Summary on SiC

Task Force 2 (Clad) meeting

Second meeting of the Expert Group on Accident Tolerant Fuels for Light Water Reactors, 23-25 Sep. 2014, OECD/NEA HQ

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KAERI Korea Atomic Energy Research Institute

Outline

- Background
- US's contribution
- France's contribution
- Japan's contribution
- Korea's contribution
- China's contribution

Background

Oak Ridge National Laboratory [1,2]

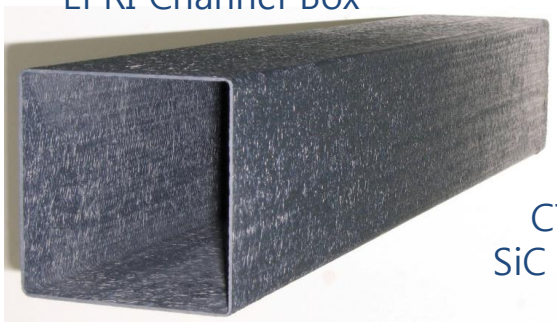
1. L. Snead*, SiC development related to ATF applications,* EPRI/INL/DOE Joint Workshop on Accident Tolerant Fuel, San Antonio, TX. February 27-28, 2014.
2. L. Snead*, Composites for Nuclear Applications,* Slides for Consideration/ EGATF

SiC & Composites for Nuclear Applications

- SiC has been used in nuclear applications for more than four decades as a nuclear fuels→ the pressure vessel of a TRISO fuel

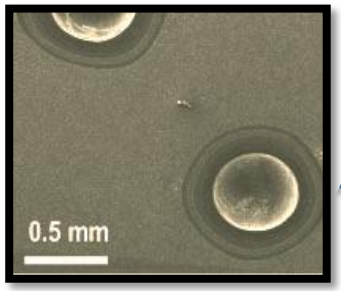
- Currently, there are several fission applications of SiC/SiC undergoing R&D.
  - Channel box for BWR(EPRI BWR Channel Box initiative)
  - SiC composite clad(DOE NGNP and AHTR, GA-EM2)
  - Advanced fuel (fuel matrix for TRISO compacts)

EPRI Channel Box



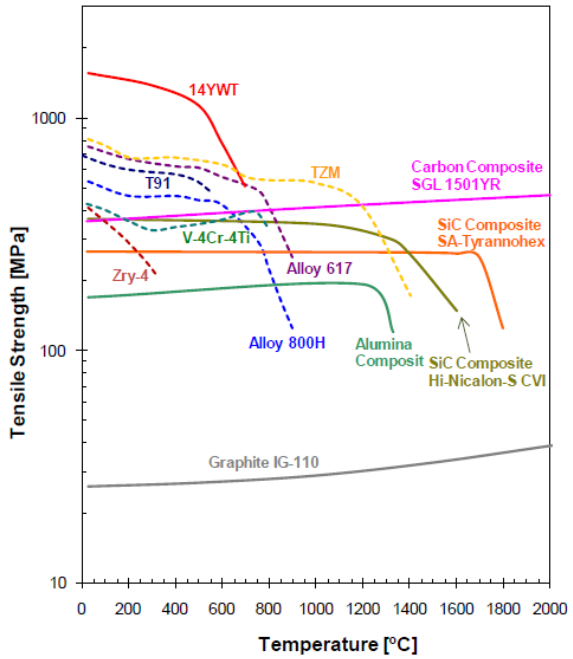
CTP
SiC Clad

FCM Fuel



SiC composite*

- SiC/SiC Composites : Benefits for Accident Tolerance
  - Significantly reduced reaction with steam (less Hydrogen, less heat)
  - High temperature strength/toughness improves fuel relocation performance (cladding)
  - Compared with alternative cladding, cross-section is low
  - Creep resistance could eliminate channel bow (Channel box)



Application of SiC/SiC for LWR core internals

- SiC/SiC is inherently “leaky”, ceramic solutions for FP retention superior to zircaloy may not be feasible at industry standard. This is potentially impossible. ⇨ ”hybrid” designs employing metallic inserts or bladder are being pursued.
- SiC joining is important for many nuclear applications and is challenging, though recent research shows potentially radiation stable joints
- As compared to the clad application, the BWR channel box application appears both technically important and an appropriate technological “leap” for entry into a commercial system. Important issues such as corrosion and corrosion product mitigation need to be addressed.
- The minor effort in codes and standards are critical to development and should be strengthened.

US's Contribution & Plan

DOE[1], WEC[2], General Atomics[3], EPRI[4]

1. Jon Carmack, *DOE Fuel Cycle R&D FOA Program on ATF*, EPRI/INL/DOE Joint Workshop on Accident Tolerant Fuel, February 2014
2. Sumit Ray, *Update on Westinghouse Accident Tolerant Fuel Program*, EPRI/INL/DOE Joint Workshop on Accident Tolerant Fuel, February 2014
3. Christina A. Back*, Advanced Fuel Technologies at General Atomics,* OECD/NEA Workshop on Accident Tolerant Fuels of LWRs, 2012
4. Andrew Sowder, *EPRI Update Since the 2nd OECD/NEA Meeting on ATF,* OECD/NEA Start-Up Meeting of The EG on ATFs for LWRs, April 2014.

Funded ATF Projects

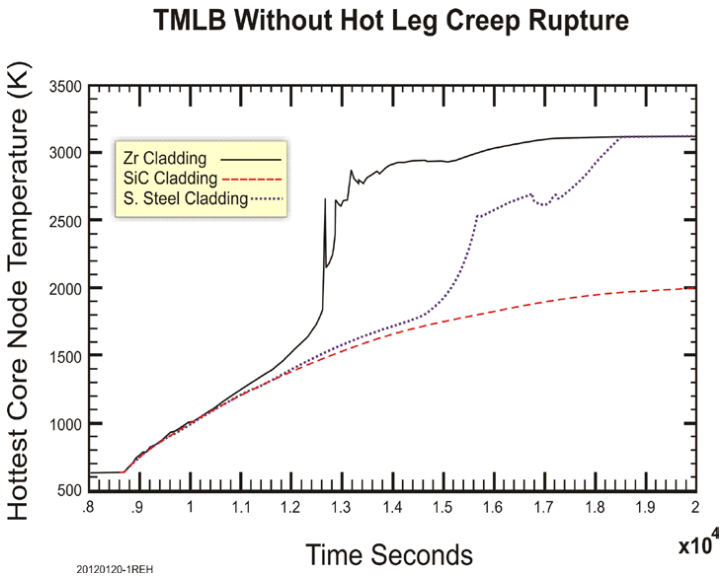
- DOE : SiC composite cladding

Lead Organization	Category – Major Technology Area	PI	Team Members	FOA, IRP, Lab, NEUP
AREVA	Protective materials, MAX phase, and high conductivity fuel	Paul Murray	U. Wisconsin, U, Florida, SRNL,TVA, Duke	FOA, NEUP
Westinghouse	SiC Cladding, U-Si-N Fuel	Ed Lahoda	General Atomics, MIT, EWI, INL, LANL, TAMU, Southern Nuclear Operating Company	FOA, NEUP

- EPRI Breakthrough Fuel Technology Program focusing on two accident tolerant fuel applications (pre-Fukushima initiation):
  - Coated Mo-alloy cladding
  - SiC composite for BWR fuel channels
  - EPRI/INL/DOE Joint Workshops

SiC clad-WEC & GA

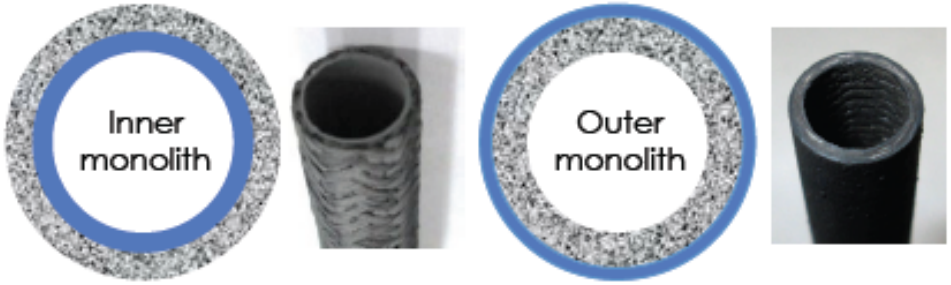
- SiC composite cladding is a long term project to
  - increases maximum tolerable cladding temperature from current 1200°C up to 2000°C
  - increases corrosion resistance at normal operating conditions (~300°C)
- SiC clad fuel would provide significant "grace time" to cope with the accident like Fukushima.

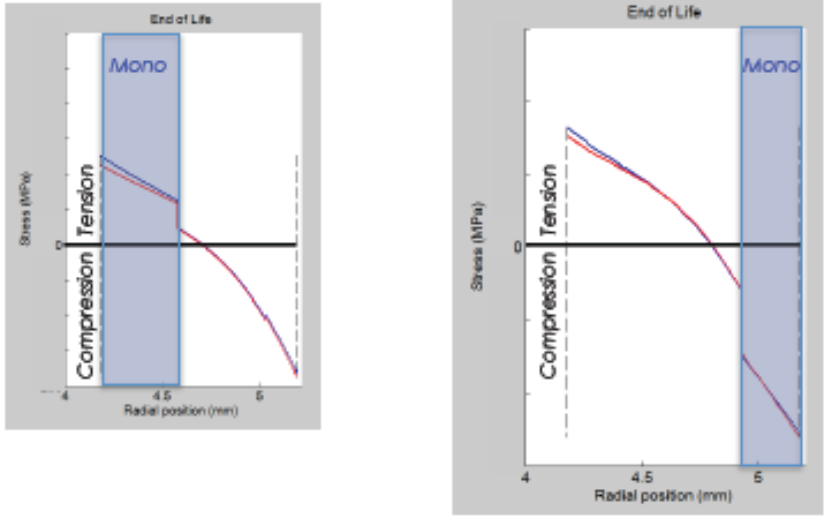


SiC clad-WEC & GA

- Westinghouse Electric Company LLC – project management, ATF engineering, licensing
- General Atomics – SiC cladding development and manufacture
- Overall Timeline of Development Program
  - 2012 to 2014 : Manufacture test specimens for experimental evaluations
  - 2014 to 2016 : Preparing for test reactor irradiation of rods (ATR, HIFR, & MITR)
  - 2016 to 2022 : Licensing, Long term test reactor testing of integrated cladding/pellet concept(s), develop economic manufacturing technology

SiC Cladding Mechanical Modeling





Designs with monolith on the outside are promising - monolith remains in compression

Cladding Variations

Monolith provides hermeticity
Composite provides structural integrity

Model	Inner Monolith	Composite	Outer Monolith
	µm	µm	µm
Duplex	400	600	
Standard		750	250
Intermediate		630	250
Thin		500	250

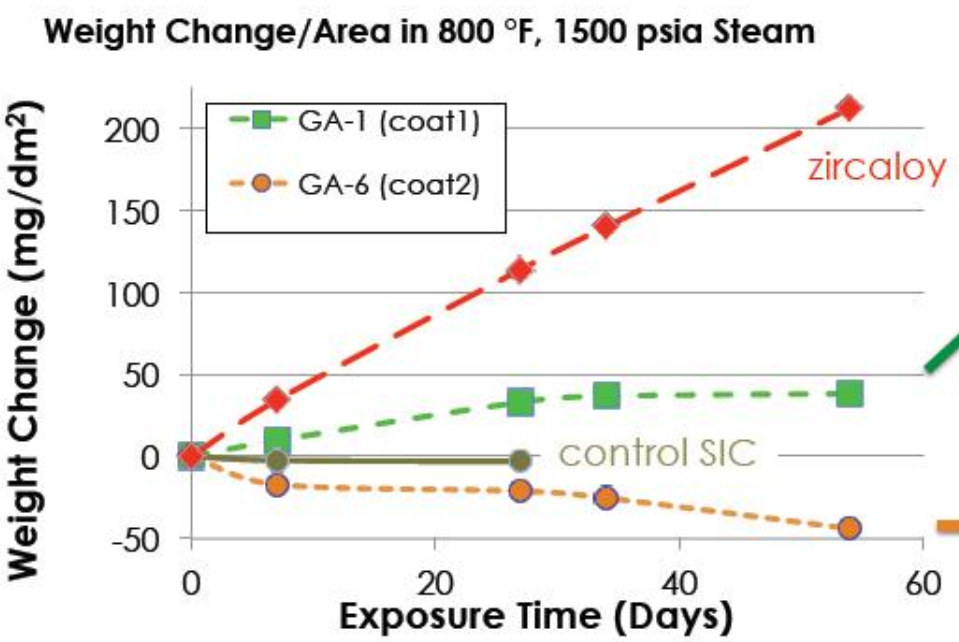
Model Inputs

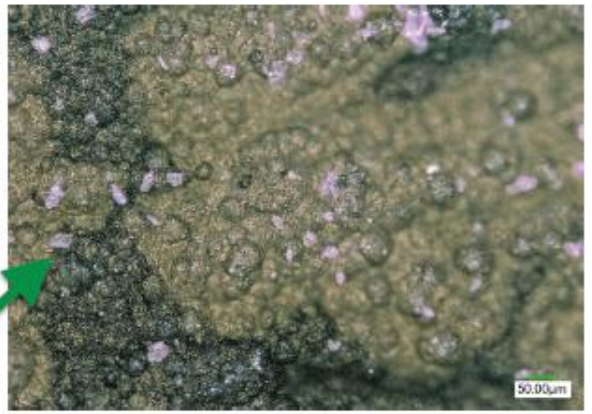
- LHR =42.7 kW/m
- Internal pressure
  1-20 MPa in operation
  16.8 MPa final
- External pressure 15.5 MPa (2250 psi) until shutdown
- Uses GA swelling, thermal conductivity, and Weibull failure models

These studies indicate a high confidence in maintaining hermeticity with the outer monolith concept

SiC Corrosion at Normal Operating Conditions

- **SiC-SiC coupons - autoclave testing at WEC**
  - Used monolithic SiC, and Zircaloy control samples
  - Exposed for 57 days





Corrosion at both high and low temperatures much lower than that of zirconium alloys

In-Reactor Corrosion of SiC

(a) C1-3

(b) F1-1

(c) H2-1

- Cut ends must be sealed with a significant thickness of CVD'd SiC to keep coolant away from fibers
- Outside monolith will reduce or eliminate coolant/fiber contact
- In-reactor tests showed minimal corrosion depending on manufacturing process

EPRI SiC Composite BWR Channel Program

Scope

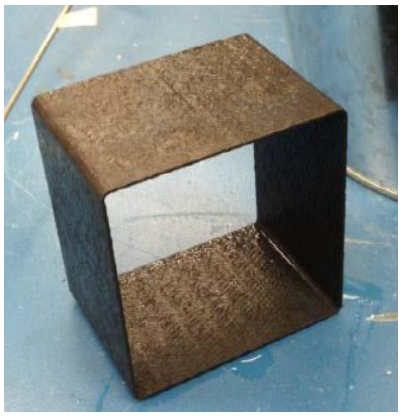
- Initial design screening (complete)
  - Fragmentation resistance and Irradiation induced swelling issues resolved
  - Eliminated polymer infiltration pyrolysis (PIP) process
- Material property characterization and issue resolution
  - Generate data to support the insertion of a commercial lead channel
  - Resolve remaining issues
- 1/3 Scale integral sample demonstration in Oak Ridge National Laboratory HFIR reactor
- Post irradiation mechanical testing
- Data evaluation and commercial demonstration decision

SiC Composite BWR Channel

- Test article fabrication : SiC/SiC matrix composite fabricated for impact testing via CVD process
- Material Characterization
  - Measured strength lower than expectation
  - New test coupons for strength improvement planned; Increase fiber content, Optimized fiber orientation
- Quench survivability
  - Test article remained intact without cracking
  - Post Quench tensile tests showed no strength degradation

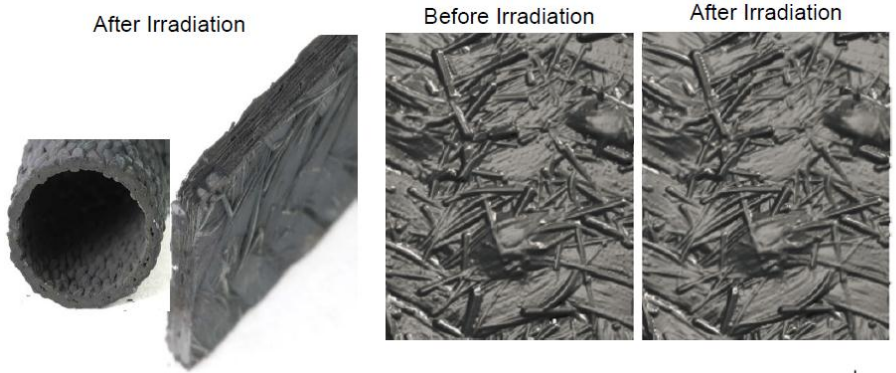
Flexible Woven Fibers Infiltrated with SiC

EPRI SiC/SiC Channel Box



SiC Composite BWR Channel

- MIT corrosion test (Pure water at 280°C without hydrogen injection)
  - High weight loss measured after one cycle; Mostly edge and some surface degradation
- Corrosion Mitigation Options
  - Metal coating
    - ORNL : coat SiC with various metal alloys
  - Stabilize SiO_2
    - Co-deposit a surface layer additive to stabilize SiO_2 ; Co-deposition of ZrC + SiC, $ZrSiO_4$ is insoluble in water



Summary-US

- SiC cladding development proceeding without any major issues , on target to meet the 2016 date for lead test rods in a test reactor
- Evaluations conducted thus far suggest SiC composite could meet BWR Channel mechanical design requirements
- Material recession in BWR water chemistry may be an issue; Strategies to protect SiC in BWR environment is being explored

France's Contribution & Plan

CEA [1-6]

I3P- THREE PARTIES INSTITUTE CEA-EDF-AREVA[7]

1. M. LE FLEM et al., *Evaluation of potential alternative nuclear fuel cladding materials for LWRS – CEA STUDIES*, OECD/NEA Workshop on Accident Tolerant Fuels of LWRs, 2012.
2. J.-C. Brachet et al., *CEA studies on nuclear fuel claddings for LWRs enhanced accident tolerant fuel: recent results, pending issues and prospects*, OECD-NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, 2013
3. *CEA : expectations and provisional contribution to a collaborative activity on ATF*, OECD-NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, 2013
4. M. Zabiégo et al*., « Improved multilayer tube made from ceramic-matrix composite material, the resulting nuclear fuel cladding and associated production methods »,* CEA patent, WO2013017621 A1, (February 7th 2013).
5. M. Zabiégo et al*., « Overview of CEA's R&D on GFR fuel element design: from challenges to solutions »,* IAEA-CN-199/282, FR13 conference, Paris, France, (Mars 4-7, 2013)
6. C. Sauder et al., *« Assessment of SiC/SiC cladding for LWRs »,* proceeding of 2013 LWR Fuel Performance Meeting/TopFuel, Charlotte, USA, (Sept. 15-19, 2013)
7. T. Forgeron et al., *ATF R&D STATUS AND PERSPECTIVES,* OECD/NEA Start-Up Meeting of The EG on ATFs for LWRs, April 2014.

SiC/SiC+liner composite

Development of SiC/SiC cladding optimized for GRFs , with possible LWR transposition

- Significant R&D at CEA in terms of fabrication of suitable cladding
- "Sandwich" concept with a metallic liner providing gas-tightness
- Tailorable mechanical properties thanks to optimizations of interphase and braiding
- Very good dimension control and fabrication reproducibility

- Preliminar corrosion testing performed for PWR (up to 1400℃ with air/H2O))
- Mechanical tests & caracterization :

No change in mechanical behavior
No diminution of stress to rupture

Results updates

- Oxidation testing in nominal conditions
  - First oxidation tests of SiC/SiC in LWR nominal conditions for 3,500h are promising even if oxidation mechanism must be clearly understood.
  - Pyrocarbon interphase is not affected : no reduction of mechanical strength
  - SiC recession is estimated to be 0.5μm after 3,500h of LWR nominal oxidation conditions

⇨ **Sandwich SiC/SiC cladding must be suitable for LWR**

Prospects

- Clad characterizations and evaluation programs are now undertaken with the support of the French Industrial partners AREVA and EDF.
- Short/mid term Prospects
  - Numerical simulation of rod behavior in Normal operation (PCI, design)
  - Fuel-SiC interface issues
  - Corrosion/wear in nominal conditions (sandwich concept)
  - High temperature oxidation
  - Irradiation testing
- International collaborations (benchmarking and evaluation)
  - SiC-SiC sandwich with Ta liner are candidates to experimental comparisons and numerical approach evaluations

Japan's Contribution & Plan

JAEA [1]

1. *Challenges in Japan on SiC as for ATF material in LWR*, provided by Dr. Kurata, 2014

Challenges in Japan on SiC as for ATF material in LWR

OASIS: Organization of Advanced Sustainability Initiative for Energy System/Material, Muroran Institute of Technology

- Five projects ongoing.
- Project leaders are Muroran Institute of Technology (OASIS) and Toshiba Corp.

Muroran (OASIS) leading projects:

- Innovative SiC Fuel-Pin Research (INSPIRE project, 2012-)
  - Production of SiC tube (200mm x 10mmϕ, 1mmt) with sufficient gas tightness
  - Checking its soundness by irradiation of fuelled SiC/SiC segment in Halden Reactor (up to 10GWd/t, BWR condition)
- SiC Fuel Cladding/Assembly Research Launching Extra-Safe Technology (SCARLET project, 2012-)
  - Fabrication technology of SiC/SiC
  - Basic coolant compatibility, irradiation effects, LOCA effects for SiC/SiC cladding (PWR condition)
- LWR Fuel with Increased Accident Tolerance (FIAT project, 2014-)
  - Feasibility of various ATF concepts in LWR

Toshiba leading projects:

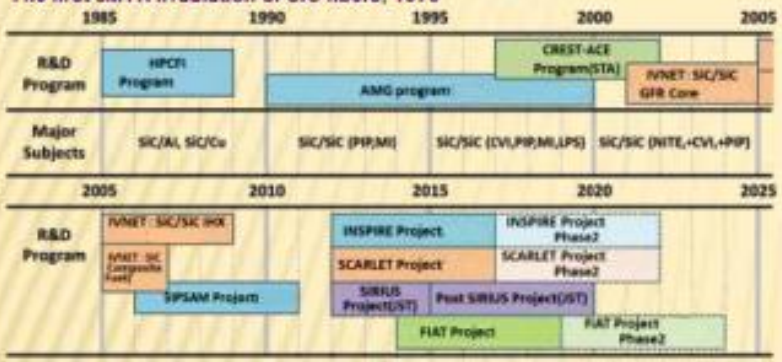
- Research & Development of Innovative Technologies for Nuclear Reactor Core Material with Enhanced (2012-)
  - Core, Fuel and plant performance in application of SiC
  - Material properties for corrosion resistance under LWR coolant condition
  - High resistance as accident tolerance to steam oxidation above 1200°C
- Development of Innovative Material for Light Water Reactor Core with Enhanced Safety (2012-)
  - Base process and apparatus to fabricate products of SiC fiber ceramic matrix composite

MAKING BREAKTHROUGHS UNDER OASIS PROJECTS

- TECHNOLOGY AND RESOURCE FOR SIC/SIC -

SiC development history and plans in near future

The first JMTR irradiation of SiC fibers; 1976



Material Resources for OASIS

- Fibers: Cef-NITE production is aiming over 1 ton/year from 2008.
- Woven fabrics production (1.5m width) has been started since 2008.
- Coatings: Continuous and large-scale R&D has just started in OASIS.
- SiC/SiC Composites: Cera-NITE is commercially available.

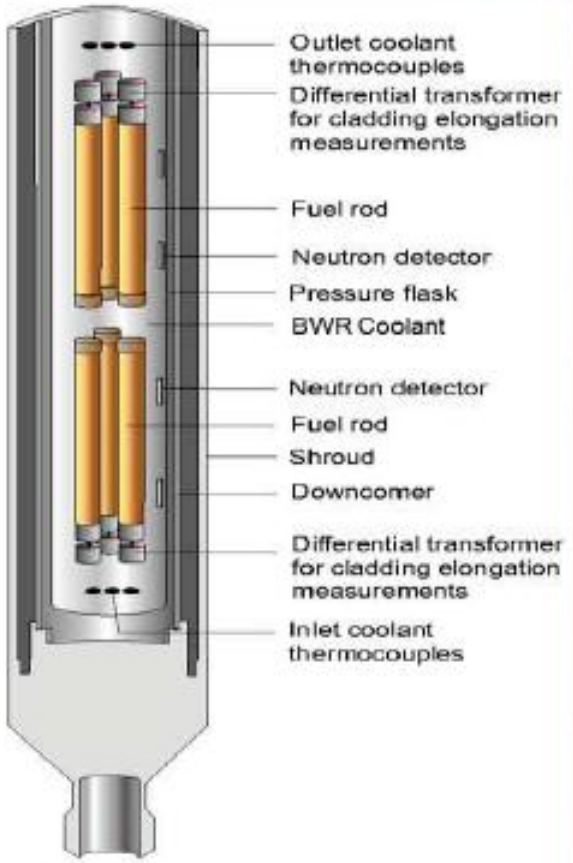
The Current Technologies

- Large-scale supply capability of advanced intermediate materials for SiC/SiC: ***Green sheets, Prepreg sheets, PCR, etc.***
- Automated/continuous fabrication technology for long SiC/SiC tube (SCARLET)
- Near-net shaping of ATF components with helium gas leak tightness (SCARLET and INSPIRE)
- Brazing and Joining for SiC/SiC segment and ATF components
- Reactor irradiation technology of SiC/SiC segments with/without nuclear fuels under LWRs. (SCARLET and INSPIRE)

"INSPIRE" PROJECT IRRADIATION PLAN

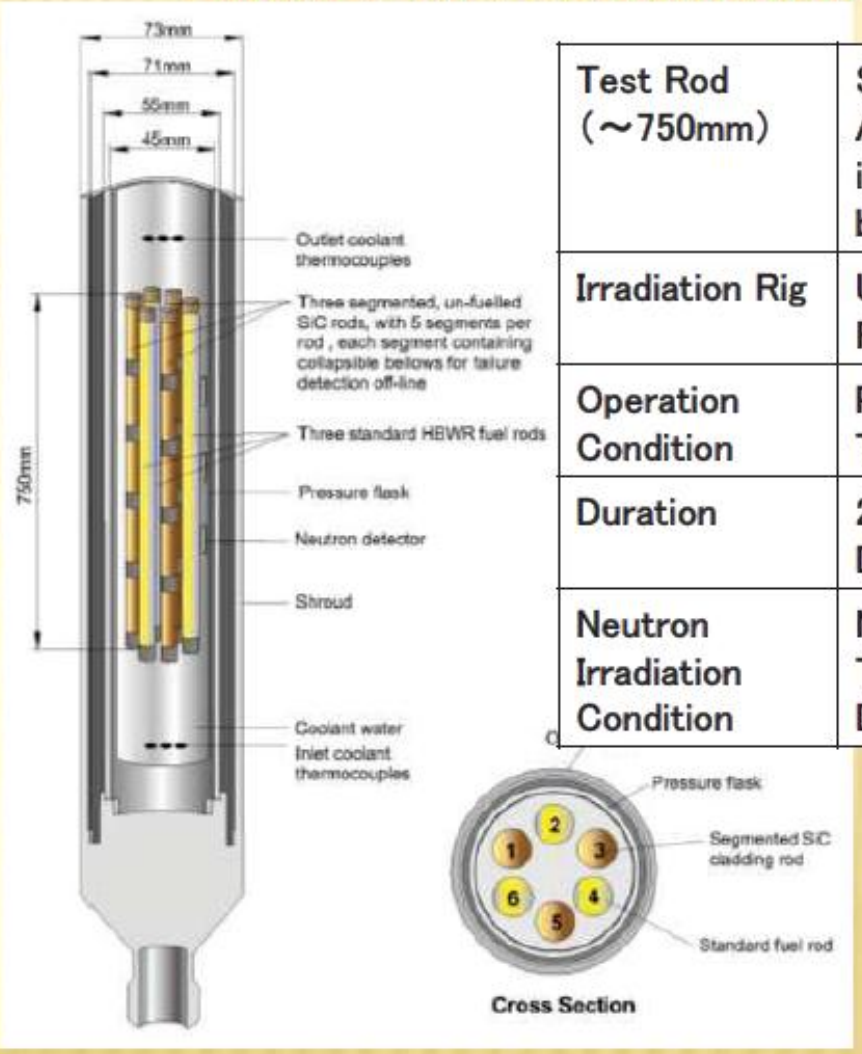
FUELED RODS UNDER BWR CONDITION IN THE HALDEN REACTOR

Test Rig (~750mm)	Test fuel rod (200mm) with cladding elongation detector on-line: 6 in Two clusters, inside a pressure flask
Test rods	SiC/SiC cladding, UO_2 fueled; 4 Zircaloy cladding, UO_2 fueled; 1 SiC/SiC cladding, un-fueled; 1
Test Condition	BWR thermal-hydraulics and chemistry; Starts with 20-25kW/m nuclear power and gradually decreasing
Burn-up	10GWd/t



Irradiation at HBWR will be started before August 2015.

"SCARLET" Project Irradiation Test Under PWR Condition in the Halden Reactor



Test Rod (~750mm)	SiC/SiC Cladding Tube ×5 A Collapsible Bellow for leak/fracture detection is inserted. Zircaloy endcaps are connected for both sides.
Irradiation Rig	Un-fuelled SiC/SiC tube ×3 Fuelled Zircaloy tube ×3
Operation Condition	PWR condition Temp.: 290°C, Pressure:15.5MPa
Duration	2 Halden Reactor Cycles (80-100EFPD) During 2014-2015
Neutron Irradiation Condition	Neutron flux (Anticipated) 5×10^{17} n/m^2/s Total fluence $3.4\text{-}4.3 \times 10^{24}$ n/m^2 Displacement Damage in SiC: 0.3-0.4 dpa

Irradiation at HBWR will be started before March 2015.

SiC development program Partners and Roles

R&D Program (2012-2014)

- **Design of CMC material applicable for channel box and clad**
  - Toshiba
  - The university of Tokyo
  - Tohoku University
- **Trial fabrication of SiC channel and clad**
  - IBIDEN
- **Thermal shock and mechanical/chemical testing**
  - Toshiba
  - IBIDEN
- **Core and plant performance analyses**
  - NFI (in application for SiC under PWR condition)
  - Toshiba (in application for SiC under BWR condition

132.5mm×800mmL Channel Box (SiC_f-SiC)

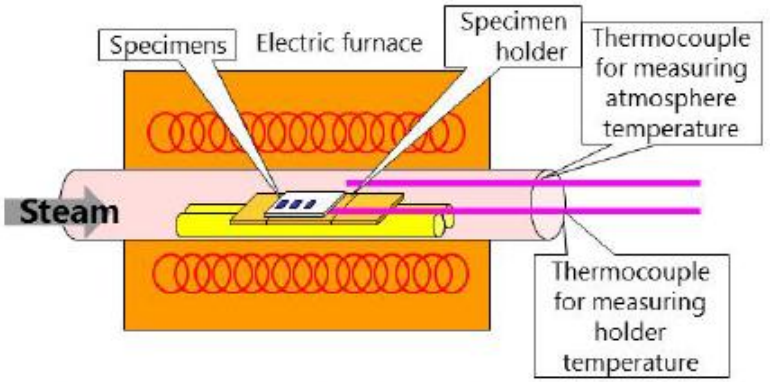
Φ10mm×280mmL Cladding Tube (SiC_f-SiC)

TOSHIBA/IBIDEN, Trial fabrication

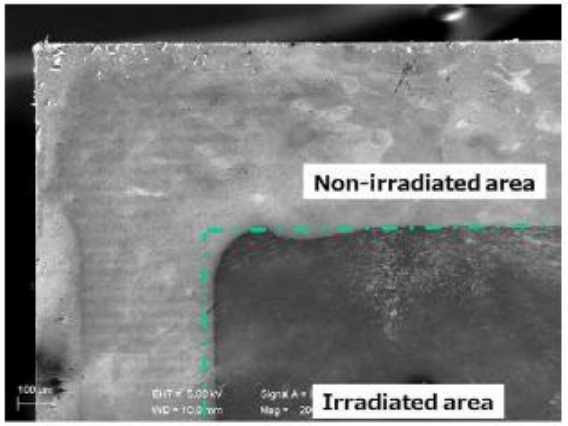
SiC development program Partners and Roles

MEXT R&D Program (2012-2015)

- **Preparation of SiC specimens in possible ways**
  - Kyoto University
- **Water corrosion/Steam oxidation testing**
  - Toshiba
  - Kyoto University
- **Ion irradiation testing**
  - Kyoto University
- **Electron beam testing**
  - Hokkaido University
- **Water Reactivity characteristic experiment**
  - Toshiba
- **Joining test and strength testing**
  - Toshiba



Test equipment configuration in high temperature steam



Appearance after high temperature water corrosion tests after ion irradiation

Summary-Japan

- Various knowledge on SiC being accumulated mai nly in universities in Japan.
- In 2012, several projects were launched for SiC-ut ilization to LWRs, in which innovative fabrication te chnology being developed and various fundament al tests including irradiation tests being progresse d.
- In 2014, feasibility study for common and synerget ic R&D started, in which collaboration among insti tutes, universities, and industries discussed.

Korea's Contribution & Plan

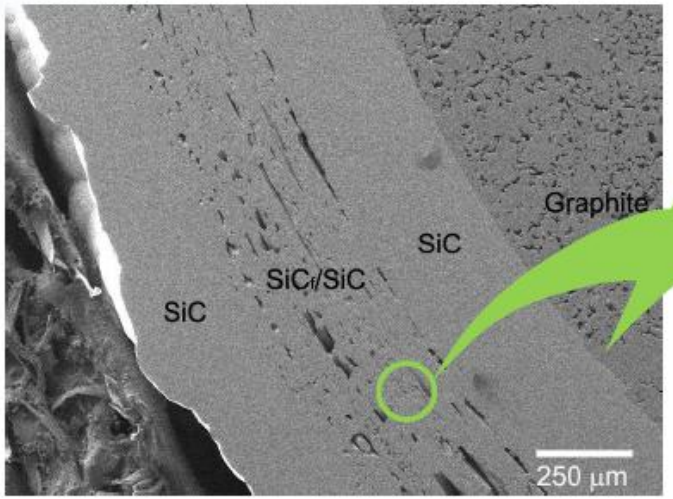
Korea Atomic Energy Research Institute [1]

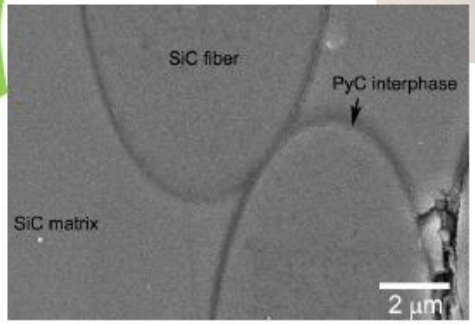
1. Jeong-Yong PARK et al., *Current status of accident tolerant fuel development in the Republic of Korea,* OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, Oct. 2013

Korea's SiC cladding program

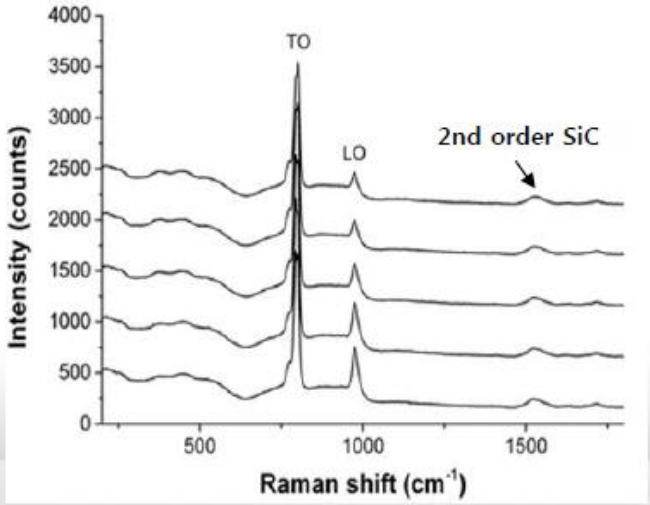
- R&D program for Accident Tolerant Fuels, which is funded by Korean government, was launched at 2012.
- **SiC/SiC composite cladding & Hybrid cladding** are being developed.
- Objectives of this 5-year project (2012-2016) are to
  - Determine the potential candidates for ATF cladding.
  - Test out-of-pile performances & establish DBs for ATF cladding
  - Irradiate in research reactors
- Long-term goal is to develop Lead Test Rods technology of ATF by 2022.

SiC triplex tube: fabrication & characterization



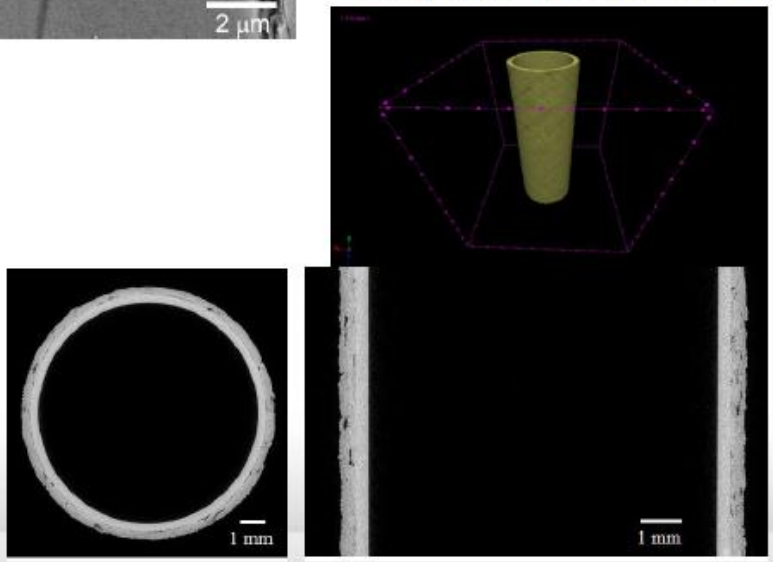


Triplex composite tube
(surface machined)



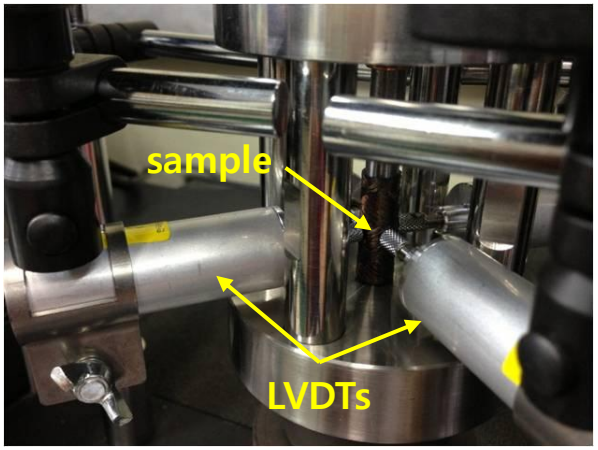
Raman micro spectroscopy on CVD SiC

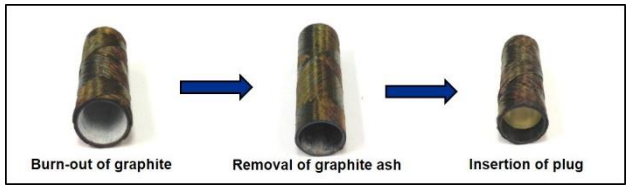
X-ray mCT volume image

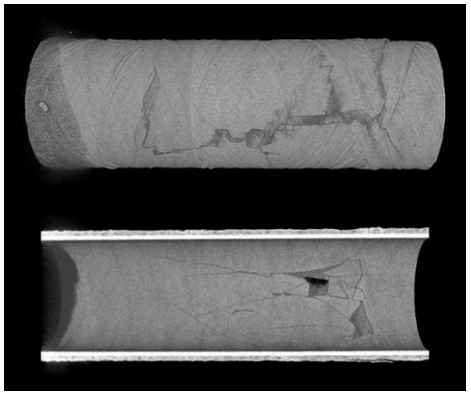


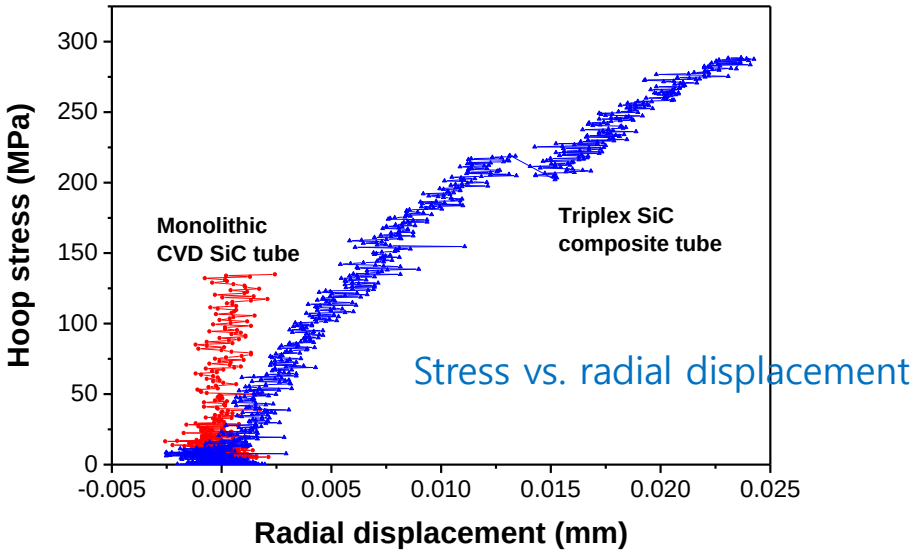
X-ray mCT sliced images

Evaluation of Hoop Stress of Triplex SiC Tube

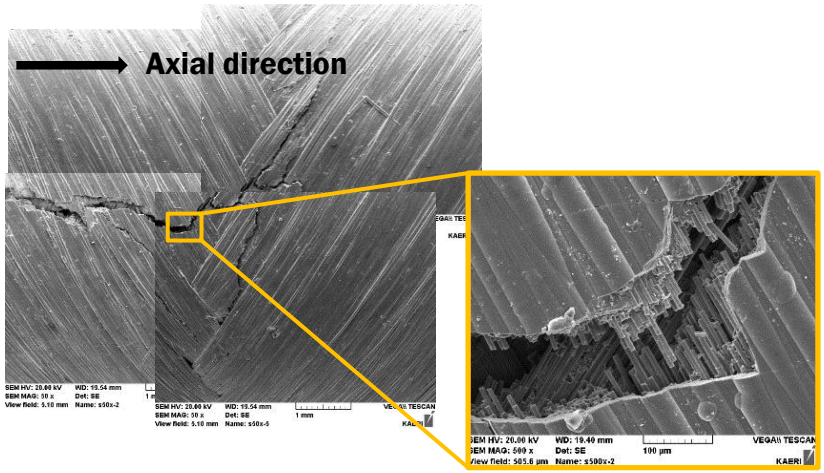








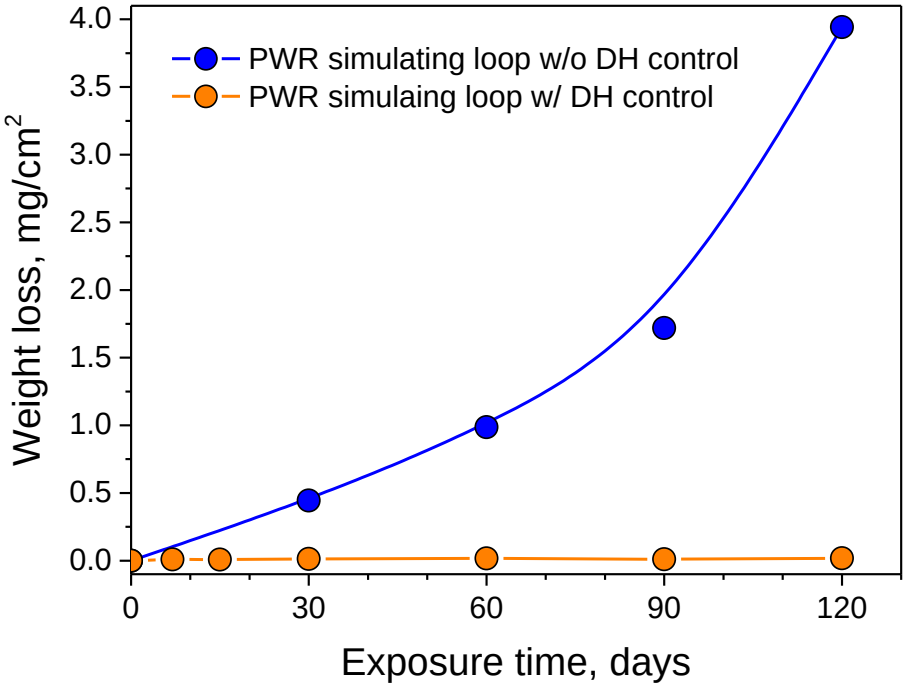
Stress vs. radial displacement



Fracture behavior of triplex SiC composite tuebe

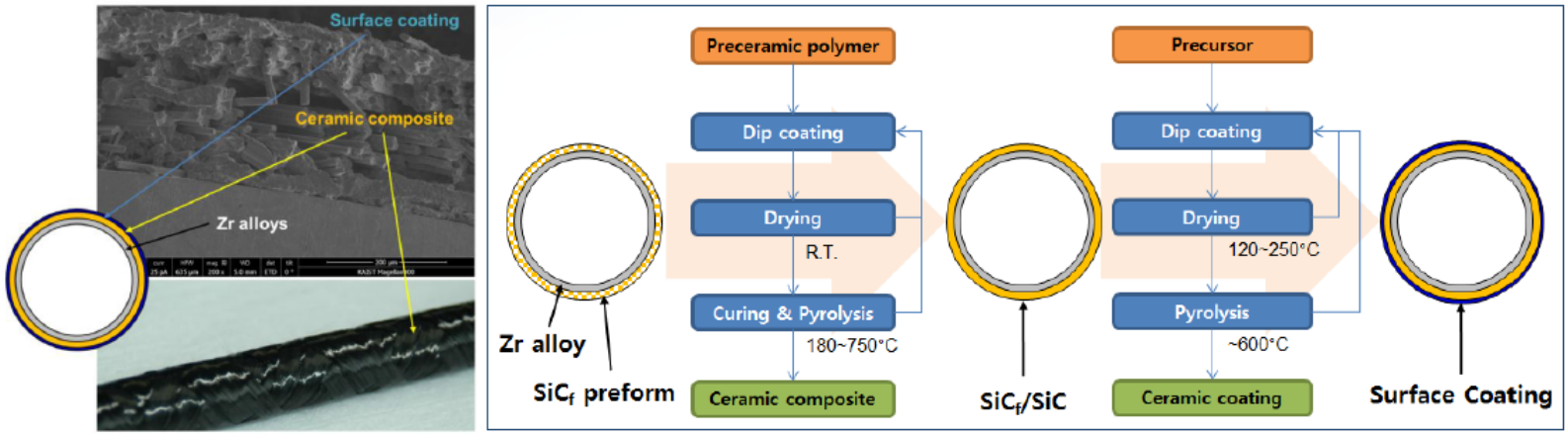
Effect of Dissolved Hydrogen on the Corrosion of CVD SiC

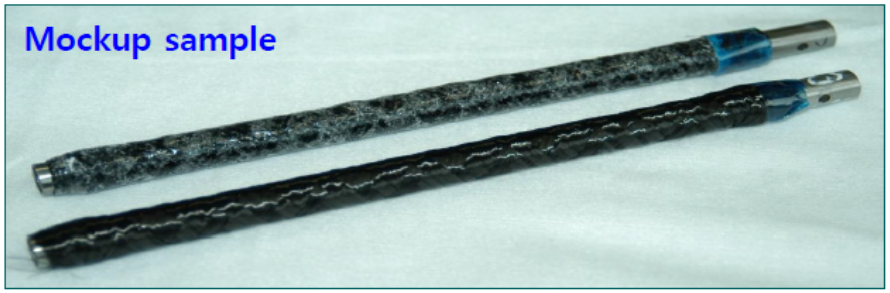
	Temp.	Pressure	Dissolved oxygen	Dissolved hydrogen	pH	Li/B
PWR-simulating loop **(without DH control)** ●	360°C	18.5 MPa	< 5 ppb	-	6.8	2.2ppm/ 650ppm
PWR-simulating loop **(with DH control)** ●	360°C	20 MPa	< 5 ppb	**~2.7 ppm**	6.3~6.5	2.2ppm/ 1200ppm



Hybrid Technology Development for ATFC

- Combination of advantages of metal and SiC material
  - → Inner Zr alloy for ductility and fission gas retention
  - → Mid SiC/SiCf for reducing H generation and increasing mechanical strength
  - → Outer coating for preventing dissolution of SiC in normal condition





China's Contribution & Plan

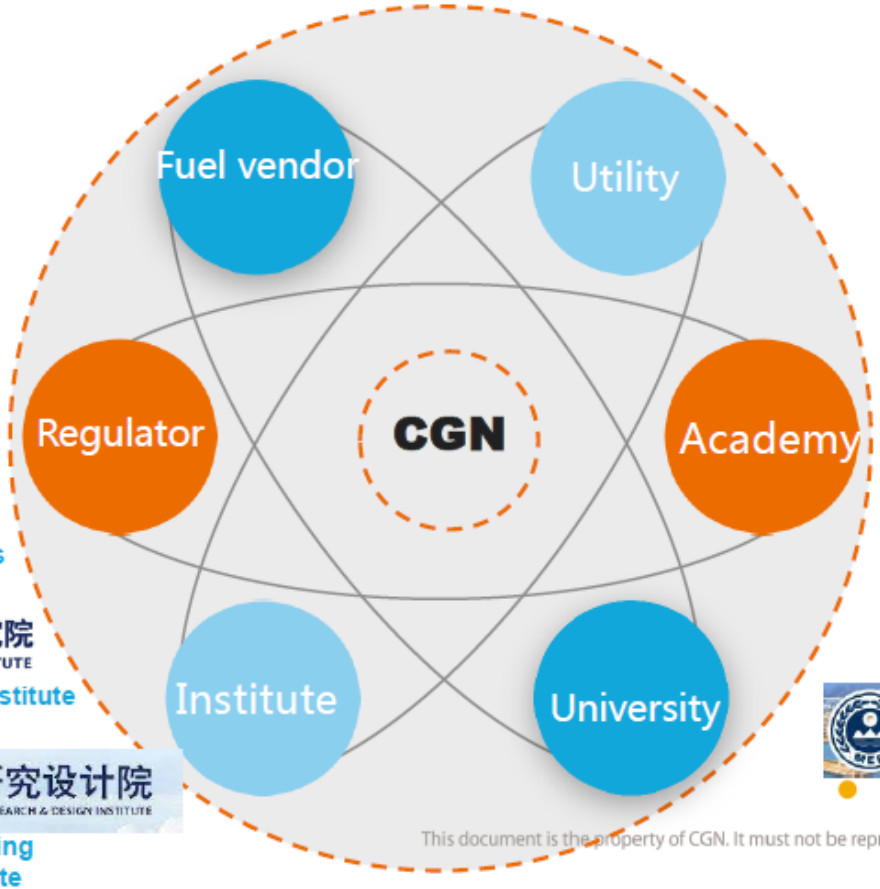
China General Nuclear Power Corporation(CGN) [1,2]

1. *CGN's Vision for Accident Tolerant Fuel Development Collaboration*, OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, Oct. 2013
2. *Accident Tolerant Fuel Research Activities in CGN,* OECD/NEA expert meeting, April 2014

ATF Development Union

ATF development union

- The ATF development union has been established to promote ATF R&D in China, led by CGN and with extensive domestic superior organizations participated in, including vendor, utility, regulator, institute, university and academy.



China Academy of Engineering Physics

China North Nuclear Fuel Co. Ltd

Chinese Academy of Sciences

Wuhan Univ.

Xi'an Jiaotong Univ.

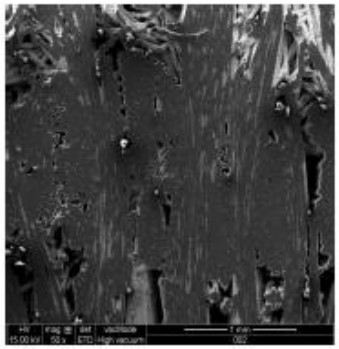
State Nuclear Power Research Institute

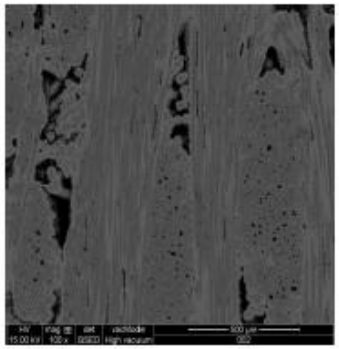
Shanghai Nuclear Engineering Research & Design Institute

Nuclear and Radiation Safety Center

SiC ceramic cladding

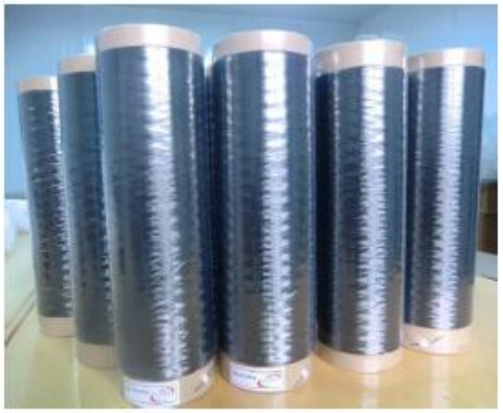
- **SiC ceramic cladding development**





■ SiC composite

Shanghai Institute of Ceramics
Chinese Academy of Sciences



■ SiC/SiC$_f$ composite tube

国核(北京)科学技术研究院
STATE NUCLEAR POWER RESEARCH INSTITUTE

Summary-China

- Under the background of international Accident Tolerant Fuel research, China has launched the national ATF R&D project, initiated by CGN and with extensive domestic superior organizations participated in;
- Existing or under construction research facilities and abilities in China will contribute to the implementation of ATF R&D activities;
- CGN is of great interest to ATF development.
- SiC cladding is one of the interesting options for ATF.

Thank your for your attention!