High temperature corrosion phenomena during a nuclear severe accident - The corium-concrete interaction

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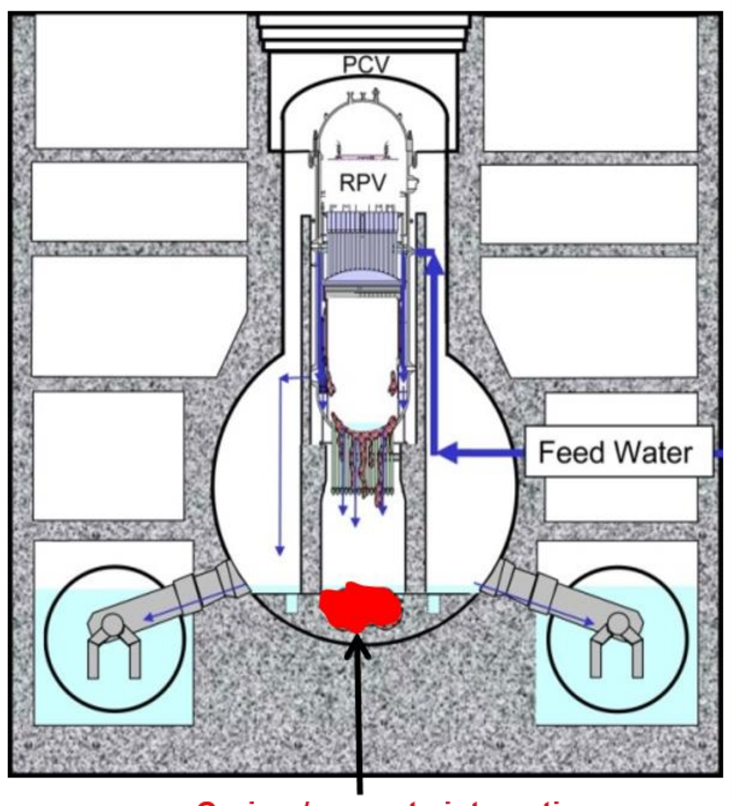
CONTEXT AND PURPOSE OF THE WORK

During a severe accident in a nuclear reactor, extreme temperatures may be reached (T>2500 K). In these conditions, the nuclear fuel may react with the Zircaloy cladding and then with the steel vessel, forming a mixture of solid-liquid phases called in-vessel corium. In the worst scenario, this mixture may pierce the vessel and start corroding the concrete underneath the reactor. Many phenomena take place during MCCI (Molten Core Concrete Interaction) [1]: high temperature concrete ablation/decomposition, heat transfer due to gas bubbles agitation, formation of several phases, oxidation of metals, etc. Several studies on the high temperature corrosion of concrete by corium were published starting from the 1980s; in particular numerous large scale experiments were performed on this subject [1]. Although large scale experiments answer to macro-scale phenomena, such as ablation profile, corium flooding behaviour, coolability of the molten core, density and viscosity evolution, the interpretation of the microstructure of the post-experiments sample is rather challenging. **In this framework a campaign of small-scale experiments is ongoing on prototypic corium+concrete system U-Zr-Ca-Si-Al-O**. These tests provide useful data for the comprehension of the corrosion phenomena occurring during a severe accident, when the molten corium reaches the concrete underneath the damaged steel vessel. It has been observed that depending on the composition of the concrete (more of less rich in SiO_2), the final configuration of the ex-vessel corium (i.e., after the in-vessel corium/concrete interaction) can be significantly different.

Fukushima Unit 1



Corium/concrete interaction

[1] C. Journeau, P. Piluso, 2.25 - Core Concrete Interaction, in: R.J.M. Konings (Ed.), Compr. Nucl. Mater., Elsevier, Oxford, 2012: pp. 635–654. doi:10.1016/B978-0-08-056033-5.00048-3.

EXPERIMENTAL METHOD

- 2 samples (mixtures of UO_2, ZrO_2, CaO, SiO_2 Al_2O_3)

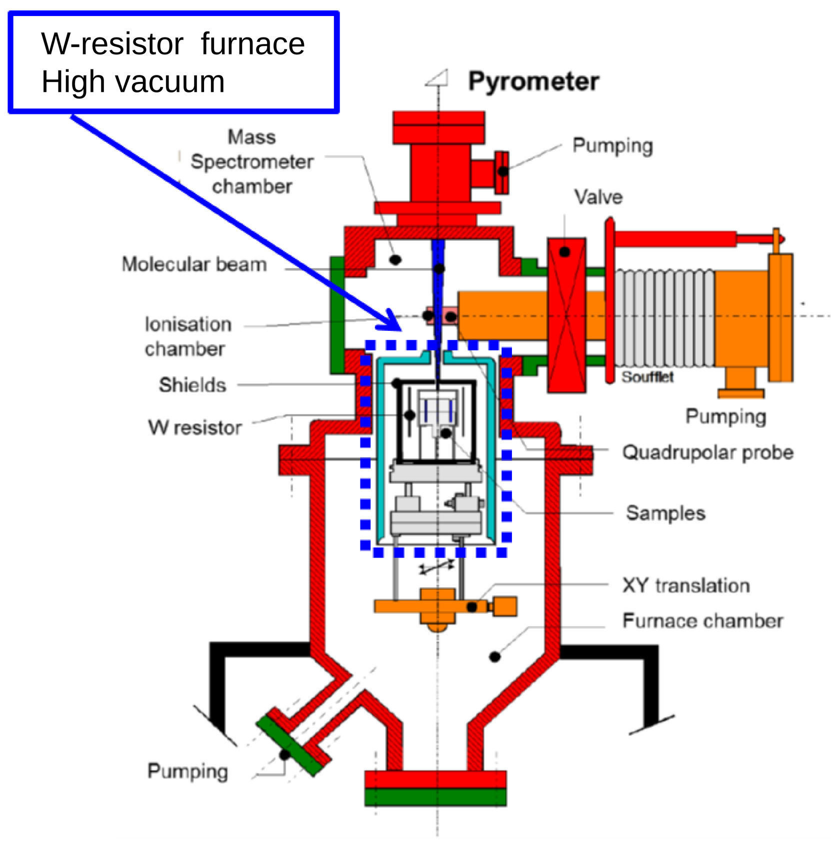
CORIUM_1: 80%UO_2+20%ZrO_2 + limestone concrete

CORIUM_2: 80%UO_2+20%ZrO_2 + silica-rich concrete

→ Simplified oxidized corium + concrete

Composition of the corium-concrete liquid pool after 24h of the MCCI

W-resistor furnace
High vacuum



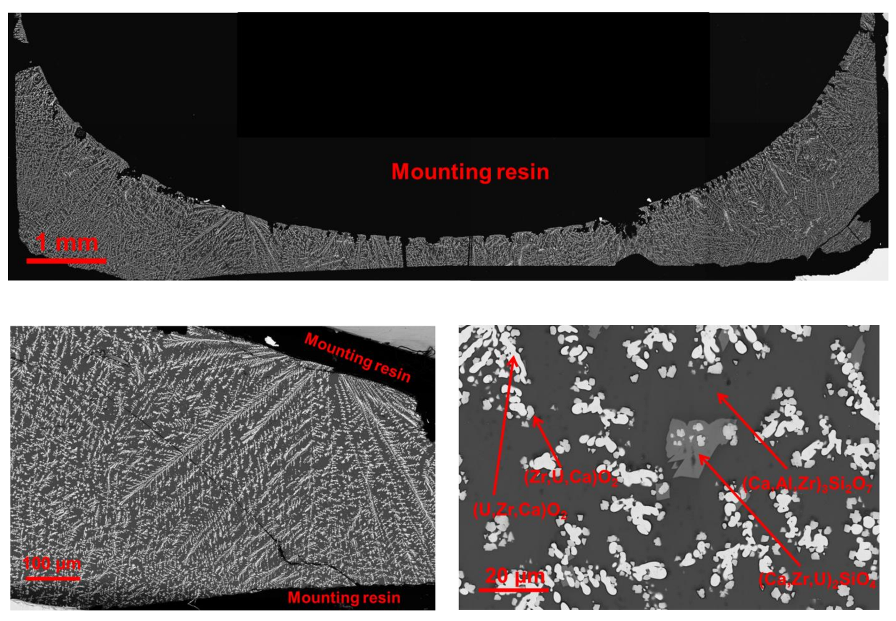
wt%	CORIUM_1	CORIUM_2
Al_2O_3	1,8	2,1
CaO	32,4	11,0
SiO_2	24,6	64,0
UO_2	30,8	15,4
ZrO_2	10,4	7,8

Starting materials: powders
Crucible: W with screwed lid

- **Heated at 2500±25 K for 30 minutes**
- W-resistor furnace
- High vacuum ≈10^{-7} Pa

RESULTS

Corium + limestone-rich concrete

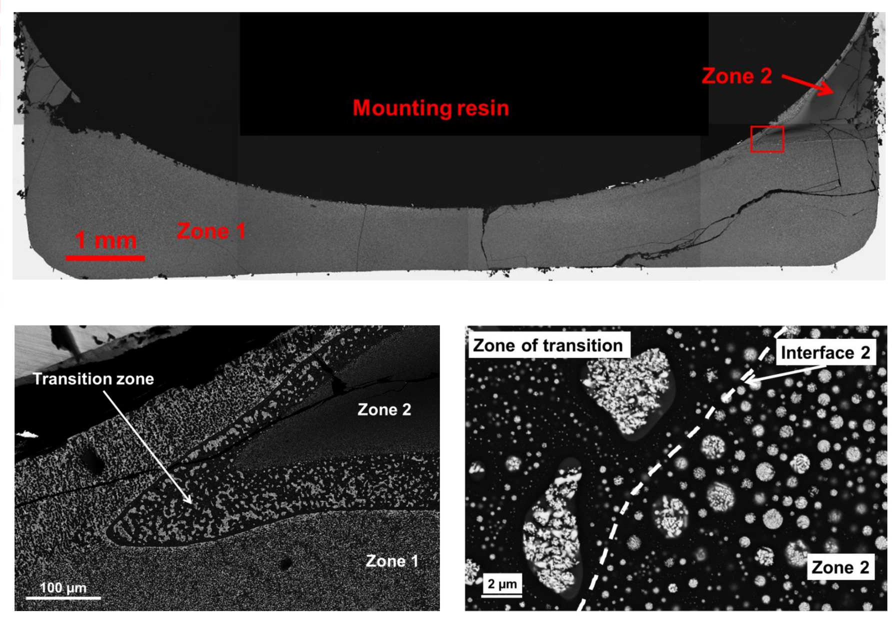


Dendritic structure: $(U,Zr,Ca)O_2$ and $(Zr,U,Ca)O_2$

Oxide matrix: Rankinite-like phase $(Ca,Al,Zr)_3Si_2O_7$

Solidified single liquid phase at 2500 K

Corium + silica-rich concrete



Two distinct zones separated by a transition layer:
- White droplets (enriched in U) within a black SiO_2 amorphous matrix
- SiO_2 droplets within a white matrix (dendrites rich in U)

Two immiscible liquids in equilibrium at 2500 K

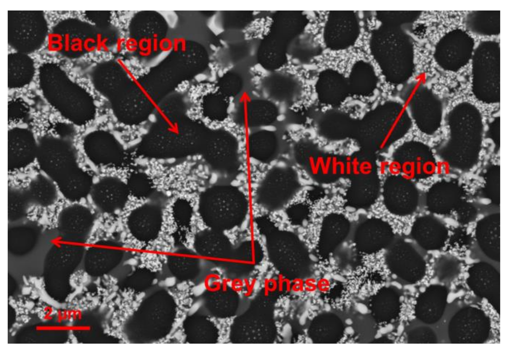
What is the driving parameter?

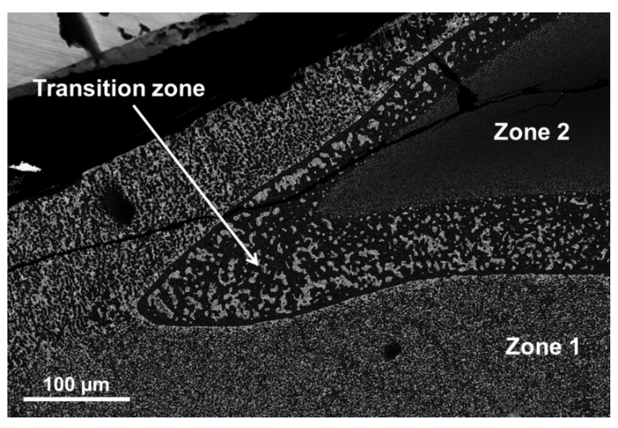
DISCUSSION

Effect of the SiO_2 content on the high temperature configuration of the ex-vessel corium

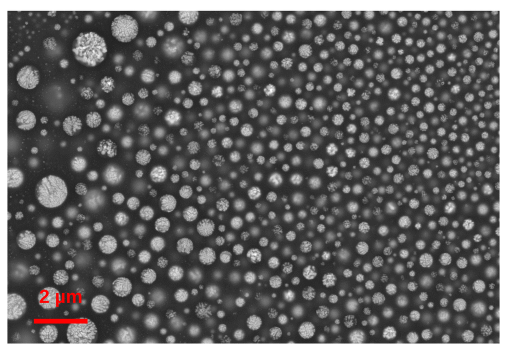
Oxidized corium + Silica concrete → liquid demixing

Zone 1

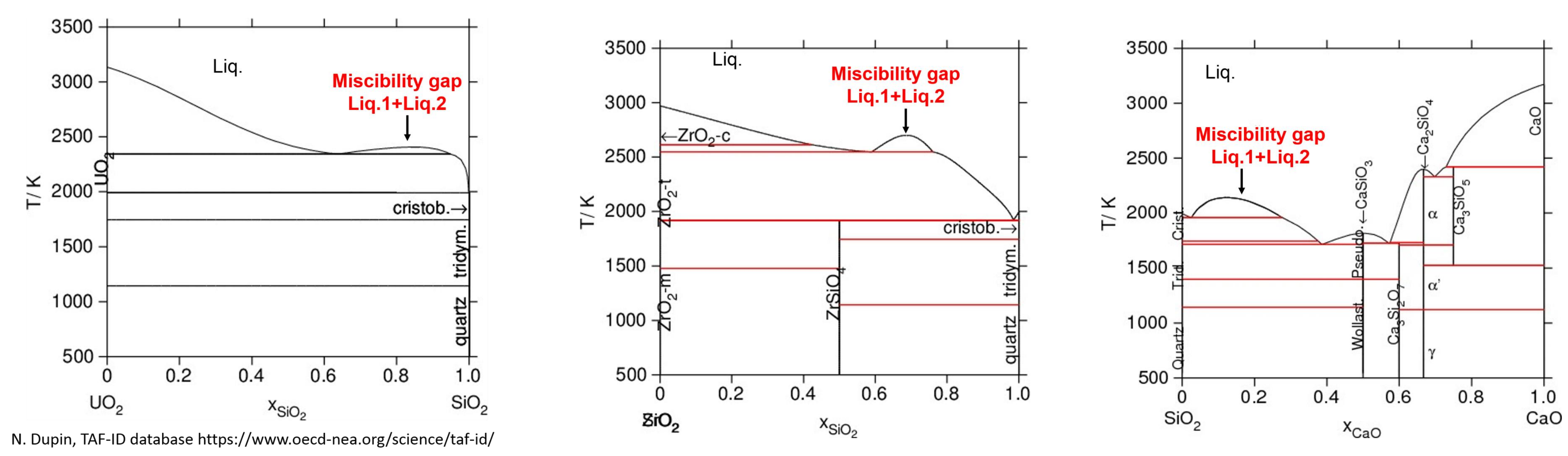




Zone 2



Miscibility gap originates from the isopleth sections UO_2-SiO_2, CaO-SiO_2 and ZrO_2-SiO_2



N. Dupin, TAF-ID database https://www.oecd-nea.org/science/taf-id/

Stratification → separation and accumulation of fissile material
→ **compaction and re-criticality**

CONCLUSION

➡ **Corium / limestone concrete interaction**
- Single liquid phase at 2500 K
- Dendritic microstructure
- Homogenous distribution of the constitutional elements

➡ **Corium / silica concrete interaction**
- **Two liquid phases at 2500 K → miscibility gap**
- Amorphous matrix + droplets
- Demixing originates from the UO_2-SiO_2, CaO-SiO_2 and ZrO_2-SiO_2 isopleth sections

U-enriched liquid
Non-containing U liquid

Stratification driven by viscosity and density difference

Relocation of most of the available U in one single zone may lead to re-criticality