PRODUCTION OF RADIOISOTOPES AND NTD-SILICON IN THE BR2 REACTOR

B. PONSARD, H. BLOWFIELD
Belgian Nuclear Research Centre (SCK•CEN),
Mol,
Belgium
bponsard@sckcen.be

1. INTRODUCTION

BR2 is characterised as a 100 MW_{th} high flux, light water tank in pool type Materials Test Reactor (MTR). It is operated by the Belgian Nuclear Research Centre (SCK•CEN) to provide a primary role as a multipurpose nuclear research tool in support of major national and international scientific research programmes. However, BR2 is also exploited commercially by SCK•CEN to provide the global radioisotope and semiconductor industry with irradiation services that are managed and operated on a highly competitive basis. This is aimed at generating a continuous revenue stream in support of BR2's operating costs to thereby reduce its 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 it will be heavily relied upon to meet the increasing world demand for radioisotope and neutron transmutation doped (NTD) silicon production. It will also play an important role in the development and commercial exploitation of new technologies in these particular areas of business.

In this endeavour, BR2 will be commercially exploited to maximise profitable income by safely utilising all of its available resources while operating a quality system for radioisotope and NTD silicon production that is certified as being managed to the requirements of EN ISO 9001:2000.

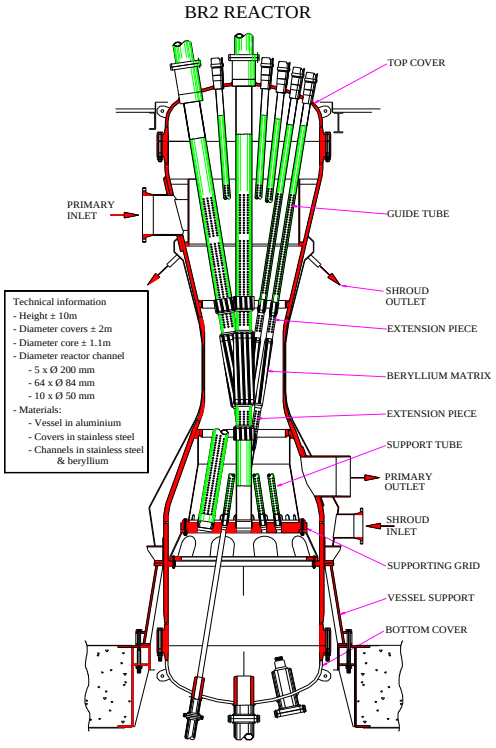

Fig. 1. BR2 reactor.

2. THE BR2 HIGH FLUX REACTOR

The BR2 reactor (see Figure 1) is a 100 MW_{th} high flux Materials Test Reactor that first became operational in 1963 and has since been refurbished in 1995–1997. It is operated by the Belgian Nuclear Research Centre, SCK•CEN, in the framework of programmes related to the development of structural materials and nuclear fuels for fission and fusion reactors. The availability of a high thermal neutron flux up to 10^{15} $cm^{-2}s^{-1}$ allows for the important routine production of radioisotopes characterized by high specific activities for medical and industrial applications. The BR2 reactor is also a major supplier of NTD silicon worldwide. Serious maintenance efforts are currently made by SCK•CEN to secure its safe operation until at least 2023. This would guarantee the continuity of the activities in which the BR2 reactor is involved until its replacement by an accelerator driven system (ADS), MYRRHA, scheduled to be operated by SCK•CEN beginning in 2023.

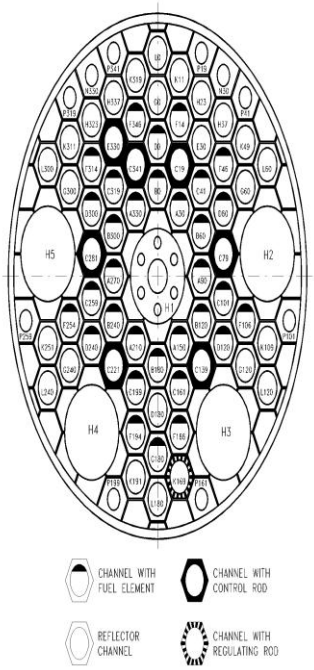

Fig. 2. Typical BR2 core configuration.

Currently, BR2's annual operating regime is based on 5 to 6 irradiation cycles, i.e., 120 to 140 operating days per year. Each standard irradiation cycle consists of 3 or 4 weeks of operation at an operating power between 55 and 70 MW_{th} depending on the irradiation programme. The reactor uses highly enriched uranium (HEU, 93% ^{235}U) fuel; it is moderated by light water and beryllium. The core is composed of beryllium hexagons with central irradiation channels of 200, 84, 50 and 33 mm diameter. The cooling water (40–45°C) is pressurized at 12 bar. The aluminium pressure vessel is located in a pool filled with demineralised water. A typical core configuration is characterized by 32 fuel elements, 7 hafnium control rods and a regulating rod (see Figure 2). It is arranged around the central beryllium plug H1 and can be easily adapted.

3. PRODUCTION OF RADIOISOTOPES

3.1. Introduction

The BR2 reactor plays a key role in the production of radioisotopes worldwide for various applications in nuclear medicine, industry and research [1]. The availability of a peak thermal neutron flux up to 10^{15} $cm^{-2}s^{-1}$ in the seven irradiation channels of the central H1 beryllium plug allows the production of radioisotopes such as ^{192}Ir, ^{188}W, ^{75}Se, ^{89}Sr, ^{169}Yb, and others, which are characterized by their high specific activities. Other irradiation positions are located in peripheral reflector channels (peak thermal neutron fluxes between 10^{14} and 3.5×10^{14} $cm^{-2}s^{-1}$) for the production of ^{99}Mo, ^{131}I, ^{133}Xe, ^{153}Sm, ^{186}Re, ^{90}Y, ^{177}Lu, ^{125}I, ^{169}Er, ^{203}Hg, ^{82}Br, ^{41}Ar, ^{79}Kr, ^{147}Nd, and many more. In case a fast neutron fluxis required, for the production of ^{117m}Sn or ^{67}Cu for example, the targets are loaded into an irradiation basket inside a BR2 fuel

element where the neutron flux above an energy of 0.1 MeV is between 10^{14} and 5×10^{14} $cm^{-2}s^{-1}$, depending on the burnup and the location of the fuel element in the core configuration (see Figure 3). The routine production of radioisotopes is carried out in standardized cold welded aluminium "CSF" capsules which contain an inner graphite or aluminium cylinder and helium gas. If necessary, the target material is loaded into quartz ampoules. 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 (PRF, DG) allow the loading and unloading of the target material intended for shorter irradiation periods during the operation of the reactor.

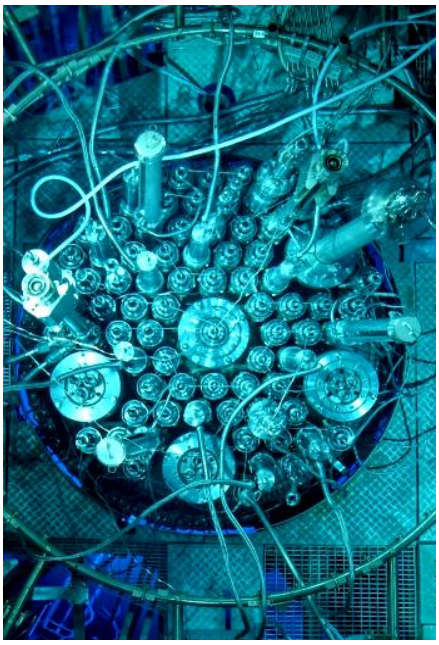

Fig. 3. Top view of the BR2 reactor.

3.2. Production of radioisotopes for nuclear medicine

3.2.1. Production of ^{99}Mo/^{99m}Tc for radiodiagnosis

The international supply of ^{99}Mo relies on a limited number of research reactors and processing facilities. Its production is essential for nuclear medicine as ^{99m}Tc, obtained from ^{99}Mo/^{99m}Tc generators, is used in about 80% of diagnostic nuclear imaging procedures. These applications represent yearly approximately 30 million examinations globally. The short half-life of ^{99}Mo ($T_{1/2}$=66 h) as well as its daughter ^{99m}Tc ($T_{1/2}$=6 h) requires a regular supply of ^{99}Mo/^{99m}Tc generators to hospitals or central radiopharmacies. Currently, there are only five nuclear reactors involved in the production of ^{99}Mo on an industrial scale worldwide: NRU (Canada), HFR (Netherlands), BR2 (Belgium), OSIRIS (France) and SAFARI (South Africa). They irradiate highly enriched uranium targets for the production of about 95% of the available ^{99}Mo issued by four processing facilities: AECL/MDS NORDION (Canada), COVIDIEN (Netherlands), IRE (Belgium) and NTP (South Africa). However, these ageing reactors are subject to unscheduled shutdowns and longer maintenance periods, making the ^{99}Mo supply chain vulnerable and unreliable.

Access to the reactors and processing facilities for the ^{99}Mo supply has been a matter of concern for the nuclear medicine community for more than ten years. To compensate for the expected limited availability of the NRU, HFR and OSIRIS reactors in 2010, SCK•CEN decided in April 2010 to increase BR2's irradiation capacity for ^{99}Mo production by 50% through the installation of additional new equipment and to operate a dedicated cycle to secure this production [2]. BR2's peak irradiation capacity represents currently about 65% of the ^{99}Mo world demand, which is reported to be approximately 12 000 Ci '6 day' calibrated weekly for North America (53%), Europe (23%), Asia (20%) and the rest of the world (4%). BR2's average irradiation capacity represents about 25% of the ^{99}Mo global demand, taking its limited operating regime into account (140 days per year).

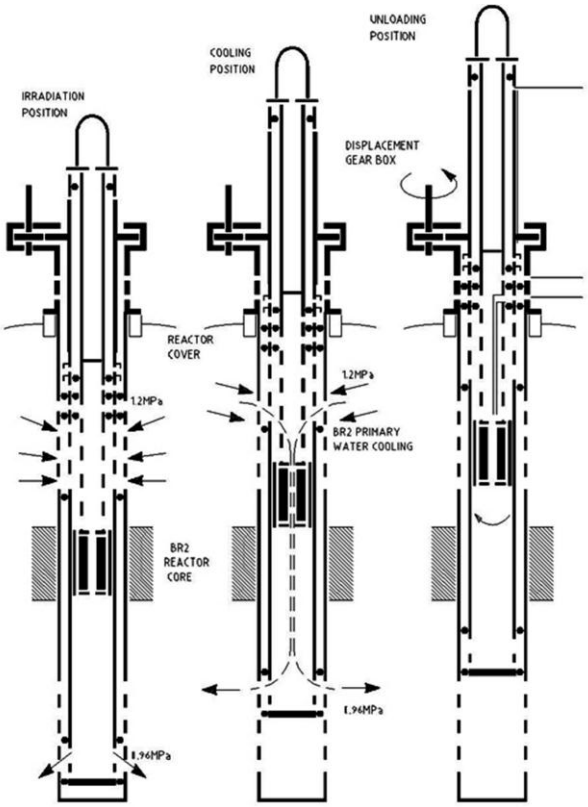

Fig. 4. PRF irradiation device for ^{99}Mo production.

The major isotope produced by the BR2 reactor is ^{99}Mo ($T_{1/2}$=66 h). It is obtained by the irradiation of highly enriched uranium targets (93% ^{235}U) of 4 to 5 g ^{235}U. Six primary reloadable water cooled devices for fissile targets (PRF) irradiation devices (see Figure 4) are routinely loaded in reflector channels, providing a total simultaneous irradiation capacity of 75 targets. These devices are designed to be cooled by primary reactor water and to be loaded and unloaded during reactor operation using an ingenious water lock. A typical irradiation of 150 hours in a thermal neutron flux of 2.5×10^{14} $cm^{-2}s^{-1}$ yields up to 1000 Ci per target at the end of the irradiation (EOI), i.e., 120 Ci '6-day' calibrated per target. After irradiation, the targets are moved from the irradiation position to the cooling position where they are cooled by the reactor primary water for 6 hours. They are then brought to the unloading position for loading into containers at EOI+12 hours, which are shipped to the processing facilities where ^{99}Mo and other fission isotopes such as ^{131}I ($T_{1/2}$=8.02 d) and ^{133}Xe ($T_{1/2}$=5.24 d) are recovered. ^{133}Xe is used for diagnostic imaging of lung functioning.

3.2.2. Production of radioisotopes for radiotherapy

In addition to the existing use of ^{131}I in the treatment of hyperthyroidism and metastatic thyroid cancer, the beta emitters are also used in the treatment of primary cancer by localized irradiation (^{192}Ir) or by the selective administration of radiopharmaceuticals (^{177}Lu, ^{188}Re, ^{90}Y, ^{32}P, ^{166}Ho, etc.). Another application for these beta emitters is for pain palliation (^{186}Re, ^{188}Re, ^{153}Sm, ^{89}Sr, ^{90}Y, ^{177}Lu, ^{169}Er, etc.), providing significant improvement in the quality of life of cancer patients suffering from pain associated with bone metastases as well as for the treatment of joint pain from rheumatoid arthritis. Some radionuclides, encapsulated in a titanium welded capsule and decaying by electron capture with the emission of characteristic X rays have applications in brachytherapy (^{125}I, ^{103}Pd, etc.) for the treatment of prostate cancer by local implantation of the activated seeds.

The BR2 reactor is routinely producing ^{192}Ir for Curietherapy and several radioisotopes for metastatic bone pain palliation such as ^{186}Re ($T_{1/2}$=3.8 d), ^{153}Sm ($T_{1/2}$=46.7 h), ^{90}Y ($T_{1/2}$=64 h) and ^{89}Sr ($T_{1/2}$=50.5 d). The BR2 reactor is also routinely producing the very attractive isotope ^{177}Lu ($T_{1/2}$=6.7 d) for targeted therapy of small tumours such as in the 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; and

— Indirect route: ^{176}Yb (n_{th} , γ) ^{177}Yb → ^{177}Lu; yield = 0.07 Ci/mg of ^{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.

^{188}Re ($T_{1/2}$=16.9 hours) is one of the most attractive radioisotopes for a wide variety of therapeutic applications in nuclear medicine, oncology and cardiology because of its availability from a generator and not least because of its highly advantageous radionuclidic and chemical properties. ^{188}Re decays with emission of an energetic beta particle (maximum energy of 2.12 MeV) and a gamma photon (155 keV, 15%) which permits imaging for treatment targeting and dosimetric purposes. The generator system ^{188}W/^{188}Re has a very long useful shelf life of several months, which makes this technology very cost effective, especially for use in developing regions of the world. Since ^{188}W production by double neutron capture of enriched ^{186}W (see Figure 5) is a function of the square of the thermal neutron flux, the specific activity reached at BR2 (1.0–1.1 Ci/g at EOI) was sufficiently high to permit fabrication of 1 Ci generators suitable for clinical uses as bone pain palliation, restenosis, liver cancer and, arthritis therapy. A nice collaboration for the purpose of developing and producing this radioisotope has therefore been established with the High Flux Isotope Reactor (HFIR) reactor at Oak Ridge National Laboratory, Tennessee, US) [3].

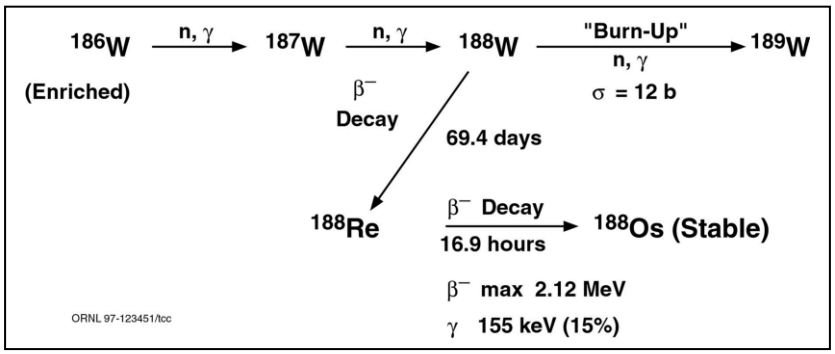

Fig. 5. Production and decay of ^{188}W to ^{188}Re.

^{117m}Sn ($T_{1/2}$=13.6 d) is a promising radionuclide for therapeutic applications as the treatment of metastatic bone pain. It is produced using the neutron inelastic scattering reaction ^{117}Sn (n_{fast} , n' γ) ^{117m}Sn characterized by a threshold behaviour for neutron energies above 100 keV and a small cross-section of about 230 mb. In contrast to beta emitters, ^{117m}Sn emits low energy conversion electrons that deposit their intense energy (127, 129, 152 keV) within a short range (0.22–0.29 mm) and which can destroy tumours with lesser damage to the bone marrow and other healthy tissues. Furthermore, the 159 keV emitted gamma photons allow for imaging of targeting and dosimetric purposes. Test irradiations of 92% enriched ^{117}Sn inside standard BR2 fuel elements demonstrated that the production of ^{117m}Sn in the BR2 high flux reactor in Mol, Belgium, could supply Brookhaven National Laboratory in Upton, New York, US, with sufficiently high specific activity (6–10 Ci/g at EOI) to establish a production strategy together with HFIR, as already demonstrated in the past for the production of ^{188}W [4].

3.3. Production of radioisotopes for industry

Fig. 6. ^{192}Ir production.

The major radioisotope produced in the BR2 reactor for industrial applications is ^{192}Ir ($T_{1/2}$=74 d), mainly for radiography of welds to detect a lack of cohesion and cracks. The successful use of radiography depends on the ability of the radiation source, be it X ray or gamma, to provide sufficient radiation to penetrate the material and produce an image of acceptable contrast and definition on the processed radiographic film within an acceptable and economic timescale. Welds and thick wall inspections of pipelines are typical applications for the use of gamma radiography. The size of the radiation source, low cost and weight of the equipment in comparison to X ray tubes of comparable power are advantages of gamma radiation equipment. Gamma equipment does not need a power supply and it is therefore very useful for mobile inspection and access in space restricted areas. 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, etc.) depending on the application. The target material is irradiated in standardized cold welded aluminium "CSF" capsules (see Figure 6) which contain an inner aluminium cylinder and helium gas. The capsules are mainly irradiated during a whole reactor cycle (3 or 4 weeks) in baskets loaded in the peripheral channels of the central beryllium plug H1, characterized by a thermal neutron flux of up to 10^{15} $cm^{-2}s^{-1}$. The specific activities achieved at EOI range from 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. Due to irradiation capacity restrictions resulting from conflicting situations with other irradiation programmes and operational parameters such as anti-reactivity, extra production capacity has been developed in the H3, H4 and H5 peripheral channels characterized by thermal neutron fluxes up to 3.5×10^{14} $cm^{-2}s^{-1}$. However, the highest specific activities achieved at EOI in these channels are about 750 Ci/g for enriched iridium and 375 Ci/g for natural iridium. The maximum ^{192}Ir production capacity is about 180 kCi EOI per reactor cycle. The large anti-reactivity effect associated to the production of this particular radioisotope has a direct impact on the operational parameters (cycle length, safety margins, etc.) of the reactor and its fuel cycle. Other radioisotopes such as ^{203}Hg, ^{24}Na, ^{82}Br and ^{41}Ar are irradiated on demand.

3.4. Production of radioisotopes for research

The BR2 reactor is producing various radioisotopes for research projects, mainly for universities. For example, ^{67}Cu ($T_{1/2}$=2.58 d), has been produced via the ^{67}Zn (n,p) ^{67}Cu reaction to evaluate its properties as a candidate radiotracer for copper related pharmacokinetic and toxicokinetic research [5]. A target of 250 mg zinc (89.6% enriched in ^{67}Zn) has been irradiated during 21 day cycles inside a fuel element in an effective fission neutron flux of 3.0×10^{14} $cm^{-2}s^{-1}$. The irradiation yielded 12.4 mCi of ^{67}Cu at EOI. Both radiochemical methods and biological influx experiments, using fish, were used to check the properties required for the radiotracer. The study was able to conclude that ^{67}Cu is a reliable radiotracer for copper.

4. PRODUCTION OF NTD SILICON

4.1. Introduction

Neutron transmutation doping (NTD) silicon on an industrial scale (see Figure 7) has been carried out in many of the world's MTRs since the early 70s. The demand for this process has mainly been driven by the ever increasing need for semiconductor applications that require a high degree of dopant homogeneity in order to maximise post irradiation manufacturing yields and to ensure the operational integrity of electronic devices. This is especially important for high power applications such as thyristors and insulated gate bipolar transistors (IGBTs) for use in so-called green technologies such as:

Fig. 7. Silicon ingots.

— High speed electric locomotive trains;
— Wind turbine electricity power generators;
— Hybrid electric vehicles and electric vehicles;

The constant drive to intensify production yields in order to reduce component costs has forced silicon producers to develop crystal manufacturing techniques that are capable of producing diameters that currently exceed 300 mm. This development has seen the application of NTD silicon become increasingly important as a means of achieving the desired degree of dopant homogeneity. However, the normal maximum crystal diameter for this process is currently 8 inches. This has put pressure on NTD silicon producers to respond by finding ingenious ways to accommodate progressively larger diameter crystals in high thermal neutron flux environments within their reactors.

When SCK•CEN entered the NTD silicon market in1992 with its Silicon Doping by Neutron Irradiation Experiment (SIDONIE) 5 inch irradiation device, the demand for 2 and 3 inch NTD silicon production capacity was already being overtaken by a predominant requirement for 4 and 5 inch. In more recent years, the demand has become more focused on production capacity that will accommodate 6 and 8 inch crystals. In order to capitalise on this trend, SCK•CEN commissioned its Pool Side Equipment for Irradiation and Doping of silicon by Neutrons (POSEIDON) device in the autumn of 2008. The combined output from these two devices provides SCK•CEN with an NTD silicon production capability of approximately 30 tonnes per year.

4.2. The principles of neutron transmutation doping silicon

Silicon has three natural isotopes:

— ^{28}Si (92.2%)
— ^{29}Si (4.7%)
— ^{30}Si (3.1%)

During neutron irradiation, ^{30}Si atoms are transmuted by neutron capture to the unstable radioisotope ^{31}Si. With a radioactive half life of 2.6 hours it subsequently decays to the stable isotope ^{31}P by beta particle emission.

The NTD reaction is the following:

$^{30}Si\ (n,\gamma)\ ^{31}Si \rightarrow\ ^{31}P + \beta^-$

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 global 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 [6]:

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

where:

N = number of atoms of ^{30}Si in the initial silicon material;
σ = effective cross-section of neutrons for ^{31}Si generation (b);
$\varnothing_t$ = the neutron fluence (cm^{-2}).

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 becomes:

$$N = 1.544\times10^{21}\ cm^{-3}$$

The effective cross-section of the neutrons has been set at 0.118 b. This value was measured during the neutron transmutation doping development phase at the Harwell Laboratory in the United Kingdom.

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:

$$C = C_D + C_S \tag{2}$$

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:

$$C = 1 / (\rho\ \mu\ \varepsilon)\ [\Omega\cdot cm] \tag{3}$$

where

μ = the displacement mobility of electrons in the crystal lattice which can be set at 1350 V/cm^{2}s^1 for silicon;

ε = electron charge, 1.6×10^{19} C.

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:

$$\varnothing_t = 2.54\times10^{19}\ (1/\rho - 1/\rho_0) \tag{4}$$

where

ρ_0 = the average resistivity measured in the original material.

4.3. Description of the SIDONIE facility

SIDONIE is a single channel light water device that is located in a 200 mm diameter beryllium channel (H2) within BR2's reactor pressure vessel (RPV). It is designed to irradiate 5 inch diameter batches of silicon by continuously rotating and traversing them through the reactor neutron flux at predetermined, computer controlled speeds. This provides an exceptionally uniform exposure to neutrons (see Figure 8) whilst controlling the neutron dose, and thereby produces the desired electronic characteristics within very precise limits. The baskets used to accommodate the silicon during irradiation are manufactured from aluminium and are of an "open" design. Accordingly, 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. This water is highly purified, and it is continuously monitored for contaminants, temperature and coolant flow.

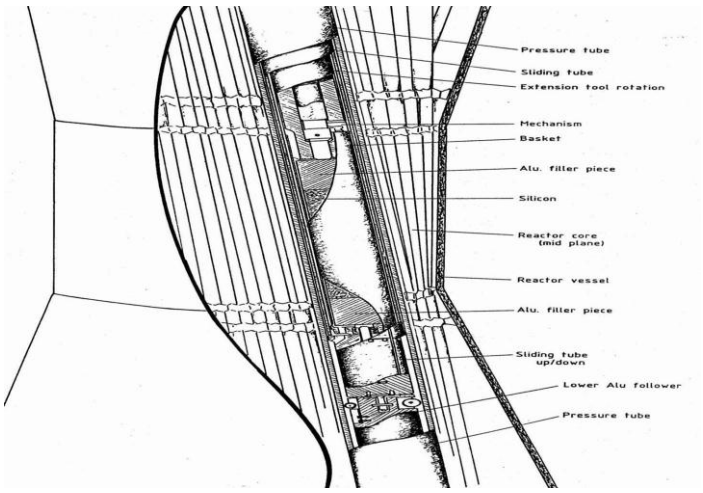

Fig. 8. SIDONIE facility.

The SIDONIE facility is characterized by:

— A perturbed integrated "conventional" thermal neutron flux of approximately 5.5×10^{13} $cm^{-2}s^{-1}$ as measured within the axis of specially prepared silicon crystals; to produce a typical target resistivity of 35 Ω·cm, starting from a resistivity of about 2000 Ω·cm (for n-type), requires a thermal neutron dose of approximately 7.13×10^{17} cm^{-2}; this is achieved by an irradiation time of approximately 3.6 hours when operating at a normal reactor power of 55 $MW_{th;}$
— A 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 800 mm (maximum);
— A silicon core temperature of <200°C during irradiation; and
— An NTD silicon production capacity of approximately 15 tonnes per year based on 140 days (over 6 cycles) of reactor operation in 2010 and an average target resistivity of 35 Ω·cm.

SIDONIE's NTD silicon irradiation performance is characterised by:

— 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%; and
— An NTD silicon target resistivity production range from 5 to 500 Ω·cm.

4.4. Description of the POSEIDON facility

POSEIDON is a multi-channel, graphite moderated device that is located in the BR2 reactor pool on the outside of the RPV (see Figure 9). It has the capability to simultaneously expose 6 batches of 6 and 8 inch diameter silicon to a highly homogenised "conventional" thermal neutron flux in a relatively low (about 26°C) temperature environment.

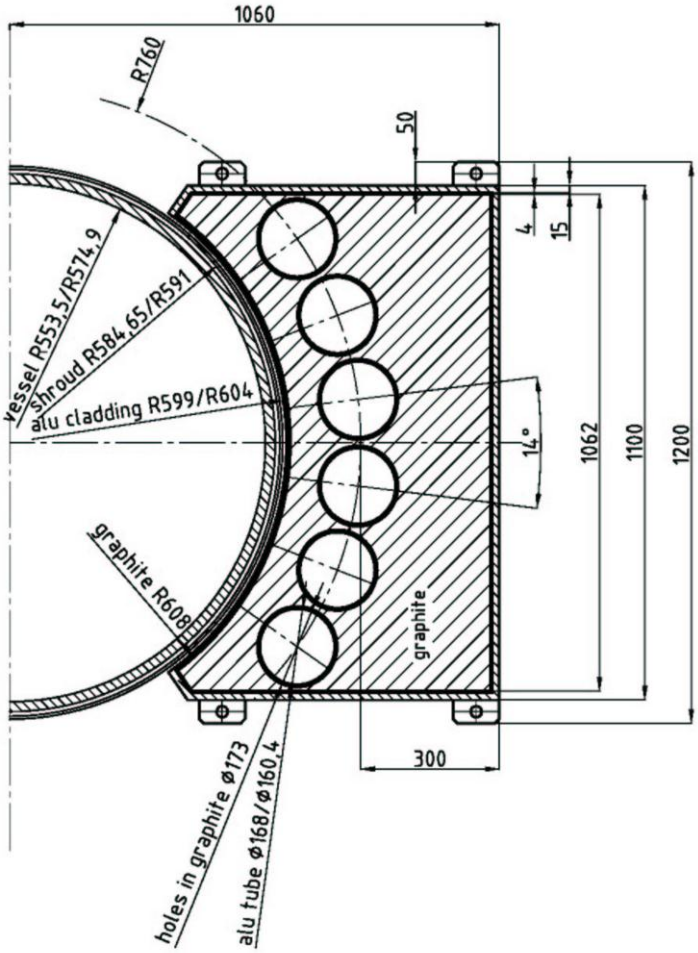

Fig. 9. Cross-section of POSEIDON at reactor mid-plane.

POSEIDON basically consists of a robust aluminium box of all welded construction to provide a sealed containment for high purity graphite. This serves as an economical medium for preserving the "conventional" thermal neutron flux that would otherwise be totally lost from the reactor core through unavoidable leakage into the reactor pool. The external dimensions of the box are approximately 1.4×1×0.75 meters (W×H×L). However, one side of the box has been manufactured to conform to the radial profile of the RPV shroud while its height of 1 metre approximately spans the distance between the top and bottom of the reactor core. The box is penetrated by six vertical irradiation channels (through-holes) that form a concentric array around the curved profile of the box. This geometry enables the box to be brought into very close proximity to the RPV shroud so that each channel is of equal distance from the reactor core. During irradiation, the box is presented to the reactor so that the silicon is exposed to the optimum "conventional" thermal neutron flux. The irradiation is terminated by withdrawing the box a short distance away from the reactor and hence the neutron flux. This also provides the operational access required for charging and discharging the silicon from POSEIDON. POSEIDON's irradiation containers (see Figure 10) are manufactured from aluminium and are designed to accommodate 500 mm long batches of 8 inch diameter silicon consisting of 2 crystals approximately equal in length (250 mm) in a one-on-one arrangement. Using the same 'two-crystal' configuration, batches of 6 inch diameter silicon are located in the same irradiation containers using graphite adaptor sleeves. These reduce the 8 inch bore of the containers to accept 6 inch diameter silicon without unduly compromising the intensity of the "conventional" thermal neutron flux that is available for irradiating the silicon. A uniform neutron exposure is obtained by continuously rotating the silicon throughout its irradiation and by replacing the top crystal with the one from beneath it and the bottom crystal with the one from above it at the midpoint during the irradiation.

Throughout irradiation, the silicon crystals come into direct contact with the reactor pool water which under natural convection serves to keep the surface temperature of the silicon considerably below 100°C.

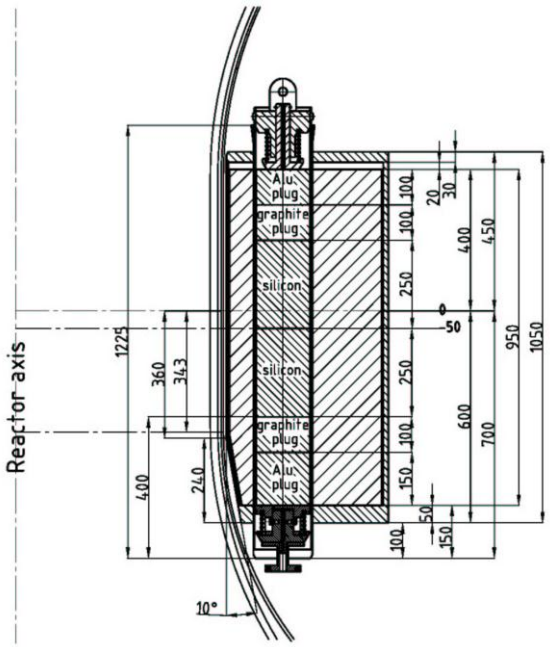

Fig. 10. Axial cross-section of POSEIDON.

The POSEIDON facility is characterized by:

— A perturbed integrated 'conventional thermal neutron flux' of about 5.26× $cm^{-2}s^{-1}$; for a typical target resistivity of 48 Ω·cm, starting from a resistivity of about 2000 Ω·cm (n-type), the required thermal neutron dose and irradiation time at 55 W_{th} are respectively 5.16×10^{17} cm^{-2} and 27 hours;
— A cadmium ratio >50:1;
— Silicon irradiation batch diameters of 6 and 8 inches;
— Silicon crystal lengths of 250 ±5 mm;
— Silicon irradiation batch length 500 mm (maximum);
— A silicon core temperature of<200°C during irradiation; and
— An 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's NTD silicon irradiation performance is characterised by:

— A deviation from target resistivities of typically <+/-5%;
— ARG over 500 mm of <±3% (for n-type silicon);
— RRG for 6 inch diameter of <4%; and
— An NTD silicon resistivity production range from 20 to 500 Ω·cm.

4.5. Post irradiation procedures and customer feedback

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 for post irradiation manufacturing operations before incorporation into many and diverse industrial and domestic products. Customer feedback on resistivity accuracy confirms the quality of BR2's services in the NTD silicon business as illustrated by Figure 11.

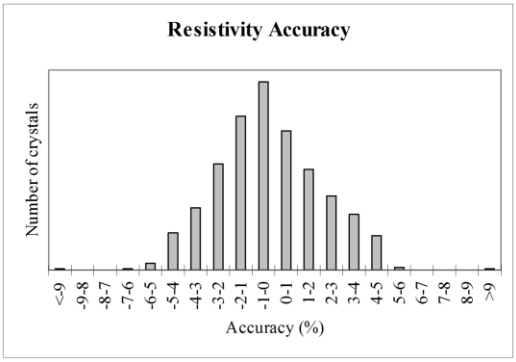

Fig. 11. Results of resistivity accuracy.

5. CONCLUSIONS

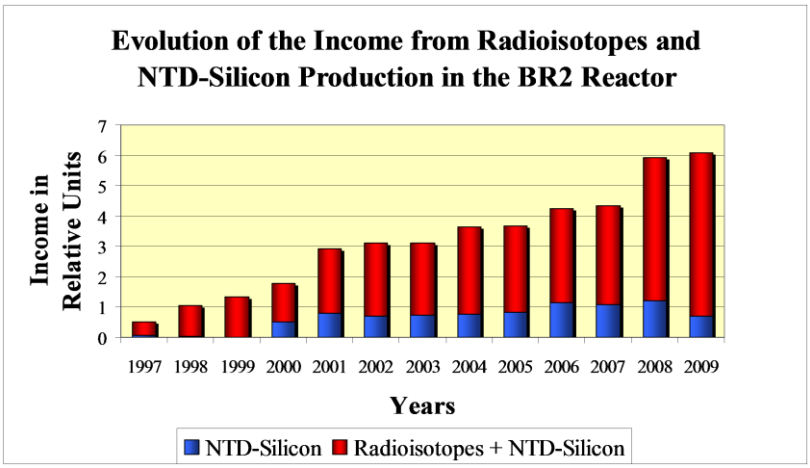

Fig. 12. Evolution of the revenues from commercial activities.

The commercial production of radioisotopes and NTD Silicon has been actively developed since the early 1990s to generate additional revenue. Since the restart of the BR2 reactor after its refurbishment in 1995-1997, the revenue (see Figure 12) 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 1990s, the production of ^{99}Mo was especially seen as a by-product that could bring additional revenue. The real costs (investment, operating, dismantling, etc.) 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 economic reality.

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