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Temperature ramps for severe accident instrumentation in nuclear reactor cavity concrete

**Christophe Journeau, Viviane Bouyer, Arthur Denoix, Jean-François Haquet, Anne Boulin,
Quentin Souquet, Laurent Maurin, Gwenaél Jouvin and Hamid Makil**

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Research institute on nuclear systems for low-carbon energy production

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- Context - Objectives
- Numerical simulation of concrete heat-up
- Experimental simulation of heatup due to Molten Core Concrete Interaction
- Conclusion

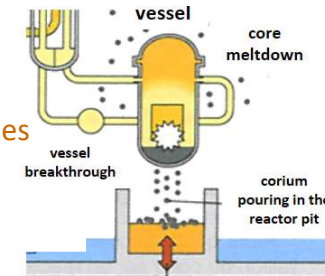
▪ Distributed Sensing for Corium Monitoring and Safety – DISCOMS

◆ Post-Fukushima Daiichi accident project

- Total loss of electrical power sources following tsunami, TEPCO operator with almost no data about accident status and its evolution

◆ 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 detection
 - Corium interaction with concrete monitoring until its prospective breakthrough
 - Long term corium cooling monitoring



Molten Core – Corium Interaction (MCCI)

◆ 2 technologies: long length SPNDs-TC & Distributed Optical Fiber Sensors

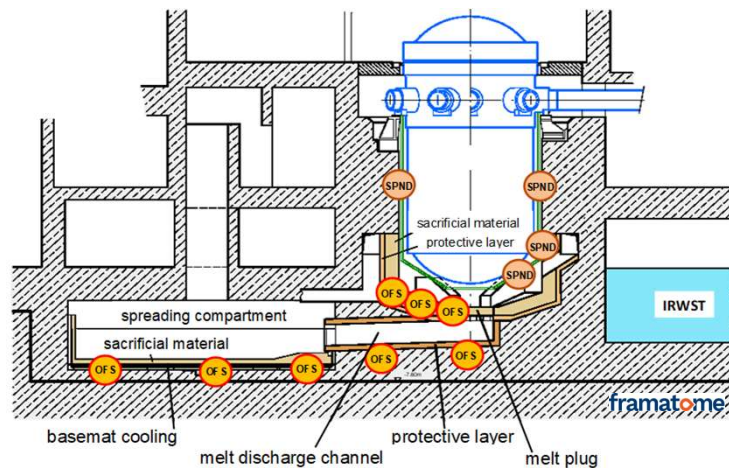
- **ex-core** measurements designed for Gen II & Gen III (EPR)

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

◆ Ended in Dec. 2018



- *ex-vessel* candidate positions (reactor pit, melt discharge channel & spreading compartment) for long length SPNDs-TC & OFS cables



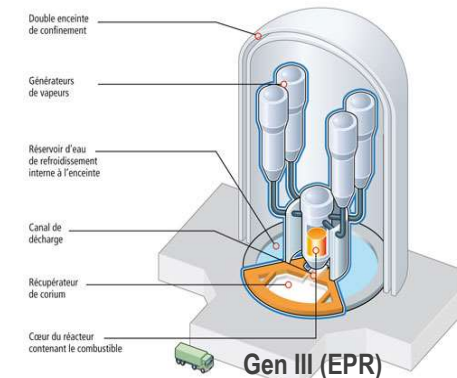
- currents generated under radiations – battery operated capable monitoring system
- long (several meters) lengths SPNDs to get the adequate sensitivity for *ex-core* detection



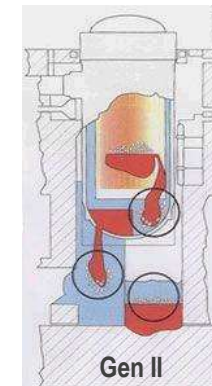
- rely on the properties of the backscattered light in optical fibers and reflectometry
- passive sensors with remote measurement systems up to several km away from the NPP area

Information, remotely obtained, even in case of total loss of power supplies:

- to **increase** the nuclear **safety**,
- to **reduce** operator **exposition** to ionizing radiations,
- to **avoid** the **breach of last containment barrier & environmental consequences** with on-time & appropriate mitigation strategies



Gen III (EPR)



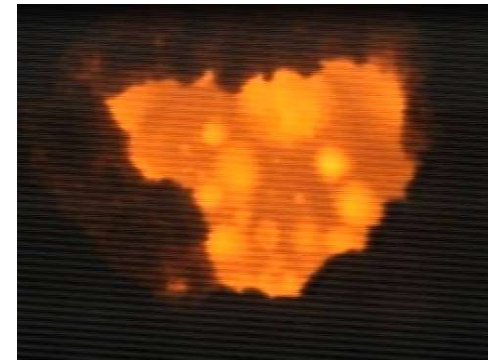
Gen II

Interaction of hot and heated corium with basemat concrete

- Thermal ablation of concrete
- Mixing of melted concrete with oxidic corium pool
- Sparging of concrete decomposition gases in corium pool
- Concrete thermal diffusivity is small : a few $10^{-7} \text{ m}^2/\text{s}$

Issue:

- Temperature ramp that will be experienced by a sensor embedded in basemat concrete to monitor its ablation ?





NUMERICAL SIMULATION

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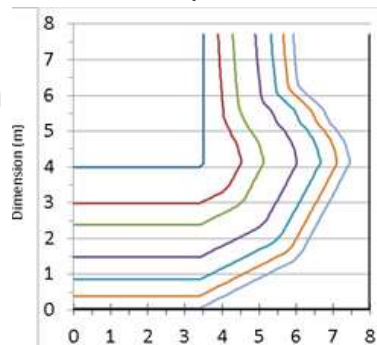
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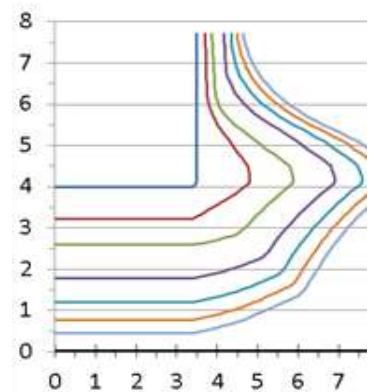
Typical scenarios computed for a generic 900 MWe PWR

Lines correspond to ablation profiles after 0.5, 1, 2, 3, 4, 5, 6 and 7 days

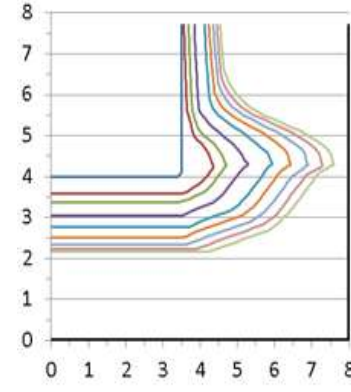
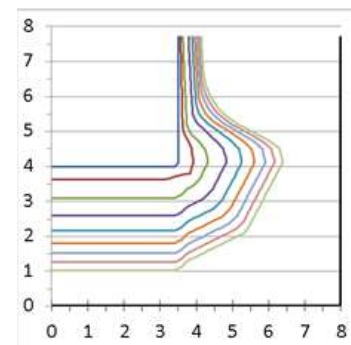
Limestone-rich
concrete



Silica-rich
concrete

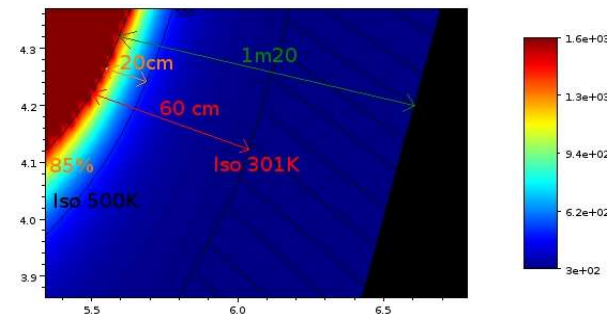
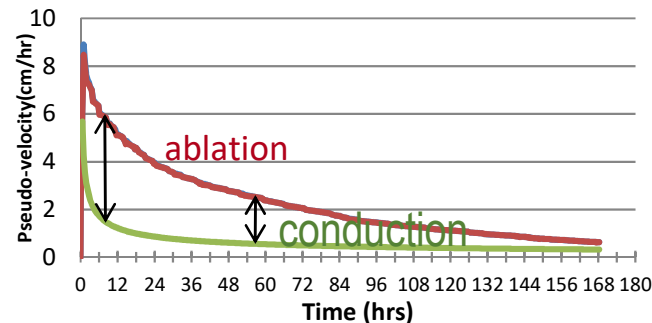


Interaction starts 2 hours after SCRAM



starts 60 hrs after SCRAM

- Low thermal diffusivity
- It is possible to compute heat conduction pseudo-velocity
 - ☐ Conduction is always slower than ablation
 - ☐ For 10 cm depth, characteristic diffusion time is ~ 5 hrs
 - ☐ Concrete will not be significantly preheated before the ablation front approaches
- Sensors will not be submitted to a long-term high temperature rise before they are close to ablation.
- Finally, small-scale experiments are representative of the temperature transient that would be experienced by a sensor inside the concrete.



After 4 1/3 days of interaction,
+200 K at 20 cm from front
only 1 K heat up at 60 cm from front !



EXPERIMENTAL SIMULATION VULCANO VB-U10

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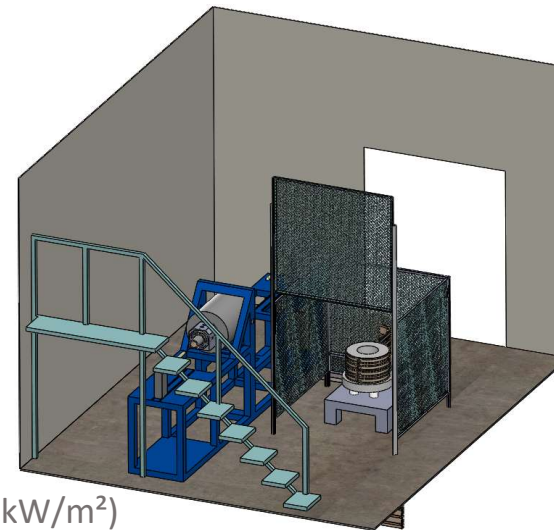
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○ Objective: Test in prototypic conditions DISCOMS sensors and provide data on temperature ramps

- Corium with chemical composition close to what is expected for a severe accident but with different isotopic composition (depleted uranium, no Fission Products)
- Radioactive decay heat simulated by induction heating
- Limestone-Common Sand concrete, typical of some Gen2 plants maximizes oxidizing gas releases

○ Test device

- Concrete crucible $\varnothing 250$ mm x 300 mm
- 50 kg corium
 - Chemical melting
 - 2100°C in 1 minute
- Inductive heating
 - 1h30 interaction
 - Representative heat fluxes (100-200 kW/m²)
 - After 3'40" at high power

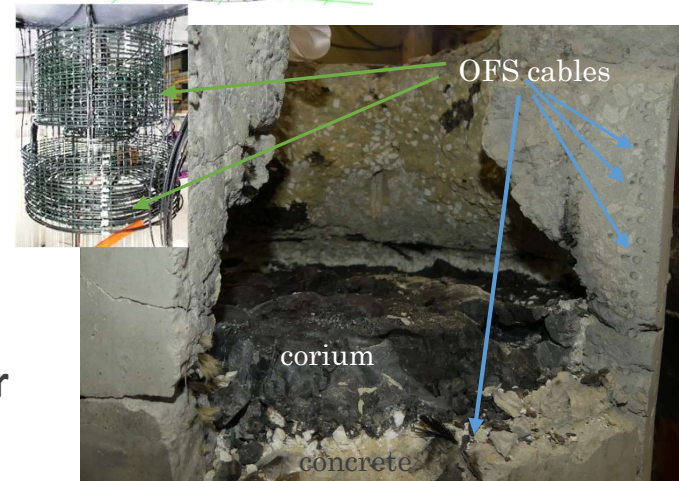
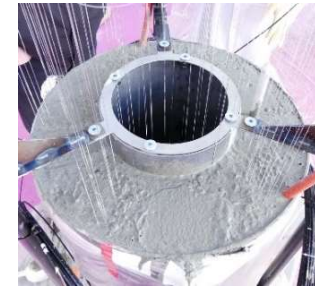
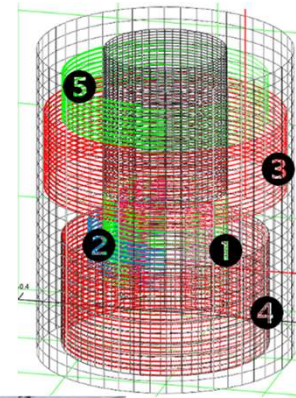


5 distributed Optical Fiber Sensors

- Telecom OTDR
- photon-counting OTDR,
- Rayleigh OFDR,
- Raman DTS
- Brillouin B-OFDA reflectometers,

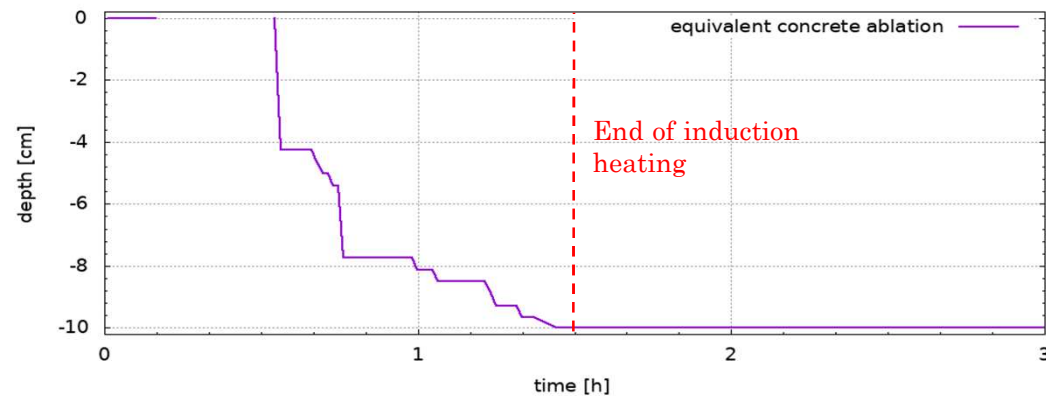
connected to the winded OFS cables installed in the concrete test section

Concrete had been poured over the optical fiber sensor cables



■ Winded Raman DTS sensor: Radial ablation

equivalent concrete depth ablation during DISCOMS Vulcano experiment
DTS Raman LIOS™ OTS3 PRE.VENT - cable #5



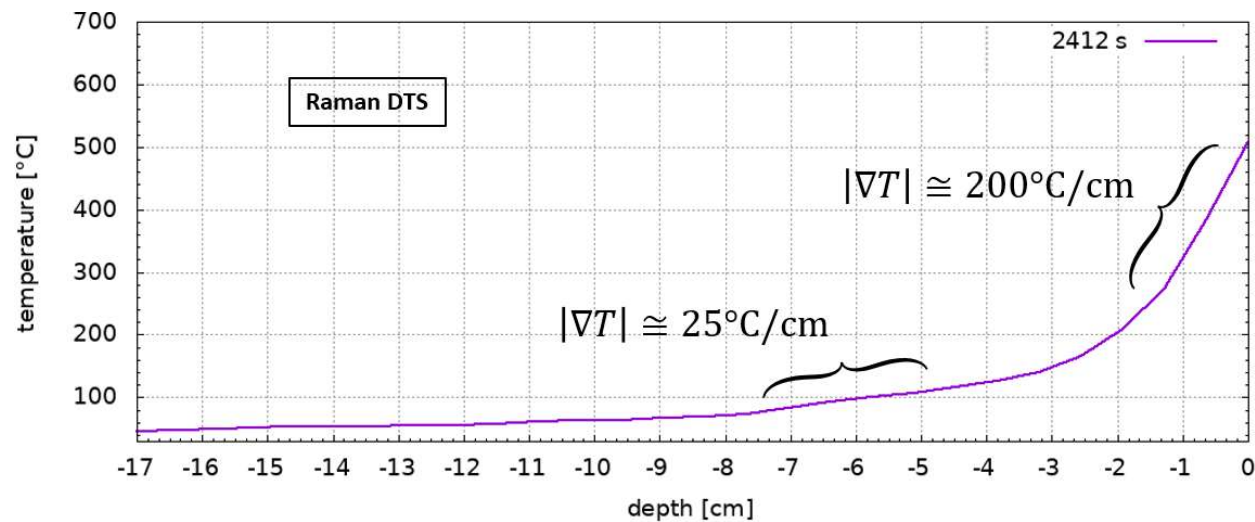
- ☐ Stepwise ablation process
- ☐ Average radial ablation rate $\sim 1 \text{ mm/min}$

■ Winded Optical Time-Domain Reflectometer: Axial ablation

- ☐ Stepwise $\sim 0.4 \text{ mm/min}$

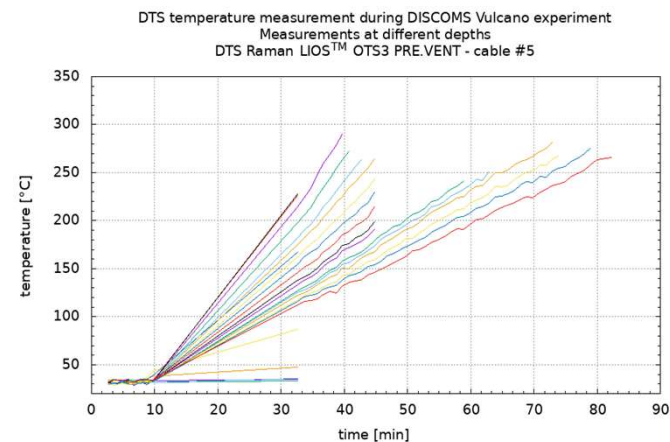
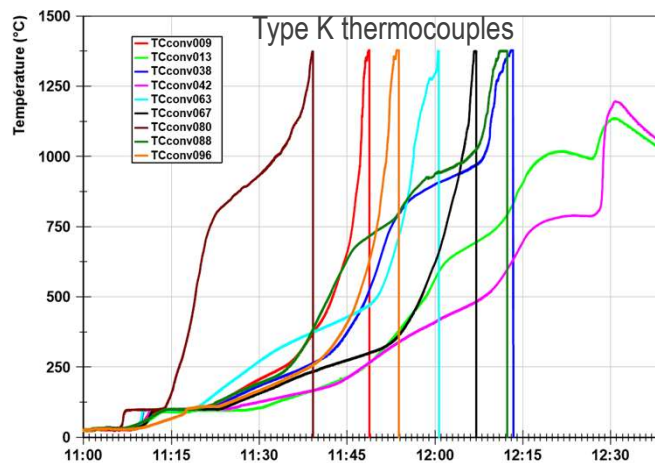
Winded Raman DTS fiber

- **Example of thermal gradients after 2400 s**
 - $2 \cdot 10^4$ K/m in top 2 cm (near the melt)
 - $2.5 \cdot 10^3$ K/m 5 cm deeper...



■ Temperature has been measured in concrete by thermocouples and Raman DTS Optical Fiber sensors at various locations.

- Heating rates of ~ 200 K/min have been observed by TCs when temperatures over 700°C are reached.
- Optical fibers are destroyed at lower temperatures.
 - Steady temperature ramps of the order of 10 K/min observed in the 100 - 300°C range



- **Due to the low thermal diffusivity of concrete compared to expected ablation rates, concrete heat-up would affect only a limited depth close to the moving ablation front.**

- ☐ This justifies the use of small scale experiments to simulate the reactor case.

- **Thanks to VULCANO VB-U10 test, Optical Fiber Sensors have been successfully tested.**

- ☐ They withstood 2.10^4 K/m thermal gradients

- ☐ and heat-ups of about 10 K/min until damages starts in the 200-300°C range

- ☐ This is satisfactory for accident progression monitoring purposes.



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