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Manuel A. POUCHON, Jiachao CHEN

Suggestion of a novel failure tolerant fuel element & SiC related experiments at PSI
• New Pin Concept
  • Hollow pin concept for LWR from KAERI
  • Suggestion of internally cooled Sphere-pac concept
    – Design
    – Production aspects
    – Performance calculation for SFR
    – Concept for LWR with SiC cladding

• SiC related research at PSI
  • EXAFS experiment of irradiated monolithic SiC
  • Mechanical testing of neutron irradiated SiC/C & SiC/SiC
Suggestion of hollow pellet design in order to limit the temperature


- Effective concept to lower the temperature (+)
- Very sophisticated fuel production necessary (-)

US Patent 2008/0013667 A1
GFR Fuel - Pin design: SP option

Cladding:
- Ceramic (SiC/SiC) with inner liner
- Thickness: 1mm
- Diameters: 6.15mm/8.15mm

Pellet:
- Carbide
- Diameter: 5.92

Suggestion of SP filling:
→ Favorable swelling behavior (softer)

AC3- Experiment
Carbide fuel in fast reactor
→ low FCMI (soft)

Conceit suggested for SFR → GFR, LWR with SiC
**Internal gelation:**
Aqueous process to produce spherical fuel particles (gelation triggered by heat) → microwave heating

Droplets after cavity:
- 14 kHz
- 10 m/s

(A): the feed container,
(B): the vibrator with the nozzle,
(C): the cooling unit,
(D): the control unit for the vibrator,
(E): the microwave unit with the resonant cavity (F)

HMTA → $\text{Me(NO}_3\text{)}_x + \text{NH}_3 \rightarrow \text{Me(OH)}$
Filling procedures

Infiltration filling

Parallel filling
Temperature distributions for different concepts

normal 293 W·cm⁻¹, annular 626 W·cm⁻¹
• **Sphere-Pac:**
  3 instead of 2 size fractions
  (less room for swelling necessary, higher conductivity) →
  total smear density 87% instead of 81%

• **Hollow Pin:**
  Larger diameter

• **Cladding:**
  SiC/SiC for inner and outer tube.
  (Eventually inner tube as monolithic as only under compression)

**Advantages:**
- Easier production (even from reprocessing, similar to DUPIC fuel)
- Allowance for swelling (see fast reactor experience for carbide fuel)
- Lower temp. increase across fuel section (see SFR case)
- Higher cladding surface per fuel volume (4% more, evt. 23% monolithic)
- Higher mechanical stability because of double structure and large diameter
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Irrad. with 0-24 MeV He-ions at RT+

Reference sample

<table>
<thead>
<tr>
<th>sample</th>
<th>He concentration (appm)</th>
<th>damage (dpa)</th>
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</thead>
<tbody>
<tr>
<td>Reference</td>
<td>-</td>
<td>-</td>
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<tr>
<td>T3</td>
<td>194</td>
<td>0.012</td>
</tr>
<tr>
<td>T7</td>
<td>600</td>
<td>0.036</td>
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<tr>
<td>T8</td>
<td>1500</td>
<td>0.090</td>
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<td>T2</td>
<td>2451</td>
<td>0.147</td>
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Irradiation temperature: 782-810 °C (Ø 796 °C)

Sample: Total fluence (>0.1 MeV) \[10^{21} \text{ neutrons}\cdot\text{cm}^{-2}\] dpa (crosssection SIC-WWSL) (±15%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total fluence (10^{21}) neutrons\cdot cm(^{-2})</th>
<th>dpa (crosssection SIC-WWSL) (±15%)</th>
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<tbody>
<tr>
<td>H018</td>
<td>3.39</td>
<td>1.96</td>
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<tr>
<td>H028</td>
<td>3.24</td>
<td>1.87</td>
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<tr>
<td>A032</td>
<td>3.07</td>
<td>1.77</td>
</tr>
<tr>
<td>A034</td>
<td>3.33</td>
<td>1.92</td>
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</table>
What is EXAFS (extended x-ray absorption fine structure)

Selected Atom probing its environment

Constructive               Destuctive

Absorbance (a.u.)

Energy (eV)
Experiment on Si edge

<table>
<thead>
<tr>
<th></th>
<th>K 1s</th>
<th>L₁2s</th>
<th>L₂2p₁/₂</th>
<th>L₃2p₃/₂</th>
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<tbody>
<tr>
<td>Value</td>
<td>1839</td>
<td>149.7</td>
<td>99.82</td>
<td>99.42</td>
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</table>

Lucia Beamline – SLS

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy range</td>
<td>0.8 - 8 keV</td>
</tr>
<tr>
<td>Flux on sample</td>
<td>2 x 10¹² ph/s/400 mA</td>
</tr>
<tr>
<td>Spot size on sample</td>
<td>1.2 x 1 µm²</td>
</tr>
<tr>
<td>Polarization</td>
<td>linear horizontal</td>
</tr>
<tr>
<td>Polarization</td>
<td>circular left &amp; right</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

(→ follow up at PSI:)

Phoenix Beamline - SLS

0.4 keV to 8 keV

See http://www.psi.ch/sls/phoenix/phoenix-i

(transferred to Soleil →)
Results – Ion irradiated α-SiC

Measured on Lucia

Result:
Decrease of coordination number in the 1\textsuperscript{st} and 2\textsuperscript{nd} shell (corresponding to Si-C and Si-Si).
Preliminary result from bulk SiC

Measured on Phonenix

Similar change compared to ion irradiated α-SiC
Damage modes

- **Crack**
  - Platelet-formation under He-irradiation (!)

- **Track**
  - Amorphous along ion track (??)

- **Interstitials**

- **Vacancies**

Modelling - Simulation of the EXAFS – Spectra

$\alpha$-SiC

FEFF

Atom-clusters

$ab\ initio$ multiple scattering calculations of XAFS & XANES

scattering ampl. and phases, …

e.g. EXAFS spectra

Structure $\rightarrow$ Atom Cluster $\rightarrow$ introduction of damage

Si

C

2.0 Å

0.5 Å
Modelling – He platelets

α-SiC

Results - Comparison of Experiment and Simulation

Structure

Original

Nano-crack

FEFF

|F(ω(k)·X(k),K^2)| (Å⁻³)

0 1 2 3 4 5

R (Å)

from:
ion
irradiated
α-SiC
MD simulation using LAMMPS code (hybrid Tersoff/ZBL potentials)

coordination number:

PKA:
10 keV @ 1070 K

β-SiC
8E6 Atoms

162 Vacancies (Si:C = 5:1)

Plot of atoms with coordination numbers ≠ 4 (normal case = 4)
Directly calculated radial distribution function

Only very initial analysis with peak height at two first neighbors. First peak shows more important decrease than in experiment, second peak decreases stronger, which is compatible with experimental data

→ Next step is FEFF calculation
Temperature: up to 700 °C
Max. proton Φ: \( \sim 6 \cdot 10^{25} \text{ m}^{-2} \)
Max. neutron Φ: \( \sim 1 \cdot 10^{26} \text{ m}^{-2} \)
Proton Energy: 550 MeV
Neutron Energy: 0 → 550 MeV
3 Point Bend testing

Active 3-point bend test

Hot cell for active samples
Results of all composite SiC/(Si)C\textsubscript{f} bending tests

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Designation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SiC\textsubscript{f}/SiC - CVI</td>
<td>1417 II</td>
<td>2D grid, Tyranno\textsuperscript{TM} fiber</td>
</tr>
<tr>
<td>C\textsubscript{f}/SiC - CVI</td>
<td>5054 II</td>
<td>2D grid, amorphous fiber</td>
</tr>
<tr>
<td>C\textsubscript{f}/SiC - LSI</td>
<td>PH 970 P</td>
<td>2D grid, amorphous fiber</td>
</tr>
<tr>
<td>C\textsubscript{f}/SiC - LSI</td>
<td>HP 164 P</td>
<td>irregular fibers, amorphous fiber</td>
</tr>
</tbody>
</table>

LSI: Deutsches Zentrum für Luft- und Raumfahrt (DLR)
CVI: MT Aerospace AG

Results before and after irradiation
Bad example for old SiC fiber type

**Bend-test before and after irradiation**

**Non-nuclear Tyranno fiber:** substantial amount of oxygen and excess carbon  
→ irradiation-induced **densification**  
→ **New:** near-stoichiometric, polycrystalline SiC
Conclusions Hollow Pin Concept

• Easy, dustless production of SP fuel
• Mechanical advantages
• Higher cooling surface (compatible with SiC)
• Promising first calculation results of hollow pin performance for SFR

Conclusions SiC investigations

• Investigations leading to understanding of SiC basic damage mode under irradiation
• Mechanical testing leading to understanding of different fiber types in SiC based composites