

Distributed temperature monitoring for liquid sodium leakage detection using OFDR-based Rayleigh backscattering

Ekaterina Boldyreva, Romain Cotillard, Guillaume Laffont, Pierre Ferdinand, D. Cambet, J. -P. Jeannot, P. Charvet, S. Albaladejo, G. Rodriguez

▶ **To cite this version:**

Ekaterina Boldyreva, Romain Cotillard, Guillaume Laffont, Pierre Ferdinand, D. Cambet, et al.. Distributed temperature monitoring for liquid sodium leakage detection using OFDR-based Rayleigh backscattering. 9157, SPIE-INT SOC OPTICAL ENGINEERING, pp.91576N, 2014, 10.1117/12.2059531 . cea-01828512

HAL Id: cea-01828512
https://cea.hal.science/cea-01828512

Submitted on 24 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/271359890

Distributed temperature monitoring for liquid sodium leakage detection using OFDR-based Rayleigh backscattering

Conference Paper *in* Proceedings of SPIE - The International Society for Optical Engineering · June 2014

DOI: 10.1117/12.2059531

CITATIONS
7

READS
300

9 authors, including:



Romain Cotillard
Atomic Energy and Alternative Energies Commission
30 PUBLICATIONS **212** CITATIONS
SEE PROFILE



Guillaume Laffont
Atomic Energy and Alternative Energies Commission
104 PUBLICATIONS **1,260** CITATIONS
SEE PROFILE



Pierre Ferdinand
Atomic Energy and Alternative Energies Commission
132 PUBLICATIONS **2,140** CITATIONS
SEE PROFILE



Jean-Philippe Jeannot
Atomic Energy and Alternative Energies Commission
44 PUBLICATIONS **301** CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Acoustics for ASTRID Nuclear Reactor View project

Study of gas detection method in Sodium by electromagnetic means for Gen IV Sodium Fast Reactor View project

All content following this page was uploaded by Romain Cotillard on 26 January 2015.

The user has requested enhancement of the downloaded file.

Distributed temperature monitoring for liquid sodium leakage detection using OFDR-based Rayleigh backscattering

E. Boldyreva*[a], R. Cotillard[a], G. Laffont[a], P. Ferdinand[a], D. Cambet[b], J.-P. Jeannot[b], P. Charvet[b], S. Albadéjo[b], and G. Rodriguez[b]
[a]CEA LIST, Optical Measurement Laboratory, 91191 Gif-sur-Yvette cedex, France.
[b]CEA DEN, DTN, 13108 Saint Paul lez Durance cedex, France.

ABSTRACT

For the first time, a gold coated single mode optical fiber has been used to detect a liquid sodium leakage on a pipe of secondary circuit pipe mock-up of nuclear fast reactor (Gen IV) by means of Optical Frequency Domain Reflectometry-based on Rayleigh backscattering. During 150 min of the experiment we were able to detect and monitor the evolution of a liquid sodium leakage on the surface of the pipe.

Keywords: Optical Fiber Sensor, OFDR, Rayleigh backscattering, leakage detection, liquid sodium, fast reactor

1. INTRODUCTION

Expected increase of electricity demand and decrease of fossil resources to come, lead up to develop sustainable energy sources as Generation IV nuclear reactors. Among various concepts of 4th generation reactors, a promising R&D is being performed on Sodium-cooled Fast Reactor. Improving the safety of such future Nuclear Power Plants is the major priority request that implies development of new monitoring tools. In such a context, liquid sodium leakage detection along pipes of secondary circuits is one of the most important safety related issue that claims for new monitoring methodologies. Optical Fiber Sensors (OFS), and especially distributed OFS based on fiber core backscattering (*i.e.* Raman, Brillouin or Rayleigh scattering phenomena), provide many innovative advantages for these emerging reactor designs[1,2,3]. As now well known, OFS are free of electromagnetic interferences, low intrusive, able to provide metrological performances, wide multiplexing, and remote monitoring on several sensing parameters, even in severe environments. A smart deployment of such distributed OFS allows complete and continuous monitoring of critical structures for of temperature or strain sensing, or both. Regenerated FBGs haves already been considered for temperature sensing[4], as well as Raman-based Distributed Temperature Sensing (Raman DTS) for coolant leakage monitoring[5]. Despite of 1°C resolution, which good enough for an alarm purpose, the metric spatial resolution prevents from early detection of localized temperature changes, as far as the leakage size remains small. In this paper we overcome this limitation thanks to the use of an OFDR and Rayleigh scattering sensing approach[6]. Moreover, we propose an innovative solution for liquid sodium leakage detection at temperature up to 450°C, using a gold-coated single mode fiber as a distributed temperature transducer. In such approach, to enhanced detection reliability, the centimetric spatial resolution and the 1°C thermal resolution allow both the leakage detection and the monitoring of Na flow front inside the pipe, through temperature change measurements on surface.

2. EXPERIMENTAL CONSIDERATIONS

2.1 OFDR-based Rayleigh backscattering

Inelastic Raman scattering method based on Optical Time Domain Refectometry (OTDR) is limited to a metric spatial resolution while OFDR technique based on elastic Rayleigh backscattering of coherent tunable laser light attaints centimetric resolution. Due to molecular silica structure and to defects linked to fiber manufacturing process, fiber core heterogeneities are frozen while fiber drawing, inducing Rayleigh backscattering.

*ekaterina.boldyreva@cea.fr; phone: +33 1 69 08 29 22; www-list.cea.fr

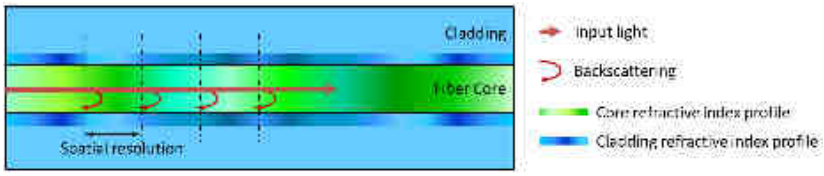


Figure 1. Ramdom optical fiber core and cladding refractive index fluctuations at molecular scale and Rayleigh Backscattering.

Figure 1 shows how light traveling along a single-mode fiber is reflected back towards the reflectometer (OTDR or OFDR), due to: a) *Rayleigh Scattering* due to non-homogeneous structural changes at the molecular level, b) *Reflections* due to localized changes in the refractive index of the silica, c) *MFD (mode field diameter) variations* caused by fiber geometrical changes, d) *Fresnel peaks*, where there is a sudden change in density, *e.g.* from silica-to-air at fiber ends. If we consider the Rayleigh Backscattering, its amplitude is known to be a function of both core and cladding refractive index (through $\Delta n = n_{core}-n_{clad}$ in the capture fraction definition). So, as micro random fluctuations of material density at the molecular level are frozen during fiber drawing, the fiber suffers micro fluctuations of both core and cladding refractive index. They are the origin of Rayleigh backscattering, whose random character renders the backscattering profile unique for each fiber. This is the reason why it can be considered as its own fingerprint.

In ODFR, the light of a linearly tunable laser is injected in the fiber core, and its backscattering is detected by homodyne detection. This is done by mixing the backscattering signal with a reference wave coming from the laser source, which creates a frequency beat, whose value allow to determine the exact position of the fiber core region from where the light has been backscattered. This could be done with about 1 cm spatial resolution all along the fiber of typical length up to ~ 100 m. Temperature (or strain) changes affect the optical path (refractive index and fiber length, as well as Δn), inducing spectral shifts of the fiber backscattering profile. By correlating a reference profile obtained before temperature (or strain) change be applied, with a second one done after the temperature (or strain) be modified, the spectral shift value provides the temperature (or strain) changes. This differential method allows measuring the temperature (or strain) profile changes, all along the fiber.

2.2 FUTUNA mock-up

A mock-up pipe 2 m-long (scale 1 in diameter), called FUTUNA and based at CEA Cadarache, France, has been used for this experiment. To ensure safe operation during the experiment, the pipe covered by a heat insulator, is first emptied and heated at the same temperature as the liquid sodium. The liquid sodium is moved through an injection pipe inside the mock-up pipe and flows on the top of it. The temperature of the pipe is monitored by eighteen thermocouples. The progression of the liquid sodium inside the injection pipe is monitored by three other thermocouples. When the sodium reaches the top of the pipe mock-up, the experiment starts.

2.3 Optical fiber deployment around the pipe mock-up

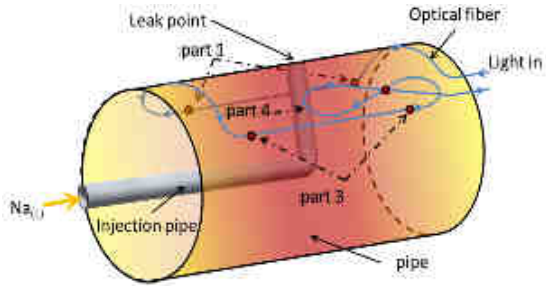


Figure 2. Optical fiber route on the FUTUNA mock-up pipe

A single mode gold-coated fiber has been chosen as transducer. Such metal coating improves fiber mechanical resistance at high temperature, up to 700°C, while traditional polymer coatings degrade and may induce fiber damages. Furthermore, few tens micron thickness of the gold coating maintains low thermal mass and assures fast response time to temperature variations. Destroyed by any direct contact with the liquid sodium, the optical fiber plays role of a wick, able to follow the liquid sodium flow along the pipe. The fiber length which remains operational after the sodium has reached the silica remains available for temperature monitoring. The fiber deployed around the pipe was divided in 4 zones. Zones 1 and 3 were disposed on both sides, at 45° from the top. A fiber loop was placed close to the leakage point in zone # 4 (Fig. 2). Transitions between zones were easily localized on backscattering profiles (Fig. 3).

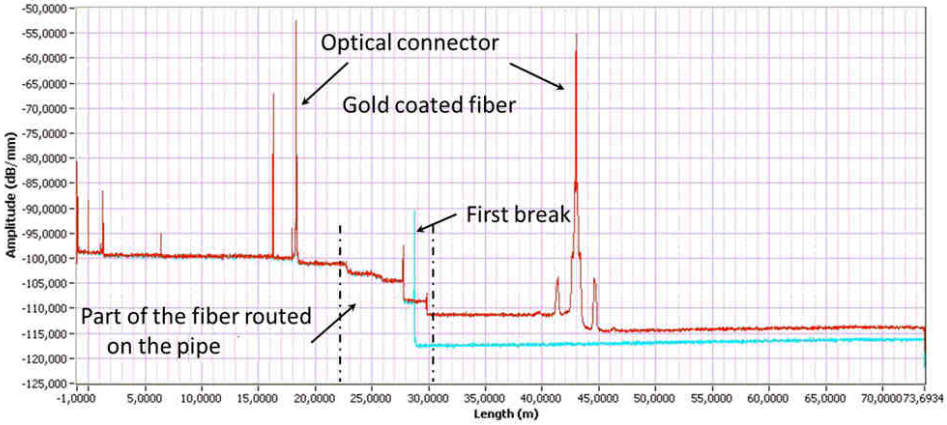


Figure 3. Backscattering profiles before the experiement (in red) and after the first break (in blue)

3. SODIUM LEAKAGE EXPERIMENT

3.1 Experiment

Before the experiment starts, the mock-up pipe had been heated at 450°C during several days, to homogenize its temperature. The sodium was contained in a warm-up circuitry preceding the mock-up pipe, heated at 450°C one day before the experiment, and then moved up to the injection pipe. During the experiment, the liquid sodium flowed at the rate of $3cm^3$/min. The external heat insulator absorbs the liquid sodium and burns in contact with it (Fig. 4).



Figure 4. FUTUNA mock-up pipe after the leakage experiment (on top, the heat insulator burned by the liquid sodium)

Therefore it is possible to detect and to localize a liquid sodium leakage by monitoring the temperature along the pipe. A reference measurement was taken while the pipe was heated, so that the measured temperature is equal to its surface temperature. Temperature changes all along the fiber deployed on surface have been measured during the experiment.

3.2 Results

The experiment started when the liquid sodium began to leak. The temperature increase along the optical fiber have been immediately visualized on OFDR traces, and localized on the part # 4, where the fiber is next to the leakage point (at ~ 20 cm). Then, 32 minutes after the experiment started we observed the first optical fiber break on the part # 4. So, at this moment the liquid sodium got in contact with the fiber. At the same time we detected two temperature peaks in zones # 1 and # 3. During two hours and half, the temperature peaks were slowly increasing up to 120°C above the initial mock-up pipe temperature (450°C), due to the liquid sodium approach (Fig. 5). Then, the second break occurred in zone # 1 due to a direct contact with the sodium. Later on, the liquid sodium has flowed slowly on each side of the pipe. The most important flow was detected on the side of zone # 1, leading to conclude that the pipe is slightly inclined on this side. Some additional information about the heat insulator combustion temperature, and the temperature at the input, could give an estimation of the fiber distance from the sodium front, even without any direct contact between the fiber and sodium.

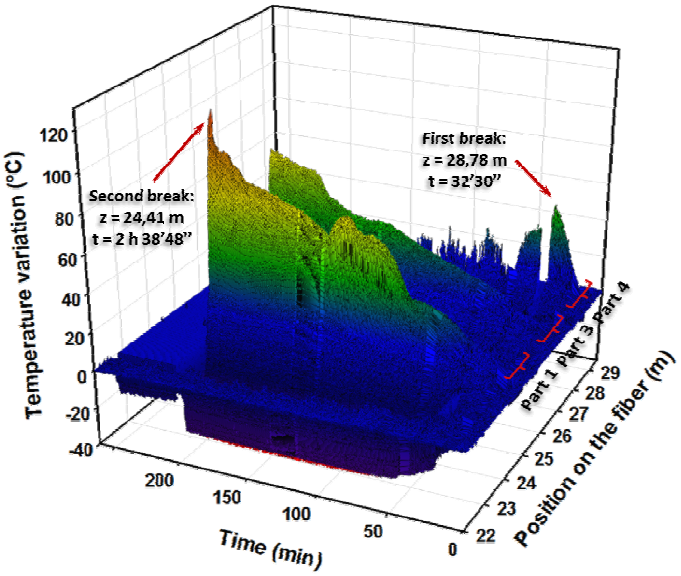


Figure 5. Evolution of the temperature above the initial mock-up pipe temperature along the optical fiber during the leakage experiment

4. CONCLUSION

For the first time, an innovative distributed temperature sensing along a gold-coated single mode fiber using the OFDR-based Rayleigh backscattering technique has been applied to the detection of liquid sodium leakage on pipes. The Rayleigh sensing techniques provides 1°C temperature resolution with a centrimetric spatial resolution. Thus, this approach enables accurate and early detection of sodium leaks. It provides a useful and innovative solution for improving the safety of fasts reactors, based on liquid sodium. This method gives the possibility to detect sodium leakages even without any direct contact with the fiber, allowing quick and safe intervention to stop the leak, and fix the pipe.

Moreover, in order to find optimized spiral pitch, a complete modeling of the phenomena is required including heat conduction and radiation due to pipe insulation combustion. By solving these equations, it is possible to obtain the temperature distribution at any time and any point of the pipe. Careful choice of temperature threshold above the initial pipe temperature could permit to avoid false alarms. Thus, it is possible to determine maximal distance at which the fiber must be, to detect such temperature increase. Considering the worst case when the leakage appears at mid-distance between two spiral whorls, the spiral pitch must be chosen as twice this distance. Further works will be focused on such modeling in order to optimize fiber routing and minimize fiber length deployed on pipes.

REFERENCES

[1] A. R. Fernandez, A. I. Gusarov, S. Bodart *et al*, "Temperature monitoring of nuclear reactor cores with multiplexed fiber Bragg grating sensors", Optical Engineering, Vol. 41, n°6, pp. 1246-1254, (2002).

[2] P. Ferdinand, S. Magne and G. Laffont, "Enhancing safety in Nuclear Power Plants with Optical Fiber Sensors", Int. Conf. on Fast Reactors ans Related Fuel Cycles, Safe Techn. and Sustainable Scenarios (FR13), Paris, 4-7 March (2013)

[3] P. Ferdinand, S. Magne and G. Laffont, "Optical Fiber Sensors to improve the safety of Nuclear Power Plants", Asia Pacific Optical Sensors, APOS2013, Wuhan, China, 17th-21st Oct. 2013.

[4] G. Laffont, R. Cotillard, P. Ferdinand, G. Blevin, J.-Ph. Jeannot, G. Rodriguez, "Regenerated Fiber Bragg Grating sensors for high temperature monitoring in Sodium-cooled Fast Reactor", Int. Conf. on Fast Reactors ans Related Fuel Cycles, Safe Techn. and Sustainables Scenarios (FR13), Paris, 4-7 March (2013),

[5] C. Pandian, M. Kasinathan, S. Sosamma *et al*, "Raman distributed sensor system for temperature monitoring and leak detection in sodium circuits of FBR", ANIMMA, 2009 First Intern. Conf. on Advancements in Nuclear Instrumentation Measurement Methods and their Applications, IEEE, pp. 1-4, (2009).

[6] A. K. Sang, M. E. Froggatt, D. K. Gifford *et al*, "One centimeter spatial resolution temperature measurements in a nuclear reactor using Rayleigh scatter in optical fiber", Sensors Journal, IEEE, Vol. 8, n°7, pp. 1375-1380, (2008).

View publication stats