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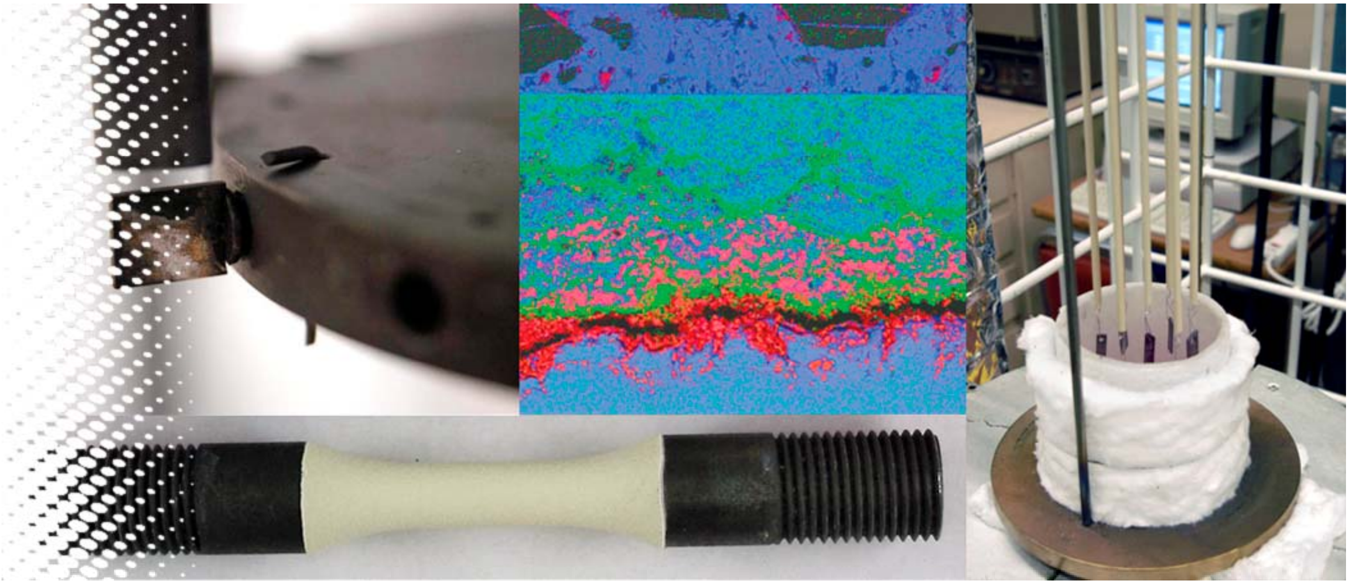

# Materials Performance in USC Steam FY10.MSE.1610222.682

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U.S. DEPARTMENT OF ENERGY

*FE Materials Conference, Pittsburgh, PA, May 25-27, 2010*

# Outline

## Introduction

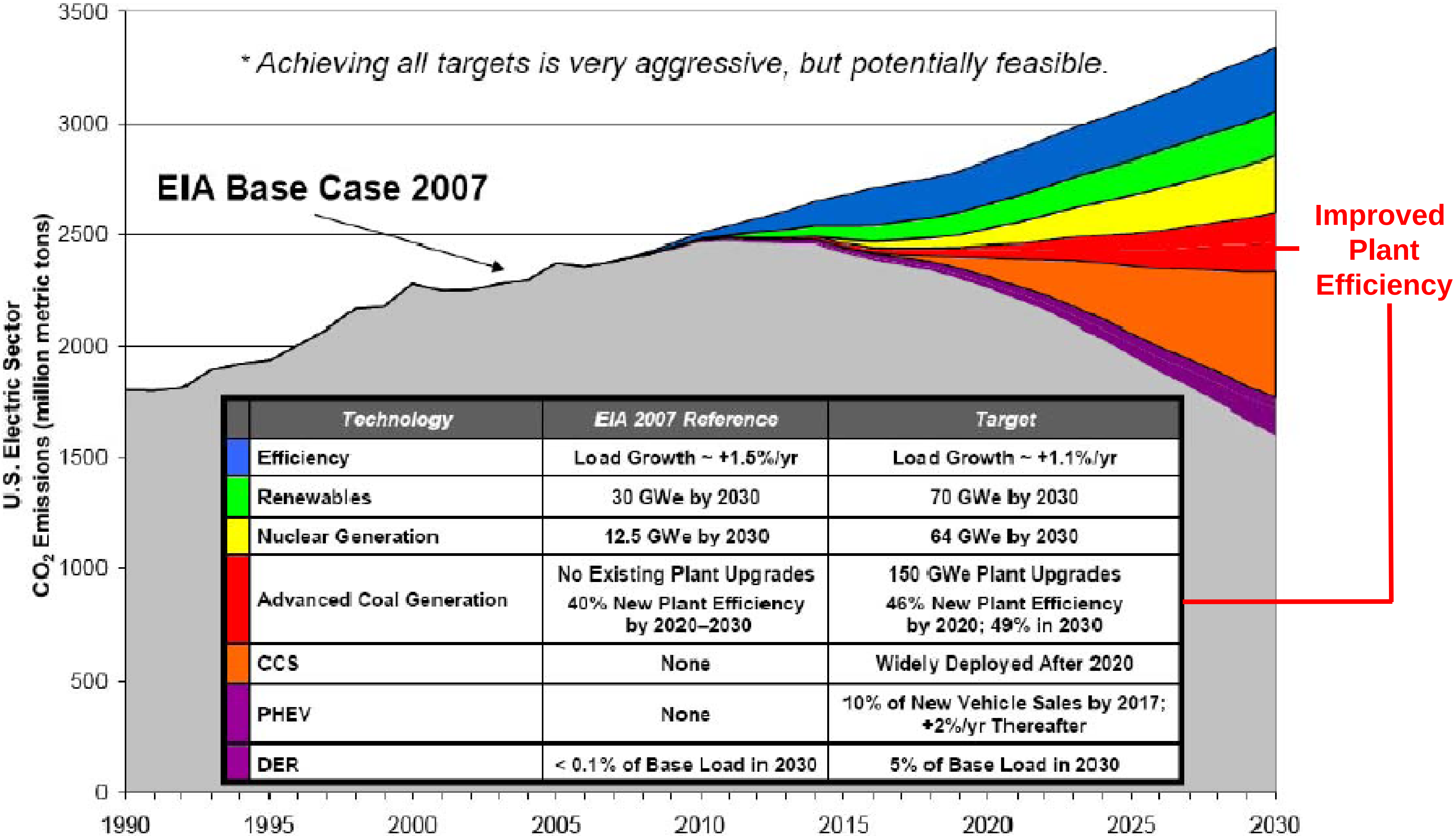
- Ultra Supercritical Steam Turbines
- Research Aims and Project Information

## Results

- Casting and Homogenization
- Oxidation Behavior

## Summary

# Impact of Advanced Coal Generation on $CO_2$ Emissions




| Technology | EIA 2007 Reference | Target |
|---|---|---|
| Efficiency | Load Growth ~ +1.5%/yr | Load Growth ~ +1.1%/yr |
| Renewables | 30 GWe by 2030 | 70 GWe by 2030 |
| Nuclear Generation | 12.5 GWe by 2030 | 64 GWe by 2030 |
| Advanced Coal Generation | No Existing Plant Upgrades<br>40% New Plant Efficiency by 2020–2030 | 150 GWe Plant Upgrades<br>46% New Plant Efficiency by 2020; 49% in 2030 |
| CCS | None | Widely Deployed After 2020 |
| PHEV | None | 10% of New Vehicle Sales by 2017; +2%/yr Thereafter |
| DER | < 0.1% of Base Load in 2030 | 5% of Base Load in 2030 |

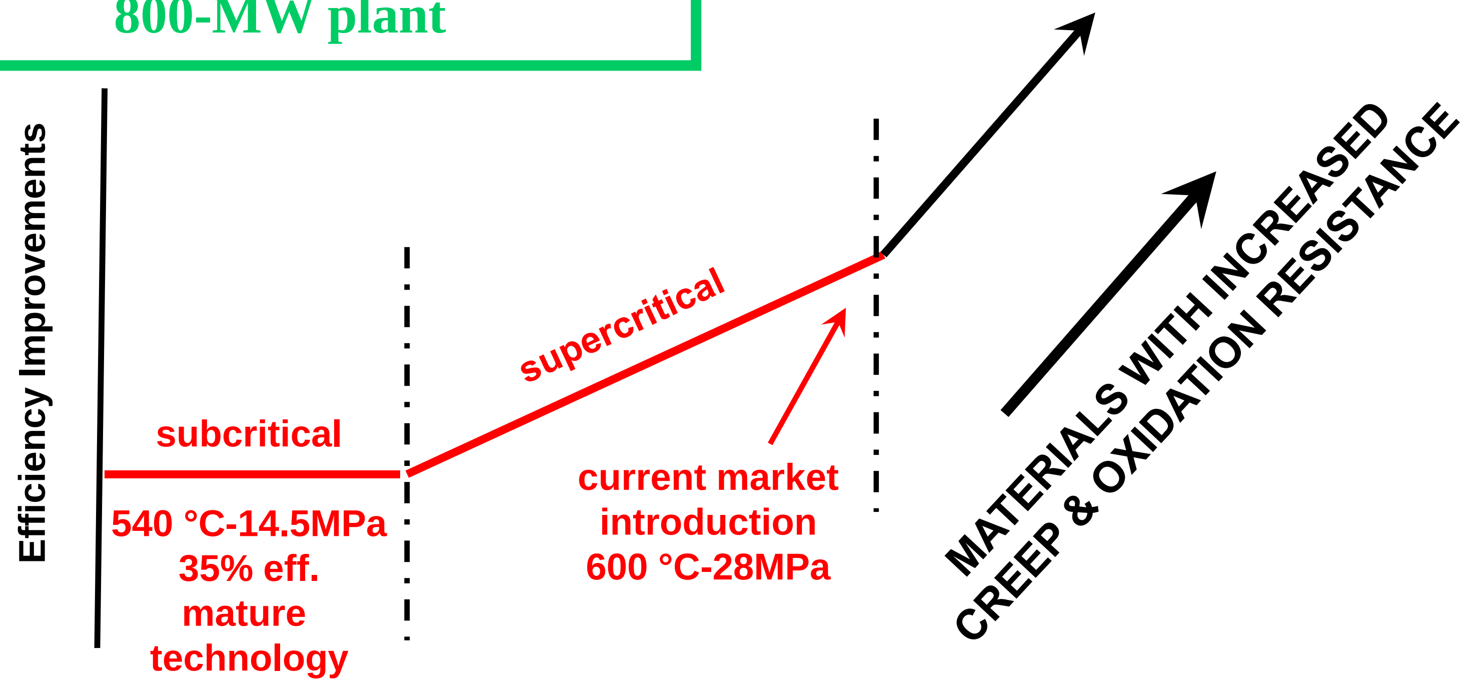



EPRI, 2007

# Increasing Efficiency

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

***US-DOE Advanced Power Systems:***
***46%-48% efficiency from coal generation***
***Steam condition: 760 °C - 35MPa***
***~ 5ksi***




**Subcritical: < 22 MPa**
**Supercritical (SC): > 22.1 MPa, 538 to 565 °C**
**Ultra Supercritical (USC): 565 to ~675 °C (advanced ferritic & austenitic steels required)**
**Advanced Ultra Supercritical (A-USC): > ~675 °C (nickel-base superalloys required)**



*Adapted from: Viswanathan, et al , 2005 and Swanekamp, 2002*

# Technological Issues

**Higher T&P place greater demands upon Materials**

- **Large castings are required for some components—many technical issues**
- **Pressure effects not entirely understood**
- **Earlier research on chomia evaporation showed that it may be of concern in HP turbine**

**FY'10 Project goals are to understand steam oxidation for these three issues**

# 2010 Milestones 1 & 2

Complete 2000 hr exposures of cast and wrought A-USC alloys in steam, 3/31/2010

- Modified research plan from 7 to 3 alloys to focus on successful alloys
- Complete

Identify effects from casting and homogenization procedures on the oxidation behavior of cast A-USC alloys, 6/30/2010

- Ongoing
- **The basis of most of the presentation**

# 2010 Milestones 3 & 4

**Complete installation and shakedown of autoclave, 9/30/2010**

- Mechanical installation complete
- Control system out on bid
- Dual rated 1 liter autoclave
  - 4500 psi at 1400°F (310 bar at 760°C)
  - 5000 psi at 1375°F (345 bar at 746°C)

**Refine/validate chromia evaporation model based on oxidation kinetics at high gas velocities and surface analyses of chromia-depleted scales, 9/30/2010**

- Samples being designed and machined
- Will allow tests at up to 40 m/s in moist air

# 2009 Milestones

**Obtain cost estimates for autoclave design. Decide to go forward or not with design development**

- Completed, elected to go forward with design and procurement

**Compete sample preparation on cast (NETL produced) and forged versions of candidate nickel-base superalloys**

- Completed (and used in 2010 tasks)

**Complete cyclic oxidation tests on cast and forged versions of candidate nickel-base superalloys**

- Elected to do exposures in steam environments instead of cyclic tests in moist air (became a 2010 task)

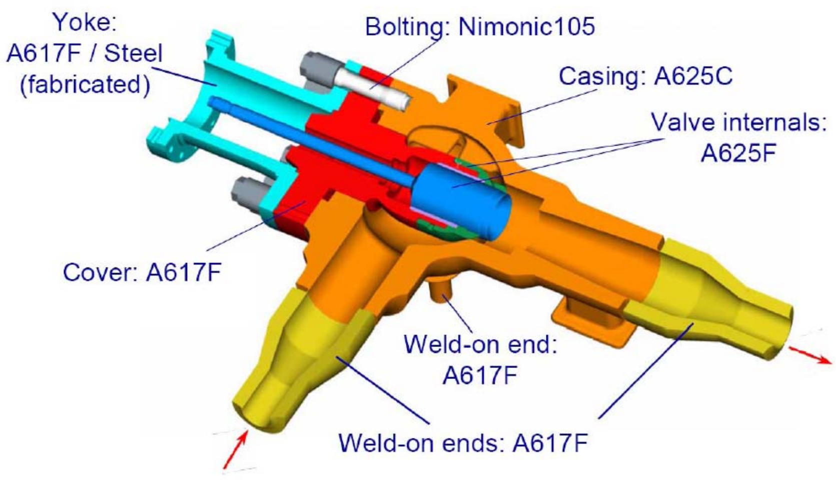
**Update chromia evaporation model based improved understanding of the underlying processes**

- Complete. Updated model for:
- Improved thermodynamics of $Cr_2(OH)_2(g)$ from Opila (NASA)
- Partial saturation of $Cr_2(OH)_2(g)$ in the gas phase
- Translated evaporation rate into alloy lifetime prediction

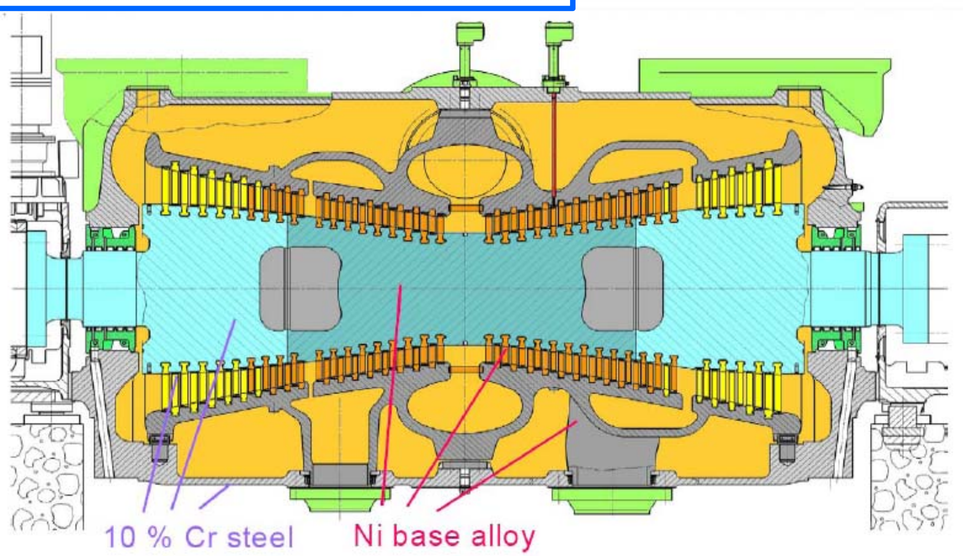
# Large Castings for A-USC Components

## Casting Challenges

- 1-15 tons
- Up to 100 mm in thickness
- Slow cooling rates
- Segregation prone alloys




***Valve Bodies***




***Turbine Casing***





*Courtesy Alstom*

# Cast Materials for A-USC Steam Turbines

## Examined a suite of traditionally wrought Ni-based superalloys cast under conditions designed to emulate the full sized casting

- Traditionally wrought alloys are being considered due to proven weldability in thick sections—Input from USC Consortium
- A computationally optimized homogenization heat treatment was developed to improve the performance of these materials—Paul Jablonski

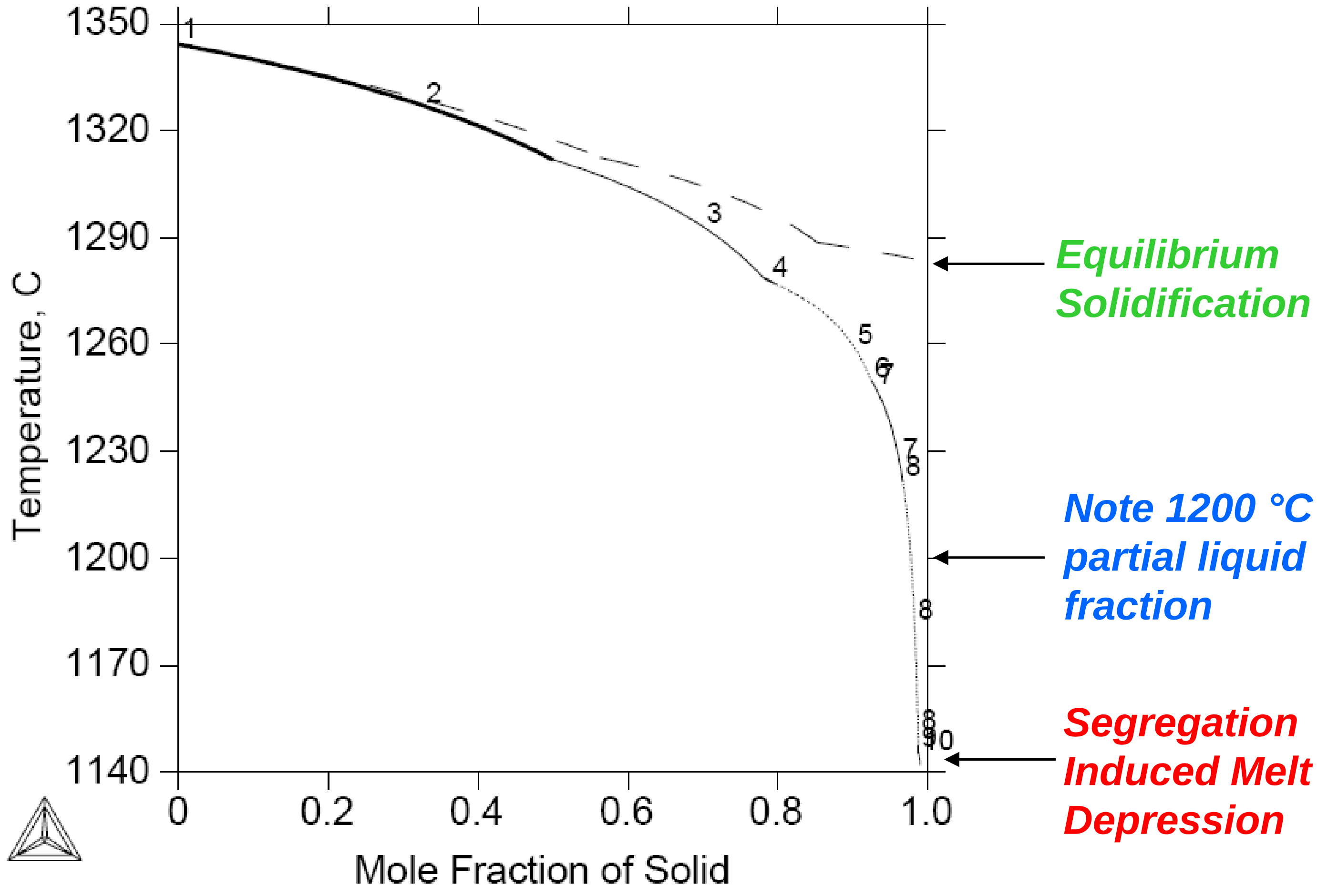
## Steam oxidation resistance

- Compare the steam oxidation behavior of cast versions of candidate Ni-based superalloys with their wrought counterparts

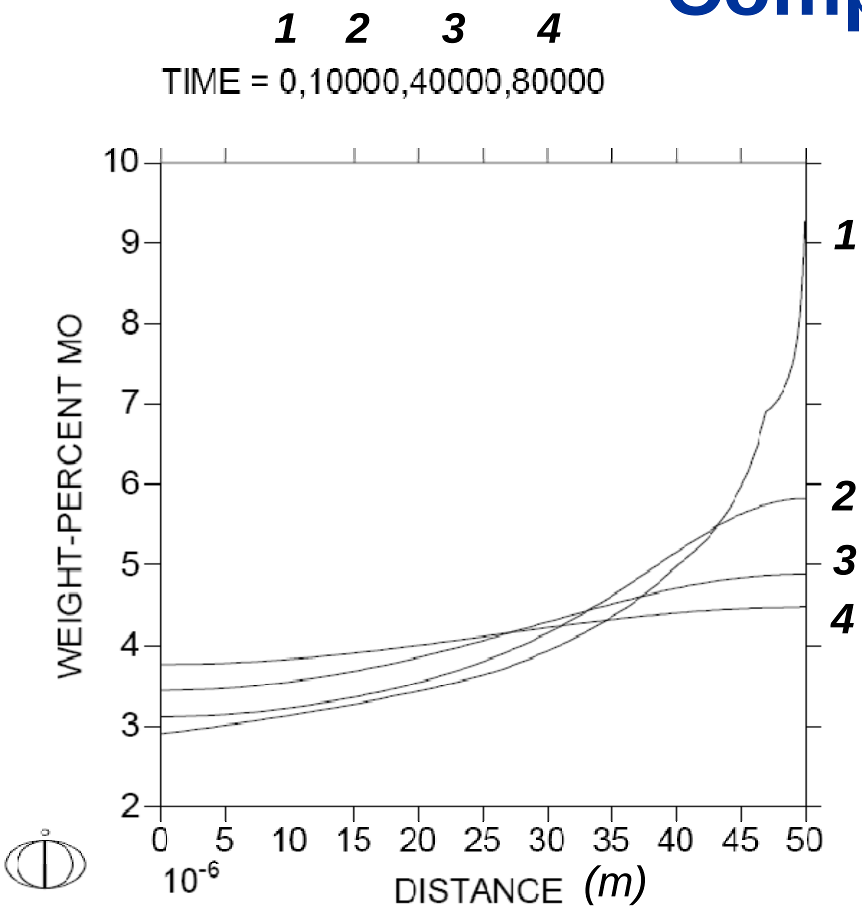
# Ingot Chemistries

| | C | Cr | Mo | Co | Al | Ti | Nb | Mn | Si | B | W | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **N105** | **0.15** | **14.85** | **5.00** | **20.00** | **4.70** | **1.10** | | **0.50** | **0.50** | **0.05** | | ***Aims*** |
| | ***0.16*** | ***14.61*** | ***5.02*** | ***20.04*** | ***4.43*** | ***1.10*** | | ***0.51*** | ***0.51*** | ***0.05*** | | ***Results*** |
| **H230** | **0.120** | **22.00** | **2.00** | | **0.35** | | | **0.70** | **0.50** | | **14.00** | |
| | ***0.12*** | ***21.59*** | ***2.01*** | | ***0.37*** | | | ***0.69*** | ***0.50*** | | ***13.91*** | |
| **H263** | **0.070** | **20.00** | **5.80** | **20.00** | **0.35** | **2.10** | | **0.50** | **0.35** | | | |
| | ***0.07*** | ***19.68*** | ***5.74*** | ***19.89*** | ***0.40*** | ***2.04*** | | ***0.50*** | ***0.34*** | | | |
| **H282** | **0.070** | **19.50** | **8.50** | **10.00** | **1.50** | **2.10** | | **0.25** | **0.15** | **0.005** | | |
| | ***0.07*** | ***19.22*** | ***8.48*** | ***9.84*** | ***1.44*** | ***2.08*** | | ***0.24*** | ***0.15*** | ***0.01*** | | |
| **IN617** | **0.120** | **22.00** | **9.00** | **12.50** | **1.10** | **0.30** | | **0.50** | **0.50** | | | |
| | ***0.12*** | ***21.73*** | ***8.96*** | ***12.35*** | ***1.04*** | ***0.31*** | | ***0.50*** | ***0.49*** | | | |
| **IN625** | **0.070** | **21.00** | **9.00** | | **0.10** | **0.10** | **3.60** | **0.50** | **0.35** | | | |
| | ***0.07*** | ***20.71*** | ***8.92*** | | ***0.15*** | ***0.089*** | ***3.58*** | ***0.49*** | ***0.34*** | | | |
| **IN740** | **0.030** | **25.00** | **0.50** | **20.00** | **1.30** | **1.50** | **1.50** | **0.30** | **0.30** | **Fe:** | **0.70** | |
| | ***0.04*** | ***24.71*** | ***0.50*** | ***20.03*** | ***1.24*** | ***1.48*** | ***1.50*** | ***0.30*** | ***0.31*** | | ***0.57*** | |

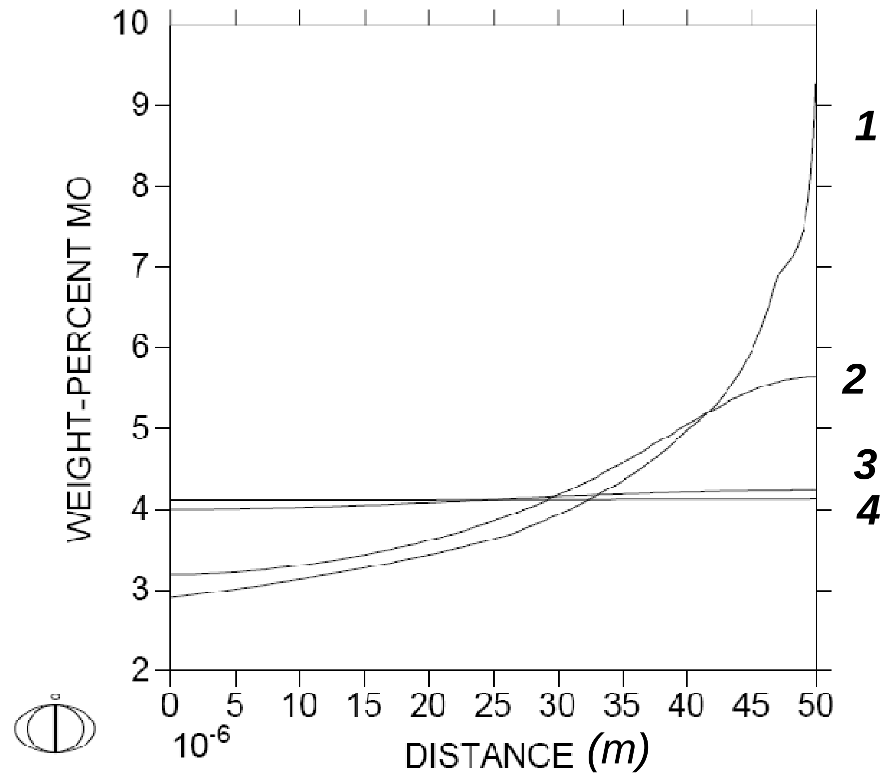
# N105—Solidification



# N105—Homogenization Heat Treatment Comparison




**Isothermal at 1100 °C**

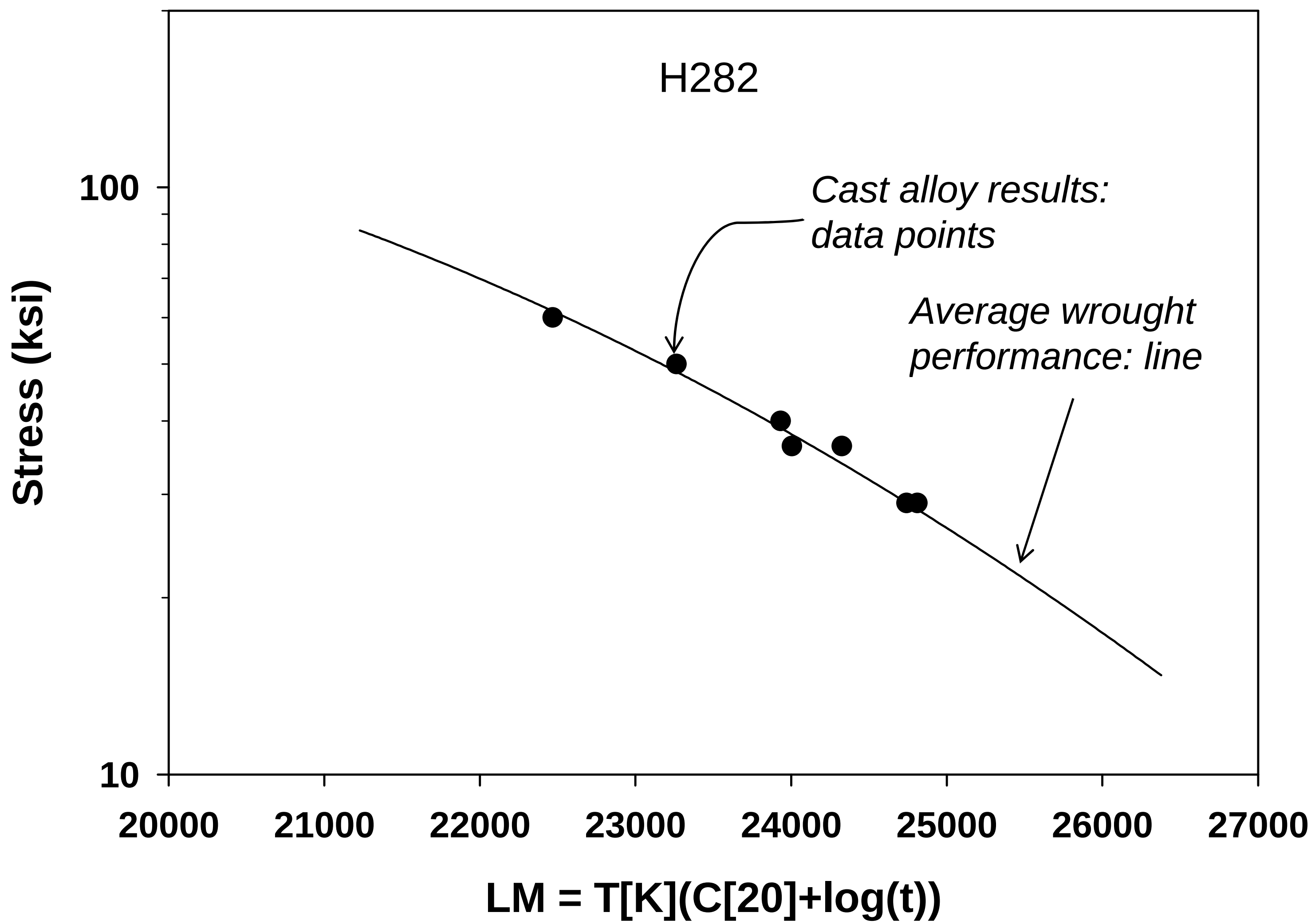



**1100 °C/10,000s+1200 °C/remaining time**

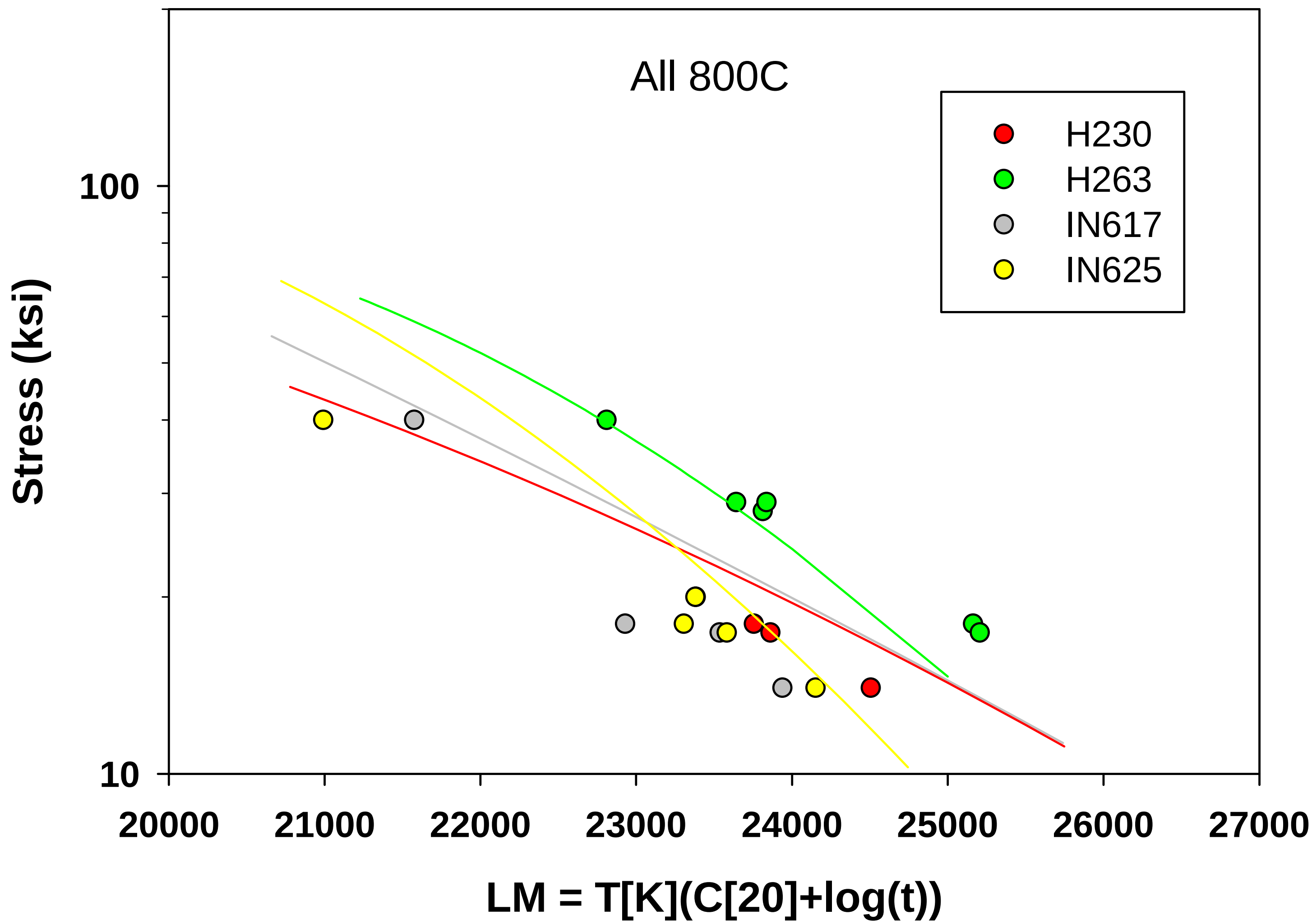
*Patent Pending*

*Metall. Trans. B, **40B**, (2009) 182.*

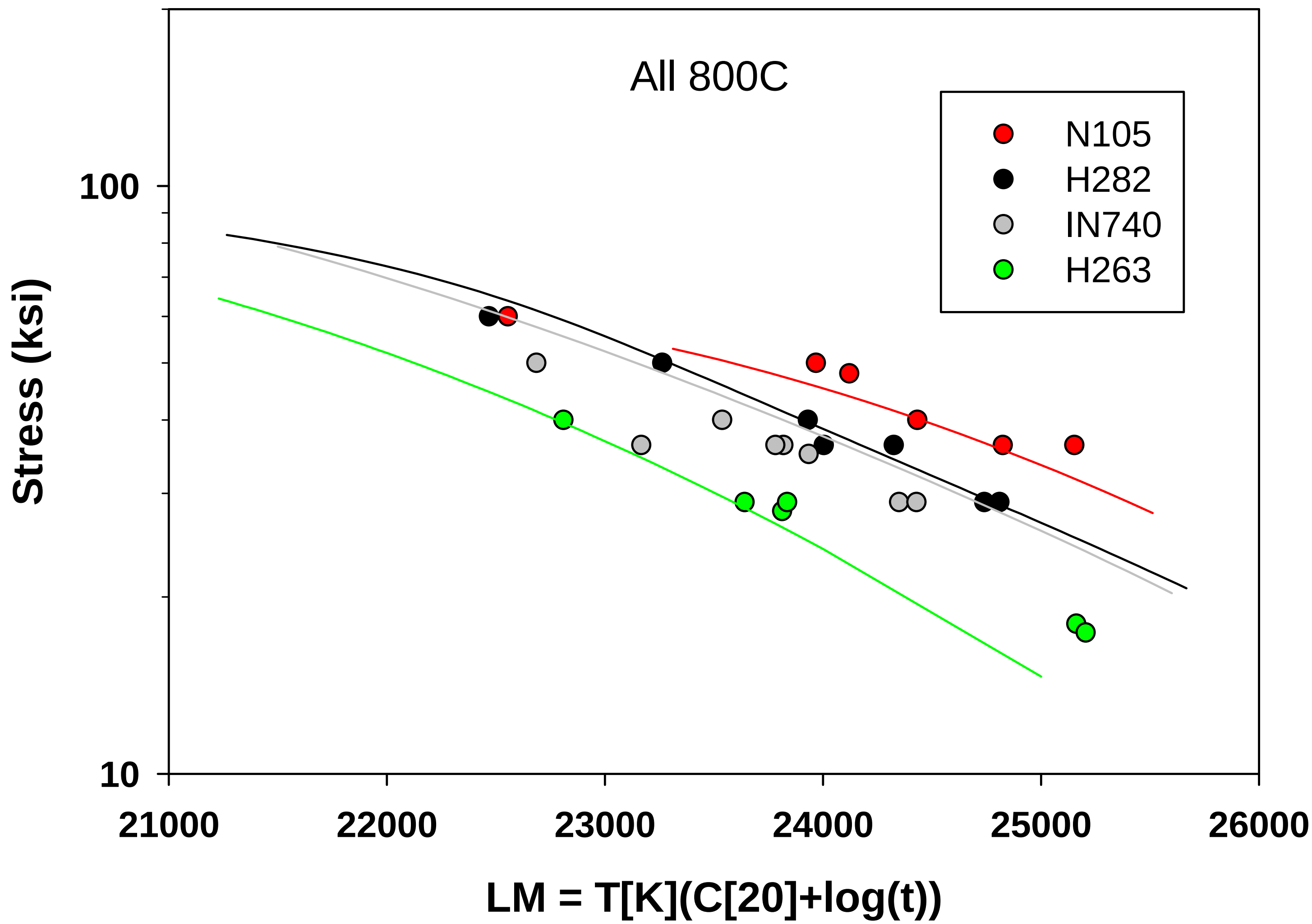
# 800 °C Creep Results



# Solid Solution Alloys



# Gamma Prime Formers

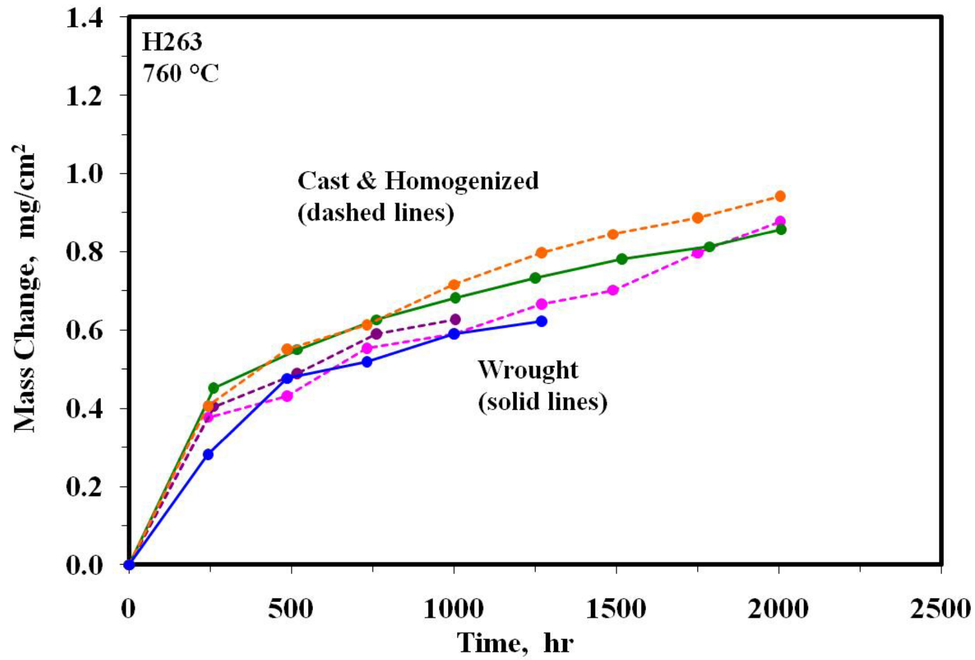


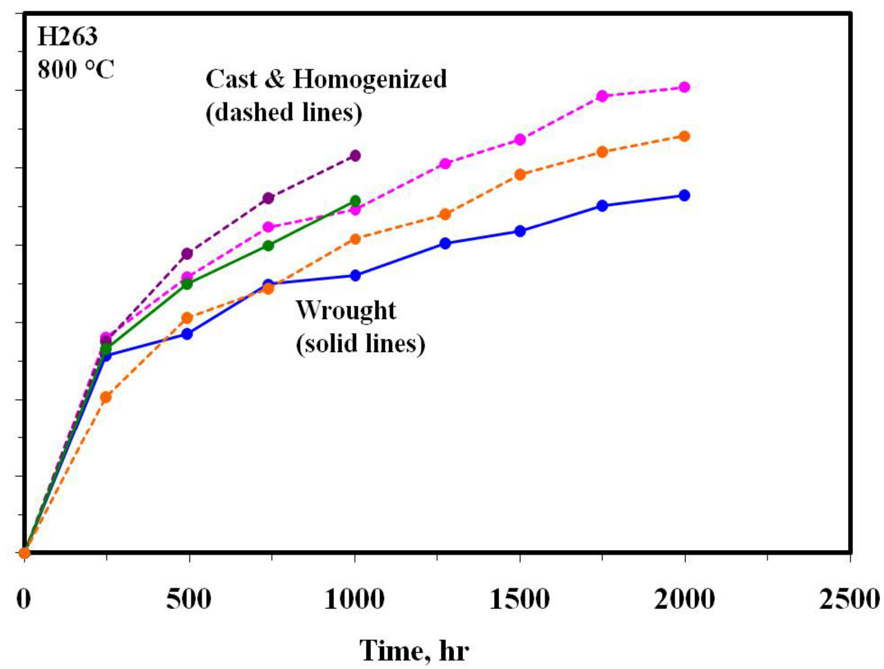
# Alloys Under Consideration for Steam Oxidation Resistance

| Solid Solution | Age Hardenable |
|---|---|
| H230 | N105 |
| IN617 | H263 |
| IN625 | H282 |
| | IN740 |

- *Isothermal tests in steam using deaerated water*
- *760 and 800 °C*
- *250 hour cycles for 1000 and 2000 total hours*

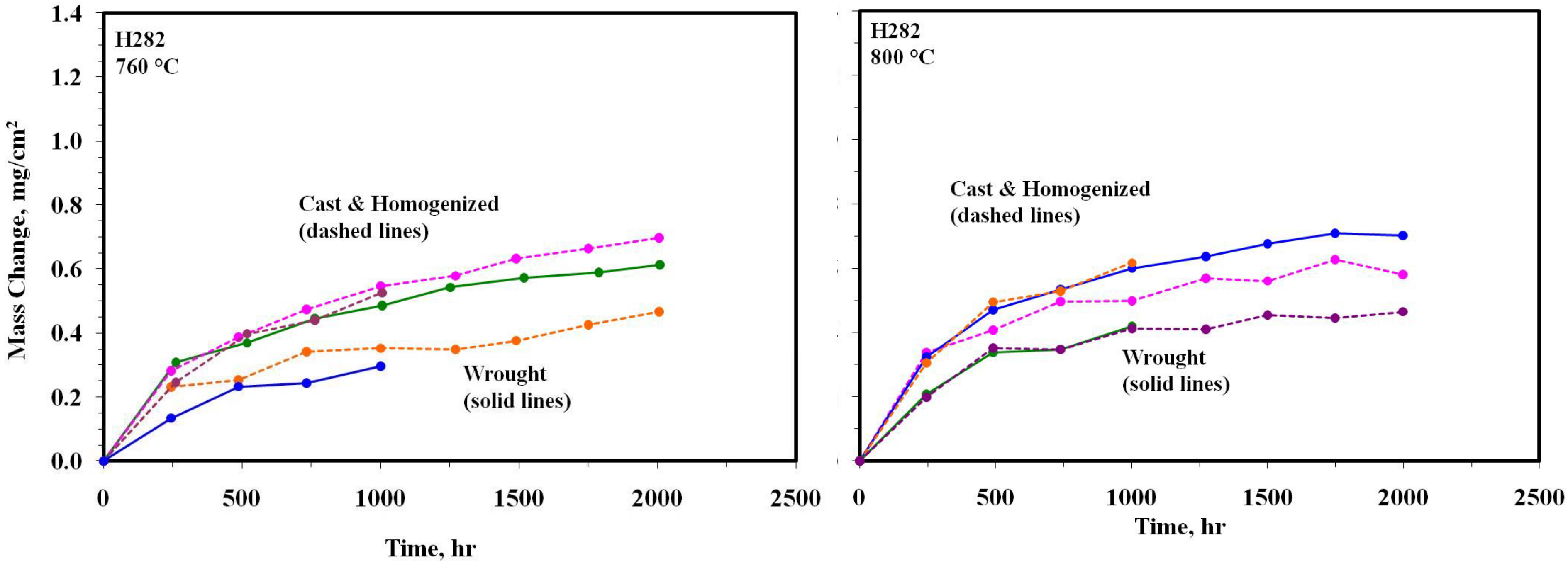
# Oxidation Results H263



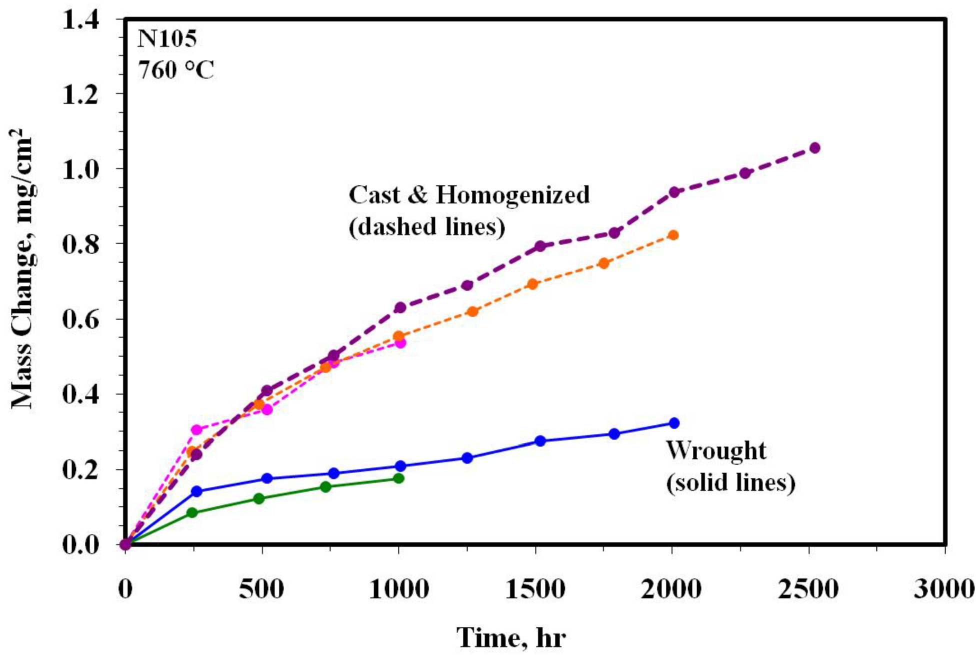

***No significant differences between cast & homogenized and wrought***

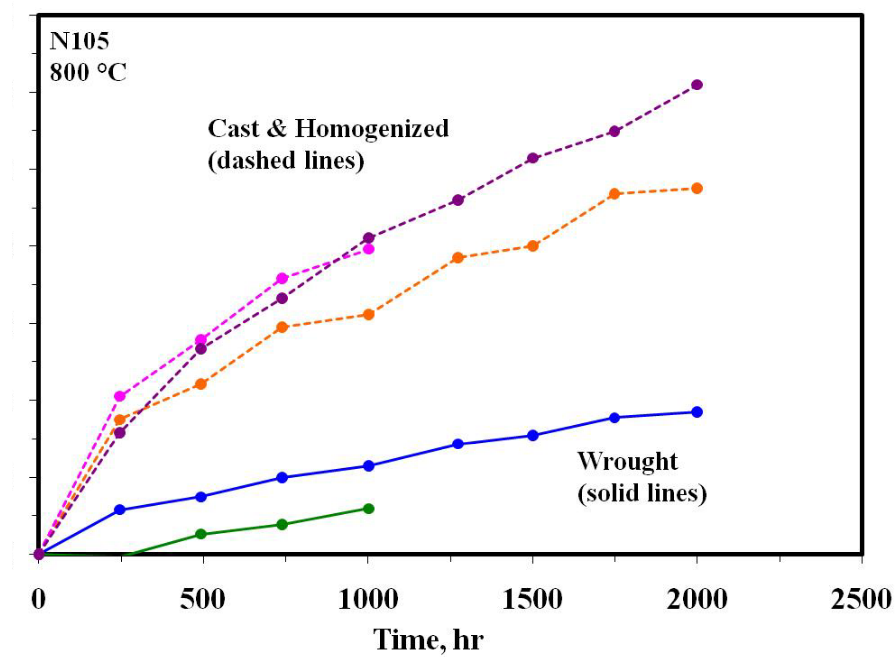
# Oxidation Results H282




***No significant differences between cast & homogenized and wrought***

# Oxidation Results N105




***Significant differences between cast & homogenized and wrought***

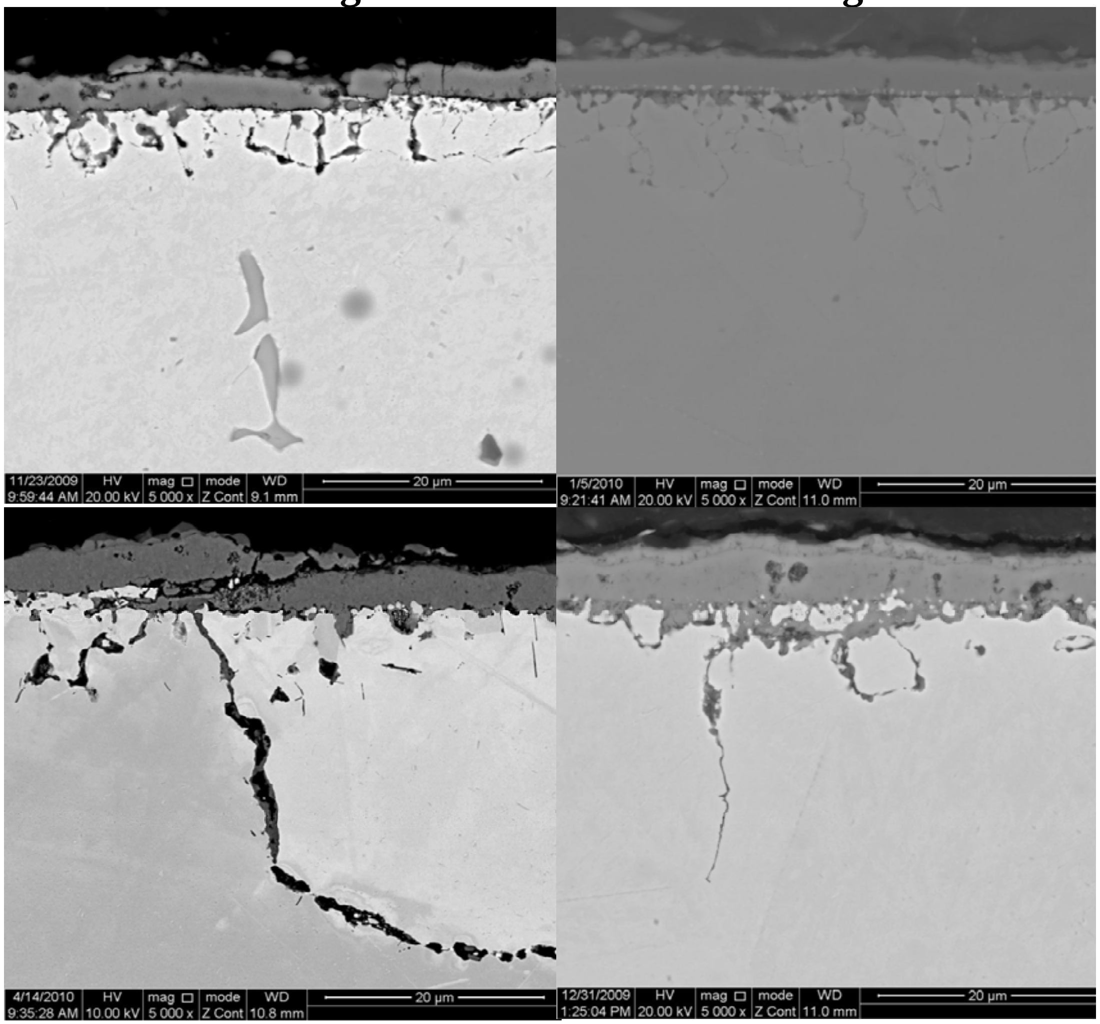
***Wrought versions show much less mass gain with time***

# Exposure in Steam for 1000 hr—H263

Cast and Homogenized | Wrought

760 °C

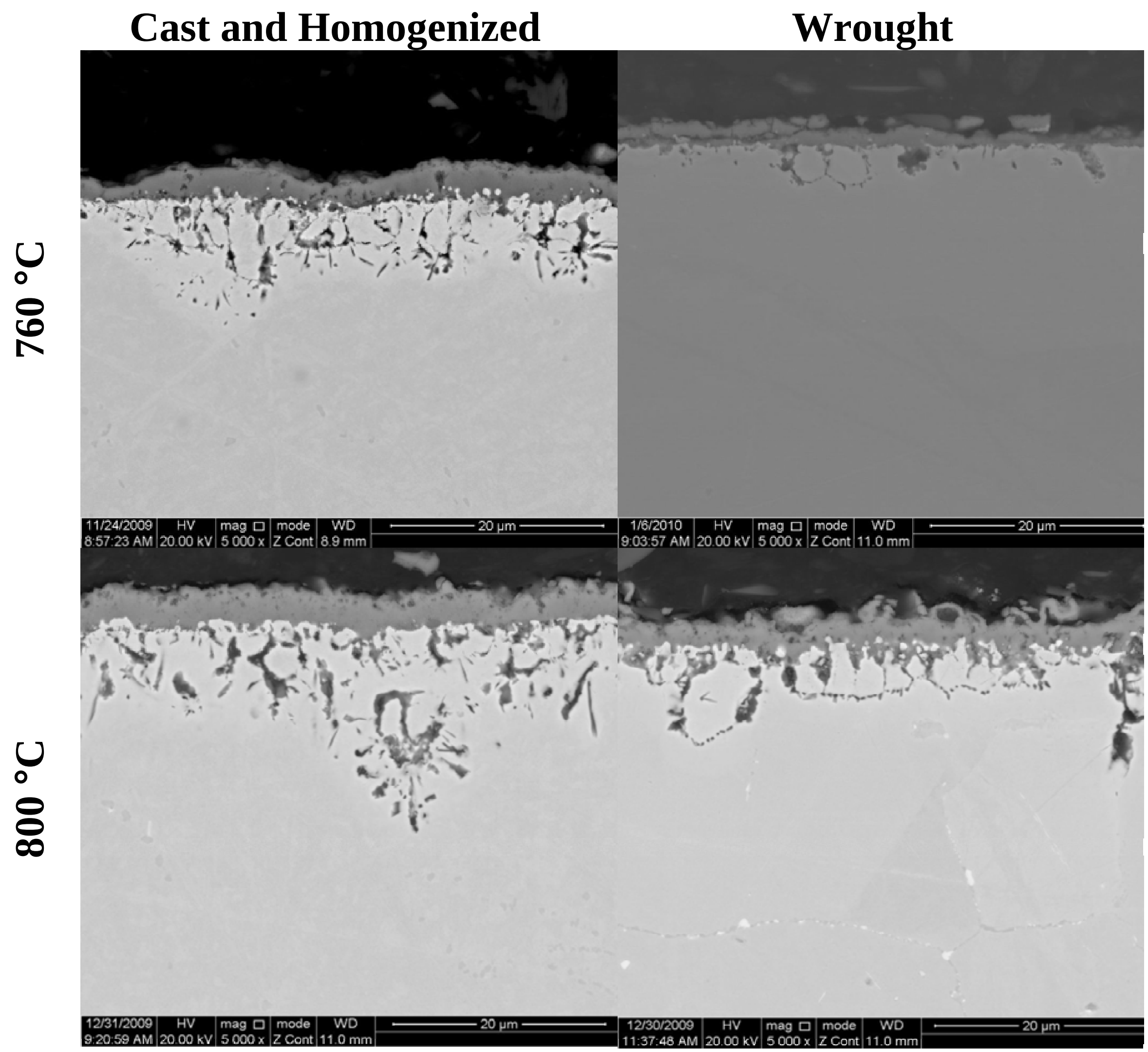
800 °C




*External chromia scales*

*Internal oxidation of Ti and Al was more pronounced in the C&H alloys*

# Exposure in Steam for 1000 hr—H282




*Over much the same as in H263*

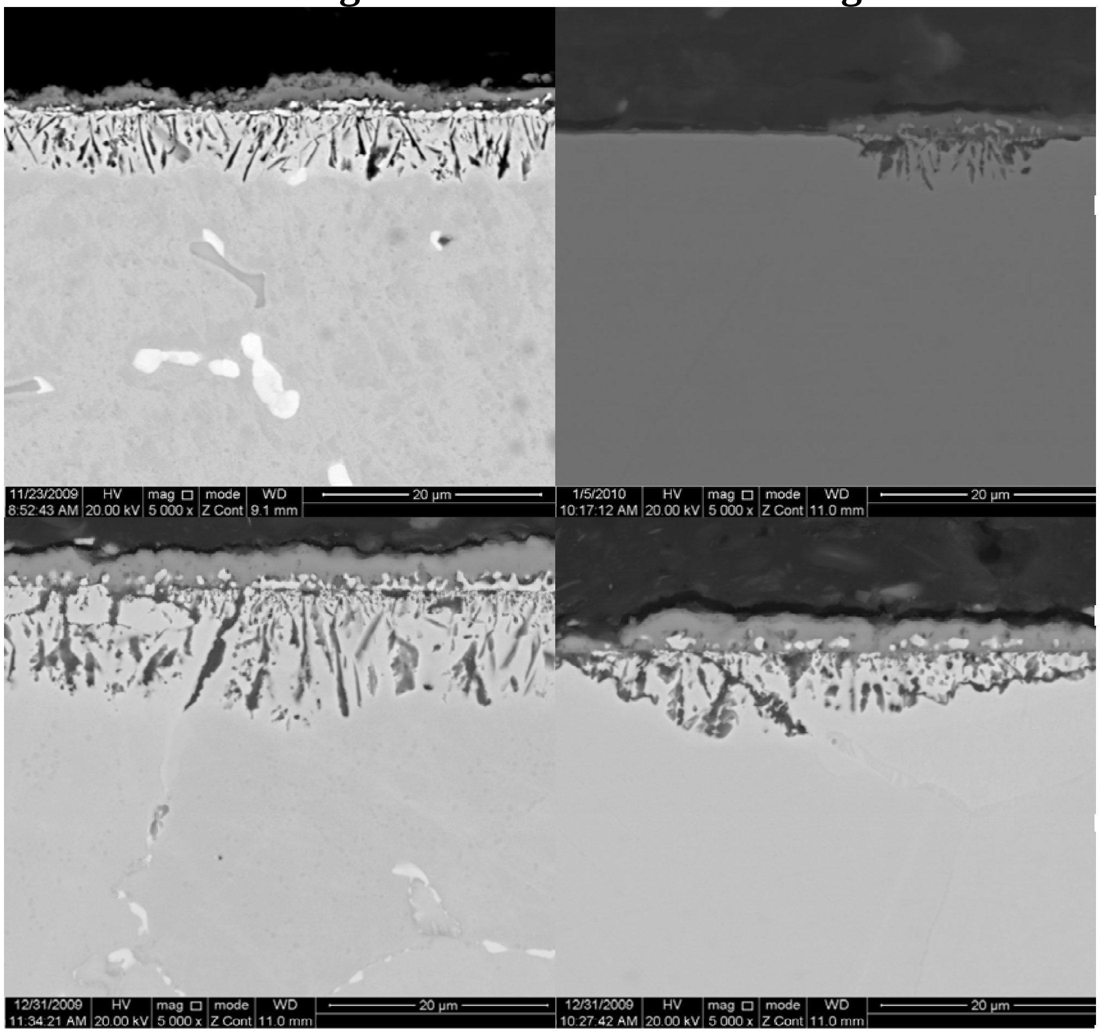
*External chromia scales*

*Internal oxidation of Ti and Al was more pronounced in the C&H alloys*

# Exposure in Steam for 1000 hr—N105

**Cast and Homogenized** | **Wrought**

**760 °C** / **800 °C**




*Two types of structures were found*

- *Chromia external scale and internal oxidation of Al and Ti*
- *Very thin alumina external scale—found on sections of the wrought alloys at both temperatures*

*Alumina scales are much more protective*

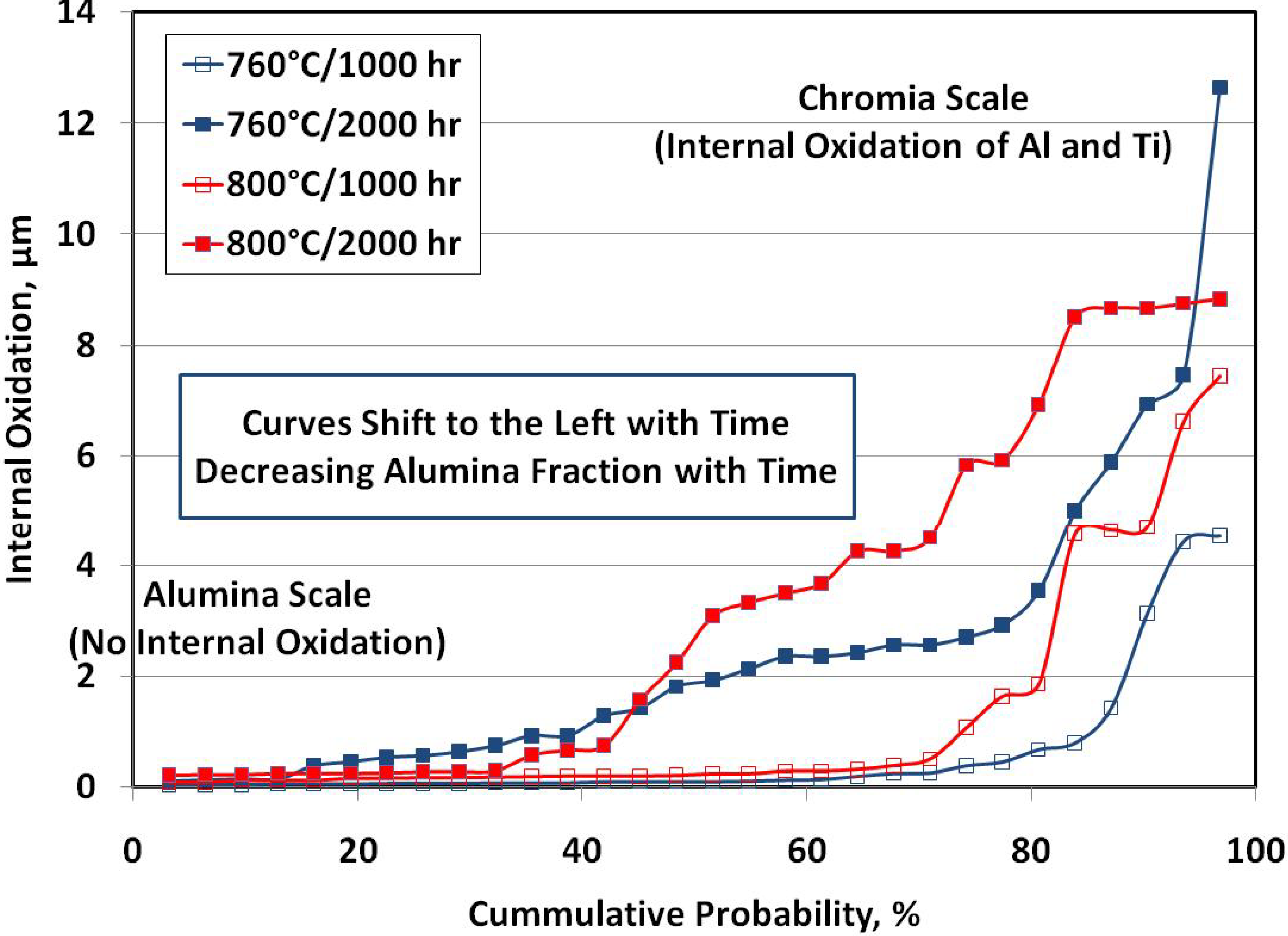
# Scaling Behavior

External Scale and Internal Oxidation Behavior, 760 °C

| Alloy | | T hr | External Scale Thickness µm | External Scale std % | Internal Oxidation Thickness µm | Internal Oxidation std % | Internal Oxidation Maximum µm |
|---|---|---|---|---|---|---|---|
| H263 | C&H | 1000 | 2.81 ± 0.63 | 22% | 4.70 ± 4.08 | 87% | 28.2 |
| | | 2000 | 3.34 ± 0.97 | 29% | 9.79 ± 5.35 | 55% | 42.6 |
| | Wrought | 1000 | 2.79 ± 0.37 | 13% | 7.11 ± 3.49 | 49% | 16.4 |
| | | 2000 | 4.36 ± 0.64 | 15% | 5.18 ± 2.68 | 52% | 23.9 |
| H282 | C&H | 1000 | 2.54 ± 0.43 | 17% | 6.92 ± 3.73 | 54% | 34.2 |
| | | 2000 | 4.53 ± 1.36 | 30% | 6.26 ± 4.73 | 76% | 38.0 |
| | Wrought | 1000 | 1.13 ± 0.35 | 30% | 1.81 ± 1.07 | 59% | 10.2 |
| | | 2000 | 3.00 ± 0.55 | 18% | 5.09 ± 2.20 | 43% | 25.1 |
| N105 | C&H | 1000 | 1.52 ± 0.50 | 33% | 5.95 ± 0.69 | 12% | 9.9 |
| | | 2000 | 2.86 ± 0.81 | 28% | 10.09 ± 1.90 | 19% | 17.6 |
| | Wrought | 1000 | 0.39 ± 0.47 | 119% | 0.60 ± 1.22 | 201% | 9.3 |
| | | 2000 | 0.98 ± 0.86 | 89% | 2.46 ± 2.75 | 112% | 14.9 |

***H263 & H282—External scaling similar between C&H and Wrought***
***H263 & H282—Internal scaling more pronounced in C&H***
***N105 Wrought clearly shows partial alumina coverage***
***Alumina coverage shrinking with time as shown by scaling kinetics***

# Wrought N105—Borderline Alumina Protection



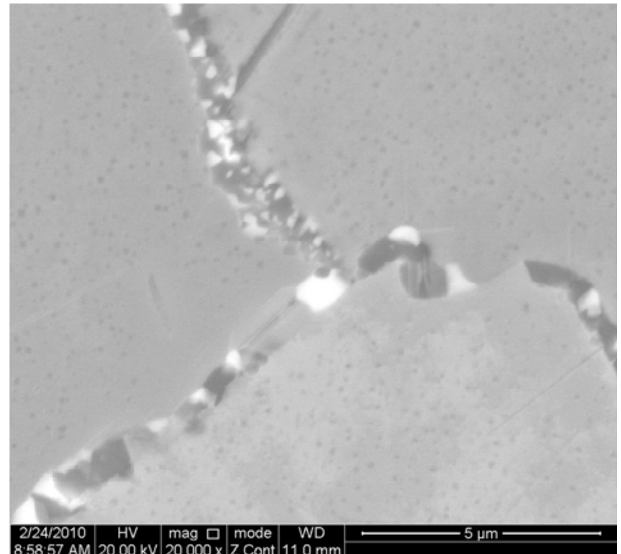
# Microstructure after 1000 hr at 800 °C—H263

*Light precipitates are Mo-rich carbides*

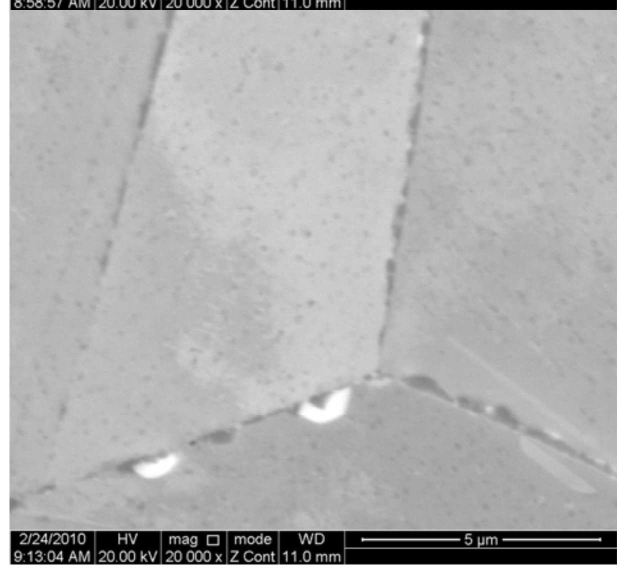
*Dark precipitates are Cr-rich carbides*

*More gb precipitate coverage in C&H alloy*

Cast and Homogenized




Wrought



# Microstructure after 1000 hr at 800 °C—H282

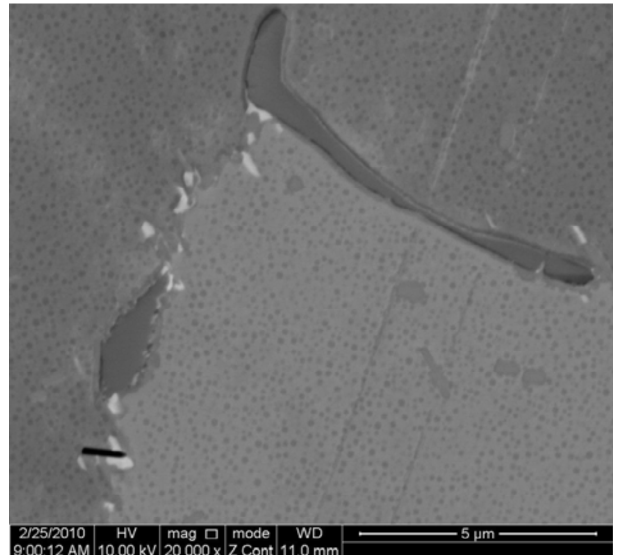
*Light precipitates are Mo-rich carbides*

*Large dark precipitates are Ti-rich carbides*

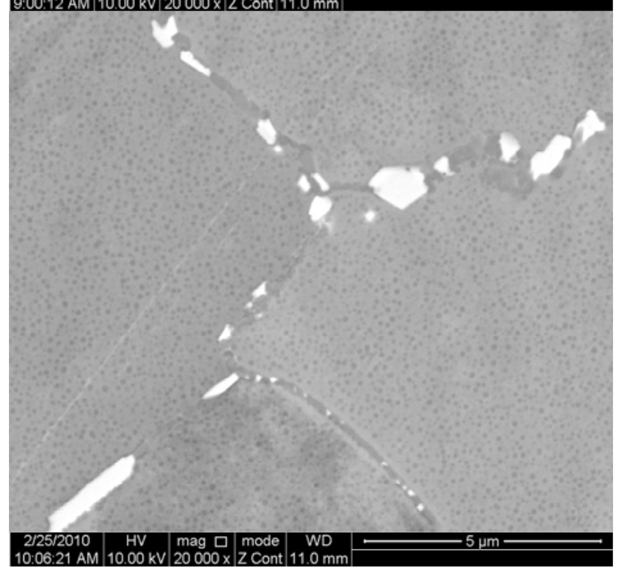
*Smaller dark precipitates are Cr-rich carbides*

*More gb precipitate coverage in C&H alloy*

**Cast and Homogenized**




**Wrought**



# Microstructure after 1000 hr at 800 °C—N105

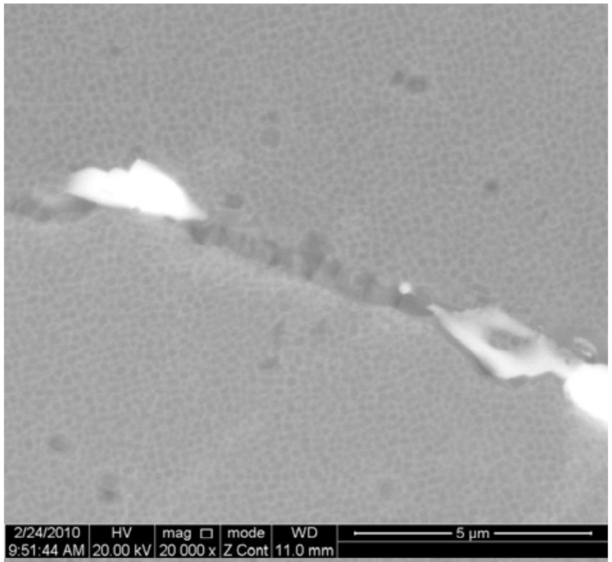
*Light precipitates are Mo-rich carbides*

*Dark precipitates are Ti and Cr-rich carbides in C&H alloy*

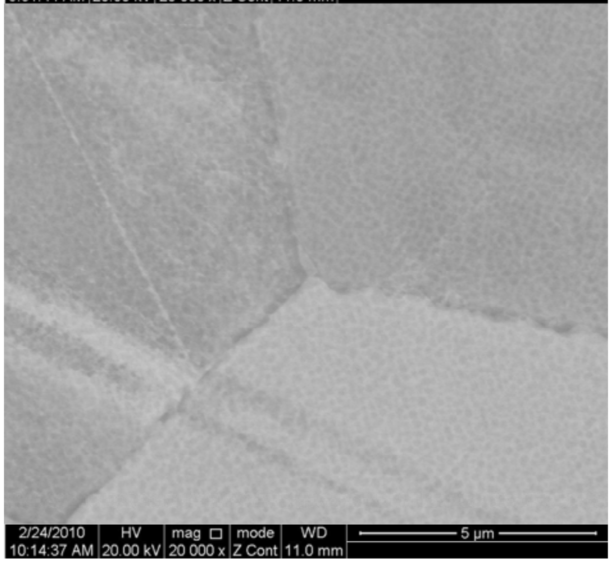
*Dark precipitates are Cr-rich carbides in wrought alloy*

*More gb precipitate coverage in C&H alloy*

**Cast and Homogenized**




**Wrought**



# Summary I

The development of high creep strength and steam oxidation resistant cast alloys for use in A-USC steam turbines is required to meet the need of some of the large components that comprise the turbine

A computationally optimized homogenization heat treatment was developed to improve the performance of these materials

H263, H282, and N105, were selected based on good cast-alloy creep resistance for further examination in terms of steam oxidation resistance

# Summary II

## H263 and H282

- External chromia scale (both C&H and wrought alloys)
- Internal oxidation of Al and Ti (both C&H and wrought alloys)
- The overall mass gain and parabolic kinetics were similar
- The depth of internal oxidation was greater in the C&H alloys
- More Mo-rich and Cr-rich carbides were found at gbs of the C&H alloys
- Ti-rich carbides were found along gbs of the C&H H282 alloys

## N105

- Wrought alloys exhibited lower oxidation kinetics than the C&H alloys
- Some of the surface of the wrought alloys was covered by a very protective alumina scale
- Where alumina was not present, a chromia scale was present with internal oxidation of Al and Ti
- Fraction of the surface protected by the alumina scale decreased with time
- C&H gbs contained Mo-rich carbides, Ti-rich carbides, and Cr-rich carbides
- Only Cr-rich carbides on the wrought N105 gbs