RERTR-2022 International Meeting
Oct. 2nd ~ 5th 2022, Vienna

# Overview of Research Reactor Fuel Development at KAERI

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**2022. 10. 04.**


Korea Atomic Energy Research Institute

# History of Research Reactor in Korea

Technology Introduction

Technology Accumulation

Technology Localization

Technology Enhancement

KRR-1 (1962)

FOUNDATION

KRR-2 (1972)

GROWTH

HANARO (1995)


CHALLENGE

2009.10
JRTR Start

2012.4
KJRR Start

2014.6
OYSTER Start

**TRIGA Mark-II**
**(Pool Type)**
**250 KW**
**Education & Training**
**RI Production**
**NAA**

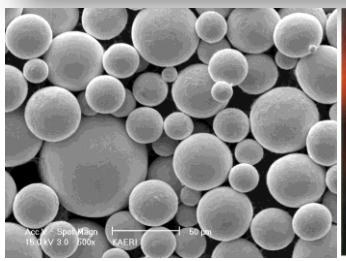
**TRIGA Mark-III**
**(Pool Type)**
**2,000 KW**
**RI Production**
**NAA**
**Neutron Beam Experiments**

**(Open-Tank In-Pool Type)**
**30,000 KW**
**Cold Neutron Laboratory : 2009**
**Neutron Beam**
**Fuel/Material Irradiation**
**RI Production / NAA**
**NTD**

# HANARO Fuel Localization

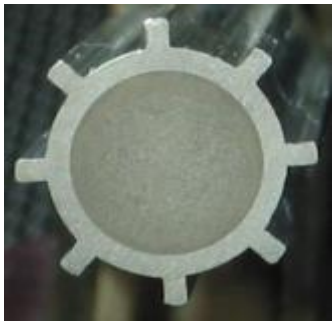
**~1992**

- Development of Atomization Technology ($U_3Si$ powder)



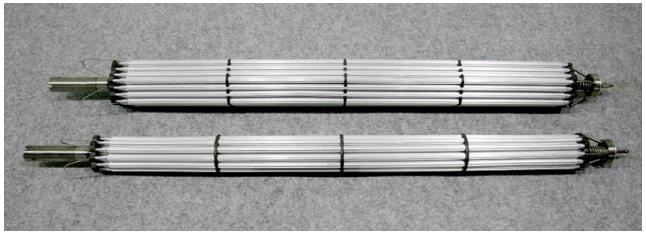
**~2000**

- HANARO Fuel Localization Program Launched
- R&D of Fab. Process
- Irradiation Test of Atomized $U_3Si$/Al Dispersion Fuel



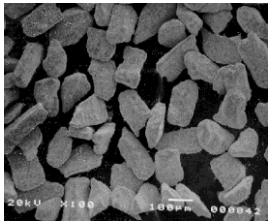

**~Now**

- Facility Construction (2003)
- Licensing (2004)
- Start HANARO Fuel Supply (2005)
- Fabrication Capacity (55 set/yr)



# Fabrication Process (HANARO Fuel)

## Conventional Process



Melting & Casting → U-Si Ingot

Heat Treatment → $U_3Si$ Ingot

Machining → Chip

Pulverizing → Powder

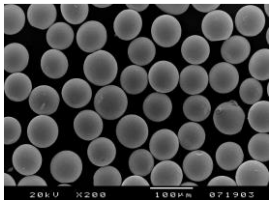
Magnetic Separation → Powder

Sieving → Powder

## Atomized Process

Melting & Atomizing → U-Si powder

Heat Treatment → $U_3Si$ powder



Sieving → Powder

Al powder → Blending & Compacting → Compacts

Extrusion → Fuel meat

Co-extrusion → Fuel Rod

Welding → Fuel Rod

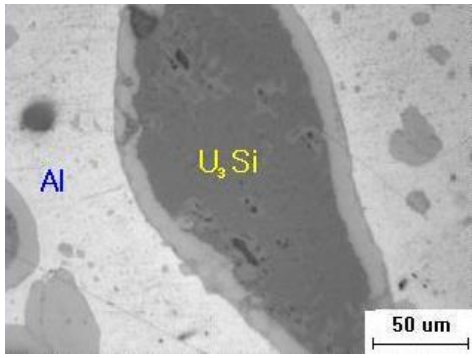
Assembly Parts → Assembling → Fuel Assembly

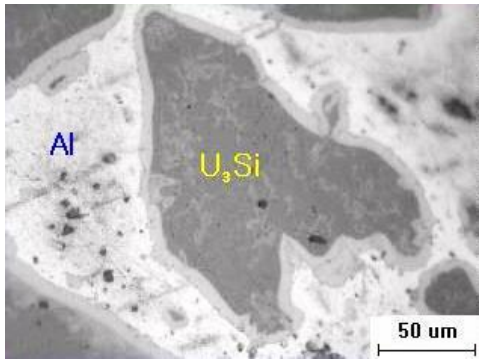
Atomized Process
→ 25 steps for Fabrication/Inspection

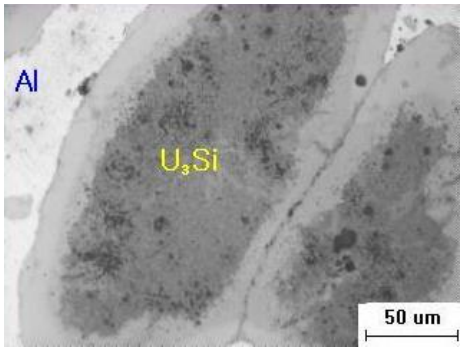
# Irradiation Performance ($U_3Si$/Al)

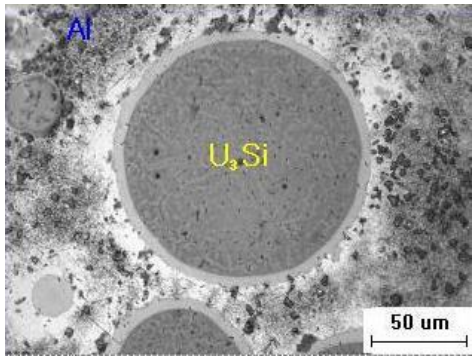
## High-power irradiation test (KH99H-001) 121kW/m

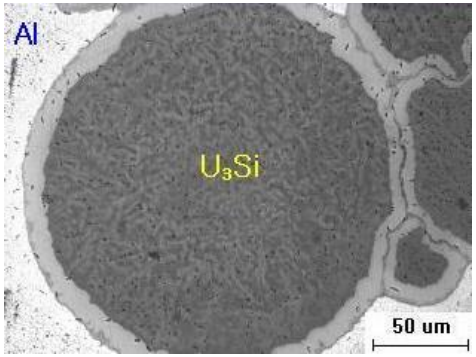
**Irr. Test : 173 EFPD('99.06~'00.08) at CT hole, HANARO**

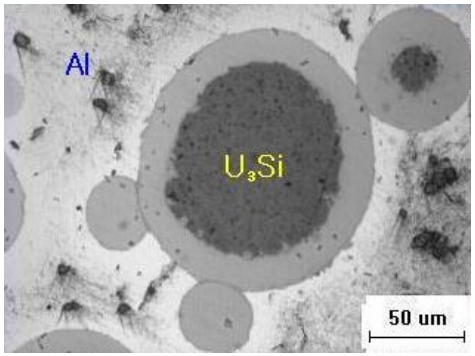


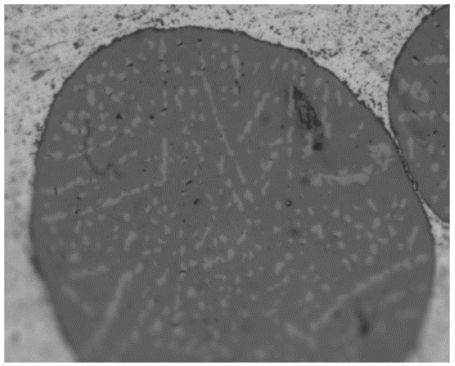




39 at.% BU　　60 at.% BU　　76 at.% BU



**Un-irradiated $U_3Si$**

After HT (800 °C, 6 hr)

- Dark grey phase : $U_3Si$
- Light grey phase : $U_3Si_2$

➢ Measured fuel swelling

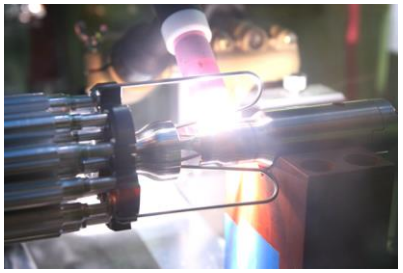
- atomized fuel < 5.7%　　- comminuted fuel <7.0%

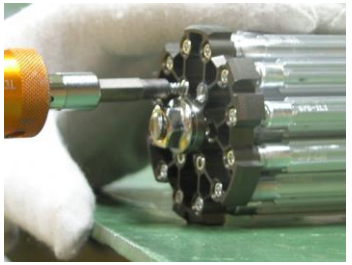
# Construction of the Fabrication Facility

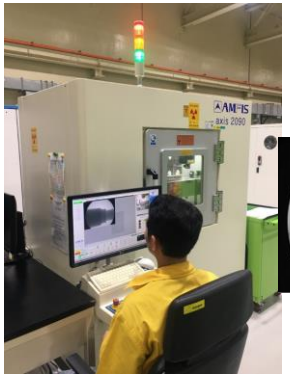
- Construction of the fabrication facility for HANARO fuel production
  - decided upon with the permission of government in Dec. 1998
  - including advanced nuclear fuel R&D
- Design and Construction
  - Designed by KOPEC (~June 2000) : Seismic design
  - Constructed by DHEC (April 2001 ~ Nov. 2002)
- All the equipment was moved by early 2003
  - upgraded to satisfy the production scale capability
  - Atomization system, Co-extruder, EB welding M/C were installed

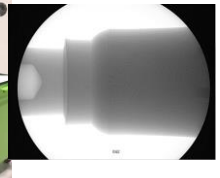
# Production of HANARO Nuclear Fuel

- Two driver (atomized fuel) bundles were fabricated and delivered to HANARO
  - Lead bundle(KFC-001) was loaded in HANARO (March 10, 2005)
- HANARO Fuel has been supplied successfully since 2005 (Supply record > 400 FAs)

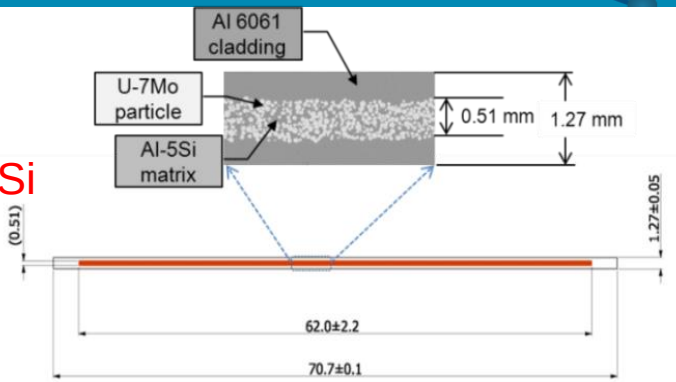


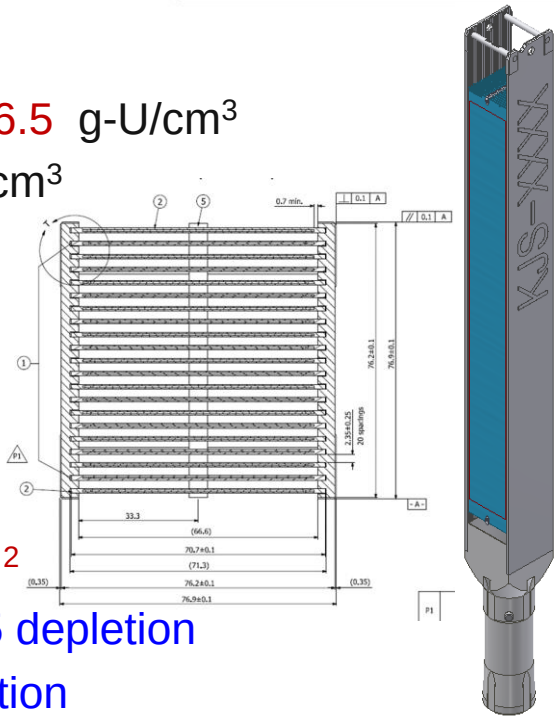




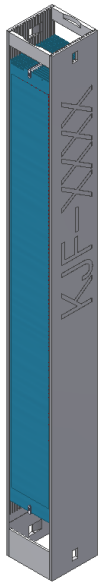
# U-Mo Fuel for KJRR

- Fuel (Fuel Meat & Fuel Plate)
  - ✓ LEU : 19.75±0.2 wt% $U^{235}$
  - ✓ Meat : U-7wt%Mo dispersed in Al-5wt%Si
  - ✓ Cladding/Components : Al-6061
  - ✓ Meat (mm) : 62.0 x 600 x 0.51
  - ✓ Plate (mm) : 70.7 x 640 x 1.27
- Uranium Density in Fuel Meat
  - ✓ Inner(19)/outer(2) fuel plate : 8.0/6.5 g-U/$cm^3$
  - ✓ Initial core : LDU 5.2/3.9/2.6 g-U/$cm^3$
- U-235 mass
  - ✓ FA : ~ 620 g
- FA dimension
  - ✓ SFA (mm) : 76.2 x 76.2 x 1010
  - ✓ FFA (mm) : 76.2 x 76.2 x 760.5
- Heat flux(nom./max.) : 41.5/110 W/$cm^2$
- Burnup (FA average) : ~65 at% U-235 depletion
- Burnup (Peak) : ~80 at% U-235 depletion
- Cycle length/Operation day/yr : ~50 days/~300 days/yr



(SFA)



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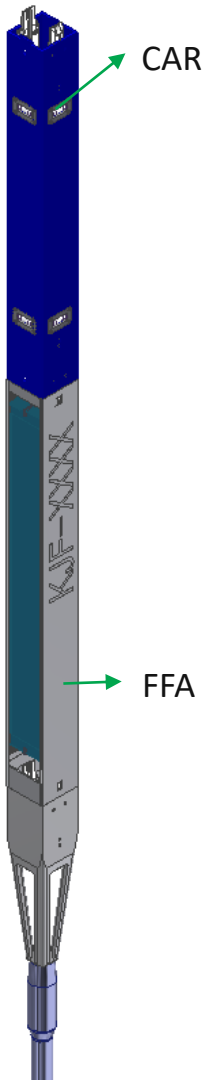
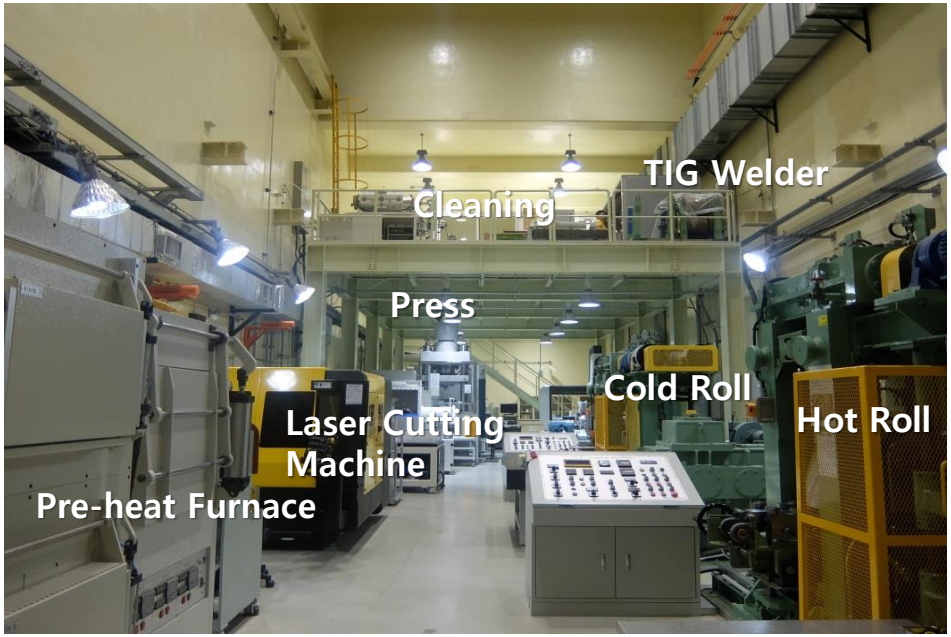


# Plate Fuel/Target Fabrication Facility

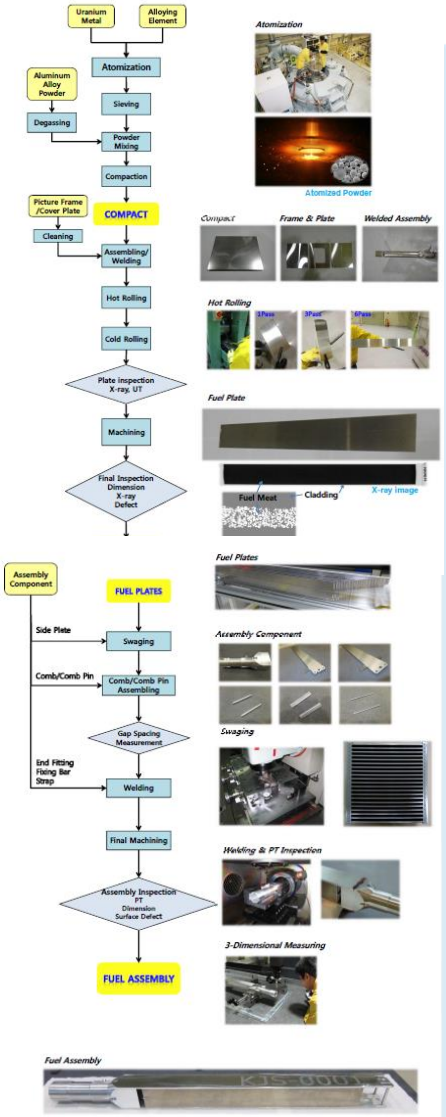
- Plate fuel/Target fabrication facility was successfully established within 3 years (2012-2014), based on localization experience of HANARO fuel
- Fabrication Capability: 100 Ass'y/yr (> 2,000 Plate/yr)






| Use | Process | Equipment |
|---|---|---|
| Plate Fab. | Powder heat treatment | • 2 Vacuum degassing furnace ($10^{-7}$ torr) |
| | Mixing | • TUBULAR shaker mixer (three dimensional movement)<br>• Glove Box |
| | Compaction | • 300 ton Press |
| | Etching & Cleaning | • Cleaning room with scrubbing system |
| | Welding | • TIG welder |
| | Hot rolling | • Pre-heat furnace<br>• Hot roller (dia. 400mm) |
| | Cold rolling | • Cold roller (dia. 380mm)<br>• Leveler |
| | Machining | • Laser cutting machine, CNC milling machine |
| | Etc. | • Shearing machine, Laser ID marking |
| Assembly Fab. | Swaging | • Swaging machine |
| | Welding | • Electron Beam (EB) welder |
| | Machining | • Machining center(MCT) |
| Inspection | Inspection | • 2 X-rays (CT & location, homogeneity, stray particle)<br>• UT<br>• 3-dimensional measuring system<br>• Gap spacing measuring system<br>• MTS for tensile test of swaged side plates |

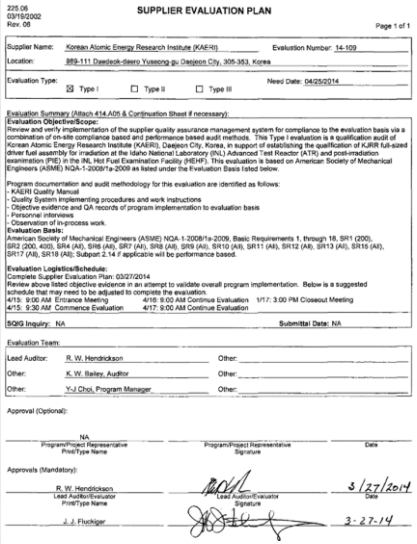
# Fuel/Target Fabrication Process




- All equipment of fabrication/inspection processes were digitalized to control variables consistently.
- QA/QC system has been implemented based on KEPIC/QAP-2000 and ANSI/ANS-15.8, “Quality Assurance Program Requirement for Research Reactors”.

→Satisfy Global QA Standards

## INL Audit for KAERI’s QA/QC System



SUPPLIER EVALUATION PLAN

225.06
03/19/2002
Rev. 06

Page 1 of 1

Supplier Name: Korean Atomic Energy Research Institute (KAERI) Evaluation Number: 14-109

Location: 989-111 Daedeok-daero Yuseong-gu Daejeon City, 305-353, Korea

Evaluation Type: ☒ Type I ☐ Type II ☐ Type III Need Date: 04/25/2014

Evaluation Summary (Attach 414.A05 & Continuation Sheet if necessary):

**Evaluation Objective/Scope:**
Review and verify implementation of the supplier quality assurance management system for compliance to the evaluation basis via a combination of on-site compliance based and performance based audit methods. This Type I evaluation is a qualification audit of Korean Atomic Energy Research Institute (KAERI), Daejeon City, Korea, in support of establishing the qualification of KJRR full-sized driver fuel assembly for irradiation at the Idaho National Laboratory (INL) Advanced Test Reactor (ATR) and post-irradiation examination (PIE) in the INL Hot Fuel Examination Facility (HEHF). This evaluation is based on American Society of Mechanical Engineers (ASME) NQA-1-2008/1a-2009 as listed under the Evaluation Basis listed below.

Program documentation and audit methodology for this evaluation are identified as follows:
- KAERI Quality Manual
- Quality System implementing procedures and work instructions
- Objective evidence and QA records of program implementation to evaluation basis
- Personnel interviews
- Observation of in-process work.

**Evaluation Basis:**
American Society of Mechanical Engineers (ASME) NQA-1-2008/1a-2009, Basic Requirements 1, through 18, SR1 (200), SR2 (200, 400), SR4 (All), SR6 (All), SR7 (All), SR8 (All), SR9 (All), SR10 (All), SR11 (All), SR12 (All), SR13 (All), SR15 (All), SR17 (All), SR18 (All); Subpart 2.14 if applicable will be performance based.

**Evaluation Logistics/Schedule:**
Complete Supplier Evaluation Plan: 03/27/2014
Review above listed objective evidence in an attempt to validate overall program implementation. Below is a suggested schedule that may need to be adjusted to complete the evaluation.
4/15: 9:00 AM Entrance Meeting 4/16: 9:00 AM Continue Evaluation 1/17: 3:00 PM Closeout Meeting
4/15: 9:30 AM Commence Evaluation 4/17: 9:00 AM Continue Evaluation

SQIG Inquiry: NA Submittal Date: NA

Evaluation Team:

| | | | |
|---|---|---|---|
| Lead Auditor: | R. W. Hendrickson | Other: | |
| Other: | K. W. Bailey, Auditor | Other: | |
| Other: | Y-J Choi, Program Manager | Other: | |

Approval (Optional):

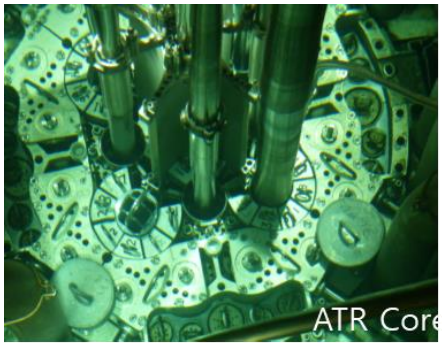
NA
Program/Project Representative Print/Type Name — Program/Project Representative Signature — Date

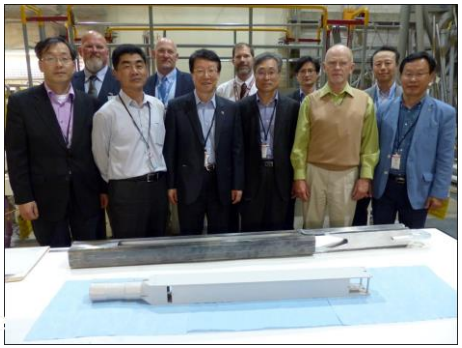
Approvals (Mandatory):

R. W. Hendrickson
Lead Auditor/Evaluator Print/Type Name — Lead Auditor/Evaluator Signature — 3/27/2014 Date

J. J. Fluckiger — 3-27-14

- Period : ‘14.4.15 ~ 17
- Evaluation List (5 categories)
  - KAERI Quality Manual
  - Quality System Implementing procedures and work instructions
  - Objective evidence and QA records of program implementation to evaluation basis
  - Personnel interviews
  - Observation of in-process work

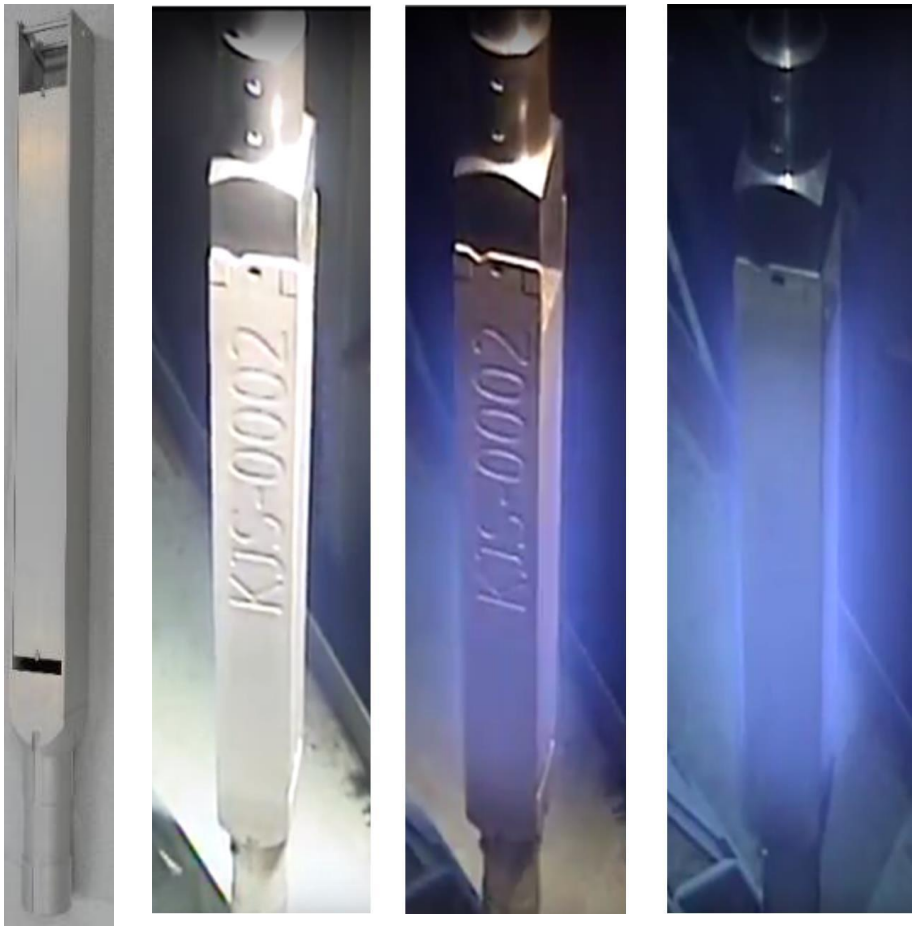


KJRR-LTA
ATR/ATRC Insertion (Apr. 28. 2015)

# KJRR-LTA Irradiation Test

## Irradiation test & PIE at INL successfully completed




KJRR Lead Test Assembly (KJS-0002) :
Before and After irradiation test in the ATR core

| Irradiation Test (finished) | 2015.10.26 – 2017.02.23 |
|---|---|
| Achieved Burnup, FA average | 70 % U-235 Depletion |
| Achieved Burnup, Local peak | 83.1 % U-235 Depletion |
| Peak heat flux ($W/cm^2$) | 182 |
| Effective Full Power Day (EFPD) | 216.6 |
| **PIE** | **NDE : 2018.2 ~ 2019.9**<br>**DE : 2019.10 ~ 2022.4** |

After final cycle (ATR 160B Cycle)

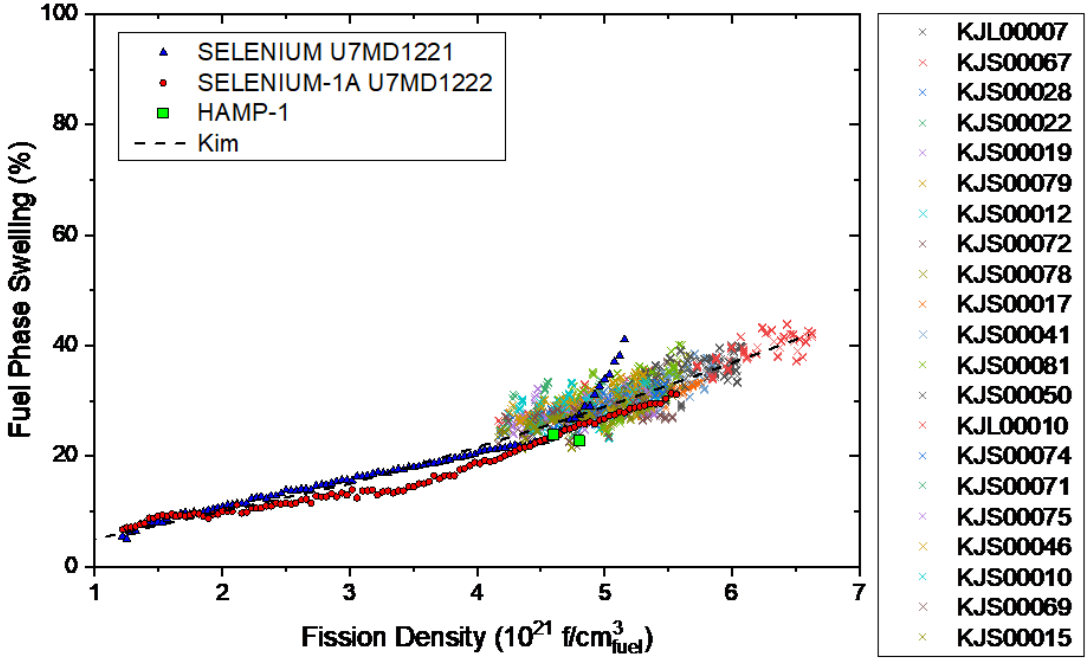
# Fuel Swelling Comparison(KJRR U-Mo)

PIE results of KJRR-LTA are enough to show

- very stable irradiation fuel performance
- predictable fuel behavior

SELENIUM dataset from A. Leenaers, RRFM (2017)

* Kim model from U-10Mo monolithic dataset [Y.S. Kim, JNM, 419 (2011)291]



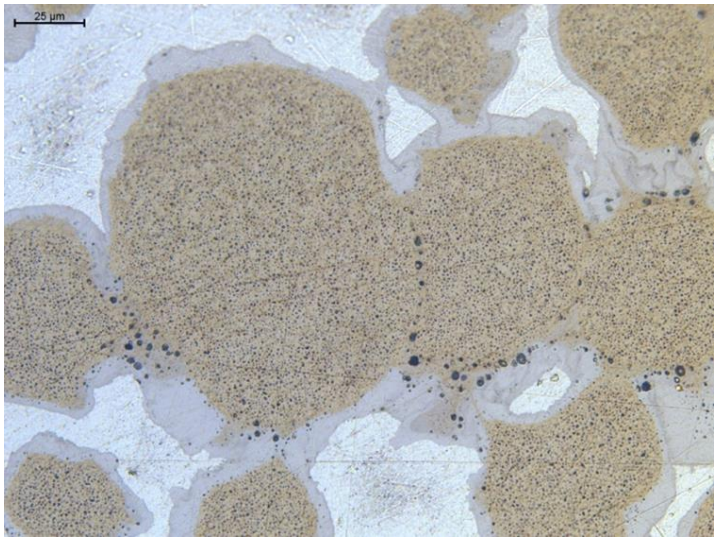
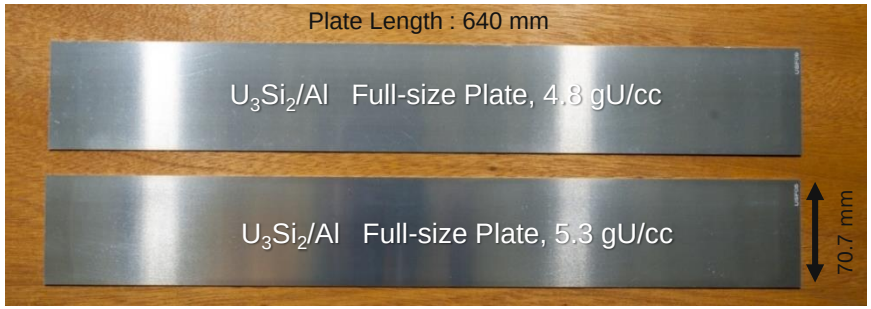




Plate No. 20 (KJS00050)
Local peak BU : 83 at%U-235

## Future Plan

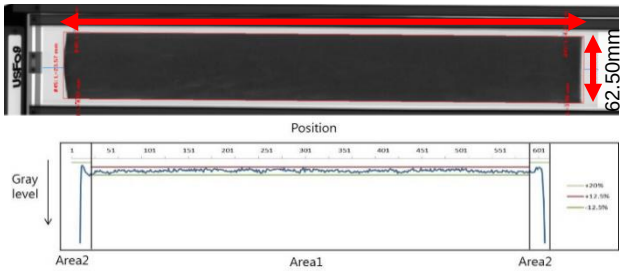
- Submit FSAR to get operation license of KJRR(June 2023)
- Start to fabricate KJRR driver fuel for initial core (2025~2026)
- First criticality (June 2027)

# Fabrication Capability (Ato. $U_3Si_2$ Fuel)

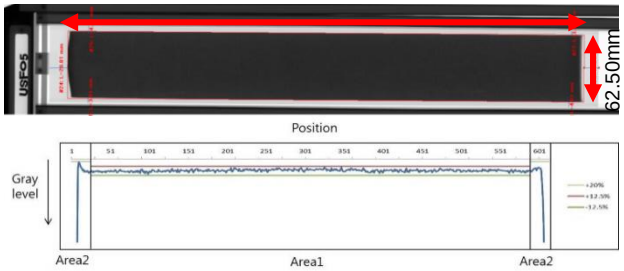



- Full-size $U_3Si_2$/Al fuel plate was also successfully fabricated (4.8 gU/cc and 5.3 gU/cc)
  - Improved homogeneity
  - Satisfy all inspection criteria

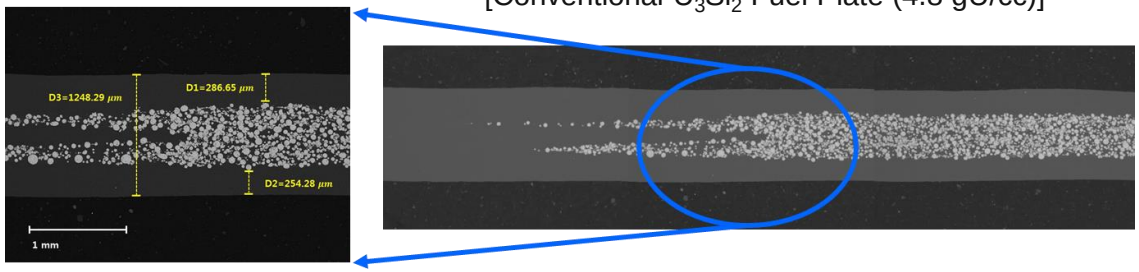
Fuel meat: 599.20 mm



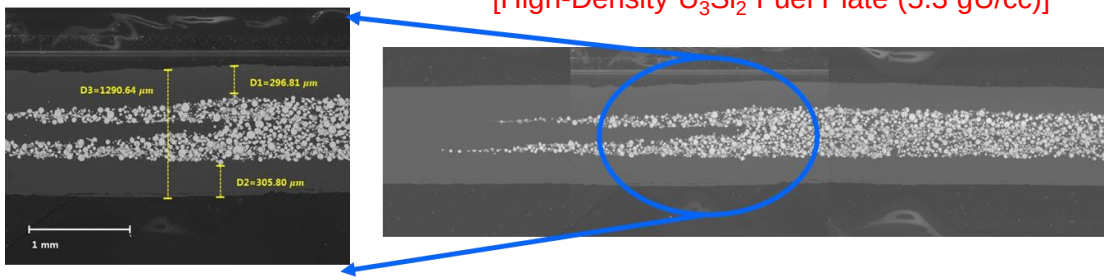

Fuel meat: 601.20 mm



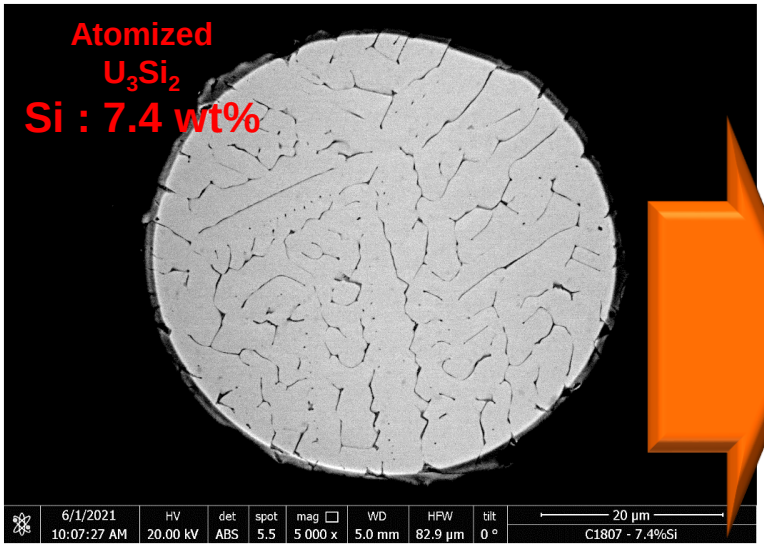

[Conventional $U_3Si_2$ Fuel Plate (4.8 gU/cc)]



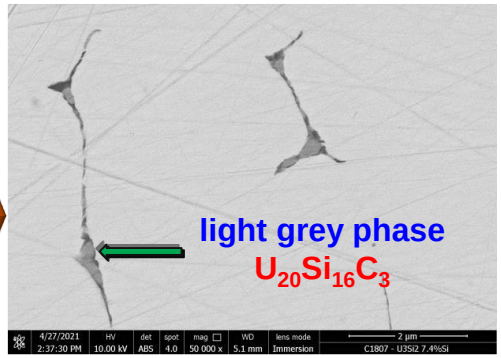

[High-Density $U_3Si_2$ Fuel Plate (5.3 gU/cc)]

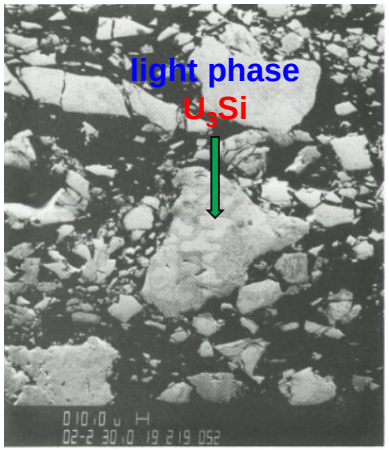


# Phase Identification in Ato. $U_3Si_2$ Powder

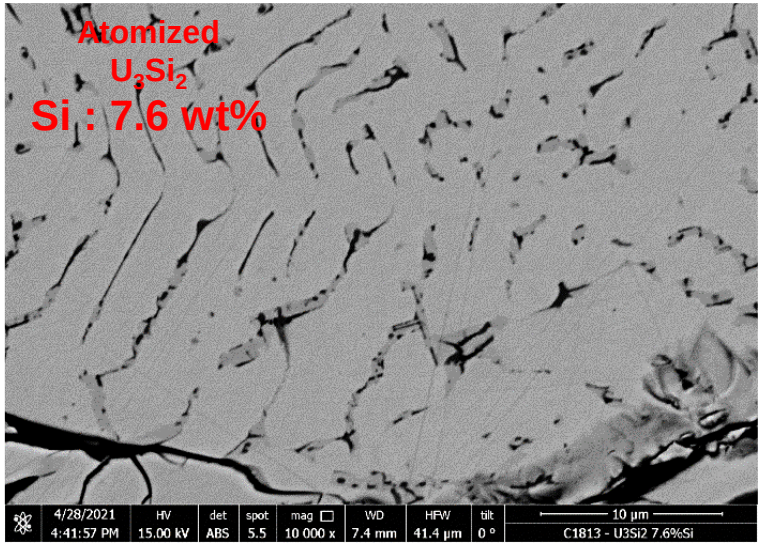



- Microstructural Characterization was co-worked with CEA by Dr. Iltis et. al.

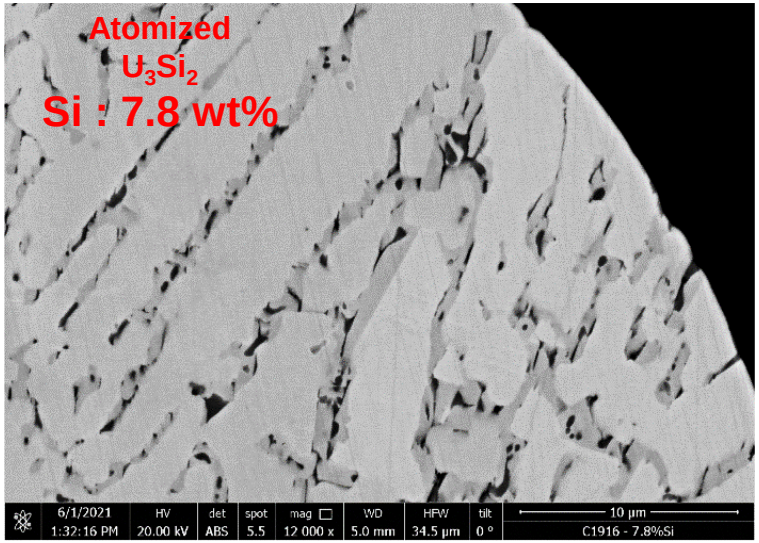



Un-irradiated $U_3Si_2$ (NUREC-1313)




light grey phase
$U_{20}Si_{16}C_3$
+
dark grey phase
$U_3Si_5$ and $U_3M_4Si_4$

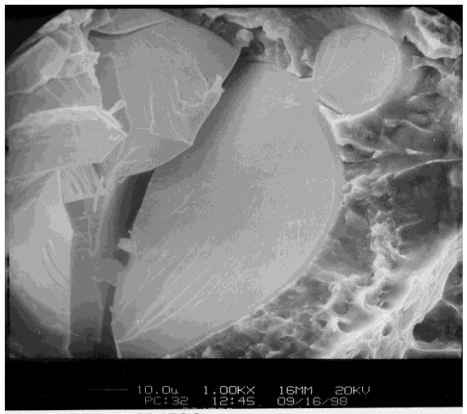


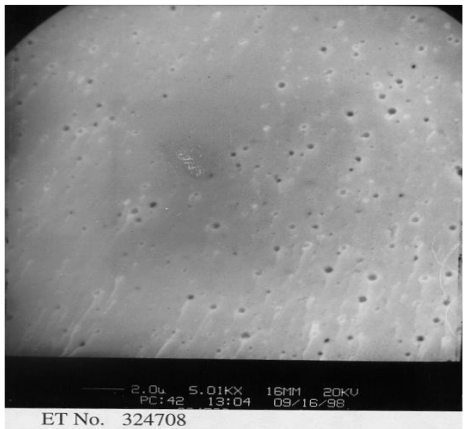
# Irradiation Results of $U_3Si_2$ Fuel

## RERTR 1&2 Test

Atomized $U_3Si_2$

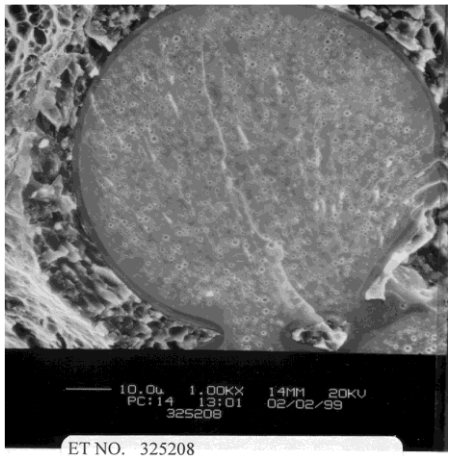
40 at.% BU

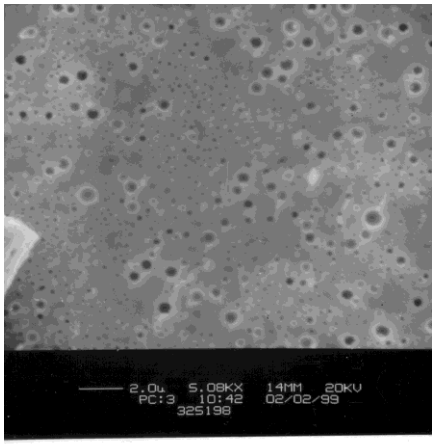


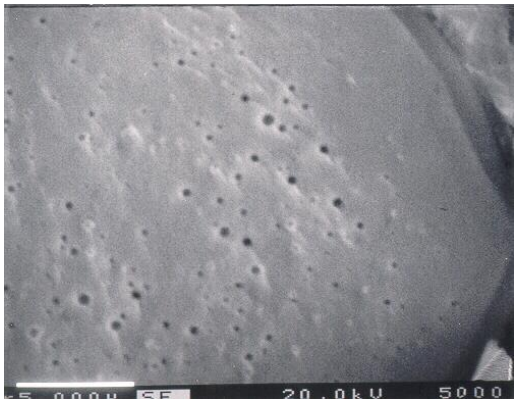

Atomized $U_3Si_2$

70 at.% BU




## HANARO Mini-plate Test




Atomized $U_3Si_2$

50 at.% BU

## NUREC-1313

Ground $U_3Si_2$

97 at.% BU

BSI-202

# Qualification of High Density Atomized $U_3Si_2$ Fuel

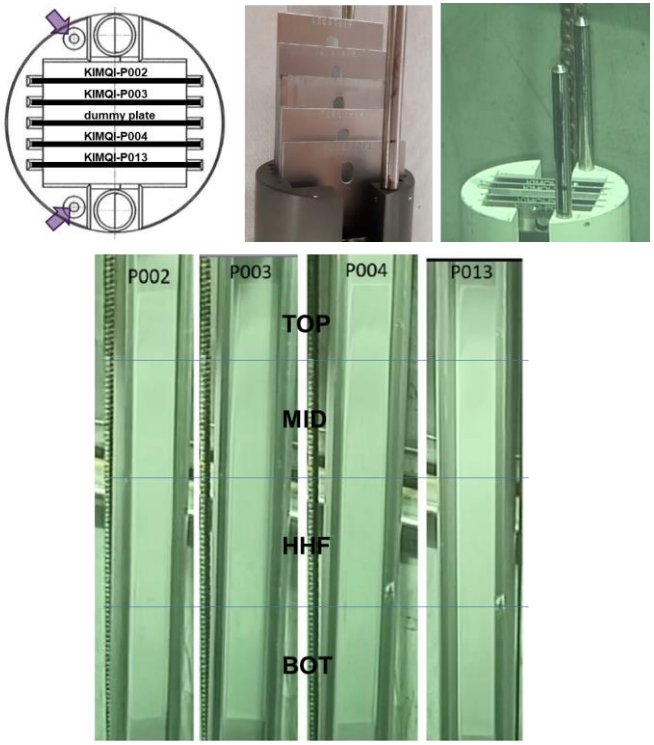
**KIMQI (KAERI High Density AtoMized Silicide Fuel Qualification Irradiation) Project**

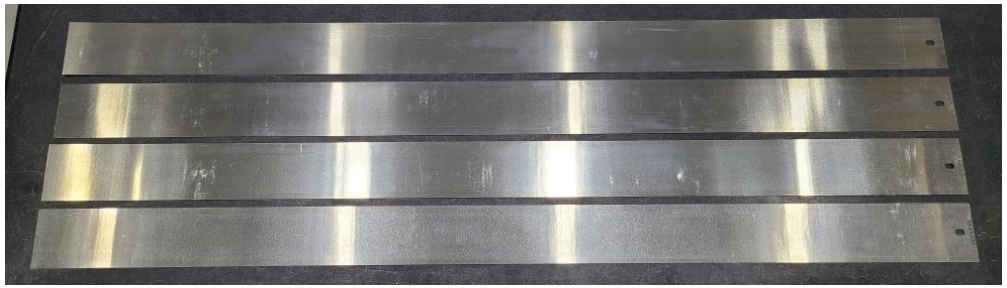
☞ Presentation will be given by Tae-Won Cho during next session

Irradiation Campaign in cooperation with SCK CEN (BR-2)

- Phase 1 (2021~2023): KIMQI-FUTURE for Fuel Performance Confirmation
  - ✓ Irradiation test and PIE with 4 full-size **5.3 gU/cc $U_3Si_2$ flat fuel plate**
  - ✓ **Max. surface heat flux of 470 W/cm$^2$ and peak burnup of 70% U-235 (3 cycle)**
- Phase 2 (2023~2025): KIMQI-GTA Generic Fuel Qualification Program
  - ✓ Irradiation test and PIE 1 full-size 5.3 gU/cc $U_3Si_2$ Generic Test Assembly with ~10 curved plates
  - ✓ Max. surface heat flux of 470 W/cm$^2$ and peak burnup of 70% U-235 (3 cycle)

  ⇒ Qualification for fuel assemblies with HD silicide fuel



[Prototype of full-size 5.3 gU/cc $U_3Si_2$ flat fuel plate]

- Irradiation test (2 cycles) of KIMQI-FUTURE was completed successfully (Jan. 2022)

  **Peak BU : 70.8~72.6 at%U-235**

# *Thank you for your kind attention !*