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Fibre Optic Sensors for Nuclear Power Reactors

B. G. MAQABUKA[1 3], D. NICHOLLS[1 3], S.H.CONNELL[1 3], P NAIDOO [1 3], F. PIETERSE [1] ,
J. SLABBER[2 3], L. BEDHESI [4], E. CHINAKA [4], G. DANIELS [4]
University of Johannesburg[1], University of Pretoria[2], SAIEE Nuclear Chapter[3]
South African Nuclear Energy Corporation [4]
South Africa

SUMMARY

The paper describes the preparatory work of experimental research associated with exposing specifically prepared fibres to the harsh environment within a nuclear reactor where the dose may be 2 GGy in two weeks of operation. The experimental methods include inserting into the research reactor at SAFARI-1 of the Nuclear Energy Corporation of South Africa (NECSA) fibre optic samples. Fibre Optic Sensors (FOS) are comprised of fibres having a specific preparation or functional coating, which endows the sensitivity for various applications and for sensing various environmental parameters. The sensor can be very well adapted for extreme environments, in particular, the environment of a nuclear reactor core. The radiation dose from the reactor may exceed 2 GGy, within two weeks of operation. The technologies envisaged in this paper are based on Fibre Bragg Gratings (FBGs) and Long Period Gratings (LPGs). Using such FBGs and LPGs written into the fibre, one can measure length changes at the sensing region with 2 pico-meter (sub-atomic) precision, over a length of the order of a centimeter. There is growing interest in optical fibre based sensors for application in nuclear reactors due to their radiation hardness, compactness, high bandwidth, multiplexing, remote read-out in real time and immunity from electromagnetic interference. In-core, real-time, on-line, multi-parameter information gathering sensors throughout the nuclear power system could have the potential to improve efficiency and subsequently the overall cost incurred by nuclear power systems. In addition, the safety case would be greatly enhanced.

KEYWORDS

Nuclear Reactor Temperature Monitoring, Nuclear Engineering, Nuclear Safety, Fibre Bragg Gratings, Long Period Gratings, Radiation Immunity

1 INTRODUCTION

Nuclear reactors are reliable and low-cost, carbon free dispatchable energy sources to provide scalable base-load electricity generation. They enable intermittent renewable energy production. They can also provide high temperature green thermal energy for a range of applications (desalination, hydrogen production, coal gasification, synthetic fuels, etc.). South Africa operates two pressurized water reactors at Koeberg Nuclear Power station [1]. This nuclear station was built in the 1970s and would benefit from novel advanced systems that would provide additional real-time in-core monitoring for various parameters in a nuclear reactor. The ability to manage and optimize the power output in a nuclear reactor often requires accurate, real-time, measurement of the different parameters, such as temperature, neutron dose levels, water levels, etc. at multiple points and locations. The limitation with the conventional sensors, such as fission fragment detectors for neutron flux and thermocouples for temperature, is that one may have indirect measurements, sensing by proxy not at the optimal locations and at all times and working with a limited amount of sensor data. A single fibre is able to generate a continuous stream of data, for example, temperature and neutron flux mapping, with individual sensing locations, and can also be multiplexed to extract such parameters along the fibre line. This information can ensure that hot spots are avoided within the nuclear reactor.

2. LITERATURE REVIEW

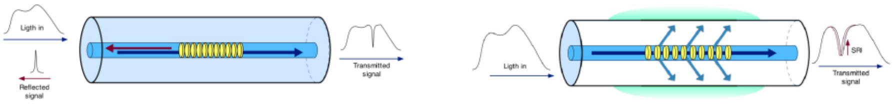
Fibre Optic Sensors (FOS) are comprised of fibres having a specific preparation or functional coating, which endows the sensitivity for application for various environmental parameters The sensor can be designed to withstand extreme environments. Specifically, the environment of a nuclear reactor core, where the dose may be 2 GGy within two weeks of operation. Fibres introduce a very small amount of low Z non-metallic material into the controlled area of a nuclear reactor, and therefore reduce the generated secondary waste. All the technologies considered here are based on FOS, which are configured as Fibre Bragg Gratings (FBGs) with a shorter grating period of 1 μm, or Long Period Gratings (LPGs) with a grating period of 100 μm – 1 mm. The FBG/LPGs are simple low sized, intrinsic sensors which are written into the silica fibre core. A fibre grating is a periodic modulation of the refractive index in the fibre core formed by a spatially periodic exposure to intense light or other suitable radiation [2–4]. For either of the FBG and LPG sensors, a broadband pulse of infra-red (IR) light (of about 1510 nm – 1600 nm wavelength) is injected into the single mode fibre core. When the light travelling in the fibre core reaches the grating, there will be a wavelength dependent reflection and/or absorption of energy. In the case of the FBG grating, one analyses the reflected light for a frequency shift caused by an optical path length period change in the grating. Such a change can result from a strain, a temperature dependent length change, or a change in the local refractive index [5]. A functional coating can be applied to the grating sense area so as to endow additional sensitivities. For example, a hygroscopic functional coating can endow humidity sensitivity. In general, there is a wide range of external parameters than can be sensed by careful design of the sensor. The wavelength of the reflected light, called the Bragg wavelength (λ_B) is given by the equation [5]

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \qquad (1)$$

where n_{eff} is the effective refractive index of the grating in the fibre core and Λ is the grating period. Once exposed to change in the environment parameter being measured, the FBG period Λ is affected by stretching due to the parameter variation thus shifting the reflected λ_B. So to extract an environmental parameter such as temperature, the Bragg wavelength as a function of temperature is given by the relationship [5]

$$\lambda_B(T) = \lambda_B(T_0) + \alpha(T - T_0) \qquad (2)$$

where α is the temperature sensitivity coefficient with a typical value of about 10 pm/K at 1550 nm and T_0 is the reference temperature. But in a nuclear environment it is not only temperature that can cause a Bragg wavelength shift (BWS) in the sensor, other parameters like radiation can also cause a shift in the grating period optical path-length. For example due to radiation induced lattice dilation in the functional coating, or radiation induced refractive index changes. The sensitivity is considerable, and one can measure length changes at the FBG sensor with 2 pico-meter precision over a FBG length of some centimeters. Figure 1 below shows how a broad injected light pulse has a component at a specific wavelength reflected by a FBG.



(a) (b)

Figure 1 : Schematic operation of a (a) Fibre Bragg Grating (FBG) and (b) Long Period Grating (LPG) written into silica fibre [6].

In the case of the LPG grating, the transmitted radiation has valleys due to resonant absorption of energy by the cladding when there is phase matching between the mode propagating in the core and the modes forward- propagating in the cladding, as given by the equation [7].

$$\lambda_B = (n_{eff} - n^i_{clad}) \cdot \Lambda \qquad (3)$$

Here i labels the cladding modes. The n_{clad} can collectively include the optical coupling of the cladding to the functional coating and the environment beyond the functional coating. 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 also sensitivity [7].

Yet another FOS technology of interest for Nuclear Energy is the class of Distributed Optical Fibre Radiation Sensing (DOFRS). Radiation sensors based on this effect, whereby radiation damage creates scattering centres and refractive index changes deferentially along the fibre length, imply that such DOFRS FOS can sense radiation damage continuously along the entire fibre with centimeter resolution [8]. Special arrangement of the fibre path allows a 3D mapping view, for irradiation dose, within for example, a reactor.

Thus, development and implementation of radiation-hardened advanced sensors in reactor cores is a major theme for increased efficiency and safety ofexisting and future nuclear power plants. There is therefore 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 [9]. In-core, real-time, on-line and multi-modal information gathering sensors throughout the nuclear power system could have the potential to improve efficiency and subsequently the overall cost incurred by nuclear power systems. In addition, the operational safety would be greatly enhanced. FOS are a remarkable new opportunity for sensing, especially in all kinds of extreme environments, and they representa niche opportunity in the context of nuclear energy generally.

In this work, we discuss the progress of a research programme to develop FOS for Reactor applications.

3. EXPERIMENTAL DISCUSSION

The idea of deploying FOS for in-core sensing in power reactors appearedsince late 1990's [10]. The radiation environment is extremely harsh, with typically 2 GGray of radiation given to the sensor within two weeks of in-coreexposure. Table 1 below summarises several experiments on the radiation hardness of various types of FOS.

Table 1 : Review of irradiation data for a neutron flux φ for a time period leading to the accumulated fluence ϕ equivalent to a given irradiation dose D.

φ [n/cm^2/s]	Φ [n/cm^2]	Time	D [GGy]	Energy Spectrum	Reference
1.7×10^{13}	1.30×10^{20}	91 d	16.0	Fast	[11]
–	2.90×10^{19}		4.60	Fast	[12]
2.50×10^{13}	4.76×10^{19}	22 d	3.80	Fast	[13]
2.18×10^{13}	4.15×10^{19}	22 d	3.80	Fast	[13]
1.48×10^{13}	2.83×10^{19}	22 d	3.80	Fast	[13]
1.20×10^{14}	5.70×10^{20}			Fast	[14]
1.00×10^{14}	1.47×10^{17}		0.16	Fast	[15]
1.00×10^{13}	5.00×10^{19}	1012 h	2.00	Fast	[16]
–	16.90×10^{17}	8 y	0.01	Thermal	[17]

The energy deposition by the neutron flux into the fibre is dependant onthe neutron energy spectrum. Data has been obtained on different types ofreactors that ranges from Power Reactors (PR) to Materials Test Reactors(MTR). The PRs neutron spectrum is more in the thermal range when compared to MTRs. The radiation damage of the fibres would be greater for the epithermal and fast neutron range. Also important is the companion flux of gamma radiation/heating. Because of this there is not a simple correlation between the integral neutron flux and the radiation dose. However, the data reviewed in Table 1 is plotted to display the observed relationship between integral neutron flux and the radiation dose for these measurements in these different cases. A linear regression line indicates a simplified relationship between these two quantities. In a given. situation, it is only microscopic simulations that will establish the actual correlation. Tests of the FOS in a MTR could be mapped across to the context of a PR using such simulations.

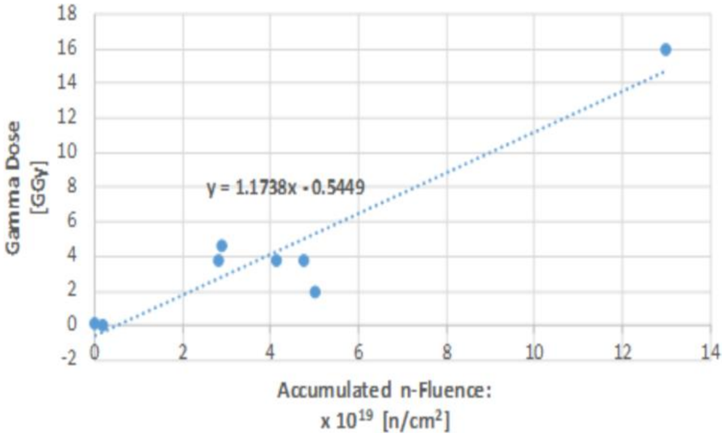


Figure 2 : Linear model to guide the eye for the relationship between neutron flux and radiation dose.

There are strict regulatory issues to be adhered to when introducing new materials and sensors into power reactors. A MTR is an appropriate facility for the study of the irradiation damage of FOS technologies, and for tests of the various sensors that are developed. The South African Nuclear Energy Corporation (Necsa) operates a 20MW MTR known as SAFARI-1 [18, 19]. SAFARI-1 is a light water-cooled, beryllium reflected, pool-type research reactor. A top view of the reactor is shown in Figure 3.

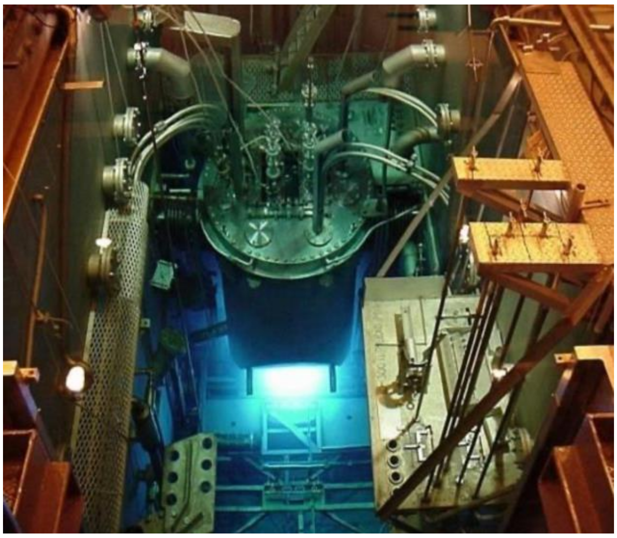


Figure 3 : The SAFARI Materials Test Reactor (MTR) at the Nuclear Energy Corporation of South Africa [18, 19]

Table 2 indicates the overall fluences possible as a function of irradiation time within the SAFARI-1 Reactor at Necsa [19].

There are various in-core and ex-core radiation facilities. For the irradiation damage studies, we have selected an in-core irradiation position, accessed by a pneumatically delivered capsule system. The neutron flux is well characterised using the OSCAR-4 deterministic reactor calculation code system [20].
The Fibres selected for the radiation tests are single mode with an inner core diameter of $\varphi = 7\mu$m, a cladding layer of $\varphi = 125\mu$m and in some cases a buffer layer of $\varphi = 245\mu$m. The details of the buffer (or no buffer) are:

- Polymide coated,
- Acrylate coated,
- UV treated resin coat,
- Naked fibre

A naked fibre (core, cladding, no buffer) has the elements ^{16}O, ^{28}Si, ^{1}H ^{14}N, ^{12}C in the atomic percentage rations 0.4047, 0.2825, 0.0104, 0.0290, 0.27 respectively.

Table 2: Total fluences possible as a function of irradiation time with the SAFARIMTR Reactor at Necsa in South Africa [19]

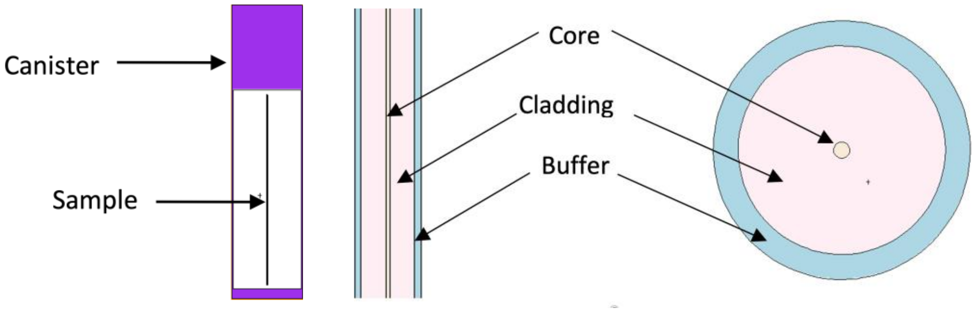
Total Fluence (n/cm^2)	3.13×10^{19}	5.48×10^{19}	7.84×10^{19}	1.02×10^{20}
No. of days	28 days	56 days	84 days	112 days

FOS Simulation

A simulation was performed to study the extent of irradiation damage and activity of the Fibre Optic Sensors (FOS) after irradiation in the SAFARI-1 reactor core. The two codes that were used to do the analysis are MCNP6.2 [21] and FISPACT-II [22]. MCNP is a probabilistic transport code that has the capability of calculating most of the heating contributions due to particle interactions with matter, as well as neutron flux. FISPACT-II is an inventory handling code that has the capability of tracking transmutation of nuclides, radioactive decay due to neutron activation, and burn-up. This is a necessary safety control before insertion of material into the SAFARI-1 MTR.

MCNP

Figure 4a shows the schematic representation of the FOS sample that was modelled in MCNP. It further shows the sample fibre that was placed in an aluminium canister. The inside of the canister is vacuum. A 5 cm sample length was placed vertically in the canister. Figure 4b shows an enlarged portion of the fibre optic cable in the canister. The core, the cladding and the buffer can be seen. These have the cross-section dimensions mentioned above. The protective sleeve was not modelled, as it will not be part of the final assembly in a reactor core. The activity, dose rate and gamma heating calculations were done using FISPACT-II.



(a) (b)

Figure 4 : MCNP model of Sample and Canister (a) and of the FOS fibre to be irradiated (b). The fibre is inserted into the canister and the system is modelled within where the reactor local flux is also characterised with MCNP.

A typical flux of 3.5 x 10^{14} neutrons/cm^2/s was used. The irradiation was performed in steps up to an estimated total accumulated neutron fluence of 10^{20} neutrons/cm^2. The sample irradiations were simulated for four irradiation times i.e. 28 days, 56 days, 84 days and 112 days. The activity, dose rate and gamma heating from the samples were calculated for the first 24 hours after irradiation. The results show that these three parameters, from the four irradiation times are indistinguishable, especially within the first few hours after irradiation. The MCNP results show very low neutron and gamma heating, therefore the samples can be irradiated in the usual isotope production rigs withoutany modifications to either the rig itself or the standard operating procedures. The neutron damage as represented by the Damage Per Atom (DPA) also showed very low damage to the sample material.

FISPACT

FISPACT results show that the sample activity just after irradiationis approximately 1.5 Ci which goes down to approximately 0.5 mCi after 24hours. The dose rate starts off at about 150 */mu*Sv/h and becomes insignificant after 24 hrs. As an example Figure 5 shows the expected activity after 56 days and then 84 days of irradiation, and then the activity after indicated cool-off period. The results from simulation 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 ionising radiation is produced. No specialised handling equipment will be required.

IRRADIATION CAMPAIGN

In the initial test, 10 cm lengths of fibre without inscription of a grating are used. The examination before and after radiation is limited to an evaluation of the mechanical integrity and the optical darkening. Irradiation of the samples will be done in steps up to an accumulated dose level of 10^{20} n/cm^2. The flux level together with the achieved integrated neutron flux (i.e.nvt) over each interval is recorded. The measurement point where the total accumulated dose shows little or no damage to the fibre will be validated. More sophisticated tests will be used in subsequent evaluations, leading to in-situ readout of light attenuation and FBG performance as well as temperature sensing stability for the duration of the irradiation.

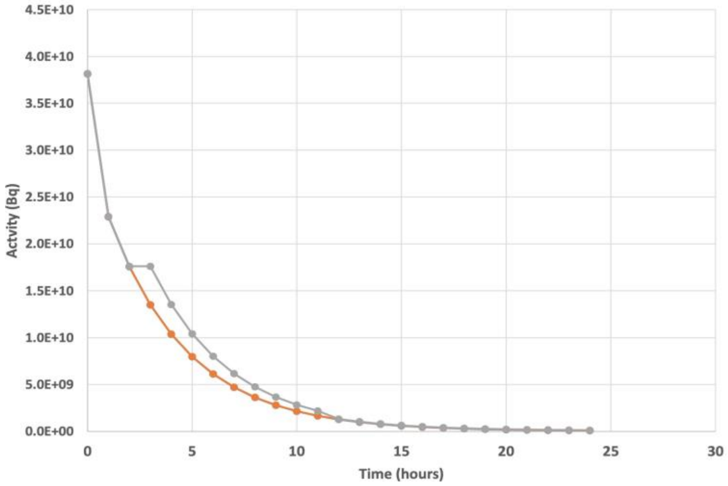


Figure 5 : Expected activity after 56 days and then 84 days of irradiation, and then activity after the indicated cool-off period.

Status of Experimentation

There is currently a FOS sensor irradiation programme underway at the SAFARI-1 MTR at Necsa in South Africa. The programme envisages achieving integrated neutron fluence of 1020 n/cm2 or a dose of about 12 GGy.

4. POTENTIAL APPLICATION FOR FOS RETROFIT IN A PWR LIKE KOEBERG

A typical PWR nuclear energy generator, such as the Koeberg Nuclear Power Station can be considered in discussing the retrofit of FOS technology. Koeberg is situated 30 km North of Cape Town. It has 2 units of the pressurised Water Reactor (PWR) type and generates about 5% ofthe countries' electricity. It has been operating since 1984. Measurements on neutron flux are made as per regulation at specific monthly intervals. At these occasions a thimble sized fission fragment detector is inserted via a manifold and blind tube system from outside of the shielded zone into the pressure vessel of the reactor core. In the case of Koeberg, there are more than 40 such penetrations where measurements can be made. It is therefore conceivable that these could serve as ports also for FOS sensors. Figure 6 shows schematically the manifold system outside of the shielding and access to the in-core blind tube penetrations which may accommodate fibres on a medium term basis. If the fibres could survive for a period of two weeks, this may be sufficient on a cost-benefit basis to retro-fit such PWRs with FOS sensors in this fashion.

The in-core FOS system can be monitored in real-time and online viaan interrogator which both injects the light pulse and receives the reflected or transmitted light back for analysis. Many FOS sensors can be polled bya single interrogator using a mechanical-optical switch, where models are available with up to 128 dual ports (inject-receive). The poll time per sensor need only be every minute, or of that order.

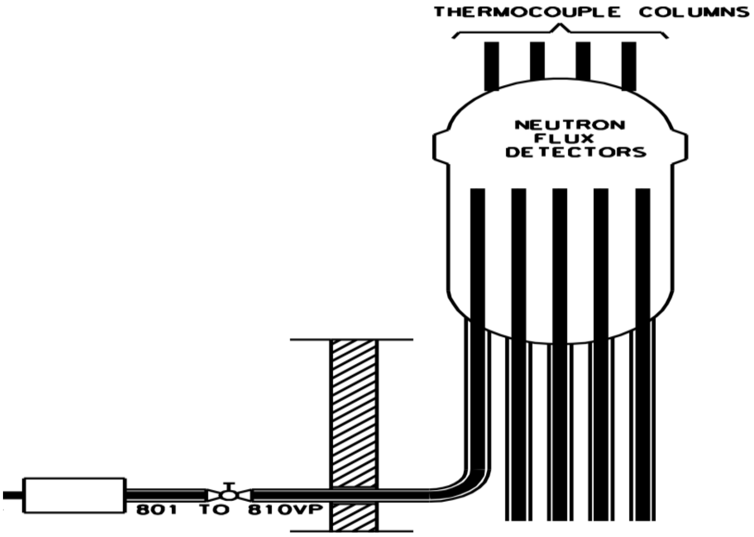


Figure 6 : Typical PWR showing provision for regular insertion of sensors in the core.

5 CONCLUSION

We have discussed the use of FOS sensors for sensing various parameters in power reactors. A review of the literature has shown that the FOS sensors can be expected to withstand the harsh radiation environment of a power reactor for significant time periods, approaching several weeks. It is therefore important to progress FOS technology, in terms of its radiation hardness and range of sensor modalities and sense parameters. A suite of FOS sensor materials of various types is currently undergoing long term exposure in the SAFARI-1 reactor at Necsa in South Africa. If the tests confirm the results from the literature, then it motivates a concerted study of developing these sensors for a range of sensing applications in a reactor environment. The FBG sensors are best know for measuring strain and temperature, but a wider range of parameters can be sensed, with more sophisticated sensor design, including radiation dose, but also, conceivably, the seperation of dose into the Total Ionising Dose (TID) or Displacement Damage (DD) components, and more exotic parameters, such as water level, and yet other parameters. The paper also discussed that such real-time, online, in-core sensing capacity would have a trans-formative impact on the efficiency and safety of operations for nuclear reactors.

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