Distributed corium monitoring in case of severe accident in a Nuclear Power Plant

Pierre Ferdinand, Frédéric Pouillé, B. Ricque, O. Meziani, Jean-Michel Bourbotte, Hassen Hamrita, Vladimir Kondrasovs, Hamid Makil, Laurent Maurin, Stéphane Rougeault, et al.

Distributed corium monitoring in case of severe accident in a Nuclear Power Plant

P. Ferdinand[1], F. Pouillé[1], B. Ricque[1], O. Meziani[1], J.-M. Bourbotte[2], H. Hamrita[2], V. Kondrasovs[2], H. Makil[2], L. Maurin[2], S. Rougeault[2], G. Cheymol[3], F. Damian[3], D. Duval[3], J-C. Jaboulay[3], P. Le Tutour[3], H. Maskrot[3], L. Barbot[4], J.-F. Haquet[4], C. Journeau[4], Q. Souquet[4], J.-F. Villard[4], G. Musoyan[5], M. Brovchenko[6], I. Duhamel[6], S. Fourrez[7], G. Helleux[7], L. Pichon[7], et Y. Ouerdane[8]

[1]LMP S.A. 49-51 rue du Moulin des Prés, F-75013 Paris, France. p-ferdinand-lmpsa@sfr.fr
[2]CEA, LIST, F-91191 Gif-sur-Yvette, France. [3]CEA, DEN, F-91191 Gif-sur-Yvette, France.
[4]CEA, DEN, F-13108 St Paul-lez-Durance, France.
[5]Framatome, 1 place Jean Millier, F-92084 Paris-La Défense cedex, France.
[6]Institut de Radioprotection et de Sûreté Nucléaire (IRSN), F-92262 Fontenay-aux-Roses, France.
[7]THERMOCOAX BP 26, Lieu-dit Planquivon, F-61430 Athis-de-l'Orne, France.
[8]Univ Lyon, UJM-CNRS-IOGS, Laboratoire Hubert Curien UMR 5516, F-42100 St Etienne, France.

Abstract

This project addresses the development of a remote monitoring solution, able to improve the Nuclear Power Plants safety, and strengthen the third containment barrier, in case of severe accident with reactor breakthrough and corium casting. To overcome any consequence of electrical power supplies loss, distributed sensing technologies are considered. Carefully characterized and selected, rad hard single mode optical fibers have been inserted into cables, with the aim to be embedded in the concrete floor below the reactor vessel, at depths determined by modelling, to resist high temperatures and ionizing radiations. Complementary, Self Powered Nuclear Detectors have been developed to identify the reactor core fusion when deployed in the vicinity of the reactor vessel. Optical sensors are interrogated by Raman, Brillouin and/or Rayleigh-based instrumentations, along with SPND by an innovative multichannel ultra-low current threshold detection system. In case of serious accident, such dual monitoring system will be able to detect the reactor breakthrough, the corium casting, the erosion phase of the concrete floor and the corium cooling.

Introduction

In March 11, 2011, an earthquake ranked 8 on the Richter scale, occurred on the East coast of Japan. The ensuing tsunami devastated the Tohoku region, causing widespread destruction of infrastructures and untold suffering for the population [1]. Such disaster also caused major damages on the Fukushima Dai-ichi Nuclear Power Plant (NPP), which led to a core meltdown in three nuclear reactors, followed by nuclear vessels break and corium pouring on their concrete basement. Large amounts of radioactive materials were released into the environment. The accident was rated Level 7 on the International Nuclear Event Scale. This nuclear catastrophe showed to the world that the need for safety must always prevail. Few months after, the French Government published a research call, with 50 M€ allocated to stimulate R&D in the field of nuclear safety and radiation protection. 23 projects were selected and are now operated by the French National Research Agency (ANR).

In this context, 12 French teams built a 5-year research project called DISCOMS (DIstributed Sensors for Corium Monitoring & Safety) bringing together a multidisciplinary community of researchers and engineers. DISCOMS aims at developing an innovative under-vessel remote monitoring instrumentation to improve NPPs safety in operation (Pressurized Water Reactors, Gen2), under construction (European Pressurized Water Reactor, *i.e.* the Evolutionary PWR design, Gen3), as well as for any next generations of reactors. At Fukushima, the loss of electricity power supplies has quickly led most of the instrumentation to be inoperative and the operator TEPCO with no suitable solution to monitor the accident status and evolution. In order to overcome these drawbacks, taking advantage of the considerable potential of distributed sensing technologies based on both "OFS" (Raman, Brillouin, and Rayleigh Reflectometry) and long-length "Self Powered Neutron Detectors" (SPNDs) is considered. The aim consists in inquiring the status of the 3rd confinement barrier and defining possible mitigation strategies in case of severe accident, namely: *i)* reactor pressure vessel breakthrough and corium relocation outside this vessel, *ii)* concrete floor erosion and *iii)* corium cooling. Such monitoring should consist in "sensing cables" inserted in the concrete floor, below the reactor vessel, and interrogated by operators from a remote base in a safe work environment.

1. Distributed Sensors state-of-the-art to improve NPPs' safety

It has been established for several decades that OFSs allow detection, measurement and localization of abnormal conditions. This is especially true for distributed OFSs which are able to be imbedded in structures to provide remote measurements or monitoring. To fulfil market requirements, over the last 20 years, optoelectronic distributed measurement systems have made great progress. This is the reason why, due to their performances and robustness, they are now increasingly deployed in demanding applications (oil & gas, civil engineering, fire detection, etc.). In the meantime, international R&D devoted to rad hard optical fibers has been successful, and it is now legitimate to consider their use in the vicinity of a nuclear reactor. In addition, over the last decade, we have observed industrial developments leading to the availability of sensitive optical cables dedicated to harsh environments. All these products give the possibility, to end users, to increase the safety by addressing many specific monitoring applications (*e.g.* Structure Health Monitoring) as those encountered in the NPPs [2, 3, 4, 5]. Of course, the great potential benefits of OFS technologies for the nuclear industry have been identified for a long time [6, 7]. But in this very conservative sector, for four decades, only few CFOs have been implemented. However, this situation is now evolving with the new generation of decision-makers and more open-mind engineers, especially since the Fukushima accident, as several risks remain a matter of concern for safety [8, 9, 10]. NPPs safety is depending on the type of reactors and nuclear buildings, but we always may consider three situations: *i/* Normal operation, *ii/* Severe Accident situation, and *iii)* Post-accidental situation.

2. Selected sensors for corium monitoring

Two kind of sensing technologies have been pragmatically chosen. First, we selected distributed OFSs based on reflectometry to remotely provide sensing profiles (mainly the temperature, even if measuring strain is still possible) and optical fiber lengths thanks to sensing cables (OTDR), embedded at different depths in the basemat concrete to benefit from its radiation protection. And second, we decided to use Self-Powered Neutron Detectors (SPND) already in service in nuclear reactors for on-line in-core neutron fluxes monitoring since 1960 [11]. Considering they will be deployed in the reactor core vicinity, such sensors are considered within the project for their sensitivity to both neutrons and γ. Strategically processed, SPND signals will then provide key information to the operators in any normal and severe accidental reactor conditions.

3. Ionizing radiation and thermal modellings

To design SPND and to determine the most appropriate fiber's depth of embedment in the reactor basemat, Monte Carlo simulations with MCNP [12] and TRIPOLI-4 [13] transport code, were performed to determine neutron flux energy spectra and γ doses, at various locations outside the vessel and in the basemat of a PWR. Calculations were performed for both Gen2 and Gen3 reactors considering various corium locations and compositions in case of severe accident. In order to verify that fibers will still be efficient after 60 years of operation. Calculations were also performed for normal operation conditions [14]. Depending on several parameters (concrete type, corium composition…) we consider the dose to be reduce by an order of magnitude every 15-20 cm in the concrete. Thermal modelling has also been conducted [15] and has concluded that the heat propagates at a slower speed than ablation, so that the optical cables were only heated by a few decimeters ahead of the ablation front.

4. Optical Fibers and cables testing

It is widely accepted that ionizing radiations affect silica fibers through the formation of color centers. Depending on the irradiation conditions (radiation type, dose, dose rate, temperature, or chemical/dopants composition, as well as the elaboration process of the fiber), these color centers introduce an attenuation much higher than the one encountered in the fibers currently used in telecom or in distributed sensors. And even with quite short length (100 m) considered for corium monitoring, it was necessary to assess the RIA (Radiation Induced Attenuation) and to select the less sensitive fibers to be compliant with measurement systems optical budgets, in the frame of 60 years of monitoring, followed by the accident at the NPP end of life. In that objective, two γ irradiations have been conducted on fibers, then on sensitive cables containing these fibers, in the POSEIDON irradiator based in Saclay. Various irradiation conditions have been tested, up to ~ 2 MGy at 6 kGy/h dose rate during more than 300 h. The first test permitted to assess the RIA at various wavelengths and to select 3 radiations tolerant fibers (RIA < 5 dB/100 m, at 1550 nm, the smaller RIA being ~ 1 dB/100 m for one of them). The second test was conducted on more voluminous strands of sensitive cables encapsulating the selected fibers, with approximately the same dose, at two temperatures: 30°C and 80°C. A noticeable increase of RIA ~ a factor 2 appeared in fibers when inserted into cables, correlated with the increase of the hydroxyle attenuation peak at 1380 nm. The reasons of that increase are still under investigation. Nevertheless, considering short fiber lengths (< 100 m) subjected to radiations in the reactor building, we may consider such optical cables as good candidates for future deployments.

5. Optical fiber measurement loop

The optical fiber measurement loop, including 5 different monitoring systems based on Brillouin, Raman and Rayleigh backscattering in single-mode optical fibers at 1.55 µm, is still on preparation for the ultimate "Vulcano" experiment [8] which should take place by mid-2018 to demonstrate, at a small scale, their ability *i)* to detect the corium pouring on the basemat, *ii)* to monitor the concrete floor erosion and *iii)* for long term monitoring of the corium temperature once relocated in the core catcher (EPR).

Five 'security' cables (Ø 4 mm) equipped with 2 single-mode fibers at 1.55 µm, and already qualified up to 750°C during 1.5 h according to IEC 60331-25 standards (waveguide integrity) will be embedded in the Vulcano concrete slab. Each one will be connected to a dedicated measurement system to get temperature profiles (DTS Raman), a combination of strain and temperature variations profiles (BOTD-A Brillouin; OFDR Rayleigh) and the length of the cables burnt by the corium during the concrete erosion (telecom and photon counting OTDRs). Due to its limitations, it is expected that Brillouin measurements can take over DTS Raman above 500°C up to 1000°C for temperature indications (project specifications are from 20°C up to 1300°C, with ± 50°C uncertainty). Two extra sensing cables have also been qualified, but will not be used during the Vulcano test. On one hand, the strain cables exhibit a maximum operating temperature close to 400°C, which can be explained by the thermal expansion discrepancy between their steel reinforcements and the silica fibers, leading to equivalent additional mechanical strain $\Delta\varepsilon$ applied on the fiber close to 1%, and its subsequent failure at long term. On the other hand, the temperature sensing cables diameter is too large for the concrete slab, which could have led to its anticipated mechanical embrittlement (cracks). Redundancy will be provided during the Vulcano experiment by optical fiber switches in case of cable or instrument failure. The measurement systems (synchronized with a reference clock) and the switches will be located far from the corium facility, and secured by Uninterrupted Power Supplies. Measurements will be stored in real-time on a dedicated server mirrored by a second PC located in a secured place. At this location, measurements acquired from the instrumentations will be stored in a real-time database feeding a specific Human Machine Interface software application, developed in LabVIEW®. The operator will be able to access to usual trends and, if needed, to historian SCADA functions. In such a way, optical measurements are transformed into process related variables enabling the operator to get quickly and simply an understanding of the status of the installation in front of the corium cast. This specific configuration will enable to control the measurement loop from any remote station to ensure the measurements availability, or to take appropriate decisions in case of failure during the experiment, until the end of the corium cooling.

6. Self-Powered Neutron Detectors

The SPND design has been performed using a simulation toolbox named 'MATiSSe', developed since 2010 for SPND material selection and geometry design, as well as for their respective partial neutron and γ sensitivity calculations. MATiSSe output is a direct electrical current comparable to the current generated in the SPND when irradiated, in given neutron and γ conditions. Rhodium and Platinum emitter SPNDs, encapsulated in a specific instrumented pole, have been designed using MATiSSe, and their performances calculated for different locations on the reactor vessel side, and on the reactor concrete basemat. Simulations demonstrate that SPNDs will allow to monitor the corium progression towards the concrete basemat in case of severe accident [16]. Coupled temperature measurement would also provide additional data on corium migration. Another challenge is related to the reading and the interpretation of information delivered by such sensors. Their low sensitivity has required the development of robust and reliable multi-channel electronics able to acquire very low currents (1 pA lower limit), with low energy consumption to be autonomous with regards to energy management, in case of external power supply loss. The complete monitoring equipment (instrumented pole and electronic) has been fruitfully tested in January 2018, in realistic irradiation conditions, thanks to the Slovenian TRIGA Mark II reactor (Ljubljana, JSI, pool type research reactor 250 kW). In a NPP, such remote electronics will be installed (over a length > 200 m), *e.g.* in the save bunker used by operators in case of a severe accident.

7. Sensing validation with corium casting

A general validation is planned with prototypic corium (made with depleted Uranium oxide and structural material components) in the CEA Cadarache Vulcano facility [17]. During this test, OFS sensing cables will be installed in a concrete crucible. It is planned to install up to 5 sensing cables in the 500-mm diameter concrete crucible. Liquid prototypic corium at temperatures above 2000°C will interact with the concrete and the interaction will be remotely monitored by the distributed instrumentations. Following this experimental validation, final specifications of the monitoring system will be established, and recommendations will be prepared and submitted to both French governmental authorities and to utilities.

Conclusion

The DISCOMS project and its issues, regarding current scientific challenges and potential benefits for nuclear plant safety in case of severe accident with reactor vessel failure, have been discussed. We claim such remote monitoring solution based on state-of-the-art of quasi-distributed OFS and specific long-length SPND should greatly contribute to enhance the quality of real time information during such event, providing first responders and nuclear safety people with direct data concerning both the corium location and the health of the 3rd barrier of confinement. In such context, the monitoring system developed in the scope of the DISCOMS project will enable the crisis teams in charge of handling the emergency situations on NPP to reduce the uncertainties associated to some tools currently used for severe accident mitigation (*e.g.* computations aids based on calculations of pre-defined Severe Accident scenarios). In particular, after the reactor pressure vessel failure, DISCOMS monitoring will provide the precise and real-time view of the progression front of core melt inside the reactor building basemat or the core catcher (if any). Based on this actual representation of the basemat ablation, the crisis team will be able to optimize the recommended mitigation actions, both for accident management on-site and population protection. In April 18, 2016 the International Atomic Energy Agency records 444 Nuclear Power Plants (NPPs) currently in operation and 64 under construction, located in 31 countries, which means the potential market for the DISCOMS solution is worldwide.

Acknowledgements

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

References

[1] Anonymous, report from the IRSN. http://www.irsn.fr/en/publications/thematic-safety/fukushima/Pages/overview.aspx

[2] P. Ferdinand and S. Magne, *Applications of optical fiber sensors for nuclear power industry,* in Handbook on OFS Technology – Principle & Appl., Ch. 6, Ed. by J.M. Lopez-Higuera, ISBN 0471820539, J. Wiley & Sons, Ltd., 2001

[3] K.-I. Matsuba, C. Ito, H. Kawahara, and T. Aoyama, *Development of fast Reactor Structural Integrity Monitoring Technology Using Optical Fiber Sensors*, Journal of Power and Energy Systems, pp. 545-556, Vol.2 n°2, 2008

[4] H. M. Hashemian, *EPRI Sensor Roadmap: The State-of-the-Art in Nuclear Power Plant Sensors*" EPRI, Palo Alto, CA: 2009. March 2010

[5] H. M. Hashemian and W. C. Bean, *Sensors for next generation nuclear plants: Fiber-Optic and Wireless*, 2011 Nuclear Science and Engineering, Vol. 169, pp. 262-278, 2011

[6] C. L. Carter *et al.*, *Research Planning Study of Fiber-Optic Sensors*. EPRI, Research Project 8004-1, August 1989

[7] P. Ferdinand *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

[8] Anonymous, *Évaluations 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] P. Ferdinand *et al., Optical Fiber Sensors to improve the safety of Nuclear Power Plants*, Asia Pacific Optical Sensors, APOS2013, Wuhan, China, 17th-21st Oct. 2013

[11] J. W. Hilborn, Self-powered neutron detectors for reactor flux monitoring, *Nucleonics*, vol. 22, no 2, pp 69-74, 1964

[12] X-5 Monte Carlo Team, MCNP - Version 5, Vol. I: Overview and Theory, LA-UR-03-1987 (2003)

[13] TRIPOLI-4 Project Team, TRIPOLI-4 v8 User Guide, CEA-R-6316, Feb. 13. www.oecdnea.org/tools/abstract/detail/nea-1716/

[14] M. Brovchenko *et al*., *Neutron-gamma flux and dose calculations for feasibility study of DISCOMS instrumentation in case of severe accident in a GEN 3 reactor.* EPJ Web of Conferences 153, 07030 (2017) - *ICRS-13 & RPSD-2016.* 25 Sept. 2017. https://doi.org/10.1051/epjconf/201715307030

[15] P. Ferdinand *et al*., DISCOMS: DIstributed Sensing for COrium Monitoring and Safety, CANSMART, Vancouver, BC, Canada, 15-17 July 2015

[16] L. Barbot *et al.,* "The Self-Powered Detector Simulation 'MATiSSe' Toolbox applied to SPNDs for severe accident monitoring in PWRs". ANIMMA 2017, 19-23 juin 2017, Liège, Belgique

[17] V. Bouyer *et al.*, PLINIUS Prototypic Corium Experimental Platform: Major results and Future Works, 15th Int. Mtg. Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago IL, Aug. 30-Sept. 4, 2015.