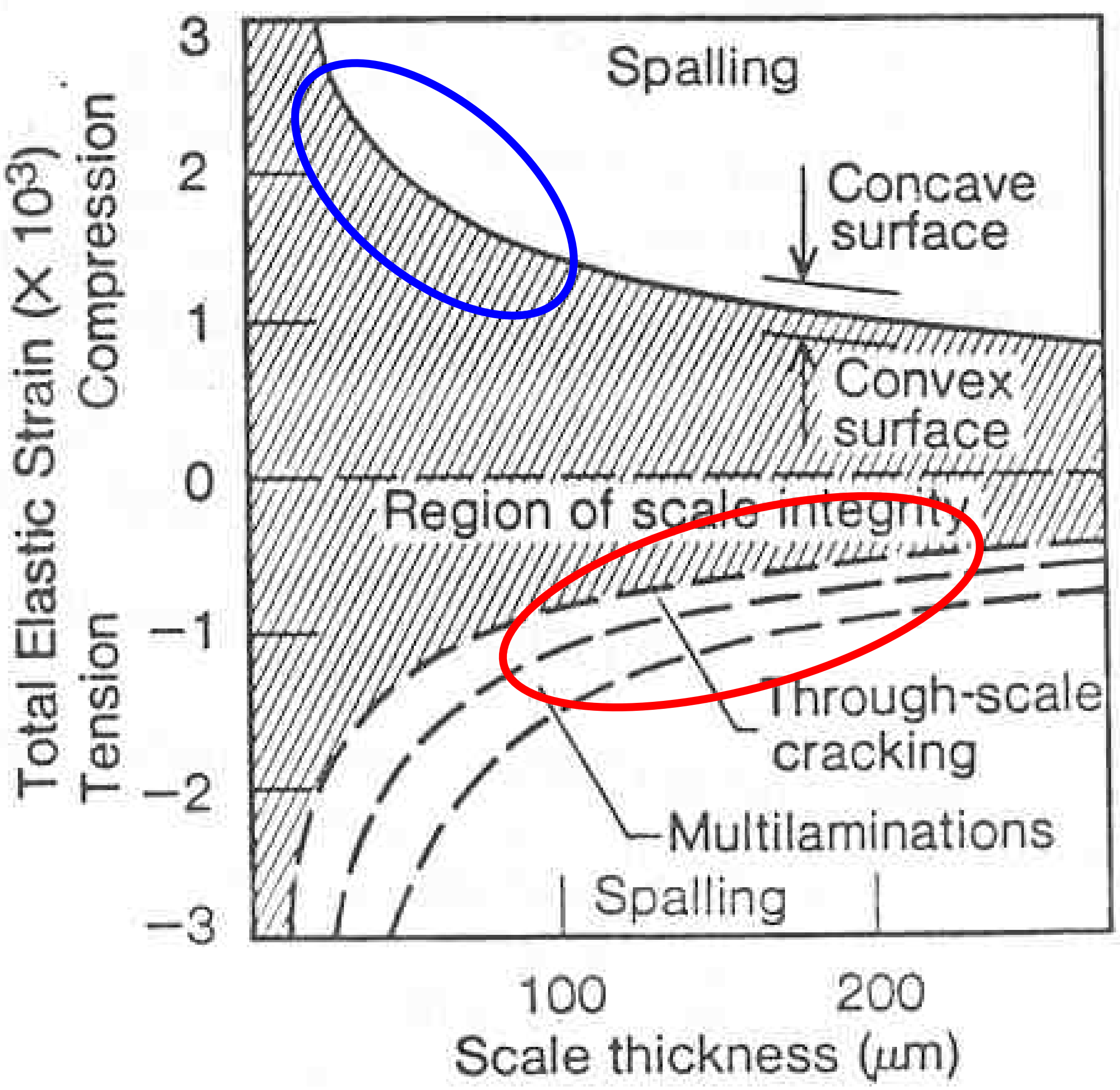
Temperatures up to 800°C
Flowing steam/air mixture
Atmospheric pressure
Hourly cycles
7 samples at a time

Curvature Samples

12
10.5 Cr
2” O.D.

Concave Convex

Stored Energy Model

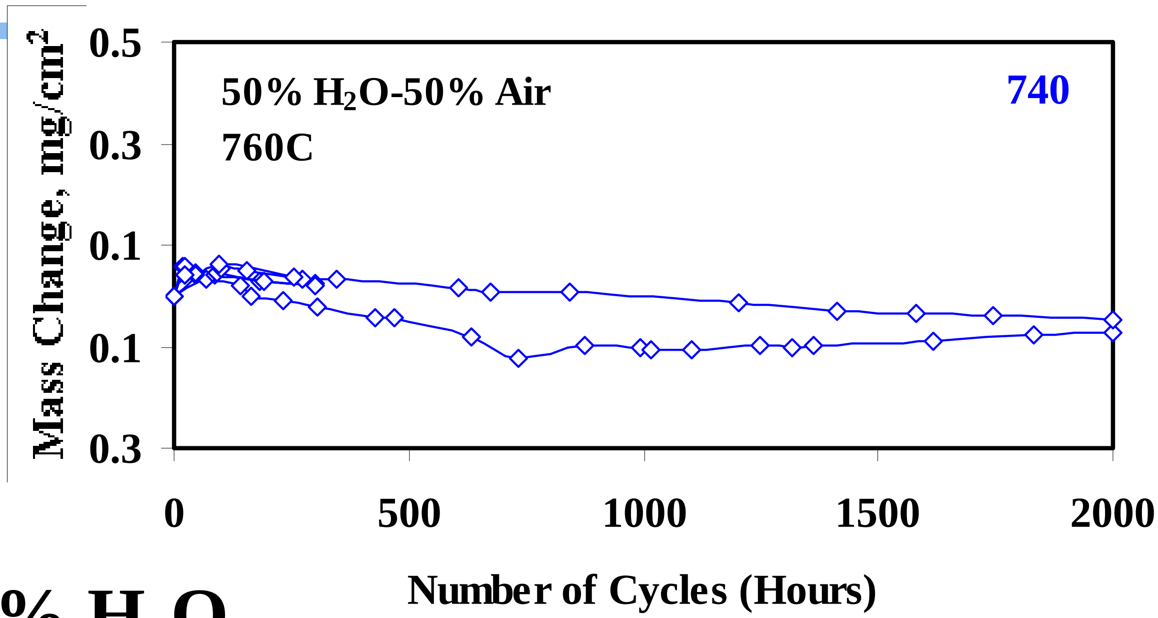


Austenitic Steels

Ferritic Steels

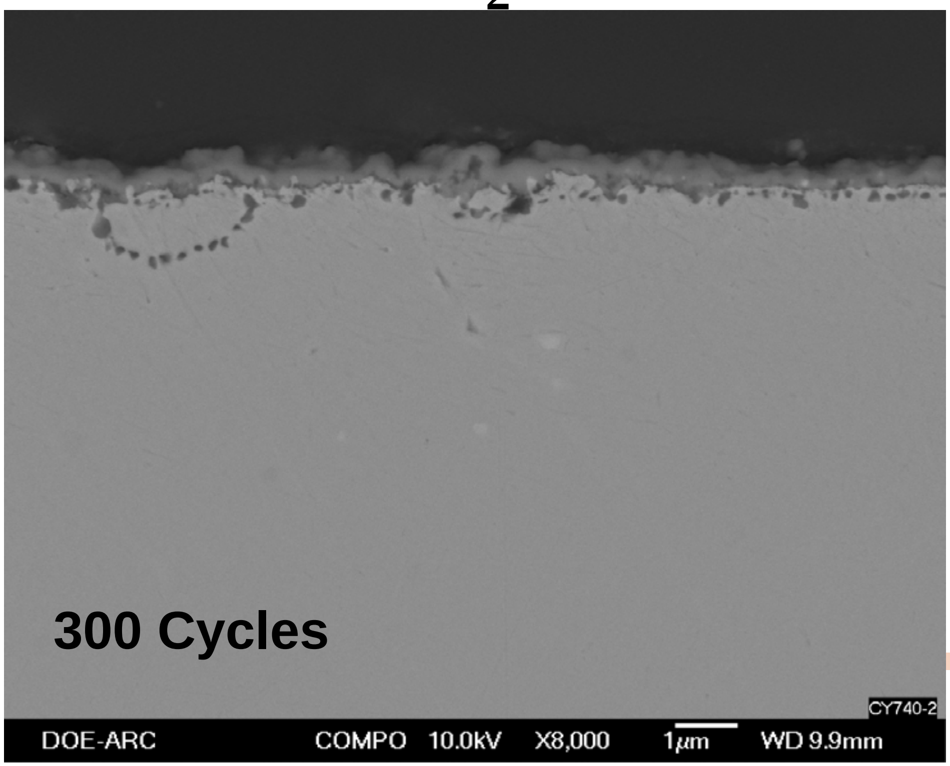
Armitt *et al.*, 1978

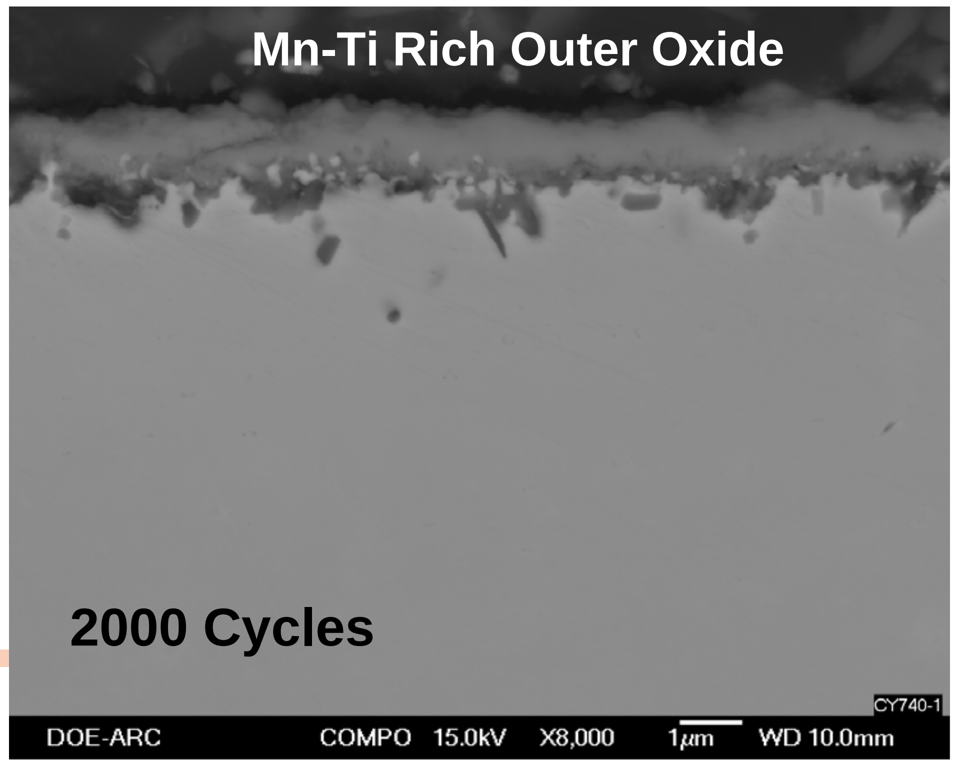
740



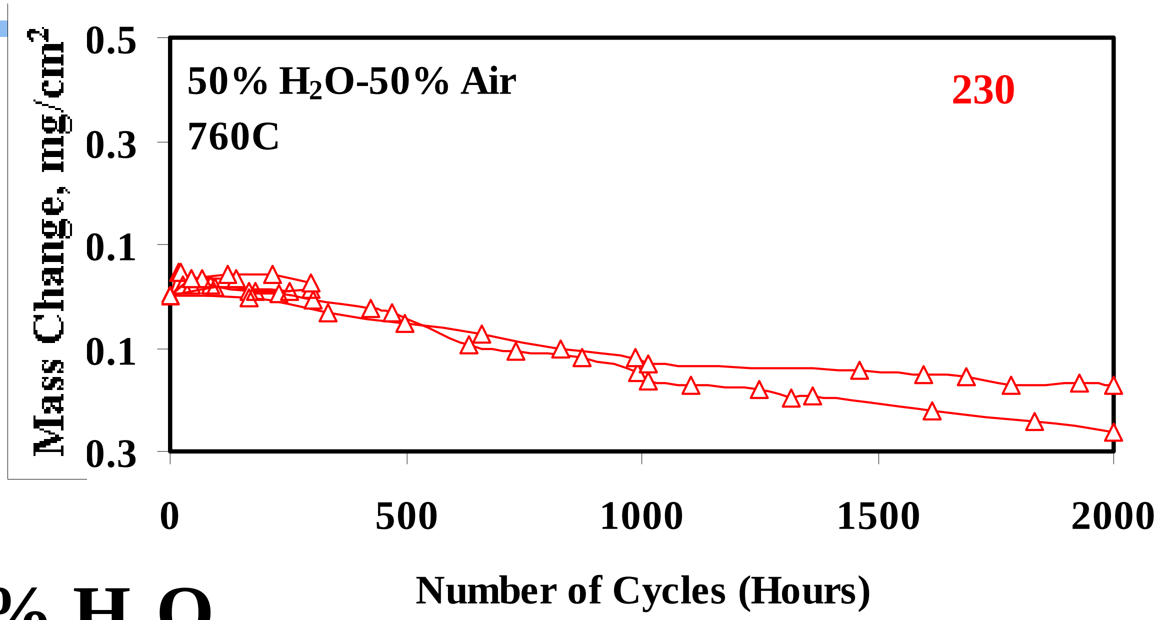
760°C

Air + 50% H_2O

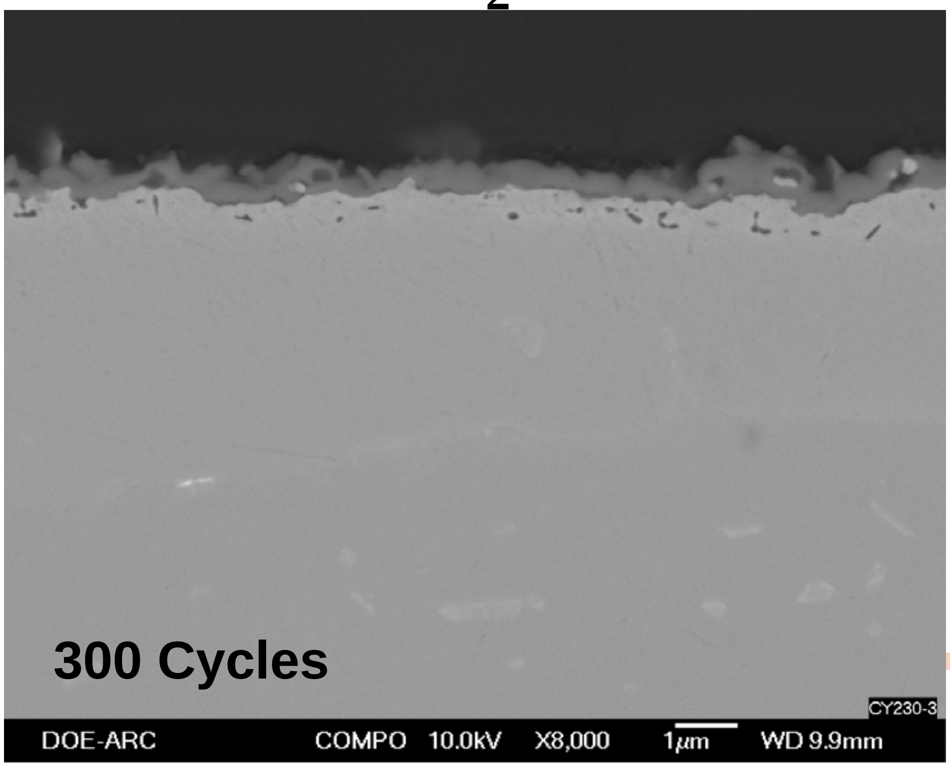


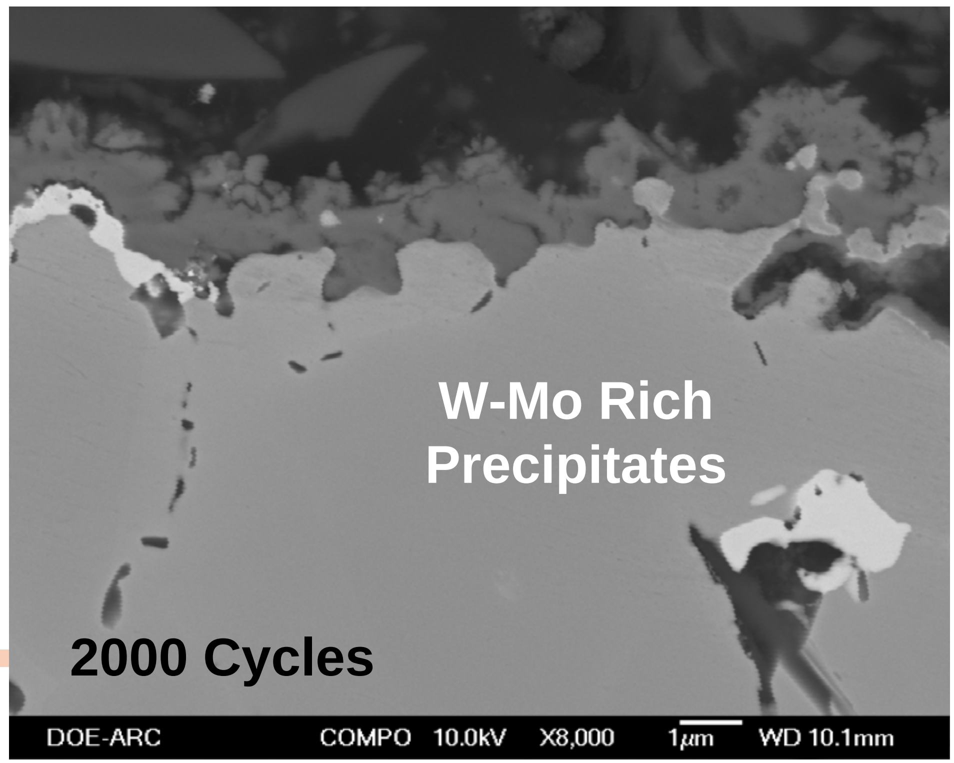


230

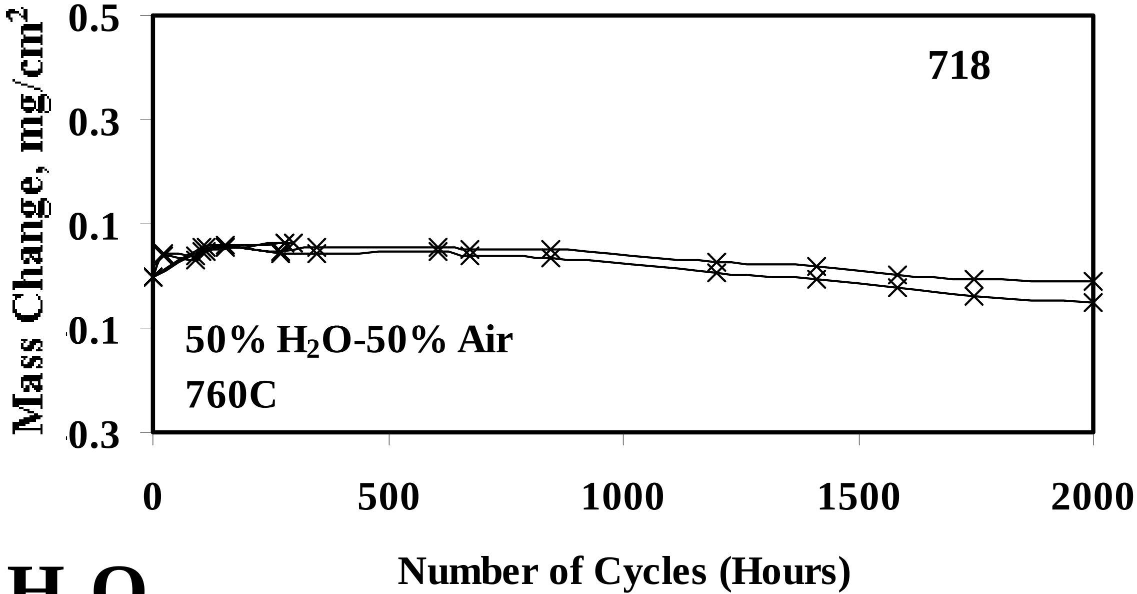


760°C
Air + 50% H_2O

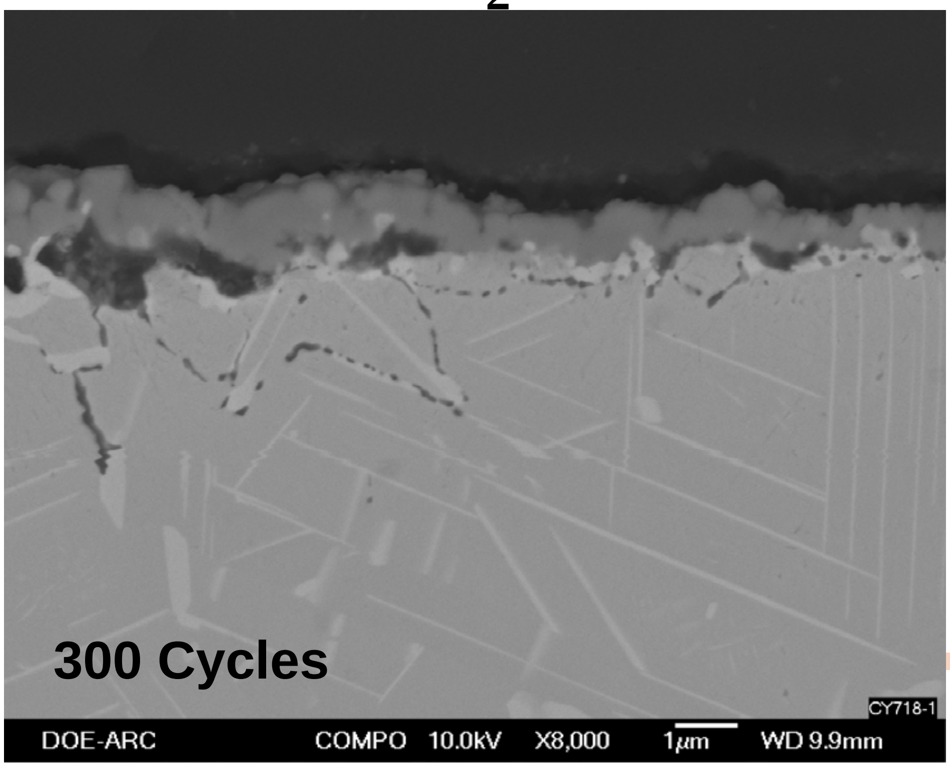


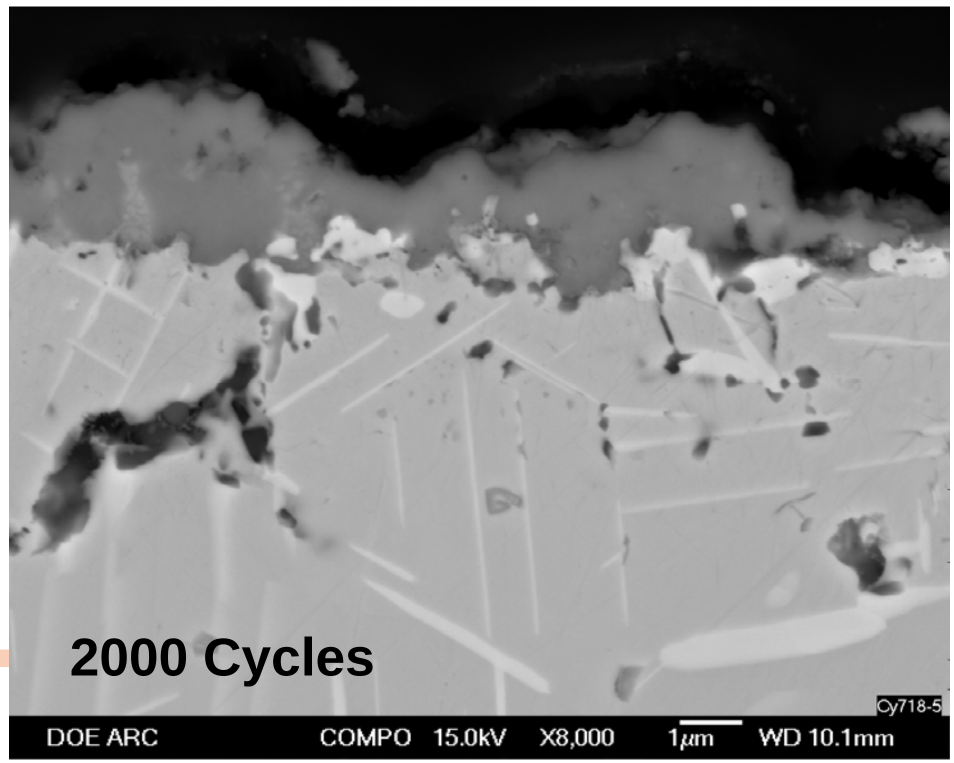


718



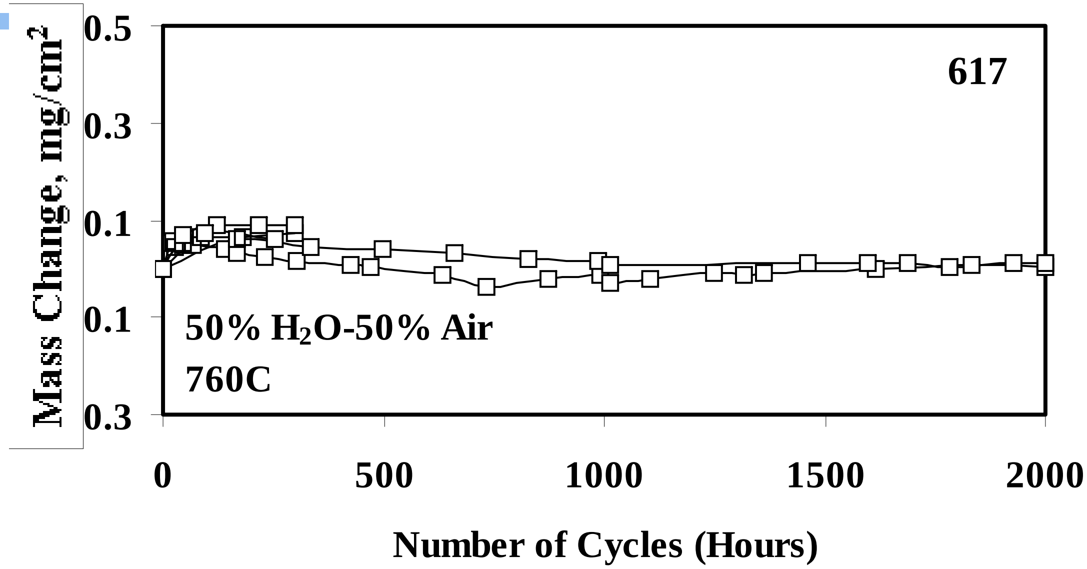
760°C
Air + 50% H_2O

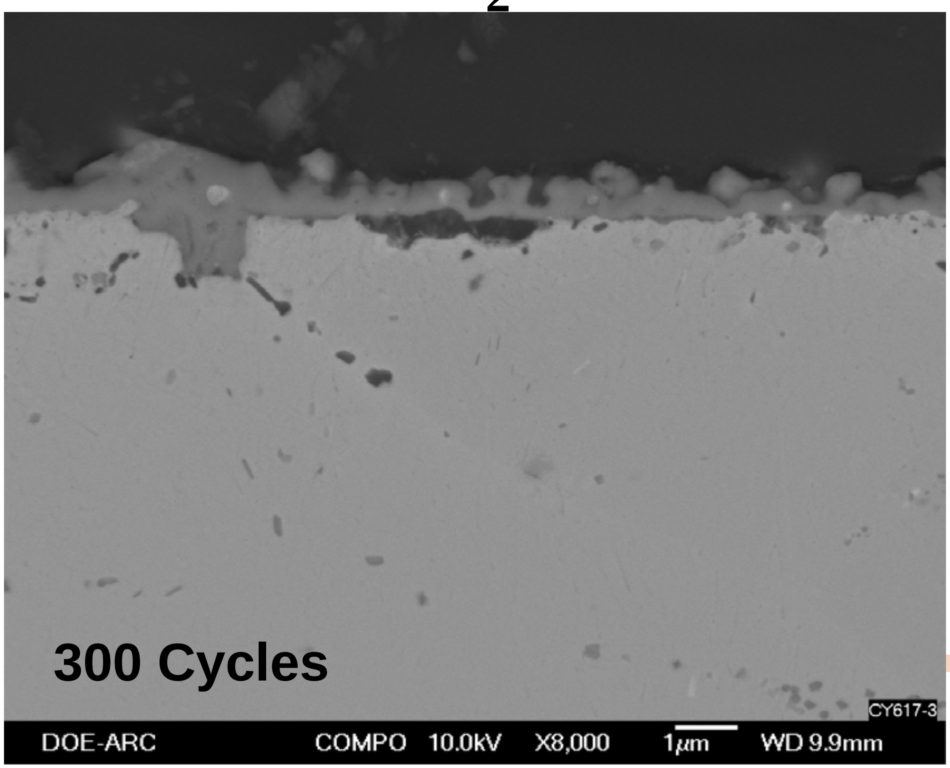


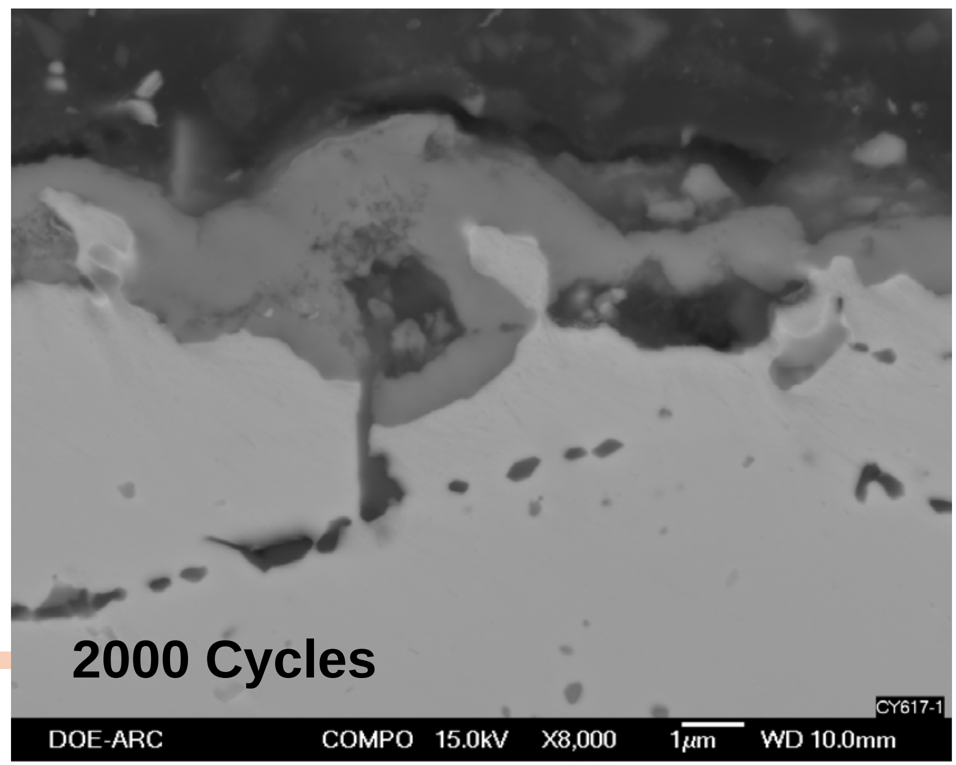


617

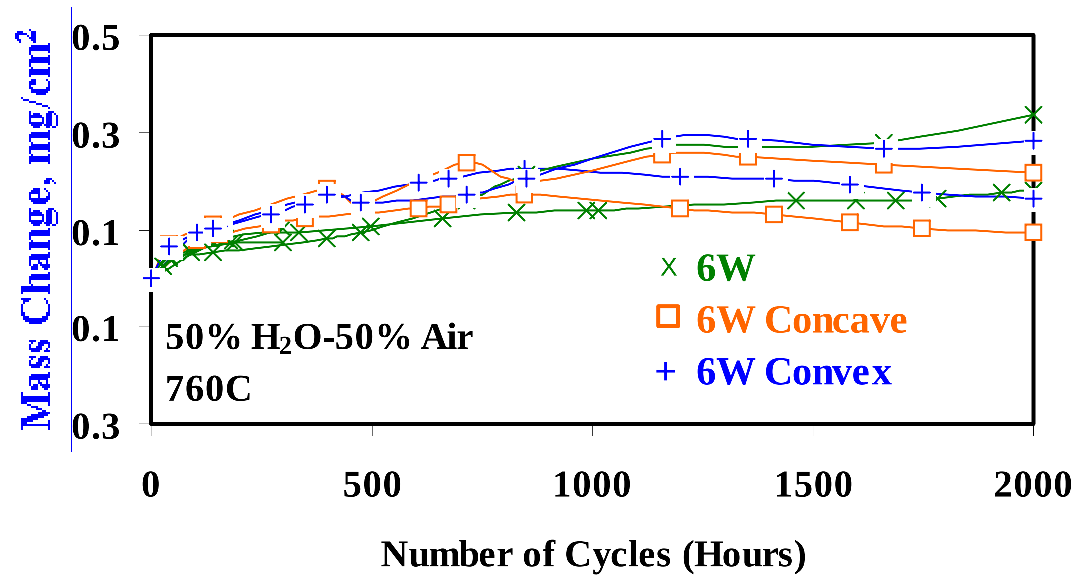
760°C
Air + 50% H_2O



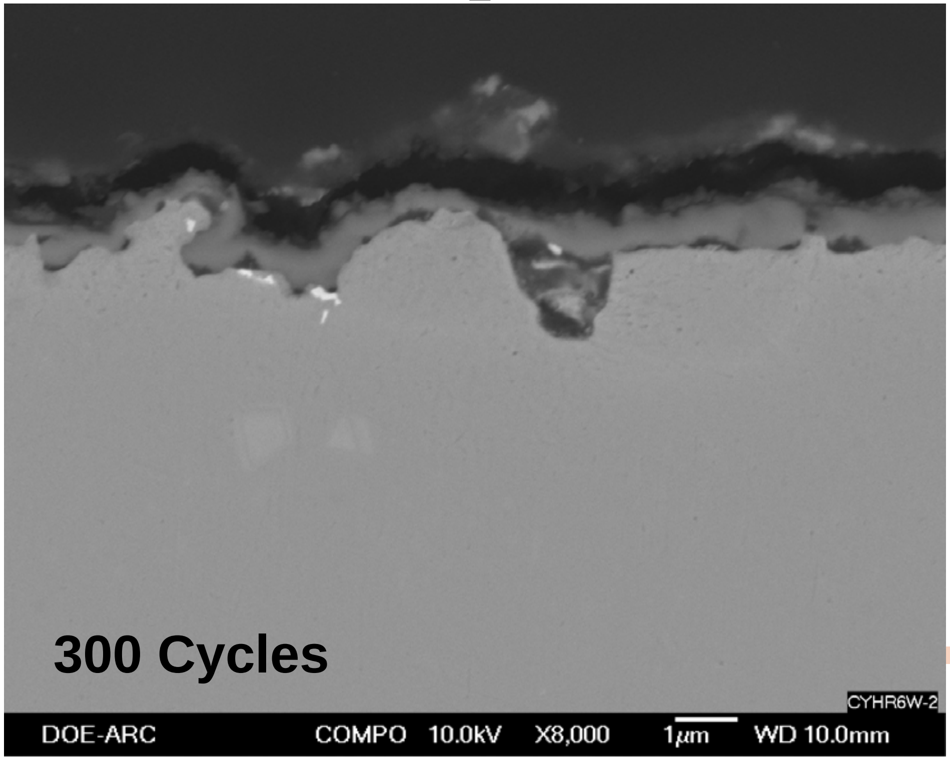


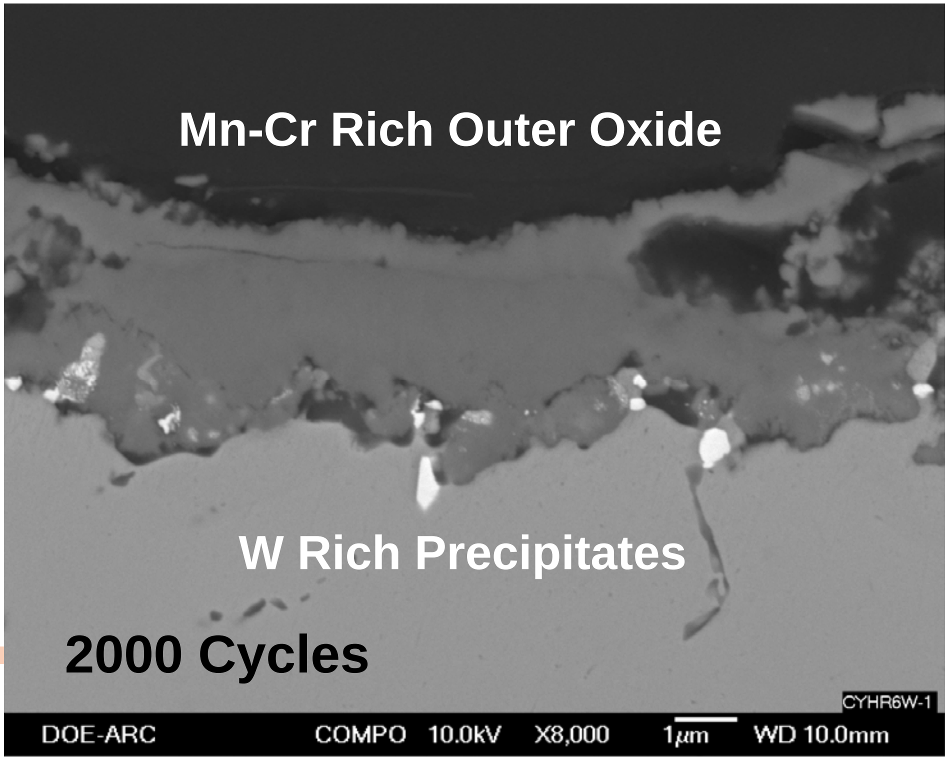


6W

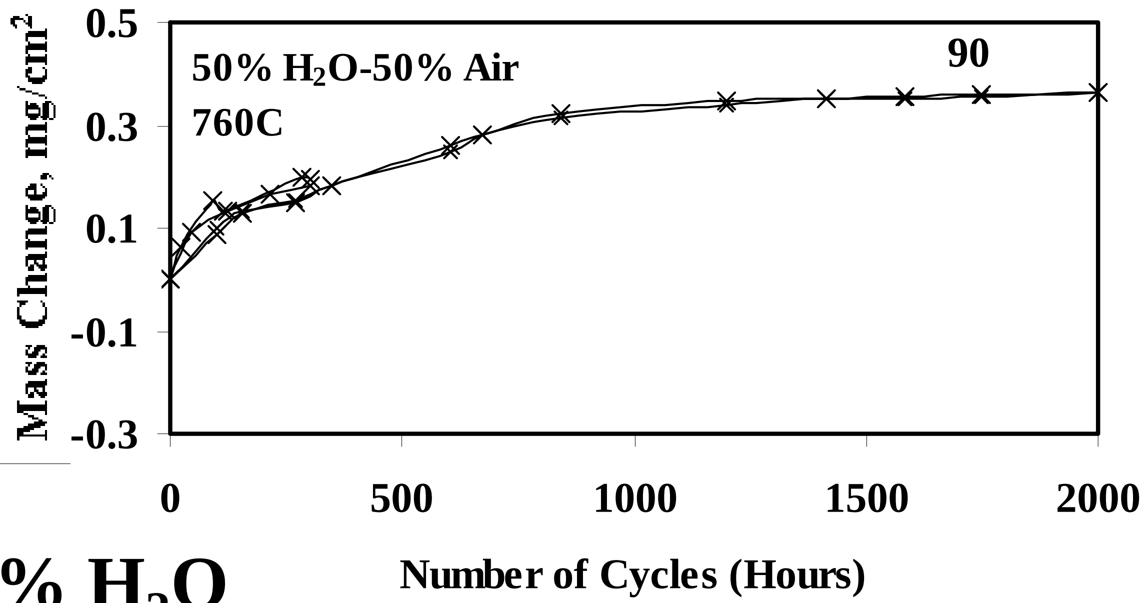


760°C
Air + 50% H_2O

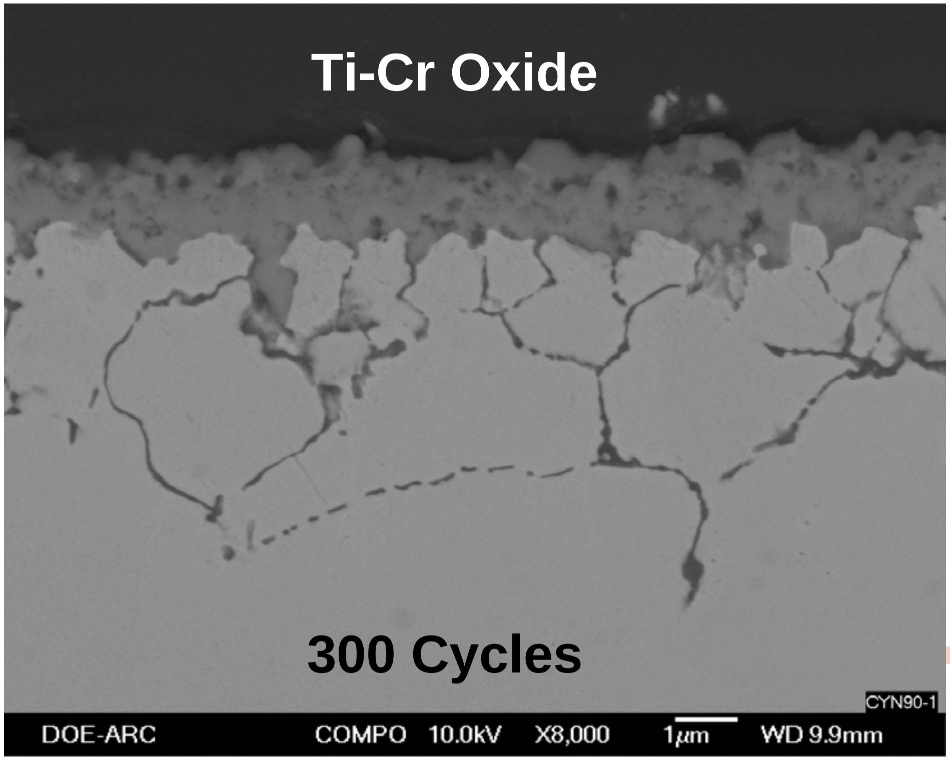


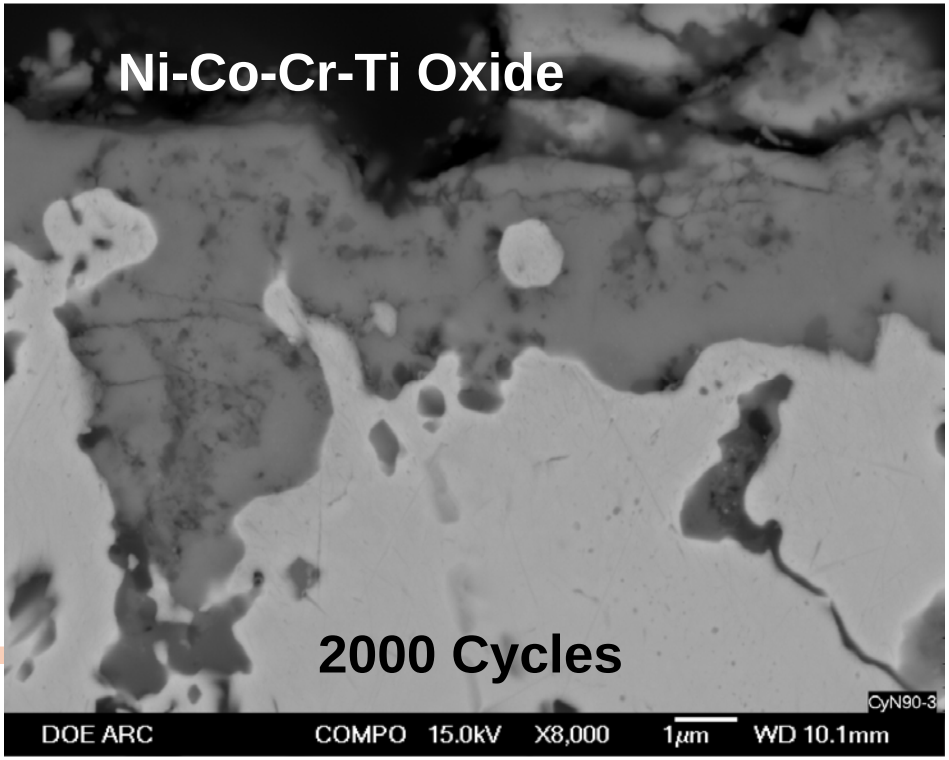


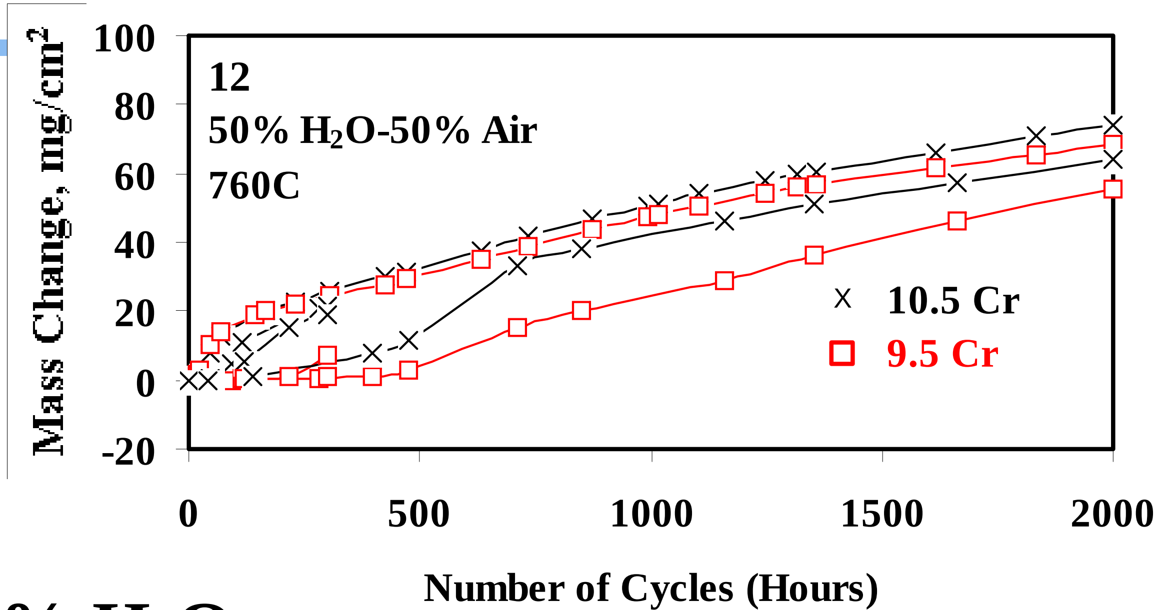
90



760°C
Air + 50% H_2O

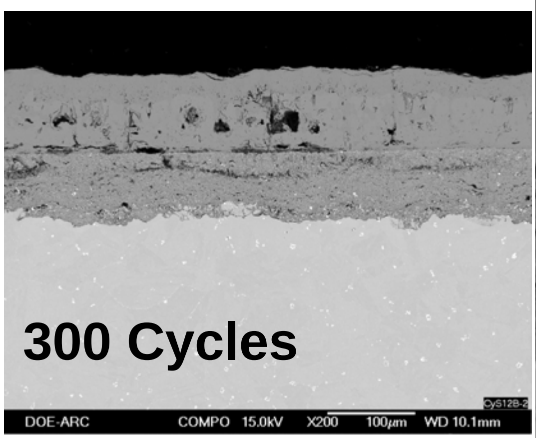




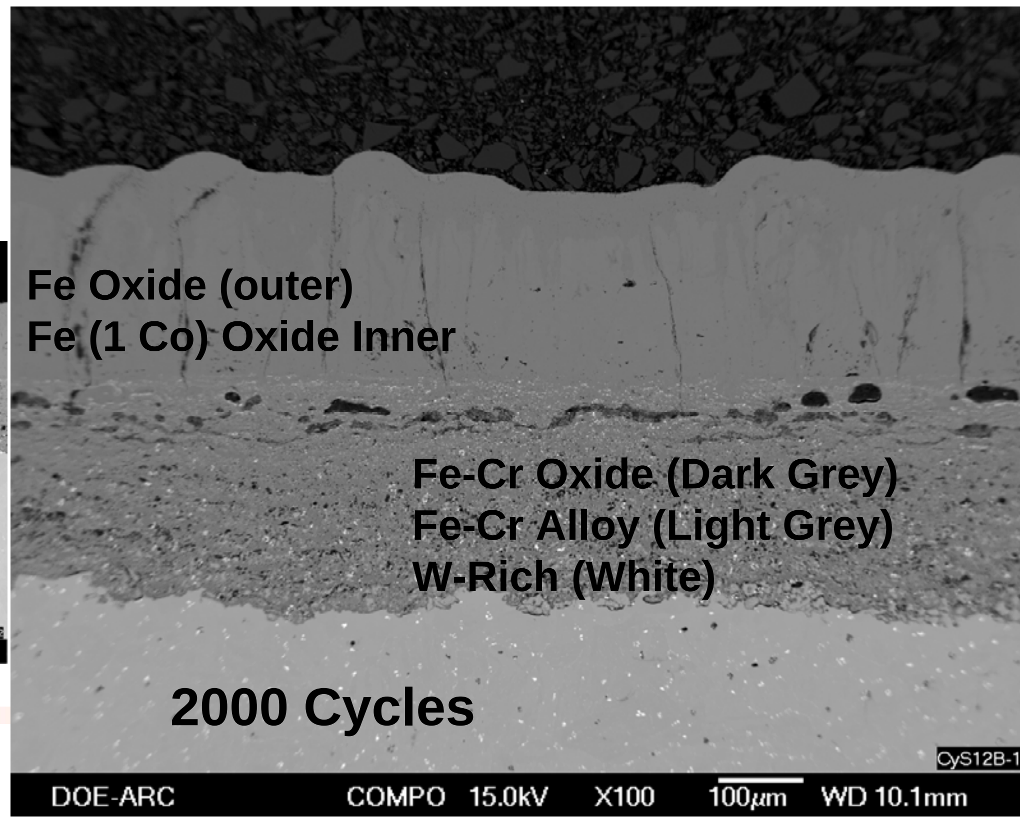


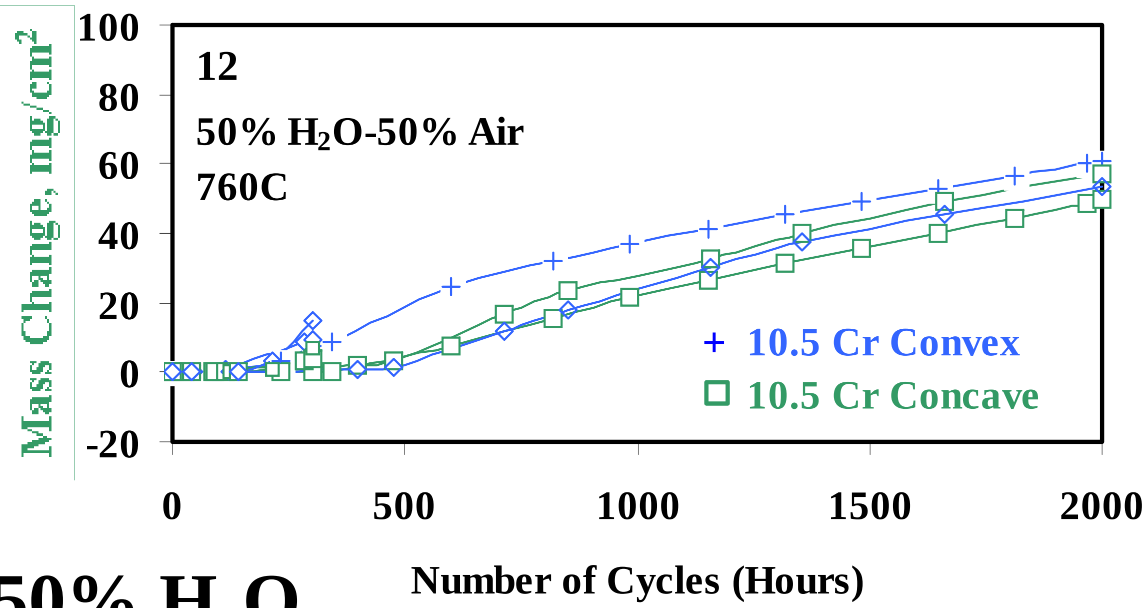
12

760°C
Air + 50% H_2O



12 10.5 Cr

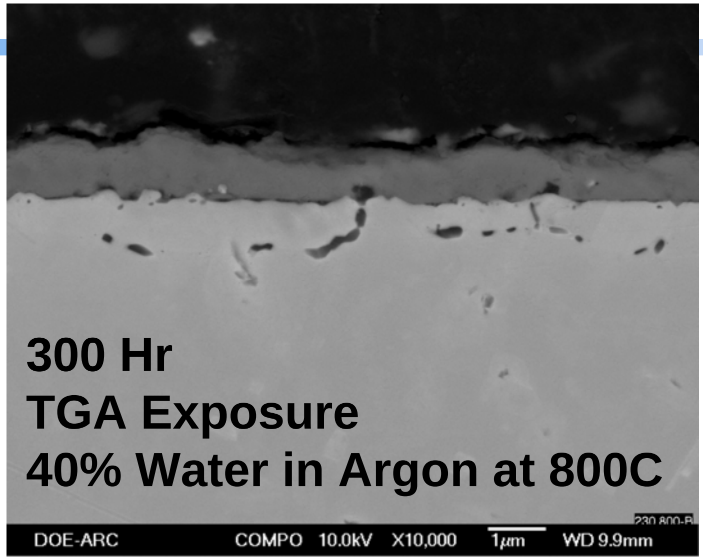


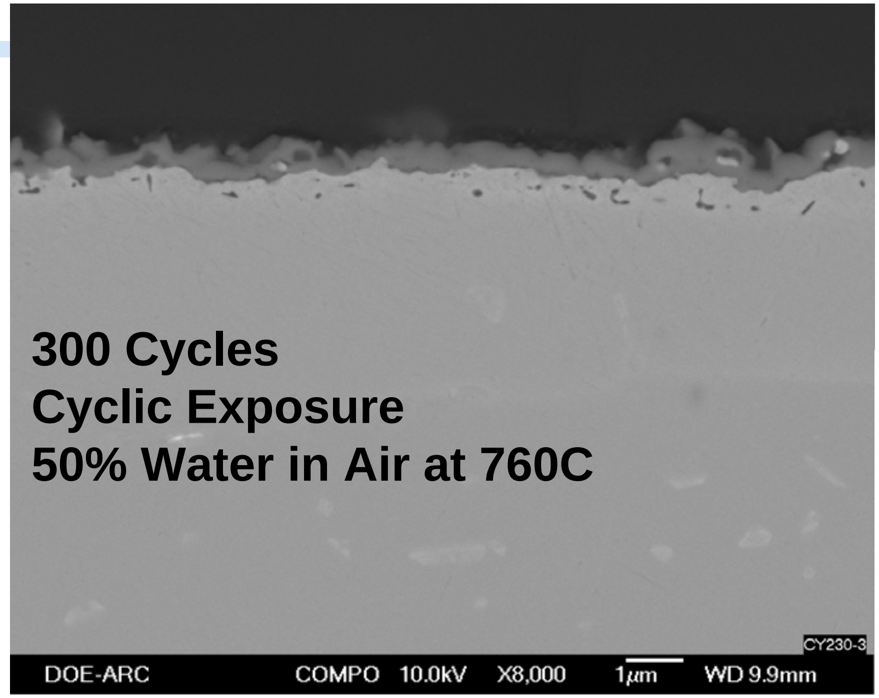


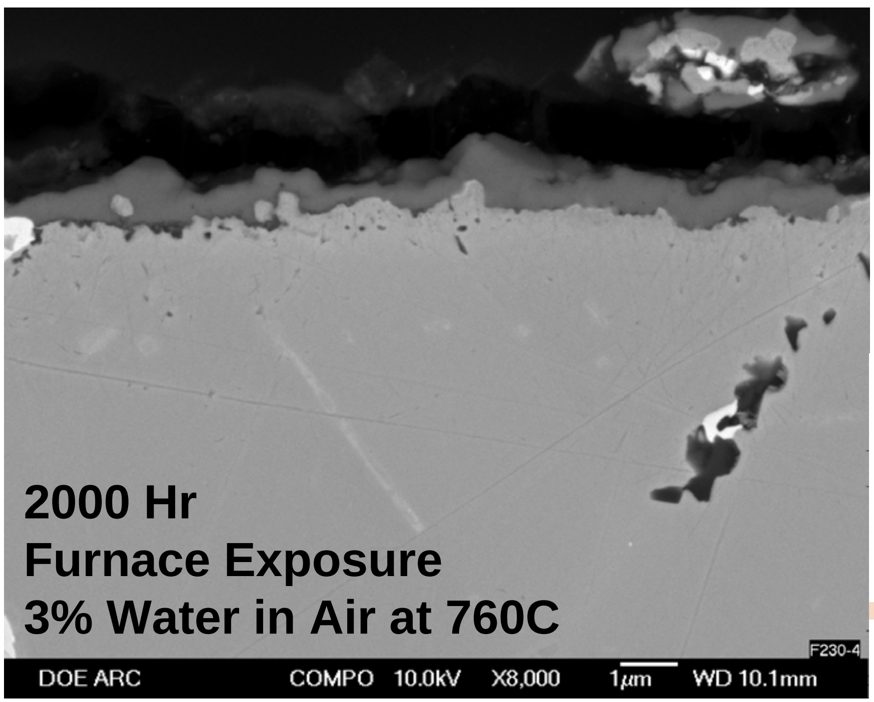
12 Curvature

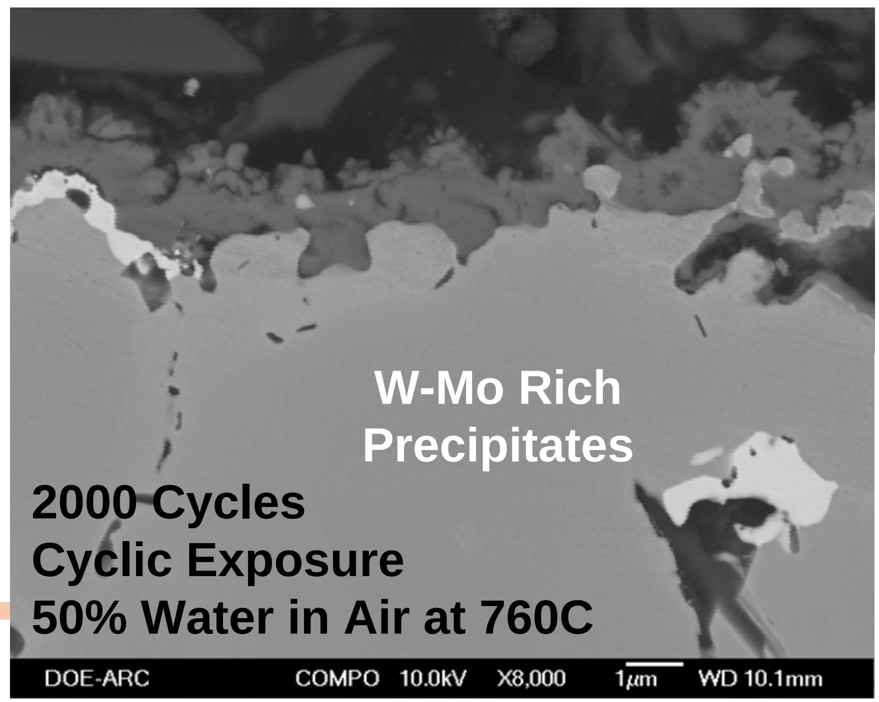
760°C
Air + 50% H_2O

230


300 Hr
TGA Exposure
40% Water in Argon at 800C
DOE-ARC COMPO 10.0kV X10,000 1µm WD 9.9mm


300 Cycles
Cyclic Exposure
50% Water in Air at 760C
CY230-3
DOE-ARC COMPO 10.0kV X8,000 1µm WD 9.9mm


2000 Hr
Furnace Exposure
3% Water in Air at 760C
F230-4
DOE ARC COMPO 10.0kV X8,000 1µm WD 10.1mm


W-Mo Rich
Precipitates
2000 Cycles
Cyclic Exposure
50% Water in Air at 760C
DOE-ARC COMPO 10.0kV X8,000 1µm WD 10.1mm

Summary

- **DOE Advanced Power System goal of 60% efficiency from coal generation**
  - Require USC steam turbine conditions of 760°C & 37.9 MPa

- **Mass Change Results:**
  - From a simplistic mass change standpoint, all of the Ni-base alloys look acceptable at up to 800°C, and Alloy 12 up to 700°C

- **Alloy Degradation Below Oxide Scale**
  - All alloys show degradation below the oxide scale
    - 740 shows the least
    - 230 is next best

- **Curvature**
  - No evidence of curvature effects shown