Marc Decréton

Instrumentation

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Background

Instrumentation technology made spectacular advances. Smart sensors with distributed processing intelligence, high-speed optical communication and sensing have found rapid applications in many industrial sectors. For nuclear environments, however, safety constraints impose careful assessment procedures when adopting such new systems. Continuous assessment is needed, not only to benefit from the increase in performance of new technology, but also to avoid working with obsolete equipment. The latter may become hard to find and very expensive.

There is a clear need for advanced state-of-the-art sensors in *reactor instrumentation*, remote *handling operations* and *monitoring networks*. The value of in-pile tests depends on the detailed follow-up of the irradiation conditions and radiation induced properties changes. New reactor concepts, like fusion or accelerator driven designs, set new challenges to what and how to measure. New, more challenging remote handling tasks appear due to the ageing of nuclear installations, with more maintenance needs, repair interventions, and eventually dismantling tasks. Most of these new tasks require sensors and control strategies to cope with constrained environments. Waste management requires also efficient monitoring networks to evaluate the storage parameters status and their long-term reliability needs set unprecedented requirements on the measuring networks.

Objectives

The project aims at evaluating the potentials of instrumentation technologies under the severe constraints of nuclear applications. It focuses on the one hand on the tolerance of existing sensors to high radiation doses (including optical fibre sensors, and on the related intelligent data processing) and on the other hand to the development of new sensors and instrumentation techniques.

Programme

The project involves the assessment and development of sensitive measurement systems used under radiation environment. Evaluation of design upgrades as well as the conduct of extensive tests under radiation, using the gamma and neutron irradiation facilities of SCK•CEN, are the important parts of the work. Particular attention is devoted to the assessment of optical fibre components and their adaptability to radiation environments. This work involves also the evaluation of ageing processes in the instrumentation of fission plants as well as the development of specific data analysis strategies to compensate for ageing induced degradation of sensor and cable performance. In 2000, we put more attention on in-core reactor instrumentation, applied to fusion, accelerator driven and water-cooled fission reactors. This involves studying and developing more performant instrumentation for irradiation experiments in the materials testing reactor BR2, to contribute to the new instrumentation needs for MYRRHA, and for diagnostics systems of the ITER reactor.

The research is partly covered by several contracts with Electrabel, the European Commission (Fusion Technology), ESA (space applications) and INTAS (collaboration with Russia). Three doctoral research works are also on going on this subject. On the subject of fibre dosimetry, active collaboration of the Waste Disposal Department is acknowledged.

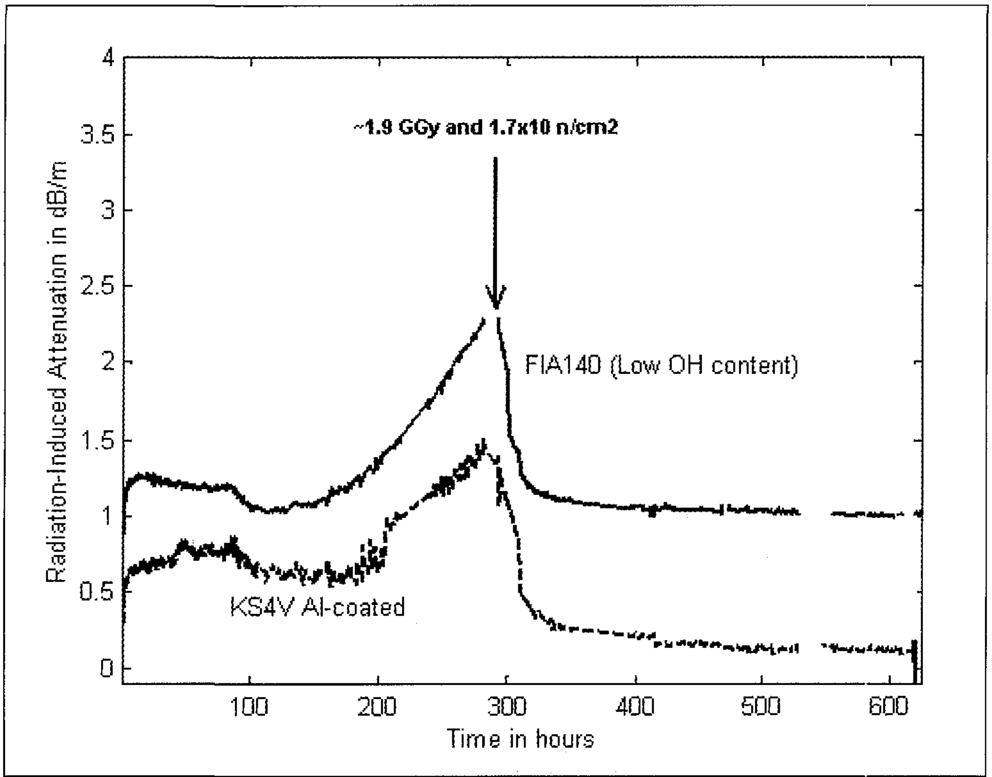
Achievements

Photonics for the nuclear environment

Nuclear infrastructure, including power plants, waste disposals, reprocessing plants and thermonuclear fusion reactor installations can benefit from the unique advantages of fibre-optic communication and sensing systems. The deployment of such systems in nuclear environments has been limited up to now, mainly due to reliability and safety constraints. In particular, the influence of ionising radiation on photonic devices is a main source of concern. In that respect, and in a continuing effort to assess novel technologies in nuclear environments, we investigated the radiation response of state-of-the-art fibre optic devices such as optical fibre Bragg gratings, vertical cavity surface emitting lasers (VCSELs), light emitting diodes (LEDs) and photodiodes. We exposed optical fibres to the particularly harsh radiation environment inside a nuclear reactor. We also paid particular attention to the possible use of optical fibres as radiation dosimeters.

Optical fibres

Pure-silica core fibre is known to be radiation resistant in the infrared region. A series of neutron irradiation experiments have been conducted on different types of fibres at a very high thermal neutron flux of



Typical radiation-induced attenuation response of optical fibres at 850 nm in BR2, followed by a recovery period.

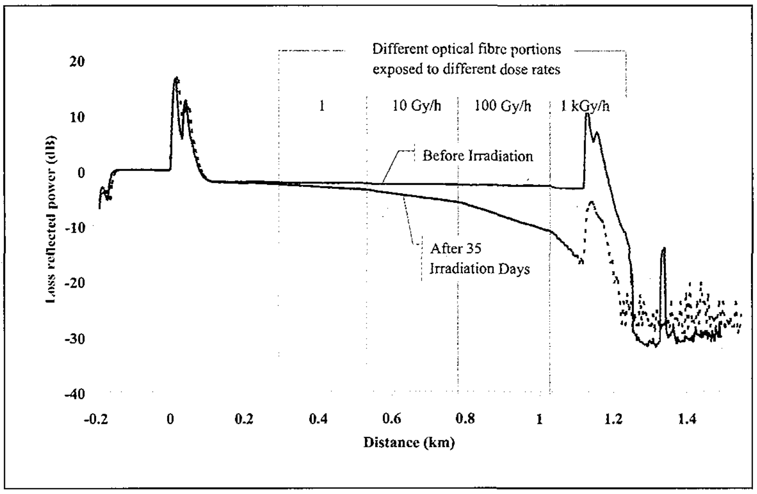
10^{14} n/cm^{2}s and a gamma dose-rate of about 5 MGy/h in the BR2 reactor. The results show that a strong saturation occurs first (see figure). However at a given threshold in fluence, the radiation-induced absorption starts to grow again. Aluminium coated optical fibre gives the best result. We observed also radioluminescence effects.

Bragg grating sensors

In-fibre Bragg-gratings (FBGs) have a rapidly growing area of application, as filter elements in Wavelength Division Multiplexing (WDM) systems and as temperature and strain sensors. An essential characteristics of such gratings is their Bragg resonance wavelength λ_B, which is defined by the grating period L and the effective refractive index n_{eff} : $\lambda_B = 2 \cdot \Lambda \cdot n_{eff}$. Previously, a series of gamma irradiations of FBG revealed a shift of the Bragg peak depending on the optical fibre type in which the grating was written and on its fabrication method. Several types of gratings have been irradiated in BR1. They were exposed to a thermal neutron flux up to 1.2×10^{10} n/cm^{2}s and a gamma dose-rate of 180 Gy/h during the reactor operation (50 kGy residual dose rate during the reactor shutdown). The major conclusion of this irradiation is that the hydrogen loading not only increases the photosensitivity but also the sensitivity to ionising radiation. The next step in the evaluation of FBG sensing technology as candidate for nuclear instrumentation was to irradiate them at higher flux levels in the BR2 reactor. There is clearly a threshold in fluence, above which the drift in Bragg wavelength becomes too large to use FBGs as reliable sensors. But FBGs have been shown to have useful potentialities to monitor temperature and strain in the vicinity of the reactor core and in the primary circuit.

Dose measurement with optical fibres

We study the use of optical fibres for radiation dose measurements in nuclear power plant facilities. The methodology relies on two distinct approaches. The first one considers a robust modelling of the behaviour of standard optical fibres to account for combined total dose, dose rate and temperature effects on the optical power budget. We showed that it is possible to reconstruct the dose from radiation induced attenuation data at a standard fibre-optic wavelength of 1310 nm. The method relies on distributed meas-



Optical Time Domain Reflectometer measurement of an optical fibre with different portions exposed to different dose rates.

urements performed in-situ, as illustrated in the figure. Current efforts aim at including both temperature effects and a larger dose-rate range for the applied predictive model. This work is performed in collaboration with Tractebel-Electrabel.

The second approach makes use of specially doped optical fibres, with a response tailored to account only for a total dose effect, minimising the influence of dose rate and/or temperature variations. A detailed characterisation and modelling of the radiation-induced attenuation in such optical fibres has been carried out. The samples studied originated from several batches of pure silica and custom made, doped fibres (through a collaboration with the Fibre Optic Research Centre, Moscow) and were irradiated in a spent fuel facility. We studied the radiation-induced attenuation in the kinetic and spectral domains, mainly by identification and deconvolution of the individual absorption bands related to the different types of generated defects. The dependencies on temperature and dose-rate were investigated in well-controlled, standardised experiments. The subsequent signal processing and modelling results were used to construct a robust, multiple wavelength annealing free dose-estimator for the case of pure silica fibres. Furthermore, as opposed to the attenuation data at a single wavelength, this alternative dose estimator proved to be temperature independent from room temperature up to at least 90°C. The main component in this dose estimator is believed to reflect the stability of a well known defect type, the peroxy radical. The potential for (distributed) dosimetry was also investigated for samples of Phosphorous doped fibres which showed almost no annealing in the telecom window from 1500 to 1600 nm. With respect to temperature variations, the induced attenuation after irradiation was almost insensitive up to 120 °C, which is an asset in applications like the geological disposal of nuclear waste.

Glasses for space applications

Our know-how in radiation effects on optical devices also allows us to participate in other research programmes such as evaluating the influence of space radiation on spaceborne optical systems. In a research programme funded by the European Space Agency (ESA), in collaboration with Astrium (France) and the Cyclotron department of the Vrije Universiteit Brussel, we defined a methodology to assess the effects of space radiation on glasses used in optical satellite payloads. So far one assumed that to avoid space radiation effects, conventional glass types could simply be replaced by their cerium-doped counterparts, which show significantly lower radiation induced absorption. However, these cerium-doped glasses now prove to show much larger radiation induced refractive index changes.

Remote handling components and materials for fusion reactor maintenance

Through neutron and gamma irradiation tests, SCK•CEN is developing an expertise in the field of radiation tolerance of materials and components, used in instrumentation systems. For some applications, these devices have to survive and to ensure their working capabilities in high radiation environment. This is specially true under the severe conditions foreseen in future fusion reactors, during maintenance tasks. The work makes an intensive use of the existing gamma and neutron irradiation facilities at SCK•CEN (the reactors BR2 and BR1, the gamma irradiation facilities RITA, BRIGITTE and GEUSE), which cover the wide range of foreseen operational conditions.

Insulation materials

In collaboration with Kabelwerke Eupen, we performed an evaluation study of new types of halogen free polymers with fire retardant characteristic used as insulating materials in electrical cables. After gamma irradiation at different total doses and dose rates, the elongation to rupture parameter was measured. Based on the threshold dose at which the elongation to rupture was half the original value, the different materials were compared and a we made a selection for radiation hardened cables. In particular a new fibre optic cable was designed. It was interesting to see that some of the tested polymers have a better resistance to radiation at lower dose rates, which is not usually the case with most other polymers.

Motors

Evaluation of rad-hard motors is an on-going activity. Driving systems are key components on nuclear remotely operated systems. Based on previous study identifying the most sensitive components and a resistant design based on lubricant-free silver-coated bearings and polyimide insulation, two motors are now tested with the aim of getting a very high radiation tolerance. In a fusion reactor in-vessel maintenance operation, one expects indeed to get 100 MGy as total dose during one shutdown maintenance turn. The present on-going tests have reached half that value and the motors do not show any significant degradation trend. We expect to have at the end of next year, a proven rad-hard design, unique in terms of total dose and temperature resistance.

Sensors

Previous gamma irradiation results have demonstrated the good radiation tolerance of various transducer, sensors, optical fibre and electronic components. We further irradiated these components in order to assess their performances under neutron. This covered accelerometers, electronic and optoelectronic circuits and ultrasonic ranging systems.

Cable management

The management of umbilical links to remote systems is often a major source of unreliability. Along with improved cable insulation, multiplexing techniques decrease the number of cables. This makes cable handling easier and reduces the number of penetrations in the shielding barriers, with substantial gain in terms of reliability and safety. We put particular attention on the assessment of prototype electronic multiplexing circuits based on the COTS (Commercial Off The Shelf) approach. We perform the work in close collaboration with CEA. It also involves the evaluation of new promising technologies, such as CoolMOS, for instance.

Using rad-hard sensors to locate objects without cameras

Complex removal/installation tasks on vacuum-vessel components, such as divertors, are to be done remotely under such a high dose rate environment, that cameras will not be available for on-line close-range imaging. Radiation-resistant sensors, such as touch probes or ultrasonic sensors, can be used, but they return only very sparse, local data. These data are therefore difficult to interpret by the human operator. This situation is comparable to a blind man, who explores the environment with his white cane. He uses a model of the environment, stored in his memory, and verifies it occasionally with a few well-chosen measurements of his cane. We applied such an approach to the control system of the dextrous robot arm, to be mounted on the in-vessel mover, during part of the divertor replacement operation. A control module was developed, called BLINE, to verify and update locally the geometric environment model (to find a lost object, or relocate a jammed mover for instance). BLINE uses measurements taken by simple sensors on the robot arm. The operator can then use the updated model to conduct his actual intervention. The task is performed in collaboration with CEA, who delivers the robot arm, its controller and the graphical supervisory system. A first demonstration of the BLINE module showed its perfect integration into the control system and the high reliability of the provided information. Further demonstrations will be conducted at Brasimone on the divertor cassette replacement platform, with tasks such as locking/unlocking the cassette locking system, installing/removing the cassette cooling pipe in the ducts, rescuing a partially failing cassette toroidal mover, etc.

Our collected know-how on radiation tolerance has been confirmed by the continuation of our co-ordination work within the European Fusion Programme and is used furthermore to answer an increasing number of consultancy requests, coming not only from the fusion programme community itself, but from different SCK•CEN projects and from the industry. In particular, we collaborated with CERN to evaluate communication links for the Large Hadron Collider installation, and with SGN to study the radiation tolerance of insulation materials used in the design of crucibles for high activity waste vitrification.

Development of new in-core reactor instrumentation

In 2000 we put a renewed attention on developments for an improved in-core reactor instrumentation, to be applied in BR2 irradiation rigs, on future instrumentation of accelerator-driven systems such as MYRRHA, as well as for fusion reactor diagnostics.

Feasibility studies for the future instrumentation of accelerator-driven systems

The MYRRHA design requires an accurate monitoring of the level of the liquid lead-bismuth spallation source. A laser time-of-flight measuring approach is considered as a suitable option and preliminary measurements with a first set-up have been performed at laboratory scale and with a simulated mercury target in Riga, Letland. Further tests are planned on a representative lead-bismuth mock-up (VICE experiment). Another exploration study concerns under-lead ultrasonic viewing, to assist fuel rod manipulations in the liquid lead. A first set of suitable sensor materials and system characteristics has been determined and collaboration with other research institutes is presently negotiated. In a common effort, one will develop high temperature, radiation and corrosion resistant piezoelectric transducers.

Gamma sensors for in-core irradiation experiments

High flux gamma sensors are being developed in the 1-50 kGy/h range. They allow on-line gamma flux measurements to be achieved in a range where electronic systems (used for space applications for instance) are not able to operate. These systems based on a self-powered gamma detector approach or on a newly developed miniature calorimeter will complement the presently used dosimetry with Perspex targets (off line). Furthermore, a third option, based on photoconductive effects in insulators, is also in the conceptional state.

Hydrogen measurement in PWR loops

We also tested and designed an in-core hydrogen sensor for PWR conditions. In PWR reactors, hydrogen is dissolved in the water to suppress radiolytic dissolution of water. In this way, the corrosion potential of stainless steel can be kept below the critical cracking potential related to irradiation-assisted stress corrosion cracking. It is therefore quite important to be able to quantify on-line the water chemistry radiation-induced modification. The new hydrogen sensor consists in a set of miniature gamma thermometers with selective diffusion casing (one into which hydrogen can diffuse through a palladium membrane, another impermeable for hydrogen). The in-diffusion of hydrogen leads to an increase of the inner gas (argon/hydrogen mixture) thermal conductivity and hence to a decrease of the inner temperature of the gamma thermometer. Tests in BR2 of this new sensor (in the CORONA experiment) showed for the first time the capability to monitor on-line changes in the dissolved hydrogen concentration in the core of a reactor.

Development of sensor connections

For certain types of in-core measurements (conductivity, electrochemical noise, reference electrode, crack-growth measurements, fission chambers, ..), electrical feedthroughs tolerating high temperatures (350 °C), high-pressures (150 bar), high radiation and PWR relevant chemical environments must be available. New types of electrical feedthroughs have thus been developed, one of which for instance uses an innovative magnetic compression technique.

Instrumentation developments have also been included in large projects related to fuel characterisations and material corrosion evaluations: *reinstrumention of irradiated fuel rods* with centreline temperature and fission gas pressure sensors, as well as modelling of pressure sensors and development of leak-tight cable penetrations for advanced instrumented fuel rods (THOMOX project); instrumentation of irradiation tests (COFUMA) in BR2 to study the effect of radiation on the *corrosion* potential of fusion candidate materials; development of an in-pile reference electrode (special miniature flow-through design) for the European project LIRES on corrosion studies); detection by acoustic emission of the initiation of cracks in corrosion tests, etc. These contributions are mainly performed in collaboration with the Reactor Material Department.

Partners

- Astrium (Toulouse, France)
- Kabelwerk (Eupen, Belgium)
- Laborelec (Linkebeek, Belgium)
- Tohoku University (Tohoku, Japan)

CEA	Commissariat à l'Energie Nucléaire (Saclay and Fontenay aux Roses, France)
CERN	Organisation Européenne de Recherche Nucléaire (Geneva, Switzerland)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Madrid, Spain)
EFDA-CSU	European Fusion Development Agreement – Close Support Unit (Garching, Germany)
ENEA	Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (Brasimone, Italy)
FORC	Fibre Optics Research Centre (Moscow, Russia)
FPMs	Faculté Polytechnique de Mons (Mons, Belgium)
JAERI	Japan Atomic Energy Research Institute (Ibaraki and Tokaymura, Japan)
TEE	Tractebel Energy Engineering (Brussels, Belgium)
ULB	Université Libre de Bruxelles (Brussels, Belgium)
VTT	Technical Research Centre (Finland)
VUB	Vrije Universiteit Brussel (Brussels. Belgium)

Sponsors

-	Electrabel (Brussels, Belgium)
EC	European Commission - Fusion Technology Programme (Brussels, Belgium)
ESA/ESTEC	European Space Agency (Noordwijk, The Netherlands)
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

Publications

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Organisation of Conferences

RADECS 2000 Workshop on Radiation Effects on Components and Systems, Louvain-la-Neuve, September 11-13, 2000, organised by Alcatel, UCL, SCK•CEN, IMEC and BIRA-IASB.

Topical Day on Photonics for Nuclear Environments, Mol, December 2000, organised by SCK•CEN with contributions from VUB, Naval Research Laboratory, CIEMAT, ESTEC and CERN.