SiC composite-based materials for enhanced accident tolerant fuel of LWRs :

Recent results on the chemical compatibility with UO_2

(Extracted from PhD of J.BRAUN, CEA, 2014)

(I3P – *French Nuclear* **3-P***arties* **I***nstitute*, AREVA-CEA-EDF)

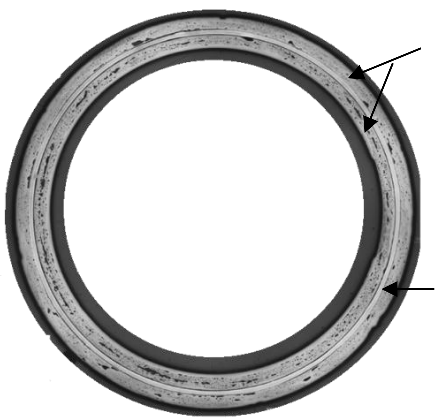
OECD-NEA 3rd meeting of the Expert Group on ATF of LWRs
Task Force 2 session
OECD-HD, Issy-les-Moulineaux

March 3-5, 2015

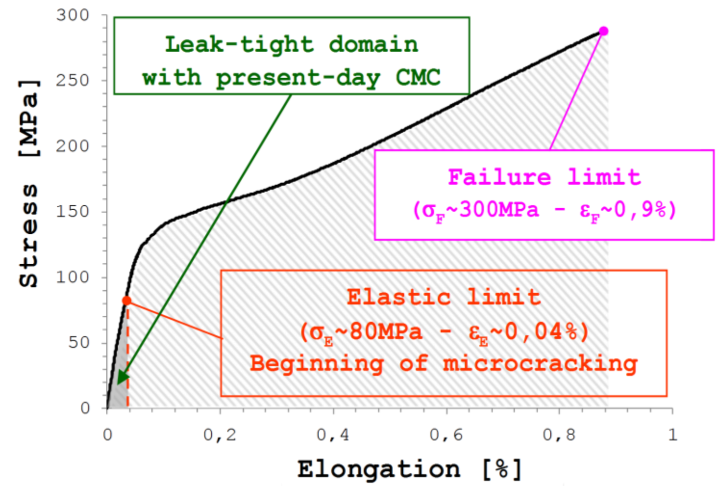
J. Braun, C. Sauder, C. Lorrette et al. (CEA)
J. Bischoff et al. (AREVA)
A. Ambard et al. (EDF)

- *Development of metal/ceramic hybrid cladding : a solution to leak-tighness*

CEA « SANDWICH » CLADDING DESIGN



Candidate materials for liner selected on various criteria (thermochemical, neutronic, others)
– Current reference is Ta –



Patent WO 2013/017621 A1

Development of "sandwich" cladding has been driven by GEN IV nuclear systems
Transposition to LWR is under investigation with the current manufacturing process

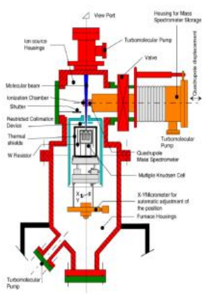
To define the overall fuel performances under normal condition and to anticipate the potential of SiC sandwich cladding to enhanced tolerance accident
Chemical interaction with UO_2 is a foreground issue and must be evaluate

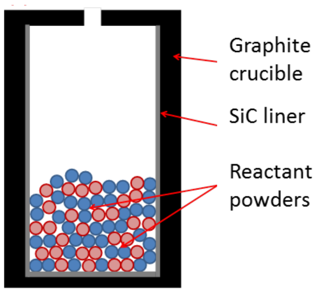
Fuel compatibility – Approach

- *Investigate the chemical compatibility of SiC towards UO_{2+x} in:*

Opened systems

Knudsen cell mass spectrometry



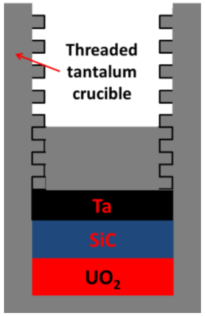


Loss of gas-tightness (Accidental conditions)

Monitoring of the reaction along time

Closed systems

Diffusion couples

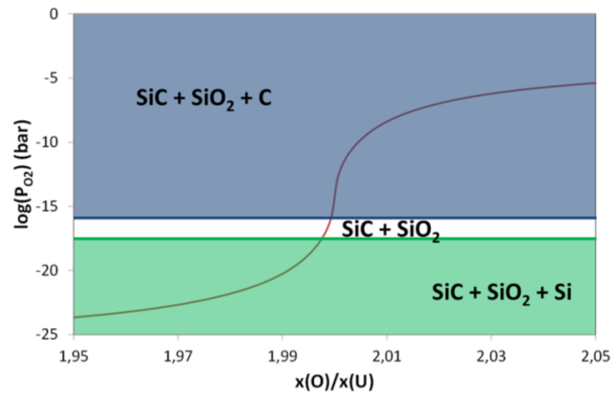


Gas-tightness (Nominal and accidental conditions)

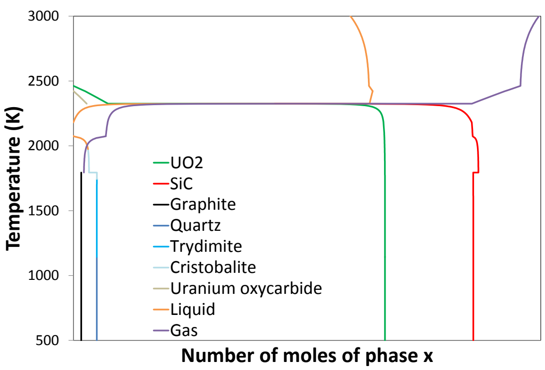
Diffusion

Thermodynamics assessement

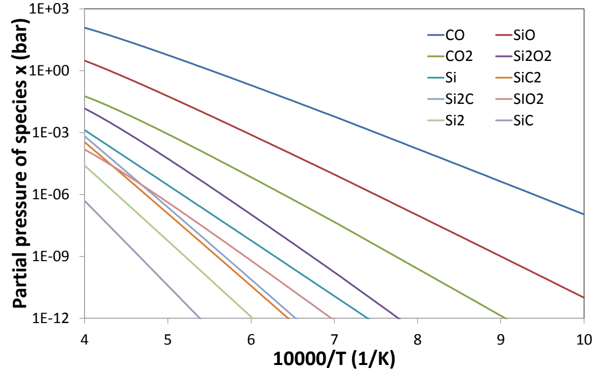
Stability of SiC towards UO_2



$UO_{2,15}$/SiC system



Partial pressures of gases



Calculations need to be confirmed by experimental analyses (no kinetics consideration)

FUEL COMPATIBILITY – EXPERIMENTAL RESULTS

Opened systems

Gases **CO,** SiO, CO_2

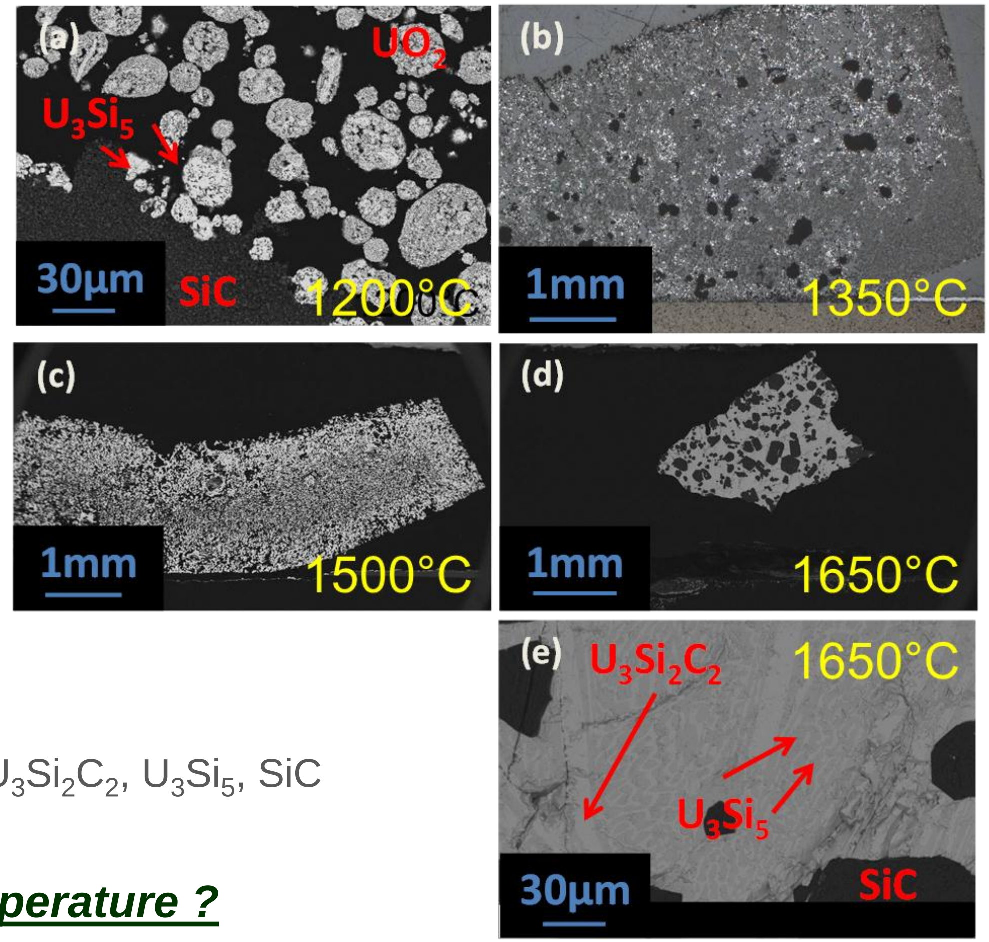
Samples

(a) ***1200°C :*** Limited reaction : U_3Si_5 formation at the UO_2/SiC interface

(b) ***1350°C :*** U_3Si_5/UC – **Reaction by contact**

(c) ***1500°C :*** U_3Si_5/UC – **Reaction on surface** (gaseous species)

(d)
(e) ***1650°C :*** **Solidified liquid phase** $U_3Si_2C_2$, U_3Si_5, SiC



What is the formation temperature ?

FUEL COMPATIBILITY – EXPERIMENTAL RESULTS

- ***Closed systems***

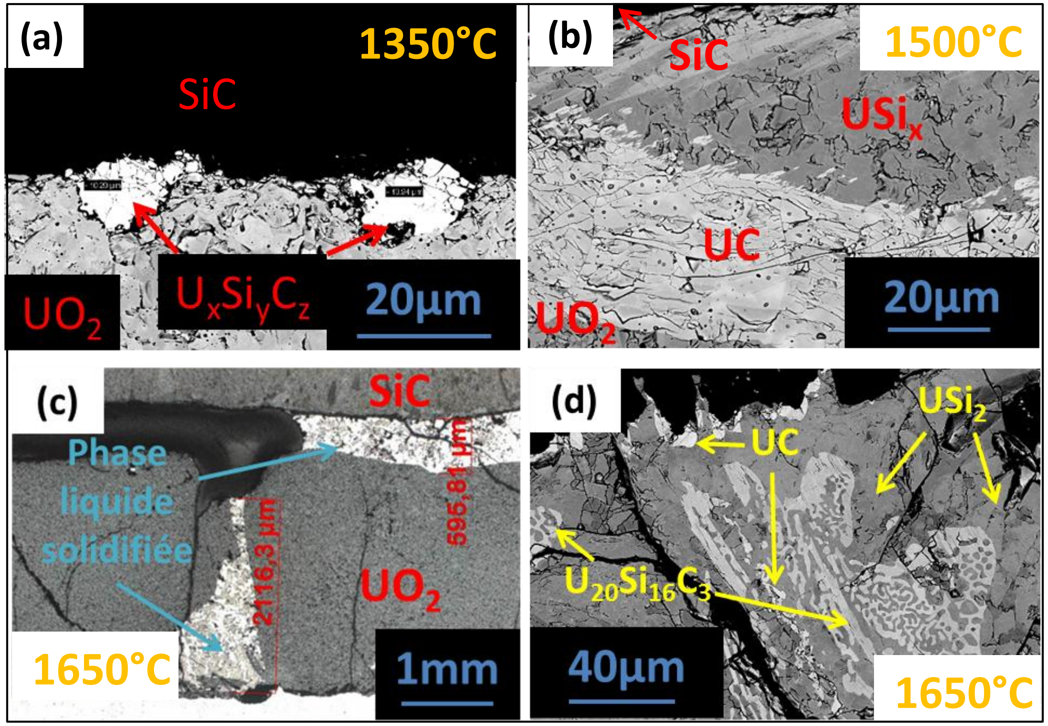
Samples

(a) ***1350°C :*** **Limited reaction :**
Formation of $U_xSi_yC_z$
Composition ?

(b) ***1500°C :*** USi_x/UC
Arrangement ?
100 µm after 12h of HTTT

(c) (d) ***1650°C :*** **Solidified liquid phase**
$U_{20}Si_{16}C_3$, USi_2, UC and SiC

Formation temperature ?



- ***Opened/closed systems confrontation***

Similarities

- Very limited reaction under 1200°C
- Liquid phase over 1500°C
- Formation of uranium silicides

Differences

- Higher fraction of uranium carbides in closed system (UC)
- Displacements of chemical equilibria (less reactivity)

APPLICATION AND CONCLUSIONS

UO_2 Fuel compatibility with SiC for Light Water Reactors applications

Nominal operating conditions	***Accidental conditions***
Closed system ≈ 500°C at the UO_2/SiC interface ➡ **Not investigated** **(long term experiments needed)** **No reaction expected (extrapolations)**	**1. No loss of gas-tightness** ➡ ***Closed sytem*** **Limited reaction** at the UO_2/SiC interface **up to 1350°C** for few hours **Liquid phase** formed between 1500 and 1650°C **2. Loss of gas-tightness** ➡ ***Opened system*** **Limited reaction up to 1200°C**, formation of CO **Liquid phase** between 1500 and 1650°C

Key conclusions

- ***Limited reaction*** *up to 1200°C (opened system) and 1350°C (closed system) for few hours*
- *Formation of mainly* ***CO*** *in opened system / equilibrium in closed system*
- ***Investigations :***
  - *Determination of the reactivity in nominal conditions (long duration experiments)*
  - *Precise temperature of formation of liquid phases*
  - *Use of a « buffer » material to limit the UO_2/SiC reaction at high temperatures (T > 1500°C)*
  - *Reaction with fission products*

Technical update on SiC/SiC research (2014)

- **Autoclave tests results** in LWR nominal operating conditions for 3500h are positive even if mechanisms must be clearly understood
- **High temperature strength in steam** was demonstrated (up to 1400°C, > 100h)
- **Chemical compatibility between SiC and UO_2 was confirmed** but limited by the appearance of a liquid phase between 1500 and 1650°C

Although many progresses have been accomplished, many prospects have been raised to confirm the feasibility of using SiC/SiC for LWR

On-going, further work and pending issues

- **Transposition of sandwich clad to LWR requirements** (design, most suitable liner)
- **Manufacturing of elongated and closed clad** (closure by welding in the « sandwich » design)
- **Tests in pressurized water loop to assess the impact of the coolant chemistry** in AREVA facilities
- **Confirmation of gas-tightness for sandwich cladding after long duration exposure in LWR conditions** *(on-going)*
- **Numerical simulation of cladding in operation** both at CEA and AREVA
- **Evaluation of neutron irradiation**