Temperature ramps for severe accident instrumentation in nuclear reactor cavity concrete

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ABSTRACT

Distributed Optical Fiber Sensing and Self-Powered Nuclear Detectors are potential innovative instrumentation for the management of severe accidents. The former can monitor temperature, strain, and/or presence of hot melt while the latter is more dedicated to gamma radiation measurements and can also be coupled to thermocouples for temperature measurement purpose. These sensors could be installed in the basement concrete to monitor corium progression (arriving in lower head, later on in the reactor pit, reaching a predefined level in concrete before melt through…). In order to assess the temperature evolution that these sensors may experience, thermal conduction in concrete structures was modelled coupled with TOLBIAC-ICB calculation results for several typical scenarios. This confirmed that, due to concrete low thermal conductivity, ablation progresses more rapidly than conduction, except in a small zone close to the ablation front. Therefore experimental temperature profiles from prototypic corium-concrete interaction experiments can be used to specify the temperature profiles that sensors inserted in the reactor cavity can withstand during such severe accident. A first experiment, VULCANO VB-U10, has been carried out to study the behavior of 5 distributed optical fiber sensors that were installed inside a concrete crucible experiencing ablation by prototypic corium. These instruments have been used in this test to monitor the concrete temperature and/or its ablation. During this test, 50 kg of prototypic uranium-containing corium have interacted for 98 minutes with a lime-siliceous concrete leading to an axial ablation of 25 mm and a radial ablation of 80 mm. Optical fiber length measurements with Rayleigh OFDR technique have been found to be coherent with data from thermocouples installed in the concrete as in previous VULCANO experiments. Raman DTS measurements provided satisfactory temperature evolution results. This good performance of the distributed temperature measurement has been validated in conditions representative of a severe accident.

KEYWORDS: Severe Accident, Distributed Optical Fiber Sensor, Thermocouples, Corium, MCCI, High Temperature

1. INTRODUCTION

During Station Black Out severe accidents, such as the accidents in Fukushima Daiichi Nuclear Power Station, there is almost no instrumentation available to inform about the progression of the accident due to the absence of electrical power. The French national project DISCOMS [1] has been carried out to develop innovative instrumentation to monitor severe accident progression: Distributed Optical Fiber Sensing and Self-Powered Nuclear Detectors. The former can monitor temperature and/or strain profiles, and/or presence of hot melt while the latter is more dedicated to gamma radiation measurements and can also be coupled to thermocouples for temperature measurement purpose.

Several concepts have been proposed for molten core ex-vessel stabilization and retention [2], both for existing and future plants. Even if these concepts rely on passive operation, monitoring of molten core (corium) progression by sensors that could continue operations even in the absence of electrical power supply in the reactor building.

These sensors could be installed in the concrete to monitor corium progression (arriving in lower head, later on in the reactor pit, reaching a predefined level in concrete before melt through, and, in case of external core catcher such as in EPR [2], in the melt discharge channel and core catcher concrete layers). Typical positions (for an external core-catcher layout case) are presented in Figure 1.

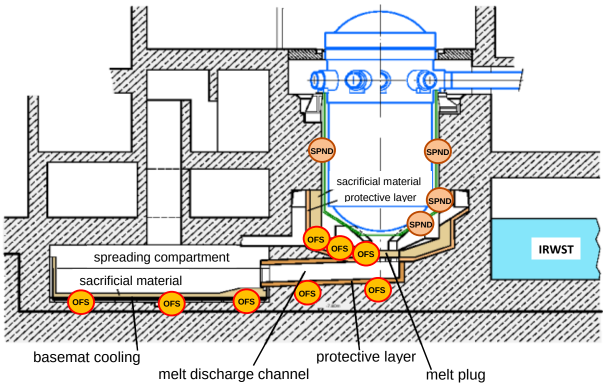

Figure 1 – SPNDs-TC & optical fibre sensing cables (OFS) *ex-core* locations for Severe Accident monitoring

In order to assess the temperature evolution that these sensors may experience, thermal conduction in concrete structures has been modelled coupled with TOLBIAC-ICB calculation results for several typical scenarios. Then, temperature measured during a dedicated Molten Core Concrete Interaction experiment in VULCANO facility [4] are presented.

2. SIMULATION OF CONCRETE HEAT-UP

Molten Core Concrete Interaction experiments have shown a significant influence of concrete composition on ablation profiles [5]. Therefore simulations have been conducted both for silica-rich and limestone-rich concretes. In addition, since corium decay heat decreases with time, the effect of vessel melt through time has been considered with calculations made for assumed melt through 2 hours and 60 hours after SCRAM. Figure 2 presents the evolution of ablation profiles computed with TOLBIAC-ICB for a generic 900 MWe PWR.

As concrete diffusivity is small (some $10^{-7} m^2/s$ depending on composition, temperature and concentration in reinforcement bars), the progression of the heat wave caused by thermal conduction is essentially slower than that of the ablation front during reactor basemat ablation, as visible for instance in Figure 3.

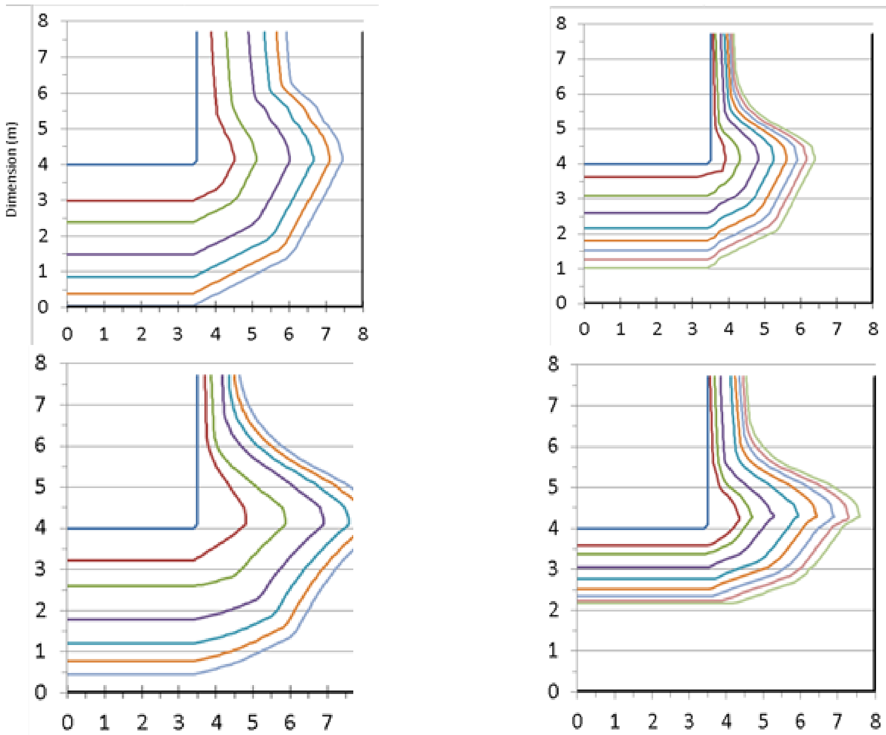

Figure 2 – Computed MCCI progression for limestone-rich (upper line) and silica-rich (lower line) concretes for an interaction starting 2 hours (left column) or 60 hours (right column) after SCRAM.
Lines correspond to ablation profiles after 0.5, 1, 2, 3, 4, 5, 6 and 7 days.

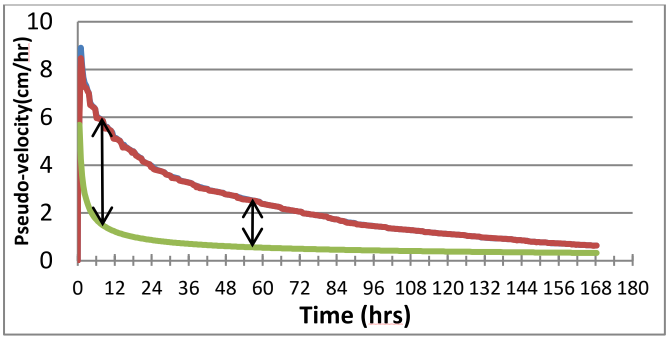

Figure 3 – Comparison of ablation (in red) and conduction (in green) pseudo-velocities.

For severe-accident sensors, this implies that there will be no significant temperature signal before the ablation front is close to the sensor (for a depth of 10 cm below the front, characteristic heat diffusion time is already of the order of 5 hours). A finite volume modelling of heat conduction in concrete, linked to the moving melting front from TOLBIAC-ICB calculations has been considered. It shows that even after a long interaction (in Figure 4, 4 days 8 hours leading to the ablation of about 3 meters of concrete) 85% of the thermal gradient is concentrated in a 20 cm layer. At 60 cm from the ablation front, heat-up is of only 1 K, whereas corium is more than 1000 K hotter than concrete initial temperature. Another result of this analysis is that the shape of the temperature profile is not affected by the progression of the ablation front.

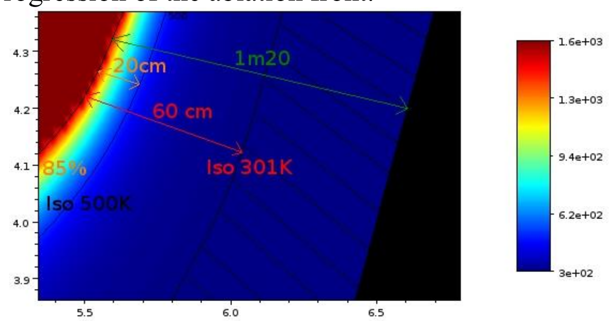

Figure 4 – Zoom on computed temperature map in concrete after 4.33 days of interaction

It implies that the sensors will not be submitted to a long term high temperature rise before they are close to ablation. Finally, it implies that small-scale experiments are representative of the temperature transient that would be experienced by a sensor inside the concrete.

3. VULCANO VB-U10 EXPERIMENT

A dedicated MCCI experiment, VULCANO VB-U10 [4], has been carried out to study the behavior of 5 distributed optical fiber sensors that were installed inside a concrete crucible experiencing ablation by prototypic corium (Figure 5). Telecom and photon-counting OTDR, Rayleigh OFDR, Raman DTS and Brillouin B-OFDA reflectometers, connected to the OFS cables installed in the concrete test section, were used to monitor its temperature and/or its ablation.

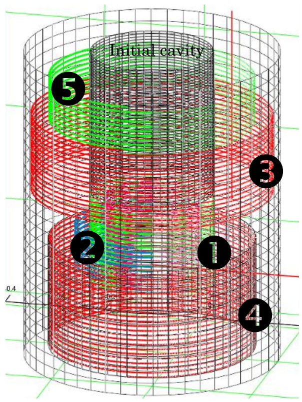

Figure 5 – Drawing of the 5 OFS cables tested in VULCANO VB-U10 concrete

During this test, 50 kg of prototypic uranium-containing corium have interacted for 98 minutes with a lime-siliceous concrete leading to an axial ablation of 25 mm and a radial ablation of 80 mm. Figure 6 presents a view of VULCANO VB-U10 ablated concrete test section with corium pool after an angular sector of concrete has been cut out. Some Optical Fiber Sensor cables are shown by arrows.

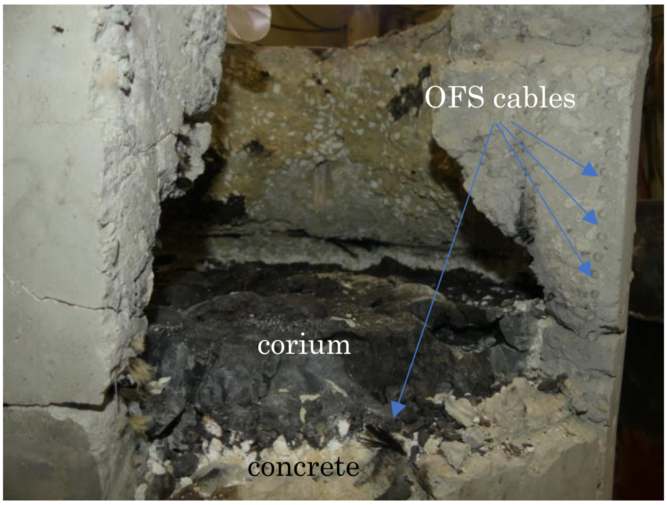

Figure 6 – Post test view of VULCANO VB-U10 after partial cutting of concrete

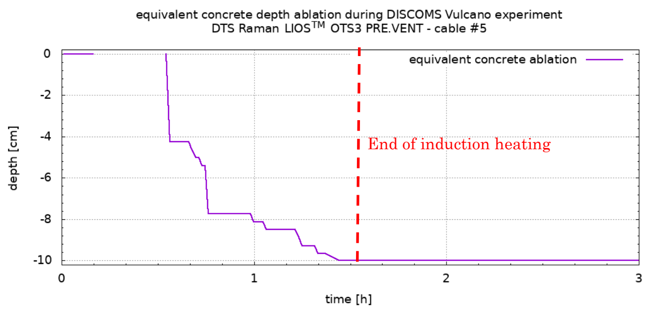

Figure 7 –Raman DTS sensor: radial ablation depth

Winded Raman Distributed Temperature Sensor (DTS) [Fiber # 5 on Figure 5] has been used to assess the progression of radial ablation (Figure 7). Ablation is discontinuous, with an average velocity of the order of

1 mm/min during the period in which decay heat was simulated by induction in the corium melt. For the axial ablation, the winded Optical Time-Domain Reflectometer (fiber #1 in Figure 5) gives also a stepwise ablation with a smaller average velocity (~0.4 mm/min).

Winded DTS fiber #5 indeed provides temperature profiles. For instance, Figure 8 shows, after 40 minutes, a maximum gradient of about 2.10^4 K/m in the top 2 cm, while thermal gradient was much smaller (~2500 K/m) 5 cm farther.

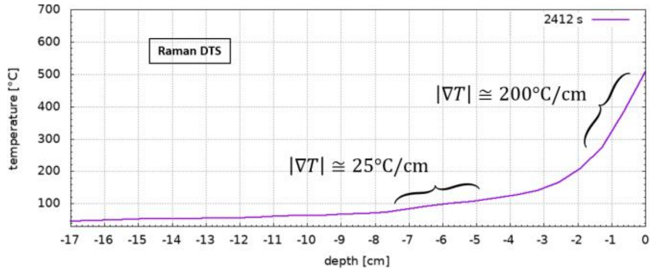

Figure 8 – temperature profile vs. concrete depth (Raman DTS fiber #5)

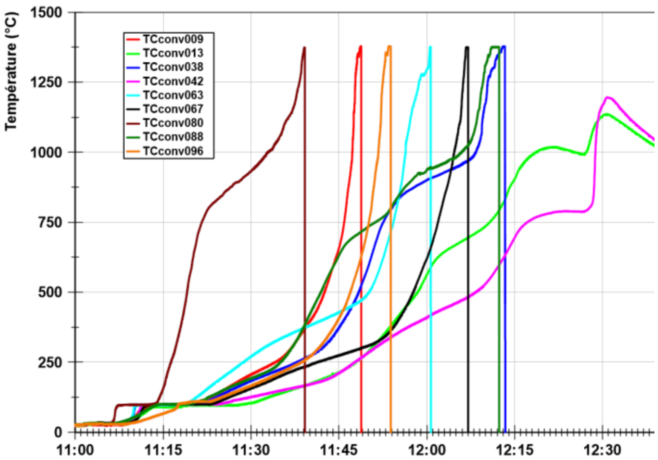

Figure 9 – Evolution of thermocouples positioned close to fiber #5

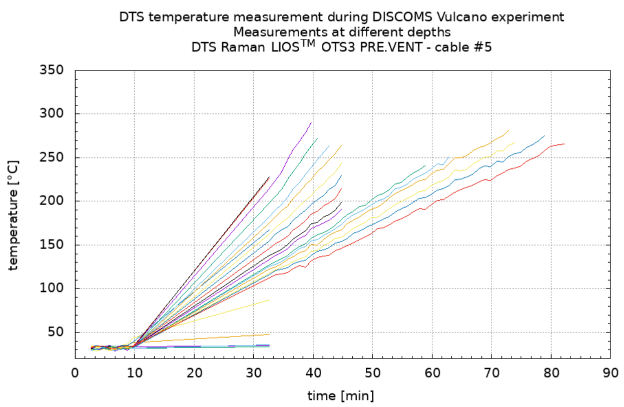

Figure 10 – Evolution of DTS temperature at various depths from 1.5 to 10.05 cm

Type-K thermocouples have also been embedded in the concrete near optical fibres. Figure 10 presents the evolution of 9 sensors positioned close to this optical fiber. Typical heating rates of 200 K/min have been observed when high temperatures (> 700°C) are reached, while, as measured by Raman DTS (Figure 9), it is around 10 K/min in the 100-200°C range.

4. CONCLUSIONS

Due to the low thermal diffusivity of concrete compared to expected ablation rates, concrete heat-up rate 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, which is satisfactory for accident progression monitoring purposes.

5. ACKNOWLEDGEMENTS

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