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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

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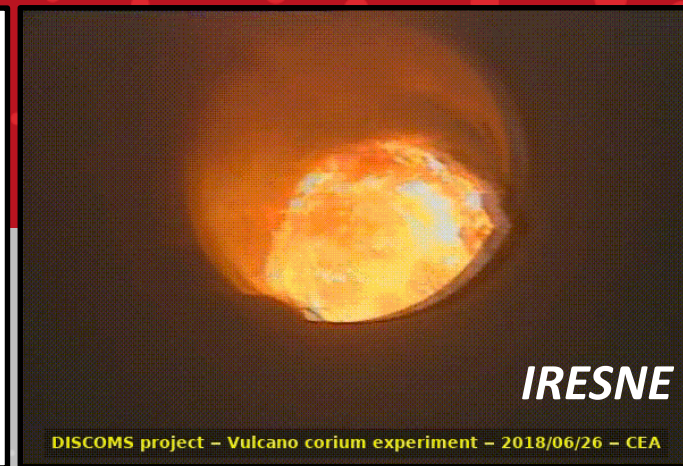
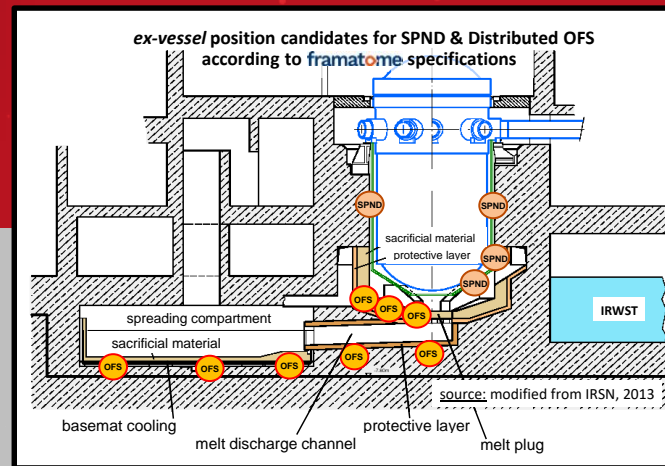
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Long length SPNDs and Distributed Optical Fiber Sensors for Severe Accident remote monitoring & their contribution to Nuclear Safety in the post-Fukushima context

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**

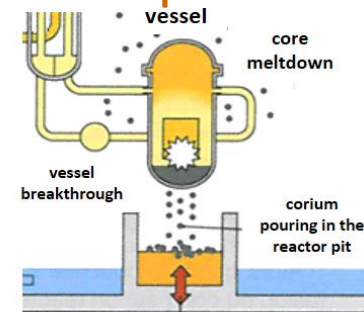
Distributed Sensing for Corium Monitoring and Safety – DISCOMS

▶ 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

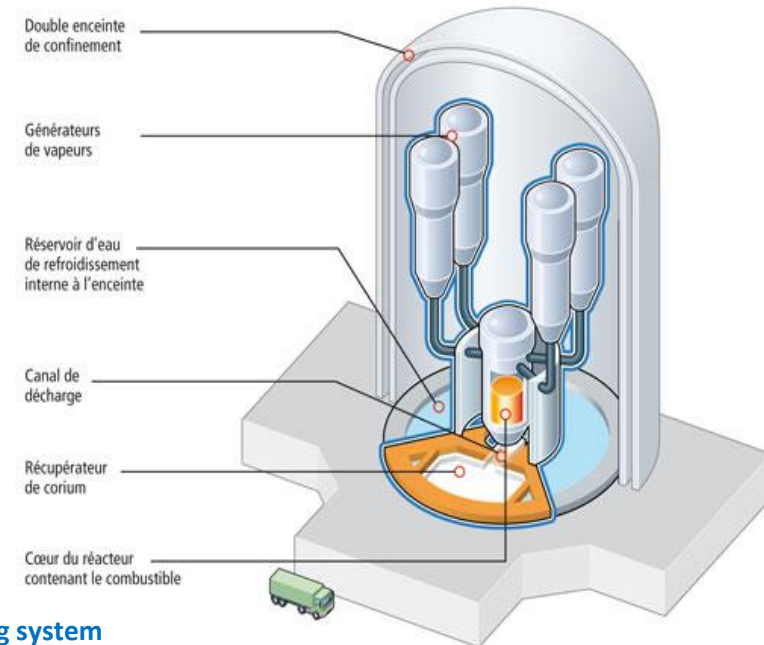
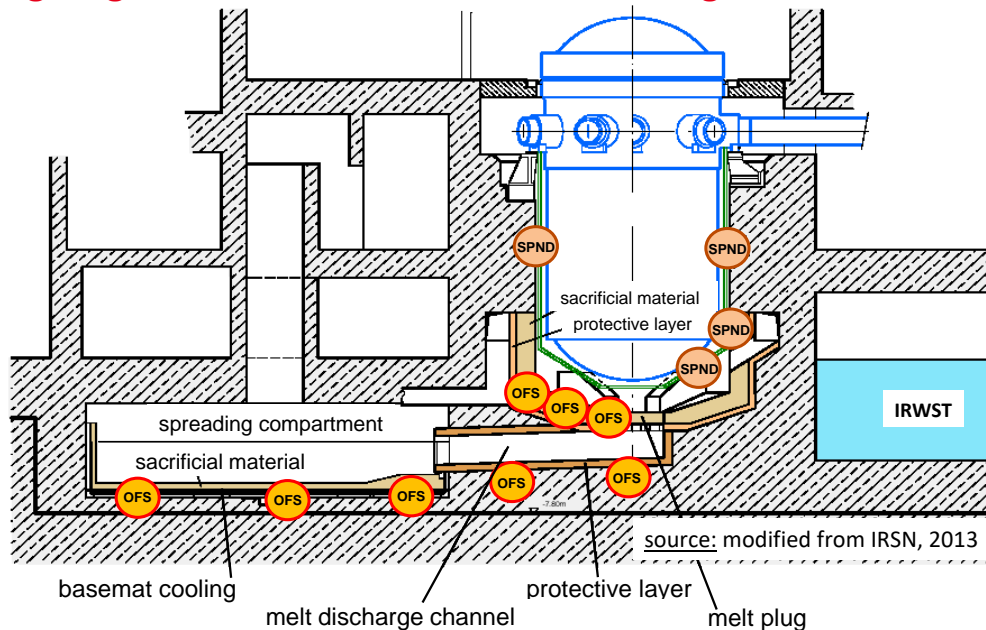
▶ 2 technologies: **ex-core** long length SPNDs-TC & Distributed OFS

- **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 3rd 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

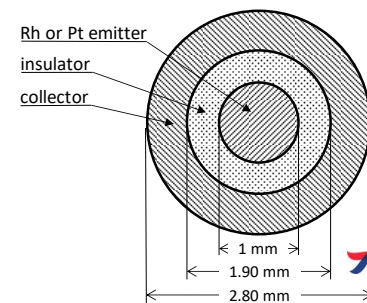
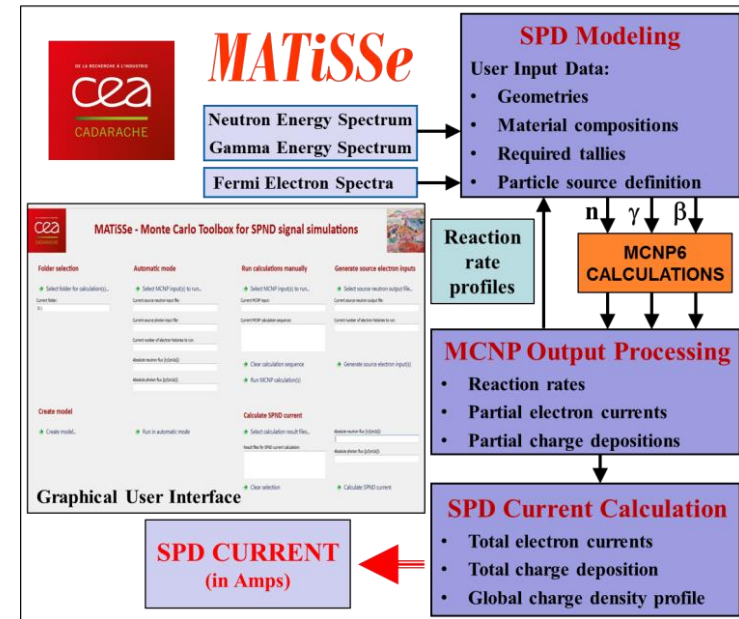


3 main sources:

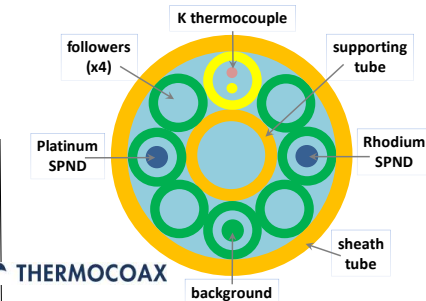
- n: rate of (n, β^-) reactions & $(n, \gamma)(\gamma, e)$ contributions
- e: β^- transport
- γ : (γ, e) contributions

- 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



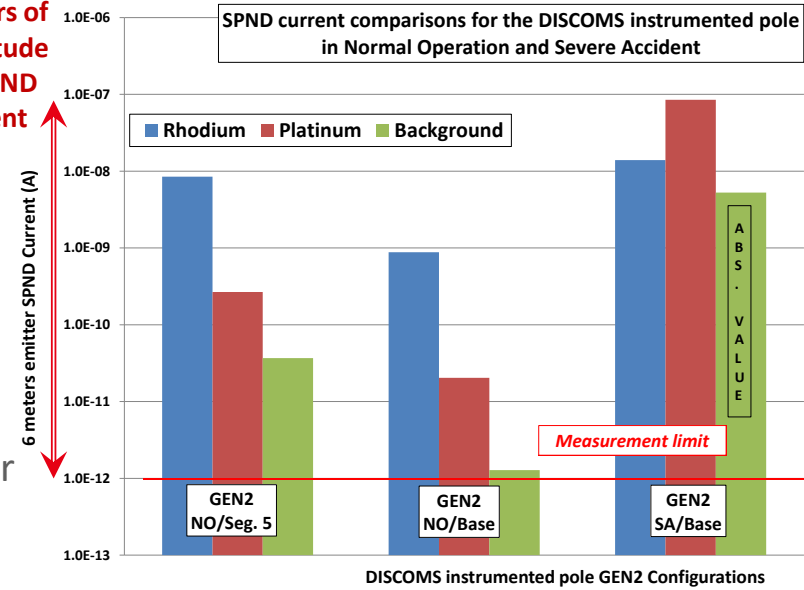
instrumented SPNDs-TC pole
structure modelled with CEA
MATiSSe toolbox

instrumented pole
section overview

Electronics current amplification device design & qualification

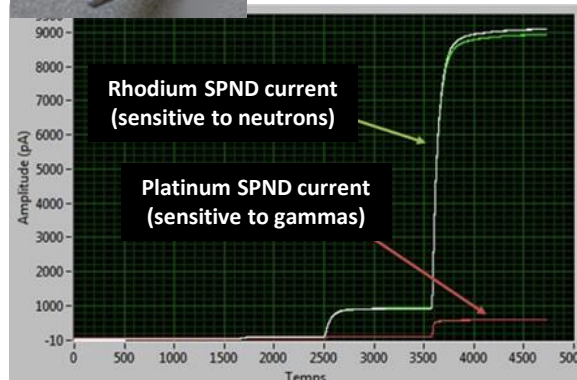
- **1 pA current detection threshold**
 - From Normal Operation to Severe Accident with corium in the vessel (no relocation)
 - Vessel breakthrough with corium pouring on the floor
- **Dedicated amplification device [1 pA 100 nA]**
 - Qualified with ^{60}Co source projector & in research reactor

5 orders of magnitude for SPND current

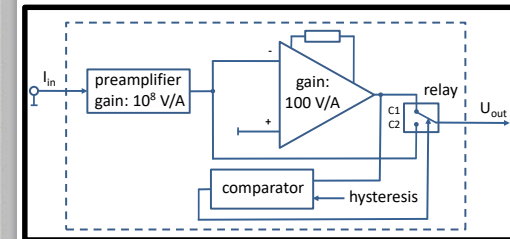


source: L. Barbot et al., 2018

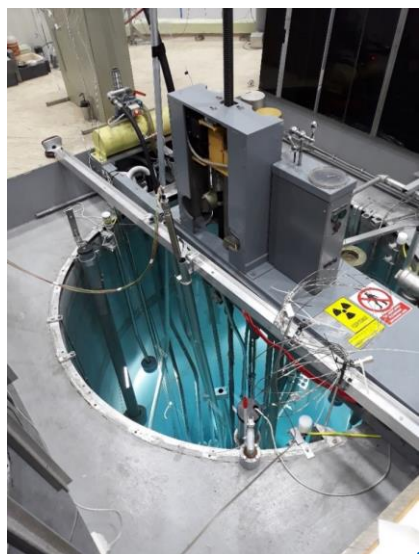
6 m long instrumented pole manufactured by THERMOCOAX



Rhodium & Platinum SPNDs current measurements during tests in reactor



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



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

Results achieved in DISCOMS project prior to final MCCI VULCANO experiment

- Modelling γ 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 2×10^{16} to 2×10^{14} $\div 100$	from 5.7 to 0.7 $\div 8.1$
Gen III (EPR)	from 2×10^{14} to 10^{12} $\div 200$	from 2.1 to 0.022 $\div 95$

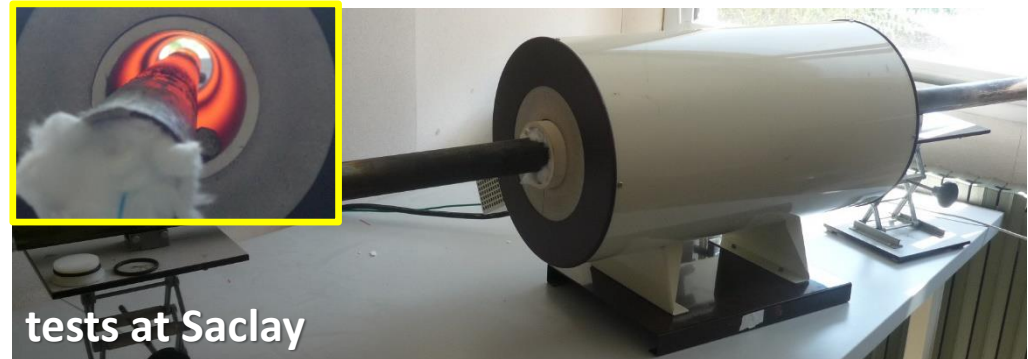
NO: Normal Operation / SA: Severe Accident

- **60 years NO is the most damaging process in comparison with 24 hours SA**
- Rad-Hard optical fibers selection & qualification in γ 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 H₂**
 - ✓ **Protective carbon layer against** diffusion of di-hydrogen **H₂** 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

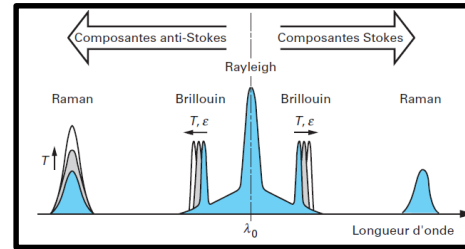
strain cables	temperature cable	security cable
optical fiber systematically broken between 400°C & 450°C	pass (but not a product specification)	pass

the two most interesting cables are:

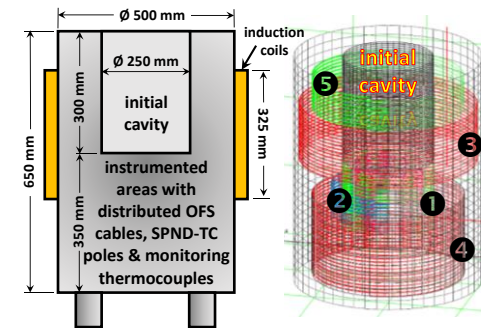
- the **security cable** → up to 750°C (90+ min)
- the **strain sensor cable** → earlier break

Concrete crucible instrumentation

- **5 OFS cables connected to 5 optical reflectometers for sensing**
 - Photon-counting & telecom **OTDRs** → **cables length**
 - **Brillouin B-OFDA** (closed loop) → **{ $\Delta\varepsilon$ & ΔT }**
 - **Rayleigh OFDR** → **high-resolution { $\Delta\varepsilon$ & ΔT }**
 - **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



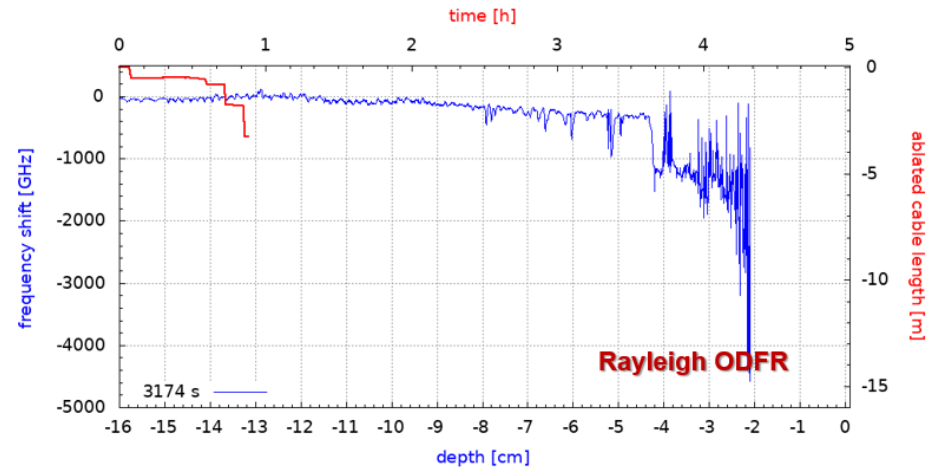
concrete crucible installed with the induction coils at CEA in Cadarache
PLINIUS facility

- **50 kg prototypical UO₂ (no radiation)**
 - Corium obtained with strong exothermic thermite reaction
- **100+ thermocouples to monitor the temperature propagation front**

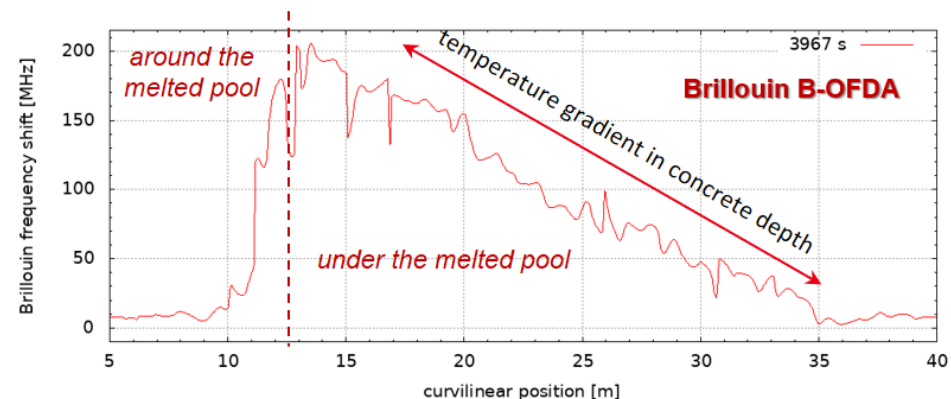
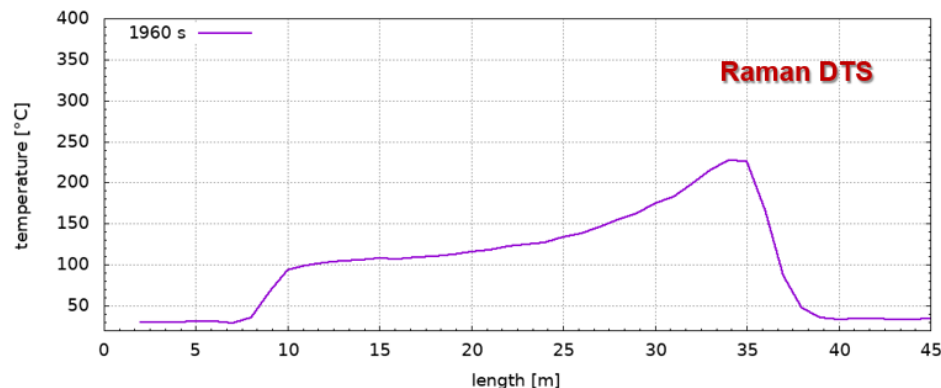
Distributed Optical Fiber Sensors measurements during MCCI (animated GIFs)



thermite reaction ignition to produce corium



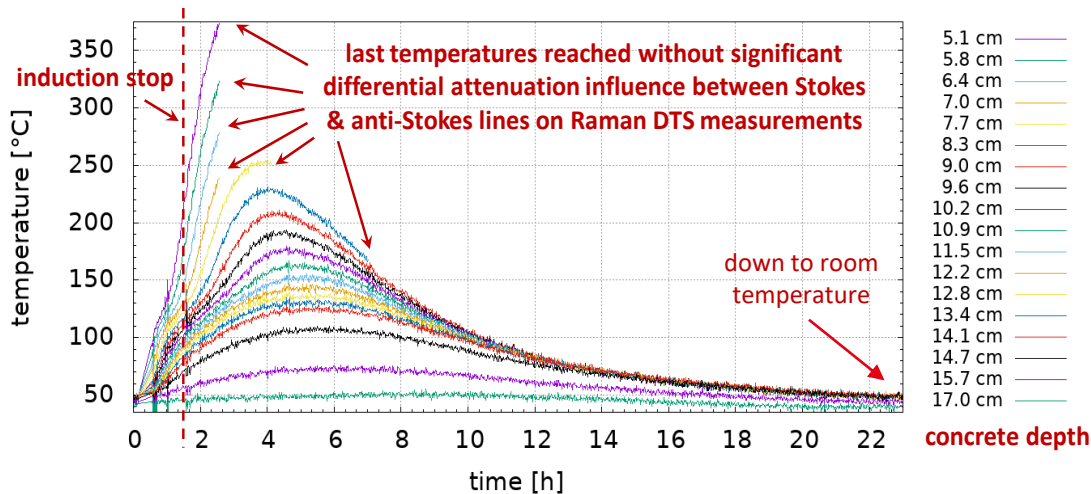
✓ **corium vicinity detected** only a few minutes after the ignition



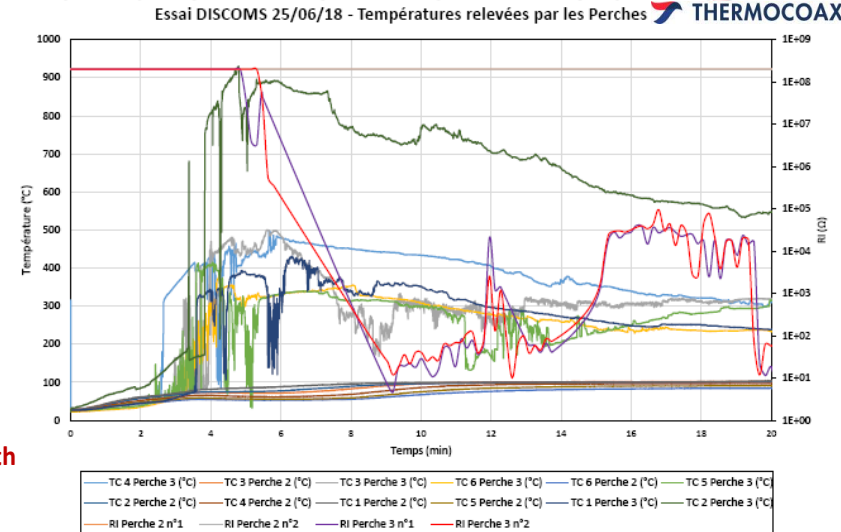
Temperature (Optical + SPNDs-TC instrumented poles) measurements during MCCI

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
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