Systematic Technology Evaluation Plan for SiC/SiC: Execution Update

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Systematic Technology Evaluation Program for SiC/SiC Composite

- The report identifies General Technology Gaps and specific tasks under a Systematic Evaluation Program to identify and address go/no-go issues
- The document has been socialized among laboratory and industrial peers and serves as a discussion and planning basis to perform these tasks in a collaborative and objective manner.
- The document is routinely updated to capture the latest results and achievements.

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Systematic Technology Evaluation Program for SiC/SiC Composite-based Accident-Tolerant LWR Fuel Cladding and Core Structures

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Critical Challenges/Opportunities for SiC/SiC

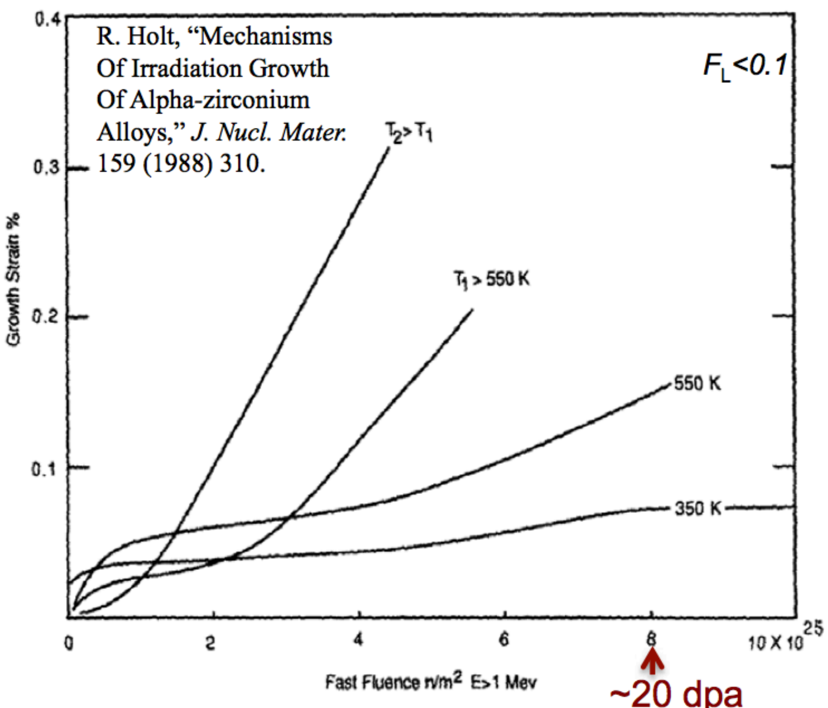
◉ Primary relevance
○ Secondary relevance

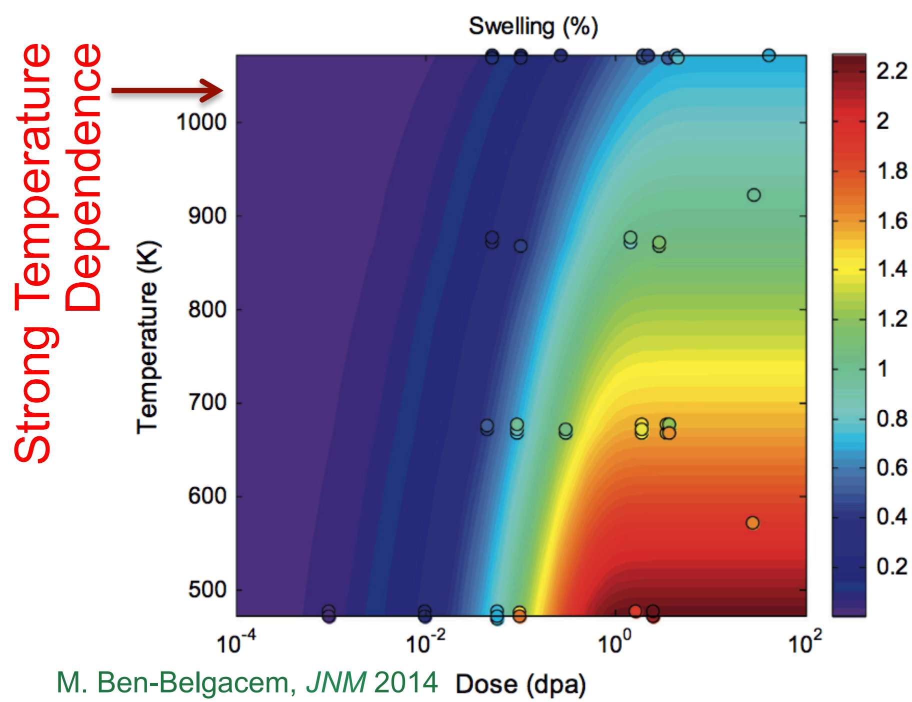
	Critical feasibility issues				Critical performance issues
Task	**Coolant compatibility**	**Cracking-induced failure**	**Fuel compatibility**	**Accident-tolerance**	**Fission product retention**
Design & Failure					
Comprehensive analysis tool		◉	◉		◉
Statistical failure assessment		◉			◉
Fission product transport			○		◉
Design and manufacture	◉	◉	○	○	◉
Environmental Effects					
Hydrothermal corrosion	◉			○	○
FCCI and FCMI			◉	○	◉
Irradiation effects	◉	◉	◉	○	◉
Off-normal Behavior					
Steam oxidation		○		◉	○
Thermal shock		○	○	◉	○
Accident analysis		○	○	◉	○

State of Stress Across SiC/SiC Cladding and Probabilistic Failure

Great Difference in Irradiation Effects on Zr Alloys and SiC/SiC

	Zr Alloys	SiC/SiC Composite
Thermal Conductivity	~18 W/m-K - Constant	Drops to ~3 W/m-K
Dimensional Stability	Anisotropic growth – no sat	Isotropic swelling – sat at <1 dpa
Creep	Thermal and irradiation creep are both significant	Negligible (two orders of magnitude less than Zr)
Strength	Temperature dependent	Constant with T and Irrad
Design Approach	Deterministic	Probabilistic

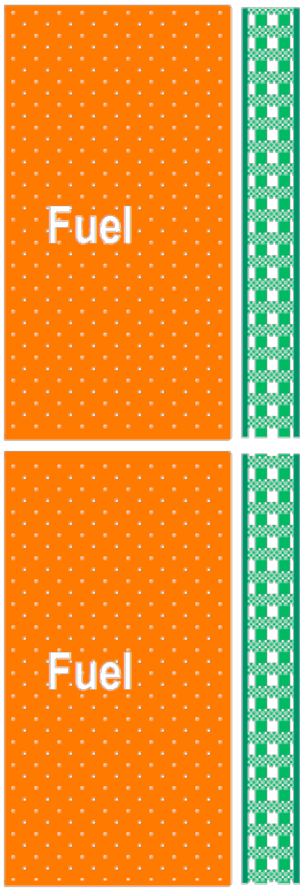




M. Ben-Belgacem, *JNM* 2014

SiC Clad Stress Profile different from Zr

Drop in thermal conductivity → Strong temperature-dependent swelling (cold swells more) → Max tensile stress is on inner surface of SiC clad

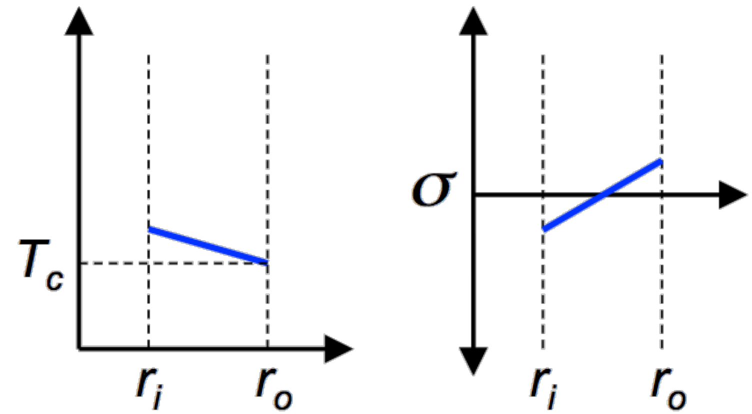


Stress driven by temperature gradient

t = ~0

K_{th} = high

Swelling = ~0

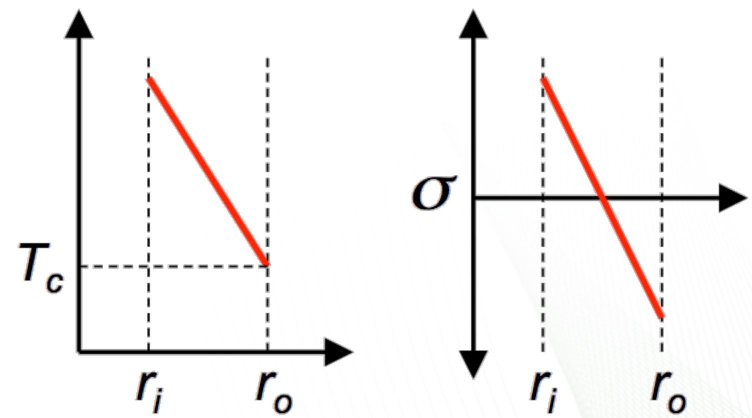


Stress driven by swelling gradient

$t >> 0$

K_{th} = low

Swelling = saturated

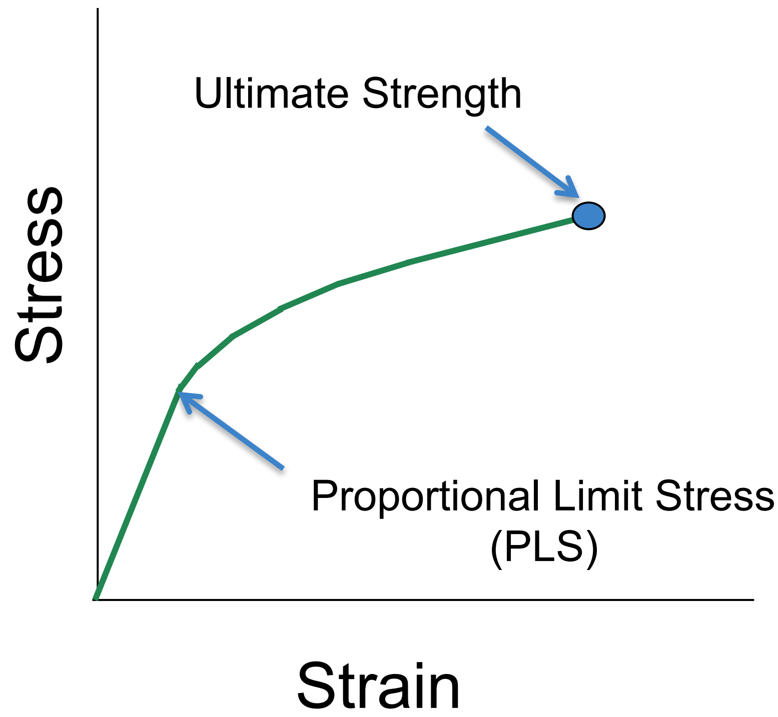


Stresses on the order of 100 MPa can readily appear on the inner SiC clad surface

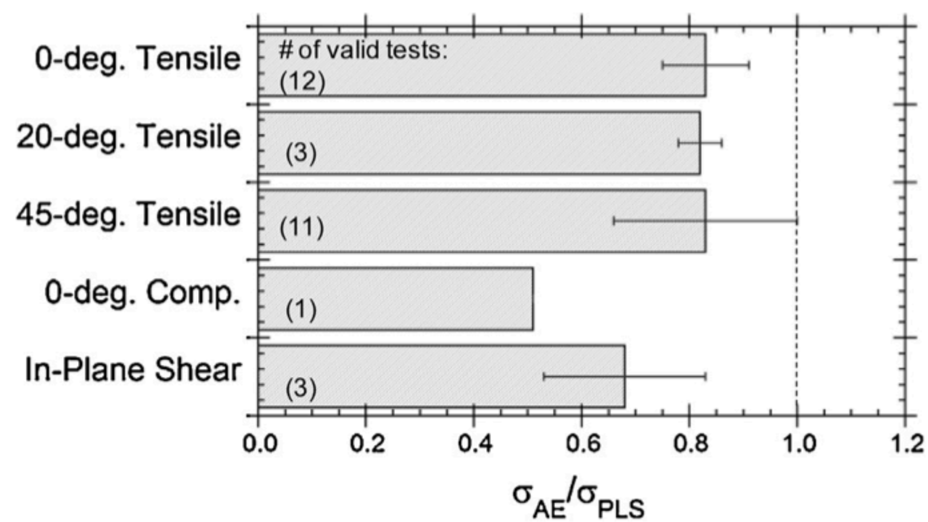
M. Ben-Belgacem, et.al., "Thermo-mechanical analysis of LWR SiC/SiC composite cladding," *J. Nucl. Mater.*, **447** (2014) 125.

Critical Gaps: Design and Failure Issues: Statistical Failure Assessment

Engineering Stress-Strain curve for a SiC/SiC composite



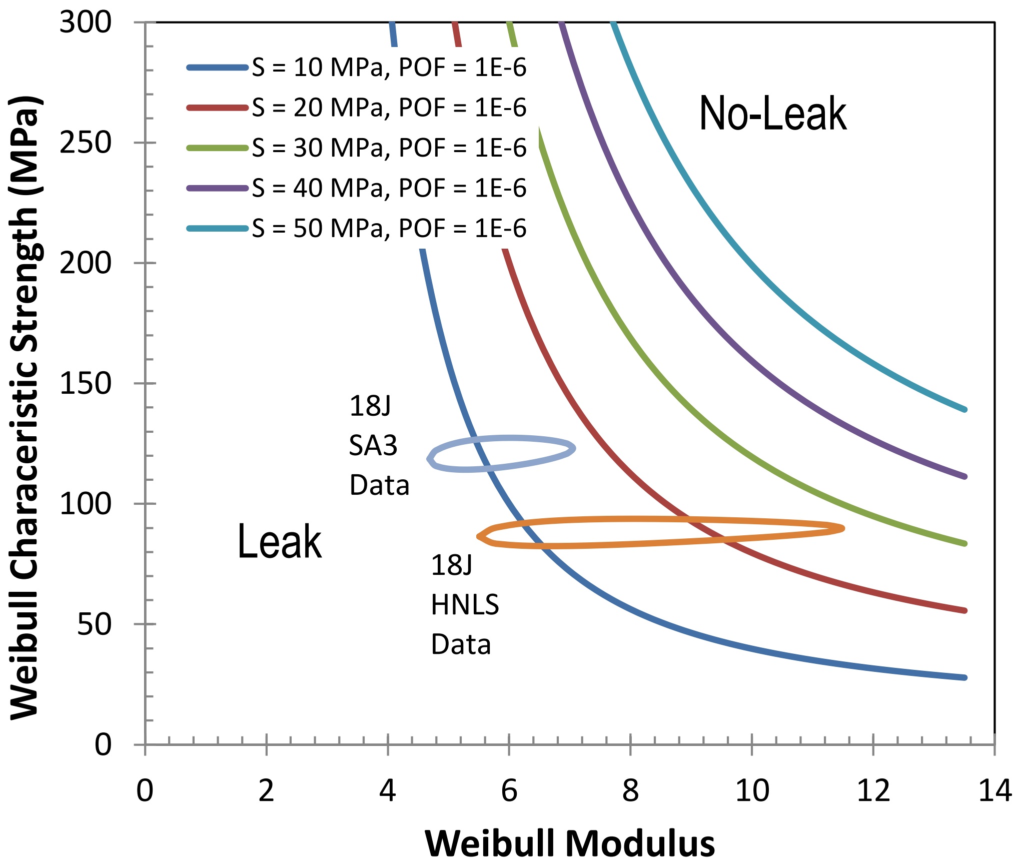
Recent studies show that matrix micro-cracking occurs at stresses below PLS



T. Nozawa, et.al., "Re-defining failure envelopes for silicon carbide composites based on damage process analysis by acoustic emission," *Fus. Eng. Des.*, **88** (2013) 2543.

Critical Gaps: Design and Failure Issues: Statistical Failure Assessment related to Fission Product Release

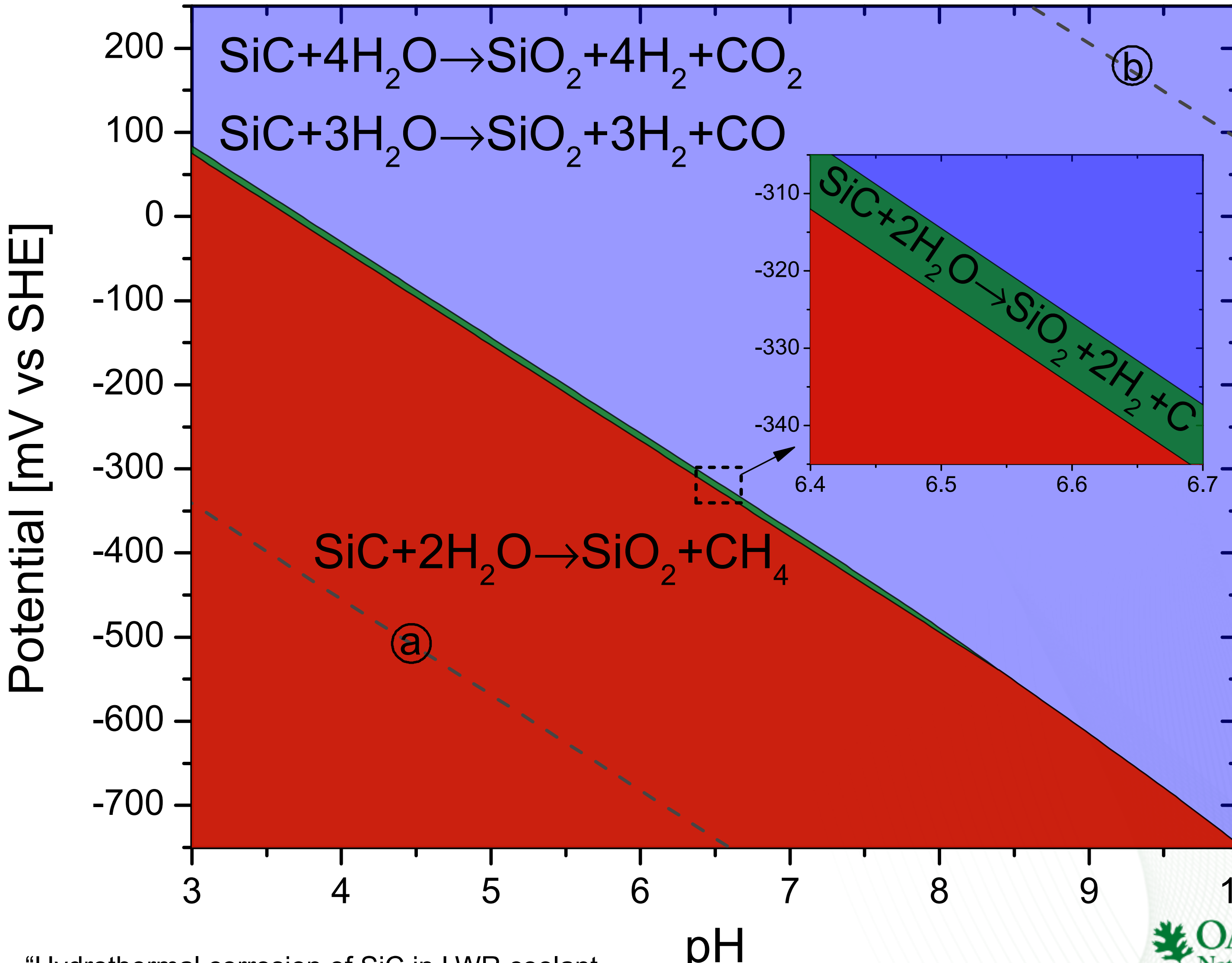
- Need to understand whether matrix micro-cracking relates to cladding failure.
- The permeation studies to date have been performed on as-fabricated specimens
- If the fully-ceramic cladding reliability is challenging, a metallic layer could potentially alleviate these concerns.



Hydrothermal Corrosion of SiC in LWR Coolant Environments

Thermodynamic Basis for SiC Oxidation in LWR Water

300°C and 15 MPa



K. Terrani, et al., "Hydrothermal corrosion of SiC in LWR coolant environments in the absence of irradiation", *J. Nucl. Mater.*, submitted (2015)

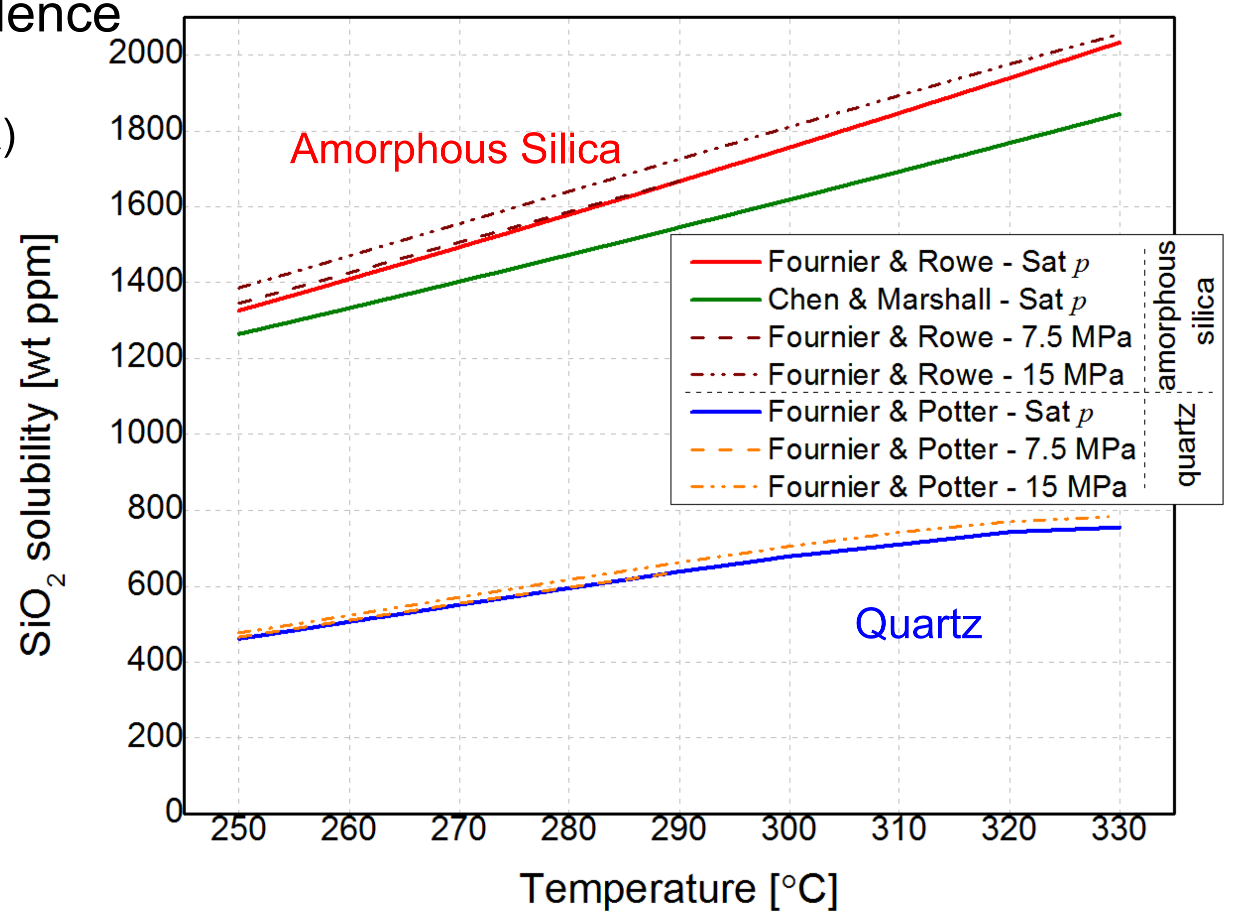
Thermodynamics of SiO_2-H_2O Reactions

- Water reacts with silica to form silicic acid:

$$SiO_{2(s)} + 2H_2O_{(aq)} \leftrightarrows Si(OH)_{4(aq)}$$

- Silicic acid readily dissolves in water with high solubility
- Strong temperature dependence
- Strong structure dependence
- Small pressure dependence
- Small pH dependence

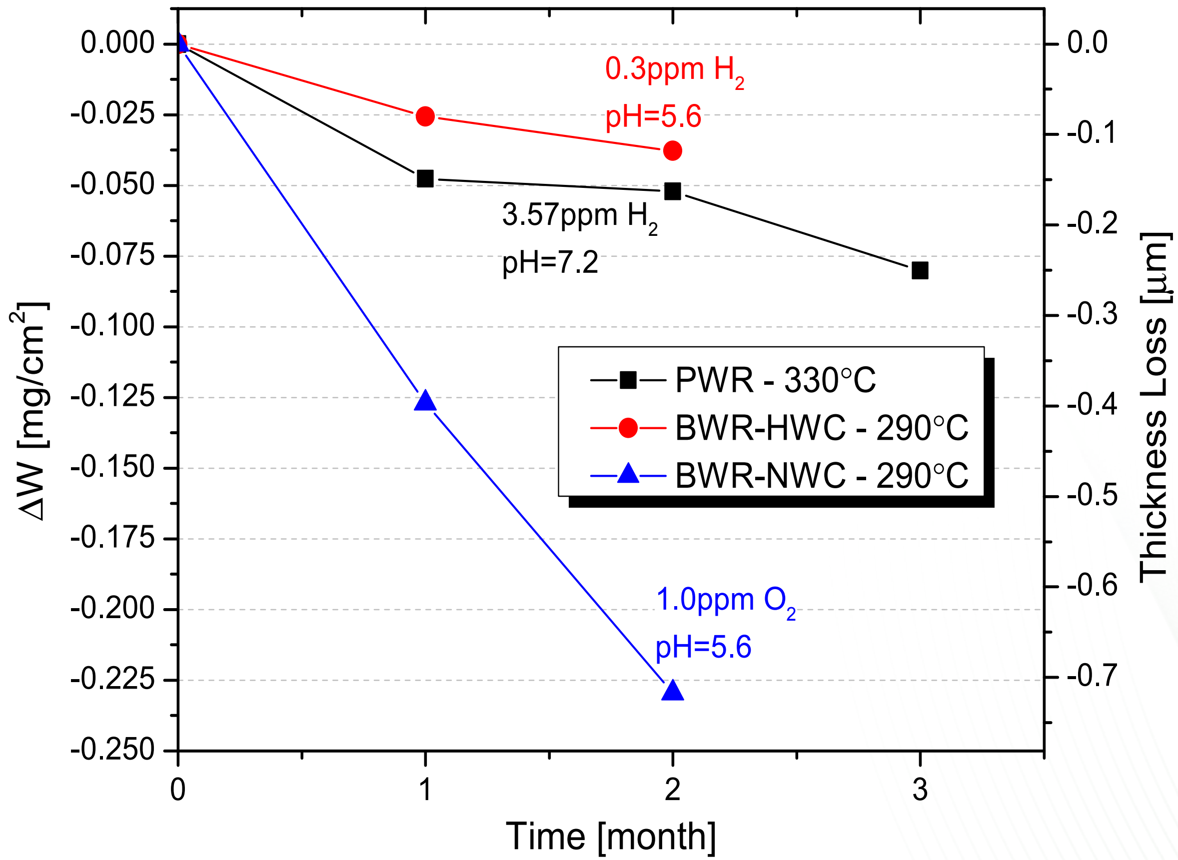
(in the range of interest for LWR)



- R. O. Fournier; J. J. Rowe, *Am. Mineral.* 1977, *62*, 1052-1056.
- R. O. Fournier; R. W. Potter II, *Geochimica et Cosmochimica Acta* 1982, *46* (10), 1969-1973.
- C.-T. A. Chen; W. L. Marshall, *Geochimica et Cosmochimica Acta* 1982, *46* (2), 279-287.

SiC LWR Immersion Tests Results

- CVD-SiC specimens experienced mass loss, the rate of which appeared to accelerate with oxygen activity in the system.
- Sintered SiC materials showed similar trends, however, the observed mass loss rate was least 50 times faster.
- Silica is not stable on the surface of SiC and dissolves into coolant.



K. Terrani, et al., "Hydrothermal corrosion of SiC in LWR coolant environments in the absence of irradiation", *J. Nucl. Mater.*, submitted (2015)

Summary

- A Systematic Technology Evaluation Program to identify and address go/no-go issues of SiC/SiC cladding is being implemented.
- Two areas among critical feasibility issues are undergoing active investigation:
  - Differential swelling driven stress induced micro-cracking leading to cladding failure (FP release)
  - Hydrothermal corrosion of SiC in LWR coolant environments with and without ionizing radiation
- Detailed thermo-mechanical analysis of the cladding coupled with in-pile testing is necessary to fully understand the state of stress and nature of failure in SiC/SiC structures
- Hydrothermal corrosion in the presence of irradiation could prove problematic. One mitigation strategy is incorporation of a thin protective metal layer on the outer surface of the cladding.