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FIBRE OPTICS COMPATIBILITY WITH RADIATIVE ENVIRONMENT INSIDE PWR CONTAINMENT

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SUMMARY

Fibre optic links operating with multiplexed sensors data are potentially attractive for nuclear power plant applications. It hence became essential to test for radiation vulnerability not only transmission support - fibres - but also fibre-end electro-optical components which could be exposed to hostile environment, perhaps in worse conditions than fibres.

Present paper gives results of multimode silica-based fibre behaviour during long-term steady-state low dose-rate gamma ray exposure - one year under 0.1 to 0.2 Gy/h. Studies concerned radiation-induced loss (ΔL) measurement of eight different commercially available fibres and bit error-rate (BER) recording of four 1100 m length data links operating with a 100 m part exposed to gamma-rays. Main result is the good behaviour of pure silica-core fibres, especially a step-index polymer-clad fibre transmitting 850 nm light but also a graded-index fluorine-clad fibre for 1300 nm window. Mean ΔL values are respectively 3 dB/km and 4.5 dB/km at the exposure end. Complementary result is no influence of gamma-ray exposure upon data link initial 10^{-9} BER.

Concerning electro-optical components irradiation tests were made with a short-term steady-state medium dose-rate exposure - three weeks under 80 Gy/h. Tested components were standard and improved GaInAsP light-emitting diodes (LED), injection-laser diodes (LD) and InGaAs p-i-n photodiodes (PD) all designed for 1300 nm wavelength operation. Pigtailed improved LED and PD only show a small degradation of optical characteristics for 50 kGy total dose : respectively a slight output power decrease and a signal-to-noise ratio decrease due to dark current growth (x 50). Pigtailed GaInAsP LD included in multicomponent laser-diode modules (LDM) were tested up to about 17 kGy. Two degradation processes clearly appear : a wrong decrease of stimulated light emission after 3 kGy and a bad operation of thermoelectric cooler beyond 9 kGy. Nevertheless LDM stable operation can be ensured up to 2 kGy.

Although further irradiation tests must be made, these first results show good fibre optic components radiation tolerance is consistent with PWR non-accidental environment and allow to envisage (near) future implementation of all optical sensors networks in special niche areas (structure monitoring, crack detection, distributed temperature sensing, ...) where fibre optics offers distinct advantages over conventional technologies. This paper presents some practical applications concerning R & D projects currently carried out in many laboratories.

A key area of interest for nuclear power plant instrumentation improvements is also represented by optically-powered sensors and other hybrid networks where data from conventional electrical sensors (e.g. thermocouples) are light-converted, optically multiplexed before transmission. Sensors multiplexing, and especially optical multiplexing in future PWR plants will decrease the number of sealed penetrations which could sometimes be considered as an intrinsic threat for containment integrity in case of severe accident.

High potentialities and intrinsic advantages of optical transmissions (electromagnetic interference immunity, high data-rate capability, intrinsic safety, compactness, lightness, ...) are as many arguments to justify and increase the trend for optics implementation inside reactor buildings.

Some capabilities of fibre optics for non-safety monitoring systems in future nuclear power plants are significant. Modern optical fibres and optoelectronic components are now able to operate under medium steady-state gamma-rays exposure without appreciable lack of performances.
High immunity data transmissions inside PWR containment from conventional or optically-powered sensors to external processing are conceivable. Some new relevant components (optical multiplexing and penetration) are still necessary to evaluate with optical fibre sensors.

1. INTRODUCTION

Optical fibre links operating with multiplexed sensors data are potentially attractive for nuclear power plant (NPP) applications. It hence became essential to test for radiation vulnerability not only transmission-support fibres but also fibre-end optoelectronic components which could be exposed to hostile environment in worse conditions than fibres.

2. RADIATION EFFECTS ON OPTICAL FIBRES

2.1 Optical fibre (OF) composition

If excluding plastic OFs commercially available optical waveguides are made with high purity-silica glasses. Small change of refractive index of core or cladding is obtained by adequate dopants, especially phosphor or germanium for the core, boron and fluorine for the cladding. These elements have a strong influence on structure of vitreous-silica defects and hence on radiation-exposed fibre response.
Main concerned defects are :

- additional atoms in anomalous sites or interstitial atoms
- atom lacks in normal sites
- substitutional atoms of dopants : Ge^{4+}, B^{3+}, P^{5+} ions in place of Si^{4+} ions.

Defects annealing by trapping of electrons or holes is occurring to maintain electrostatic neutrality.

2.2 Radiation-induced optical loss

In radiation-exposed silica-based OFs, complex interaction processes can lead to different optical effects, nominally :

- a decrease of transmitted luminous intensity due to colour centres production, [1,2,3,4]
- a growing of transmitted intensity by emergence of radioluminescent photons, [5]
- a paramagnetic resonance associated with unpaired electrons. [6]

Colour centres are trapping sites of electrons or holes issued from radiation-induced electron-hole pairs. Small related energy-levels induce light-absorption in UV and visible spectra.
Breaking of bonds by ionising radiation also creates trapping sites of charges in vitreous matrix, hence absorption in visible spectrum.
These radiation-induced losses are often no linearly growing versus absorbed dose and are generally dependent on exposure dose-rate. Two regenerative processes can occur in silica-based fibres : thermal annealing and photobleaching. In this case, optical absorption strongly changes with luminous wavelength and intensity and is to some extent reversible.
These processes have been described in several papers. [7,8,9]

2.3 Silica fibre radiation-response key parameters

DOPANT	Small dose rate $< 0,2\ Gy.h^{-1}$	High dose rate $\geq 5\ kGy.h^{-1}$	Pulsed irradiation $10^{10}\ Gy.s^{-1}$
Germanium in core	weaker loss than in pure silica core	higher loss for $\lambda < 1300$ nm	high transient loss changes
Phosphorus in core	much higher loss than in pure silica core		no transient loss, no regenerative process

DOPANT	Small dose rate < 0.2 Gy.h^{-1}	High dose rate ≥ 5 kGy.h^{-1}	Pulsed irradiation 10^{10} Gy.s^{-1}
Boron in clad	rather bad response (B-O binding absorption)		
Fluorine in clad	rather higher loss due to fluorine diffusion from cladding		higher transient loss, efficient regenerative process
OH ions	best radiation response for small rate	best radiation response for high rate	-

Table 1 : Dopant and OH ions effects on silica multimode fibre radiation-response [6,10,11]

PARAMETER	INFLUENCE ON RADIATION RESPONSE
total dose	*not sufficient to describe radiation response*
dose-rate	*the* significant parameter relative to colour centre production rate or (and) bonds breaking-rate
optical wavelength	*the* basic parameter of radiation-response relative to large spectra of light-absorbing defects
light intensity and temperature	both parameters can lead to regenerative processes : photobleaching and thermal annealing
fibre dopants	see table 1
radiation-history	hardening phenomenon : a fibre exposed to high dose-rate steady-state radiation can have a better response to a second irradiation than a pristine same fibre

Table 2 : Common multimode *silica fibre radiation-response* [12,13]

3. EXPERIMENTAL

3.1 Fibre irradiation facility [14]

A special gamma-ray irradiator was built in "LAMBDA" cell located on Saclay Nuclear Centre to expose at the same time 18 coils of optical fibres under the same dose-rate. Weak dose-rate dispersion between spools was obtained by axial setting of ^{60}Co radioactive sources into 3 fibre spool piles (± 15 %). A one-year on-board dosimetry with aniline dosimeters gave final total doses. Initial mean dose-rates for 18 fibre spools were 125 ± 15 mGy.h^{-1} during the first irradiation sequence and 228 ± 12 mGy.h^{-1} during the second one. Relative value-error was ± 10 %.

3.2 Optoelectronic component irradiation facility [15,16]

Irradiation facility used was "SIGMA" cell located at DEIN on Saclay Nuclear Centre site. Axial ^{60}Co sources of irradiation volume had a total activity of about 250 Ci.
Fibre-end optoelectronic components were exposed to gamma-rays with a mean dose-rate of 80 Gy.h^{-1}. Care was taken to irradiate standard components and improved components with the same dose-rate (± 10 %).

3.3 Equipment apparatus

Measurement equipment is set out of "LAMBDA "and "SIGMA" cells and included two distinct apparatus (figures 1 and 2).

3.3.1 Induced loss measurement

Emitting sources were pigtailed light-emitting diodes (LED) allowing an efficient coupling with tested fibres (splices). On fibre outputs same coupling with p-i-n photodiodes was made. Automatic data storage with adequate timing led to compute fibre induced-loss values ΔL.
Ambient temperature was also recorded to take account of possible electronics shift, especially LED intensity-shift. An OTDR was used to verify final induced-loss of every fibre.

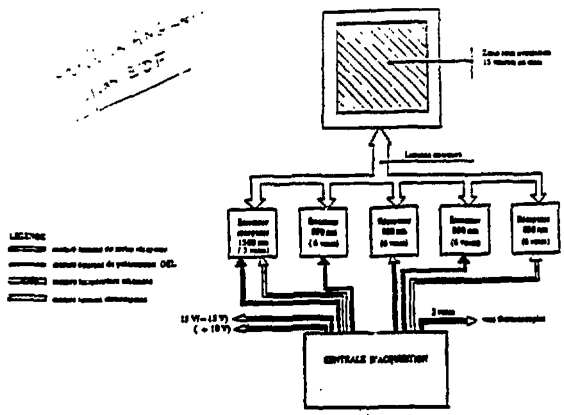


Figure 1 : Fibre attenuation test

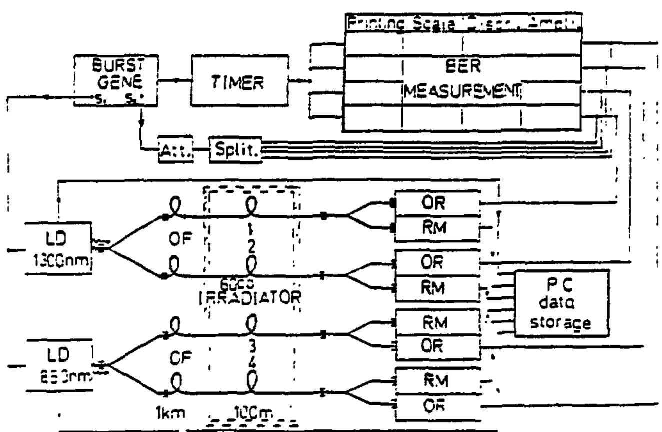


Figure 2 : Fibre transmission test

3.3.2 *Bit error-rate measurement*

A 10^6 bit-burst was used every hour to drive two 850 nm and 1300 nm laser-diode emitters (LD) and to initiate electronics counting and BER storage timing. Data luminous bursts were injected into 1 km multimode fibre for full mode coupling and lossy mode vanishing. A 100 m exposed fibre spool was connected with it by a splice. An output coupler carried data to an analog receptor (OR) and a radiometer (RM). Analog electronics threshold was adjusted to TTL low level. LD emitters shifts must remain small because of internal light power control and temperature stabilisation. Nevertheless possible deviations were recorded on PC. Data processing allowed to evaluate ΔL induced loss and related budget decrease of every link.

4. TESTED FIBRE OPTICS

4.1 Tested fibres

Seven step-index multimode fibres (SI) and one graded-index multimode fibre (GI) were tested. Characteristics are given in table 3. OH^- rates are weak (≤ 5 ppm), small (≈ 30 ppm) or high

(≥ 300 ppm). 50/125 fibre (named G) presents the best intrinsic characteristics, it is telecom type without phosphorus (P) either in core or in clad. Other fibre cores are in pure silica.

Fibre	A	B	C	D	E	F	G	H
Type	SI						GI	SI
Size (μm)	100/140	200/230					50/125	100/140
Core	pure silica						doped silica Ge + F	pure silica
Cladding	fluorine acrylate	hard polymer					silica without P	doped silica
Coating	epoxy acrylate	Tefzel					epoxy acrylate	polyimide
OH rate	weak	high	small	weak	high	weak	-	weak
Intrinsic loss (dB/km) @ 850 nm	4	12	6	5	12	6	2.6	4
@ 1300 nm	-	-	20	15	-	12	0.6	7.3
Bandwidth (MHz.km) @ 850 nm	20	17	17	17	20	20	255	44
@ 1300 nm	-	-	-	-	-	-	730	44

Table 3 : Main tested fibre characteristics

4.2 Tested optoelectronic components

All STANDARD commercially available components are pigtailed with multimode graded-index "telecom fibre". Heavily doped core and presence of P make it very sensitive to radiation : for a moderate dose-rate of 2 $Gy.h^{-1}$ induced-loss growth shows no saturation beyond 1 kGy and reaches 40-50 dB/m for 10 kGy. [1]
Therefore this fibre is quite bad to be used as component pigtail. Another fibre without P was tested under 120 $Gy.h^{-1}$ medium dose-rate and showed a saturating growth above 3 kGy with induced-loss value of 100 dB/km for 10 kGy. [16] Also IMPROVED components are especially manufactured with it.

Type	TL2005/61610			TL2005/61640			
	69	94	191	350	367	382	414
Threshold current (mA)	44.20	36.00	28.70	37.90	16.30	36.70	16.50
Mean value (nm) *	1309	1296.6	1311.3	1309.4	1321.8	1312.1	1315.7
Spectral width (nm) *	1.82	1.59	0.663	1.27	1.08	1.53	1.57
Mode number *	4	4	3	5	3	6	2
Pigtail fibre	50/125 standard telecom			100/140 telecom without phosphorus			
Drive current (mA)	17.50	18.90	18.00	15.70	21.30	23.30	17.30
Fibre output power (mW)	4.02	3.75	3.57	3.13	3.18	3.01	2.72

* at a drive current frequency of 200 MHz

Table 4 : Main tested laser-diode characteristics

5. FIBRES RESULTS

5.1 Induced -loss values

Tables 5 and 6 give final induced loss values for one year exposure.

$\dot{D}$ = 125 $mGy.h^{-1}$

Induced loss (dB/km)	A	B	G
850 nm	90 (120 days)	2	75 (240 days)
1300 nm	-	-	7

D = 228 mGy.h^{-1}

Induced loss (dB/km)	B	C	D	E	F	H
850 nm	(> 80)	8	6	2	6	52
1300 nm	-	13	32	-	14	23

Tables 5, 6 : Multimode fibre induced loss results

Worse fibre A behaviour is probably due to a badly controlled manufacturing. Further ageing tests showed a very poor mechanical resistance.
Graded-index fibre G takes a high final loss for 850 nm : 75 dB/km, but shows a small value for 1300 nm (7 dB/km). No phosphor content is very favourable. [1,12,13]
Fibre B has the best behaviour during the first irradiation sequence (final loss 2 dB/km) but shows a growth to 80 dB/km for the second sequence. This anomalous result is probably due to a manufacturer winding error.
Fibre E with same characteristics presents also good final loss : 2 dB/km at second exposure end.
Pure silica-core fibres C, D, E and F show very good radiation-resistance. This fact is consistent with all published papers [12,13,17,18,19,20], but hydroxyl-ions rate effect has not been here clearly proved. [3]
Fibre H shows rather high final loss : 60 dB/km at 850 nm and 43 dB/km at 1300 nm. [21] This "almost step-index" fibre has a core made only partly of pure silica because of fluorine diffusion from cladding. But its advantage lies in good polyimide-coating temperature-resistance.

5.2 Bit-error rate results

Three step-index fibres and the graded-index fibre were used as four 1100 m data links with each 100 m final part being radiation-exposed.
Strong optical budget decrease could affect initial 10^{-9} BER. In fact laser-diode emitter power (-3 dBm) and optical detector threshold (-33 dBm) were continuously remained stable. Also BER changes would be only due to exposed section high growth ΔL.
Table 7 shows ΔL values are under 6 dB/100 m during one year irradiation. Therefore output optical power of four links remains above -33 dBm threshold and BER is unchanged one year over.

Multimode fibre	B	G		D		E
Transmission wavelength (nm)	850	850	1300	850	1300	850
Mean dose-rate (mGy.h^{-1})	125 ± 15			228 ± 12		
Total dose for 1 year (Gy)	648	533	655	1470	1635	2313
ΔL (dB/100 m)	1.70	6.0	< 0.2	1.87	2.18	1.37
Final margin (dBm)	-18	-12	-3.7	-10	-21	-18
BER +	better than 10^{-9}					

+ for constant -33 dBm receiver threshold

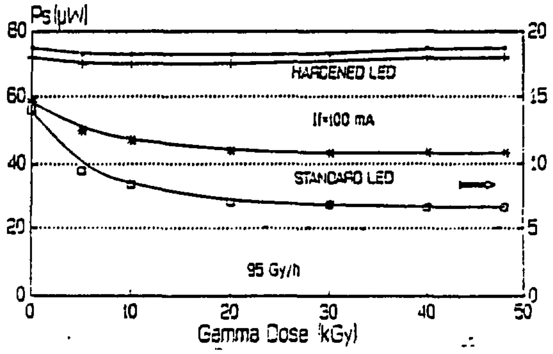
Table 7 : 1100 m data link transmission performance

6. OPTOELECTRONIC COMPONENTS RESULTS

6.1 GaInAsP-LED

Tested device was a double heterojunction light-emitting diode (DH-LED) in GaInAsP epitaxied on InP. For a 40 μm active area diameter mean output power is -20 dBm (150 mA) for standard LEDs and -10 dBm for improved (hardened) ones.
Figure 3 gives irradiation results of both types. A clear light output decrease appears for standard LEDs while hardened LEDs present good behaviour up to almost 50 kGy. This result is consistent with Japanese DH-LED data which show optical degradation only occurs beyond 100 kGy. [22]

Figure 3 :
Standard and hardened LEDs output power vs. total dose



6.2 GaInAsP-LD

Tested device is a double buried heterojunction injection-laser (DBH-LD) with a low threshold current (15-30 mA). Active material is quaternary semiconductor GaInAsP epitaxied on InP substrate. Mean emission wavelength is 1310 ± 10 nm and spectral width less than 1.6 nm. Standard device fibre output is 3 mW for 50 mA forward current.
In fact easy-to-use laser-diode modules (LDMs) were tested.
Figure 4 shows three components are currently used with pigtailed LD : a monitor photodiode in view of LD rear-face, a thermoelectric cooler (TEC) and a thermistor matted to device substrate.

Figure 4 :
General diagram of a laser diode module

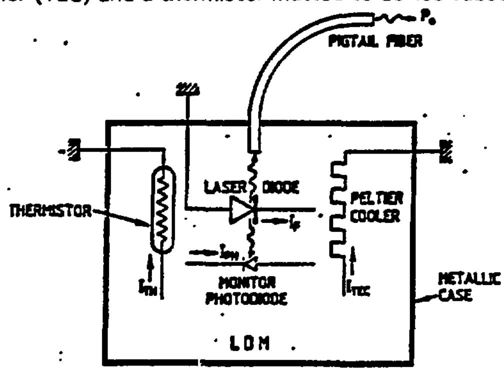


Figure 5 presents compared data of standard and improved LDMs. Hardened LDMs optical behaviour is clearly better (standard LDMs are unusable beyond 1 kGy). Nevertheless a slow output power decrease early appears beyond 3.5 kGy.

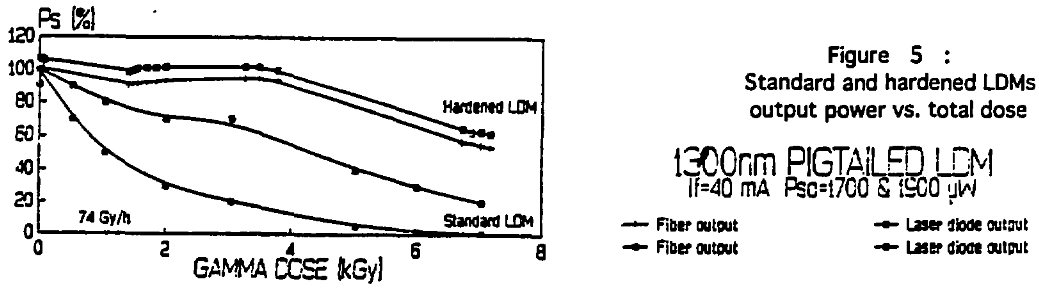


Figure 5 :
Standard and hardened LDMs output power vs. total dose

Forward current and case temperature are constant all over exposure. Also this optical degradation could be due to LD threshold current increase (internal quantum efficiency decreases with radiation-induced non-radiative recombination). Indeed it was possible to regenerate initial output powers by increasing drive currents of a few mA.
Figures 6 and 7 show data obtained during a second exposure from 7.5 to 16.5 kGy. LD forward currents remain quite stable while case temperature is growing to +3 °C beyond 10 kGy. It is probably

due to a slight TEC damage (and not that of passive thermistor) because temperature increase must decrease optical power.

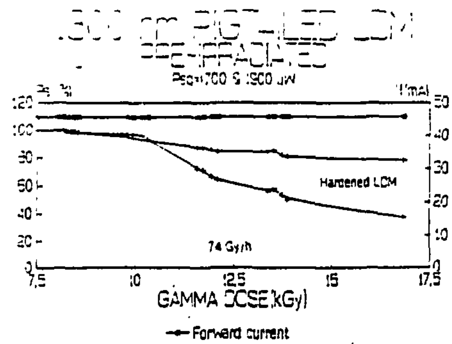


Figure 6 : Hardened LDM output powers vs. total dose after forward current increased

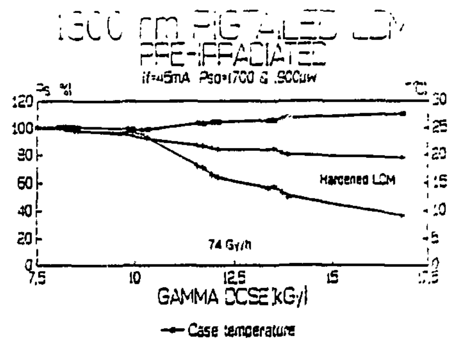


Figure 7 : Hardened LDM output powers and case temperature vs. total dose

Upper graph best LDs had lowest threshold currents and consequently highest drive currents. Worst hardened LDs present optical degradation more than 50 % for 16.5 kGy.

6.3 InGaAs p-i-n PD

In a photodiode (PD) the same physical process is responsible of producing photocurrent whether the photon comes from luminous energy or energetic gamma-rays. But gamma-ray interaction is a bulk effect (electron-hole pairs generating in the whole volume of semiconductor) while optical signal creates carriers in the small active region only.
Also tested p-i-n- PD was a small volume homojunction in InGaAs epitaxied on InP substrate. Active area diameter is 70 μm and thickness less than 1 μm. High responsivity is 0.7-0.9 A/W for 1.3 μm wavelength. Small voltage (-5 to -6 V) is sufficient to complete depletion and full carrier collection. Typical dark current is 10 nA (-6 V).
Biased PDs were tested up to 40 kGy exposure with 1.3 μm LEDs. Mean dose-rate was 65 Gy/h. Received light power was about 1 μW and ambient temperature 25 ± 2 °C.
Figures 8 and 9 show results for a few PDs.

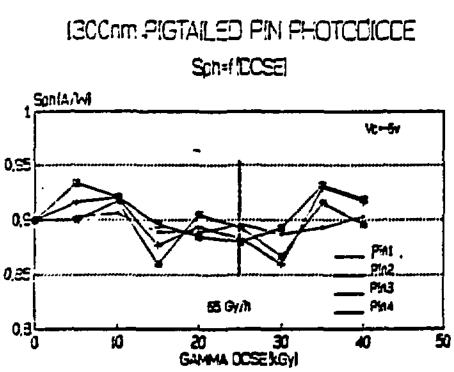


Figure 8 : Photodiode sensitivity vs. total dose

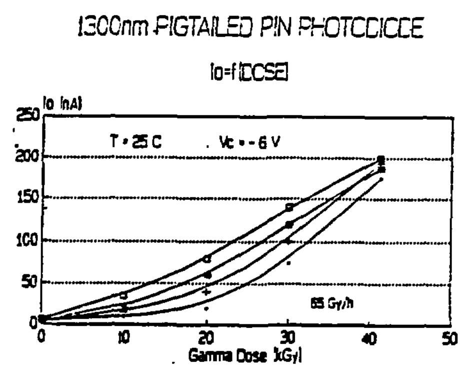


Figure 9 : Photodiode dark current vs. total dose

0.9 A/W normalised optical sensitivity remains constant all over the exposure. On the contrary surface leakage effects strongly increase initial dark currents (x50) : resultant signal-to-noise ratio deviation Δ (S/N) is about -8 dB for 10 kGy. Also signal-to-noise ratio degradation would be the highest variation of long-term medium dose-rate totally exposed fibre link budget.

7. FUTURE FIBRE OPTICS TRENDS

Present results show the good fibre-optics tolerance towards ^{60}Co gamma-ray irradiation. Indeed several fibres and all improved components are able to operate under 0.1-0.2 Gy/h dose-rate exposure up to 600 Gy total dose.
This fact promotes implementation of optical fibres inside NPPs. If optoelectronics radiation resistance does not ensure operation during an accident (cf main radiation parameter : 600 kGy integrated dose), operation in normal conditions seems to be conceivable during the whole reactor lifetime (40 years) or at least a part of it.

Two main classes of optical fibres (and eventually fibre-end optoelectronics) applications are possible :

- transmission medium alone : as for local area network (LAN), optical fibres are only used for carrying information without creating it ; data from standard sensors (i.e. electrical measurements) will be (rather digitally) converted into light pulses then launched into optical fibre, this one carrying the information down to processing unit where double inverse conversion (optical-to-electrical and digital-to-analog) will be realised
- optical fibre sensors : here no electrical-to-optical (E/O) converter is required, environment parameters will directly interact with light propagating inside fibre and one (or more) basic parameter(s) of this lightwave will be modulated.
  Only optical-to-electrical (O/E) conversion will be provided by reception units.

In any case, whether sensors are conventional (electrical) or optical, optical information transmission presents specific advantages related to intrinsic optical fibres characteristics :

- electromagnetic interference (EMI) immunity
- galvanic isolation
- large bandwidth
- small size and weight
- high signal security (confidential transmission).

7.1 Transmission medium

The most direct and obvious application to NPPs of optical fibres lies in remote transmission of control and instrumentation signals requiring distances up to about 100 m between information generation and processing.

7.1.1 Data transmission from conventional electrical sensors

Presently radiating electromagnetic fields inside reactor buildings produce significant conduction currents (up to 100 mA) flowing onto cable shielding and able to perturbate signal acquisition and conditioning operation. Also coaxial cables could be replaced by optical waveguides the main feature of which is to be EMI immune. Of course, great care must be taken in shielding additional electronic interfaces.
The principle for such an instrumentation holds usual advantages of optical fibres transmission concurrently with those of existing electrical sensors. It would not require any facility modification and could be adapted to qualified conventional sensors.
However, 2 options are conceivable :

- either inside O/E converter and outside E/O converter implementation allows to use existing electrical penetrations, but two interfaces are added as possible failure sources
- or the link becomes all-optical : no electrical conversion of light data is needed before sealed penetration and inversely

This second solution would require to qualify optical penetrations having the same leaktightness warranty as present ones. But it appears to be more attractive because of signal multiplexing compatibility.
In fact, fibres high bandwidth makes an electronic multiplexing for many signals (e.g. thermocouples) to be realisable before optical conversion and injection into fibre.
Hence, numerous point-to-point electrical lines could be replaced by one optical link (or a few ones according to redundancy principle).

7.1.2 Data transmission from optically-powered sensors

Optical transmission from another class of sensors is conceivable : optically-powered sensors could be an intermediate solution between conventional electrical sensors and all-optical ones usually named "optical fibre sensors" (OFS).
Principle of optically-powering consists in converting a lightwave into electrical power using a photovoltaïc cell. This technical approach when applied to different types of sensors (pressure, temperature, angular position, ...) brings optical fibres advantages to already existing sensors by making them "smart" (alarm, calibration, ...).
Optical power source is a pigtailed laser diode which is connected to an optical fibre carrying light power (from 5 mW up to some hundreds of mW) to where sensor is located. Then a photovoltaïc cell realises the conversion into electrical power (AsGa converter efficiency could be greater than 50 % at 20 °C). Command signals and messages are extracted from power which is stored.
Sensor operates according to the following principle. During energy storage step, electronic devices are in stand-by mode and their power consumption is quite low. When enough energy is stored, measuring cycle begins and transducer is excited for a very short time but sufficient for measurement stabilisation. Measured values are memorised, then digitally converted and transmitted using a LED, for instance. [23] One can also use bidirectional light propagation in a single optical fibre with time-sharing operation. [24]
Optically-powering principle enables networking and could add simple optical link advantages and properties for an optically-powered sensors system to alert user if any problem occurs, to display sensors state or to interrogate individually sensors about their operation mode or their measurement. But present limitations to this technique are mainly caused by low optical power provided by laser diodes and that could be injected into multimode fibres. This imposes low power consumption sensors tc operate at limited sampling frequencies (less than some hundreds of Hz).

7.2 Optical fibre sensors

OFS represent a new branch of optical engineering which has known a fast development these last years. [25]

7.2.1 Principle

OFS are defined as systems with one or more fibres able :

- either to carry information collected between fibre ends and environment : these sensors are called "extrinsic sensors" and optical fibres only fit to bring light to added measuring components (e.g. distance, spectral absorption, ... measurement)
- or to optically code information related to physical quantity to be measured which directly acts on fibre (or indirectly via special coating) : these sensors are called "intrinsic sensors" and their main application fields are for temperature, current, voltage, humidity, ... sensing.

7.2.2 Applications [26]

Concerning NPPs, a French working group (CORA 2000) including operators, manufacturers and designers (CEA, Atomic Energy Commission - FRAMATOME, Nuclear Reactor Manufacturer - EDF, Electric Power Supplier) was formed in 1991.
Main assignments are :

- to list OFS and related networks already commercially available (or still in development and field-test stages)
- to select most valuable applications for next generation NPPs.

Conclusions of this group are that OFS present a great interest for :

1. thermal monitoring of stator copper bars in generators
(e.g. measurement of local thermal changes of refractive index along the fibre)
2. vibration monitoring of generators
(accelerometers network to analyse vibration spectrum and detect any operating faults)

3. structure and containment integrity monitoring
(stress measurement using OFS embedded in concrete of monitored structures)
4. transformers monitoring
(temperature, dissolved H_2 or combustible gases in transformer oil, ..)
5. detection of valves position
(OFS able to detect very low amplitude motion)
6. leak detection of primary system pressurised water or secondary system steam
(e.g. in-service piping and pressure vessel systems detection of hot spots caused by small cracks)
7. hydrogen detection inside containment in particular during a Loss-of-Coolant Accident
(in that case, system will have to withstand specific accidental conditions)
8. fire detection inside containment and especially inside reactor coolant pump bunkers
(e.g. pyrometers using Planck blackbody radiation from the flame or OFS based on light absorption or diffusion due to smoke)
9. (thermal) monitoring of lightning arresters, suburban power transmission lines, power cables, composite material piping, ...

While EDF has already carried out some studies on particular applications (e.g. thermal and vibration monitoring of generators, pressurised water leak detection, ...), CEA is greatly involved in :

- structure monitoring : one of the most promising studied principles is optical sensing with Bragg grating sensors (deformation of a periodic index modulation written inside fibre will shift the normally reflected wavelength as a direct function of strain, pressure, ... acting on the grating)
- hydrogen concentration measurement using specific property of palladium
- optical fibre dosimetry : applying fully distributed OFS network to radiation sensing for integrated dose profile determination along optical fibres uncoiled in hazardous area (using either radiation induced attenuation and photobleaching phenomena or mechanisms of radiation electron transfer between fibre dopants).

8. CONCLUSIONS

When compared with metallic transmission medium (coax or twisted pairs) optical fibres offer undeniable well-known advantages : EMI immunity, galvanic isolation, high transmission security, low loss into large bandwidth, ... Moreover several present fibres and various improved optoelectronic components show good radiation resistance under long-term low dose-rate gamma-ray exposure (0,1 $Gy.h^{-1}$ - 1 to 10 kGy). And optical sealed penetration could be henceforth manufactured with appropriate leaktightness warranty.
About electronics some component technologies present now a rather good radiation behaviour : bipolar technology up to some 10 kGy, AsGa technology above 100 kGy.
On condition that the whole optical fibre system owns the above-mentioned properties transmission quality of analog signals (SNR) or digital data (BER) is higher.
Also after representative laboratory ageing tests complete monitoring systems with electronic coding and optical transmission could be thought for NPPs in non-accidental operation.
All-optical control systems seem presently unreliable to bring into operation because of serious lack of qualified industrial OFS able to replace efficiently conventional sensors.

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