Schmidt + Clemens Group

Assessment of Remaining Tube Life in Steam Cracking Service: From Destructive Evaluation to Online Monitoring

01 Introduction

- Steam cracking furnaces operate under extreme conditions with high temperatures, reactive gas atmospheres, and long run lengths
- Radiant coils degrade over time due to carburization, oxidation, nitridation, mechanical stresses, and high-temperature microstructural ageing
- Tube integrity directly impacts furnace safety, reliability, and on-stream performance

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1. <u>Destructive</u> metallographic testing is the established standard for condition assessment but requires shutdowns and localized sampling
2. Magnetic <u>non-destructive</u> testing provides broader coverage but presents interpretation challenges, especially for alumina-forming alloys
3. Process data and temperature monitoring are emerging as promising tools for <u>continuous</u> online assessment of remaining tube life

DESTRUCTIVE METALLOGRAPHIC TESTING

Established standard for assessing radiant coil condition and integrity

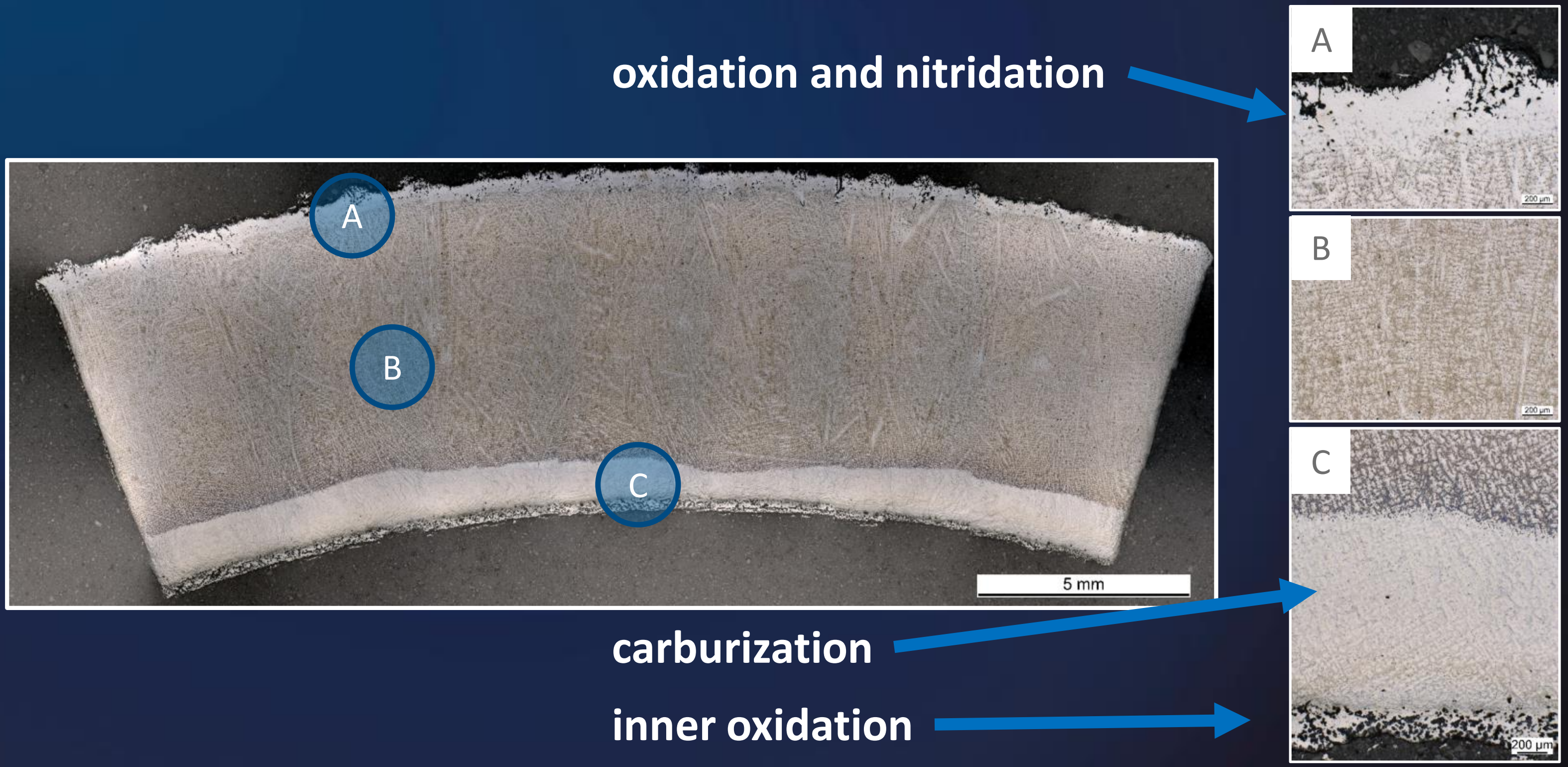
Pro:

- High accuracy based on decades of experience in corrosion engineering and metallography

Cons:

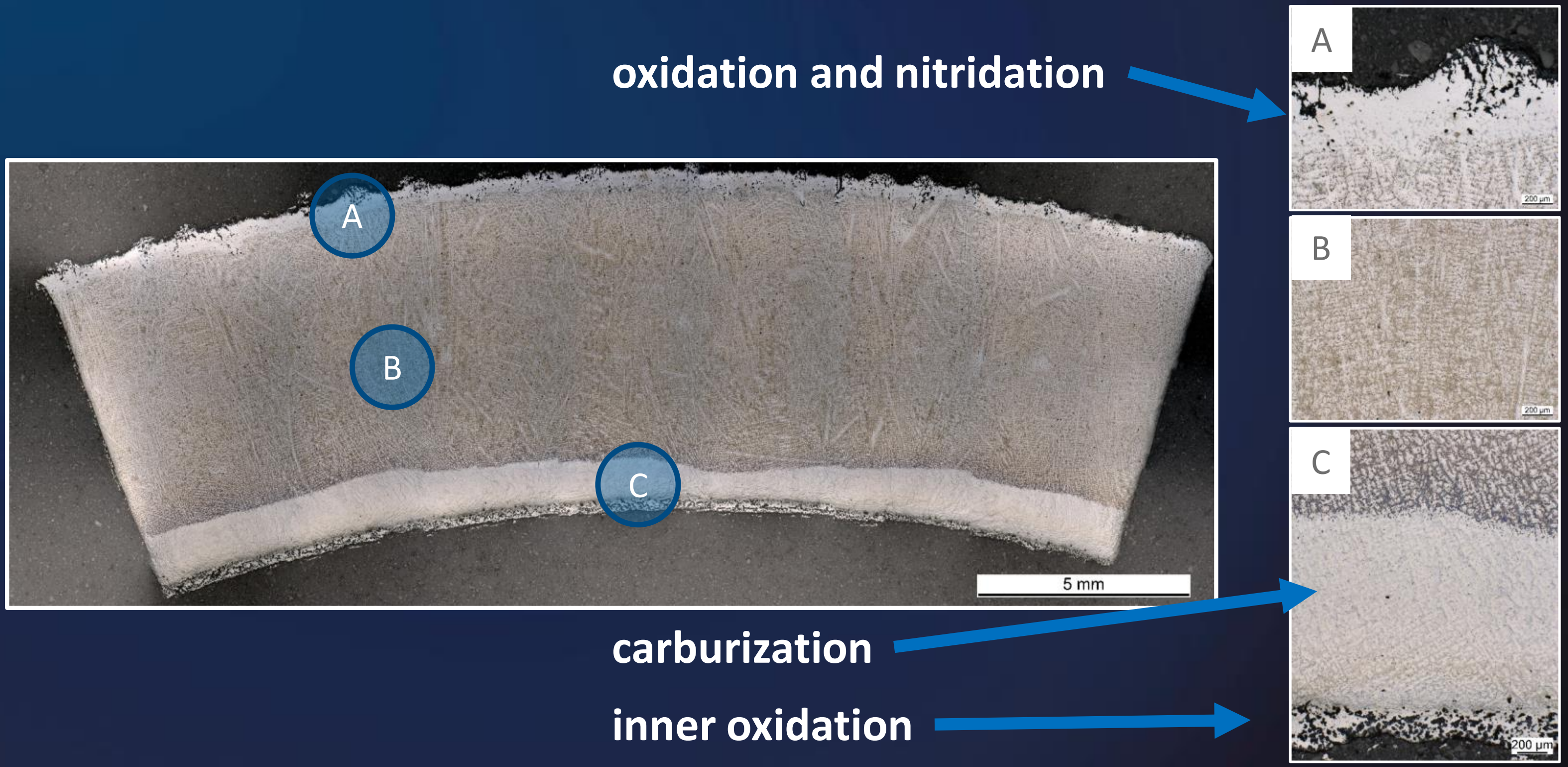
- Requires full furnace shutdown, <u>localized</u> sampling, and subsequent repair welding
- Repair welding can be challenging for aged materials and requires suitable spare material

02 Destructive Testing of Radiant Coils



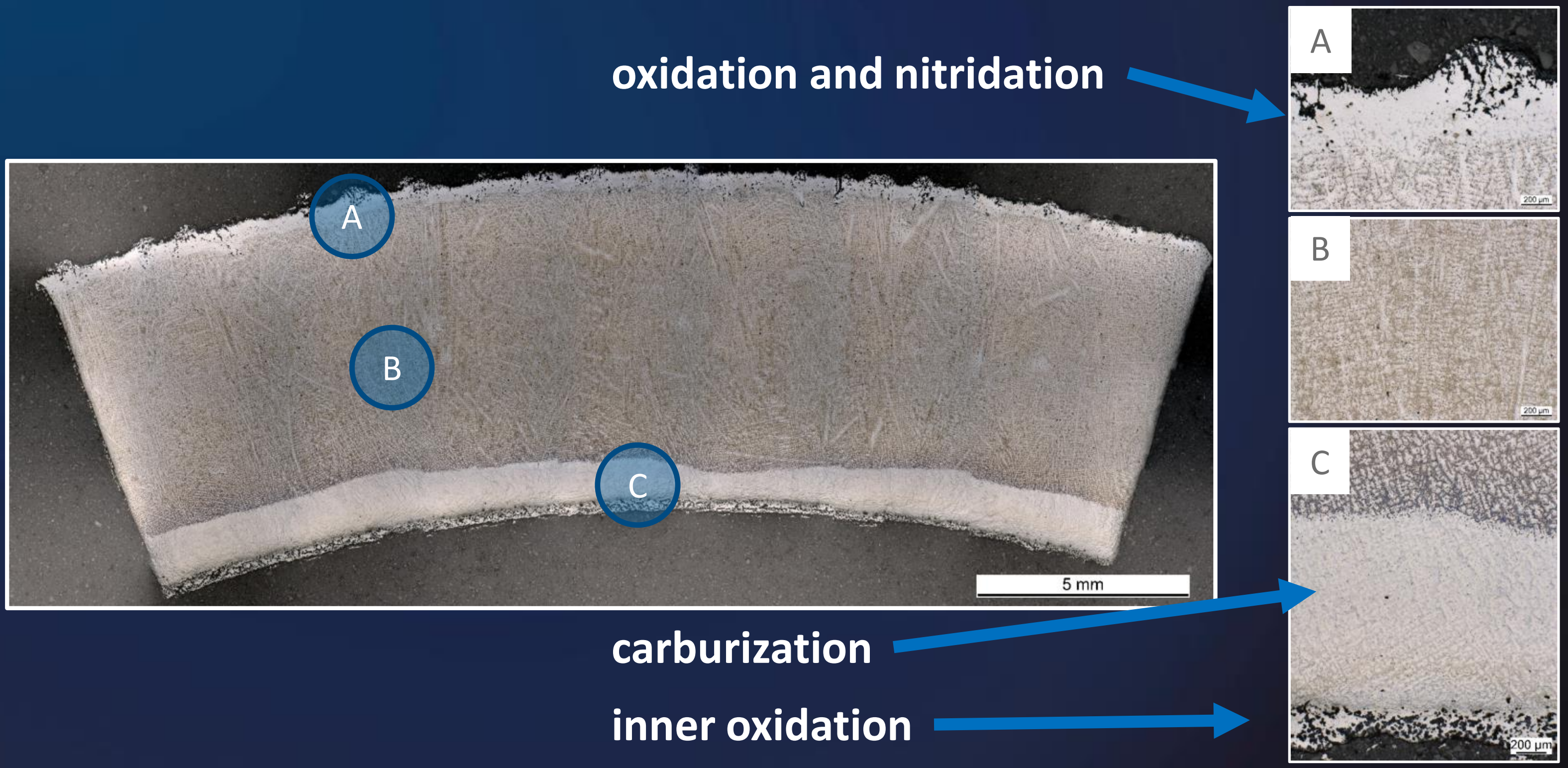
- **Inner surface (ID):** alternating carburizing and oxidizing atmospheres during cracking and decoking
- **Carburization:** degradation of protective Cr-oxide enables carbon ingress, carbide coarsening, and Cr depletion

02 Destructive Testing of Radiant Coils



- **Inner surface (ID):** alternating carburizing and oxidizing atmospheres during cracking and decoking
- **Inner oxidation:** Cr or Al depletion allows oxygen ingress and formation of non-protective internal oxides

02 Destructive Testing of Radiant Coils

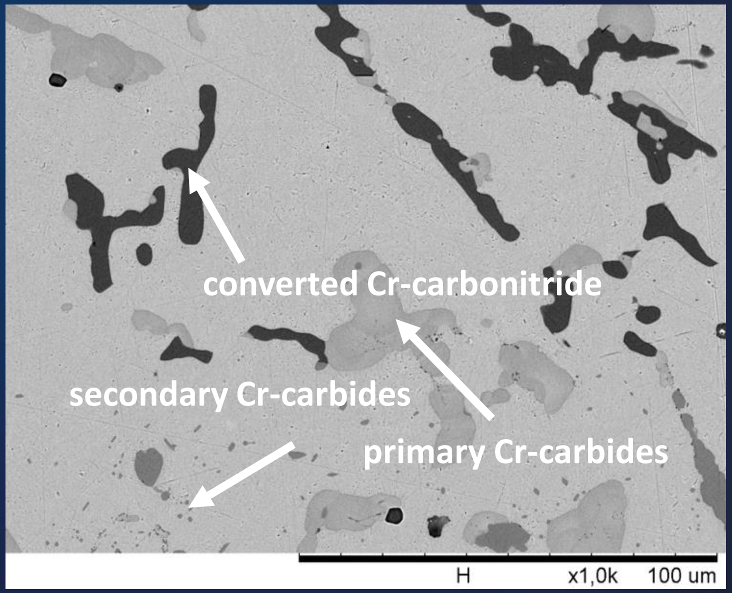


- **Outer surface (OD):** exposure to nitrogen-rich flue gas at temperatures above ~1100 °C (~2010 F)
- **Nitridation:** formation of Cr-nitrides in conventional alloys and Al/Ti-nitrides in alumina-forming alloys

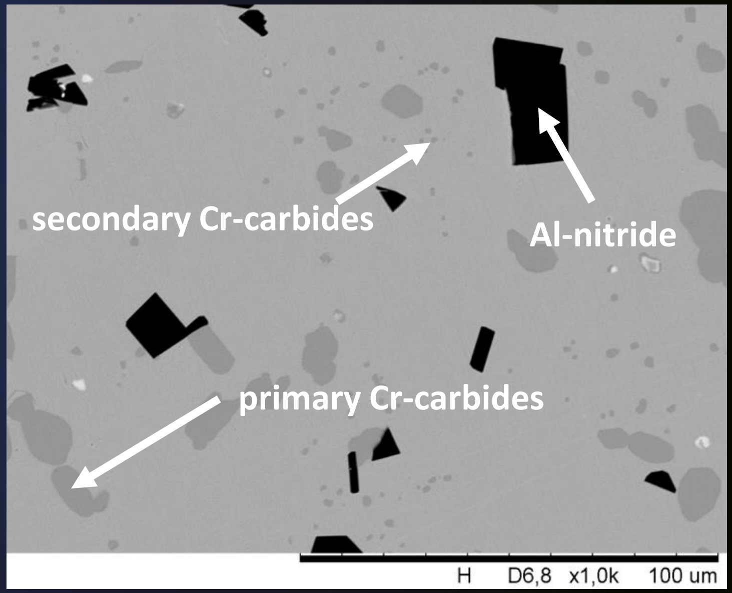
02 Destructive Testing of Radiant Coils

Key mechanisms of microstructual ageing:

- Precipitation of secondary carbides
- Coarsening of existing carbides
- Accumulation of creep damage



chromia-forming alloy



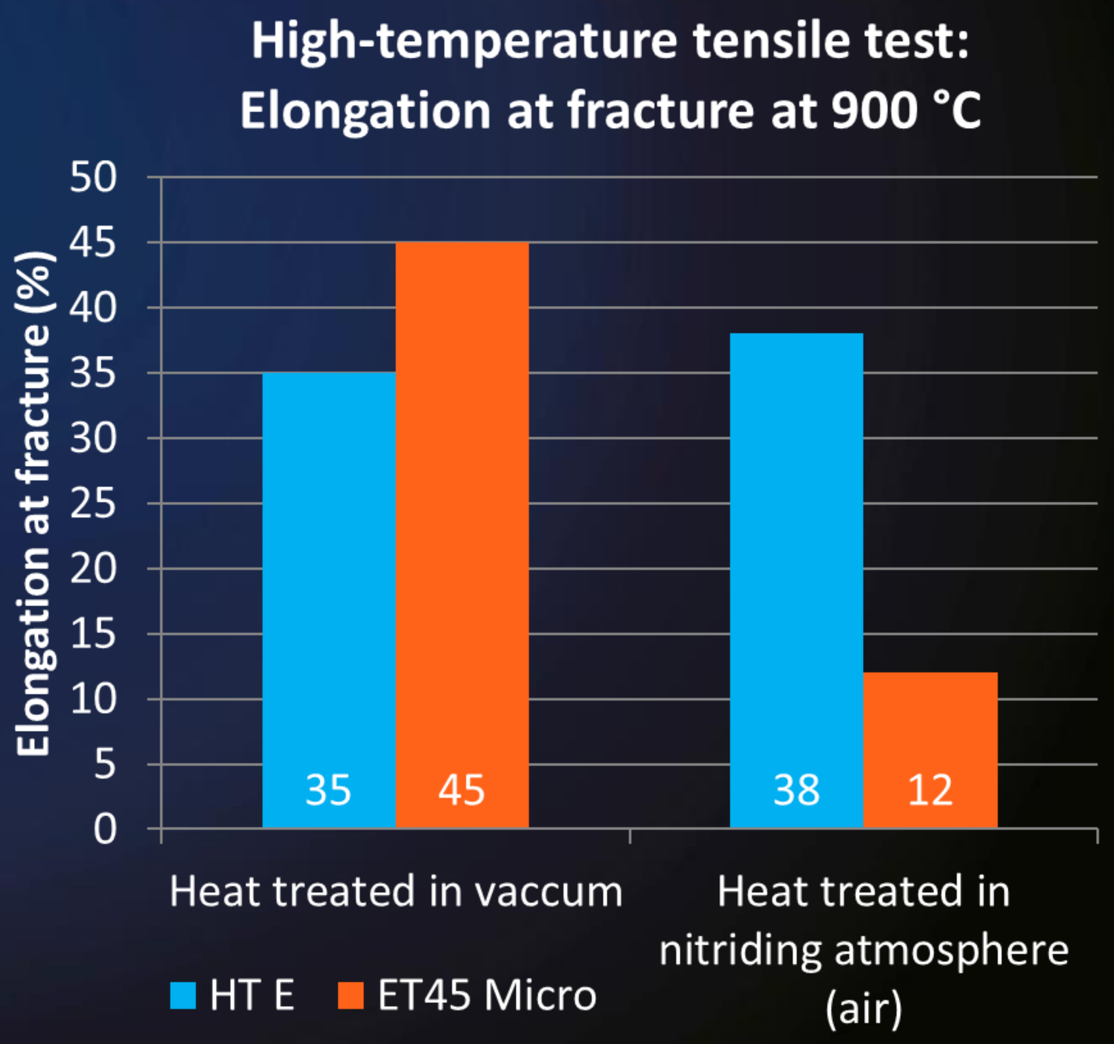
alumina-forming alloy

FeCrNi: conversion of carbide network to Cr-carbonitrides → embrittlement

FeCrNiAl: fine internal AlN precipitates with limited impact on mechanical integrity

02 Destructive Testing of Radiant Coils

- **Mechanical testing confirms severe embrittlement for chromia formers**
- **No embrittlement for alumina former – indicates better weldability in aged condition**

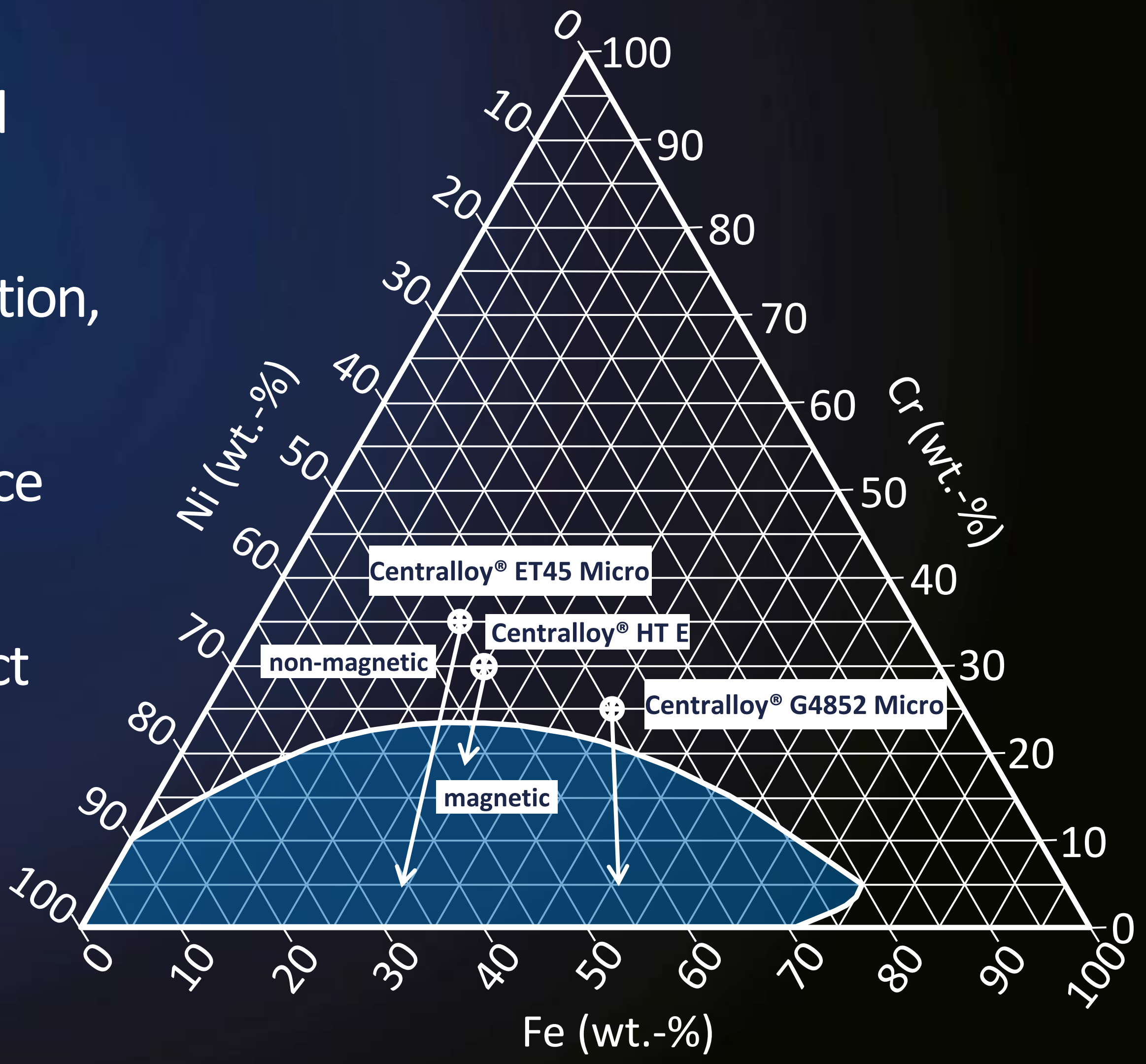


MAGNETIC NON-DESTRUCTIVE TESTING

- NDT methods have become viable alternatives to destructive testing over the past two decades
- Crawling robots allow scanning of large coil sections without cutting or repair welding
- Furnace shutdown is still required, but overall operational impact is reduced
- Enables broader spatial coverage compared to destructive sampling
- Local resolution is lower than metallographic investigation

03 Magnetic non-destructive testing

- Radiant-coil alloys are non-magnetic in the unaged condition
- High-temperature corrosion (carburization, nitridation, oxidation) depletes chromium
- Chromium depletion below ~20–22 wt% can induce magnetization
- Magnetic sensors apply an external field and detect changes in magnetic permeability
- Increased magnetization indicates chromium depletion caused by degradation mechanisms



03 Magnetic non-destructive testing

- Sensors can only be applied from the outer tube surface
- Each measurement reflects the combined effect of multiple degradation mechanisms
- Inner and outer surface effects cannot be separated with a single measurement
- **Nitridation poses a major challenge:**
    - **Conventional alloys**: nitridation correlates with embrittlement
    - **Alumina formers**: nitridation increases magnetization but has little mechanical impact

!

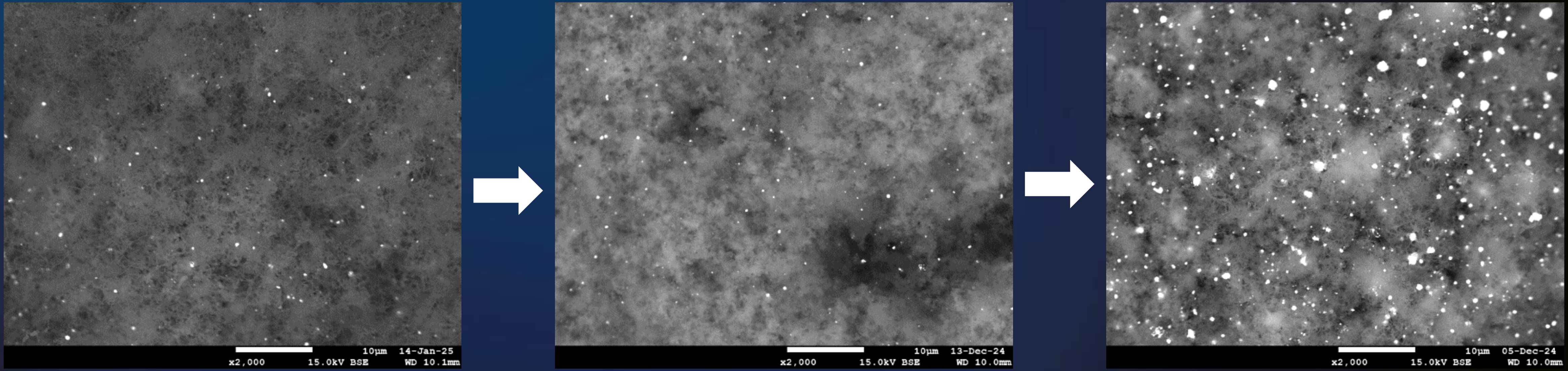
- Risk of misinterpreting harmless degradation as severe damage
- Advanced NDT methods with depth-resolved or multi-signal capability are required

Process-Data-Based Ageing Assessment

- Process data is attractive for continuous coil condition assessment
- Coil ageing results from multiple mechanisms acting simultaneously
  - Carburization, oxidation, nitridation, microstructural degradation
- Strong dependence on temperature, gas composition, and oxide-scale stability
- Highly non-linear interactions and transient effects (e.g. decoking hot spots)
- Simple first-principle or diffusion-only models are insufficient

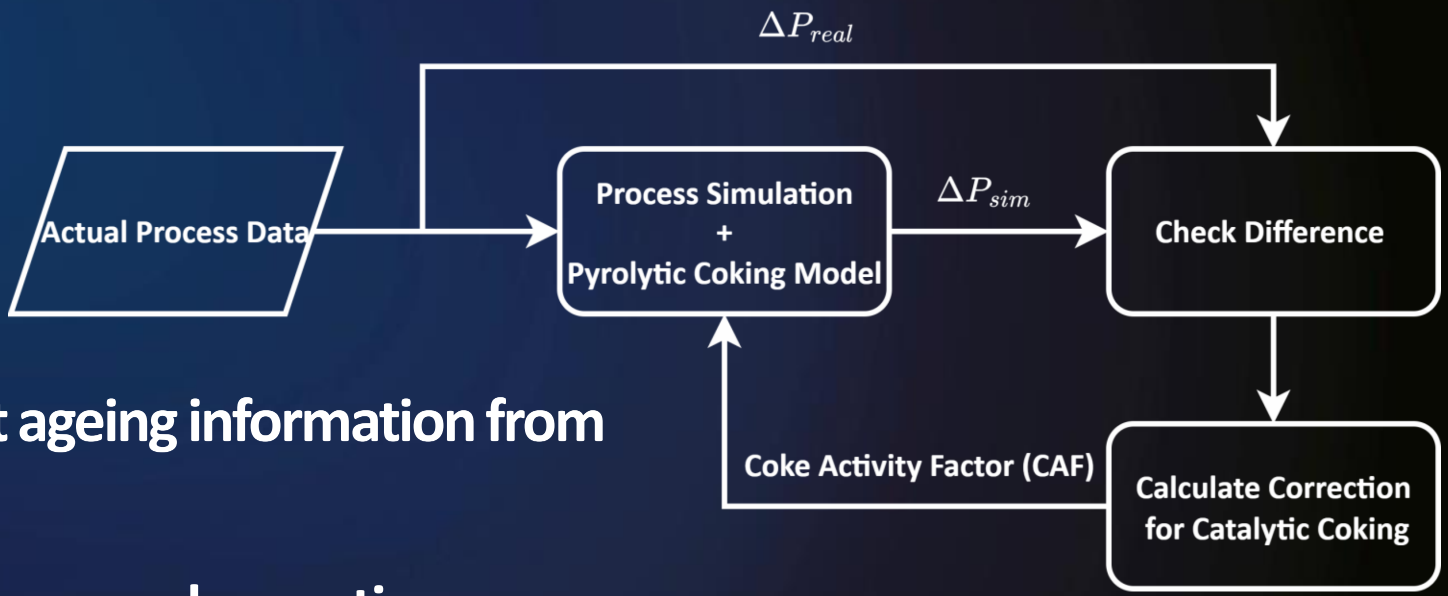
04 Process-Data-Based Ageing Assessment

Same magnification



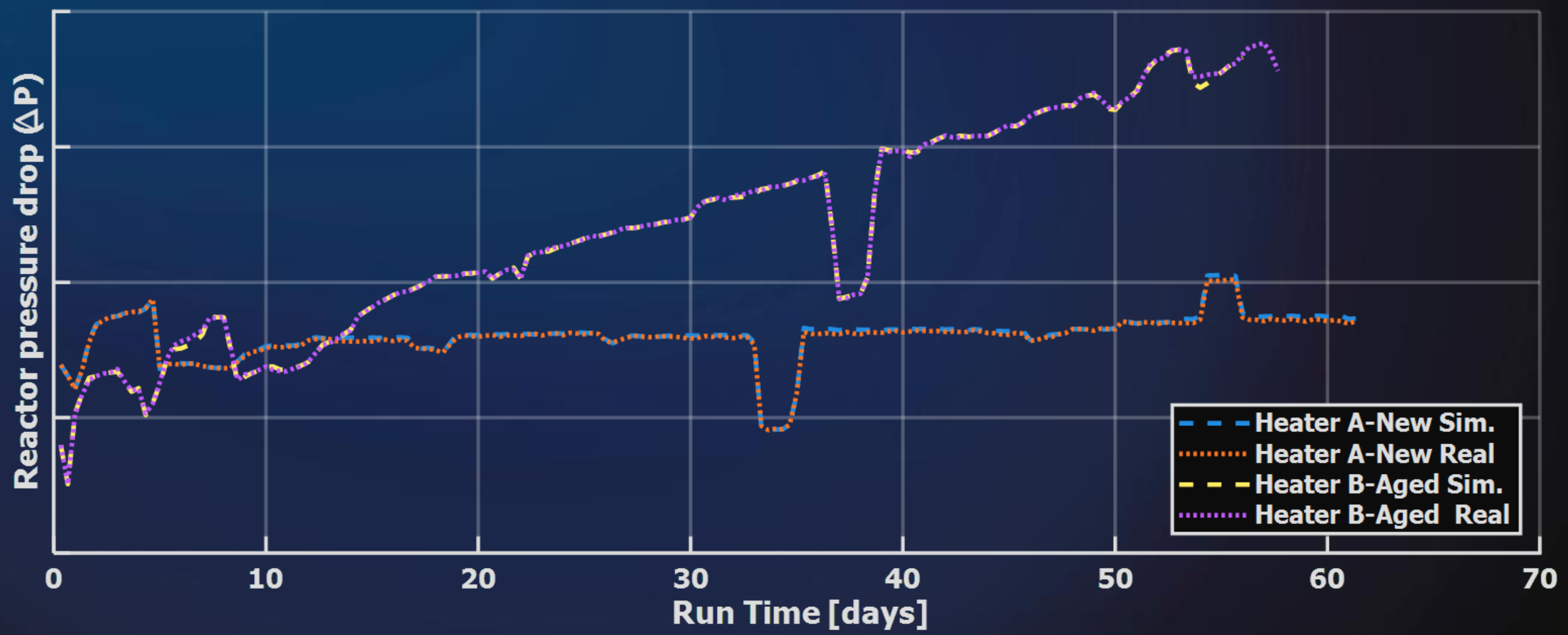
- **Corroded inner surfaces lead to faster coking rates, as more catalytic particles like Ni, Fe are exposed on the surface**
- **This effect is often not obvious, as other process parameters also have a big effect on the coking rate or runs are interrupted for other reasons**

04 Process-Data-Based Ageing Assessment



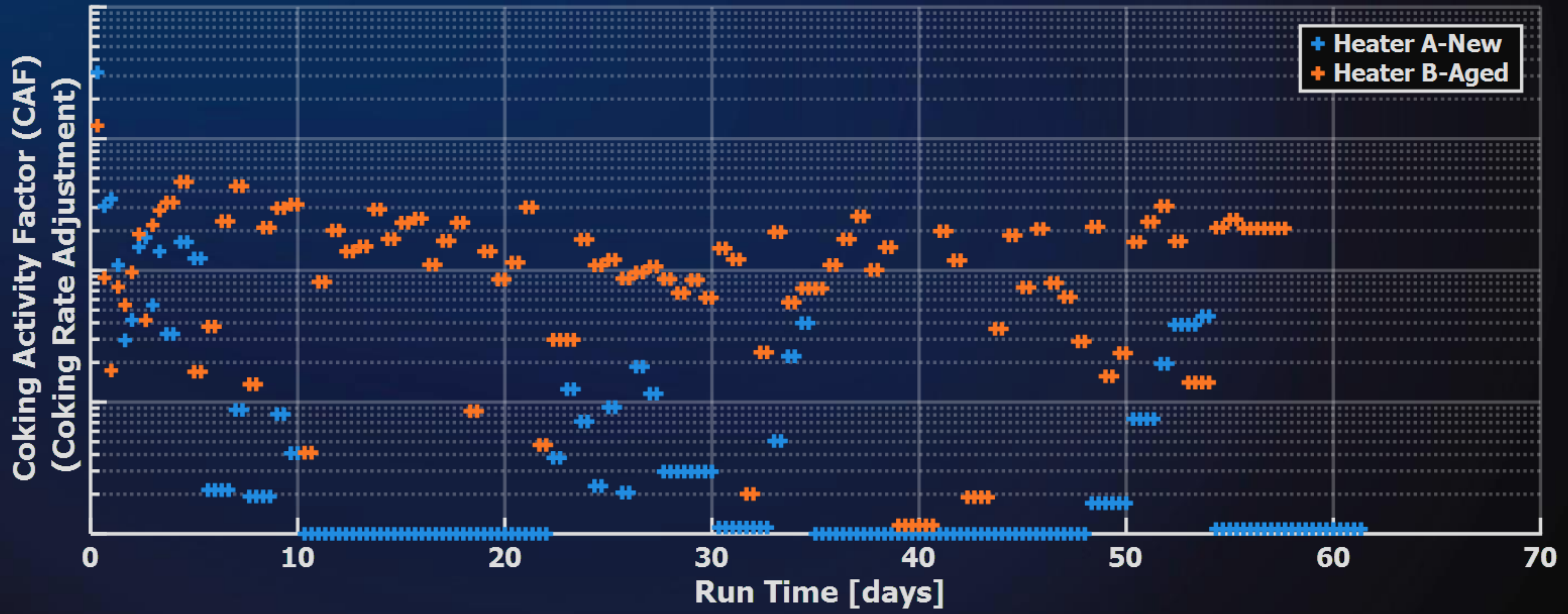
- **Dynamic simulation used to extract ageing information from process data**
- **Detailed furnace-coil model with measured operating variables as time-dependent inputs**
- **Kinetic coking model predicts coking based only on operating conditions**
- **Ageing manifests as deviations between predicted and observed coking behavior**
- **Coke deposition drives the increase in coil pressure drop (ΔP)**

04 Process-Data-Based Ageing Assessment



- **Coking model scaled using a Coking Activity Factor (CAF)**
- **CAF adjusted so simulated ΔP matches measured ΔP for each data point**

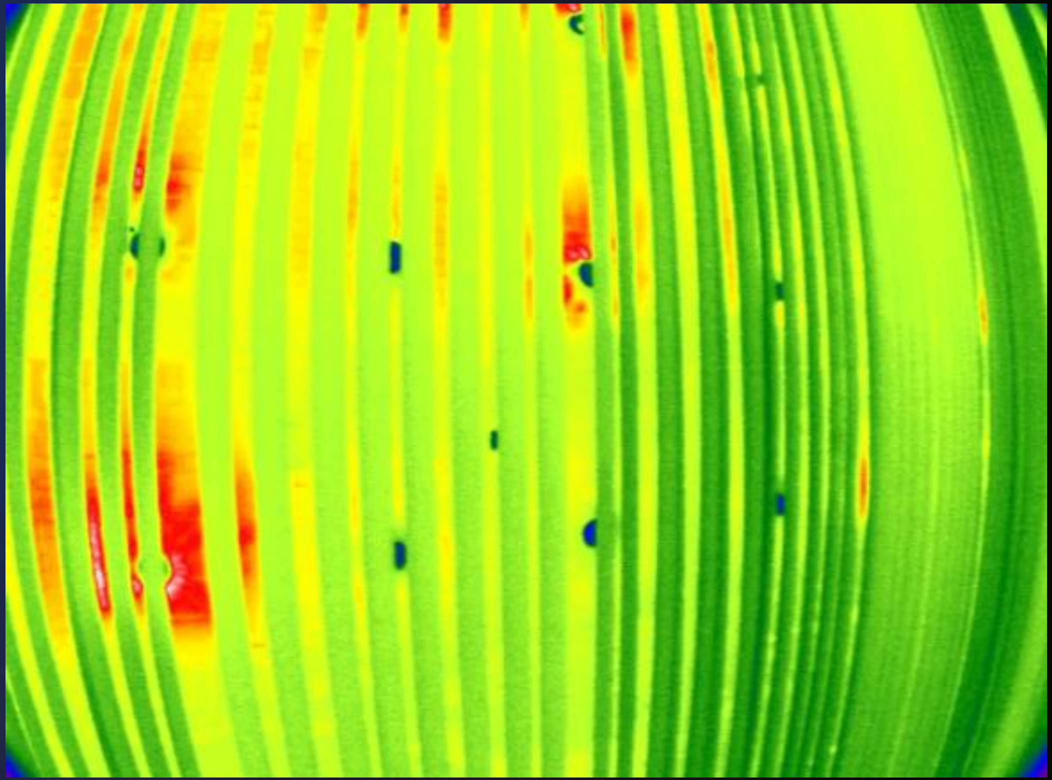
04 Process-Data-Based Ageing Assessment



- **Sequential calibration yields time-resolved CAF evolution over the run**
- **Increasing CAF indicates enhanced coking tendency and progressive ageing**
- **Historic CAF trends enable assessment of current condition and remaining life**

04 Process-Data-Based Ageing Assessment

- **Dynamic simulation strongly depends on the quality of temperature input data**
- **Conventional TMT measurements often lack accuracy, continuity, and spatial resolution**
- **Thermal imaging enables continuous and spatially resolved tube metal temperature monitoring**
- **High-quality TMT data is essential for interpreting coking behavior and simulation results**
- **Reliable temperature data allows ageing effects to be separated from normal process variability**



05 Take aways

- **Destructive testing remains the most accurate method for assessing radiant coil degradation, but is intrusive and locally limited**
- **Alumina-forming alloys require a fundamentally different assessment approach, especially with respect to nitridation**
- **Current magnetic NDT methods have limitations and may misinterpret degradation in alumina-forming alloys**
- **Process-data-driven simulation offers strong potential for continuous ageing assessment, but requires sophisticated modeling and filtering to distinguish ageing from process effects**
- **Combining improved NDT methods with data-driven simulation and online TMT monitoring provides the most reliable pathway for predicting remaining coil life**

THANK YOU FOR YOUR ATTENTION

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