Corrosion and decommissioning

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CORROSION
&
DECOMMISSIONING

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Croydon, London, UK / 11-12 June 2018

CONTENT

Introduction / background

Thermodynamics (corium)

ATTILHA setup
Database

Material behavior & irradiation

Experimentation
Carbon & Stainless steels

Long term issues

Atmospheric corrosion

Fukushima Unit 3

Chooz

Nuclear facility life cycle

IAEA
International Atomic Energy Agency

- Siting of nuclear facility
- **Design of nuclear facility**
- **Construction & commissioning**
- **Operation, management & maintenance**
- **Severe accident management**
- **Decommissioning of nuclear installations**
- **Nuclear waste management**

Bold type: corrosion issues

Decommissioning of nuclear reactors

- 110 commercial power reactors, 48 prototypes and over 250 research reactors have been retired from operation.
- About 17 of these had full decommissioning.
- 12 reactors closed following an accident/incident, including 8 (partial) core melts:
    - TMI (USA-1979)
    - Chernobyl (Ukraine – 1986)
    - Fukushima Daiichi (Japan, 2011)
- **Corrosion issues**
    - During the dismantling when it is not immediate
    - Specific issues after core melt
    - Nuclear waste interim & geological storages

Data: September 2017 from IAEA

INTRODUCTION

Importance of corrosion management during decommissioning

- Structural materials have been chosen for reactor standard operation, investigated for their behavior during accidents, but not for decommissioning conditions while they still have functions (mechanical, tightness,…)
- Long term issues (deferred dismantling)
- After core melt:
    - knowledge of the corium interactions, fuel debris and fission products (physico-chemical status) & behaviour
    - corrosion & radiations
    - behavior of key components after accident conditions

⇨Development of fundamental knowledge

INTRODUCTION

Subjects related to decommissioning investigated at the CEA “Corrosion Service”

Thermodynamics (corium)

Experimental facilities

Database

Material behavior & irradiation

Experimentations *and radiolysis calculations*

Carbon steels & Stainless steels

Long term issues

Atmospheric corrosion / *Microbial Influenced corrosion*

Corrosion modelling & simulation

HIGH TEMPERATURE THERMODYNAMIC TOOLS FOR THE INVESTIGATION OF CORIUM BEHAVIOR

Experimental setup

Thermodynamic modeling

In-vessel & Ex-vessel Core Melts

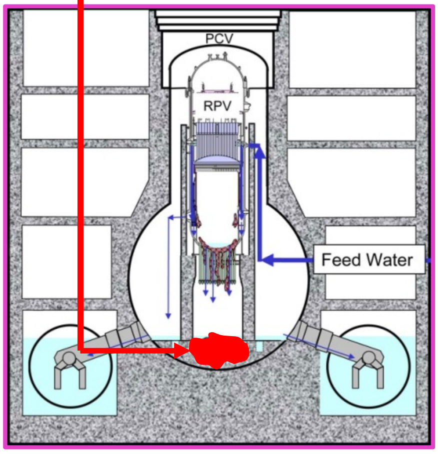
Issue: core melt configurations

In-vessel corium Interactions:
MOx + Zircaloy + stainless steel + Inconel + B_4C + Fission Products
"Prototypic" in-vessel corium system: U-Zr-Fe-O

The **Molten Corium Concrete Interaction** starts:

- The components of the concrete (CaO, SiO_2, Al_2O_3, MgO, H_2O, CO_2) are added to the already complex in-vessel system (U-Zr-O-Fe)
- As a first approximation the **Fe-U-Zr-Al-Ca-Si-O** system is representative of an ex-vessel corium

Fukushima



A better thermodynamic description of the in & ex-vessel corium sub-systems is needed to improve the thermal and thermo-hydraulics codes accuracy

Need of exp. data at very high temperatures
1500°C ≤ T ≤ 3200°C

Development of a specific exp. setup

Experimental development

Advanced **T**emperature and **T**hermodynamics **I**nvestigation by a **L**aser **H**eating **A**pproach

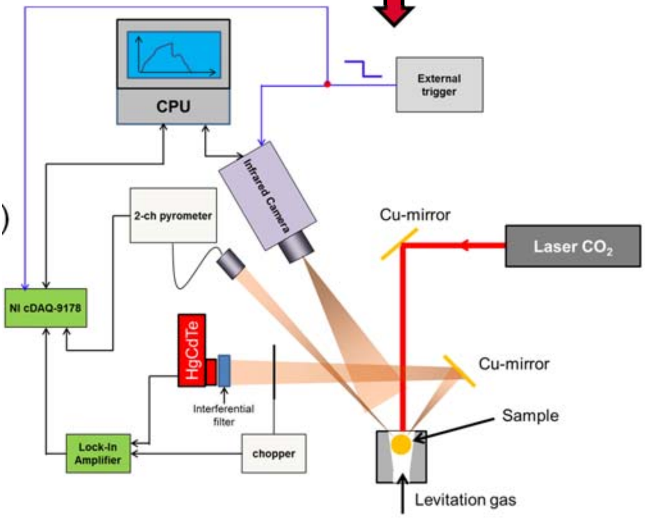
ATTILHA: Development of a setup for high solid/liquid transitions

2 different ATTILHA configurations: Contactless → Aerodynamic levitation
Containerless

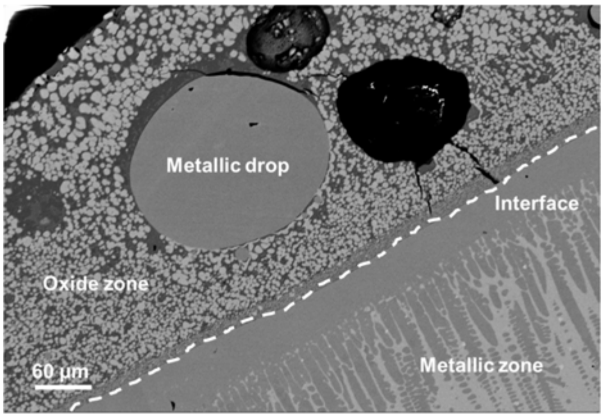
Acquisition of data on corium systems

- Phase diagram data (liquidus, solidus)
- Thermo-radiative properties (IR emissivity)

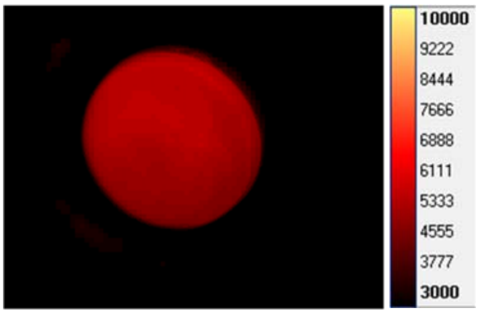
All the instruments are synchronized
Validation on transitions in oxide systems
Al_2O_3
Al_2O_3-ZrO_2



Miscibility gap in the Fe-Zr-O system



Infrared camera footage



Real speed 200 Hz
Video player 12.5 Hz

New result

Starting composition: $Fe_{0.85}Zr_{0.15}$

↓ Levitation gas: He

Composition moved into the ternary Fe-Zr-O system

tie-line: $Fe_{0.97}O_{0.03}$ – $Fe_{0.05}Zr_{0.32}O_{0.63}$

Observation of dynamic phenomena:
→ **Formation of 2 liquids in-situ**

Estimation of the emissivity ratio between the two liquids
→ $\varepsilon_{oxide} \sim 2\varepsilon_{metal}$

MATERIAL BEHAVIOR & IRRADIATION

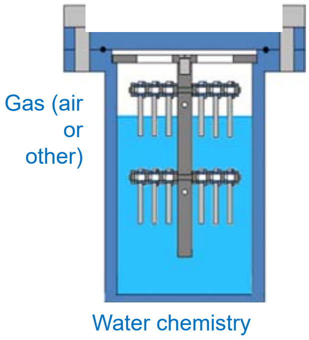
- EXPERIMENTATION

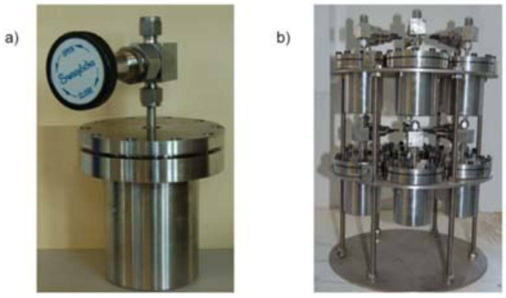
- CARBON & STAINLESS STEELS

CORROSION & IRRADIATION

Experimental facility: CASIMIR

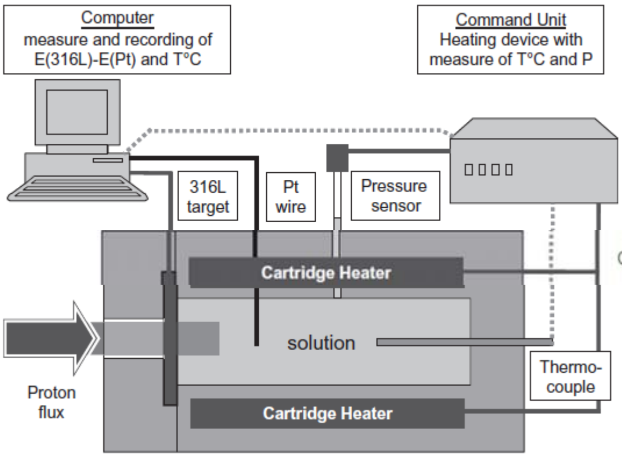
Irradiation gamma performed in the POSEIODON pond, at CEA-Saclay



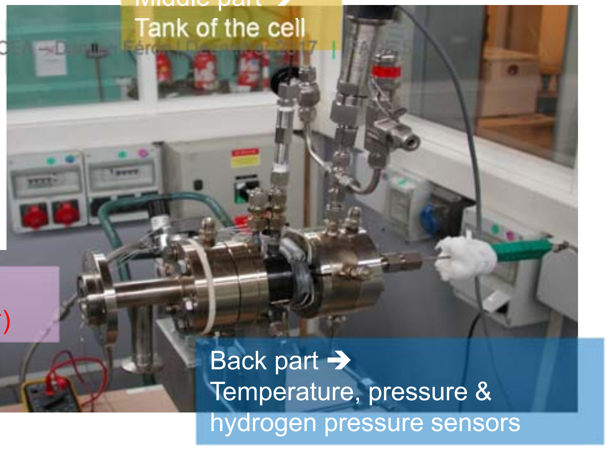


S. Perrin & al., LTC2016, Toronto, 2016

High temperature and high pressure electrochemical cell



Temperature ➔ 300 (°C)
Pressure ➔ 90 (bar)
Hydrogen pressure ➔ 400 (mbar)
Free potential ➔ E_{316L} vs. Platinum (V)



Middle part ➔
Tank of the cell

Front part ➔
link to the cyclotron (H^+)

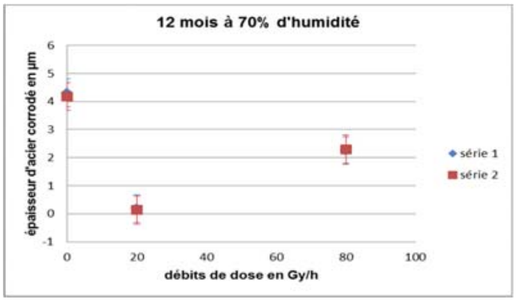
Back part ➔
Temperature, pressure &
hydrogen pressure sensors

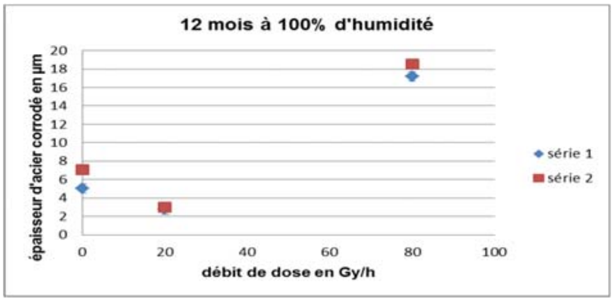
Brevet n° 08 56970
du 15.10.2008, CEA (DEN & DSM)-LSI

ATMOSPHERIC CORROSION OF CARBON STEEL

Corrosion of carbon steel (A37) in a closed humid atmosphere

Influence of the humidity at temperature 80°C,
and of irradiation gamma (20 & 80 $Gy.h^{-1}$)

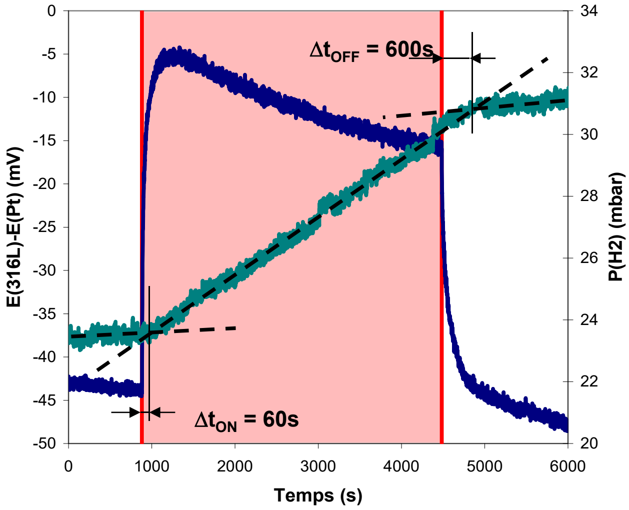




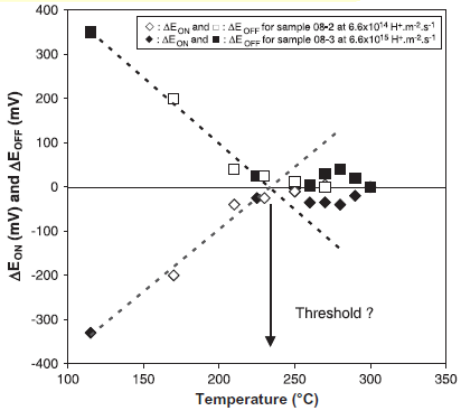
S. Perrin & al., LTC2016, Toronto, 2016

Generalized corrosion, but not uniform
Lower corrosion rate at 70% HR than at 100% HR, with or without irradiation
Higher corrosion rate at 100% HR and 80 $Gy.h^{-1}$

Effects of radiolysis on the electrochemical behaviour of stainless steels



Potential and hydrogen partial pressure evolution at 300°C, proton **flux = 6.6×10^{11} $H^+.cm^{-2}.s^{-1}$**



- ➢PWR water chemistry (300°C) /316L
- ➢*in situ* measurement of the radiolytic production of H_2
- ➢Importance of the temperature

B. Muzeau & al., JNM 419 (2011) 241–247

LONG TERM ISSUES

- ATMOSPHERIC CORROSION

- *MICROBIAL CORROSION*

- *CORROSION MODELLING & SIMULATION*

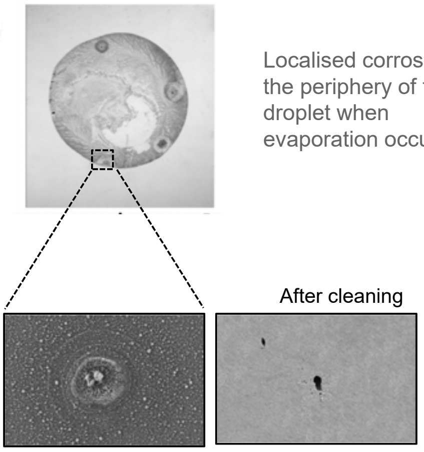
ATMOSPHERIC CORROSION

Phenomena: outdoor and indoor atmospheric corrosion, including closed atmospheres.

Applications: deferred dismantling, interim storage, first period of geological disposal.

Observations: shape of localised corrosions not in accordance with the well-known “Evans” droplet

Evans droplet scenario
- Pitting in the middle of the droplet
- No corrosion at the periphery (cathodic reaction)



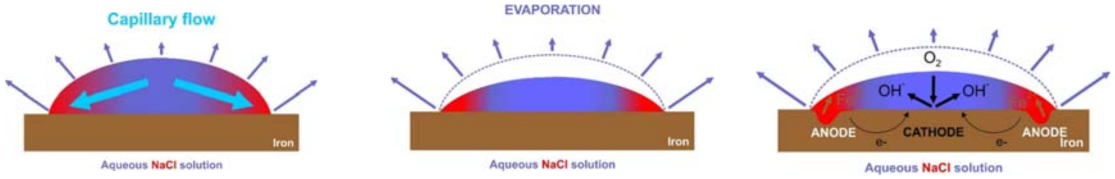
Localised corrosion at the periphery of the droplet when evaporation occurs

After cleaning

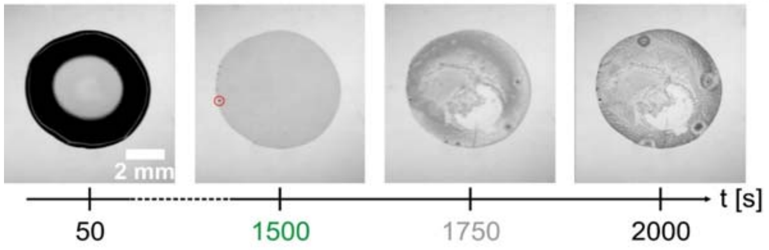
Evaporating corrosion droplet

Corrosion under Evaporating Salty Sessile Droplets

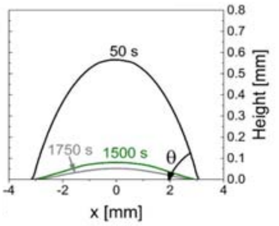
Low salt concentration: $c_0 = 10^{-3}$M NaCl



Top view



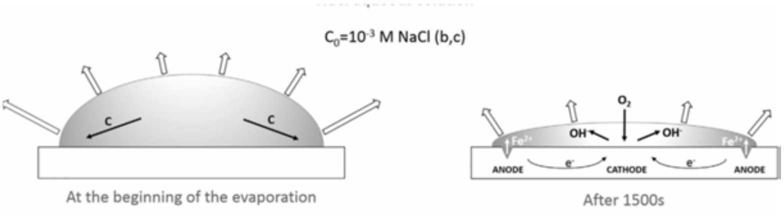
Side view



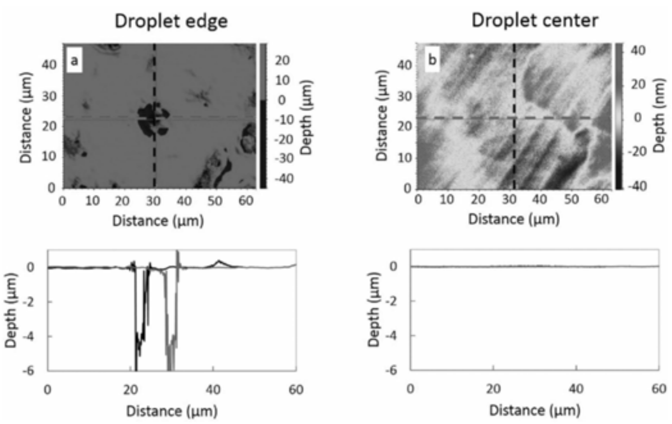
Evaporation of pinned salty sessile droplets causes **peripheral salt enrichment**
Local chloride enrichment promotes the **initiation of corrosion**

Evaporating corrosion droplet

Strong correlation between evaporation process and localization of corrosion phenomena



Schematic diagram of the processes



Experimental observations on iron

Soulié, Lequien & al., Materials and Corrosion, Sept. 2017, Vol. 68 Issue 9, p927-93

CONCLUSION

Decommissioning and corrosion

Fundamental knowledge needed in several areas

Thermodynamics

Effects of irradiation (low & high doses)

Corrosion phenomena even at low temperatures

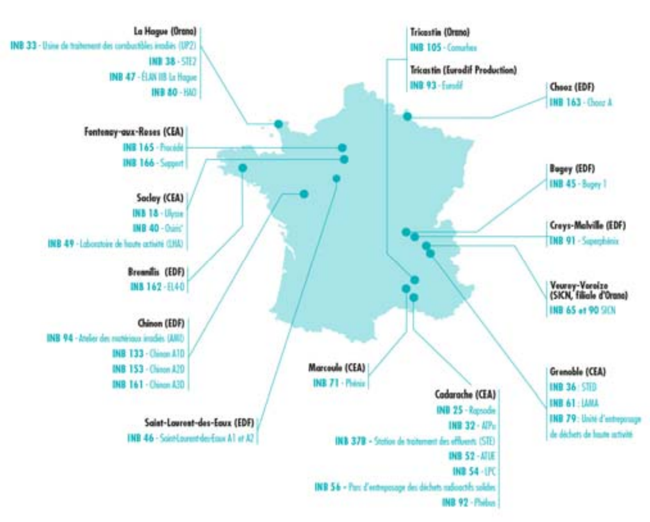
Modeling and simulation

Prediction of phases and compounds in melt core

Long term prediction & coupling of multi-corrosion issues

Protective measures

THANK YOU FOR YOUR ATTENTION



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