Summary on FCM

Task Force 3 (Fuel concepts) 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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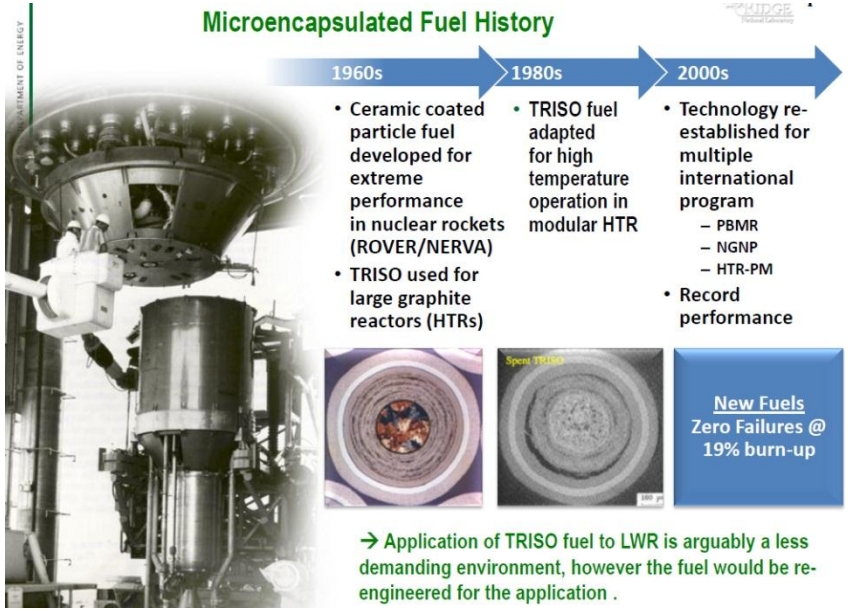
KAERI Korea Atomic Energy Research Institute

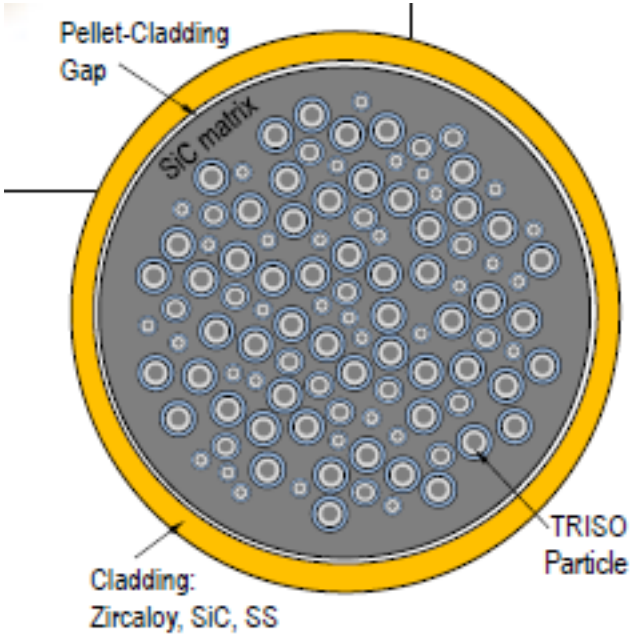
Outline

- FCM concepts & benefit
- US's contribution & Plan
- Korea's contribution & Plan
- Japan's contribution & Plan
- China's contribution & Plan
- Summary

FCM concepts

- FCM : Fully Ceramic Micro-encapsulated Fuel
  - Developed by ORNL under the DOE-NE Advanced Fuel Campaign
- Enabling TRISO fuel technology for LWR application
  - Graphite replaced with radiation stable, high thermal conductivity SiC.





FCM benefits

- High fission product retention
  - High thermal conductivity ⇨ Low fuel temperature
  - Low centerline temperature in LWRs should eliminate Fission Product migration issues, mitigate LOCA concerns
  - SiC matrix provides secondary FP barrier
  - Benign reaction with water under operating/LOCA conditions.
- UN kernel replaces UO_2 to enhance Heavy Metal

US's Contribution & Plan

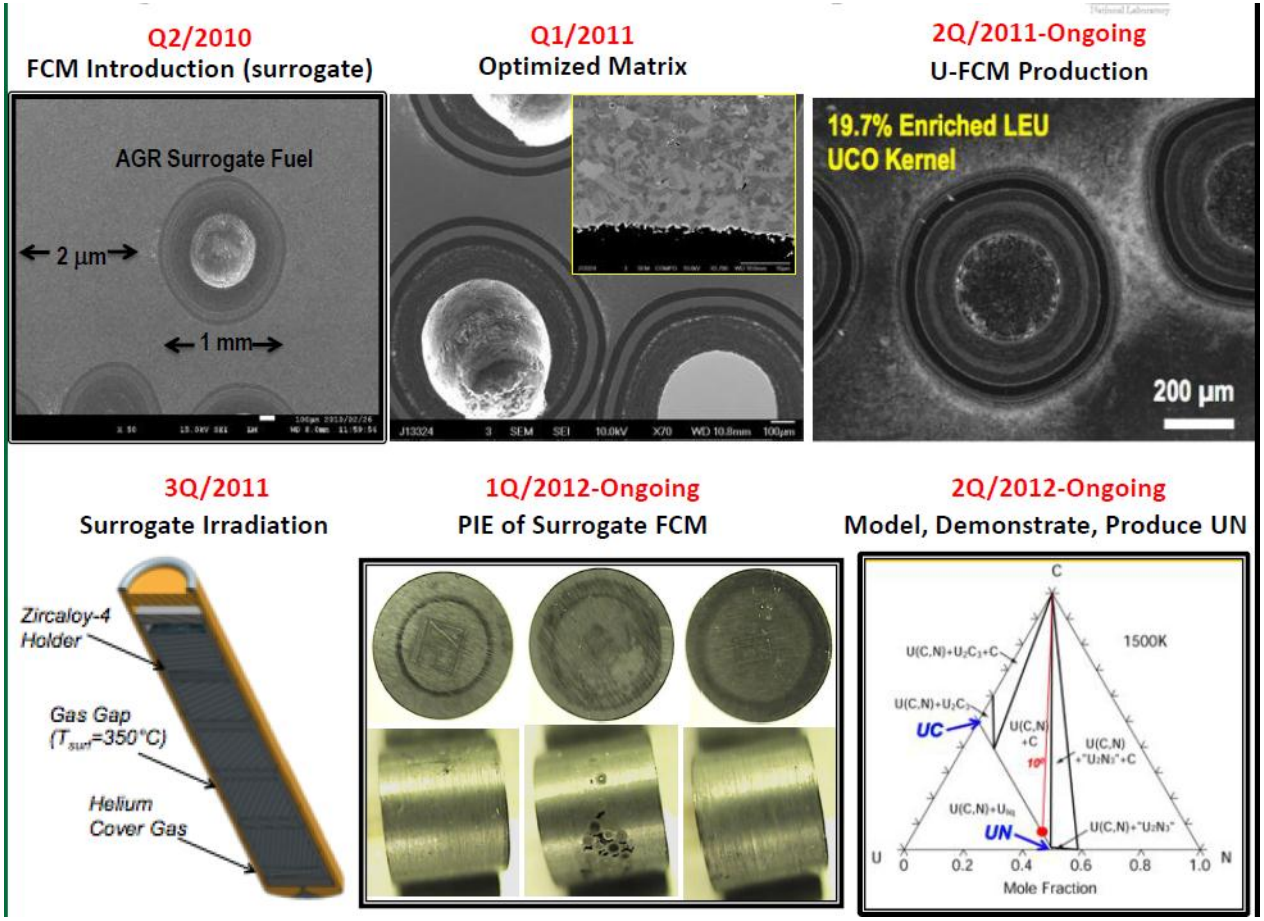
Oakridge National Laboratory[1]

General Atomics [2]

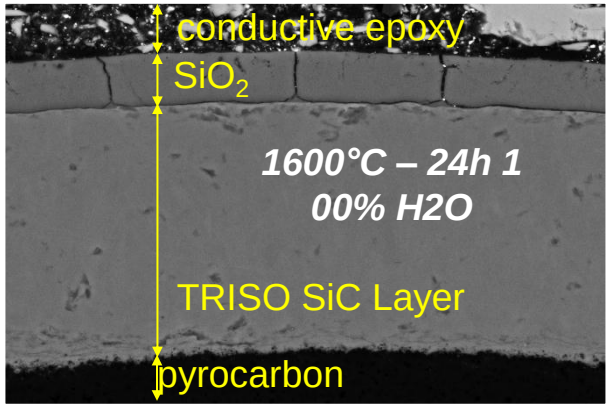
1. L.L. Snead et al., *Fully Ceramic Microencapsulated Fuel Design and Irradiation Testing,* OECD/NEA Workshop on Accident Tolerant Fuels of LWR's, December 2012.
2. Christina A. Back, *Advanced Fuel Technologies at General Atomics,* OECD/NEA Workshop on Accident Tolerant Fuels of LWR's, December 2012.

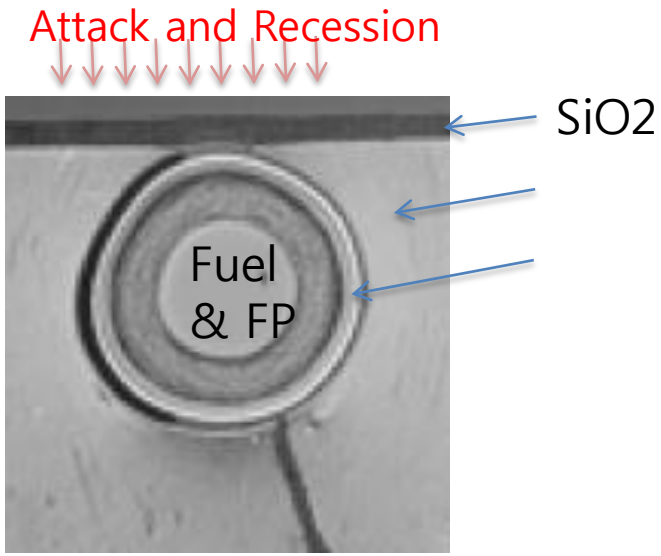
FCM development

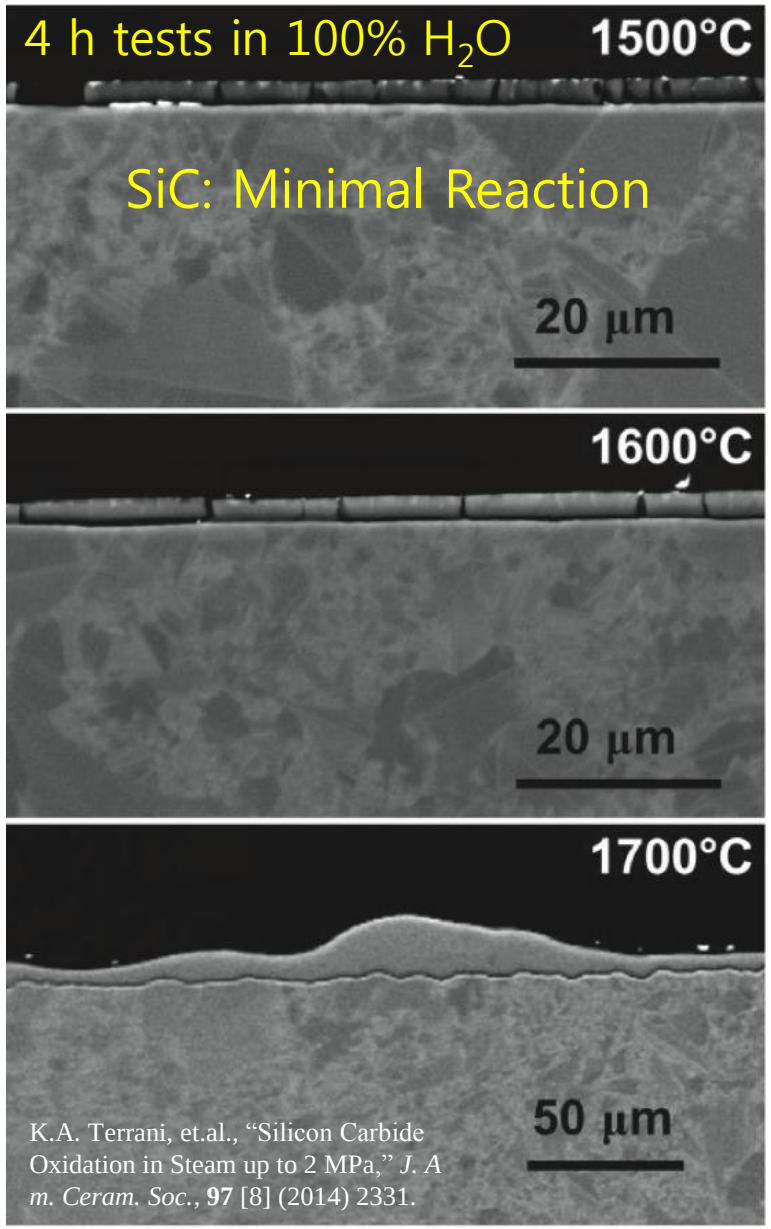
- ORNL under the DOE-NE Advanced Fuel Campaign is studying and developing a FCM technology.



Steam Attack in FCM Matrix and TRISO Shell Mechanisms and Models Elucidated

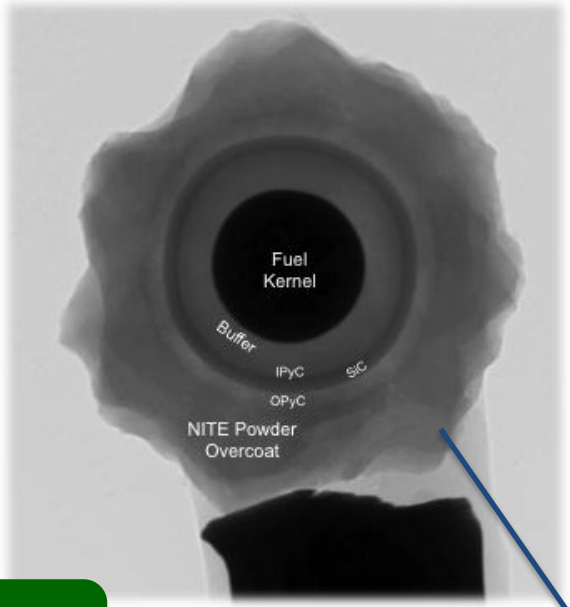


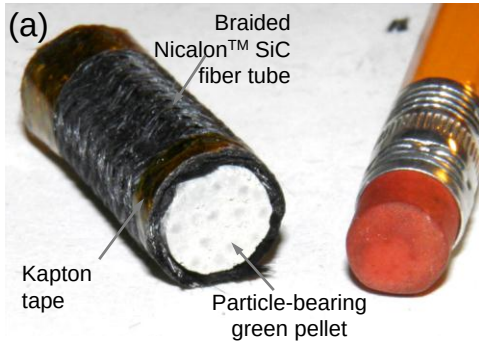


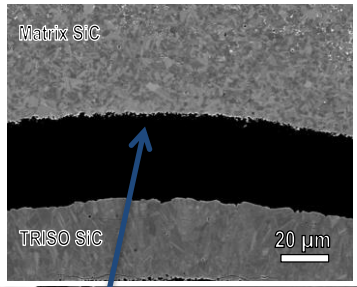


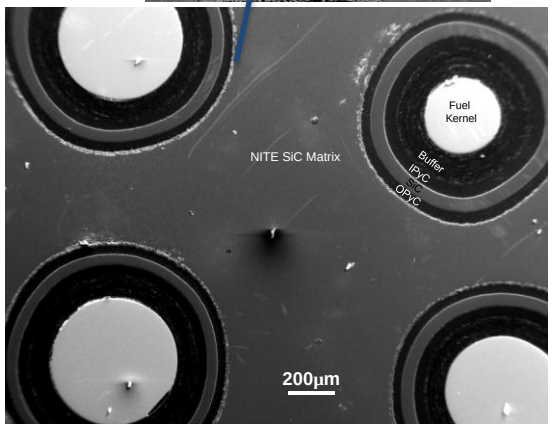
K.A. Terrani, et.al., "Silicon Carbide Oxidation in Steam up to 2 MPa," *J. Am. Ceram. Soc.*, **97** [8] (2014) 2331.

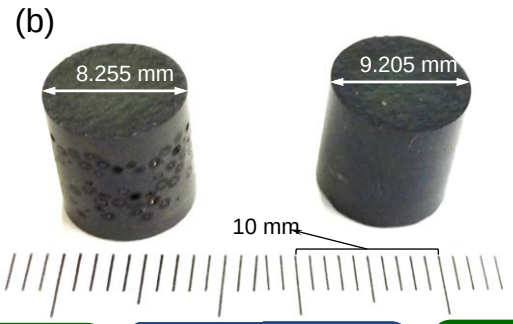
FCM Fuel Fabrication











SiC Nanopowder

Al_2O_3 + Rare Earth Oxides

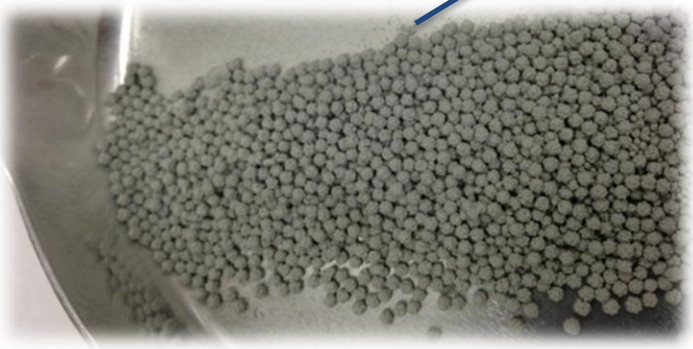
Milling / Dispersing

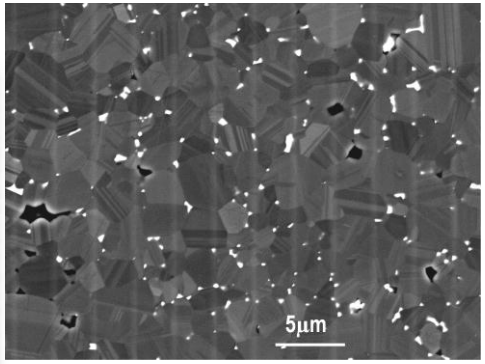
Particle Over coating

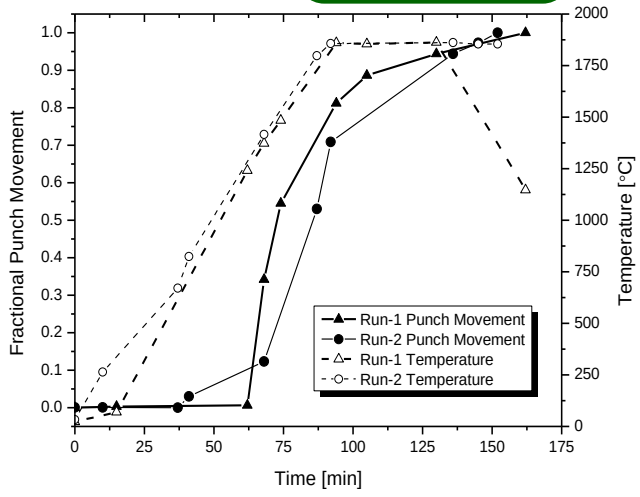
Pellet Buffer In corporation

Cold Compaction

Hot Pressing / Sintering

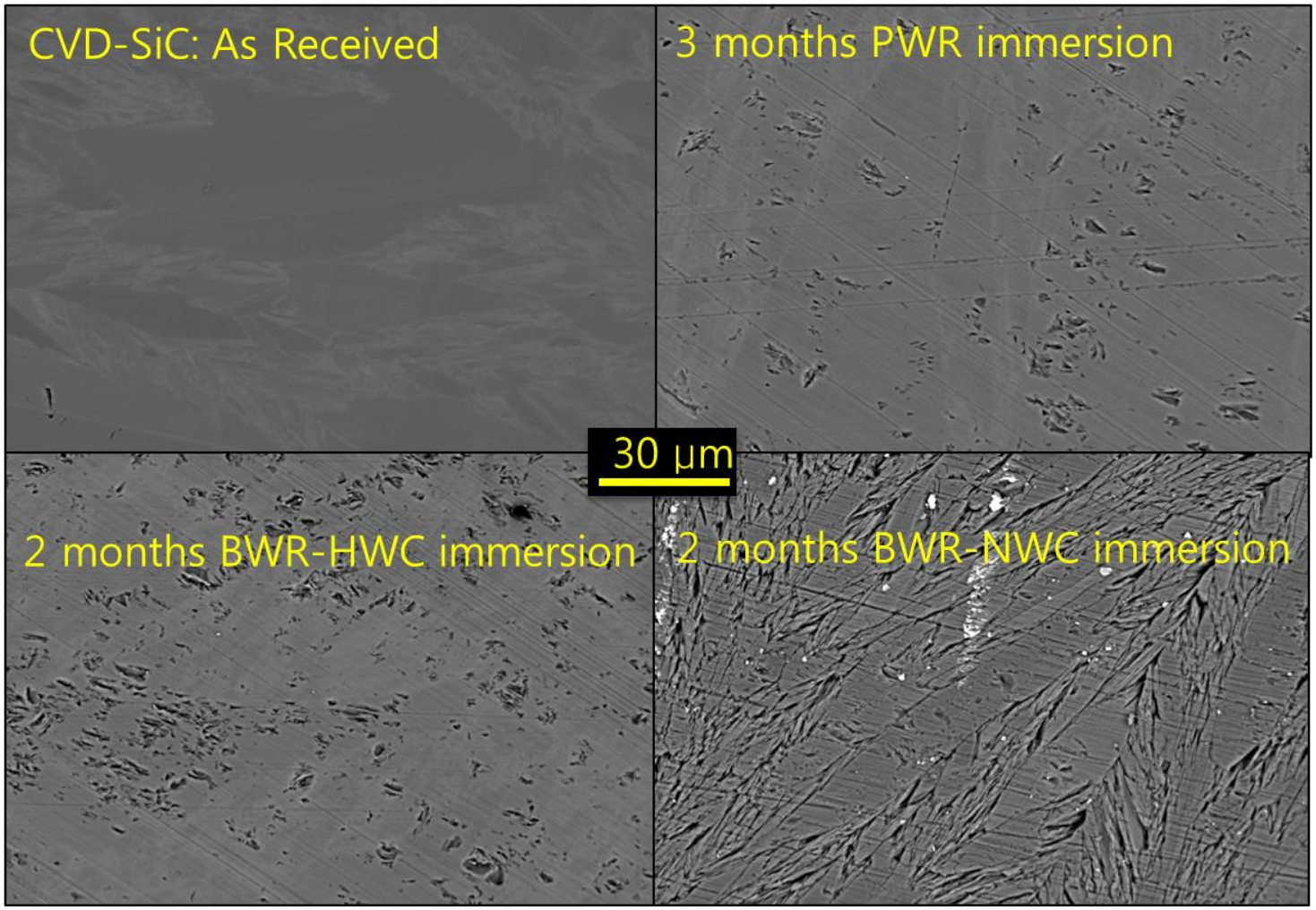






Hydrothermal Corrosion of SiC

- Recession rate of SiC in water was significantly influenced by SiC purity and hydrogen concentration in water.
- Dissolution rate can be reduced by enhancing SiC purity and controlling the hydrogen concentration in water.



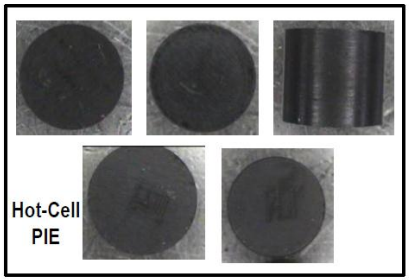
FCM Irradiation test

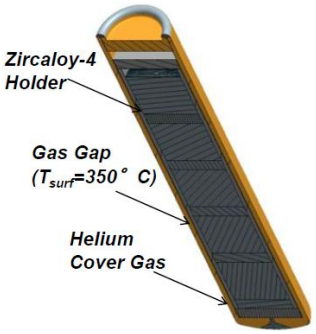
- Swelling, integrity and thermal conductivity of surrogate FCM have been evaluated.

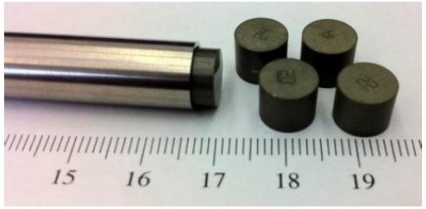
FCM HFIR Irradiation

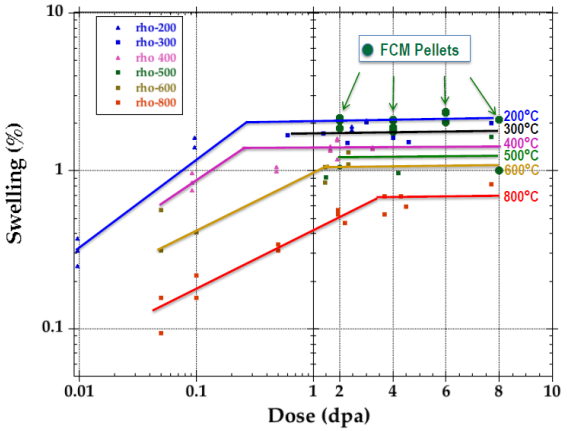
9

- 20 FCM pellets with variable loading of surrogate particles irradiated in 4 capsules (to 130% LWR lifetime)
- TRISO loading fractions : 0 - 41 vol%
- FCM pellets are in 17x17 PWR rod geometry and are clad in Zircaloy-4
- Pellet temperature : 425 °C

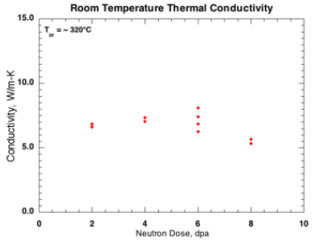


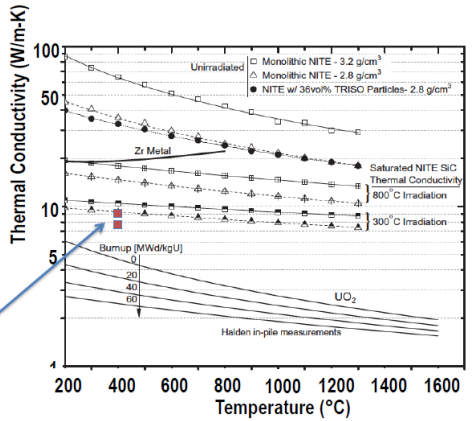






- Swelling of SiC Matrix saturates at a few percent (compared with >10% swelling for UO2).
- Samples upon removal from reactor appear unchanged.

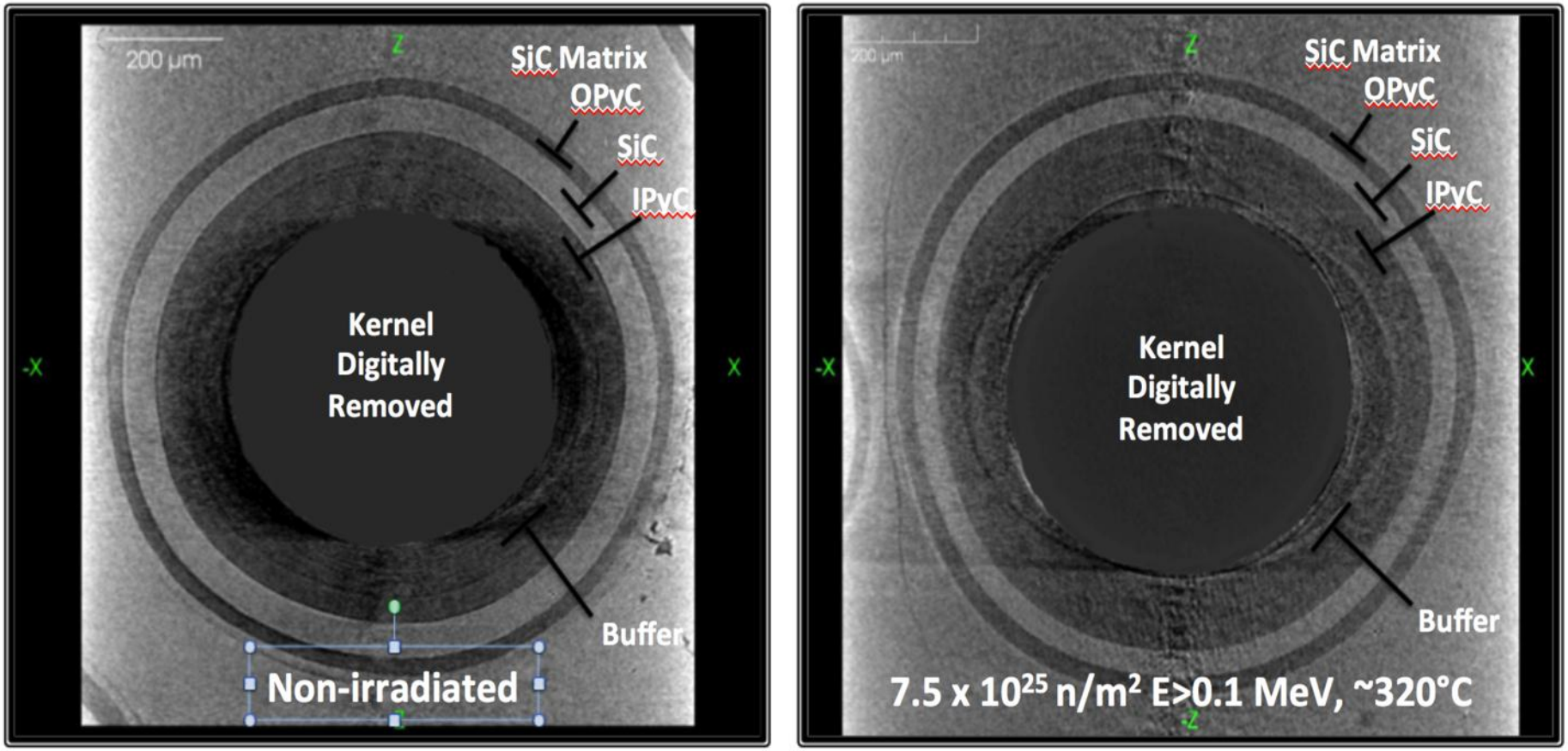




HFIR Irradiated Surrogate Fuel

- Saturation Conductivity Reached
- Somewhat lower than calculated based on CVD SiC Data.

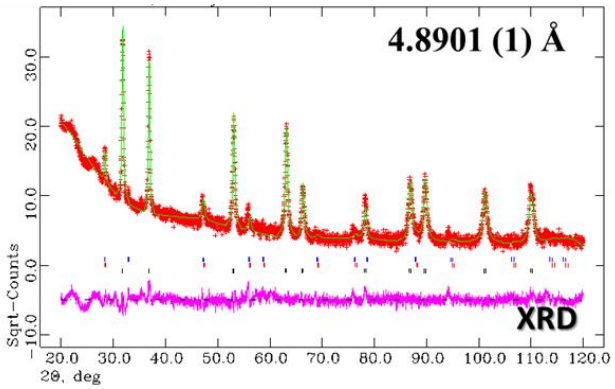
Post Irradiation Examination
- Tomography of Irradiated Surrogate FCM –

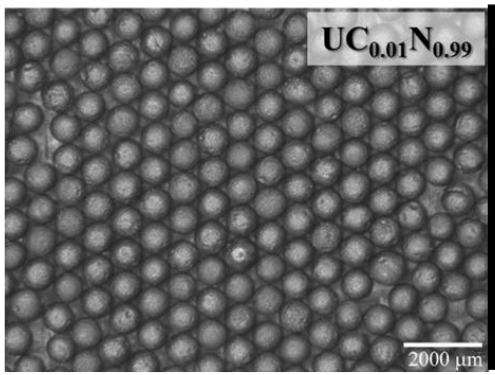


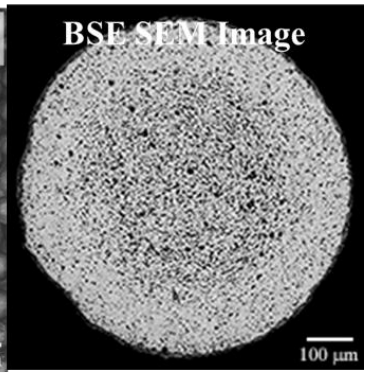
Even for this historically low application temperature, the constituent elements of the TRISO appear to be well-behaved with only a small delamination in the IPyC occurring. This contrast with the normal very large dimensional change/delamination that occurs in HTGR application of TRISO fuel.

Fuel Load

- **High-density kernels (UN) required to drive today's LWR core geometry for today's core lifetime.**
  - "high-normal" kernel diameter ~650 microns
  - "high-normal" packing fraction, ~ 45 %
- While kernel enrichment is ~15-19.7%, fuel smear density ~ 6 %.
- Total core fissile fuel inventory ~10% greater than conventional LWR core.
- Small batch conversion to UN carried out to > 94% theoretical density
- Large batch processing underway.
- Coating studies for LWR-engineered TRISO began FY-14 to be completed FY-15







UN-UC Kernel

GA Sol-Gel Fabrication Laboratory Produces High-density Uranium Fuels

Sol-gel column

drying

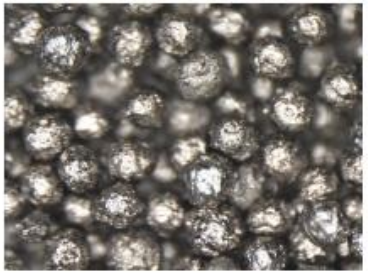
calcining

sintering

UC pellets

UC kernels

UN kernels



Sol-Gel particles with carbon

- Materials achieve highly uniform composition
- Kernel size and morphology can be controlled

Summary-US

- ORNL has demonstrated the benefit of FCM.
  - High thermal conductivity
  - Irradiation resistance (low swelling, negligible FCI)
  - Simulated accident resistance (steam tests)
- Development is continuing
  - Analysis (Operational and Accident Scenarios)
  - Fuel Manufacture (LWR-Optimized TRISO, Compacting Studies, UN Kernel Development)
  - QA and Irradiation Campaign for Prototypical Zircaloy/UN Rodlet (2014 ATR Irradiation)
  - Simulated Accident Testing (LOCA and Beyond Design Basis Testing)
- General Atomics has UN, UC kernel technology.

Korea's Contribution & Plan

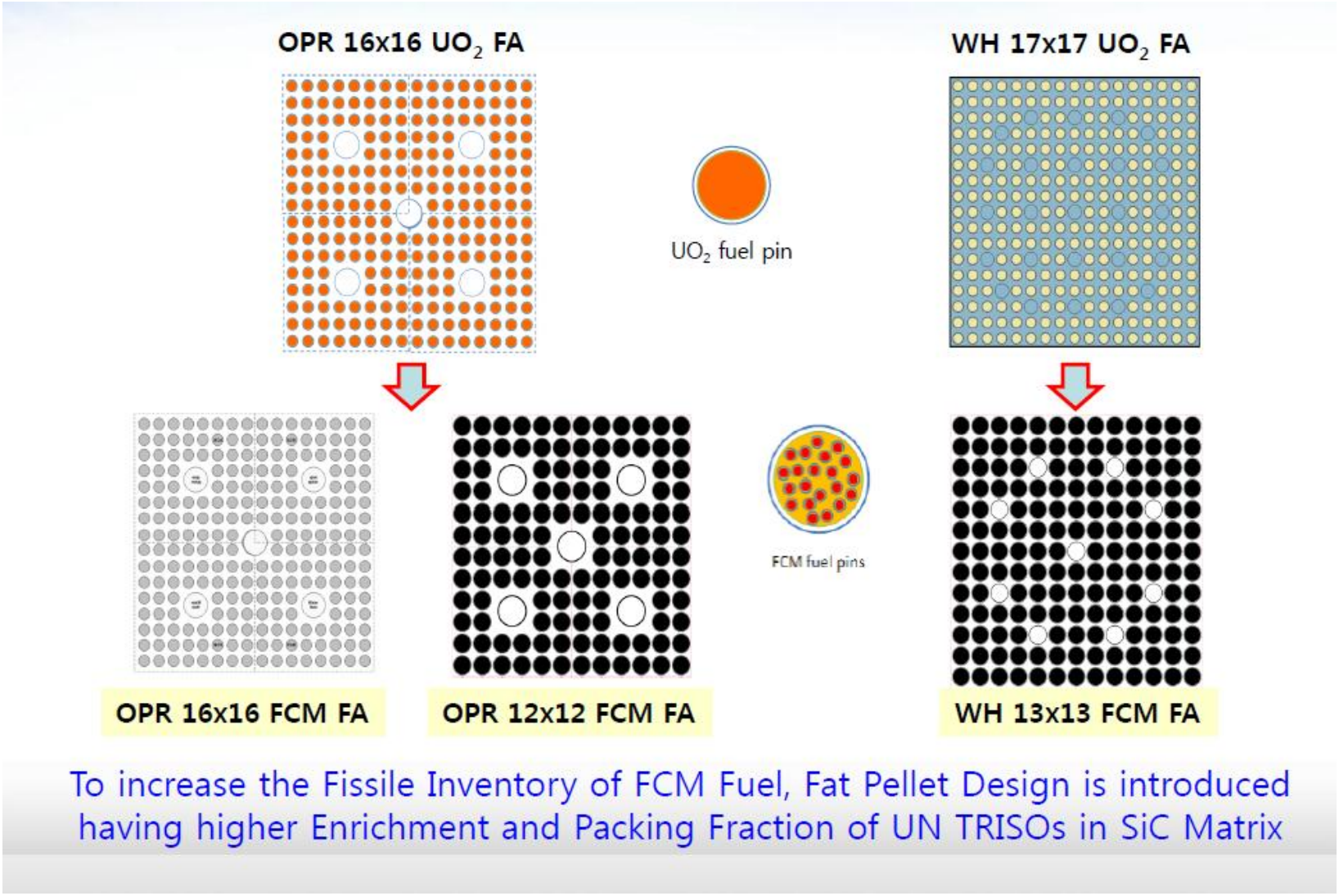
Korea Atomic Energy Research Institute [1]
KepcoNF

1. Jonghwa Chang, *FCM Replacement Fuel for LWRs,* OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, Oct. 2013

Korea's FCM program

- Fully Ceramic Microencapsulated (FCM) Replacement Fuel for LWRs-KAERI
  - KAERI is studying the feasibility of replacing the conventional UO_2 fuel assemblies (FAs) of the existing fleet of LWRs with accident-tolerant FCM FAs with ORNL and USNC under INERI(international nuclear energy research initiative) program
  - The project consists of the four tasks; 1) core neutronics exploration, 2) core thermal-hydraulics assessment, 3) safety assessment and 4) fuel qualification.
  - The reference cores selected for demonstration are the OPR-1000 core with 16x16 FA and a Westinghouse 1000MWe core with 17x17 FA.
- KepcoNF are developing SiC matrix sintering and joining technology to enhance the pellet fabrication economy.

Candidate FCM FAs



To increase the Fissile Inventory of FCM Fuel, Fat Pellet Design is introduced having higher Enrichment and Packing Fraction of UN TRISOs in SiC Matrix

Feasibility evaluation results

- **Neutronics Exploration**
  - Loading Pattern Search up to Equilibrium Core for both the Core initially fully loaded with FCM FAs and the Mixed Core (UO_2 and FCM FAs)
  - Generation of Core Physics Parameters
- **Core TH Assessment**
  - Full Core Subchannel Analysis Model and Method
  - Core Thermal Margin Assessment for Transition and Equilibrium Cores
- **Safety Assessment**
  - Core Model for Mixed Transition Core (UO_2 and FCM FAs)
  - Safety Margin Assessment for Transition and Equilibrium Cores under Design and Beyond-Design Basis Accident Scenarios
  - Assessment of Accident Tolerance of FCM Fuel under Severe Fuel Damage Conditions
- **Fuel Qualification**
  - FCM Coated Particle Performance Analysis under PWR Operating Conditions

Japan's Contribution & Plan

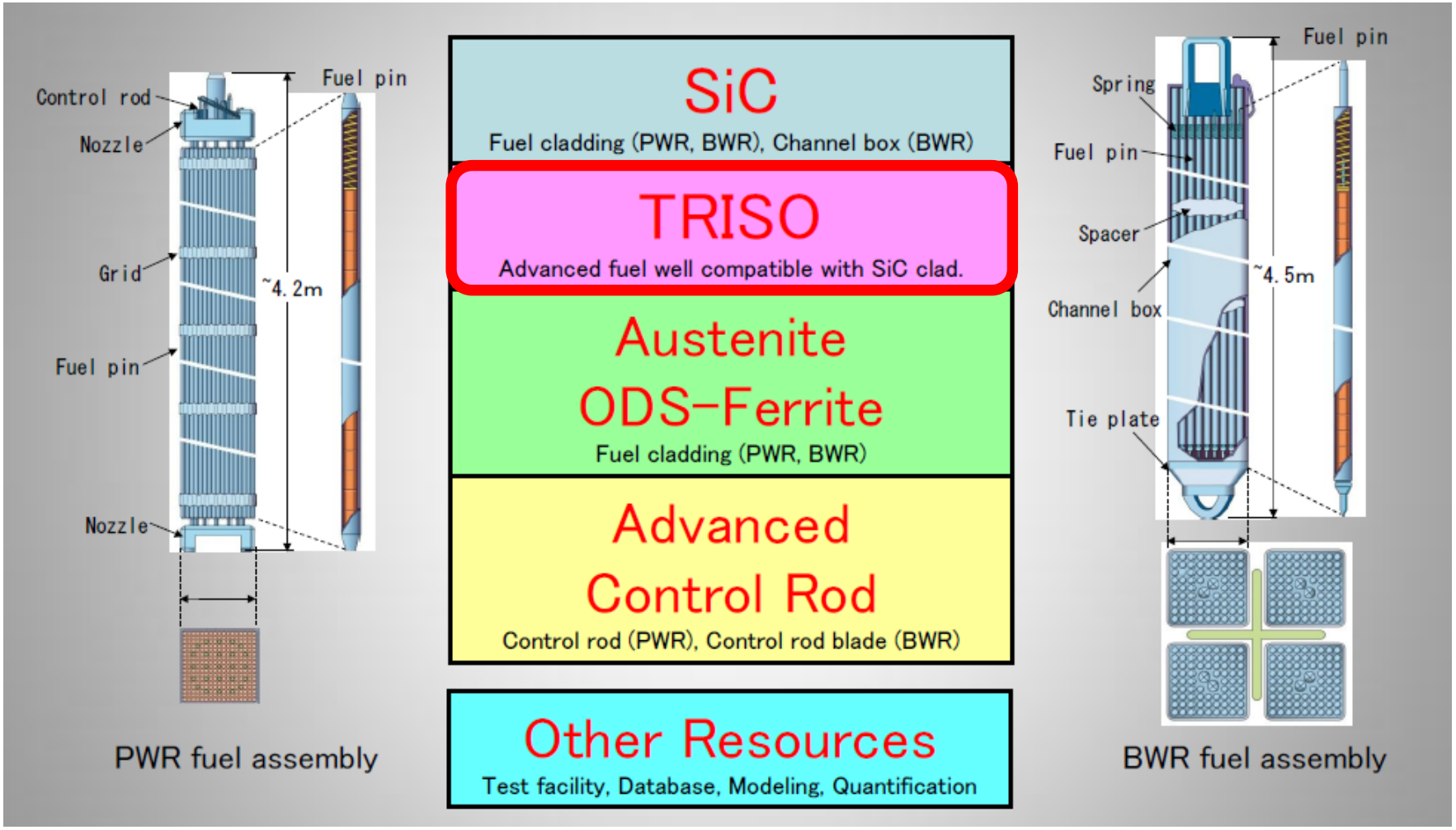
Kyoto University [1]

JAEA [2,3]

NFI [3]

1. Tatsuya Hinoki, *ATF Related Research Plan in Japan,* OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, Oct. 2013
2. Masaki Kurata, *Overview on ATF R&D in Japan,* OECD/NEA expert meeting, April 2014
3. Jun AIHARA[a],Masaki Honda[b] et al., Development Plan of High Burnup Fuel for High Temperature Gas cooled Reactors in Future, J.Nucl.Sci.Tech.(2014) [a]JAEA [b]NFI

Various ATF-concepts in Japan



Fabrication Technology of TRISO

- Fabrication technology of TRISO is already established for HTGR in NFI.
  - ✓ Fuel Kernel : Fabrication technology for UO_2 is established.
  - ✓ Coated Particle : Thickness of coated layer is well controlled for UO_2 Kernel.
  - ✓ Fuel Compact : Filling rate of particles in graphite matrix based compact is ca. 30% for HTGR fuel.

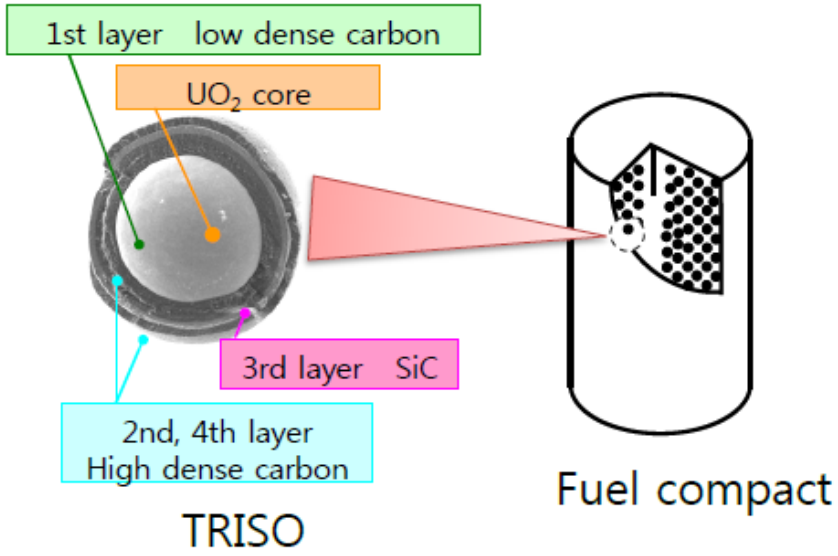
Kernel Fabrication Equipment

CVD Coater Furnace

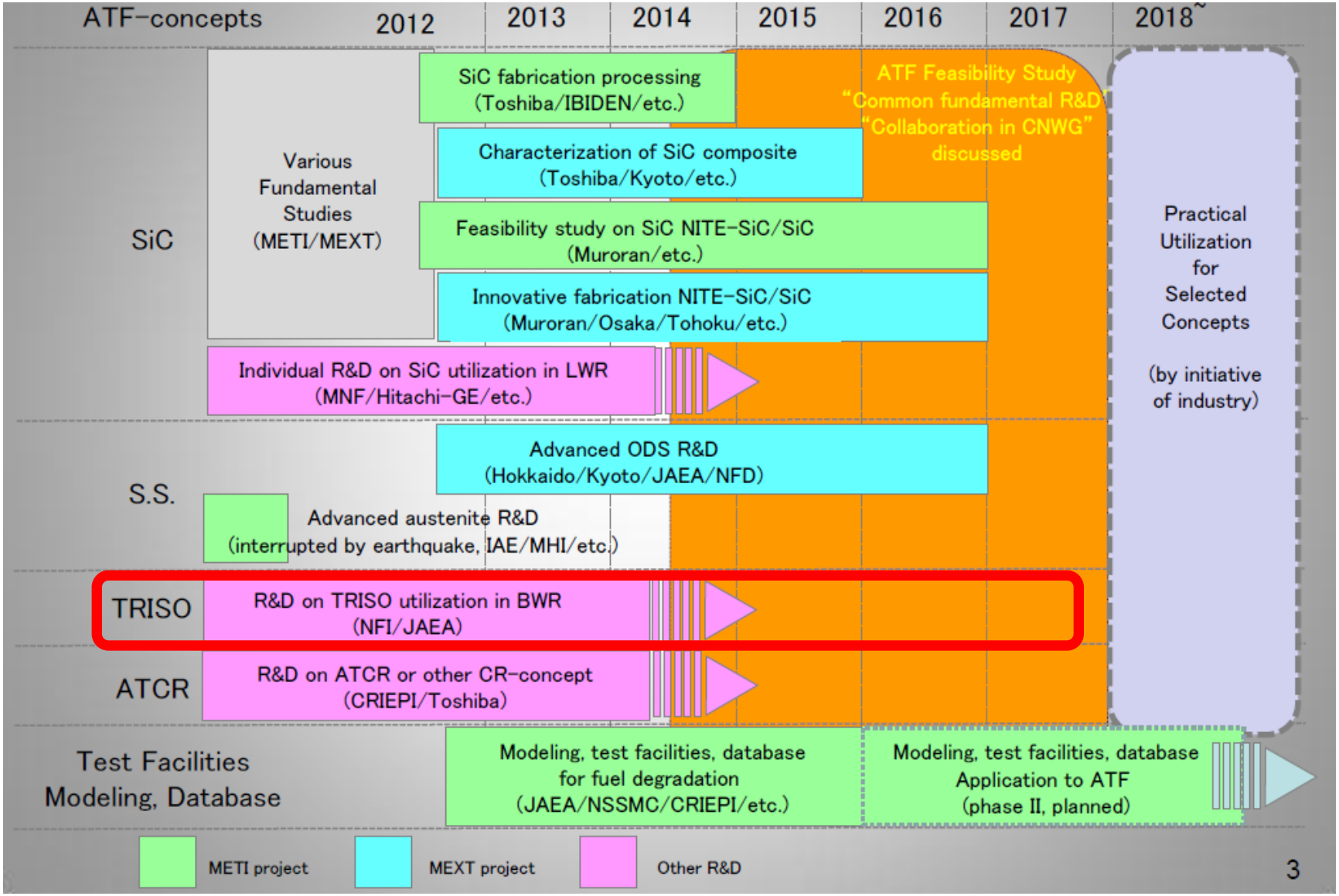
Fuel Compact Fabrication Equipment

Application of TRISO to LWR

- Fabrication process for TRISO
  - comparable U-inventory to current LWR
- Development of SiC Matrix for TRISO
- Core design for TRISO
- Study on data base for UN and UC as Fuel Kernel
  - JAEA developing nitride/carbide property database



R&D programs on ATF in Japan (2012~)



Summary-Japan

- TRISO is one of the ATF-concepts being considered.
- R&D know-hows on TRISO are accumulated by NFI for the application to Gas-cooled reactor.
- Discussion on compatibility between TRISO and SiC in LWR condition starts in 2014.
- Fundamental nitride/carbide property database is being developed by JAEA.

China's Contribution & Plan

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

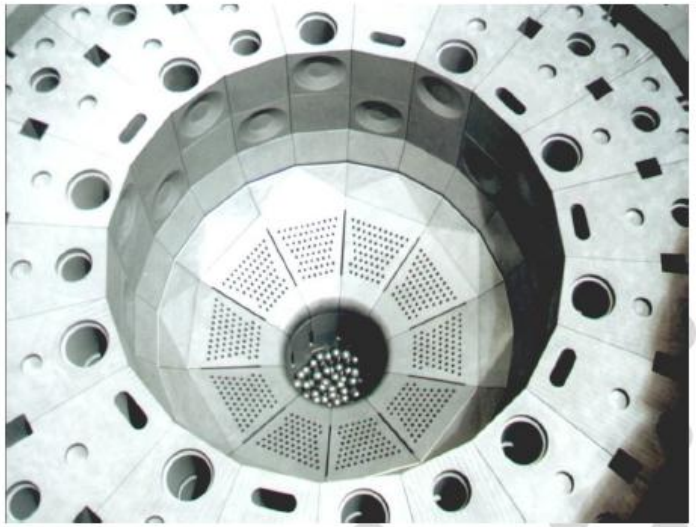
1. *CGN's Vision for Accident Tolerant Fuel Development Collaboration*, OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs, Oct. 2013
2. *Accident Tolerant Fuel Research Activities in CGN,* OECD/NEA expert meeting, April 2014

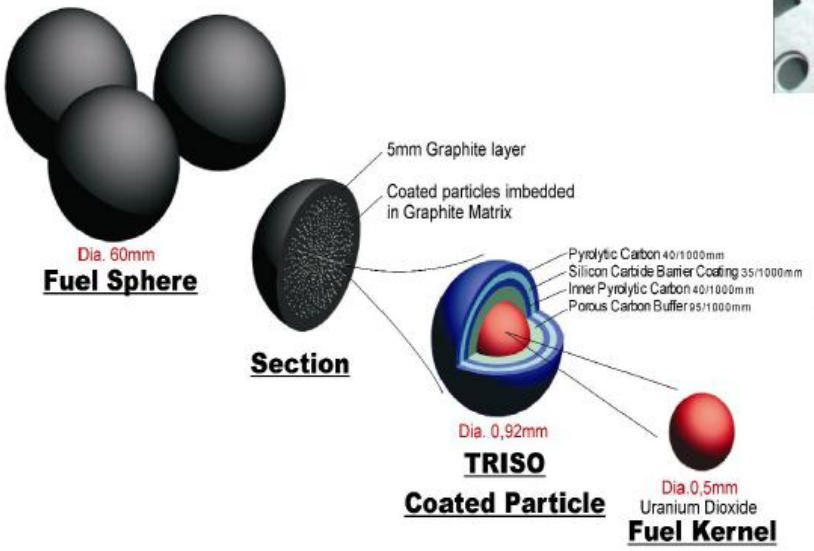
TRISO technology

- CGN is interested in innovative TRISO fuel

2.2 Innovative fuel

- TRISO coated fuel particle was used for High Temperature Gas-cooled Reactor, HTR-10 in Tsinghua University
- Capability of fabrication and test.

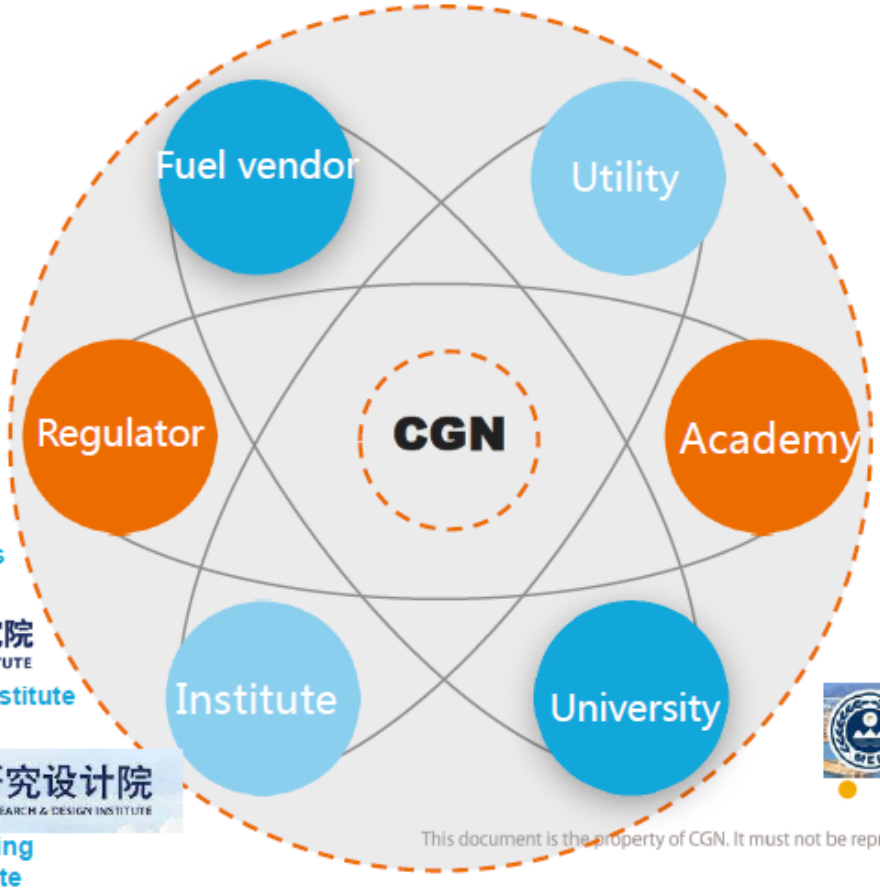




Plan

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

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, and international collaboration would be very beneficial.
- Innovative TRISO fuel is one of the interesting options for ATF.

Organizations

ORNL (US)
- Leading the FCM technology

GA (US)
- UN, UC Kernel fabrication technique

KAERI/KNF (Korea)
- Replacing the UO_2 of existing fleet of LWRs with FCM
- I-NERI program (2011~)
- SiC fabrication technology

NFI/JAEA(Japan)
- TRISO utilization in LWR
- ATF feasibility study (2014~)

CGN(China)
- Innovative TRISO fuel
- Research on key technology of ATF (2014~)

Summary

- ORNL in US is leading the FCM technology.
- ORNL is developing an optimized FCM fuel form and investigating operational aspects of incorporation of FCM fuels into LWRs.
- KAERI in Korea is developing FCM replacement FAs for LWRs with ORNL and USNC.
- JAEA and NFI started discussion on compatibility between TRISO and SiC in LWR condition in 2014.
- CGN established the ATF development union and launched a preliminary research program on key technology. TRISO fuel is one of the fuel options.