DISCOMS: DIstributed Sensing for COrium Monitoring and Safety

Pierre Ferdinand, Laurent Maurin, Stéphane Rougeault, Hamid Makil, G. Cheymol, H. Maskrot, P. Le Tutour, D. Duval, Christophe Journeau, J.-F Villard, et al.

CANSMART 2015: International Conference on Smart Materials and Structures
SMN 2015: 5th International Conference on Smart Materials and Nanotechnology in Engineering

DISCOMS: DIstributed Sensing for COrium Monitoring and Safety

[1]P. Ferdinand, [1]L. Maurin, [1]S. Rougeault, [1]H. Makil, [2]G. Cheymol, [2]H. Maskrot, [2]P. Le Tutour, [2]D. Duval, [3]Ch. Journeau, [3]J.-F. Villard, [3]J-F. Haquet, [3]Q. Souquet, [3]L. Barbot, [4]J. Miss, [4]I. Duhamel, [4]B. Dechenaux, [4]M. Brovchenko, [5]G. Musoyan, [5]S. Balleydier, [6]F. Pouillé, [7]G. Helleux, [7]S. Fourrez, and [7]L. Pichon

[1]CEA, LIST, F-91191 Gif-sur-Yvette, France. pierre.ferdinand@cea.fr
[2]CEA, DEN, F-91191 Gif-sur-Yvette, France. guy.cheymol@cea.fr
[3]CEA, DEN, F-13108 Saint Paul-lez-Durance, France.
christophe.journeau@cea.fr, jean-francois.villard@cea.fr
[4]Institut de Radioprotection et de Sûreté Nucléaire (IRSN), 92262 Fontenay-aux-Roses, France.
joachim.miss@irsn.fr
[5]AREVA, 1 place Jean Millier, 92084 Paris-La Défense cedex, France. grigor.musoyan@areva.com
[6]LMP S.A. 49-51 rue du Moulin des Prés, 75013 Paris, France. f-pouille-lmpsa@sfr.fr
[7]THERMOCOAX BP 26, Lieu-dit Planquivon, 61430 Athis-de-l'Orne, France.
laurent.pichon@thermocoax.com

ABSTRACT

The Fukushima-Daiichi nuclear disaster showed that the need for safety must always prevail. This paper discusses the development of remote monitoring technologies to improve Nuclear Power Plants (NPPs) safety, in operation (Pressurized Water Reactors), under construction (the EPR reactors, *i.e.* the GEN 3 PWR), or for any other next generations of reactors. At Fukushima, the total loss of electrical power supplies has quickly led most of the instrumentation inoperative and the operator (TEPCO) with no way to monitor the status and the evolution of the accident. To overcome these important drawbacks, advantage can be taken from the considerable potential of distributed sensing technologies based on both “Optical Fiber Sensors” (Raman, Brillouin, and Rayleigh Reflectometries) and long-length “Self Powered Neutron Detectors” (SPNDs). The goal consists in inquiring about the status of the third barrier of confinement and to define possible mitigation strategies in case of severe accident, namely: *i)* reactor pressure vessel breakthrough and corium relocation outside the vessel, *ii)* concrete basemat erosion and *iii)* corium cooling. Such monitoring should consist in “sensing cables” embedded in concrete basemat below the reactor vessel and interrogated from a rear base where operators can work safely. In this context, DISCOMS, which stands for “DIstributed Sensing for COrium Monitoring and Safety”, is a five-year project, managed by the French National Research Agency (ANR), dealing with the NPP safety improvement, from normal situation to severe accidents. Monitoring phases include reactor vessel breaching, corium flow, along with post-accidental period (corium cooling ex-vessel). Thus, optical fibers selected for their resistance to ionizing radiations and long length SPNDs, both judiciously deployed within the reactor concrete basemat, and the structures around it, will provide a useful real-time or on-demand monitoring, in normal operation, and more important in accidental and post-accidental situations.

Keywords*:* Nuclear safety, Corium Monitoring, Distributed sensing, Optical Fiber Sensor, SPND.

1. INTRODUCTION

In the years following the Three Miles Island (USA, March 1979) and Chernobyl (Ukraine, April 1986) accidents, nuclear safety rules were improved. Nevertheless, the magnitude and the consequences of the Fukushima-Daiichi disaster (Japan, March 2011) have highlighted the need for more researches in both nuclear safety and radiation protection. The French authorities wishing to learn more from the conditions that led to major nuclear accidents, promptly decided to stimulate R&D by supporting projects in that field, launching the so-called RSNR Program.

Concerning the instrumentation, which completely failed at Fukushima Daiichi NPP, due to the lack of electricity, we propose, in order to enhance the safety of existing and new NPPs, to take advantage of possibilities offered by dedicated Self-Powered Nuclear Detectors (SPNDs), as well as those provided by Optical Fiber Sensors (OFSs) based on three decades of R&D in both instrumentation and telecommunications [1]. Today, distributed OFSs are reliable, based on mass market components, and increasingly used in many sectors dealing with Structural Health Monitoring (oil & gas, fire detection, civil engineering, composite materials...). They make it possible to remotely perform reliable sensing and monitoring, based on large scale multiplexing without equivalent (a single fiber is equivalent to several 10,000s of sensors), offering really new features. For nuclear safety, they may provide: *i)* passive sensing (no need for local power supply), *ii)* electromagnetic immunity, *iii)* remote measurement (no risk for operators), *iv)* redundancy (fibers deployed over many paths, ability to query both fiber ends), *v)* wide sensor multiplexing, *vi)* diversification (no common failure mode with traditional technologies), and *vii)* resistance to ionizing radiation.

2. NUCLEAR POWER PLANTS SAFETY CONCEPTS

The design of GEN 2 reactors, in the world, did not originally include equipments against the consequences of a severe accident (SA). Following TMI-2 and Chernobyl accidents, the French Safety Authorities performed an in-depth assessment of the 58 French PWRs robustness against SA. As a result, modifications have been done, including the implementation of passive H_2 recombiners to master H_2 release, containment filtered venting systems, and the emergency organization reinforcement as well. To prevent the risk of containment basemat melt-through, the main mitigative strategy considered French operating (GEN 2) reactors consists in systematically injecting water inside the reactor pressure vessel, to cool and keep the core debris inside, and, in case of vessel failure, to stabilize the corium in the reactor pit, by stopping the molten core interaction with the concrete basemat (MCCI, Molten Core Concrete Interaction). During a SA, thermocouples positioned inside the reactor pit enable the operating staff and the crisis team to detect the pressure vessel failure.

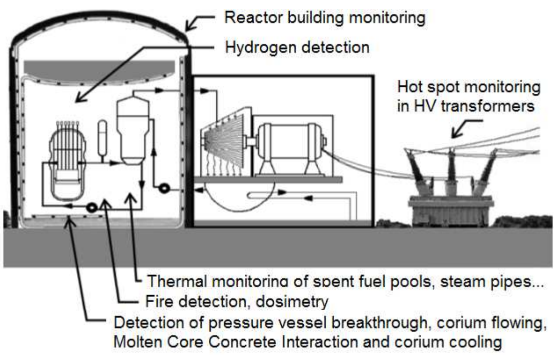
On EPR and ATMEA1 reactors (GEN 3 reactors with respectively a nominal power of 1650 MW and 1100 MW), by design, the risk of basemat melt-through during a SA has been taken over (CMSS, a dedicated Core Melt Stabilization System). The CMSS of ATMEA1 and EPR reactors are very similar. After failure of the Reactor Pressure Vessel (RPV), at first, the core melt is collected in the reactor pit that is cladded with sacrificial concrete and backed-up by protective refractory bricks. Then, during the erosion of the sacrificial concrete, all the melt coming from the reactor core will be collected, independently from the initiating accident scenario and the melt release history. Finally, when the sacrificial concrete, at the bottom of the reactor pit, has been eroded, the melt plug is reached. In contact with the melt, the gate rapidly fails and opens the flow path into the transfer channel and up to the core catcher. Then, the melt is spread on a large surface, supporting the cooling.

The core catcher is a metallic crucible including cooling channels inside its bottom and sidewalls. The inner side is covered with a sacrificial concrete layer to protect this structure, during the initial phase and before the cooling channels are filled with water, against the hot melt thermal attack. When the first melt reaches the core catcher the flooding valves from the In-containment Refueling Water Storage Tank (IRWST) are passively opened (*via* thermal destruction of steel cables by the arrival of the melt) and the gravity driven flooding of the cooling channels is initiated. After filling of the cooling channels, the water will spill over and is poured on top of the melt. In the long term the melt is surrounded by water and stabilized. The operating staff and the crisis team are able to follow the above described phases of core progression, thanks to dedicated instrumentation (thermocouples and valve position sensors).

3. HOW DISTRIBUTED OPTICAL FIBER SENSORS MAY IMPROVE NPPS' SAFETY?

For a long time, technical reports indicate that improvements of existing and future NPPs are required, and that some of them may benefit from OFS technologies [2, 3, 4, 5]. Safety improvements concern many topics: i) nuclear shield efficiency, ii) protection against external hazards (earthquake, aircraft crash, external explosion, lightning, EMI, groundwater, weather, extreme flood, ice, as well as toxic, corrosive, and flammable products...), *iii)* protection against *internal* failure of components subject to pressure, internal flood, fire, explosion, internal projectile (missile effect), falling load... *iv)* prevention of H_2 detonation, *v)* prevention of fusion in spent fuel pools, and *vi)* instrumentation [6]. Many recommendations were then taken into account in the EPR design [7].

Several risks are still a matter of concern after Fukushima [8, 9]. Concerning NPPs safety, depending on the type of reactors and nuclear buildings, we may consider two situations: 1/ **Normal operation**: *i)* reactor building monitoring, *ii)* thermal monitoring of pipes, pools, transformers, and fire detection. 2/ **Severe Accident situation**: *i)* Detection of pressure vessel failure, corium, concrete basemat erosion , *ii)* Nuclear building monitoring, *iii)* Thermal monitoring of spent fuel pools and fire detection, i*v)* H_2 risk, *v)* Radiation monitoring; *i.e.* many of the problems encountered at Fukushima.



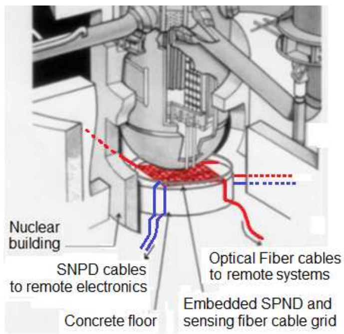


Fig. 1: *Left:* OFS applications to enhance safety. *Right:* Distributed sensing for corium monitoring.

At Fukushima Daiichi, reactors 1, 2 and 3 experienced a core meltdown. A few hours after the tsunami, temperatures inside Unit 1 vessel reached 2300˚C to 2500˚C, causing fuel assembly structures, control rods and nuclear fuel rods to melt and turn into corium which dropped down to the concrete basemat before to be cooled down by injected water. The reactor core isolation cooling system (RCIC) was successfully activated for Unit 3, but it stopped at 11 am on March 12, relayed by HPCI up to 2 am the day after, followed by the core fusion one hour later. Unit 2 has retained RCIC functions up to 1:12 pm on March 14, but nuclear fuel has melted at 7 pm, prior the corium pool spreads on concrete [10].

4. « DISTRIBUTED SENSING FOR CORIUM MONITORING AND SAFETY »

4.1 DISCOMS Consortium & Objectives

The DISCOMS project began on Jan 2014 and will end by Dec 2018. Partnership includes experts in Optical Fiber Sensing and others in the behavior of silica fibers submitted to ionizing radiations; specialists in SPND design and manufacturing; experts in modeling (dose and temperature in the reactor vicinity); others in irradiator-based components testing and in corium flow experiments (Vulcano facility), as well as some specialists coming from the NPP design and manufacturing industry to define the industrial objectives of such monitoring.

Global objectives aim to: *i)* increase the safety in existing and future NPPs, *ii)* lower the amount of radiations the workers may receive in case of accident, *iii)* inquire about the status of the third barrier of confinement and define possible mitigation strategies in case of SA, as well as environmental impact and sanitary consequences. From the instrumentation point-of-view, objectives are as follows: detect reactor vessel breach and corium pouring on concrete reactor pit basemat, monitor the Molten Core Concrete Interaction, and the corium location (up to the spreading compartment [core catcher] in the EPR), as well as the corium cooling kinetics. Thus, instrumentations, we intend to develop, will allow a strengthened follow-up of the corium evolution during a SA of various GEN 2 and GEN 3 light water reactors in the world.

4.2 Remote distributed sensing based on optical fibers

OFS Distributed sensing means technologies based on Reflectometry. They take advantages of the optical scattering phenomena in optical fibers, *i.e.* the Rayleigh, Raman and Brillouin effects.

4.2.1 Optical Time Domain Reflectometry (OTDR).

The traditional OTDR, based on the elastic Rayleigh backscattering, is widely used by operators in telecoms, since it helps to ensure the availability of the distribution networks (detection of changes in the fiber attenuation profile, location of problems for data transmission like fiber bending, breakage or bad connection). Several types of such instruments are available, mainly for long distances (up to several tens of km) and offer spatial resolution as low as 50 cm, while some provide, for a more limited spatial range, a very accurate spatial resolution (*e.g.* a few cm with the "ν-OTDR" instrument based on photon counting). In an OTDR, powerful short optical pulses are repetitively injected into the fiber core, the Rayleigh backscattering being detected from the same fiber end. The localization of any event, along the fiber, is based on the spatio-temporal duality (*e.g.* 10 ns laser pulses providing 1 m resolution). So, at the same wavelength as the laser pulses, the backscattering intensity, due to fiber core refractive index fluctuations (Rayleigh scattering) and also to Fresnel reflections associated with optical waveguide discontinuities (connectors, splices, ends), analyzed *vs* time, provides a spatial image of fiber losses, defects and discontinuities.

4.2.2 Distributed Temperature Sensor (Raman DTS).

The DTS principle is based on the Raman scattering in the fiber core analyzed by reflectometry. In Raman, we analyze the light spectrally shifted of a few tens of nm from the excitation wavelength (~ 40 nm @ 1 µm): The inelastic Raman scattering mechanism leads to generate two symmetrical lines with respect to the laser excitation at ν_0. They are respectively called Stokes ($\nu_S = \nu_0 - \nu_B$) and anti-Stokes lines ($\nu_{AS} = \nu_0 + \nu_B$), ν_B being the characteristic vibration frequency of the silica core.

Since the anti-Stokes line corresponds to an electronic transition starting from an excited energy level, its intensity I_{AS} is temperature-dependent according to the Boltzmann law. On the contrary, the Stokes signal I_S, corresponding to a transition coming from the fundamental level remains free from temperature influence. Thus, the ratio I_{AS}/I_S is only function of the temperature. Finally, any influence of the instrument transfer function drift (power, losses, detector sensitivity...) is removed by this normalization, and a selective temperature sensing may be obtained [11, 12].

4.2.3 Distributed Brillouin Optical Time Domain Analyzer & Reflectometer (BOTDA-R).

Brillouin systems are based on the inelastic interaction of the light wave propagating in the fiber core with acoustic phonons. The interest lies in the dependence of this Brillouin shift with both temperature [1 MHz /°C] and strain [50 kHz / (µm/m)] [13]. Two techniques co-exist, named BOTDR and BOTDA. The advantage of the BOTDR is that it does not require access to both fiber ends. Its drawback is the lower efficiency leading to long averaging times. The advantage of the BOTDA lies in a better signal-to-noise ratio, but the fiber must be looped on the instrument. Due to its Brillouin gain, the BOTDA provides useful signals whose intensity exceeds by 20 dB the Rayleigh backscattering (wider range; lower measurement time). Today, typical specifications of commercial instruments are: 30-50 km range (100 km recently in Labs); 1 m resolution (or even better, with a smaller range), while the Brillouin shift resolution remains ~ 1 MHz, equivalent to 1°C in temperature or 20 µm/m in strain.

4.2.4 Distributed Rayleigh Optical Frequency Domain Reflectometer (OFDR).

This approach also involves the Rayleigh backscattering, but needs a frequency analyzis to determine temperature/strain profiles (like Brillouin, it is a non-selective measurement). It is based on a homodyne interferometer scan: the laser source is modulated by frequency ramps, and its beam splited into two sub-beams, one of them being sent into the fiber under test (FUT) and the other one used to interfere with the FUT backscattered light [14]. OFDR allows fine structures monitoring, when equipped with an embedded/attached fiber, with a 1 cm spatial resolution and a sensing strain resolution of few µm/m, or 0.1°C in temperature. The acquisition time is ~ 10 s without signal processing and about 1 min including data treatment. The range is limited to 70 m, but a 2 km option (by successive windowing) has recently been proposed. So, considering its performances, we may resume the OFDR as a low speed sensing method, metrologically equivalent to a chain of 100s Fiber Bragg Gratings. Recently, a faster instrument (250 Hz) has been proposed but its range (strain, length) is limited.

4.2.5 State-of-the-art of remote OFS distributed instruments to improve NPPs' safety.

In case of severe accident, we propose to increase the NPPs' operators real-time knowledge, concerning the reactor breaching and the corium relocation outside the vessel, up to its cooling, thanks to such instruments connected to sensing cables embedded into the reactor concrete basemat and related structures. This distributed sensing 'grid' could then be remotely interrogated, even in case of total lack of electricity, as it occurred in the Fukushima-Daïchi NPP. In this way, several specific sensing parameters may be obtained thanks to:

- OTDR Reflectometry: fuse-fibers end detection to monitor the corium progression,
- Raman DTS: thermal profiles in the concrete basemat,
- Brillouin (B-OTDR or B-OTDA) and OFDR: strain / temperature profiles.

These instrumentations will be able to interrogate any embedded single-mode fiber cable, providing instrumentation redundancy. Moreover, redundancy will also benefit from several paths accessing the sensing cables, in this way securing measurements in case of partial plant destruction [*e.g*. H_2 deflagration].

The typical state-of-the art of commercial distributed sensing instruments is depicted in Table 1.

Specification	**Rayleigh OTDR**	**Raman DTS**	**Brillouin BOTDR / BOTDA**	**Rayleigh OFDR**
Spatial resolution	1 m (ν–OTDR: 1.3 cm)	1 m	50 cm (to 5 cm)	3 cm (OTDR mode: 2 mm)
Spatial Range (L)	50 km (ν–OTDR: 20 km)	30 km	30 km and more	70 m (up to 2 km by windowing)
Measur[t]. speed	10 sec. typ.	10 s to hours	2-3 s up to 10 min	10 s (L < 70 m) + post process N*10 s (N = L/70 m) + post proc.
Dynamic (budget)	50 dB (ν–OTDR: 35 dB)	20 dB typ.	10 dB (loop 20 dB)	70 dB in OTDR mode
Temp. resolution	---	+/- 0.1°C @ 2 σ (1 h averaging)	+/- 1°C @ 2 σ (min averaging)	+/- 0.1°C
Temp. uncertainty	---	+/- 1°C	>1°C (with calibration)	
Temp. range	---	- 200°C; 700°C *(vs. fiber specif.)*	700°C *(vs. fiber specif.)*	+/-175°C relative to reference
Strain resolution	---	---	+/-10 µm/m	+/- 1 µm/m
Strain uncertainty	---	---		< 10 µm/m (L < 70 m) +/- 25 µm/m (L > 70 m)
Strain range	---	---	> 2% (20 000 µm/m)	+/- 0.425 % (L < 70 m) +/- 0.13 % (L > 70 m)

Table 1: Main specifications of distributed OFS technologies.

4.3 Optical fiber behavior under ionizing radiations

Optical fibers carry signals over long distances, due to their low attenuation (~ 0.2 dB/km) consequence of the Rayleigh scattering, but it is well known that γ radiations affect their transmission. High energy neutrons may also produce radiation induced emission, and silica compaction, which may disturb the measurement signals. Nevertheless, that happens at very high neutron flux or dose levels. In our safety related project, even if optical fibers sensing cables will be embedded into reactor pit concrete basemat, and surrounding structures, the radiation induced attenuation (RIA) remains an important phenomenon to be taken into account. The behavior of fibers under irradiation, especially γ radiations, has been widely studied upon the last decades, theoretically and experimentally [15, 16].

Single Mode Fibers (SMFs) consist in a 9 µm diameter core, a 125 µm diameter optical cladding made of amorphous silica, surrounded by a protective coating made of polymer or even metal, leading to an outside fiber diameter typically ranging from 155 µm to 250 µm. Obviously, optical fiber behavior under ionizing radiation essentially concerns the fiber core, where lightwaves propagate. At first glance, highly Pure Silica Core (PSC) fibers may be used to avoid preexisting flaws (defects), as we know that ionizing radiations create absorbing defects, depending on dopant(s) added in the core to create its refractive index difference. Germanium (Ge) is the common dopant for classical SMFs but many Ge-related absorbing defects are generated under ionizing radiation. Consequently, PSC fibers remain good candidates for applications dealing with high radiation levels (then the expected index profile is generated by a decrease of cladding refractive index). Nevertheless, recent studies show that fluorine (F) doped core fibers operate even well [17, 18]. Other parameters also influence the fiber behavior under ionizing radiations: the fiber drawing process, and also its temperature, as increasing temperature enhances the defects recovery. For a given dose, the RIA depends much on the radiation dose rate.

The coating also strengthens fibers, and protects them against any kind of impurities that could diffuse down to the core. Generally, the highest temperature addresses in the application guides the coating material selection. Acrylate, the standard one, may be used below 100°C. Polyimide may be used up to approximately 350°C and metal may resist to 400°C (aluminum) or even 700°C (gold).

A first part of the project consists in selecting the best SMF according to the state-of-the-art, followed by γ irradiation testing (fibers sensing cable irradiation testing is planned later, during the course of the project). Tests will be carried out at the Applied Radiation Laboratory (LABRA), a CEA Saclay facility. NPPs' ex-core sensors are designed to withstand radiations over 60 years (*i.e.* 250 kGy with ~ 0,5 Gy/h mean dose rate) plus those corresponding to a SA (450 kGy dose in 24 hours; Standard NF M 64-001), so a total dose = 700 kGy. Figure 2 shows a typical graph of RIA *vs* gamma dose for one of the best commercially available radiation resistant SMFs.

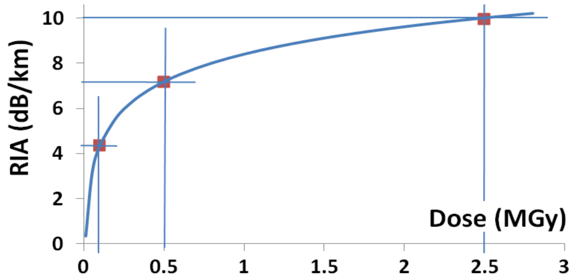


Fig. 2: RIA *versus* gamma radiation dose for one of the best radiation resistant single mode fibers.

If we assume that radiation dose is attenuated by 80 % / dm of concrete thickness [16], and that the γ dose at the concrete basemat surface reaches 2 MGy, the RIA decreases from ~ 10 dB to 7 dB when the fiber is embedded at 1 dm depth into concrete, while ~ 4 dB when embedded at 2 dm. Thus, embedding fibers into concrete greatly reduces their radiation hardening specifications.

4.4 Long length Self Powered Neutron Detectors (SPNDs)

SPNDs have been efficiently used as in-core flux monitors for over three decades in nuclear power reactors worldwide. In SPNDs, interactions of neutrons and atomic nuclei are used to produce a current which is proportional to the neutron fluence rate (flux). Compared to other in-core detectors, they feature some advantages: *i)* no need of power supply, *ii)* simple and robust structure, *iii)* good stability under temperature and pressure conditions, and *iv)* generation of a linear signal [19]. There are two types of SPND respectively with a prompt, or a delayed, response. Technically speaking, their response time depends on the half-life of formed isotopes and may vary from a few seconds, up to several minutes. Depending on the emitter material, we may enhance the detection of gamma rays or neutrons. Neutron sensitivity of mostly used conventional SPNDs ranges from 10^{-23} to 10^{-21} A/n.cm^{-2}.s^{-1} per cm of emitter length. In case of a SA, parameters for corium tracking and monitoring may be listed as follows: *i)* SPNDs location in reactor pit *ii)* neutron flux decreasing from the SA initiation until the core meltdown, *iii)* gamma flux increasing with the corium arrival on the concrete basemat, and *iv)* temperature evolution. These parameters constitute the set of input data to model and design SPNDs.

Another challenge is related to the reading and the interpretation of information delivered by such SPNDs: their low sensitivity requires the development of robust and reliable electronic able to acquire very low currents with low energy consumption. These electronics will have to be installed remotely, *e.g.* in the save bunker used by operators in case of a SA. So, a direct wired connection, without discontinuity, is needed between the SPNDs and this bunker, over a length beyond 200 m.

Thus, such electronics connected to dual sensing based on thermocouples and SPND, integrated into a single coaxial structure, will allow to obtain online characterization of corium and to monitor its progression rate as well as the core-catcher cooling kinetics.

4.5 Main sensor locations for corium monitoring

The main sensor locations proposed are essential for the doses and temperature levels OFSs and SPNDs will have to sustain. The main objective for both technologies is the corium follow-up and evolution in the ex-vessel stage during a SA.

For GEN 2 reactors, distributed sensors could be implemented below the reactor pressure vessel: close to the surface[1] of the reactor building concrete basemat and, if technically feasible, embedded into the concrete. They will enable real-time monitoring of the corium stabilization in the basemat, *i.e.* one of the major objectives of the SA management. While for the EPR and ATMEA1 GEN 3 reactors, which are equipped with a core melt stabilization system (CMSS), sensors could be deployed at several locations, including (Fig. 3):

- Near to the concrete surface[1] and beneath the sacrificial layer (~ 50 cm) of the reactor pit, to monitor the MCCI evolution in the temporary retention phase, (Fig. 3; Positions 1 and 2),
- Underneath the zirconia protective layer of the transfer channel between the reactor pit and the core catcher itself, to detect eventual damage of this layer (failure of CMSS), (Position 3),
- Close to the surface[1] and beneath the core catcher sacrificial layer (~ 10 cm), to monitor the MCCI during the first stage (first hours) of core melt final retention phase, (Position 5a),
- Below the core-catcher horizontal cooling elements, to detect an eventual cooling structure damage on the whole surface (> 100 m^2), due to the lack of water cooling, (Positions 5c),
- Inside the basemat structural concrete itself (above and below the containment metallic liner), to detect unexpected extension of MCCI (failure of CMSS), (Position 6),
- At mid-high of the reactor, close to the pressure vessel, to monitor the reactor activity in normal operation, as well as to detected a vessel breakthrough in case of SA, (Position 7).

An extra role of the instrumentation is to provide information concerning the corium evolution inside the vessel (formation of corium pool, relocation of corium to the RPV lower head, RPV lower head failure). This objective could be fulfilled by using gamma SPNDs implemented in the reactor pit, as classical neutron SPNDs will not be efficient enough due to a very low neutron population during a SA. In the same way, distributed OFSs located outside the RPV will not be eligible here, as they may detect temperature, strain and rupture, but not radiations. The proposal of sensor locations presented above both for GEN 2 and EPR / ATMEA1 type GEN 3 reactors are of high level. Our goal consists to assess the feasibility of such instrumentations. For the other GEN 3 designs, location may be re-analyzed and adapted. In case of applications of DISCOMS-based instrumentation, to GEN 2 or GEN 3 reactors, sensors' locations will be defined in more details, case-by-case.

[1] Any sensor directly implemented on the concrete surface will be instantaneously destroyed by the hot corium as soon as it is released from the Reactor Pressure Vessel (and, for the EPR reactor, from the reactor pit at the melt plug opening). It is thus suggested to position the distributed sensors beneath a thin concrete layer to estimate the first effects of the MCCI.

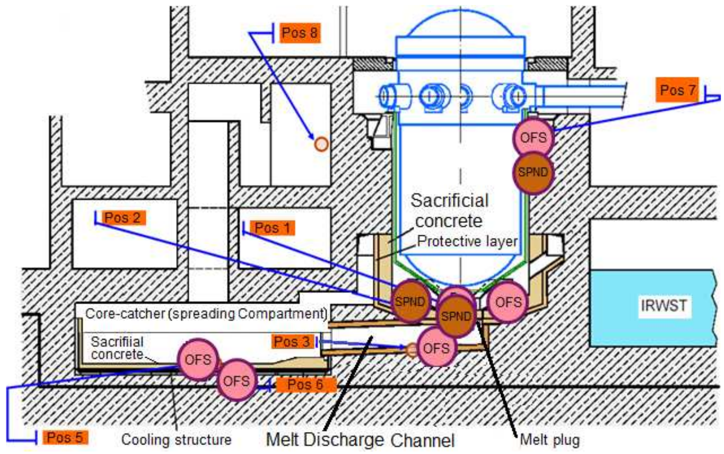


Fig. 3: Typical OFS & SPND distributed sensing-based corium detection locations (EPR reactor).

4.6 Thermal modelling within the reactor concrete basemat

In order to estimate the environmental conditions the OFS and the SPND will have to sustain, thermal fields in the reactor pit concrete have been estimated by using the TOLBIAC-ICB Molten Core Concrete Interaction software [20]. Series of calculations have been performed for various SA scenarios. Left-side of Figure 4 presents the evolution of the concrete ablation on a typical reactor pit (the concrete wall has been artificially enlarged for an easier visualization). Due to the low thermal conductivity of concrete, even in the presence of concrete reinforcement rebars, ablation front progresses more rapidly than the conduction heat wave (Fig 4, right side). Therefore, the thermograms observed during MCCI experiments [21] can be used to specify the DISCOMS' sensors. Moreover, the relatively slow progression of the heat will provide a sufficient time period for signal validation before the corium front reaches and destroys the sensors.

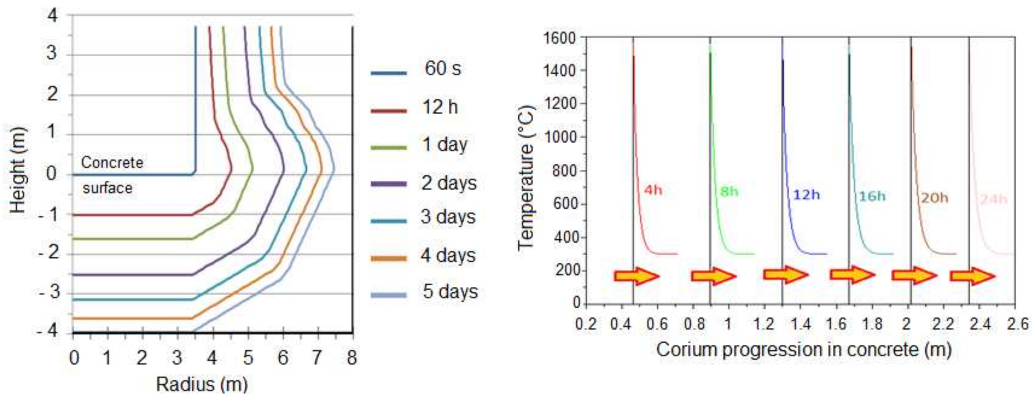


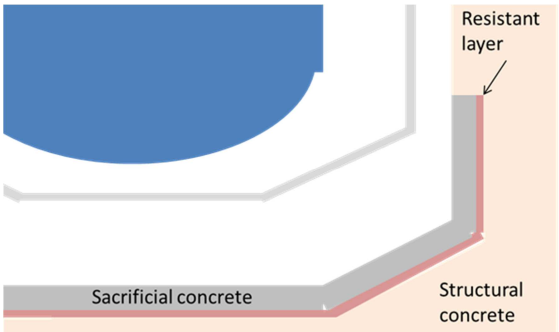
Fig. 4: Typical results of MCCI calculations: Ablation fronts (*left*) & Temp. profiles (*right*) *vs* time.

4.7 Radiation modelling within the reactor concrete basemat

Since optical fiber sensing cables need to be resistant to radiations, during the normal operating conditions (scenario 1) and also during a SA (scenario 2), doses and dose rates were assessed close to corium locations during a SA. These quantities are essential to specificy and operate OFSs.

For such calculations (evaluation of fission source distributions in the core and deep penetration simulations inside the basemat), the standard MCNP US code has been used. Essential inputs and data for such calculations are isotopic composition of the reactor materials (fuel and structures) as precise as possible, history of irradiation and decay during normal operation and corium composition to define source terms when considering a SA.

Probabilistic simulations techniques implemented in codes such as MCNP are currently used to solve problems in three major areas: criticality, reactor neutronics, and radiation shielding. Although the same probabilistic simulation method, known as "Monte Carlo method" (MC), is used in all these three areas, the mathematical algorithms used to track particles differ. Radiation shielding or dosimetry simulations (such as performed here) are "fixed-source" simulations: the spatial distribution of emitted particles is supposed to be known and fixed at the beginning of the simulation (induced or spontaneous fissions or γ radioactive sources have been used). The coupling between neutron and gamma transport can also be taken into account, as it plays an essential role for the simulation of normal condition. Moreover, such simulations require the use of massive variance reduction techniques (VRT) due to the large absorption in structures and the consequent large flux drops (more than 6 orders of magnitude considering the flux).



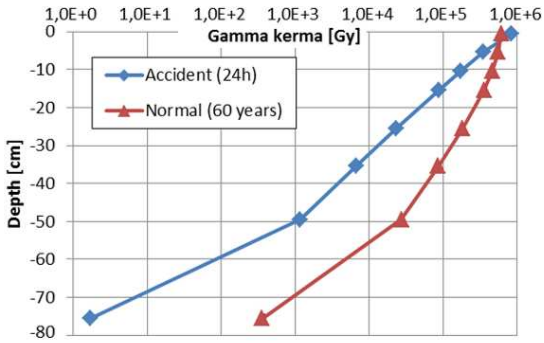


Fig. 5: *Left*: Schematic view of the geometry outside the reactor vessel bottom. *Right:* Example of γ kerma *vs* depth in the basemat. Results used to define the OFS specifications for scenarios 1 and 2.

Same kind of evaluations have been also performed to provide information to the SPNDs' manufacturers, who use them not for ensuring the resistance to radiation damages but for determining the dimensions of their detectors to receive the best possible signal. As for scenario 1, configurations with corium as source term (scenario 2) have been also provided and have given the best possible locations for those detectors, in order to ensure their availability during an accident occurring after 60 years of reactor's operation in normal conditions.

4.8 VULCANO: the final testing

When the sensors will be fully developed and tested, a final validation test will consist in submitting them to prototypic corium (mixture simulating corium with an actual chemical composition of corium but with natural or depleted isotopic composition). This validation experiment will be conducted in the VULCANO facility [21] (Fig. 6). The prototypic oxidic corium is molten in a rotating plasma-arc furnace, while steel is molten and superheated in 3 '1-liter induction furnaces'. Oxide and metal phases are then poured in a concrete test section. Radiological decay heat is simulated by induction heating during several hours of interaction.

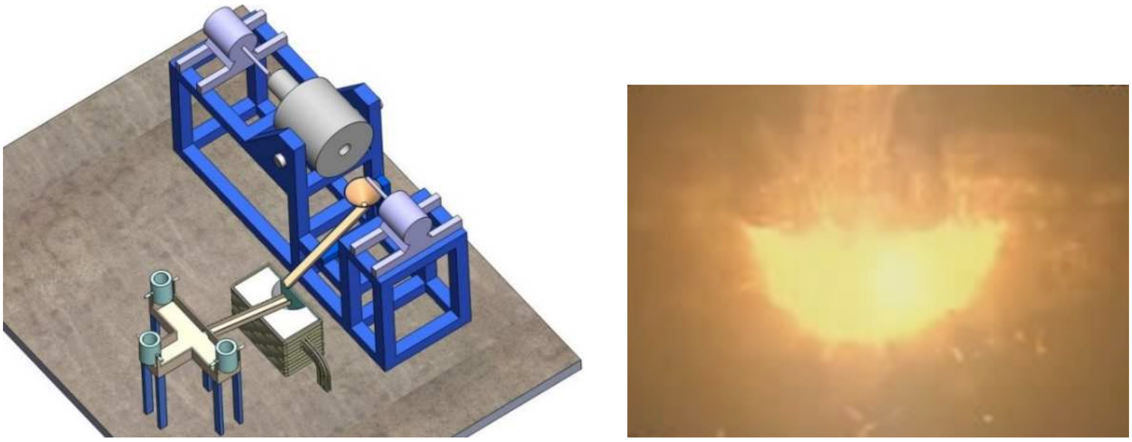


Fig. 6: The VULCANO Facility. *Left*: scheme - *Right*: Photograph of corium in half cylindrical concrete test section.

In the DISCOMS final test, both instrumentations and sensors (OFS cables + SPNDs) will be embedded into a test section of concrete basemat at previously selected depths. Corium will be poured to ablate the concrete (MCCI) until sensors locations are covered by the hot melt. Sensor survival and measurement points will be monitored by remote instrumentations throughout this test.

CONCLUSION & PERSPECTIVES

After the Fukushima nuclear disaster, in France, a national program called RSNR has been implemented to improve the safety of existing and future NPPs. As the Fukushima accident showed, instrumentation able to perform sensing, remotely and without local power supply, is a key issue.

In such context, the DISCOMS project deals with SPNDs and OFSs, based on fibers selected for their resistance to ionizing radiations, able to improve instrumentation availability to monitor the nuclear installations in case of severe accident, including corium melting and relocation, where high temperatures and strong radiation levels take place. The OFS ability to provide unrivaled capabilities, as distributed sensing for temperature, strain… is now an industrial reality. Such capabilities, coupled to many other intrinsic advantages, confirm OFSs and SPNDs as very promising solutions for extremely harsh-environment applications, like NPP safety, where data integrity is clearly paramount.

Thus, for safety concerns, benefits of such monitoring will guaranty: the data availability in nominal, accidental and post-accidental situations while complete loss of power supply occurs; the possibility of remote measurements to protect operators, up to several kilometers if required; the redundancy (multiple fibers and cables connected from different paths) and the diversification (no common failure mode with other sensing technologies).

ACKOWLEDGEMENTS

This project is co-funded by the French *Programme d'Investissements d'Avenir* and managed by the ANR (*National Research Agency*). Our special thanks go to A. Lebeau for his encouragements during the preparation of the DISCOMS proposal, and also his help over the course of the project.

REFERENCES

1. P. Ferdinand, *"The evolution of Optical Fiber Sensors Technologies during the 35 last years and their applications in Structural Health Monitoring"*, 7th EWSHM, 8-11 July 2014, Nantes, France
2. P. Ferdinand, Y. Denayrolles *et al.*, *The potential for distributed sensors and optical fiber sensors network in the electric power industry*, Meas. Sci. Technol., Vol.1, n°9, pp.908-916, Sept. 1990.
3. P. Ferdinand and S. Magne, *Applications of optical fiber sensors for nuclear power industry*, in Handbook on Optical Fiber Sensing Technology – Principle and Applications, Ch. 6, Edited by J.M. Lopez-Higuera, ISBN 0 471 82053 9, John Wiley and Sons, Ltd., 2001
4. P. Ferdinand, S. Magne, « *De l'intérêt des capteurs à fibres optiques pour le renforcement de la sureté des centrales nucléaires* », CMOI, 21-25 nov. 2011, Lille, France, *in French*
5. P. Ferdinand, S. Magne, and G. Laffont, "*Optical Fiber Sensors to improve the safety of Nuclear Power Plants*", APOS2013, 4th Asia-Pacific Optical Sensors Conf., Wuhan, China, 15-18 Oct. 2013
6. N. C. Rasmussen, *et al.*, "Reactor safety study. An assessment of accident risks in U. S. commercial NPPs," *Tech. report n°WASH-1400 (Nuclear Regulatory Com. NUREG-75/014)*, Oct. 1975 www.osti.gov/energycitations/product.biblio.jsp?query_id=6&page=0&osti_id=7134131
7. Anonymous, "EPR, Europ. Pres. Water Reactor", *Rapport Préliminaire de Sûreté Flamanville 3, EDF*, 2006
8. Anonymous, "Evaluations complémentaires de la sûreté des installations nucléaires prioritaires au regard de l'accident survenu à la centrale de Fukushima," Avis ASN n° 2012-AV-0139, 3 jan. 2012, *in French* www.asn.fr/index.php/Les-actions-de-l-ASN/La-reglementation/Bulletin-officiel-de-l-ASN/Avis-de-l-ASN/Avis-n-2012-AV-0139-de-l-ASN-du-3-janvier-2012
9. A. Omoto, "The accident at TEPCO's Fukushima-Daiichi Nuclear Power Station: What went wrong and what lessons are universal?" *Nuclear Instruments and Methods in Physics Research A* 731 (2013) 3-7
10. K. Campbell, Lessons from Japan's nuclear crisis, *Creamer Media's Engineering News Online*. Creamer Media (Pty) Ltd. Retrieved Nov. 4, 2011
11. A.H. Hartog and, A.P. Leach, *Distributed temperature sensing in solid-core fibers*, Elect. Lett., *21*, no 23, pp. 1061- 1062 (1985)
12. J. Dakin and D.J. Pratt, *Temperature distribution measurement using Raman ratio thermometry*. SPIE, *566*, Fiber Optic and Laser Sensor III (1985)
13. L. Thénenaz, M. Fachini, A. Fellay, P. Robert, D. Inaudi and, B. Dardel, *Monitoring of large structure using distributed Brillouin fibre sensing*, 13th International Conference on Optical Fiber Sensors (OFS-13), Kyongju, Korea, SPIE, *3746*, pp. 345-348 (1999)
14. D.K. Gifford, B.J. Soller, M.S. Wolfe and, M.E. Froggatt, *Distributed Fiber-Optic Temperature Sensing using Rayleigh Backscatter*, 31st Eur. Conf. on Optical Com. ECOC2005, 25-29 sept. 2005, Glasgow
15. S. Girard, J. Kuhnhenn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter, and C. Marcandella, "*Radiation Effects on Silica-Based Optical Fibers: Recent Advances and Future Challenges*", IEEE Trans. Nucl. Sci. 60, 2015 (2013)
16. M. Perry, P. Niewczas, and M. Johnston, "*Effects of neutron-gamma radiation on fiber Bragg grating sensors: a review*," IEEE Sensors, vol.12, no. 11, pp. 3248–3257, 2012
17. T. Wijnands, L. K. De Jonge, J. Kuhnhenn, S. K. Hoeffgen, and U. Weinand, "*Optical absorption in commercial single mode optical fibers in a high energy physics radiation field*," IEEE Trans. Nucl. Sci., vol. 55, no. 4, pp. 2216–2222, Aug. 2008
18. X. Phéron, S. Girard, A. Boukenter, B. Brichard, S. Delepine-Lesoille, J. Bertrand, and Y. Ouerdane, "*High -ray dose radiation effects on the performances of Brillouin scattering based optical fiber sensors*," Opt. Exp., vol. 20, pp. 26978–26985, 2012
19. L. Vermeeren, H. Carcreff, L. Barbot, V. Clouté-Cazalaa, S. Fourrez, and L. Pichon, *Irradiation tests of prototype selfpowered gamma & neutron detectors*. ANIMMA 2011, Gent, Belgium, 6-9 June 2011
20. B. Spindler, B. Tourniaire, J.M. Seiler, *"Simulation of MCCI with the TOLBIAC-ICB code based on the phase segregation model"*, Nucl. Eng. Des., 236 (19-21), pp. 2264-2270, 2006
21. C. Journeau, P. Piluso, J.F. Haquet, E. Boccaccio, V. Saldo, J.-M. Bonnet, S. Malaval, L. Carénini, L. Brissonneau, *"two-dimensionsional interaction of oxidic corium with concretes: The VULCANO VB test series*", Ann. Nucl. Energy, 36, pp.1597-1613, 2009.