Hamid Aït Abderrahim

Reactor Physics

Background & Objectives

The Reactor Physics & MYRRHA Department has over the years developed an expertise in various reactor physics fields, such as neutron and gamma calculations, reactor dosimetry, reactor operation and control, reactor code benchmarking and reactor safety calculations. This expertise is applied within the Department's own research projects in the VENUS critical facility (presently for the burn-up credit programme), in the BR1 reactor (mainly for neutron detector calibration, neutron dosimetry calibration and neutron activation analysis) and in the MYRRHA project, aiming at designing a prototype ADS (Accelerator Driven System) for R&D applications (reported in a separate chapter). This expertise is also used in programmes external to the department such as the pressure vessel steel programme, the BR2 materials testing reactor dosimetry and the preparation and interpretation of irradiation experiments in BR2 by means of neutron and gamma calculations. The activities of FLINS, Fuzzy Logic and Intelligent Technologies in Nuclear Science, carried out within the department, also cover several domains outside the department.

Programme

The Reactor Physics Programme aims at maintaining, developing, improving and exploiting the experimental and theoretical reactor physics expertise of the Department. The main topics in 2001 were:

- REBUS, a burnup credit experimental programme in the VENUS critical facility;
- modification of the VENUS critical facility in order to load fuel pins of 1-m active length instead of 0.5-m active length and to load irradiated fuel;
- services in the BR1 reactor;
- reactor dosimetry services for internal and external clients;
- neutron and gamma calculations in support of the operation of, and the irradiation in, various reactors (e.g. BR2) as well as support of R&D programmes;
- reactor safety studies;
- fuzzy logic applied to nuclear safeguards.

Achievements and Perspectives

The BR1 reactor services

BR1, Belgian Reactor 1, is a research reactor of the "natural uranium-graphite-air" type. SCK•CEN uses the reactor mainly as a neutron reference source for reactor physics experiments, neutron activation analysis and calibration of nuclear detectors and instruments. During the year 2001, BR1 has been operated during 150 days for a total of 550 hours. We performed about 160 irradiations: most of them were short irradiations of a few hours for neutron activation analysis, but also experimental campaigns of several weeks have been performed. The specific topics covered in 2001 for the BR1 reactor services programme were:

Reactor Safety

The re-evaluation of the BR1 reactor has been completed successfully.

Irradiation Services for R&D Programs

In the framework of the MUSE programme an extensive calibration programme of miniature fission chambers has been performed in collaboration with CEA-Cadarache. About 70 miniature fission chambers with various fissile deposits (^{237}Np, ^{235}U, ^{238}U, ^{239}Pu, ^{241}Am, ^{243}Am) have been calibrated using the BR1 large cavity for thermal neutrons and the MARK III irradiation device for ^{235}U fission spectrum calibrations.

A collaboration with Delta Services Industriels (DSI) has been initiated for the qualification of neutron activation techniques of motor oil and additives. DSI has developed several techniques for very sensitive on-line measurements of wear & corrosion mainly for combustion engines. These techniques are based on the measurements of the radioactivity of motor parts that have been activated by proton or neutron irradiation. Their latest development involves the neutron activation of lubricants and specific additives. At this moment, the preliminary feasibility study and a first series of irradiations have been performed to quantify the amount of produced activity and to identify possible additives to be considered for further investigation.

Education & Training

As every year, BR1 welcomed industrial nuclear engineering students for training on reactor physics

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Jozef Verrees,
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Marcel Huysmans,
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Jozef Oeyen,
Leopold Truyens,
Steffi Van Genechten,
Francis Van Gestel,
Ivo Verwimp

and kinetics behaviour. In the framework of the continuous training of the operators of the BR2 reactor, a one-week course on nuclear and reactor physics has been organised, later extended to all SCK•CEN members. In collaboration with SCALDIS, the education & training division of the operators of the nuclear power plants in Doel, a course on reactor kinetics has been worked out and given to the operators of the units Doel 3 and Doel 4. Currently we are negotiating with SCALDIS to extend this course to other aspects of reactor physics and to Doel 1 and 2.

REBUS: A Burnup Credit Experimental Programme

General description of the REBUS programme

Safety criticality calculations for the storage, transport, reprocessing or final disposal of irradiated fuel often require the assumption that the fuel is considered as fresh. This assumption is very conservative and in most cases not necessary. It leads e.g. to larger dimensions of storage ponds and more transports than necessary for safety reasons. Taking into account the decrease in reactivity due to the consumption of fuel and the presence of neutron-absorbing fission products (the so-called burnup credit) results in less storage and transport costs and in some cases, in higher safety.

We have initiated together with BELGONUCLEAIRE an international programme called Rebus (reactivity tests for a direct evaluation of the Burnup credit on Selected irradiated LWR fuel bundles) for the investigation of the burnup credit. The programme aims at establishing a neutronic benchmark for reactor physics codes that calculate the burnup credit. The REBUS programme is sponsored by EdF from France, VGB, representing German nuclear utilities and NUPEC, representing the Japanese industry. It is executed in the VENUS critical facility, the hot-cell laboratory and the radiochemistry department.

In comparison to last year, the scope of the experimental programme has been adapted to fulfil better the needs of the participants. The new scope includes the following configurations:

- reference test bundle;
- fresh commercial PWR UO_2 fuel;
- irradiated commercial PWR UO_2 fuel (50 GWd/tM);
- fresh PWR MOX fuel;
- Irradiated PWR MOX fuel (20 GWd/tM).

We can investigate other fuel types in future extensions of the programme, like BWR fuel and high burnup MOX fuel.

Measured quantities in each configuration are the critical height, the reactivity effect of the water level, the fission rate distribution and/or the neutron flux distribution. We will also measure the accumulated burnup of all rods non-destructively by gamma-spectrometry and analyse some rods destructively with respect to accumulated burnup, actinides content and TOP-19 fission products (i.e. those non-gaseous fission products that have most implications on the reactivity). Preliminary calculations showed that the expected reactivity effects are in the order of 1 500 to 2 000 pcm, which is sufficiently high for core physics code validation.

In 2001 we have finished the adaptation of the VENUS reactor internals as described in the next sections.

Description of the VENUS critical facility

The VENUS critical facility is a water-moderated zero-power reactor. It consists of an open (non- pressurised) stainless-steel cylindrical vessel including a set of grids which maintain fuel rods in a vertical position.

After a fuel configuration has been loaded manually rod by rod, criticality is reached by raising the water level within the vessel. Reactivity control is obtained by controlling the water level in the vessel. With the help of the pumps the water level can be controlled in a rough way (about 0.5 mm). Fine-tuning is done by the so-called water level control rods (WLCR), which are thick aluminium bars. By regulating their insertion into the water, the water level can be controlled in principle in steps of 0.0001 mm. The water level can be determined with an uncertainty of 0.2 mm.

The adaptation of the VENUS facility to fuel pins with an active length of 100 cm

During the almost forty years of its operation, VENUS has dealt with the manual loading of unirradiated fuel rods with an active length of 50 cm. In the framework of the REBUS-project fuel rods with an active length of 1 m have to be inserted into the reactor and also for the first time world-wide an irradiated fuel assembly with a burnup ranging from 20 to 50 GWd/tM will be loaded into a critical facility.

Therefore in a first step, a series of modifications were carried out to adapt the VENUS reactor for fuel rods with an active length of 1 m. As a consequence the following actions were undertaken:

- adaptation of internal structure parts of VENUS:
  - lowering of the intermediate reactor grid which is used for guiding the fresh fuel during loading;
  - lowering of the lower reactor grid which is used to support the fuel rods;
  - insertion of special insert-grids for the positioning of the REBUS bundle containing the irradiated fuel;
  - shortening of the safety table which serves to absorb the kinetic energy in case of failure of the reactor grids;
- shortening of the partial overflow and lowering of the "contact relais" "water level at fuel bottom";
- lowering of the ionisation chambers and BF_3-counters.

Also all the existing UO_2 fuel with an active length of 50 cm had to be lengthened to obtain fuel rods with an active length of 100 cm. Therefore we developed a specific installation and procedure. In two-coupled isotope boxes installed in a lab next to the VENUS reactor hall, the 50-cm fuel rods were dismantled and the individual 1-cm UO_2-oxide pellets were taken out. By dismantling two 50-cm fuel rods, one obtains hundred 1-cm UO_2-pellets that are then inserted into a new Zircaloy cladding with a welded end plug. Finally, after sealing the claddings with top end plugs, the fuel rods are checked for contamination and then released. In 2001, all the 1 200 50-cm UO_2-fuel rods with an enrichment of 3.3% and about half of the 1 800 50-cm UO_2-fuel rods with an enrichment of 4.0% were lengthened.

The adaptation of the VENUS facility to the loading of irradiated fuel pins

The loading of irradiated fuel into a critical facility, which will be a première in the world, has imposed several additional modifications to the VENUS installation. First of all, in order to be able to insert the shielding container which will contain the REBUS container with the irradiated REBUS fuel, the VENUS building has been refurbished: a new floor has been installed covered by an epoxy-layer to facilitate decontamination after a possible contamination resulting from the presence of irradiated fuel. The existing gantry was replaced by a new one to handle the REBUS container. In addition, due to the loading of the container above the reactor core, structure materials and attached electrical circuits had to be removed. A complete refurbishment and rationalisation of the electrical circuit in the reactor room was conducted. Also the WLCR system which was hung up on the supporting structure above the reactor had to be removed and replaced by a completely new system for the operation of control rods.

After the design and construction of the shielding container in spring 2002, dummy tests will be performed and the first irradiated fuel bundle can be loaded in the fall of 2002.

Reactor dosimetry services and research programmes

The reactor dosimetry group provides services for internal and external clients. These services comprise the determination of neutron fluxes or fluences by means of the irradiation and subsequent measurement of activation foils. The determination of the incident number of neutrons is required in most irradiation experiments executed in an experimental reactor like BR2.

BR2 pressure vessel surveillance

During the refurbishment of BR2, the ageing of the BR2 pressure vessel was investigated thoroughly and it was concluded that this could not cause any safety problem. For a follow-up of the embrittlement of the BR2 pressure vessel SCK•CEN decided to install several monitor capsules in a high flux position in order to irradiate mechanical strength test samples and to measure the integrated neutron fluence at this location. Some of these samples were unloaded in 2001 and the accumulated neutron fluence was measured by the section reactor dosimetry.

RETROSPEC

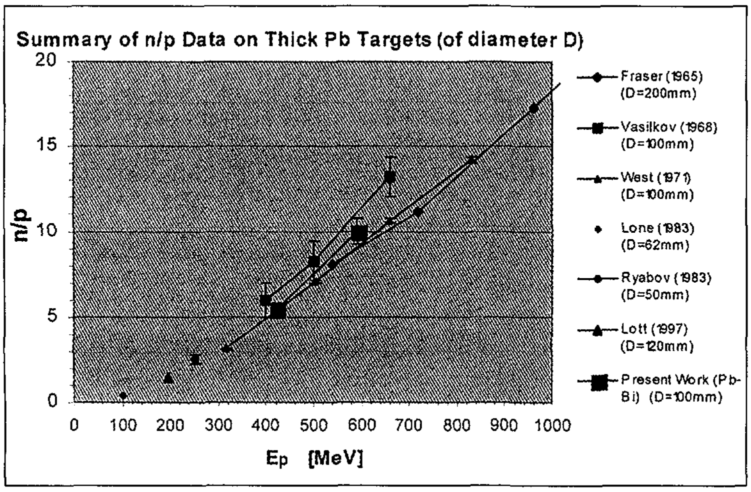
SCK•CEN participates in the 5th Framework programme RETROSPEC. The partners in this programme are NRG, the Netherlands and VTT, Finland. This programme aims at developing a measurement procedure that is able to estimate the neutron fluence in the reactor pressure vessel without surveillance capsules, so-called retrospective dosimetry. It is based on the activation of ^{93}Nb, present as a contamination in the pressure vessel or as an additive in the pressure vessel cladding. In some older types of VVERs (Russian PWRs) no surveillance capsules were foreseen to monitor the neutron fluence. In other types these surveillance capsules are placed at positions that are not representative for the hot spots of the reactor pressure vessel. Retrospective dosimetry will reduce the uncertainty from which the present neutron fluence estimates suffer and will therefore contribute to a safer operation of these reactor types.

In the framework of this programme SCK•CEN has investigated several ways to separate Nb from samples of a VVER pressure vessel cladding.

TACIS 96/02 programme

The TACIS 96/02 programme is funded by the European Commission and aims at reducing the measurement uncertainties inherent to VVER pressure vessel surveillance capsule location (see above: RETROSPEC). The section reactor dosimetry participated in the TACIS 96/02 programme by executing the following tasks:

- delivery of temperature monitors that were placed in a special dosimetry capsule in order to verify that no large temperature gradients existed and to verify that the temperature was in the range required for proper testing of the mechanical samples. The results were very satisfactory and lead to the conclusion that no large temperature gradients existed in the dosimetry capsules;
- delivery of a special dosimetry capsule that contained an extensive quantity of different dosimeters, both from Western and Russian origin. Some of these dosimeters were measured both by Kurchatov Institute and by SCK•CEN. The aim was to compare dosimeters of different origin, to compare the results of different dosimeter types and to compare the results of the two labs. The comparison of both dosimeters of different origin and different dosimeter types gave satisfactory results. The evaluation of the results of the comparison between the two labs is still in progress.



Measurements of neutron over proton ratios in a lead-bismuth spallation target

In the framework of the MYRRHA programme we have executed in 1999 the n/p experiment at PSI, Switzerland in collaboration with PSI and NRC, SOREQ, Israel. This experiment comprised the experimental determination of the number of neutrons produced per incident proton in a thick Pb-Bi target. Furthermore we determined the neutron flux distribution in a water bath around the target. The experiment has been performed at three different proton energies, viz. 300, 420 and 590 MeV. For all three proton energies the neutron flux distribution has been determined. The determination of the n/p ratio posed several problems due to significant noise of other particles in the proton beam, but an additional proton beam calibration by Al foils solved this problem. Intermediate results are shown in the figure.

Neutron and gamma calculations

The Reactor Physics and MYRRHA department performs neutron and gamma calculations in support of the safe operation of SCK•CEN's reactors, of the experimental programmes carried out in these reactors and of several internal and external R&D programmes.

Neutron and gamma calculations for BR2

Neutron and gamma calculations were performed in one-dimensional geometry with the DTF-IV multigroup neutron transport (S_N) code, in two-dimensional geometry with the DORT3.1 multigroup neutron and gamma particle transport (S_N) code or in three-dimensional geometry with the Monte Carlo code MCNP-4C.

The main irradiation programmes for which calculations were performed were:

- BACCHANAL, in which nine water-cooled fuel rods (in a square lattice) are irradiated in a CALLISTO loop under PWR conditions up to high burnup values;

- REVE, in which model alloy samples are irradiated in a CALLISTO loop. A detailed MCNP-4C model of BR2 was used to perform the calculations;
- OMICO (THOMOX), in which eight water-cooled fuel rods (in a square lattice) will be irradiated under PWR conditions in a CALLISTO loop. The rods are of very different types: UO_2, $(U,Pu)O_2$ and $(Th,Pu)O_2$, and are fabricated according to various methods (sol-gel, MIMAS...) leading to different grain sizes;
- the BR2 vessel surveillance programme. Fast flux ratios in BR2 vessel surveillance capsules irradiated in various BR2 channels were determined, both with DORT and with DTF-IV;
- SMIRNOF-1A and SMIRNOF-1B, for which neutron flux spectra in the irradiation channels L120 and L180 were calculated and fitted to thermal, epithermal and fast flux dosimeter measurement results.

In addition, an estimation of the thermal fluence in the BR2 aluminium vessel for the end-2000 situation was made, based in part on data used in the past for the estimation of the thermal fluence at mid-1995. With respect to this mid-1995 situation, the thermal fluence (nv_0t) increases by about 5% according to the calculations, which does not lead to important reactor operation modifications.

An estimation was also made of the fast fluence and the dpa value in the pressure tubes of the three CALLISTO loops for the mid-2001 situation.

Finally, we made a preliminary assessment of the thermal neutron fluxes that could be obtained in a poolside (i.e. outside the reactor vessel) irradiation facility at BR2.

Neutron and Gamma Calculations Performed for the VENUS Reactor

The very detailed MCNP-4C model of VENUS developed in 1999 in order to replace 2-D deterministic transport calculations methods was modified to take into account the VENUS active core length extension. The new 3-D Monte Carlo model was used for safety parameter evaluation: the reactivity coefficients with respect to water height variation for MOX and UO_2 core were calculated.

Neutron and Gamma Calculations Performed for the BR1 Reactor

An exact MCNP-4C model of the BR1 reactor was developed in order to test the ability of a Monte Carlo code to cope with very large reactors (6.6m x 6.8m x 6.8m). The first results obtained are very encouraging: the source convergence is attained in a reasonable cpu time (8 hours for a $\sigma[k_{eff}]$ of 0.0025) and the maximum difference between calculated and experimental values is 15%. The 15% error appears only in certain channels and seems to be a systematic one. This last point will be investigated in the future.

Benchmark based on KRITZ experiments

A set of KRITZ 2 experiments with light water moderated lattices with uranium rods and mixed-oxide rods, at room and at elevated temperatures, were performed in the early 1970s at Studsvik. Using the results of these experiments, an international benchmark was developed and launched by the OECD/NEA in co-operation with ORNL. The objective of this benchmark was to validate and to compare the nuclear data sets and production codes (for UO_2 and MOX-fuelled cores at different temperatures) in NEA member countries. The Reactor Physics and MYRRHA department took this opportunity to validate the nuclear data based on JEF-2.2 evaluations and the Monte Carlo code MCNP-4C (mostly used as calculation tool within the department activities). The calculated results, compared to the experimental values, show a good agreement for both the k_{eff} values and the pin power distributions at various temperatures. The discrepancy of k_{eff} with respect to the critical value does not exceed 600 pcm and most of the pin power deviations are within ±2%. These results give more confidence in the tools used for the calculations.

Updating of Neutron and Gamma Cross-Section Libraries

Neutron and photon cross-section libraries in VITAMIN-B6 multigroup structure, based on JEF-2.2, ENDF/B-6 and JENDL-3.2 evaluated data, and MCNP-compatible continuous-energy cross-section libraries, based on JEF-2.2 and JENDL-3.2 data and on JENDLD99 dosimetry data, have been produced using NJOY97 versions 95-114 and NJOY99 version 50. The multigroup cross-sections, in NJOY/GENDF format, have been converted into coupled neutron/photon AMPX master format using the code NSLINK42. Each library contains cross-section data for about 180-200 nuclides/elements, including the most important actinides, structural materials, moderators and fission products. Besides, it includes thermal scattering data for some important moderators.

As part of a validation study of the JEF-2.2 and JENDL-3.2-based continuous-energy cross-section libraries, derived as described above, a number of criticality benchmarks for MOX lattices, fast mixed uranium/plutonium metal systems and some benchmarks for mixed uranium/plutonium nitrate solutions have been selected and analysed with the Monte Carlo continuous-energy code MCNP-4C.

Fuel Cycle Studies

A nuclide concentration evolution code was written solving the Bateman equations for the most occurring actinides (including the minor actinides). The input needed, next to the initial nuclide concentrations and the irradiation and cooling times, is the absolute total flux and the spectrum-averaged microscopic cross-sections.

SCK•CEN joined the CAPRA/CADRA project in 2000 as a full-part member and participated in various CAPRA/CADRA meetings.

A study was made, examining the neutron-induced evolution of minor actinides (MAs) irradiated in LWRs, MTRs and ADSs, viz. in a typical 1000 MWe MOX-fuelled PWR, in the high flux materials testing reactor BR2 and in the multipurpose R&D ADS MYRRHA. While fast spectrum systems such as the proposed ADS immediately burn the MAs, but at relatively low rates because of the small cross-sections, thermal spectrum systems, with large (n,γ) cross-sections, first transmute the MAs into higher isotopes, some of which ultimately are also fissile in the thermal energy range. In the case of MTRs, in which high (thermal) fluxes prevail, large fractions of MAs are thus transmuted and ultimately incinerated in relatively short times, but at the cost of several neutron captures before fission occurs and therefore with bad neutron economy.

Reactor Safety

In 2001 SCK•CEN pursued its activities on the international PHEBUS-FP programme to prepare its participation in the International Standard Problem ISP-46 (OECD) on the FPT1 test. This ISP officially began in July 2001 and a preparatory workshop was held in November to check and update the data book. Completion of the exercise is planned for 2003.

SCK•CEN also worked with the last beta version of the SCDAPSIM code, which is a PC version of RELAP5/SCDAP developed by Innovative Systems Software, LLC. A comparison exercise between SCDAPSIM and RELAP5/SCDAP was performed on the FPT1 and FPT2 tests of the PHEBUS-FP programme, but unsuccessfully because of residual bugs in SCDAPSIM. Blockages occurred in the calculations during the fuel delocalisation phase. The improvement of this beta version is now completed and new tests are foreseen in 2002.

FLINS

The activities during the first months of 2001 are reported in the Chapter "Safeguards and Physics Measurements"; they are further illustrated in the reports and references cited.

Partners

-	BELGONUCLEAIRE (Dessel, Belgium)
PSI	Paul Scherrer Institute (Villigen, Switzerland)
KI	Kurchatov Institute (Moscow, Russia)
NRC	Nuclear Research Centre (Soreq, Israel)
NRG	Nuclear Research & consultancy Group (Petten, The Netherlands)
VTT	Technical Research Centre of Finland (Epoo, Finland)

Sponsors/Licensees

-	Electrabel (Brussel, Belgium)
-	Process Vision (Brussels, Belgium)
DSI	Delta Services Industriels
DSM	DSM Research BV, (Geleen, The Netherlands)
EDF	Electricité de France (Paris and Fontainebleau, France)
IPSN	Institut de Protection et de Sûreté Nucléaire (Fontenay-aux-Roses, France)

IRMM	Institute for Reference Materials and Measurements (Geel, Belgium)
NUPEC	Nuclear Power Engineering Corporation (Tokyo, Japan)
UCL	Université Catholique de Louvain (Louvain-la-Neuve, Belgium)
Ulg	Université de Liège (Liège, Belgium)
USNRC	US Nuclear Regulatory Commission (Rockville, USA)
VGB	VGB Kraftwerkstechniek GmbH (Essen, Germany)

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