Updates on Accident Tolerant Fuel R&D in Korea

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Objective: Develop & select ATF concepts for irradiation test in a commercial reactor by 2021

Near Term Concepts
- Surface modified claddings w/wo ODS treatments
- Microcell UO$_2$ pellets with enhanced FPs retention and thermal conductivity

Mid- & Long-Term Concepts
- Metal-Ceramic hybrid claddings
- Ceramic claddings
- High U density pellets
- TRISO based composite pellets

Bring revolutionary change

Use existing infrastructure, experience and expertise
ATF Cladding & Fuel Concepts

- **Claddings:** Enhanced Oxidation Resistance & Strength
  - Surface modified Zr-tube (coating/ODS/Zr)
    - Coating: CrAl, FeCrAl/Cr
    - ODS: Y₂O₃, Er₂O₃, Gd₂O₃...
  - Ceramic Composite
    - SiCₓ/SiC composite
  - Metal/Ceramic Hybrid
    - Metal(coating)/Ceramic-composite(SiCₓ/SiC)/Metal(Zr)

- **Fuels:** Enhanced Thermal conductivity & Fission Products Retention
  - Microcell UO₂
    - Ceramic wall: Si-Ti-O, Cr-Si-O, BeO,...
    - Metallic wall: Mo, Cr, alloys,...
  - High uranium density pellets
    - UN, U-Si: composite for waterproof
  - Coated particle fuel (SiC-TRISO)
    - SiC-TRISO: Pressure-less sintering
1. Surface Modified Cladding-Highlights

- **Alloy & structure design**
  - **Cr-Al alloy**: Superior oxidation resistance & no pitting corrosion
  - **FeCrAl/Cr multi-layer**: thin Cr-barrier to prevent Fe-Zr eutectic reaction
  - **Partial ODS (Y₂O₃, Gd₂O₃, Er₂O₃)**: Increase deformation resistance, Economic & flexible reactivity control

- **Fabrication processes**
  - 3D laser coating: coating & ODS treating
  - Arc ion plating: thin layer and alloy coating

**FeCrAl/Cr/Zry-4**

**CrAl/Zry-4**

**ODS(Y₂O₃)/Zry-4**
1. Surface Modified Cladding - Highlights

- **Performance evaluation**
  - Oxidation tests in PWR simulation loop & high T. steam (1200°C)
  - Integral LOCA tests
  - 4-point bending tests after the oxidation and integral LOCA tests

- **PWR simulation loop test**
  - Performance evaluation
    - Oxidation tests in PWR simulation loop & high T. steam (1200°C)
    - Integral LOCA tests
    - 4-point bending tests after the oxidation and integral LOCA tests

- **Integral LOCA**

- **High T. steam test**
  - Oxidation tests: 1200°C for 2000h
  - 4-point bending after high T. steam oxidation
  - 4-point bending after LOCA-simulation

- **Integral LOCA Rupture Behavior**

- **CrAl coated cladding**
  - Ref. cladding
  - Fractured

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2. Ceramic Composite Cladding-Highlights

- Installation of CVI reactor for ~30 cm long SiC composite tubes
- Analysis of crack formation by acoustic emission for different structural designs
  - triplex structure
  - duplex structure

- Development of joining process
3. Micro-cell UO₂ Pellets-Highlights

- **Material selection, Structure Design & Fabrication Processes**
  - **Material candidates:** Mo, Cr, BeO, Si-Ti-O, Cr-Si-O, ...
  - **Structure:** Cell size 100~350μm, wall thickness 1~8 μm
  - **Fabrication:** Conventional pressure-less sintering

- **Property tests & Performance modeling**
  - Thermo-physical properties
  - Modeling & simulation: Hoop stress calculation to simulate pellet fracture
  - Oxidation tests in autoclave & high T. steam (500~1100°C)
  - Pellet integrity tests under LOCA simulated thermal shock and high temperature (~2600°C)

### Steam oxidation tests for UO₂-5vol%Mo

- **at 500°C**
  - **0h, 510h, 1100h**
  - Pellet sample was partially oxidized.
  - Oxidation tests in autoclave & high temperature steam (500~1100°C)

- **at 800°C**
  - **0h, 195h, 299h, 371h**
  - Pellet sample cracking was occurred due to Mo-oxide formation.
  - Nevertheless, pellet structural stability of micro-cell UO₂ pellet was preserved.

- **at 1100°C**
  - **0h, 40h, 80h**
  - Pellet sample cracking was occurred due to Mo-oxide formation and stabilization.
  - Pellet structural stability of micro-cell UO₂ pellet was preserved in spite of the sample weight loss by Mo-oxide volatilization.
4. High U-density & Coated Fuel

- **High U-density pellets**
  - **UO₂-UN pellets**: UO₂ matrix delay oxidation (further improvement required)
  - **U-Si-O pellets**: Simple mixing & conventional pressure-less sintering is being explored

- **SiC-TRISO pellets**
  - Pressure-less sintering process: Over-coating & Additive to ensure crack-free pellets
  - High temperature steam oxidation test for additives doped-SiC matrix (1200°C)
  - Reaction between additives and TRISO
Irradiation Test-Highlight

- **Two ATF Pins in Halden reactor**
  - IFA-790 (with Thor Energy)
  - **Pin #8**: Ceramic micro-cell pellet (0.6wt%Si-Ti-O) + CrAlFe/Cr coated Zircaloy cladding
  - **Pin #11**: Metallic micro-cell pellet (5vol%Cr) + CrAl coated Zircaloy cladding
  - Linear power: ~30 kW/m
  - Irradiation period: ‘15.12~’17.12. (25 GWd/MTU)
  - Burnup reached: 7.5 GWd/MTU

**Fuel centerline temperature**

- \( \Delta T = \sim 200 \degree C \)

**Rod internal pressure**

**Rod elongation**

Fig. 2 - Fuel temperatures (normalised at 300 W/cm) for the KAERI rods and two rods used as reference. As one can notice, the KAERI fuel rods exhibit lower temperature.
Further Irradiation Test Plan

- OECD/NEA Halden Reactor Project for ATF cladding and pellet: 2017
  - 4 kinds of ATF cladding samples were delivered (2016)
    - CrAl coating on Zircaloy-4 w/wo ODS layer
    - FeCrAl/Cr coating on Zircaloy-4 w/wo ODS layer
  - Microcell UO₂ pellets having optimized cell composition

- Cooperation with MIT
  - Mechanical test and Irradiation tests in MITR: Interface behaviors of surface modified Zr coupons and tubes provided by KAERI
  - Samples were provided & expected to be loaded at December 2016.