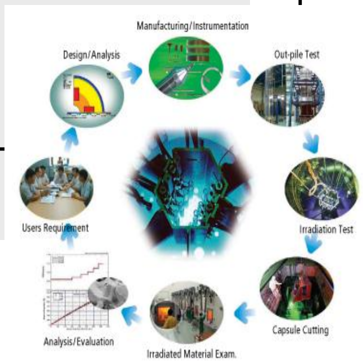
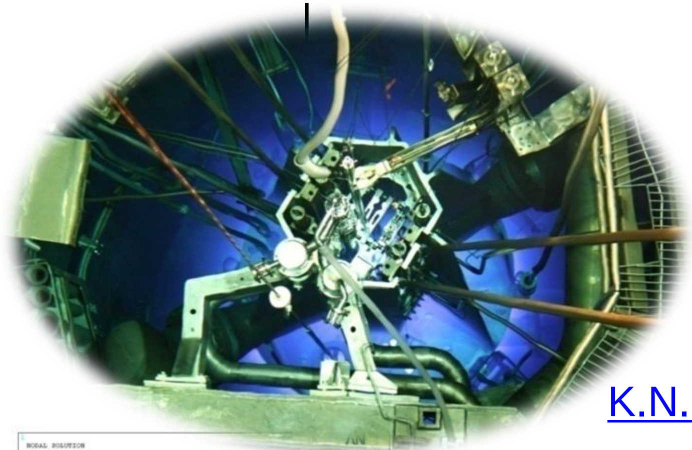
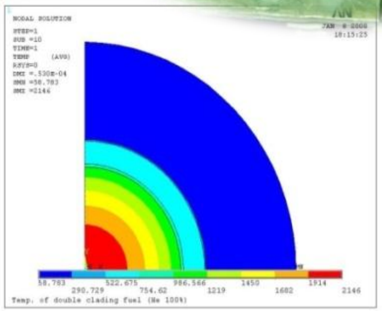


Contribution of HANARO to the R&D relevant to the SMART & VHTR Systems



K.N. Choo, M.S. Cho, J.S. Park, W.J. Lee, I.C. Lim, J.J. Ha



Material Irradiation in HANARO

Korea Atomic Energy Research Institute

Outline

- Status of Irradiation Facilities in HANARO
- Contribution of HANARO to the R&D on Commercial Reactors
- Contribution of HANARO to Future Reactor Systems

  (for VHTR and SMART Systems)

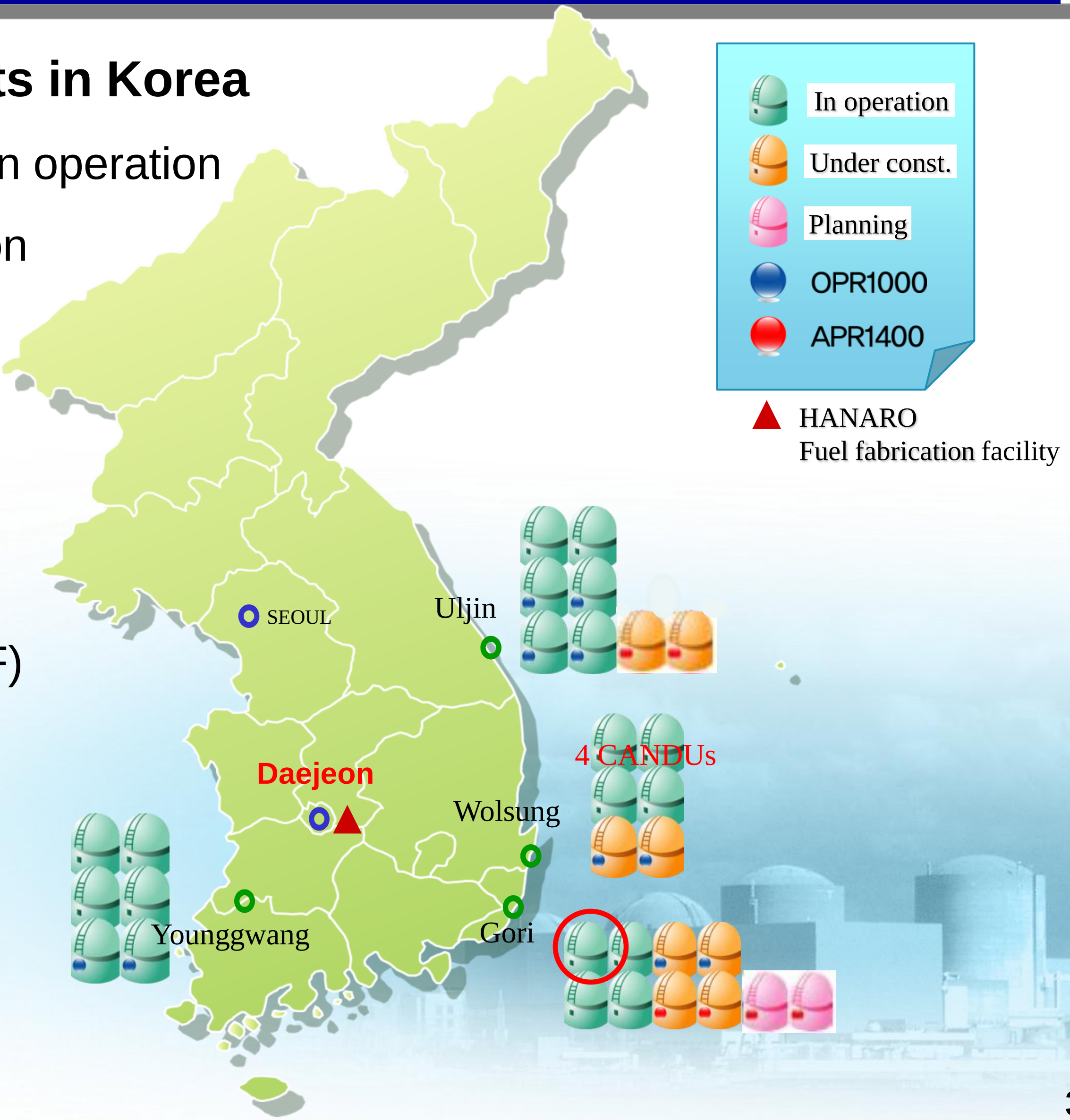
Status of Nuclear Plants in Korea

❑ Nuclear Power Plants in Korea

- 20(16 PWR, 4 CNADU) in operation
- 8 PWR under construction
- 2 PWR construction plan

❑ Daejeon Area

- KAERI (HANARO)
- Korea Nuclear Fuel (KNF)

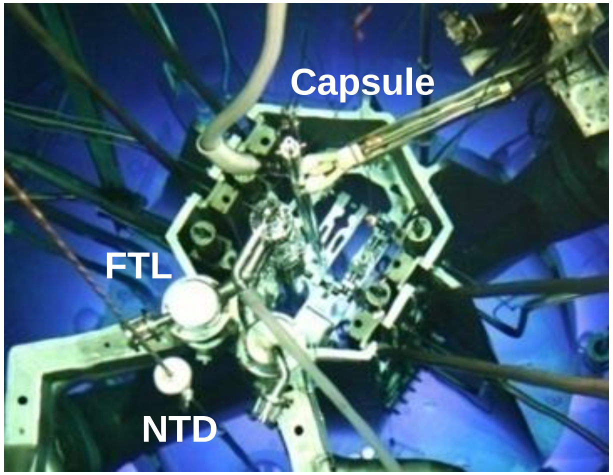


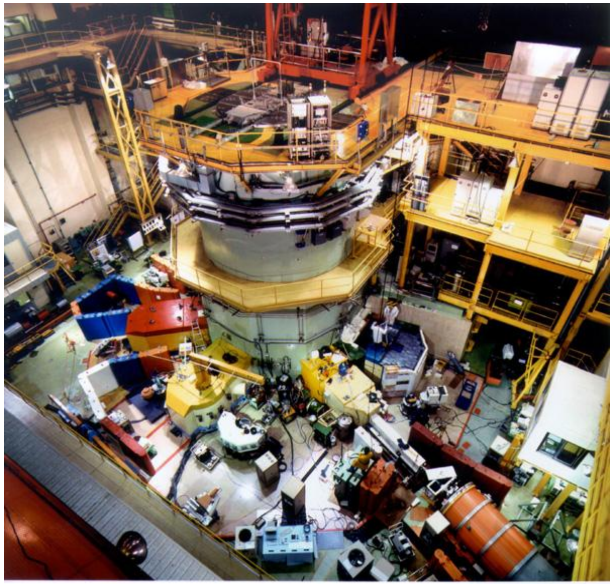
HANARO & Irradiation Facilities

HANARO (High-flux Advanced Neutron Application ReactOr)

HANARO : Multi-purpose Research Reactor

HANARO Building





Panoramic views of HANARO

Reactor Hall

Chronology of HANARO

- ○ 1985.05 KMRR (Korea Multi-purpose RR) Project Approval
- ○ 1990.12 Detail Design Completed
- ○ 1994.12 Construction Completed
- ○ 1995.03 Commissioning Completed
- ○ 1995.04 First Criticality Achieved
- ○ 1996.01 RI Facility Operation Started
- ○ 1998.01 NAA Started
- ○ 1998.01 Material Irradiation (Capsule) Research Started
- ○ 2000.01 Thermal Neutron Beam Research Started
- ○ 2002.12 NTD Commercial Service Started
- ○ 2008.12 Fuel Test Loop Completed (Test Operation)
- ○ 2010.04 Cold Neutron Research Facility Completed

Korea Atomic Energy Research Institute (KAERI)

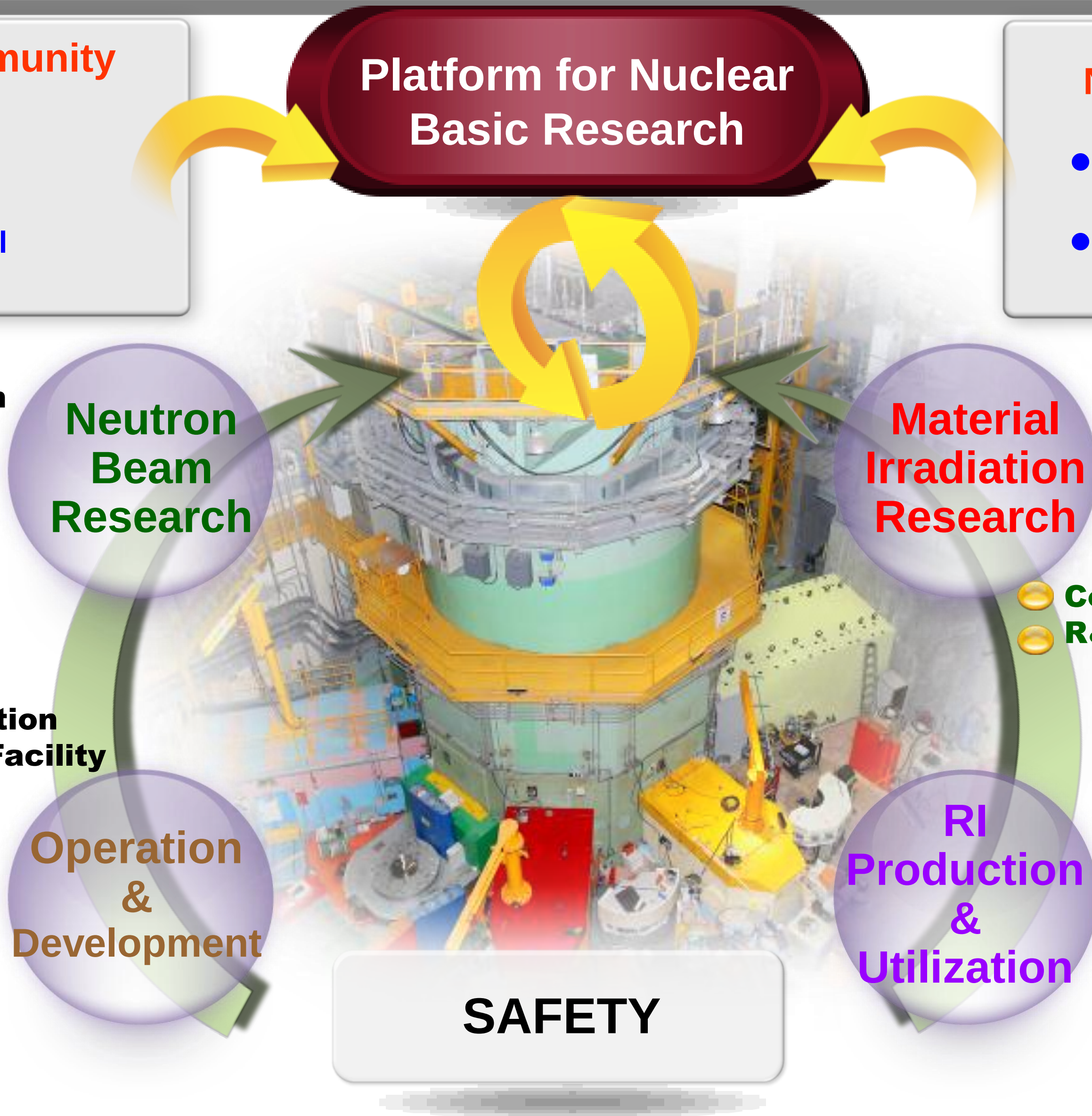
Mission of HANARO

User Community

- Industry
- University
- Institute
- International Cooperation

National Demand

- Competitiveness in Technology
- Basic R&D



- Neutron Beam
- Radiography
- NAA

- Fuel Test Loop
- Material Irradiation
- NTD

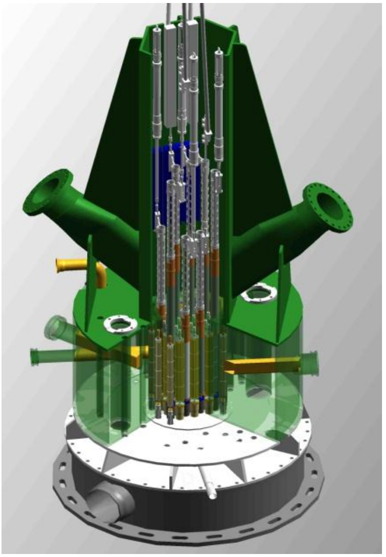
- Commercial Rx Safety
- R&D on Future Rx

- Reactor Operation
- Experimental Facility Operation

- Public Welfare
- Industrial Application

General Features of HANARO

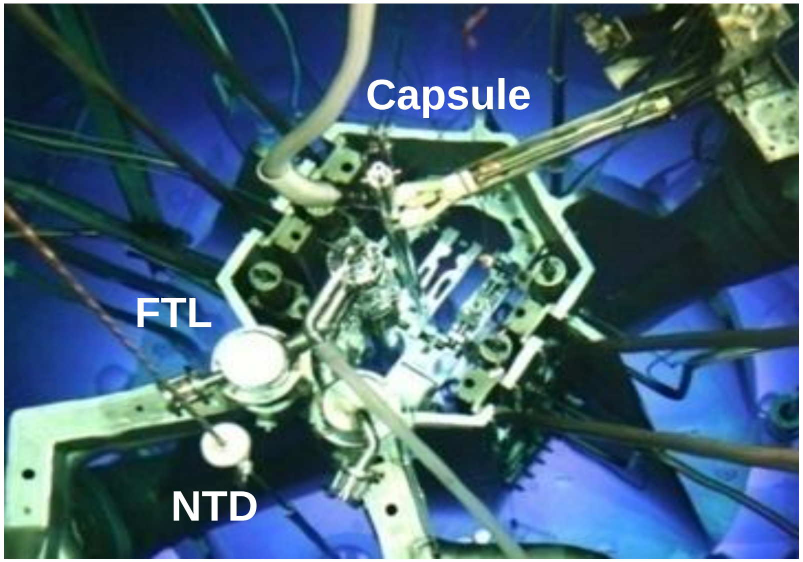
Type	: Open-tank-in-Pool
Maximum Thermal Power	: $30MW_{th}$
Max. thermal neutron flux	: $4.4x10^{14}$ n/cm^2·sec
Max. fast neutron flux	: $2.1x10^{14}$ n/cm^2·sec
Coolant	: Light Water
Reflector	: Heavy water
Fuel Materials	: U_3Si, 19.75% enriched
Absorber	: Hafnium
Reactor Building	: Confinement

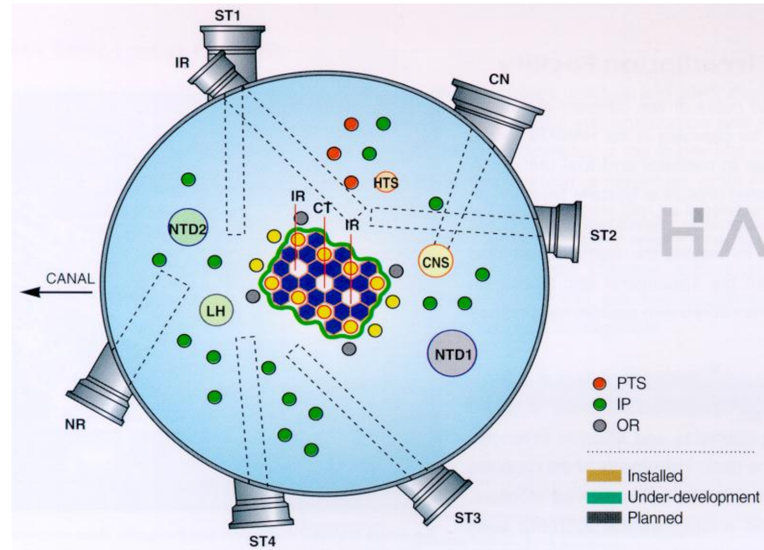


HANARO has two kind of fuel assemblies.

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

HANARO Reactor Core

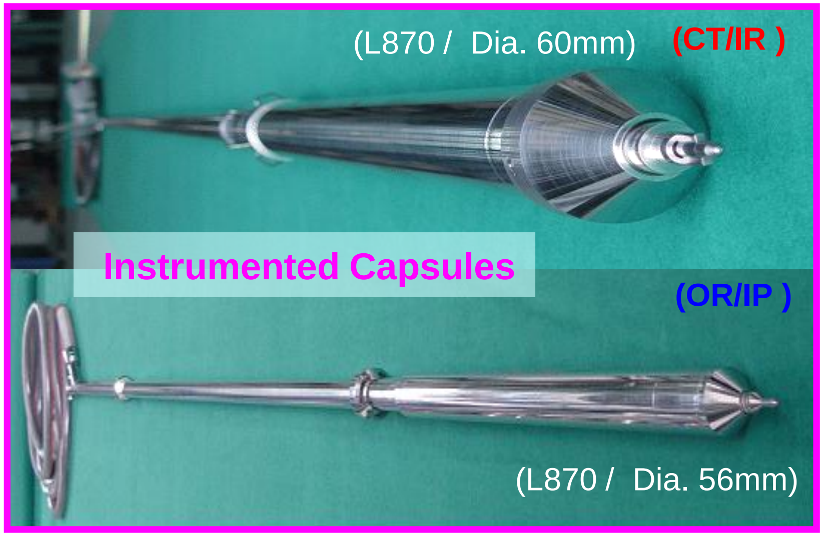


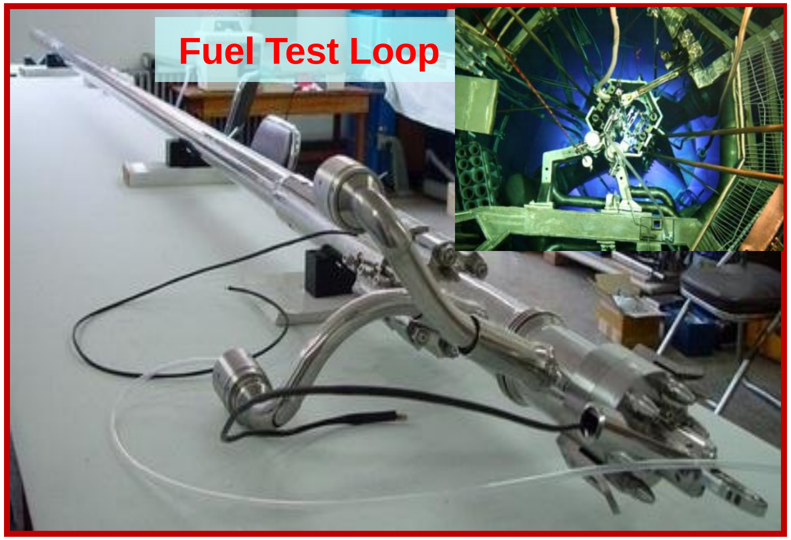


Location	Hole		Inside Dia. (cm)	Neutron Flux (n/cm² . sec)		Remarks
	Name	No.		Fast Neutron (E>1.0 Mev)	Thermal Neutron (<0.625 ev)	
Core	CT IR OR	1 2 4	7.44 7.44 6.00	1.54×10^{14} 1.50×10^{14} 2.07×10^{13}	4.39×10^{14} 3.93×10^{14} 3.36×10^{14}	**Fuel/material** isotope production
Reflector	LH HTS IP	1 1 17	15.0 10.0 6.0	6.62×10^{11} 9.44×10^{10} 1.45×10^{9} – 2.20×10^{12}	9.77×10^{13} 47.97×10^{13} 2.40×10^{13} – 1.95×10^{14}	**Fuel/material** Isotope, semi-conductors

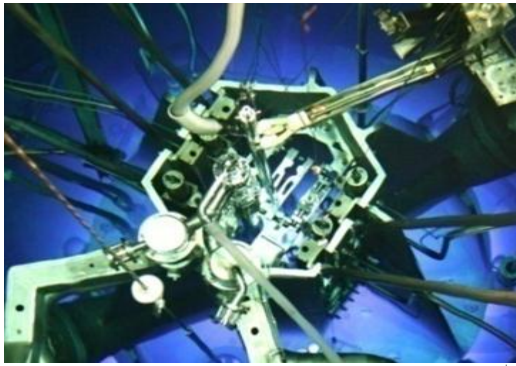
(E>0.82 MeV for Fast Neutrons of the Holes in Reflector)

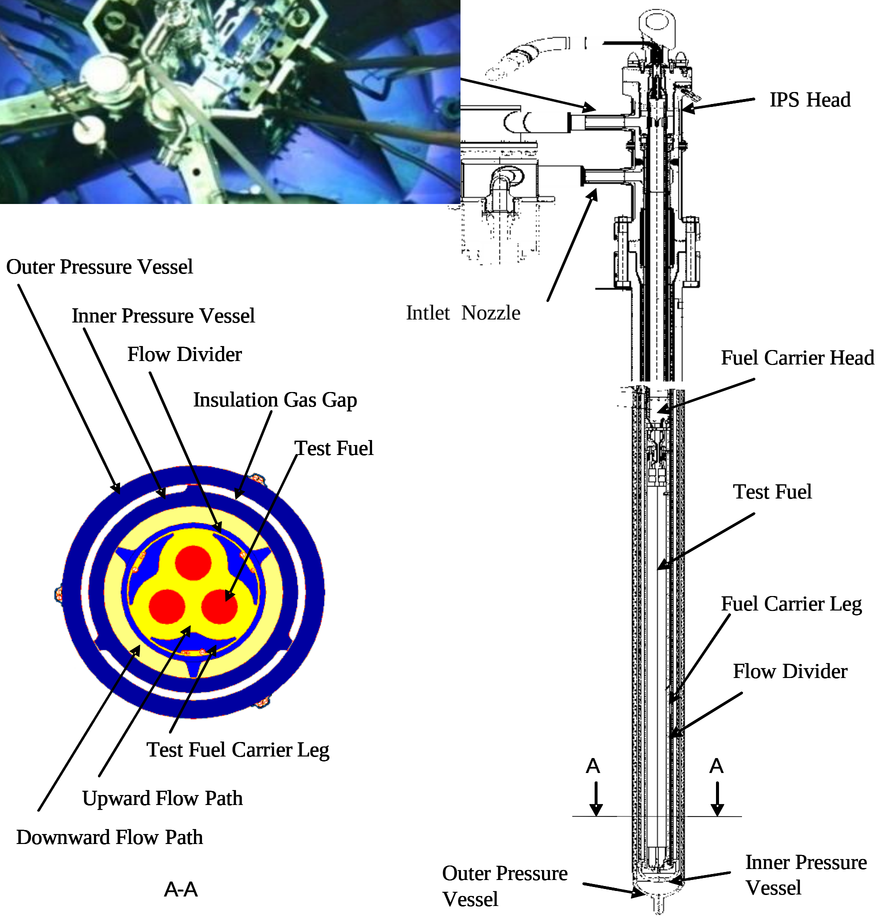
Irradiation Facilities in HANARO





HANARO FTL (Fuel Test Loop)

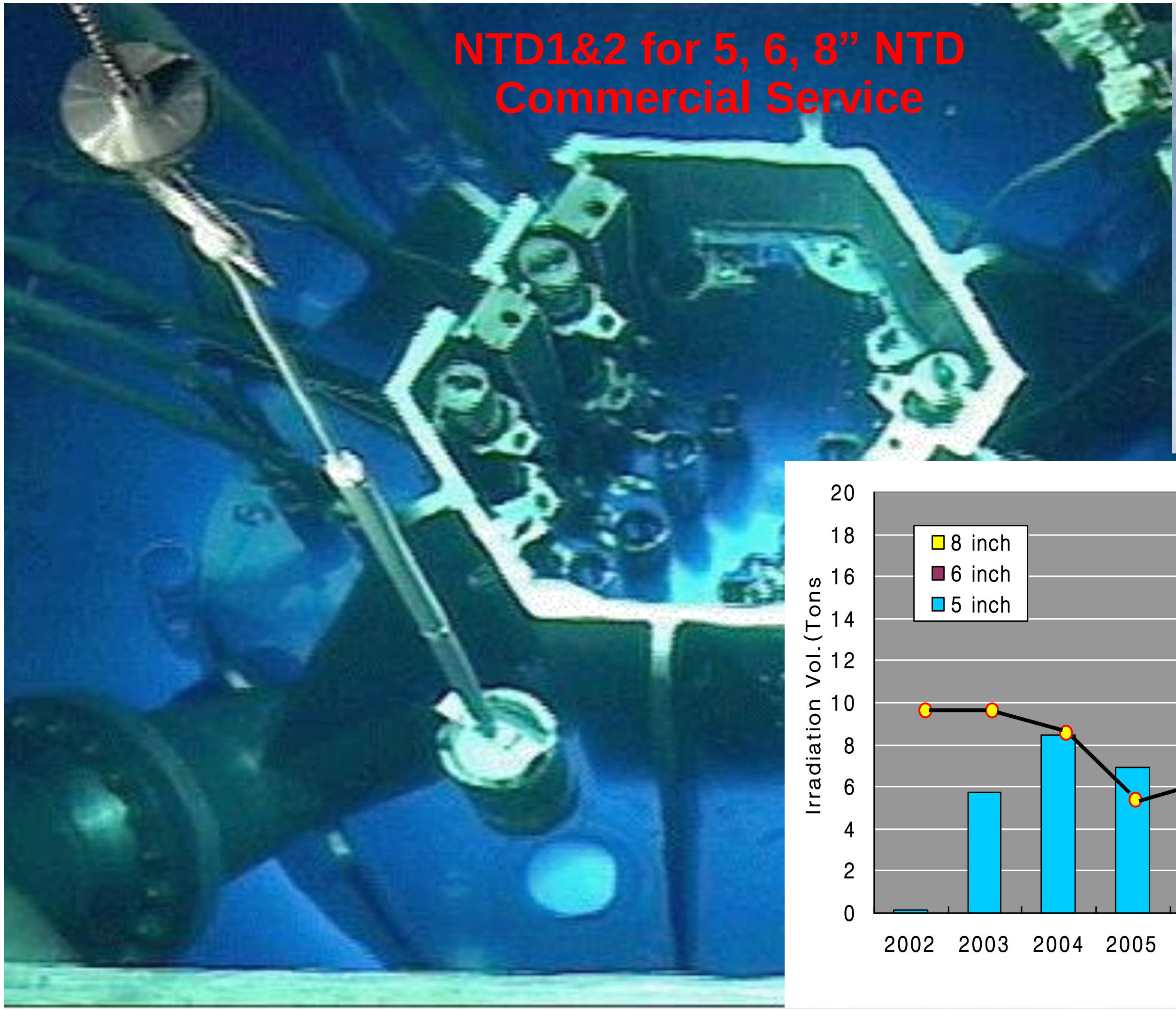


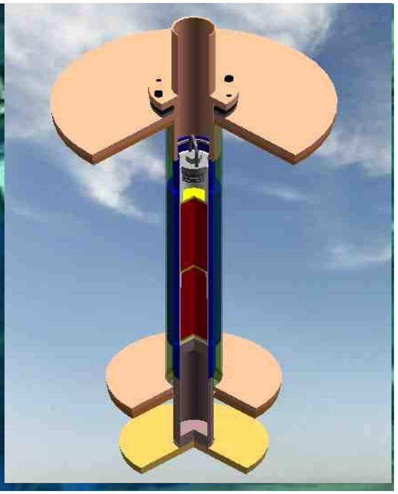


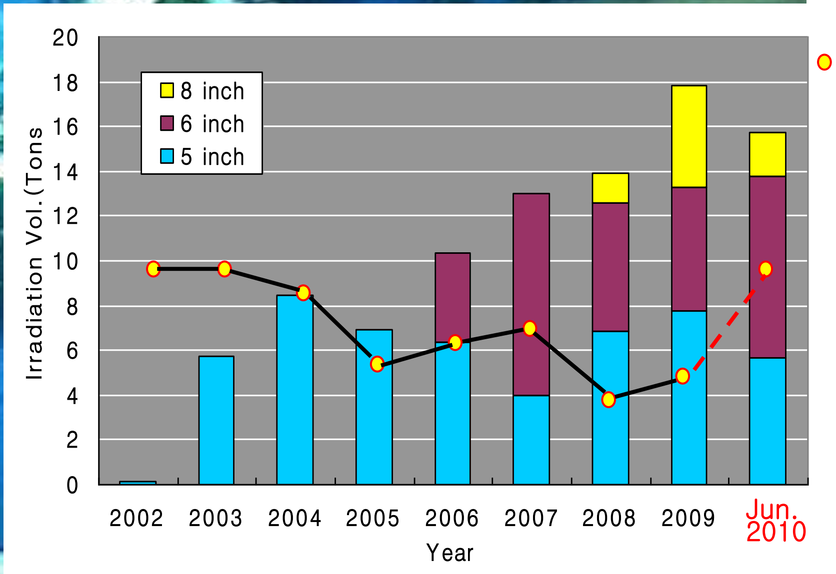
- HANARO IR-1 Test Hole
- Double Pressure Tubes
- Max. 3 Test Rods

Test conditions (PWR Condition)	HANARO
Reactor operation cycle (per year)	9
Effective Full Power Day/cycle (days)	24
LHGR (W/cm)	≤ 320
Peak to average heat rate	≤ 1.16
Coolant operation temperature (°C)	300~308
Coolant operation pressure (kg/cm^2)	150~159
Coolant operation velocity (kg/s)	1.37~1.84
B (ppm)	≤ 1500
Dissolved Oxygen (ppm)	≤ 0.1
pH at 300 °C	5.5~8.0
Electric Conductivity (µS/cm)	≤ 100
Cl^- (ppm)	≤ 0.15
F^- (ppm)	≤ 0.15
SO_4^{-2} (ppm)	≤ 0.15

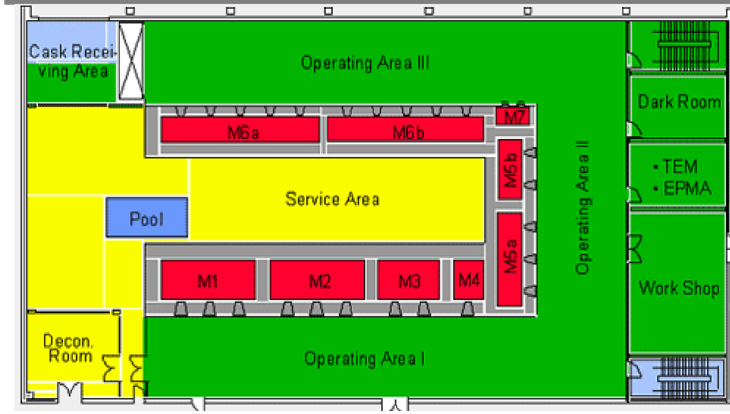
Neutron Transmutation Doping





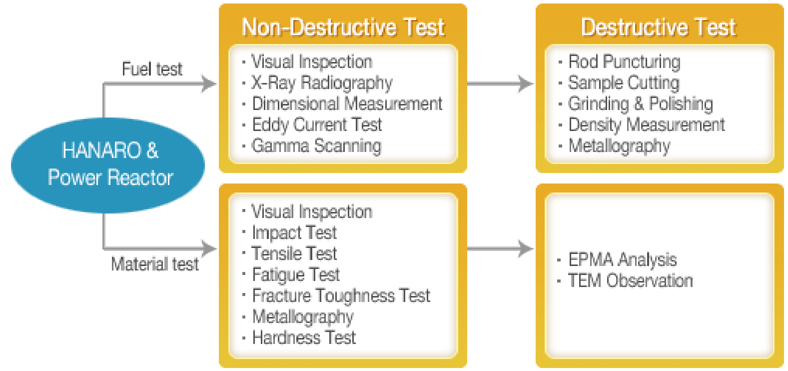


IMEF (Irradiated Material Examination Facility)
PIEF (Post-Irradiation Examination Facility)



Layout of IMEF

IMEF : 8 concrete & 1 lead hot cells, 1 pool



PIEF : 4 concrete & 2 lead hot cells, 1 pool

- Pool examination on post-irradiated fuel assembly
- Non-destructive tests & Destructive Tests
- Experiments in relation to reactor safety and fuel design and fabrication improvement

IMEF is to provide PIE services for the irradiated fuels and materials in the HANARO.

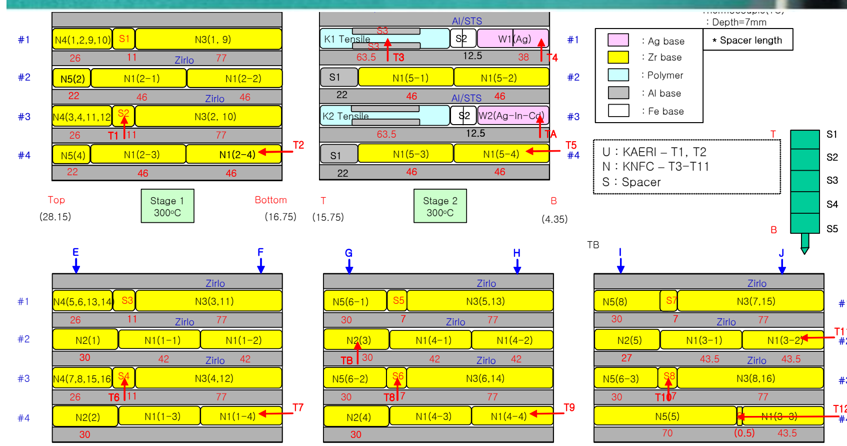
PIEF is to provide PIE services for the irradiated fuels from commercial reactors.

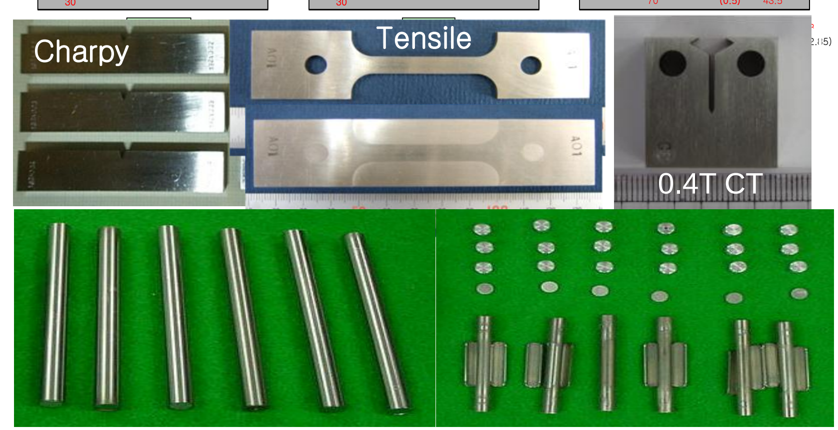
Irradiation Capsule

Korea Atomic Energy Research Institute

Specification of Instrumented Capsule

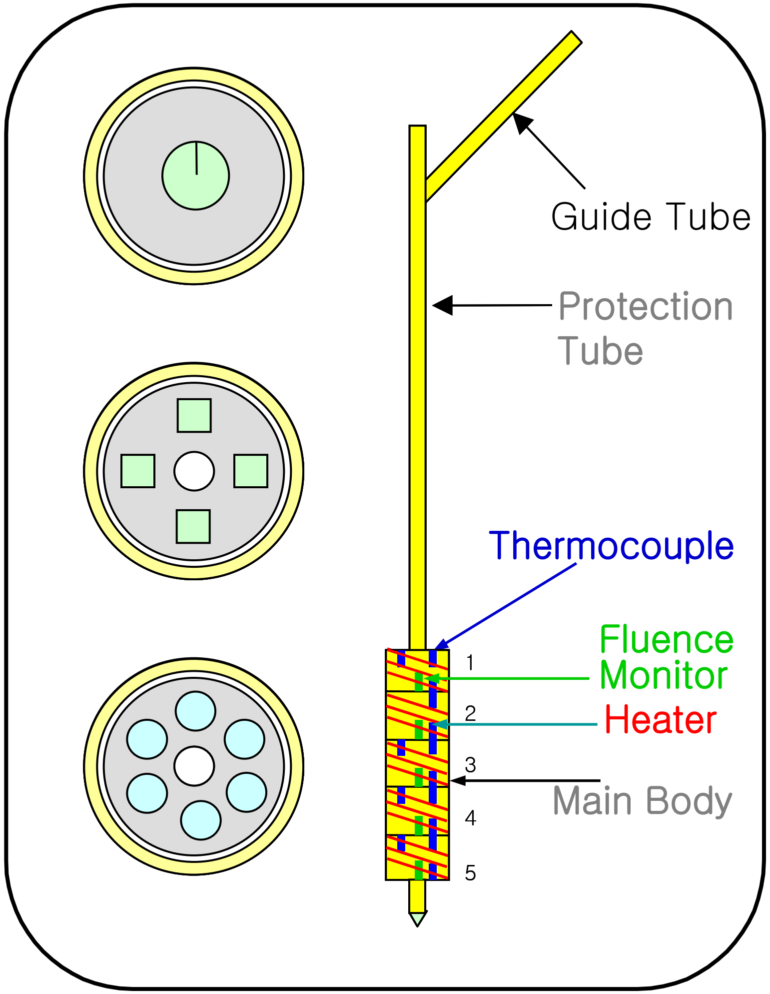
- **Test Hole :** CT, IR2, OR, IP
- **Dimension**
  - 5 Stages with each Heater
  - Main body : 56/60mm D x 870mm H
- **Materials**
  - External Tube / Internal : STS / Al (Ti)
- **Instrumentations**
  - Micro-heater : 263W/cm, 5 sets
  - T/C : K-type, 14 sets
  - Fluence Monitor: Fe-Ni-Ti / Ag-Nb
  - He Gas Control
- **Specimens**
  - RPV, Fuel Tube, Basic Materials
  - Charpy, Tensile, CT, SP, TEM etc.



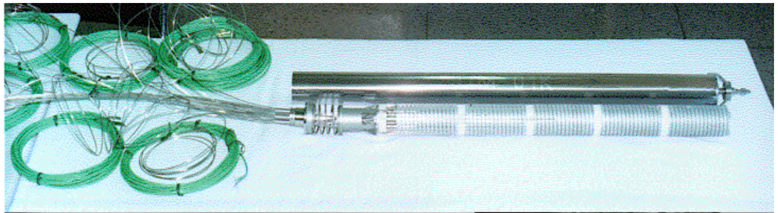


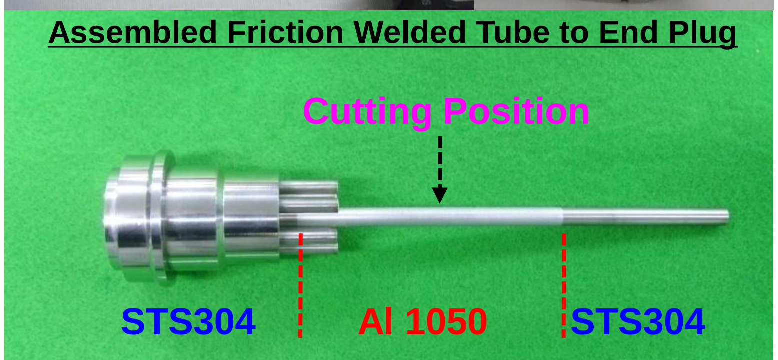
Capsule Design and Analysis

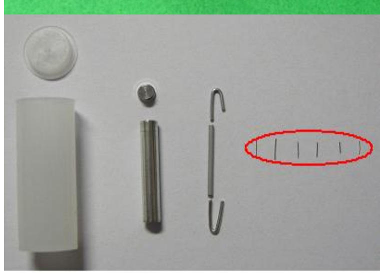
- **Basic Design of Capsule**
  - Specimen & Instrumentation
- **Nuclear Property Analysis**
  - MCNP, VENTURE
    (Reactivity, Neutron Flux, Gamma Heat)
- **Thermal / Structural Analysis**
  - GENGTC / ANSYS
- **Irradiation Analysis**
  - Fluence Monitor Analysis (SAND II)
  - DPA Analysis (SPECTOR)
    (Displacement Per Atom)
  - Activation Analysis (ORIGEN-II)

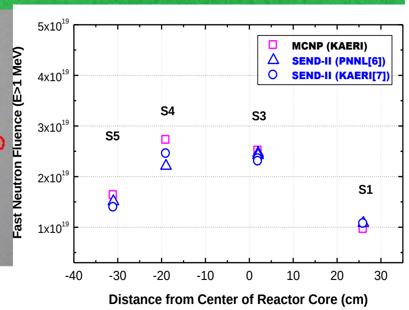


Instrumentation of Capsule









❑ Micro Heater & Thermocouples

- 5 Independent Heaters (3 kW)
- 14 K-type Thermocouples

❑ He (Ne / Ar) Gas Control

- 10 – 760 torr Control

❑ FWT (Friction Welded Tube)

- STS-Al-STS Friction Welded Tube
- Prevent Coolant Leakage during Cutting

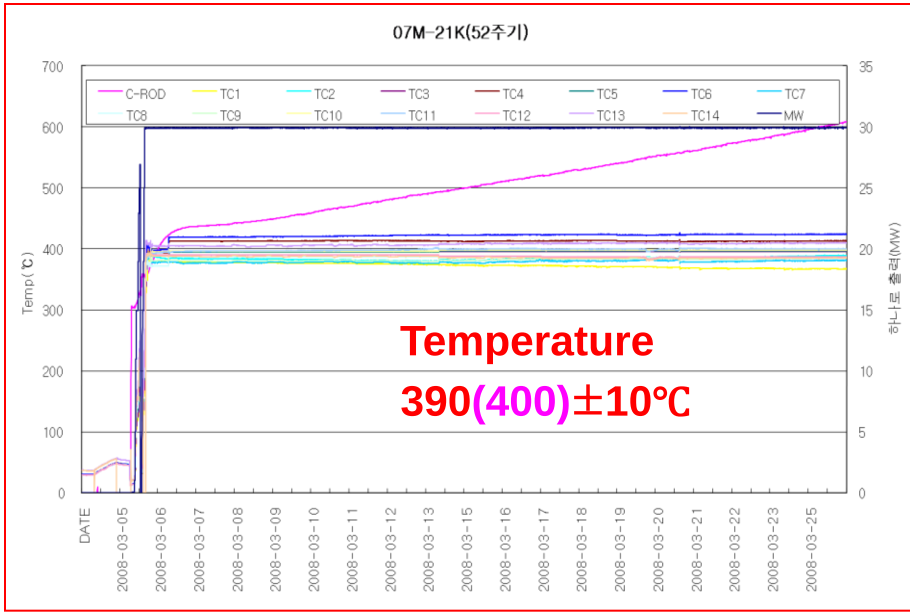
❑ Neutron Fluence Monitors

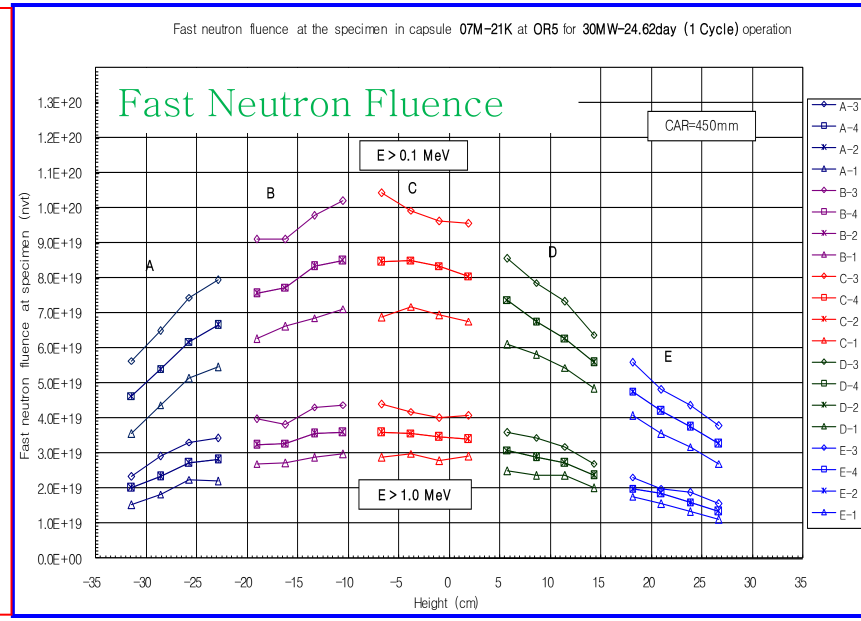
- Fast F/M Wires (Fe, Ni, Ti) in Al Tube
- Thermal F/M Wires (Ag, Nb, Co)
- SAND-II (±20% Error Range with MCNP)

❑ Temp. Monitor

- Eutectic Alloys : In-Bi (150℃), Pb-Sn-Sb (250℃), Cd-Ag(395℃) etc

Irradiation Result





- **HANARO** (OR5 hole (30W), 24.6 days (731 MWD))
- **Irradiation Temperature Control** (**Gamma heating > He gas > Heater Control)**
- **Temperature (CTCS) :** 14 K-types T/C, Controlling & Monitoring
- **Fast Neutron Fluence** (E>1.0MeV : 1.1 ~ 4.4x10^{19} n/cm^2)
  (E>0.1MeV : 0.27 ~ 1.04x10^{20} n/cm^2)
- **DPA (Displacement Per Atom) :** 0.034 ~ 0.07

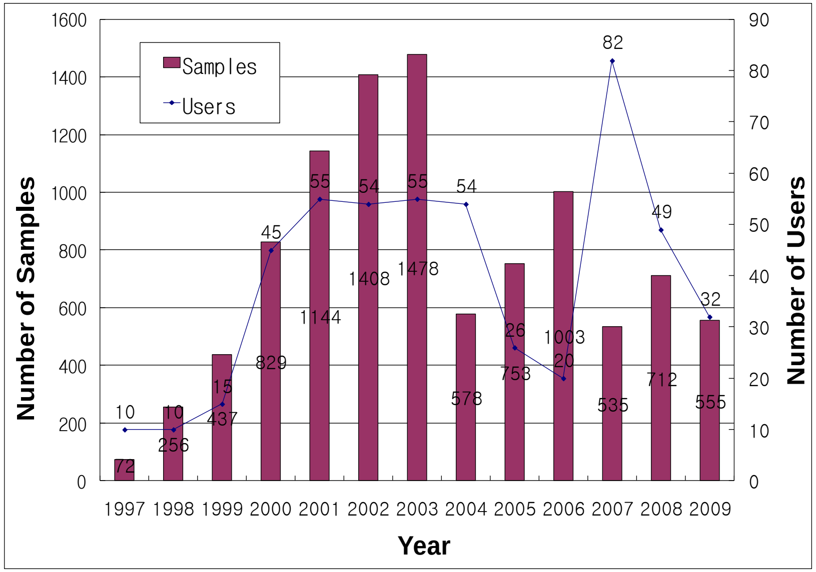
Utilization & Contribution

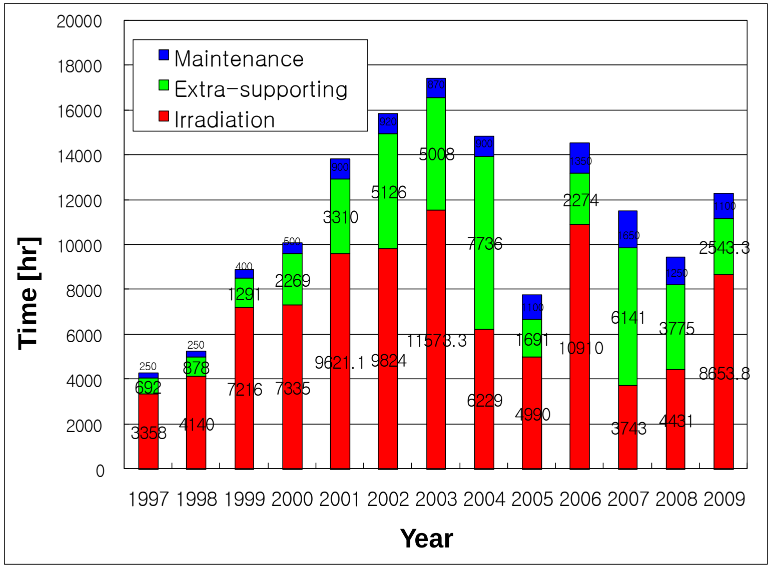
Korea Atomic Energy Research Institute
KAERI

HANARO Irradiation Capsule

- **R & D of Instrumented Capsule (1997~)**
- **Utilization of Irradiation Facilities**
  - Research Institute, Industry, University, International Projects
  - 10,000 specimens : Nuclear, Advanced/Basic Researches
  - Disturbed trends by the recent installations of CNRF / FTL
- **Most Tests are closely connected to National R&D Projects**

  Commercial Reactors > Future Reactor Systems





Contribution of Neutron Irradiation

U.S. DEPARTMENT OF ENERGY | GEN IV International Forum

KAERI Korea Atomic Energy Research Institute

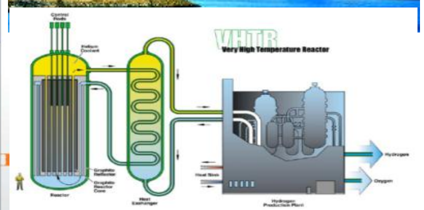
KNF 한전원자력연료 Korea Nuclear Fu

Institutt for energitek

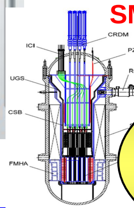
OECD HALDEN RE

DOOSAN 두산중공업

KORI Nuclear Power Plant



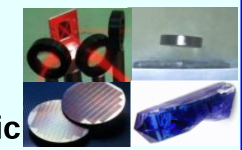
SMART



Neutron Irradiation

Research & Development

- ❑ **National Nuclear Energy Researches**
  - SMART Reactor Fuel/Material Design Data
  - Gen IV (VHTR, SFR) & Fusion Reactor R&D
- ❑ **International Research Cooperation**
  - I-NERI Project for Gen IV (2006~)
  - JAEA, Halden, Westinghouse, etc.
- ❑ **Basic Researches**
  - Superconductors, Electro-Magnetic Semiconductors, Gem-stone Coloring



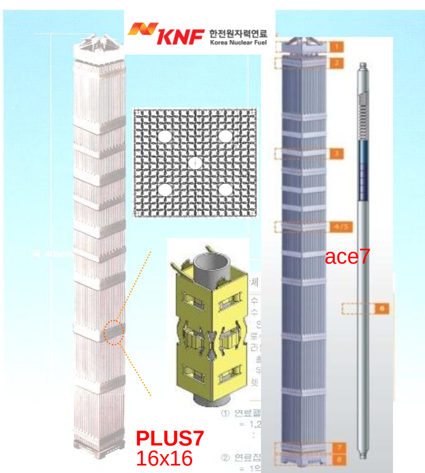
Support for Commercial Reactor

- ❑ **Reactor Safety Analysis**
  - PWR/CANDU Reactor Integrity
- ❑ **Extension of Reactor Life Time**
  - Material Database & Safety Analysis
- ❑ **Improvement of Fuel Performance**
  - KNF Fuel Assembly Development
- ❑ **R&D on Nuclear Materials**
  - Doosan (RPV, S/G) & POSCO (Zr/Fe alloys)

Current Projects

- ❑ **SMART Projects**
  - Design Data on S/G & Fuel Assembly
- ❑ **Gen IV Projects (SFR/VHTR)**
  - SFR : Fuel Irradiation & LBE tests
  - VHTR : High-Temp. Core Material (Cr-Mo) TRISO Fuel irradiation test
- ❑ **Near Future Industry Projects**
  - KNF : HiPER Fuel Assembly test
  - KHNP : Kori-1/Yonggwang-5 RPV test

Contribution to Commercial Reactors



❖ PWR Reactor Extended Operation

- Fracture Toughness of RPV materials
- Kori-1 (1978.4 > 2008.4 > 2017)

❖ PWR RPV Material Development

- Korean made RPV material (by Doosan Heavy Industry Co.)
- Development of Improved RPV Model Alloys

❖ Parts of Nuclear Fuel Assembly Tests

- UO_2 Fuel pellet and Advanced Fuel Development
- Database of part materials of Korean Fuel Assembly
- Development of New Cladding Materials

❖ CANDU Pressure Tube Material

- Zr-2.5Nb Pressure tube materials

❖ Others

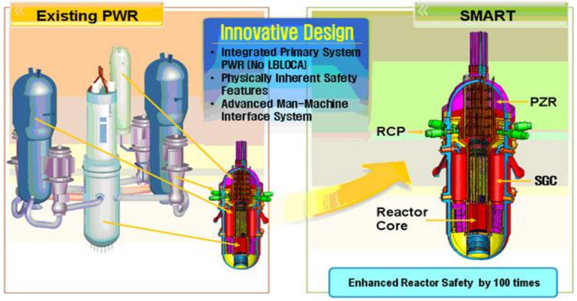
- Control Rod Materials by WEC (USA)
- Inconel, STS, Zr alloys

Contribution to Future Nuclear Systems

Future Nuclear Energy Systems in Korea

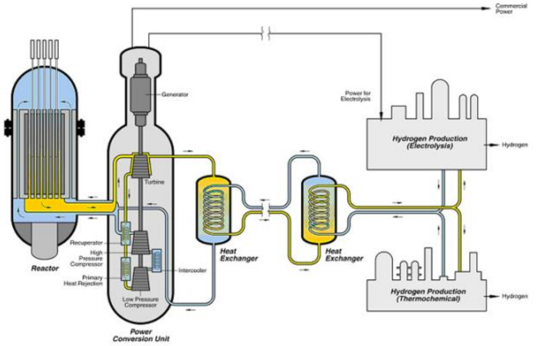
❖ SMART (System-integrated Modular Advanced ReacTor)

- Heat Exchange Tube in Steam Generator : Alloy 690 TT
- Material Irradiation Database for Standard Design
- Irradiation Test in HANARO by 2011



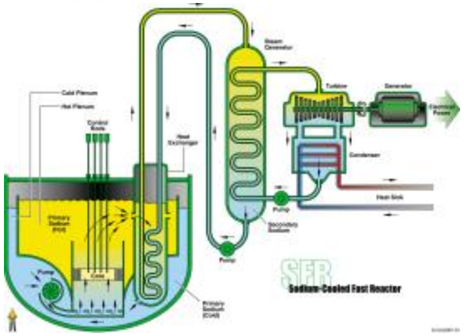
❖ VHTR (Very High Temperature gas-cooled Reator)

- >900℃ High Temp. Irradiation (Instruments)
- Irradiation of Improved Structural Materials for VHTR
- Irradiation of Nuclear Fuels (coated-fuel, TRISO)



❖ SFR (sodium cooled Fast Reactor)

- Sodium (Na) Irradiation Technology
- Fuel/Material Irradiation Test Technology in Na



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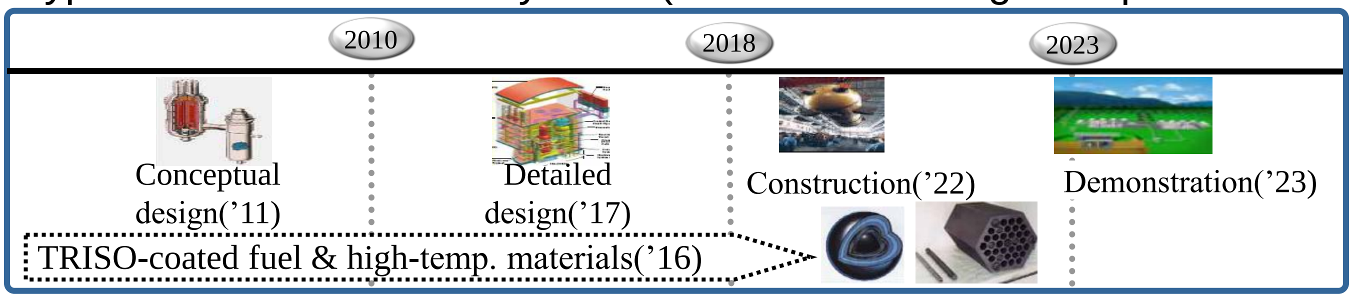
National R&D Program (2008.12/2009.03, NNC)

❑ SMART (System-integrated Modular Advanced ReacTor)

- Commercial reactor construction **by 2016**

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

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



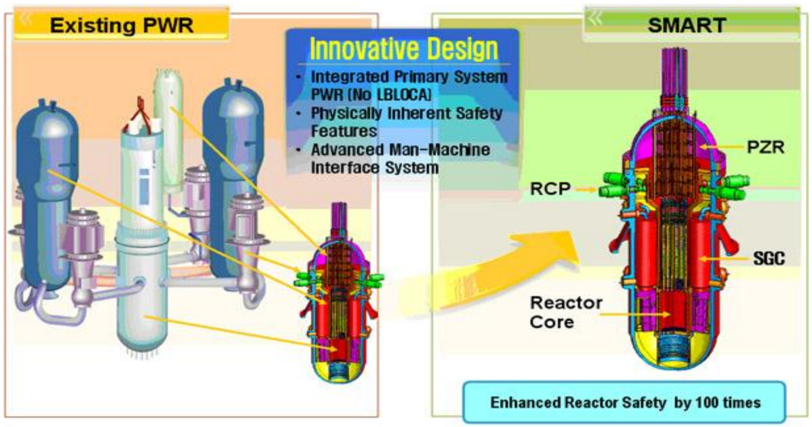
❑ SFR (Sodium-cooled Fast Reactor) for Gen-IV

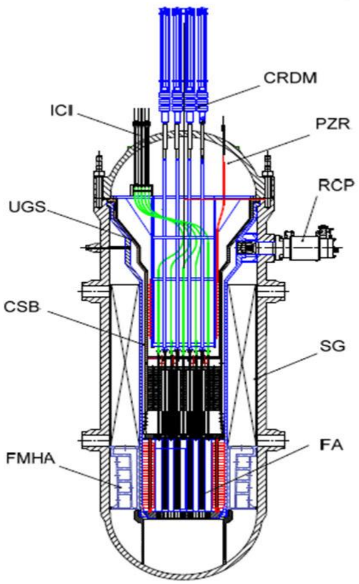
- Prototype SFR construction by **2028** (Na coolant)

KAERI Korea Atomic Energy Research Institute

Contribution to SMART Project

System-Integrated Modular Advanced Reactor





SMART

Steam Generator In RPV

CRDM : Control Rod Drive Mechanism
ICI : Incore Instrumentation
UGS : Upper Guide Structure
CSB : Core Support Barrel
FMHA : Flow Mixing Header Assembly
PZR : Pressurizer
RCP : Reactor Coolant Pump
SG : Steam Generator
FA : Fuel Assembly

❑ SMART

❖ One of the most advanced SMRs

❖ Global demand 500-1000 units by 2050 by U.S. DOE (2007)

❑ Design Features (-300MWth)

❖ Enhanced Safety by Intrinsic Safety Features & Passive Safety Systems

❖ System-Integrated Modular Reactor
- Coolant System (Pressurizer, Pump, Steam Generator) in a Reactor Vessel

❖ Capability to diverse functions (electricity, seawater desalination, district heating etc.)

❑ Project in Korea

❖ Launched from 1996 by KAERI

❖ One of New Growth Engine of Korea (2010)

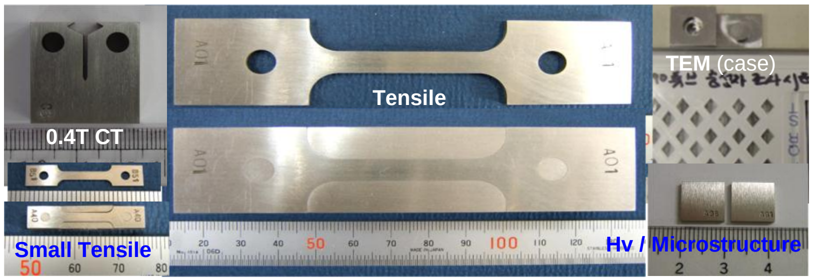
❖ Commercial Reactor by 2016
(Design Approval by 2011)

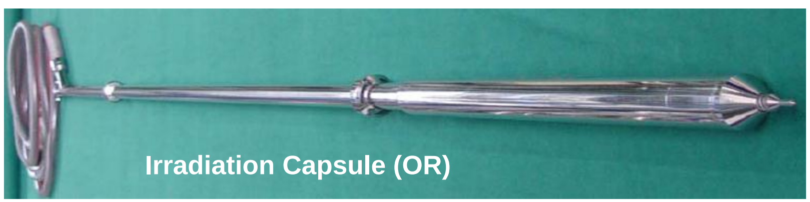
❖ KAERI-13 companies' Consortium (2010)

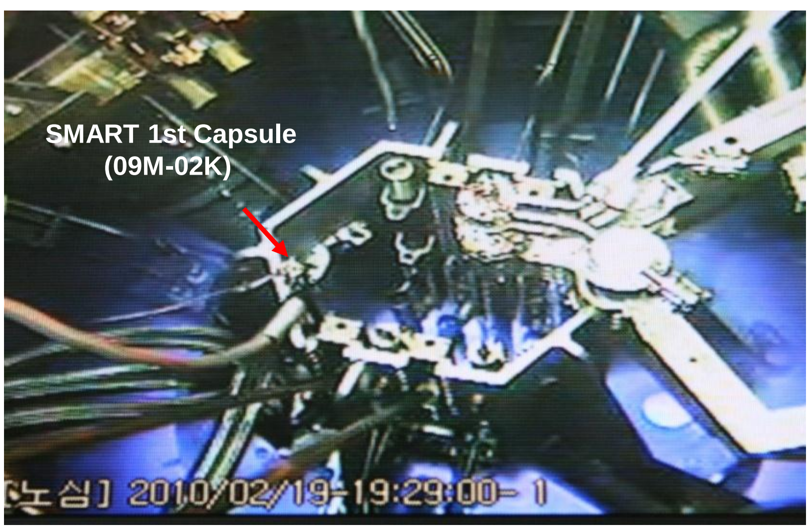
Korea Atomic Energy Research Institute

Irradiation Tests of Alloy 690

◆ **Alloy 690 Specimens**







❑ Irradiation Purpose

- Irradiation properties of **Alloy 690 (S/G)**
- Data for 'engineering verification and approval of standard design' of SMART

❑ Capsule Design

- Test Condition
  - Irradiation at 250±10℃
  - $1x10^{19}$ / $1x10^{20}$ / $1x10^{21}$ n/cm^2 (E>1 MeV) (1.56x10^{19} n/cm^2 for design life of 60 yrs)
  - Post Irradiation Test at RT / 250 / 360℃
- Nuclear / Thermal Design / Safety Analysis
- HANARO at OR/CT Test Holes
  - Compact Tension, Tensile, Hv, Microstructure Specimens
  - He gas / Heater / TC Control System

❑ Results

- 1st & 2nd Irradiation and Post-Ir. Tests
- 0.14~3.17x10^{20} n/cm^2 (0.04~0.53 dpa)
- Preparation for 3rd Irradiation by 2011

Contribution to I-NERI VHTR Project

U.S. DEPARTMENT OF ENERGY

GEN IV International Forum

I-NERI Project

Oak Ridge National Laboratory

Argonne National Laboratory

INL Idaho National Laboratory

KAERI Korea Atomic Energy Research Institute

DOOSAN 두산중공업

I-NERI Project (U.S.A – Rep. Korea)

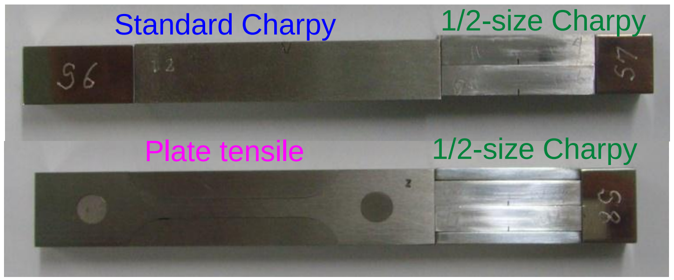
- **International Nuclear Energy Research Initiative (I-NERI) Project**
  - **High-Temp Materials R&D in U.S. Gen IV Program**
    - **- Effects of VHTR helium environments & Irradiation on mechanical properties**
- **2007-2009 sponsored by ORNL/ANL/INL/KAERI**
- **Irradiation effects of High-Temp. Materials at KAERI/HANARO**
  - **KAERI : Material R&D / Irradiation / PI Test (IMEF) - He effect (KAIST)**
  - **Neutron Irradiation by Capsule**
  - **OR/IP, 390-400℃, Neutron Fluence 10^{18} ~10^{19} n/cm^2 (E>1.0MeV)**

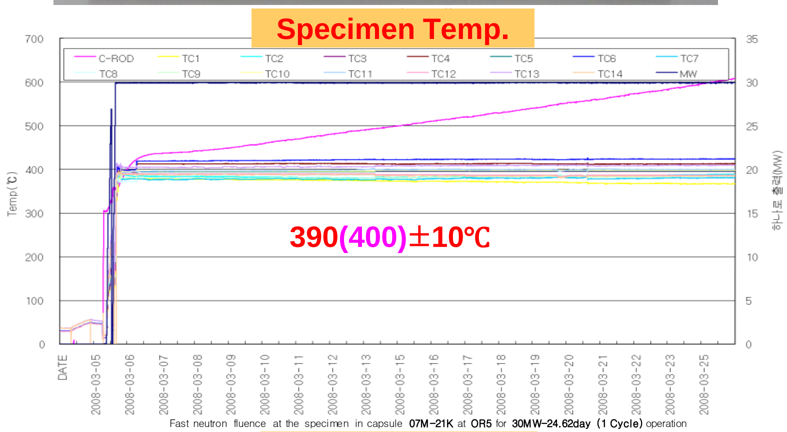
❖ **After 2010, Irradiation Tests for VHTR Project**

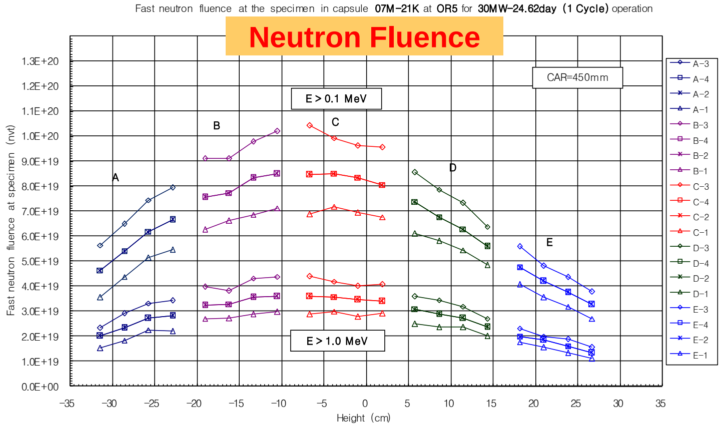
Korea Atomic Energy Research Institute

Irradiation Tests for VHTR RPV materials

◆ High Temp. Materials (Fe-Cr-Mo-W)







❑ Test Materials

- HTM of 9Cr-1Mo(-1W) steels
  - Matrix, Welded, HAZ parts
  - Made by Doosan Heavy Industry Co.

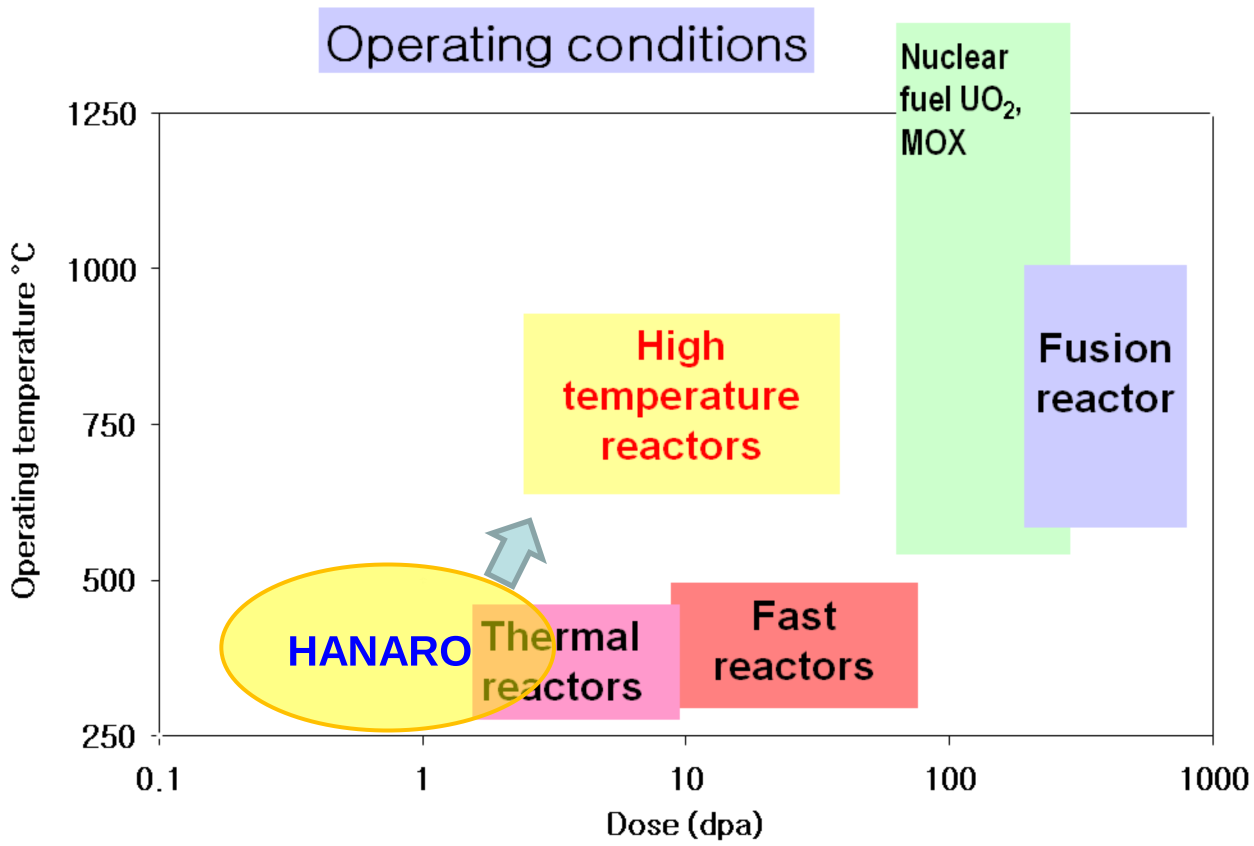
❑ Capsule Design

- Test Condition
  - Irradiation at 390(400)±10℃
  - 1~5x10^{19} n/cm^2 (E>1 MeV)
  - Post Irradiation Tests at -100~700℃ (Fracture Toughness, DBTT, Tensile property)
- Nuclear / Thermal Design / Safety Analysis
- HANARO at OR Test Hole
  - Standard & ½ Charpy, Tensile Specimens
  - He gas / Heater / TC Control System

❑ Results

- 1^{st} & 2^{nd} Irradiation and Post-Ir. Tests
- 1.1~4.4x10^{19} n/cm^2 (0.03~0.07 dpa)
- Preparation for Next Stage of I-NERI Project

Capability of HANARO



By Ákos Horváth, KFKI AEKI, Hungary TM-34779, IAEA, 17-21 Nov. 2008.

International R&Ds for Future Nuclear Reactor Systems in High Temp. & Fluence Environments

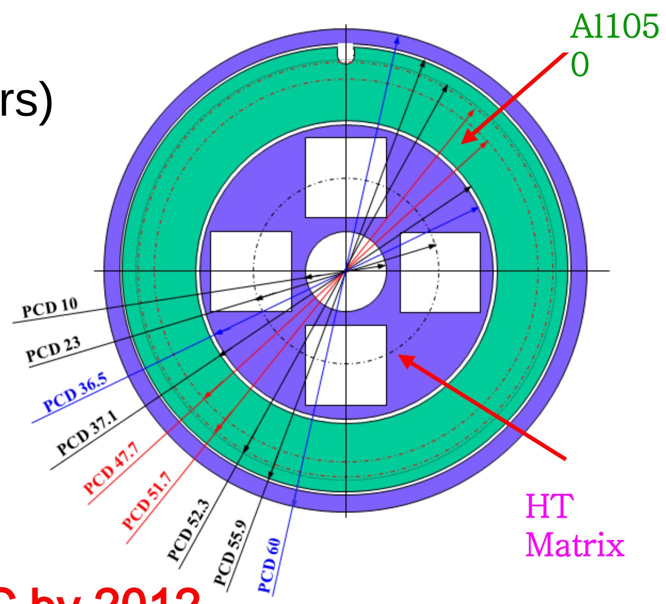
R&D on High Temp. Irradiation Technology

❑ Irradiation up to 500℃

- ❖ Standard Capsule Design (Al Thermal Media)
  - 522℃ for 4h Out-pile Test
- ❖ Application : VHTR Materials (Graphite, Cr-Mo-W Alloys)

❑ Irradiation up to 700～1000℃

- ❖ Instrumentation (Inconel Sheathed T/C & Heaters)
- ❖ Thermal Media for High Temperature
  - Candidates : Ti, Mo, Nb, Zr, Fe, Graphite
- ❖ Double Layered Structure
- ❖ HANARO Irradiation at 700 ℃ in 2009
- ❖ Application : VHTR, FBR, Fusion Materials



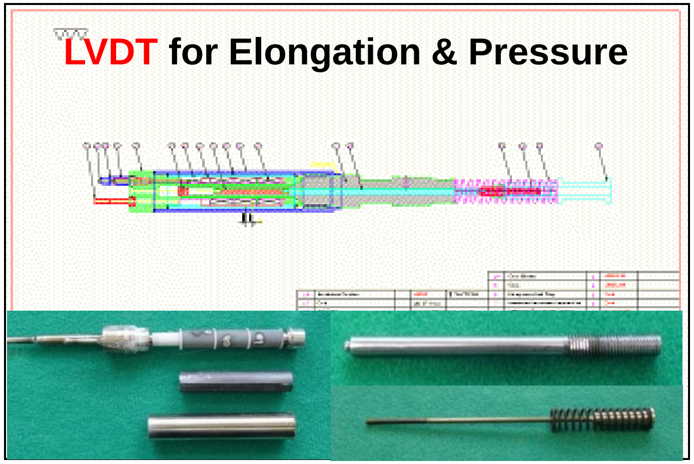
➢ **Plan of Irradiation of VHTR Graphite at ~700℃ by 2012**

R&D on Instrumentation

Instruments Localization

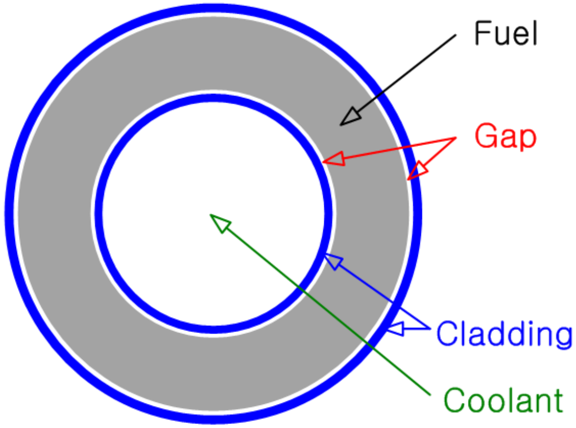
Instrumentation & Analysis

Precise Welding Technology



SiC Temperature Monitor

Dual-Cooled Fuel

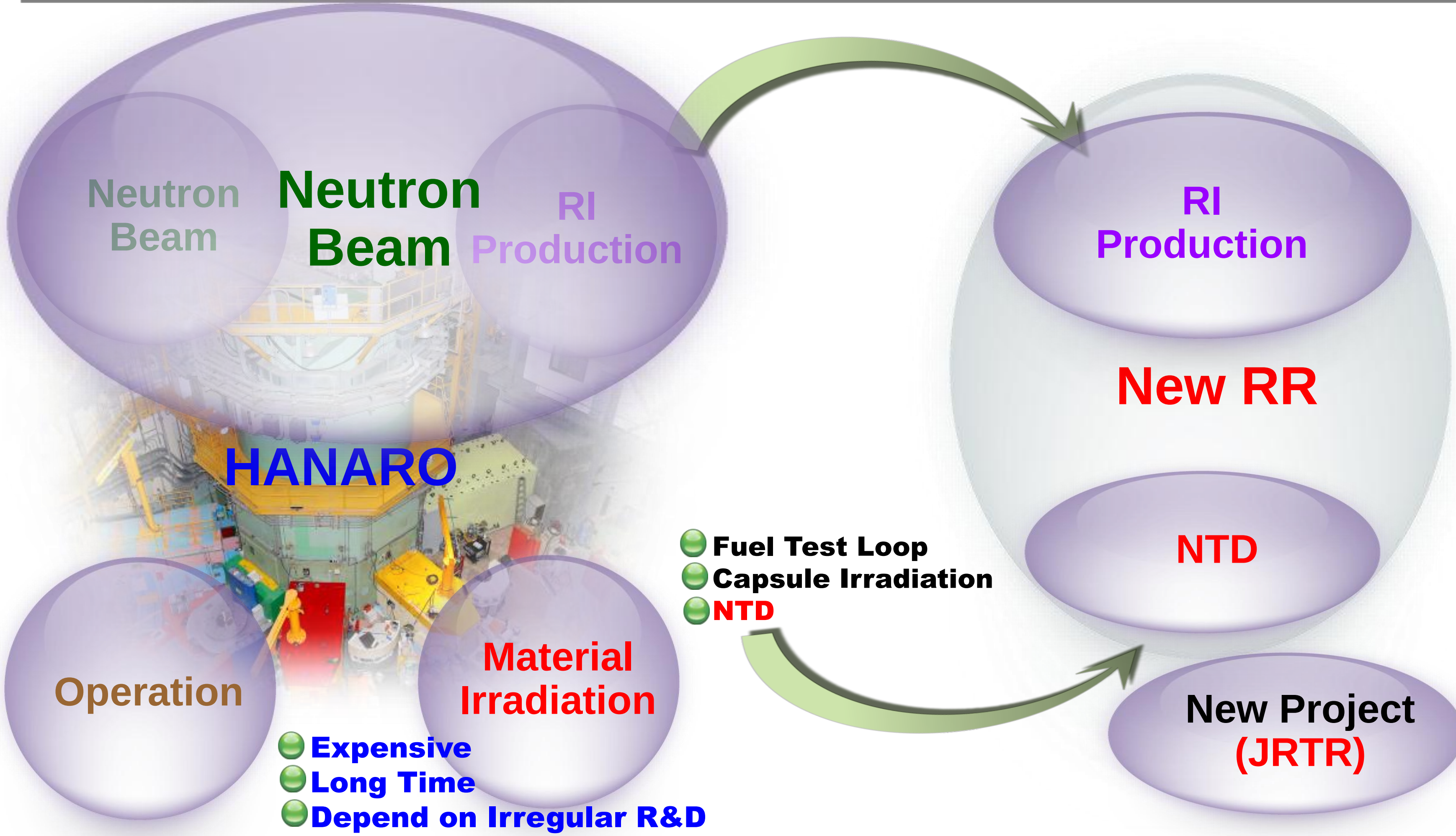


Fiber laser Welder

www.ipgphotonics.com
Nasdaq: IPG Photonics (IPGP)

Advanced Instrumentation Technology
Localization of LVDT & Precise Welding

Future of Material Irradiation



"Choose & Concentrate"

Strategy : International Cooperation !

Conclusion

- For material irradiation tests, various irradiation facilities such as capsule and FTL systems and related techniques have been developed at HANARO.
- The HANARO irradiation capsule system has been actively utilized for the irradiation tests of fuels & materials of the commercially operating nuclear reactors in Korea.
- Based on the accumulated experience and the users' sophisticated requirements, HANARO has recently started new support of R&D relevant to the future nuclear systems of the SMART and VHTR.
- To effectively support the R&D relevant to future nuclear systems, the irradiation technologies concerning high-temperature irradiation test is being preferentially developed in HANARO.
- To extend the utilization of HANARO limited to the domestic applications, it's the time to give a serious consideration for the international cooperation.

HANARO is available for
international research programs and cooperation.

Thank You