Status of SFR Metal Fuel Development

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  - Fuel fabrication
  - Cladding development
  - Fuel performance evaluation
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Introduction

- Metal Fuel Recycling in Sodium-cooled Fast Reactor
  - Enhanced utilization of uranium resource
  - Efficient transmutation of minor actinides
  - Inherent passive reactor safety
  - Proliferation resistance with pyro-electrochemical fuel recycling

- To meet the goals of Generation IV SFR
  - Sustainability, Safety, Economy and Proliferation Resistance
Utilization of uranium resource can be enhanced by 100 times
Space for high level waste can be reduced by 1/100
Duration needed for radio toxicity decrease can be reduced by 1/1,000
High proliferation resistance by handling TRU together
SFR metal fuel targets and technical challenges

Fuel Performance Targets

<table>
<thead>
<tr>
<th></th>
<th>Gen-IV Target</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Burnup (at.%)</td>
<td>≥20</td>
<td>High burnup</td>
</tr>
<tr>
<td>Peak Cladding Damage(dpa)</td>
<td>≥ 200</td>
<td>High burnup</td>
</tr>
<tr>
<td>Peak Cladding Temperature (°C)</td>
<td>≥ 650</td>
<td>High thermal efficiency</td>
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Technical Challenges

- Remote fabrication of metal fuel with radioactive minor actinides
  - Control of Am vaporization during metal fuel casting
  - Reliable remote fuel fabrication

- Advanced cladding for high burnup and high temperature
  - High strength FMS(ferritic martensitic steel), ODS(oxide dispersion steel)

- Verification of Irradiation performance of U-TRU-RE-Zr metal fuel
  - Effect of minor actinides and rare earths(RE) in fuel
  - High burnup performance
Fuel Slug Fabrication

Fuel slug gravity casting system
- Advanced fuel casting system to control evaporation of volatile americium during melting of U-TRU-RE-Zr fuel alloy with minor actinides
- The melt was poured downward into a graphite distributer where the quartz mold assembly were attached.

Casting process investigation
- Casting conditions
  • batch size, casting temp., casting pressure, heating rate, etc
- Casting components
  • Crucible, distributer, mold
- Coating materials and method in crucible
  • $Y_2O_3$, TiC, ZrC, HfC, etc
  • Plasma, slurry coating

Test rods of coating materials
melt dipping test of plasma coated $Y_2O_3$ in U-Zr melt
Fuel Slug Fabrication

- **Fuel slugs by gravity-casting**
  - Varying fuel composition: U-(5,10,15)Zr, U-10Zr-(2,4,6)RE, U-10Zr-5Mn, U-10Zr-RE-Mn
  - Dimensions: (5.0~10mm) Φ x 300mmL
  - Retention of volatile surrogate Mn: ~94% at 1 bar(Ar) casting pressure
  - Radiography: gamma and neutron

- **Characterization of fuel slugs**
  - Alloying composition
  - Density
  - Microstructure
  - Thermal properties
  - Mechanical properties

- **Microstructure of U-10Zr and U-10Zr-Ce fuel slugs**

- **Thermal conductivity**

- **Thermal expansion coefficient**
Injection Casting

- Injection casting of fuel slug
  - Vacuum injection casting of U-Zr and U-Pu-Zr is a proven technology with vast experience in US
  - The method to control evaporation of volatile elements during casting needs to be developed

- Establishment of small versatile injection casting equipment
  - Capacity: 1 kg/batch max. U alloy
  - Fabrication tests of surrogate (Cu) fuel slug
Particulate Fuel

- Fuel particle fabrication followed by vibro-compaction or consolidation of fuel particles

Advantages
- Casting Mold not needed
- Process loss reduction
- Fuel without Na bond (potential)

Fabrication of atomized powder
- U-10wt%Zr fuel particles were fabricated by atomization process
- Particle size: avg. 60µm and 300µm

Future work
- Consolidation of fuel particles
- Characterization and irradiation test

Centrifugal atomization
U-10wt% Zr powder
U-Zr compaction
Remote Fuel Fabrication

- Remote fabrication in Hot Cell
  - Accessibility, manipulation, maintenance and viewing
  - Reliability and practicality
  - Experience: DUPIC (: Direct Use of spent PWR fuel In CANDU reactors) fuel rod fabrication in hot cell

- Preliminary conceptual design of TRU fuel fabrication facility
  - Establishment of design criteria
  - Fuel fabrication equipments and facility

DUPIC fuel rod fabrication  Operation simulation
Cladding material Development

- **Objective**
  - Development of high strength FMS(HT9M) cladding for high burn-up and high temperature application

- Creep rupture strength (650°C) improved by more than 35% from HT9

**Strengthening mechanisms of FMS**

- **Solid Solution Strengthening**
  - + Mo + W
  - + V + Nb
- **Precipitation Strengthening**
  - C, N, B
  - Ta

Alloy design for advanced cladding

Creep test (650°C)
Objective
- Development of cladding tube fabrication process

Status
- Fabrication of cladding tube
  • Fabrication of mother tube
    ✓ Melting (1 ton ingot)
    ✓ Fabrication of Hollow billet
    ✓ Hot extrusion and pilgering
  • Fabrication of cladding tube (HT9, Gr.92)
    ✓ Drawing and intermediate heat treatment
    ✓ Final heat treatment (1050°C, 760°C)
    ✓ Final dimension of cladding tube
      (OD 7.4mm, T 0.56mm, L 3,000mm)

Future work
  - Fabrication of cladding tube (HT9, HT9M) with optimized process
Evaluation of cladding tube

Objective
- Production of performance data

Status
- Setting of cladding test equipment
  • Tube creep/burst test machine
  • Cladding/sodium compatibility facility
- Evaluation of cladding tube
  • Tensile test (R.T. ~ 700°C)
  • Burst test (R.T. ~ 658°C)
  • Creep test (650°C)

Future work
- Fast neutron irradiation tests
  • creep, swelling, tensile, fracture toughness, microstructure, etc.
Study on Barrier between Fuel and Cladding

- **Barrier to prevent interaction between fuel and cladding**
  - Eutectic melting at high temperature
  - Degradation of cladding by rare earth fission products

- **Investigation of barriers**
  - Effective barrier material: Cr, V, Cr₂O₃..
  - Barrier fabrication methods: electroplating, oxidation, nitrification, metal liner..
  - Barrier on fuel slug: Surface oxidation of metal fuel slug
Irradiation Test of Metal Fuel in HANARO

- **Objectives**
  - Evaluation of metal fuel fabrication and design parameters
  - Evaluation of the effect of impurities to define the allowable levels
  - Evaluation of barrier performance

- **Status**
  - Irradiation capsule design and fabrication
    - 12 test fuel rods: U-10Zr and U-10Zr-5Ce
    - Electroplated Cr barrier (20μm)
    - Irradiation up to 3 at.% burnup (‘10.11~‘12.1)
  - Post-irradiation examination
    - γ-scanning
    - Fission gas release measurement
    - Fuel rod cutting and destructive tests

- **Future Work**
  - Transient simulation tests in hot cell
Metal fuel rod performance analysis code

- **PUMA**
  - Performance of Uranium Metal fuel rod Analysis code
    - Applicable only to metal fuel
    - Mechanistic models are employed

- **Code structure**
  - 1D FE-based thermal & mechanical modules
    - Thermal analysis is followed by mechanical analysis
  - Coupling between thermal and mechanical analyses
  - Models such as fission gas release and the fuel element redistribution were incorporated

- **Code verification and validation**
  - Comparison of code prediction with fuel performance test data and prediction of other code is underway.
SFR-Fuel-Pyroprocessing Milestone

'S11 '12 '16 '20 '21 '23 '24 '25 '27 '28 '30 '34 '39

- SFR Specific Design
  - STELLA-1('12)
  - STELLA-2('16)
- U-Zr Fuel Fabrication Tech.
  - UFMF D/C.
  - TFRF D/C
- Remote Fuel Fabrication Tech.
  - 1 Phase ('11-'12)
  - 2 Phase ('13-'16)
  - 3 Phase ('17-'20)
- Korea-US Joint Fuel Cycle Study (Pyro-electrochemical Recycling)
  - PRIDE Operation
  - DFDF/ACPF Operation
- Specific Design Approval('20)
- PSAR('20)
- FSAR('26)
- C/P('22)
- O/P('28)
- SFR (150 MWe) Operation
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- U-Zr Fuel
Conclusion

- Metal fuel recycling in SFR
  - Enhanced utilization of uranium resource
  - Efficient transmutation of minor actinides
  - Inherent passive reactor safety
  - Proliferation resistance with pyro-electrochemical fuel recycling

- Demonstration of technical feasibility of recycling TRU metal fuel by 2020
  - Remote fuel fabrication
  - Irradiation performance up to high burnup
Thank You
감사합니다
Nuclear Power Plants in Rep. of Korea

**Sites and Units [MWe]**

<table>
<thead>
<tr>
<th>Site</th>
<th>In Operation</th>
<th>Under Construction</th>
<th>Total (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Sin)Kori</td>
<td>5 (4,137)</td>
<td>3 (3,800)</td>
<td>8 (7,937)</td>
</tr>
<tr>
<td>(Sin)Wolsong</td>
<td>4 (2,779)</td>
<td>2 (2,000)</td>
<td>6 (4,779)</td>
</tr>
<tr>
<td>Yonggwang</td>
<td>6 (5,900)</td>
<td>-</td>
<td>6 (5,900)</td>
</tr>
<tr>
<td>Ulchin</td>
<td>6 (5,900)</td>
<td>2 (2,800)</td>
<td>8 (8,700)</td>
</tr>
<tr>
<td>Total</td>
<td>21 (18,716)</td>
<td>7 (8,600)</td>
<td>28 (27,316)</td>
</tr>
</tbody>
</table>

**Plants Under Construction**
- OPR1000: Shin-Kori (#2), Shin-Wolsung (#1,2)
- APR1400: Shin-Kori (#3,4), Shin-Ulchin (#1,2)

**Radioactive Waste Disposal Facility (Under construction)**

**Power Generation Mix (%)**
- Fossil Fuel: 66.9%
- Nuclear: 31.4%
- Hydro: 0.5%
- Etc: 1.3%

*[Ref: www.kosis.kr(2010)]*
SFR Metal Fuel Development Plan

- **U-Zr Metallic Fuel Fabrication Tech. Dev.**
  - Fuel Slug (U-Zr)
  - Fuel Rod (U-Zr)
  - Fuel Assembly (U-Zr)
  - Non-fuel Bearing Assembly
  - U-Zr Fuel Fab.
  - Cladding/U-Zr Fuel Irradiation
  - U-Zr Fuel (3 t-HM/yr)
  - Prototype SFR (150 MWe)

- **U-Zr Slug HANARO Irradiation**

- **Cladding Fabrication**
  - Performance Evaluation
  - Prototype Duct Perf. Eval.

  - ATR Irradiation
  - TRU Rod Fab. and Irradiation
  - Joint Fuel Cycle Study of Korea and US

- **Batch Loading**
  - LTR
  - LTA

- **TRU Fuel Fab. Facility**
  - KAPF
  - UFMF: U-Zr Fuel Manufacturing Facility
  - TFMF: TRU Fuel Manufacturing Facility
  - LTR: Lead Test Rod
  - LTA: Lead Test Assembly
  - 2 kg-TRU/y (20FA/y)
  - 297 kg-TRU/y (20FA/y)

- **Supply of U-Zr fuel as starting fuel of prototype SFR**
- **Transition to TRU fuel through demonstration of TRU LTA fuel**
SFR Metal Fuel

- Fuel material: U–Zr & U–TRU–Zr
- Active fuel length: 900 mm
- Fuel rod length: 3,700 mm
- Cladding & duct material: Ferritic/martensitic steel
- Cladding diameter & thickness: 7.4 mm & 0.6 mm
- Overall assembly length: 4,600 mm
Metal Fuel Fabrication Process

Pyroprocessing

Zr

Fuel Ingot (U+TRU+RE+others) → Fuel composition (U-TRU-Zr) → Fuel Slug Casting → Fuel Rod (Na insertion, End cap welding) → Fuel Assembly

Cladding

Fuel Assembly Components

Scrap Recycling

SFR
Continuous Casting

- Continuous casting has advantages in preventing the evaporation of volatile Am because inert over pressures can be easily applied.

- Waste can be reduced due to no use of casting molds (e.g., quartz), and product yields can be increased due to little heel left in the crucible after casting.

- Preliminary surrogate fuel (Cu) slugs were cast under inert atmospheric pressure of 760 torr. The surrogate fuel slug had diameter of about 7 mm and length of about 2.3m.
Schematic Flow of Cladding Tube Fabrication

**Process Development**

**Off-gas Treatment**
- FP gases

**Declading/Voloxidation**
- UO₂ + (TRU + FP) Oxide (Granule)

**Oxide Reduction**
- (U + TRU + FP) Metal

**Salt Treatment**
- Clean Salt

**Electrowinning**
- Used Salt (U + TRU + FP)

**Salt Recycle/Immobilization**
- Clean Salt

**Salt Recycle/Immobilization**

**Uranium Recovery**

**Reuse/Storage**

**Sodium Cooled Fast Reactor**

**TRU Metal Fuel Fabrication**

**TRU : Transuranic elements**
**NM : Noble metal elements**
**FP : Fission products**