Hamid Aït Abderrahim

Reactor Physics

Scientific Staff

Hamid Aït Abderrahim,
Thierry Aoust,
Baudouin Arien,
Peter Baeten,
Luc Borms,
Simon Coenen,
David De Maeyer,
Charles De Raedt,
Simone Heusdains,
Dominique Lamy,
Nadia Messaoudi,
Da Ruan,
Klaas van der Meer,
Paul Van Uffelen,
Bernard Verboomen,
Harm Wienke,
Victor Willekens

Supporting Staff

Emiel Caeyers,
Jan Cools,
Stefan Dekelver,
Marcel Huysmans,
Jozef Leeuws,
Jozef Oeyen,
Leopold Truyens,
Steffi Van Genechten,
Francis Van Gestel,
Jozef Verrees,
Ludovicus Verstrepen,
Ivo Verwimp

Background and Objectives

The Reactor Physics & MYRRHA Department gathered expertise in various reactor physics fields, namely neutronics calculations, reactor dosimetry, reactor operation, reactor safety and control and non-destructive analysis of reactor fuel. This expertise is applied within the Reactor Physics & MYRRHA Department's own research projects in the VENUS critical facility (dealing presently with MOX fuel core physics), in the BR1 reactor (dealing with neutron-irradiation hardening, neutron dosimetry calibration, ex-core neutron transport and shielding problems) and in the MYRRHA project, aiming at designing a prototype ADS (Accelerator Driven System) for R&D applications. 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, the Fuzzy Logic and Intelligent Technologies in Nuclear Science, carried out within the department, also cover several domains outside the department. The activities related to the MYRRHA project development are reported at the end of this chapter.

Programme

The Reactor Physics Programme aims at developing, improving and maintaining the experimental and theoretical expertise of the department and using it for a large number of applications. The main topics in 2000 were:

- REBUS, a burn-up credit experimental programme in the VENUS critical facility;
- the IMP Programme (investigation of the recycling of military plutonium as MOX in LWRs) in the VENUS critical facility;
- services in the BR1 reactor;
- neutron and gamma calculations and neutron dosimetry performed in support of the operation of, and the irradiation in, various reactors as well as in support of R&D programmes;
- reactor safety studies;
- assessment of the structural material activation in nuclear installations;
- FLINS applied to nuclear safeguards programmes.

Achievements

REBUS, a burn-up credit experimental programme in the VENUS critical facility

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 burn-up credit) results in less storage and transport costs and in higher safety. We have initiated an international programme called REBUS (REactivity tests for a direct evaluation of the Burn-Up credit on Selected irradiated LWR fuel bundles) for the investigation of the burn-up credit. The programme aims at establishing a neutronic benchmark for reactor physics codes that calculate the burn-up credit. The experimental programme will investigate the following fuel types with associated burn-up:

- reference absorber test bundle;
- fresh commercial PWR UO_2 fuel;
- irradiated commercial PWR UO_2 fuel (50 GWd/tM);
- fresh BR3 PWR UO_2 fuel;
- irradiated BR3 PWR UO_2 fuel (30 GWd/tM);
- fresh PWR MOX fuel;
- irradiated PWR MOX fuel (20 GWd/tM).

In future extensions of the programme we can investigate other fuel types, like BWR fuel and high burn-up MOX fuel.

Each test bundle will be loaded as a 7x7 fuel assembly having as outer zone 24 4% enriched UO_2 driver fuel rods. The 7x7 assembly is chosen because the VENUS reactor has removable grids where this assembly fits in. We will measure reactivity effects. In addition, we will determine after the irradiation the fission rate distribution induced in the fuel rods along the main axes. Due to the impossibility of measuring this parameter in the spent fuel assembly, we will measure the axial distributions of the thermal and epithermal neutron fluxes between the fuel rods by means of Co wire activation. The accumulated burn-up of all rods will be measured non-destructively by gamma-spectrometry. We will also analyse some rods destructively with respect to accumulated burn-up, 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 1500 to 2000 pcm. These reactivity effects are sufficiently high for criticality code validation.

In 2000 we started the experimental preparation of the programme. This comprised mainly infrastructure works in the VENUS reactor in order to change the active length of the fuel from 50 cm to 1 m.

The REBUS programme, initiated by SCK•CEN and BELGONUCLEAIRE, is at present sponsored by USNRC, EDF (France), VGB (representing German nuclear utilities) and NUPEC (Japan).

The IMP Programme (investigation of military plutonium) in the VENUS critical facility

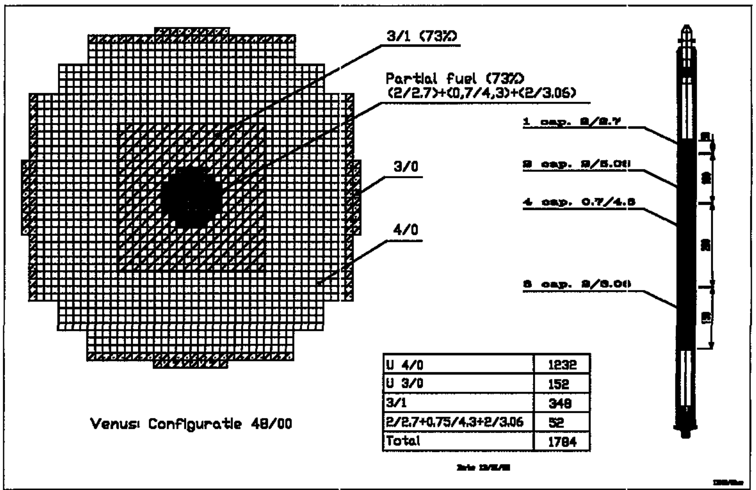
The dismantling of nuclear warheads in the US and Russia creates a stockpile of weapon-grade plutonium that should be made inaccessible for future use in nuclear weapons. One of the proposed solutions to diminish these stockpiles is to use the plutonium in commercial power reactors as MOX fuel. The envisaged stockpile for reactor-based disposition in the US and Russia together represents an amount - about 59 tonnes of weapon-grade plutonium - equal to an energy quantity of 12.2 10^3 GWd, which can be used for peaceful purposes, or the year production of 39 1000 MWe power plants. Since the neutronic behaviour of weapon-grade plutonium MOX is different from that of civil MOX, the international scientific community considers it necessary to investigate this neutronic behaviour for the validation of core physics codes.

In the past SCK•CEN performed some experiments in the VENUS reactor with MOX having a Pu-vector of 96% ^{239}Pu, 4% ^{240}Pu. Based on this experience we loaded a UO_2 reference configuration and a weapon-grade MOX configuration in VENUS in the course of November/December 1999 to investigate the validity of the previous experiment with modern measurement methods and to perform the experiment in a lattice representative of modern PWRs. In the first quarter of 2000 we loaded another weapon-grade MOX configuration and performed similar experiments as those done with the UO_2 reference configuration. Neutron-physical parameters were calculated and compared with the experimental results.

The aim of the IMP programme is to provide data for validating core physics codes for weapon-grade plutonium. Basic data for such a validation are in general k_{eff} and local fission rate distributions. Additional data are e.g. spectrum indices and the delayed neutron fraction β_{eff}.

The amount of available rods at VENUS with 0.7/4.3 weapon-grade plutonium (0.7% ^{235}U, 4.3% weapon-grade plutonium) is very limited (25 rods of 50 cm length). This means that especially a k_{eff} validation is very hard to obtain with these rods, since the difference in k_{eff} is only in the order of several 10's to maximum 100 pcm, while the average core physics code calculates k_{eff} with an uncertainty of about 500 pcm. However, there are also about 400 MOX rods available with 3/1 weapon-grade plutonium. A major drawback of these rods is that they contain only 1% Pu, but due to the large available quantity these rods can provide a valuable benchmark for k_{eff} calculations. They have less value for fission rate distribution measurements.

Space-dependent parameters like the local fission rate distribution with respect to UO_2 can be better differentiated with the 0.7/4.3 rods than with the 3/1 rods. Calculations on different configurations have shown that differences in local fission rate distributions between uranium and weapon-grade plutonium are large enough to be useful for code validation. Other calculations have shown that the fission rate distribution measured at mid-plane of partial fuel is not significantly different from that of homogeneously loaded fuel (partial means that the central part of the fuel column is filled with 0.7/4.3 MOX fuel pellets (weapon-grade Pu), while the upper and



VENUS Configuration 48/00

lower parts are filled with 2/3.06 MOX fuel pellets (civil Pu). Fifty-two partial fuel rods were loaded in the centre of the VENUS-configuration 48/00 (see figure).

The partial weapon-grade MOX configuration is loaded with the purpose of having a benchmark for validating fission rate distribution calculations. This configuration gives in its centre a better approximation of the asymptotic behaviour of the weapon-grade MOX rods. The same is true for spectrum index validation.

Calculations of the k_{eff} of the UO_2 reference configuration resulted in a value of 0.996. The calculated fission rate distribution had a standard deviation of 1.7% for the whole configuration and 1.2% for the central assembly with respect to the measured fission rate distribution. The calculated k_{eff} for the 3/1 configuration was 0.997.

Calculations of the k_{eff} of the partial weapon-grade MOX configuration resulted in a value of 0.997. For the fission rate distribution the standard deviation is 3.0% for the whole configuration and 1.9% for the central assembly.

The BR1 Reactor: Operation and Services

BR1, Belgian Reactor 1, in operation since May 1956, 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. The main objectives of the BR1 Operations & Services programme are:

- to operate the reactor in a safe way;
- to provide our customers for research and service purposes a high degree of flexibility in terms of neutron flux, reactor power and availability of the reactor;
- to use the reactor for education and training purposes for nuclear engineering students as well as for reactor operators.

Although at a glance these objectives seem to be contradictory, a good synergy between the operational staff and operational safety limits has been achieved allowing to fulfil them.

Our continuous efforts to maintain and improve this synergy are reflected by the programme and achievements. The BR1 reactor is operated on a daily basis with start and stop of the reactor determined by experimental needs. During the year 2000, we operated BR1 during 150 days for a total of 550 hours. We performed about 160 irradiations, most of them are short irradiations of a few hours for neutron activation analysis, but also experimental campaigns of several weeks have been performed. Following domains were covered:

Reactor Safety

- *Assessment of the Wigner energy*: neutron irradiation of graphite induces an accumulation of the internal energy of the graphite. This energy can suddenly be released at temperatures above 150°C and thus can produce locally extremely high temperatures. A thorough follow-up of this Wigner energy is therefore imperative. We assessed the Wigner energy successfully by extracting small samples of the graphite near the reactor core and analysing them by means of DTA (Differential Thermal Analysis) techniques. The measured energy (180 J/g) is below the acceptable limit of 250 J/g and hence no treatment to remove this energy by a controlled heating is necessary at the present time.
- *Upgrade of the sampling system of the cooling air*: the BR1 reactor is equipped with a sampling system to measure the radioactivity of the cooling air of the fuel channels. Sampling is performed by groups of 2, 3 or 4 channels, and, in case of a break in the fuel cladding, this sampling system allows us to determine quickly the channel containing the defective fuel element. We upgraded the existing system, based on mechanical rotational selectors by a new system based on electro-pneumatic valves controlled by a PLC system. This new system provides a higher flexibility with respect to the selection of channels to be sampled as well as more quantitative measurements of flow rate and activity.
- *Nuclear measurements for the Belgian nuclear power plants:* during revision periods and for the reloading of the nuclear power plants of Doel and Tihange (Electrabel), we provide complete nuclear measurement chains that serve as back-up measurement chains.

Irradiation Services for R&D Programmes

We performed several irradiation campaigns related to different R&D programmes such as:

- qualification of the Co-Ag method for reactor dosimetry
- radiation tolerance assessment of optical fibre Bragg gratings for temperature measurements with on-line measurements for the Instrumentation Department
- radiation tolerance assessment of multiplexer circuits for the fusion remote handling programme
- qualification of special electronics for space applications in collaboration with ALCATEL-ETCA
- qualification of bubble neutron detectors.

Irradiation Services for Industry and Universities

About 50 % of the irradiations are related to activation analysis for industry (DSM Research, Process Vision), universities (UCL, ULg) and research institutes (IRMM).

Education and Training

- As every year, BR1 welcomed in 2000 nuclear industrial engineering students for a training on reactor physics and kinetics behaviour.
- In October 2000 we gave in the framework of the ISTC 371.2 project for weapon-grade Pu recycling as MOX in LWRs an extension of a practical course on reactor dosimetry measurement techniques in the VENUS critical facility to Russian scientists from IPPE at Obninsk, Russia.

The BR1 irradiation facilities have been presented at the RADECS 2000 Workshop with specific emphasis on the possibilities of the BR1 large cavity for the study of displacement effects on electronic devices for space and high energy physics applications.

Neutron and Gamma Calculations

The Reactor Physics & MYRRHA Department is carrying out on a regular basis support studies for the SCK•CEN irradiation facilities in the field of neutron and gamma calculations. In 2000, these activities were directed towards the renewal of the calculational tools of the department as well as towards support studies for BR2, VENUS, CAPRA/CADRA and MYRRHA.

Neutron and Gamma Calculations Performed for BR2

We performed most calculations either 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 (version 4B).

The main irradiation programmes for which we performed calculations 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 burn-up values;
- CHIVAS, in which LWR pressure vessel steel samples are irradiated in a CALLISTO loop;
- THOMOX, in which eight water-cooled experimental fuel rods (in a square lattice) are to be irradiated in a CALLISTO loop. The rods are of very different types: UO_2 (serving as reference fuel), $(U,Pu)O_2$ and $(Th,Pu)O_2$, with various grain sizes, and are fabricated according to various methods (sol-gel, MIMAS...);
- MTR fuel testing in a BR2 fuel element. The purpose of the irradiations is to investigate the behaviour of novel fuel plates with very high density meat under severe reactor operation conditions. The novel fuel plates are inserted in two standard six-tube BR2 fuel elements in the locations normally occupied by the standard outer fuel plates. Due to the detailed analysis required for this experiment detailed neutron Monte Carlo calculations of the whole BR2 core containing the two experimental fuel elements were carried out. A typical BR2 loading, as represented in an MCNP-4B calculation, is shown in the following figure. In addition to the detailed description of the fuel elements and of the experiments, the axially varying burn-up distribution in each fuel element was introduced into the calculations.
- The effect of neutron and gamma ray spectra on the sensitivity of beta and prompt self-powered neutron detectors (SPNDs) was further analysed in the framework of the DOLMEN project of the technology department.

Neutron and Gamma Calculations Performed for the VENUS Reactor

We developped a very detailed 3-D MCNP-4B Monte Carlo model of VENUS in 1999 in order to replace 2-D deterministic transport calculation methods used up to now for the determination of the design of new experiments and the evaluation of irradiation conditions. The 3-D geometrical model is a nearly exact reproduction of the VENUS facility. In particular, each fuel rod is modelled separately. ENDFB-VI and/or JEF-2.2 continuous-energy cross-sections sets are used throughout.

Preliminary calculations for the programme IMP (Investigation of Military Plutonium) described above have been performed with the MCNP-4B model in order to benchmark the code with measured VENUS configurations: comparisons with measured configurations (with and without Pu) give a difference of about 0.4% for the keff and about 1.5% to 3.0% for the power distributions.

Updating of Neutron and Gamma Cross-Section Libraries

The Reactor Physics & MYRRHA department has continued in 2000 its policy of renewing its neutron and gamma cross-sections libraries based on the most recent nuclear data files available. Coupled neutron/photon cross-section libraries in VITAMIN-B6 multigroup structure and in the MCNP-compatible continuous-energy ACE format, based on JEF-2.2 as well as on ENDF/B-6.6 data, have been produced using the NJOY97 code system. The multigroup cross-sections, in NJOY/GENDF format, have been converted into AMPX master format using the code NSLINK42 [P.W.F. de Leege, NSLINK42, unpublished, Delft Technical University, Delft, Netherlands]. Each library contains cross-section data for about 188 materials (including thermal scattering data for H_2O, D_2O, polyethylene, graphite, metallic beryllium and zirconium hydride). Results of pin cell benchmark calculations, performed using SCALE-4.3 and the multigroup libraries, showed good agreement with the ones of corresponding calculations performed with MCNP-4B and the continuous-energy libraries.

A neutron 230 multigroup cross-section library in AMPX master format has been derived, using NJOY99, from the new 150 MeV ENDF/B-6.7 neutron evaluations. The library has been designed for neutron transport calculations with the discrete-ordinate method (DORT, TORT) in order to compare the results with those of corresponding transport calculations performed with the MCNPX code.

OECD/NEA Benchmark Calculations

Benchmark calculations have been completed in the framework of SCK•CEN's participation in the OECD/NEA benchmark for an Accelerator-Driven Minor Actinide Burner. We performed the transport calculations involved with the Monte Carlo code MCNP-4B. The activation and decay results, necessary for the burn-up calculations, were obtained with ORIGEN-2 and a home-made code, solving the Bateman equations. We derived the cross-sections used in the transport calculations from JEF-2.2 data with the cross-section data processing code system NJOY97 for the appropriate temperatures. The results are consistent with those from the RIT group, Sweden, which also used MCNP-4B and cross-sections derived from JEF-2.2 data with NJOY97.

Fuel Cycle Studies

The final European Atomic Energy Commission reports on the studies "Supporting Nuclear Data for Advanced MOX Fuels" and "Evaluation of Possible Partitioning and Transmutation Strategies and of the Means for Implementing Them", in both of which SCK•CEN participated, were issued in 2000. SCK•CEN joined the CAPRA/CADRA project in 2000 as a full-part member and participated in various CAPRA/CADRA meetings. The SCK•CEN contribution to the CAPRA/CADRA project will consist mainly in studying the ADS impact on the minor actinide reduction scenarios. To this end SCK•CEN implemented the ERANOS code system and its associated adjusted cross-section library ERALIB-1.

We compared the performances of BR2 and MYRRHA in the domain of transmutation of MAs and LLFPs. According to static neutronic calculations performed with MCNP-4B and completed with evolution calculations (i.e. solutions of the Bateman equations for the various actinides involved in the transmutation schemes), a very high thermal flux reactor ($\sim 10^{15}$ n/cm^2.s) such as BR2 could burn high quantities of ^{237}Np and Am in relatively short times but with a bad neutron economy as compared to an ADS system such as MYRRHA.

Reactor Dosimetry

The group reactor dosimetry provides services for internal and external clients. These services comprise the determination of neutron fluxes or fluences by means of the irradiation 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 Experiments and BR2 Operation

SCK•CEN executed several experiments in BR2, for which neutron dosimetry was required. For some experiments oriented towards the study of structural materials (like CHIVAS, IRMAS and FINC) we measured only the fast flux, while for other experiments aiming at developing instrumentation (like DOLMEN and SMIRNOFF) we measured also the thermal and epithermal fluxes. In these cases we determine the fast flux with the $^{54}Fe(n,p)^{54}Mn$ reaction, while the thermal and epithermal fluxes are determined with Co and Ag (n,γ) reactions. For CHIVAS we determined the fast neutron flux also with the $^{93}Nb(n,n')^{93}Nb$ reaction.

Each cycle we measure, at several positions in the BR2 reactor, the thermal, epithermal and fast fluxes in a routine way. These measurements are in support of the reactor physics calculations for BR2.

Neutron Dosimetry for Belgian Nuclear Power Plants

In 2000 we didn't analyse surveillance capsules. Nevertheless we dedicated a special effort to the improvement of the analysis of the fissile detectors included in the neutron dosimetry sets of the Belgian PWR surveillance capsules. We have thus studied the influence of several parameters on the behaviour of fissile dosimeters ^{238}U and ^{237}Np. These parameters comprise the presence of impurities like ^{235}U, photofissions, burn-up and build-up of fissile isotopes. We concluded that due to the large corrections for ^{238}U (see table below), ^{237}Np seems to be more appropriate for long-term pressure vessel surveillance fluence measurements.

In the table below the calculation results, based on either an analytical calculation or an ORIGEN2 calculation, are summarized. Two dosimeter types were investigated, originating from SCK•CEN and Tractebel.

RETROSPEC

SCK•CEN participates in the 5th framework programme RETROSPEC (partners: NRG, Petten; 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, the so-called retrospective dosimetry. It is based on the activation of ^{93}Nb, present as an impurity 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.

Intercomparison Exercises

In order to keep our dosimetry expertise we regularly participate in intercomparison exercises, where samples are measured by several international laboratories and compared. In this way our competence is confirmed and a permanent discussion is established with other dosimetry laboratories.

Apart from the RETROSPEC programme, which we consider also as an intercomparison exercise, we participate in two other intercomparison programmes. One programme is situated in the framework of a TACIS project, in support for the VVER surveillance

Summary of the calculation results expressed in % correction (negative correction)							
		Impurities		Burn-up	Build-up	Photofissions	Total
		SCK•CEN	Tractebel				
^{237}Np	anal. calc.	0	0	+0.15	0.26	1.1	1.2
	ORIGEN2	0	1.5-3.6	0	0.5		2-4.1
^{238}U	anal. calc.	0.1	4-5	+0.06	4-8	7.0	14.3-18.8
	ORIGEN2	0.5	17.5	+0.3	4.3		26.8

programme improvement. The project involves an as complete as possible mapping of a VVER-1000 (Balakovo unit 1) dosimetry capsule. This mapping is done with SCK•CEN and Russian dosimeters. Additionally a complete temperature monitoring is performed by SCK•CEN temperature monitors. All dosimeters will be measured by SCK•CEN and Kurchatov Institute. This permits a comparison of SCK•CEN and Russian dosimeter material in order to validate the latter, and a comparison of SCK•CEN and Russian measurement procedures. The SCK•CEN measurement procedure is based on ASTM standards.

The second programme is in cooperation with BAS, the Bulgarian Academy of Sciences, and involves similar delivery of dosimeter material and measurements. A likewise comparison will be executed of the SCK•CEN and Bulgarian dosimeter material and measurement procedures. In the framework of the latter programme we have hosted a visiting scientist from BAS in order to discuss our measurement equipment and analysis system for gamma-spectrometry.

Co-Ag method validation

The Co-Ag method is used for the determination of the thermal and epithermal neutron fluxes. The method has been compared with the reference method, where Co foils are irradiated with and without a Cd cover. We found no significant differences for the measured thermal flux, but significant differences for the epithermal flux. Several error sources have been eliminated, but the search for the actual reason of this discrepancy is still in progress. The results obtained in the BR1 reactor are illustrated in the table below.

	Thermal Flux	Epithermal flux
Co (Cd cover)	3.76 E11	1.13 E10
Co/Ag	3.92 E11	3.14 E9

Reactor Safety

In the framework of its activities in reactor safety, SCK•CEN pursued in 2000 its participation in the international PHEBUS-FP programme. This programme conducted by IPSN at CEN Cadarache aims at performing irradiations of in-pile test sections to simulate severe accidents in LWRs and at analysing the consequent fission product releases. SCK•CEN's participation consists in modelling the experiments with the RELAP/SCDAP computer code in order to assess the ability of the code to simulate severe accidents.

In 2000 SCK•CEN concentrated its effort on the simulation of the FPT1 and FPT2 experiments. The objectives of both experiments were to study the phenomenology of a low pressure severe accident sequence with high burnup fuels (23.4 GWd/tU for FPT1, 24.5 GWd/tU for FPT2), but under reducing conditions for FPT2 in order to analyse the effects of vapour starvation during the clad oxidation.

Simulation of these tests with the mode3.1f INEL version of the SCDAP code gives a general blockage in the bundle with the melting fuel and some difficulties to follow with this version the simulation of the experimental test to its final time.

The new version mode3.2 contains significant improvements with several late phase models and a transition smoothing methodology in the calculation of a gradual transition from an intact core geometry through different core damage states. SCK•CEN has also simulated the FPT experiments with SCDAP-SIM, which is a PC version of SCDAP mode3.2.

SCK•CEN has decided to participate in the future ISP-46 (International Standard Problem) organised by OECD on the FPT1 experiment. Such an exercise would be a unique opportunity of taking an important benefit of the PHEBUS-FP programme as it could contribute to the assessment of our severe accident codes on an integral simulation, closer to a real situation than most of the experiments on which the codes have been validated.

Assessment of the Structural Material Activation in Nuclear Installations

This activity is reported in the Chapter "Site Restoration".

Fuzzy Logic and Intelligent Technologies in Nuclear Science (FLINS)

FLINS, an acronym for Fuzzy Logic and Intelligent Technologies in Nuclear Science, launched in line with SCK•CEN's objective to give young talented people the opportunity to carry out future-oriented research. FLINS was initially built within one of the postdoctoral research projects at SCK•CEN in 1994. Following a successful FLINS project on the specific prototyping of fuzzy logic control of the BR1 research reactor (1995-99), which was chosen as FLINS's first priority, we initiated a new research project on development of intelligent systems for safeguards application at SCK•CEN (2000-02). This project is executed in collaboration with the Safeguards Department in the framework of the Belgian Support Programme to the IAEA for safeguards implementation (task # BEL C 01323). As the main activities within the FLINS group in 2000 were related to the latter project the achievements within this project will be reported in the Safeguard Department activities. We dedicated the other activities within FLINS to organise the FLINS'2000 international conference and to publish the results of the achievements of the former activities in various international journals.

Partners

-	ALCATEL-ETCA
-	Kurtchatov Institute (Moscow, Russia)
BAS	Bulgarian Academy of Sciences (Sofia, Bulgaria)
BN	BELGONUCLEAIRE (Dessel, Belgium)
NRG	Nuclear Research Group (Petten, The Netherlands)
VTT	Technical Research Centre of Finland (Helsinki, Finland)

Sponsors

EDF	Electrcitité de France (Paris and Fontainebleau, France)
NUPEC	Nuclear Power Engineering Corporation (Tokyo, Japan)
USNRC	US Nuclear Regulatory Commission (Rockville, USA)
VGB	VGB Kraftwerktechnik GmbH (Essen, Germany)

Customers

-	Electrabel (Brussels, Belgium)
-	Process Vision (Brussels, Belgium)
DSM	DSM Research BV, (Geleen, The Netherlands)
IRMM	Institute for Reference Materials and Measurements (Geel, Belgium)
UCL	Université Catholique de Louvain (Louvain-la-Neuve, Belgium)
Ulg	Université de Liège (Liège, Belgium)

Scientific Output

Publications

P. Baeten, J. Paepen, K. van der Meer, H. Aït Abderrahim, "Absolute Measurement of ↓ -eff and l on Weapon-Grade Fuel at the VENUS Critical Facaility by means of the Rapja Technique", Annals of Nuclear Energy 28 (4), pp. 287-295, 2001.

X. Li, D. Ruan, "Novel Neural Algorithms Based on Fuzzy Δ-Rules for Solving Fuzzy Relation Equations: Part 3", Fuzzy Sets and Systems, 109 (3), pp. 355-362, 2000.

X. Li, D. Ruan, "Comparative Study of Fuzzy Control, PID Control, and Advanced Fuzzy Control for Simulating a Nuclear Reactor Operation", Int. Journal of General Systems, 29 (2), pp. 263-279, 2000.

D. Ruan, E.E. Kerre, "Fuzzy IF-THEN Rules in Computational Intelligence: Theory and Applications", Kluwer Academic Publishers, Boston, USA, 322 pp., 2000.

D. Ruan, H. Aït Abderrahim, P. D'hondt, E.E. Kerre, "Intelligent Technologies and Soft Computing in Nuclear Science and Engineering", World Scientific, Singapore, 544 pp., 2000.

D. Ruan, "Flins '98", guest editor, International Journal of General Systems, 29 (1/2), Gordon and Breach Science Publishers, 2000.

L. Liu, D. Ruan, Z. Sons, Y. Xu, "On Optimization with Fuzzy Constraint Conditions" in: R. Hampel, M. Wagenknecht, and N. Chaker, Eds., Fuzzy Control, Theory and Practice, pp.166-173, Physica-Verslag , 2000.

Y. Xu, D. Ruan, J. Liu, "Approximate Reasoning Based on Lattice-Valued Propositional Logic Lvpl", in: D. Ruan and E.E. Kerre, Eds., Fuzzy IF-THEN Rules in Computational Intelligence: Theory and Applications, pp. 81-105, 2000.

C. Zhou, D. Ruan, "Fuzzy Rules Extraction-Based Linguistic and Numerical Heterogeneous Data Fusion for Intelligent Robotic Control", in: D. Ruan and E.E. Kerre, Eds., Fuzzy IF-THEN Rules in Computational Intelligence: Theory and Applications, pp. 243-265, 2000.

P. Van Uffelen, "Modelling the Variable Precipitation of Fission Products at Grain Boundaries", Journal of Nuclear Materials, 280, pp. 275-284, 2000.

Presentations

B. Verboomen, Th. Aoust, A. Beeckmans de West-Meerbeeck, Ch. De Raedt, "Irradiation of New MTR Fuel

Plates in BR2", 4th International Topical Meeting Research Reactor Fuel Management (RRFM), Colmar, France, ENS, CH, pp. 135-139, March 19-21, 2000.

D. Ruan, "Recent Development of Intelligent Systems and Softcomputing", Southwest Jiaotong University, Chengdu, China, April 2000.

D. Ruan, "Fuzzy Logic Control: Theory and Applications", the Nuclear Power Institute of China, Chengdu, China, April 2000.

A. Vasile, G. Vambenepe, J.C. Lefevre, K. Hesketh, W. Maschek, Ch. De Raedt, D. Haas, "The CAPRA-CADRA Programme", ICONE 8, the 8th International Conference on Nuclear Engineering, Baltimore, MD, April 2-8, 2000 .

P. Van Uffelen, "Parametric Study of a Fission Gas Release Model for LWR Fuel", Proceedings International Topical Meeting on Light Water Reactor Fuel Performance, Park City, Utah (USA), April 10-13, 2000.

Y. Xu, E.E. Kerre, D. Ruan, Z. Song, "A Study on Fuzzy Reasoning Mechanism Based on Extension Principle", the proceedings of the 9th IEEE Int. Conf. on Fuzzy Systems, pp. 185-190, San Antonio, Texas, USA, May 7-10, 2000.

Ch. De Raedt, E. Malambu, B. Verboomen, Th. Aoust, "Increasing Complexity in the Modelling of BR2 Irradiations", In PHYSOR 2000 International Topical Meeting "Advances in Reactor Physics and Mathematics and Computation into the Next Millennium", Pittsburgh, PA, May 7–11, 2000, ANS, USA, 2000.

S. Pilate, R. Jacqmin, Ch. Chabert, Ch. De Raedt, J.C. Kuijper, Th. Maldague, G. Nicolaou, St. Van Winckel, A. Ventura, "Validation of Nuclear Data for Transmutation from the Evaluation of Mox Fuel Irradiations", PHYSOR 2000 International Topical Meeting "Advances in Reactor Physics and Mathematics and Computation into the Next Millenium", Pittsburgh, May 7-11, 2000, ANS, USA, 2000.

D. Ruan, "Soft Computing: Applications in Power Plants", I&C Energo, Prague, Czech, May 30, 2000.

H. Aït Abderrahim, P. Kupschus, E. Malambu, K. Van Tichelen, Ph. Benoit, B. Arien, F. Vermeersch, S. Bodart, Th. Aoust, Ch. De Raedt, "MYRRHA, a small ADS Actinide-Transmuter Prototype. Current Status of the Project", Sixth CAPRA/CADRA Seminar, Newby Bridge, Cumbria, England, June 26-28, 2000.

K. van der Meer, P. Baeten, S. Van Winckel, L. Sannen, D. Marloye, H. Libon, B. Lance, J. Basselier, "REBUS: A Burn-Up Credit Experimental Programme", IAEA Technical Committee Meeting on the Evaluation and Review of the Implementation of Burnup Credit in Spent Fuel Management Systems, Vienna, Austria, July 10-14, 2000.

C. Kahramana, D. Ruan, E. Tolga, "Discounted Possibilistic Cash Flows versus Probabilistic Cash Flows", in: D. Ruan et al., Eds., Intelligent Techniques and Soft Computing in Nuclear Science and Engineering, the Proc. of the 4th Int. FLINS Conf., pp. 214-223, Bruges, Belgium, August 28-30, 2000.

J. Liu, D. Ruan, "Lattice-Valued Linguistic Expression and its Application to the Safety Evaluation for Transmission Lines", in: D. Ruan et al., Eds., Intelligent Techniques and Soft Computing in Nuclear Science and Engineering, the Proc. of the 4th Int. FLINS Conf., pp. 389-396, Bruges, Belgium, August 28-30, 2000.

J. Liu, Y. Xu, D. Ruan, "a-Automated Reasoning Method Based on Lattice Valued Propositional Logic Lp(X)", the Proceedings of the 8th Zittau Fuzzy Colloquium, pp. 60-67, Zittau, Germany, September 6-8, 2000.

S. Coenen, H. Aït Abderrahim, "BR1 Irradiation Facilities", RADECS 2000 Workshop, Leuven (Belgium), September 11-13, 2000.

S. Ganesan, H. Wienke, "On the Criticality Property of ^{233}Pa Derived from Various Nuclear Data Files using the NJOY and the MCNP Codes", Proceedings of the 10th International Conference on Emerging Nuclear Energy Systems, Petten, The Netherlands, September 24-28, 2000 (Ed. H. van Dam and J.C. Kuyper), pp .305, 2000.

P. Van Uffelen, "Modelling the Influence of the Athermal open Porosity on Fission Gas Release in LWR Fuel", Proceedings International Seminar on Fission Gas Behaviour in Water Reactor Fuels, Cadarache, France, September 26-29, 2000.

D. Ruan, "Introduction to Intelligent Systems and Soft Computing Methods and Applications", University of Antwerp (UIA), October 12, 2000.

D. Ruan, "Fuzzy Control Applications", University of Antwerp (UIA), October 19, 2000.

B. Verboomen, A. Beeckmans de West-Meerbeeck, Th. Aoust, Ch. De Raedt, "Monte Carlo Modelling of the Belgian Materials Testing Reactor: Present Status", International Conference MC2000, Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Lisbon, October 23-26, 2000.

D. Ruan, "Aggregation Operators and Decision Making under Uncertainty", University of Antwerp (UIA), November 9, 2000.

D. Ruan, "Safe Experiments on Fuzzy Control for Nuclear Reactor Operations" (invited), Proceedings of Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT 2000, Washington, D.C., USA, November 13-16, 2000.

D. Ruan, "Industrial Applications of Soft Computing Techniques", University of Antwerp (UIA), November 23, 2000.

Ch. De Raedt, B. Verboomen, Th. Aoust, E. Malambu, A. Beeckmans de West-Meerbeeck, P. Kupschus, Ph. Benoit, H. Aït Abderrahim, L. H. Baetslé, "MA and LLFP transmutation in MTRs and ADSs : The typical SCK•CEN case of transmutation in BR2 and MYRRHA.

Position with respect to the global needs", Sixth International Information Exchange Meeting on Actinide and Fission Product Separation and Transmutation, Madrid, December 11-13, 2000.

Reports

B. Verboomen, "Calculs Neutroniques Préparatoires au Premier Cycle d'Irradiation de deux Eléments Combustibles de Type Mixte RJH-BR2", BV/bv-34/A001052-211/00-1, SCK•CEN, 15 Février 2000.

V. Sobolev, Ch. De Raedt, E. Malambu, M. Weber, "Dependence of the Sensitivity of a Self-Powered Neutron Detector on Radiation Spectrum of BR2", Report BLG-836, March 2000.

B. Verboomen, "Calculs Neutroniques Préparatoires au Second Cycle d'Irradiation de deux Eléments Combustibles de Type Mixte RJH-BR2", BV/bv-34/A001052-211/00-2, SCK•CEN, 02 Mars 2000.

Ch. De Raedt, B. Verboomen, "Calculated Plutonium Production, during BR2 Cycle 99/5, in the two Experimental BR2 Fuel Elements Containing RJH Fuel Plates", ChDR/chdr-34/A001052/211/00-3, March 3, 2000.

H. Wienke, Ch. De Raedt, "Results of Calculations for an Accelerator-Driven Minor Actinide Burner. An OECD/NEA International Benchmark Exercise", HW/hw-34/B043001/49/00-13, May 2000.

Th. Aoust, "Predetermination of the Linear Power Value of Single Mox Pin Irradiated in Channel D180", ThA/tha-34/D083070/82/00-11, May 2000.

Th. Aoust, "Thomox Neutronic Calculation", ThA/tha-34/D085012/82/00-08-B, May 18, 2000.

F. Druyts, "Meting van de Wigner Energie van Grafietmonsters uit BR1", Rapport IR-0004, Juni 2000.

Ch. De Raedt, B. Verboomen, A. Beeckmans de West-Meerbeeck, "Modelling of the Axial Burn-Up Distribution in BR2 Fuel Elements: Proposed Calculation Procedure", ChDR/chdr-34-A001052-211/00-04, June 16, 2000 - updated January 30, 2001.

Th. Aoust, "Determination of the dpa Value, the Fluence > 1 MeV and the Fluence > 0.1 MeV of the Pressure Tube of the CALLISTO IPS2, Irradiated from Cycle 0692A till Cycle 0100B", ThA/tha-34/D085012/260/00-01, June 26, 2000.

K. van der Meer, P. D'hondt, H. Aït Abderrahim, "Additional Data for the 3-D VENUS-2 Benchmark", TN-report - 0008, SCK•CEN, Mol, September 2000.

C. Delveau, "Comparaison des Méthodes Co/Ag et Co Recouvert de Cd pour la Détermination des Flux Thermique et Epithermique", Thesis, Institut Supérieur Industriel de Bruxelles, (in French), September 2000.

K. van der Meer, Th. Aoust, H. Aït Abderrahim, P. D'hondt, M. Willekens, "Evaluation of the Influence of Impurities, Photofissions, Burn-Up and Build-Up in Fissile Neutron Flux Dosimeters", SCK•CEN report R-3479, December 2000.

P. Van Uffelen, "Optimisation of the Numerical Parameters in the Fission Gas Release Model for LWR Fuel", report R-1330, Mol, December 2000.

Th. Aoust, Ch. De Raedt, "Thomox: Evolution Calculation", ThA/tha-34/D055420/82/00-19, December 11, 2000.

S. Pilate, T. Maldague, R. Jacqmin, Ch. Chabert, S. Van Winckel, Ch. De Raedt, J.C. Kuijper, G. Nicolaou, A.Ventura, "Nuclear Data for Advanced Mox Fuels", Final Report, EUR 19126 EN, 2000.