NTD-Si Alliance 4 Net Zero – new initiative to support and promote Neutron Transmutation Doping Silicon at Research Reactors

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TU München, Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II),
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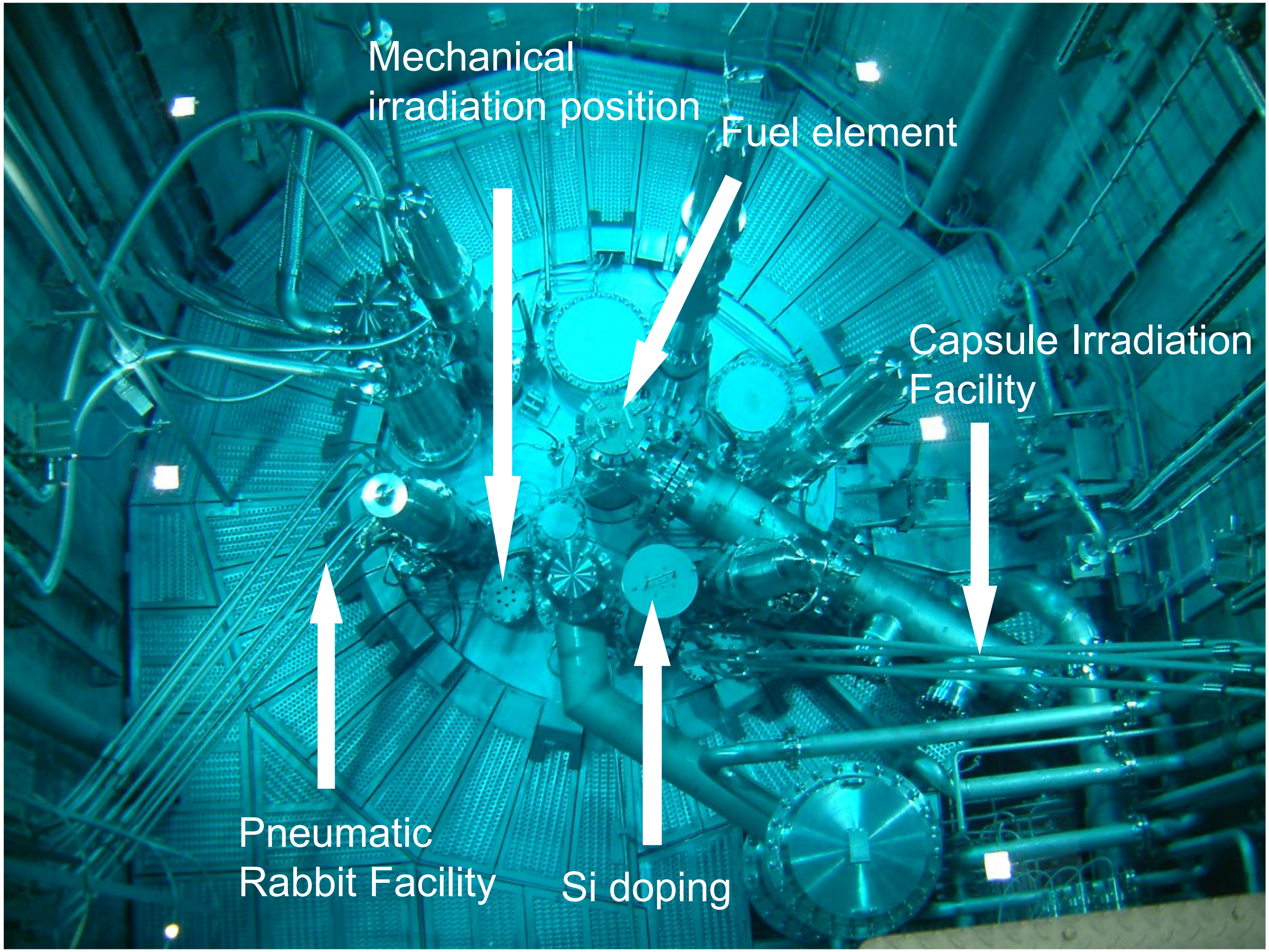
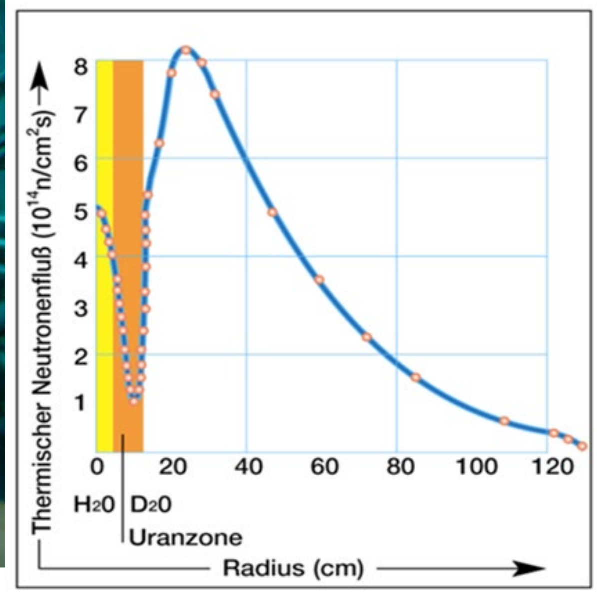
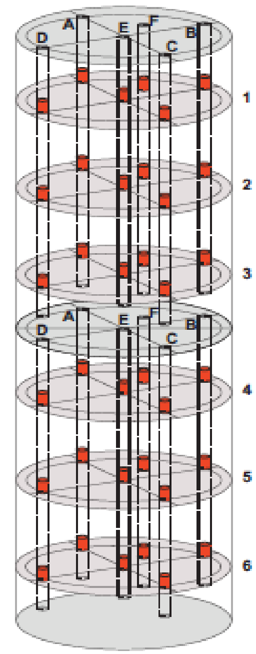


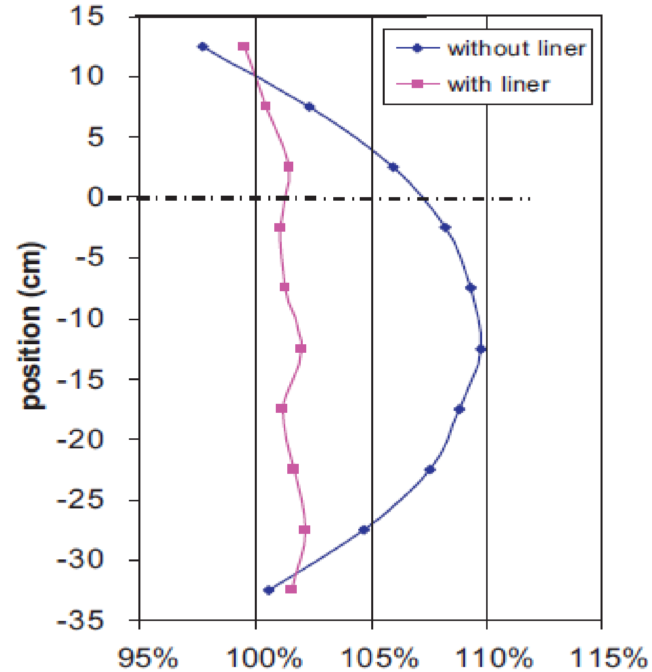
Irradiation positions at FRM II

- 100 mm tube (SDA1)
- 200 mm (SDA2)
- 2 x spare flanges



Silicon Doping Facility SDA at FRM II





Vertical irradiation tube at 1 m distance to FE

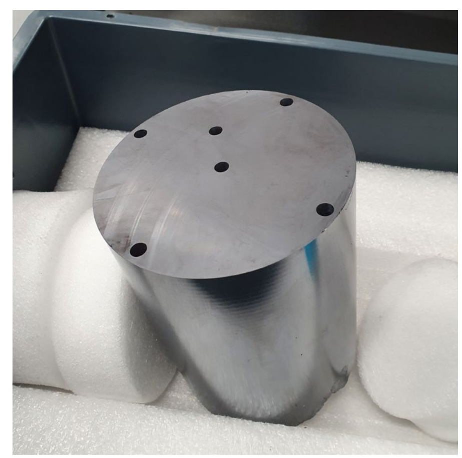
- Stack length 500 mm
- 4 diameters (4', 5', 6', 8') ingots suitable
- Φ_{th} = 1.7E13 $cm^{-2}s^{-1}$
- Φ_f = 1.0E10 $cm^{-2}s^{-1}$
- Φ_{th}/Φ_f = 1700 (probably world highest !)

Irradiation time

$$t = A/\Phi(1/\rho_E - 1/\rho_A) \text{ for n} - \text{type};$$

$$t = A/\Phi(1/\rho_E + 2.8/\rho_A) \text{ for p} - \text{type};$$

(0.5 ÷ 20) h



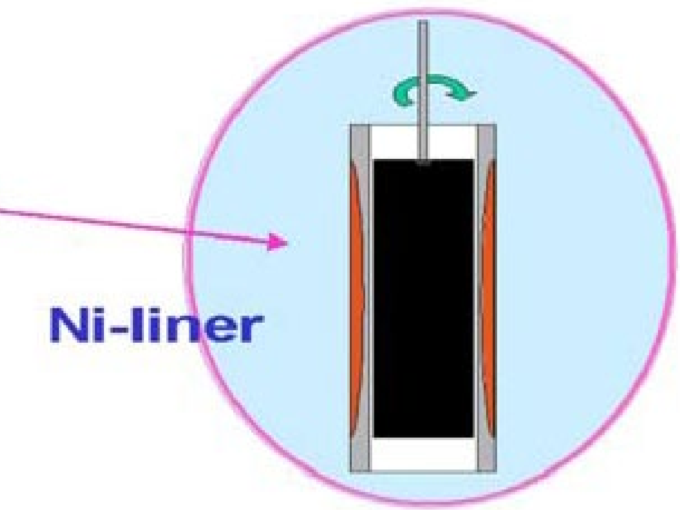
X. Li et al. Applied Radiation and Isotopes 67 (2009) 1220

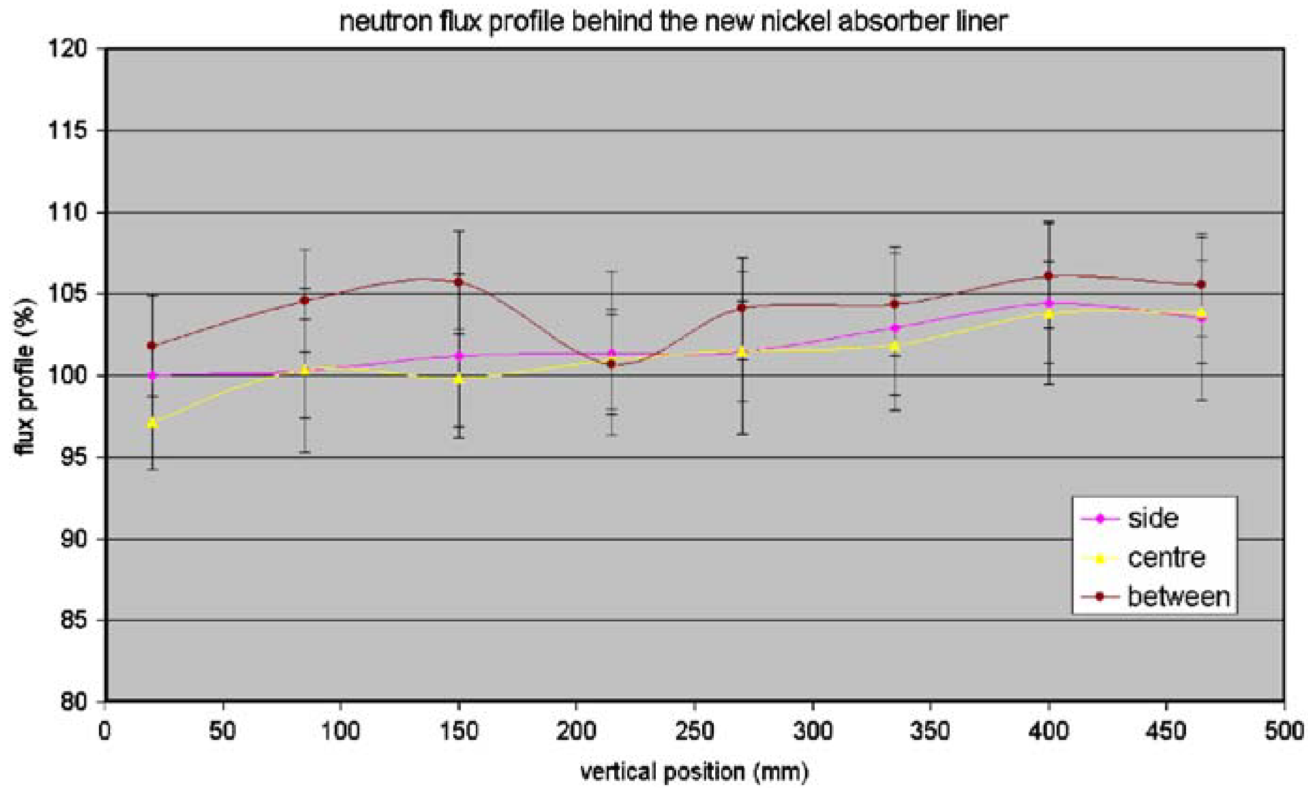
Silicon Doping Facility SDA at FRM II

Radial homogeneity: by rotation 6 rot. / min. - better than 5% (6'), 7% (8')

Axial homogeneity: by absorbing Ni-liner – better than 3%

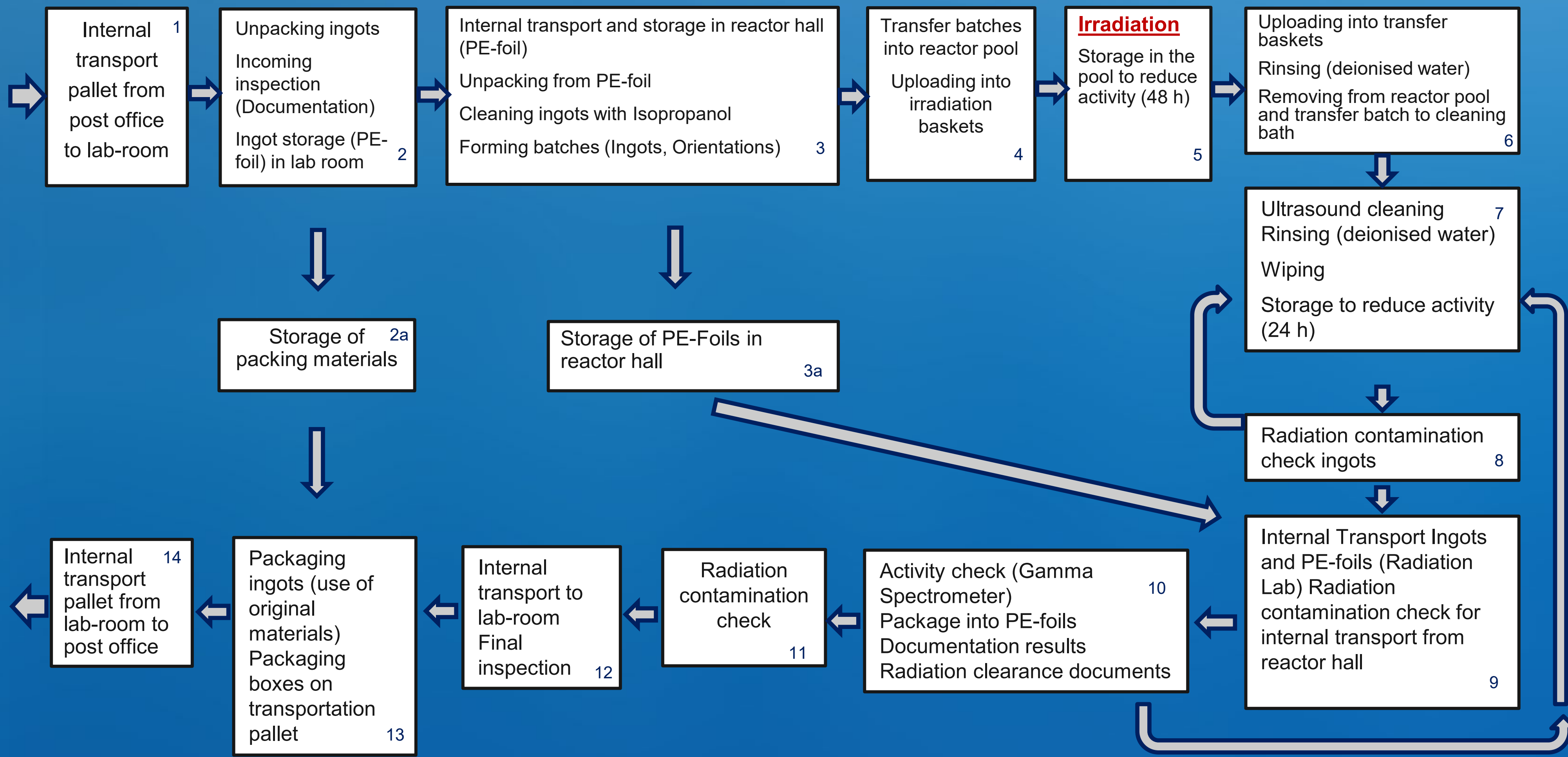
MCNP optimization



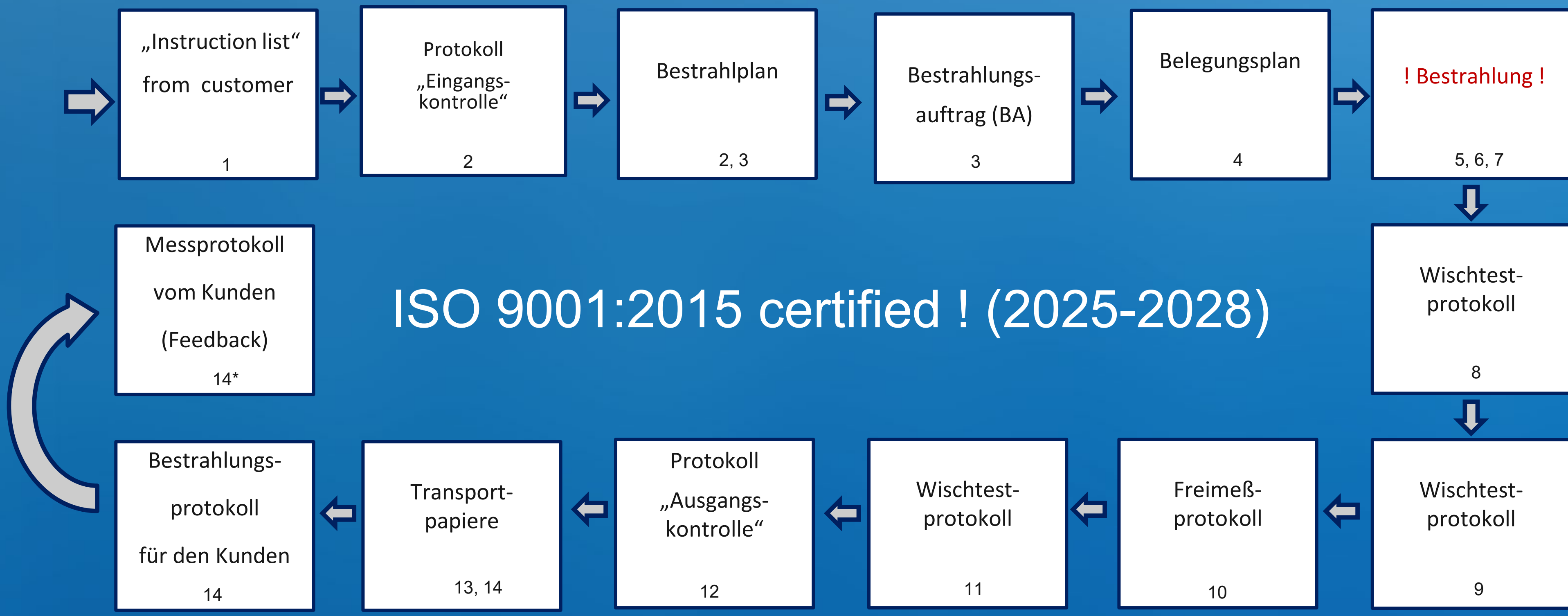


X. Li et al. Applied Radiation and Isotopes 67 (2009) 1220

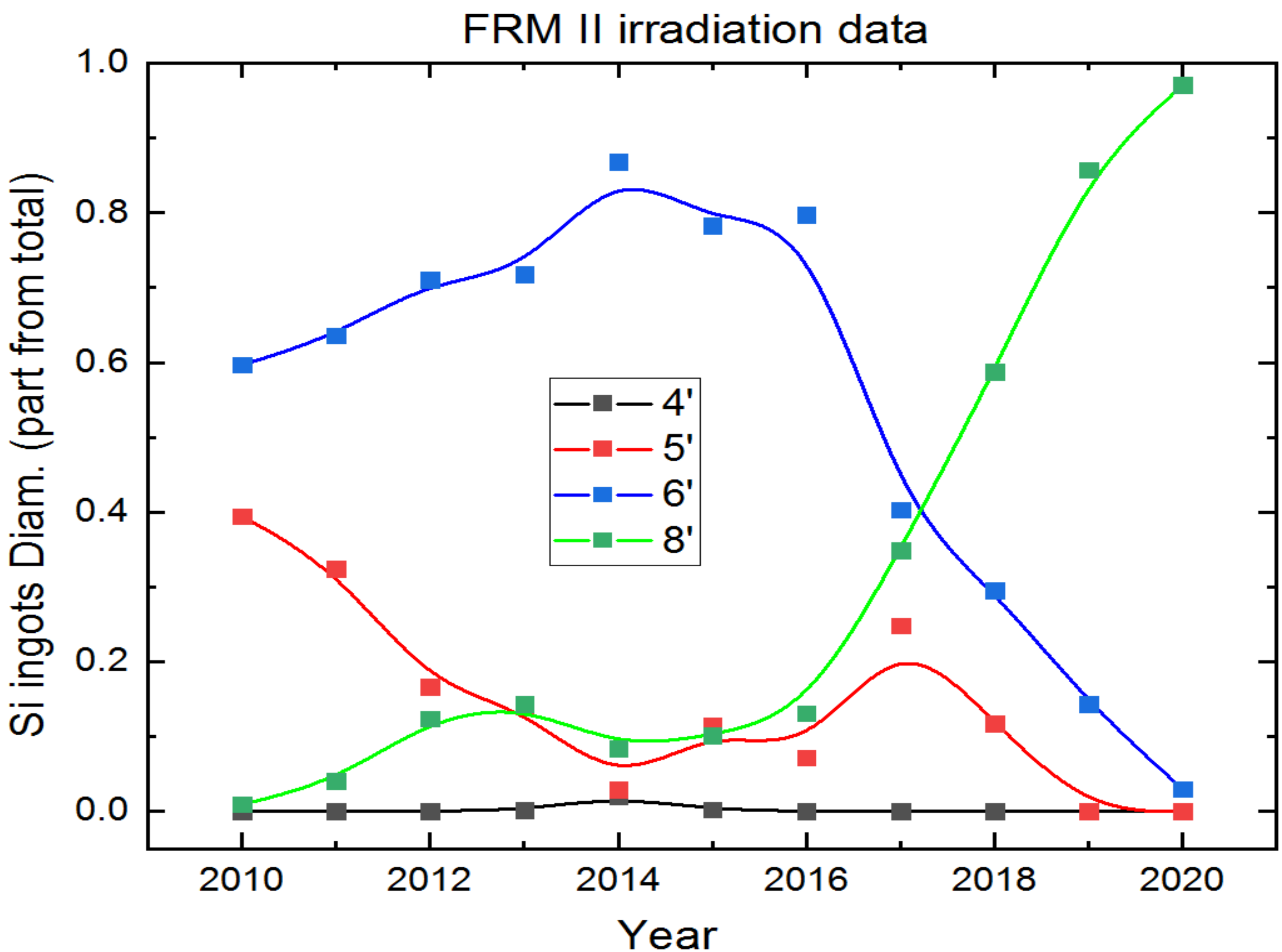
1) Si NTD work-flow at FRM II



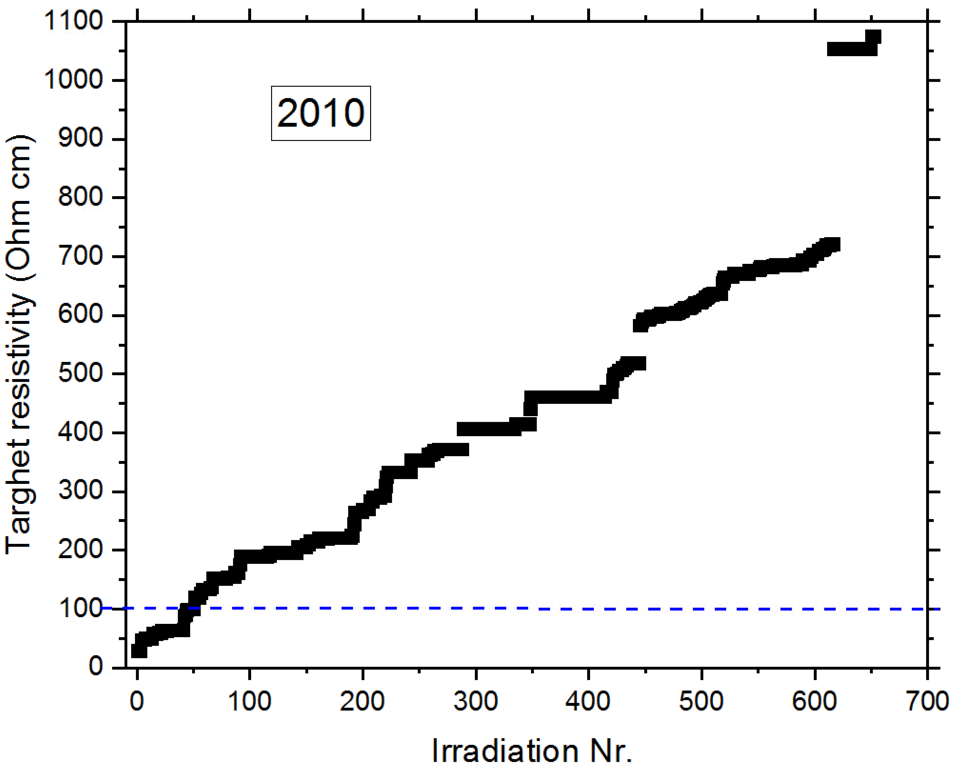
2) Si NTD document work-flow at FRM II

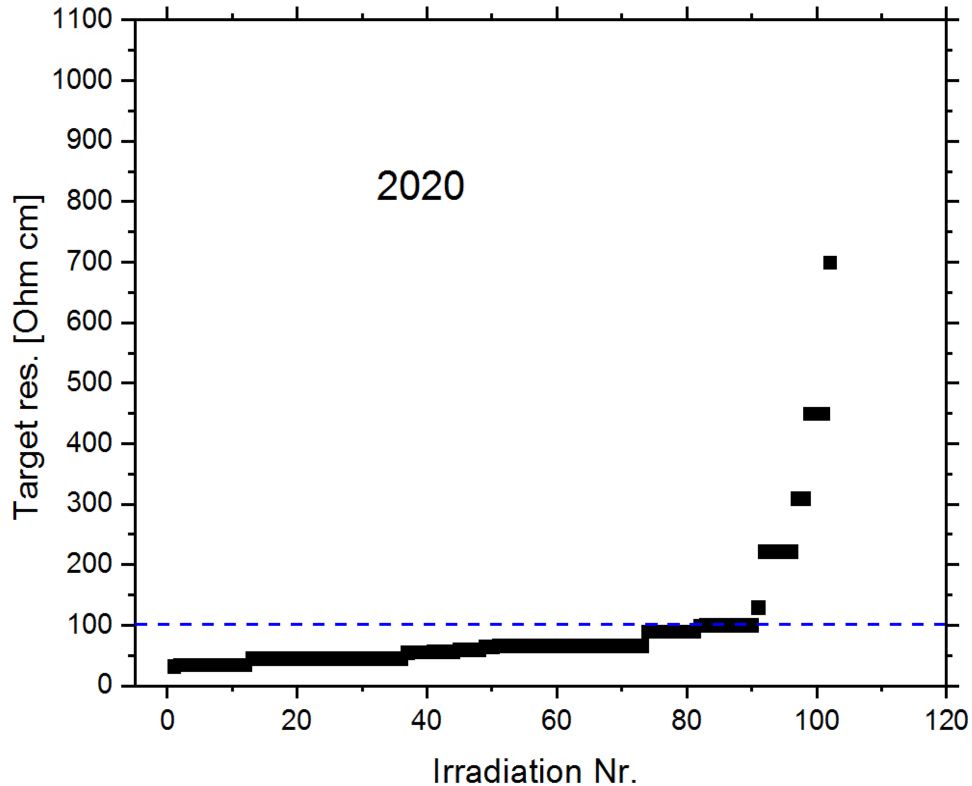


Quality Management System

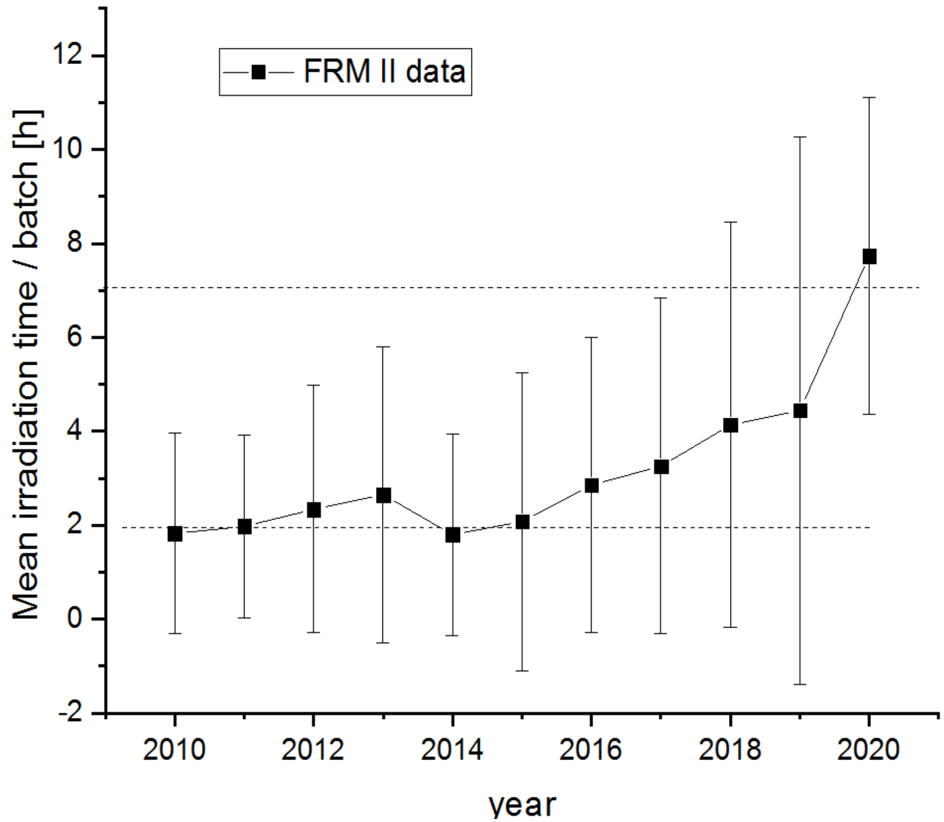

FRM II irradiation data
Si ingots Diam. (part from total)
1.0
0.8
0.6
0.4
0.2
0.0
2010
2012
2014
2016
2018
2020
Year
4'
5'
6'
8'

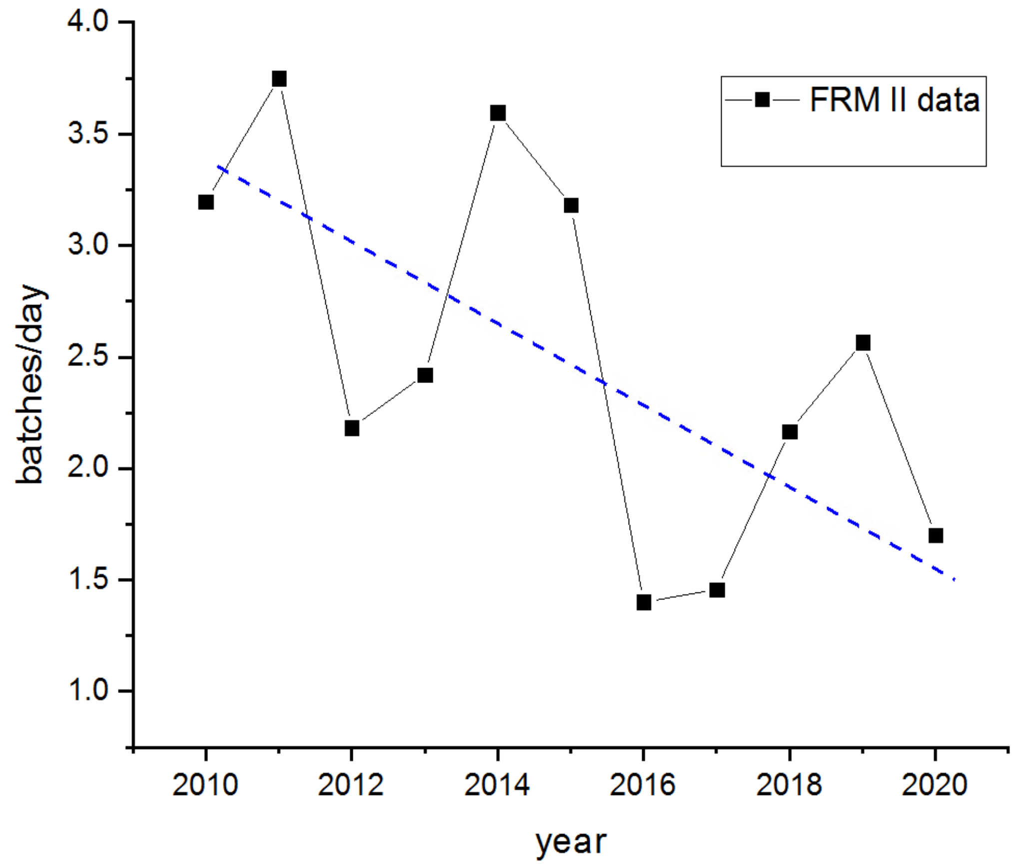
Time evolution of the customer request on target resistivity (FRM II Data)

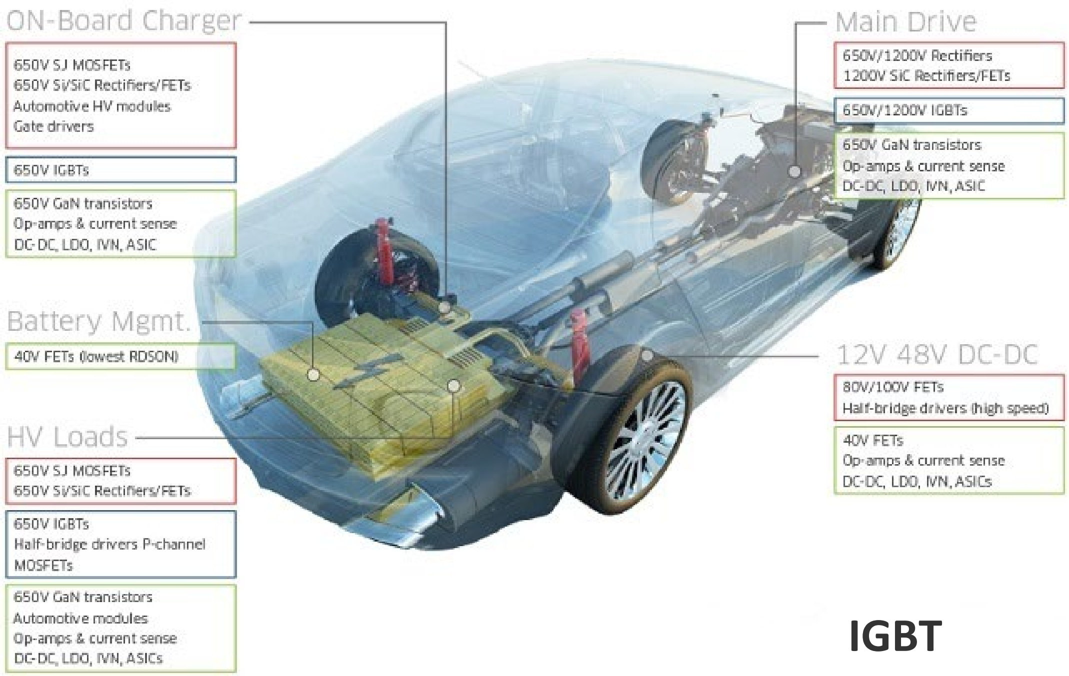


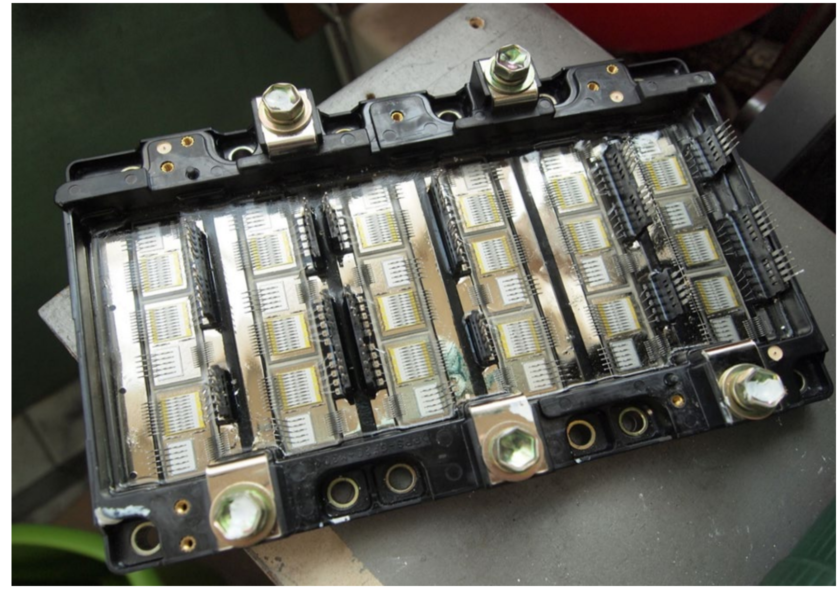


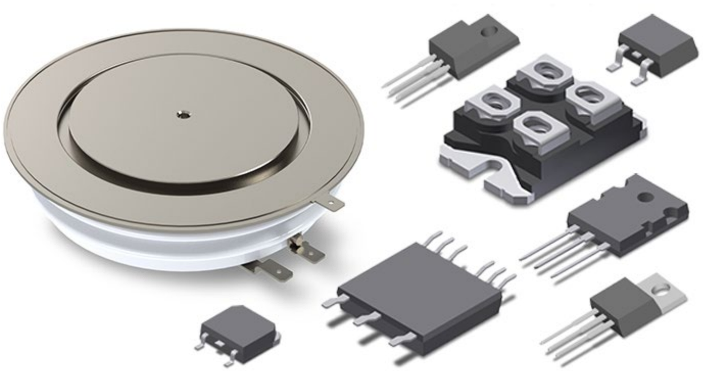
Time evolution of the customer request on target resistivity and it results on NTD availability (FRM II Data)











IGBT

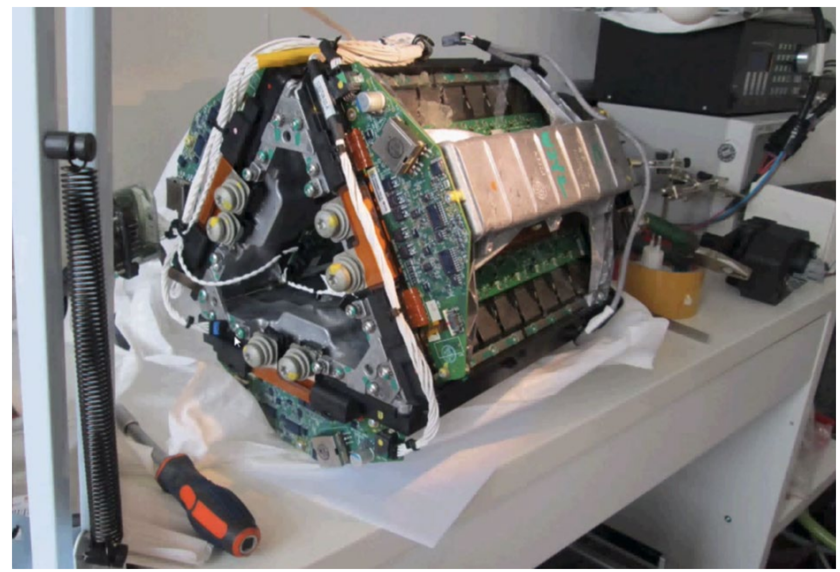
Insulated-Gate

Bipolar Transistor

600-1200 V

> 10 kHz

Lower power, higher frenquency



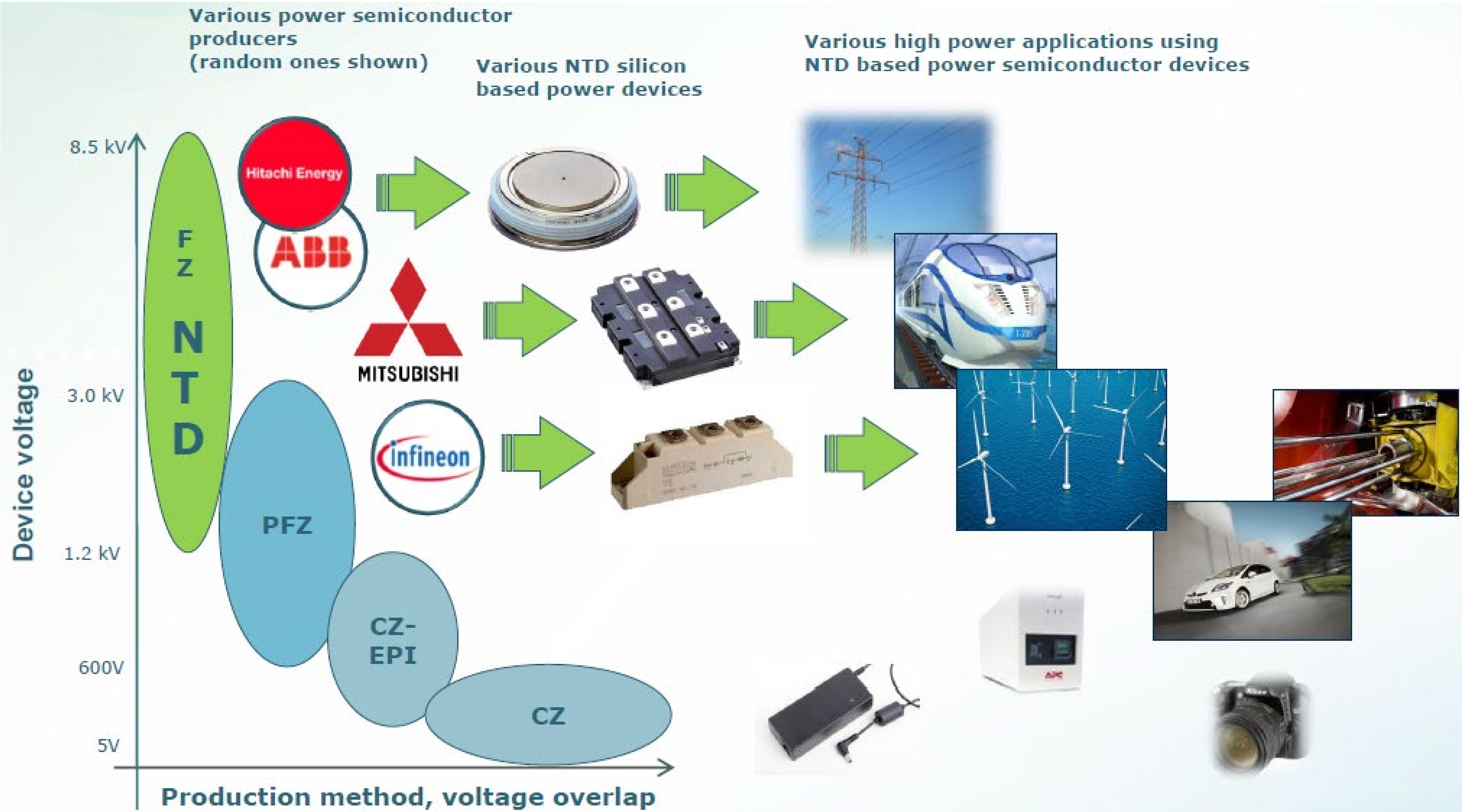
Estimation of future demand for neutron-transmutation-doped silicon caused by development of hybrid electric vehicle and its supply from research reactors

Myong-Seop Kim, Sang-Jun Park and In-Cheol Lim
KOREA ATOMIC ENERGY RESEARCH INSTITUTE
1045 Daedeok-daero, Yuseong, 305-353

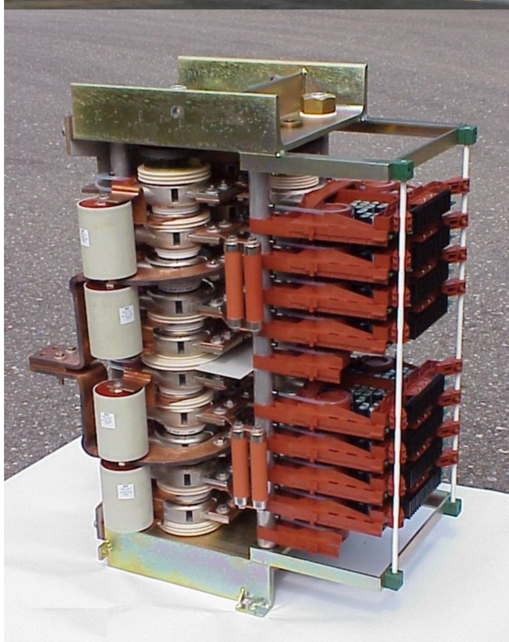
Table V: A rough prospect for HEV production and related need for 6 inch NTD-Si

Year	2010	2015	2020 2023	2030
HEV production [in million vehicles]	1	3	10 14	50
Need for 6 inch NTD-Si ingot [tons]	16-51	47-153	157-510 x(220-715)	786-2550

Now NTD- Si plays no major (if any) role in electromobility components ☹ - IGBT7, SiC,… !!!



Graphics from: TOPSIL GlobalWafers Co., Ltd. 環球晶圓股份有限公司



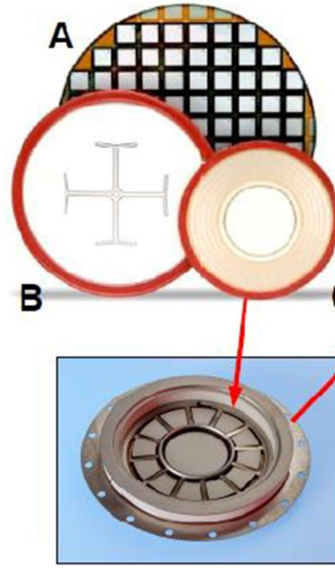
IGCT

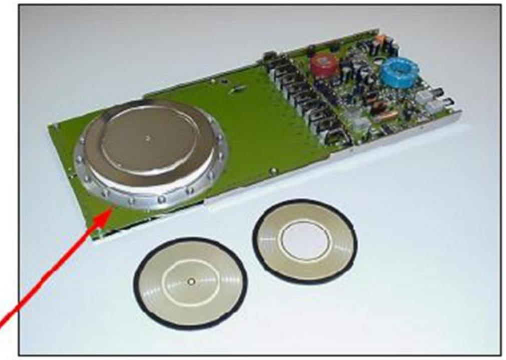
Integrated Gate Com-mutated Thyristors

> 4200 V

> 500 A

- 6 MW single phase H-bridge





Reverse Conducting Discharge Device
P/N: 5SPR 36L4506
Driver Unit integrated
Vdrm=4500V, Vrrm=0V (Integrated Diode)
Wafer diameter 91 mm
I pulse up to 80 kA (10µs)
Di/dt capability ≤ 30 kA/µs
Designed for series connection

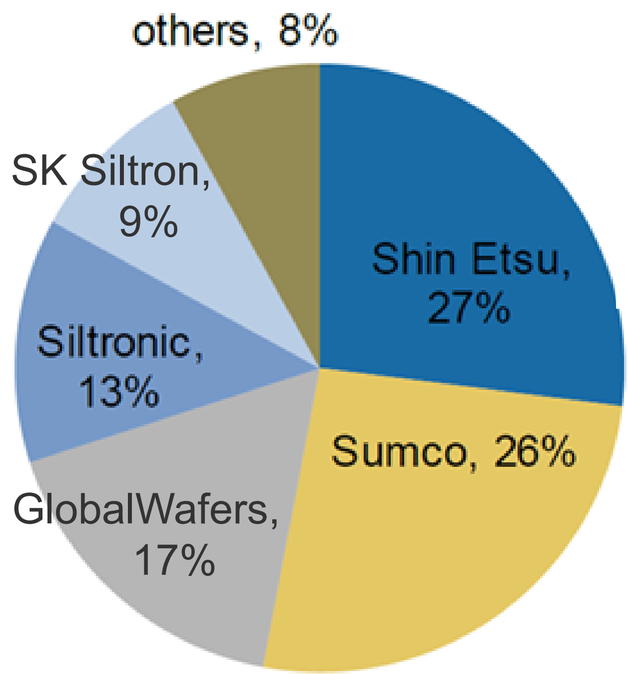
Global Market Share of NTD-Si active irradiators
(according to industry and IAEA-RR available data)

RReactor	Country	op.days	best past	cap. 2023	max. cap*.	best use%
OPAL	Australia	300	90?	>80	250(5‘+6‘+8‘)	36?
HANARO	S. Korea	200	23.7	2.5	21(6‘+8‘) 80d	45
BR2	Belgium	203	37?	37	83(8‘)+25(5‘)	34?
FRM II	Germany	240	15.1	0	50(8‘)	30
MITR-1	USA	200	11	0	17(4‘+6‘)	64
SAFARI-1	S. A. R	305	25?	21	96(6‘)	26?
Total:	**world**		**~202**	**~141**	**493**	**34(41)**

* Maximal **theoretical** NTD capacity calculated for starting resistivity of 5000 Ohm cm and target res. of 200 Ohm cm according to formula 4 from Ref. [https://ieeexplore.ieee.org/document/52788291] **.**

Global Market Share of Si Wafer in 2018

Source: globalmarketmonitor.com



SK siltron css – South Korea

siltronic perfect silicon solutions – Germany

Shin-Etsu – Japan

SUMCO CORPORATION – Japan

GlobalWafers Co., Ltd. 環球晶圓股份有限公司 – Taiwan

TOPSIL – Denmark

- The number of players is rather low for both, industrial companies and irradiators (no real robust market)

- The industry prefere to work with very specialised high quality and large capacity reactor partners, laborious and long qualification (dificult to enter the market for small or new facilities)

- Irradiator countries are often not the wafer producer countries, and even no semiconductor device or equipement produsers and vice versa the established semiconductor nations lack on iradiation facilities (global issue).

Ref. No.: EVT2403367

IAEA Consultancy Meeting on the Current Status and Future of Neutron Transmutation Doping Silicon at Research Reactors

Vienna, 5-7 August 2024

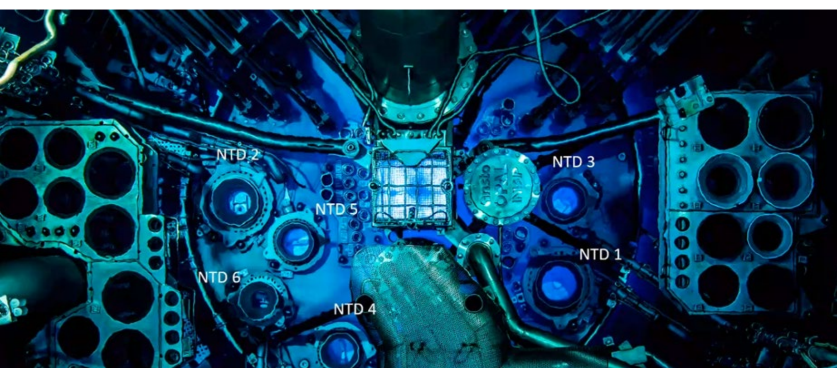
https://www.iaea.org

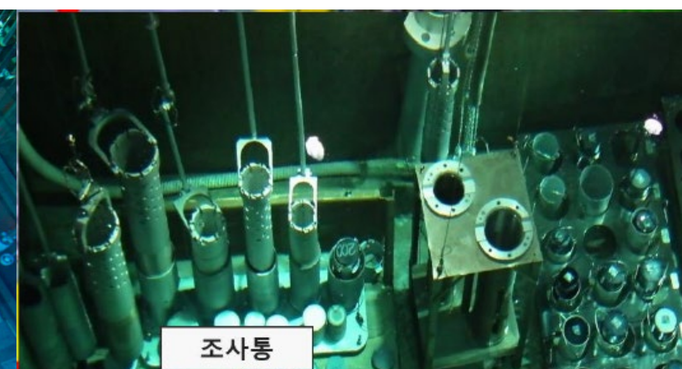
RECOMMENDATIONS to the NTD-Si research reactor facilities from semiconductor industry:

- Double the NTD-Si irradiation capacity within next 10 years.
- Increase amount of Si irradiated to the target resistivity larger than 200 Ohm cm.
- Increase the diameter of the Si ingots to larger 6-inch, standard 8-inch, and 12-inch in the future.
- Consider design of new reactor for NTD-Si employing D_2O moderator and 12-inch irradiation tubes.
- Continue to maintain and improve the quality of the product in order to remain competitive to the other semiconductor doping technologies like e.g. PFZ (target resistivity and the axial homogeneity of the resistivity to +/- 3% and <3% respectively from the currently 5 to 7 %.
- Implement efficient quality management system. Ensure compliance of the NTD-Si production with ISO 9001:2015 standard, other certifications may become also mandatory.

RECOMMENDATIONS to the semiconductor industry from research reactor community:

- Provide better NTD-Si inventory management to overcome the reactor shutdown periods.
- Consider balanced cost/benefit distribution through the whole value chain and balance between public and private costs and benefits.
- Provide more involvement of all industrial supply chain player into improving forecasting the demand volumes and visibility to enable better planning.





RECOMMENDATIONS to the national authorities and Member States:

- Consider NTD-Si production at new research reactors, i.e. Jordan, Argentina, Republic of Korea, and other countries.
- Modernize/upgrade the existing NTD Si irradiation facilities to enable irradiations of the larger Si ingots such as 8-inch and implementing of 12-inch in the future.
- Invest in R&D of the NTD-Si production to meet the increasing quality and quantity requirements.
- Consider participation in information exchange platform between research reactors providing NTD Si for the coordination of operational planning and major outages to facilitate timely reaction by the industry to avoid or mitigate the shortages in the supply.
- **Consider participation in a new initiative “NTD Si Alliance 4 Net Zero”** to facilitate NTD-Si as a key technology, important to achieve the climate policy targets, both locally and on the global scale.
- Create a sustainable economic model through the whole value chain and balance between public and private costs and benefits.

RECOMMENDATIONS to the IAEA:

- Upgrade the existing research reactor database on NTD activities with more detailed and specific information like provided amount of NTD services in tons at certain defined resistivity, provided NTD irradiation diameters, thermal/fast neutron flux ratio at NTD position and include NTD irradiation positions at RR in neutron instruments IAEA database.
- Organize a follow-up webinar and other dissemination activities, e.g. on the upcoming research reactor conference in Nov. 2024 on informing large RR communities about NTD initiatives and current meeting results.
- **Initiate and support working group initiative "NTD-Si Alliance 4 Net Zero".**
- Consider revision of the IAEA TECDOC 1681 including updating of the NTD-Si research reactor facilities and other relevant information.
- Present NTD initiative and related activity in the annual IAEA Nuclear Technology Review.
- Present, promote and popularise socio-economic impact of the NTD-Si technology for the current and future society and its critical role in achieving global Net Zero goal in other agencies publications and communications in the future.

NTD Association Initiative: „NTD Si Alliance 4 Net Zero“

(in analogy to SoS working group and European Observatory for medical radioisotopes)
Coordination of irradiators and processors to serve society for guaranted avalability of the certain agreed critical ammount of NTD Si for reaching sustainable global green targets.

- Irradiators – existing RR like: FRM II, ANSTO, BR2, Hanaro, MITR, LR-15, SAFARI, others… and new research reactors like: RA-10, JRTR, others...

- Industry (e.g. ShinEtsu, Sumco, Topsil, Siltronic, LG, Hitachi, Mitsubishi, Infineon, others…) to have guaranted ammount of NTD Si on the market for the high power electronics on the long term basis.

- Politics: e.g. national: GE, JP, AUS, USA, EU, others… to support national industry and research in targeting decarbonisation goals, by guaranting eventl. full-costs NTD production recovery in the national research reactors.

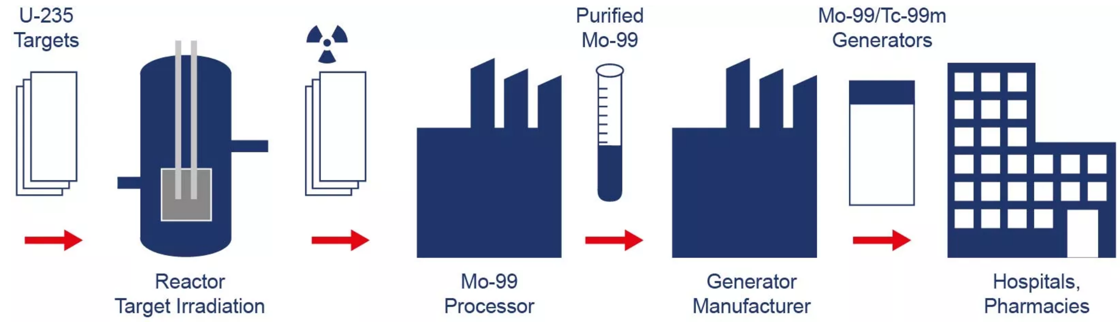
- International agensies (e.g. IAEA, OECD, EU, etc.) by promoting international collaboarations, sustainable world, peaceful use of nuclear technologies, and Net Zero Goal.

Radioisotope Production Worldwide: Challenges

- **No stockpiling of radioisotopes** due to short half-life -> need for **just-in-time-production**
- **Global shortages of Mo-99/Tc-99m in 2009** due to outage of 2 main producing ageing reactors
- Since 2009 **worldwide cooperation** between all stakeholders: irradiators (reactors), processors (radiopharmaceutical industry) and generator manufacturers and users (medical centers) to **prevent further serious shortages of medical radioisotopes**: High-level Group on the Security of Supply of Medical Radioisotopes **(HLG-MR)** established by OECD/NEA -> successor group (political): **European Observatory on the supply of medical radioisotopes, mainly for Mo-99** (established by ESA)
- **Nuclear Medicine (NM) Europe (European Industrial Association): cooperation of all industrial stakeholders**

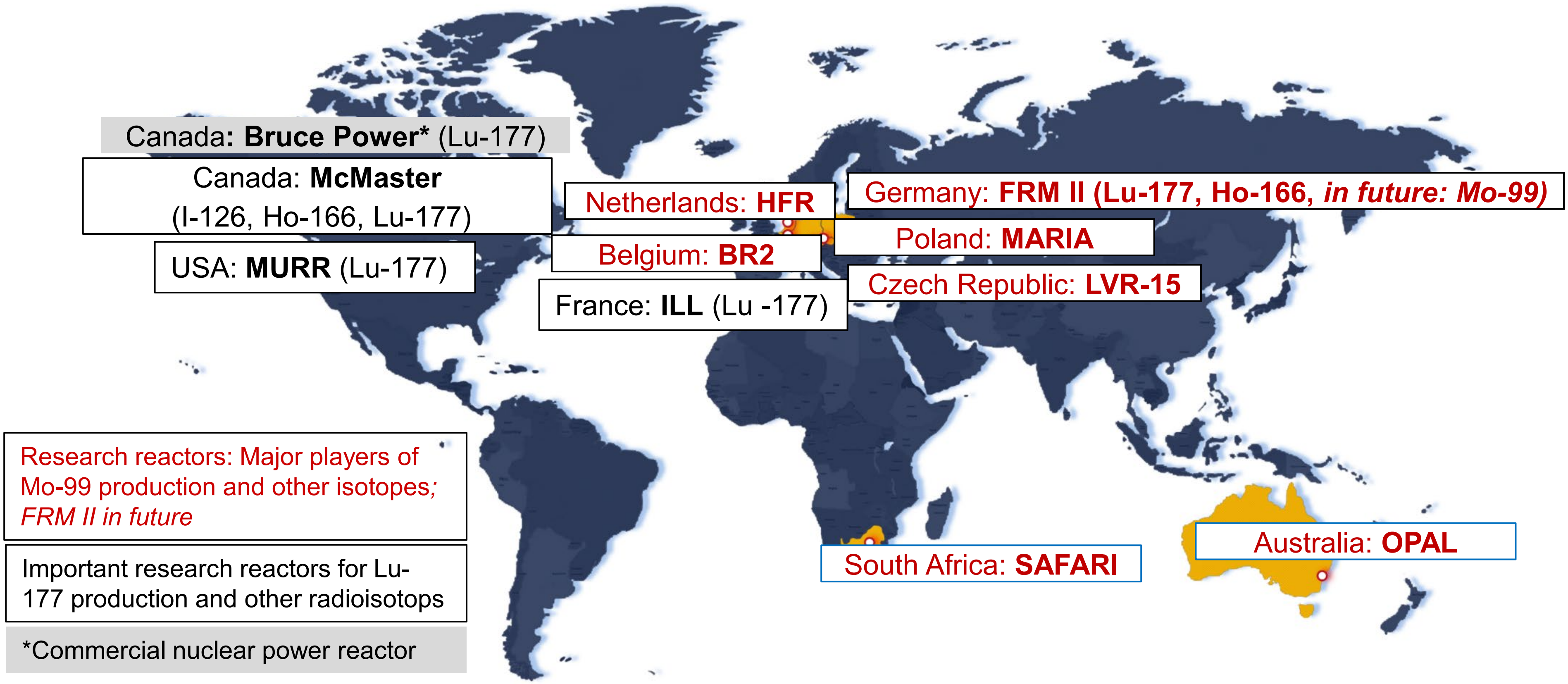
  → **FRM II is member** of these 2 groups

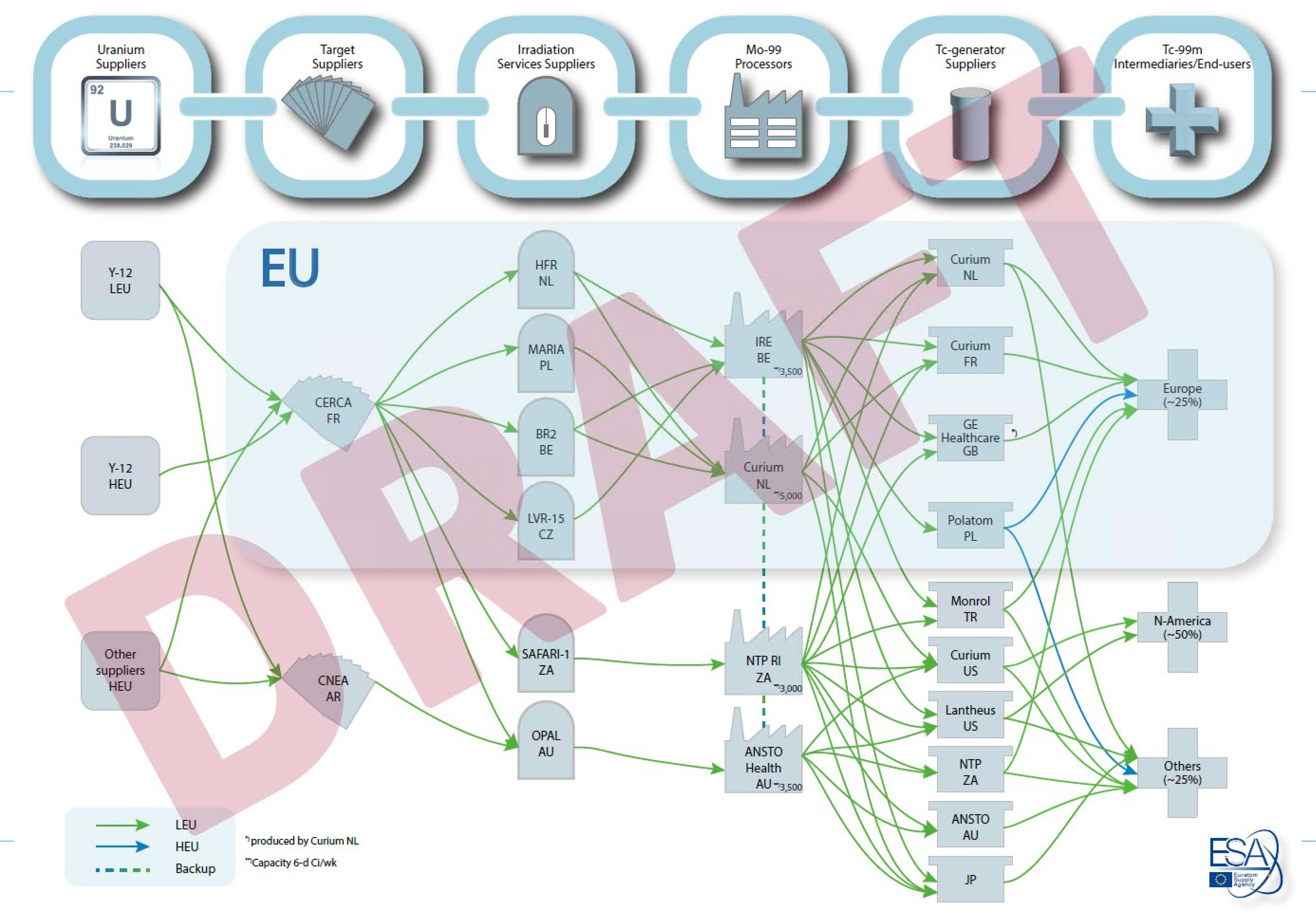
ESA Euratom Supply Agency | EUROPEAN OBSERVATORY on the supply of medical radioisotopes | NUCLEAR MEDICINE EUROPE



Radioisotope Production Worldwide

Reactors for current and future medical supply (worldwide)





Uranium Suppliers
92
U
Uranium
238.029
Target Suppliers
Irradiation Services Suppliers
Mo-99 Processors
Tc-generator Suppliers
Tc-99m Intermediaries/End-users
EU
Y-12 LEU
Y-12 HEU
Other suppliers HEU
CERCA FR
CNEA AR
HFR NL
MARIA PL
BR2 BE
LVR-15 CZ
SAFARI-1 ZA
OPAL AU
IRE BE **)3,500
Curium NL **)5,000
NTP RI ZA **)3,000
ANSTO Health AU **)3,500
Curium NL
Curium FR
GE Healthcare GB *)
Polatom PL
Monrol TR
Curium US
Lantheus US
NTP ZA
ANSTO AU
JP
Europe (~25%)
N-America (~50%)
Others (~25%)
LEU
HEU
Backup
*) produced by Curium NL
**) Capacity 6-d Ci/wk
DRAFT
ESA
Euratom Supply Agency

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Security of Supply

Nuclear Medicine Europe working group

Mission Statement

The **Security of Supply Workgroup** brings together the members of **Nuclear Medicine Europe** who operate Research Reactors or use their output for medical isotope production purposes. This involves either the production of fission isotopes (e.g. Molybdenum, Iodine, Xenon) by splitting Uranium targets or the neutron activation of isotopes (e.g. Strontium, Iridium, Samarium, Lutetium) by bombarding stable target materials.

The main goal of this Workgroup is to achieve the best possible coordination of the periods during which the different Reactors are operating, to provide adequate global coverage during planned reactor shutdown periods for refuelling and maintenance. This coordination is necessary to ensure the production continuity of the mother isotopes and ensure the supply of final Radiopharmaceutical products and Therapy sources to hospitals all year round. The Workgroup also provides a forum for the Research Reactor operators and the Radiopharmaceutical producers to keep each other informed

The Group

Chairman: Ira Goldman
Vice President, Global Public Policy and Government Relations – Lantheus

Vice-Chairman: Bernard Ponsard
Radioisotopes Project Manager – SCK CEN

Supervisor: Erich Kollegger
CEO – IRE

Auke Attema
Senior Manager Supply Chain Planning – Curium Group

David Barnes
Business Unit Director – RLS

Nil Neda Bedro
Purchasing Manager – Monrol

Laurent Bigot
Head of Stable Isotopes Division – Orano Chemistry

EUROPEAN OBSERVATORY on the supply of medical radioisotopes — NUCLEAR MEDICINE EUROPE the industry association

NUCLEAR MEDICINE EUROPE the industry association — EMERGENCY RESPONSE TEAM security of supply working group

Communication from NMEU to EU Observatory for the Supply of Medical Radioisotopes

NTP Approved to Resume Mo-99 Processing

Brussels, 19 March 2025

The Emergency Response Team (ERT) composed of Mo-99 processors, research reactors, and generator manufacturers was informed by NTP Radioisotopes (South Africa) that they have received approval from the National Nuclear Regulator of South Africa to restart its Mo-99 and I-131 production activities. As the SAFARI-1 reactor is still in its scheduled shutdown period, the processing of irradiated targets will restart next week.

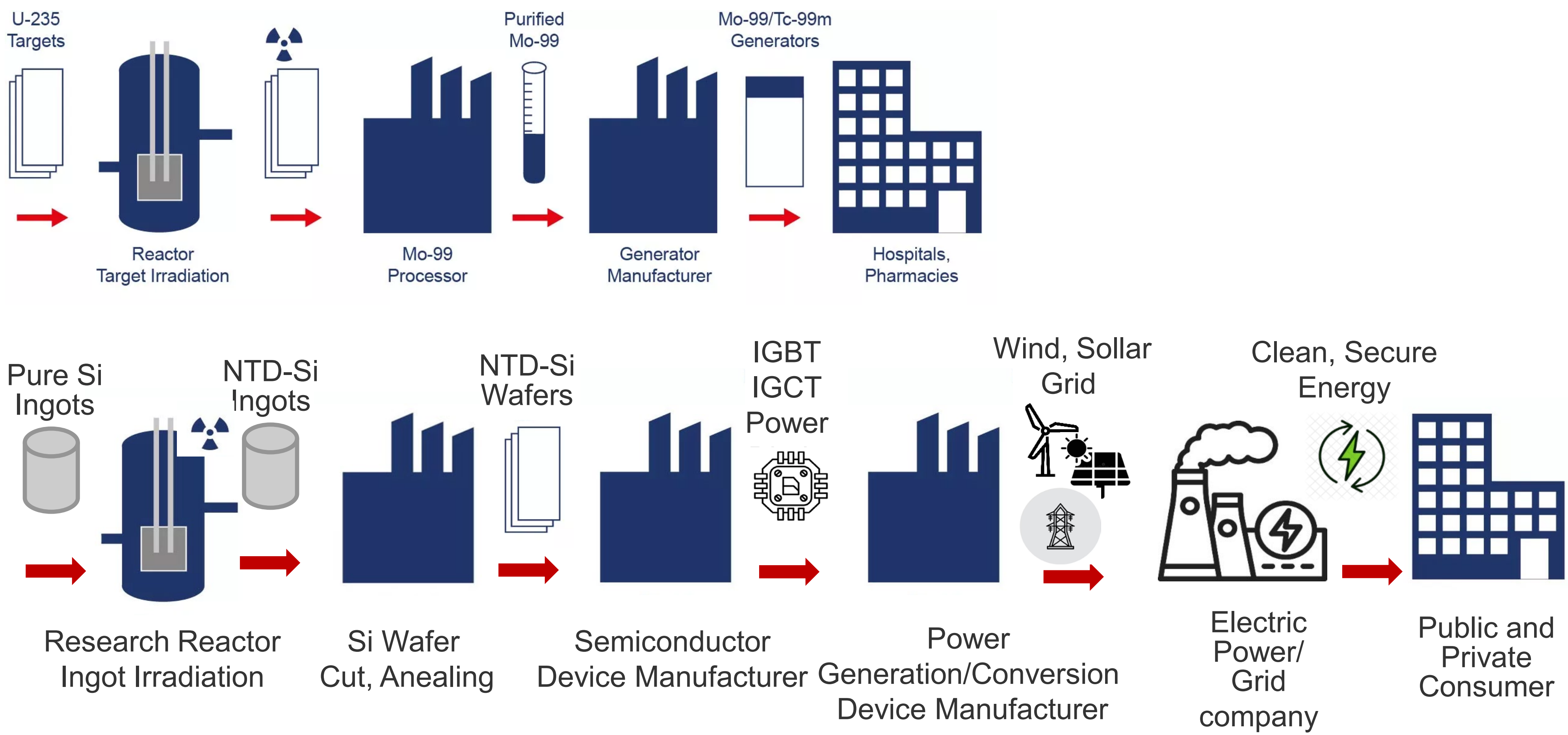
Nuclear Medicine Europe believes that any shortages currently being experienced will be resolved after NTP restart.

SIGNED

Bernard Ponsard
Chairman SoS WG
Chairman ERT

Ira Goldman
Vice-Chairman SoS WG

Analogy between critical supply chain for **medical radioisotopes (top)** and **NTD-Si (bottom)**



S. Van Dyke, director of BR2, Belgium:

The NTD-Si production service is in general a commercial/economic activity, performed by operating organizations which are in general publicly funded.
As it is recommended for the production of radioisotopes, a full cost determination should be done in order to establish the societal cost of the NTD-Si service.
The full cost covers both the part of reactor operational cost that can be attributed to the silicon doping, as well as the specific cost of the silicon doping service itself.
The full cost shall consider the direct operational cost (staff, consumables, fuel cycle, ageing management and decommissioning) as well as the same cost elements directly associated to the NTD activity itself (investment, operation and ageing management/decommissioning of the NTD-Si irradiation device).
The full cost needs to be considered by all stakeholders against the benefits from the NTD-Si process and a justification shall be made for the balance between public and private costs and benefits, linked to the NTD-Si irradiation services.

Scott Stoermer, ccommercial strategy manager, Avalanche Energy, USA:

….. we will not be able to achieve our goal of producing 400+ MT of NTD-Si by 2030 if we are unable to demonstrate that it can be a profitable endeavor.

New Research Reactors targeting NTD production capacities
(acording to IAEA-RR available database and private interviews)

RReactor	Country	planed op.days	max. cap*.
RA-10	Argentina	324	540(6‘+8‘+10‘)
JRTR	Jordan	200	40(6‘+8‘)
KJRR	S. Korea	300	>200 (6‘+8‘)
others…	Japan ?		
Total:	**world**	**next 5 years**	**> doubling to current**

* Maximal **theoretical** NTD capacity calculated for starting resistivity of 5000 Ohm cm and target res. of 200 Ohm cm according to formula 4 from Ref. [https://ieeexplore.ieee.org/document/52788291] **.**

FRM II NTD future activity plan:

- Reactor restart after refurbishment: 2026
- Future operation: ~3 cycles (180 days) / year
- Reactor converting to LEU (after 2032)
- To concentrate mostly on higher resistivity 8‘ NTD Si (~/>15 ton /year)
- Current potential NTD capacity increase: 25% e.g. by implementing third shift
- The implementing of new irradiation channels (100, 200, 300 mm) is not yet planned, but could be possible in future by indusrtry request and collaboration.
- Stronger industry involvement is welcome both on research at TUM, and NTD Si production. We would like to keep **and to strength** our collaboration to Japanise NTD customers in the future as well.


Thank you for your attention!
vladimir.hutanu@frm2.tum.de