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Neutron Transmutation Doping at JRTR to Strengthen Global Semiconductor Supply Chain for Net-Zero Emission Technologies

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Affiliation: JRTR / JAEC / JORDAN

16 June 2025

RR: Jordan Research and Training Reactor (JRTR)

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1. Semiconductor Market

(Silicon)

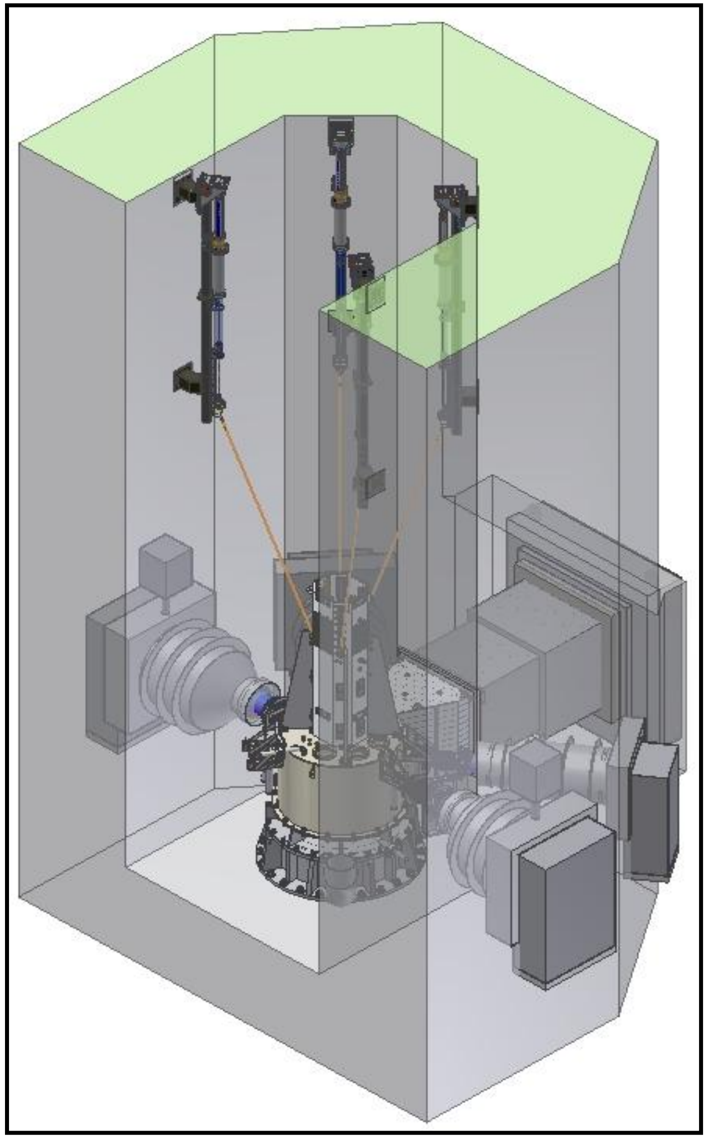
Item	Description / Status
Criticality Of Material	✓ Semiconductors (Si) are **critical** electronic components ✓ Serve a **vital** role across numerous industrial sectors ✓ Especially in **emerging green energy technologies** using high-quality, HV devices
Why Silicon	✓ Although **Ge** is used for various key products, **NTD primarily focuses on Si** ✓ N-doped NTD-Si semiconductors are still **widely used** ✓ Especially in **high-performance, HV power devices**

Item	Description / Status
Statistics And Trends	✓ According to the Historical Billings Report (**2025**) of the World Semiconductor Trade Statistics (**WSTS**) Organization, global semiconductor sales are projected to reach **~ $697 billion** (**11.2% increase** from 2024) (**to grow by 8.5% in 2026** to **$760.7 billion**) ✓ Making semiconductors **the world's fourth largest trade product** **(**after crude oil, refined oil, and automobiles) ✓ **Driven by** the Logic and Memory sectors, EV, and HV-electronics (expected to be **broad-based**, with **continued** expansion across all global regions) ✓ COVID-19 chip shortages and trade tensions **have exposed supply chain issues**, pushing countries **to seek more control over semiconductor production** ✓ Hence, **strengthening** the global semiconductor production system is thus **essential**

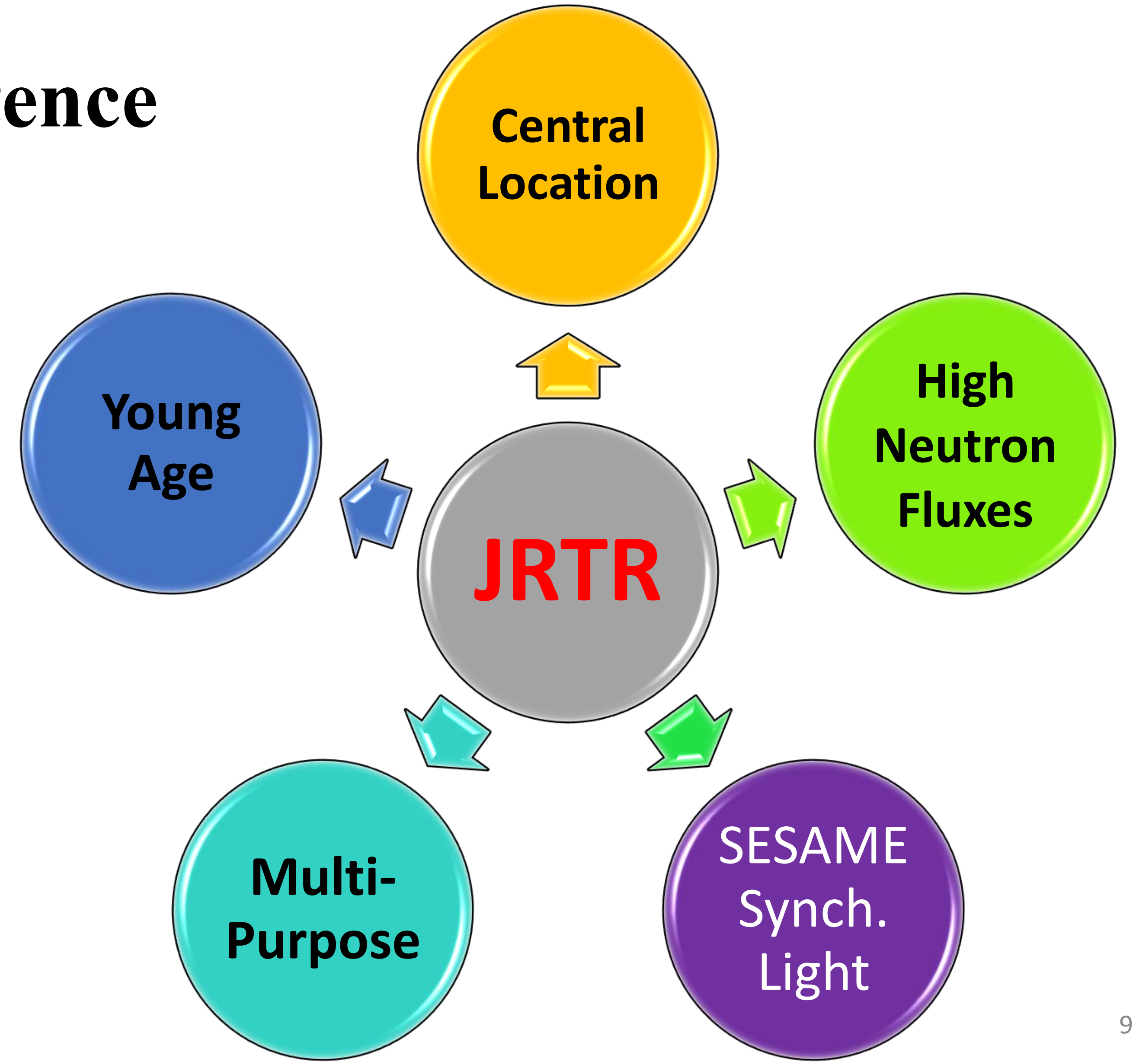
2. Introduction about JRTR

Characteristics of the JRTR

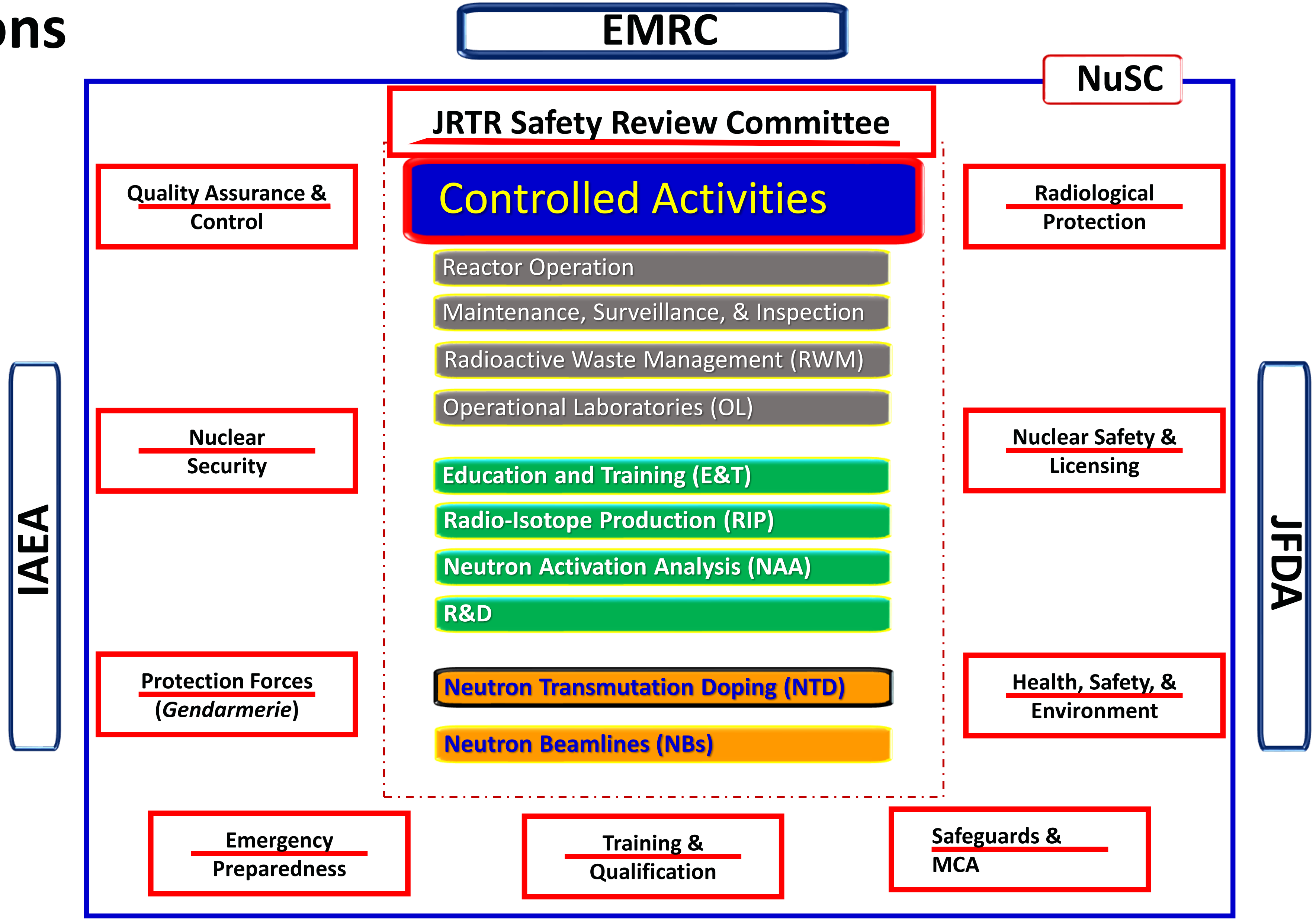
Rx. type:	Open-tank-in-pool (**multi-purpose**)
Thermal power (MW_{th}):	**5** (upgradable to 10)
Max. **Th.** neutron flux ($n/cm^2/s$):	**1.5×10^{14}** ➔ in the core (central trap) **4.0×10^{13}** ➔ in the reflector region (**D_2O tank**)
Fuel type:	Plate type, **19.75%** enriched (U_3Si_2 matrix)
Fuel loading:	**18** FAs, 7.0 kg of **U-235**, aluminum **cladding**
Coolant/Moderator:	Light water (demineralized **H_2O**)
Cooling methods:	Natural/Forced convection **flow**
Reflector:	**Be** assemblies + heavy water (**D_2O**)
Utilization: (multi-purpose)	✓ Education & Training (**E&T**): (**Training center** + **MCR Experiments**) ✓ Neutron Irradiation Services (**35 Vert**.): (**RIP**, **NAA**, **NTD**… etc.) ✓ Neutron Beamline Applications (**4 Horz.**): (Neutron **Radiography** & **Scattering**) + 1 Th. column



Importance and Competence of the JRTR



Conduct of Operations

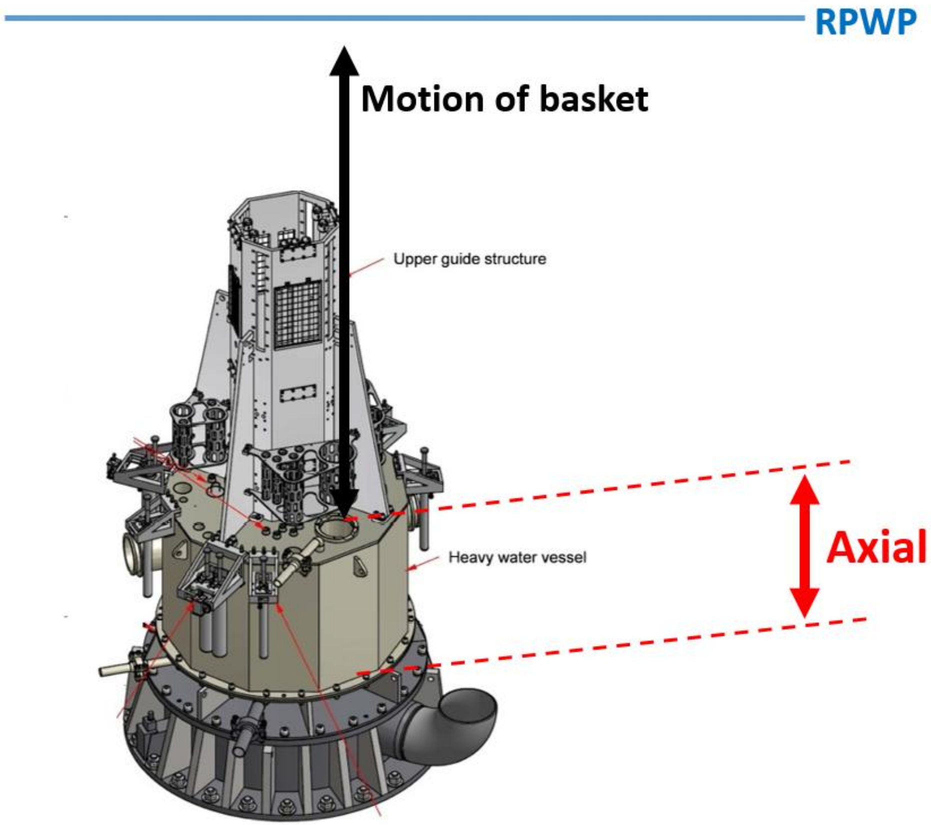


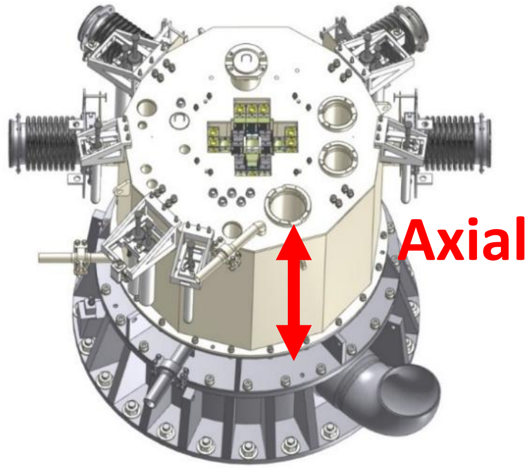
- Stakeholders for Safety & QA
- Binding Document
- Essential Operations
- Active Utilization
- Ongoing Utilization

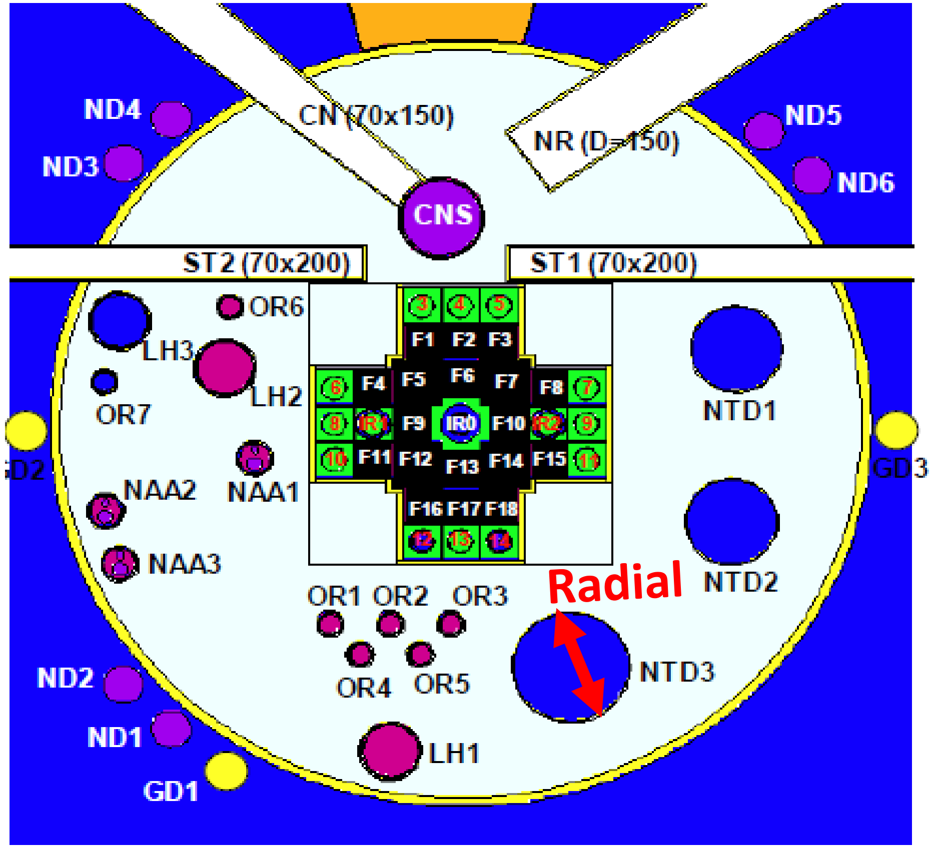
3. NTD Facility at JRTR

3.1 Design and Geometry

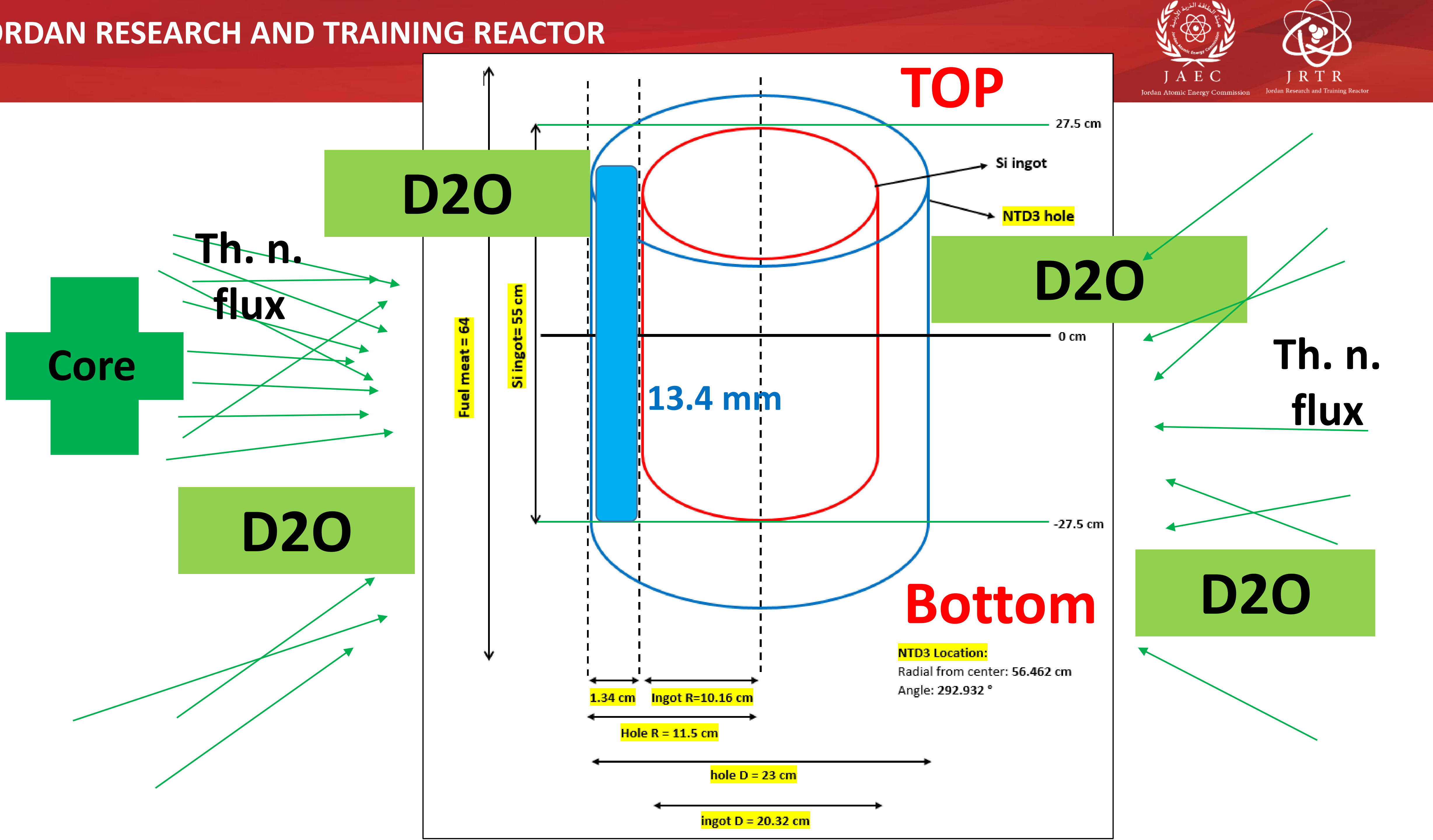
JORDAN RESEARCH AND TRAINING REACTOR







Hole name & Diameter		Ingot Dia.	
NTD1	18 cm	**6”**	15.24 cm
NTD2	18 cm	**6”**	15.24 cm
NTD3	23 cm	**8”**	20.32 cm



JAEC
Jordan Atomic Energy Commission
JRTR
Jordan Research and Training Reactor
TOP
27.5 cm
Si ingot
NTD3 hole
D2O
D2O
Th. n. flux
Core
Fuel meat = 64
Si ingot= 55 cm
0 cm
13.4 mm
Th. n. flux
-27.5 cm
D2O
D2O
Bottom
NTD3 Location:
Radial from center: 56.462 cm
Angle: 292.932 °
1.34 cm
Ingot R=10.16 cm
Hole R = 11.5 cm
hole D = 23 cm
ingot D = 20.32 cm

3.2 Neutron Flux Characterization

JAEC Jordan Atomic Energy Commission · JRTR Jordan Research and Training Reactor

Ref: FSAR, Rev.4

Country	RR name	Φ_{th}/Φ_f at NTD hole
Germany	FRM-II	1700 = 1.7×10^{13} /1.0×10^{10}
Australia	OPAL	800 = 1.6×10^{13} /2.0×10^{10}
Jordan	JRTR	> 180 = 6.9×10^{12} /3.7×10^{10}
Poland	MARIA	133 = 6.0×10^{12} /4.5×10^{10}
China	CARR	100 = 1.0×10^{14} /1.0×10^{12}
China	HFTER	4.8 = 1.2×10^{14} /0.25×10^{15}
Belgium	BR2 (SIDONIE)	27 = 5.5×10^{13} /0.2×10^{10}
Check	LVR-15	12 = 2.7×10^{13} /2.2×10^{12}
Belgium	BR2 (POSEIDON)	5.3 = 5.3×10^{12} /1.0×10^{12}
South Africa	SAFARI-1	1.6 = 1.5×10^{14} /9.3×10^{13}
China	MJTR	0.54 = 4.5×10^{13} /1.9×10^{14}
Brazil	IAE-R1.	---
Korea	HANARO	400

Most of info extracted from the IAEA-TECDOC-1681 and Valentina email

Table 5.5-5 Neutron Fluxes at Utilization Positions (Eq. Core, BOC)

Utilization Position	Neutron Flux (n/cm² s)				Material in the hole
	Thermal Flux (E<0.625 eV)		Fast Flux (E>1.0 MeV)		
	Maximum	Average	Maximum	Average	
NTD1	9.8E+12	8.3E+12	3.0E+10	2.3E+10	Water
NTD2	8.9E+12	7.4E+12	3.2E+10	2.2E+10	Water
NTD3	8.4E+12	7.0E+12	5.0E+10	3.8E+10	Water

Th./fast ratio

(Max./Max.):

NTD1 ~ 325

NTD2 ~ 280

NTD3 ~ 170

Th./fast ratio

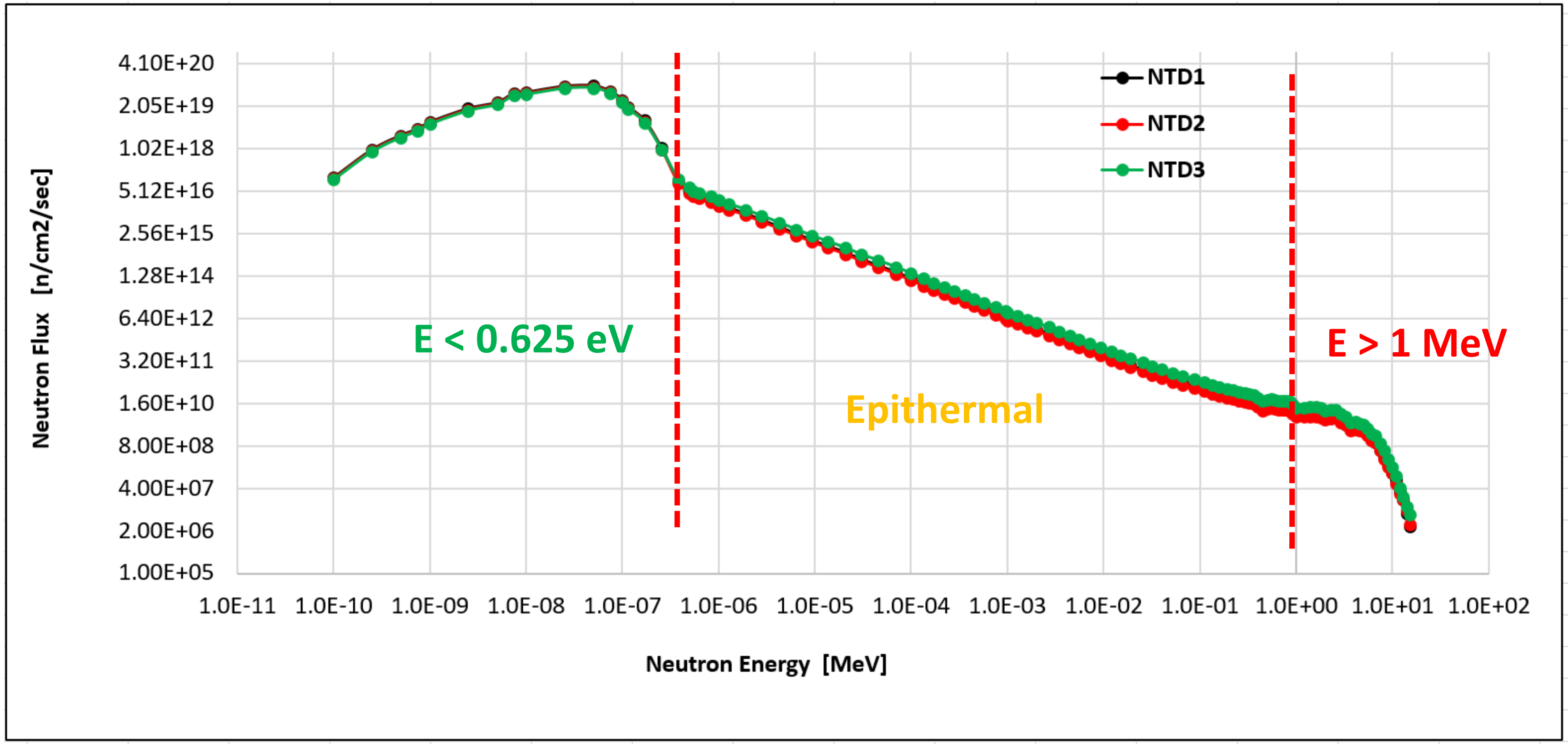
(Avg./Avg.):

NTD1 ~ 360

NTD2 ~ 335

NTD3 ~ 185

➢ Neutron Spectrum (McCARD)

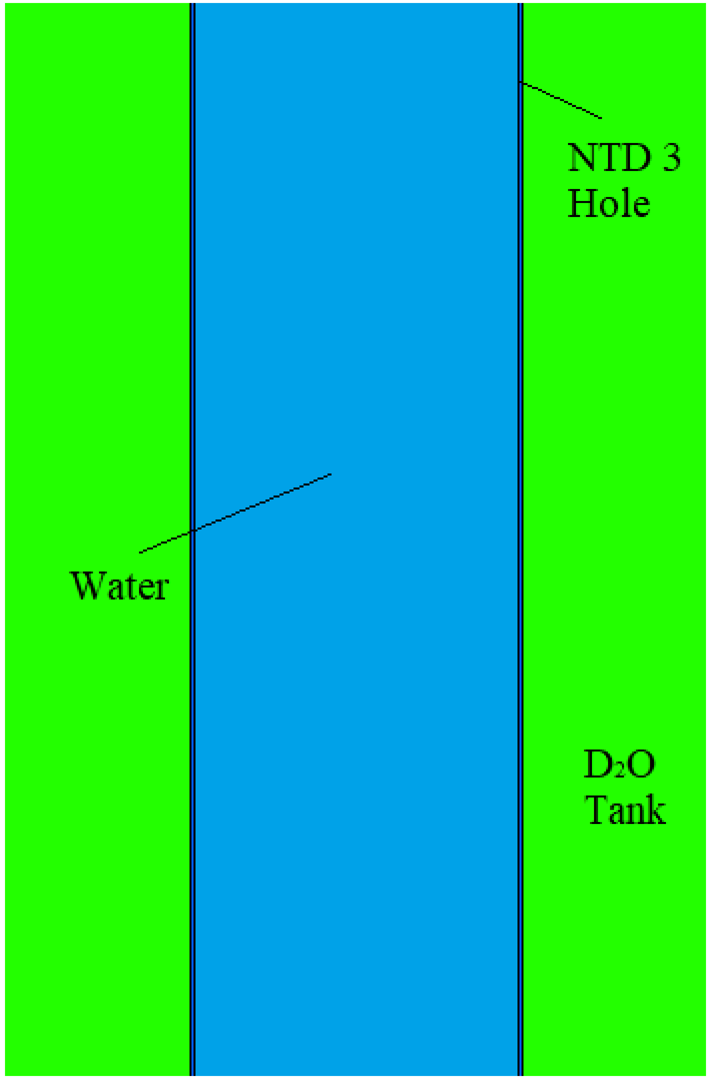


Th./fast ratio

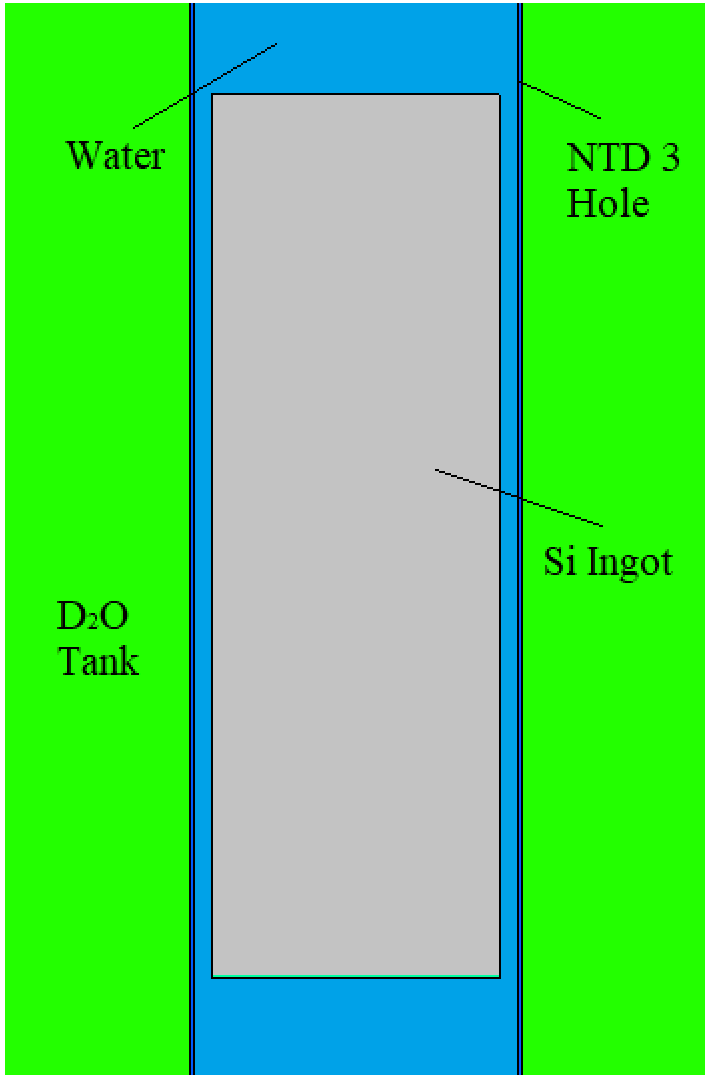
NTD1 ~ 360

NTD2 ~ 335

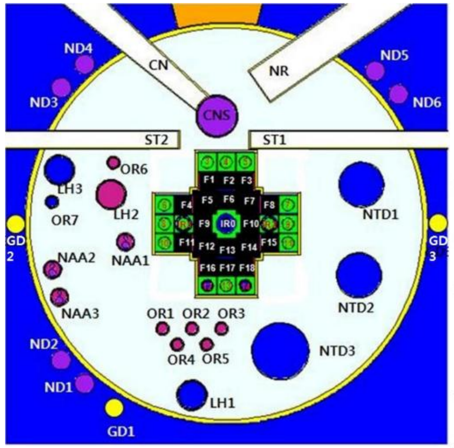
NTD3 ~ 185

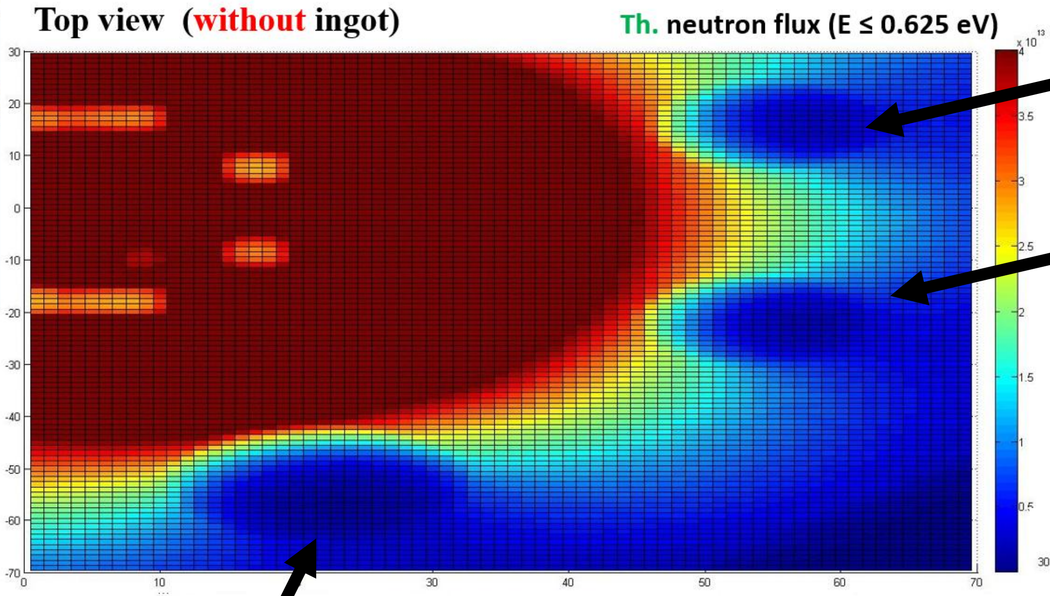


Without Si ingot



With Si ingot

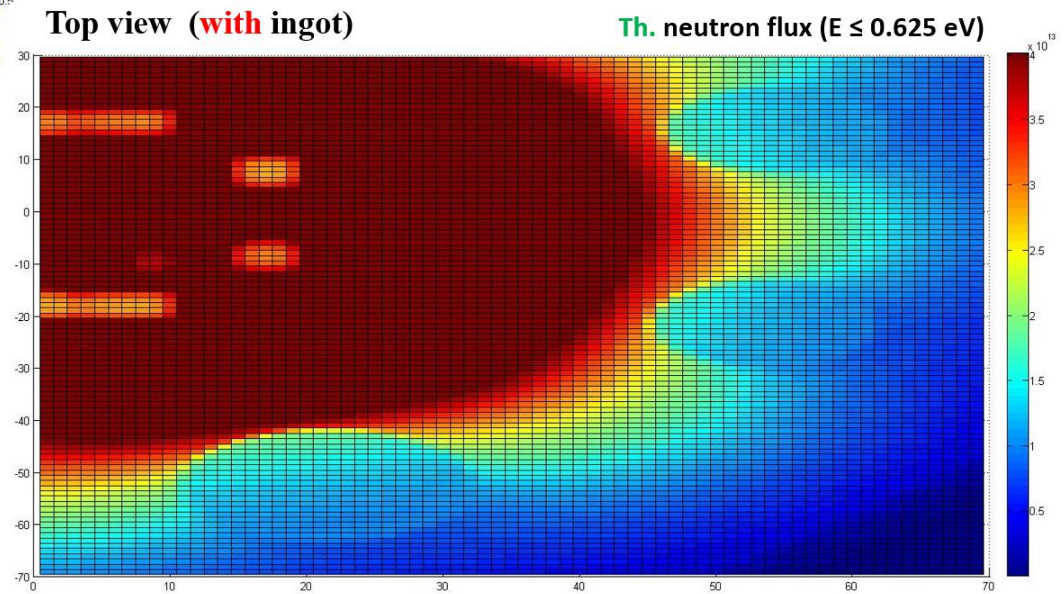




NTD#1

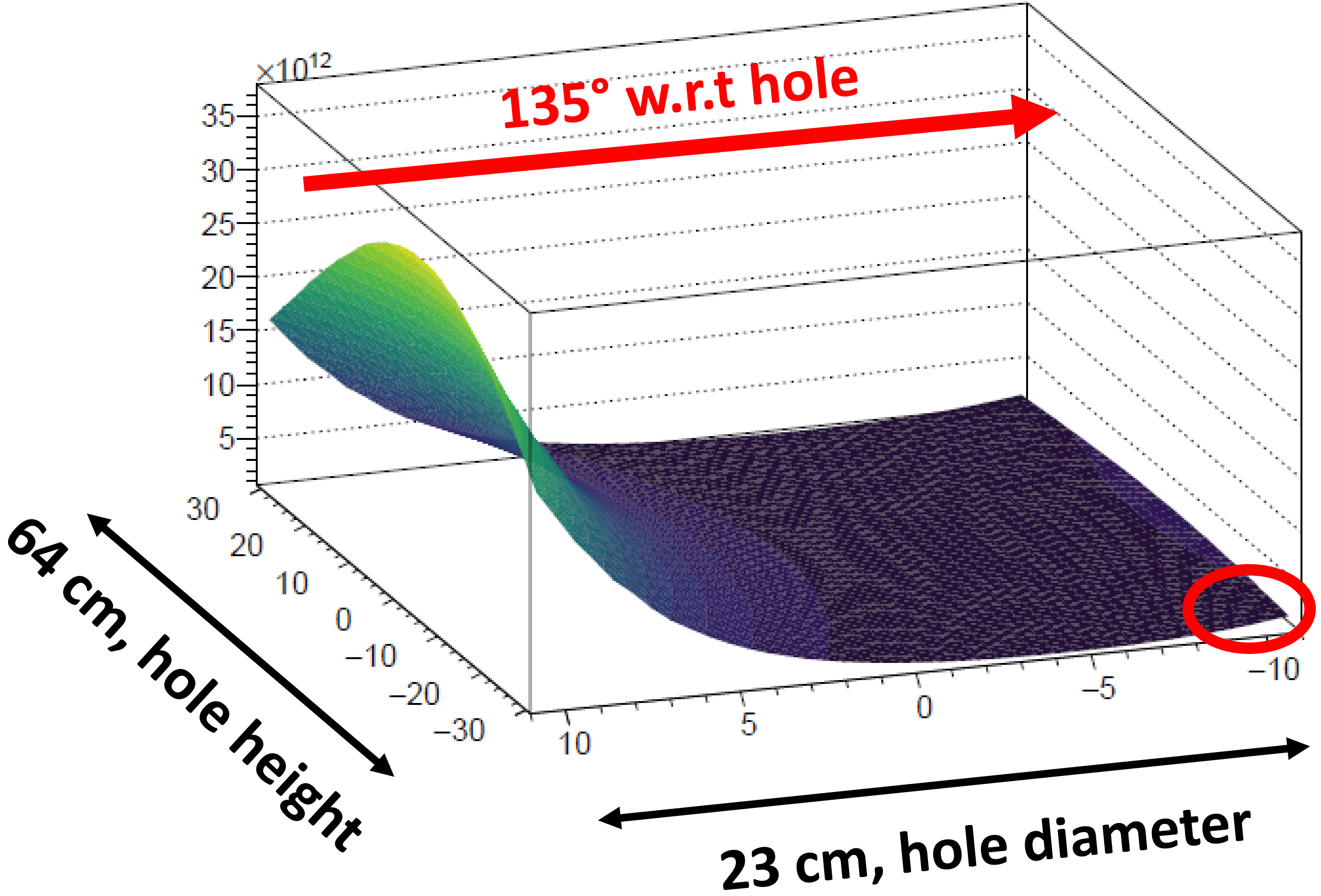
NTD#2

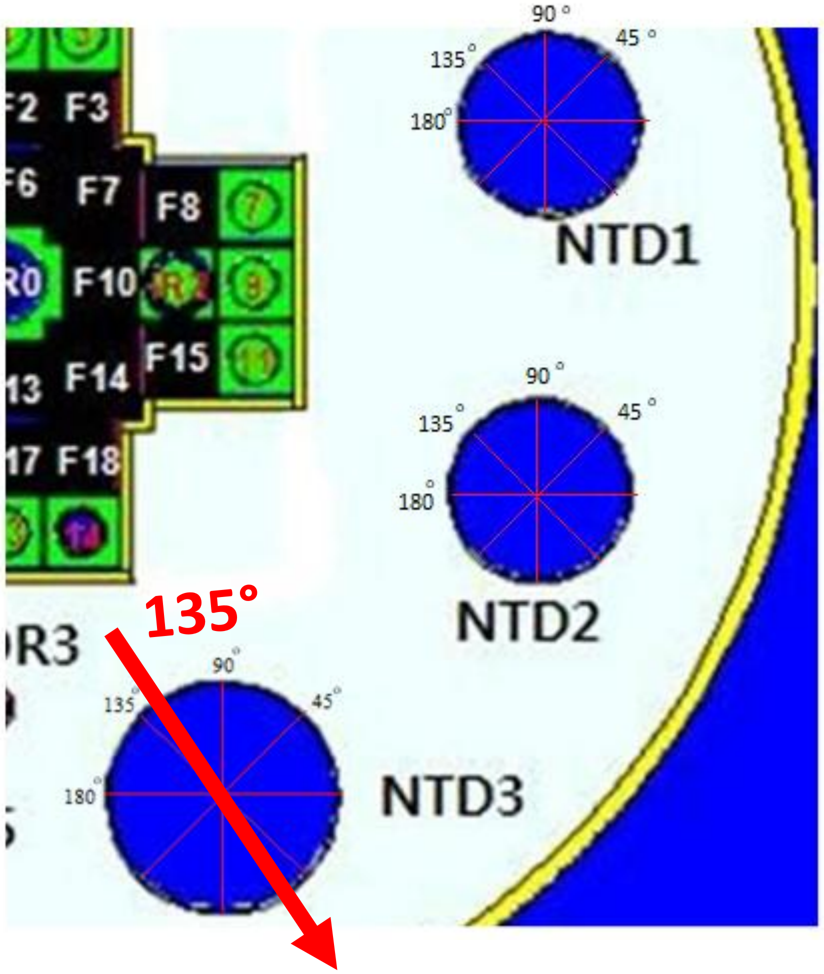
NTD#3



- **Analysis:**
  - ✓ Thermalization due to water / silicon
  - ✓ Backscattering (reflection back) effect
  - ✓ Hole center angle (flux direction)
  - ✓ Others ….

➢ Flux along the 135° line NTD3 McCARD using Point Detectors





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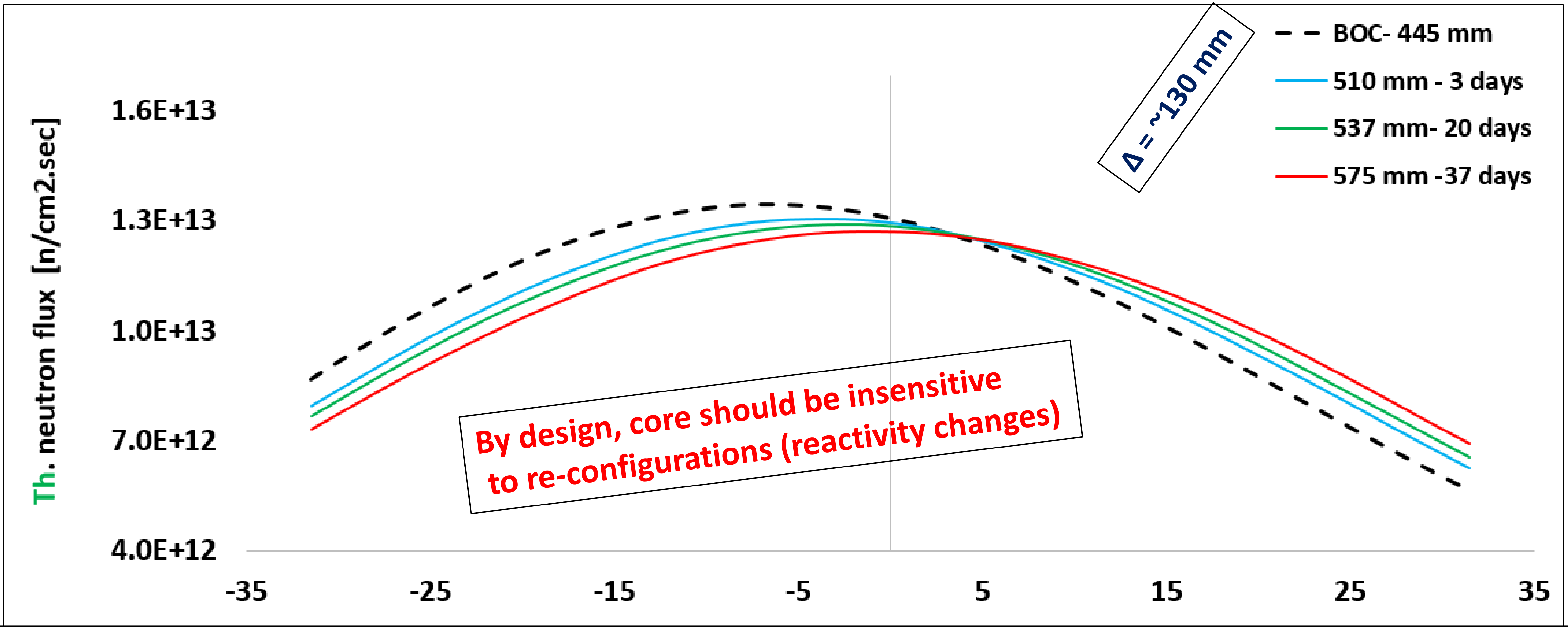
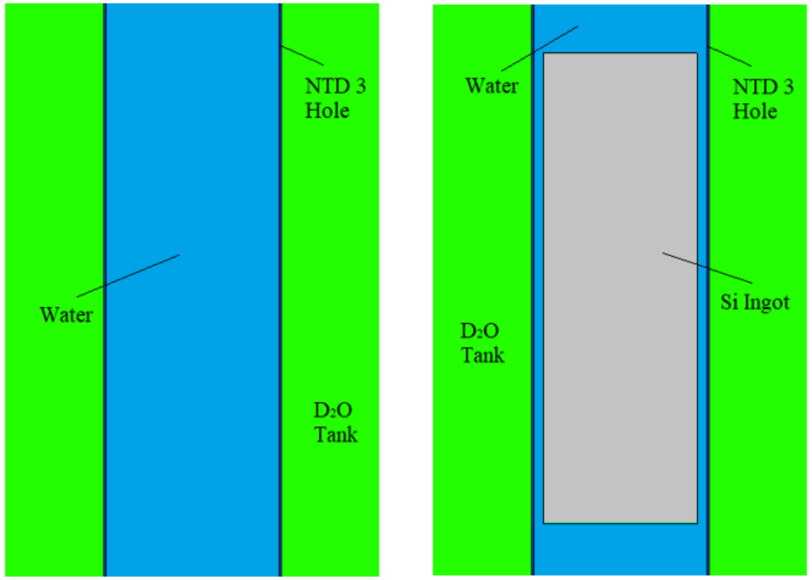
Th. neutron flux at NTD#3 at different points in time of cycle (BOC, MOC, EOC)



Axial [cm]

Axial Neutron Flux Distribution (McCARD)



Without Si ingot   With Si ingot

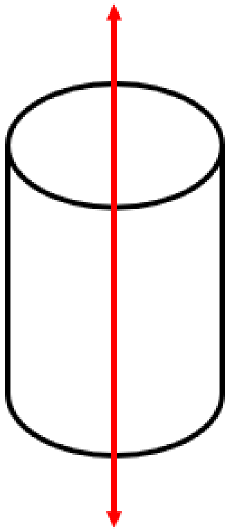
TOP

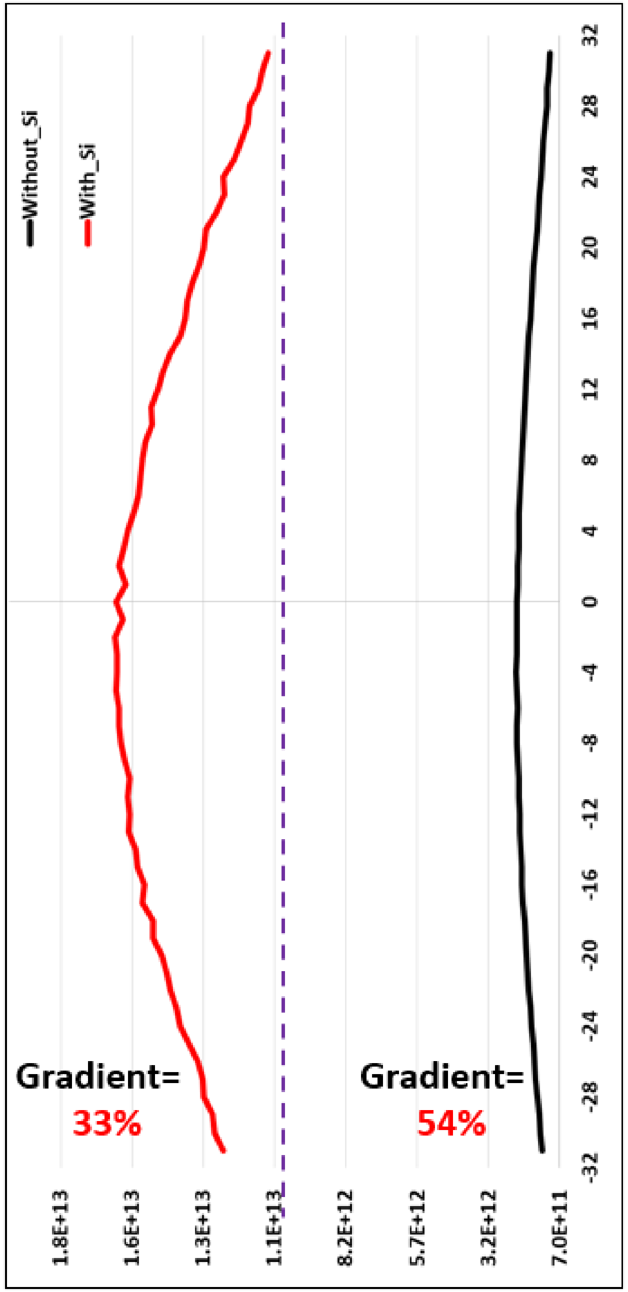
NTD3

Hole
Central
Axial Line

x= 220
Y= -520
Z= -310 ~ 310

θ= constant
r = 0





Bottom

Th. neutron flux

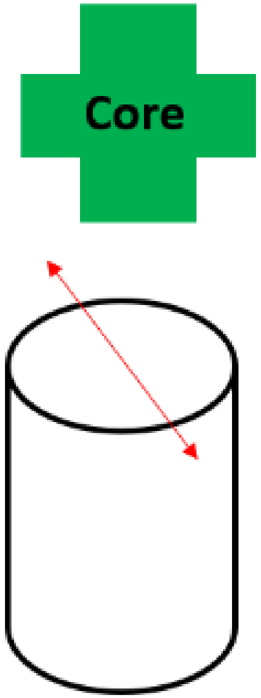
Axial: -310 mm to 310 mm

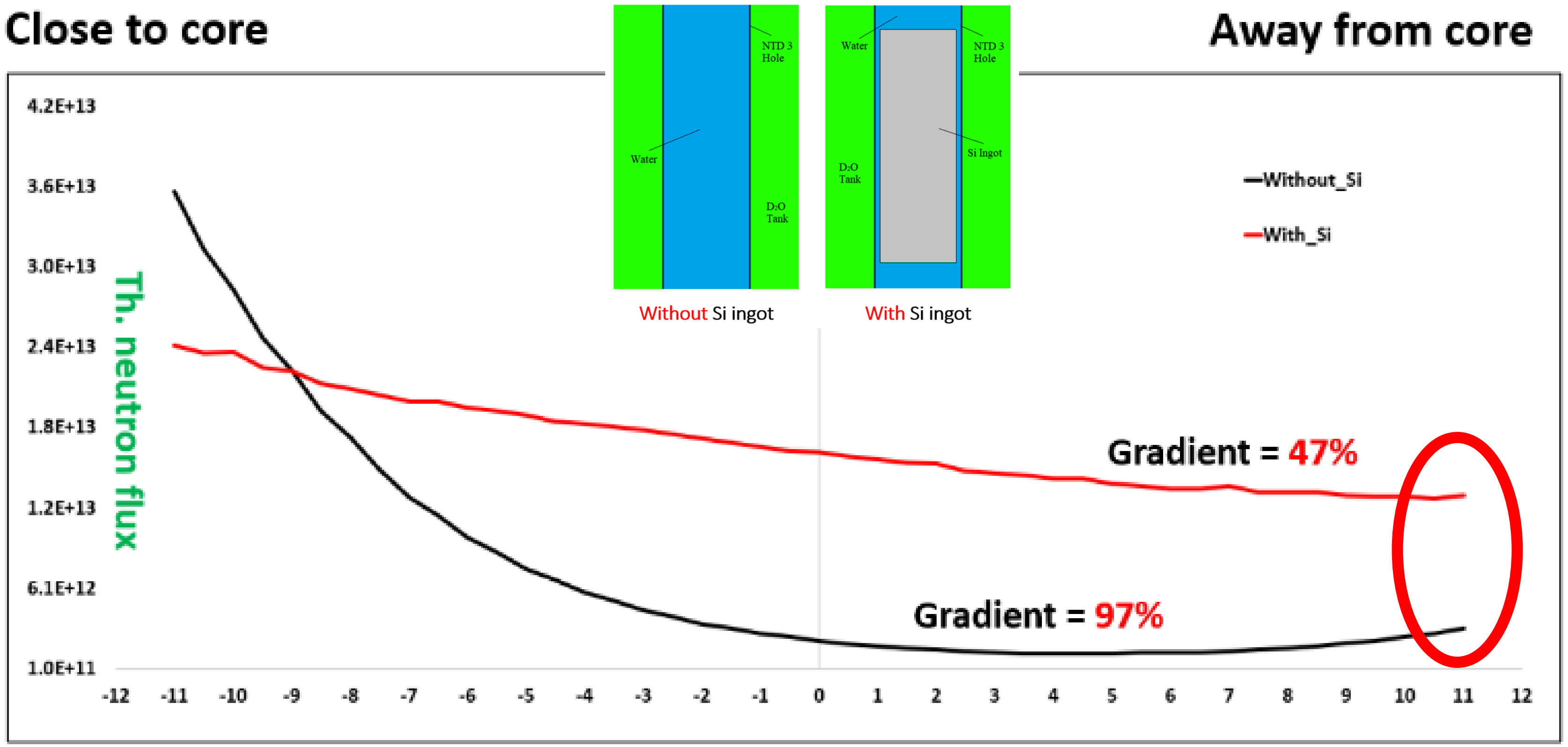
Radial Neutron Flux Distribution (McCARD)

NTD3

Hole
Central
Radial Line

Z= 0
θ= constant
r= -11.5 to 11.5 cm





Radial: -115 mm to 115 mm

3.4 Doping Uniformity Control

Hole: silicon ingot
Gap: water with screen

Actual configuration

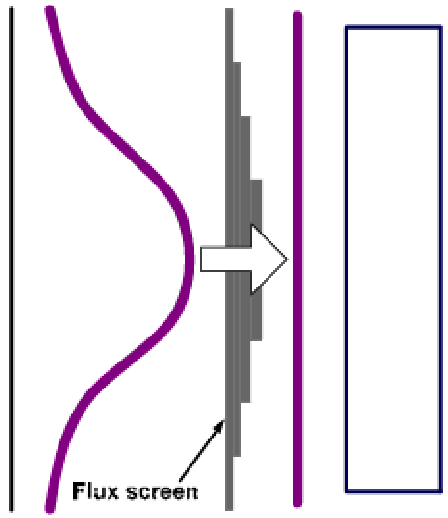
Optimum doping uniformity across all ingot volume (gradients)

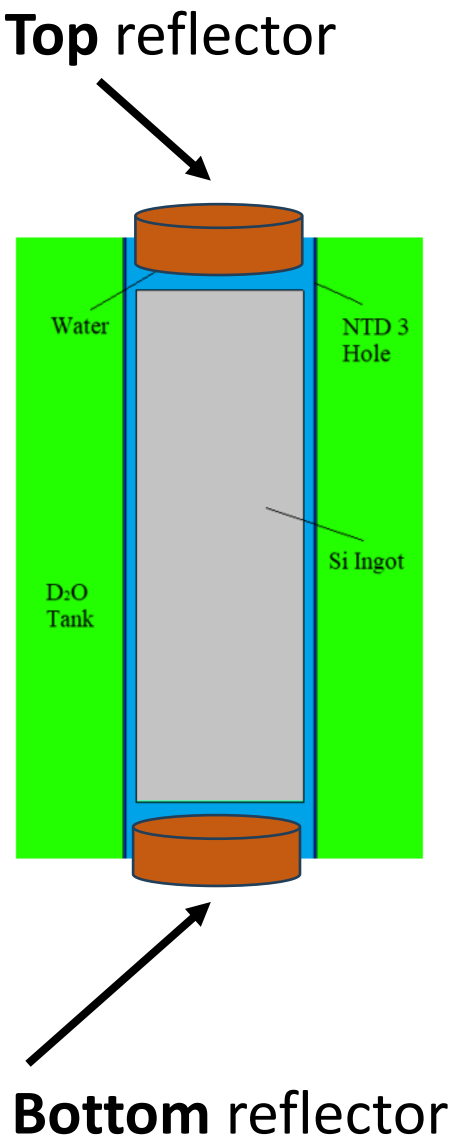
Axial Uniformity

Radial Uniformity

Screen

Rotate





Type of Ingot	Type of flattening Filter (screen)	NTD Hole	Type of Reflector (top & bottom of ingot)	Max. Th. Flux [$n.cm^{-2}.s^{-1}$]	Avg. Th. Flux [$n.cm^{-2}.s^{-1}$]
Si	Al sheet + Water = 13.4 mm Gap	NTD3	Aluminum	1.39E+13	1.28E+13
			Graphite	**1.43E+13**	**1.34E+13**
			Silicon	1.40E+13	1.30E+13
			Water	1.41E+13	1.30E+13

3.5 Irradiation Capacity of Si ingots

(Estimation of Annual Production)

Constants

- Si density	= 2.329 g/cm^3
- Si abundance	= 3.0782 %
- Si-30 Molar Mass [g/mole]	= 29.97377
- Si-30 Th. capture-XS	= 107 mb
- Electron mobility, μe (@ 300K)	= 1350
- Electron charge, qe	= 1.602E-19 Coulomb

NTD Facility

- ➢ Height & Diameter for:
- NTD1,2,3
  Holes, batches (ingots)

Assumptions

- Calc. fluxes using **Monte Carlo Codes**
- Effect of initial resistivity was subtracted
- Effective holes height = 50~55 cm
- Full Op. days = 150~200 / year

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JRTR Jordan Research and Training Reactor

	Ingot (14-Si-30)				
Silicon bulk density [g/cm^3]	rho	2.329			the drift m
Si-ingot volume [cm^3]	V	17827.06			
tarting material amount (natural pure silicon)	ingots mass [g]	41519.23	41.52	kg	
Natural abundance of Si-30	θ	0.030872			Irr. calibration c relationship bet
Starting material amount	Si-30 mass [g]	1281.78	1.28	kg	
Avog. # (1/mol)	N_Avog.	6.022E+23			
M(gram/mol or [amu]) for parent nuclide	M [g/mol]	29.97377			
the Si ingots (2 or 3 in a batch of 60 cm)	N0 [#]	2.58E+25			Parent
the Si ingots (2 or 3 in a batch of 60 cm)	N0 [#/cm^3]	1.445E+21	1.445E+21	[#/cm^3]	
					Irr. ca
Given initial risistivity	ρi [Ω.cm]	4000	this indicates No,P [#/cm^3] to be subtracted (less time)=		1.156E+12
Required final risistivity	ρf [Ω.cm]	200	this requires net Nact. [#/cm^3] to be =		2.20E+13
al neutron capture cross-section of Si-30	σc [cm^2]	1.07E-25			
Thermal neutron Flux @ NTD3	ϕth [n/cm^2/sec]	7.00E+12			
Irradiation time	ta [s]	20299.34			
Irradiation time assuming no initial dopnats	ta [hr]	5.6			
iation time (without initial dopnats effects)	ta [hr]	5.64	338	min	
eutron Fluence (Neutron Dose) @ NTD3	ϕt [n/cm^2]	1.42E+17			
eutron Fluence (Neutron Dose) @ NTD3					
eutron Fluence (Neutron Dose) @ NTD3					
Rel. Err. [%]	RPE [%]	-100%			
		-100%			
Irradiation time	ta [sec]	20299.34			
Irradiation time	ta [hr]	5.64			

IAEA International Atomic Energy Agency
Atoms for Peace and Development

Published October 2008 | Version v1

Miscellaneous | Metadata-only

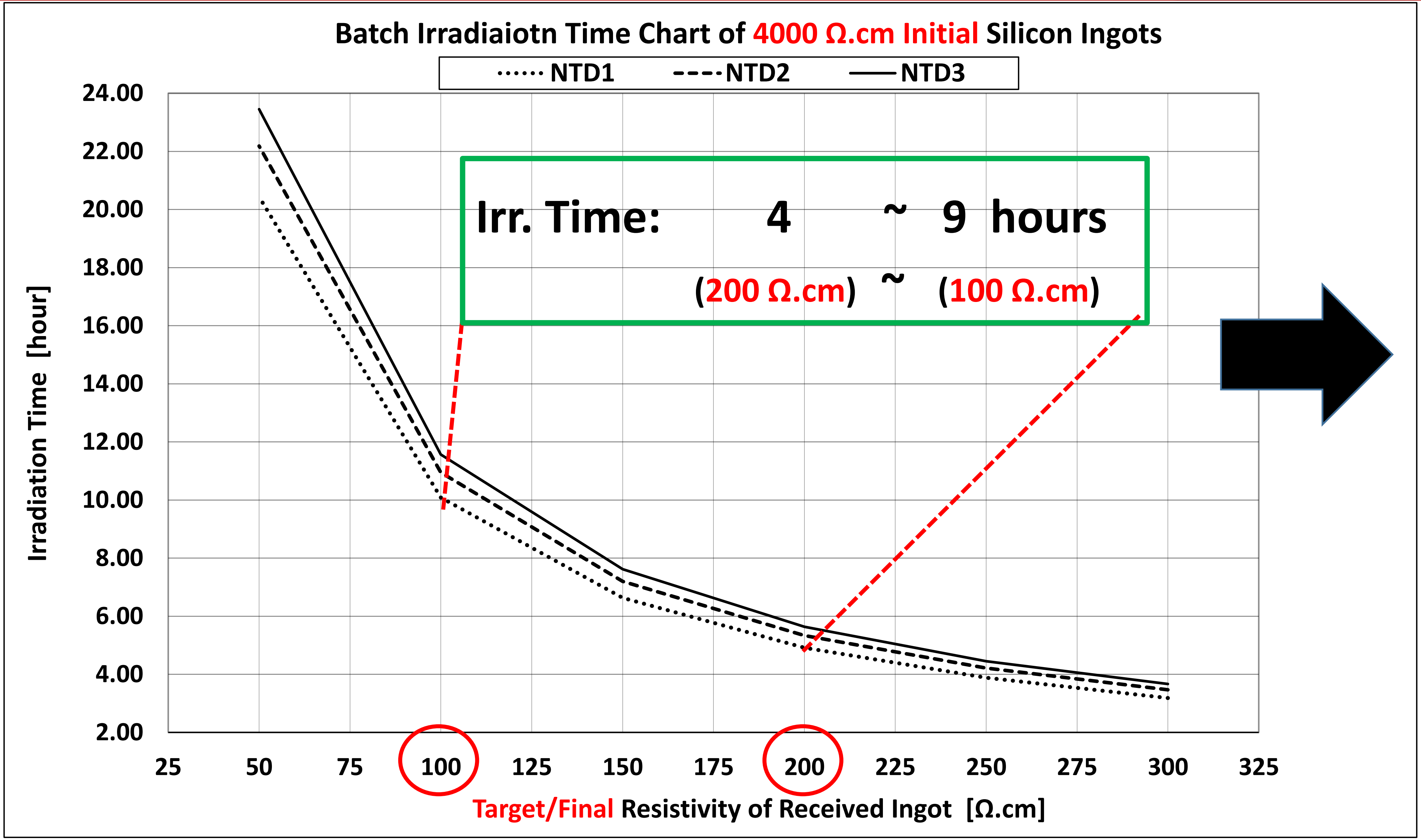
Estimation of Future Demand for Neutron-Transmutation-Doped Silicon Caused by Development of Hybrid Electric Vehicle

Kim, Myong Seop[1]; Park, Sang Jun[1]

Hide affiliations

1. Korea Atomic Energy Research Institute, Daejeon (Korea, Republic of)

Target ? ohm.cm → **Activation Equation Excel** → **Irradiation Time ?** → **Tons**


Batch Irradiaiotn Time Chart of 4000 Ω.cm Initial Silicon Ingots
NTD1
NTD2
NTD3
Irr. Time: 4 ~ 9 hours
(200 Ω.cm) ~ (100 Ω.cm)
Irradiation Time [hour]
24.00
22.00
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
25
50
75
100
125
150
175
200
225
250
275
300
325
Target/Final Resistivity of Received Ingot [Ω.cm]

Tons ?

JORDAN RESEARCH AND TRAINING REACTOR

JAEC — Jordan Atomic Energy Commission
JRTR — Jordan Research and Training Reactor

Country	RR name	Annual Capacity (t)
Germany	FRM-II	15
Australia	OPAL	25
Jordan	JRTR	47.8 max
Poland	MARIA	15.7
China	CARR	50
China	HFTER	10
Belgium	BR2 (SIDONIE)	15
Check	LVR-15	1.5
Belgium	BR2 (POSEIDON)	45
South Africa	SAFARI-1	20
China	MJTR	20
Brazil	IAE-R1.	1.2
Korea	HANARO	20

Irr. Time:
5.5 ~ 7.5 hours

Initial resistivity [Ω.cm]		5000
Target resistivity [Ω.cm]		150

	Irradiation time per 50cm batch [min]		
	NTD1	NTD2	NTD3
FSAR (average flux, water medium, without screen, without graphite)	8.300E+12	7.400E+12	7.000E+12
	388	436	461
McCARD (min flux, silicon medium, without screen, without graphite)	9.662E+12	9.002E+12	9.277E+12
	334	358	348

E.g.: 150 days, 6”, 6”, 8”
150 Ω.cm ➔ 33 ton

E.g.: 150 days, 6”, 6”, 8”
200 Ω.cm ➔ 40 ton

E.g.: 200 days, 6”, 6”, 8”
150 Ω.cm ➔ 44 ton

E.g.: 200 days, 6”, 6”, 8”
200 Ω.cm ➔ 50 ton

Production [ton/year]:

up to 50~55

(depends on
resistivity, Dia., and operation days)

Under conservative operation conditions:
150 FPD,
100% 8” & 30% 6”
23 tons

4. Financial Considerations

Item	Description / Status / Plan / Goal
2025 Demand	✓ Larger-diameter ingots (5", 6", and **especially** 8") has increased ✓ Driven by **EV** and **HV**-electronics markets
Key RR Suppliers	✓ OPAL (Australia), HANARO (S. Korea), and BR2 (Belgium) **can process** these sizes ✓ But overall **supply** still falls **short** of projected needs
Irradiation Service Pricing	✓ **Negotiated** case by case ✓ Commands a premium due to NTD's superior **resistivity uniformity**
Contracting	✓ International contractors will be **invited to bid** on design, construction, and commissioning

Item	Description / Status / Plan / Goal
Project Timeline	✓ A **2-year** design and installation phase // A **20-year** operations phase ✓ All statutory levies and taxes **incorporated into** the capital budget
Production Scenario	✓ **Conservative** conditions: (150 FPDs/year, three holes in use, **res.** **4000** to **150**) ✓ The facility expects to process roughly **20–25 tons** of NTD-Si annually
Running Expenses	✓ Maintenance, staffing, and fuel, are projected to grow **modestly** over time ✓ But remain **predictable**
Revenue Assumptions	✓ **Align** with premium NTD service rates ✓ **Adjusted** for ingot size and resistivity ✓ The facility can **cover** costs and **generate** sustainable returns
Overall Plan	✓ JRTR's NTD-Si project is structured **to meet** global demand **gaps** ✓ While developing **local** technical **expertise** and industrial progress
Ultimate Goal	✓ By **providing** a reliable, high-quality irradiation service ✓ JRTR-NTD facility will **enhance** Jordan's role in the semiconductor supply chain ✓ **Support** long-term economic diversification

❖ Summary of NTD Progress

- Serious Plans for entering the NTD **Market** soon.
- Discussing with **Partners**.
- Collecting NTD **Proposals:**
  - ✓ Descriptive
  - ✓ Technical
  - ✓ Financial
- **Stakeholders**.
- **Manpower**.
- **Funding**.

THANK YOU ありがとう شكراً