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# Optical Fiber Sensors to improve the safety of Nuclear Power Plants

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**Abstract:** Safety must always prevail in Nuclear Power Plants (NPPs), as shown at Fukushima-Daiichi, in March 2011. So, innovations are clearly needed to strengthen instrumentations, which went inoperative during this nuclear accident as a consequence of power supply losses. Possible improvements concern materials and structures, which may be remotely monitored thanks to Optical Fiber Sensors (OFS). We detail topics involving OFS helpful for monitoring, in nominal conditions as well as during a severe accident. They include distributed sensing (Rayleigh, Raman, Brillouin) for both temperature and structure monitoring as well as H<sub>2</sub> concentration and ionizing radiation monitoring. For future plants, Fiber Bragg Grating (FBG) sensors are considered up to high temperature for sodium-cooled fast reactor monitoring. These applications can benefit from fiber advantages: sensor multiplexing, multi-km range, no risk-to-people, no common failure mode with other technologies, remote sensing, and the ability to operate in case of power supply loss in the NPP.

**Keywords:** Fukushima, Safety, Optical Fiber Sensor, distributed sensing, Fiber Bragg Grating, remote measurement.

## 1. Introduction

Following the accident at Three Miles Island (USA, March 1979) and Tchernobyl (Ukraine, April 1986), the nuclear safety rules were improved. But, it is clear that the magnitude and the consequences of the Fukushima disaster (Japan, March 2011) which far exceed the worst nightmare, have highlighted the need for researches in nuclear safety and radiation protection. The French Government wishing to learn more from the conditions that led to major nuclear accidents, recently decided to stimulate R&D by supporting projects in that field.

In order to enhance the safety of existing or new NPPs, we may now take advantage of OFS based on 3 decades of R&D in instrumentation and telecoms [1, 2, 3]. Today, OFSs are reliable, based on mass market components, and increasingly used in several sectors (oil & gas, fire monitoring, civil engineering...). OFS make it possible to remotely perform reliable sensing of many parameters and allow for large scale multiplexing without electronic equivalent (a single fiber is equivalent to several 10,000s sensors), offering new features. For nuclear safety, they provide: *i*) Passive sensing (no need for local power supply), *ii*) ElectroMagnetic immunity,

*iii*) Remote sensing (no risks for workers), *iv*) Redundancy (fibers deployed over different paths, ability to query both fiber ends, *v*) Multiplexing, *vi*) Diversification (no common failure mode with traditional technologies), *vii*) Radiation-resistance, *viii*) and, last but not least, the ability to localize cracks with the help of reflectometry technique.

## 2. OFS may enhance NPP' safety

For a long time, reports [4] indicate that safety improvements of existing or future units are required, for many topics: *i*) The efficiency of the nuclear shield, *ii*) Protection against external hazards (earthquake, aircraft crash, external explosion, lightning, EMI, groundwater, weather & extreme floods, ice, toxic, corrosive, flammable...), *iii*) Protection against internal failure of components subject to pressure, internal floods, fires, explosions internal projectiles (missile effect), falling loads... *iv*) Prevention of H<sub>2</sub> detonations, *v*) Prevention of fusion in spent fuel pools, and *vi*) Instrumentation.

Many of these recommendations were then taken into account in the design of the EPR (European Power Reactor) [5]. But, several risks are still valid after Fukushima [6-7]. They relate to all NPPs, being dependent on the type of reactors and buildings.

In this paper, we consider two kinds of situations:

- **In service:** *i*) Nuclear building monitoring, *ii*) Thermal monitoring of pipes, pools, transformers, fire detection...
- **During an accident or in post-accidental situation:** *i*) Detection of reactor breakthrough, corium casting, concrete floor erosion, *ii*) Nuclear building monitoring, *iii*) Monitoring of spent fuel pools, steam pipes, *iv*) Fire detection, *v*) Hydrogen Risk, *vi*) Radiation monitoring (dosimetry). In the next sections, the most relevant techniques are discussed for accidental and post-accidental situations.

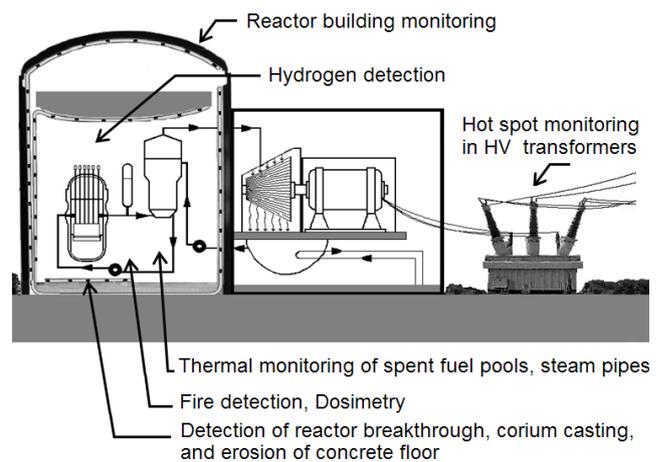


Fig. 1 OFS applications to enhance NPP's safety.

### 2.1 Continuous temperature measurement – Raman Distributed Temperature Sensing (DTS)

The DTS is based on the inelastic Raman backscattering in the fiber core analysed by reflectometry. The effect generates two symmetrical frequencies, respectively called Stokes ( $\nu_S$ ) and anti-Stokes ( $\nu_{AS}$ ) lines. The anti-Stokes signal  $I_{AS}$  is temperature dependent according to the Boltzmann statistics:  $\exp(-h\nu_B/kT)$ ; while the Stokes signal  $I_S$  is not. The ratio  $R(T) = I_{AS}/I_S = (\lambda_S/\lambda_{AS})^4 \exp(-h\nu_B/kT)$ , where  $h$  and  $k$  are the Planck and Boltzmann constants, is only function of the temperature, leading to a very selective measurement of the temperature profile all along the fiber.

Since many years, DTS are commercially available, and could therefore be used in NPPs to provide temperature profiles of equipments and structures on, or in which, fiber optic cables have been deployed. That is to say offer a remote thermal monitoring of abnormal temperatures (hot spots), as well as fire detection on thousands of points, without need for local power supply. Such feature could become crucial in case of reactor core fusion associated to reactor vessel perforation leading to corium release.

Extra needs concern thermal monitoring of spent fuel pools, detection of leakages on primary steam pipes.

## 2.2 Reactor breakthrough and corium detection

In case of fusion of the reactor core and vessel breakthrough, the corium flows on the concrete floor. So, concrete erosion by the corium is a strong matter of concern. Concerning the EPR (Generation III), improvements have been made to the concept of Pressurized Water Reactor (PWR, generation II, *i.e.* the main French reactors). It has been thickened (4 m), and the lower part of the building has a spreading compartment, made of sacrificial concrete where the corium may spread, itself followed by an optimized recovery area (metallic structure of wide surface able to cool the corium). Moreover, a refractory material (zirconia) is placed on the lower walls to protect the building while corium casting; leading to corium solidification in few days by flooding. But, existing NPPs are not designed that way. So, to increase the information provided to the operators/authorities, about the reactor breakthrough in case of a severe accident, we propose that NPPs be equipped with dedicated optical sensing cables, *i.e.* a grid below the reactor (into the concrete to be protected). This fiber mesh could then be remotely interrogated, with dedicated OFS systems, even in case of total loss of control, or lack of electricity in the plant. Silica fibers used in such application are radiation-resistant enough to withstand ionizing radiations over 40 years (*i.e.* 250 kGy with a mean dose rate  $\sim 0,7$  Gy/h) plus those corresponding to the accident (600 kGy dose; 1 kGy/h dose rate; Standard NF M 64-001).

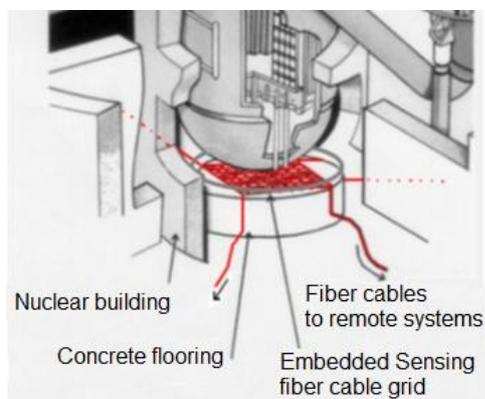


Fig. 2 Distributed sensing-based corium detection.

## 2.3 Temperature sensing in nuclear reactors

FBGs reflecting a narrow spectral line ( $\lambda_B$ ) offer many advantages, and so are widely used in sensing applications, but usually limited for long-term use in high temperature environments. Nevertheless, through thermal engineering, FBGs are now made highly resistant even for temperature reaching  $900^\circ\text{C}$  during several thousands of hours. The so-called regenerated FBG transducers exhibit considerable improvements of their thermal stability with respect to standard FBGs. The deployment of ultra-stable FBG temperature sensing arrays in extreme temperature environment is now a reality [8], and they are promising candidates for nuclear applications. Ultra-stable regenerated FBG withstand operating temperatures well beyond  $500^\circ\text{C}$  as expected in several Generation-IV nuclear core designs, as Sodium-cooled Fast Reactors (SFR) in which the coolant reaches  $550^\circ\text{C}$ . So, regenerated FBG temperature sensors have been evaluated to assess their compatibility with liquid Sodium ( $500^\circ\text{C}$ ) and to confirm low response time  $< 0,2$  s [9]. Recently, regenerated FBGs have been annealed at temperatures up to  $890^\circ\text{C}$  during 9000 h, to assess their long-term stability. The reflectivities and  $\lambda_B$  of four regenerated FBGs, simultaneously annealed at respectively  $760^\circ\text{C}$ ,  $810^\circ\text{C}$ ,  $850^\circ\text{C}$  and  $890^\circ\text{C}$  are stable [10]. So, ultra-stable regenerated FBG have now levelled the challenge of long-term temperature stability. Their deployment as sensing arrays within the core of SFR reactor needs to progress regarding their qualification *vs* ionising radiation hardness. Once their behaviour under combined high temperature and high energy neutron flux assessed, FBGs could provide fruitful insight to accurately monitor temperature profiles within liquid Sodium coolant but also to improve SFR's core health and safety. FBGs could address needs beyond the temperature sensing: innovative packaging and mounting procedures will trigger their use as strain and pressure sensors.

## 2.4 Steam pipe monitoring

Primary circuits of PWR NPP operate at 155 bar and 325°C, with a complex circuitry (tank, pump, steam generator, pressurizer) including many welds. In case of pipe failure, *e.g.* due to thermomechanical aging, steam leaks can lead to a Loss-Of-Coolant Accident (LOCA). So, each NPP includes an automatic emergency shutdown system, and, in the reactor building, spray cooling systems are activated to condense the steam to avoid concrete building cracking under overpressure. To improve exchangers and pipes monitoring, it may be useful to detect and localize steam leaks, especially those which could lead to cracks. The deployment of optical cables all along the pipes and their remote interrogation with a Raman DTS would be a convenient way to accurately detect any hot spot, due to a steam leak, before a break occurs. These sensing cables could also specifically control the elbows, valves... Such an idea, proposed to NPP operators more than twenty years ago [1] was considered as too far from industrial objectives. This should be reconsidered today, due to significant technological improvements since then.



Fig. 3 Example of steam pipes able to be monitored with optical fibers for distributed leakage detection.

## 2.5 Monitoring of temperature in spent fuel pools

At Fukushima, the cooling of spent fuel, stored in pools, became a problem when pumps stopped. Many options (dropping water with helicopters, high power water pumps) were used. But, during several days, TEPCO ignored the water level in pools, or

even if water was evaporating. In NPPS, such pools are located at different locations depending on their design (in France, they are in a building able to withstand an earthquake). Measuring the temperature would be very useful to know if water boils and evaporates. So, we also recommend the use of optical cables and Raman DTS as well as OFDR technologies.

## 2.6 Fire detection in NPPs

Fire detection remains an important issue as related to NPPs' safety and availability (it is classified "Important For Safety" by regulators). It is currently provided by conventional smoke or flame sensors, connected in series along loops. Nevertheless, with more than 400 reactors in service worldwide, we count thirty serious fires per year. As a major fire would induce: plant damages, loss of production, and a possible safety degradation, the fire detection remains an important topic. To be efficient, such system must be redundant, without common mode, and selectivity must be guaranteed to avoid false alarms. The temperature increase is often considered as a non-essential parameter due to its later appearance. Nevertheless, the availability of distributed sensors able to provide temperature profiles along a single cable may lead to reconsider this point-of-view. It may be useful to use DTS as continuous fire detector (1 measuring point every metre), in reactor building, and wherever narrowness makes it difficult to detect fire, close from risk factors: in the casemates, around electric power cables which tend to heat up, as in confined spaces, "hot spots" in transformers, etc.

## 2.7 Containment building monitoring by sensing optical cables and Brillouin reflectometry

The civil engineering plays an important role in NPP safety since it ensures the confinement. The containment building remains the ultimate barrier, and it is designed to withstand an hypothetical H<sub>2</sub> explosion. Although a pressure integrity test is

performed every decade, a complementary approach based on a monitoring system able to provide local, accurate and continuous information would improve safety and reduce maintenance costs. In such a context, optical cables to measure concrete strains by Brillouin sensing may be considered. Very few number of available cables may be selected for such application. One of these sensing cables (CEA patent) is called the "3D" cable, [11]. It includes 3 optical fibers at 120° on its periphery and provides simultaneously strain [traction; compression], bending, plane of curvature as well as temperature, at each measurement point defined by the interrogation system (< 1 m with a Brillouin system).

The use of such "3D" cable embedded in a concrete containment building, or attached to its surface, may allow operators to monitor its behavior, remotely and in real time, to detect loss of prestress, and so to increase the NPP safety level.



Fig. 4 Multi-parameters cable to simultaneously determine: strain, curvature, plane of curvature and temperature profiles.

## 2.8 Dosimetry based on fiber remote Optically Stimulated Luminescence (OSL)

Fiber remote OSL dosimetry finds electronuclear applications such as radiation protection, recycling and dismantling, long-term nuclear storage [12]. The readout unit is placed away in safe area and dose plus dose rate are remotely recorded online through a fiber by laser stimulation. The integral (*vs* time) of the OSL signal is proportional to the dose absorbed since the previous stimulation, so the average dose rate is

estimated taking into account the elapsed time since then. Several OSL materials may be used depending on applications (radiation protection requires highly sensitive, low-Z materials to provide a tissue-equivalent sensing), and may be inserted inside compensation packages providing both angular and energy compensations.

Dosimetric-grade alumina crystals ( $\text{Al}_2\text{O}_3:\text{C}$ ) remains a low-cost material for this purpose. Two generations of OSL Fiber Optic systems have been developed by the CEA [12]. First generation (OSL1) were devoted to dismantling (AREVA NC) and relies on RE-doped AES, operating in the near IR. These single channel units were integrated into an industrial PC (Range [1 mGy -10 Gy]). AREVA used day-long integration times to improve the resolution (< 50  $\mu\text{Gy/h}$ ).

The second generation (OSL2) relies on alumina crystals. We have shown that the dose resolution is well < 50  $\mu\text{Gy}$  [13], enabling for instance, an average dose rate measurement as low as 50  $\mu\text{Gy/h}$  with 1 h integration [12]. The OSL2 system is a CW multichannel unit (16 outputs) built in a 19" enclosure including a diode-pumped solid-state laser (532 nm), and a 16-channel fibre switch. It is linked by USB to a laptop running with a dedicated LabView® software [13].



Fig. 5 OSL Instrument: 16 channels ; Range 100 m (Transducers  $\text{Al}_2\text{O}_3$  – Visible spectrum Range.

It includes PMMA fibers and tiny alumina crystals ( $0.3 \times 0.3 \times 1 \text{ mm}^3$ ) inserted into fiber tips. Such 1-D dosimeters connected to the multichannel readout may be used for dismantling applications. A

multi-sensor cable might incorporate a plurality of crystals placed along, depending on installations and dose gradients. Such a sensing cable would be let in place during dismantling operations to provide online check-up of the remaining activity during the cleanup.

## 2.9 Hydrogen detection

In case of LOCA, the melting of the nuclear core may releases a large quantity of  $H_2$  due to both oxidation of zirconium sheaths (protecting nuclear fuel rods) and concrete-corium interaction. Depending on air- $H_2$  and water vapour concentration, a spark may initiate a deflagration or a detonation (Tchernobyl, Fukushima).

Traditional controls consist to extract part of the gas out from the containment to be analyzed by conventional way. But, sampling is not satisfactory as gas accumulate along tubes leading to delayed and biased estimation. And, it is whorthwhile reminding that most analytical methods require a local power supply. *In situ*  $H_2$  remote sensing is thus an added value for safety.

Raman spectroscopy is a very selective and versatile method and the basics may be found in many papers. Such sensing may provides distributed measurements inside the containment building with the help of passive rad-hard gas cells providing a local measurement of all gases of interest for post-accidental supervision ( $H_2$ ,  $O_2$ ,  $N_2$ ,  $H_2O$ , CO and  $CO_2$ ).

Preliminary tests performned at CEA LIST are described in an earlier book chapter [2]. So, fiber Remote Raman Spectrometry can be used for industrial analytical applications in a cost-effective design and more particularly for real-time monitoring of nuclear accidents ( $H_2$  risk). The response time of the detection system should be of the same order than that of the  $H_2$  production rate (related to the number of oxidized zirconium sheaths) and also compatible with the delay for action (typically several minutes).

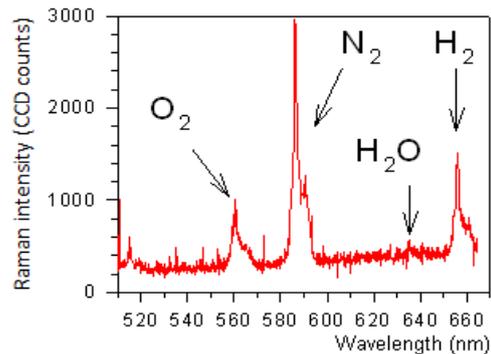


Fig. 6 Multi-gas sensing by Raman spectroscopy in containment Building.

## Conclusion

We have analyzed OFS advantages for remote monitoring, to improve NPP' safety, both in service (PWR), for the future generations, as EPR or fast reactors. At Fukushima, the loss of power supplies rendered instrumentations inoperative. To overcome such drawbacks, we have proposed to take advantage of the wide potential of (quasi-)distributed fiber sensing, to strengthen both monitoring and NPP' safety. Sensing approaches spatially continuous, namely the distributed sensors, are the best candidates for such objectives. Sensing arrays of multiplexed and temperature resistant FBGs are promising candidates for in-core continuous thermal monitoring to improve reactor health and safety. With both wavelength multiplexing and long-term stability under hostile environments, they may be deployed as dense and reliable sensing arrays in NPP, especially within high temperature nuclear reactor cores. Of course, R&D needs to be pursued focusing especially on testing and qualification for nuclear environments. For NPP safety, benefits are: no need for local power supply, remote sensing, redundancy (multiple fibers/cables connected from different paths), diversification (no common mode failure with other technologies). Thus, optical fibers (some of them selected for their resistance to ionizing radiation), judiciously deployed in NPPs, may provide monitoring in nominal situation or during accidental or post-accidental situations.

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