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POL GUBEL

REACTOR BR2

Reactor BR2: Reactor Operation

Exploitation

The reactor was operated in 1999 for a total of 112 days at a mean power of 58 MW in order to satisfy the irradiation conditions of the internal SCK•CEN R&D programmes using mainly the CALLISTO PWR loop.

At the request of an important commercial customer, the BR2 reactor entered the third millennium at power and so contributed to an uninterrupted supply of the main radiopharmaceuticals required for medical applications. This was only possible after months of preparation, testing and auditing by the licensing authorities to demonstrate that no Y2K problems could impair the safety of operation.

The availability of the installations reached a very high level of 99.97 % with an interruption of only 0.75 hour during the 112 days of operation. Only two incidents were included in our INRIBUAN reporting system. The first one involved a scram that was initiated by a high pressure in the primary cooling circuit. The cause of this was a spurious signal induced by a perturbation on the external electrical network. This resulted in all main secondary-cooling pumps being automatically stopped. Consequently, all necessary remedial modifications have been carried out on the actuation system. The second one concerned an irradiated fuel element that was accidentally dropped during its transfer from a storage rack. Fortunately, the fuel element was only superficially damaged. In future, the correct coupling between the handling tool and fuel element will always be checked with the help of an underwater camera.

Fuel cycle

In order to optimise the utilisation of the available HEU inventory, we continued to use a "mixed core strategy". This was based on the irradiation of standard 93 % U235 enriched fuel elements together with 72 % U235 enriched fuel elements using uranium recovered from the reprocessing of BR2 spent fuel at UKAEA-Dounreay. The 72 % U235 fuel elements have been routinely irradiated since 1998 – they occupied up to 36 % of the channels loaded with fuel elements until they reached a maximum burn-up of 50 %. The mean consumption of fresh fuel elements (both types) was 5.36 per 1000 MWd. The shutdown of all main fuel cycle activities in Dounreay prevents us from continuing to use our recovered HEU inventory.

Only one batch of 30 fuel elements could be transported to La Hague with the IU04 cask for reprocessing. Other transfers, planned with the new TN-MTR cask were delayed until a full agreement can be obtained for it from the Belgian Licensing Authorities.

Refurbishment

Phase 5 of the refurbishment programme was originally to be completed by the end of 2000. This is now to be continued with only a few projects remaining:

- Automatic regeneration of the Pool Ion Exchangers: all mechanical adaptations are completed. Automatisation of the regeneration process will be installed in 2000.
- Recuperation of effluents from the monitoring system: a new system was designed to collect the effluents from the primary coolant monitors and provide their re-injection into the primary loop. The installation is foreseen in 2000.
- Mitigation of consequences from an earthquake: all additional horizontal restraints for the primary piping have been installed.
  The design principles for the separation of the ventilation pipe-bridge and the protection of the reactor building isolation valves have been identified. The necessary modifications will be implemented in 2000.
- Fire prevention and mitigation
  New ideas to mitigate the consequences of fires in the Reactor Building have been conceptualised. They tend to improve the isolation of the different compartments in the building. Actions foreseen in 2000 concern mainly the power and instrumentation cable penetrations between compartments.

Training

As foreseen in the Safety Analysis Report training sessions (505 man.days in total) were organised to fulfil the minimum requirement of 10 days per year and per operator. These sessions combined technical, theoretical (348 man.days) as well as practical aspects (157 man.days). The programme for the training sessions is scheduled one year in advance; the content of this programme as well as the global summary report after execution is submitted to the Licensing Authorities for evaluation.

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INSARR

An INSARR (INtegrated Safety Assessment of Research Reactors) inspection by a team of the International Atomic Energy Agency was held during the last week of April 1999 and the first week of May on request of the Belgian Authorities. INSARR missions are an IAEA safety service offered, to assist Member States in ensuring and enhancing the safety of operating research reactors. The team was composed of a team leader, who is an IAEA staff member, and three experts from France, Israel and USA respectively. The scope of the mission is discussed in a preparatory meeting between representatives of the IAEA, the regulators and the operating organisation. It was agreed during this meeting that the inspection should be concentrated on the operational safety and recent modifications to the installations. The selected subjects were: licenses and regulatory supervision, organisation, training and qualification of the personnel, operational limits and conditions of the reactor, implementation and follow-up of modifications, operating procedures, maintenance and periodical testing, data management, radiation protection, waste treatment, emergency planning and physical protection.

The findings and conclusions of the mission are written in a report to the Belgian Authorities. The conclusions are summarised in recommendations, suggestions and good practices. A recommendation is an advice on how improvements in operational safety can be made.

Generally it is an indication of shortcomings in satisfying excellence. Two recommendations were identified for BR2. The first concerned the absence of a formal Quality Assurance programme, although the team agreed that most of the operations are covered by QA procedures. The second recommendation stated that the safety report of BR2 is not consistent with the IAEA standard. The cause of this shortcoming is because the actual report is composed of revisions and extensions of older versions. Regarding the suggestions, these are intended to indicate possible superior alternatives to the ongoing expansion of existing programs. Seven suggestions were identified by the team. They deal with the content of the operating licence, organisational aspects, safety committees, operational limits and conditions, experiments and modifications and fire protection. Whilst Good practices are indications of an outstanding performance markedly superior to that observed elsewhere, not just fulfilment of current requirements or expectations. Four good practices were observed about the training programme for the operating personnel, the inclusion of a list of incidents in the safety report, the way of loading the reactor and the use of the new dose limits for personnel.

Quality Assurance

In 1999, we started a project to implement a formal QA programme (ISO9002) centred on all our commercial activities in order to satisfy the requirements and needs of our customers. In a later phase, the operational aspects of the reactor operation will be integrated to comply with the above-mentioned recommendation of the INSARR mission.

Reactor BR2: Utilisation of the CALLISTO loop

The CALLISTO Loop is designed for the in-pile testing of fuel and materials under PWR conditions (e.g. pressure, temperature and water chemistry). The facility comprises three in-pile sections (IPS) connected to out-of-pile equipment consisting primarily of 3 circulating pumps, a heat exchanger, an electrical heater, a pressuriser, feed-bleed circuits and water purification systems. Adequate instrumentation and the use of regulating valves provide the necessary control over its operating parameters.

Irradiation programme

LWR fuels (BACCHANAL)

Although 1999 was a period of reduced activity for the BACCHANAL programme, since 1997 an in-pile section of CALLISTO (IPS 1) was used for increasing the burn-up of nine fuel rods that had been pre-irradiated in BR3. Since the beginning of the programme, the rods have been irradiated in BR2 for a total of eight reactor cycles.

Intermediate non-destructive examinations on the fuel were carried out and post-irradiation testing using the technique of independent gamma-spectrometry confirmed the precision of the linear power on-line measurements.

The BACCHANAL programme will continue in 2000.

LWR pressure vessel materials (CHIVAS)

Two irradiation campaigns for the "Round Robin Exercise on WWER 440 RPV Weld Material Irradiation, Annealing and Re-embrittlement" IAEA R&D programme occurred in 1999. A total of 240 specimens where irradiated in the CHIVAS 7

(Callisto Hot Irradiation of Vessel Alloys Steels) experiment at 270°C and these received a fast neutron fluence (E > 1 MeV) of up to 7.10^{19} n/cm^2.

61 of these specimens underwent a thermal treatment followed by a further irradiation in the CHIVAS 8 experiment to reach a final fast fluence of $1.3.10^{20}$ n/cm^2.

IASCC of LWR structural materials (CORIOLIS & CORONA)

The CALLISTO in-pile section (IPS2) which is specially dedicated to IASCC programmes occupies a region in the BR2 core where the fast neutron flux (E > 1 MeV) reaches values of about 1.10^{14} n.cm^{-2}.s^{-1};

The experimental device for the CORIOLIS programme has remained loaded continuously in IPS 2 since cycle 02/97. This experiment was unloaded at the end of cycle 05/99 after reaching a fluence, which produced 2.4 dpa in the specimen.

During the development of the CORONA project, which aims at on-line crack initiation detection on pressurised tube specimens, the installation was modified to allow the penetration of instrumentation wires through the head of the IPS.

Fusion reactor materials and components

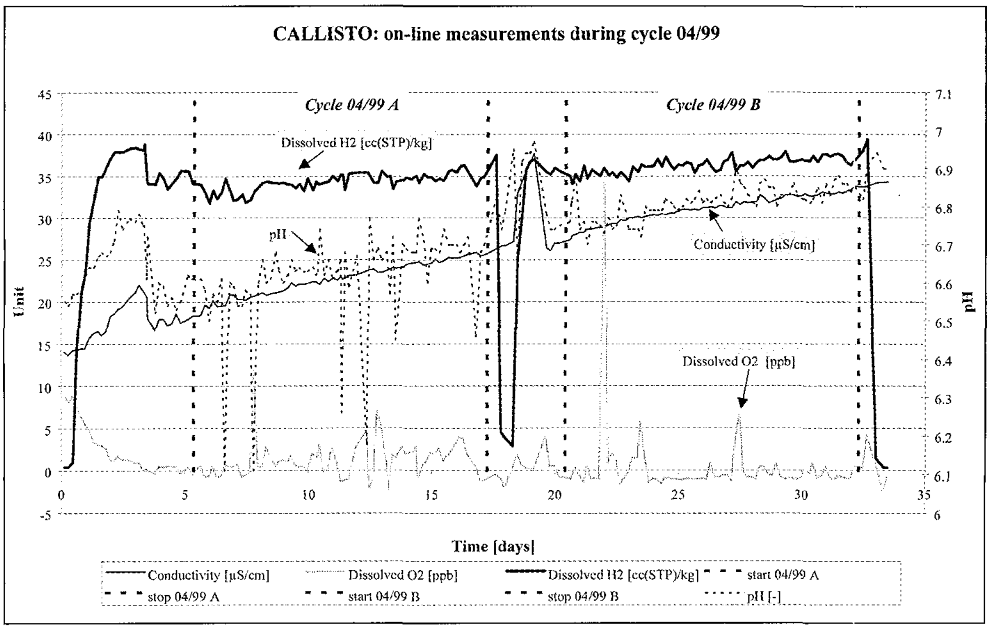
The ITER shield modules use Inconel 718 bolts. Whilst there are some data on the effects of irradiation on the mechanical properties of Inconel 718, little is known about its dimensional stability due to irradiation creep effects. Therefore, in the framework of "EU Task No. V62", we have irradiated an experiment called FINC (Fusion INConel), which was loaded in the CALLISTO IPS 2. This was aimed at obtaining accurate measurements of creep deformation from conventional sample tubes that were irradiated at a working pressure of up to 1000 bars. Only one pressurised tube out of twenty-one failed 4 days before the end of the irradiation when the specimen had 0.5 dpa.

Irradiation of Martensitic Steel

The IRMAS (IRradiation MArtensitic Steel) experiment consists of charging the positions of the CALLISTO basket which remain free, after loading the specimens for the FINC experiment, with impact (Charpy V- notch) and tensile specimens of a 12% Chromium (martensitic) steel, with denomination 56 B.I., and with tensile specimens of chromium alloys called DUCROPUR and DUCROLLOY. This type of steel is foreseen as a very strong candidate for use in ADS (i.e. for the construction of MYRRHA) and fusion reactor systems.

Loop Operation behaviour

In 1999, the water chemistry on-line unit was completely refurbished. This system allows the pH, the conductivity and the concentration of dissolved hydrogen and oxygen in the loop to be continuously measured, even in the case of a fuel rod failure. The figure below shows some typical results of measurements taken in reactor cycle 04/99.



In the year 2000, the sampling system will be improved so that very highly activated water samples can be taken and diluted to enable them to be chemically analysed in the hot labs.

The inspection of several components and in particular checking and re-calibration of the numerous instrumentation sensors were carried out according to the maintenance plan. At the beginning of the year, one main pump became seriously damaged. A component had to be decontaminated and repaired. As a consequence in 1999 the loop was operated with two circulating pumps instead of three.

Preparation of the loop decontamination process is in progress.

Perspectives for the CALLISTO loop

CORONA will start irradiation in cycle 01/2000 for at least 4 cycles.

A new irradiation on fusion materials (IRFUMA for IRradiation of FUsion MAterial) is now in preparation and it will be loaded into CALLISTO in year 2000.

The THOMOX project is concerned with an instrumented irradiation under PWR representative conditions for a series of advanced nuclear fuels (all ceramic oxides, and include $(Th,Pu)O_2$, $(U,Pu)O_2$ and UO_2). The irradiation will be performed in one in-pile section of CALLISTO during a period of 4 years, starting in 2001.

In the framework of the 5th European R&D Programme, we will prepare an experimental device (to be loaded in CALLISTO) for the LIRES project ("Development of Light Water Reactor Reference Electrodes"); irradiation foreseen in 2003.

Reactor BR2: Development of Irradiation Technology

Objective

In view of current and emerging needs for irradiation testing of nuclear fuels, materials and components, it is an important objective for the BR2 division to prepare itself proactively by developing the required irradiation technology in terms of experimental facilities and in-pile instrumentation. Also it is important to maintain its existing experimental infrastructure in a reliable and safe operational condition.

Programme

Our programme focuses on three main activities:

- Development of new concepts of irradiation devices for emerging needs. Most of the work in 1999 concerned the following:
  - COSAC device: pressurised water capsule for testing fuel rods up to and beyond clad failure.
  - Fusion reactor breeder blanket: design of experiments to test the performance of double-walled tubes and tritium-permeation barriers for the WCLL blanket modules.
  - MISTRAL device: multipurpose, reusable rig for materials irradiation under high fast neutron flux.
  - MTR fuel testing: design of dedicated irradiation rig for the qualification of advanced MTR fuel plates.
  - SMIRNOF: design of dedicated rig for the testing of optical fibres under combined neutron and gamma fluxes.
  - RIED: design of dedicated rig for neutron testing of ceramic materials for the fusion reactor.
  - Preliminary studies for the irradiation of several materials in response to requests to offer (e.g. irradiation of graphite for gas cooled reactors).
- Development of in-pile instrumentation: The ongoing work concerns mainly R&D to adapt or to improve the behaviour of on-line neutron and gamma sensors for use inside BR2 irradiation devices and to allow their correct interpretation through modelling. Other types of in-pile sensors will also be researched.
- Refurbishment of available irradiation facilities: Most of the work done in 1999 relates to the CALLISTO loop (ref. to the section: Utilisation of the CALLISTO loop).

Achievements

Specific achievements in 1999 based on the programme list of reported activities are highlighted.

Fusion reactor breeding blanket modules

Water Cooled Lithium-Lead (WCLL) is one of the candidate concepts for the tritium-generating blanket of future fusion reactors. In this concept, tritium is generated in a 17Li-Pb liquid metal bed, cooled by pressurised water circulating in Double-Wall Tubes (DWT). The permeation of tritium to water is limited by Tritium Permeation Barriers (TPB), which are a coating applied at the outer surface of the DWT. The DWT and the TPB constitute critical elements of the WCLL concept. Therefore, two experiments were proposed to test the TPB performance and the DTW behaviour in conditions as realistic as possible. The experiment aimed at confirming the general behaviour of the components and in particular the tritium permeation rate in an environment as close as possible to the future operation conditions.

A proposal was submitted for the experiments. From discussions with the task management, it became apparent that the budgets available would not allow any irradiation experiment linked directly to the WCLL blanket development to be performed in the near future. Hence, we proposed to re-orient the project towards a multipurpose device for the irradiation of fusion reactor materials (see the section: MISTRAL device).

MISTRAL device

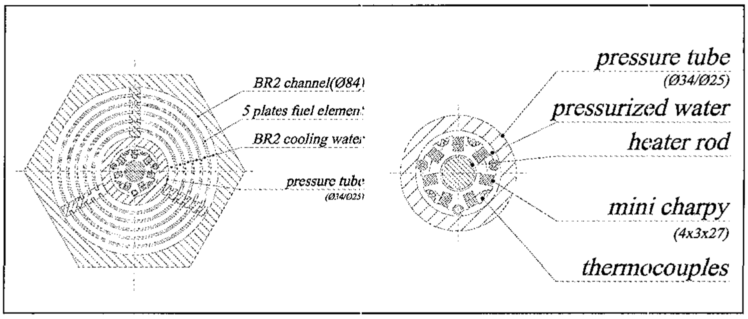
MISTRAL stands for Multipurpose Irradiation System for Testing of Reactor ALloys.

Its objective is to provide BR2 with a reusable device for the irradiation of metallic specimens (such as tensile and Charpy specimens) under fast neutron flux in extended temperature range (200 – 350 °C) with an accuracy of +/-5°C.

In 1999, we studied and compared all the different concepts available or already used at BR2 to irradiate reactor alloys with the highest fast neutron dose and the fastest dpa accumulation rate. The irradiation device has to meet the following minimum requirements:

- It has to be reusable as far as possible for subsequent loading of samples.
- It has to be installed in the central hole of a BR2 5-plates fuel element.
- It has to be easy to manipulate, especially in the hot cells.
- It has to fit the temperature range with the required accuracy.
- It has to be efficiently instrumented to monitor the irradiation parameters on-line.

After a detailed analysis of the possible solutions, a single wall pressurised water capsule was found to be the best compromise between the dpa accumulation rate and the simplicity of the device. The in-pile section will be composed of one thick pressure tube containing a basket that can contain up to 127 tensile or



mini-Charpy (or 14 Charpy) specimens, 5 dosimeters and 20 thermocouples. A heating element is inserted in the basket centre. During the irradiation, the heating elements control the temperature.

In 2000, we will finalise the design of the device and start to manufacture two rigs for operation at 200 °C. Their first utilisation concerns the SPIRE project, with the aim to start irradiation in 2001 of structural materials for the ADS development, namely 18 tensile and 144 mini-Charpy specimens to reach 3 to 6 dpa.

MTR fuel qualification

New fuel designs for Material Testing Reactors require to be qualified under representative conditions, that is geometry, neutron spectrum and flux, heat flux and thermohydraulic conditions. We have designed a dedicated device for full-size fuel plates irradiation to derive the maximum benefit from BR2's capacities. This design will be the basis for constructing the rig and loading it into the reactor for qualification testing.

The fuel plates can be easily extracted from the rig during a shutdown to undergo non-destructive examinations. An important test is the measurement of the thickness changes along the fuel plate. For this purpose a facility in the reactor water pool has been draught to measure the fuel swelling with an accuracy of 5 μm using inductive probes. SCK•CEN can also perform the full range of non-destructive and destructive PIE, including γ-scanning, wet sipping, surface examination, etc.

In-pile instrumentation of nuclear parameters

The objectives of this project are multifold:

- to increase the scientific knowledge of the studied phenomena occurring in the detector and its cable,
- to improve the quality of interpretation of the data,
- to improve the piloting of experimental devices during the irradiation,
- to possibly reveal and understand unsuspected phenomena occurring during the irradiation.

We follow a scientific approach, namely the modelling of the detector behaviour, the selection of the most suitable sensor for the specific application, the testing of the measurement devices in the BR2 environment and the assessment of the whole instrumentation line.

In 1999, we manufactured the experimental device (called DOLMEN for Device for On-Line MEasurement of the Neutron flux). This instrument contains self-powered neutron detectors (SPND), activation dosimeters and gamma thermometers that can be moved vertically in any BR2 channel.

As a preparation we successfully irradiated a Rhodium-SPND and two specifically designed g-thermometers in various BR2 reactor channels. Promising results gave us valuable information that can be used to optimise the DOLMEN experiment.

In parallel, we theoretically studied the sensitivities of each type of SPND versus the neutron and the gamma spectra. The home made computer model SEDEIRA (SElf-powered DEtector of Ionising RAdiation) showed clearly the importance of the insulator in the SPND and the role played by the neutron spectrum on the detector selectivity. The development of a new model, based on the Monte-Carlo technique, has begun with the aim of evaluating the signals from in-pile monitoring devices in the BR2 reactor and parasitic effects of neutron and gamma fluxes in the instrumentation chain.

In 2000, we will irradiate the DOLMEN device in the BR2 reactor in addition to the development of the new Monte-Carlo model. The fourfold purpose of this irradiation is: to elaborate an algorithm leading to the actual neutron flux using the measured electric signal, to identify the sensitivity to each parameter (neutron spectrum, gamma spectrum), to qualify a calibration method and to assess the best suitable SPND for a specific application.

In parallel, another irradiation campaign is planned to test and to qualify subminiaturised fission chambers in collaboration with CEA (DER/SSAE/LSMN).

Based on the scientific needs of other projects (e.g. "Advanced Fuel R & D and Modelling", "Fuel Behaviour", "Pressure Vessel Steel Projects", "Corrosion",...), we will continue to improve and innovate the in-pile instrumentation.

Reactor BR2: R&D programme

Objective

This programme started several years ago and is directed to the improvement of the BR2 utilisation: refined determination of the irradiation conditions, theoretical support for the development of new irradiation devices, improvement of the in-core instrumentation and data acquisition systems

Achievements

- A coupled neutronics/hydraulics/heat-conduction model of the BR2 reactor core has been under development for about 2.5 years. The neutron transport phenomenon has been implemented as a steady state and time dependent nodal diffusion. As a result a hexagonal 3D nodal diffusion core code, called NH3D, has been rendered operational this year.

  The non-linear heat conduction equation inside fuel elements has been solved with a time dependent finite element method. To allow coupling between functional modules and to simulate subcooled regimes, a simple single-phase hydraulics has been introduced, while the two-phase hydraulics is under development. Multiple tests, general benchmark cases as well as calculation/experiment comparisons demonstrated a good accuracy for both neutronic and thermal hydraulic models, numerical reliability and full code portability. A refinement methodology has been developed and tested for better neutronic representation in hexagonal geometry.

  Much effort is still needed to complete the development – extended cross section library with kinetic data and two-phase flow representation.

  The establishment of macroscopic cross sections sets (MCS) has been started as part of a post-doctorate work. Some research for optimization of the procedure (assembly representation, collapsing method, number of meshes) was performed. Two sets of MCS have been prepared with MULCOS and 5 sets have been prepared with SCALE.

The latter MCS have been used for BOC calculations with NH3D.

Much work still lies ahead: introduction of burn-up, axial distributions, 2D representation of the fuel assemblies, organization of the MCS in readily usable formats.

- The safety studies with RELAP5-mod.3 have been temporarily stopped due to the departure of the responsible scientist.
- The BR2 integrated data acquisition system for survey and experiments (BIDASSE) has been further upgraded. All 384 digital channels of the CALLISTO loop have been integrated. Further analogue channels will be soon implemented for the future use by experiments.
- The automatic reactor control system (both flux and power feedback) has been fully integrated in the new control desk according to the recommendations of the ergonomic assessment of the control rooms.

Reactor BR2: Commercial productions

The main commercial activities carried out in the BR2 reactor are the productions of radioisotopes and NTD-Silicon.

Production of radioisotopes

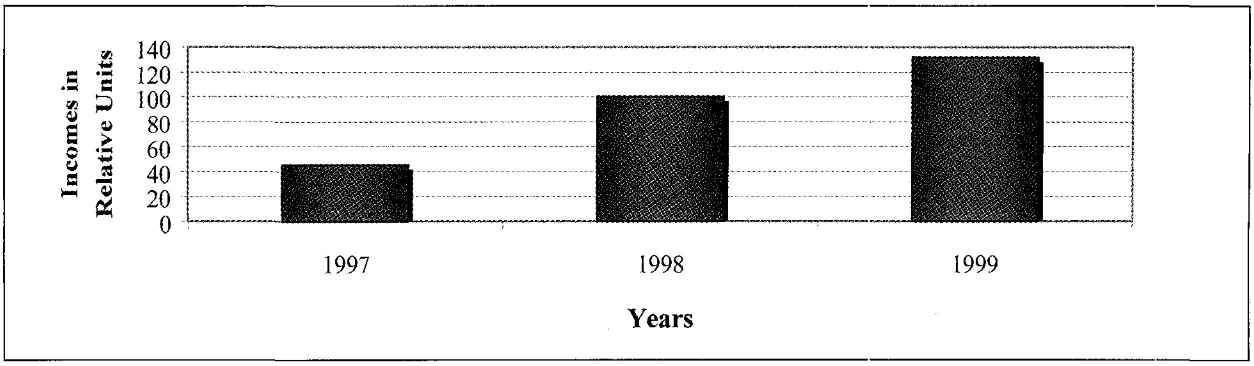
The radioisotopes are produced for various applications in the nuclear medicine (diagnostic, therapy, palliation of metastatic bone pain), industry (radiography of welds, ...), agriculture (radiotracers, ...) and basic research. Due to the availability of high neutron fluxes (thermal neutron flux up to 10^{15} n/cm^2.s), the BR2 reactor is considered as a major facility through its contribution for a continuous supply of products such ^{99}Mo (^{99m}Tc), ^{131}I, ^{133}Xe, ^{192}Ir, ^{186}Re, ^{153}Sm, ^{90}Y, ^{32}P, ^{188}W (^{188}Re), ^{203}Hg, ^{89}Sr, ^{60}Co, ^{169}Yb, ...

Since the restart of the BR2 reactor in 1997, the incomes from the productions of radioisotopes increased considerably as shown – in relative units - in the figure below.

In particular, the production of ^{99}Mo ($T_{1/2}$=66 h) - the major isotope produced in BR2 for the manufacture of ^{99}Mo/^{99m}Tc ($T_{1/2}$=6 h) generators - increased by 40% in 1999 when compared to 1998. This increase was mainly due to an additional PRF irradiation device that became operational in 1999. Four irradiation devices are now routinely loaded in the reflector channels and these provide a total irradiation capacity of 24 high enriched ^{235}U targets for each of 3 irradiations per cycle, i.e. 24 targets X 3 irradiations = 72 targets per reactor cycle. The loading of an additional PRF device - foreseen in 2000 – will enhance the position of BR2 in the European market by increasing the irradiation capacity up to 108 targets per reactor cycle.

A considerable effort has been made to take advantage of the high thermal neutron fluxes available in the central beryllium plug (up to 10^{15} n/cm^2.s). Test irradiations of high enriched ^{186}W targets have already been performed in 1998 with encouraging results for the production of ^{188}W ($T_{1/2}$=69 d). European EUREKA project started in 1999, in which the BR2 reactor is actively involved; the ^{188}W activity produced will be used for the manufacture of ^{188}W/^{188}Re generators. The use of liquid-filled balloons with ^{188}Re ($T_{1/2}$=16.9 h) is considered as an

Evolution of the Income from the Radioisotope Production in BR2.



attractive new therapeutic candidate in cardiology for uniform coronary vessel wall irradiation in order to inhibit the restenosis after percutaneous transluminal coronary angioplasty (PCTA).

In the same way, test irradiations of high enriched iridium targets have been irradiated in the central beryllium plug for the production of ^{192}Ir ($T_{1/2}$=74 d) – used for curietherapy -characterized by specific activities of up to 1500 Ci/g at the end of the irradiation. This product will provide BR2 with more flexibility to satisfy the demand of the customers during its shutdown periods.

Production of NTD-Silicon

BR2 is ideally suited to the volume production of irradiated silicon for the semiconductor industry. This is carried out in a dedicated facility called SIDONIE (SIlicon DOping by Neutron Irradiation Experiment). SIDONIE is located within the beryllium reflector and is designed to continuously rotate and traverse the silicon through the neutron flux. The speed at which the silicon is traversed through the reactor is computer controlled to ensure that the correct neutron dose is received. The effect of continuously rotating and traversing the silicon produces exceptional dopant homogeneity. SIDONIE can accommodate batches of silicon measuring 3-inch, 4-inch and 5-inches diameter by up to 900 mm in length. For n-type silicon, the average axial and radial resistivity variation can be controlled within about 3% whilst the resistivities produced are normally within +/- 5 % of the specified (target) value.

During recent years, semiconductor device manufactures have opted to use newly developed 'premium quality' chemically doped silicon as cheaper alternative to NTD material. This was primarily responsible for causing a significant downturn in world demand resulting in very low production levels in BR2 since 1997. Consequently NTD prices have been forced down and this is partly responsible for its market recovery, as it has now become a cheaper option to premium chemically doped silicon for some applications of which the most notable are transistors as used in the potentially enormous market for domestic 'flat-screen' televisions.

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