# Contents Scientific Report 2003

## Introduction  
Organisational chart  

### Reactor Safety  
Introduction  

#### Materials Research  
- Dislocation Density of Low-Alloy Reactor Pressure Vessel Steels  
- Stress Corrosion Crack Growth Simulation of Steels in LWR Conditions  
- Qualification of Uranium Silicide Dispersion Fuel for Research Reactors  
- Fracture Toughness by Broken Charpy V-notch Specimens  

#### Reactor Physics Research  
- REBUS-PWR International Programme at the VENUS Critical Facility  
- MYRRHA  
  - MYRRHA, a Multi-Purpose Irradiation Facility  
  - Vacuum Interface Compatibility Experiment (VICE) for MYRRHA  

#### Instrumentation  
- Optical Fibre Sensors for Temperature Monitoring in the BR1 Reactor  

### Radioactive Waste and Clean-up  
Introduction  

#### Low Level Waste  
- Performance Assessment for a Surface Repository in Mol-Dessel  

#### High Level Waste  
- Bentonite Barriers in a Performance Assessment: the BENIPA Project  
- Corrosion of Steel Containers for the Disposal of Radioactive Waste  
- Transport of Radionuclides in a Reducing Clay Sediment  
- Microfocus X-ray Tomography for Characterisation of Porous Materials  
- Modelling and Instrumentation Programme in the Connecting Gallery  

#### Decommissioning of Nuclear Power Plants  
- Industrial Decontamination and Recycling of Contaminated Metal Structures  
- Saving Money and Radiological Doses: the VISIPLAN Tool  

#### Conditioning of Waste  
- Reconditioning of Bituminised Radioactive Waste  

#### Minimization of Waste  
- Treatment of Tritiated Waste  

### Radiation protection  
Introduction  

#### Space  
- Physiological Approach to Monitor Space and Stress Responses in Bacteria  

#### Health Effects  
- How Normal and Cancerous Cells Respond to Radiation  
- Ionising Radiation on the Gene Expression of the Mouse Brain Embryo  

#### Radioactivity in the Environment  
- Sources and Exposures of Ionising Radiation in Flanders  
- Remediation of Uranium Mining Tailings in Mailuu Suu, Kyrgyzstan
INTRODUCTION

Excellence within the European Research Area

The national nuclear research centres were founded in the early fifties of previous century within a cocoon of national protection. The globalisation and the liberalisation of the nuclear supply and production markets led more and more to a loss of this protection. Moreover, the European Commission identified the loss of efficiency by fragmentation. The initiative of the European Research Area transformed research to a common product on the free market. Competition on a free market requires excellence and optimisation of services.

SCK•CEN recognised this evolution and is ready for an open collaboration and competition within the European Research Area, based on its intrinsic scientific qualities. The first call of the sixth Framework Programme of the Euratom fission research programme challenged the European research centres to enter a European matrix organisation of integrated projects and networks of excellence. SCK•CEN will participate to:
- NF-PRO (IP = Integrated Project): Near-field processes in geological repositories (as co-ordinator);
- ESDRED (IP): Engineering studies and demonstrations of repository designs;
- PERFECT (IP): Prediction of irradiation damage effects on reactor components;
- EURANOS (IP): European approach to nuclear and radiological emergency management and rehabilitation strategies;
- HOTLAB (NoE = Network of Excellence): European network on hot laboratories (as co-ordinator);
- ACTINET (NoE): Physics and chemics of actinides.

Moreover, SCK•CEN is involved in several co-ordination actions, specific targeted research projects and specific support actions in waste management, nuclear safety, radiation protection and training.

The fifth Framework Programme introduced already IP-like projects, such as ADOPT, on the development of accelerator driven systems for the transmutation of long living actinides (leading to EUROTRANS in FP6) and ENEN, on the harmonisation of nuclear education. The latter led to the creation of a European non profit organisation with extended objectives.

Last but not least, SCK•CEN continues its contribution to the worldwide fusion research and to specific aspects of the European space research. In this context we participate to NEMO, the network of excellence on micro-optics.

Networks of excellence aim the sharing of post irradiation examination infrastructures in Europe.
Availability to the community

Being a national nuclear research and service centre, SCK•CEN has to ensure a flexible support function to the Belgian authorities, the industry and the public. We keep the needed know-how and the infrastructure available to cope with current problems of the Belgian nuclear community in a broad sense.

SCK•CEN is the scientific partner of the utilities for problems related to the ageing of power plants and of the waste producers and the waste management agency for the search of an accepted solution for the long term policy for each kind of radioactive waste. The safety authorities rely on SCK•CEN for its radiation protection expertise, e.g. in the context of the nuclear emergency preparedness plan and the radiological survey of the territory and for the Belgian support to the safeguards programme of IAEA.

Focus on the core competencies

The identity of a research centre is largely related with the core capacities, in particular with the large research infrastructures. SCK•CEN operates three research reactors (BR1, VENUS and BR2). The MYRRHA project, aiming the construction of an accelerator driven system, is planned to be continued within the future EUROTRANS integrated project. In parallel with the generic work within the European contract, such a device is still considered as the first candidate to replace BR2 as a material testing facility.

The expertise proven for nuclear problems is today more and more extended to the mastering of medical exposures and to the policy with respect to naturally occurring radioactive materials outside the fuel cycle.

SCK•CEN launched also a programme related to the integration of societal aspects in the nuclear dialogue. Several young scientists with a non-technical or a mixed background perform research on topics as e.g. ethical aspects of waste disposal, risk perception and decision making, sustainability of nuclear power, liabilities, ... This initiative triggered a mutual fertilisation of the technical and human science communities.

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Reactor Physics & MYRRHA Department
Scientific Staff

Supporting Staff
The Reactor Safety Division focuses its programme on the development of expertise on materials behaviour under irradiation with emphasis on phenomena that occur in light water reactors. Within the Belgian context, the programme supports the safe exploitation of its nuclear power plants and the extention of the burn-up of reactor fuel for economic reasons. Furthermore, as nuclear energy needs international public acceptance with respect to safety and efficient management of generated nuclear waste, the Reactor Safety Division enhanced its efforts on the MYRRHA project. MYRRHA, an accelerator driven sub-critical system, might have the potential to cope in Europe with the above mentioned constraints on acceptability.

The Reactor Safety Division gathers three research entities: the Reactor Materials Research department (RMR), the Reactor Physics and MYRRHA department (RF&M) and the Instrumentation department (INSTR).

The objectives of RMR are:
- to evaluate the integrity and behaviour of structural materials used in nuclear power industry;
- to perform research to unravel and understand the parameters that determine the material behaviour under or after irradiation;
- to contribute to the interpretation, the modelling of the materials behaviour;
- to develop and assess strategies for optimum life management of nuclear power plant components.

The programmes within the Reactor Materials Research department concentrate on four distinct disciplines:
- Fusion (mechanical testing and corrosion);
- Irradiation Assisted Stress Corrosion Cracking (IASCC);
- Nuclear Fuel;
- Reactor Pressure Vessel Steel (RPVS).

The fusion research activities at RMR are an integral part of the SCK•CEN fusion research programme reported elsewhere in this report.

The corrosion research programme aims to clarify the mechanisms that contribute to IASCC. Three complementary activities are developed:
- the modelling of IASCC and related phenomena in a computer code, that takes crucial parameters of the material, its environment and their interaction into account;
- experimental studies of IASCC in LWR conditions in order to generate reference data for modelling;
- the development of dedicated instrumentation to detect and monitor the occurrence of (IA)SCC.

The fuel research activities combine both applied and fundamental research. The latter focuses on solid state research of nuclear fuel, on modelling of fuel behaviour and on the definition, technical preparation and execution of in-pile instrumented irradiation experiments. The applied research essentially remains market-driven. The tendencies of future research are the long-term intermediate storage of spent fuel and issues related to further increase discharge burn-ups.

Safe operation of nuclear power plants relies a.o. on the integrity of the reactor pressure vessel. Neutron exposure induces temperature dependent embrittlement of the vessel and alters the mechanical properties of the vessel materials. It is, therefore, of prime importance to monitor the material degradation by surveillance programmes. SCK•CEN is in charge of the RPVS surveillance of the Belgian nuclear power reactors and runs in parallel a research project called the Electrabel Framework agreement that supports the development of tools of use for the Belgian NPP’s. Important efforts are made to integrate the discipline of material modelling into the research programmes and to support experimental projects with modelling tools. The programme on multi-scale modelling of material degradation has its applications not only for pressure vessel steel but also for candidate fusion materials.

In 2003, the RMR succeeded successfully to incorporate its activities and competencies in material research and modelling into the integrated project PERFECT within the 6th Framework Programme of the EU.

The objectives of the Reactor Physics & MYRRHA department are:
- to design, complete and analyse benchmark experiments in SCK•CEN facilities (VENUS, BR1, BR2 and BR3) or elsewhere, leading to reference data for code validation in the fields of:
  - reactor dosimetry;
  - core physics;
  - reactor physics;
  - neutron and gamma shielding;
  - ADS systems;
and for specific conditions or new situations such as:
- MOX fuel in LWR;
- transmutation of transuranium elements (TRUs) and long lived fission products (LLFPs) in burner reactors;
- development of MYRRHA;
- burn-up credit.

- to maintain, improve and develop experimental and computational capabilities and tools in the above fields and new areas such as:
  - high energy particle physics;
  - reactor physics in sub-critical systems.

To comply with these objectives RF&M in collaboration with RMR has continued the international programme 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. In the frame of this programme a world premiere experiment has been completed in 2003, consisting in loading a MOX burned fuel bundle in the zero power light water critical facility VENUS.

Maintaining high level skills in the nuclear field can only be ascertained if ambitious and innovative projects with clear objective and with realistic milestones are conducted. This is the main objective behind the MYRRHA project that in a first phase aims to design an experimental ADS followed by its construction if the technical and financial requirements are met. As such it was decided to continue the conceptual design of MYRRHA until mid-2004 and to focus the R&D-activities on those topics that could influence its design. These are:
- the hydraulic flow design of the window-less target;
- the vacuum interface compatibility for the window-less design;
- the corrosion behaviour of the structural materials in liquid metal;
- the structural material behaviour under irradiation;
- the visualisation under liquid metal;
- the remote-handling operation of MYRRHA.

In 2003, the MYRRHA design activity has been focused on upgrading the total thermal power of the sub-critical reactor up to 50 MW in order to fulfil the objectives assigned to the MYRRHA irradiation facility in terms of fast flux. As a consequence the core and associated components have been adapted accordingly. MYRRHA, being intended to be operated with remote handling, particular attention has been given to the conceptual design of in-vessel robots. These devices are to be deployed inside the vessel either for visual inspection by on-line ultrasonic sensing or for repair in case of incidents such as fuel element or spallation loop circuit failure.

Within the 6th Framework Programme of the EU, the MYRRHA-team intends to play an important role in IP-EUROTRANS, an integrated project on transmutation.

In all irradiation experiments, appropriate instrumentation technology is of primordial importance. The Instrumentation department evaluates the potentials of instrumentation technologies under severe constraints of nuclear applications, such as the control of nuclear power plants and the remote monitoring of waste repositories and hazardous materials.

The Instrumentation department pays particular attention to:
- the application of optical fibre technology in the umbilical link of a remote handling unit for use during maintenance of a fusion reactor;
- the radiation hardening of plasma diagnostic systems;
- the study on new reactor instrumentation.

Its projects cover also:
- space applications related to radiation-hardened glasses;
- developments of new approaches for dose, temperature and strain measurements;
- assessments of radiation-hardened sensors and motors for remote handling tasks;
- studies of dose measurement systems, including the use of optical fibres.

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Scientific Report 2003
Dislocation Density of Low-Alloy Reactor Pressure Vessel Steels

Background
Many physical properties of materials are related to the arrangement of the atoms in the crystal lattice of the material. Mechanical properties such as tensile strength are governed by the amount of defects in the crystal lattice and their mobility. Irradiation alters the distribution (size and density) of these defects and therefore the dislocation motion through these defects. It is therefore important to determine the dislocation density of materials before irradiation as an input parameter in radiation damage modelling.

Objectives
To determine the dislocations density present in different commercial reactor pressure vessel steels, thin foil samples were examined by transmission electron microscopy (TEM). The chemical compositions of the materials used are listed in a table on the next page.

Principal results
The thin foil samples are examined with a JEOL JEM3010 scanning transmission electron microscope at an accelerating voltage of 300 kV. A series of micrographs, two of them are shown on the next page, was taken in the weak beam dark field mode at a magnification of approximately 30000x. Each bright line in the micrograph corresponds to one dislocation. For a precise determination of the dislocation density in a thin foil, it is necessary to determine first the thickness of the observed region. The sample thickness is determined by recording convergent beam electron diffraction (CBED) patterns. CBED patterns present diffraction disks containing fringes as in the figure on the next page. The spacing between the fringes is related to the thickness of the sample. To calculate the thickness the following formula is used

\[ \frac{1}{t^2} = \frac{S_i}{n_i} + \frac{1}{n_i} \left( \frac{1}{\xi_g} \right)^2 \]

with \( t \) the effective specimen thickness, \( n_i \) the number of the dark fringe (1, 2, 3, ...) and \( \xi_g \) the extinction distance. \( S_i \), the so-called deviation parameter, can be determined using

\[ S_i = \frac{\lambda}{d_{hkl}^2} \frac{\Delta \theta_i}{2 \theta_B} \]

where \( \lambda \) is the electron wavelength, \( d_{hkl} \) the d spacing corresponding to the chosen diffraction spot, \( \Delta \theta_i \) the distances from the central bright fringe to the dark fringes in the dark-field disk and \( 2 \theta_B \) the distance in the CBED pattern corresponding to the Bragg angle of the diffracted beam. Based on the measurement a diagram is made in which \((S_i/n)^2\) is plotted against \((1/n)^2\) and a line is fitted through the data points. The intercept of this line with the \((S_i/n)^2\) axis gives \((1/t^2)\) and hence the thickness of the sample, while the slope gives the extinction distance \((1/\xi_g)^2\).

Provided that the dislocations are randomly oriented, their densities are given by

\[ \rho = \frac{2NM}{Lt} \]

where \( N \) is the number of intersections that a test circle laid on the micrograph makes with the dislocations, \( L \) is the circumference of the test circle, \( M \) is the magnification of the micrograph and \( t \) is the thickness of the sample.

The resulting dislocation densities of the various pressure vessel steels are found to be about \(10^{14} \text{ m}^{-2}\), as can be seen in the table on the next page.

Main contact person
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### Chemical composition of various pressure vessel steels examined by TEM.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cu</th>
<th>Ni</th>
<th>P</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>JRQ</td>
<td>0.14</td>
<td>0.84</td>
<td>0.017</td>
<td>0.18</td>
<td>0.24</td>
<td>1.42</td>
<td>0.004</td>
<td>0.14</td>
<td>0.51</td>
</tr>
<tr>
<td>HSST-03</td>
<td>0.12</td>
<td>0.62</td>
<td>0.011</td>
<td>0.25</td>
<td>0.26</td>
<td>1.36</td>
<td>0.017</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>18MND5 BM</td>
<td>0.13</td>
<td>0.64</td>
<td>0.008</td>
<td>0.18</td>
<td>0.25</td>
<td>1.55</td>
<td>0.002</td>
<td>0.18</td>
<td>0.5</td>
</tr>
<tr>
<td>18MND5 W</td>
<td>0.12</td>
<td>1.01</td>
<td>0.021</td>
<td>0.05</td>
<td>0.19</td>
<td>1.3</td>
<td>0.008</td>
<td>0.12</td>
<td>0.45</td>
</tr>
<tr>
<td>A508 W</td>
<td>0.05</td>
<td>0.78</td>
<td>0.017</td>
<td>0.07</td>
<td>0.22</td>
<td>1.57</td>
<td>0.005</td>
<td>0.14</td>
<td>0.48</td>
</tr>
<tr>
<td>20MnMoNi55</td>
<td>0.11</td>
<td>0.8</td>
<td>0.007</td>
<td>0.19</td>
<td>0.20</td>
<td>1.29</td>
<td>0.008</td>
<td>0.12</td>
<td>0.53</td>
</tr>
</tbody>
</table>

### Dislocations in sample JRQ (left) and 20MnMoNi55 (right).

### CBED pattern of sample 18 MND5 Weld.

### Dislocation density of various pressure vessel steels.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample thickness (Å)</th>
<th>Measured dislocation density (m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JRQ</td>
<td>1428</td>
<td>1.80 x 10⁴</td>
</tr>
<tr>
<td>HSST-03</td>
<td>1735</td>
<td>2.10 x 10⁴</td>
</tr>
<tr>
<td>18MND5 BM</td>
<td>1152</td>
<td>5.70 x 10⁴</td>
</tr>
<tr>
<td>18MND5 W</td>
<td>1571</td>
<td>2.39 x 10⁴</td>
</tr>
<tr>
<td>A508 W</td>
<td>442</td>
<td>4.46 x 10⁴</td>
</tr>
<tr>
<td>20MnMoNi55</td>
<td>1671</td>
<td>1.14 x 10⁴</td>
</tr>
</tbody>
</table>
STRESS CORROSION CRACK GROWTH SIMULATION OF STEELS IN LWR CONDITIONS

Background
Stress corrosion cracking (SCC) is a significant age-related degradation mechanism for nuclear reactors. The complex interaction between a stressed material and its LWR environment under neutron irradiation warrants an in-depth study of numerical simulation to complement experimental work.

Objectives
The objective of the research is to (1) evaluate the phenomena participating in stress corrosion cracking of stainless steels in a light water reactor environment, (2) to predict the SCC behaviour of in-reactor components and (3) to use the developed tools for the design against SCC.

Principal results
The electrochemical conditions at the crack tip determine the mechanism of crack propagation and strongly influence the crack propagation rate. These conditions have been calculated for a wide range of parameters (e.g. crack length, dissolved oxygen concentration, kinetics) using finite element simulations. The obtained results show that, with increasing crack length, the crack-tip conditions (e.g. pH, chloride concentration, electrode potential) reach a plateau at about 7 mm crack length.

In order to understand the mechanism behind SCC of stainless steel in a boiling water reactor environment and to develop a mitigation strategy, the role of the electrochemical processes, inside and outside the crack, has to be examined. The question as to where, internally or externally to the crack, the anodic crack-tip current is balanced has raised quite some international debate. The performed numerical calculations demonstrate that in short cracks the metal dissolution current emanating from the crack tip is balanced mainly by oxygen reduction on the external wall. As the crack propagates the pH of the internal crack environment decreases. This stimulates the hydrogen evolution reaction inside the crack, whilst the oxygen reduction reaction is unaffected. Hence, the anodic crack-tip current and the passive internal wall current are increasingly balanced by hydrogen evolution within the crack.

Stress corrosion cracking of stainless steel in a light water reactor environment is considered to be electrochemical in nature, yielding a fixed relation between the crack propagation rate and the crack-tip current (described by Faraday's law). This makes it feasible to split the numerical simulation into two parts, both yielding a potential-current relation at the crack's tip. A first potential-current relation can be obtained by considering a fixed external environment and geometry. Numerical simulations for a range of crack tip currents show the decrease of the crack tip potential with the crack tip current (curve 1, the last figure on the next page). A second current-potential relation can be obtained from a constitutive relation of the crack tip interface. Indeed, the crack propagation rate is assumed to be dependent on the crack tip's potential and the stress intensity (curve 2, ibid). The intersection of both curves yields the actual crack tip potential and current, and consequently the actual crack propagation rate.

Future developments
The presently developed simulation tool predicts the electrochemical conditions in cracks and crevices in high temperature water. Future developments include the incorporation of radiolysis, the implementation of boron-lithium water chemistry and the effect of stress intensity. Some of these efforts will be pursued in a EU 6th Framework Integrated Project called PERFECT.

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Main reference
Percentage of the anodic crack-tip current balanced by the hydrogen evolution (HE) and oxygen reduction (OR) as a function of crack length.

<table>
<thead>
<tr>
<th>Crack depth, mm</th>
<th>HE</th>
<th>OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1%</td>
<td>99%</td>
</tr>
<tr>
<td>2.5</td>
<td>43%</td>
<td>57%</td>
</tr>
<tr>
<td>5</td>
<td>83%</td>
<td>17%</td>
</tr>
<tr>
<td>7.5</td>
<td>95%</td>
<td>5%</td>
</tr>
<tr>
<td>10</td>
<td>97.5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Variation of the pH and the electrode potential at the crack-tip as the crack grows.

Current density profile along the crack and external wall. The anodic crack-tip (not shown) and passive wall currents are balanced by the hydrogen evolution and oxygen reduction reactions.

Two potential-current relations. Curve 1 represents the constitutive behaviour of the tip's interface. Curve 2 represents the environment's response to the tip current. The intersection yields the actual tip potential and current and the crack's propagation rate.
QUALIFICATION OF URANIUM SILICIDE DISPERSION FUEL FOR RESEARCH REACTORS

Background
The international intention to withdraw highly enriched uranium (HEU ≥ 90% 235U) from the commercial market, to eliminate any proliferation risk, requires the development of new fuels based on low enriched uranium fuel (LEU ≤ 20% 235U). In LEU fuel the reduction of the enrichment or fissile material is compensated by a higher uranium loading density in order to preserve the irradiation characteristics, i.e. high neutron flux densities. The qualification of LEU fuels requires irradiation tests to demonstrate the ability of the fuel to withstand research reactor operating limits (i.e. high power densities) up to economically viable burn-up values. Among the fuels considered is U3Si2 fuel dispersed in an aluminium matrix. U3Si2 has been found to perform well under irradiation tests, even with uranium densities up to 5.0 gU/cm3.

Objectives
In order to gain insight on the performance limits of U3Si2 fuel, fuel plates with a fissile material density of 5.1 and 6.1 gU/cm3 have been irradiated in our BR2 reactor. The plates have been subjected to severe conditions corresponding to a maximum mean hot plane heat flux of 520 W/cm². The irradiation program was stopped after the second cycle based on the visual inspection and wet sipping tests of the elements, showing degradations on the outer aluminium surfaces of the U3Si2 plates and the release of fission products. In a post-irradiation examination (PIE) program the microstructure changes causing this degradation were analysed.

Principal results
A special device has been designed and constructed in the hot-cells permitting to scan the thickness of the complete fuel plate surface with an accuracy of ± 5 µm. The result of the thickness measurement of the fuel plate with a density of 6.1 g U/cm³ is presented on the next page. An appreciable swelling of the plate is revealed, located at the left side of the plate, at a position azimuthally located near the stiffener, where the fission density shows a maximum.

Future developments
The FUTURE experiment includes the irradiation in the BR2 reactor, in envelope conditions, of two U-7wt% Mo dispersion fuel plates, another LEU candidate fuel for high flux research reactors. Currently the post irradiation campaign is being performed.

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Main reference
The burn-up profile (left) and the thickness measurements (right) of the fuel plate, show that the most deformed area coincides with an area of high burn up c.q. high heat flux.

Respectively an image of the fuel plate over the fuel width and a micrograph of the meat obtained from the section of the fuel plate that has been submitted to ~450 W/cm² (a,b), and ~550 W/cm² (c,d).

A first layer (L1), at the outer waterside surface of the cladding, is a dense oxide layer, without precipitates but containing some Mg. Below this layer, a pitting corrosion layer with characteristic corrosion pits can be seen (L2). Underneath, a network of grain boundaries is clearly delineated in the Mg and O X-ray maps (L3). It is also noticed that in this layer the grain interiors have been oxidised and contain oxidised Mg. In layer 4 (L4) only the grain boundaries have been affected and the grain interior shows clustering of Mg but as yet unoxidised. At layer L4 and L5, one can observe that the Mg and Si particles are associated and form precipitates (MgSi₂) in the cladding material. Close to the meat (L5), a layer of relatively intact cladding is still present. At the interface between cladding and the meat, a layer of oxidised Mg is observed (L6).
Background
The vessel of a Pressurized Water Reactor (PWR) is an essential component for which integrity should be guaranteed during the whole lifetime of the reactor. In the core region, the Reactor Pressure Vessel (RPV) base material and welds are subject to high neutron fluence and thermal ageing. Both these phenomena can induce embrittlement of the reactor vessel materials. To ensure safe operating conditions of our Belgian PWR’s, the RPV material properties are monitored within a mandatory surveillance programme, that contains Charpy specimens made of representative RPV material. The principal purpose is to evaluate the fracture toughness of the RPV material within a structural integrity assessment programme. In Belgium an enhanced surveillance program has been developed to better assess reactor vessel integrity. One component of this enhanced surveillance program is the direct fracture toughness evaluation using the recently standardized master curve concept.

The amount of remaining representative irradiated material for the RPV’s is very limited and consists mainly of half broken Charpy specimens. Therefore, fracture toughness measurements should be obtained from small or miniaturized specimens. The most widely used technique is to reconstitute Charpy specimens from broken halves. On the other hand, we carefully designed the Miniature Compact Tension, MC(T), geometry that uses four times less material. In addition, the machining cost for the MC(T) is two to three times lower than for reconstitution.

Objectives
The objective is to qualify the use of the MC(T) specimen on an actual surveillance program of a Belgian nuclear power plant. The qualification is performed by comparing results with reconstituted Precracked Charpy (PCCv). In addition, the conservatism associated with the semi-empirical classical surveillance approach can be assessed.

Principal results
The results in the transition using PCCv and MC(T) are in excellent agreement (Fig. 1). MC(T) is a promising geometry that is easy to obtain and that uses a smaller amount of valuable material.

The conventional regulatory ASME approach demonstrates the safety of the RPV. However, the direct fracture toughness master curve methodology shows that additional safety margins are available (Fig. 2).

Future developments
Future development will be mainly concentrated on the determination of the initiation fracture toughness and tearing resistance in the upper shelf region using the attractive MC(T) geometry.

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Main reference
Fig. 1: Results in the transition using PCCv and MC(T) are in full agreement.

Fig. 2: Fracture toughness measurement compare to conservative ASME lower bound curve.

Machined 10 mm MC(T) specimen prior precracking

Specimen instrumented with a clip gauge.
Background
Present criticality safety calculations of irradiated fuel often have to model the fuel as fresh fuel, since no precise experimental confirmation exists of the decrease of reactivity due to accumulated burn-up. In other occasions only fissile depletion is allowed to be taken into account and the influence of fission products has to be disregarded. The fact that this so-called “burn-up credit” cannot (completely) be taken into account has serious economical implications for transport, storage and reprocessing of irradiated fuel. For long-term geological storage it is almost imperative to apply burn-up credit.

Objectives
The aim of the REBUS-PWR programme is to establish an experimental benchmark data base for validation of reactor physics codes for the calculation of the loss of reactivity due to burn-up for PWR (and BWR) fuel, both for UO₂ and MOX fuel bundles.

The programme consists of the loading of five different configurations at the VENUS critical facility: an entire fresh UO₂ reference configuration, a fresh and a spent UO₂ fuel configuration and, a fresh and a spent MOX fuel configuration. The spent UO₂ fuel coming from the German Neckarwestheim NPP has a burn-up of 51 GWd/tM, whereas the spent BR3 MOX fuel has a burn-up of 20 GWd/tM. For all these configurations, the critical water level and reactivity effect are determined. Except for the reference configuration, fission-rate and flux distributions are measured in the different configurations.

To allow a thorough validation of reactor physics codes, the fresh and spent fuel are well characterised by non-destructive and destructive techniques.

Principal results
In June 2003, the irradiated BR3 MOX bundle was successfully loaded into the VENUS reactor. This event can be considered as a world-premiere, since it is the first time that an irradiated fuel bundle is loaded into a zero-power critical facility such as VENUS. Consequently, the entire experimental programme associated with this first irradiated configuration was successfully completed. The reactivity effect of replacing a fresh MOX bundle by the same bundle after irradiation in a power reactor was hence determined experimentally.

Future developments
Next year, the current REBUS-PWR project will be extended with a BWR phase. This BWR phase will contain a configuration with 16 1m irradiated BWR-rods with a burn-up ranging between 50 GWd/tM and 70 GWd/tM. Besides the determination of the reactivity effect, a thorough destructive and non-destructive characterisation of the investigated fuel rods will be performed.

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Lifting of the REBUS container out of the transport container.

Positioning of the REBUS container on the supporting structure over VENUS.

REBUS BWR MOX bundle made of 16 irradiated BWR fuel rods + 8 fresh PWR MOX. Fission rate and flux measurements positions are indicated. A and R stand for the axial and radial fission rates. The black dots indicate the axial flux measurement positions.

Gross gamma scan of a 4m spent fuel rod and identification of cutting schemes.
MYRRHA, a Multi-Purpose Irradiation Facility

Background
Since 1997 SCK•CEN is developing MYRRHA in collaboration with various European laboratories as a multipurpose Accelerator Driven System (ADS) for R&D applications. In its present status, the MYRRHA project is based on the coupling of a (350 MeV * 5 mA) proton LINAC with a liquid Pb-Bi windowless spallation target, with a neutron multiplying sub-critical core (SC) of 50 MWth cooled by Pb-Bi. The spallation target circuit is fully separated from the core coolant as a vacuum tight unit whose internal heat production is removed to the SC pool. The fast core is fuelled with typical fast reactor fuel hexagonal assemblies with an active length of 600 mm. The three central hexagon fuel assembly positions are housing the spallation module. The MOX fuel has Pu contents of 30% and 20%. The facility is designed to be operated to a large extent thanks to remote handling (RH). Therefore, the design called for a dedicated building containment arrangement made compatible with Remote Handling (RH) operation.

Objectives
The MYRRHA project team is developing a multipurpose neutron source for R&D applications on the basis of an ADS. This project is intended to fit into the European strategy towards an ADS Demo facility for nuclear waste transmutation. It is also intended to be a European, fast-neutron-spectrum, irradiation facility allowing various applications.

Principal results
In 2003, the main effort was devoted to revisit the main components dimensions as the total nominal power of MYRRHA was upgraded to 50 MWth in order to have a more capabilities of transmutation demonstration in the facility. The ex-vessel operation being based on the remote handling (RH) approach such as presently in use at the JET Fusion machine (figure 1), the feasibility study of such a system has been successfully completed in collaboration with Oxford Technology Ltd, OTL (figure 2).

As concern the in-vessel robotics design a feasibility study has also been completed in collaboration with OTL for the In-Vessel Inspection Manipulator (IVIM) (figure 3) that consists of a robotic arm equipped with an ultrasonic camera as well as for the In-Vessel Repair Manipulator equipped with various tools to perform repairs and maintenance under Pb-Bi (figure 4).

The development of the ultrasonic sensors to be used for visualisation under Pb-Bi at temperatures up to 400°C and in hard radiation conditions has been progressed. LiNbO3 sensors as well as GaPO4 are under investigation and have been tested under Pb-Bi for ultrasonics transmission and reception. Resistance for gamma radiation up 2.5 MGy has been successfully tested for the LiNbO3 and is planned for the GaPO4. Resistance to neutron radiation is planned in 2004.

A five year support R&D programme has been established covering the following topics:
- problems of thermo-hydraulic feasibility of the windowless spallation target;
- the Vacuum Interface Compatibility with the hot liquid Pb-Bi spallation target reservoir through VICE (Vacuum Interface Compatibility Experiment);
- structural Material studies under irradiation focused on T91 and A316L;
- fuel pin and assembly development and qualification;
- structural material corrosion under Pb-Bi studies and mitigation;
- robotics development for In Service Inspection & Repair (ISI&R);
- instrumentation development for O2 control, sub-criticality monitoring, free-surface sensing and monitoring, ultrasonic visualisation under Pb-Bi;
- Large components feasibility development and testing (HX, mechanical primary pumps, MHD pumps, Pb-Bi conditioning and filtering in pool configuration).

Future developments
In 2004 the objectives of the MYRRHA project are to finalise the pre-design phase with the new power level including the safety assessment of the proposed design and to fit MYRRHA in the prospective of the FP6 integrated project for serving as an eXperimental Transmuter Accelerator Driven System (XT-ADS). It is also decided to launch the above support R&D programme taking into account the developments at the international level.

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Main reference
Figure 1: JET Remote Handling Boom carrying a Radio Frequency antenna (Reproduced by permission of EFDA-JET).

Figure 2: Virtual reality picture showing two of the booms and telemanipulators working above the MYRRHA lid.

Figure 3: Virtual Reality view of the In-Vessel Inspection Manipulator in action.

Figure 4: IVRM (In-Vessel Repair Manipulator) Concept – Manipulating at the Fuel Handling Robot.
**Vacuum Interface Compatibility Experiment (VICE) For MYRRHA**

**Background**

Lead bismuth eutectic (LBE) is the spallation target and cooling material in MYRRHA. However, “off-the-shelf” LBE cannot be used in a spallation loop because possible insoluble contaminations may accumulate at ridges in the loop giving rise to obstructions in the flow. Also, in order to sufficiently retard the corrosion of LBE on stainless steel, the oxygen level in the LBE must be controlled to the level of about $10^{-6}$ wgt%.

As untreated LBE will have a much higher oxygen content, a cleaning and conditioning procedure must be developed. For MYRRHA a windowless target is chosen due to the high proton current density enforced by the required neutron flux performance of the compact subcritical core. The target and the proton beam-line share a common vacuum and thus the LBE must be vacuum compatible to avoid plasma formation that would otherwise lead to sputtering of the beam-line walls and in extreme cases even to beam clogging. As MYRRHA is the first ADS project to adopt a windowless design, a quantitative experimental compatibility assessment of the free LBE target surface with the vacuum of the beam tube in realistic circumstances must be obtained.

**Objectives**

The VICE set-up consists of two vessels that serve the double goal of the project. In the barrel-shaped Pre-Conditioning ultra-high (UHV) vacuum Vessel (PCV) the initial outgassing and conditioning of about 100 kg of liquid Pb-Bi is studied. This includes skimming, plasma surface cleaning and oxygen control/monitoring by H$_2$/H$_2$O gas treatment up to 500°C. The VICE apparatus is a 5 m high one-to-one UHV scale model of the vacuum conductance geometry of the lowest part of the MYRRHA beam line connecting to the target. Here, long-term outgassing and target material evaporation, and the gas transport properties of the beam line are studied as a function of pressure and temperature by gas differential calibration combined with high-resolution quadrupole mass spectrometry. Also the dynamic behaviour of non-radioactive volatile spallation products that is related to issues of waste management and long-term operation of the spallation loop, is to be investigated.

**Principal results**

In 2003 efforts were mainly focussed on the PCV. Commissioning tests showed that the relative spread of the temperature at various positions on the vessel is less than 2% while the long-term temperature stability is better than 1°C. The empty outgassing rate after a 6 h bake-out at 400°C was $3.2 \times 10^{-3}$ mbar l/s corresponding to a base pressure of $4 \times 10^{-5}$ mbar. The vessel was then loaded with 100 kg of LBE. Characteristic spikes in the pressure readout due to the release of gaseous inclusions in the LBE ingots during melt, were observed. At 150°C a pressure of $1 \times 10^{-4}$ mbar was reached in 24 h. Yet, even after several days, stirring of the melt induced additional gas emanation that increased the pressure to above $10^{-3}$ mbar showing the importance of stirring the melt for outgassing. When heating the LBE to 400°C we found that even when the LBE is liquid, outgassing often occurs through the release of bubbles. After 7 days of pumping, a pressure of $4 \times 10^{-6}$ mbar was achieved. This corresponds to an outgassing level that is about two orders below the critical level for plasma formation albeit that gas treatment for oxygen control had not yet taken place. Subsequently, the vessel was opened at 150°C in order to skim the surface layer (PbO) off the LBE. Also, the effectiveness of the magneto-hydrodynamic stirring was verified visually. After skimming, outgassing reduced to a level where a pressure of $8 \times 10^{-4}$ mbar at 150°C could be obtained. Also, the first gas treatment tests have taken place. However, initially a diffuser with a 100 µm sintered stainless steel filter was used to distribute the H$_2$/H$_2$O mixture in the carrier Ar gas in the melt to produce very fine bubbles. The sintered material appeared not to withstand immersion in LBE for extended periods of time which is probably due to wetting of the LBE on the large surface of the sintered part. Tests are undertaken with a much coarser diffuser using thick walled stainless steel tubing and 2 mm holes.

**Future developments**

At present the project is concentrated on the development of the LBE cleaning and conditioning procedures. When these are established, the transfer of the treated LBE to the VICE apparatus can take place. Here, detailed LBE outgassing and evaporation experiments will take place.

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The inside of the upper lid of the PCV (Pre-Conditioning ultra-high (UHV) vacuum Vessel) showing internal thermocouples, glow discharge electrode, inspection window and inlet tube for gas treatment.

Right: The oxygen probe.

The pre-conditioning vessel being loaded with LBE (Lead bismuth eutectic) ingots.

The LBE (Lead bismuth eutectic) outgassing curve between 200°C and 400°C. Outgassing mainly occurs in spikes (bubble formation).
OPTICAL FIBRE SENSORS FOR TEMPERATURE MONITORING IN THE BR1 REACTOR

Background
Our previous work showed that commercially available fibre optic sensors may need to be redesigned to withstand substantial radiation doses, in particular when their working principle relies on broad spectrally-encoded and intensity-based measurements. We already showed that fibre optic sensors which spectrally encode the sensing information on a narrowband of wavelengths ($\Delta \lambda < 5$ nm) have a higher radiation acceptance level because of their insensitivity to broadband radiation-induced loss. Starting from this conclusion, we extensively evaluated FBG (Fibre Bragg Grating) sensors in various nuclear environments, both gamma and mixed gamma-neutron fields. Our results evidenced the radiation hardness of COTS (Commercial Off The Shelf) temperature sensor FBGs written in naturally photosensitive optical fibres during accelerated irradiation tests.

Objectives
Predicting the response of components or systems exposed to low dose rate ionising radiation based on accelerated tests is often very difficult. In 2002, we evaluated the long term reliability of FBG temperature sensors, in operation since January 2000, in our BR1 reactor. These sensors are multiplexed on a single optical fibre, as shown on the next page. They were therefore exposed to low dose rate mixed gamma-neutron radiation during more than three years.

Principal results
The FBG sensor is an all-fibre intrinsic fibre optic sensor that acts a wavelength selective mirror that reflects a narrow band of wavelengths centred around the so-called Bragg wavelength $\lambda_B$. The Bragg wavelength varies linearly with temperature with a sensitivity of about $10 \text{ pm/}^\circ\text{C}$. When exposed to ionising radiation, the centre wavelength of FBG sensors shifts towards longer wavelengths. In March 2003, the FBG sensors have experienced a total gamma dose of 3 MGy and a total neutron fluence of $10^{18}$ n/cm². The sensors were measured in reflection using industrial fibre optic sensor instrumentation (FBG-IS system, Micron-Optics, USA). A typical temperature measurement is shown on the next page.

The spectral characteristics of the FBGs written in naturally photosensitive fibre have reached long term stability. The temperature sensitivity was found to remain unaffected by the long term irradiation allowing to perform a temperature measurement change with an accuracy better than 3°C, which is acceptable for many temperature measurement applications in nuclear installation monitoring.

Future developments
We showed the long term reliability of COTS fibre optic sensing technology in nuclear environments. Future work will be focused on radiation-tolerant all-fibre data link architecture that could manage FBG sensors using wavelength division multiplexing.

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Main reference
Figure 1: Spectra of multiplexed FBGs (Fibre Bragg Grating) inserted in the nuclear reactor after more than three years. (November 2002)

Figure 2: In-reactor core temperature measure using FBG (Fibre Bragg Grating) sensors (March 2003)
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Waste Management for a Sustainable Development

Mission
The primary mission of the “Radioactive waste and clean-up” division is to propose, develop, and assess solutions for a safe, acceptable and sustainable management of radioactive waste.

Therefore, and according to Agenda 21\(^1\) the Radioactive Waste and Clean-up division:

- “Promotes research and development of methods for the safe and environmentally sound decommissioning of nuclear installations”;
- “Promotes research and development of methods for the safe and environmentally sound treatment, processing and disposal, including deep geological disposal, of high level radioactive waste”;
- “Conducts research and assessment programs evaluating the health and environmental impact of radioactive waste disposal.”
- “Provides, as appropriate, assistance to developing countries to establish and/or strengthen radioactive waste management infrastructures, including legislation, organisations, trained manpower and facilities for the handling, processing, storage and disposal of wastes generated from nuclear applications”.

Although most of these activities are performed in the frame of a Belgian institutional program, the division anticipates also future potential problems and new orientations in the nuclear fuel cycles.

- We are developing processes to “mineralize” previously conditioned waste as well as not yet conditioned radioactive waste (e.g. bitumen and sodium);
- We test and assess alternative to the PUREX process in the frame of bilateral collaborations with foreign institutions;
- We participate in a European “Transmutation & Partition” Network of Excellence.

Science and citizenship
Although we know that sound and safe solutions are proposed or available for the disposal of radioactive waste, we understand distrust of the population towards proposal implying the safety of many future generations. Therefore the SCK•CEN is developing the Program of Integration of Social Aspects in Nuclear Science and Technology (PISA). SCK•CEN started three years ago this structured program on social aspects in nuclear science and technology projects, with the support of a number of young scientists, coming from different disciplines and universities. Societal challenges are covered by five research tracks and three horizontal reflection groups. The division is more involved with the “waste” issues, namely ethics and expert culture and their influence on nuclear waste decision making, taking into account the involvement of relevant actors (public, workers, policy advisory councils). The program contributes to a transdisciplinary learning process to improve trust by increasing proactive problem solving capacity, internal/external communication.

Training, education and consultancy
Because we consider that knowledge leading to safety is not the property of a limited numbers of scientists but is a part of the world scientific patrimony, we try to deal our experience with other societies and countries.

- Training activities are organized mainly towards the former East-European countries;
- The HADES underground laboratory is one of the 6 underground laboratories involved of the IAEA network of URL’s. The training program for European countries is being developed through the channel of the ICT (International Training Centre), an initiative of Swiss partners under the leading of NAGRA.
- Other training programs will be organised within the framework of BNEN (Belgian Nuclear higher Education Network) and the 6th Framework Program of the European Commission.
- Training and education sessions are organised in the field of Decommissioning in the framework of the EC program but also in the frame of other bilateral and multilateral agreements.

\(^1\)Agenda 21 is a comprehensive plan of action to be taken globally, nationally and locally by organizations of the United Nations System, Governments, and Major Groups in every area in which human impacts on the environment.
The division performs numerous consultancies and expert appraisals in the fields of waste storage, waste disposal, decommissioning, etc… in the frame of international missions (IAEA, OECD) as well as in the frame of bilateral contracts.

“We do not inherit the Earth from our Ancestors, we borrow it from our Children”

We believe that nuclear energy will be necessary for the sustainable development of mankind in the 21st century, but we well understand that it would not be maintained if it is not proven that within benefits of nuclear energy a better protection of the environment is included. Therefore we want to maintain and even develop knowledge and techniques which could restore the acceptability of nuclear energy. In this sense, one of the challenges of the division in the coming years will be to keep the high level of its skills and infrastructure, among others in the field of radiochemistry and analytical techniques. But this is another story….

To be followed….

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PERFORMANCE ASSESSMENT FOR A SURFACE REPOSITORY IN MOL-DESSEL

Background
By the year 2060 the Belgian nuclear programme will have produced an estimated volume of 60,000 m³ of conditioned LLW (low-level and short-lived radioactive waste). In 1998 the Belgian Government decided that disposal of LLW at the surface or in deep clay formations must be considered as the best solution for long-term waste management. At two nuclear zones, viz. Mol-Dessel and Fleurus-Farciennes, disposal concepts are being evaluated by NIRAS/ONDRAF.

Objectives
In support of NIRAS/ONDRAF’s assignment, SCK•CEN carried out long-term performance assessment (PA) calculations to quantify the radiological impact for the post-closure phase of a deep and a surface repository. This summary emphasizes on the surface repository at Mol-Dessel.

Principal results
In line with international developments with regard to PA, a series of conceptual models were defined on the basis of a thorough analysis of features, events, and processes. The conceptual model combined all important scientific knowledge concerning the various components of a repository, and was the basis for the mathematical calculations. Main components of the multi-barrier disposal system included in the modelling are (1) concrete containers (monoliths) with conditioned waste, (2) concrete disposal units (modules) that host the monoliths, (3) and a multi-layer cap. These components are the cornerstone of long-term confinement and thus prevent an unacceptable release of radioactive material to the environment. For each of these components, best estimate parameters were assigned to physical and chemical processes governing the leaching of radionuclides from the conditioned waste towards the geosphere (i.e., groundwater) and biosphere. In addition to the radiological impact, the post-closure PA also addressed the chemical toxicity due to the presence of large amounts of solid inorganic non-radioactive waste.

For each component of the multi-barrier system a specific model was developed. For example, unsaturated water flow calculations were done for the multi-layer soil cover as a means of estimating the infiltration rate affecting the concrete disposal units. The deterministic and stochastic PA calculations demonstrated that the primary barrier against radionuclide spreading is the concrete waste container or monolith. In the calculations the lifetime of the container was an important parameter, for it determined when accelerated leaching started. Source term models were developed to calculate leaching of inorganic components (lead, etc.) from metallic pieces and cemented incinerator ashes. Geochemical calculations supported building of the source term models. The post-closure performance assessment calculations demonstrated that the radiological and chemical consequences were negligible, with the annual maximum dose much below the natural background dose.

Future developments
To further support the PA and increase its defensibility, degradation studies of concrete are much needed. Furthermore, sensitivity analysis have indicated which parameters are controlling most the leaching process. Characterization studies on migration parameters in concrete (sorption, solubility) are the preferred way to determine representative values.

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Main references
Schematic of corrosion model used for calculating toxic metal dissolution (for example lead) and leaching from conditioned waste.

Calculated tritium leaching from disposal unit (generic concept). After ~180 years the concentration has fallen below the background concentration of 2000 Bq/m³.
Bentonite Barriers in a Performance Assessment: The BENIPA Project

Background
Bentonite barriers are integral components of many repository designs for the geological disposal of highly radioactive waste. Considerable resources have been and are being devoted to their study and testing, justified by the importance of bentonite barriers for the design, operation and post-closure safety of the geological disposal systems. Bentonite barriers are characterised by their low hydraulic conductivity, plasticity, swelling capacity and sorption capacity. They act by themselves against the migration of radionuclides after canister failure, or as mechanical and chemical buffers protecting other barriers.

Objective
The objective of the BENIPA project was to review the current treatment of bentonite barriers in integrated performance assessment, evaluating the consistency of methods and data available to justify the capacity of bentonite to perform its assigned safety functions.

Principal results
In BENIPA bentonite barrier concepts for repositories in crystalline and clay host rock have been reviewed. Scientific and technical bases for the analysis of the processes relevant to the performance of the bentonite barriers have been identified. Model analyses have been carried out on the impact of mechanical, hydrological, thermal and chemical conditions on the evolution of the bentonite barriers and the transport of radionuclides through them. Process-level and system-wide, integrated calculations have been performed using assorted modelling tools to check the consistency and sufficiency of the available body of knowledge in fulfilling the needs of performance assessment (PA).

Process level models try to describe in detail the various physical and chemical processes occurring inside a repository system. Such models are typically built to represent single processes or strongly coupled processes in a specific sub-component of the system. In general, as much as possible of the scientific knowledge available on the process or coupled processes is embodied in such models. Hence, these models are sometimes considered as research models. A typical process level model is the one used to calculate the saturation of a bentonite buffer after emplacement.

Integrated level models, on the other hand, are tools used to assess the overall safety of a complete repository system given a well-defined scenario of evolution of that system. Although the dominant physicochemical processes are represented in integrated-level models, the focus lies primarily on the behaviour of the repository system as a whole and in particular on its long-term radiological impact. These models are thus mainly used in the framework of performance and safety assessments. A typical integrated level calculation is the assessment of the impact of defective bentonite seals on the overall performance of a repository system.

In other words, process level modelling is about investigating basic processes while integrated level modelling is about assessing system performance. From a modeller’s point of view, BENIPA was about how knowledge gained from process level modelling of the bentonite barriers can be transferred to integrated level modelling as done in the assessment of the overall performance of a geological disposal system.

Conclusions and future developments
Integrated level calculations have shown that bentonite barriers achieve their function within the repository system in conjunction with other engineered barriers and the host rock. Conversely, process-level models have shown that the assumed performance of other essential components of the repository often rely on the particular properties of the bentonite. Hence, detailed modelling of the engineered barrier system in general and bentonite barriers in particular is sometimes unavoidable to duly justify PA assumptions, particularly in connection with altered evolution scenarios. To this aim, it is necessary to extrapolate results obtained from models that were developed on the basis of laboratory or in situ experiments to the time frames and the spatial scales relevant to PA. This can only be achieved in a sound way through a tight collaboration between experimentalists, modellers and PA specialists.

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Main reference
Example of **process level** calculations: saturation of a bentonite buffer. At the time of emplacement, the bentonite buffer is only partially saturated with water. According to calculations, it takes about 2 years to fully saturate this buffer. If the suction in the bentonite is reduced by a factor 10, the buffer can still be fully saturated in 5 years. In this case, the process is in fact mainly controlled by the host formation, not by the buffer.

Example of **integrated level** calculation: effect of defective seals on radionuclide releases from a repository in a clay formation. In this case, the sealing defect has only a minor impact, mainly because diffusion into the host clay formation acts as a considerable sink all along the advective pathway through the galleries and shaft.
CORROSION OF STEEL CONTAINERS FOR THE DISPOSAL OF RADIOACTIVE WASTE

Background
The function of the metallic container in the geological disposal of high-level radioactive waste, is to isolate radionuclides during, at least, the thermal phase of the waste disposal. This phase lasts up to 500 years for conditioned high-level waste and up to 2000 years for spent fuel. In the SAFIR-2 disposal concept, the conditioned waste containers (the vitrified waste is directly poured into stainless steel AISI 309S containers) are placed one after the other in a tubular overpack. The reference candidate material for this overpack is stainless steel AISI 316L hMo. The space between the overpack and the concrete lining of the disposal galleries is backfilled with either Boom clay or a bentonite/sand/graphite mixture. It is the purpose of our research to investigate whether the 316L hMo overpack will remain intact in the changing physical and chemical environment of the backfill during the thermal phase. In addition, we investigated the higher alloyed stainless steel UHB 904L.

Objectives
The main objective of the research programme is to evaluate candidate container materials for high-level radioactive waste.

Principal results
We used a laboratory approach consisting of electrochemical experiments and immersion tests to complement earlier results from in situ tests. This approach entailed the use of potentiodynamic polarisation experiments to determine the values of the critical potentials for localised corrosion, e.g. pitting corrosion, of AISI 316L hMo and UHB 904L in clay water solutions (bentonite and Boom clay water) and to investigate the influence of critical anions (like chloride, Cl\(^-\), and thiosulphate, S\(_2\)O\(_3\)\(^2-\)). In addition, we performed intermediate-term immersion tests in clay slurries.

Our results show that AISI 316L hMo does not suffer from pitting corrosion at normal chloride and thiosulphate concentration levels encountered in candidate backfill materials (27 mg/L Cl\(^-\) in Boom Clay, 90 mg/L Cl\(^-\) in bentonite). However, taking into account the tenfold chloride concentration ([Cl\(^-\)] > 1000 mg/L) observed in the OPHELIE mock-up experiment, care has to be taken in considering AISI 316L hMo, as our results do predict the possibility of immediate pitting at these increased chloride levels.

We also found that UHB 904L is more resistant to pitting corrosion than AISI 316L hMo.

One element of concern was the presence of graphite in the backfill, which could cause galvanic corrosion when in contact with the container. However, our immersion experiments, which lasted up to 42 month and exposed the samples to a bentonite backfill containing graphite at 140°C, showed no detrimental effect of the graphite on the corrosion behaviour of 316L hMo.

Future developments
The next step in our corrosion research programme is to link our own experimental database to a model that simulates the long-term corrosion of container materials during geological disposal.

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Main reference
Influence of the chloride concentration on $E_{\text{p}}$ (pitting potential) of type 316L hMo stainless steel in synthetic oxidised clay water containing 216 mg/L $\text{SO}_4^{2-}$ at 140°C (aerobic condition) with an indication of the corrosion potential ($E_{\text{corr}}$). For metal/environment combinations with $E_{\text{corr}} > E_{\text{p}}$, pitting is likely to occur. The figure indicates that pitting will occur at chloride concentrations above approximately 1000 ppm.

Comparison of a pitted surface of an AISI 316L hMo and UHB 904L specimen tested in Synthetic Oxidised Claywater containing 216 mg/L $\text{SO}_4^{2-}$ and 50,000 mg/L $\text{Cl}^-$ under aerobic conditions at 140°C. (a) AISI 316L hMo, magnification: 50×; (b) UHB 904L, magnification: 50×.
TRANSPORT OF RADIONUCLIDES IN A REDUCING CLAY SEDIMENT

Background
In Europe, clay formations become more and more important as candidate geological formations (e.g. Boom Clay, Callovo-Oxfordian, Opalinus,…) for the deep disposal of HLW waste. In demonstrating the suitability of a geological site for the disposal of radioactive waste, it is essential to consider the potential mobility of critical radionuclides through the relevant “rock” types. Therefore an EC 5FP project (2000-2003) was initiated and co-ordinated by SCK-CEN in collaboration with KULeuven (B), Lougborough University (UK), Galson Sciences Ltd. (UK), Armines (F) and co-financed by NIRAS-ONDRAF, which addressed the migration behaviour of radionuclides, identified as important for the long term safety (U, Se, Pu, Am), in a reducing clay environment, with special emphasis on the role of the Natural Organic Matter (NOM). The presence of NOM may jeopardise the expected low concentration and sorption by solubility enhancement due to complexation/colloid formation with NOM or by influencing the sorption behaviour and might act as a radionuclide carrier.

Objectives
The major objective is to develop and demonstrate a conceptual model for the description of the migration of radionuclides in a reducing, NOM rich clay environment that can be implemented in performance assessment models.

Principal results
The experimental programme revealed that in general, the transport mechanism of the studied radionuclide species (except for SeO₄²⁻) is dominated by an immobilisation process (reduction-precipitation in case of U and Se, or a strong quasi irreversible interaction with the solid phase for Am) combined with a constant release of a low concentration of the radionuclide.

Am (used as analogue for trivalent Pu) becomes immobilised upon interaction with the Boom Clay solid phase but the immobilisation is not controlled by a solubility limit. Am complexes easily with mobile NOM, but upon interaction with the Boom Clay, the bulk of these complexes dissociate instantaneously and only a small part persists as a “stabilised” complex with slow dissociation kinetics. In presence of an Am inorganic solid source, this results in a constant release of “stabilised” Am-NOM complexes at a concentration level some orders of magnitude lower than its solubility. The experimental identified processes that govern the immobilisation-transport of Am in the Boom Clay are shown in the figure on next page (bottom).

For Pu, the underlying processes are not understood and the question remains whether Pu will be present as Pu(IV) or Pu(III) under the reducing Boom Clay conditions. The behaviour in the migration experiments resembles that of Am.

Colloids were in most cases evidenced but found to be either unstable in, or filtered by, the Boom Clay. The NOM in the Boom Clay has an influence on the migration behaviour but it does not lead to an increased radionuclide flux to the biosphere, on the contrary.

The general conceptual model was handled by PA using a limited set of parameters: concentration limit or solubility limit, diffusion coefficient, retardation and diffusion accessible porosity.

Future developments
Investigation of the role of the immobile NOM on the retention of radionuclides and to further clarify the filtration capacity of the Boom towards colloids.

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Main reference
To investigate if the migration of the RN in Boom Clay is linked to NOM, mixtures of $^{14}$C-labelled NOM and RN solutions (e.g. $^{233}$U(IV)-solutions) were used in migration experiments on undisturbed Boom Clay cores (percolation type) so both the fate of the RN and NOM are followed in time. In case of Uranium, as can be seen from the curve, the U(IV) and NOM are transported independently.

Schematic representation of the identified processes that govern the immobilisation-transport of Am in the natural organic matter rich Boom Clay.
MICROFOCUS X-RAY TOMOGRAPHY FOR CHARACTERISATION OF POROUS MATERIALS

Background
Clay is considered a major barrier for all kinds of waste, among which radioactive waste. In that perspective, the Boom Clay is studied as a potential host rock for an underground repository and bentonite is investigated as a suitable material for sealing shafts and boreholes of such a repository. However, a good understanding of the hydromechanical behaviour of these materials is necessary in building confidence in their use. Classical techniques in the hydromechanical characterisation of porous materials consist of indirect measurements or time-consuming destructive tests. The µCT (microfocus X-ray computer tomography) instrument allows a non-destructive qualitative and quantitative evaluation of the specimens.

Objectives
The EC funded project RESEAL, with the international participation of ANDRA, CEA, CIEMAT and UPC, aims at demonstrating the feasibility of using a mixture of bentonite pellets and powder to seal shafts and boreholes in plastic clay. The complex hydromechanical behaviour of such a mixture is a basic input for modelling large scale experiments. On the other hand, the EC funded project SELFRAC, with the international co-operation of EPFL, L3S, G3S, KULeuven, Nagra and Solexpert, studies the evolution of fractures that might be created during shaft and gallery construction within the Boom Clay. Within these projects the objective of the use of the µCT instrument was the non-destructive follow-up of the hydromechanical behaviour of clay materials.

Principal results
The hydromechanical behaviour of a pellet/powder mixture of bentonite is studied in a Plexiglas cell with an internal diameter of 3.8 cm with constant volume. A calibration procedure allows the conversion of measured linear attenuation coefficients into density. Six measurements of the set-up at several stages of hydration allow concluding that

- the pellets have a preferential suction of water and neighbouring pellets might form a preferential path of water up-take;
- the pellets show a volume increase that can be as high as 50%;
- at full saturation a homogenisation of the pellets and powder takes place;
- once saturated remnants of the original pellets cannot be found, not even after drying.

Consequently, the mixture of pellets and powder is a promising technique for constructing a homogeneous seal of access shafts.

For the evaluation of the fracture evolution in Boom Clay, a cylindrical Boom Clay sample of 3.8 cm in diameter was pressed into a Plexiglas cell, while being cut into two parts by a steel wire of 0.5 mm in diameter. The sample was scanned after cell preparation and at several intervals during a permeability test. It can be concluded that

- a large part of the fracture has closed or has shrinked to at least one tenth of its original aperture (resolution is 55 µm or lower). This is in agreement with the first permeability measurements having similar results as for undisturbed Boom Clay samples;
- the fracture apertures near the edges of the sample have increased, due to infill of the fracture with clay from its surroundings.

These are the first direct observations of sealing of fractures in clay, an important aspect to be considered in the performance assessment of a repository.

Future developments
Additional calibration will allow a more exact fracture aperture determination. Tests of fracture evolution in oxidised clay samples might allow characterising the chemical coupling with the hydromechanical behaviour.

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Main reference
Reconstructed vertical µCT slices (3.8cm by 7cm) through the centre of the Plexiglas cell filled with a 50/50 mixture of bentonite powder and pellets and the difference images, illustrating the homogenisation of the mixture during hydration. In the difference images the red colour is a density decrease and corresponds with swelling, while the blue colour is a density increase and corresponds with compaction.

µCT images (about 1.4 cm by 1.2 cm) through Boom Clay sample with artificially made fracture, before and after permeability tests, together with the smoothed profiles of attenuation. An infill and sealing of the fracture can be noticed after the permeability tests.
Background
The extension of the underground laboratory HADES has been accompanied by an extensive instrumentation programme CLIPEX (Clay Instrumentation Programme for the Extension of an Underground Research Laboratory). As the connecting gallery was excavated from the second shaft to the existing facility, a unique and original opportunity was given to monitor hydro-mechanical parameters in the zone to be excavated. An important part of the project was also devoted to blind prediction allowing a good evaluation of our understanding of the coupled Hydro-Mechanical behaviour of the Boom Clay. The CLIPEX project was financially supported by the European Commission. The project was co-ordinated by EIG EURIDICE. It was a joint project with ANDRA and ENRESA acting as main contractors and G3S, GEOCONTROL and UPM acting as associated contractors.

Objective
The aim of the CLIPEX project was to further characterise the hydro-mechanical behaviour of the Boom Clay formation and the Excavation disturbed Zone, during the excavation phase of the connecting gallery. Comprehensive instrumentation was installed in situ in order to monitor the hydro-mechanical parameters ahead of the excavation front, which was realised with a tunnel boring machine. This enabled comparison of the in situ measurements with the blind prediction performed earlier. This type of exercise is quite important to test our capabilities to predict the behaviour of the host-rock and to built confidence.

Principal results
For the first time in Boom Clay, it was possible to measure the hydro-mechanical response ahead of the face of the advancing gallery. The host-rock was instrumented in the zone to be excavated and around the gallery (see Fig. 1). Displacements, pore water pressure and total stress were monitored. The choice for the location and magnitude of the sensors was based on the results of the blind predictions.

The instrumentation programme allowed a full characterisation of the instantaneous Hydro-Mechanical response around the gallery during its excavation, with a high level of confidence on the results. The results demonstrate that it is possible to construct galleries by an industrial technique at great depth in Boom Clay keeping the disturbance of the host-rock at an acceptable level for the long-term safety of the repository. The numerical simulations (see Fig. 2) gave reliable blind predictions in terms of displacement and pressure on the lining allowing an optimum design of the tunnel machine. One important finding of the project is the un-predicted observation of hydraulic perturbation around the gallery (see Fig. 3) deep inside (~60 m) the formation. These hydraulic variations have however no impact on the long-term safety of a repository, since the permeability is not affected in this zone. Future model developments are therefore necessary to explain the variation of pore water pressure in the far-field considering a fracturing process and the delayed effects through the viscosity of the clay skeleton.

Future developments
Future works necessitate the development of model to explain the far extent of variation of pore water pressure around the excavation. The fracturation processes and the self-healing effect will be studied in the frame of the EC SELFRAc project (Fractures and Self-Healing within the Excavation Disturbed Zone in Clays).

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Main reference
Figure 1: The CLIPEX instrumentation programme (not on scale)

Figure 2: Modeling results: contour plot around the connecting gallery (2D axisymmetric configuration)

Figure 3: The hydraulic pressure drop around the connecting gallery is more important than predicted
Background
The dismantling of nuclear facilities produces various kinds of contaminated material that needs to be treated or recycled in order to reduce the volume of radioactive wastes. For the BR3, even if it is a small PWR plant with an electric power output of 10 MWe, there are more than 40,000 tons of slightly contaminated metals originating from equipments and buildings, made of concrete, ferrous metals, lead and some other specific materials, which are concerned. Instead of considering this huge amount of material as radioactive waste, the SCK•CEN developed alternative decontamination and recycling techniques and routes.

Decontamination and recycling of materials
The MEDOC® process (MEtal Decontamination by Oxidation with Cerium), based on the use of a cerium IV sulphuric acid solution with a regeneration using ozone, has been initially commissioned to treat complex metallic pieces after cutting. For large pieces with a simple geometry, we use a wet sand blasting unit where the mixture water / abrasive is continuously recycled. Up to now, these two facilities available at BR3 allowed us to clear more than 110 tons of contaminated metals. Even if this batchwise decontamination has been successfully implemented with a clearance (remaining activity lower than 0.1 Bq/g for Co-60) of more than 80% of the treated materials, this technique is not appropriate in some cases when the metallic pieces are made of different materials (ie. Carbon steel with a stainless steel cladding) or when the pieces are too small to achieve decontamination at a reasonable cost.

Nevertheless, our team succeeded to select some innovative techniques; for example for the treatment of the Steam Generator and the Pressurizer: These equipments have been decontaminated in a closed loop with the MEDOC® process before dismantling. The main advantage was that only the contaminated part (primary circuits) had to be decontaminated, so that the production of secondary waste was reduced. Moreover, the risk of spreading contamination during the post cutting and dismantling operations becomes negligible.

Furthermore, the shielded wall placed in the BR3 refuelling pool, for shielding the first set of reactor internals, was dismantled this year: This wall, made of 7 shielding elements each weighing about 5 tons, contained lead casted in a stainless steel casing. The casing is contaminated and slightly activated (close to 100 Bq/g Co-60 for the external part of the shielding) and need to be evacuated as radioactive waste. Nevertheless, the activation calculation on lead that’s inside the casing has shown, thanks to the high purity of the lead inside (99.94%), that the activity should be lower than the clearance level.

The risk to contaminate the lead during the cutting of the elements was high enough to propose an alternative for the extraction of lead before dismantling. The shielding elements were heated batchwise up to 450°C by means of thermal resistance placed around the casing. With an electric power of about 127 kW, the melting temperature of the lead was reached after 5 hours. Then, the liquid lead was drained from the casing into 300 kg casts. For the treatment of all elements, we produced 120 ingots for a total mass of 34 tons. The SCK•CEN has developed a specific procedure for the clearance of such material based on the activation calculation and a statistic measurement of samples taken during the casting of molten lead. The activation and contamination products, likely to be present in the lead matrix are the Ag-108m, Sb-125, Co-60 and Cs-137. This methodology allowed us to clear all lead ingots. They have been sent to the scrap dealer for recycling either in nuclear or non nuclear industry.

Beyond the extensive use of decontamination and melting techniques on site, the BR3 considers also, several nuclear foundries abroad either for clearance or reuse in nuclear industry. More than 50 tons of very low contaminated material has already been sent to Studsvik (Sweden) for direct clearance after melting.

Thanks to the experience acquired during the dismantling, the SCK•CEN showed that the volume of radioactive waste can be greatly minimized taking into account all technical, safety, radioprotection and economical aspects.

Future developments
The studies are now focusing on the treatment of concrete from the decontamination and demolition of buildings. Instead of considering this huge amount of material for conditioning as radioactive waste, an alternative is to try to re-use the radioactive part of it as raw material for the production of "radioactive" cement grout. This cement grout can then be used for the conditioning of heterogeneous radioactive waste or for the conditioning of the compacted disks arising from the super-compaction.

Main contact person
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Main reference
M. Ponnet, M. Klein, V. Massaut, H. Davain, G. Aleton, "Thorough chemical decontamination with the MEDOC Process: Batch treatment of dismantled pieces or loop treatment of large components such as the BR3 Steam Generator and Pressurizer" WMM'03, Tucson- Arizona, USA, February 23-27, 2003.
The primary pumps cleared after decontamination with MEDOC.

Disassembling of the last element of the shielding wall in the refuelling pool.

Sampling of lead during the melting of activated shielding elements.

34 tons of lead ingots have been extracted and unconditionally cleared.
Background
The optimisation of radiological protection of the workers in nuclear industry is an important part of the safety culture and is becoming nowadays an obligation for performing any activity in the nuclear industry. But the actual “optimisation” and the application of the ALARA concept (As Low As Reasonably Achievable) is not always straightforward. In a good ALARA pre-job study the analyst must be able to predict dose in the work area and must also be able to investigate the effects of geometry, material and source or work position changes. In order to be able to handle this information SCK•CEN developed the user-friendly VISIPLAN 3D ALARA planning tool. This software, based on up to date and assessed calculation processes, allows performing this predicting task in complex and changing environment. It has already been distributed in various countries in Europe and is used for different activities, but mostly concerning decommissioning, site restoration or large maintenance operations. At the SCK•CEN it is used in the decommissioning of BR3 and hot cell 41.

In the decommissioning of nuclear installations, one of the challenges for predicting doses and optimising the radiological protection is the complexity of the systems to be modelled, coupled with a continuously changing environment including the removal or transfer of sources, shielding and protections. The optimising of the radioprotection also brings deeper reflection on the way to proceed and therewith allows not only performing dose savings but also valuable costs savings for operations which are applied only once.

Objectives
■ Improvement to the software leading to a version 4.0, including new volume and source types and an increased calculation speed.
■ Improvement in the output modules by creating an HTML output system allowing easy transmission of calculation results;
■ New radiological input systems, including the VISIRAD easy-to-use dose measurement system, the interface to gamma scanning systems;
■ Preparation of a users group day

Principal results
The release 4.0 of the software, including new geometrical building blocks, improved calculation methods and improved user interfaces, is ready to be tested on actual case, like the replacement of the steam generators in one of the Belgian nuclear power plants. The geometrical input data will use an improved version of the VISIMODELLER interface allowing to directly link 3D-CAD software with the VISIPLAN input module. The VISIPLAN web generator is operational and enables the user to produce automatically an ALARA report in a format that is easily distributed over the intranet of a company.

A system called VISIRAD is developed in order to facilitate the radiological characterisation of a site, it integrates the 3D localisation of the measuring position and the dose rate measurement. The system is in the testing stage.

Future developments
The VISIPLAN software has proven to be a very valuable tool for use in nuclear decommissioning activities. Further developments for input/output modules and user-friendly interfaces are already started. Moreover, to improve the feedback experience of the various users, it is also intended to create a users group and to organise a meeting of this group to gather the experience and further improve the software.

We are currently developing interfaces to gamma scanning and gamma camera devices in order to introduce and interpret the data in the VISIPLAN 3D ALARA tool and increase the capability of the system to derive radiological models from the remote gamma scan or gamma camera data.

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Main references
The Visirad system showing the counter holder (on the left), the camera to locate the position of the sensor (on the right) and the computer integrating the information on position and dose rate.
Background

Bituminisation processes have been widely used since the late sixties to immobilise low and intermediate level radioactive waste. In the Eurobitum facility at Belgoprocess (formerly EUROCHEMIC) in Belgium, a specific process was elaborated to immobilise mixtures of liquid waste concentrates and fuel decladding slurries into bitumen. The resulting Eurobitum waste contains 40% salt and 60% bitumen. Prior to the incorporation into bitumen, the liquid decladding wastes were treated to remove or transform thermal unstable compounds and to insolubilise the radionuclides by complexation or co-precipitation. The resulting slurries contain approximately 70% by weight of water soluble salts (mostly NaNO₃) and 30% by weight of water insoluble inorganic species such as sulphates, hydroxides and fluorides and a small amount of complexing agents such as ferrocyanide complexes; the ratio of the compounds varies depending on the availability of the wastes during the solidification processes.

The Belgian reference scenario for disposal of this type of radioactive waste consists of a disposal in a deep underground repository in a stable geological formation (such as Boom Clay). Ongoing compatibility studies at SCK•CEN, funded by NIRAS/ONDRAF, address the different processes that might occur upon underground disposal of this waste form: gas generation, effect of degradation products with complexing properties, generation of a swelling-pressure build-up due to water uptake of the dehydrated salts, and the reaction of the leached NaNO₃ with the surrounding Boom clay. However, if the conclusions of various R&D and safety assessment studies would be that the underground disposal of Eurobitum BRW (bituminised radioactive waste) is unacceptable, re-treatment of this waste will be necessary. This is why SCK•CEN started up an exploratory study on BRW re-treatment very recently.

Objectives

The main objective of this preliminary reconditioning study till 2006 is to define methods to recondition BRW based on a thorough study of the physico-chemical behaviour of this waste under possible reconditioning conditions. The selected reconditioning methods should be applicable to the existing BRW batches.

Principal results

Browsing through documents on the historical production of BRW, we try to reconstruct the inventory. Validation of this inventory by comparison with real waste samples will be performed using analytical techniques suitable for characterising black opaque samples. On top of the next page you can see significant differences in the infrared spectra as a function of the amount of nitrate and sulphate salts incorporated in a bitumen matrix in a broad concentration range. Whereas classical nitrate and sulphate determination in BWR is destructive and time consuming, this non-destructive spectroscopic technique would be much less time consuming if we can validate this technique using multi-component analysis.

A range of cold simulates representative for the BRW inventory are used to study the physico-chemical behaviour of BRW during possible re-treatment conditions. Using our home-made microscopic desalting device for example, we investigated electric desalting as a tool to separate water-soluble salts from BWR: we treated bituminous water-in-oil emulsions using a wide range of electrical field strengths. The photographs in the middle of the next page show the demulsifying effect of an electric field (6.10³V/m) between two parallel plates on such an emulsion during 10 seconds. Without the application of an electric field the emulsion remains stable.

The behaviour of black BRW solutions, emulsions or suspensions is related to the presence or formation of suspended particles, a second liquid layer, sediments or foams. This can be investigated by scanning the near infrared back-scattering as a function of the height of a sample tube. The relative back-scattering profile of an unstable bitumen solution in a particular solvent as a function of time is shown on the last figure of the next page. This is a typical example of flocculation.

These are examples how we screened the physicochemical behaviour of BRW under several re-treatment conditions. Based on these results we defined recently a novel chemical re-treatment method aiming at waste minimisation and stabilisation. We started studying all steps of this re-treatment method in closer detail.

Future developments

For the next 3 years, we will continue the reconstruction of the Eurobitum inventory. The physicochemical study related to the re-treatment of BRW is also going on. We will start to prepare re-treatment experiments of BRW with incorporated radiotracers.

Main reference

Newly initiated research. No publications yet.

Main contact person

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A bituminous water-in-oil emulsion in an electric field (6V/mm) between two parallel plates after 0, 2, 4, 7 and 10 seconds. Without electric field, the emulsion is stable. The width of each picture is 2.6 mm.

Relative changes in backscattering (ordinate) of a particular bitumen solution as a function of the sample height (abscissa) and as a function of time (hour: minute).

Infrared spectra of Eurobitum simulates with different amounts of incorporated salts.
TREATMENT OF TRITIATED WASTE

Background
Since a few years SCK•CEN has been focusing on the treatment of tritiated organic liquid waste. For the purpose of oxidising SCK•CEN’s own tritiated organic liquid waste, we developed a method for the complete oxidation of the organic waste and capture of the formed water. Our technology is both technically feasible and safe and can be adapted for the treatment of various categories of problematic tritiated liquid waste, which will undoubtedly be produced in existing installations and in future fusion installations.

Objectives
Our final goal is the reduction of tritiated waste and tritium discharges by treatments that allow trapping all tritium as tritiated water. This tritiated water could be conditioned and stored or even better its tritium content could be recovered for recycling. The experimental method that we are studying is a complete two-stage combustion with thermal and catalytic oxidation of the organic liquid into tritiated water for further treatment and tritium free off gases for discharge. For this purpose we built an installation capable of accepting liquid organic flows of different origins and compositions of up to the order of 1 L/h with activities up to 0.2 TBq/L.

Principal results
Our first task concerned the treatment of about 200 litres of tritiated organic solvent generated by the pharmaceutical industry. The main components of the solvent were methanol, chloroform and water. Total activity was around 17 TBq. We realised an appropriate infrastructure that allows a controlled and safe handling of this volatile, highly flammable, toxic and highly radioactive material. The installation comprises a first cell equipped for unpacking and sampling the waste and a second cell which houses the oxidation installation and its associated water collection system, shown on the next page. A series of cold commissioning tests were completed in cooperation with Ontario Power Generation Inc. (OPGI) to assure safety authorities at SCK•CEN that safe handling and destruction of the solvents was possible and that emissions during processing could be maintained at negligible levels. After that we were able to completely treat this solvent with only limited discharges to the environment. Appropriate measures were taken for coping with the highly corrosive hydrochloric acid that was formed during the treatment. As shown on the next page, less than 0.5 % of the activity was vented during normal treatment and liquid discharges were negligibly small. The produced tritiated water has been neutralized and analyzed, and is now waiting for further processing or final disposal.

Our second task is a study on the treatment of tritiated organic liquids from the Joint European Torus (JET). It concerns vacuum pump oils and scintillants mixed with water. Non-active samples have been sent to SCK•CEN and they are now being analysed for sulphur and phosphor; two problematic elements. Flash point and boiling point curve will also be measured. We refurbished the existing installation and adapted it for the purpose of the treatment of vacuum pump oil. The renewed installation is being commissioned. Soon we will start cold tests using virgin and inactive oil and liquid scintillation cocktail. These preliminary experiments will determine a set of conditions for the destruction of the concerned waste.

Future developments
As a next step in this last task, batches of tritiated feedstock will be treated. The tests with JET feedstock will demonstrate the viability of the facility and will be used to compare against results obtained from the inactive tests. Also, the implications of the proposed detritiation technique with respect to production of secondary waste, health and safety issues shall be assessed.

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Main reference
The installation for treating tritiated organic liquids comprises a glove box for handling and unpacking of the waste, a two-stage combustion furnace, multiple condensers and molecular sieves to ensure tritium free exhaust gasses.

During solvent treatment, the hourly tritium discharge from the tritium laboratory remained far under the limits of 152 MBq/h for HTO and $3.8 \times 10^6$ MBq/h for HT. Furthermore less than 0.5% of the solvent’s tritium content was discharged to the environment under normal operation.
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Introduction

The nuclear world is changing. Legislators in Belgium have decided to phase out of nuclear energy; other countries like Finland, France and the USA seem to want new nuclear power stations. Europe will enlarge in 2004 and is in the process of rethinking the organisation, the tasks and the implementation of possible new approaches for an enlarged Euratom. The International Atomic Energy Agency (IAEA) is reviewing its relations with Euratom and the European member states on the implementation of the additional protocol concerning the Non-Proliferation Treaty to come to Integrated Safeguards. This is a challenge for the international research community, as well in radiation protection as in safeguards to find ways to improve protection and to include non-technical issues in the research programmes.

In Belgium, SCK•CEN considers it as its responsibility to be a primary reference point for radiation protection issues. Therefor it will maintain an active state-of-the-art expertise on each aspect of radiation protection from health physics measurements, dosimetry, radiological assessment and optimisation, radioecology, radiobiology and radiation epidemiology to radiation protection management techniques and policy support. We apply this expertise not only for the own needs of the Centre, but also in interdisciplinary actions in the field of nuclear emergency management, for the surveillance of the Belgian territory, for the remediation of radioactively contaminated sites, in medical applications and for the study of the effects of low doses of ionising radiation. Research projects in social sciences deal with non-technical aspects of radiation protection and nuclear energy and waste. Space projects are attractive opportunities, but basic radiation protection knowledge is the priority.

Relations with government

Emergency planning and response remains an item of concern for the Belgian government. SCK•CEN contributes to the continuous improvement of the organisation of the Belgian Crisis Centre of the Government (CGCCCR). The elaboration of procedures for the evaluation cell of the Crisis Centre went on and we participated in the newly established socio-economic cell ECOSOC. We continued the evaluation of the possible impact of a radiological dispersion device, the so called “dirty bomb” and applied this knowledge in a Belgian emergency exercise concerning the detonation of such a device. Another important aspect of emergency planning is the harmonisation of the national efforts in a European context.

Therefor we participate in several European projects and co-ordinate some of them. The European Commission, Directorate General Research, evaluated two of these projects (SAMEN and MOZES) as “Success Stories”. Involvement of stakeholders is a common point in many of these projects. We involved the people responsible for the Belgian emergency organisation in a European attempt to model the decision process in emergency situations and to harmonise measures to mitigate possible consequences in agriculture.

The programme for surveillance of the radioactivity on the Belgian territory has been expanded in consultation with the Federal Agency for Nuclear Control (FANC) and the involved laboratories and services of SCK•CEN.

Health effects

The public is concerned about the impact of radiation doses due to the nuclear sector in Belgium. We collect the data on cancer mortality amongst the workers in the Belgian nuclear sector; The results are pooled by the International Agency for Research on Cancer (IARC), part of the World Health Organisation (WHO). This institute collects data from many countries to enhance the statistical relevance of the results. In 2003, FBFC International, joined the co-operation between SCK•CEN, Belgroprocess, BELGONUCLEAIRE and the nuclear power plants of Doel and Tihange.

Last year, the radiobiology and microbiology groups started programmes in the frame of European space research. (see “Space: Physiological approach to monitor space ...”). The European Space Agency (ESA) was so satisfied with the work done that it assigned complementary contracts. The main objective of these projects is to investigate the response of bacteria to space conditions (micro gravity, cosmic radiation), including the expression and the transfer of genes. These projects are in line with the more general focus of the radiobiology research group on evaluating the potential risk of low doses and the understanding of the mechanisms involved. We investigate biological and molecular response of different human cell types to irradiation. We use the mouse model to explore the gene expression in the developing mouse brain embryo (see “Health effects: Effects of ionising radiation on the gene...”) after irradiation. Flow cytometry is another powerful technique to measure the response of cells to radiation and other environmental factors. It is used to evaluate the physiological status of large numbers of cells in a short time. (see “Health effects: Physiological basis of radiosensitivity ...”)
Doses from medical applications are increasing in the western world in general and in Belgium in particular. In Belgium, about half of the average effective dose to the population is due to “natural” sources. Almost the entire other half is a result of medical diagnosis (radiology and nuclear medicine). This makes it worthwhile to study a possible limitation of medical doses. Recent legislation also imposes the optimisation of patient dose and image quality in radiology. We contribute to the mapping of the situation and to the search for improvement in techniques and procedures. We continue to investigate angiography of the lower limbs, angiography of the cerebral arteries, and cerebral embolisation. We collaborated also with the Belgian High Council for Health in the elaboration of several recommendations e.g. on fire alarm devices, on cremation of patients having been subjected to administration of radioactive products and on radiation protection in nuclear medicine.

**Radioactivity in the environment**

Radioactivity is a natural part of our environment but public concern and awareness are mainly focussed on man-made addition of radioactivity to this environment. The Flemish Environment Agency publishes an annual report on the environmental situation in Belgium. SCK•CEN is the main author of the theme on the exposure to ionising radiation. (see Radioactivity in the environment: Sources and exposures...).

Potential problems concerning Naturally Occurring Radioactive Materials related to non-nuclear industry, future waste disposal sites and areas contaminated as a result of nuclear tests and accidents remain points of focus, but also historic contaminated sites require attention.

SCK•CEN has acquired the necessary skills to perform the radiological impact assessment for these various sites. We continue to perform research on the behaviour of radionuclides in our living environment focussing on uranium contamination, but maintaining the existing knowledge on the behaviour of radioceasium.

We use this knowledge to characterise contaminated sites, evaluate possible solutions and propose measures to reduce the radiological exposure of the population. We inform the stakeholders and coach the practical remediation efforts.

Examples are the Olen case in Belgium and a European TACIS project on the remediation of former uranium mining tailings in Kyrgyzstan. (see Radioactivity in the environment: Remediation of Uranium...). In this case SCK•CEN was responsible for all radiological and management aspects and our international partners dealt with the geological aspects, mainly the risk of landslides.

**Methods of measurement**

For many years, SCK•CEN developed the appropriate measurement methods, instruments and skills for radiation protection. Our laboratories perform measurements with certified quality as well for routine applications as for more specialised and difficult analysis procedures. Projects of the research divisions at SCK•CEN and the big operational infrastructures are the main clients for these laboratories. External clients have also access to the offered services. The Belgian Federal Agency for the Safety of the Food Chain, for example, asks us to measure the radioactivity in food samples by gamma spectrometry.

We want to maintain and expand the existing knowledge and the possibilities of the laboratories. The organisation of continued training is a valuable tool to this respect. A specialised course on emergency planning and response was organised and we co-organised a course on “Optimisation of monitoring for internal exposure”, both in the frame of a European project. (see Methods of measurement: Optimising uncertainty...)

In the frame of the European project called “Evaluation of Individual Doses in mixed neutron-gamma fields” (EVIDOS), we characterised the radiation field at SCK•CEN’s VENUS reactor, together with a team of European scientists. The purpose is to compare the response of many different instruments in real operational radiation fields. The same exercise will be repeated in various installations in Europe. Final results will be available in 2004.

“Emergency planning and response” relies on calculation models to predict possible consequences of a nuclear accident. We developed a tool including a user friendly interface, a calculation module and reporting modules to assist in evaluating these consequences (see Methods of measurement: The use of radiological...). Most nuclear operators in Belgium are using this tool. It is also available in the Belgian Crisis Centre of the Government. Other developments in the frame of a European project include software to support easy and reliable data exchange between the various decision aiding systems used in Europe.

SCK•CEN is responsible for the Belgian Support Programme to the IAEA for Safeguards Implementation. The programme is focussed on “Integrated Safeguards” and on Non Destructive Analysis techniques. In the frame of this support programme, we calibrated measuring instruments of IAEA and Euratom. Apart from this structured support, we have placed our expertise at the disposal of IAEA for the elaboration of technical and safety reports and guidelines and we have assisted in putting a laboratory for anthropogammametry into operation in Greece.

**Contact**

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Background
Measuring physiological responses of bacteria resulting from exposure to stress (radiation, spaceflight conditions, temperature, pH, \( \mathrm{H}_2\mathrm{O}_2 \), ...) is central to our microbiological work. The susceptibility and sensitivity of bacteria to damage differs between bacterial types and the kind of applied stress. In order to monitor physiological status of bacteria, flow cytometric methods have been developed at SCK•CEN. Briefly, flow cytometry refers to the simultaneous measurement of several physical (e.g., size and shape) and biochemical (e.g., proteins, DNA, RNA) characteristics made on individual cells providing an indication of thousands of cells within minutes. Furthermore, it is also possible to identify subpopulations of bacteria or to even detect contaminants as well as to distinguish between dead and viable cells. Flow cytometry has a wide range of potential applications in microbiology ranging from the assessment of antibiotic susceptibility of clinical samples to the monitoring of bacteria and other micro-organisms in anything from food, water to sea water and sewage. Still, the potential of flow cytometry in microbiology is far from fully utilised by the scientific community.

Objectives
One of the aims of our current microbiological research is to develop fast and reproducible ways of estimating physiological status of bacteria. Therefore, methodologies have been elaborated in order to monitor a wide variety of fine physiological changes under stress in bacteria (space, \( T^\circ \), pH, \( \mathrm{H}_2\mathrm{O}_2 \), ...), namely, fine changes in bacterial size, shape, viability, membrane properties, enzymatic activity, intracellular pH, \( \mathrm{Ca}^{++} \) concentration, DNA/RNA ratio as well as the response to oxidative stress (intracellular \( \mathrm{H}_2\mathrm{O}_2^+ \), \( \mathrm{O}_2^- \) and thiol concentrations) can be followed.

Principal results
For the MESSAGE project (Microbial Experiments in the Space Station About Gene Expression, project supported by the European Space Agency, ESA) in which various bacterial strains were sent into space for a few days, flow cytometry has allowed to investigate the effects of space conditions on the physiology and metabolism of bacteria. We show that a bacterial trip of a few days into space induces fine physiological changes not only at the level of the bacterial membrane but also at the metabolic level.

The MELISSA project (Micro Ecological Life Support System Alternative, project supported by ESA) aims to develop the technology required for a future biological life support system for long term manned space missions. It consists in a loop of different compartments populated with pure bacterial cultures able to recycle human faecal material and urine as well as converting sunrays into oxygen for the astronauts. The utility of flow cytometry resides in
1. the detection and the effect on the metabolism of undesired micro-organisms that would contaminate the pure bacterial populations and
2. the monitoring of bacterial behaviour under stress conditions (\( T^\circ \), \( \mathrm{H}_2\mathrm{O}_2 \), pH, irradiation).

In Arthospira species and Rhodospirillum rubrum, both chosen for their potential use in life support systems in space and more specifically in the MELISSA loop, we showed that small physiological alterations that occur after temperature, \( \mathrm{H}_2\mathrm{O}_2 \) or pH stress can be monitored.

Future developments
Work is still needed to better understand the behaviour difference of bacteria in function of the stresses applied. A phenotypic description of bacterial mutants affected in a membrane component (essential in the response to heavy metals and radionuclides) is also planned.

Main contact person
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Main References
Flow cytometry principle: The cell sample is introduced into the centre of a stream of sheath fluid which intersects a laser. When cells interact with the laser, some of the light is scattered out of the beam in the forward direction. In addition to light scattering (giving an estimation of cell size), flow cytometry can evaluate the shape of the cell as well as its fluorescence relative to specific cellular component (e.g. DNA, RNA, proteins, ...).

MESSAGE 1 (ESA) project
Detection of physiological changes induced in space

Ground

Space

MELISSA (ESA) project
Physiological changes induced in R. rubrum following T° stress

4°C

28°C (control)

45°C

membrane potential

cysterase activity

intracellular pH

Fluorescence
Background
Exposure of cells to ionising radiation induces DNA damage. Cells have the ability to sense DNA damage, and to activate repair pathways that efficiently remove such damage and restore the integrity of the DNA. Highly sophisticated mechanisms further enable cells to actively stall growth and division after sensing DNA damage or alternatively to induce programmed cell death (apoptosis). Research performed at SCK•CEN has the goal of expanding the knowledge of the cellular and molecular mechanisms that determine the sensitivity or resistance to ionising radiation of normal (adult and embryonic) and cancerous cells. In particular, the physiological effects induced by ionising radiation are studied in the light of the biochemistry of the p53 protein that is an integrator of stress signals from various damaging exposures and that fulfils the function of “genome guardian” by regulating the checkpoints of the cell cycle, DNA reparation and apoptosis. A part of the physiological studies aims at testing various natural substances for their potential radiation protective effects.

Objectives
To develop methods to identify fine changes in cell cycle and apoptosis in normal and cancer cells

Principal results
The GEMRATE project aims at understanding the genetic factors predisposing to radiation induction of mutation during early gestation (supported by European Union). Gastrulation (corresponding to the 2nd week of foetal development) is associated with the start of extreme proliferation and differentiation. In human reproduction, where this early embryonic development (first two weeks after conception) cannot be detected by existing hormonal tests, irradiation for medical purposes during this period poses a risk of damaging DNA within the cells of the newly formed embryo leading to later foetal malformation. We demonstrated that X-irradiation during mouse gastrulation induces a G2-arrest of the cell cycle allowing cells to repair the DNA damage induced by the X-irradiation. Apoptosis (or programmed cell death) is a fundamental aspect of any multicellular organism. It is involved in morphogenesis of embryonic tissues as well as in homeostasis of adult organs and tissues. We have shown that apoptosis can be induced not only by X-irradiation but also by natural compounds (like Spirulina or tea components) as well heavy metals (like uranium or mercury).
Telomeres containing noncoding DNA repeats at the end of the chromosomes are essential for chromosomal stability, replication and senescence of cells. Our hypothesis is that telomere length changes are associated with the development of radiation-induced foetal malformations. We are currently investigating telomere length in normal versus abnormal foetuses with different p53 genotypes.

Future developments
The lines of our physiological work performed on normal (adult and foetal) as well as on cancerous cells help the scientific community to refine the understanding of teratogenic and apoptotic radiation-induced processes. On the technological point of view, further technical developments using flow cytometry combined with microarrays in order to study gene expression are under progress.

Main contact person
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Main Reference
GEMRATE EU project

Irradiation induces a G2-arrest in mouse gastrula embryo

![Graph showing DNA content distribution](image)

Irradiation induces cell death in human cancer cells

![Graph showing Annexin V and Propidium Iodide staining](image)

Telomere length estimation

![Graph showing telomere length against DNA content](image)
Background
Many studies of prenatally exposed atomic bomb survivors have shown that exposure to a high level of ionising radiation during gestation has harmful effects on the developing brain. Embryonic brain development is a complex process characterised by genetic and epigenetic organisation of neural cells. The neural network is created through defined and time-dependent proliferation, differentiation and migration of neural and support cells. Ionising radiation exposure affects both glial and neural cells and may induce chromosome rearrangements, point mutations or changes in gene-expression. The outcome of these molecular pathways may involve cell death by apoptosis, interruption of migratory activity, impaired capacity to establish correct connections among cells and/or alterations in dendritic development. A high dose of ionising radiation can have an impact on the cellular entity of the tissue possibly leading to late mental retardation.

Objectives
In an attempt to elucidate the basis of this effect, we screened the global expression of genes in the embryonic mouse brain exposed to radiation using a high throughput gene-expression analysis. Significant genes are further analysed by in situ hybridization to determine their exact expression location.

Principal results
Using statistical analysis clustering techniques such as K-mean, average hierarchical linkage clustering and web-based public databases, 64 genes with significant altered expression levels were selected out of 22,572 genes spotted on the microarray slide. These genes were significantly over- or under-expressed (threshold > or < 2) after exposure to ionising radiation (0.5 Gy). Some genes involved in cell cycle regulation, apoptosis induction or nucleic acid binding, such as (mRNA) Ccng1 (Cyclin G1) and (mRNA) Stinp (Stress inducing protein) are strongly induced in the 3 irradiated stages of development analysed. Both genes are involved in P53-dependent molecular pathways triggered by DNA-damage. P53 is a key-regulator gene in deciding the cell-fate after exposure to genotoxic stress (e.g. ionising radiation). Ccng1 is well known as a mediator in stress response while the molecular function of Stinp remains elusive. Therefore, both genes are valuable candidates for further analysis.

To map the expression patterns of the genes in the developing brain, before and after irradiation, the ISH (In Situ Hybridization)-technique was applied. Embryonic mouse brains of irradiated and non-irradiated conditions are separately collected, dissected and subsequently exposed to a digoxigenin-labeled RNA probe that corresponds to a complementary mRNA-sequence of the gene of interest. At stage E13, Ccng1 is highly expressed in the cerebral hemispheres of irradiated mice while not in control mice. At later stages, E15 and E18 expression appears more and more diffused in other brain areas.

Future developments
Our first results indicate that exposure of the brain to ionising radiation induces a Ccng1 mediated P53 dependent molecular mechanism responsible for cell-fate decision. The microarray-data, further confirmed by in situ analysis, showed high over-expression of Ccng1 in the anterior area of the brain. This supports that the cerebrum might have a higher level of sensitivity to ionising radiation. However, additional experiments by real-time Quantitative PCR (fluorescence-based technique to detect the expression-level of a gene, amplified in an enzymatic reaction) ISH, protein-analysis and a P53 knock-out mouse model study are compelled.

Main contact person
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Contribution is based on the work by Joris Verheyde in preparation of a doctoral thesis.

Main Reference
First statistical analysis using the paired T-test and two sample T-test revealed 64 genes to have a significant different expression. A second, less stringent analysis revealed additional 189 genes also significantly modulated. Only the genes involved in apoptosis, cell-cycle regulation and nucleic acid binding are radio-responsive genes of interest.

Two genes: Ccng1 and Stinp (Stress inducing protein) showed distinct levels of over-expression. Both genes are involved in the p53-dependent stress response.

Preliminary in situ hybridization experiments using a digoxigenin labeled Ccng1 RNA-probe showed at irradiated stage E13 expression in the cerebral cortex (CC). At later stages expression is further spread in the cerebellum (Cbl) and spinal cord (SC).
Sources and Exposures of Ionising Radiation in Flanders

Background
Since 1996, SCK•CEN contributes to the yearly “Report on the Environment and Nature in Flanders” (MIRA - Milieu en natuurrapport Vlaanderen). This report, published by the Flemish Environment Agency (VMM), provides a broad and in-depth insight into the environmental issues in Flanders. By mapping the progress or setback of a few carefully selected indicators per theme, it describes the evolution in some 25 environmental themes, including the exposure to ionising radiation. SCK•CEN is the main author of this theme since 1999. The knowledge accumulated over the years on sources and exposures of ionising radiation in Flanders is summarised in a background document. The complete MIRA 2003 report and the topical background documents can be consulted on the website: http://www.milieurapport.be

Objectives
The aim is to provide insight into the man-made sources and exposures of ionising radiation in Flanders. Three broad categories of human activities contribute to these exposures:
- medical applications (contribution by H. Mol of the European Institute of Higher Education Brussels, EHSAL);
- the nuclear fuel cycle, and
- technologically enhanced natural radioactivity.

Principal results

Medical applications
In Flanders, like in most regions with an advanced health care system, medical exposures are now the most important single source of ionising radiation. According to social security data (RIZIV), in 2001 the average inhabitant of Flanders was subject to 1.2 X-ray examinations a year (excluding dental X-rays) of which 10% were CT-scans (a scanning method that uses computerised X-ray images to provide a three-dimensional picture of an internal part of the body). The contribution of CT-scans to the average dose of the population in Flanders doubled between 1990 and 2001 to 1 mSv/year. The increase of the CT dose is partly compensated by a decrease in conventional examinations, in particular of the spine and the gastro-intestinal tract. The average dose from medical examinations in Flanders in 2001 is estimated at 2.0 mSv/year (radiology 1.8 mSv/year and nuclear medicine 0.2 mSv/year).

Nuclear fuel cycle
The federal government decided that the nuclear power plants have to shut down after forty years of service, and that no new ones can be constructed. Because this shutdown only starts from 2015 on, it has no immediate consequences for the Belgian Kyoto-objective of 7.5% reduction of emitted greenhouse gases in the period 2008-2012. However it makes the challenge afterwards all the greater, since nuclear energy provided 57.6% of the total Belgian electricity production in 2002. The Belgian nuclear power plants process most of their radioactive waste on site. In 2002 they transferred 228 m³ of conditioned waste to ONDRAF/NIRAS - Belgoprocess.

Technologically enhanced natural radioactivity
The largest volumes of radioactively enhanced materials in Flanders are produced by the phosphate industry. Between 1920 and 2000, five phosphate plants processed 54 million tons of phosphate ore by acidulation with sulphuric acid (H₂SO₄), hydrochloric acid (HCl) or nitric acid (HNO₃). Depending on the production process the enhanced natural radioactivity of the ores turned up in the end products (fertilisers, cattle feed), were released in surface waters (Grote Laak, Winterbeek and Scheldt estuary) or were deposited as waste (phosphogypsum, calcium fluoride sludge).

Future developments
- Diagnostic reference levels are put forward for standard examinations in radiology and nuclear medicine to level down the highest exposures.
- ONDRAF/NIRAS awaits a decision by the federal government during this legislation on the location and the type of storage facility for the low-level radioactive waste.
- The implementation of the new legislation on work activities will make it easier to make an inventory of the sites in Flanders contaminated with technologically enhanced natural radioactivity.

Main contact person
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Main reference
Annual consumption of phosphate ore by the five phosphate plants in Flanders in kton/year and the total amount of phosphate ore in Mton. Two of the plants, Prayon and UCB, have stopped the acidulation of phosphate ore. The other three, BASF (HNO₃), Tessenderlo Chemie (HCl) and Rhodia Chemie (H₂SO₄), continue their activities.

Trends in annual effective dose in Flanders (1996-2001) and Belgium (1990-2001) from diagnostic radiological examinations. The large and increasing share from CT examinations is given separately.

Evolution of the total storage of conditioned radioactive waste by Belgoprocess in Dessel in anticipation of definite storage in surface and geological waste repositories. Belgoprocess is the industrial daughter company of the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS).
Background

The area of the town of Mailuu Suu, Kyrgyzstan, is polluted by radionuclides and heavy metals in tailing dumps and heaps resulting from the historic exploitation of U-mines. Radioactive substances are stored in 23 tailings and 13 mining debris heaps situated along the Mailuu Suu River. The stability of many tailings is at risk. Some of those tailings are already damaged by landslides, mudslides and floods, and some others are in high-risk areas where major landslides are expected. Tailing n°3 is considered as being the more risky deposit, because of its important radionuclide inventory and since threatened by a major landslide.

Objectives

The objective of the EC-TACIS funded project is to evaluate measures to be taken by the authorities to reduce the radiological exposure of the population and to prevent environmental pollution by radionuclides and heavy metals.

The specific project objectives are: to identify the risks (radiological and others), to propose measures to monitor and to mitigate those risks, to study and evaluate rehabilitation plans for Tailing 3 and evaluate how the approach for Tailing 3 can be applied to other tailings, to implement short term remedial measures on Tailing 3 and to study and evaluate rehabilitation plans to decrease the impact of a disaster scenario.

Principal results

An extensive radiological monitoring network was set up for assessing the actual and future radiological impact. The actual radiological situation is of no immediate concern for most of the population of Mailuu Suu. The gamma radiation monitoring campaign showed that the background radiation level is 100-120 nSv/h. On the tailings radiation is on average twice as high. The average outdoor and indoor radon concentration is 175 Bq/m³. In three of the houses monitored at Kara Agach the radon level is between the European Union action levels for new (200 Bq/m³) and old houses (400 Bq/m³). The concentration of uranium in the Mailuu Suu river water is far below the limit for drinking water set in Kyrgyzstan. Additional dose from irrigation with Mailuu Suu river water is small in present conditions (< 0.1 mSv/year). However, there is a real possibility that, triggered by an earthquake or a landslide, (part of the) tailing(s) content may be directed to the river Mailuu Suu.

Doses to the affected population may then increase to several ten mSv per annum during several years. Given the actual limited stability of Tailing N°3, the potential of such a disaster to occur can not be neglected.

Additional monitoring campaigns for assessing stability of tailings and landslides were done and remediation options were evaluated and proposed including in situ stabilization and tailing translocation for Tailing 3, translocation of additional tailings, a tunnel to deviate the river and partial protection of river from landslide blockage. It was proposed to acquire a phased approach in time. In the short term: performing urgent limited stabilization options for Tailing 3. In the medium term: improve the stability of the Tailing 3 while investigating and evaluating further two long-term remedial options: the translocation of the tailings and the right-bank river diversion tunnel.

Future developments

The Consortium was asked to actively participate with respect to information exchange and discussion of remediation options in a next project phase where the World Bank intends to implement a 5 million dollar remediation project.

Main contact person

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Main reference

Location of mill tailings and waste rock dumps in the Mailuu Suu area, Kyrgyzstan and external gamma exposure at tailing dump N° 3, the most dangerous one, containing 50% of the total activity.

Medium or long-term remedial options considered most feasible (T3= tailing dump N° 3, T5 dump N° 5 etc.)

<table>
<thead>
<tr>
<th>Options</th>
<th>Cost Mio Euro</th>
<th>Main Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ stabilisation of T3</td>
<td>2 to 4</td>
<td>■ Significant for the short to mid term due to the actual state of limited stability of T3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>■ Remaining risks for the longer term (seismic and landslide hazards)</td>
</tr>
<tr>
<td>Transfer of risky tailings to a safer site</td>
<td>3.5 (T3) &gt;23 (T3, 5, 7, 8)</td>
<td>■ Technically complex undertaking (western experience and technology required)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>■ Adequate water treatment technology and radioprotection necessary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>■ Technical feasibility to be done parallel to investigation of proposed site (T15) and development of a detailed engineering concept for disposal cell construction.</td>
</tr>
<tr>
<td>Long diversion tunnel right bank</td>
<td>28</td>
<td>■ Fully achieve the objective in terms of public safety</td>
</tr>
<tr>
<td></td>
<td></td>
<td>■ Location of main fault and potential fault displacements (if active) to be clarified</td>
</tr>
<tr>
<td></td>
<td></td>
<td>■ Location of Mining galleries and shafts to be clarified</td>
</tr>
<tr>
<td>Channelling the river</td>
<td>21</td>
<td>■ The necessary excavations could reactivate landslides during the works. Risk extremely difficult to evaluate. This makes the feasibility of the solution questionable.</td>
</tr>
</tbody>
</table>
REDUCING THE THREAT OF A “DIRTY BOMB”

Background
By the beginning of the 1990’s there was a growing concern that besides special nuclear material like HEU (highly enriched uranium) and Pu (plutonium), also non-fissionable radioactive sources might be used for hostile purposes. While HEU and Pu are the raw materials of nuclear weapons, terrorists might use radioactive sources by dispersion by conventional explosives. This is known by the general public as a “dirty bomb” or a RDD (radiological dispersion device). The aim of a RDD is to contaminate a large area with radioactive material. This could result in panic and thereby societal and economic chaos.

Objectives
SCK•CEN intends to develop a comprehensive approach with respect to the threat of a radiological dispersion device. On the one hand we try to reduce the threat by studying preventive measures and propose their implementation, on the other hand we develop an emergency response plan in case the preventive measures were not successful.

Principal results
Measures that prevent the construction or use of a RDD are a national responsibility. There are large differences regarding these preventive measures in different countries.

Preventive measures in relation to RDDs should focus on radioactive material, since explosives or other means of dispersion can be relatively easily obtained by terrorists, and many states are already trying to control access to such means as part of their general anti-terrorism measures.

Keeping track of all potentially harmful radioactive sources requires a series of measures. First, a national accountancy and verification system for radioactive sources should be established by every country. Such a system should account only for strong sources, since dispersion calculations have shown that an effective RDD contains in the order of 4-40 TBq (100–1,000 Ci). At present only a few countries have such an accountancy and verification system, most of these are established on a voluntary basis and they are based on safety rather than security considerations. Verification of both the type and the strength of each source can be performed relatively easily by non-destructive measurements.

The physical state of the radioactive material is important since it determines how dispersible the material is. Sources could be divided into several classes according to their physical state, indicating their potential for being used in a RDD. A verification system would have to take such factors into account, for example, by adjusting the inspection frequency. Secondly, an inventory of the sources should be established in the national verification system. International co-ordination could be useful, especially the participation of the main producers of radioactive isotopes. Thirdly, a “return” system for sources no longer being used should be established so that owners are encouraged to send them back. When a source is purchased, a deposit should be paid that will be returned when the source is given back. Unused sources pose a major risk of being stolen because they are probably no longer being closely supervised. Fourthly, abandoned (orphan) sources, which are no longer under anyone’s control, should be traced and secured. This could be done in a dedicated repository—preferably by the national regulatory authority.

Future developments
In 2004 SCK•CEN will investigate the implementation of preventive measures in several European countries.

Main contact person
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Main reference
Calculation of the distribution of surface contamination due to the simulated explosion of a “dirty bomb” in the downwind direction. The radioactive source contained 130 TBq (3500 Ci) of $^{137}$Cs in a highly dispersible form. The surface contamination is expressed in kBq/m².
Background

OMINEX (Optimisation of Monitoring for Internal Exposure) is an on-going international project part-funded by the European Commission within the 5th (EURATOM) Framework Programme. One of the topics covered by this project is to look at the bioassay measurements performed in the European laboratories. Alpha spectrometry is the technique most used for the determination of alpha emitters such as plutonium, americium, uranium and thorium in biological samples (urine and faeces). The different parameters influencing the uncertainties on the results and the minimum detectable amount (MDA) have been investigated.

Objectives

The aim was to compile descriptions of the procedures used by EU laboratories for monitoring of workers in the nuclear industries, and to investigate how the available methods and techniques could be exploited in such a way as to reduce the uncertainties in measurements. The targeted analytical procedures were those set up for monitoring actinides.

Principal results

After $\alpha$ spectrometry, the activity of an isotope is calculated as

$$A_i = \frac{A_T \cdot C_i}{C_T}$$

where $A_i$ is the activity of the measured isotope, $A_T$ is the activity of the tracer added, $C_i$ and $C_T$ are the number of counts observed in the region of interest of the isotope and of the tracer respectively. The uncertainty on the activity of the isotope thus depends on the tracer activity and its uncertainty, on the number of counts for the isotope and the tracer and on the uncertainties on these counts. Usually uncertainty is determined at 95% confidence level or $2\sigma$.

To reduce the uncertainty, the highest number of counts should be obtained. If the activity of the tracer and its uncertainty are more or less fixed, the uncertainty on the counts is strongly related to the technical parameters attached to the $\alpha$ spectrometry device and the chemical analytical procedure. These parameters are: volume or fraction of the sample used for the analysis, tracer activity, counting efficiency, sample-counting time, background counts, background counting time and chemical yield.

These parameters also influence the minimum detectable amount or MDA.

The optimum analytical conditions for urine analysis by $\alpha$ spectrometry are listed in the table next page. To obtain on a urine sample of 24 hours, a relative uncertainty of less than 25% for an activity of 1 mBq/24h and a MDA of less than 0.1 mBq/24h, the analytical parameters should be: a tracer activity of 6 mBq, a background count of 2 to 3 for a background counting time of 750000 seconds, a counting efficiency of 36%, a sample counting time of 250000 seconds and a chemical yield of 85%. These last three parameters are the most important and easily adaptable. For example, if the chemical yield is only 75%, to reach the same uncertainty and MDA, the counting efficiency should be increased to 38% and the counting time to 280000 seconds.

The last figure next page presents the variation of the relative uncertainty in function of the activity found in the urine or faecal sample measured by $\alpha$ spectrometry. This figure represents the best achievable uncertainty obtained for bioassay analysis by $\alpha$ spectrometry.

Main contact person

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Main references

Relative uncertainty on the measured activity of 1 mBq/24h (red curve left scale) and MDA (blue curve, right scale) as a function of the sample counting time.

Sample counting time in seconds applied by the laboratories (blue line: average sample counting time).

<table>
<thead>
<tr>
<th>Laboratoires Average</th>
<th>Optimum Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume sample</td>
<td>24h (14 lab) – 1 L (4 lab)</td>
</tr>
<tr>
<td>Tracer activity</td>
<td>32 mBq</td>
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<tr>
<td>Sample counting time</td>
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<tr>
<td>Background</td>
<td>6.2 E-6 counts / sec</td>
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<td>Background counting time</td>
<td>459 000 sec</td>
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<td>Chemical Yield</td>
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<td>Uncertainty on 1 mBq/24h</td>
<td>35 %</td>
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<tr>
<td>MDA</td>
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Average analytical conditions for the laboratories and the optimum for urine analysis by α spectrometry.

Relative uncertainty as a function of activity in urine and faeces, using the optimum analytical conditions for α spectrometry.
Background

A coherent and effective off-site emergency plan including all relevant response capabilities in case of a nuclear emergency forms the ultimate layer of the ‘defence-in-depth’ philosophy of nuclear safety. The main aim of off-site emergency management is to take balanced, accepted and feasible decisions regarding the protection of the population and the environment in case of calamity. The Royal Decree on The Emergency Plan for Nuclear Risks on the Belgian Territory describes the role and tasks of the different stakeholders involved in case of a nuclear crisis affecting Belgium. A crucial step for intervention decision making is the radiological evaluation process. The Evaluation Cell (CELEVAL) of the Crisis Centre in Brussels (CGCCR) is responsible to gather all relevant information, to analyse it and to give advice on the best intervention strategy for the Decision Coordination Committee to follow. SCK•CEN plays a role as radiological advisor within CELEVAL and elaborates user-friendly radiological evaluation tools to be used jointly by the main nuclear utilities and by CELEVAL. It is the role of the utilities to perform the relevant calculations, CELEVAL analyses the results. SCK•CEN has finalised its development of the PC model Plan d’Urgence – Zone de Production Nucléaire de Tihange to be used during the early phase of a nuclear emergency.

Objectives

SCK•CEN is inter alia involved in following tasks helping to improve the nuclear off-site emergency management process:

■ to assist the main nuclear utilities in the radiological evaluation process and to support and advise the Belgian authorities involved in nuclear emergency management regarding the best intervention strategy in case of necessity;

■ to continuously improve methods to assess in real time the radiological impact on the population and the environment during a nuclear emergency;

■ to provide adequate training and exercise sessions to the main stakeholders involved.

Principal results

The real-time module of the computer model Plan d’Urgence – Zone de Production Nucléaire de Tihange assesses the radiological impact of a radioactive release using real-time stack monitoring data and meteorological data. A database of pre-calculated accident scenarios allows for an immediate global assessment of the projected potential radiological consequences prior to any release, for decisions on precautionary countermeasures. Based on an event-based decision tree, the nuclear operator selects the most appropriate accident scenario and links it to the prevailing weather conditions. A lot of flexibility has been included to cope with the needs of the Belgian authorities involved in nuclear emergency response. Some attention has been given to differentiate the total dose expected from the release and the dose still avertable by the application of countermeasures. As an example two screen shots are given on the opposite page for a fictitious release at the Tihange nuclear power plant. Doses and depositions are presented on a map. A user-friendly interface allows access to the parameters of the map (scale, color-presentation of doses and depositions ...)

Future developments

The further harmonisation of existing radiological evaluation tools in Belgium is foreseen. Nuclear emergency exercises held on a regular basis will help to define future needs in radiological evaluation capabilities. A better integration is intended of non-radiological factors, so called socio-economical aspects, in the evaluation and advisory process. Training different aspects of emergency planning and response will remain important.

Main contact person

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Main reference

Expected surface contamination of $^{131}$I (Bq/m²) following a rupture of the primary circuit and a subsequent core melt at the Tihange nuclear power plant for a hypothetical accident scenario.

Expected thyroid dose (mSv) to a small child (1y) for the same accident scenario (close up).
BR2 Operation

Scientific Staff

Supporting Staff

Reactorexperiments

Scientific Staff

Supporting Staff
Luc Droogmans, Herman Lodewijkx, Victor Oeyen, Gerard Van Esch, Rachel Verboven.

Maintenance BR2

Scientific Staff
Stefan Declercq, Marc Hannes, Stefan Lodewyckx, Filip Ramaekers, Bart Smolders, Roger Stynen, Jan Van der Auwera.

Supporting Staff
The Reactor BR2 traditionally provides irradiation services for its internal (within SCK•CEN) and external clients. The services supplied range from the neutron and gamma irradiations of materials and fuels within the framework of scientific programs belonging to the internal and external customers, to commercial productions in the field of radioisotopes for medical and industrial uses and NTD-Silicon for the microelectronic industry. These commercial activities are exclusively directed to external customers and are of prime importance to provide financial support for the operating costs of the reactor.

For some years we have tried to exploit our know-how gained from the operation of the reactor by promoting services specifically oriented to the safety and operation of existing research reactors and the development of new ones. These efforts were fully realised for the first time in 2002 and 2003 by two contracts related to the behaviour under irradiation of structural materials and the development of new fuels.

Also the synergy between our knowledge in irradiation technology and the scientific collaboration with external partners led to the development and the successful irradiation of new and first of its kind irradiation rigs for the in-situ testing of materials.

The irradiation of samples at temperatures as high as 1000°C is considered for fusion reactors as well as for high-temperature fission reactors and Generation IV reactors. A design task was initiated to study a new irradiation rig for the BR2 reactor to meet these requirements. Different types of irradiation devices were examined, each fulfilling different requirements, with the samples either under circulating or stagnant inert gas.

Development work on a new concept of variable neutron screen started and will be continued in 2004.

Modern experimental devices now require various on-line detectors for an in-situ evaluation of the real irradiations conditions and the validation of calculation codes. Our activities in this field combine the testing of the detectors and the understanding of their behaviour by studying the underlying physics.

These activities in reactor physics and in-core instrumentation are part of a global programme that allows us to fully exploit the exceptional capabilities of the reactor facility. This programme also deals with the development of data/acquisition systems and of new multipurpose reusable irradiation devices. All instrumented irradiation devices are now connected to an in-house built data acquisition system allowing the scientific researchers and the project engineers to follow their experiments on-line using their office PC’s.

We continued the successful utilisation of a new multipurpose reusable irradiation device. It is designed to irradiate various materials in a broad range of temperatures and is loaded in the centre of a BR2 fuel element to maximize the fast neutron flux. This device called MISTRAL, was used within the framework of materials development for fusion and ADS. We foresee an intensive utilisation of two such existing devices for the next years.

The CALLISTO loop is still our most important irradiation facility for materials and fuels experiments. It comprises three in-pile sections that are connected to a common out-pile equipment. The principal purpose of this device is to simulate the irradiation conditions representative of PWR reactors. One of the in-pile sections is inserted completely within the reactor core to maximize the fast flux conditions. The main activities in 2003 concerned the irradiation of various structural materials for PWR and fusion reactors. We foresee in 2004 the further utilisation of the CALLISTO loop for testing of materials and the start of an important fuel programme subsidised by the EC.

The exploitation of the reactor was very successful in 2003. The availability of the plant reached 97.81 %, no incident was recorded and the commercial revenues reached a new record. For 2004 we foresee again various maintenance and equipment replacement activities to guarantee a continued safe and reliable operation for the future.

Contact
Pol Gubel, pol.gubel@sckcen.be
OPERATION OF THE BR2 REACTOR

Background
The BR2 is still SCK•CEN’s most important nuclear facility. After an extensive refurbishment of 22 months to compensate for the ageing of the installations, to enhance the reliability of operation and to comply with modern safety standards, it was restarted in April 1997. The facility is mainly used for the irradiation and testing of fuels and materials and for commercial productions – including radioisotopes for the medical and industrial uses, and NTD-Silicon.

Objectives
To keep the reactor facility available for the scientific irradiation programmes and commercial productions along the whole predefined operation schedule, while maintaining safety during operation as the top priority.

Principal results
The reactor was operated for 119 days at the mean power level of 53 MWth. The normal operation period was extended for a week during the summer to optimise the production of radioisotopes for the radiopharmaceutical industry. Also four special operation cycles of two days each (three between cycles 01/2003 and 02/2003, and one after cycle 05/2003) were organised to conduct transient tests on pre-irradiated high burnup fuel pins.

The reactor was operated with an availability of 97.81 % (time at power over scheduled time at power). One interruption of operation was recorded due to the reactor protection system and caused a delay of two days (xenon poisoning) in the operation schedule.

Routine maintenance activities and inspections during the scheduled shutdowns guarantee the continued safe and reliable operation of the facility and provide the basis for a secure long-term future.

The evacuation of fuel elements to Cogema-La Hague continued with two transports of 68 fuel elements each. In total, from 1998, we had 16 transports for 986 fuel elements.

Six lead test assemblies, with 73 % enriched uranium and a higher uranium density in the meat to maintain the nominal 235U content, were irradiated for 4 cycles and reached a burn-up of 50 %.

Future developments
For 2004, we foresee:
- a standard operation schedule with an extra week of operation during the summer; also cycle 02/2004 will include a scheduled two days intermediate shutdown to allow the adaptation of the experimental load;
- various maintenance activities aiming at maintaining a secure and reliable operation;
- the partial refurbishment of the storage channel;
- one transport of spent fuel elements to Cogema-La Hague;
- in collaboration with the SCK•CEN’s Physical Control, the definition of items to be studied and/or revised in the frame of the 2006 decennial safety re-evaluation: this latter should take into account a possible operation of the reactor until 2015.

Main contact person
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Main reference
Top lid of the BR2 materials testing reactor during reloading. The five 200mm experimental holes are clearly visible in the center and at 11, 1, 3 and 5 o’clock positions. The SIDONIE device for the neutron doping of silicon is installed in the 11 o’clock position. Outer 84 mm holes are filled with beryllium reflector rods. Most of the central 84 mm holes are covered with a temporary cover, awaiting loading with e.g. a fuel element. Experimental rigs show plastic or metal hoses carrying gas sample or data transmission lines.

<table>
<thead>
<tr>
<th>Year</th>
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<td>2002</td>
<td>100.00</td>
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<tr>
<td>2003</td>
<td>97.81</td>
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Plant operation data
Background

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/cm².s), the BR2 reactor is considered as a major facility through its contribution for a continuous supply of products such as $^{99}$Mo ($^{99m}$Tc), $^{131}$I, $^{133}$Xe, $^{182}$Re, $^{153}$Sm, $^{90}$Y, $^{188}$W ($^{188}$Re), $^{203}$Hg, $^{82}$Br, $^{41}$Ar, $^{177}$Lu, $^{85}$Sr, $^{169}$Yb, $^{147}$Nd, ... Neutron Transmutation Doped (NTD) silicon is produced for the semiconductor industry in the SIDONIE (Silicon Doping by Neutron Irradiation Experiment) facility, which is designed to continuously rotate and traverse the silicon through the neutron flux. These combined movements produce exceptional dopant homogeneity in batches of silicon measuring 4 and 5-inches in diameter by up to 750 mm in length.

Objectives

To provide a reliable and qualitative supply of radioisotopes and NTD-silicon to the customers in accordance with a quality system that has been certified to the requirements of the “EN ISO 9001 : 2000”. This new Quality System Certificate has been obtained in November 2003 for the “Production of radioisotopes for medical and industrial applications” and the “Production of Neutron Transmutation Doped (NTD) Silicon” in the BR2 reactor.

Principal results

1. Since the restart of the BR2 reactor in 1997, after its refurbishment in 1995-1997, the income from the production of radioisotopes and NTD-silicon increased considerably as shown in Fig.1 in relative units.
2. BR2 has consolidated its market position in the production of large quantities ‘high specifi c’ activities of $^{192}$Ir ($T_{1/2}$=74 d) for both therapeutic and industrial applications.
3. Highly enriched $^{174}$Lu targets are routinely and successfully irradiated for the production of $^{177}$Lu, which is an ideal candidate for future targeted radiotherapy with radiolabelled peptides: long half life ($T_{1/2}$=6.71 d), good physical properties, emitting both beta (maximum 0.5 MeV; average 0.17 MeV) for therapy and gamma rays (113 keV and 208 keV) useful for imaging. Furthermore, the test irradiations of seed cores preloaded with $^{125}$Xe were successful; BR2 has been validated for the routine production of $^{125}$I ($T_{1/2}$=59.4 d) seeds for the treatment of the prostate cancer.
4. BR2’s silicon irradiation service performed very satisfactorily throughout 2003 in terms of its level of business and the record income that it generated.

Future developments

1. BR2 is working on a project to supply $^{188}$W ($T_{1/2}$=69.4 d) for the manufacture of $^{188}$W/$^{188}$Re generators. Several medical applications of $^{188}$Re ($T_{1/2}$=16.9 h) are actively under consideration in cardiology and bone pain palliation.
2. Ongoing study to identify the technical feasibility of a new scheme to increase BR2’s NTD-silicon capability by more than 100% whilst also taking into account the industries increasing demand for 6-inch irradiation capacity.

Main contact person
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Main references
Evolution of the income from radioisotopes and NTD-silicon production in the BR2 reactor.
IRRADIATION OF FUELS

Background
Safe, reliable and economical operation of reactor fuels, both UO$_2$ and MOX types, requires in-pile testing and qualification up to high target burn-up levels. In-pile testing of advanced fuels for improved performance is also mandatory.

Objectives
Neutron irradiation of LWR (Light Water Reactor) and BWR (Boiling Water) fuels in the BR2 reactor under relevant operating and monitoring conditions, as specified by the experimenter’s requirements.

Principal results
In 2003 power transient tests have been done on four BWR segments. Further development work was done for preparing the long term irradiation of LWR fuel in the high-pressure facility CALLISTO in the BR2 reactor.

- Ramping of BWR (Boiling Water Reactor) fuel segments has been done in a dedicated irradiation device. The equipment consists of an in-pile capsule (PWC) surrounded by a calibration device (CCD) for determining the heat generated in the fuel. MCNP (Monte Carlo N-Particle)- calculations, modelling the irradiation device and the reactor, have been made. Code predictions are combined with data collected when irradiating a dummy rod instead of the fuel segment. This procedure allows us to accurately predict the heat generated in the structural materials by prompt and delayed neutrons, prompt and delayed $\gamma$-rays as well as $\gamma$-rays released in neutron capture reactions. A dedicated computer program was developed for determining on-line the maximum linear power of the segment using readings from thermocouples and pressure difference sensors on one hand and the relative power distribution from MCNP results on the other hand.

After reactor cycle 01/2003, three short irradiation campaigns have been performed. A fourth campaign was performed after reactor cycle 05/2003. In each campaign a power transient on a BWR fuel segment was done. Typically the segment, pre-irradiated in a nuclear power station up to a peak burnup of 37.5 GWd/tM, was subject to a rapid power increase of 100 W/cm.s from 250 W/cm up to 460 W/cm. The segment was pre-conditioned over 24 hours and irradiation was continued for an other period of 24 hours at the power level reached after the transient. A typical power versus time history is represented in the figure on the next page.

- Detail design work for the OMICO (Oxide fuels: Microstructure and COMposition Variations - THOMOX (THOrium Mixed Oxide) program has continued. A twin-bundle consisting of 8 instrumented- and 8 non-instrumented fuel pins will be tested in the high-pressure high-temperature loop CALLISTO under typical PWR-conditions. The bundle comprises UO$_2$, (U,Pu)O$_2$, as well as (Th,Pu)O$_2$ pins. A total number of 40 instrumentation wires are installed on the pins and in the upstream and downstream section of the fuel bundle. A special penetration has been developed to provide the connections from the instrumentation in the high-pressure (155 bar), high-temperature (300°C) loop to the monitoring and data acquisition system. Presently the fuel pins are under fabrication. The figure on next page shows the twin-bundle concept. The lower basket containing the 8 non-instrumented pins can be removed for hot cell examinations, coupled again to the upper basket and then the irradiation can be resumed with both the instrumented and the non-instrumented bundles.

- Presently power transients on fuel are performed in special irradiation campaigns by the modification of the BR2 reactor power. In the past a He$_3$ was used as a neutron absorber. The production of tritium however caused the degradation of seals. A study is being undertaken to develop a neutron absorbing screen in which borated water will be used. By adjusting the boron concentration the desired power level in the fuel pin inside the screen could be obtained.

Future developments
- The fuel pins for the OMICO-programme are presently under fabrication. Irradiation in BR2 is scheduled to start in the second quarter of 2004.
- Development work on the borated water neutron screen will continue.

Main contact person
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Four BWR fuel segments were subject to a power ramp in the BR2 reactor. Typically after pre-conditioning for 24 hours, power was increased at 100 W/cm sec. The reached power was then maintained for another period of 24 hours.

The twin bundle of OMICO consisting of an upper basket with 8 instrumented pins (central thermocouple and a pressure transducer) and a lower basket with 8 non-instrumented pins.
Background
SCK•CEN irradiates, in collaboration with the EFDA (European Fusion Development Agreement), several materials in the BR2 reactor at different temperatures and up to different doses to study their mechanical and physical properties during and after irradiation. Those materials are candidates for the construction of different parts of the ITER (International Thermonuclear Experimental Reactor) fusion reactor and of the long-term DEMO (DEMonstration) reactor.

Objectives
1. to irradiate up to 0.3 dpa copper, copper alloys, titanium alloys and RAFM (Reduced Activity Ferritic Martensitic) steels in the temperature range 50-350°C.
2. to investigate in-situ the dynamic effects of applied stresses in pure copper and copper alloy components of ITER on the damage accumulation and on the mechanical performance under neutron flux.
3. to design an experimental rig to perform in-situ creep-fatigue tests under neutron irradiation and its out-pile equipments.
4. to design a high temperature gas loop to perform material irradiations up to 900°C.

Principal results
1. Survey of irradiations in 2003
   In 2003 we achieved the following irradiations in BR2:
   ■ second part of the irradiation of RAFM steel specimens with implanted helium at 50 and 350°C.
   ■ second part of the irradiation of titanium alloy specimens at 150°C
   ■ irradiation of titanium alloy specimens at 50°C

2. INSIDE project
   The aim of the INSIDE project (IN-Situ Dynamic Experiment) is to investigate in-situ the dynamic effects of the applied stresses in the copper components of ITER on the damage accumulation and the mechanical performance during neutron irradiation. The second uniaxial tensile testing of pure copper and copper alloys specimens was successfully achieved in 2003

3. COFAT project
   The aim of the COFAT project (COpper FATigue) is to investigate in-situ the dynamic effects of cyclically applied stresses in the copper components of ITER on the damage accumulation and the mechanical performance during neutron irradiation. We designed the in-pile rig and the required out-pile equipment in 2003.

4. High temperature HELium LOOP (HELLO) project
   We studied a new forced convection cooled helium loop for the BR2 reactor. The high pressure requirement limits to some 650°C the temperature that can be achieved in the loop. The irradiation of samples at temperatures as high as 1000°C is also considered, for fusion reactors (refractory metals, ceramics) as well as for high-temperature fission reactors and Generation IV reactors.

Future Developments
1. complementary experiments on in-situ tensile tests of copper alloys and RAFM might be performed in BR2
2. irradiation of copper alloys under creep-fatigue loading at low temperature in water (COFAT series)
3. irradiations of copper/stainless steel joints at 150°C up to 0.1 dpa.

Main contact person
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Main reference
Results of an CuCrZr in-situ tensile test at low temperature

HELLO In Pile Section design
Background

Construction materials of LWR’s, in particular the reactor pressure vessel steel and internal core components, need adequate in-pile testing to validate modelling codes and to confirm predicted lifetime behaviour or to prove the good-behaviour of these materials for extend life service.

Objectives

Neutron irradiation of LWR materials in the BR2 reactor under relevant operating and monitoring conditions as specified by the experimenter’s requirements.

Principal results

1. TANGO programme

The objective of the irradiation is to extend the surveillance database of the CNA-1 RPV steel, to confirm the results obtained in the past and prove the good-behaviour of this material beyond end-of-life (EOL).

2. RADAMO programme

This experiment allows, within our radiation damage modeling effort, to verify our theoretical models on reactor pressure vessel steels. As most available models are based on dispersion barrier hardening theory, only tensile tests were foreseen.

The RADAMO programme (RAdiation DAmage Modeling) went further by repeating the 4 previous RADAMO experiments; RADAMO 6bis, 7bis, 8bis and 9bis were then launched.

3. MIRAGE programme

The objective of this experiment, called MIRAGE 1 (Monitoring of IRradiation embrittlement and AGEing of a thermally-sensitive RPV weld), is to investigate the post-annealing behavior of a recently fabricated weld according to Doel I specifications.

Future developments

Irradiation of mini-compact tensile (CT) specimens (10x10x4.5 mm), of Charpy V and tensile specimens coming from material of a Belgium power reactor vessel is planned in 2004.

Main contact person

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Main reference

R. Chaouadi, Decembre 2002, “Irradiation-Induced Hardening of Eight RPV Steels and Welds RADAMO Irradiation”, R-3676
RADAMO specimens

TANGO specimens and capsules containing activation dosimeters are assembled to in “rod” that can be loaded in a standard CALLISTO basket.
Background
To increase our knowledge, gained from in-pile rigs dedicated to the study of fuels and materials, it is not only important to equip the rigs with on-line detectors, but also to extract reliable data from the sensors. Hence, our activities do not merely focus on testing the detectors, but also on understanding their behaviour under actual working conditions. Therefore, we study the underlying physics and translate the sensors’ output signals into real engineering values.

Objectives
■ To study the on-line in-pile measurement of gamma and neutron fluxes in real time;
■ To study parasitic radiation-induced signals in instrumentation cables.

Principal results
1. Modelling of Self Powered Neutron Detector signals
Self-Powered Neutron Detectors (SPNDs), containing Rh, Ag or Co emitters, allow us to follow the neutron flux in our rigs on-line if we analyze the SPND signals with a Monte Carlo model based on the Los Alamos MCNP code. The model calculates all contributions (prompt and delayed) to the detector’s sensitivity and, hence, yields the absolute sensitivity. This leads to a correct interpretation of the SPND signals. Moreover, we used the model to assess the gamma sensitivity of Self Powered Gamma Detectors (SPGD) in the framework of a consulting contract.

2. Sub-Miniaturised Fission Chambers testing and performance analysis
Due to their prompt response and their larger signal, fission chambers constitute an interesting alternative to SPNDs for measuring the neutron flux on-line. The FICTIONS programme aims at testing a new Sub-Miniaturized Fission Chamber (SMFC) for the in-core detection of high thermal and fast neutron fluxes. In co-operation with CEA/Cadarache, who developed the fission chambers, we irradiated two types of these detectors. (1) Preliminary tests of the 242Pu SMFCs indicated the feasibility of the SMFC technology, but also showed that improvements would be needed to reach reliable results for the fast flux measurements. (2) We completed the qualification of the thermal neutron 235U SMFC in water at 100°C.

After manufacturing a dedicated experimental device, we began testing these SMFCs in a PWR environment. We recorded SMFC currents as a function of the polarisation voltage and deduced thermal neutron flux values from the signals of the SMFCs in the saturation regime. All these results were consistent with the calculations performed during the design phase.

3. Radiation-induced Electromotive Force (RIEMF) effects in mineral-insulated (MI) cables
MI cables with copper and stainless steel cores have been irradiated in order to study the radiation-induced currents between the core-wire and the sheath. This study is of generic interest for all low-signal instrumentation in high-radiation fields and especially for the design of ITER’s magnetic diagnostics. As expected on the basis of a detailed MCNP model, the copper cables show much larger currents than the stainless steel cables. Moreover, a systematic rig orientation dependence was observed for all cables. Future tests will concentrate on effects of thermo-electric origin.

Future developments
■ Since on-line in-pile fast neutron flux measurement remains a challenge and is of high interest, we will continue to develop the dedicated SMFCs by extending our collaboration with CEA-Cadarache.
■ The underlying phenomena occurring in a thermocouple when measuring the centre-line temperature in a fuel rod is also one of our next research subjects.

Main contact person
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Main references
Observed RIEMF currents in MI cables with copper core wires (blue) and stainless steel core wires (green) irradiated in the BR2 reactor. The difference between the three data sets for each cable type is due to the different azimuthal positions on the supporting Al tube. After about one hour, the complete rig is rotated in discrete steps, leading to strong (but internally consistent) instantaneous current variations. After removal of the rig from the reactor core, the signals show a sudden change followed by a multiexponential decay.
Background

Present-day irradiation experiments are carefully designed to determine very specific characteristics of the concerned fuels and structural materials under well-defined conditions. To increase the added value of the irradiations and increase our competitive edge, a continuous effort is undertaken to improve both prediction and evaluation of irradiation conditions.

Objectives

Meet all the request of the experimenters by an in-house dedicated cell for reactor physics evaluations at the BR2 division.

Main results

Since 2000 a three-dimensional full-scale Monte Carlo model of the BR2 reactor under MCNP-4C is under extensive use for simulation of irradiation conditions of fuels and materials loaded in various irradiation devices.

In 2003 the major evaluations that were conducted are the following:

- new MTR fuels: detailed calculations were performed for the qualification programmes of new research reactor fuels (UMo-Al, U3Si2-Al). The model has been improved by introducing detailed burn-up distributions;
- OMICO programme: feasibility studies for a 4 years irradiation programme have been successfully executed. An important effort was devoted to the preparation of the routine work to be executed during the irradiation; before each BR2 cycle the power generation in the fuel rods and the surrounding structures will be determined as well as the fission rate distributions in each fuel rod for various control rod positions. At regular intervals the absolute burn-up distributions in the rods will be updated. All these results will serve as input for the on-line follow-up programme;
- TANGO programme: detailed fluences for all samples irradiated in the CALLISTO loop and various DG irradiation thimbles have been compiled;
- GERONIMO programme: this programme concerns power transients on PWR/BWR fuel rods;
- The initial stationary conditions and the required power increase by BR2 to execute the requested power transient have been determined;
- Mo-99 production: evaluation of the irradiation conditions in a new arrangement of fissile targets for Mo-99 production in a newly proposed PRF irradiation device;
- Fusion programme: optimisation of the design of a new 200 mm irradiation device for a First Wall Panel Mock-up of the proposed for ITER Fusion reactor.

The MCNP model of BR2 itself has been improved with respect to the spatial distribution of the burn-up in the partially burned BR2 fuel elements.

Future developments

For 2004 the following evaluations are already foreseen:

- optimization calculations for the design of a proposed additional irradiation facility for Si-doping, which should be located in the BR2 reactor pool close to the vessel;
- detailed absolute heat flux distribution in the BR2 fuel elements. The MCNP model with detailed burn-up distribution is expected to give improved results in particular for the fuel element loaded in the central flux-trap position.

Main contact person

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Main reference

Model of the 16 OMICO fuel pins, the central instrumentation tube and the cylindrical shroud tube loaded in the in-pile section IPS-1 of the CALLISTO loop.

The figure on the left gives a horizontal cross section of the BR2 core at mid-plane level. The figure on the right gives an almost vertical ($9^\circ$) cross section through IPS-1 of the CALLISTO loop, showing from left to right: the 200 mm channel H2 containing the SIDONIE irradiation device, the 84 mm channels G60 with an irradiation thimble containing the CORSAIR experiment, K49 with IPS-1 containing the OMICO fuel pins, H37 with a Be obturator and a Be plug, the 50 mm channels N30 and P19 with Al obturators and Be plugs, the BR2 vessel wall, the shroud surrounding the vessel and reactor pool water.

Computations of the linear heat generation rate in a fuel rod loaded in the irradiation device PWC (pressurised water capsule).

The figure on the left gives the evaluation of the contribution of the nuclear heating to the total energy produced in the concerned reactor channel (measured with a dummy steel rod). The figure on the right gives the evaluation of the linear fission power rate in a fuel rod for a given control rod height.
Scientific Staff
Gunter Bombaerts, Michel Bovy, Benny Carlé, Marc Coeckelbergh, Pascal Deboodt, Chloé Degros, Gilbert Eggermont, Isabelle Fucks, Paul Govaerts, Frank Hardeman, Erik Laes, Steven Lierman, Gaston Meskens, Bernard Neerdael, Anne Verledens, Ludo Veuchelen.

Supporting Staff
Catherine Spect, Dominique Trépagne-Glinne.
Background
SCK•CEN started four years ago the structured programme PISA with support of young researchers in social sciences from different disciplines and universities. They joined technical teams within SCK•CEN to complete our scientific insight and objectivity. PhD and post-doc projects were organised within specific research tracks mentioned below. The concept of reflection groups on Ethics and Expert Culture was extended with a third group on Public Involvement. Reflection groups operate with external experts (e.g. university professors and promoters) and interested SCK•CEN colleagues from different levels and divisions up to management.

Objectives
The original objectives for the PISA programme were realised, while meeting some particular difficulties related to the lack of transdisciplinary culture in universities and to historical characteristics of nuclear culture. The learning process on interaction with social sciences and universities brought better scientific insight in nuclear problems and improved our solving capacity. Dialogue opportunities occurred through new networks. A feedback was organised in mutual training.

Principal results
In 2003 proactive meetings of reflection groups were organised on justification in radiation protection and public involvement in nuclear waste management. This offered new perspectives for SCK•CEN (sustainable development, precaution approaches, substantial progress in the integration of perception in risk assessment and management. A particular added value was created through in depth analysis of social justice with prof. Marc Jacquemain, Université de Liège (Ulg), in relation to justification of practices. We published an overview of 3 year reflections on making ethical choices in radiation protection.

The experiments with public involvement in nuclear waste management were followed up at local, national, European and international level, in order to set up comparative feedback with attention for critical elements (democratic representativeness, group culture influences, distributive compensations, next step preparation such as consensus conferences). Critical evaluation and benchmarking is premature. Moreover a broader nuclear dialogue on nuclear options seemed still handicapped by the polarised nuclear phase-out discussion.

The PISA research was organised in 5 tracks with more specific results and progress (updated and communicated on the PISA website: www.sckcen.be/pisa/):

1. Sustainability and Nuclear Development, (SuND project).
In line with the active participation in the preparatory process of the World Summit on Sustainable Development (WSSD) SuND members focussed on the post-WSSD process during 2003. This included as well participation in the follow-up meetings of the United Nations as such (UN Commission on SD), the summit itself as meetings at Belgian and Flemish level, where the translation of the Johannesburg Plan of Implementation to national level was studied.
Within a PhD thesis with KULeuven on nuclear energy and sustainable development, work continued along the lines of a vision assessment of involved players. We conceived different long-term energy scenarios for the Belgian context (horizon 2050), involving different options, ranging from nuclear energy to carbon capture and storage, renewables, cogeneration and energy efficiency measures. We used these scenarios in a multi-criteria mapping exercise; involved players were invited to apply their own criteria of sustainable development in assessing the outcomes of the different scenarios. Moreover a contribution was made for the EC socio-economic programme of fusion, based on these experiences.
A successful Topical Day paid attention to three thematic issues in the sustainability debate: atmospheric pollution, access and availability of water and equity in the context of world development. This broad setting allowed a discussion of present-day energy policy making in its full complexity, paying particular attention to the Belgian decision to phase out existing nuclear power plants.

2. Transgenerational ethics and group think in nuclear waste management
This research track mainly consists of a PhD thesis with UGent, which inquires cognitive and affective aspects of individuals and groups in scientific assessment. More specifically, the interpretation of the results of our psycho-social questionnaire at international level on group think, personality traits and ethics in decision-making processes is now well advanced. The general philosophical framework for this study and the possible illustration of the philosophical theory by the low-level (type A) waste decision-making process in Belgium progressed in 2003.
The philosophical model of the researcher elaborates an enlarged risk management approach including argumentation, groupthink, cognitive dissonance, contextual elements, justification and ethics. It is empirically founded on an international questionnaire and on observation of the socio scientific dynamics, e.g. in MONA.

The data handling is nearly finished. A first striking result is that personal risk concern of scientists is correlated with their scientific risk assessment. The study of the type A waste decision-making process is about to become a good illustration of theoretical statements. Empirical findings however need some more elaboration in future. This PhD aims at being finalised by September 2004.

We postponed to complement the development of this approach of dealing with uncertainties with a historical analysis in order to better understand and clarify nuclear controversies as part of nuclear waste management (NWM).

Transgenerational ethics was only continued in 2003 in the context of a master thesis but taken up for future COWAM actions (European Community Waste Management project). The global comparative study of involvement and participation experiments of COWAM in the fifth European Framework Programme (FP5) was finalised, with the report published end 2003.

3. Legal aspects and liability.

The overall aim of the project Law & Technology demonstrates a shift from the examination of liability and the effect of prevention and precaution in nuclear regulation to the analysis of effectiveness of nuclear safety law and the implementation of horizontal regulation into nuclear law (e.g. environmental law).

The objectives of legal projects were met with a certain delay, trying to establish a structural cooperation over the borders of nuclear and discipline. We collaborated to an international project on risk regulation (RISKREG), which was introduced as a Marie Curie Research Training Network by TUSstuttgart (Prof. Ortwin Renn).

The main problems encountered in the PhD projects are the result of the learning process to understand science and technology and to integrate it into logics of law as discipline. A PhD work with Université Catholique de Louvain-la-Neuve (UCL) was focalised on the regulatory framework of nuclear safety, its enforcement, as well as control and sanctions.

The legal research has now the objective to study the effectiveness and control of safety regulation in Belgium and the European Union, encountering particular constraints (nuclear package) while new opportunities of controlling safety were created (e.g. Peer Reviews of the Nuclear Safety Convention).

The research into law and regulation has strong synergies with research on ethics and trends in decision making (governance) on nuclear safety, where hard sciences and technology development have to rely on a democratic process of law-making, which was lacking in the history of the nuclear era.

The PhD thesis with University Antwerp (UA) on nuclear medical applications has been finalised. It brought along challenging questions on the application of precaution and the ALARA principle (As Low As Reasonably Achievable) in hospitals, and is presented as a highlight by Steven Lieman.

4. Risk management.

The research project “Investigating safety culture according to a social science approach” has been continued in 2003, and is presented further in this report as highlight in the contribution by Isabelle Fucks.

During November 2002, SCK•CEN has organised an enquiry within the Belgian population regarding its perception of risk and safety related issues. This was a project in collaboration with the Institut de Radioprotection et de Sûreté Nucléaire (IRSN, France). In the beginning of 2003, the results have been investigated and presented at many occasions, both within and outside SCK•CEN. Some of the main lessons that can be drawn are that technological risks are not the main concern of the population (e.g. less than social risks such as terrorism or unemployment). Within the technological risks, nuclear facilities are considered to have the largest catastrophic potential, but for routine operation, the concern for the waste issue is larger. Many of the actors in the nuclear world are not known by the public, and the general trust in them, telling the truth, is moderate to low. It’s also worthwhile mentioning that the radiation exposures which contribute the most to the dose to the general public show the least concern: medical X-rays are generally accepted to present low risks, and the policy of the authorities to protect against this risk is appreciated to be sufficient. Radon is little known and causes little concern, despite its rather large contribution to dose.
During the celebration of 40 years of the Belgian Association for Radiation Protection, a sample enquiry has been held with the participants. This showed a large difference between the opinion of the participants and the general population. Indeed, the participants consider the risk of waste to be small. The catastrophic potential of nuclear facilities is considered much less than the risk from chemical facilities. Further analysis in depth is foreseen for 2004. We also started collaboration with prof. Britte-Marie Drottz-Sjöberg (Trondheim University, Norway), to further analyse the results of this enquiry and to place it in a more general context.

5. Project preparation and feasibility studies during 2003

- Expert ethics applied to nuclear waste management and clearance

The project integrates previous sociological research results on expert culture of SCK•CEN experts with expression of the social construction of their mandate and their embedded values and contextual communicative behaviour. Some elements were developed for the FP6 project COWAM in relation to aspects of community involvement in nuclear waste management. Moreover a first approach was made to consider the perception of the expert of his behaviour and values in radiation protection and waste management, more particularly in relation to clearance.

The role of the operator and the implementation of regulatory requirements was confronted with ethical and law considerations inside SCK•CEN. This will be enlarged by embracing external experts and relevant actors.

- Public involvement

For FP6 the COWAM approach was enlarged to sustainable development and related constructive technology assessment (TA). An attempt to broaden the subject to non nuclear experiences in bio safety and energy failed as integrated project for FP6. Reflections were presented on the VALDOR workshop (Values in Decisions on Risk) in Sweden, more particular on nuclear sustainable development and phase-out, on ethics of experts and on the RISCOM model (need of guardians in socio-technological governance).

Finally the Flemish Institute on Scientific and Technological Assessment (ViWTA) accepted our research proposal to make an inventory discussion of the past social debate on nuclear energy in Flanders.

**Perspectives**

PISA contributed to self evaluation and critical analysis of results in order to redirect its activities within the adapted strategy of SCK•CEN for 2004 on.

Work should be more focussed within the limited resources for PISA (less than 1% of SCK•CEN budget). It will concentrate on the research activities energy, waste and health (RP) with 4 cross-cutting actions on:

- Ethical and regulatory references;
- Precaution (SD, ALARA, safety culture);
- Participation (fusion, waste, group think);
- decision making (emergency, phase-out, fusion, MYRRHA).

Reflection groups continue to operate in relation to these actions, but will be more product oriented with visiting meetings in universities.

**Contact**

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Background
Today, the concept of safety culture, developed in the 75-INSAG-4 report, is well-known. Researchers within academic and organisational spheres have investigated it. Safety culture is mainly focussing on human and organisational contributions to safety performance within organisations, characterised by a high level of risk. The term “safety culture” is used in different sectors, describing sometimes different things, which does not simplify its understanding. Before questioning the safety culture of an organisation and in order to develop our PhD research, it was needed therefore to clarify the theoretical approach chosen. The literature distinguishes between two visions about culture and safety culture. Firstly, safety culture can be considered as an organisational tool, which is the predominant view in the nuclear sector. This postulates that the organisation can develop, assess, enhance, and rectify culture by organisational actions. The second view considers safety culture as a metaphor of the organisation. It’s a kind of “culture of facts”. Within this anthropological approach, each organisation transports values and beliefs that are partly adopted by workers. The culture is seen as a source of description and understanding.

Objectives
The research is based on the anthropological approach. We postulate that safety culture exists outside any managerial intention. The ambition is to develop a better “understanding” of the concept as an analytical framework to encompass safety culture within organisations. The objectives are to investigate components, especially the informal component and to distinguish several safety cultures within an organisation.

Principal results
We develop an exploratory approach based upon social sciences. We used the Focus Group technique considering people at work as the best informed. The fieldwork is limited to two sites: a nuclear power plant (NPP) located in France and the Belgian Nuclear Research Centre, SCK•CEN. We considered different groups of players: workers, safety officers and managers.

Our first postulate is confirmed through our empirical investigation: safety culture exists within organisations without explicit intention to develop it. We distinguish several safety cultures which are differentiated, not by singular components but by specific articulations between them. The different safety cultures group similar components: regulatory components, organisational components, mental components (social representations), relational components and informal components. The specificity of a safety culture results from the predominance of one or two components and their ranking. The results also highlight specific topics such as the significance of social relations at work in the development of safety culture, the promotion of safety culture and the contribution of the organisational components to safety culture (as “conditional” but not as the unique condition).

Future developments
The research is in the final phase; the redaction of the PhD. The complete analysis will be delivered in October 2004. A report upon our experience in a NPP in France is already available.

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Isabelle Fucks, isabelle.fucks@sckcen.be, preparing a doctoral thesis based on this work.

Main references
The Radar graphic presents the significance of the five components which shape the safety culture. It expresses only the characteristic influence of each dimension: predominant, relative, minor. No quantitative conclusions can be drawn. The radar graphic suggests also the different “forms” that Safety culture can adopt within one organisation, given the numerous and possible articulations between the components.
Background
From a legal perspective a clear need exists for a general framework describing risk management. Specific guidelines are lacking for regulators and courts especially in case of scientific controversy and uncertainty about the health effects of an activity or a product (e.g. low doses of ionising radiation, electro-magnetic fields, genetically modified organisms, etc).

Objectives
The research area for this PhD thesis has been focussed on the medical applications of ionising radiation in the context of uncertainty. The safety approach depends on risk characterisation and differs for stochastic and deterministic effects. Deterministic effects can be identified in case of exposure above a well-known threshold, while stochastic effects, such as cancer and genetic effects, cannot be causally proofed on an individual level; the probability of effect increases with dose-level. Considering that the important diagnostic and therapeutic benefits of ionising radiation justify its use, this PhD research examines which priorities have to be dealt with for safe use for medical purposes, and how the law and jurisprudence translate this in a set of rules.

Principal results
Risk assessment and risk management that are based on traditional narrow risk-assessment models should be revisited in the light of the emerging precautionary principle. This principle cannot be used to solve conflicts in individual cases. This principle urges policy-makers to adopt a broader, more pluralistic approach, considering the societal equilibrium, i.e. the general interest of the activity at stake, the general impact of individual protective measures and the existence of “reasonable” alternatives from a sociological, economical, scientific and technological point of view. These broader considerations should already apply in radiation protection, for which optimisation approaches have been developed based on the ALARA principle. In case of scientific uncertainty about the causal relation between an activity and health effects, parties introducing a liability-claim cannot easily establish the standard of care and the causal link between fault and damage (i.e. stochastic effects).

The author argues that the precautionary principle cannot be used in individual liability cases and that liability law is not the indicated tool to prevent collective health damage. How can legal engineering or creative thinking be used to compensate victims? As a whole, causality in the nuclear field is a very delicate problem, while worldwide alternatives are under consideration such as “probability of causation”. However, such a concept, based on statistical proof, can hardly be implemented in Belgian law since our tort- and insurance-system is based on the individual relationship between responsible actor and victim. Since the civil liability system is not appropriate as a compensation mechanism in this context, occupational diseases not taken into account, the PhD student was challenged to seek other solutions that are not based on liability but on solidarity with financial guarantees. In his thesis the author proposes a no-fault compensation scheme that is not based on liability but on solidarity, at the same time improving prevention, looking for facilitation, diminishing financial cost and shortening the time-period of the procedures. In doing so, this research contributes to build bridges between safety sciences and law and between experts and judges, in the post modern era where the unconditional belief in scientific and technical expertise is being questioned.

Future developments
Steven Lierman will present his PhD research work in January 2004. There are 2 international publications in preparation; one in the field of Medical Law and one in the field of Nuclear Law.

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Managing Nuclear Knowledge

Reactor Safety
Radioactive Waste & Clean-up
Radiation Protection
Reactor BR2
Nuclear Research & Society

Managing Nuclear Knowledge

Fusion
Appendix
Managing Nuclear Knowledge

Scientific Staff

Supporting Staff
Monique Alen, Mario Bens, René Bubbe, Tom Couwberghs, Hendrik De Soete, Jan Joris, Wendy Machiels, Bart Marlein, Hans Melis, Frans Slegers, Caroline Poortmans, Catherine Spect, Cindy Verachtert, Nancy Van der Borgt, Monique Van Geel, Els Van Musscher, Viviane Van Springel, Marc Vreys.
MANAGING NUCLEAR KNOWLEDGE: a SCK•CEN Concern

Managing knowledge can be seen as the processes governing the creation, the dissemination and the utilisation of knowledge. Any organisation and specially a research centre will need a continuously updated body of knowledge as a basis of its sustained existence. Nuclear knowledge consists of scientific research reports, engineering analysis, models and countless other pieces of scientific documents and operational data. It also includes tacit knowledge embodied in professionals’ mind. Conserving and sharing this nuclear knowledge is fast becoming a topic of major concern all over the nuclear world. OECD NEA resumed already in 2001 that the aging of nuclear workforce and the decrease of the numbers of students graduating from courses in nuclear science and engineering could result in the loss of much of the present nuclear knowledge base. IAEA stressed in 2003 that the use of nuclear technology heavily relies on the accumulation of knowledge.

Preserving and enhancing of our institutional memory is becoming vital for SCK•CEN. We are therefore pursuing our efforts on sustaining Nuclear Education and Training and on stimulating preservation and sharing of Nuclear Knowledge.

1. Sustaining Nuclear Education and Training:
In October 2003 started the second academic year of the Belgian Nuclear higher Education Network (BNEN). This higher education network involves 5 Belgian universities and SCK•CEN. It aims at transferring nuclear knowledge and expertise to young scientists through selective and advanced courses on nuclear engineering. In 2003 the European nuclear engineering network (ENEN) under the co-ordination of SCK•CEN produced a handbook for a global strategy on a European Master of Science in Nuclear Engineering and organised two pilot sessions one on Nuclear Thermalhydraulics and the other on Nuclear Reactor Theory. The IAEA has supported ENEN by contributing to this network of education and training activities.

SCK•CEN has build a tradition in organising short courses in domains where his expertise is internationally recognised. The International School for Radiological Protection (iSRP), the Hogeschool Limburg, the Institut des Radioéléments (IRE) and the Institut Supérieur Industriel de Bruxelles (ISIB) launched a professional training underlying the qualification of ‘the Radiation Protection Expert’ according to the EU-directive 96/29/EURATOM and the article 73.2 of the Royal Decree of July 2001.

For the eleventh time SCK•CEN organised the European training course ‘Off-site Emergency Planning and Response to Nuclear Accidents’. Started in 1991 this course became very successful and has been lectured since then on a yearly basis at the premise of SCK•CEN and also in other (Candidate) Member States of the European Union. This Course aims at providing a state-of-the-art overview of all aspects related to nuclear accident management. A European Manual based on the training course notes has also been edited by SCK•CEN and made publicly available on the website of the European Commission. Next year the course will be extended to radiological emergency situations resulting from terrorist actions and will integrate the subject of rehabilitation strategies.

According to the principle of ‘the learning organisation’ SCK•CEN continuously organise in-house training sessions and offers a diversified education programme to all his employees. More than 25 courses going from nuclear safety, radiation protection over nuclear engineering and physics to management techniques, communication skills and languages were organised during the past year.

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2. Preserving and sharing Nuclear Knowledge

The driving force of Knowledge Management is the recognition that the knowledge generated nowadays and in the past is a valuable asset for future scientific research because it involved huge investments of scientific, human and financial resources. SCK•CEN decided in 2002 to tackle this strategic concern by establishing sustainable nuclear repositories available for present and future use. Since 2002 pilot projects in specific expertise areas have been conducted. Dedicated web-based portals sustaining interactive research communities have been further developed in 2003. They use the same underlying toolkit and offer the same basic features for collaboration and communication. They actually also include such features as editing, storing, retrieving, workflow and version control of documents.

In conclusion, knowledge management is essential for a knowledge-based organisation such as a scientific research centre. On the long term the effective management of nuclear knowledge at SCK•CEN will ensure the continued availability of essential reservoirs of both technical information and qualified people.

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Knowledge Management

Background
Since the very beginning, SCK-CEN has always been a knowledge-based organisation aiming at solving topical problems based on experience in the field, model-oriented experiments and fundamental research. This requires the preservation of a comprehensive nuclear knowledge capacity in a changing environment. Our knowledge exists in different forms and formats ranging from dispersed pieces of technical or scientific information on different media to a complex reservoir of people with the required educational background, expertise and acquired insights to apply that knowledge safely and effectively.

Objectives
SCK-CEN decided in 2001 to tackle this strategic concern by adopting a practical knowledge management (KM) approach. Our programme started in 2002 is built on ‘what already exists’. KM activities were identified all over our organisation – building databases, assembling nuclear and technical information, implementing QA procedures, conducting training, writing publications – so that every researcher or technical staff can lay claim to it. However, a co-ordinated approach to Knowledge Management requires an efficient re-use of the recorded knowledge and an effective transfer of the available knowledge. This approach ensures an added value to our research work and guarantees on the long term the preservation of our institutional memory.

The objective of the KM programme is the continuous improvement of the information management coupled with the elicitation of tacit knowledge, the stimulation of collaboration and the knowledge transfer. KM also enhances the information objects by adding or linking related additional information and tacit knowledge.

Principal Results and Future developments
KM needs were detected and prioritised. The necessary mechanisms and systems were created. In 2002, we decided to sustain existing communities of practice through web-based portals. Those knowledge systems are based on the same underlying content management framework for storing, retrieving and re-use of shared document collections and databases. Those systems offer today such features as personalised interface, editing, version control and collaboration tools for discussion.

In 2003 the basic Features, Events and Process-catalogue of the Waste and Disposal portal have been completed. This critical database summarizes relevant research and gives a current status on performance assessment. Because knowledge generated in the past is a vital asset for the future, state of the art reports and critical documents are retroactively brought in. This will act as the starting point for a review system leading to ‘knowledge tracks’ through which the tacit knowledge of experts will be recorded. Geographic Information System (GIS) databases for safety and performance assessment in the domains of geology and hydrology will be integrated in the Waste and Disposal community portal.

The Knowledge Centre portal, initially integrating external scientific information sources with online library services, enlarged this year his role to the management of the SCK-CEN Scientific Output (publications, conferences, reports etc.). In order to sustain self-assessment performance of conducted research projects, it offered to the entire SCK-CEN scientific community summarized statistics and dedicated editor interfaces. We foresee to launch in 2004 a web-based registration and review workflow for storage and dissemination of this scientific output.

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Main references
TRAINING OF THE RADIATION PROTECTION EXPERT

Background
The international school for Radiological Protection, isRP, is a task force within SCK•CEN that co-ordinates and organizes training programs on all aspects of radiological protection. Thanks to its extensive knowledge and expertise in nuclear science and technology, radiological protection and radiobiology, and its close co-operation with the Belgian authorities and the private sector, isRP has built up a solid reputation in the field of training, education and communication on all aspects of radiological protection and nuclear in general.

Objectives
Next to organizing training programs for our own personnel and for companies in the nuclear and non-nuclear industry and the medical sector, isRP also co-operates in the organization of courses together with other institutes, both on Belgian and European level.

In the framework of the European Directive 96/29/Euratom defining the ‘qualified expert’, European countries became aware of the necessity of a qualified training in this field. Since 2001, also the Belgian law contains a regulation concerning the qualification and training of the radiation expert.

Together with Hogeschool Limburg (HL, Diepenbeek), the Institut des Radioéléments (IRE, Fleurus) and the Institut Supérieur Industriel de Bruxelles (ISIB, Brussel), isRP aimed at setting up a professional training on academic level, including a broad theoretical curriculum and practical sessions, leading to a complete preparation of future radiation experts. This course is recognized by the Federal Agency for Nuclear Control (FANC) as being in complete agreement with article 73.2 of the Royal Decree of July 2001.

Principal results
A training course involving 120 h on nuclear and radiation physics, radiochemistry, dosimetry, nuclear measurement techniques, biological effects of ionizing radiation, applied radiological protection including organisation, European and Belgian regulation and legislation, was started in January 2003. In total 20 participants were registered, 12 for the Dutch and 8 for the French course.

Future developments
A second edition will be organized in 2004. In future editions, isRP wants to extend the curriculum: our opinion is that next to an in-depth technical training of the nuclear and medical personnel and of the radiological protection expert, also a multidisciplinary development of their expertise is needed. Taking into account ethical, philosophical and social aspects of the applications of radiation and nuclear energy will not only trigger the radiation expert to get a broader ‘reflective’ view on the issues themselves, but it will also help them to generate the necessary confidence in their interaction with members of the general public.

We aim at the recognition of this course on a European level and will participate in several working groups to reach this goal. In 2005 isRP will organize the 3th international conference on radiological protection training where this issue will be one of the main topics.

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Main reference

www.sckcen.be/isRP
Training of the radiation protection expert session at the Club-House of SCK•CEN
Off-Site Emergency Planning and Response to Nuclear Accidents

Background
Following the lessons learnt from the Chernobyl accident, the whole concept of off-site nuclear emergency management has been reviewed in depth at international, European and national level during the last decade. Several international organisations were at the forefront of this evolution, e.g. the International Commission on Radiation Protection, the International Atomic Energy Agency and the European Commission. Many of the resulting insights and concepts allowing for a better accident management have been translated into European directives and regulations and endorsed by national governments within the European Union. Traditionally, the Belgian Nuclear Research Centre (SCK·CEN) has been involved since the early days in national and European R&D programmes related to this topic. As a result of these activities, in 1991 SCK·CEN launched, under sponsorship of the EC (DG RTD – former DG XII, and DG ENV – former DG XI), a one-week Training Course on ‘Off-site Emergency Planning and Response to Nuclear Accidents’. This course became very successful and has been given since then on a more than yearly basis at SCK·CEN – Mol and other (Candidate) Member States of the European Union (Greece, Bulgaria, Czech Republic, Lithuania, Slovenia, Romania and Bulgaria). Meanwhile the Course itself was recently revised in depth to keep track of the latest evolutions on the European and international fora related to emergency management and to improve its didactic quality.

Objectives
Main objective of the Training Course is to provide fundamental knowledge and practical advice for everyone involved in various aspects of emergency planning and response, e.g. health physicists, technical and radiological advisors, staff responsible for the overall emergency organisation and policy, such as civil protection officers and environmental protection officers. The course offers a comprehensive overview to those entering the domain and to other people interested in a general view of nuclear and radiological emergency management in Europe.

Principal results
This Training Course provides a comprehensive state-of-the-art overview of all aspects of emergency planning and response, and stresses in particular the European dimension. The principal parts of the Course deal with topics such as principles of intervention, planning and organisation and decision-making with respect to off-site emergency. All accident phases are treated, with emphasis to urgent protective measures. Practical optimisation issues, allowing to make sensible choices between different intervention options, considering their drawbacks as well as their benefits, pervade the Course. The benefits are the reduction of potential individual and collective doses as well as the reduction of environmental contamination, and thus the reduction of direct radiological risks. The drawbacks are more related to less tangible aspects, lying in the realm of the human factor; which encompass psychological aspects, sociological aspects, even cultural aspects, but also economical and political ones. All of these aspects are dealt with in this Course. A full-day emergency response exercise simulating a nuclear accident in real time requires the students to work out an effective emergency response, facing them with uncertainties and difficulties of a real emergency. In parallel to the organisation of this, and under sponsorship of the EC DG TREN a European Manual for ‘Off-site Emergency Planning and Response to Nuclear Accidents’ based on the revised Training Course notes has been edited by SCK·CEN and made publicly available on an URL site of the EC DG TREN. An added value of the course is the interplay between participants from different cultures and backgrounds. Informal activities are organised to enhance contacts between students and with lecturers. Some snapshots of the Course 2003 are given in the following pictures.

Future developments
The next Course is foreseen for the week 21 – 25 June 2004. Under the EC Framework VI Integrated Project EURANOS the Course will also be extended to radiological emergency situations resulting from terroristic actions and integrate the subject of rehabilitation strategies.

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Main reference
Some snapshots from the Training Course on ‘Off-site Emergency Planning and Response to Nuclear Accidents’ held at SCK•CEN in June 2003. This Course gives a state-of-the-art overview of all aspects related to nuclear accident management.
Scientific staff

Fusion research was clearly worldwide in the lift during 2003. The ITER initiative grew to a major international enterprise, with a consortium grouping now the United States, China and Korea besides Europe, Japan and Russia, and a clear commitment to step forward to the joint construction of a burning plasma machine, ITER. Discussions on a fast track option for the fusion road map are even now aiming to energy production well before 2050. And the issue of where to build ITER, still unsolved at the end of the year, definitely manifests the important economic interests at stake. This increased attention to obtain finally the technological proof for this alternative emission-free and reliable energy supply should be related to the growing concern on future energy production, that appeared in 2003. There was indeed no sign at all of global CO2 emission stabilisation. On the contrary, the constant economic developments in Asia, especially in China, have even strongly increased fossil fuel world demand. And 2003 saw even in Iraq the energy related stress bursting out in an open war. Belgium did not do better. Contrary to specific signs of nuclear revival worldwide, a phase-out law was issued on fission nuclear plants, while incentives for renewal energy production did not produce any tangible results yet. In this context, it is not surprising that the fusion perspective made an entry into the governmental declaration.

The place of SCK•CEN in the Belgian, European and international fusion developments

The fusion research relies on a network of well-integrated centres of competence, and is co-ordinated in Europe under EFDA. The contribution of SCK•CEN relies on several fusion-relevant core competences:

- wide capabilities in high neutron flux material testing;
- a well-established material research know-how;
- a recognised position in radiation tolerance of instrumentation;
- an accelerator-driven spallation-source reactor project;
- a leading role in decommissioning and waste disposal issues.

The fusion involvement of SCK•CEN is therefore articulated around these strong poles. It addresses mainly one of the crucial issues for the fusion technological development: “How do materials and equipment behave under severe radiation environments?” And SCK•CEN is indeed able to tackle such an assessment in a very comprehensive way, taking full use of the BR2 material testing reactor; fully equipped hot cells, a wide range of gamma facilities and specialised laboratories for tritium and beryllium handling. The specificity of this involvement is recognised by the international co-ordination role it assumes about performance of new steels under radiation, and radiation hardening of instrumentation.

In Belgium, SCK•CEN’s task is complemented by a similar-scale research on plasma physics, where KMS/ERM2 and ULB3 are the key actors. All three institutes, grouped in the Belgian Association for Fusion, insure about 1.7% Belgian share in the total European research effort. Moreover, a presently limited but valuable industrial participation is coming from the membership of Belgatom in the EFET4 fusion industrial group.

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1 EFDA: European Fusion Development Agreement, part of the EIROforum interdisciplinary network together with CERN, ESA, ESO, EMBL, ESRF and ILL (http://www.eiroforum.org/)

2 KMS/ERM: Royal Military Academy, Brussels (http://fusion.rma.ac.be/)

3 ULB: University of Brussels (http://www.ulb.ac.be/rech/inventaire/unites/ULB106.html)

4 EFET: European Fusion Engineering and Technology, a European Economic Interest Group, acting as privileged industrial partner of the European fusion developments. Besides Belgatom, it involves Ansaldo, Fortum, Framatome, Ibertef and NNC (http://www.efetgrouping.com/).
A research with specific opportunities
The participation to the fusion developments brings specific challenges. It ensures high standard technological opportunities. And more specifically, it allows an integration into one of the most successful active network of excellence, broadly international, and characterised by a high level of openness and dynamism. This network was even the prototype of the now standard way of working during the European sixth framework research programme. The fusion community is also supported by a well organised mobility scheme, both at European level and in the upcoming ITER consortium. This triggers fruitful contact opportunities, and SCK•CEN has entered the scheme as an attractive hosting institution.

The 2003 achievements in a glance
The SCK•CEN fusion activities are distributed among several departments and they are mainly found in this report under their specific auspices.
On assessing materials under radiation, the accent was put on the new RAFM\(^5\) steels, on beryllium and copper alloys. A comprehensive assessment was for example completed on the behaviour of RAFM steels under fast neutrons up to the fluence representative of the Test Blanket Module to be installed in ITER. This work is now being extended to different metal-to-metal joints and to higher temperature testing. The new in-situ dynamic test capability in our BR2 reactor allowed for the first time to perform tensile characterisations during the actual irradiation. This allows a much more representative assessment of the materials to be used in severe environments, and could lead to standard limits to be revisited. At the same time, an increased attention was put to the modelisation of irradiation effects, starting with model alloys representative of the RAFM reference steel. Several international workshops were organised on the subject.

In the domain of radiation hardened instrumentation, a major step was made in assessing diagnostic systems under severe neutron fields, with for instance an in-pile validation of vacuum gauges, the evaluation of parasitic effects in connection cables and an assessment of the use of optical fibres under neutrons. An optical fibre data link concept was developed for remote controlled handling units, with all its components being upgraded to the required radiation tolerance.
Concerning some critical aspects of fusion waste management, an emerging activity on the detritiation issue allowed the water detritiation system planned for JET and ITER to be optimised. Particular attention was put on the conditioning of beryllium waste.
Socio-economic aspects were also considered, with the completion of studies around the public perception of fusion developments. This included an on-site evaluation around the potential ITER site of Cadarache.

Contact
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\(^5\) RAFM: Reduced Activation Ferritic Martensitic. Fusion has chosen a reference steel of this type, named Eurofer97.
OPTICAL FIBRES FOR PLASMA DIAGNOSTICS AT JET

Background
With the plasma burning conditions expected in ITER, the plasma ignition will produce a significant radiation field. This radiation field can severely degrade the performances of plasma diagnostic equipments installed close to the reactor vessel, like for instance optical fibres [1]. The optical fibre is a very convenient tool to transport the light emitted from the plasma edge to the diagnostic area, but their optical performances can degrade under radiation, in the form of a radiation-induced absorption (RIA) and a radiation-induced luminescence (RIL). This sets new challenges related to the development of radiation-resistant optical fibres, able to operate in a reliable way under the environmental conditions expected for ITER. SCK•CEN is currently assessing radiation-resistant glasses for optical fibres and developing the associated qualification procedure.

Objectives
1. To develop and propose a radiation-resistant glass optical fibres for ITER
2. To use JET as a representative test-bed for ITER

Principal results
Due to the formation of radiation-induced defects, the optical fibre strongly absorbs the light in the visible spectrum. However, when the optical fibre is treated with hydrogen, the formation rate of the defects is considerably reduced. Under radiation, the diffusion of hydrogen passivates actually the formation of the radiation-induced defects [2]. At equivalent total radiation dose, the hydrogen-treated optical fibres were shown to get a lower optical absorption, than untreated equivalent ones. glasses level. Figure 1 compares the radiation-induced absorption measured in several types of radiation-resistant fibres [3]. The lowest absorption is achieved indeed with a hydrogen-treated fibre.

The radiation qualification tests are usually conducted in continuous Co-60 or fission reactor irradiation facilities. It is however important to carry out tests in conditions that are most representative of a Tokamak environment, taking into account the temperature and radiation cycling, resulting from the pulse operation of the machine. In 2003, SCK•CEN installed an optical fibre link in the JET Torus-Hall. About 10 m of fibres were coiled inside a support tube, installed in an access hole close to the JET vessel. Figure 2 shows a schematic view of the experiment. A data acquisition system is currently monitoring the time evolution of the radiation-induced absorption and luminescence. The results of this long term monitoring will be analysed and reported in 2004.

Main contact person
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Main references
The figure compares the radiation-induced absorption level in three radiation-resistant fibres under similar irradiation conditions. The upper curve refers to the optical fibre used at JET, while the lower one is obtained with the hydrogen-treated candidate fibre for ITER.

The figure shows the experimental configuration. The tube supports the optical fibre coil (about 10 meters) close to the JET vessel. The data acquisition is synchronised with the JET plasma pulse and measures the radiation-induced absorption and the luminescence.
Background
Because of the presence of a reactive plasma in the thermonuclear fusion reactor vessel, the plasma facing materials are subject to erosion and the structural materials become highly activated. During periodic maintenance, operating tools can be exposed to total gamma doses that can reach 10 MGy and temperatures ranging from 50 to 200 °C. This calls for the use of radiation tolerant remote handling tools. Connecting the remotely operated actuators and sensors with their control unit outside the radiation fields requires bulky and shielded umbilicals. Their management could be eased by applying radiation resistant communication links with multiplexing abilities. Since more then 10 years, SCK•CEN coordinates the radiation tolerance assessment tests of components for their qualification and future integration in the remotely operated maintenance equipment. This includes fibre optic technology, since it was shown to be a potential solution to build robust bi-directional communication links with wavelength encoded multiplexing architectures.

Objectives
- Contribute to the major design of the maintenance equipment and strategy, with particular attention to the implications of radiation hardening rules and recommendations;
- study the radiation tolerance of a selected set of components and systems identified for divertor handling and refurbishment, in particular sensors and actuators;
- contribute to an effective umbilical management by studying radiation hardened multiplexing approaches with fibre optic links.

Principal results
Since 2003, SCK•CEN is directly involved in the CMM (Cassette Multifunctional Mover) design team. The conclusions of a first analysis on the list of COTS (Commercial Off The Shelf) components defined by the CMM design team regarding their radiation hardness have been discussed. Most of these sensors and actuators are being used in conventional industrial applications, some also in actual nuclear power plants. Their use under relevant ITER conditions needs however a case-by-case evaluation, based on the analysis of earlier results, or on some dedicated tests. In general, the continuous integration and increased complexity of today’s sensors and actuators make them more sensitive to radiation. This was often verified in the last years. The increased sensitivity is mainly to be attributed to an increased use of embedded electronics. Therefore it is very important to distinguish the sensitivity of such additions from the one of the sensor itself. The former can be tackled with an adapted design.

Independently from the final choices for the actuators and sensors, questions still remain as to the size of the umbilical and the connectors, their flexibility and handling abilities. This stresses the issue of signal multiplexing, keeping in mind the mandatory redundancy and safety rules. As part of a radiation tolerant bi-directional fibre-optic communication link, we built an optical transmitter, using components which had already shown a satisfactory behaviour under gamma radiation. The transmitter consists of a pulse width modulator (PWM), which is coupled to an electronic driver of a semiconductor laser assembly, which finally transmits the optical signal through an optical fibre to the control room. This optical signal could further be multiplexed in time or wavelength. For the complete link, the overall loss stems from the individual device contributions measured separately, i.e. the decrease of the driver source current, as well as the loss of the emitted semiconductor laser optical power.

Main contact person
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Main reference
Schematic diagram of the fibre-optic transmission link, using a PWM (pulse width modulator), a driver circuit and a semiconductor laser (VCSEL) to transform an incoming electrical signal into an optical signal that can be multiplexed and sent to the control room.

Comparison of the output signals of a digital driver circuit (left) and the semiconductor laser (VCSEL: right) before and after a gamma irradiation up to a dose.
External advisory committees continuously evaluate the scientific programmes of SCK•CEN. Their members are selected by the board of governors among the academic world and among senior actors of the nuclear community.

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<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
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<td>Katholieke Universiteit Leuven</td>
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<tr>
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<td>Université Catholique de Louvain-la-Neuve</td>
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</tbody>
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<table>
<thead>
<tr>
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<th>Institution</th>
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<tbody>
<tr>
<td>Chris Huyskens</td>
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#### DAC – Radioactive Waste, Dismantling & Radiochemistry

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<th>Institution</th>
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<th>Vice Chairmen</th>
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<th>Government commissioners</th>
<th>Observers of the trade union</th>
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Following the Chernobyl disaster, large forest areas have been affected by radiocaesium ($^{137}$Cs) deposits in former USSR countries and in Europe. $^{137}$Cs is a long half-life radionuclide particularly retained in forest ecosystems. Fifteen years after the contamination, important uncertainties remain however about the processes of $^{137}$Cs cycling and accumulation in trees, which may pose problems in terms of long term management of contaminated forests. In this context, this study reports on an original dynamic quantification of the $^{137}$Cs cycling and redistribution in trees, based on a multi-scale approach applied to contaminated Scots pine stands in Belarus.

We first evaluated the accuracy of the existing models of $^{137}$Cs cycling in forests. Significant discrepancies were observed in the long term tendencies of model predictions, particularly for perennial tree compartments (wood), highlighting the limitations of simplified approaches like transfer factors (TF) for forests. The age-dependant $^{137}$Cs fluxes between tree compartments were therefore derived from a detailed assessment of the $^{137}$Cs redistribution in a series of Scots pine stands. Our results showed the relative importance of $^{137}$Cs retranslocation (not considered in the existing models) compared to the uptake from the soil. Moreover, in mature stands, the current $^{137}$Cs immobilisation could not account for the total $^{137}$Cs content in wood, suggesting a remaining influence of early $^{137}$Cs interception and incorporation in trees (acute phase) and confirming the key role of wood as $^{137}$Cs sink. On this basis, at the forest stand scale, a promising proportionality between the $^{137}$Cs bioavailability in soil and the current rate of $^{137}$Cs immobilisation in wood (WIP), as alternative to TF, was highlighted. These results were integrated in a new conceptual model of $^{137}$Cs cycling in trees, based on $^{137}$Cs fluxes and including a pool of $^{137}$Cs translocation. Finally, in an applied perspective at a larger scale, the necessity to consider the spatial dimension of $^{137}$Cs deposition and ecosystems features was illustrated in a GIS-based feasibility study of contaminated wood valorisation as biofuel. The analysis shows that, notwithstanding the potential of this countermeasure, its practical implementation would require complementary site-specific data collection (biomass and $^{137}$Cs transfer) due to the important spatial variability of $^{137}$Cs deposition and the low precision of the existing maps.
Abstract
The Np behaviour in terms of solubility and speciation after its release from the vitrified waste has to be studied in the frame of the safe disposal of nuclear waste in the Boom Clay, the potential host rock formation for disposal of such waste in Belgium. The interstitial solution in the Boom Clay contains a high concentration of humic substances which can have an impact on the Np solubility due to the strong complexation by the complexing functional groups present in the humic acids. Considering the reducing conditions existing in the Boom Clay, Np will be in the tetravalent oxidation state. Np(IV) is expected to show strong interactions with humic acids.

This study aims, first, to fill the lack of data concerning the interaction of Np(IV) with humic acids in terms of complexation constants and second, to supply experimental data on the speciation of Np after its release from a Np-doped glass in the Boom Clay porewater.

As a preliminary work, the complexation constant quantifying the interaction of Np(V) with the site-specific Boom Clay humic acids is determined. The value, found in this work, is in good agreement with the literature data (log $\beta_{11} = 3.72 \pm 0.04$ for NpO$_2$HA).

Afterwards, for a better understanding of the interaction of Np(IV) with humic substances, the complexation study is started at pH 1-1.5, pH at which the hydrolysis is supposed to be minimal. The fulvic acid fraction, extracted from the Boom Clay porewater is chosen for its solubility at pH lower than 3. The complexation of Np$^{4+}$ with fulvic acid is described including the single complex NpFA(IV) and two mixed hydroxo-fulvate complexes (Np(OH)FA(III) and Np(OH)$_2$FA(II)). Then, at hydrolysis pH range, the interaction of Np(IV) with humic acids is studied through different approaches using either the Boom Clay porewater or extracted Boom Clay humic acid solutions.

High soluble Np concentrations are measured and two main Np(IV)-humate species are observed by UV-Vis spectroscopy. The two species are interpreted in terms of mixed hydroxo-humate complexes, Np(OH)$_x$HA with $x = 3$ or 4. These species are the most likely species that can form according to the pH working conditions. Finally, high complexation constants are calculated for these species under the Boom Clay conditions, i.e. log $\beta_{131}$ and log $\beta_{141}$ equal to 46 and 51.6 respectively.

The second objective is achieved through the measurements of the Np concentration in leachates from glass dissolution experiments and the spectroscopic characterisation of the Np complexes potentially present in the leaching solutions. High Np concentrations are found, higher than what we should expect from the solubility of Np(OH)$_4^-$, the solubility limiting solid phase determined to be present under the reducing conditions prevailing in the Boom Clay. Np(V) is shown to be the main oxidation state by UV-Vis spectroscopy; Np(V)-carbonate complexes being essentially present in the Boom Clay porewater. However, when good reducing conditions are applied, Np(IV) is predominant.

Comparing the data of the glass dissolution tests and the results of the study on the interaction of Np(IV) with humic substances, we can conclude that the complexation of Np(IV), one of the main critical radionuclides for performance assessment, with the humic substances may occur in a medium rich in humic substances like the Boom Clay.
Stress Corrosion Cracking (SCC) is a significant age-related degradation mechanism for loaded structural materials such as stainless steel (SS) and nickel-based alloys used in the core and in coolant circuits of light water reactors. Once cracking has initiated, the growth rate is determined or influenced strongly by the electrochemical kinetics and the nature and stability of surface films at the crack tip. Consequently, characterizing crack-tip chemistry and electrochemistry is an essential requirement for understanding and predicting SCC. The small scale of the phenomena and the complex nature of chemistry and electrochemistry formation in a crack, make mathematical modelling the most suitable approach to investigate, understand and predict SCC.

In this thesis a general applicable numerical tool is further developed and used for simulating SCC and Crevice Corrosion in sensitized stainless steel type 304 in high temperature water. The tool is based on a deterministic approach. It solves natural mass and charge conservation laws for a specific geometry. Included various chemical and electrochemical processes. The form of the output provides an easy way to interpret the results and interactions. The major advantage of such a developed framework, in comparison with already existing mathematical models of SCC, is that it considers the external and internal environments of the crack as one and treats them equally. Also the number of assumptions and simplifications is significantly reduced in comparison with already existing models of SCC.

The original tool describing mass and charge transport in electrochemical systems has been extended in order to make calculations with respect to SCC possible. A major extension concerned the incorporation of the production and consumption of species due to homogeneous reactions. It is now feasible to simulate systems with an arbitrary number of first order homogeneous reactions involving an arbitrary number of reacting species. After implementation, the tool has been validated by comparing the results to those of analytical solutions or to those of other numerical models often on simplified systems. The obtained framework is then used in a number of case and sensitivity studies. These studies show the feasibility of modelling SCC in stainless steel type 304 in high temperature water; contribute to the international discussion: where on the metal surface and by which electrochemical reactions is the crack tip current balanced; reveal a number of crucial parameters to be determined in further oriented experiments; illustrate the effect of global process variables (e.g. corrosion potential, solution conductivity, stress intensity) on crack growth; compare calculated trends with experimental observations; and point to the influence of conducting autoclave walls on electrochemical measurements in an aqueous environment at high temperature and under high pressure.

Up to the present time, theoretical modeling of stress corrosion cracking in metals and alloys, in general, and in reactor materials, in particular, has assumed idealized geometric, hydrodynamic, and electrochemical conditions, which are seldom, if ever, real life. It has been illustrated that the developed framework can, without further ado, be used as an engineering tool in the design against SCC of reactor structural components. This is demonstrated with the calculation of the chemistry and electrochemistry in the specific geometry encountered in a BWR recirculation inlet safe-end.

The developed framework is sufficiently flexible for the investigation of localized corrosion phenomena in other material-environment combinations. Even when other mechanisms are thought to be operative. In this respect, the predictive quality of the developed framework can be improved by incorporation of a more extensive description of the mechanical aspects of SCC or the description of hydrogen pick-up. In order to extend the applicability of the developed framework to Irradiation Assisted Stress Corrosion Cracking, the influence of radiation has to be incorporated. This involves implementing water radiolysis, and re-passivation kinetics and crack tip strain rate formulations that are relevant to irradiated materials in a reactor environment.
BEST UNIVERSITY AND COLLEGE FINAL-YEAR THESIS

Very keen to encourage high-quality research, the Belgian Nuclear Research Centre grants several awards. SCK•CEN attributes yearly prizes of respectively 1,500 and 1,000 € to the best university and the best college final-year theses carried out in its laboratories.

In 2003 the award for the best university theses was granted to:
Kelly Verheyen
“Positron annihilatie studie van nano-precipitaties in binaire FeCu legeringen”
Universiteit Gent
Mentor: Abdel Al Mazouzi
Promotor: Prof. Carlos Dauwe

The award for the best final-year theses was granted to:
Joris Nens
“Evaluatie van de dosisdistributie in een toekomstige fusereactor warme cel”
Hogeschool Limburg
Mentor: Marc Decréton
Promotor: Ing. Luc Lievens

SCK•CEN’S SCIENTIFIC AWARD PROFESSOR ROGER E. VAN GEEN

SCK•CEN allocates every two years 12,500 € to the best original work in nuclear research. The selection is performed by the Belgian National Fund for Scientific Research (NFWO/FNRS).

The next deadline is November 15, 2004. For details see http://www.sckcen.be.

PHD CANDIDATES & POSTDOCTORAL RESEARCHERS - SELECTION 2003

<table>
<thead>
<tr>
<th>Name</th>
<th>Research Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PhD candidates</strong></td>
<td></td>
</tr>
<tr>
<td>Sébastien Monchy</td>
<td>Association between mobile genetic elements and heavy metal resistance Ralstonia metallidurans: a tool for bioremediation.</td>
</tr>
<tr>
<td>Ivan Genchev</td>
<td>Radiation effects on active photonic components: from basic radiation-semiconductor interactions to real-world device characteristics.</td>
</tr>
<tr>
<td>Lise Duquêne</td>
<td>Plant paremeters affecting U uptake by and U distribution in plants.</td>
</tr>
<tr>
<td>Kelly Verheyen</td>
<td>Advanced experimental techniques for the comprehension of hardening and embrittlement mechanisms in RPV steels.</td>
</tr>
<tr>
<td><strong>Postdoctoral</strong></td>
<td></td>
</tr>
<tr>
<td>Velislava Ignatova</td>
<td>Corrosion of reactor materials: characterisation of surface layers.</td>
</tr>
</tbody>
</table>
## Scientific Output 2003

The SCK•CEN scientific output can be consulted on our website [http://www.sckcen.be/sckcen_nl/publications/scientrep](http://www.sckcen.be/sckcen_nl/publications/scientrep)

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<td>2</td>
<td>4</td>
<td>5</td>
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<td>Proceedings</td>
<td>11</td>
<td>14</td>
<td>33</td>
<td>56</td>
<td>46</td>
<td>55</td>
<td>60</td>
<td>49</td>
<td>37</td>
<td>73</td>
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<td>104</td>
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<td>119</td>
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<td>19</td>
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* partial results as of December 31, to be completed and confirmed later

## Visitors in 2003

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ESV: Underground Research Facility and Demonstration hall EURIDICE
BR1, BR2 and BR3: Reactors
LHMA: Laboratory for High and Medium Level Activity
SCH: Chemistry department
RP: Radiationprotection
TTS: Exhibition room

* several groups visited more than one building
Events in 2003

Conferences
■ International Workshop on P&T and ADS Development, “InWor for P&T and ADS’2003” (October)
■ The Benelux Nuclear and Plasma Science Society: 1st IEEE Evening Event (June)
■ EREM 2003: 4th Symposium on Electrokinetic Remediation (May)
■ Belgian Nuclear Society, 1st Young Generation Evening Event (April)
■ Workshop on personal dosimetry in hospitals: practical considerations and difficulties (March)
■ EURATOM FP6 Research and Training Programme, Topical Information Meeting about Infrastructures for Nuclear Fission and Radiation Protection Research (March)

Topical days
■ Cable aging in nuclear environments (December)
■ Sustainability & Nuclear Development (October)
■ Radiation damage in ferritic steels: synergy between multiscale simulation and modelling-oriented experiments (October)
■ Mixed (radioactive-chemical-toxic) Wastes: Problems and management (May)
■ Topical Day on Severe Accident Research (January)

Monthly Lunch talks
■ The isRP project: communicating the aspects of radiological protection.
■ Radiation effect at low dose: “Beneficial or harmful?” - Cancerogenesis, hormesis, adaptive response.
■ BioMoSA ‘Biosphere Models for Safety Assessment of radioactive waste disposal based on the application of the Reference Biosphere Methodology’
■ The REBUS-experiment at the VENUS-reactor of SCK•CEN
■ Can mycorrhizal fungi influence radionuclides acquisition by plants?
■ Improvement of high-energy particle-nucleus interaction model: case of the Intra-Nuclear Cascade of Liège
■ Agricultural Countermeasures
■ Thermohydraulic calculations for design & safety applications in MYRRHA
■ Kyrgyzstan
■ Corrosion of Zircaloy: A TEM investigation
■ Cable ageing issues in NPPs: a contribution from SCK•CEN
■ Problem with leaking barrels at Belgoprocess
■ VRIMOR : Virtual Reality in Inspection Maintenance, Outage and Repair (5th EU Framework project
■ Experimental research programme proposed for supporting the development of a disposal design for HLW
■ Functioning reviews
TRAINING

isRP (international school for Radiological Protection)

- Basisbegrippen stralingsbescherming (for Belgoprocess), January
- ‘Fysische basis van de biologische stralingseffecten’, Posthogeschoolvorming Stralingsprotectie, Katholieke Hogeschool Brugge-Oostende, January, May & September
- Grondige cursus Stralingsbescherming (for SCK•CEN, Belgoprocess, Belgonucléaire), May
- Cours approfondi de Radioprotecion (for SCK•CEN), May
- Cursus Bescherming tegen radioactieve straling: Nationale Vereniging voor Beveiliging tegen Brand en Binnendringing (NVBB), October
- Training session ‘Radiological Protection’ - open registration (Dutch) (Transnubel, Belgonucléaire, Electrabel, DIGI Belgium nv), October
- Cours Radioactivité; Association Nationale pour la Protection contre l’Incendie et l’Intrusion (ANPI), November
- Training session for certified technical personnel ‘Occupational Health’ Prevent, November
- Training session ‘Radiological Protection’ - open registration (French) (Belgonucléaire, Agence Fédérale de Contrôle Nucléaire (AFCN), Canberra Eurisys Benelux, SCK•CEN), November
- Training session ‘Radiactivity and nuclear physics’ and ‘Interaction of radiation with matter’ for the European Radiation Protection Course (ERPC), November
- Training session ‘Legislation’ and ‘ALARA, theory and practice’ for the European Radiation Protection Course (ERPC), December

Throughout 2003

Organisation of and contribution to the first academic year of the ‘Radiological Protection Expert Training’, in co-operation with the Hogeschool Limburg.

Outlook on Future Topical Days

- Knowledge Management in a Scientific environment (March 25, 2004)
- Radiation sensitivity of mammalian germ cells and early embryos: recent results and new perspectives (May 18, 2004)

Workshops, Conferences, Courses,... organised by SCK•CEN

- International Workshop on Information Systems for Crisis Response and Management (May 3-4, 2004)

Workshops, Conferences, Courses,... related to SCK•CEN

- 6th International FLINS Conference on Applied Computational Intelligence, FLINS 2004 (September 1-3, 2004)
- Experimental Programme of the URF HADES (January 27-29, 2004)

Interuniversity programme in Nuclear Engineering organised within the Framework of the Belgian Nuclear Higher Education Network (BNEN).

BNEN is an interuniversity programme in a collaboration between SCK•CEN and the Vrije Universiteit Brussel, VUB, Universiteit Gent, UGent, Katholieke Universiteit Leuven, KULeuven, Université de Liège, ULg, Université Catholique de Louvain, UCL. After successful completion of the programme the academic degree “Masters of Science in Nuclear Engineering” is awarded.

Courses

- Nuclear energy: introduction
- Introduction to nuclear physics
- Nuclear reactor theory and experiments
- Nuclear thermal-hydraulics
- Operation and control
- Reliability and safety
- Nuclear fuel cycle and applied radiochemistry
- Nuclear materials I
- Nuclear materials II
- Radiation protection and nuclear measurements
- Advances courses (on the above topics)
- Project and internship
ENEN (European Nuclear Engineering Network)

Supported by the 5th Framework Programme of the European Commission, the European Nuclear Engineering Network (ENEN), consisting of a representative cross section of the EU-25, prepares a coherent and practical concept for a European Master of Science in Nuclear Engineering. To demonstrate the feasibility of the concept, pilot courses were organised. The courses on Nuclear Thermal Hydraulics (6 ECTS) and Nuclear Reactor Theory (8 ECTS) part of the Belgian academic postgraduate programme on nuclear engineering, were organised in a highly modular way and taught in English to facilitate and enhance participation of European students. The course makes full use of the laboratory facilities and infrastructure of SCK•CEN. In total some 30 students, of which 50% local, participated in the courses.

Training in 2003

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(*): number of hours
www.sckcen.be

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