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Neutron Transmutation Doping in HANARO Reactor

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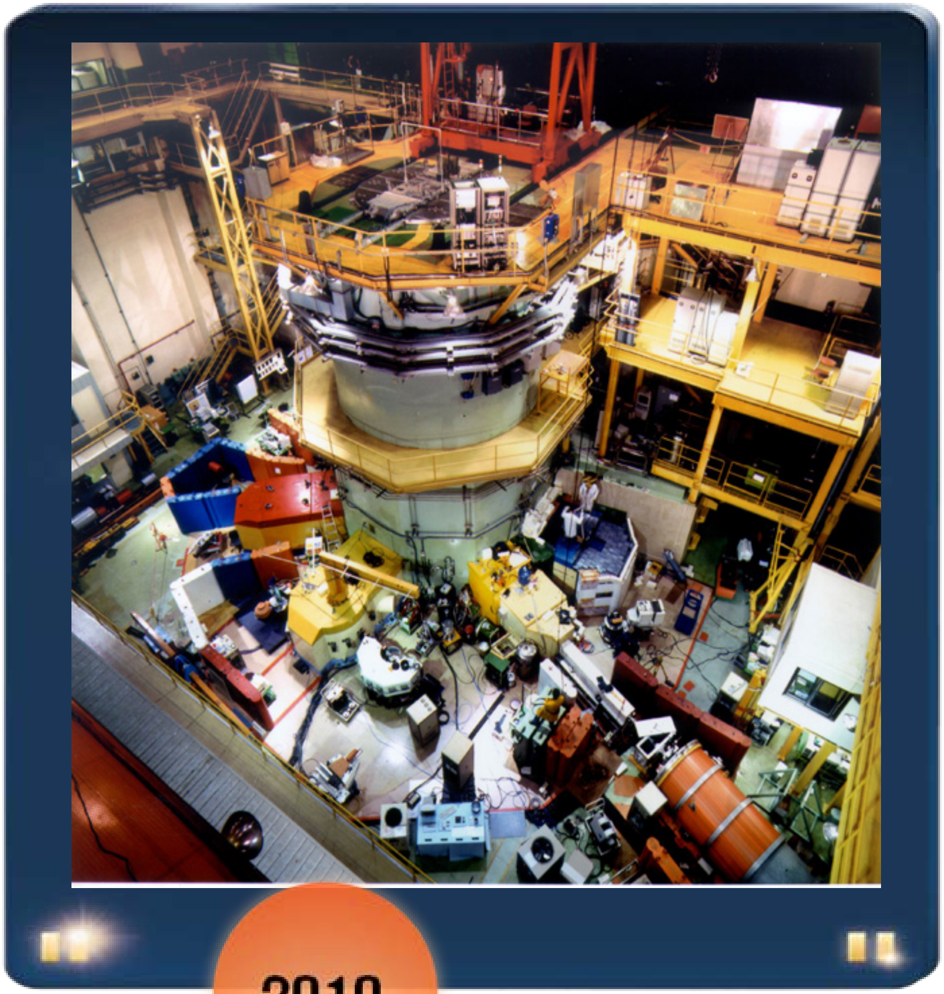
INTRODUCTION

HANARO Complex

HANARO, Past and Present

Feb., 1995



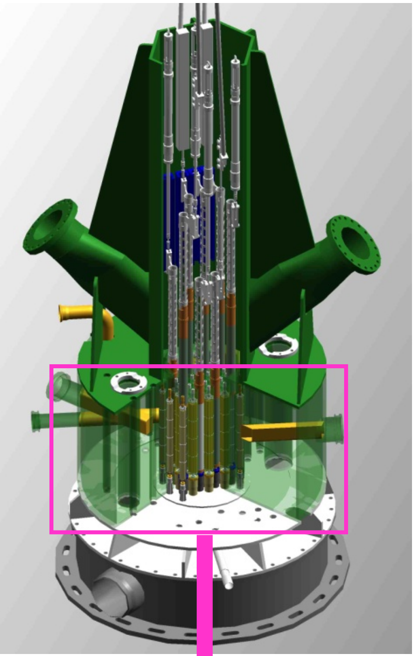
2010

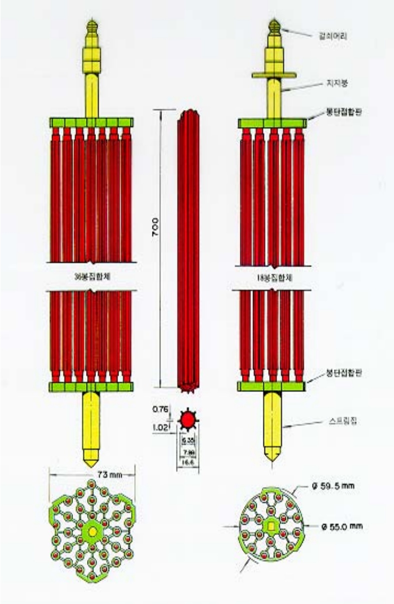
Chronology of HANARO

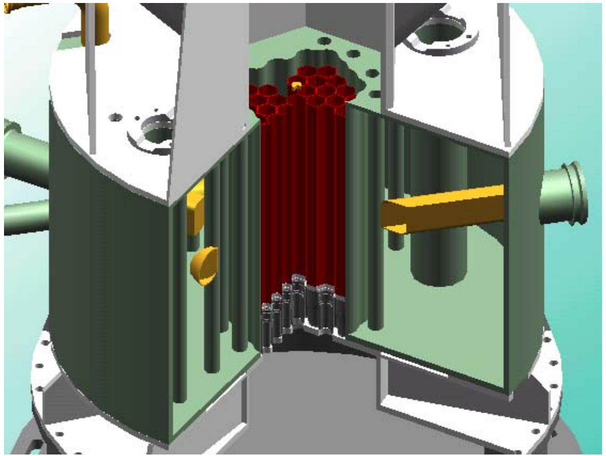
○ 1985.05 KMRR (Korea Multi-purpose RR) Project Approval
○ 1990.12 Detail Design Completed
○ 1994.12 Construction Completed
○ 1995.03 Commissioning Completed
○ 1995.04 First Criticality Achieved
○ 1996.01 RI Facility Operation Started
○ 1998.01 NAA Started
○ 1999.01 Material Irradiation (Capsule) Research Started
○ 2000.01 Thermal Neutron Beam Research Started
○ 2002.12 NTD Commercial Service Started
○ 2008.12 Fuel Test Loop Completed
○ 2010.04 Cold Neutron Research Facility Completed

HANARO Specification

Reactor Type	Open-tank-in-pool
Power	30 MWt
Fuel	LEU(19.75 % Enrichment) (U3Si-Al)
Coolant	H2O
Moderator	H2O/D2O
Reflector	D2O
Absorber	Hafnium (4 SOR + 4 CAR)
Core Cooling	Upward Forced Convection Flow
Secondary Cooling	Cooling Tower
Reactor Building	Confinement



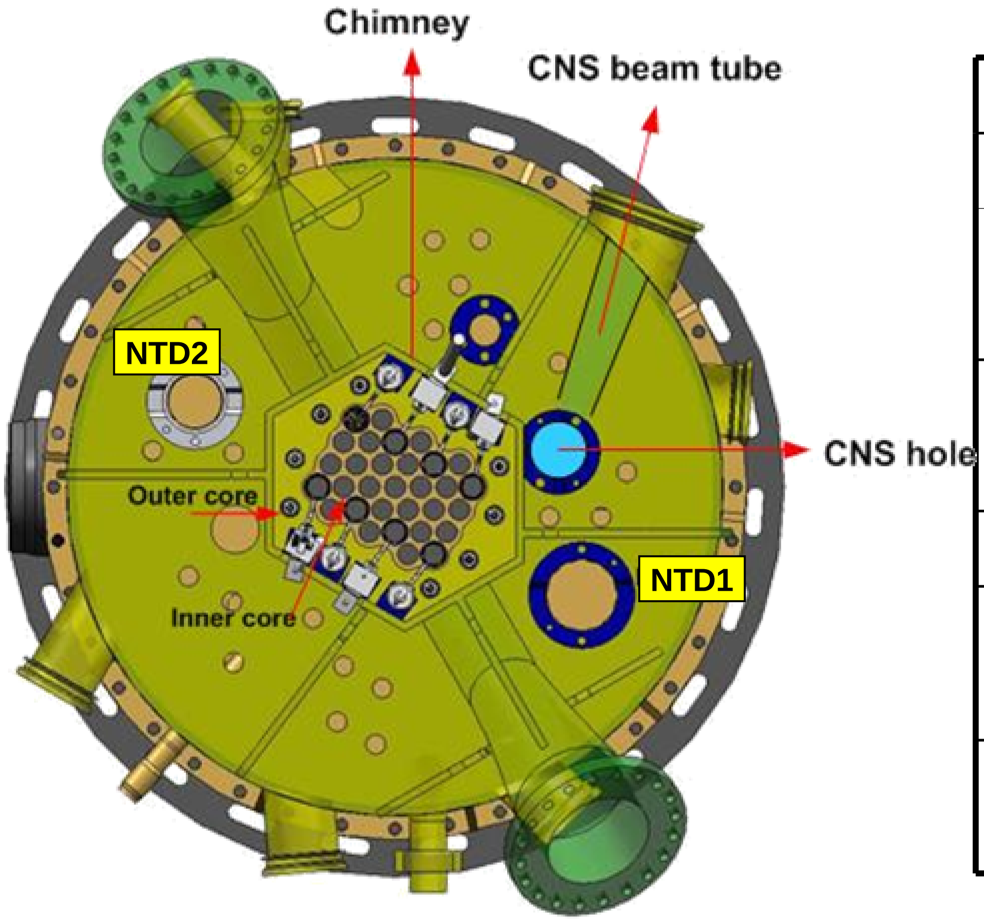




NTD at HANARO

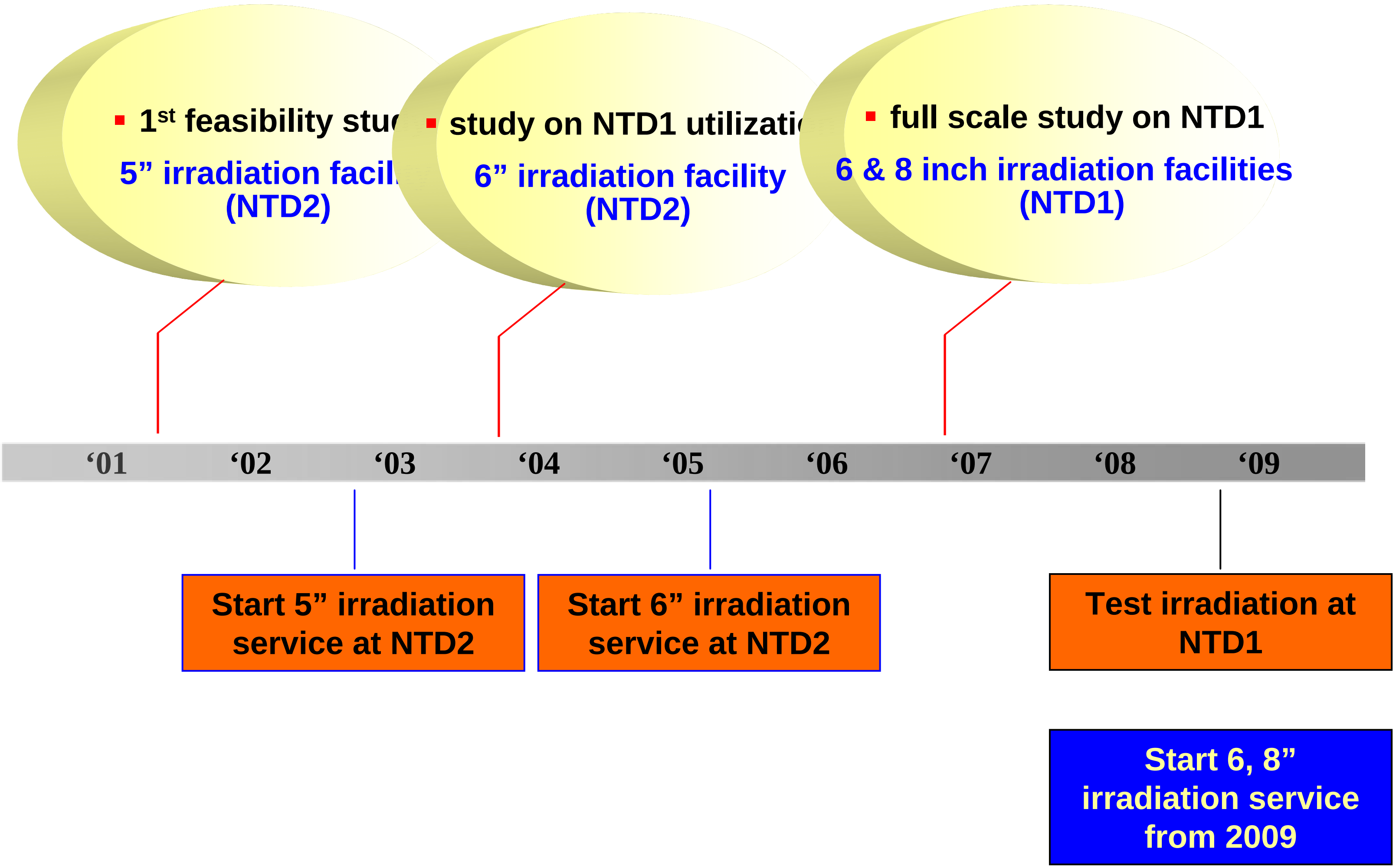
Irradiation Holes for NTD

Two vertical holes in the D_2O reflector region (NTD1, NTD2)



	NTD-1	NTD-2
Inner Dia.	**220 mm**	**180 mm**
Height total	**1200 mm (D_2O)**	
Height effective	**700 mm (Fuel)**	
Φ_{th} empty	**$\sim 5.2 \times 10^{13}$**	
Φ_{th} with Si	**$3.5 \sim 3.8 \times 10^{13}$**	
Cd Ratio (by Au)	**~20**	
max. ingot size D	**8 inch**	**6 inch**
max. ingot size H	**605 mm**	
Status	**6, 8 inch in service**	**5, 6 inch in service**

NTD Development Project



- 1st feasibility stu

5” irradiation facil
(NTD2)

- study on NTD1 utilizati

6” irradiation facility
(NTD2)

- full scale study on NTD1

6 & 8 inch irradiation facilities
(NTD1)

‘01 ‘02 ‘03 ‘04 ‘05 ‘06 ‘07 ‘08 ‘09

Start 5” irradiation service at NTD2

Start 6” irradiation service at NTD2

Test irradiation at NTD1

Start 6, 8” irradiation service from 2009

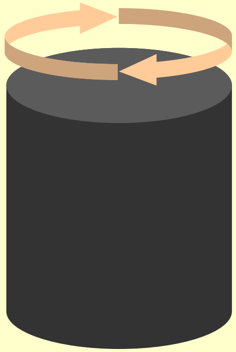
For Uniform Irradiation…

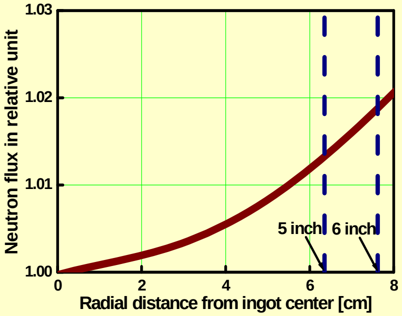
Radial Uniformity

- Rotate the ingot to compensate flux gradient in the irradiation hole
- Intrinsic neutron attenuation in the ingot is bigger for larger diameter ingot

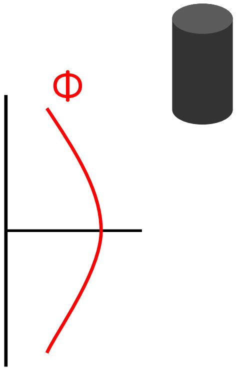
- 6 inch : RRG < 2%

- 8 inch : RRG < 5%



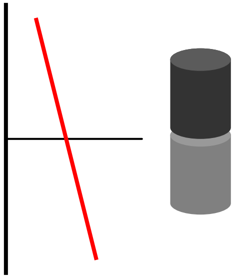


Axial Uniformity



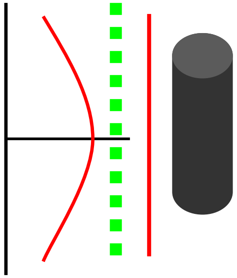
Round trip

- needs enough space for moving up/down
- simplify the system
- BR2(Belgium)



Overturning

- linear distribution of neutron flux
- two times irradiation
- JRR3-M(Japan)



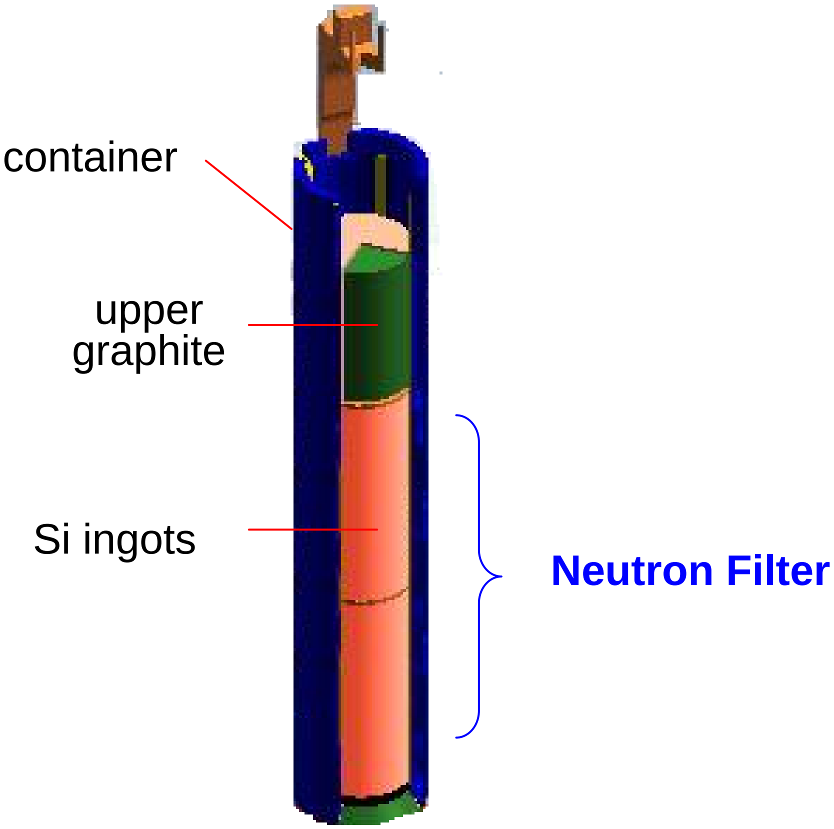
Neutron Filter

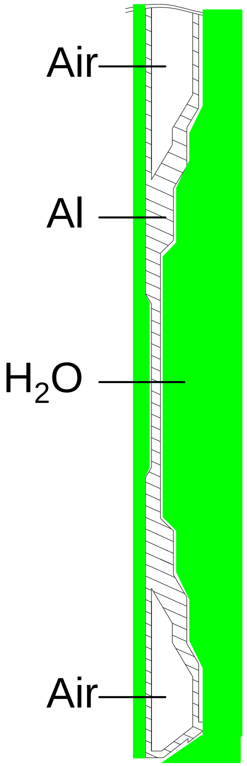
- flattened neutron flux
- fixed irradiation position
- maximize irradiation space
- HANARO, OPAL

Irradiation Rigs (I)

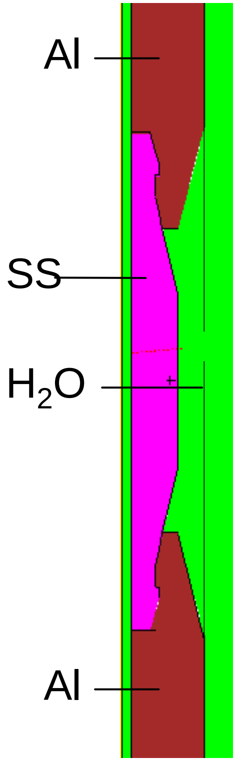
- **Neutron filter integrated into irradiation rig (ingot container)**
  - **Wall thickness of container is varied along it’s height.**
  - **Different water gap between container and ingots controls the neutron absorption probability to make axially flat neutron flux distribution.**
- **Maximize the filtered neutron flux**
  - **Containers are made of only aluminum or aluminum partially combined with stainless steel.**
  - **Water is used as a main neutron absorber → Minimize neutron attenuation**
- **Maximize the axial effective length (605 mm)**
  - **Upper and lower graphite reflectors extend the region of flat neutron flux.**
- **Active control of the irradiation position**
  - **Changes in axial flux distribution due to fuel burn-up effect (< 2.5%)**
  - **Movable neutron filter ensures a position with the best flatness of the neutron flux over the effective region during whole cycle operation (max. movement : < 50 mm)**

Irradiation Rigs (II)





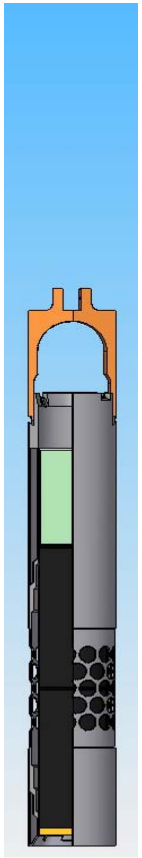
5” (NTD2) : 5~18 mm
6” (NTD1) : 20~30 mm



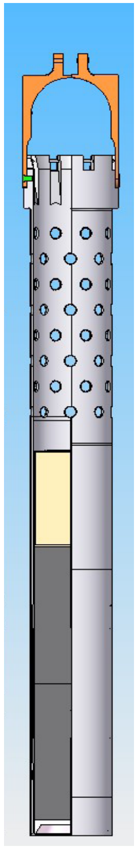
6” (NTD2) : 2 ~ 5 mm
8” (NTD1) : 2 ~ 4 mm

Irradiation Rigs (III)

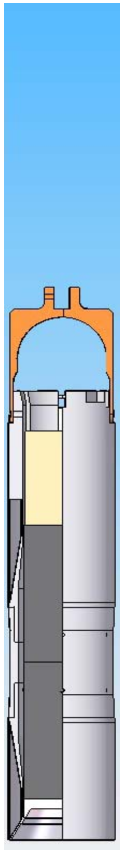
Rig types



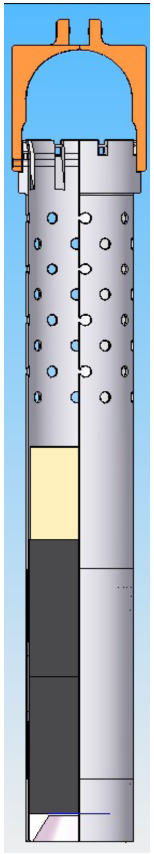
5 inch (NTD2)



6 inch (NTD2)

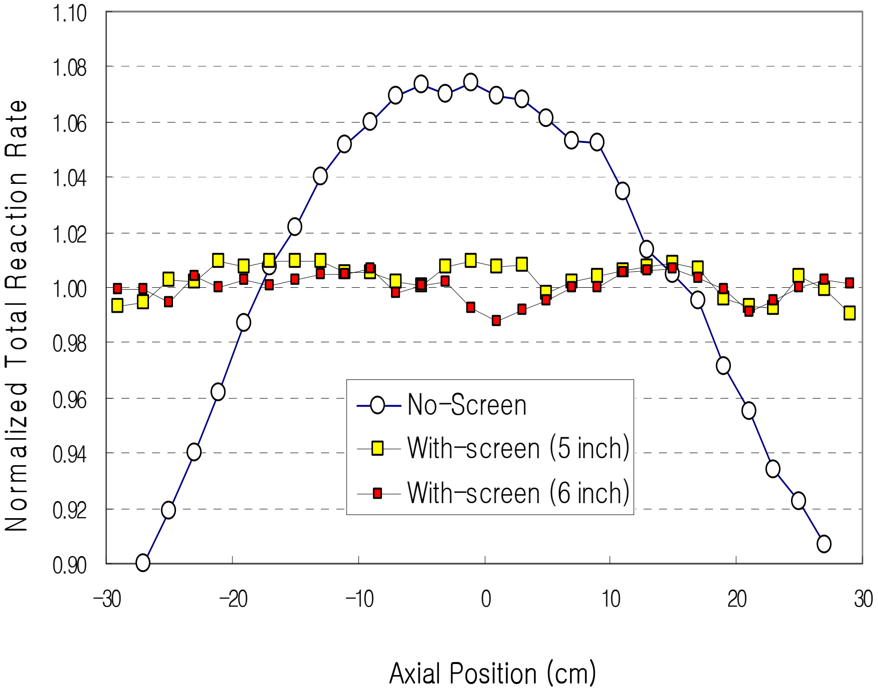


6 inch (NTD1)



8 inch (NTD1)

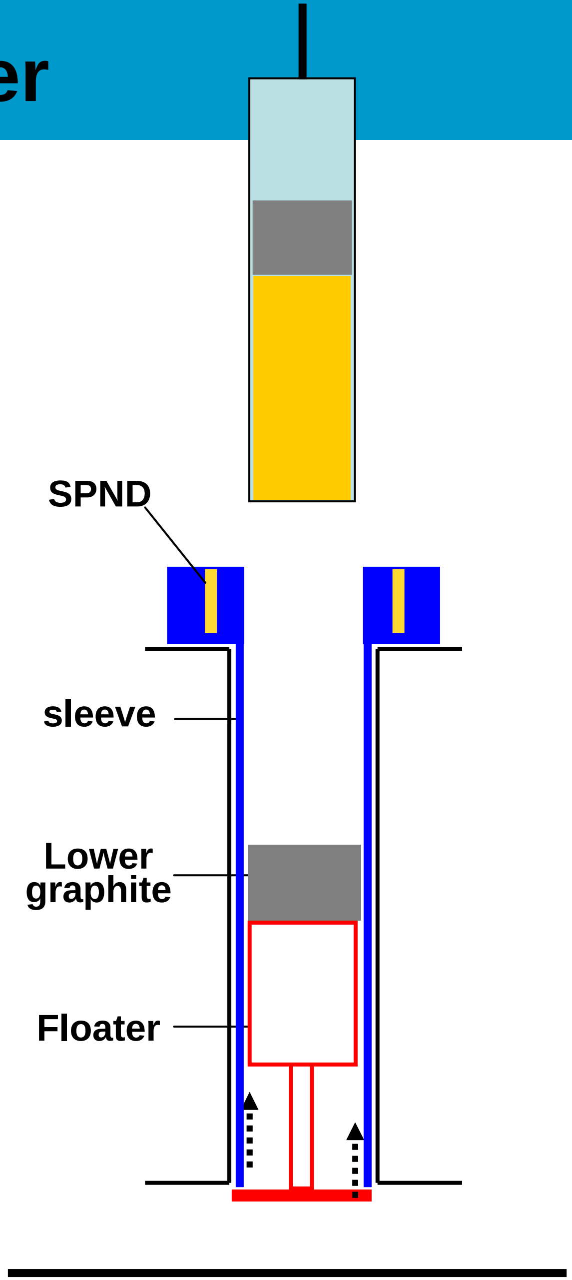
Axial reaction rate of $Si^{30}(n,\gamma)$

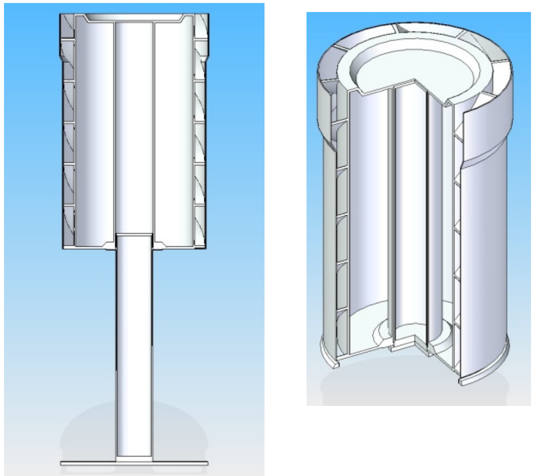


design uniformity less than ±1% over 600 mm long

Sleeve & Floater

- **Sleeve**
  - **Protect inner wall of irradiation hole from the frictional wear due to rotating container (D_2O leakage)**
  - **Accommodate neutron monitors (Rh-SPND)**
- **Floater**
  - **An empty can moving by buoyancy carrying a lower graphite reflector on the top**
  - **Prevent sudden neutron flux change at surroundings**
  - **Cooling the ingots by pumping coolant upward**

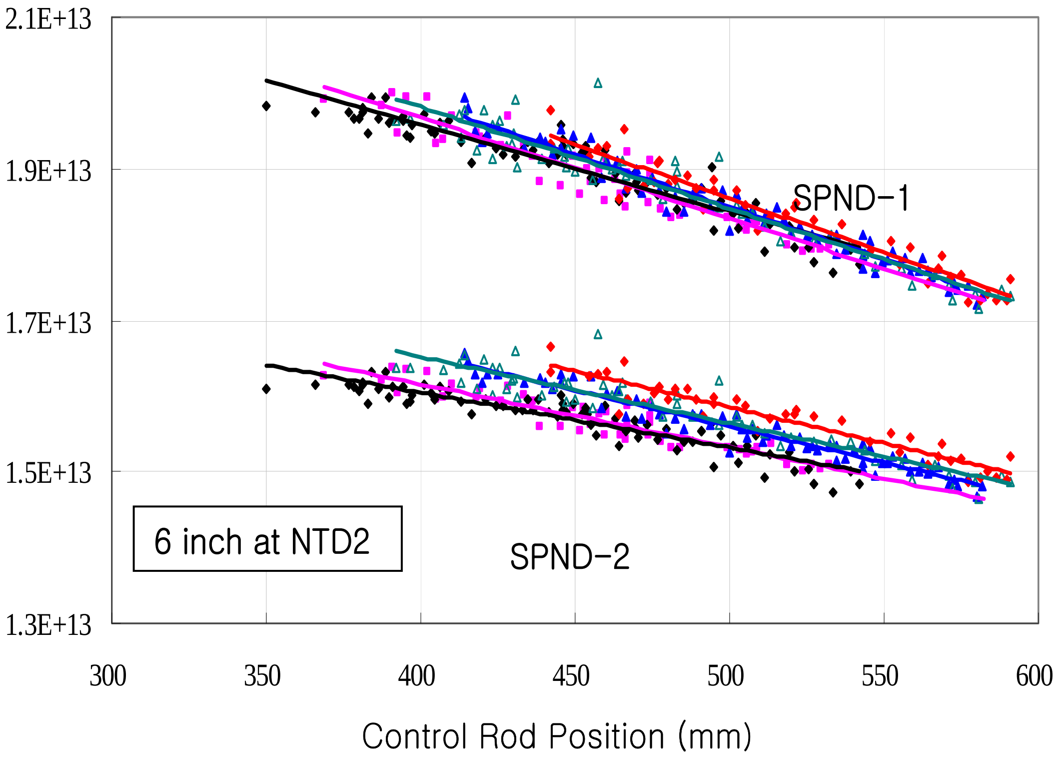




NTD OPERATION

Neutron Fluence Monitoring

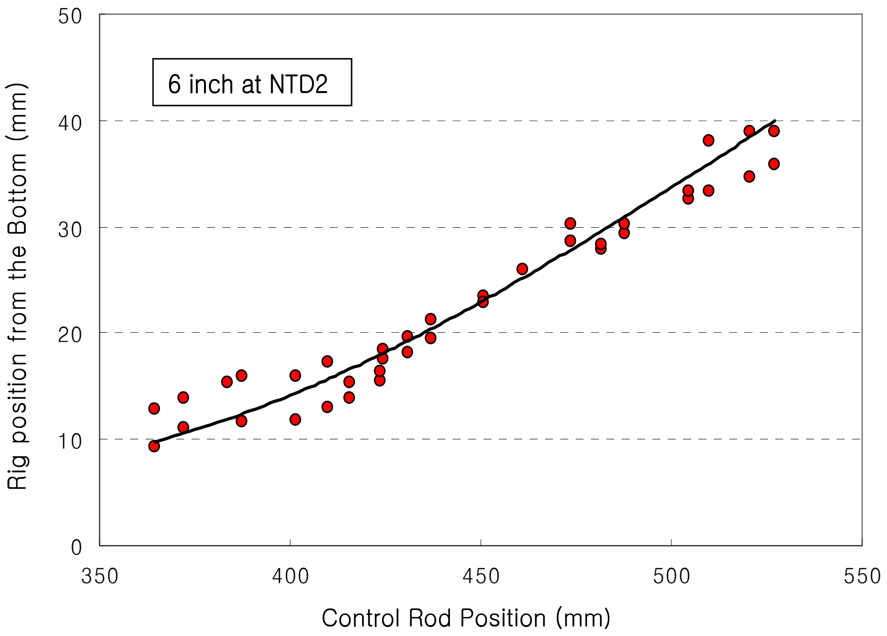
- **Reference monitor**
  - **Two Rh-SPND at each irradiation hole**
  - **Real time monitoring the accumulated neutron dose (fluence) during the irradiation**
  - **Determine the time the container is automatically drawing out**
- **Activation neutron monitor**
  - **Mount Zr foils top and bottom of each ingots in a container**
  - **Measure the actual neutron fluence at the region of ingots**
  - **Induced radioactivity from Zr → absolute fluence → resistivity expectation**
- **Correction of SPND's signal**
  - **SPNDs do not represent the actual neutron dose of the ingots due to their position.**
  - **Position change of a container also affects the neutron flux of the SPNDs.**
  - **Correlations between the average fluxes by SPNDs and by Zr foils for every irradiation during the cycle are used for the reference to the next cycle.**



Correction of SPND's signal at every irradiation positions are updated every cycle by irradiation hole and by ingot diameter.

Irradiating Position

- Movement of control rods changes the distribution and magnitude of the neutron flux in the irradiation holes.
- Proper shift of the container according to the control rod's position maintains a regular uniformity of the axial neutron distribution.
- Relations between positions of control rods and container are obtained from the irradiation results during the current cycle and feed back to the next cycle.
- Around 4 mm position shift of the container is needed to compensate 1% changes at the bottom and top of a batch of ingots at the NTD1 and NTD2 both.



PERFORMANCE

Irradiation Capacity

- **Thermal neutron flux** (n/cm^{2}sec)
  - **NTD1 : ~ 3.9×10^{13} (6 inch), ~ 3.6×10^{13} (8 inch)**
  - **NTD2 : ~ 3.8×10^{13} (5 inch), ~ 3.5×10^{13} (6 inch)**
- **Acceptable ingot dimension**
  - **length : 605 mm (max.)**
  - **diameter : 5, 6, 8 inch**
  - **resistivity : 5 ~ 1,000 Ohm-cm**
- **Irradiation capacity**
  - **Based on 200 days/year operation**

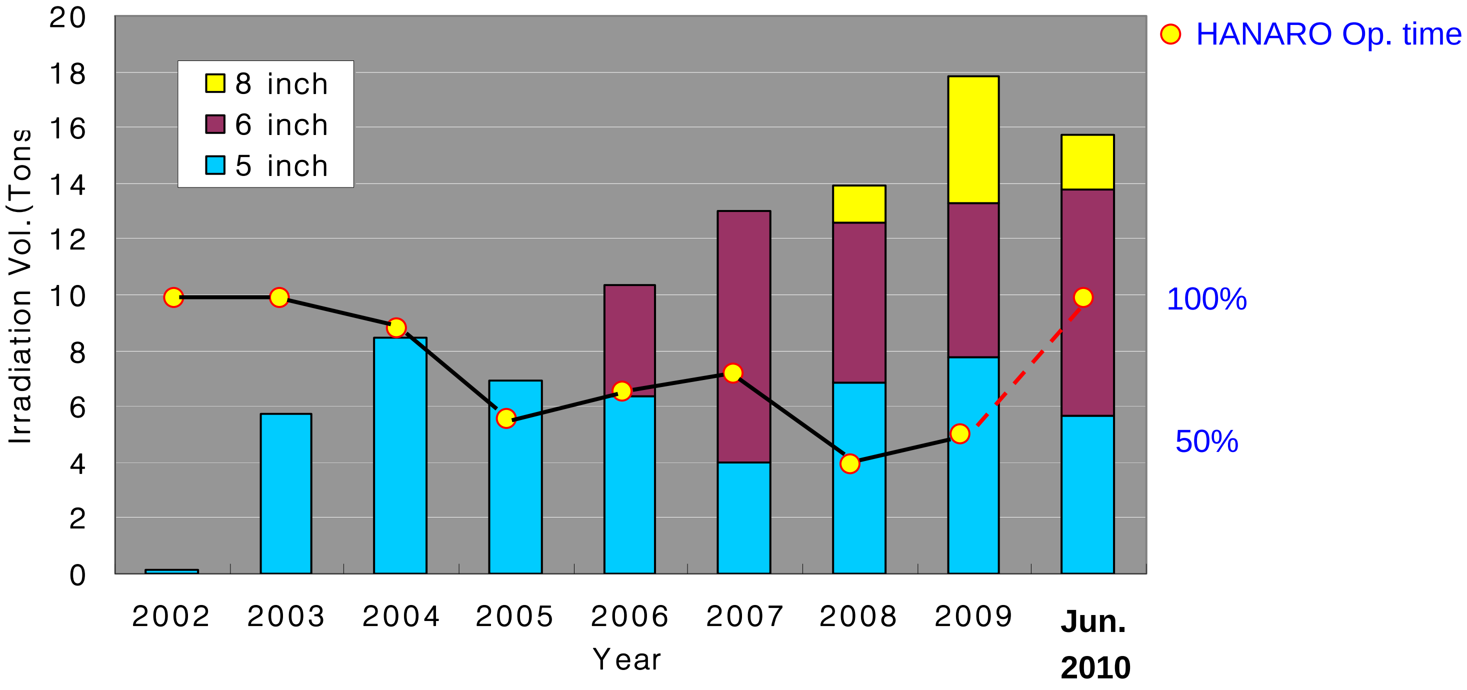
    NTD2 : ~ 20 tons (5 & 6 inch)

    NTD1 : ~ 30 tons (6 & 8 inch)

Target Res. (Ω−cm)	Net Irradiation Time (Hour)	
	5 inch	6 inch
20	8.6	9.6
30	5.7	6.3
40	4.2	4.7
50	3.4	3.8
100	1.6	1.8
300	0.5	0.5
500	0.3	0.3
1000	0.1	0.1

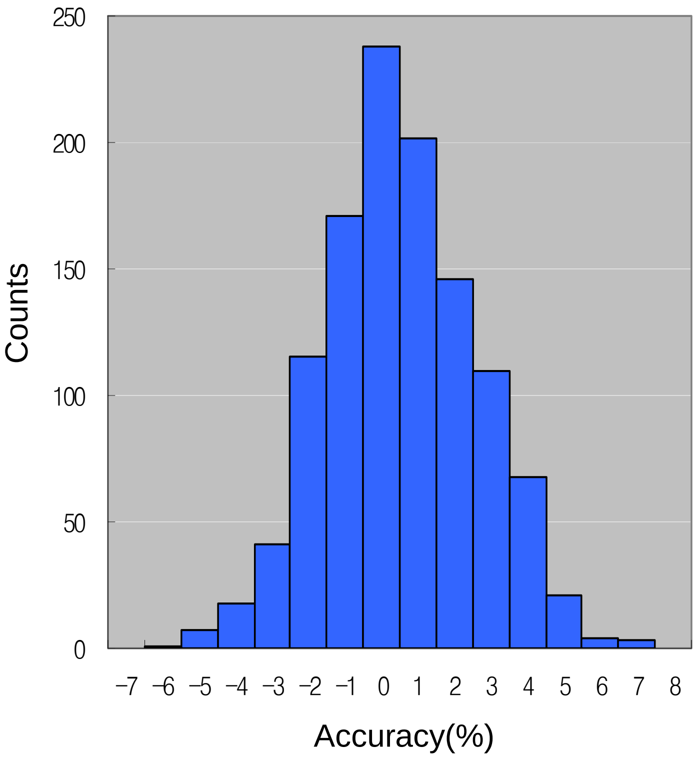
Annual Productivity

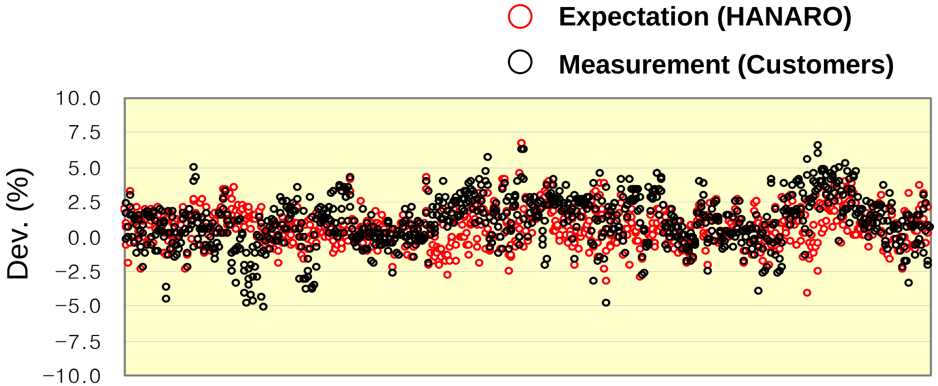
- Since 2005 HANARO had been operated around 60% in average of its annual availability due to the installation and test of the new systems such as FTL and CNS.
- Annual productivity of NTD-Si of HANARO has been increased as the market demands for 6 and 8 inch.
- In 2009 around a total of 18 tons of Si were irradiated including 5, 6 and 8 inch.
- In the 1^{st} half of 2010 around 16 tons was completed and more than 25 toms are expected.



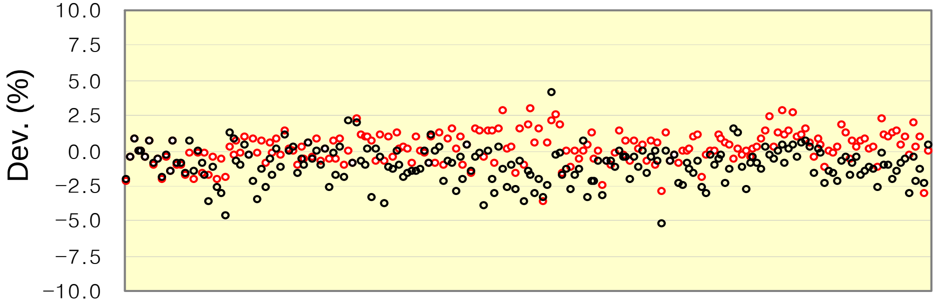
Accuracy (2009)

- **Final resistivity deviation from the target value**
- **98% within ±5% deviation**
- **Average difference less then 1.2% between HANARO's expectations and Company's measurements**





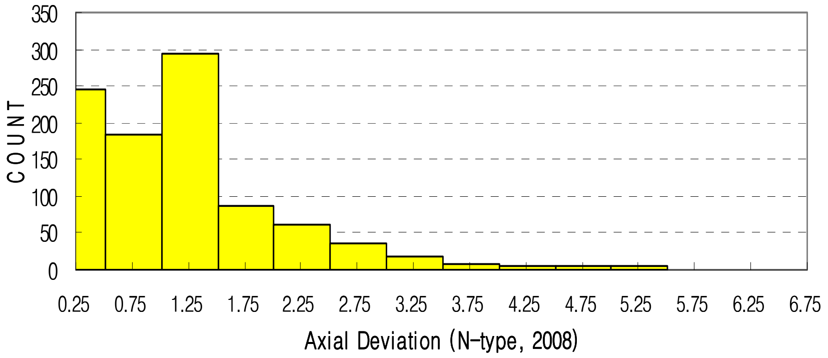
Initial n-type (FZ-Si)

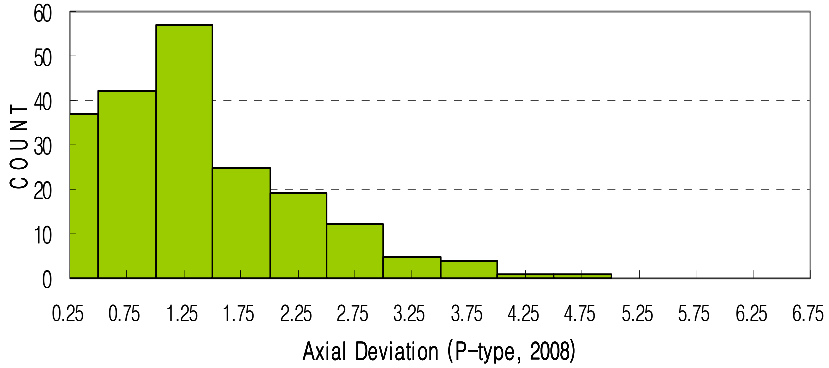


Initial p-type (MCZ-Si)

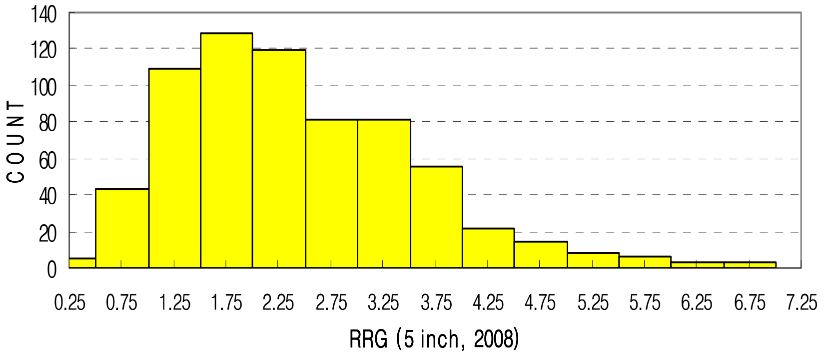
Uniformity (2009)

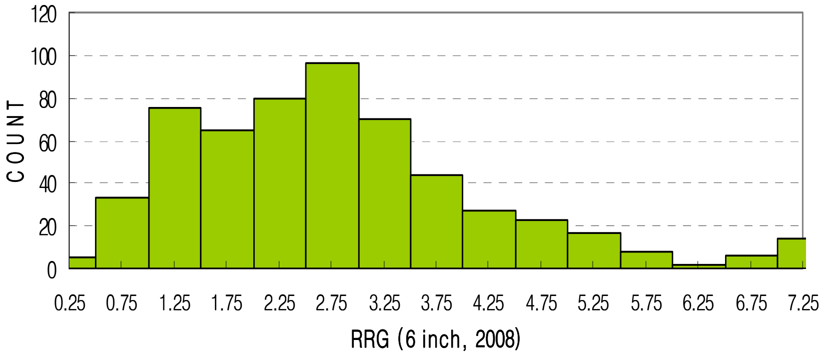
- **Axial resistivity deviation (ARD)**
  - **Less than 5% in all cases**
  - **Avg. deviation : 1.5%**





- **Radial resistivity gradient (RRG)**
  - **Avg. RRG : 2.4% (5 “), 2.8%(6 “)**
  - **Average deviation : 1.5%**





NTD Market

Market Situation

■ Power Device Market (recent market research report by a Japanese Company)

- World Market Size : ~ 120 billion US$ (2009), ~ 160 billion US$ (2015)
- IGBT : ~1.8 billion but increased gradually every year (3.4 billion US$ in 2015)

■ IGBT

- IGBT module for HEV / EV (Hybrid Electric Vehicle) is expected to lead the IGBT market and may create a rapid jump of the market need.
- Around 1.0 billion US$ in 2012 is expected for HEV only
- Other applications for global energy solution are also highly expected

■ NTD Market (forecasting by HANARO's customers)

- At present around 150 ~ 200 tons / year, will be steady increased (~ 7% every year)
- Replacement by the next generation devices (SiC, Epitax) is not realistic
- Gas-doped FZ for power device can be substituted but limited in applicable fields

Growth potential of the NTD Market is very positive but strongly depend on ability to satisfy the market need

International Efforts

- 1976 : The 1st international symposium on NTD
  - Biannual
  - Last symposium was in 1982
- 1985 : IAEA consultant meeting on NTD
- 2007 – 2008 : IAEA-RCA Project (RAS/4/026)
  - “Adding Value to Materials through Neutron Irradiation”
  - Focused on NTD, Gemstone colorization, Membrane filer
  - Regional training course on NTD in HANARO (2008)
- 2008 : 6th International Conference on Isotopes (Seoul, Korea)
  - Prepared a special session for NTD
  - Papers from a wafer company (TOPSIL) aw well as HANARO, FRM-II, SAFARI-I, JRR-3

Conclusion

- The first application of NTD was started from the early 1970s, but not highly regarded in research reactor utilizations.
- Recently the application of NTD-Si wafers becomes more widespread as the energy issues attract worldwide attention.
- The world NTD-Si market size is only 150~200 tons per year now, but a rapid growth is expected near future due to global interest in green energy and energy savings, especially due to increase of HEV / EV.
- However, the productivity would not be increased enough to meet the increasing market demands because almost RRs in the world are not NTD-dedicated and many of them already become superannuated.
- Surely NTD is the one of the most competitive commercial means for RRs.
- More lively exchanges of information and experience among the RRs are required for the stable service to the market.
- It's the time to give a serious consideration for the cooperative meeting with wafer companies.

Thank you….