The possible use of Fibre Optic Sensors in Pressurized Water Reactors

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Abstract. Fibre Optic Sensors (FOS) are fibres with optionally a specific preparation or functional coating, which endows them sensitivity to various environmental parameters. The sensor is designed for extreme environments. Specifically, the environment of a nuclear reactor core, where the dose may be 2 GGy in two weeks of operation. The technologies considered are based on Fibre Bragg Gratings (FBGs), and also Long Period Gratings (LPGs). Using sense-region-gratings written into the fibre, one can measure length changes at the sensor with 1 pico-meter precision. There is growing interest in optical fibre based sensors for application in nuclear reactors because of their intrinsic attributes, such as package compactness, high bandwidth, multiplexing, ability to measure remotely in real time, and immunity to most electromagnetic perturbations. In-core, real-time, on-line and multi-parameter information gathering sensors throughout the nuclear power system could have the potential to improve efficiency and subsequently lower the overall cost of the nuclear power systems. In addition, the safety case would be greatly enhanced. FOS are presented as a remarkable new opportunity for sensing, especially in all kinds of extreme environments, and they represent a niche opportunity in the context of nuclear energy generally (PWR, BWR). In-core, on-line technology for sensing temperature, dose, water level and other parameters can enable instantaneous Reactor State knowledge enabling novel reactor operations and management. This paper discusses the current state of our experimental and theoretical programme.

1. Introduction

There is growing interest in the nuclear industry in optic fibre technology for both data communication and sensing applications. Optic fibre applications are found in a wide range of sectors such as in civil engineering structures, accelerators, etc. Events that took place in Japan in 2011, the Fukushima earthquake disaster, have highlighted the need for more research in radiation protection and nuclear safety to improve safety in the current and future nuclear power plants. South Africa operates two pressurized water reactors at Koeberg Nuclear Power station, which contributes about 5% of the country's electricity to the national grid [1]. This nuclear station was built in the 1970s; such novel technology would provide additional real-time in-core monitoring systems for the various critical parameters in the nuclear reactor. In addition to the reactor safety, accurate real-time measurements at multiple points and locations such as measurements of temperature, neutron dose levels, water levels and other parameters would allow enhanced power output from the nuclear reactor, and that would have tremendous economic benefits for the country. Traditional sensors such as thermocouples for temperature and fission fragment detectors for neutron flux have a limitation in that one may have indirect measurements, sensing by a proxy not at the optimal positions and at all times, and working with a limited amount of sensor data. A single cable fibre can be multiplexed with tens of sensors, and in some cases, continuously sense along its length, thus equivalent to several 10 000s sensors. It can generate a continuous stream of data as a time series, e.g. temperature and neutron flux time differential mapping. Such detailed mapping would ensure that there are no hot spots occurring within the nuclear reactor.

Optic fibres potentially offer a wide range of advantages for safe operation and control of nuclear power reactors. Optic fibre sensors exhibit a number of attractive features more advantageous than their electronic counterparts: i) there is no need to power them or use with amplifiers, ii) they require small cable size and weights, which makes it easy to place in normally inaccessible areas, iii) one cable can be adapted to measure multiple environmental parameters, iv) allow for large scale multiplexing without electronics, v) and their remote sensing ability limits radiation exposure risks to workers. A nuclear reactor environment is characterised by the presence high electromagnetic interference and radiation levels, which can cause serious deterioration in the performance of the conventional sensors. Fibre optic sensors can be designed to withstand harsh nuclear reactor environments where the dose may be 2 GGy within two weeks of operation. Silica is a low Z non-metallic material, its introduction into a controlled reactor area would result in insignificant production of secondary waste. In this work, we report on the current state of our experimental and theoretical programme at Nuclear Energy Corporation of South Africa (Necsa) in Pretoria.

2. In-fibre based sensors

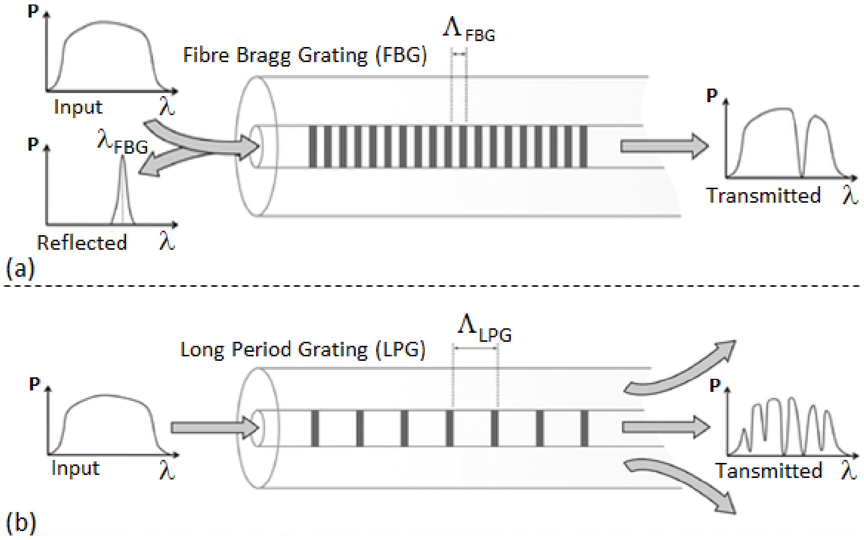

Figure 1. Schematic diagram of (a) Fibre Bragg Grating and (b) Long Period Grating written in a silica core fibre [2].

In-fibre gratings, shown in figure 1, are created by inducing periodic modulation of the refractive index in the fibre core formed by a spatially periodic exposure to intense light or other suitable radiation [3–5]. They are classified into two types based upon the period of grating.

The Fibre Bragg Grating (FBG), shown in figure 1(a) has a grating period of about 1 μm [6]. A FBG behaves as a wavelength selective filter which reflects light signals at a specific wavelength, known as the Bragg wavelength (λ_B) that is strictly dependent on the fibre effective refractive index (n_{eff}) and the grating pitch Λ of the FBG:

$$\lambda_B = 2{\cdot}n_{eff}{\cdot}\Lambda \tag{1}$$

The sensing qualities of a FBG are evident from this equation, any changes to the period Λ and/or the refractive index of the grating n_{eff} will be reflected by a shift in the Bragg wavelength λ_B. In a Fibre Bragg Grating sensor, the information on the measured parameter (temperature or strain) is wavelength-encoded and therefore insensitive to radiation-induced losses. The fractional Bragg wavelength shift for a temperature change ΔT is given by

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \tag{2}$$

where α is the thermal expansion coefficient, about $0.5 \times 10^{-6}/^\circ$C [7] at room temperature and ξ represents the thermo-optic coefficient, about $10^{-5}/^\circ$C [8]. FBGs are inherently sensitive to temperature and strain. In order to make them sensitive to other parameters, one needs to apply specialised coatings to the fibre. The coating converts the measured response into a strain on the fibre section that contains the gratings.

A Long Period Grating (LPG) has a longer grating period than an FBG, in the range 100 μm– 1 mm. The LPG shown in figure 1 (b), the transmitted spectrum has valleys due to resonant energy losses by the cladding when there is power coupling between the fundamental guided core mode and co-propagating cladding modes. Each mode coupling happens at a distinct wavelength, where the so-called phase matching condition is satisfied:

$$\lambda_B = (n_{eff} - n^i{}_{clad}){\cdot}\Lambda \tag{3}$$

where n_{eff} is the effective refractive index of the propagating core mode at wavelength λ, $n^i{}_{clad}$ is the refractive index of the ith cladding mode and Λ is the period of the LPG. The n_{clad} can collectively include the optical coupling of the cladding to the functional coating and the environment beyond the functional coating. The centre wavelengths of the attenuated bands in the transmitted spectrum are sensitive to the period of the LPG, the length of the LPG and to the refractive index of the local environment [9]. The increased sensitivity to functional coating and the environment through this optical coupling and the increased complexity of the transmitted spectrum endow LPG technology with a wider range of designer capability and sensitivity. LPGs have a wider scope as "designer" sensors, in terms of what can be sensed, how it can be tuned for the particular application, and the enhanced sensitivity.

3. Radiation hardness tests for the optic fibres at SAFARI-1

Initial tests for FOS radiation hardness are carried out in a Material Test Reactor (MTR) at Necsa. A MTR should induce more damage to the fibres than a power reactor because it has a much higher ratio of fast-to-thermal neutrons. This makes it more appropriate for such tests and validation of new materials and sensors than a strictly regulated power reactor. Necsa operates a 20 MW MTR known as SAFARI-1 [10]. It is a light water-cooled, beryllium reflected, pool-type research reactor.

It has various in-core and ex-core radiation facilities with varying neutron flux levels. For these radiation hard studies, we have selected an in-core position with high neutron flux levels. This position is accessed by a pneumatically delivered capsule system. The neutron flux is well characterised using the OSCAR-4 deterministic reactor calculation code system [11]. For an

Table 1. Total fluences possible as a function of irradiation time with the SAFARI-1 reactor [10].

Total Fluence (n/cm^2)	2.42×10^{20}	4.84×10^{20}	7.26×10^{20}	9.68×10^{20}
No. of days	28 days	56 days	84 days	112 days

assumed neutron flux value of 1.00×10^{14} n/cm^2-s, the overall expected fluences as a function of irradiation time in the SAFARI-1 reactor are given in table 1.

For current measurements at Necsa SAFARI-1 reactor, we selected single mode type fibres with no Bragg gratings as an initial assessment of the fibre's ability to survive the high radiation and temperature environment; fibres with inner core diameter of $\varphi = 7\mu$m, a cladding layer of $\varphi = 125\mu$m and with the coated layer of $\varphi = 245\mu$m. The four types of fibres selected, coated and non-coated are UV treated resin coated, acrylate coated, polymide coated and a naked fibre. Samples of 10 cm lengths for each type of fibre were irradiated. They were placed and sealed in the 2 cm diameter aluminium irradiation capsules. The irradiations will be done in steps up to an accumulated neutron fluence (i.e. n.v.t.) of $\sim 10^{20}$ n/cm^2 or a total ionising dose of about 12 GGy. In this measurement, we want to look at the mechanical and optical changes in the fibres prior- and post-irradiation.

Similar studies testing irradiation hardness of different optic fibres have been conducted in other Materials Test Reactors (MTR) or Power Reactors (PR) elsewhere [12–14]. The highest dose reached at 16 GGy and neutron fluence 1.30×10^{20} n/cm^2 [12]. These studies indicate that the silica component of the fibre does become damaged, but slowly enough and in a systematic way. One expects that with appropriate understanding of the time dependant dose induced changes, one may still deploy the fibre effectively and with significant cost-benefits.

4. Optic fibre simulation calculations

Preparatory calculations were performed for a selection of the fibre types for the fibre irradiation damage study. An important aspect is activation studies of the fibre during the irradiation and assessment of the cool-down period. This is a necessary safety control before insertion of material into the SAFARI-1 MTR. Simulation analysis of the optic fibres was done using MCNP6.2 [15] and FISPACT-II [16] to study the level of activity induced on the fibres after irradiation and the extent of radiation damage.

MCNP results

Results from MCNP calculations show very low neutron and gamma heating, therefore the samples can be irradiated in the usual isotope production rigs without any modifications or deviation from the standard operating procedures. The neutron damage as represented by the Damage Per Atom (DPA) also show very low damage to the sample material [17].

FISPACT-II results

The results from FISPACT show that the amount of induced activity after irradiation is about 1.5 Ci, which goes down to about 0.5 Ci within 24 hours. The dose rate starts at about 1.05×10^{-6} Sv/h after irradiation and goes down within 24 hrs, see figure 2. This is the case for the period after 28 days, 56 days and 84 days irradiation intervals [17].

The simulation results show that the irradiation of the fibre optic samples in the SAFARI-1 reactor will not cause any significant damage to the samples. No long-lived radioisotopes producing high ionizing radiation are populated. It will be safe to handle the samples after a 2-day cool-off period without using specialised equipment.

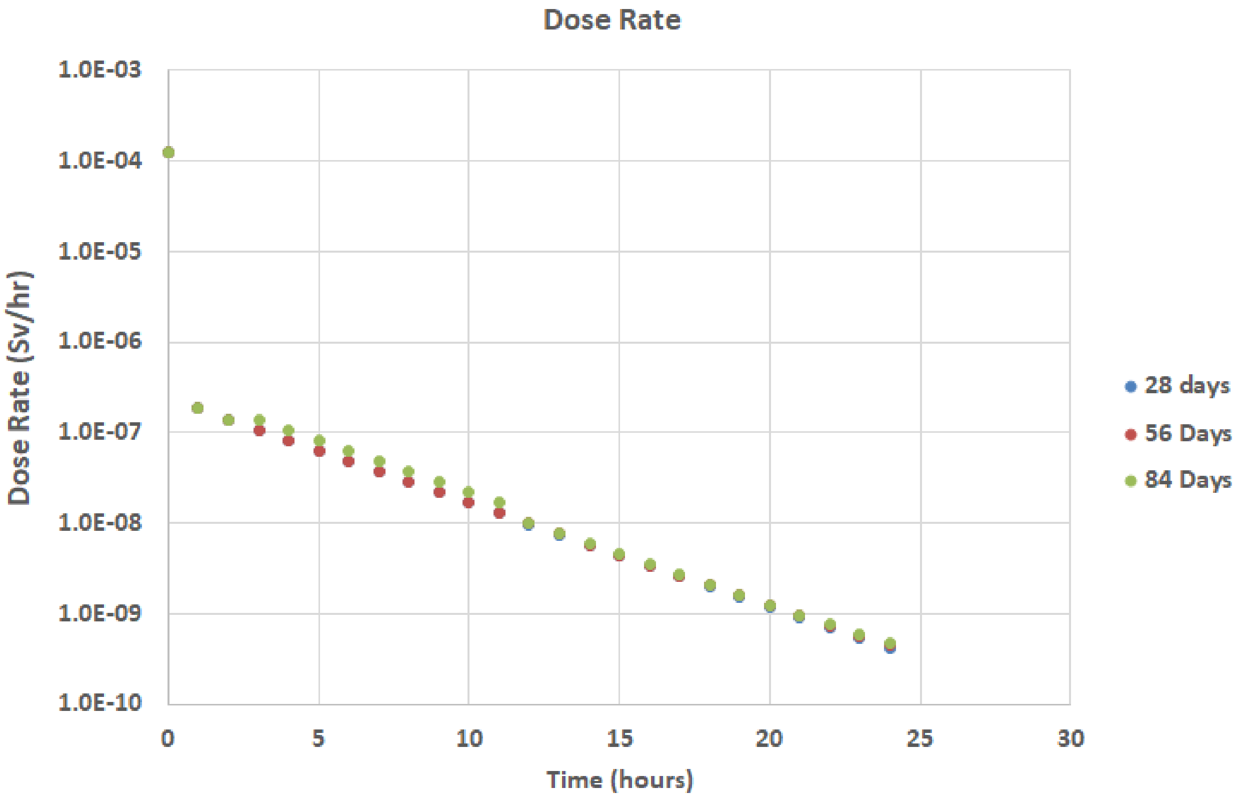

Figure 2. Expected dose rate after 28 days, 52 days and 84 days of irradiation.

5. FOS deployment to a PWR in Koeberg

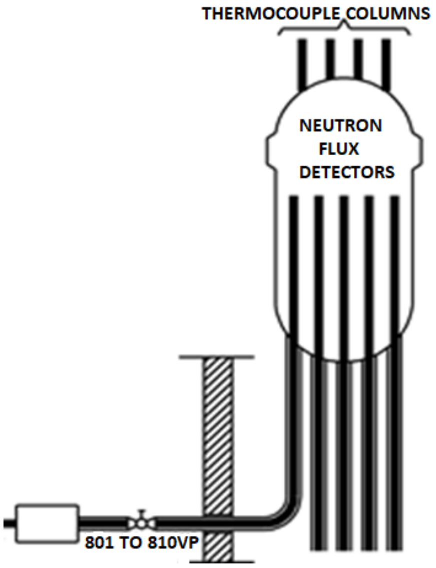

Figure 3. A schematic diagram of a PWR showing provision for regular insertion of sensors into the core.

The goal of this project is ultimately to deploy these optic fibre sensors to a PWR like in Koeberg. The Koeberg nuclear reactor has been operating for more than 30 years. Routine measurements that are done with the reactor like neutron flux measurements are carried out using a thimble sized fission fragment detector. The detector is inserted via a manifold through a blind tube system from outside the radiation shield zone into the pressure vessel of the reactor core. PWRs like in Koeberg already have about 40 built-in blind-tube penetrations into the reactor core. These blind access tubes into the reactor core could be used as access points for fibres. The fibres could be conveniently inserted into the core with little retrofit to the reactor vessel. A schematic diagram of the manifold system outside of the shielding and access to the in-core blind tube penetrations which could accommodate the fibres on a short to medium term basis is shown in figure 3.

6. Conclusions

The safety and reliability of nuclear power plants could be improved through the implementation of advanced sensing technologies like fibre optic sensors. Optic fibres can withstand the harsh radiation environment in nuclear reactors for significant time periods, for even months. The optic fibres can be innovatively adapted to measure a wide range of parameters critical for efficient nuclear reactor operation. Results from current samples being irradiated at SAFARI-1 reactor at Necsa should help us to determine the best fibres to use for further sophisticated tests, leading to in-situ readout of light attenuation and FBG/LPG performance. Simulation results using FISPACT-II show that it will be safe to handle the samples within a 24 hr period after irradiation. FOS are remarkable new opportunity for sensing, especially in all kinds of extreme environment. They represent a niche opportunity in the context of nuclear energy generally especially with nuclear reactors like PWR and BWR.

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