7th International Symposium on Material Testing Reactors,
October 20–23, 2014, Otwock-Świerk, Poland

Long-Term Irradiation Technology using Capsule at HANARO

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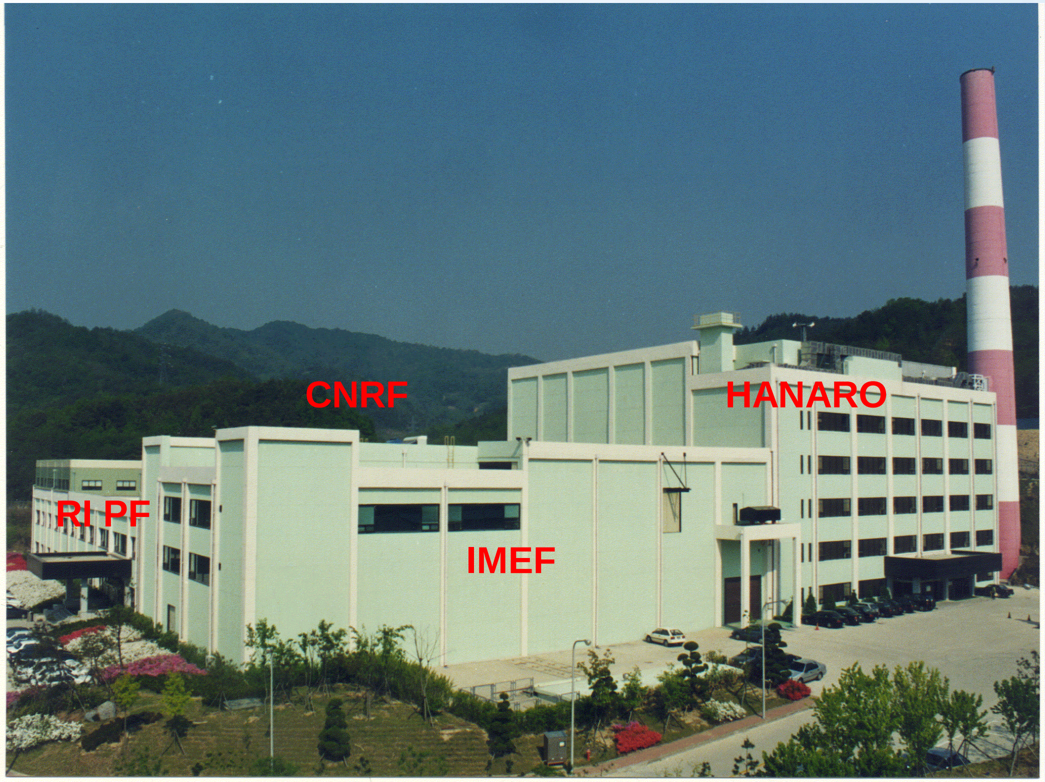
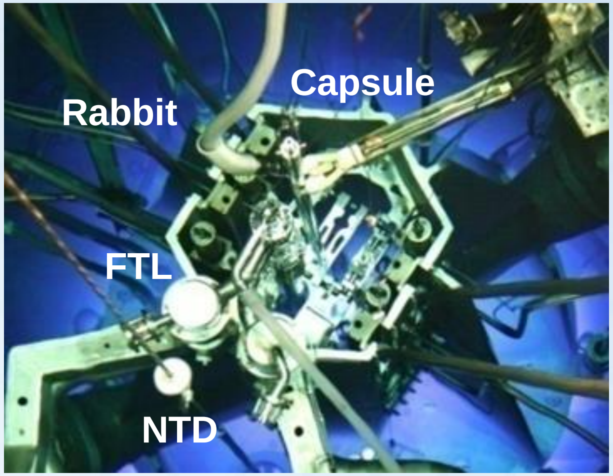
KAERI Korea Atomic Energy Research Institute

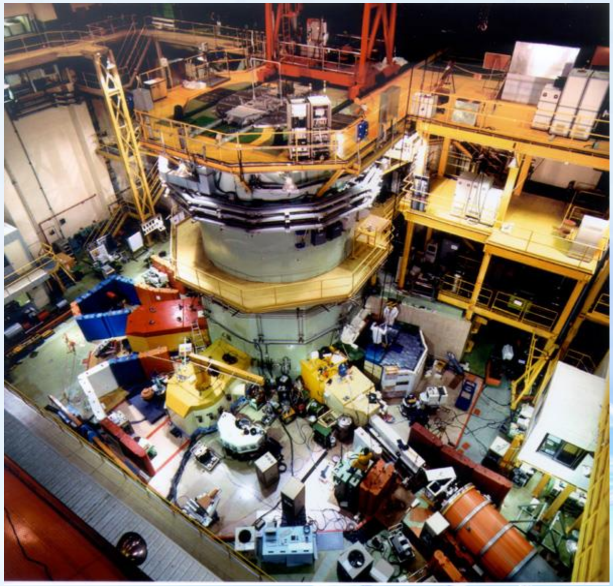
Panoramic views of HANARO

HANARO : Multi-purpose Research Reactor



HANARO Building

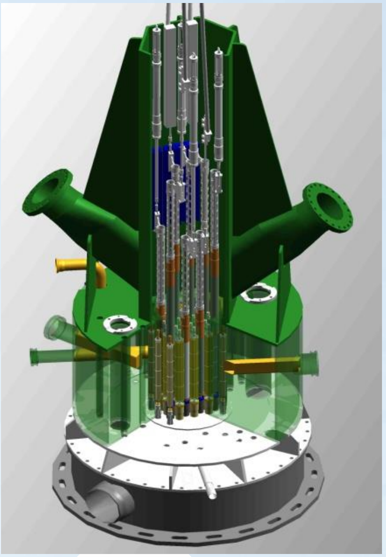




Reactor Hall

General Features of HANARO

Type	: Open-tank-in-Pool
Maximum Thermal Power	: $30MW_{th}$
Max. thermal neutron flux	: $4.4x10^{14}$ $n/cm^2 \cdot sec$
Max. fast neutron flux	: $2.1x10^{14}$ $n/cm^2 \cdot sec$
Coolant	: Light Water
Reflector	: Heavy water
Fuel Materials	: U_3Si, 19.75% enriched
Absorber	: Hafnium
Reactor Building	: Confinement



HANARO has two kind of fuel assemblies.

One is hexagonal type, 36 fuel elements, the other is cylindrical type, 18 fuel elements.

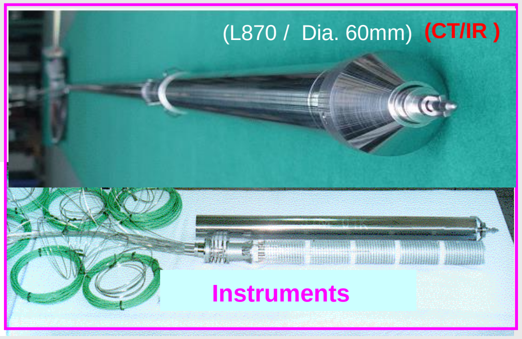
Irradiation Facilities in HANARO

Facilities

- Small Size Specimens : RABBIT
- Standard Size Specimens : CAPSULE
- Si Doping : NTD

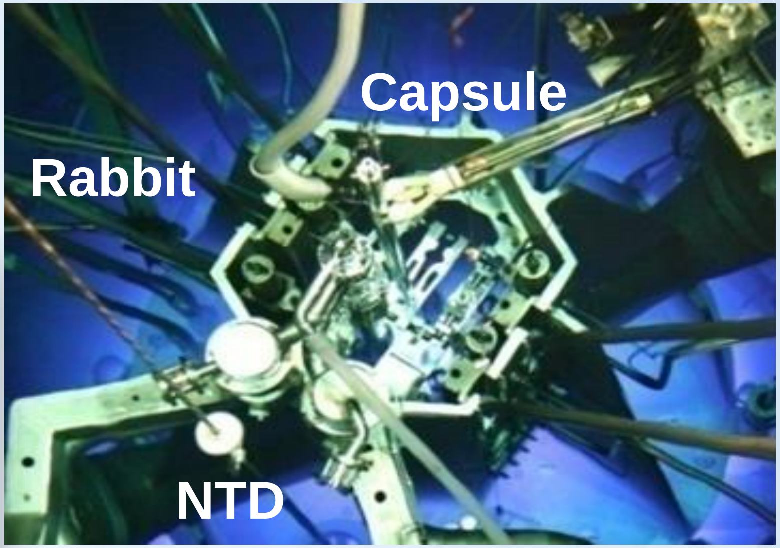
Rabbit

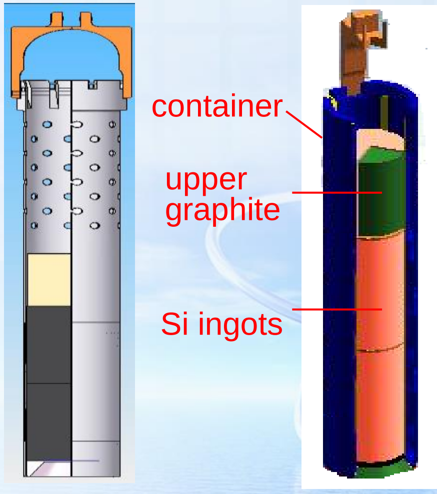
Non-Instrumented Capsule



Instrumented Capsule

Capsule Control System





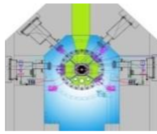
5,6,8 inch Si
(200mm)

National Nuclear R&D Programs

2010 | 2018 | 2023

❑ New Research Reactor

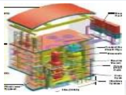
- JRTR construction by **2015** **>** KJRR Construction by **2017** (at Gijang)



('10) Jordan JRTR Contract | ('15) Operation | **U-Mo Fuel & Blanket ('16)** **2[nd] RR at Gijang ('17)** | **RR Export Market**

❑ VHTR (Very High Temp. gas-cooled Reactor) for Gen-IV

- Prototype VHTR construction by **2022** (TRISO fuel & High-temp. materials)

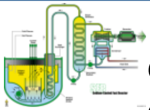


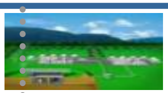
Conceptual design('11) | **Detailed design('17)** | Construction ('22) | Demonstration('23)

TRISO fuel & high-temp. materials('16)

❑ SFR (Sodium-cooled Fast Reactor) for Gen-IV

- Prototype SFR construction by **2028** (Na coolant)

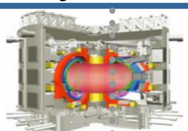


Conceptual design('11) | **Tests & Detailed design('17)** | Construction('28) | Demonstration('28)

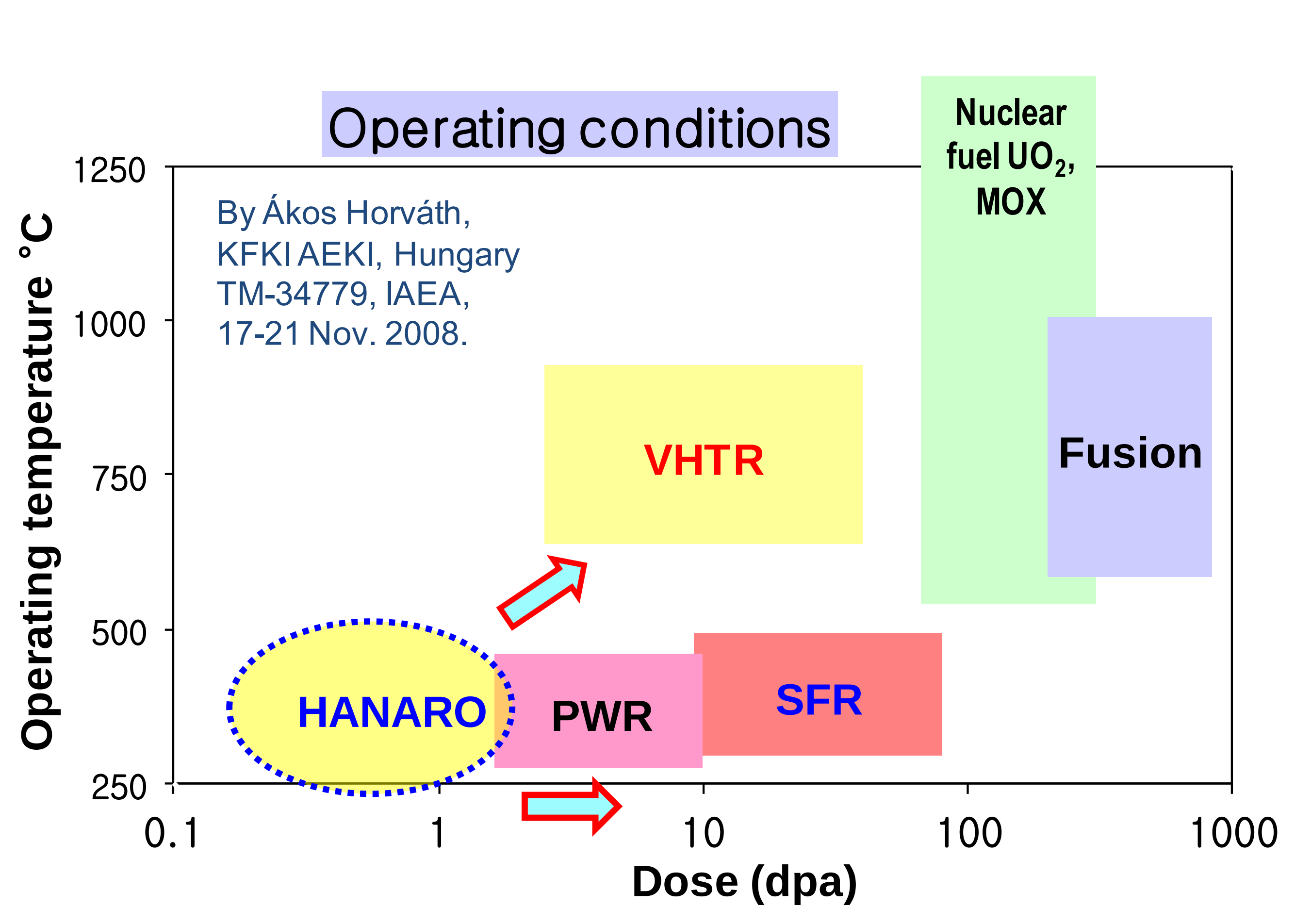
❑ Fusion Reactor

- **KSTAR** Construction by **2007** > **ITER** by **2018 > Fusion DEMO by 2036**


KSTAR Construction ('07) | **TBM Test for ITER('14)** **ITER Construction('18)** | **Fusion DEMO** Construction('36)

Next Generation Nuclear Power Plants



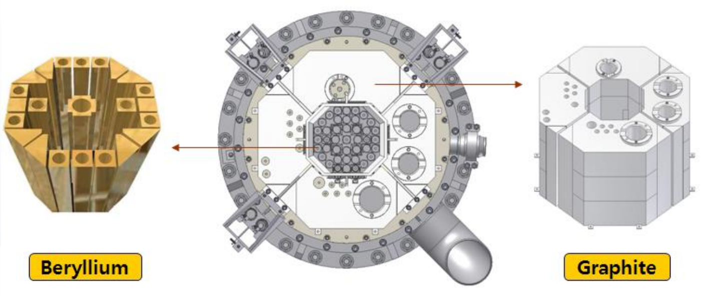
Status of HANARO Irradiation technology

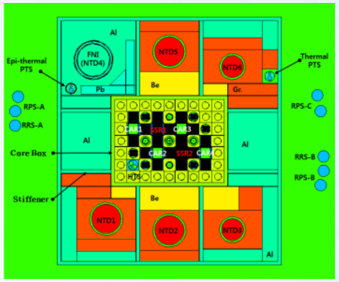
Fields	KAERI	Worldwide	R&D Target	Remarks
Temp. (℃)	250～700	60～1000	60～1000	Irradiation
	±10	±3	±5	Accuracy
Fluence Meas. Accuracy	–	±20%	±20%	Thermal
	±20%	±10%	±10%	Fast
Flux ($n/cm^2.sec$)	$6x10^{12}$～$1.4x10^{14}$	No limit	$1.5x10^9$～$1.4x10^{14}$	E>1 MeV
Long Term Irradiation Cycle (days)	4 cycles (～100 days)	No limit	20 cycles (～500 days)	
Fluence (n/cm^2)	$<1x10^{21}$	No limit	$<5x10^{21}$	E>1MeV
Instruments	K-type T/C	R/D	LVDT / SPND	

Research Reactor Project

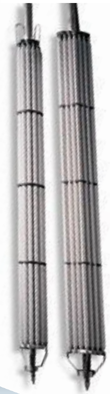
RR Irradiation Project

- Jordan Research Reactor (**JRTR**) by 2016
- Ki-Jang Research Reactor (**KJRR**) by 2017
- **Database** of Be, Graphite, Zircaloy-4 for '**Optimized Core Design**'
- **Material Irradiation**: Growth, Swelling, Tension Hardness, Conductivity, Microstructure at <100℃ up to **8 cycles** (~2×10^{21} n/cm^2, E>1 MeV)
- **U-Mo Plate Fuel irradiation**

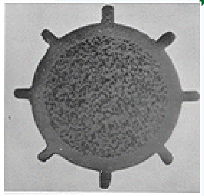


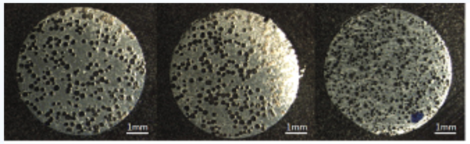


Operation below 100℃



- **HANARO**
  - **Al-U_3Si, 19.75% enriched**
  - **Rod-type 18/36 Fuel Rods**





U-Mo, Plate-type Fuel

New Capsule Design for RR materials

Capsule Design Concept

- RR Core Materials at Low Temps. (<100℃)

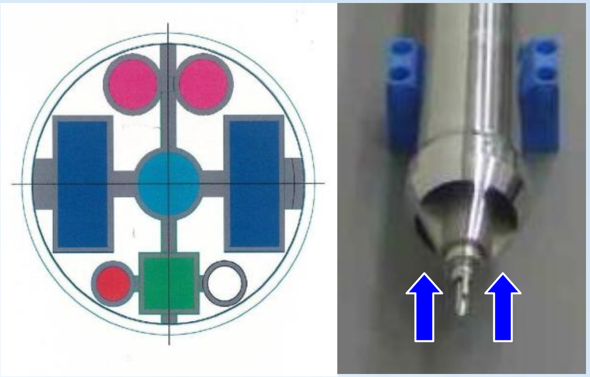
  (Standard Capsule Temp. : 250~700℃)

  - New Design : Coolant Flow into Capsule
- Long-term Irradiation Capsule (> 8 cycles (~ 3 dpa)
- Mock-up Capsule for Out-pile testing (11M-19K)

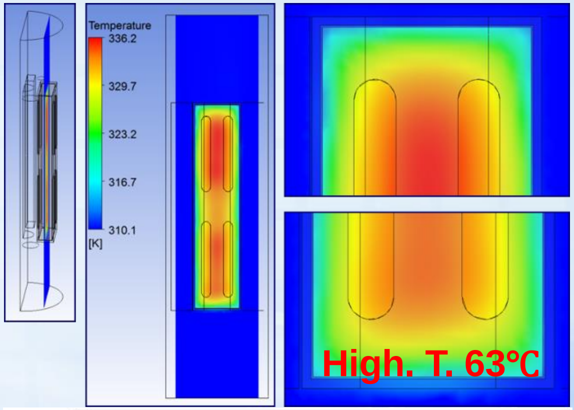
Characteristics / Safety

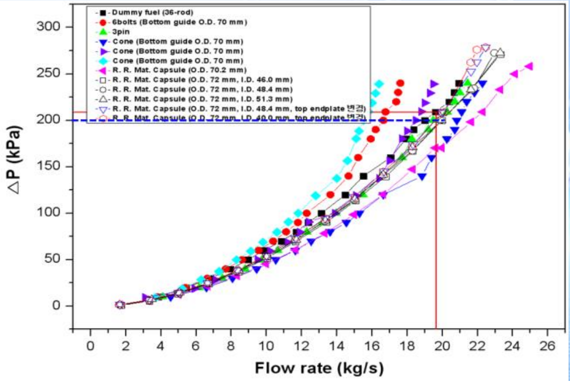
- Evaluation of Nuclear / Thermal Properties
- Hydraulics : Coolant Flow, Vibration
- Endurance Test : 110% of Coolant Flow
- Safety Evaluation and Approval for Irradiation

  (Committee of Reactor Operation)



Coolant Flow into Capsule





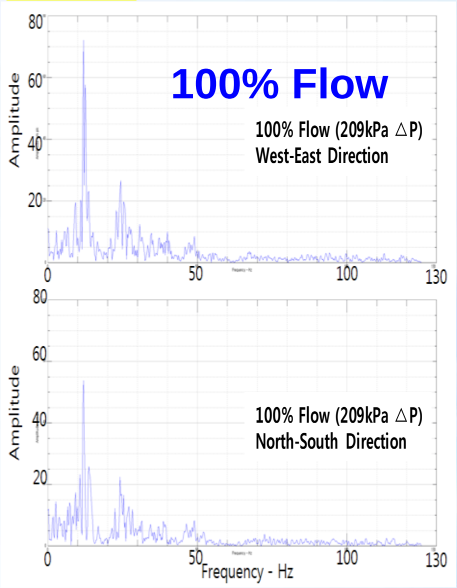
Hydraulics of Capsule in Coolant

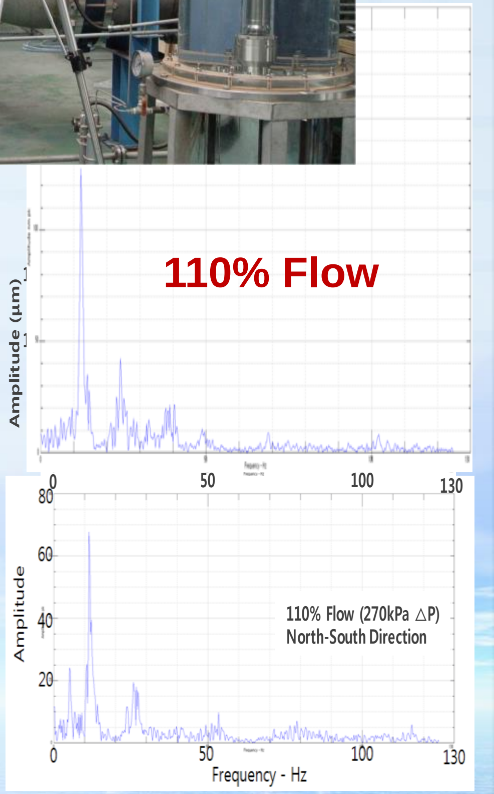
Accelerated Testing (110% Coolant)

Vibration Magnitude 175%↑
at 110% coolant flow

Laser Vibrometer

11 Hz





Flow Induced Vibration Test

Vibration of Capsule in Coolant

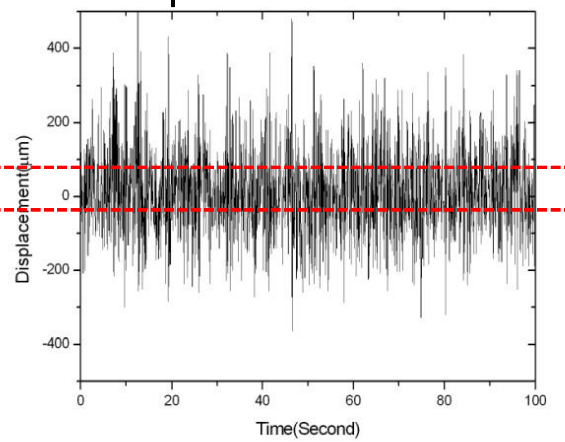
Vibration Properties

- **11M-19K Capsule in 110% Coolant Flow**
  - **Main Vibration Cycle : 11 Hz**
  - **Magnitude at 11Hz : ~120μm**

Condition	1-channel Out-pile Facility	
(1.42m Height)	Coolant Flow 110%	
Measuring	S-N Direction	E-W Direction
Max.	508	404
Min.	-388	-380
RMS*	111.18	**120.42**

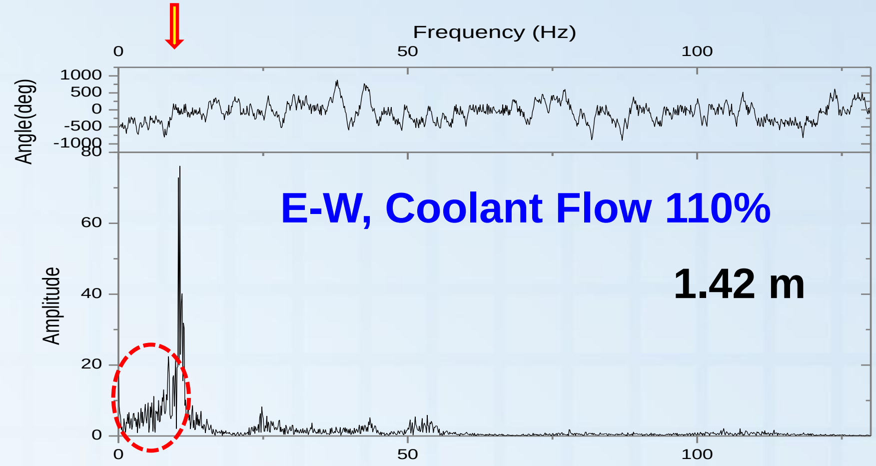
RMS = root mean square

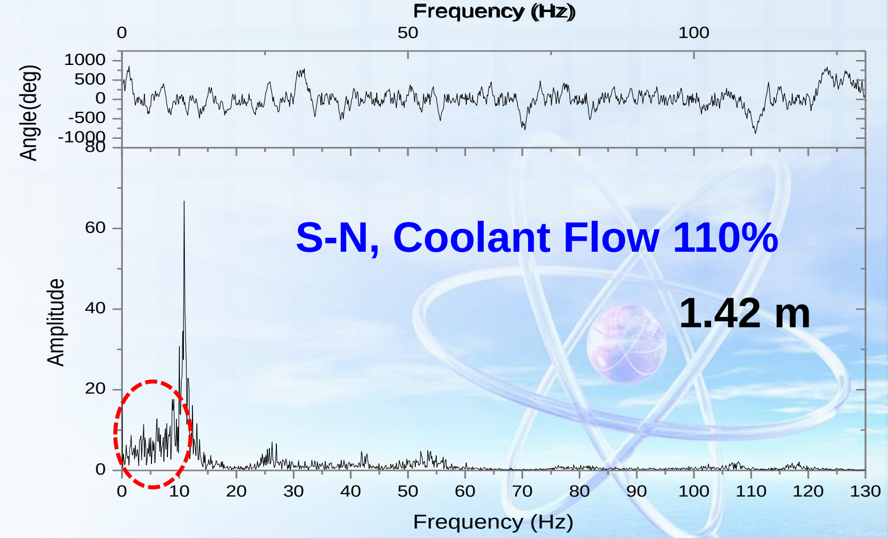
$$\sqrt{\frac{\sum_{k=1}^{n} a_k^2}{n}}$$



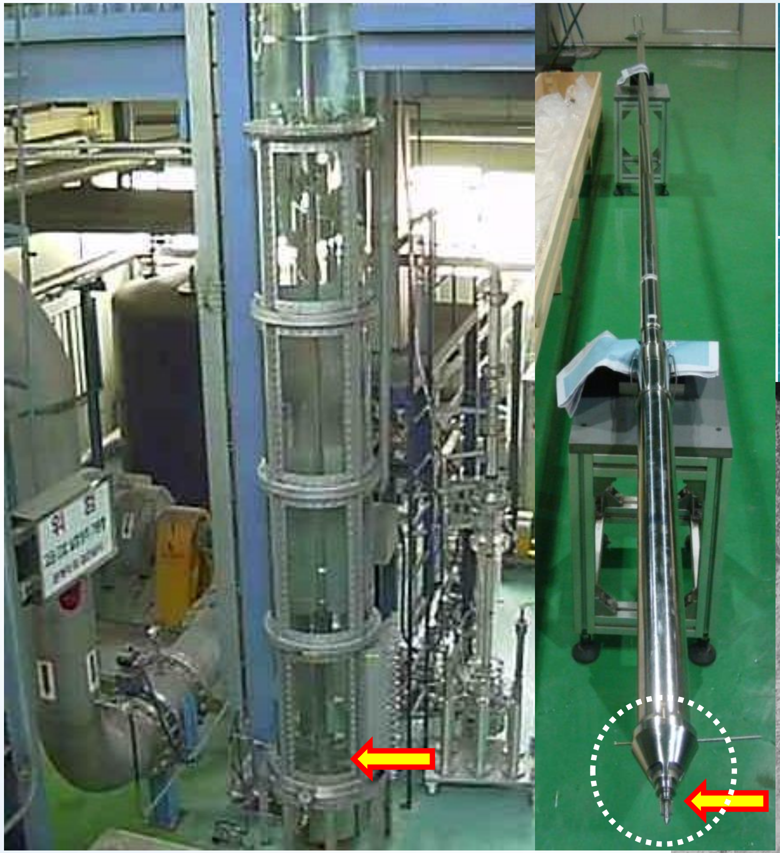
σ = ?

11 Hz

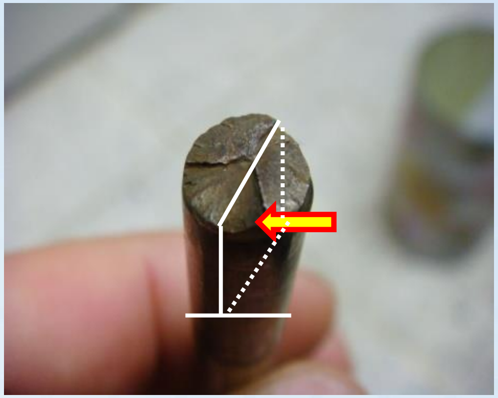


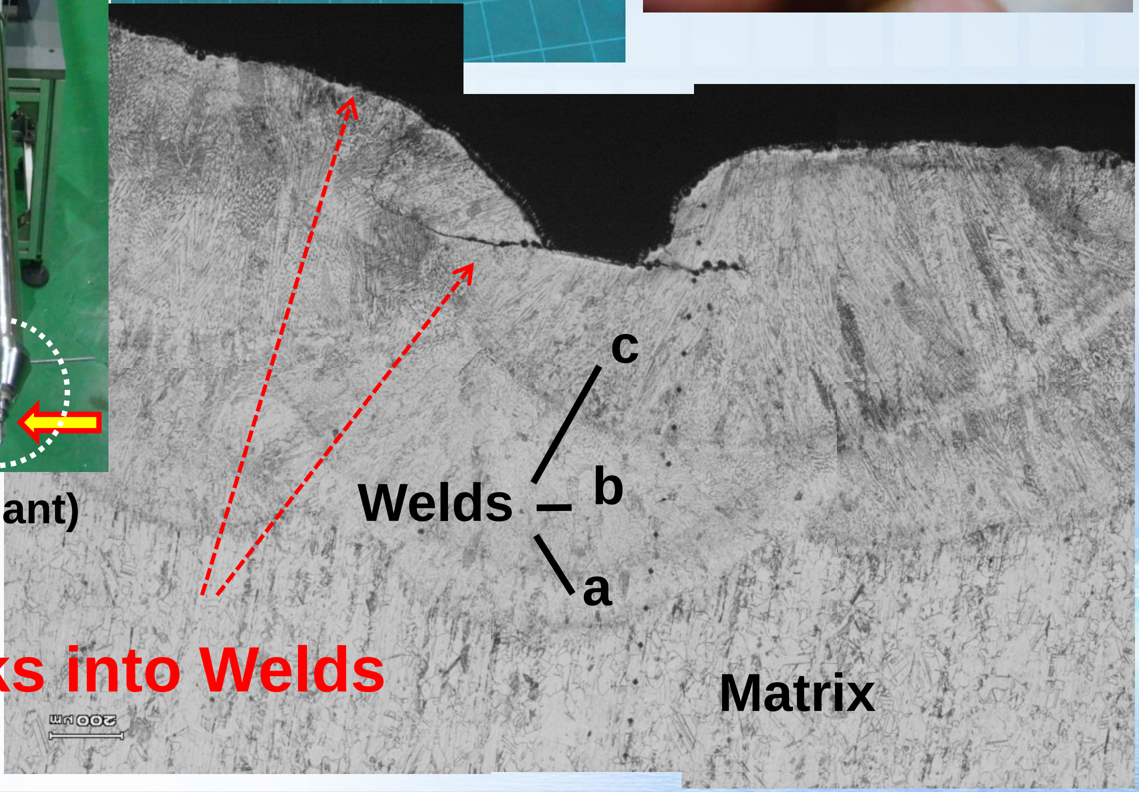


Out-Pile Endurance Test



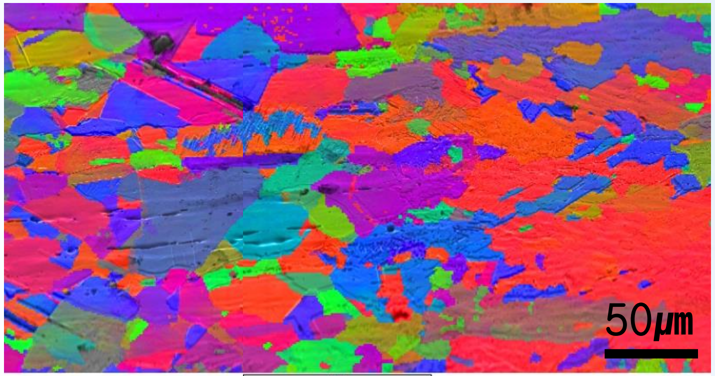
Accelerated Testing (110% Coolant)

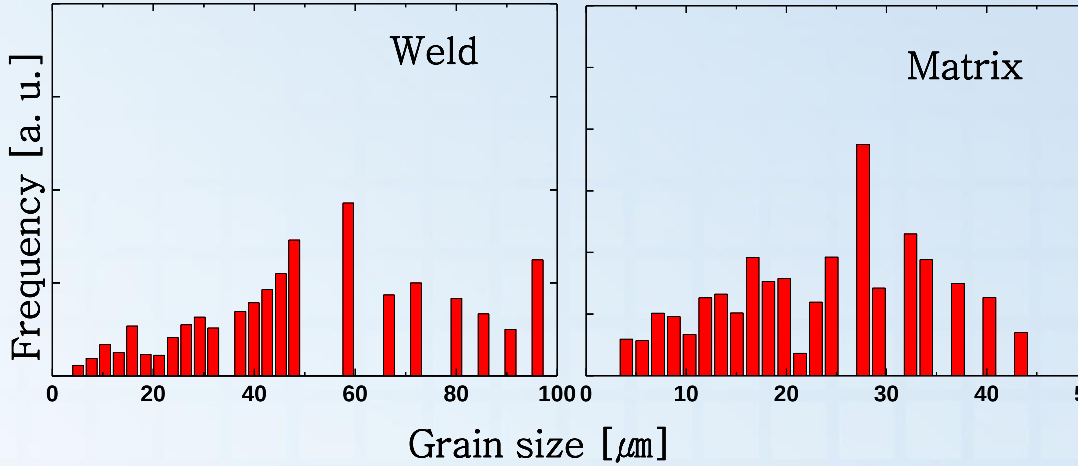


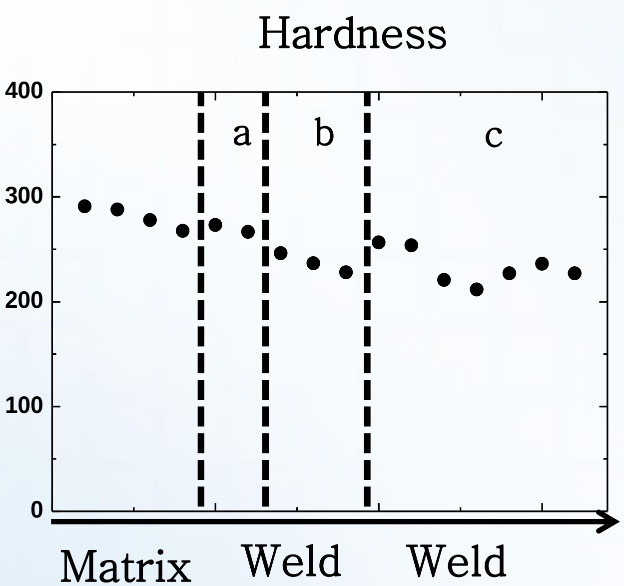


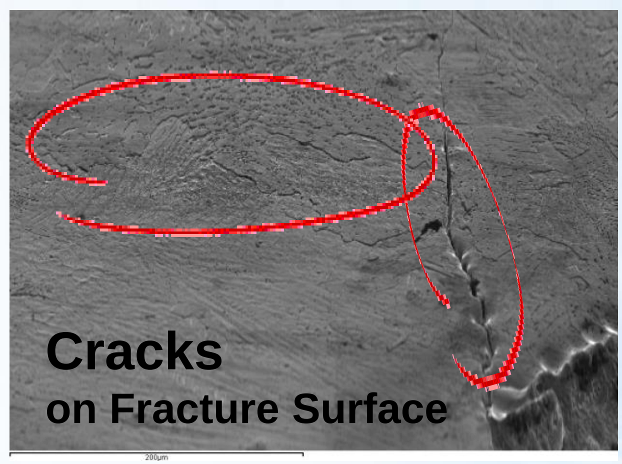
Fractured by Cracks into Welds

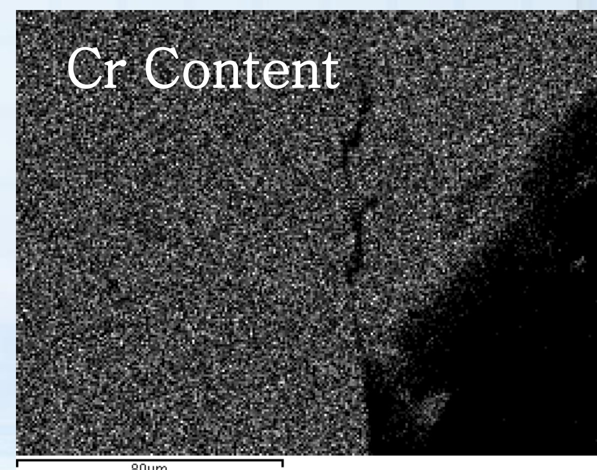
Examination of Fracture Surface







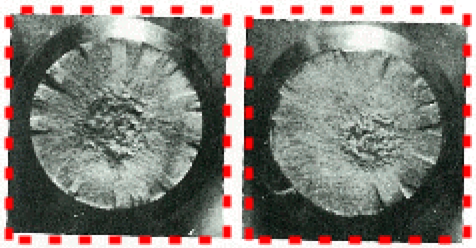


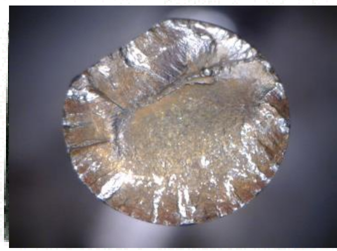


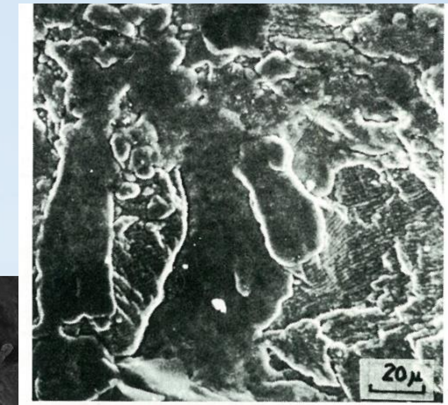
No Apparent Causes for Failure

Analysis on Fracture Surface

- **Fracture Surface : Optical Microscope / SEM**
  - Typical Fatigue Fracture
  - Cracks progress : Surface ⇒ Center region

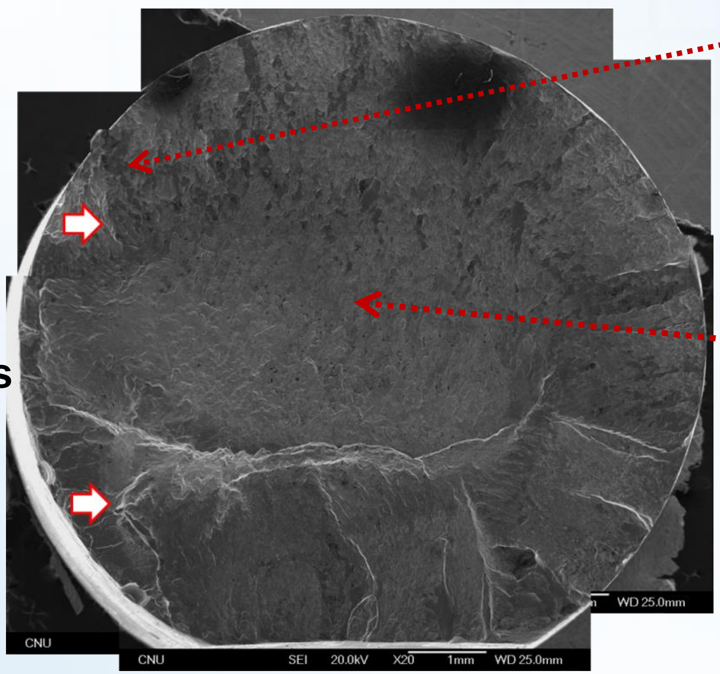


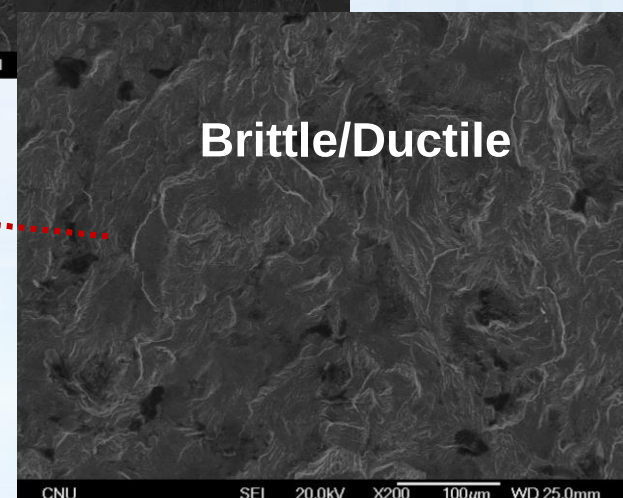




STS316L Fatigue
Material Handbook

Crack
Origins





Design Improvement of Capsule

Rod Tip Design Changes

- Impossible Shape for Stress Relieving -

1) Material Change

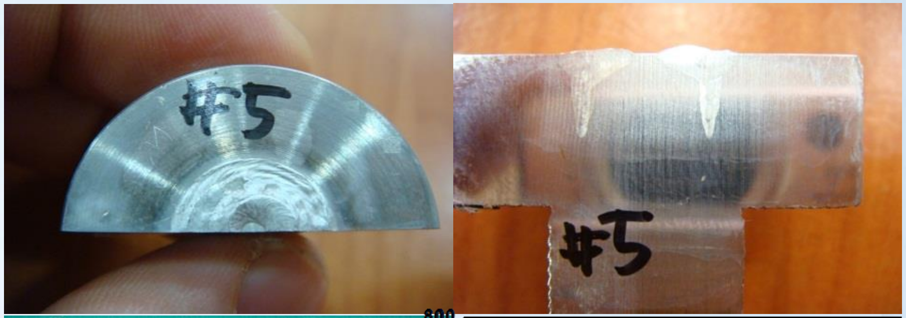
- Stainless Steel 304
- Stainless Steel 316L
  - ➢ <u>Resistant against Fatigue Cracking</u>

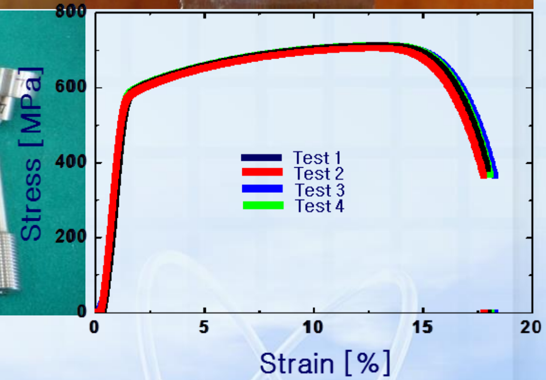
2) Welding Method Change

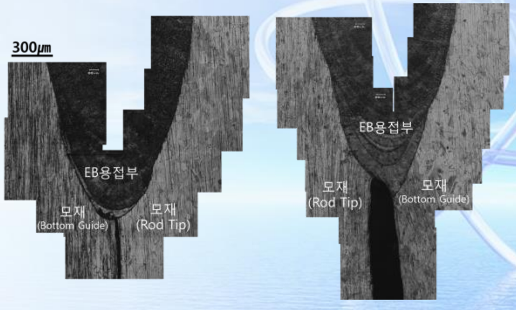
- TIG (Tungsten Inert Gas) Welding
- EB (Electron Beam) Welding
  - ➢ Precise control of Welds : small welds

3) Evaluation

- Mechanical Tests with Mock-up
  - Equivalent Strength to Base-material
- Out-pile Endurance Test
  - Extended Lifetime







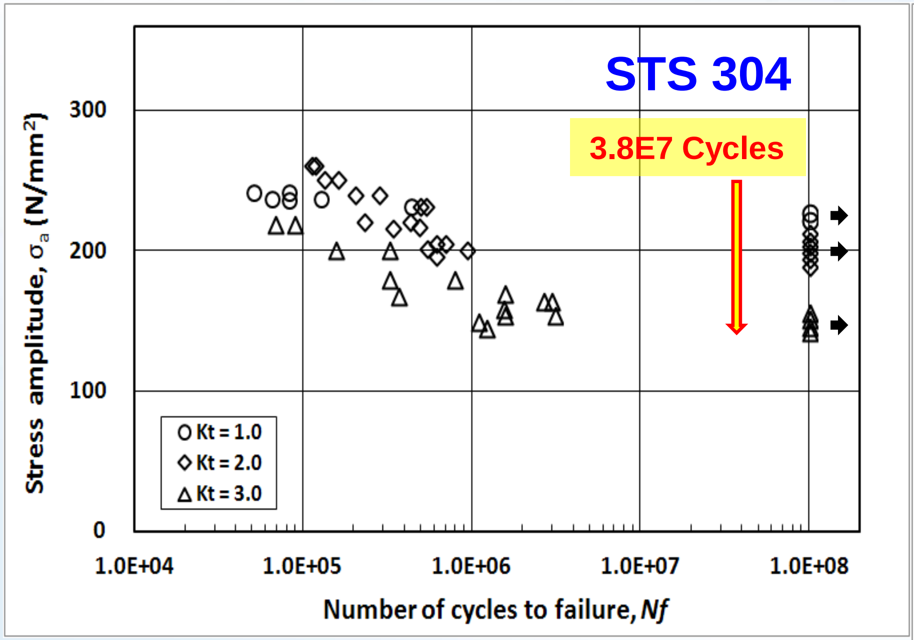
Microstructures of Rod Tip Welds

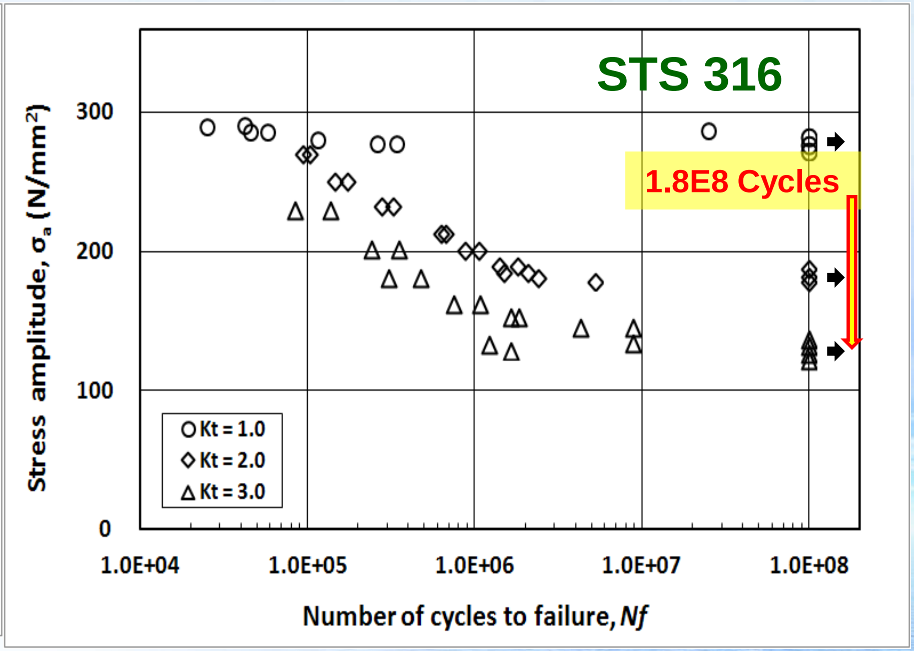
Out-Pile Endurance Tests

Test Results

- Capsule Rod Tip **1st Failure** (**STS304, TIG**)
  - **After 40days** : Cycle < **3.80E+07 Cycles** (=40x24x3600x11Hz)
- Capsule Rod Tip **2nd Failure** (**STS316, EB**)
  - **193~203 days** : Cycle > **1.83E+08 Cycles** (=193x24x3600x11Hz)

* UHCF (Ultra High Cycle Fatigue) : > 10^7 cycles   * Fatigue limit = 120-130 N/mm^2

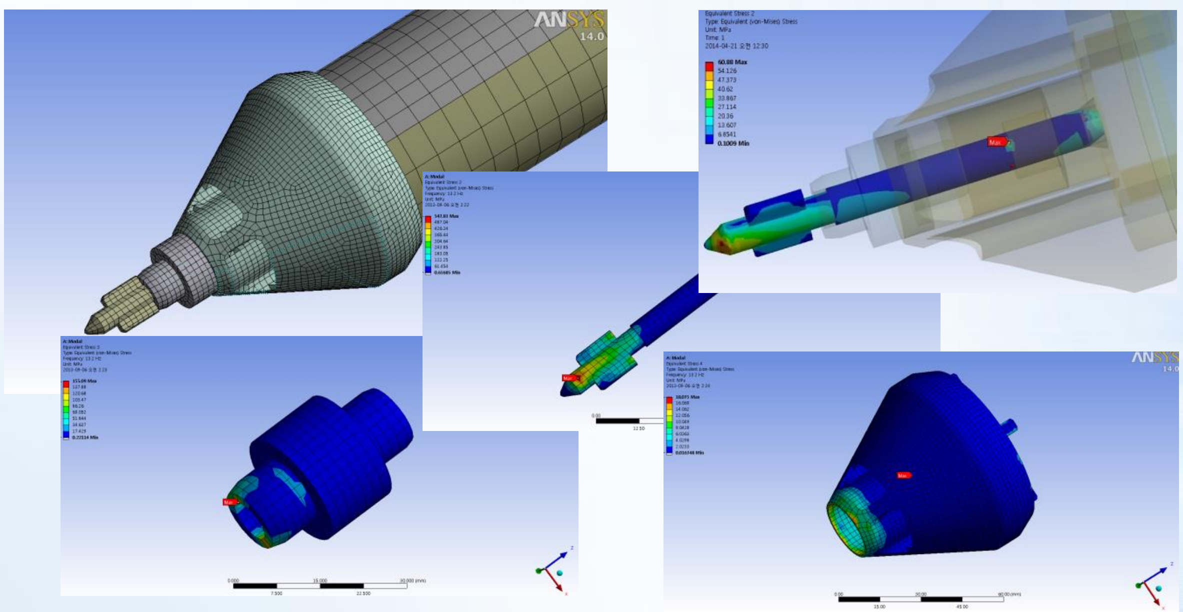


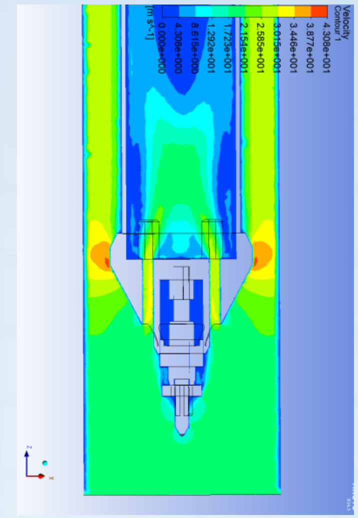


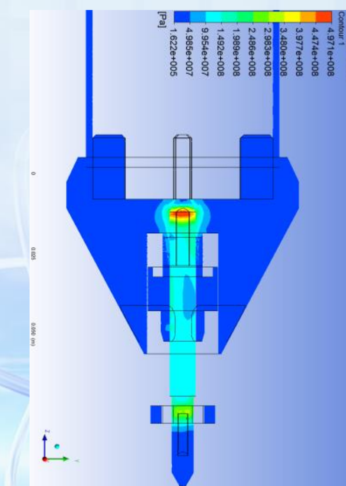
Stress Analysis

Stress/Flow Analysis

- Capsule in Coolant Flow (19 m/sec)
  - Seismic / Coolant Flow Dynamic Analysis
- Stress Analysis by Flow-induced Vibration
  - Seismic Analysis at Rod Tip (weak point) : 36.5/47.5 N/mm^2
    (less than allowed stress (124 N/mm^2 : 0.6xSTS304-UTS(206))
- Additional Data for Optimal Design for Long-Term Irradiation







Improvement of Capsule System

Design Changes

1) Guide Tube

- PVC Spring Hose : consumable
- Stainless Steel SS Braid/Bellows
  - ➢ <u>Permanent system</u>

2) Junction Box

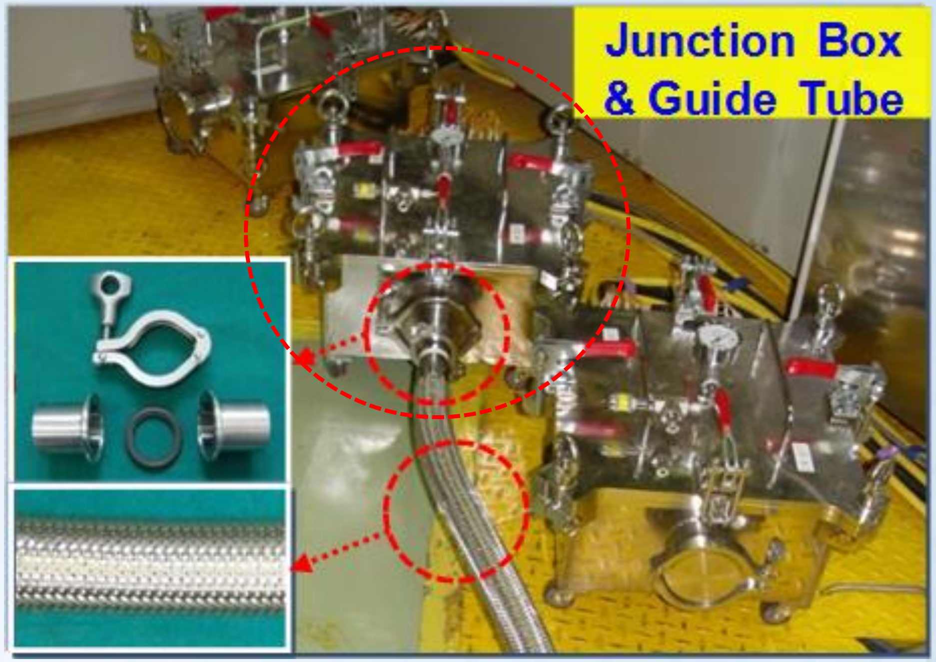
- Enlarged size for work space
- Bolt-Nut closing system

▪Quick Clamp System

- ➢ Precise power control of sealing Gasket

3) Gas Control System

- 2 gas control line
  - Inlet (Bottom) / Outlet (Top)
  - First operation in Nov. 2014



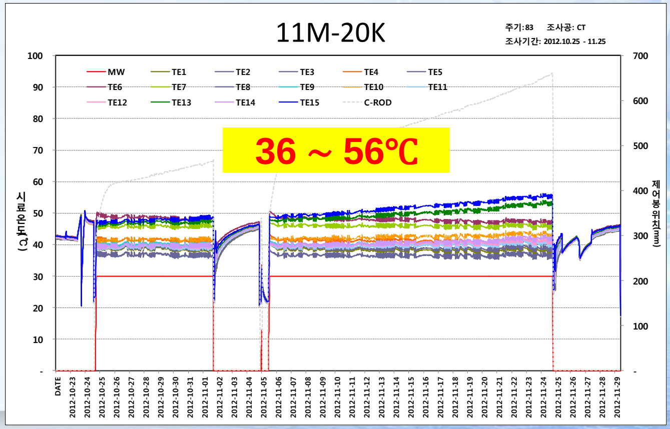

Capsule Control System

Long-Term Irradiation Capsules

Irradiation Capsule

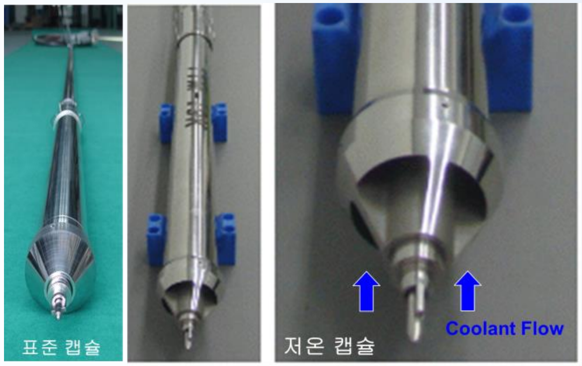
- **Specimen**
  - Material : Graphite, Be, Zircaloy-4
  - Tensile, Growth, Swelling, Hardness, Thermal conductivity
  - 532 specimens

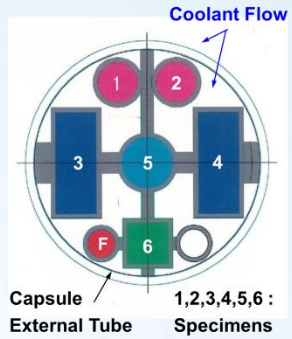
- **Capsule**
  - 11M-20K, 11M-21K
  - Thermocouple, fluence monitor (F/M)
  - 4 / 8 cycle irradiation at low temperature (36-56℃)

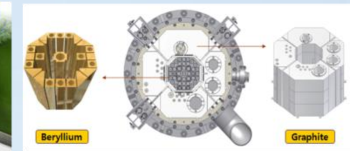


Long-Term Irradiation at HANARO

◆ Low Temp. Irradiation Technology



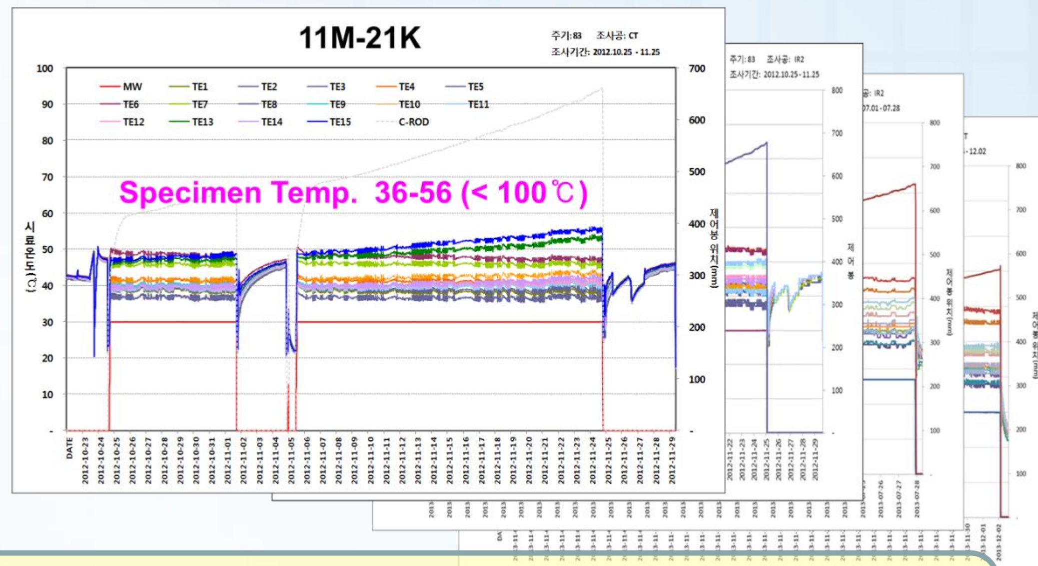




연구로 노심 최적설계 및
인허가 승인에 필수 자료 !

◆ Long-Term Technology

RR Projects



…. 8 cycles

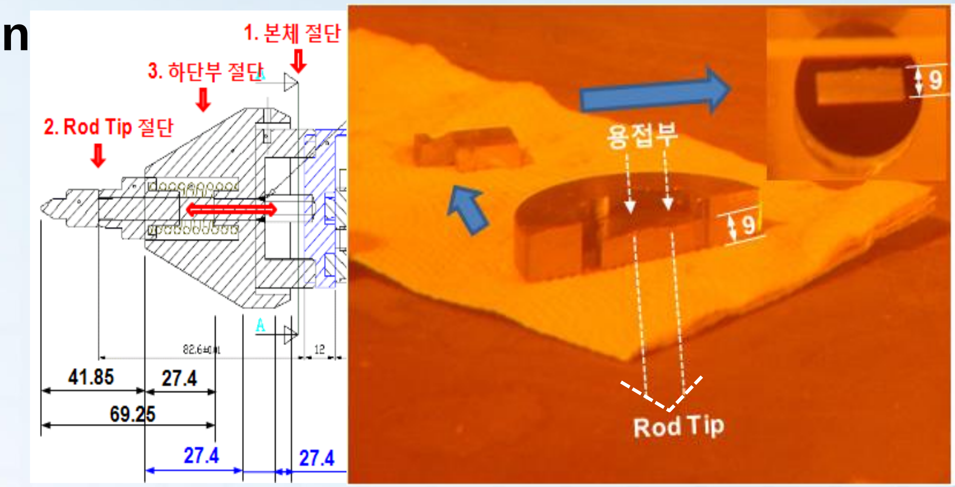
HANARO Long-Term Irradiation Technology contributes
National Nuclear R&Ds on Research Reactor

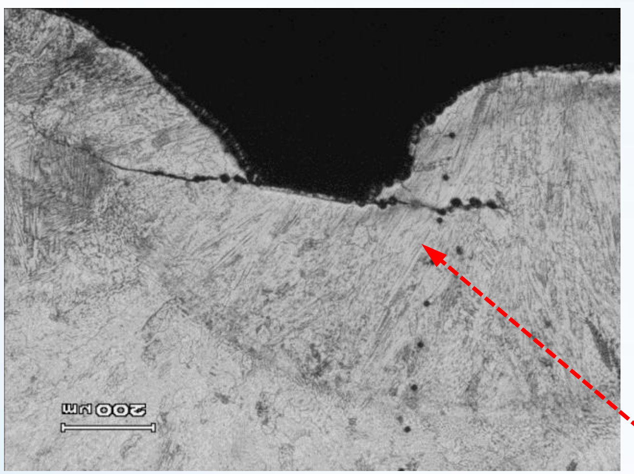
Microstructure Examination

Rod Tip after Irradiation

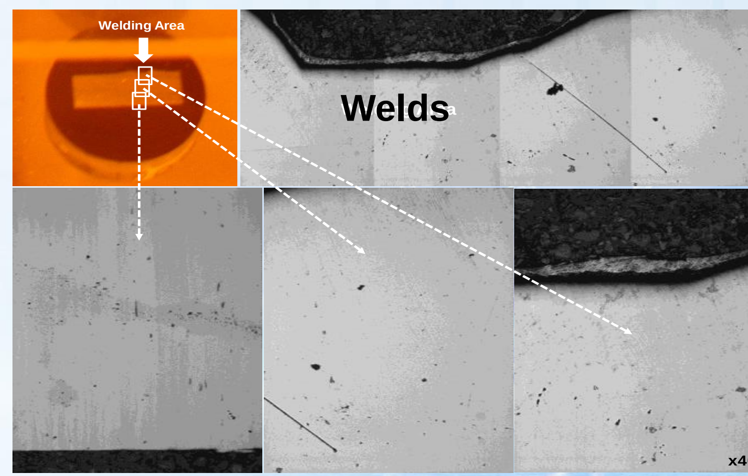
- Visual Examination after Irradiation
- Microstructure Examination
  - Optical / SEM : Integrity
  - Micro-cracks / Defects

Cutting in Hot Cell





Internal Cracks in Welds
of Out-Pile Tested Capsule

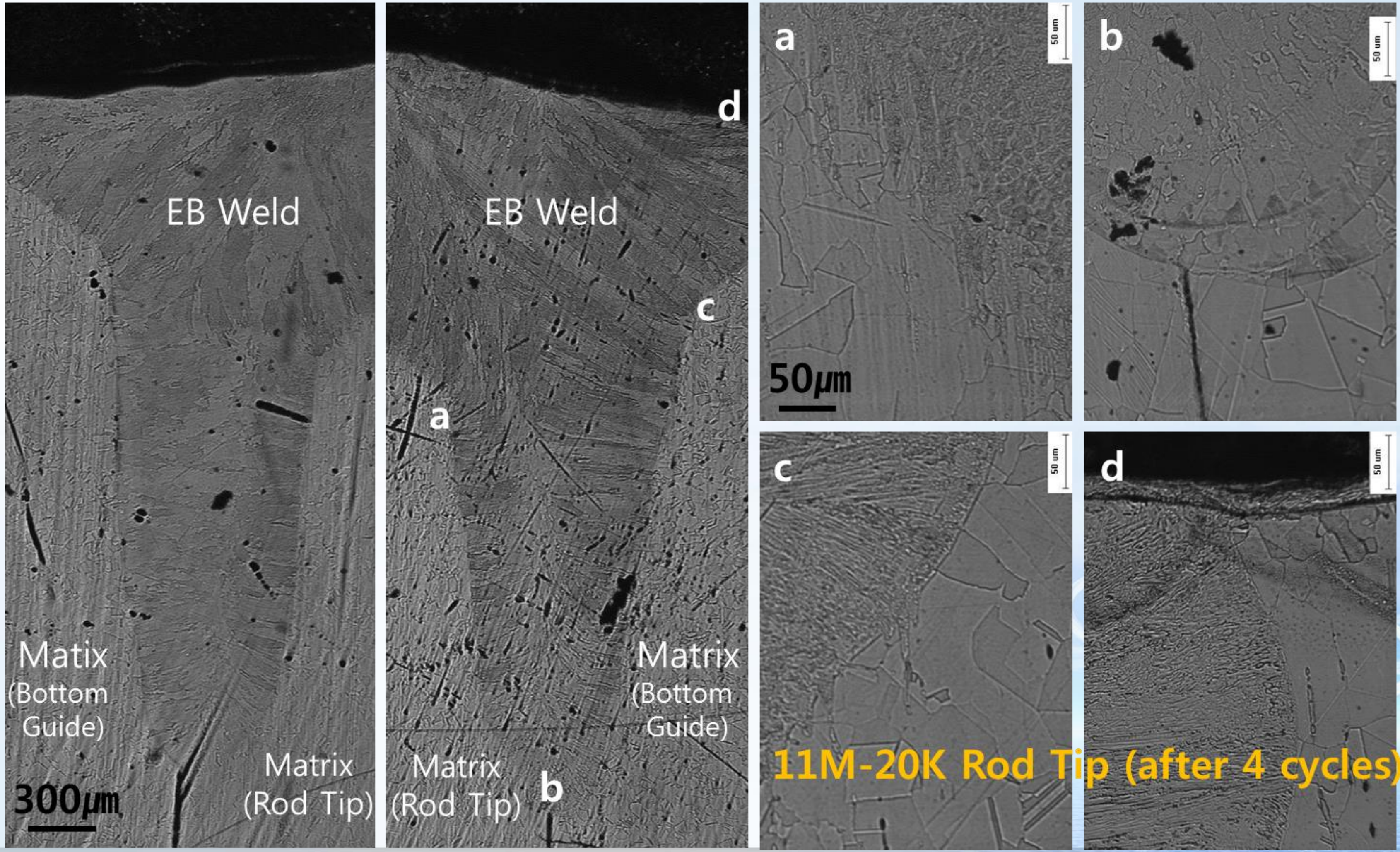


Microstructure Examination

Post Irradiation Examination (II)

Capsule (11M-20K) after 4 cycles

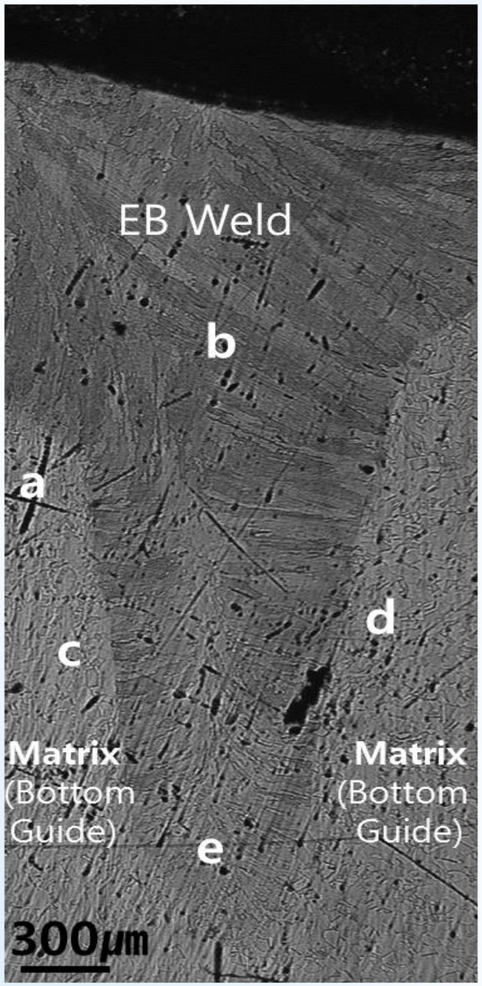
- **No cracks / defects** was observed after 4 irradiation cycles

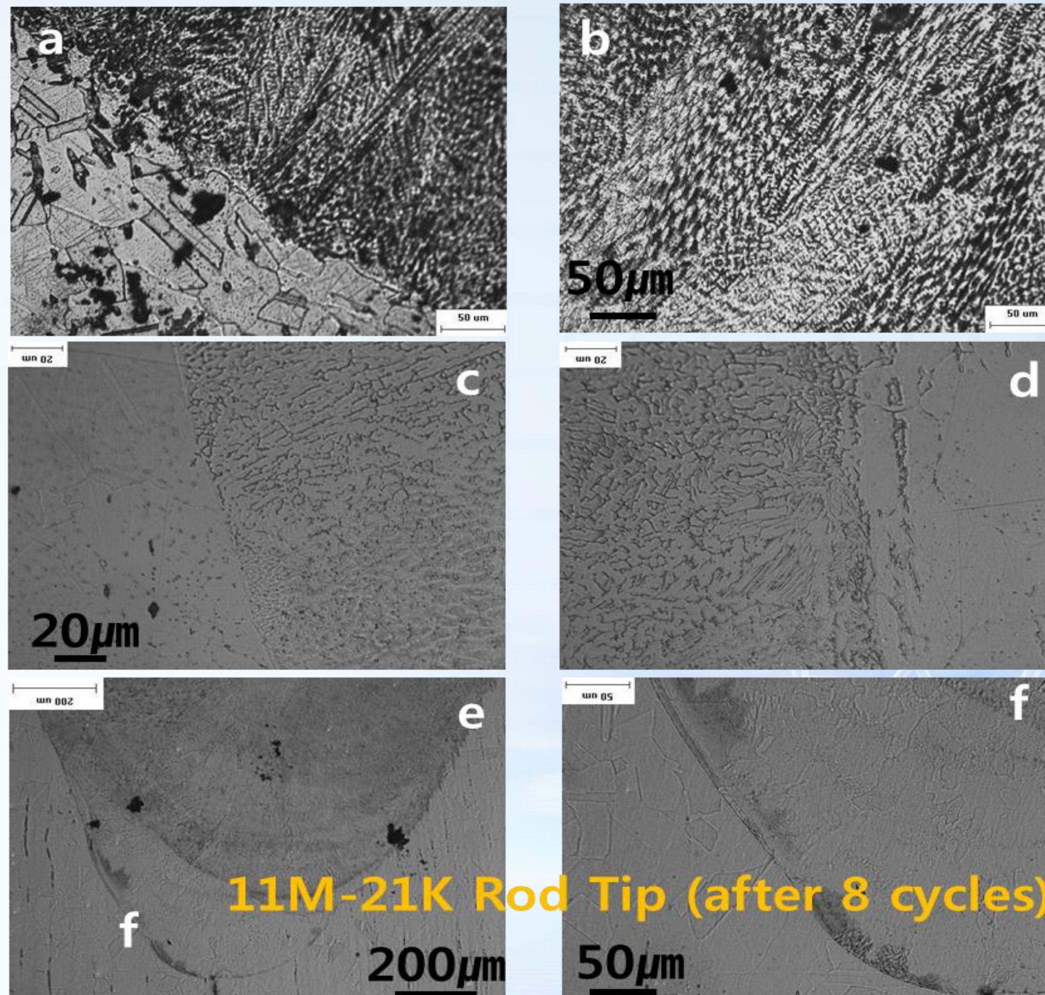


Post Irradiation Examination (II)

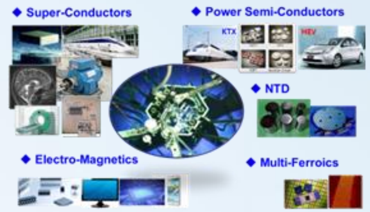
Capsule (11M-21K) after 8 cycles

- **No cracks / defects** was observed after 8 irradiation cycles (~2x10^{21} n/cm^2, E>1 MeV)





Irradiation Contribution of HANARO



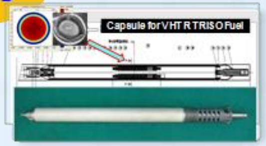
Neutron for Advanced Materials
NTD, Semiconductor, Electronics..
2018. 5

NGNP/Fusion: Core Materials
Fuels (Blanket, TRISO, U-Zr..)
2015. 6~

JRTR/KJRR : Core Materials
U-Mo Plate Fuel
2015. 5

SMART : Steam Generator Materials
2010. 04

SFR/VHTR U-Zr /TRISO Nuclear Fuels
2009.10~



OAK RIDGE National Laboratory | U.S. DEPARTMENT OF ENERGY | GEN IV International Forum

VHTR high-Temp. Materials for
I-NERI Project (Korea-US)
2008. 3

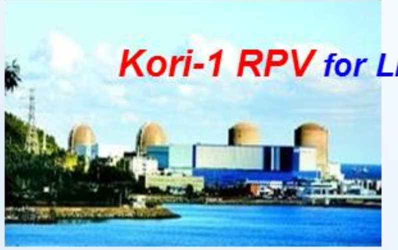
Control Rod Materials for KNF/WEC AP1000 (U.S.)
2007. 11

한전원자력연료주식회사
KNFC KOREA NUCLEAR FUEL CO., LTD.

2006. 4~
Nuclear Fuel Assembly Parts for
KEPCO Nuclear Fuel Co.

HANA Fuel Cladding

2002. 4~



Kori-1 RPV for Life-Extension
2001. 5~

DOOSAN
두산중공업

2000. 3
Korean-made RPV steel for Doosan Heavy Inc.

Summary

1) A new capsule for 'Long-Term Irradiation' was successfully designed and irradiated up to 8 cycles (~3 dpa) in HANARO.
2) It was evaluated to be safe by post-irradiation microstructure examination showing no Defects / Cracks in the vulnerable part (rod tip).
3) The rod tip of the capsule was observed to be vulnerable and it seems to be caused by fatigue failure due to vibration of the coolant flow.
4) Considering the literature [P. Fenici (1992)] that the crack initiation is quite time-consuming process (more than 50%) and that neutron irradiation retards crack initiation/growth of stainless steel, the new capsule design can be applied for a longer irradiation test.
5) Standard capsule having smaller vibration than Low-temp. capsule will be enough safe for 8 cycle irradiation in HANARO.

Vibration (μm)	Standard Capsule			Low-Temp. Capsule		
	Max.	Min.	RMS	Max.	Min.	RMS
S-N Dir.	105	-117	23	508	-512	179.74

* Vibration Properties measured by Laser Vibrometer at ½ Core Out-pile Test Facility

Thank you for your attention!

KAERI

Korea Atomic Energy Research Institute

HANARO