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### ► To cite this version:

Laurent Maurin, Hamid Makil, Jean-Michel Bourbotte, Hassen Hamrita, Gwenael Jouvin, et al.. Long length SPNDs and distributed optical fiber sensors for severe accident remote monitoring & their contribution to nuclear safety in the post-Fukushima context. IAEA Technical Meeting on Advanced Technologies and Systems for Containment Preservation in Accident Conditions, Oct 2022, Vienne, Austria. cea-03812685

**HAL Id: cea-03812685**

**<https://cea.hal.science/cea-03812685>**

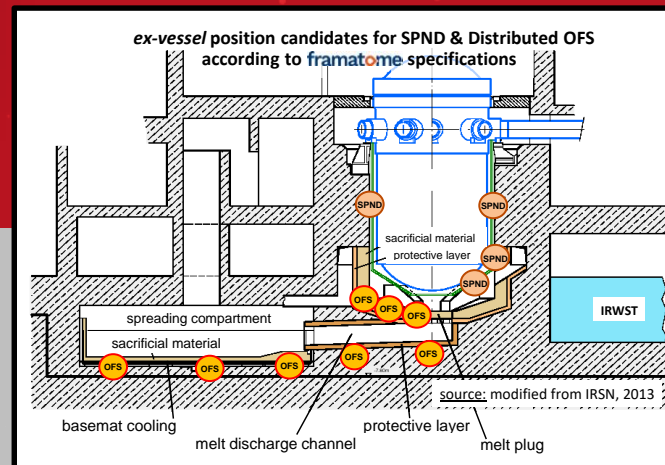
Submitted on 12 Oct 2022

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

L. Maurin, H. Makil, J.-M. Bourbotte, H. Hamrita, G. Jouvin, V. Kondrasovs, S. Rougeault, G. Cheymol, H. Maskrot, L. Barbot, J.-F. Villard, V. Bouyer, A. Denoix, C. Journeau, J.-C. Jaboulay, C. Guénaut, M. Brovchenko, I. Duhamel, L. Pichon, S. Fourrez, Y. Ouerdane and P. Ferdinand



**Technical Meeting on Advanced Technologies and Systems for Containment Preservation in Accident Conditions**  
IAEA virtual event – 11-13 October 2022



Presentation linked to SAMMI-2020 publication, available at: <https://hal-cea.archives-ouvertes.fr/cea-03324457>

## Summary

- **Distributed Sensing for Corium Monitoring and Safety – DISCOMS**
  - *ex-vessel* sensors position candidates
- **Long length SPND-TC instrumented pole**
  - SPND current modelling using CEA MATiSSe toolbox
  - Electronics current amplification device & SPND qualification
- **Distributed Optical Fiber Sensors**
  - Optical Fiber Sensors in the reactor pit makes sense
  - Optical Fibers Sensor cables qualification
- **VULCANO Molten Core – Corium Interaction (MCCI) final experiment**
  - Concrete crucible instrumentation
  - Optical measurements during MCCI (animated GIFs)
  - Temperature (OFS + SPNDs-TC instrumented poles) measurements
- **Conclusion**

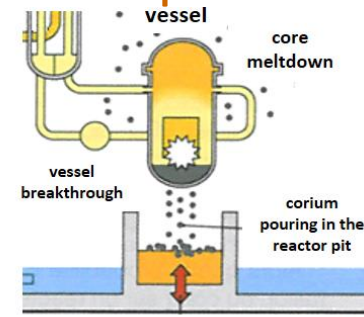
## Distributed Sensing for Corium Monitoring and Safety – DISCOMS

### Post-Fukushima project

- Total loss of electrical power sources following the tsunami, TEPCO NPP operator with almost no data about the accident status and its evolution ⇒ safety must always prevail

### Aimed at providing innovative solutions based on passive sensors operated from a remote and safe place, in order to:

- Monitor the normal operation of the reactor during 60+ years
- Monitor the Severe Accident to apply *on time* appropriate mitigation strategies & keep informed nuclear safety authorities about:
  - Vessel breakthrough
  - Corium pouring on the floor and its interaction with concrete until the prospective breakthrough
  - Long term corium cooling once relocated in the core catcher (Gen III)



Molten Core – Corium Interaction (MCCI)  
source: IRSN

Self-Powered Neutron Detectors  
Thermocouple

Optical Fiber Sensors

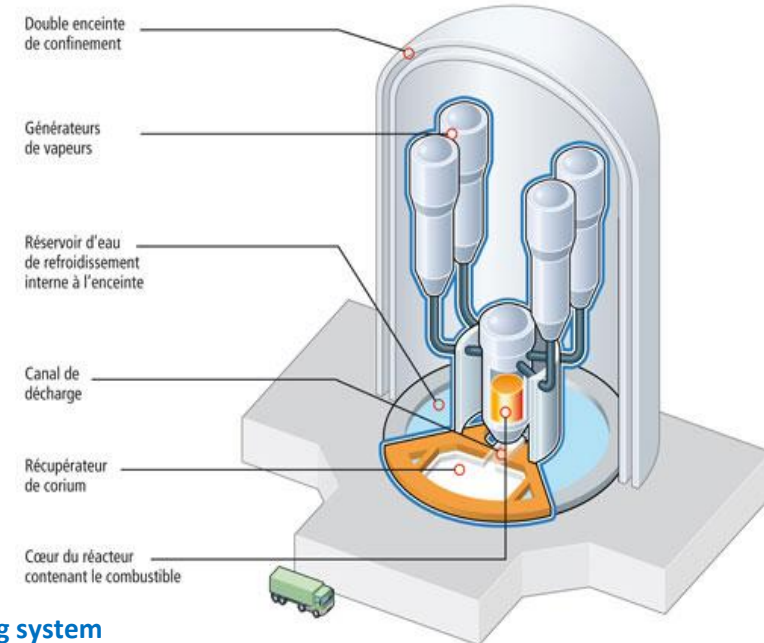
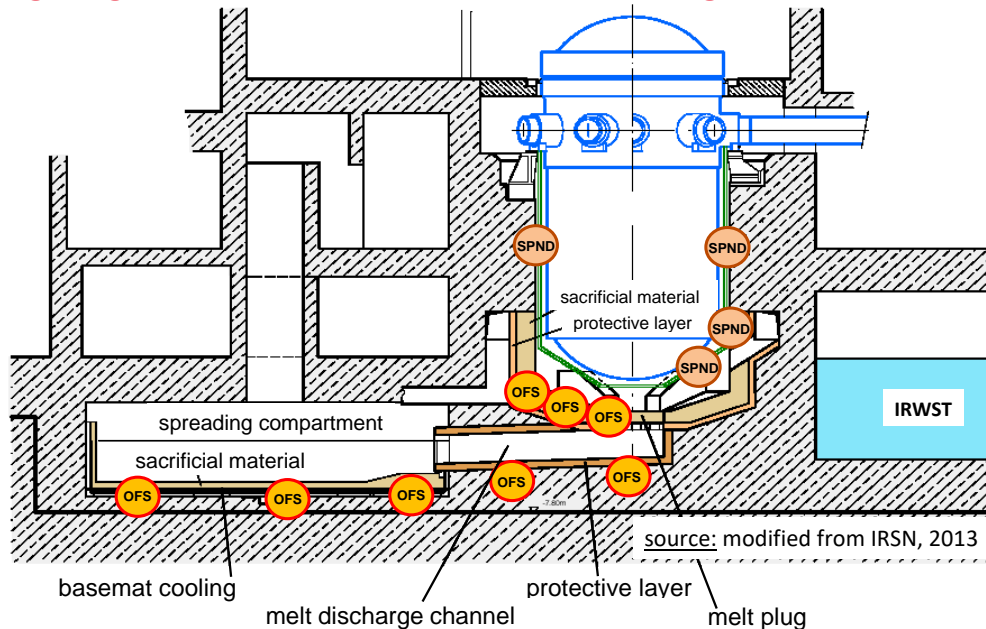
### 2 technologies: ex-core long length SPNDs-TC & Distributed OFS

- ex-vessel* measurements designed for Gen II & Gen III (EPR)

### 7 partners (Public R&D, Academic R&D, Industrials)

### Ended in Dec. 2018

**ex-vessel positions candidates (reactor pit, melt discharge channel & spreading compartment) for long length SPNDs-TC & OFS cables according to framatome specifications**



**Gen III (EPR)**

- SPND** - currents self-generated under radiations – battery operated capable monitoring system
- long (several meters) lengths SPNDs to get the adequate sensitivity for *ex-core* detection
- OFS** - rely on the properties of the backscattered light in optical fibers and reflectometry
- passive sensors with remote measurement systems up to several km away from the NPP area

**Information remotely obtained from a safe place, even in case of total loss of power supplies:**

(Fukushima 2011 scenario)

- to **increase** the nuclear **safety**,
- to **reduce** operator **exposition** to ionizing radiations,
- to **avoid** the **breach of 3<sup>rd</sup> containment barrier & environmental consequences** with on-time & appropriate mitigation strategies

## SPND current modelling

$$I_{total} \propto \sum_i \phi_n \cdot \sigma_{i(n,\beta^-)} + \sum_i \phi_n \cdot \sigma_{i(n,\gamma)(\gamma,e)} + \sum_i \phi_\gamma \cdot \sigma_{i(\gamma,e)}$$

physical equation implemented in the CEA MATiSSe toolbox for SPND current modelling

- Input data: neutron & gamma energy spectra & fluxes
- Accurate modelling of the SPND and its environment
  - { SPND instrumented pole, concrete, corium } whole set
- MONTE CARLO MCNP6.1 code using JEFF3.2 & ENDF/B-VII.1 libraries

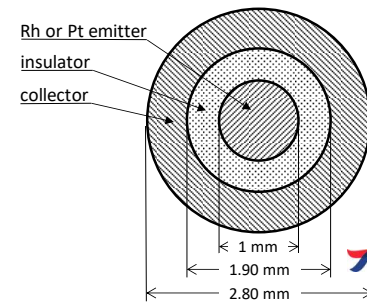
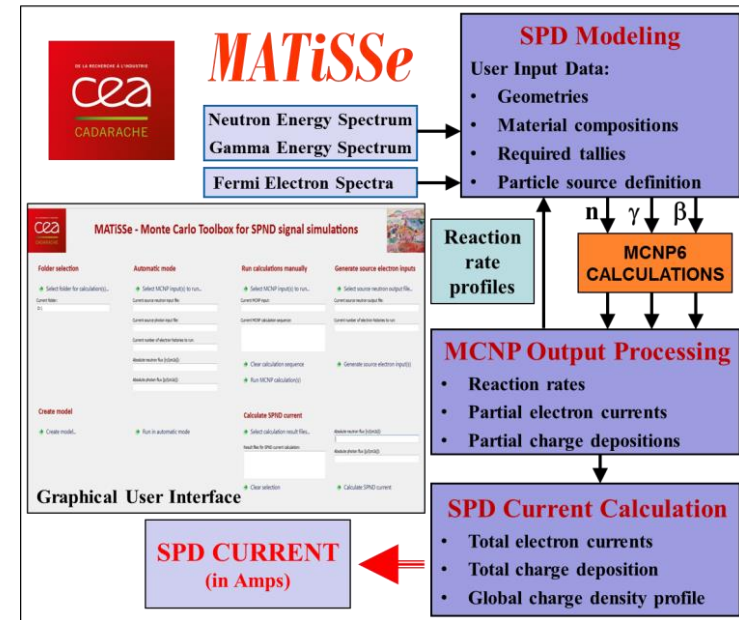


### 3 main sources:

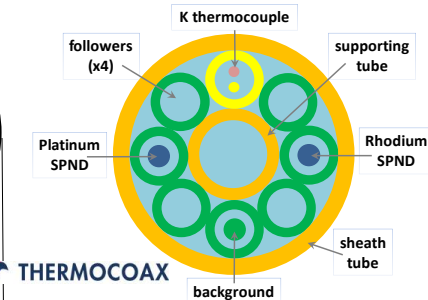
- n: rate of  $(n, \beta^-)$  reactions &  $(n, \gamma)(\gamma, e)$  contributions
- e:  $\beta^-$  transport
- $\gamma$ :  $(\gamma, e)$  contributions

- MATiSSe code qualified along with several experimental validations

- ✓ L. Barbot *et al.*, "Calculation to experiment comparison of SPND signals in various nuclear reactor environments", ANIMMA 2015, 20-24 April 2015, Lisbon, Portugal.
- ✓ L. Barbot *et al.*, "Experimental Validation of a Monte Carlo based Toolbox for SPND and PGD Simulation in the OSIRIS MTR", PHYSOR 2016, 1-5 May 2016, Sun Valley, USA.



SPND structure with  
Rh or Pt emitter



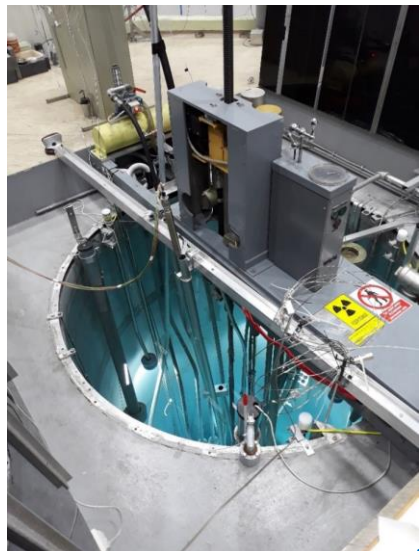
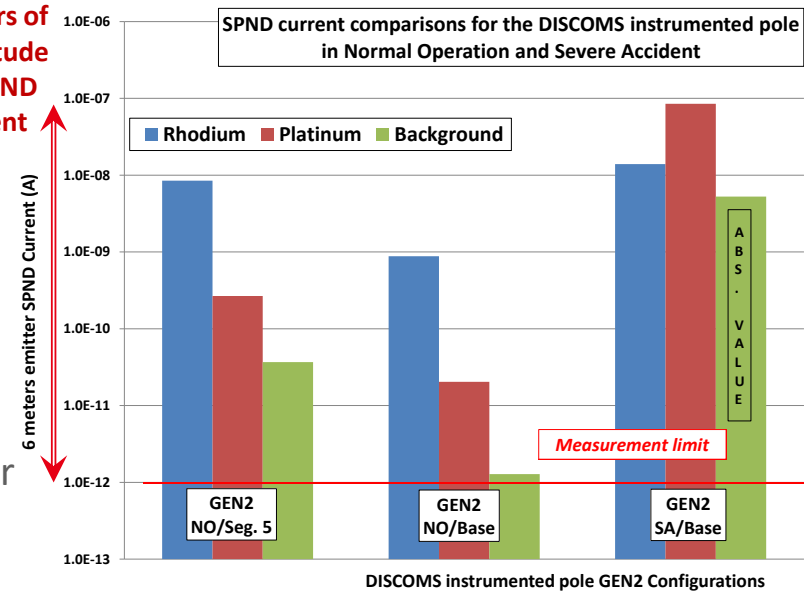
instrumented SPNDs-TC pole  
structure modelled with CEA  
MATiSSe toolbox

instrumented pole  
section overview

## Electronics current amplification device design & qualification

- **1 pA current detection threshold**
  - From Normal Operation to Severe Accident with corium in the vessel (no relocation)
  - Vessel breakthrough with corium pouring on the floor
- **Dedicated amplification device [1 pA 100 nA]**
  - Qualified with  $^{60}\text{Co}$  source projector & in research reactor

5 orders of magnitude for SPND current



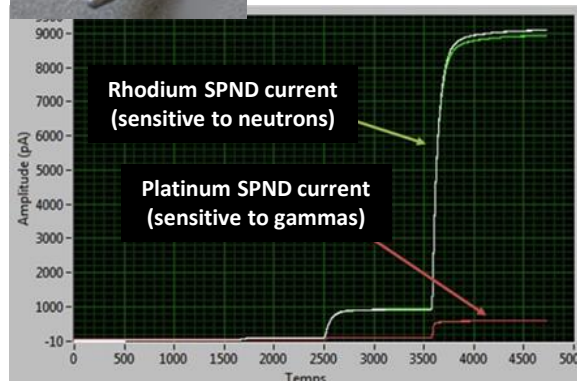
TRIGA Mark II research reactor (Slovenia)



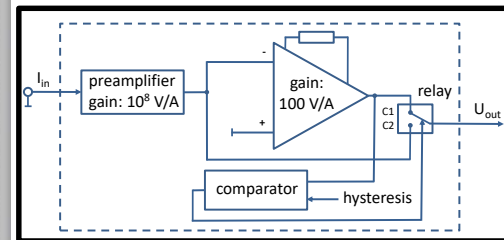
dedicated SPND multi-channel measurement device  
375 mA × 24 V power per channel up to 200 m, battery operated



6 m long instrumented pole manufactured by THERMOCOAX



Rhodium & Platinum SPNDs current measurements during tests in reactor



low currents & wide range [1 pA 100 nA] amplification device

## Results achieved in DISCOMS project prior to final MCCI VULCANO experiment

- Modelling  $\gamma$  doses & fast neutrons ( $E > 1$  MeV) fluence in the reactor pit concrete floor [M. Brovchenko, 2016]
  - Concrete floor shielding provides a good protection against ionizing radiations

from surface to -50 cm	fast neutrons (60 y NO) [ $n/cm^2$ ]	kerma gamma (60 y NO + 24 h SA) [MGy]
Gen II	from $2 \times 10^{16}$ to $2 \times 10^{14}$ $\div 100$	from 5.7 to 0.7 $\div 8.1$
Gen III (EPR)	from $2 \times 10^{14}$ to $10^{12}$ $\div 200$	from 2.1 to 0.022 $\div 95$

NO: Normal Operation / SA: Severe Accident

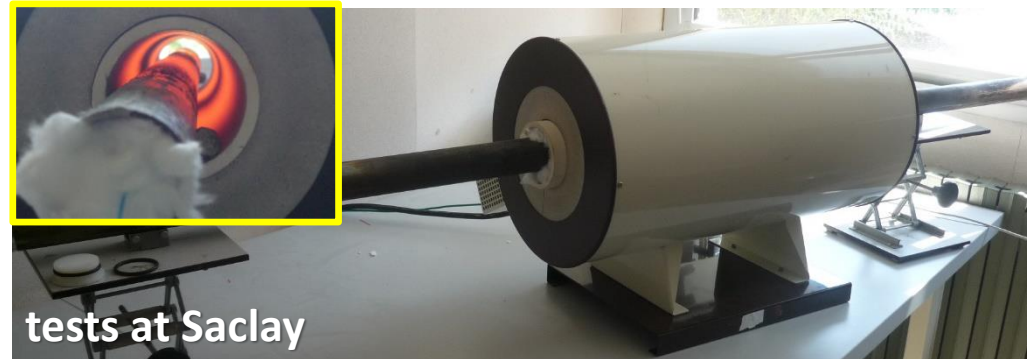
- **60 years NO is the most damaging process in comparison with 24 hours SA**
- Rad-Hard optical fibers selection & qualification in  $\gamma$  irradiator [G. Cheymol, 2020]
  - Possible to assess **RIA < 50 dB/km at 2 MGy** at both 1310 nm & 1550 nm wavelengths
    - ✓ **100 m per cable** in the reactor pit  $\rightarrow$  **5 dB optical budget** for the optical fiber under test
  - Cable **polymer compounds** under ionizing radiations **produce molecular H<sub>2</sub>**
    - ✓ **Protective carbon layer against** diffusion of di-hydrogen **H<sub>2</sub>** in fiber core **is mandatory**
- **Industrial optical sensor cables incorporating Rad-Hard optical fibers**
  - Compliance to EDF PMUC standard required in the call for tenders





## Optical Fibers Sensor (strain, temperature, security) cables qualification

- Tests up to 750°C (circuit integrity) → **Severe Accident scenario**



tubular oven with optical sensor cable in a pipe (to protect from fumes)



security cable after 2 hours at 750°C



strain sensor cable after heating up to 400°C

Optical fiber continuity during 90 min at 750°C  
 Tests performed in a tubular oven, cable in a pipe

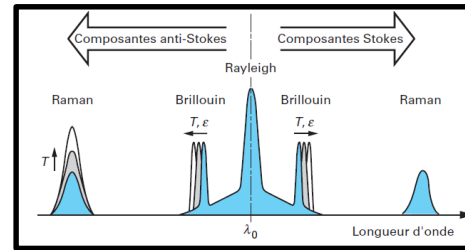
strain cables	temperature cable	security cable
optical fiber systematically <b>broken</b> between 400°C & 450°C	<b>pass</b> (but not a product specification)	<b>pass</b>

the two most interesting cables are:

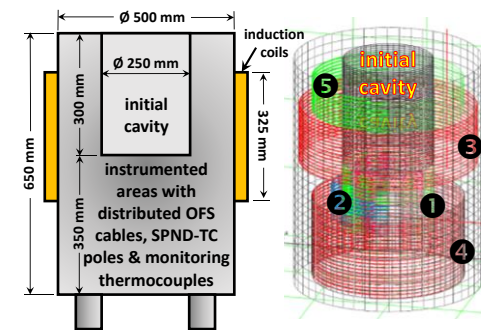
- the **security cable** → up to 750°C (90+ min)
- the **strain sensor cable** → earlier break

## Concrete crucible instrumentation

- **5 OFS cables connected to 5 optical reflectometers for sensing**
  - Photon-counting & telecom **OTDRs** → **cables length**
  - **Brillouin B-OFDA** (closed loop) → **{  $\Delta\varepsilon$  &  $\Delta T$  }**
  - **Rayleigh OFDR** → **high-resolution {  $\Delta\varepsilon$  &  $\Delta T$  }**
  - **Raman DTS** → **{  $T$  }**
- **2 (SPNDs)-TC poles**
  - **Current measurement** on the background cable
  - **Temperature measurement** with the TC in the instrumented poles



source: techniques de l'ingénieur



**DISCOMS concrete crucible for the final VULCANO MCCI experiment**  
**180 m sensing cables**

## IRESNE



Optical Fiber Sensors measurement loops



dedicated SPNDs-TC instrumented poles



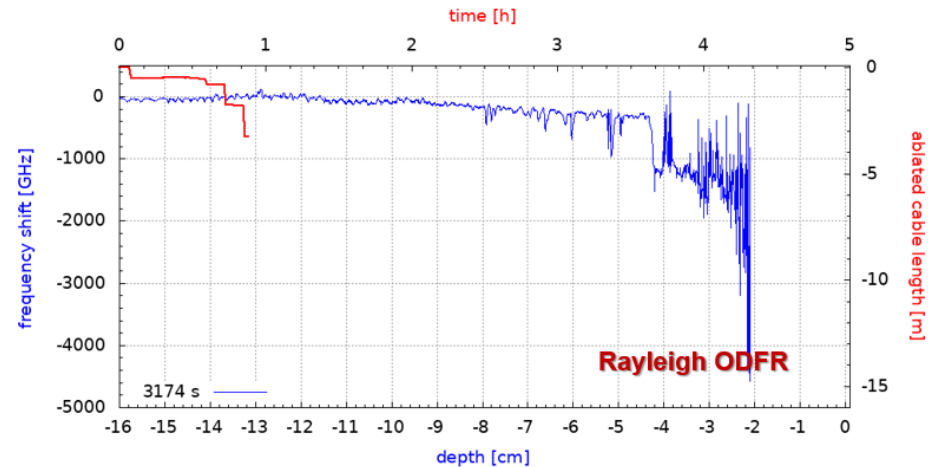
**concrete crucible installed with the induction coils at CEA in Cadarache**  
**PLINIUS facility**

- **50 kg prototypical UO<sub>2</sub> (no radiation)**
  - Corium obtained with strong exothermic thermite reaction
- **100+ thermocouples to monitor the temperature propagation front**

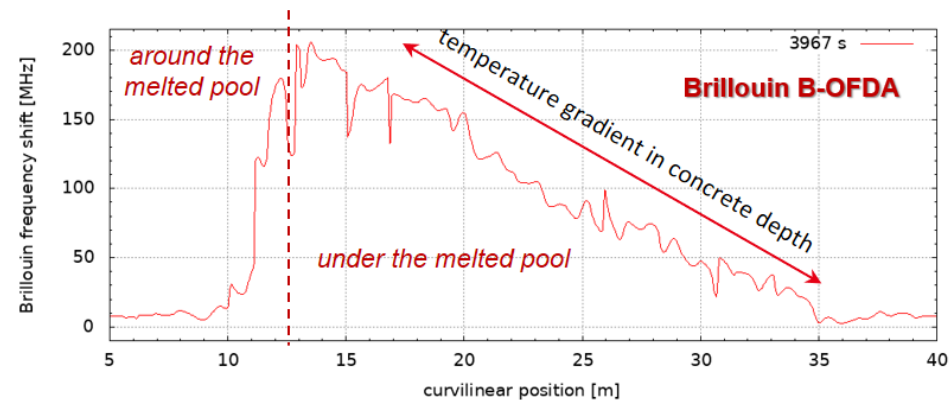
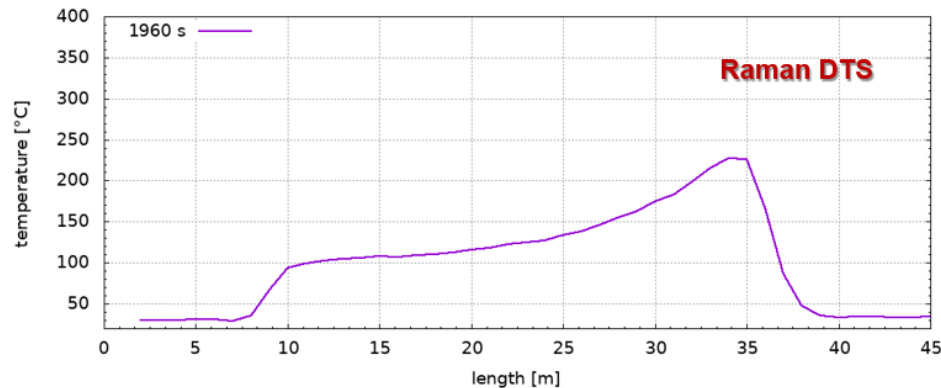
## Distributed Optical Fiber Sensors measurements during MCCI (animated GIFs)



thermite reaction ignition to produce corium



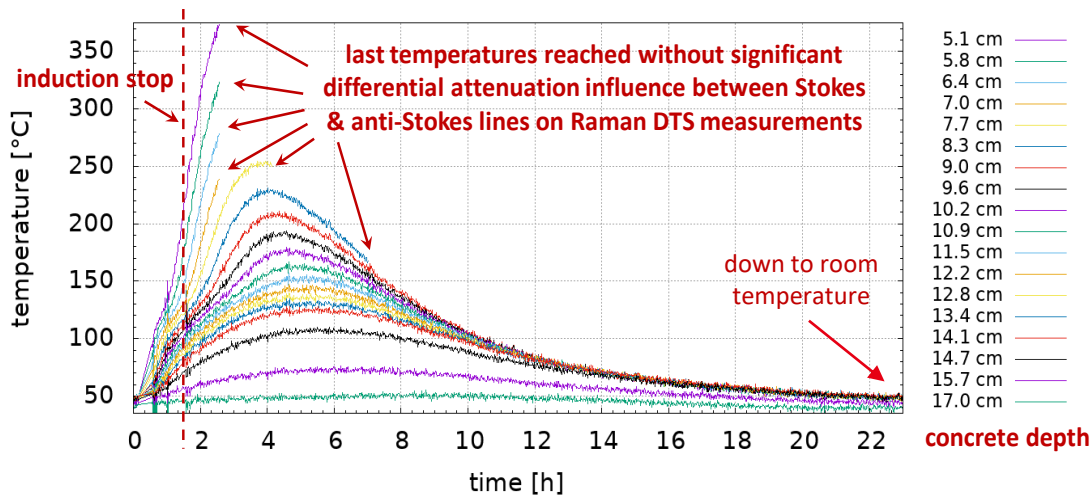
✓ **corium vicinity detected** only a few minutes after the ignition



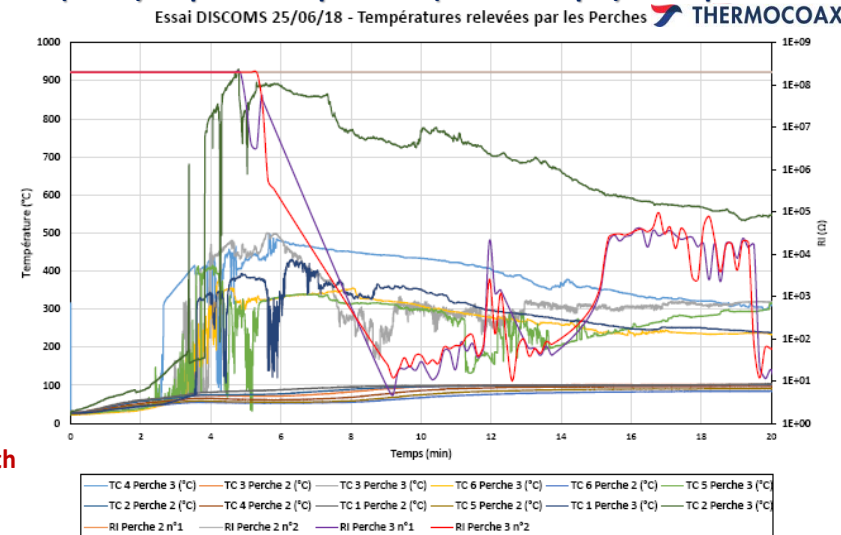
## Temperature (Optical + SPNDs-TC instrumented poles) measurements during MCCI

### Temperature profiles up to complete cooling at room temperature after 24 hours

OFS: Raman DTS temperature vs. elapsed time at different depths



(SPND)-TC poles: temperature (thermocouple) vs. elapsed time



### Remote monitoring demonstration successfully achieved during MCCI & post-MCCI

- ✓ Temperature profiles up to 580°C (single excitation wavelength **Raman DTS**)
- ✓ Strain & Temperature changes profiles (**Brillouin** B-OFDA & Rayleigh OFDR)
  - Rayleigh OFDR measurement are very noisy → not suitable for sensing (OK for reflectometry)
- ✓ Cables (optical fibers) lengths obtained with **telecom OTDR**
- ✓ OFS & SPND-TC temperature measurements in agreement with reference thermocouples

## For NPP instrumentation, it can be advised / recommended

- Long length SPNDs-TC to detect
    - ✓ The reactor shut down,
    - ✓ The onset of the Severe Accident without corium relocation,
    - ✓ The Severe Accident with corium relocation on the concrete floor.
  
  - Optical Fibers Sensor cables to detect
    - ✓ The corium pouring on the concrete floor,
    - ✓ The corium progression through the concrete floor (until its breakthrough),
    - ✓ The corium in the EPR melt discharge channel,
- ... but also to monitor the corium temperature once relocated in the core catcher.

This research project (ref.: [ANR-11-RSNR-0007](#)) was carried out within the framework of the RSNR research program, co-funded by the French *Programme d'Investissements d'Avenir (PIA)* and managed by the ANR (*French National Research Agency*).

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thank you for  
your attention



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