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CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

IAEA Technical Meeting on Products and Services of Research Reactors

Production of Radioisotopes and NTD-Silicon in the BR2 Reactor

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IAEA, Vienna - AUSTRIA
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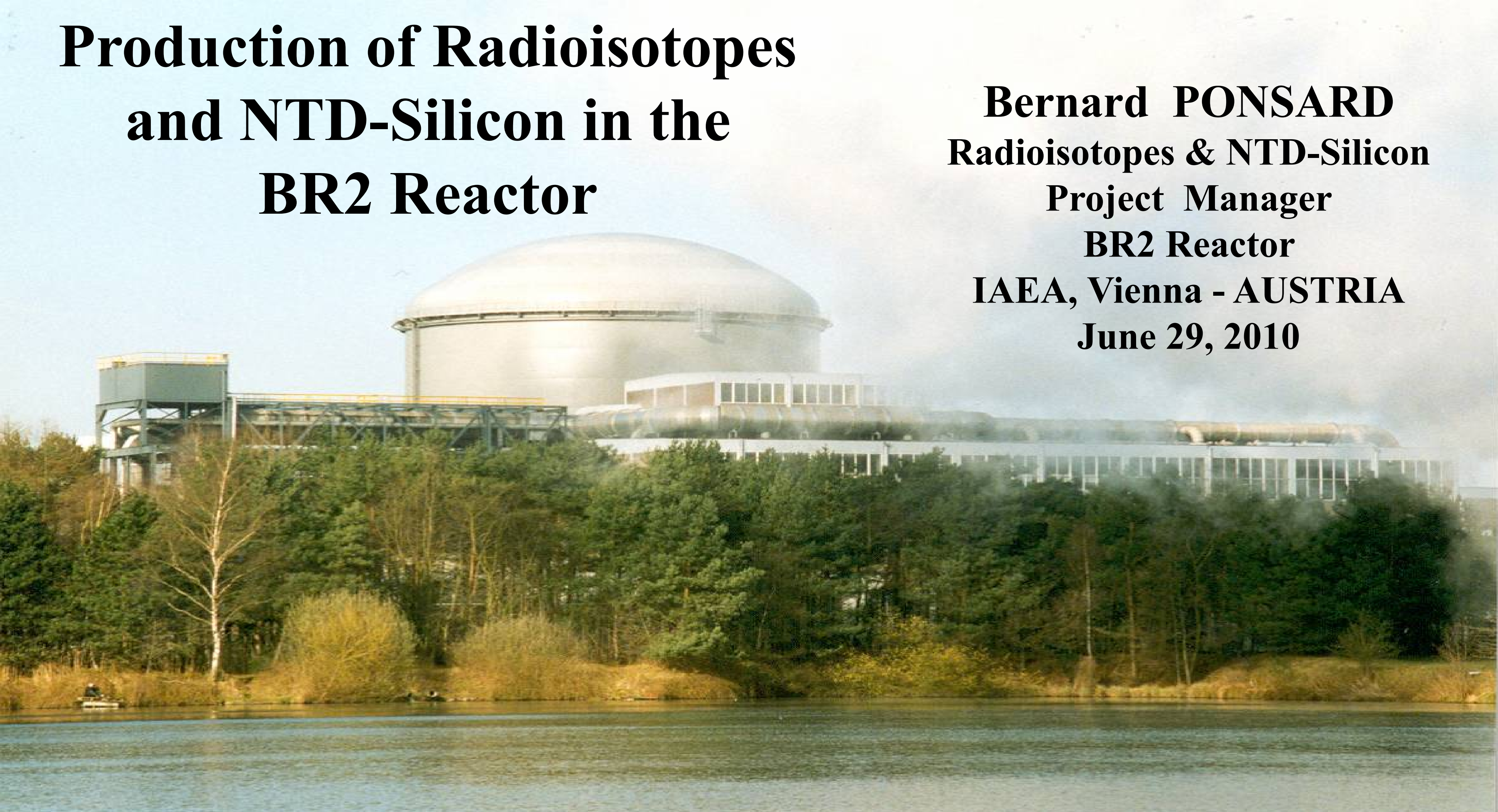

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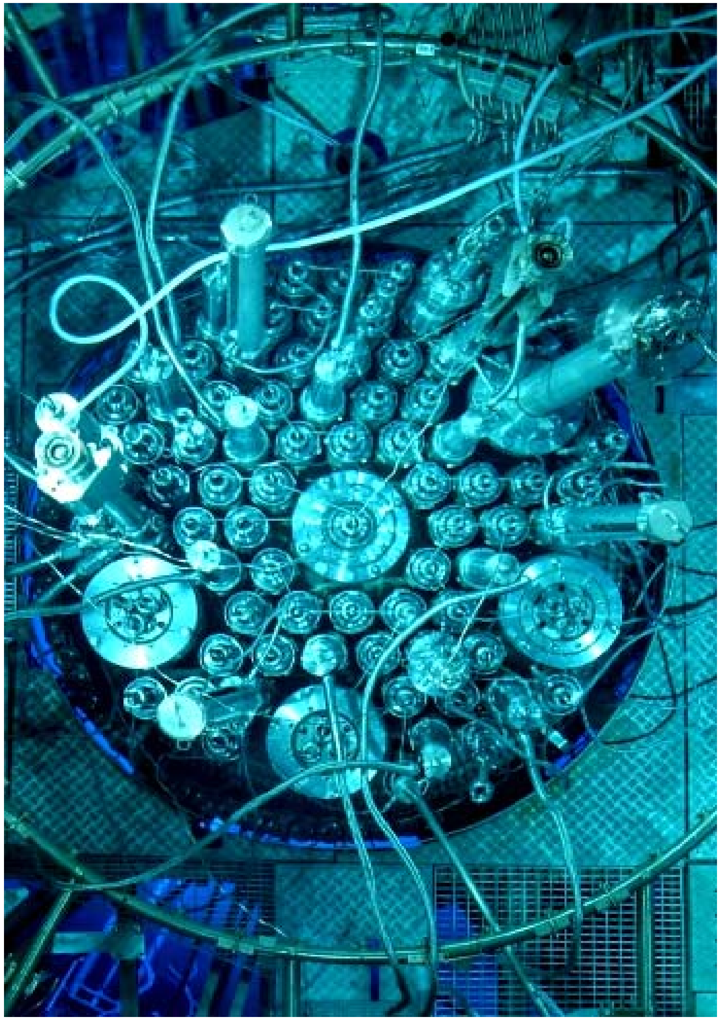
Production of Radioisotopes and NTD-Silicon in the BR2 Reactor

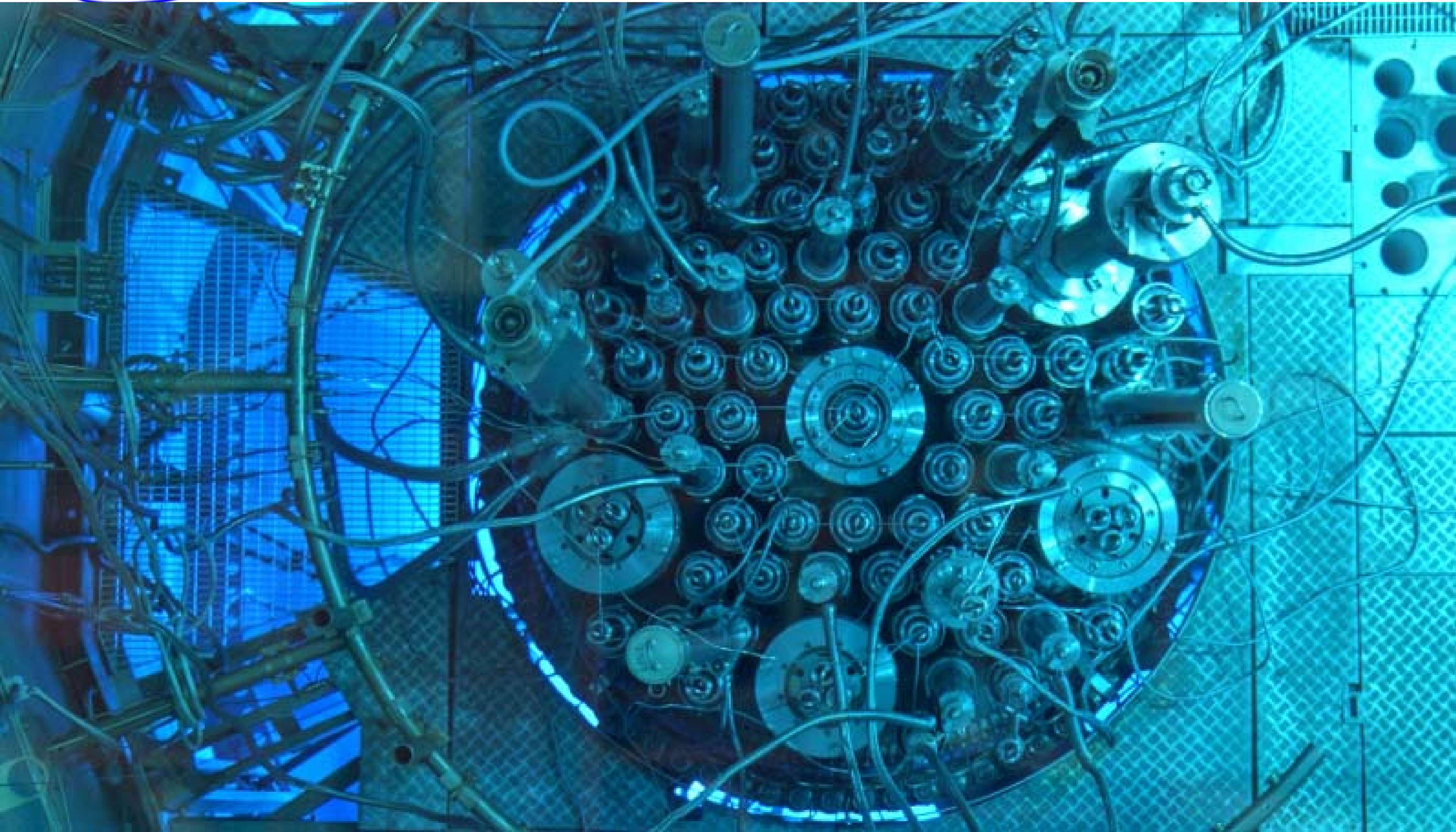


- Introduction
- The BR2 High-Flux Reactor
- Production of Radioisotopes
  - For Nuclear Medicine
  - For Industry
  - For Research
- Production of NTD-Silicon
  - Principles of Neutron Transmutation Doping Silicon
  - The SIDONIE Facility
  - The POSEIDON Facility
- Conclusions

Introduction

- The **BR2 reactor** is a multipurpose **100 MW$_{th}$** High-Flux 'Materials Testing Reactor' operated by the Belgian Nuclear Research Centre (SCK•CEN) in which various **research** and **commercial programmes** are performed.
- The commercial activities such as **radioisotope production** and **silicon doping** have been actively developed since the early 1990's to generate additional revenues and **to reduce BR2's financial dependence** on Government funding.
- Following its last major refurbishment from July 1995 to April 1997, BR2 has an operating life expectancy **until at least 2023** during which time every effort will be made to meet the increasing global demand for Radioisotope and Neutron Transmutation Doped (NTD) silicon production.
- BR2 will also play an **important role** in the development and commercial exploitation of new technologies in these particular areas of business.

The BR2 High-Flux Reactor



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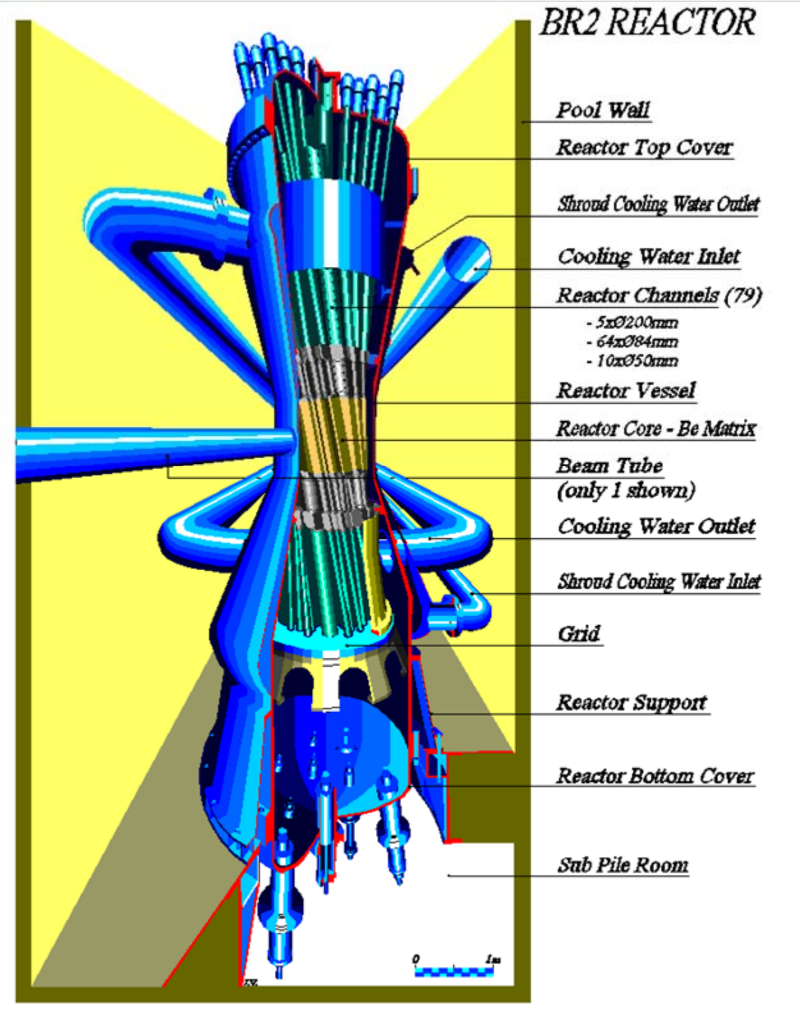
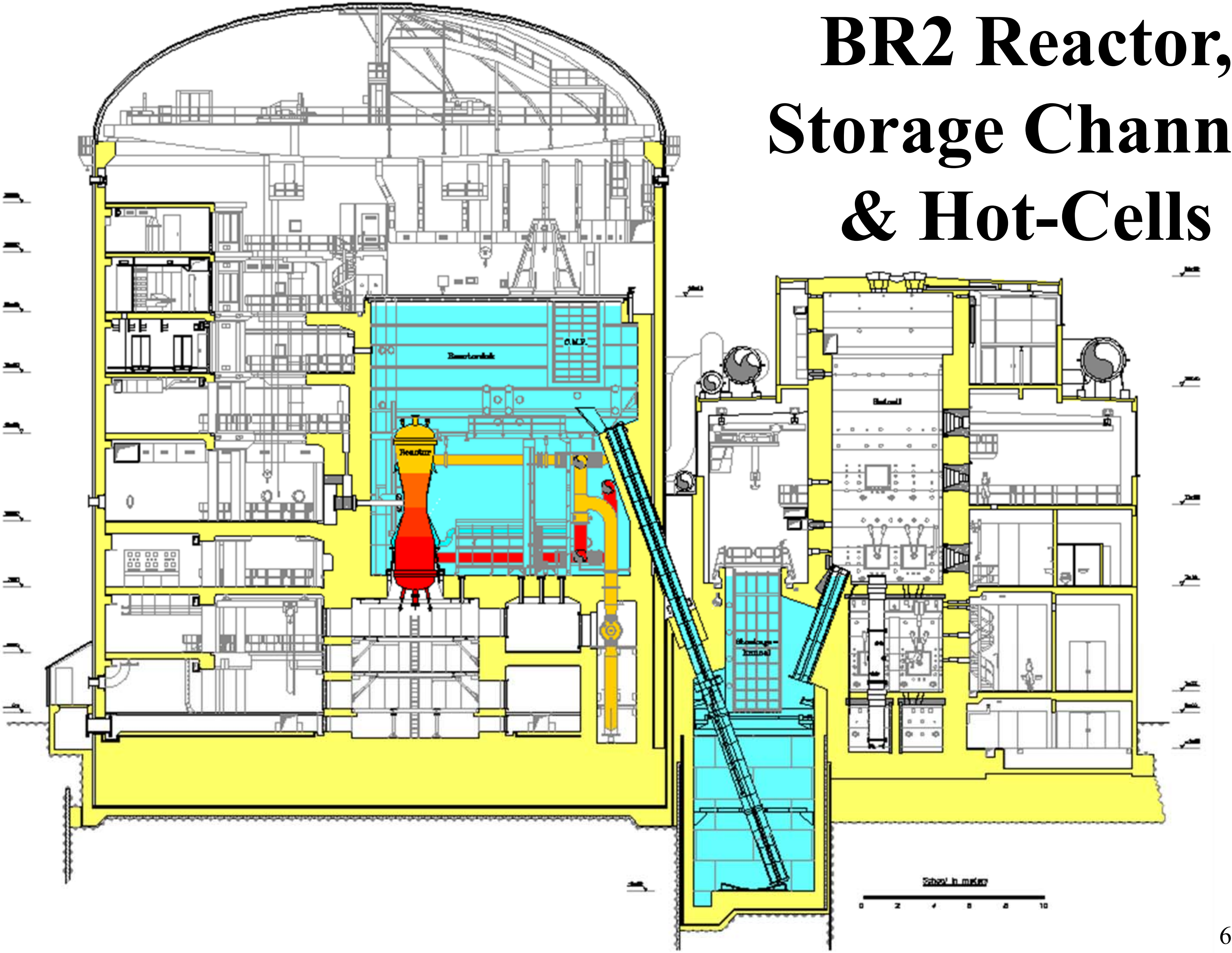
The BR2 High-Flux Reactor

- **Reactor type**
  - High Flux Materials Testing Reactor
  - In operation since 1963
  - Refurbishment : 1979 - 1980 and
    1995 - 1997
- **Aluminium pressure vessel**
  - Geometry : hyperboloid of revolution
  - Easy access to the top and bottom
- **Very compact core**
  - Diameter : 105 cm
  - Height : 91 cm



BR2 Reactor, Storage Channel & Hot-Cells



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The BR2 High-Flux Reactor

- **Operating power : 55 - 100 MW$_{th}$**
- **Basic operating regime: 120 days (5 cycles) per year**
- **Moderators : Beryllium matrix** and **Light water**
- **Primary coolant : Light water**
  - Pressure : 12 bars , Temperature : 40 - 45 °C
  - Flow-rate : 6 500 m³/h
- **Fuel : Highly Enriched Uranium (HEU) ; 93% ^{235}U**
- **Neutron fluxes**
  - Thermal ($E_n < 0.5$ eV) : up to **1.0×10^{15} n/cm².s**
  - Epithermal ($E_n \sim 5$ eV) : up to **4.2×10^{13} n/cm².s**
  - Fast ($E_n > 100$ keV) : up to **6.0×10^{14} n/cm².s**

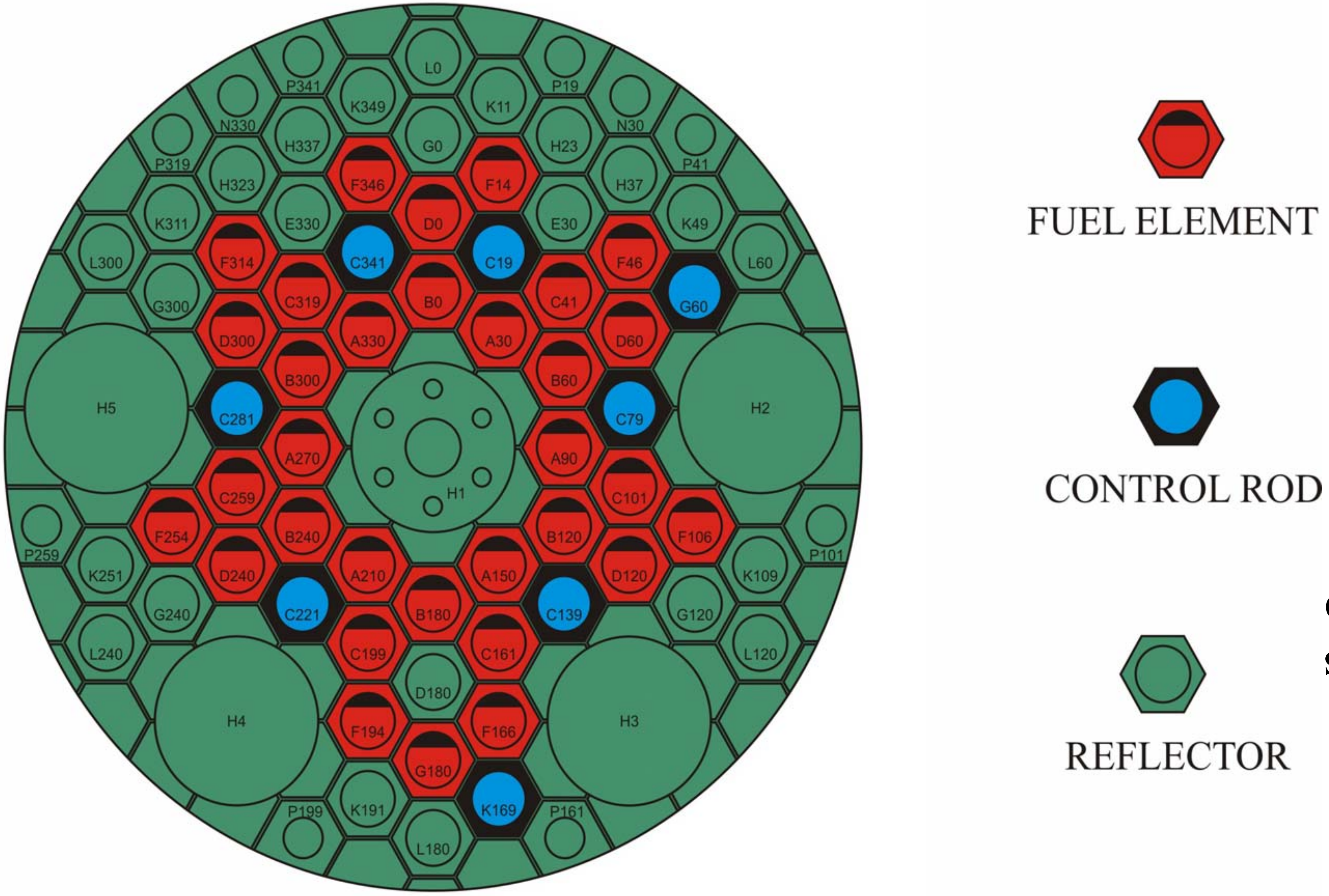
140 days
in 2010
to help the
world
^{99}Mo/^{99m}Tc
supply crisis

The BR2 High-Flux Reactor

- **Geometry: 6 concentric tubes**
  - Fuel length : 762 mm
  - Outer diameter : 77.2 mm
  - Fuel thickness : 0.51 mm
  - Plate thickness : 1.27 mm
  - Water gap : 3 mm

- **Cermet UAlx -Cladding AG3**
  - Mass : 400 g 235U ; enrichment : **93% 235U** ; 1.3 g Utot/cm^3
  - Burnable poisons : 3.8 g Bnat **(B4C)** ; 1.4 g Sm$_{nat}$ **(Sm2O3)**
  - Maximum fission density : 1.6 10^{21} fissions/cm^3

Typical BR2 Configuration: 20G



Possibility to load an additional fuel element in the H1/Central irradiation channel to compensate large antireactivity effects (^{3}He poisoning of the Be matrix or large scale production of ^{192}Ir)

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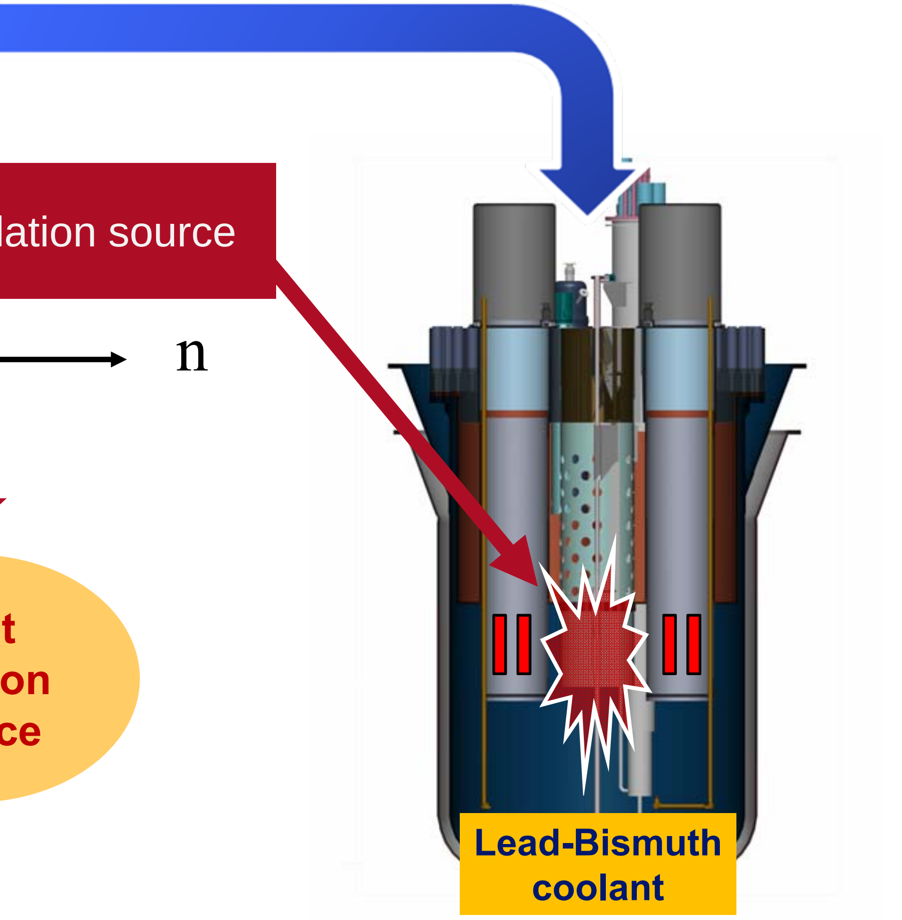
MYRRHA

p^+ **Accelerator**

High reliability



Sub-critical reactor

Spallation source

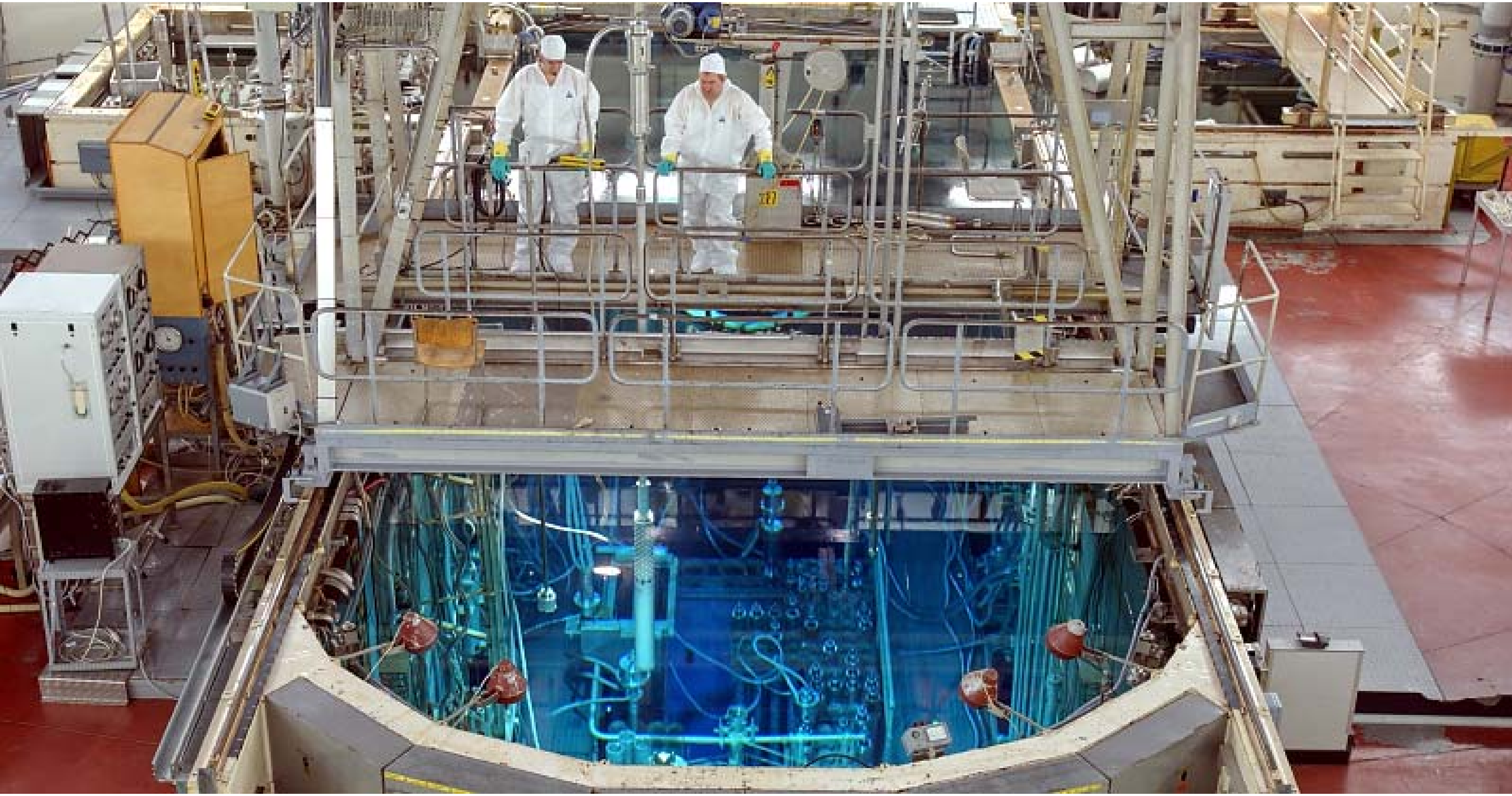
$p^+ \longrightarrow n$

Fast neutron source

Lead-Bismuth coolant

- **Serious efforts** are made by the Belgian Nuclear Research Centre to secure the **safe operation** of the BR2 reactor until at least 2023.
- This would guarantee the **continuity of the activities** in which the BR2 reactor is involved through its replacement by an **Accelerator Driven System** (ADS), **MYRRHA**, scheduled to be operated by SCK•CEN from 2023.

Production of Radioisotopes in the BR2 High-Flux Reactor



Production of Radioisotopes in the BR2 High-Flux Reactor

- The **BR2 High-Flux Reactor** is considered as a **major facility** for the **routine supply of radioisotopes** for applications in the nuclear medicine, industry and research : ^{99}Mo (^{99m}Tc), ^{131}I, ^{133}Xe, ^{192}Ir, ^{186}Re, ^{153}Sm, ^{169}Er, ^{90}Y, ^{32}P, ^{188}W (^{188}Re), ^{125}I, ^{177}Lu, ^{89}Sr, ^{117m}Sn, ...
- The availability of **high thermal neutron fluxes** (up to 10^{15} n/cm².s) and **high fast neutron fluxes** (up to 6 x 10^{14} n/cm².s above 100 keV) allows of course the **development of new radioisotopes**.
- Currently, SCK is **not performing any chemical process** on target material irradiated in the BR2 reactor in the frame of the production of radiopharmaceuticals.
- However, **special efforts** are expected to be made in the near future by SCK for the production of **^{227}Ac** by irradiation of ^{226}Ra targets to supply **^{227}Ac/^{223}Ra** generators.

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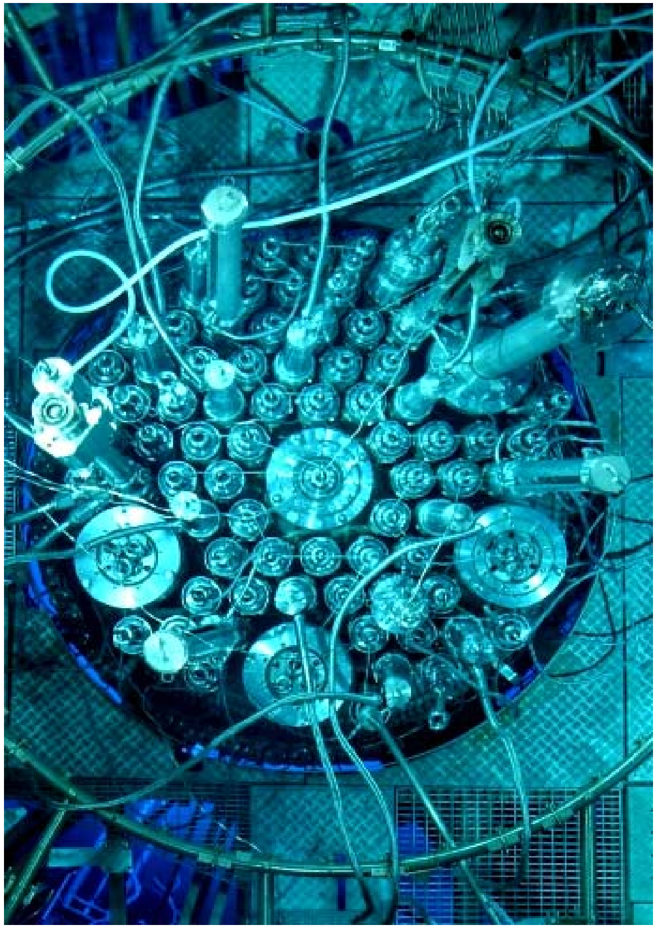
Irradiation devices

- The **irradiation capsules** are loaded into aluminium **irradiation baskets**. They are characterized by a diameter of 25 mm in the reflector and 15 mm inside a standard 6 plate fuel element.
- Loading and unloading of the irradiation baskets is only possible **during the shutdown** periods of the reactor.
- However, **dedicated irradiation devices** (6 PRF's, 4 DG's) allow the loading and unloading of the target material **during the operation** of the reactor for shorter irradiation periods.



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Production of Radioisotopes in BR2 for Nuclear Medicine

- The **nuclear fission** route is used for the production of several radioisotopes as **^{99}Mo/^{99m}Tc** (for diagnostic), but also **^{131}I**, **^{133}Xe**, …
- **^{99m}Tc** (**$T_{1/2}$= 6 hours**) remains the **most widely used** radioisotope for diagnostic in nuclear medicine. About **80%** of the nearly **30 million** annual radiodiagnostic procedures are carried out worldwide with this single isotope (**140 keV gamma rays**). This percentage share is expected to continue to grow yearly by 3% in the near future in developed countries (much more in developing countries) due to its availability from the **very convenient** and **cost-effective** **^{99}Mo/^{99m}Tc generator**.
- The short half-life's of **^{99}Mo ($T_{1/2}$= 66 h)** and its daughter **^{99m}Tc ($T_{1/2}$= 6 h)** clearly present a problem in terms of **reliable supply** since they can not be stockpiled. A **regular supply** of ^{99}Mo/^{99m}Tc generators to hospitals or central radiopharmacies is required. The problem is that the **worldwide supply** of ^{99}Mo relies on a **limited number** of research reactors and processing facilities.

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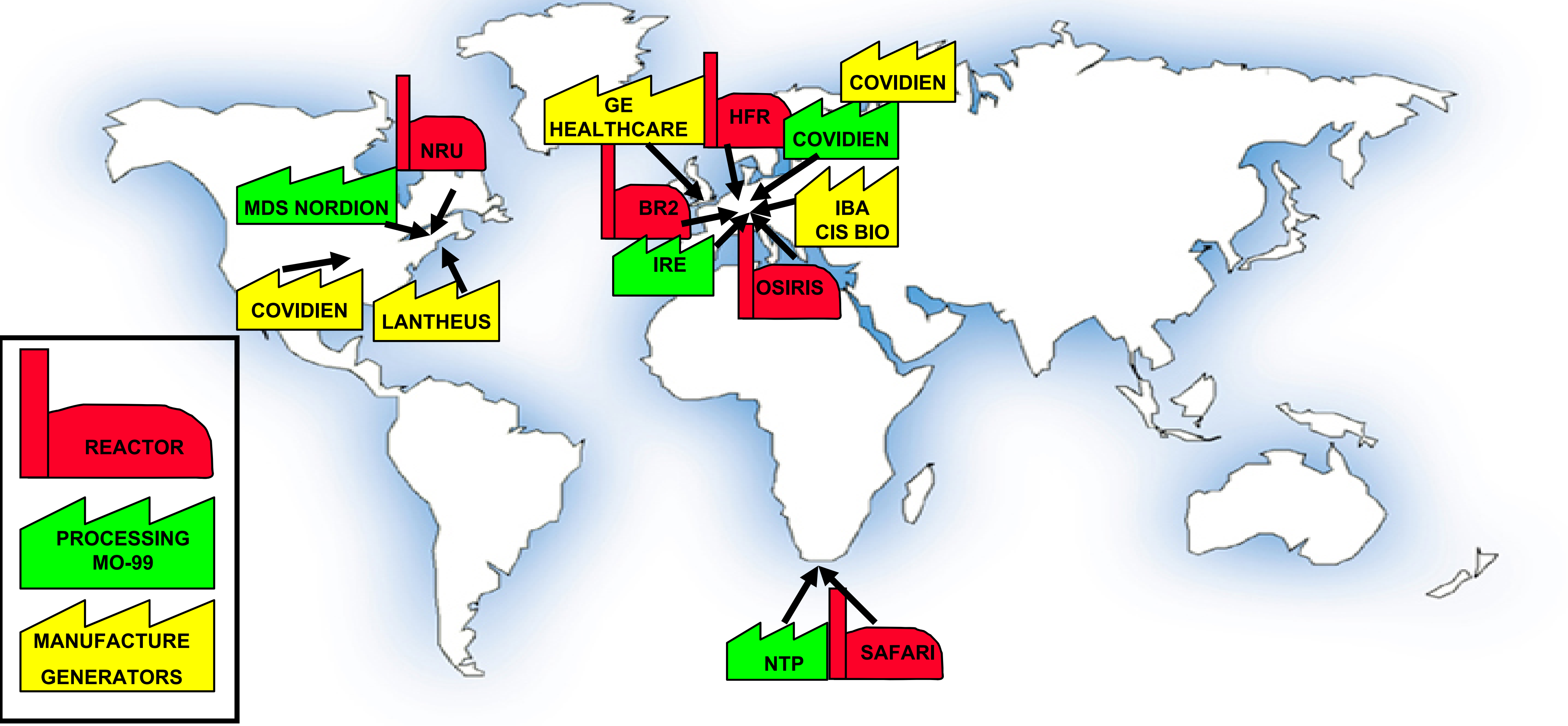
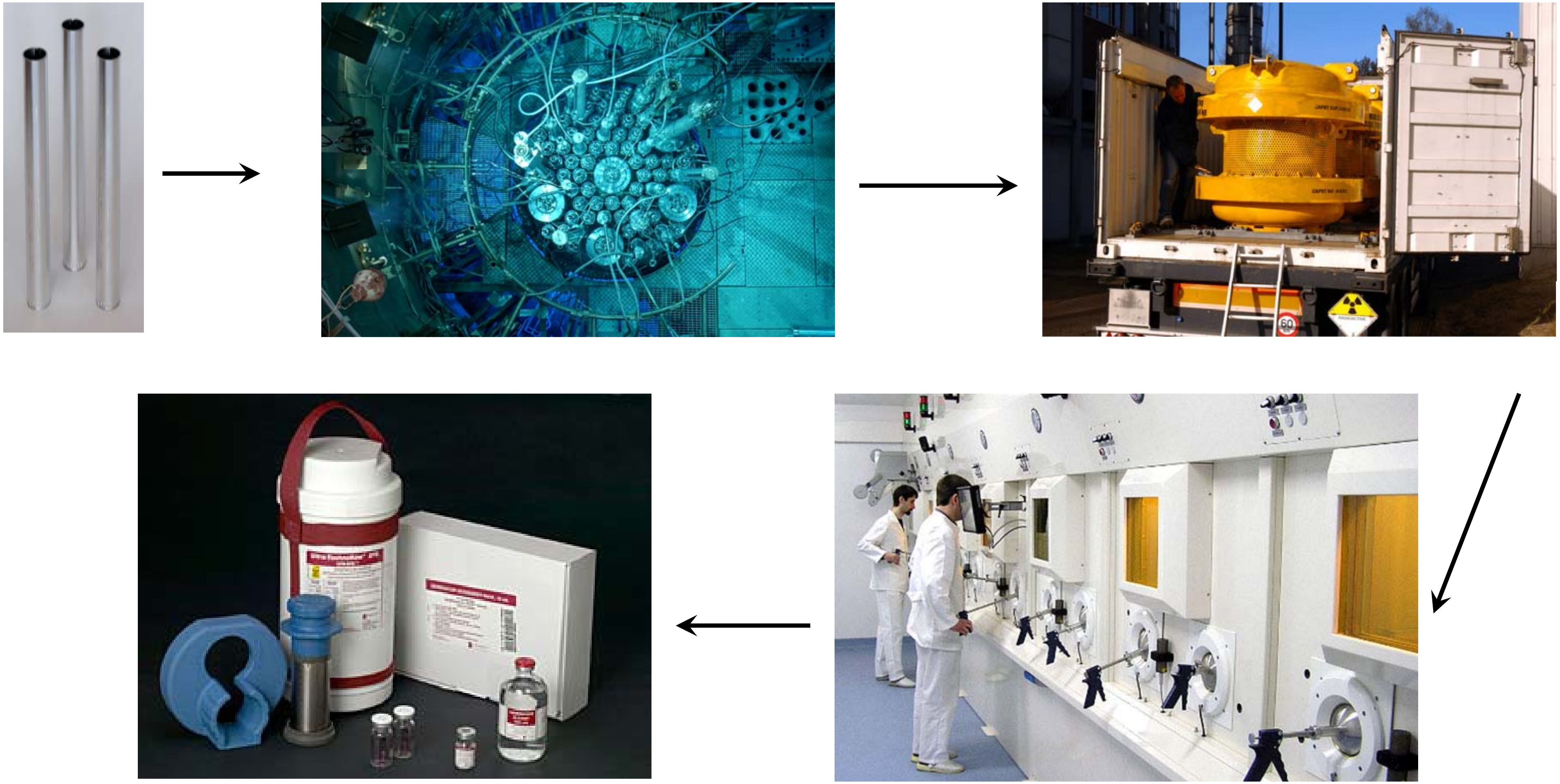
^{99}Mo Global Supply Chain



^{99}Mo Global Supply Chain



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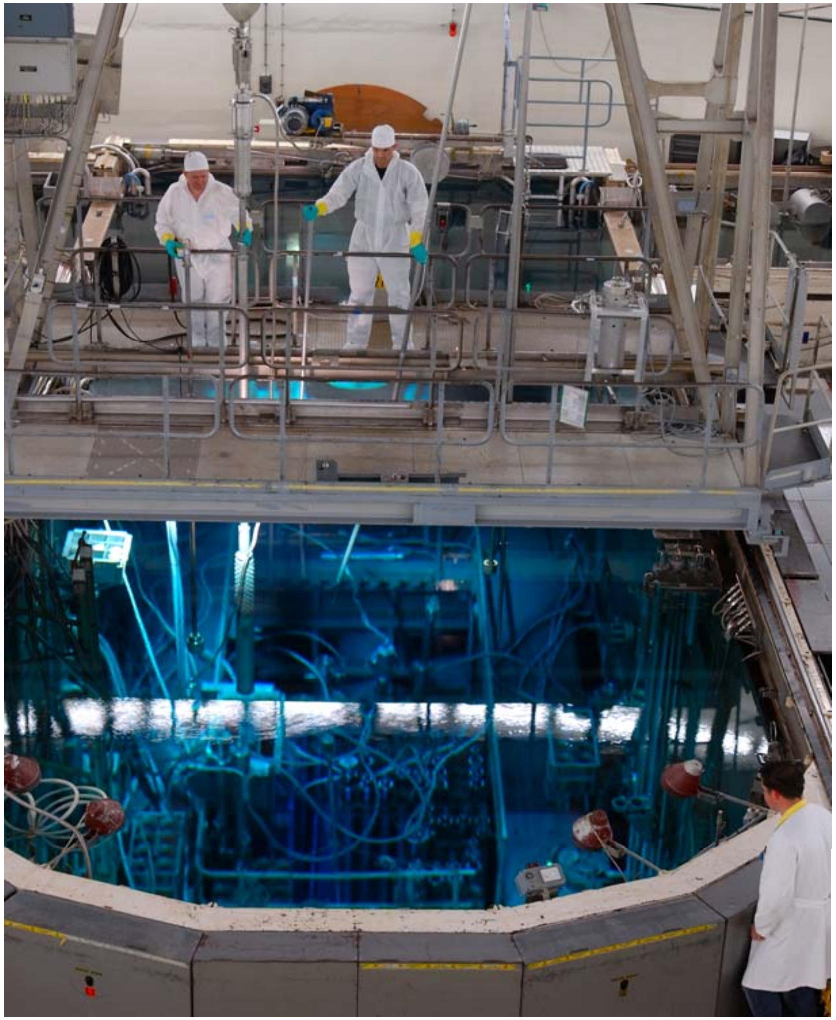
Global ^{99}Mo Reactor Production

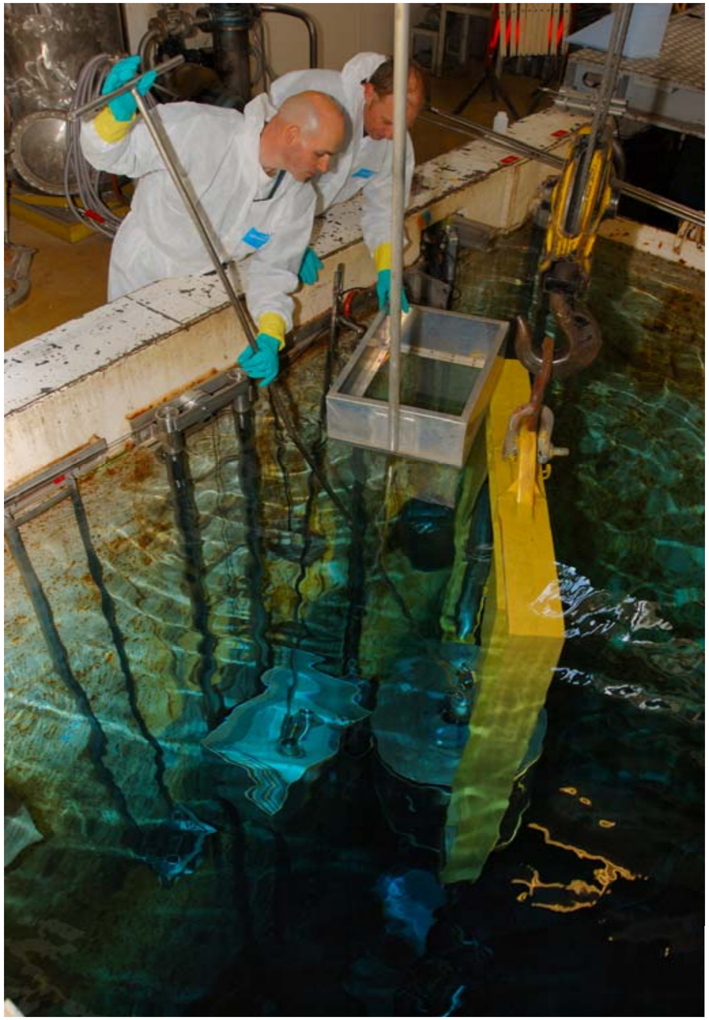
NUCLEAR REACTORS ^{235}U	OPERATING DAYS per year	PROCESSING FACILITIES ^{99}Mo	IRRADIATION CAPACITY AVERAGE/year ^{99}Mo	IRRADIATION CAPACITY PEAK ^{99}Mo
NRU	300	AECL + MDS NORDION	35%	70%
HFR	280	COVIDIEN + IRE	25%	40%
BR2	140	COVIDIEN + IRE	25%	65%
OSIRIS	180	IRE	< 10%	15%
SAFARI	300	NTP	< 10%	30%
OTHERS	?		<	5%

Production of ^{99}Mo/^{99m}Tc in BR2

From ^{235}U

To ^{99}Mo



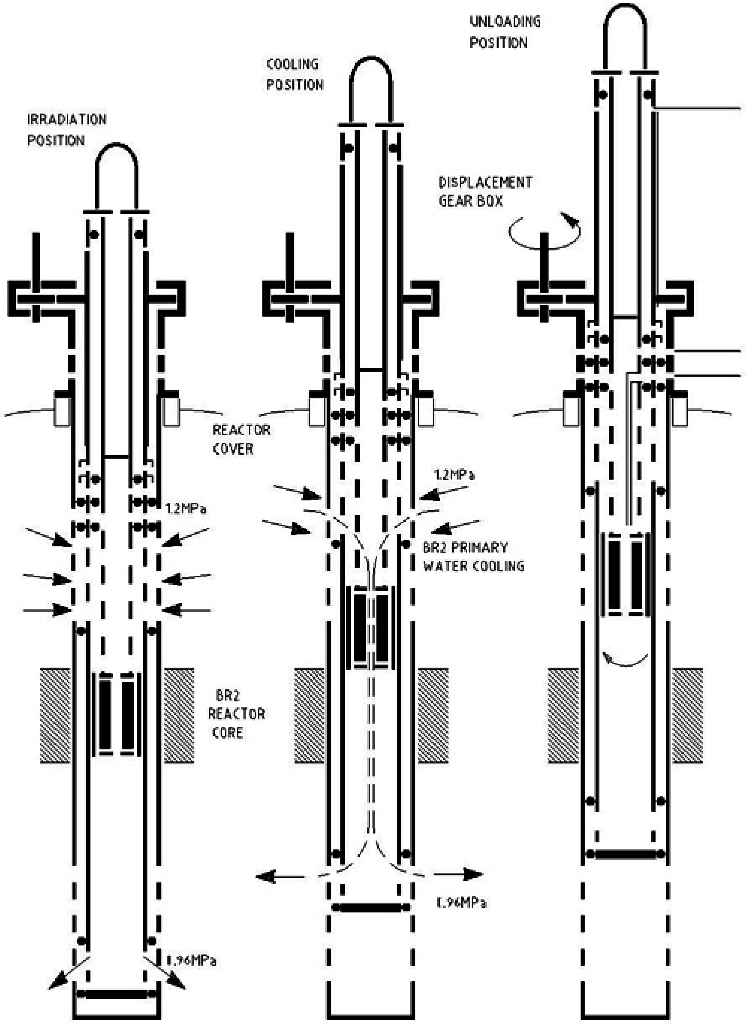


Production of ^{99}Mo/^{99m}Tc in BR2

- **Target :** **4 to 5 g of ^{235}U** (HEU; 93% ^{235}U)
- **Nuclear reaction :** fission of ^{235}U
- **Neutron flux :** $\Phi_{th} = 2.5\ 10^{14}$ **n/cm².s**
- **Irradiation time :** 150 hours
- **Irradiation devices :** **6 devices**, i.e. 75 targets at the same time
- **Irradiation capacity :** 150 targets per reactor cycle of 3 weeks
- **Activity achieved "EOI" :** about 1 000 Ci ^{99}Mo / target
- **Activity achieved "6- day calibrated":** 120 Ci ^{99}Mo / target
- **After processing :** **^{99}Mo** ($T_{1/2}$=66 h) / **^{99m}Tc** ($T_{1/2}$=6 h) ,
  ^{131}I ($T_{1/2}$=8.02 d) and **^{133}Xe** ($T_{1/2}$=5.24 d)

Production of ^{99}Mo/^{99m}Tc in BR2

- The 6 **PRF** (Primary Reloadable water-cooled device for Fissile targets) **irradiation devices** are routinely loaded in reflector channels, providing a total simultaneous **irradiation capacity of 75 targets**.
- During irradiation, these targets are cooled by **primary water** and loaded/unloaded during the reactor operation using an ingenious water lock.



Production of ^{99}Mo/^{99m}Tc in the BR2 reactor

OPERATIONS INVOLVED	TIME SCALE	EVOLUTION OF THE ^{99}MO ACTIVITY
IRRADIATION IN THE REACTOR	150 HOURS	1000 Ci ^{99}Mo 'EOI'/ target
UNLOADING FROM THE REACTOR …	12 HOURS	
LOADING CONTAINERS	4 HOURS	
SHIPMENT CONTAINERS	4 HOURS	810 Ci / target
PROCESSING IRRADIATED TARGETS	12 HOURS	640 Ci bulk ^{99}Mo
SHIPMENT BULK ^{99}MO	12 HOURS	
MANUFACTURE and DELIVERY GENERATORS	12 HOURS	500 Ci ^{99}Mo
USE IN HOSPITALS	120 HOURS	120 Ci ^{99}Mo '6-DAYS'

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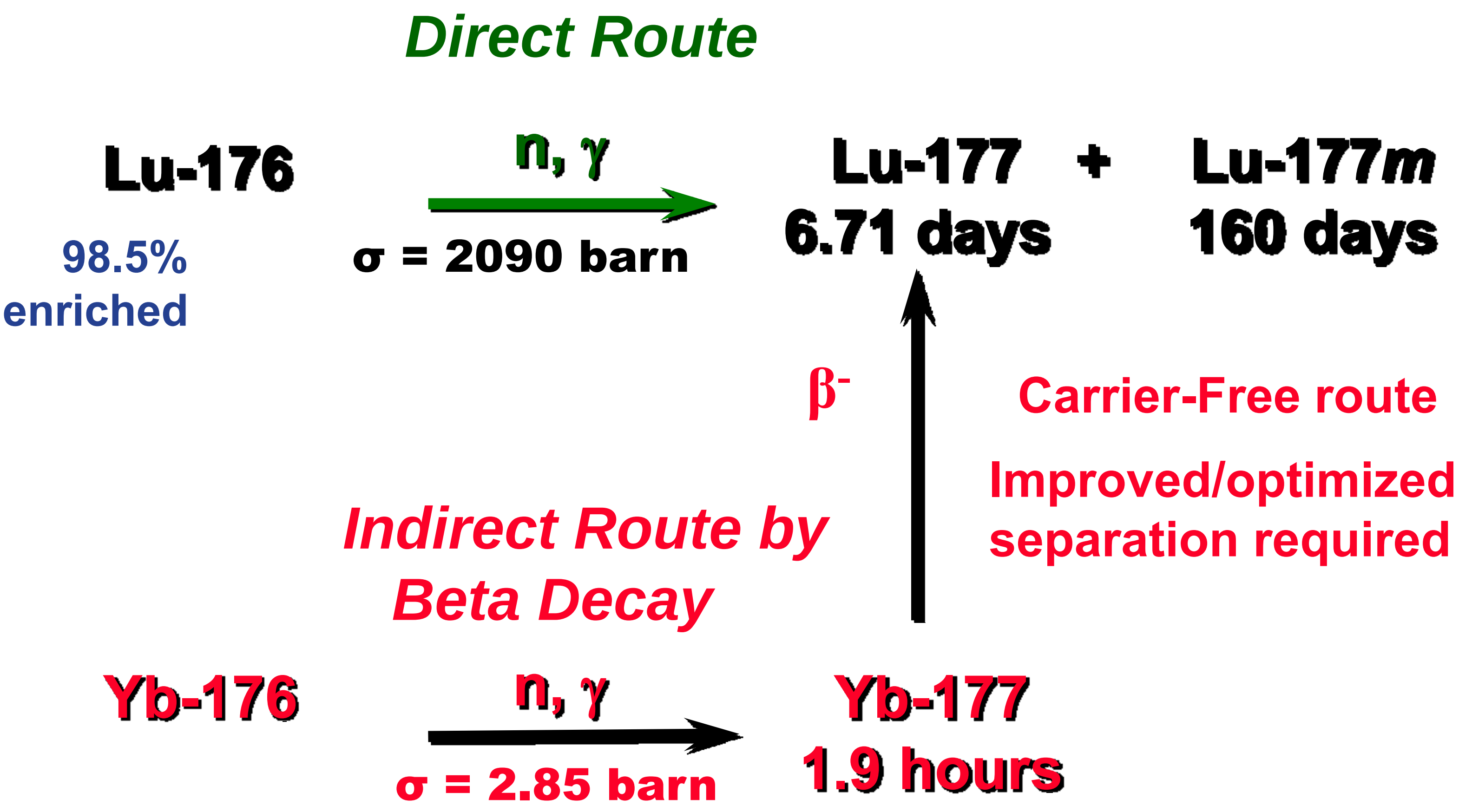
Production of Radioisotopes in BR2 for Nuclear Medicine

- The BR2 reactor is routinely producing :
  - **^{192}Ir** ($T_{1/2}$=74.2 d) for curietherapy (up to **1500 Ci/g at "EOI" from enriched ^{191}Ir)**
  - **^{186}Re** ($T_{1/2}$=3.8 d) for bone pain palliation
  - **^{153}Sm** ($T_{1/2}$=46.7 h) for bone pain palliation
  - **^{90}Y** ($T_{1/2}$=64 h) for bone pain palliation
  - **^{89}Sr** ($T_{1/2}$=50.5 d) for bone pain palliation.
- The BR2 reactor is also routinely producing the very attractive **^{177}Lu** ($T_{1/2}$=6.7 d) for targeted therapy of small tumours (prostate, …) and metastatic bone pain palliation by both direct and indirect routes.
  - **Direct route**: ^{176}Lu (n_{th} , γ) ^{177}Lu; yield = 30 Ci/mg at "EOI"
  - **Indirect route**: ^{176}Yb (n_{th} , γ) ^{177}Yb → ^{177}Lu; yield = 0.07 Ci/mg ^{176}Yb at "EOI"
- Furthermore, reactor operators have collaborated on several occasions to secure the supply of additional radioisotopes that have become more interesting such as **^{188}W/^{188}Re** and **^{117m}Sn** ($T_{1/2}$= 13.6 d), especially with the HFIR reactor at Oak Ridge National Laboratory (ORNL, USA).

Reactor Production of ^{177}Lu



Direct Route

Lu-176

98.5% enriched

n, γ

σ = 2090 barn

Lu-177 + **Lu-177*m***

6.71 days

160 days

β^-

Carrier-Free route

Improved/optimized separation required

Indirect Route by Beta Decay

Yb-176

n, γ

σ = 2.85 barn

Yb-177

1.9 hours

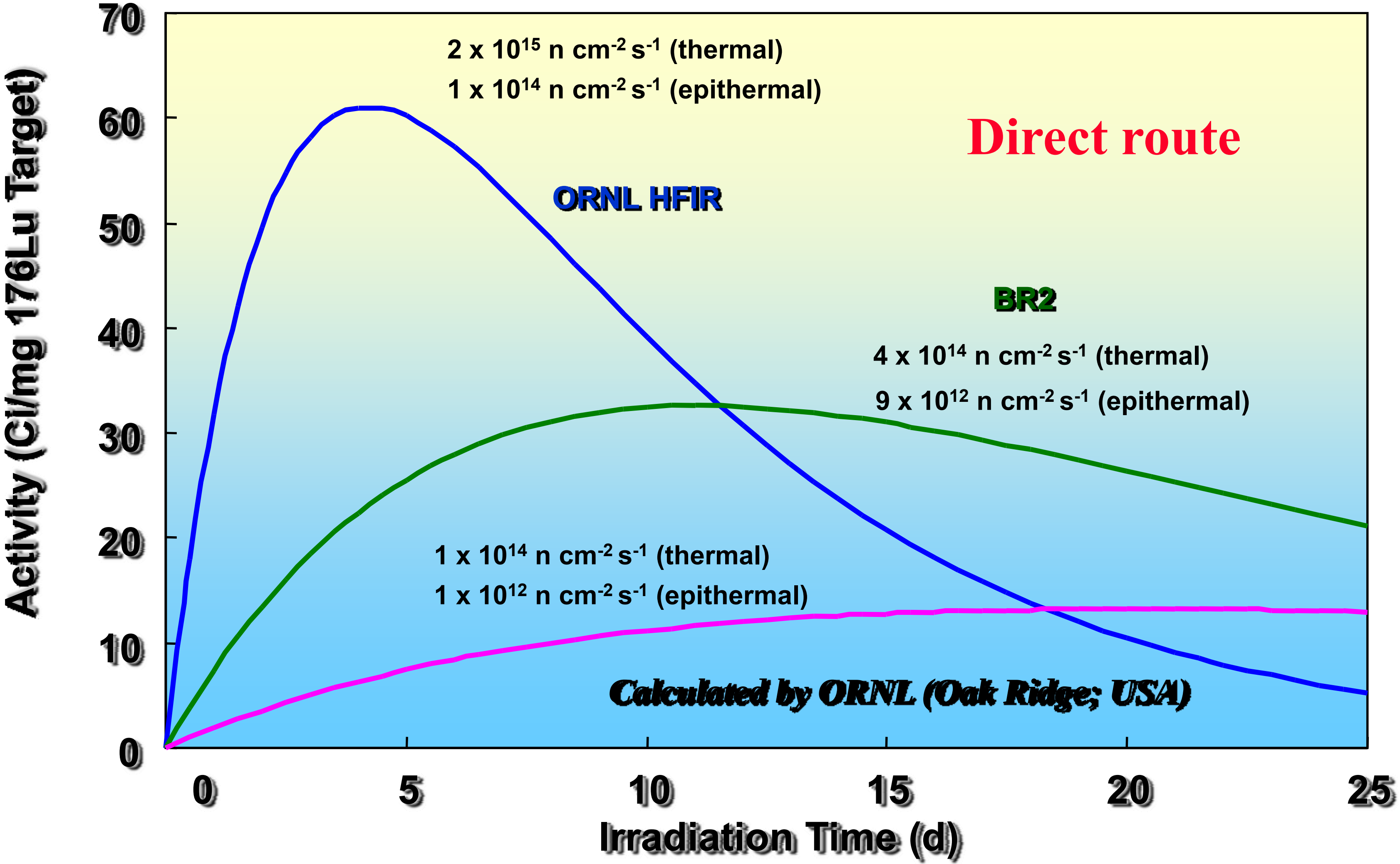
Production of Radioisotopes in BR2 for Nuclear Medicine

^{177}Lu

by the ‘direct route’

- **Properties :**
  - $T_{1/2}$= 6.7 days β^{-}_{max}= 0.497 MeV
  - γ rays of 208 keV (11%) and 113 keV (6%) suitable for imaging and dosimetry
- **Nuclear reactions and yield:**
  - Direct route (single neutron capture) : ^{176}Lu (n_{th} , γ) ^{177}Lu ; Cross section : σ_{th} = 2090 barn
  - Target material : 98.5% enriched ^{176}Lu in quartz ampoules
  - Thermal neutron flux : Φ_{th} = 3.5 x 10^{14} n/cm².s
  - Irradiation time : 7 days
  - Specific activities ^{177}Lu : up to **30 Ci/mg at “EOI”**
  - Irradiation capacity : 4 “DG” thimble devices; up to 36 irradiation cans simultaneously
- **Applications :**
  - therapy of small tumors (prostate, …), bone pain palliation, …

Reactor Production of ^{177}Lu



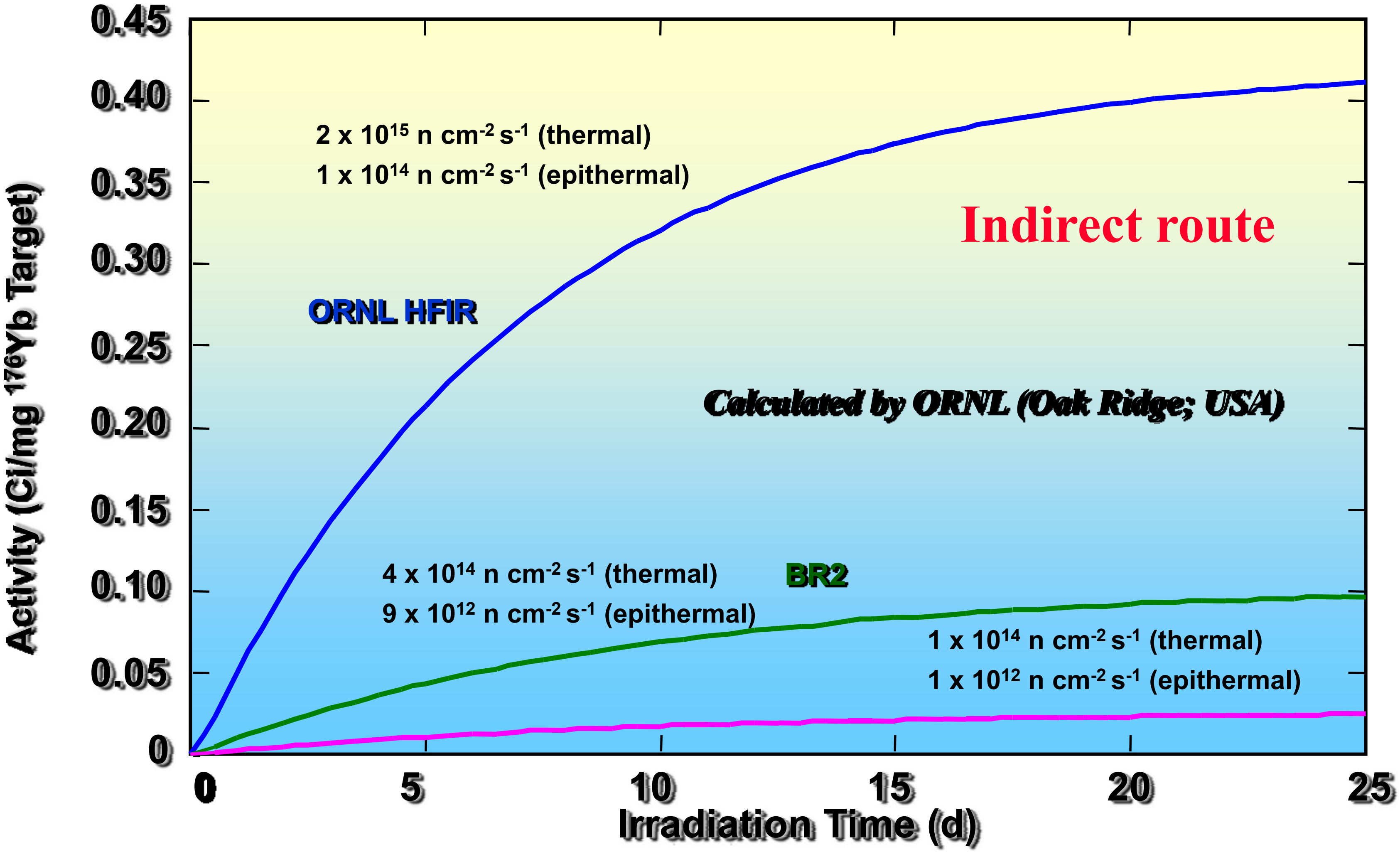
Production of Radioisotopes in BR2 for Nuclear Medicine

^{177}Lu

by the 'indirect route'

- **Properties :**
  - $T_{1/2}$= 6.7 days β^{-}_{max}= 0.497 MeV
  - γ rays of 208 keV (11%) and 113 keV (6%) suitable for imaging and dosimetry
- **Nuclear reactions and yield:**
  - Indirect route (single neutron capture) : $^{176}\text{Yb}\ (n_{th}, \gamma)\ ^{177}\text{Yb} \xrightarrow{\beta^{-}} {}^{177}\text{Lu}$
  - Target material : 99.5% enriched ^{176}Yb in quartz ampoules
  - Thermal neutron flux : $\Phi_{th} = 3.5 \times 10^{14}$ n/cm².s
  - Irradiation time : 10 days
  - Production yield of ^{177}Lu : up to **0.07 Ci/mg of ^{176}Yb at "EOI"**
  - Irradiation capacity : 4 "DG" thimble devices; up to 36 irradiation cans simultaneously
- **Applications :**
  - therapy of small tumors (prostate, …), bone pain palliation, …

Reactor Production of ^{177}Lu



Indirect route

Calculated by ORNL (Oak Ridge; USA)

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Reactor Production of ^{177}Lu

- **Advantages of the "Indirect Production Route"**
  - **Carrier-Free ^{177}Lu :** High radioactive purity (no ^{177m}Lu production)
  - **Higher specific activity ^{177}Lu**
- **Disadvantages of the "Indirect Production Route"**
  - **Low production yields :**
    - 0.35 Ci ^{177}Lu per mg ^{176}Yb target (for thermal neutron flux of 2 x 10^{15} n/cm².s) compared to the 60 Ci ^{177}Lu per mg ^{176}Lu target achieved by the "Direct Route"
  - **High target volume :**
    - many "high thermal neutron flux" irradiation positions are required to satisfy commercial production levels
  - **Requires complexe chemical separations :**
    - very expensive target material, longer process, decay losses, more waste, …

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Production of Radioisotopes in BR2 for Nuclear Medicine

^{188}Re

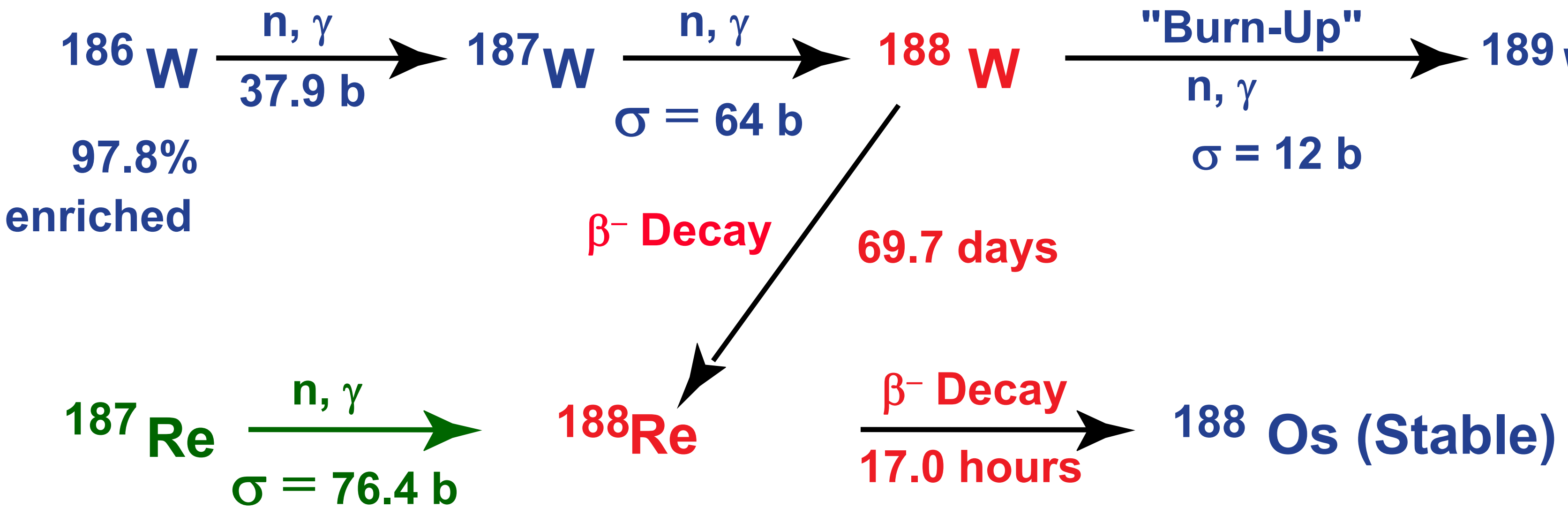
- **Properties :**
  - $T_{1/2}$= 16.9 hours β^-_{max}= 2.12 MeV
  - γ ray of 155 keV (15%) suitable for imaging and dosimetry

- **Nuclear reactions and yield:**
  - Double neutron capture : $^{186}W\ (n_{th}, \gamma)\ ^{187}W\ (n_{th}, \gamma)\ ^{188}W \xrightarrow{\beta^-} {}^{188}Re$
  - Target material : 98% enriched ^{186}W
  - Thermal neutron flux : Φ_{th} = up to 10^{15} n/cm².s
  - Irradiation time : one reactor cycle of 21 or 28 days
  - Specific activities ^{188}W : up to **1.2 Ci/g at "EOI"**
  - From the attractive and cost-effective generator ^{188}W ($T_{1/2}$= 69.7 d) /^{188}Re ($T_{1/2}$= 16.9 h)
  - Large irradiation capacity : up to 48 irradiation cans per reactor cycle

- **Applications :**
  - metastatic bone pain palliation, inhibition of coronary artery restenosis after percutaneus transluminal coronary angioplasty (PTCA) or bypass surgery, treatment of arthritis, …

Reactor Production of ^{188}W

Double Neutron Capture



^{186}W $\xrightarrow[37.9\ \text{b}]{n,\ \gamma}$ ^{187}W $\xrightarrow[\sigma = 64\ \text{b}]{n,\ \gamma}$ ^{188}W $\xrightarrow{\text{"Burn-Up"}}$ ^{189}W

n, γ

σ = 12 b

97.8%
enriched

β^- Decay

69.7 days

^{187}Re $\xrightarrow[\sigma = 76.4\ \text{b}]{n,\ \gamma}$ ^{188}Re $\xrightarrow[17.0\ \text{hours}]{\beta^-\ \text{Decay}}$ ^{188} Os (Stable)

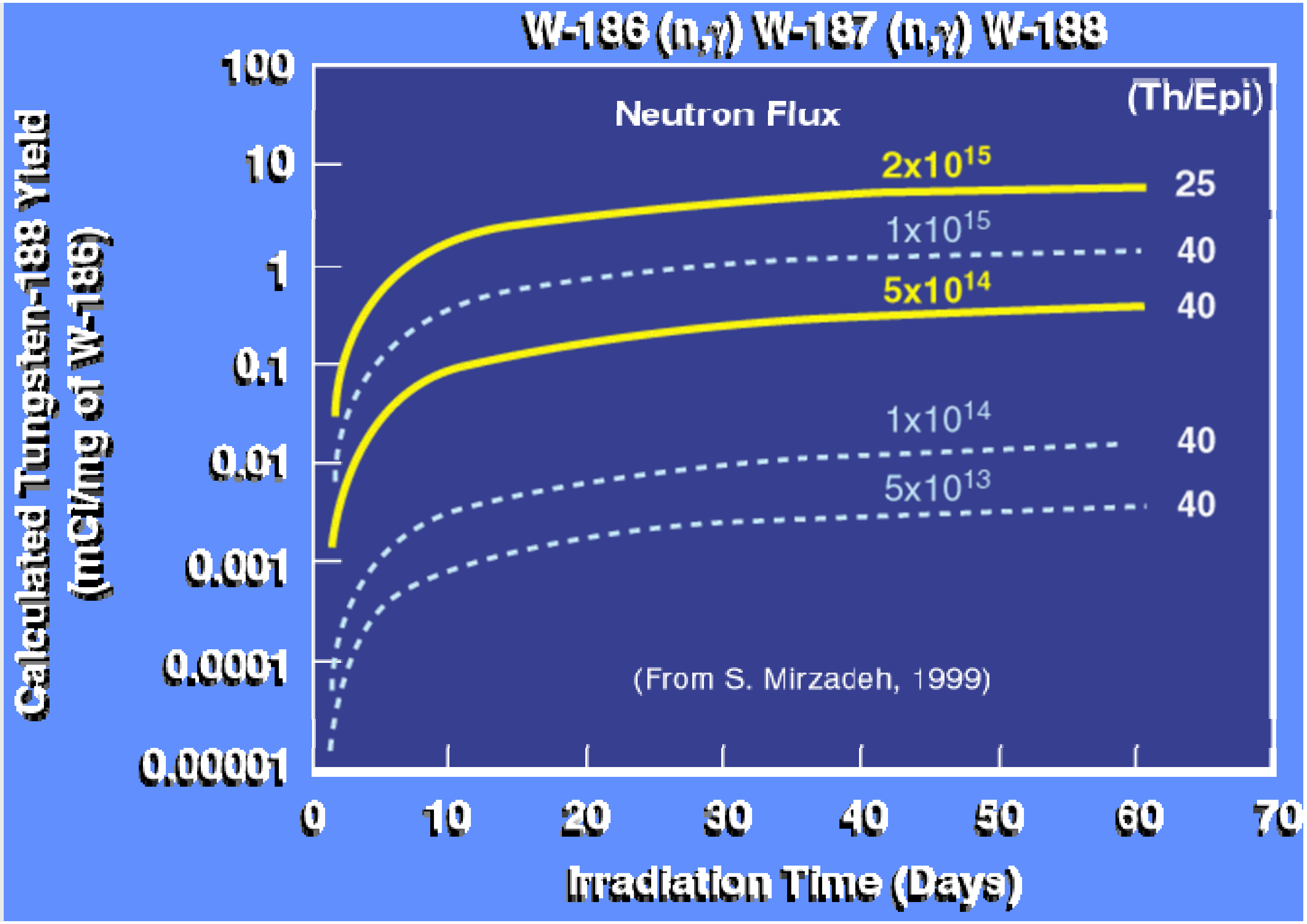
Direct Route

β max 2.12 MeV

γ 155 keV (15%)

Reactor Production of ^{188}W

The yield is proportional to the square of the available thermal neutron flux



Production of Radioisotopes in BR2 for Nuclear Medicine

^{117m}Sn

- **Properties :**
  - $T_{1/2}$= 13.6 days
  - Low-energy conversion electrons 127 keV (64%), 129 keV (10%) and 152 keV(26%)
  - γ ray of 159 keV (86%) suitable for imaging and dosimetry

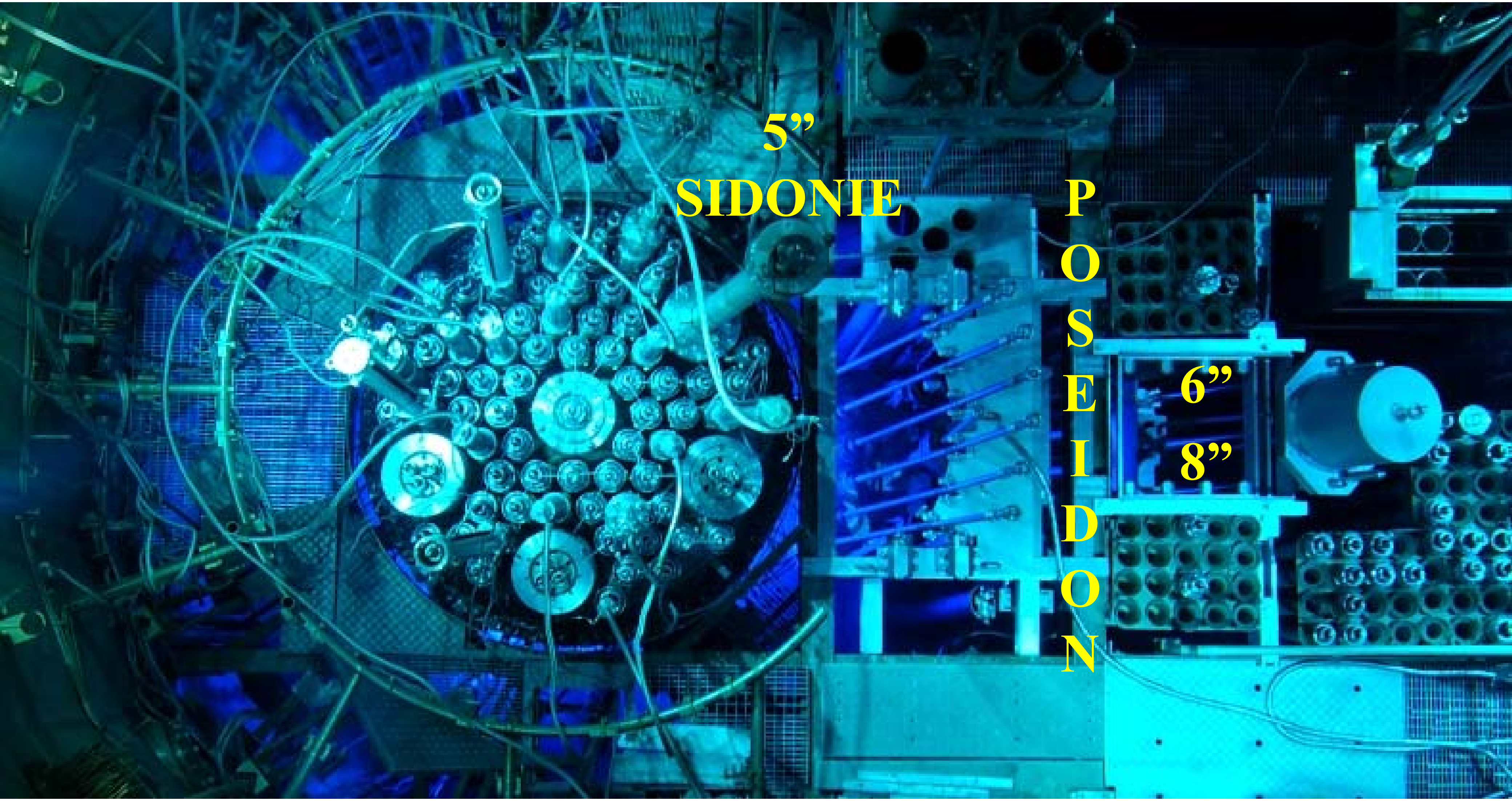
- **Nuclear reactions and yield:**
  - Inelastic neutron scattering reaction: $^{117}Sn\ (n_{\text{fast, E>100 keV}}\ ,\ n'\ \gamma)\ ^{117m}Sn$
  - Cross section : σ fast (E > 318 keV) = 222 mb
  - Target material : 92% ^{117}Sn
  - Fast neutron flux : $\Phi_{fast} = 6 \times 10^{14}$ n/cm².s
  - Irradiation time : one reactor cycle of 21 or 28 days
  - Specific activities ^{117m}Sn : up to **10 Ci/g at "EOI"**
  - Large irradiation capacity : inside 13 fuel elements; up to 40 targets simultaneously

- **Applications :**
  - metastatic bone pain palliation, treatment of finger joints inflammation, rheumatoid arthritis.

Production of Radioisotopes in BR2 for Industry and Research

- The BR2 reactor is routinely producing **^{192}Ir** mainly for radiography of welds to detect lack of fusion and cracks. Other radioisotopes such as **^{203}Hg** are also produced for industrial applications.
- **Iridium target material**, natural and enriched (80% ^{191}Ir), is irradiated in various sizes, dimensions and geometries (2.0 x 0.33 mm, 3.0 x 0.33 mm, 2.0 x 0.125 mm, 3.0 x 0.125 mm, 2.7 x 0.125 mm, 2.7 x 0.25 mm, …) depending on the application.
- The **specific activities** achieved at "EOI" range **500 Ci/g** up to **750 Ci/g** for natural iridium and up to **1500 Ci/g** for enriched iridium, depending on the size of the discs, the loading of the capsules and the axial position in the basket. The maximal ^{192}Ir production capacity is about 180 kCi "EOI" per reactor cycle.
- Radioisotopes for research are produced on demand: **^{67}Cu**, **^{147}Nd**, ….

Production of NTD-Silicon in the BR2 High-Flux Reactor



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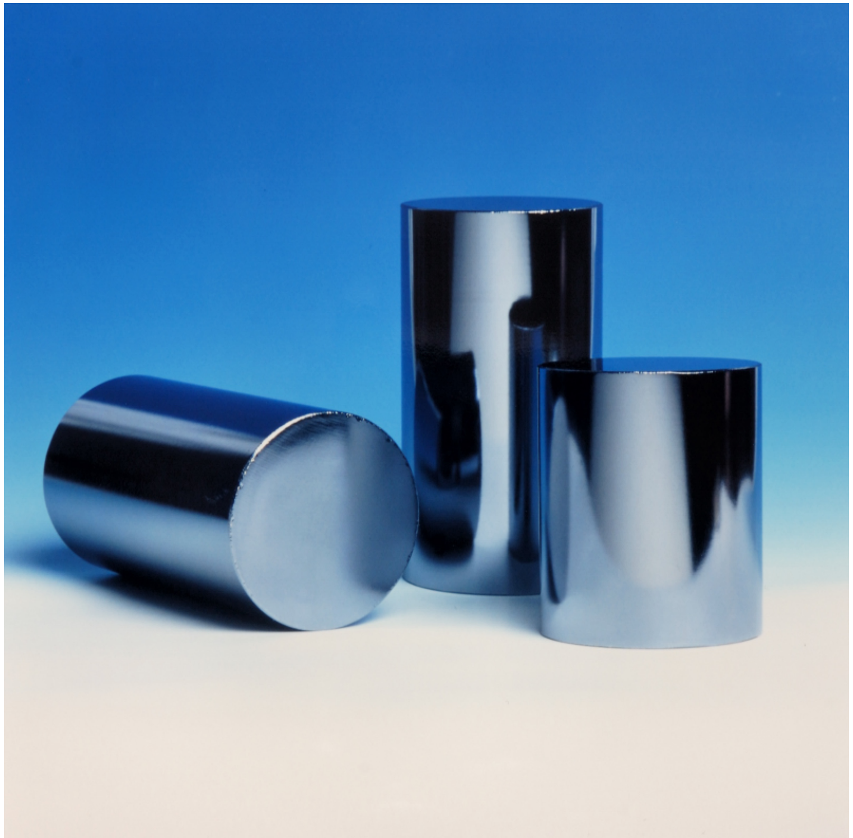
Production of NTD-Silicon in the BR2 High-Flux Reactor

- **Silicon consists of 3 natural isotopes:**
  - ^{28}Si (92.2%)
  - ^{29}Si (4.7%)
  - ^{30}Si (3.1%)
- $\mathbf{^{30}Si\ (n, \gamma)\ ^{31}Si \xrightarrow{\beta-} {}^{31}P}$
  - to change the initial resistivity of the material.
- The radioisotope ^{31}Si decays with a half-life $\mathbf{T_{1/2} = 2.62\ h}$ to the stable isotope ^{31}P.



Production of NTD-Silicon in the BR2 High-Flux Reactor

Principles of Neutron Transmutation Doping silicon :

- The phosphorous atoms act as **electron donors**, resulting in the creation of an **n-type** semi-conducting material. Only a small number of the ^{30}Si atoms – around 1 to 10 ppm – need to be transmuted to produce the range of resistivities needed by the World electronics industry.
- During irradiation, the concentration of the doping agent (**C_D**) produced by the neutrons in the silicon is determined by the number of atoms of ^{30}Si that are transmuted into ^{31}P, which can be written as follows:

$$C_D = N \sigma \varnothing_t \text{ atoms/cm}^3 \quad \text{[EQ 1]}$$

where:

- N = number of atoms of ^{30}Si in the initial silicon material;
- σ = effective cross-section of neutrons for ^{31}Si-generation (barns) = 0.118 barns ;
- $\varnothing_t$ = the neutron fluence (n/cm²).

Production of NTD-Silicon in the BR2 High-Flux Reactor

- **Principles of Neutron Transmutation Doping silicon :**
  - For silicon with a density of 2.33 g/cm^3, an atomic weight of 28.086 and an isotope ratio of 3.09% for ^{30}Si, N = 1.544·10^{21} cm^{-3}.
  - Taking into account the concentration of the doping agent in the original material (Cs), the total concentration of the doping agent (C) can be written as:

    C = CD + CS **[EQ 2]**

  - Thus, for N-type silicon the relationship between the concentration C of the doping agent ^{31}P and the resistivity ρ can be written as follows:
  - $C = 1 / (\rho\ \mu\ \varepsilon)$ [Ω·cm] **[EQ 3]**

    where

    - μ = the displacement mobility of electrons in the crystal lattice which can be set at 1350 cm^{-2} × V × s^{-1} for silicon;
    - ε = electron charge, 1.6·10^{19} Coulombs.

Production of NTD-Silicon in the BR2 High-Flux Reactor

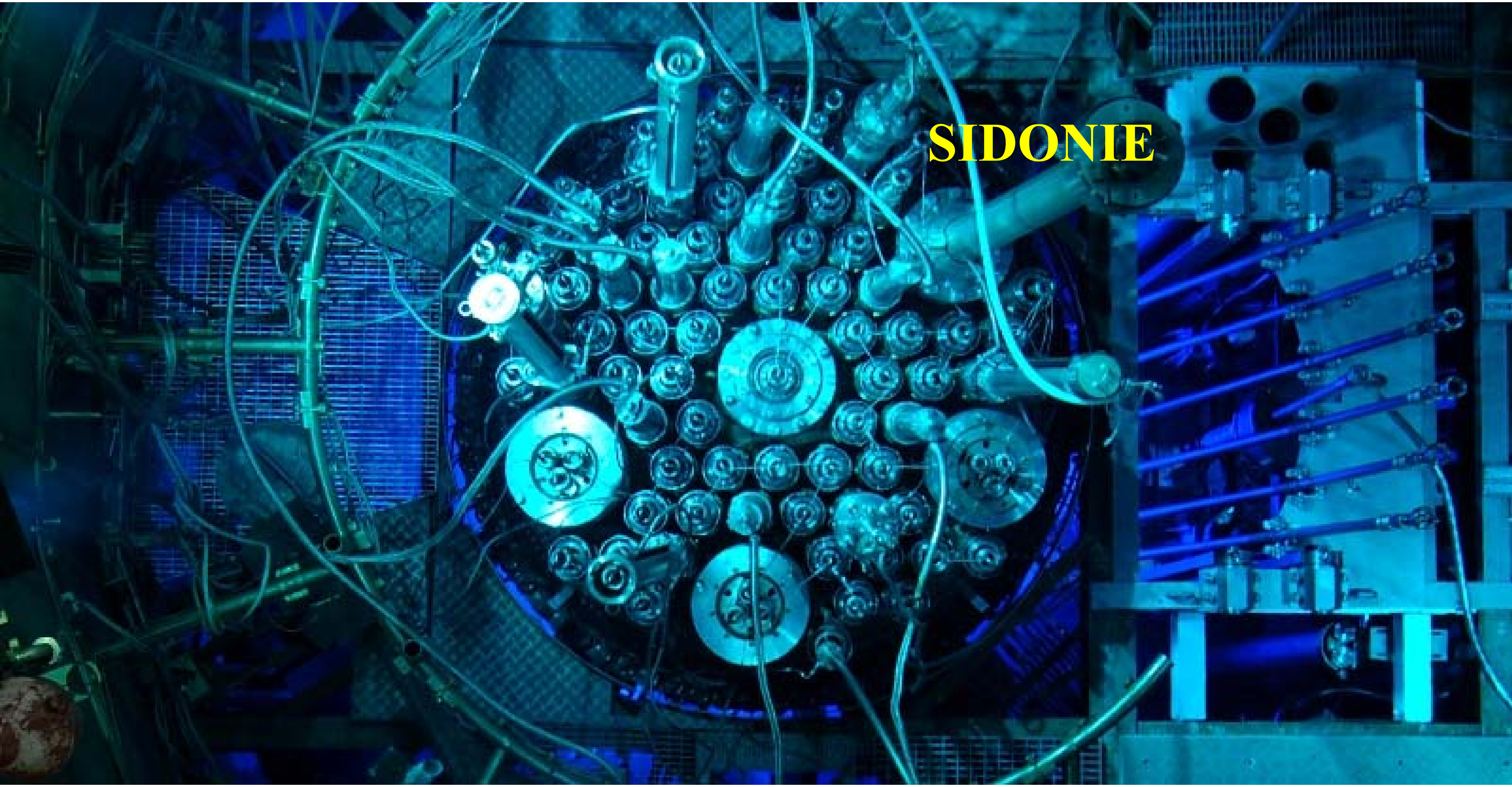
- **Principles of Neutron Transmutation Doping silicon :**
  - By combining equations **[EQ 1]**, **[EQ 2]** and **[EQ 3]** the effective neutron fluence $\varnothing_t$ for a target of specific resistivity ρ can be written as:

$$\varnothing_t = 2.54 \cdot 10^{19} \, (l/\rho - 1/\rho_0) \qquad \textbf{[EQ 4]}$$

where ρ_0 = the average resistivity measured in the original material.

- **BR2 has 2 facilities for NTD-Silicon :**
  - SIDONIE (In-Core Facility) : for 5-inch diameter Si-batches
  - POSEIDON (Pool-Side Facility) : for 6-inch and 8-inch diameter Si-batches

SIDONIE FACILITY



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SIDONIE FACILITY

- The **SIDONIE** **(SIlicon DOping by Neutron Irradiation Experiment)** facility is characterized by:
  - "In-Core" **light-water** device that is located in a 200-mm diameter beryllium channel;
  - Perturbed integrated **'conventional thermal neutron flux'** of about **$5.5 \cdot 10^{13}$ n/cm²·s**
  - **Cadmium ratio** of approximately **25:1**
  - Silicon irradiation-batch **diameter** of **5-inches** (maximum)
  - Silicon crystal **lengths** of **300-mm** (maximum)
  - Silicon **irradiation-batch length** of **800-mm** (maximum)
  - Silicon core **temperature** of **<200 °C** during irradiation
  - To produce a typical **target resistivity** of **35 Ω·cm**, starting of a resistivity of about 2000 Ω·cm (for n-type), requires a thermal neutron dose of approximately 7.13×10^{17} n/cm²; this is achieved by an irradiation time of approximately **3.6 hours** when operating at a normal reactor power of 55 MW_{th}
  - NTD-silicon production capacity of approximately **15-tonnes per year** based on 140-days (over 6 cycles) of reactor operation and an average target resistivity of 35 Ω·cm.

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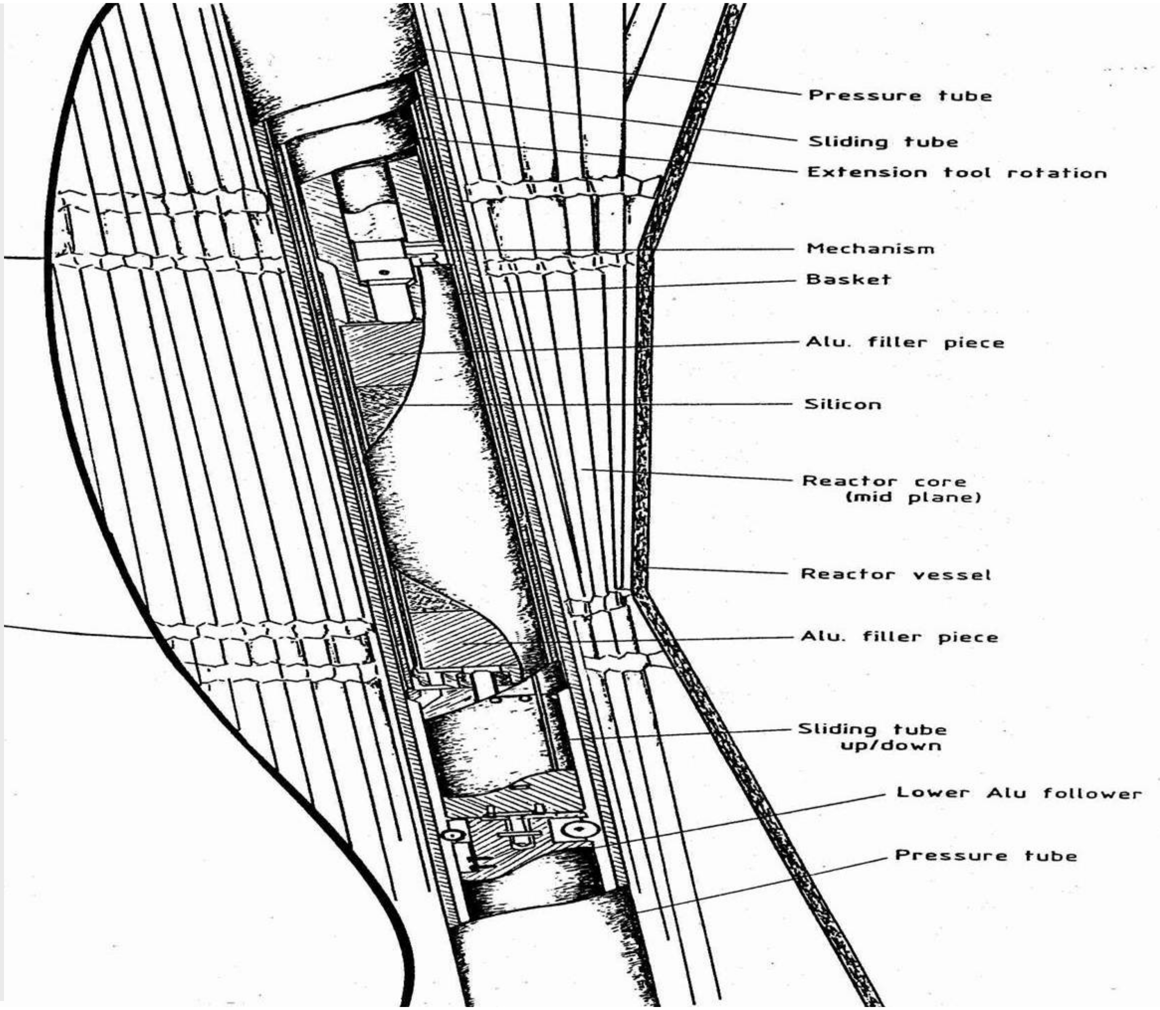
SIDONIE FACILITY

Homogeneity achieved by continuous rotation and translation of the silicon ingots at predetermined, computer controlled speeds.

The silicon is in contact with the reactor pool water which under forced convection serves to maintain the surface temperature of the silicon considerably below 100 °C throughout the entire process.



POSEIDON FACILITY

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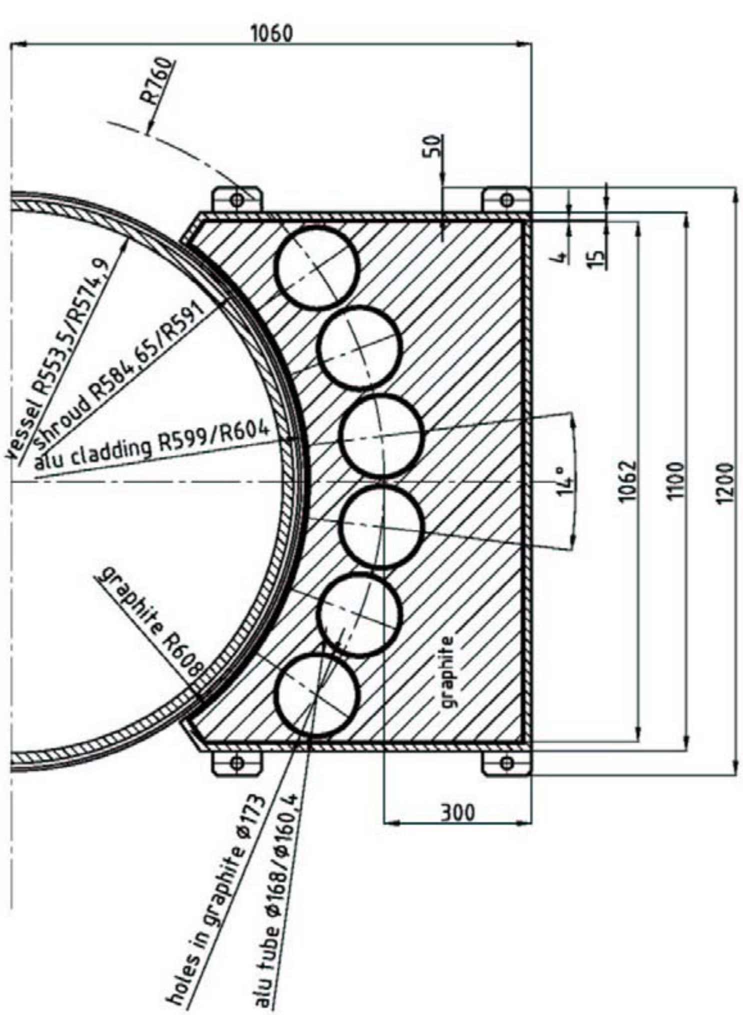
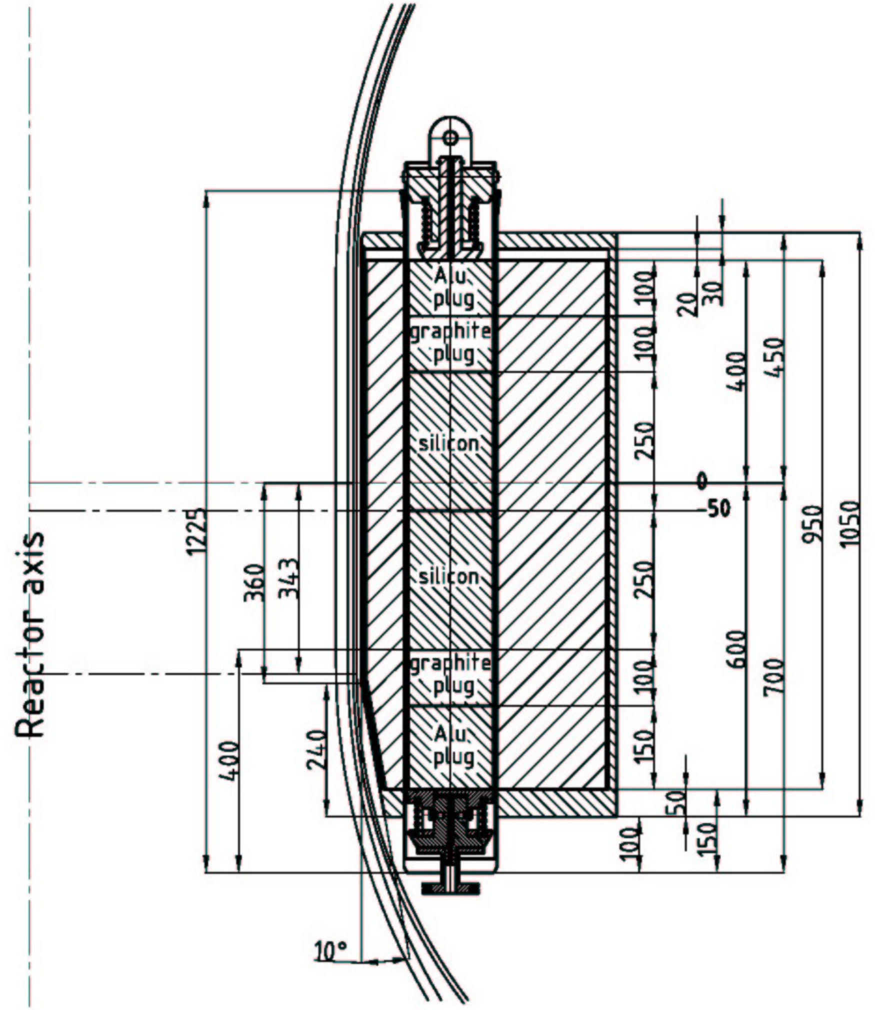
POSEIDON FACILITY

- The **POSEIDON** **(POol Side Equipment for Irradiation and DOping of silicon by Neutrons)** facility is characterized by:
  - "Pool-Side" multi-channel, graphite moderated device that is located in the BR2 reactor pool on the outside of the Reactor Pressure Vessel
  - Capability for simultaneous irradiation of 6-batches of 6 and 8-inch diameter silicon
  - Perturbed integrated **'conventional thermal neutron flux'** of about **$5.26 \cdot 10^{12}$ n/cm²·s**
  - **Cadmium ratio** > **50:1**
  - Silicon irradiation-batch **diameter** of **6 and 8-inches** (maximum)
  - Silicon crystal **lengths** of **250-mm** (+/5-mm)
  - Silicon **irradiation-batch length** of **500-mm** (maximum)
  - Silicon core **temperature** of **<200 °C** during irradiation
  - To produce a typical **target resistivity** of **48 Ω·cm**, starting of a resistivity of about 2000 Ω·cm (for n-type), requires a thermal neutron dose of approximately 5.16×10^{17} n/cm²; this is achieved by an irradiation time of approximately **27 hours** when operating at a normal reactor power of 55 MW_{th}
  - NTD-silicon production capacity of approximately **18-tonnes per year** based on 140-days (over 6 cycles) of reactor operation and an average target resistivity of 48 Ω·cm.

POSEIDON FACILITY

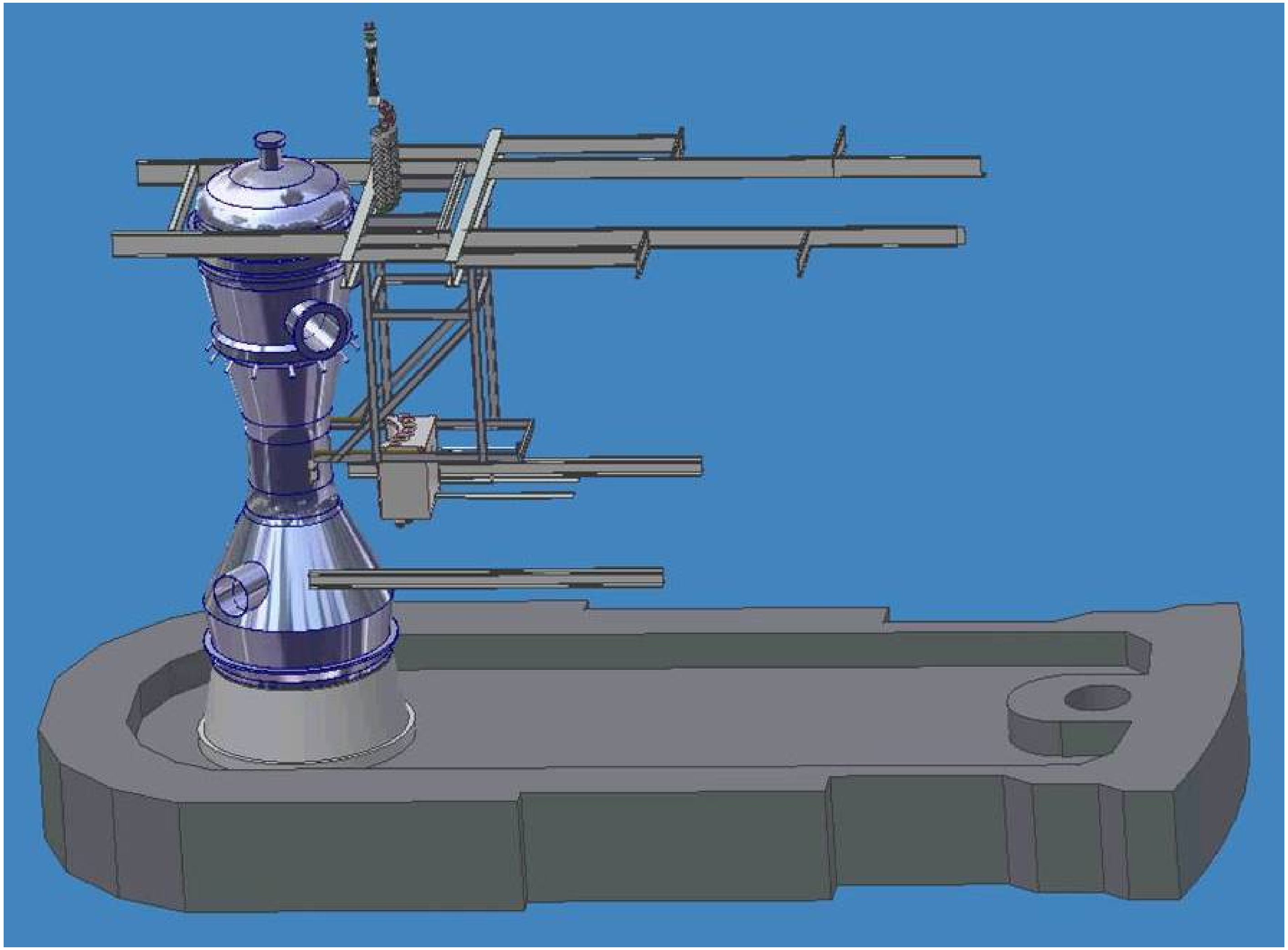




POSEIDON FACILITY

Homogeneity achieved by continuous rotation of the silicon ingots during irradiation and by replacing the top crystal with the one from under it and the bottom crystal with the one from above it at mid-irradiation.

The silicon crystals are in direct contact with the reactor pool water which under natural convection keep the silicon surface temperature below 100°C.



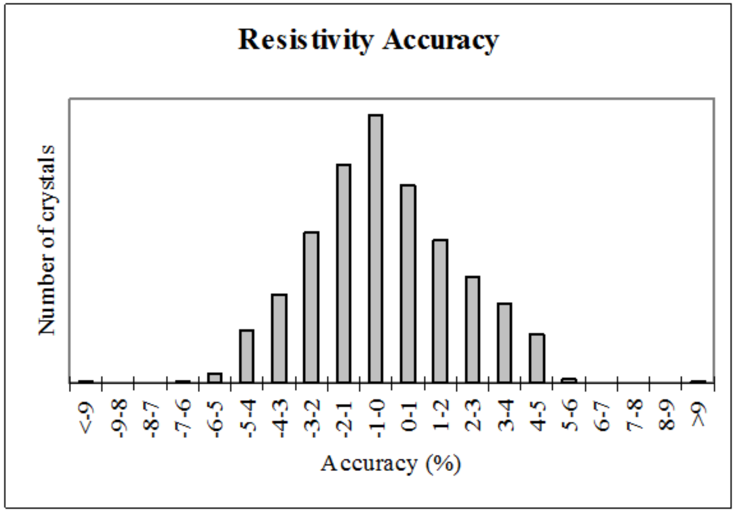
SIDONIE & POSEIDON FACILITIES

- **SIDONIE's NTD-silicon irradiation performances :**
  - A deviation from target resistivities of typically <+/-5%
  - Axial Resistivity Gradients (ARG) over 800-mm of <3% (for n-type silicon)
  - Radial Resistivity Gradients (RRG) for 5-inch dia. of <3%
  - An NTD-Silicon target resistivity production range from 5 to 500 Ω·cm

- POSEIDON's NTD-silicon irradiation performances :
  - A deviation from target resistivities of typically <+/-5%
  - Axial Resistivity Gradients (ARG) over 500-mm of <+/-3% (for n-type silicon)
  - Radial Resistivity Gradients (RRG) for 6-inch dia. of <4%
  - An NTD-Silicon resistivity production range from 20 to 500 Ω·cm

SIDONIE & POSEIDON FACILITIES

- **Results of resitivity accuracy :**
  - Customer feedback on resistivity accuracy confirms the quality of BR2's services in the NTD-silicon business as illustrated below:



- After irradiation :
  - After 4 to 5 days of radioactive decay, the silicon can be **safely removed** from the reactor pool.
  - It is then immediately **cleaned and measured** for radioactivity by the recognised authority within SCK•CEN to certify that it fully complies with the international safety standards for "exempt" radioactive material as defined in the IAEA Regulations for the Safe Transport of Radioactive Materials (1996 edition – ST-1).
  - Thereafter, the NTD-silicon can be safely released from the SCK•CEN reactor site and sent back to the customer.

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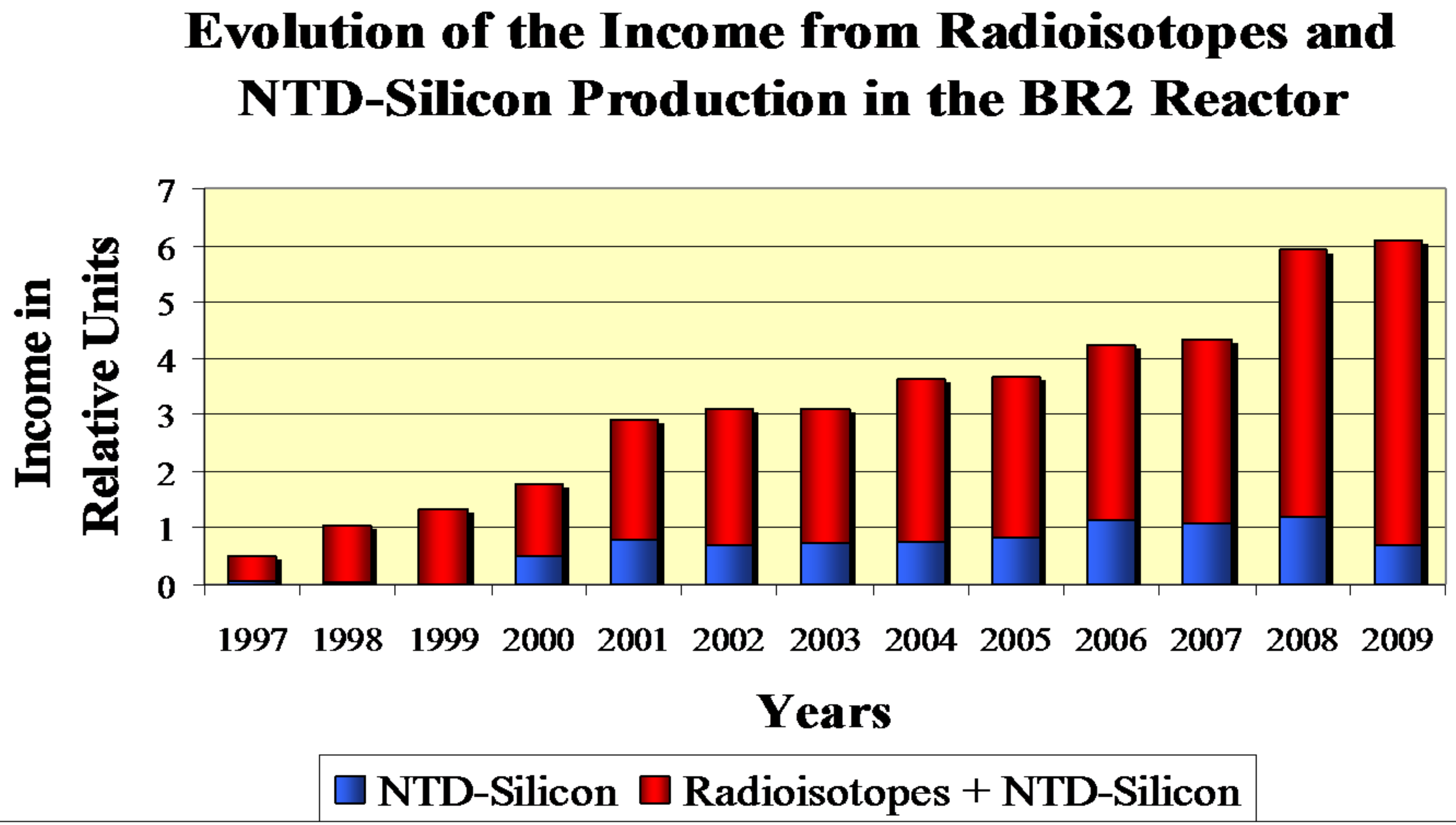
Evolution of the Revenues from Commercial Activities at BR2



Evolution of the Revenues from Commercial Activities at BR2

- The **commercial production of radioisotopes and NTD-Silicon** have been actively developed since the early 1990's to generate **additional revenues**.
- The revenues related to these activities **increased considerably** and represent currently a **significant contribution** to the reactor operating costs.
- However, the **current pricing policy** needs to be adapted to the real production costs.
- Indeed, the BR2 reactor is a **multipurpose reactor** and not a dedicated reactor for the commercial production of radioisotopes and NTD-Silicon.
- In the early 1990's, the production of **^{99}Mo** was especially seen as a **by-product** that could bring additional revenues.
- The **real costs** (investment, operating, dismantling, …) were **not taken** into account in the definition of the production price as government funding was involved.
- This approach is expected to be modified in the near future to be in accordance with the economical reality.

Conclusions

- The **extensive refurbishment** programme of the BR2 Reactor, performed in 1995 - 1997 after more than 30 years utilization, provided a **life time extension** of more than 26 years.
- A serious effort has also been made to perform all the commercial activities (production of 'Radioisotopes' and 'Neutron Transmutation Doped Silicon') in accordance with a **'Quality System'** that has been certified to the requirements of the "**EN ISO 9001 : 2000** – Quality Systems – Model for **Quality Assurance** in production, installation and servicing" (December 2006).
- The **BR2 Reactor** will thus continue to contribute to a **reliable supply** of a **wide range** of **radioisotopes** to meet **global demands** for **many years.**
- To help the **Nuclear Medicine** and the **^{99}Mo/^{99m}Tc** (radiodiagnostic) global supply shortage in particular, the BR2 reactor operates an **additional cycle in 2010** and **increased** its HEU targets **irradiation capacity** by **50%** (new irradiation devices).

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