T91 Boiler Tube Oxide Spallation Experiments in High Pressure Steam

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Introduction

The growing importance of variable renewable power sources results in coal-fired boilers being operated with more thermal cycles than envisioned when they were designed. This may lead to increased oxide spallation inside boiler tubing, which may result in downstream hot short failures or turbine erosion. The overall aim of this research project is to develop an oxide spallation model using a physics-based approach, that incorporates oxide morphologies and structures, to improve power plant performance. The research presented here is a parallel experimental approach to examine the cyclic oxidation performance and spallation of T91 boiler tubes pre-oxidized with a thick scale.

Figure 1. System Wide Wind & Solar, Illustrative Day ERCOT

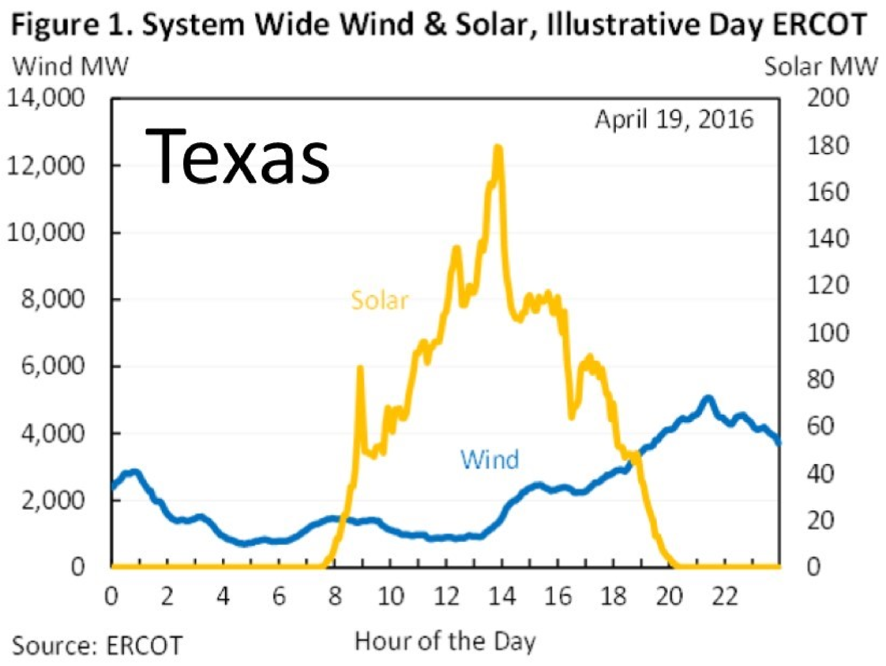
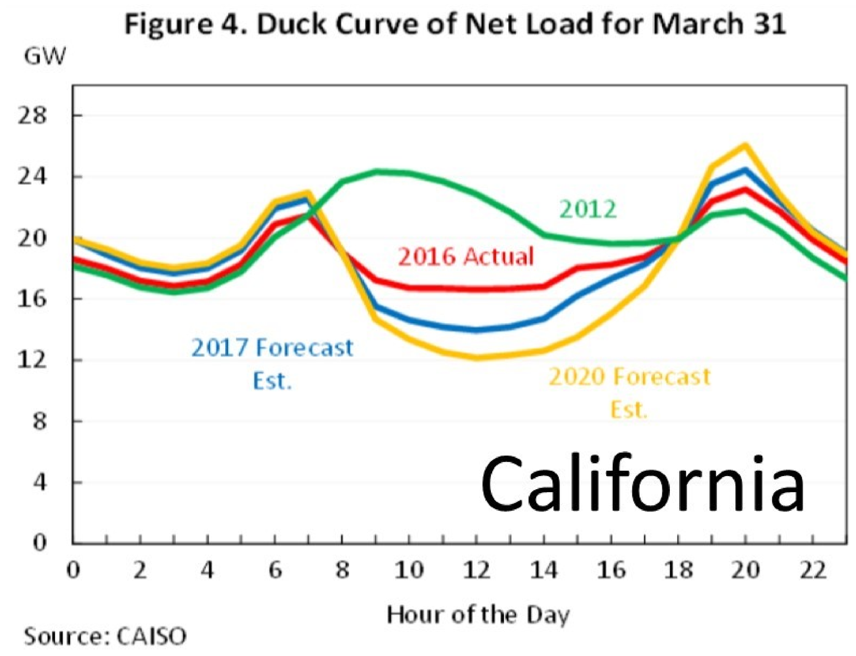


Figure 4. Duck Curve of Net Load for March 31



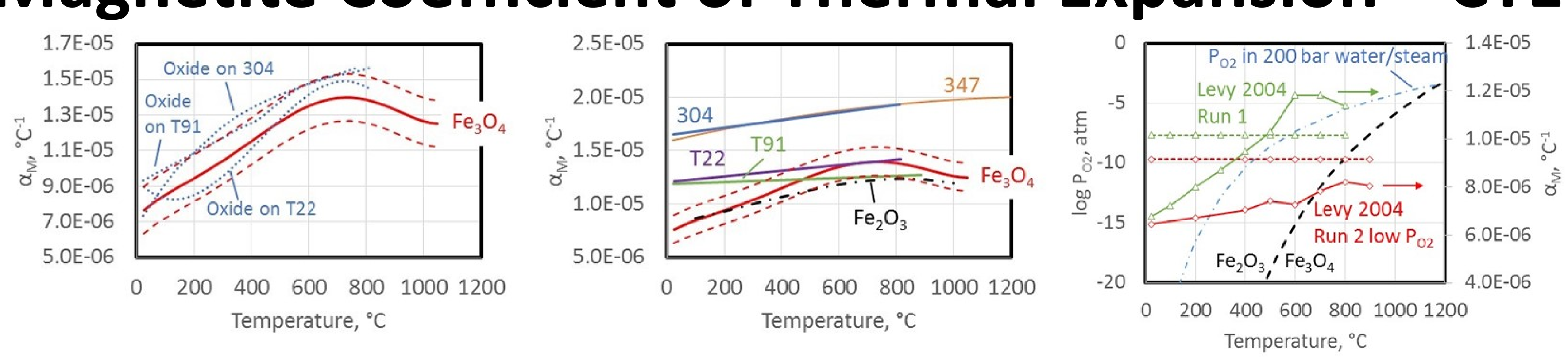
https://obamawhitehouse.archives.gov/sites/default/files/page/files/20160616_cea_renewables_electricgrid.pdf

Variable Energy Resources
- Solar and Wind
- Often Dispatched Ahead of Coal
- Increased Thermal Cycles in Coal Power Plants

Flexible Operations
- Load Following
- Hot Starts (< 24 h off line)
- Warm Starts (24-120 h off line)
- Cold Starts (> 120 h off line)

Increased Damage per Cycle

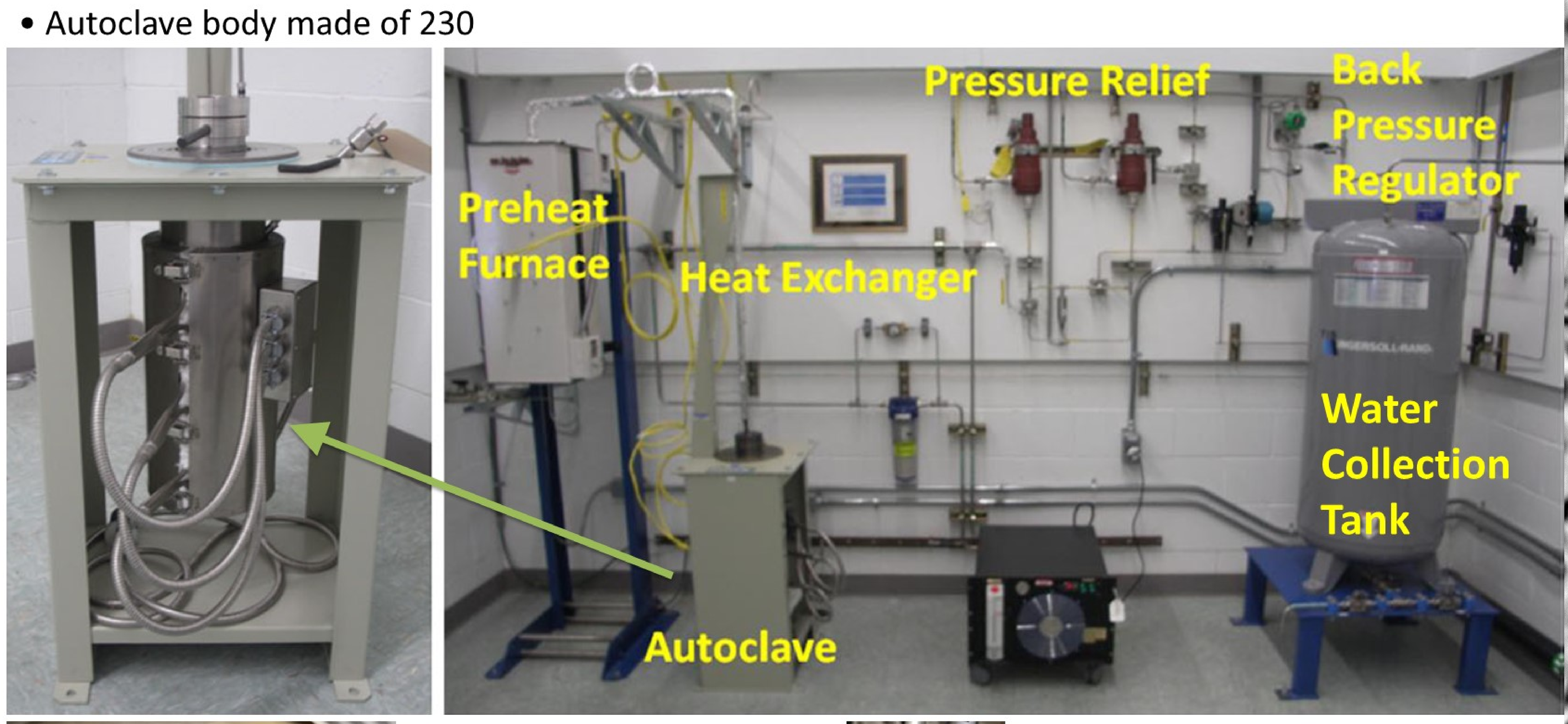
Magnetite Coefficient of Thermal Expansion—CTE



- Reinterpretation of Armitt report of magnetite (Fe_3O_4) CTE (2.4×10^{-5} °C^{-1} at 550°C)
- Overstated magnetite CTE
- NETL revisited original Russian data (Arkharov) it was based on (and also Levy, Okudera, Sharma, Takeda, Gorton and Fry)
- Different implications in thermal strains (and oxide spallation) from alloy type and oxide composition
- Oxygen activity effects on CTE will be addressed in phase field models
- G. R. Holcomb, "A Review of the Thermal Expansion of Magnetite," Materials at High Temperatures (2018)

Experimental Procedures

Advanced Ultra-supercritical (A-USC) Steam Autoclave
- Flow controlled with a high pressure pump
- Pressure controlled with a back pressure regulator
- ASME dual rated to 704°C/346 bar and 760°C/228 bar
- Autoclave body made of 230



T91 boiler tube sections

316L ¼" tubing spacers

Fe9Cr flat samples

Suspended inside the tubes

Pre-Oxidation for a Thick Scale
- 500 h at 710°C/200 bar
- 2000 h at 710°C/200 bar

Cyclic Tests at 600°C/200 bar
- Cycled down to 400°C/10 bar
- Cycled down to 200°C/10 bar

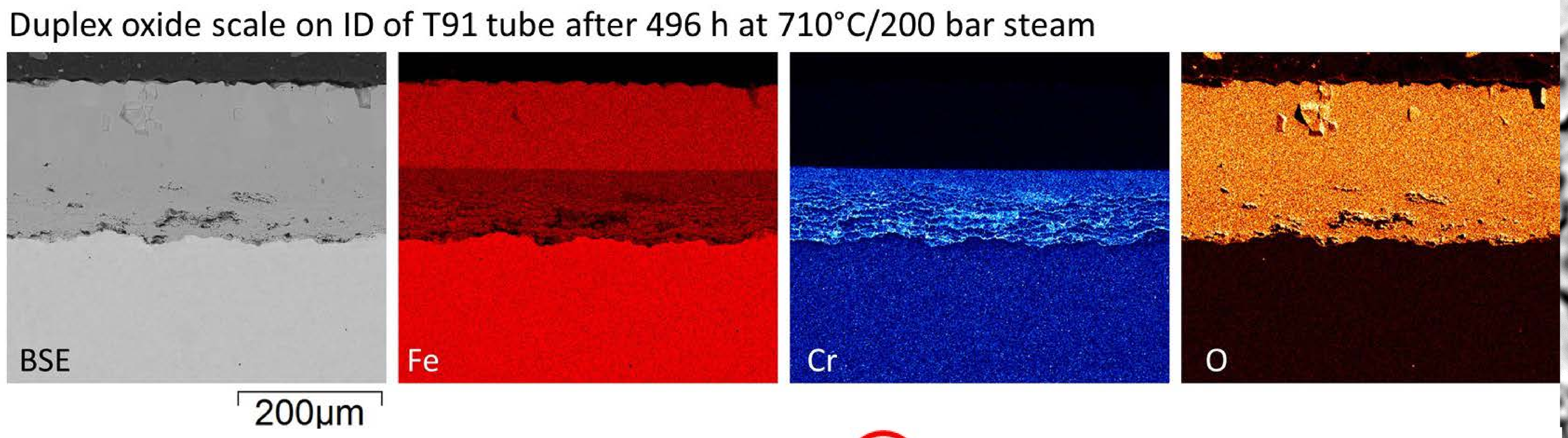
T91 Boiler Tubes

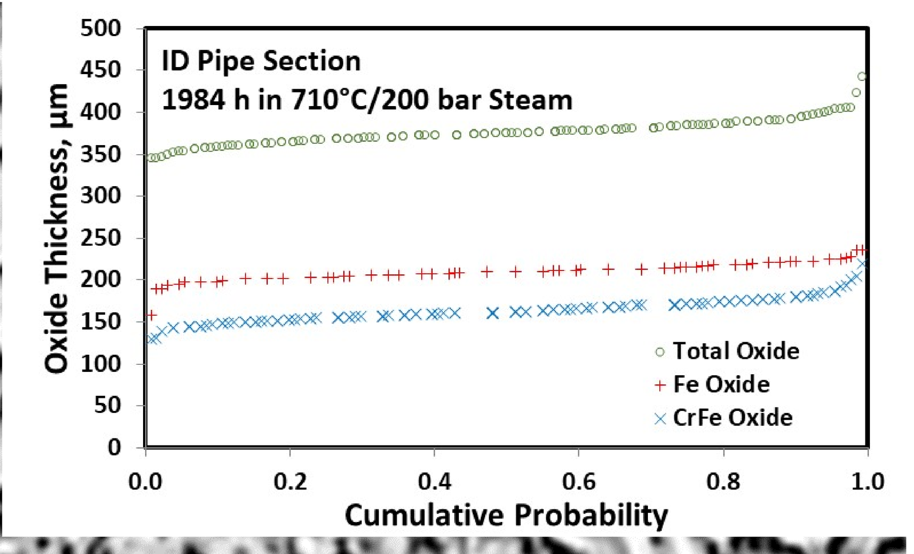
- T91 Vallourec & Mannesmann tubes, courtesy of Foster Wheeler
- 2.25" OD, 1.89" ID seamless tubes
- Hot finished, normalized at 1060°C for 20 min, tempered at 780°C for 60 min
- Cut into 2" long sections
- Machined to an equivalent to a 600 grit surface
- Background image shows microstructure

Alloy	Fe wt%	Cr wt%	Mo wt%	Si wt%	Mn wt%	Ni wt%	Cu wt%	Al wt%	Nb wt%	C ppm	N ppm	P ppm	S ppm
T91	Bal	8.46	0.95	0.36	0.44	0.14	0.16	0.01	0.08	1000	545	160	20

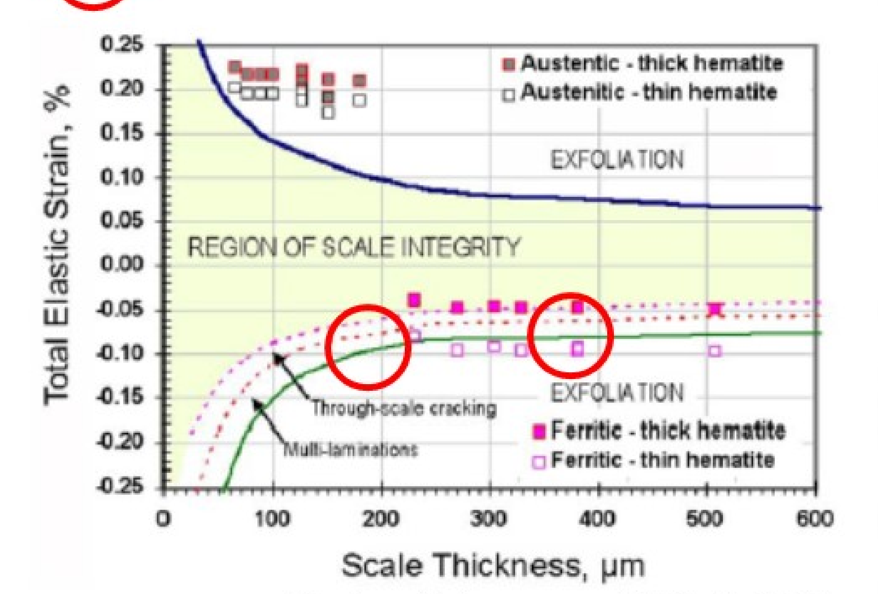
Pre Oxidation of T91 Tubes

Duplex oxide scale on ID of T91 tube after 496 h at 710°C/200 bar steam



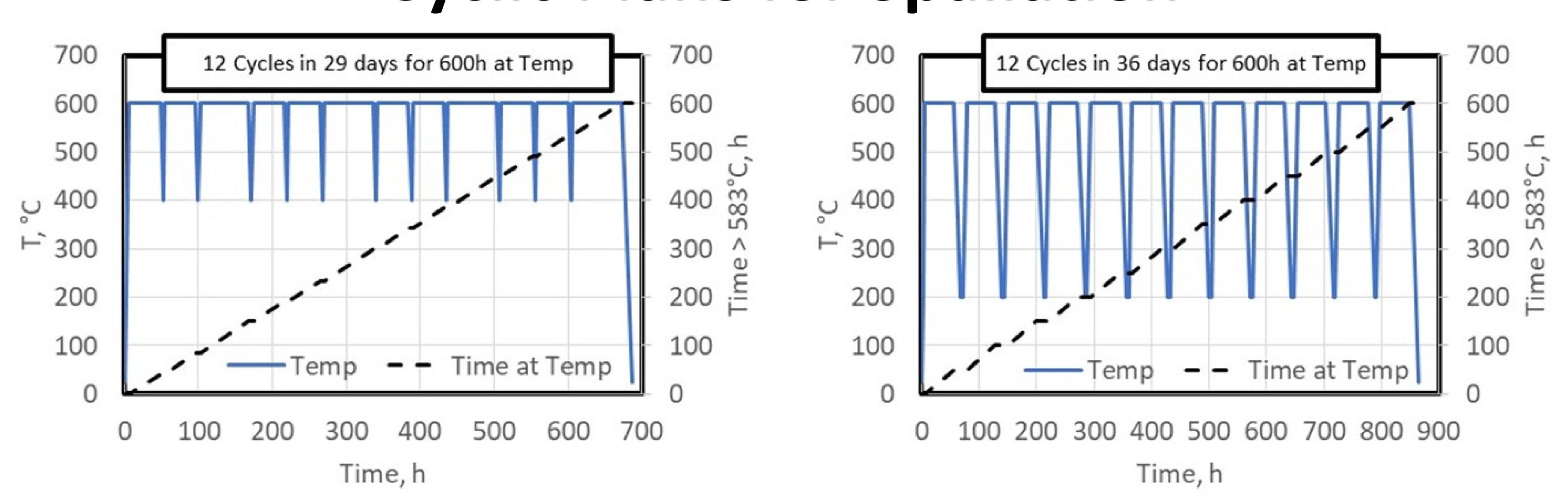


Pre-oxidation Scale Thicknesses



Dooley, Paterson and Wright 2003

Cyclic Plans for Spallation



Summary

Cyclic oxidation tests in high pressure steam on T91 boiler tube sections to support verification of boiler oxide spallation models

Progress:
- Critical review of the available CTE data of Fe_3O_4
- Pre-oxidation at 710°C/200 bar steam of T91 boiler tube sections to establish thick initial oxide scales prone to spallation
  - 210 µm after 486 h
  - 375 µm after 1984 h
- Morphology similar to that found from long-term boiler exposures
- Cyclic test plan to simulate 12 cycles in 29 days—600°C/200 bar to 400°C/10 bar
- Other cycles planned for 600°C/200 bar to 200°C/10 bar

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