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Long length SPNDs and Distributed Optical Fiber Sensors for Severe Accident remote monitoring and their contribution to Nuclear Safety in the post-Fukushima context

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ABSTRACT

The Fukushima-Daiichi nuclear accident of March 2011, and the subsequent loss of internal power supplies after the NPP (Nuclear Power Plant) water flooding caused by the tsunami, leaving the operator TEPCO with almost no information from the reactor pits, demonstrates that safety must always prevail. Accordingly, the French public authorities initiated the RSNR research program, to stimulate and fund new R&D projects to improve the safety of nuclear reactors in service and those of future NPPs.
The DISCOMS project (Distributed Sensing for Corium Monitoring and Safety) aimed at developing and testing innovative and passive sensors dedicated to Nuclear Safety, namely an instrumented pole equipped with long length SPNDs (Self-Powered Neutron Detectors)-Thermocouple poles, and Distributed Optical Fiber Sensors, to be installed *ex-core* in both the reactor pit and concrete floor. The

sensors, remotely operated from a safe place, will not only provide additional information during the Severe Accident, but also in post-accidental situation, even in case of loss of all power supplies.
The modelling of a 60 year normal operation followed by a Severe Accident for two generations of reactors (Gen II, Gen III) permitted to demonstrate that *ex-core* long length SPNDs can identify different scenarios: reactor shut down, Normal Operation, Severe Accident without corium relocation, and Severe Accident with corium pouring on the concrete floor.
Long length SPNDs were designed and manufactured, along with their electronics, to measure low currents ranging from 1 pA to 100 nA collected under radiations, and qualified in a research reactor with fluxes compliant with modelled scenarios.
Optical Fibers Sensor cables are devoted to monitor the Molten Core – Concrete Interaction (MCCI): temperature and strain profiles can be provided in the concrete depth by embedded cables, as a result of using the Raman DTS, Brillouin and Rayleigh OFDR reflectometry techniques, based on the analysis of the backscattered light in single-mode optical fibers, for distributed measurements potentially up to 1000°C with Brillouin instrumentations. Additionally, such sensor cables can be used as fuses with telecom or photon counting OTDRs to detect corium vicinity.
Sensor cables and radiation resistant optical fibers have been selected and tested to comply with the radiation conditions in the reactor pits as depicted by the modelling.
A final MCCI experiment with prototypical corium, performed at the VULCANO CEA facility, involving also two instrumented SPNDs-Thermocouple poles, has demonstrated the ability of both kinds of sensors and corresponding instrumentations to deliver useful information about the corium status and its progression through the concrete.

KEYWORDS: Severe Accident, remote monitoring, long length SPNDs, Distributed Optical Fiber Sensors, MCCI

1. INTRODUCTION

In March 2011, a tsunami with waves exceeding 30 m in some places hit the Japan North-East coast. The subsequent water submersion of the Fukushima NPP led to the loss of the external power supplies and the internal means of cooling the 4 nuclear reactor cores, thus leading to a severe nuclear accident ranked at level 7 on the INES scale.

The aims of the DISCOMS project [1], involving public R&D, SMEs and a major actor from the nuclear industry, were to develop and test new instrumentations based on innovative passive sensors (free of any local electrical power supply) which could be remotely operated from a safe place in order to provide useful and real-time information during the first 24 hours of the Severe Accident, and also for corium long term monitoring once relocated in the EPR core catcher.

2. THE POST-FUKUSHIMA CONTEXT

The lack of essential information coming from the reactor pits after the loss of internal power supplies prevented the operator TEPCO to apply the most appropriate mitigation strategies, hence demonstrates that safety must always prevail, and the worst anticipated.

In the framework of the French RSNR research program dedicated to fund and stimulate new R&D projects in nuclear safety, DISCOMS is one answer to provide new instrumentation means to improve nuclear safety of reactors in service as well as future reactors.

The solutions put forward rely on *i)* long length SPNDs (up to 6 m long) located *ex-core* in the reactor pit to detect the onset of the Severe Accident, the reactor vessel breakthrough and the corium pouring on the floor, and *ii)* distributed Optical Fiber Sensor cables embedded at several depths in the concrete floor to detect the corium progression through it during the MCCI.

The additional information provided by these sensors during the first 24 hours of the Severe Accident are meant to help the crisis team to apply *on time* the best mitigation strategies, even in case of total loss of local electrical power supplies (Fukushima-Daiichi scenario).

2.1 Radiation levels in the reactor pit

Both SPNDs and Optical Fiber Sensor (OFS) cables were designed to be still operational after 60 years of normal operation followed by a Severe Accident thanks to modelling for both Gen II (French fleet) and Gen III (EPR) nuclear reactors [2, 3].

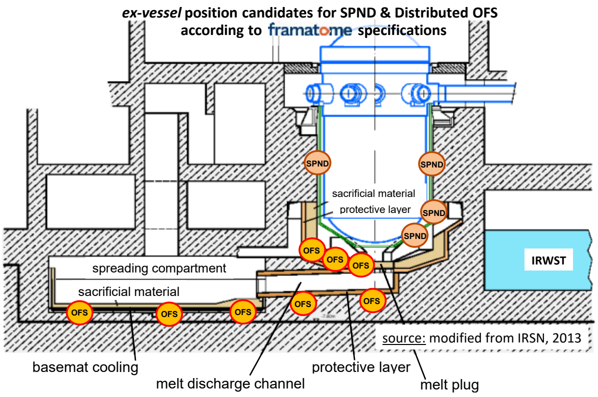

Figure 1 – SPNDs-TC & OFS cables *ex-vessel* position candidates for Severe Accident monitoring (*e.g.*: EPR)

Depending on the scenario, the nuclear reactor type and the sensors position in the reactor pit (Fig. 1), modellings show that neutrons fluxes range from $2x10^8$ $n.cm^{-2}.s^{-1}$ up to $4x10^{10}$ $n.cm^{-2}.s^{-1}$, while gamma fluxes range over ~5 decades, from $6x10^7$ $\gamma.cm^{-2}.s^{-1}$ in normal operation up to $7x10^{12}$ $\gamma.cm^{-2}.s^{-1}$ during the Severe Accident (Table I).

TABLE I [2, 3]

NEUTRON & ɣ FLUXES IN THE REACTOR PIT

scenario	location	fluxes		
corium poured in the reactor pit	reactor pit surface	Gen 2:	$7x10^{12}$	$\gamma.cm^{-2}.s^{-1}$
		Gen 3:	$6x10^{12}$	$\gamma.cm^{-2}.s^{-1}$
normal operation	vessel side	Gen 2:	$2x10^{10}$	$\gamma.cm^{-2}.s^{-1}$
			$4x10^{10}$	$n.cm^{-2}.s^{-1}$
		Gen 3:	$5x10^{9}$	$\gamma.cm^{-2}.s^{-1}$
			$1x10^{10}$	$n.cm^{-2}.s^{-1}$
	reactor pit surface	Gen 2:	$5x10^{8}$	$\gamma.cm^{-2}.s^{-1}$
			$2x10^{9}$	$n.cm^{-2}.s^{-1}$
		Gen 3:	$6x10^{7}$	$\gamma.cm^{-2}.s^{-1}$
			$2x10^{8}$	$n.cm^{-2}.s^{-1}$

The study also shows that the most damaging parameter for the Optical Fiber Sensor cables is the 60 years of normal operation period compared with the first 24 hours of the Severe Accident. But fast neutrons (E > 1 MeV) fluence can be reduced by a factor of 100 under 50 cm of concrete, and for the kerma ɣ in silica, up to a factor of 25 for Gen III, underlying the concrete floor prominent role to protect the sensor cables from ionizing radiations (Table II).

TABLE II [2, 3]

FAST NEUTRONS FLUENCE & KERMA ɣ IN CONCRETE

location	60 years Normal Operation	24 h Sev. Acc^{nt}
floor	Gen 2: $2x10^{16}$ n/cm^2 – 4 MGy	Gen 2: 1.7 MGy
	Gen 3: $2x10^{14}$ n/cm^2 – 0.5 MGy	Gen 3: 1.6 MGy
-50 cm	Gen 2: $2x10^{14}$ n/cm^2 – 0.7 MGy	Gen 2: 2.6 kGy
	Gen 3: $1x10^{12}$ n/cm^2 – 0.02 MGy	Gen 3: 2.2 kGy
-100 cm	Gen 2: $2x10^{12}$ n/cm^2 – 0.01 MGy	Gen 2: 5.6 Gy
	Gen 3: $2x10^{10}$ n/cm^2 – 0.0003 MGy	Gen 3: 3.2 Gy

Based on these specifications, several SPNDs embedded in a single instrumented pole, also including a K-thermocouple, were designed by Thermocoax SAS in order to detect from *ex-core* measurements different scenarios (reactor shutdown, normal operation, Severe Accident with corium in vessel, and corium pouring on the floor after vessel breakthrough), with a lower limit in terms of current detection set to 1 pA.

Also, the maximum RIA (Radiation Induced Attenuation) for the optical fibers was set to 50 dB/km @ 1550 nm, since the maximum length per sensor cable expected to be embedded in the concrete floor would typically not exceed 100 m.

2.2 Instrumentations design consequences

Currents generated under radiations by each SPND have been computed with the CEA MATiSSe toolbox [4] from neutron and gamma energy spectra in normal and accidental situations [2, 3]. Simulations results have then been used to size SPNDs length, and design a dedicated amplification device for SPNDs current measurements over 5 decades without bias or saturation [5] (Fig. 2).

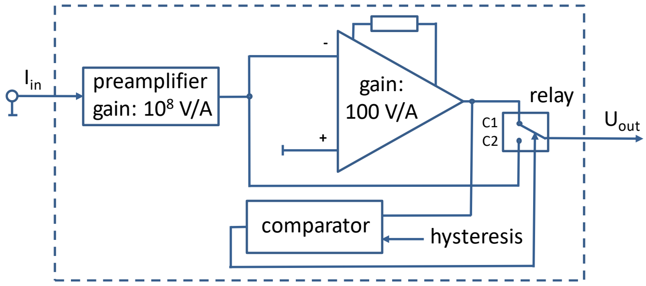

Figure 2 – Low currents & wide range [1 pA, 100 nA] amplification device for SPND current measurements

On their side, several radiation resistant commercial optical fibers were selected and tested, standalone as well as embedded in sensor cables, in the CEA POSÉÏDON gamma irradiator, demonstrating the need to protect the optical fibers core from diffusion of H_2 (generated under radiations by cable polymer compounds) to avoid uncontrolled RIA increases [6].

3. SPND-TC INSTRUMENTED POLE

SPNDs are widely used in nuclear reactors since 1960s as *in-core* neutrons fluxes monitoring devices. They were considered in the frame of the DISCOMS project as part of an *ex-core* innovative instrumentation to improve nuclear safety in case of Severe Accident.

3.1 Instrumented pole structure

The innovative instrumented pole includes one Rhodium (Rh) SPND for thermal neutrons fluxes measurement. Its slow response but high sensitivity is adequate for normal operation monitoring. A second Platinum (Pt) SPND is adapted to mixed neutrons / gamma measurement. Its prompt response dedicates it to normal and accidental situations. A K-thermocouple (TC) gives the temperature information to detect corium vicinity, and a background cable is used to subtract the noise generated by radiations on other cables (Fig. 3).

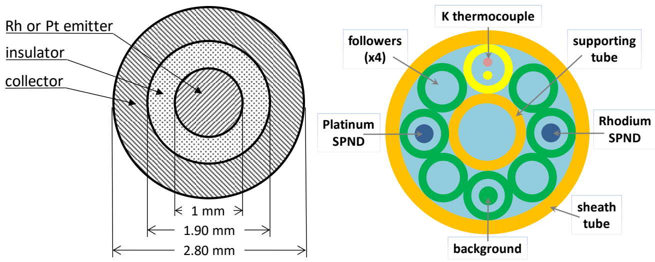

Figure 3 – Left: SPND structure with Rh or Pt emitter – Right: instrumented SPNDs-TC pole structure

3.2 Manufacturing and tests

One 6 m long instrumented pole was manufactured by Thermocoax SAS. In parallel, a dedicated trans-impedance amplifier device was manufactured by the CEA, then validated by laboratory tests on standard Rh and Co SPNDs with gamma (^{60}Co source projector) and neutrons radiations (CEA SAPHIR LINAC accelerator).

Last, a measurement campaign in a research reactor (TRIGA Mark II) permitted, by comparison with simulations [2, 3, 4] and adjustment of the reactor power for several locations of the 6 m long instrumented pole in the reactor pit, to conclude that such instrumentation can detect the onset of the Severe Accident as well as the corium relocation on the concrete floor, without any saturation of the associated current monitoring device.

4. OPTICAL FIBERS SENSOR CABLES

Optical sensor cables are passive distributed sensors dedicated in this project to detect the corium once poured on the floor, and monitor its progression through the concrete until this last containment barrier breakthrough.

4.1 Distributed sensing and reflectometry

Associated with 5 complementary sensing techniques based on the analysis of the backscattered light in optical fibers, such sensor cables can provide temperature *profiles* (Raman DTS), non-dissociated temperature and strain *profiles* (Rayleigh ODFR, Brillouin B-OFDA) and position of local defects (telecom and photon counting OTDRs) from several km away for some techniques.

4.2 Optical fibers qualification

Selected radiation resistant optical fibers were tested with 100 m long samples in CEA gamma irradiator, up to 6 kGy/h dose rate & 1.9 MGy cumulated dose, with 80°C temperature influence for some of them [6].

The optical fibers with an RIA lower than 5 dB at both 1310 nm & 1550 nm (compatible with reflectometers optical budgets) were then selected for cabling.

4.3 OFS cables qualification

Temperature, strain, and fuse cables were all three selected from the market thanks to a call for tenders. Some of them were equipped with the same single-mode radiation resistant optical fibers previously selected by means of dedicated tests in gamma irradiator [6].

These tests have also demonstrated that molecular hydrogen H_2 generated under radiations by the cable polymer compounds can migrate towards the optical fiber core, and be responsible for additional RIA: one solution qualified in a research reactor is the carbon coating acting as a barrier against H_2 diffusion [6].

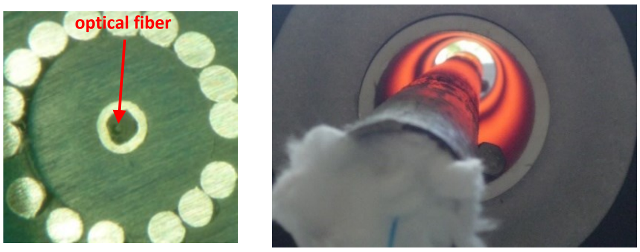

Figure 4 – Left: strain sensor cable section – Right: sustainability to temperature qualification test

Sensor cables were also tested in temperature, and strain sensor cables in elongation up to 0.2% strain. Tests in oven (Fig. 4) demonstrated the high temperature sensitivity of the strain sensor cable, thus well suited for earlier corium vicinity distributed detection once embedded in the concrete floor [7].

5. FINAL VULCANO EXPERIMENT

The final experiment was performed at PLINIUS facility at the CEA Cadarache, with a dedicated small scale test with 50 kg of prototypical corium [8]. The concrete crucible was equipped with 5 OFS cables (~180 m total length) and 2 SPND-TC short length poles (Fig. 5).

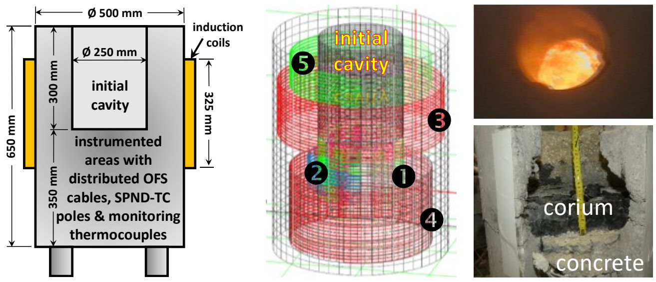

Figure 5 – VULCANO concrete crucible with OFS cables arrangement and thermite ignition

Temperature profiles provided up to 580°C by the OFS cables, and up to 1200°C by the thermocouples integrated into the SPND-TC poles, were compliant with the hundred or so TC measurements used to control the VULCANO experiment, with temperature gradients close to 200°C/cm in concrete depth [7, 8] (figure 6).

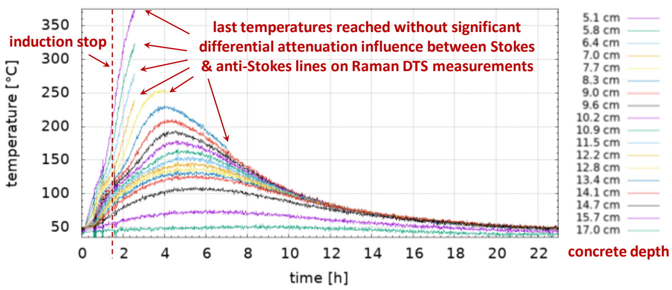

Figure 6 – OFS cables temperature *vs.* time during VULCANO experiment (Raman DTS reflectometry)

6. CONCLUSION

Long length SPNDs and distributed OFS cables have demonstrated their ability to provide complementary information about the Severe Accident status from *ex-core* measurements in the reactor pit: the onset of the Severe Accident, the corium relocation on the concrete floor and its progression through the concrete floor until the breakthrough of this last containment barrier. Each of these sensors can be operated from a remote and safe place, even in case of all local power supplies breakdown, in order to apply on time the most appropriate mitigation strategies, thereby improving overall nuclear safety.

TABLE III

LIST OF ACRONYMS

B-OFDA	Brillouin - Optical Frequency Domain Analyser
DTS	Distributed Temperature Sensor
EPR	Evolutionary Power Reactor
INES	International Nuclear and Radiological Event Scale
kerma	kinetic energy released per unit mass
LINAC	Linear Accelerator
MCCI	Molten Core – Concrete Interaction
NPP	Nuclear Power Plant
OFDR	Optical Frequency Domain Reflectometer
OFS	Optical Fiber Sensor
OTDR	Optical Time Domain Reflectometer
RIA	Radiation Induced Attenuation
RSNR	Recherche en Sûreté Nucléaire et Radioprotection
SME	Small & Medium Enterprise
SPND	Self-Powered Neutron Detector
TC	Thermocouple
TEPCO	Tokyo Electric Power Company

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REFERENCES

[1] P. Ferdinand *et al.*, "DISCOMS: DIstributed Sensing for COrium Monitoring and Safety", CANSMART 2015, 15-17 Jul. 2015, Vancouver, Canada, https://hal.archives-ouvertes.fr/cea-02151741.

[2] M. Brovchenko, B. Dechenaux, K.W. Burn, P. Console Camprini, I. Duhamel and A. Peron, "Neutron-Gamma Flux and Dose Calculations in a Pressurized Water Reactor (PWR)", *EPJ Web Conf.*, vol. 153, Art. no. 05008 (2017), doi: 10.1051/epjconf/201715305008.

[3] M. Brovchenko, I. Duhamel and B. Dechenaux, "Neutron-gamma flux and dose calculations for feasibility study of DISCOMS instrumentation in case of severe accident in a GEN 3 reactor", *EPJ Web Conf.*, vol. 153, Art. no. 07030 (2017), doi: 10.1051/epjconf/201715307030.

[4] L. Barbot, J.-F. Villard, S. Fourrez, L. Pichon and H. Makil, "The Self-Powered Detector Simulation 'MATiSSe' Toolbox applied to SPNDs for severe accident monitoring in PWRs", *EPJ Web Conf.*, vol. 170, Art. no. 08001 (2018), doi: 10.1051/epjconf/201817008001.

[5] H. Hamrita, J.-M. Bourbotte, V. Kondrasovs and H. Makil, "Electronic amplification device, measurement apparatus and associated measurement method", patent no. WO2018/046830.

[6] G. Cheymol *et al.*, "Irradiation Tests of Optical Fibers and Cables Devoted to Corium Monitoring in Case of a Severe Accident in a Nuclear Power Plant", *IEEE Transactions on Nuclear Science*, vol. 67, no. 4 (2020), pp. 669-678, doi: 10.1109/TNS.2020.2978795.

[7] L. Maurin *et al.*, "Remote monitoring of MCCI experiment with Optical Fibre Sensors and perspectives to improve nuclear safety – DISCOMS project", *EPJ Web Conf.*, vol. 225, Art. no. 08004 (2020), doi: 10.1051/epjconf/202022508004.

[8] C. Journeau, V. Bouyer, A. Denoix, J.-F. Haquet, A. Boulin, Q. Souquet, L. Maurin, G. Jouvin and H. Makil, "Temperature ramps for severe accident instrumentation in nuclear reactor cavity concrete", SAMMI-2020, 7-10 Dec. 2020, Fukushima, Japan.