Marc Decréton

Instrumentation

Introduction

Advanced instrumentation is essential for most nuclear applications, such as the control of nuclear power plants, the remote monitoring of waste repositories or the remote manipulation of hazardous materials. In this respect, instrumentation issues are becoming of increasing importance for several reasons. First, there is the continuous effort in the nuclear industry to reduce human exposure to radiation and contamination. This calls for the use of advanced instruments which allow performing a multitude of tasks remotely, while providing comprehensive and credible data up to the remote working area. Second, the number of maintenance and repair tasks increases due to the ageing of existing nuclear installations. Regarding the ageing of installations, specific instrumentation replacement schemes face problems when the original technology has become obsolete or simply inaccessible. Advanced alternatives are available but must be assessed. In this respect, a major problem when dealing with instrumentation in a nuclear environment is that most new sensors and electronic devices are very sensitive to ionising radiation.

Background

Over more than ten years, SCK•CEN Instrumentation Department has gained considerable expertise in the area of radiation effects on components and materials, including motors, strain gauges, accelerometers, ultrasonic transducers, electronic devices and circuits, polymers and cabling materials, glasses, optical fibres and opto-electronic devices. The group uses a number of irradiation facilities and consists of eight scientists (among whom four PhD's), supported by a staff of skilled technicians.

Objectives

Existing resources and infrastructure enable us:

- to develop advanced instrumentation systems for nuclear applications;
- to assess their performance in a radiation environment;
- to give consistent advice on equipment to be used under harsh nuclear conditions;
- to offer a variety of irradiation and testing services at very competitive rates.

Programme

The activity pays particular attention to the following problems:

- the use of an optical fibre as umbilical link of a remote handling unit for use during maintenance of a fusion reactor;
- the radiation hardening of plasma diagnostic systems;
- the launching of studies on new instrumentation for the future MYRRHA accelerator driven system.

Our projects cover also:

- space applications related to radiation-hardened lenses;
- 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.

Two doctoral research works were completed in 2001 and one is about to be finalised.

Our research is partly covered by a number of contracts with the European Commission (Fusion Technology), the Electrabel-Tractebel Belgian utilities, the European Space Agency (ESA) and the INTAS programme.

Achievements

The presentation of achievements is structured along three main lines:

- photonic communication and sensing systems dedicated to nuclear applications;
- radiation hardening, irradiation technology and irradiation services;
- advanced reactor instrumentation.

Photonic communication and sensing systems dedicated to nuclear applications

A radiation-tolerant optical transmitter prototype for fusion environments

Most reported data on radiation tolerance of opto-electronic components concern only individual optical parts, for instance fibres, emitters, receivers. Very often however, the driving electronics for controlling

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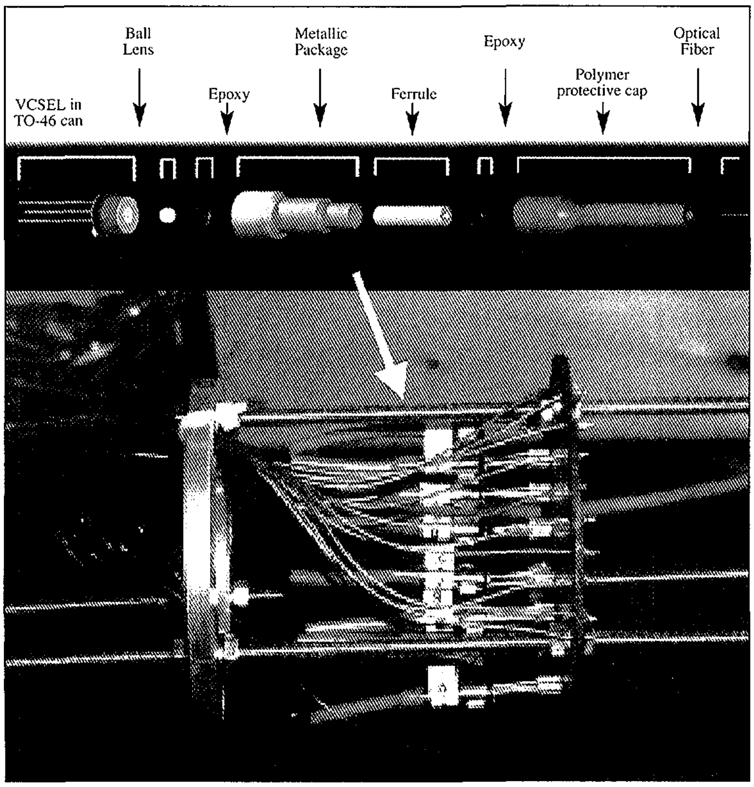
the optical link are omitted. Commercial-off-the-shelf (COTS) drivers are usually sensitive to radiation and can therefore not be applied in optical fibre communication systems, to be operated under harsh nuclear radiation environments. This is particularly true when high total dose levels are involved. SCK•CEN therefore decided to design a complete radiation tolerant transmitter, using the vertical-cavity surface-emitting laser (VCSEL) and a dedicated electronic driver circuit. The total dose tolerance of specially designed VCSEL assemblies (next figure) reaches 10 MGy. The design of the driver circuit was based on discrete COTS bipolar transistors. When the radiation induced degradation of these components is considered within the design of the circuits, total dose levels larger than 1 MGy can be tolerated. We succeeded in demonstrating with a SPICE software simulation and with complementary experiments, that at a total dose of 1 MGy, the measured decrease of the forward current is only 8 %. This induces an optical output power decrease that can still be tolerated with irradiated VCSELs.



VCSEL assemblies mounted on irradiation rig and exploded view of a single VCSEL assembly

Fibre-optic wavelength division multiplexing components for fusion applications

The design of the radiation tolerant transmitter described above opens perspectives for a new approach to data-communication along the umbilical link connecting remote-handling tools inside the future ITER thermonuclear fusion reactor vessel, to the control equipment. We started investigating the capabilities of analogue transmission along an optical-fibre, instead of digital transmission, with the opportunity to reduce the amount of radiation sensitive electronic devices and with the idea of taking benefit of the wavelength division multiplexing (WDM) capabilities of optical fibre transmission. A preliminary comparison was made, in terms of compatibility with ITER requirements, intrinsic performance and complexity. However, the high total dose radiation tolerance of a complete WDM optical link still needs to be assessed. We characterised two key components of such a link: fused tapered couplers and fibre Bragg gratings (FBGs), at very high total gamma dose (13 MGy) and neutron fluence.

We demonstrated that the coupler insertion loss increases due to the radiation-induced attenuation in the standard optical fibre used. Moreover, the coupler isolation decreases to 10 dB. The broadband coupler, however, keeps its multiplexing capabilities. The narrow-band couplers can operate up to the MGy dose levels. The wavelength channels drift indeed, but without the channel separation being modified. This effect can be ascribed to a gamma-radiation-induced change of the refractive index.

For FBGs, our earlier results have already shown that:

- the radiation sensitivity depends on the fibre's chemical composition;
- FBGs written in "rad-hard" fibres show paradoxically the highest sensitivity to radiation, in terms of Bragg wavelength shift. These fibres are hydrogen-loaded;
- the temperature sensitivity coefficient remains unaffected by radiation.

To assess the use of such FBGs at high neutron fluence and very high gamma dose-rate, we performed additional experiments in the BR2 reactor. The sensors were gamma pre-irradiated to increase their neutron resistance. Four FBGs, used as temperature sensors, were multiplexed by splicing them along one rad-hard fibre. To ensure safe handling within the BR2 reactor, a dedicated procedure was developed to insert the fibre into stainless steel capillary tubes. The response of the FBGs was compared to calibrated thermocouples. The observed FBG drifts follow a power law without any saturation. The reflection properties of the FBG sensor irradiated at low temperature remain unaltered during the irradiation, indicating that only the mean refractive index changes, with a near linear evolution with dose, while the refractive index modulation remains unaltered. We therefore evidenced, for the first time, that FBG sensors could withstand extreme nuclear environments.

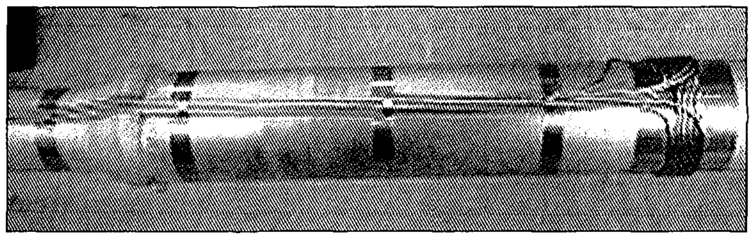
Optical fibres for radiation dose measurements

Radiation induced attenuation (RIA) can have detrimental effects on the use of optical fibres for data-communication or diagnostics, but can also be exploited as a sensing mechanism to develop a fibre-based dosimeter or for hot spot detection. The amount of RIA at a particular wavelength can be taken as a measure for the absorbed radiation dose. To that purpose, an ideal fibre dosimeter should not only exhibit a significant radiation sensitivity, but also a negligible recovery (or fading) effect, in order to be used as a reliable integrating device. This is generally difficult to obtain with standard commercially available optical fibres, which then requires a descriptive model that is able to account for the different parameters affecting the fibre response under radiation. Using existing pragmatic models, we demonstrated the feasibility to determine the absorbed dose in these fibres at room temperature, with an accuracy of about 20 %. On the other hand, we evidenced previously for a special phosphorous doped optical fibre that there is an optimum wavelength (around 1 300 nm) at which we observe a very limited recovery. Using radiation induced attenuation data in this wavelength region, we also showed that it is possible to reconstruct the dose with an accuracy of about 20 %. In collaboration with Tractebel, we continued our work on gathering consequent information on RIA for a series of both commercial-off-the-shelf (COTS) and dedicated optical fibres for dosimetry applications, at particular dose-rates, total doses and temperatures. To this end, we performed additional experiments in order to assess the temperature dependency during irradiation and under post-irradiation conditions.

We demonstrated the robustness of P-doped multimode fibres against a limited temperature perturbation (up to 65 °C) at wavelengths above 1 200 nm. A single-mode P-doped fibre, fabricated by FORC (Moscow), was tested using the optical time domain reflectometry (OTDR) technique. We also investigated erbium-doped fibres at a gamma dose-rate of 80 Gy/h, and observed a linear radiation response depending on the Er concentration. Photobleaching was evidenced as a possible way to "reset" the fibre and the temperature dependency showed a decreased sensitivity at higher temperatures. The tested fibres were identified as suitable but not necessarily ideal. Finally, custom made fibres and COTS fibres will provide us with complementary results, depending on the environmental conditions and the envisaged applications, enabling remote on-line monitoring of cable-ageing effects in NPPs and waste storage facilities.

Optical fibres for optical plasma spectrometry in fusion diagnostics

The successful operation of a fusion reactor relies on reliable plasma diagnostic systems. These systems have to operate near radiation and heat source for many hundreds of hours. In the case of optical plasma diagnostic systems, the optical path usually involves a complex set of mirrors, lenses and windows. The use of optical fibres is attractive in order to simplify the optical path, and the related engineering design. Nevertheless, the approach is only valid if sufficient radiation tolerance can be guaranteed, and that proper fibre specifications can be issued. Taking into account our previous work on special rad-hard fibres, a series of round-robin tests was initiated with Japanese and Russian partners, in order to assess a set of candidate fibres for the specific diagnostic environment. Particular attention was put on radiation-induced attenuation in the visible and ultraviolet spectrum and on radio-luminescence effects. A flexible irradiation rig, called SMIRNOF, was designed and successfully operated in the BR2 reactor (next figure), up to a fluence of 2 10^{20} n/cm^2. The facility allows temperature control through variable air flow cooling, between 100 and 500°C. A new procedure to install the optical fibre has been developed, in view of extrapolating it to the intricate optical path to be followed through the fusion reactor first wall. The temporal and spectral response of the light absorption and luminescence were monitored on-line. The best radiation tolerance was achieved with fibres preloaded with hydrogen, at least for small flu-



BR2 irradiation rig with stainless steel tube containing the optical fibres

ences. This confirms the positive role of hydrogen on retarding the formation of colour centres. For higher fluences, above 2 10^{18} n/cm^2, all fibres were showing a similar behaviour, suggesting a common optical degradation mechanism, independent of the fibre type and manufacturing technique. A remarkable radiation induced effect is the growth of the vibrational OH-absorption bands. This effect is observable in polymer-coated fibres and is caused by neutron-induced recoil protons in the coating. The use of metal-coated fibres would eliminate this effect, but on the other hand, this OH-absorption band increase could be interesting as potential principle for on-line neutron dosimetry at high fluence.

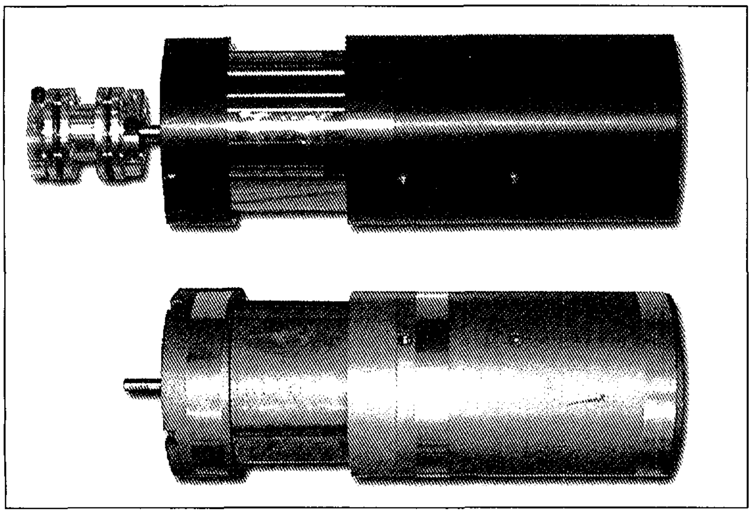
Radiation effects on glasses for space applications

It is well established that the physical properties of optical materials can be modified in an irradiation environment. For this reason optical glass manufacturers provide a range of so called radiation-hardened glasses, analogues of standard glasses, but with the addition of small amounts of cerium oxide. This stabilises the glasses against "solarisation" or darkening caused by radiation-induced colour centres in the material. Spectral transmittance is most commonly the only control parameter used to characterise the radiation hardness. Recent works, however, have suggested the need for a new methodology when dealing with the radiation impact on optical glasses, and addressing specifically the refractive index issue. In a contract funded by ESTEC-ESA and performed in collaboration with Astrium (Toulouse), the VUB (Cyclotron) and FPMs, we addressed specifically the issue of how to systematise the approach to performance characterisation of optical materials, typically used for components operating in space radiation environment. Particular emphasis was put on the study of refractive index stability. A set of carefully chosen commercially available glasses, including those commonly used in space optical systems, were subjected to proton and gamma radiation fields to accumulate total absorbed doses similar to those expected in a range of earth orbit scenarios. Both normal and radiation hardened glasses were tested, and additional experiments were conducted on gradient index materials and pre-fabricated micro-lenses. A number of important conclusions were drawn regarding the unexpected behaviour of the materials and with respect to the experimental approach. The induced refractive index changes are small and strongly material specific. Cerium doped glasses, chosen usually for their superior stability in light transmission, have appeared to be more sensitive with respect to refractive index. However, the most important issue for space optics remains anyway induced absorption.

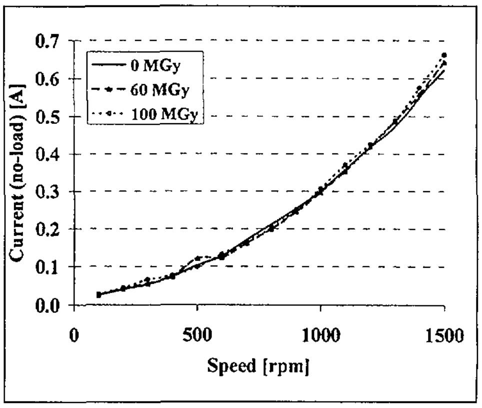
Radiation hardening, irradiation technology and irradiation services

Servomotors withstand a record 100 MGy total dose

To move the remotely controlled manipulators, telescopic devices and mirrors inside fusion reactor vessels, motor drives should be available, withstanding total doses up to 100 MGy. We started studying motors ten years ago in collaboration with FZK. Successive experiments were performed on individual motor parts and sub-assemblies. These components, in particular the insulation material for the cabling and the coils, and the bearing lubricant, were



The tested 2N servomotor before the irradiation campaign and after a total dose of 100 MGy



The current-speed characteristics of the motor are practically not changed even after the very total dose of 100 MGy

steadily upgraded. As a result, two final motor prototypes were ordered from the Maccon Company in Munich. These are brushless servomotors with a nominal torque of 2 Nm, a peak torque of 6 Nm, a maximum speed of 3 000 rpm at 150 V and an operating temperature of 180°C. The motors were equipped with two thermocouples in the windings, a brake (KEB Combiperm) with a 3 Nm holding torque, and an ARTUS pancake resolver. The following figure shows one of these motors before and after the 100 MGy total dose campaign that was completed in 2001, at a dose rate of 30 kGy/h. The current-speed characteristics of the irradiated motors before irradiation, after 60 MGy and at the end of the test at 100 MGy are shown in the next figure. As it can be observed, the difference is insignificant. It is to be noted that standard motors usually fail before reaching 1 MGy and that available rad-hard versions do not go at present beyond 10 MGy. The task was therefore completed with a "world première" on radiation hardening of motors, as such high total doses were never reported before. It offers a suitable solution for all ITER remote handling system, which are to be driven electrically.

Remote handling sensors for fusion reactors

A series of sensors used on the divertor test platform at ENEA-Brasimone have been identified in collaboration with ENEA and VTT. It involves laser sources, ultrasonic sensors, proximity switches, inclinometers, accelerometers and potentiometers. These are to be tested in representative gamma environment, including the possible effect of recovery during storage between missions inside the vessel. The activity also includes the irradiation of optical encoders used in the laser inspection system developed at ENEA-Frascati and of seals to be used by VTT on the water hydraulic articulated systems.

Cable management

Polymer and composite materials play an important role as thermal and electrical isolation in various devices installed in nuclear facilities. These materials may become the weakest part because of their expected high sensitivity to radiation. Irradiation experiments were therefore conducted to assess and determine the lifetime for some of these materials. We study in particular, the ageing of the instrumentation and its related cabling, as installed in nuclear power plants. Starting from the tests on insulation material, in collaboration with Kabelwerke (Eupen), the study is now extended to cables aged under real power plant conditions. This latter is performed together with the Belgian utilities and their measurement laboratory, Laborelec. The objective is to find the optimum ageing marker: rupture to elongation, infrared spectroscopy signature, electrical permittivity.

Irradiation services

A number of customers use our irradiation facilities to assess the radiation tolerance of specific materials and devices. On-going irradiation programmes for COGEMA and CEA aim at developing a better insight in the degradation mechanisms induced by gamma radiation in polymer and composite materials, used as electrical and thermal insulators. CEA is also using our gamma irradiation equipment to assess the radiation resistance of electronic circuits, parts of an electronic multiplexer to be used for sensor data in fusion remote-handling applications. Finally, with CERN, we are testing photonic parts of the optical read-out of particle trackers and detectors, which are to be installed on the Large Hadron Collider.

Database

We maintain a database with all the fusion-relevant data about radiation tolerance of remote handling components and systems. These data were obtained for the last ten years, by the European and Japanese teams. It forms the reference for the construction of the ITER reactor remote handling units.

New in-core reactor instrumentation for fusion and fission reactors

Radiation-induced electro-motive forces (RIEMF) in mineral insulated cables

The concern about RIEMF effects is motivated by its impact on magnetic coil fusion diagnostic systems. The mineral-insulated cables used for these coils are exposed to very high gamma and neutron fluxes. Induced voltages and currents can seriously interfere with the measurements. It is important to understand the degradation mechanisms involved, in order to minimise, or even cancel, unwanted effects. The problem came to the attention of the fusion community only recently but has been studied already in depth within the fission community. We therefore started a literature study, complemented with extensive theoretical modelling work. It is shown that mitigation measures are possible by carefully selecting the mineral insulation composition. The mitigation must, however, be tuned to the actual radiation environment. We prepare experimental tests to confirm these conclusions.

Radiation tolerance of neutral gas pressure gauges for fusion diagnostics

ITER plans to use hot-filament vacuum gauges previously designed for the ASDEX experimental stellarator. The parameters of the neutral gas environment are indeed important to be measured, in the main plasma region, but also near the divertor. The upgrade of these gauges to ITER standards involves a detailed assessment of their radiation tolerance. The critical parts in such a pressure gauge are the electrical feedthroughs, which are used for the various electrodes of this gauge. To assess their reliability under neutron radiation, we designed an experiment for the BR2 reactor. In this experiment, a novel approach is applied for vacuum tests: the pressure gauges will be mounted inside hermetically-sealed vacuum containers, equipped with on-line instrumentation connections and special getter material to absorb desorbed gases.

Feasibility studies for the future instrumentation of an accelerator driven system

In accelerator-driven systems, such as the MYRRHA design, the core is cooled by means of a liquid metal. During in-core maintenance operation, standard visual inspection is impossible. For safety reasons however, such a visualisation capability is required. For this reason, we started work on an alternative "ultrasonic camera", capable to inspect the inner vessel structures and to guide robotic manipulators manipulating the fuel rods. SCK•CEN initiated a collaboration with the Ultrasound Institute of the Kaunas University of Technology, Lithuania. The first phase of the joint work involves the development and testing of ultrasonic sensors, capable to operate in a high-temperature liquid lead-bismuth (Pb-Bi) eutectic. In addition, the acoustic properties of Pb-Bi are to be studied. A second phase will consider the radiation hardening of the sensors. Tests are prepared under gamma and neutrons irradiation in Mol. The final objective is to get a full visualisation system for MYRRHA. In 2001, the experimental testing facility in Lithuania has been made operational. The first studies show the importance of processes taking place at the surface, including corrosion. In particular, we demonstrated that the coupling of ultrasonic waves from sensor to liquid metal depends strongly on the wettability of the transmitting surface. The wettability is in turn related to the corrosion of the surface. On the other hand, a collaboration with the University of Dayton, USA, on the radiation hardness of aluminium nitride piezoelectric material was initiated. This material is the most promising ultrasonic transducer. We prepared an experimental test under gamma irradiation, allowing for on-line monitoring of the transducer characteristics.

An exploratory study was also made on laser systems, as one possible approach to measure the level of liquid metal above the spallation source of MYRRHA. A preliminary series of simulations on water and on mercury, as well as the study of a first set of specifications stressed the importance of a detailed knowledge of the liquid metal free surface condition.

Development of on-line gamma radiation sensors

On-line gamma dosimeters are only commercially available for low dose (radiation protection). For higher dose rates (0.1 to 100 kGy/h, and even up to in-core conditions) on the other hand, we developed some prototype gamma thermometers, but they are not readily available and are usually bulky and expensive. This intermediate range of gamma fluxes is typical of spent fuel or cobalt sources manipulation, near-vessel operation, or waste handling. It is also typical of most irradiation tests required for the assessment of radiation tolerance of instrumentation. At present, gamma dose measurement relies basically on off-line tests performed with so-called Red Perspex samples, based on radiation induced optical absorption. An uncertainty of up to 30% is inherent to the method. A promising on-line alternative is the self-powered gamma detector (SPGD) approach, developed for very high fluxes, but that could be adapted to the dose rates of interest here. An SPGD gives certain definite advantages: wide range of gamma flux (10^3 to 10^8 Gy/h), small size (outer diameter around 4 mm), easy operation, fast response. Tests in representative conditions revealed a relative precision better than 1 %, in the dose-rate range 0.1-100 kGy/h. A detailed theoretical model, based on Monte Carlo calculation, showed good agreement with the experimental results. The SPGD offer thus a very good relative gamma measurements. For absolute measurement, independent of the energy spectrum, the only technique is calorimetry. Due their complex operation and large size, calorimeters cannot however be easily used for routine monitoring. A new type of extremely sensitive gamma thermometer was therefore designed and tested. The first results show very good overall behaviour. These gamma thermometers will offer a way to get an absolute calibration of Red Perspex or SPGD gamma dose measurements.

Hydrogen sensors, sensor connections and fuel reinstrumentation

An in-core hydrogen sensor for PWR reactor conditions has been previously designed and tested. A more accurate and reliable version is now under study and a prototype manufactured. An assessment in representative conditions in the BR2 CALLISTO loop is being prepared. For such sensors (conductivity, electrochemical noise, crack-growth measurements, fission chambers), electrical feedthroughs tolerating high temperatures (350 °C), high-pressures (150 bar), high radiation and PWR relevant chemical environments are crucial. We developed such new feedthroughs, which are now the subject of a patent request. For the European project LIRES on in-pile corrosion studies, a special leak tight connection, between inconel and zirconium oxide tubes, was developed as part of the construction of an in pile reference electrode. The first tests in autoclaves show promising results.

A detailed instrumentation investigation is being carried out as part of the preparation of fuel characterisation, involving reinstrumentation of irradiated fuel pins: centreline temperature and fission gas pressure measurement. The equipment for the reinstrumentation of fuel rods is presently being designed, in collaboration with the Halden Reactor Project (Norway).

Perspectives

The present involvement is focused on the behaviour of instrumentation under the severe conditions existing in nuclear applications. It forms a specific niche where SCK•CEN has developed an expertise, answering crucial needs in several applications. The activity will therefore further concentrate along the following four strategical lines:

Fusion energy

It is essential to take an optimum share in the evolution of the fusion international programme towards a more objective-driven scenario: the construction of the ITER prototype reactor. This will give particular opportunities, in privileged partnership, with industry and scientific bodies, in high need of specialised advise to analyse the radiation tolerance of their developments, to propose upgrades, and to perform final qualification tests. Such a partnership will be particularly sought by the industry for the design of remote handling units, and by plasma physics institutes for the improvement of their diagnostics systems.

Advanced fission reactor concepts

A specific attention will be kept on the new challenges set by improved or new reactor concepts, related to reactor instrumentation. Their specifications, in terms of accuracy and reliability, rise often well above the usual state of the art of commercially available equipment. This concerns accelerator- driven systems, or high temperature reactors, but is also covering the improvement of in-pile sensing during irradiation tests in research reactors, such as BR2.

Monitoring of present reactors and waste disposal sites

A particular challenge is set by the ageing of the cables in our power reactors and the need of an optimum replacement scheme. A good monitoring is needed to follow the ageing phenomena. Intelligent monitoring systems, such as for instance distributed radiation and temperature watch-dogs, all along the cable lines, are particular perspectives, where the present close collaboration with our utilities is appreciated and should be amplified. Similar technological requirements appear in new measurement requirements for waste disposal sites, in particular when the retrievability option imposes a reliable long-term remote monitoring of the waste canisters and the barriers performance.

Space and medical applications

It is also our objective to extend the field of application to radiation tolerance problems outside the classical nuclear industry. Space and medical applications are also confronted with radiation resistance issues. The present collaboration with industry and university around space projects is essential and complements our capabilities, both in terms of field of expertise and infrastructure.

Partners

-	Astrium (Toulouse, France)
-	Kabelwerk (Eupen, Belgium)
-	Kaunas University of Technology (Kaunas, Lithuania)
-	Laborelec (St. Genesius Rode, Belgium)
-	Tohoku University (Tohoku, Japan)
-	Tractebel (Brussels, Belgium)
-	University of Dayton (Dayton, USA)
CEA	Commissariat à l'Energie Atomique(Saclay, Fontenay-aux-Roses and Tours)
CERN	Organisation Européenne de Recherche Nucléaire (Geneva, Switzerland)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Madrid, Spain)
COGEMA	Compagnie Générale de Matières Nucléaires (La Hague, France)
EFDA-CSU	European Fusion Development Agreement – Close Support Unit, (Garching, Germany
ENEA	Ente Per Le Nuove Tecnologie, l'Energia E l'Ambiente (Brasimone and Bologna, Italy)
ESTEC – ESA	European Space Research and Technology Centre (Noordwijk, Netherlands)
FORC	Fibre Optics Research Centre (Moscow, Russia)
FPMs	Faculté Polytechnique de Mons (Mons, Belgium)
FZK	Forschungzentrum Karlsruhe (Karlsruhe, Germany)
IFE – HRP	Institute for Energy and Technology; Halden Reactor Project(Halden, Norway)
JAERI	Japan Atomic Energy Research Institute (Ibaraki and Tokay, Japan)
ULB	Université Libre de Bruxelles (Brussels, Belgium)
VUB	Vrije Universiteit Brussel (Brussels, Belgium)
VTT Energy	Valtion Teknillinen Tutkimuskeskus (Helsinki, Finland)

Sponsors and customers

-	Electrabel-Tractebel (Brussels, Belgium)
EC	European Commission (Fusion Technology Programme)
ESA	European Space Agency
INTAS	International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union
ISTC	International Science and Technology Centre (Moscow, Russia)

Scientific output

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