Performance Evaluation of Metallic Fuel for SFR

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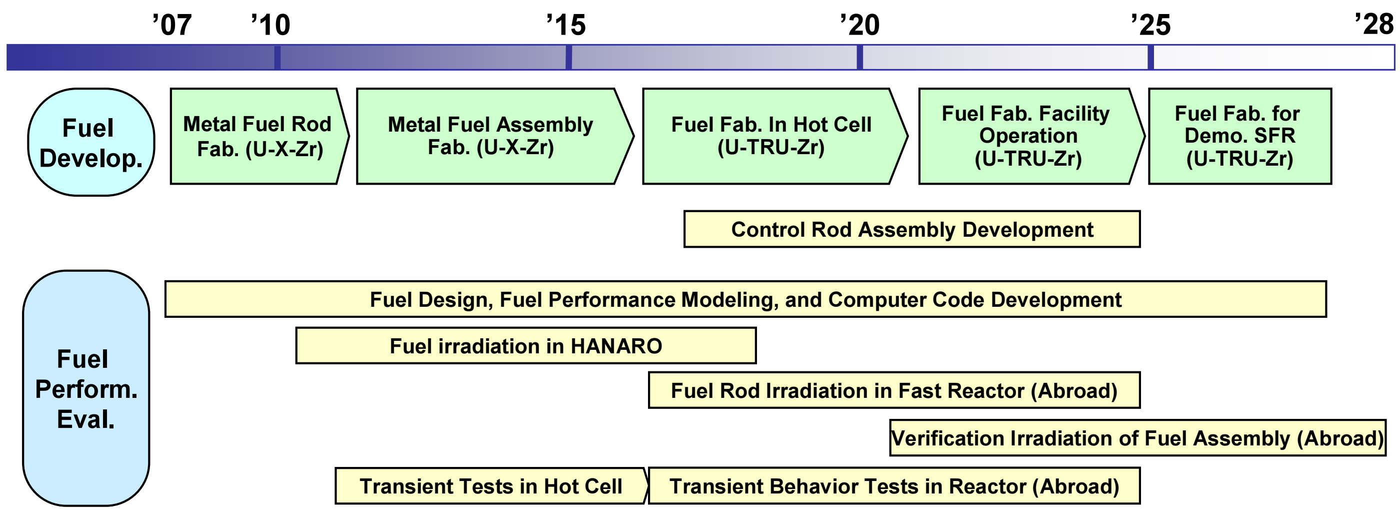
Outline

I

Introduction

Introduction

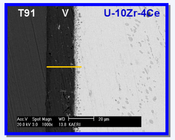
- Metal fuel development project for SFR in Korea
  - U-TRU-Zr metallic fuel
  - Cladding material : FMS
- The performance analysis is essential to assure an adequate fuel performance and its integrity
- The present study represents progress results of evaluating the performance of metal fuel for SFR in Korea

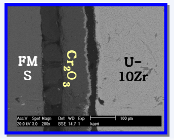


Fuel Performance Evaluation

Diffusion Couple Tests

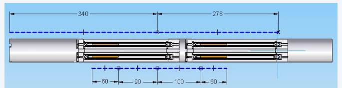
- Diffusion couple test between metal fuel and cladding
  - U-Zr-X vs. HT9 or T91 or Barrier cladding





Irradiation Test

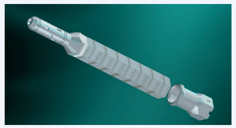
- Verification of Fuel Performance
- Design and fabrication of Irradiation Capsule in HANARO

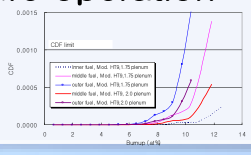


Metal Fuel Performance Evaluation

Fuel Design

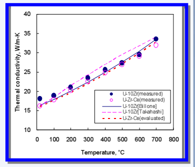
- Evaluation of Design Limit by MACSIS etc
- Fuel Spec for High burnup and high temperature operation



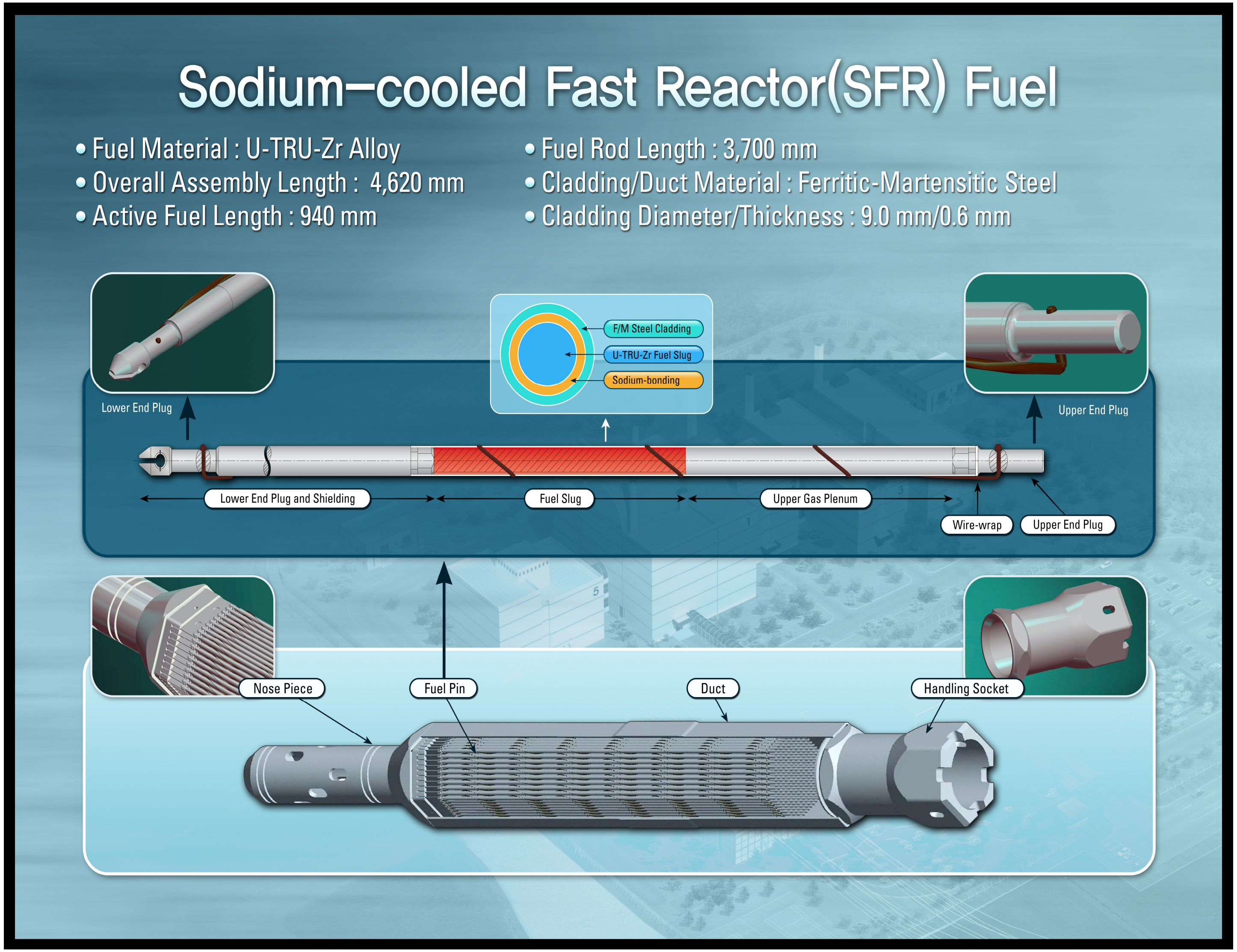


Modeling

- Thermal Conductivity
- FGR
- Fuel constituent migration
- Deformation etc



Metal Fuel Configuration



II Diffusion Couple Test

I.1 Diffusion couple tests without barrier

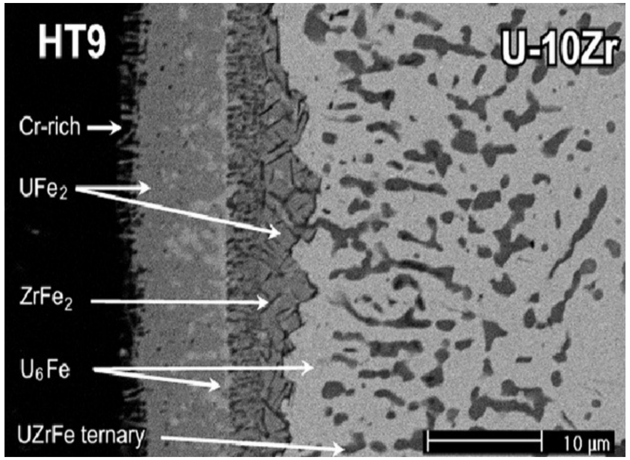
I.2 Diffusion couple tests with a metallic foil barrier

I.3 Diffusion couple test with a surface treatment

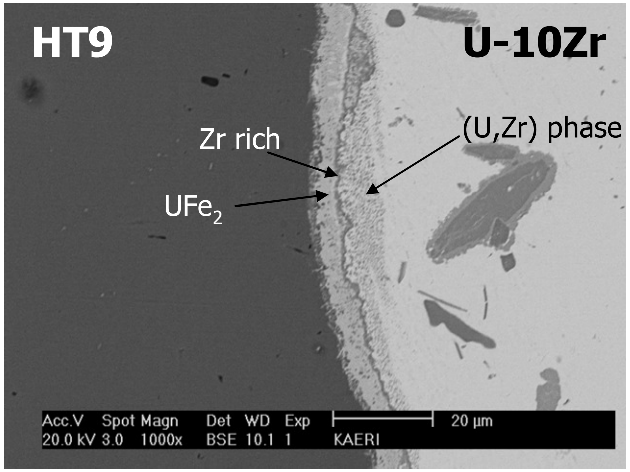
II.1 Diffusion couple tests without barrier

- Diffusion couple tests of U-Zr-(0, 2)Ce with FMS (700℃)
  - Various interaction phases
  - Major phase : UFe_2, U_6Fe, and $ZrFe_2$
  - Similar results of US and JAPAN

- Diffusion couple tests of U-Zr-(0, 2)Ce with FMS (740℃)
  - Thickness of the interaction region : different from Keiser's observation
    - microstructures were similar
  - Gray phase of UFe_2, dark one of Zr rich-line layer, and mixed phase with U and Zr were observed



U–10Zr vs. HT9 (700 ℃, 96 h)



U–10Zr vs. HT9 (740℃, 96 h)

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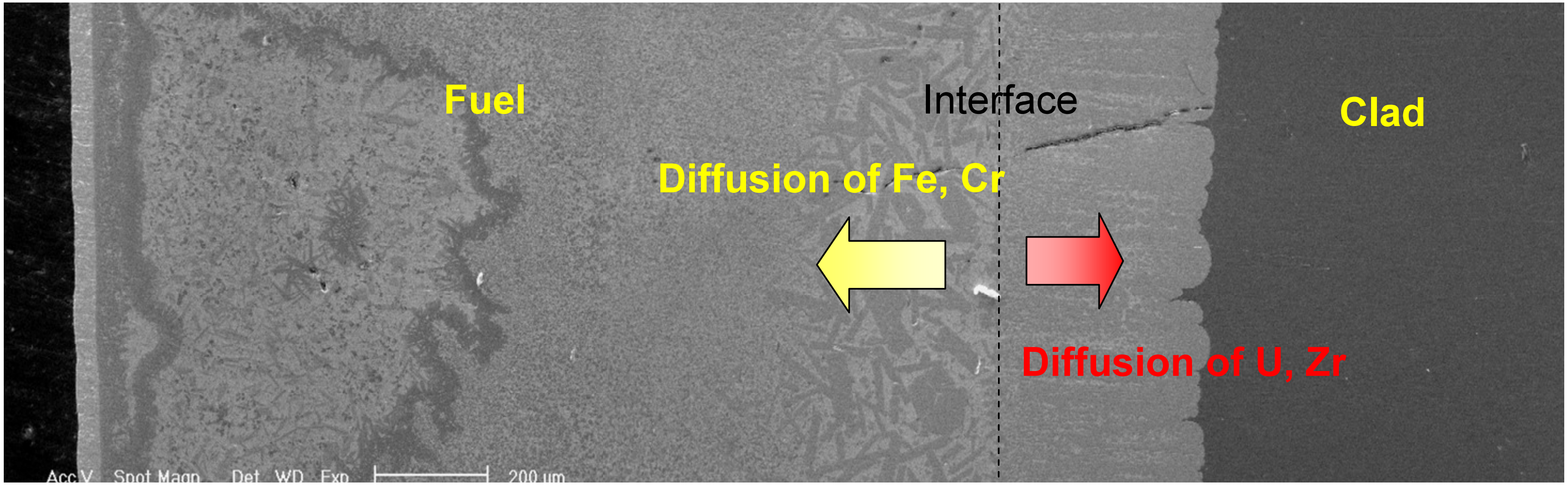
II.1 Diffusion couple tests without barrier

- U-10Zr and HT9 (800℃, 25h)
  - SEM revealed that the clad lost about 250㎛ of its thickness
  - From the EDX
    - U, Fe and Cr diffused into each other at the opposite direction
      - ✓U-Zr-Fe-Cr compound as $U_6(Fe,Cr)$, $Zr(Fe,Cr)_2$, and $U(Fe,Cr)_2$



U–10Zr vs. HT9 (800℃, 25 h)

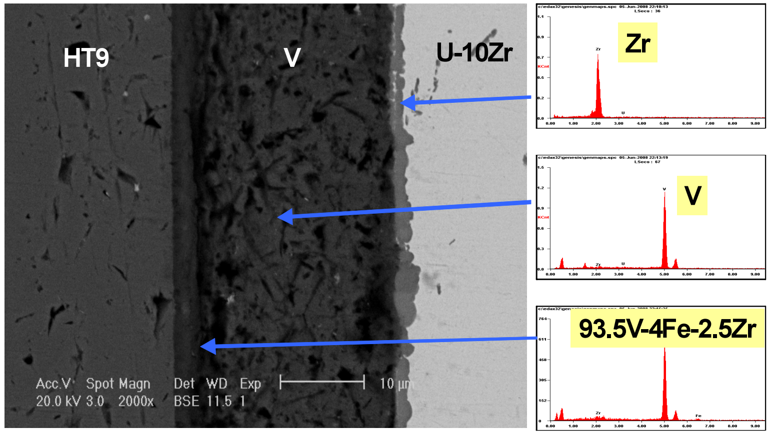
II.2 Diffusion couple tests with a metallic foil barrier

- Diffusion couple tests of U-Zr-(0, 2)Ce were carried out for the barrier foils
  - Zr, Mo, Nb, Ti, Ta, V, and Cr

- Zr
  - dissolved into the matrix
  - its thickness was significantly reduced
- Mo
  - part of the Mo element reacted with the U-10Zr fuel
- Nb, Ti
  - barrier elements and the fuel diffused into each other so that the reaction layer was formed.
- Ta
  - EDX analysis revealed that Ta reacted with the fuel, where it diffused into the fuel component.

II.2 Diffusion couple tests with a metallic foil barrier

- ❑ **V**
  - – no reaction between the barrier material and the fuel component
    - Inter-diffusion was completely prevented
  - – EDX analysis revealed that there was no U in the V layer.
  - – V–Fe–Zr layer was observed between the V foils and the FMS
    - measured composition :
      93.5 at.%V–4 at.%Fe–2.5 at.%Zr.
    - Reduction of V foil thickness
- ❑ **Cr**
  - – Neither inter-diffusion nor eutectic reaction
- ❑ **V and Cr exhibited the most promising performance**



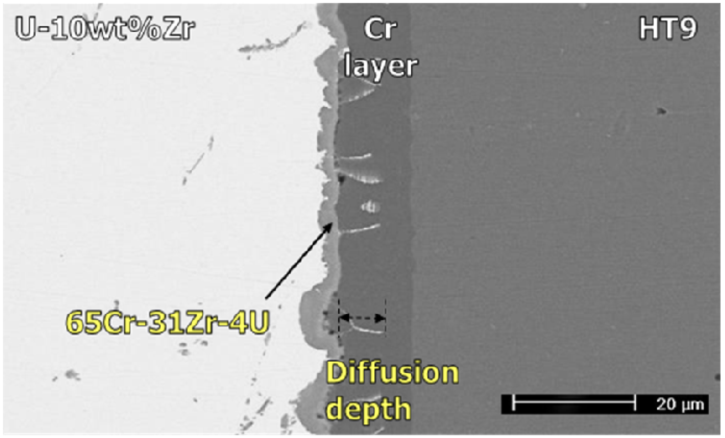
U–10Zr and HT9 with a V barrier foil (800℃, 25 h)

Summary of the metallic foil barrier performance

Element	Eutectic melting prevention	Element Interdiffusion	Reaction with fuel
Zr	Yes	Yes	Yes
Nb	Yes	Yes	Yes
Ti	Yes	Yes	Yes
Mo	Yes	No	Yes
Ta	Yes	No	Yes
V	Yes	No	No
Cr	Yes	No	No

II.3 Diffusion couple test with a surface treatment

- ❑Final application of a barrier cladding requires the barrier in the surface of a cladding tube
  - Electroplating (for Cr) and vapor deposition (for Zr and V)



U-10Zr and HT9 with the electroplating of Cr after the diffusion couple test (800℃, 25 h)

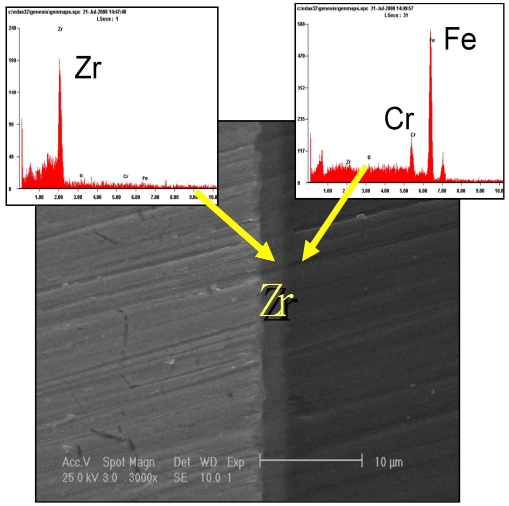
- ❑Cr barrier electroplated on FMS
  - Cr prevented the eutectic melting between U-10Zr and HT9 at 700, 740, and 800 ℃.
  - Fuel constituent such as U have penetrated locally along the crack in the barrier
    - uranium compound along the clad surface

- ❑ It seems that a crack affects the fuel-cladding interaction in a negative way
  - further analysis will be carried out to investigate the exact phenomenon

II.3 Diffusion couple test with a surface treatment

❑Zr-vapor-deposited barrier

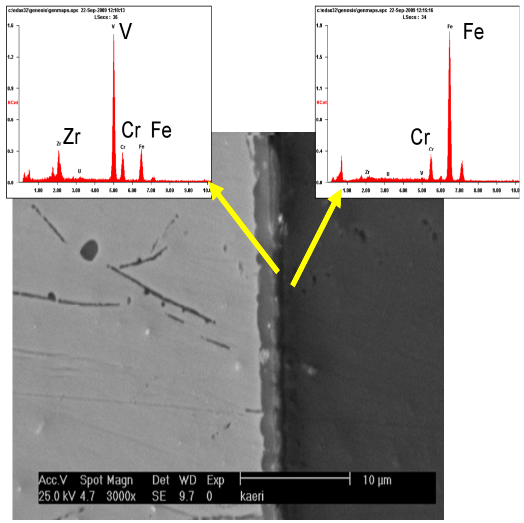
- no visible phase formation
- excellent barrier performance, contrary to the case of the Zr metallic foil
- further analysis will be continuously carried out



U-10Zr vs. HT9 with the Zr vapor deposition (800℃, 25 h)

❑V-vapor-deposited barrier

- not effectively prevent inter-diffusion contrary to the V foil
- It seems that the thickness of V (~1.3 µm) was too thin
- Diffusion couple test will be carried out with thick barrier cladding



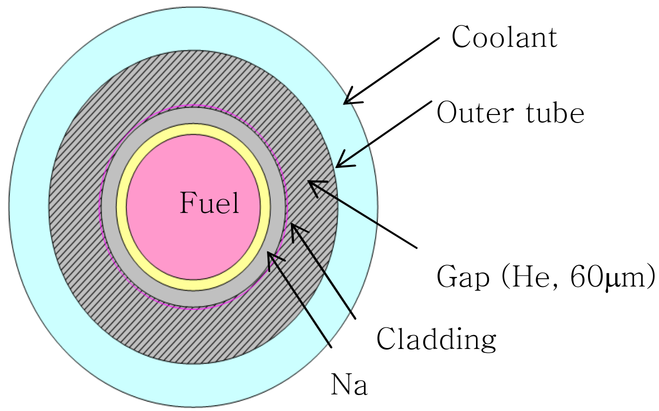
U-10Zr vs. HT9 with the V vapor deposition (800℃, 25 h)

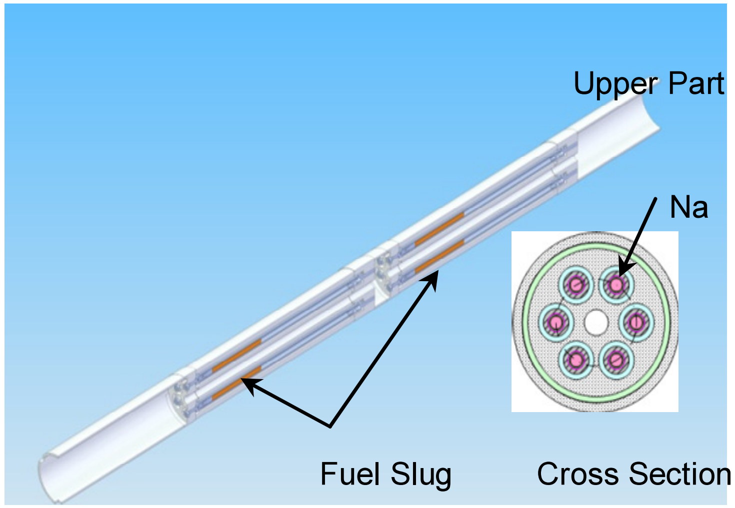
III

Irradiation Test

Fuel irradiation test

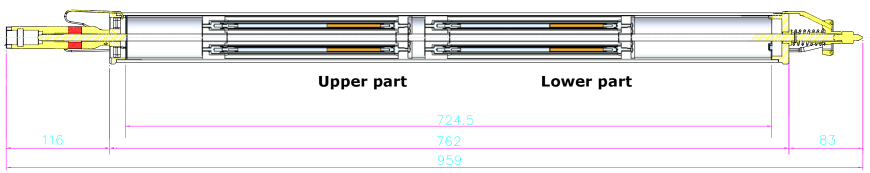
- Schedule
  - 2010 : irradiation in HANARO
  - 2008-2009 : irradiation capsule design and fabrication
- Objectives
  - Identify the Ce-bearing fuel performance and the characteristics of barrier cladding
- Irradiation condition
  - Fuel : U-10Zr and U-10Zr-6Ce
  - Cladding : FMS
  - Maximum burnup : 3 at% (1st HANARO irradiation test)
  - Linear power : 306 W/cm,
  - Expected duration : ~150 EFPD
- Fast reactor condition
  - Thermal neutron flux filter : Hf or Boral plate
  - Fuel temp. control : He gap
  - Fuel/cladding gap bonding :Na

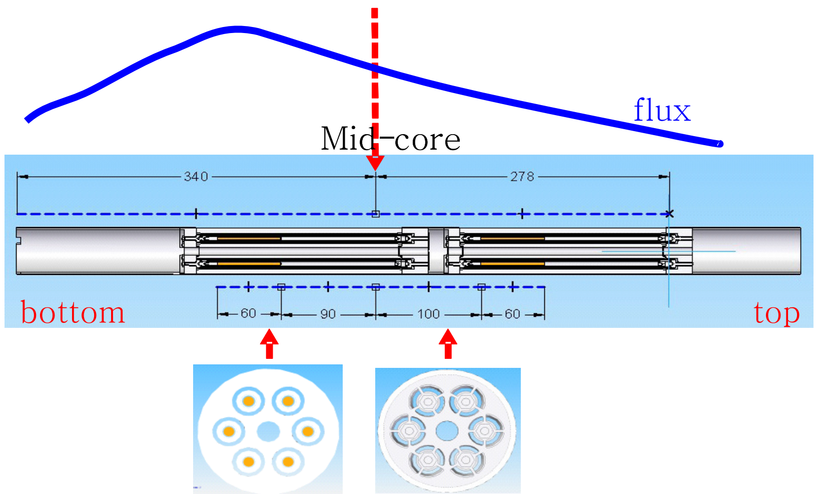




Irradiation capsule

- Capsule design
  - Two test sections
    - each section accommodates six rodlets
  - The fuel rod is contained in the sealing tube for safety in case of sodium leakage from the cladding





Irradiation capsule dimension

Fuel		Cladding		Outer tube	
Dia. (mm)	Density (g/cm^3)	Outer dia.(mm)	Inner dia.(mm)	Outer dia.(mm)	Inner dia.(mm)
3.7	15.8	5.5	4.6	8.62	5.62

IV Modeling

IV.1 Thermal conductivity model

IV.2 Fuel constituent migration model

MACSIS CODE

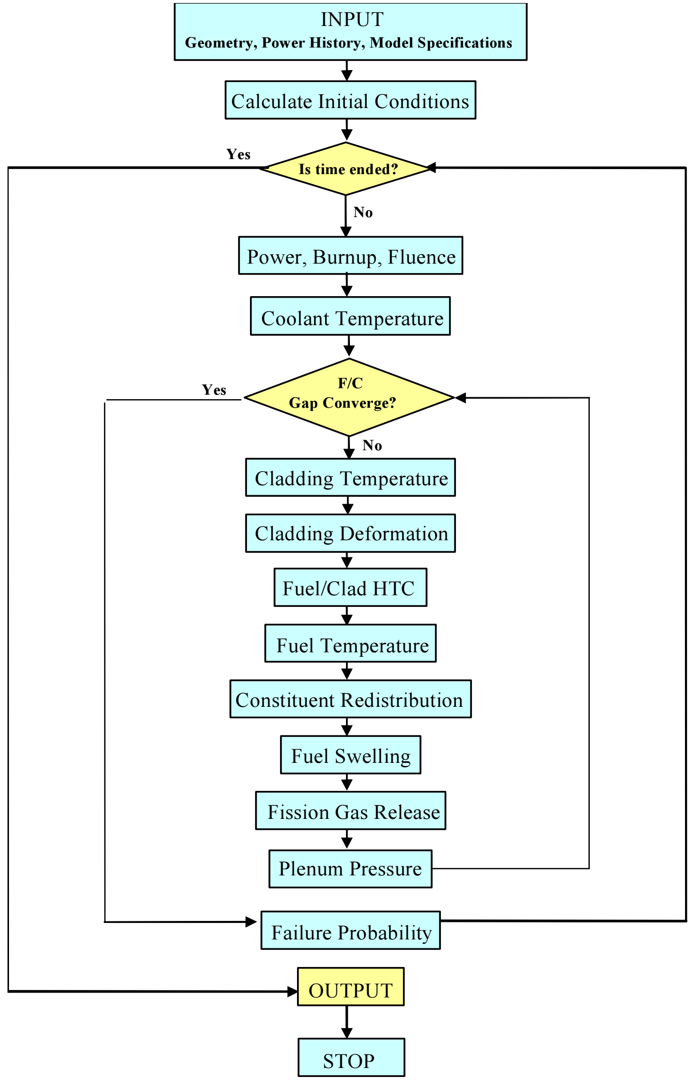
❑ Main structure

- ➢ Fuel temp. calculation routine
- ➢ FGR calculation routine
- ➢ Cladding deformation calculation routine

❑ Main Function

- ➢ Axial and radial temperature distribution
- ➢ Fission gas release including He release
- ➢ Fuel constituent migration
- ➢ Cladding deformation by plenum pressure
- ➢ Cumulative damage fraction (CDF)
- ➢ Probabilistic estimation of CDF in connection with Weibull analysis
- ➢ Cladding wastage effect by eutectic melting
- ➢ FCMI by solid fission product

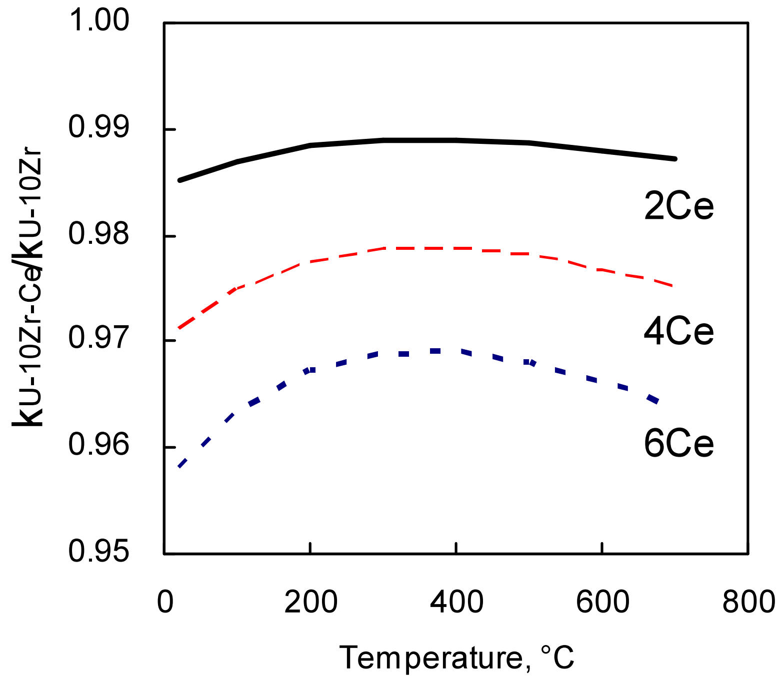
⇨ MA (+ RE) bearing metal fuel behavior model is now developing



MACSIS Flow Chart

IV.1 Thermal conductivity model

- RE is precipitated in the U-Zr matrix
  - cause a variation of fuel properties
- The effect of the Ce precipitates on effective thermal conductivity is evaluated
  - based on models for heterogeneous materials such as Maxwell and Bruggeman models
- Thermal conductivity of the U-Zr alloy is reduced
  - with an increasing Ce content
- Addition of Ce up to 6 wt%
  - reduce the thermal conductivity of the U-Zr alloy by less than 5%.
    - low volume fraction of the Ce phase
    - relatively high thermal conductivity of Ce



Effect of the Ce content on the thermal conductivity of U-10Zr

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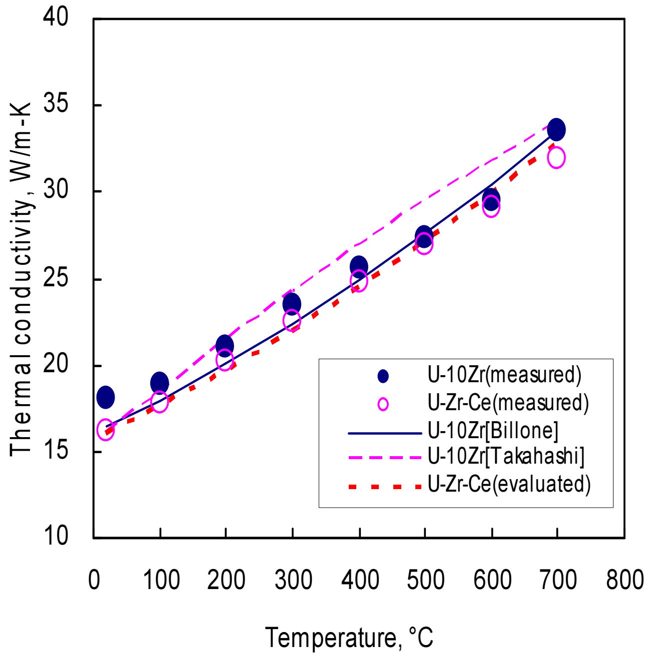
IV.1 Measured thermal conductivity

- The measured thermal conductivity of the U-Zr-Ce alloy
  - by the product of the thermal diffusivity, density, and specific heat
    - Thermal diffusivity : laser flash method
    - Density : immersion technique
    - specific heat : Kopp-Neumann's law

- Thermal conductivity of U-Zr lies in between the Billone or Takahashi's evaluation
  - The effect of Ce on the thermal conductivity of U-Zr alloy is well described by the present heterogeneous mixture models



Comparison of the thermal conductivities for U-Zr-Ce alloys

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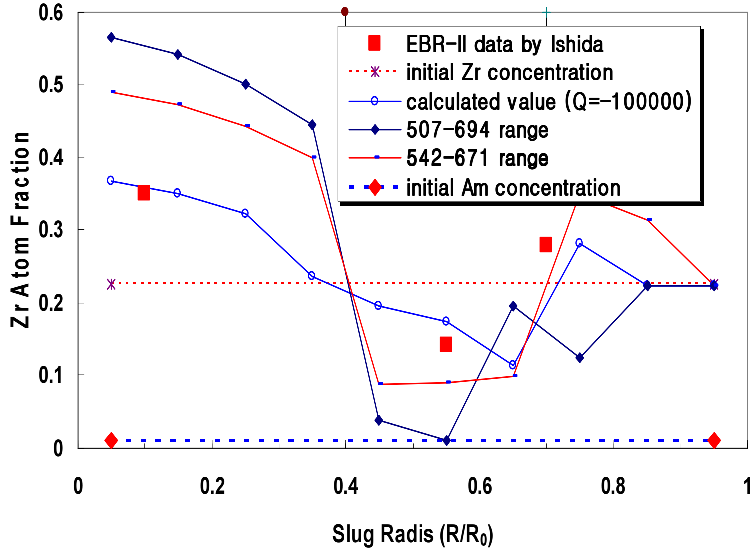
IV.2 Fuel constituent migration model

- U-Pu-Zr Migration
  - Based on the Ishida's model and Hofman's theory
  - Reconstruct the quasi-binary U-Zr phase diagram by Ishida's Concept
  - Assumption of the diffusion coefficient by Hofman's theory
- Am migration model for U-TRU-Zr
  - by using the U-Pu-Zr migration model
- The radial profile of Zr redistribution
  - The main reason for the migration is the radial solubility change of Zr
  - The heat of transport also plays an important role in the migration
  - depletion of Zr in the middle zone was simulated
  - value of the heat of transport : more than -100,000kJ/mole.



Radial distribution profile of Zr

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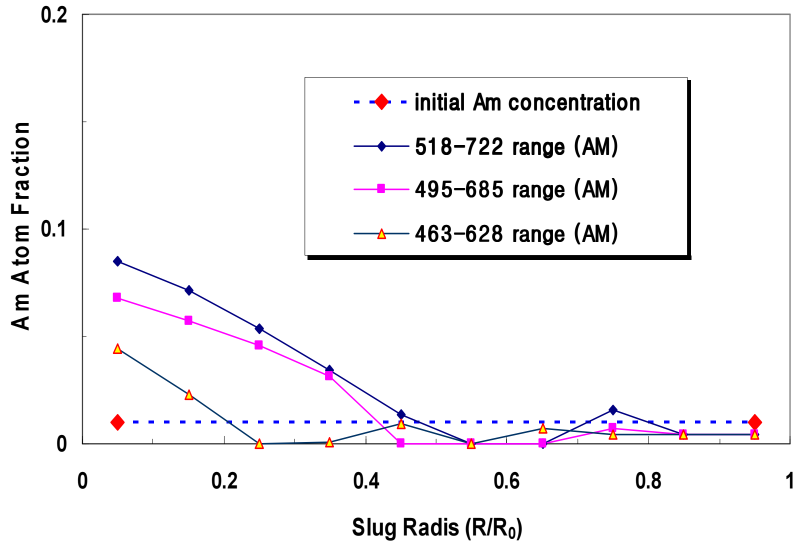
IV.2 Am migration

- **Am migration**
  - calculated by using the MACSIS code and the X501 data
- **The migration behavior of Am is similar to that of Zr**
  - -100,000kJ/mole of the heat of transport was also used
- **Simulated Am migration for the X501 fuel**
  - Am migration along with the migration of Zr was simulated
  - At around 700℃ of the fuel centerline temperature, the model predicted that the Am fraction in the fuel center reaches its peak
  - There were no centerline Am depletions expected in all range of temperature



Radial distribution profile of Am

V Metal Fuel Design

Design Criteria

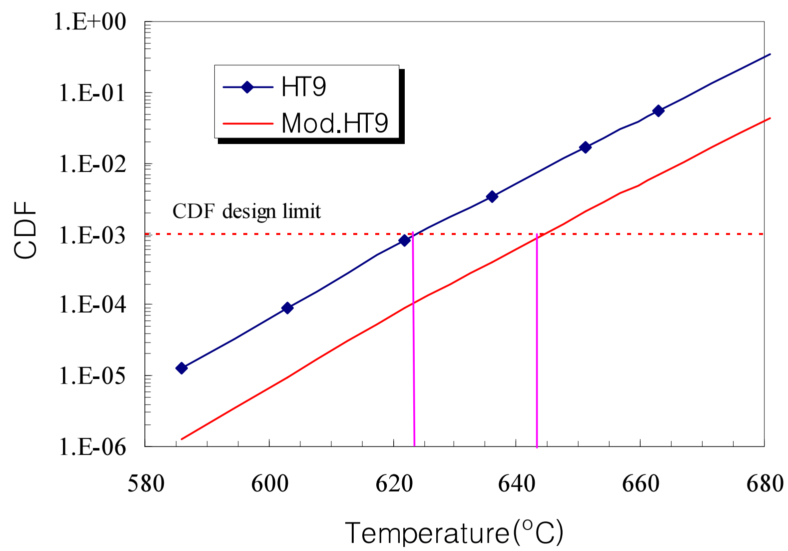
- No Fuel Melting
  - Fuel Temperature ≤ solidus temperature
- No Eutectic Melting
  - No eutectic liquifaction
    - Fuel Surface Temperature (TRU% < 19wt%) ≤ 700 ℃
    - Fuel Surface Temperature (TRU% ≥19wt%) ≤ 650 ℃
- Cladding Limit
  - Strain limit criteria
    - Thermal creep strain : 1%
    - Total strain : 3%
    - Swelling : 5%
  - Cumulative Damage Fraction (CDF) limit criteria
    - Steady state operation : 0.001
    - Transient operation : 0.2

Key design parameters

	KALIMER-600 (case 1 core)	Preliminary case 1 of SFR conceptual design
Fuel Slug Contents (wt%)	U-12.6Pu-0.5Am-0.09Cm-0.06Np-10Zr	U-30TRU-Zr
Smeared Density (%)	75	75
Cladding Material	Mod.HT9	Mod.HT9
Pin Outer Diameter (mm)	9.0	7.0
Cladding Thickness (mm) - Inner/middle/outer	1.00/0.72/0.59	
Plenum-to-fuel ratio	1.75	2.25
Fuel Slug Length (mm)	940	868

CDF Limit Analysis for KALIMER-600

- **HT9**
  - CDF > 0.001
  - when the cladding temperature becomes higher than 625 ℃
- **Mod.HT9**
  - CDF > 0.001
  - when the cladding temperature becomes higher than 645 ℃.
- **625 and 645 ℃ are selected as the peak clad temperature**
  - for the HT9 clad and the Mod.HT9 clad for the Case-1 core, respectively.



CDF as a function of operating temperature for KALIMER-600 (Case-1 core)

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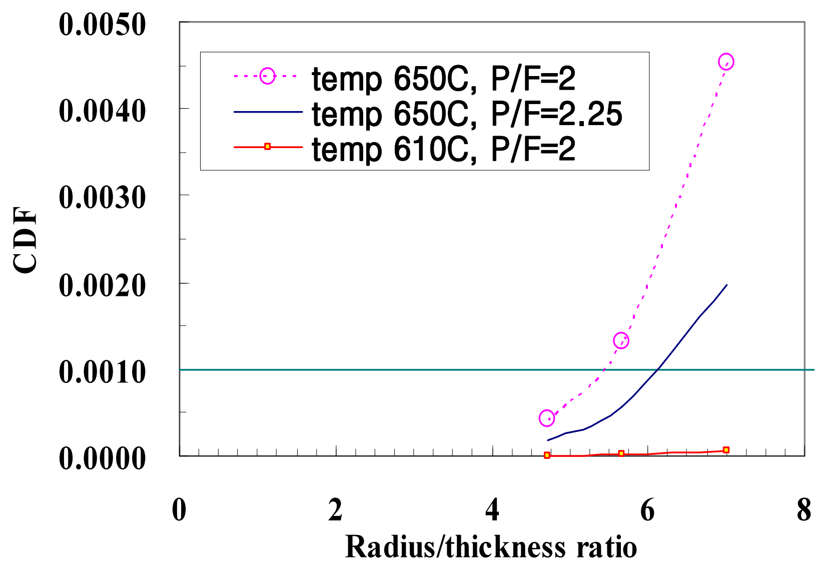
CDF LIMITS FOR SFR Preliminary design

- CDF <0.001
  - Cladding temperature :650℃
  - P/F ratio : 2
  - R/th ratio : 5.5

- If the P/F ration was enlarged to 2.25
  - R/th ratio needed to satisfy the CDF limit : 6

- If the plenum-to-fuel ratio was enlarged
  - It was expected that the Mod.HT9 cladding satisfied the CDF limit at the discharge burnup goal

- Sensitivity analysis according to the design parameter will be performed continuously



CDF according to the cladding temperature, P/F ratio, and R/th ratio

VI Summary

Summary

- Sodium-cooled fast reactor(SFR) is being developed in combination with the pyro-processing of spent fuel
  - U-TRU-Zr metallic fuel is a reference fuel for SFR
- Fuel performance evaluation is being performed in the following tasks;
  - fuel-cladding diffusion couple tests
  - fuel irradiation test
  - performance analysis model development
  - fuel design
- This work forms the basis for establishing key technology that will evaluate the performance of U-TRU-Zr metallic fuel.