

## Oxide-Metal Corium –Concrete Interaction Test in the VULCANO Facility

Christophe Journeau, Pascal Piluso, Jean-François Haquet, Sylvie Saretta, Eric Boccaccio, Jean-Michel Bonnet  
CEA Cadarache

*Severe Accident Mastery experimental Laboratory (DEN/DTN/STRI/LMA)*

*Building 708, F-13108 St Paul lez Durance, France*

*Tel: +33 (0)4 42 25 41 21 , Fax: +33 (0)4 42 25 77 88 , Email: christophe.journeau@cea.fr*

**Abstract** – *In the hypothetical case of a severe accident, the reactor core could melt and the formed mixture, called corium, could melt through the vessel and could interact with the reactor pit concrete. Corium is made of a UO<sub>2</sub>-rich oxidic part, in which most of the decay heat is dissipated, and of a metallic part, mainly molten steel. Up to now, due to experimental constraints, most of the experiments have been performed with solely oxidic prototypic corium, or were designed so that most of the simulated decay heat was dissipated in the metallic layer. An experiment has been set up in the VULCANO facility in which oxidic and metallic mixtures are molten in separate furnaces and poured in a concrete cavity. Induction heating is provided to the pool upper part thanks to shielding coils, so that, in case of stratification, the lighter oxidic corium-concrete mixture receives most of the power. Pre-calculations with the TOLBIAC-ICB corium-concrete interaction code based on the phase segregation model have provided valuable information for the dimensioning of this test: a thick metallic layer (>10 kg or 4 cm) has been chosen in order to obtain significant cavity ablation profiles depending on the selected heat transfer and stratification models. Stratification of the two liquid phases is predicted to occur in less than 10 minutes. On September 21st, 2006, the experiment was performed in the VULCANO facility. The corium was made of about 15 kg of steel at 1700°C and 30 kg of oxides (70% UO<sub>2</sub>, 16% ZrO<sub>2</sub> and 14% concrete load) above 2000°C. It was poured in a limestone-rich concrete. This concrete type was selected for the first test, since the ablation is isotropic except for the initial transient, during oxidic corium-concrete interaction tests. 32 kW of induction power have been provided to the pool during the 4-hour test. The destruction of in-concrete thermocouples indicates that ablation was first mainly radial then became isotropic. This is quite similar to the ablation progression observed during previous tests with oxidic corium interacting with this type of concrete. Important “volcanic activity” has been observed at the corium pool surface, compared to the previous oxidic corium experiments at VULCANO. Post-test analyses are underway and should provide useful insight in the phenomena that occurred and will be compared to the pre-calculations.*

### I. INTRODUCTION

In the hypothetical case of a nuclear reactor severe accident, the core could melt and, in some scenarios, reach the reactor pit. In this configuration, the molten mixture, called *corium*, is interacting with concrete. Experimental research programs<sup>1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11</sup> have been conducted worldwide to study the phenomenology of corium-concrete interaction.

Corium is made from a UO<sub>2</sub>-rich oxidic part, in which most of the decay heat is dissipated, and from a metallic part, mainly molten steel. Most of these experiments have been conducted with only an oxidic corium pool. In some

experiments<sup>1, 7</sup>, non-miscible oxide and metal phases were present in the corium, but the sustained heating was mainly generated in the metallic phase, whereas, in reactor case, around 85% of the decay heat is generated in the oxide phase<sup>12</sup>. The objective of the VULCANO VBS test series is to study experimentally with prototypic materials the 2-D interaction with concrete of a corium containing a metallic and an oxidic phase, in a configuration for which much of the sustained heating is provided to the oxidic phase layer.

In the first section, the test facility will be presented. Then precalculations with the TOLBIAC ICB code<sup>13</sup> will be discussed. Finally, preliminary results of the first test,

VBS-U1, performed with limestone-rich concrete will be shown.

## II. DESCRIPTION OF THE FACILITY

### II.A. The VULCANO Furnace

The VULCANO facility<sup>14, 15</sup> is mainly composed of an oxidic furnace<sup>16</sup>, metal furnaces and a concrete test section, which can be adapted to the specificity of each experiment. In order to conduct experiments with depleted uranium dioxide under acceptable safety conditions, the furnace has been developed according to the following characteristics:

- § Highest acceptable melting temperature of the load: 3000°C;
- § Ability to melt mixtures of various compositions [in-vessel corium (UO<sub>2</sub>- ZrO<sub>2</sub>, Fe), ex-vessel corium (in-vessel + concrete decomposition products: SiO<sub>2</sub>, CaO, FeOx, Al<sub>2</sub>O<sub>3</sub>, MgO,...)];
- § Capacity to melt and pour up to 80 kilograms of corium;
- § Continuous low pouring rates (0.1 to 1 L/s)

A study of the candidate technologies resulted in choosing a transferred plasma-arc furnace.

Two graphite plasma torches are ignited by an electrical short circuit. The main arc is then created and transferred between these two torches, each having opposite polarity. The plasma generator gases are argon and/or nitrogen plus, in some cases, corium fumes. The maximum available power is around 600 kW (1000 A – 600 V). For our operating conditions, the maximum arc voltage is below 200 V, i.e. an effective maximum power lower than 200 kW.

The mixtures to be melted are inserted as powders in a cylindrical rotating cavity (400 mm diameter – 500 mm long) and centrifugation (between 150 and 300 rpm) coats these mixtures against the furnace wall. The furnace external surfaces are water-cooled.

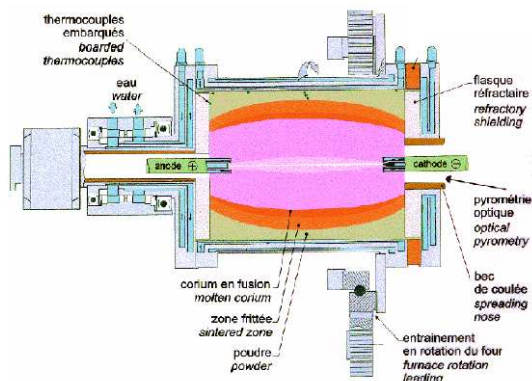


Fig. 1. The VULCANO furnace

First, a self-crucible of refractory oxides is achieved; then the corium powder is loaded and melted. The heating

process is controlled by optical pyrometers and on-board thermocouples.

When a sufficient quantity of corium has been melted, the arc power is reduced and the anode is withdrawn. The furnace is then tilted so that the melt pours out in the test section. The plasma arc is maintained during the pouring operation, in order to prevent too much cooling of the melt.

### II.B The Metal Furnaces

In order to melt the stainless steel necessary for the test, three induction furnaces have been used (Fig. 2). Each has a capacity of 8 kg. The steel is heated and molten thanks to induction coils and a RF generator operating around 22 kHz. The furnaces are covered by removable lids. Superheated molten steel is poured in the test section by tilting the cylindrical furnaces. The pouring phase has been done just after the oxidic melt has been poured in the concrete cavity.

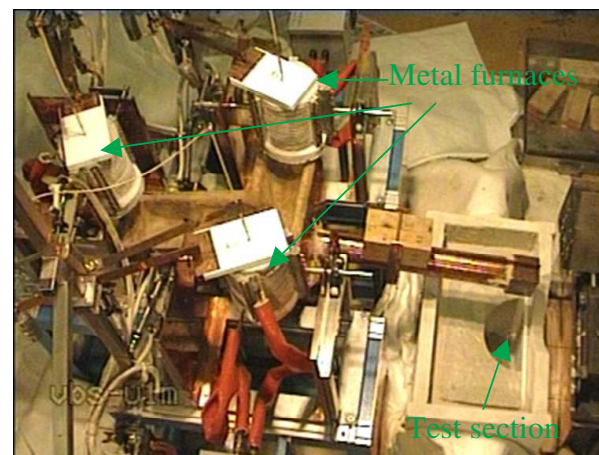


Fig. 2. Top view of the three metal furnaces and test section.

### II.C. The Concrete Test Section

The concrete selected for this test is similar to that of the VB-U6 test with oxidic corium<sup>17</sup>. It was made of CEM-I 52.5 N concrete and a mixture of limestone-siliceous and limestone aggregates (0-16 mm) from the Durance Granulats Peyrolles ballast Pit and the La Nerthe Quarry (Jean Lefebvre Méditerranée). Its global composition is about 25 wt. % SiO<sub>2</sub>, 41 % CaO, 2% Al<sub>2</sub>O<sub>3</sub>, 25% CO<sub>2</sub>, 3% H<sub>2</sub>O.

The test section (Fig. 3) is a 600 x 300 x 400 mm concrete block with a Ø300 x 250 mm hemicylindrical cavity in which corium is poured. More than 100 K-type thermocouples have been installed in the concrete to monitor its ablation as well as some high temperature C-type thermocouples. 4 parallel induction coils surrounds the section and provides sustained heating. Non-connected

copper coils are used to shield the magnetic field so that more than 80% of the heat is provided in the volume that will be filled by oxides after stratification. During the initial period when both phases make an emulsion, the heat will be provided to the continuous phase rather than to the dispersed phase, but this shall not affect the pool thermalhydraulics due to the fact that both phases are well mixed.

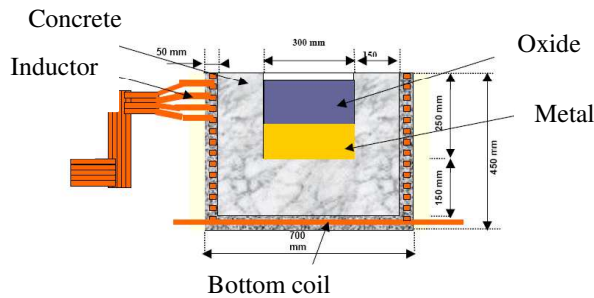


Fig. 3: Scheme of the concrete test section

### III. TOLBIAC-ICB PRECALCULATIONS

In case of vessel melt through, the exact process of the transfer of molten material from the vessel to the reactor pit will vary depending on scenari. During this period exothermal oxidation of the remaining metallic zirconium will also take place. It has been chosen, in a long-term retention perspective (tens of hours), to study the configuration when all the corium has been poured and all the zirconium has been oxidized.

For a typical PWR 900 MWe reactor, the materials obtained by melting the core and the internals are given in Table I. Two configurations are considered, one where the proportions of metals and oxides are conserved between the reactor case and the experiment and one with a thicker metal layer. In both these compositions (Table II), there is the same mass of oxides (31.5 kg) and the oxide phase is made of UO<sub>2</sub>, fully oxidized ZrO<sub>2</sub> and some concrete decomposition products.

TABLE I

Masses (in kg) of the core inventory

	Core	Internals
UO <sub>2</sub>	79600	
Zr	15580	
Fe	2712	18277
Cr	931	5876
Ni	965	3225

TABLE II

Oxide-metal Corium compositions (in kg)  
 used for calculations

	20%metal	50%metal
UO <sub>2</sub>	21.3	21.3
ZrO <sub>2</sub>	5.6	5.6
SiO <sub>2</sub>	3.6	3.6
CaO	1.0	1.0
Fe	5.6	18.8
Cr	1.8	6.0
Ni	1.1	3.7

In these calculations, a silica-rich concrete, similar to that of VB-U5<sup>11</sup> and CCI-3<sup>9</sup> tests, has been considered.

Stratification time is estimated from the BALISE<sup>18</sup> criterion: initially, the metallic and oxidic phases form an emulsion and stratification occurs when the gas superficial velocity is below the following threshold:

$$J_{g,lim} = 0.054 \frac{\rho_{heavy} - \rho_{light}}{\rho_{light}} \text{ (m/s)}$$

The stratification criterion is reached after 1175 s (20 min) for the 20% metal corium, and 575 s (~10 min) for the 50% metal configuration. Thus much of the test duration is expected to be in the stratified configuration.

TOLBIAC-ICB leaves the user to chose between two boundary conditions<sup>19</sup> at the interface between two liquid layers:

- The oxide and metal phases are supposed to be in thermodynamic equilibrium. There is no crust at the oxide-metal interface. Both phases have a common liquidus temperature that is assumed to be the interface temperature at the pool boundaries.
- The “out of thermodynamic equilibrium” configuration for which each pool is surrounded by a crust. In this case the crust compositions are different for each pool, and so are the interface temperatures. This configuration is thought to be the most probable on the long term.

Experimental evidences are needed to determine which hypothesis must be made for oxide-metal corium interaction with concrete.

Calculations have been made for the two considered compositions and both equilibrium and out of equilibrium hypotheses (Fig. 4 and Fig. 5). The sustained heating power has been set respectively to 36 and 28 kW, in order to have heat fluxes of 150 kW/m<sup>2</sup> for both configurations.

It appears that the choice of boundary condition at the interface does not significantly affect the ablation profiles. Posttest analyses should provide information on the differences since oxide debris should fall inside the metallic layer in the out-of-equilibrium configuration.

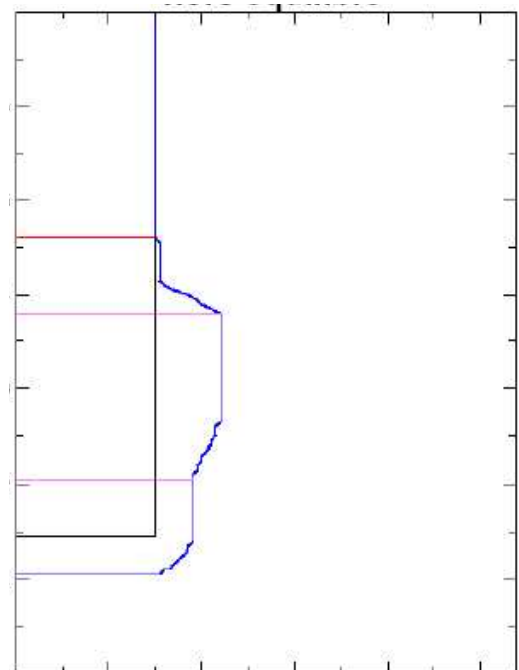
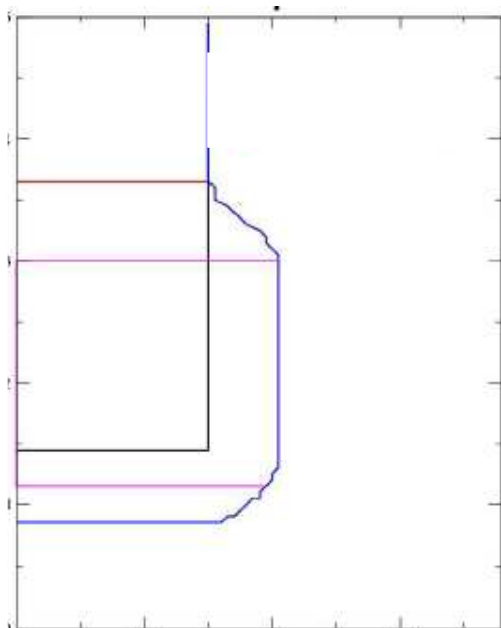
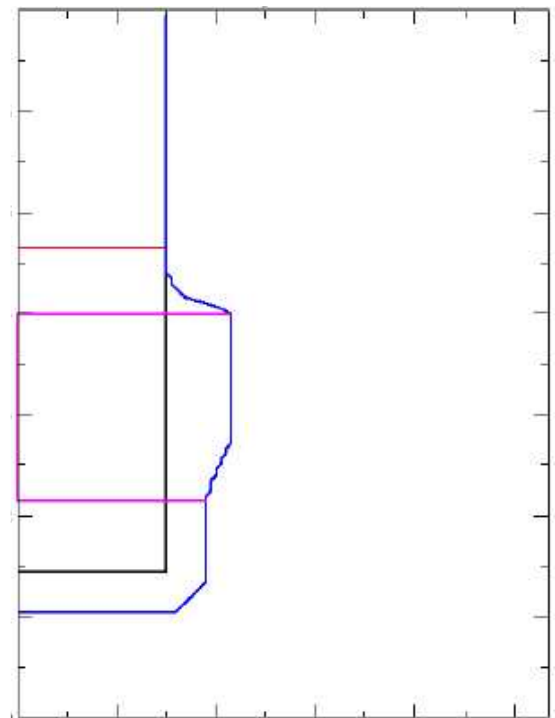
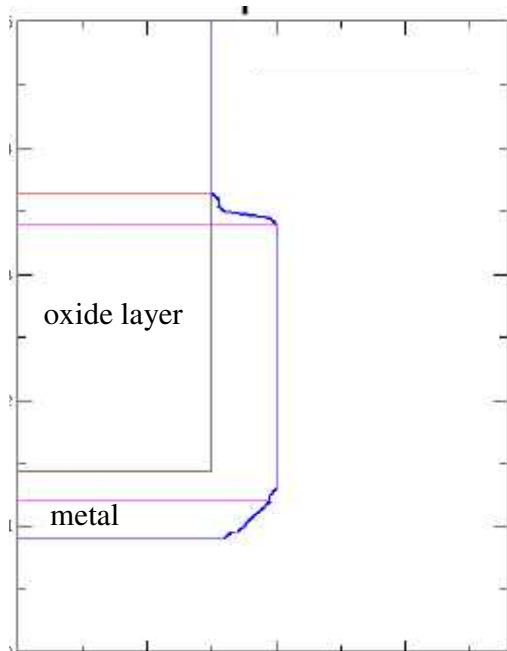


Fig. 4. Estimated ablation profiles at  $t=30$  s (black) and  $t=1$  hr (blue) for the composition with 20% metal. top : equilibrium; bottom: out of equilibrium at the oxide-metal interface. [purple lines indicate the upper levels of the metallic and oxidic layers at  $t=1$  hr, the red-orange line indicates the surface of the emulsionned pool at  $t=30$  s]

Fig. 5. Estimated ablation profiles at  $t=30$  s (black) and  $t=1$  hr (blue) for the composition with 50% metal. top : equilibrium; bottom: out of equilibrium at the oxide-metal interface. [purple lines indicate the upper levels of the metallic and oxidic layers at  $t=1$  hr, the red-orange line indicates the surface of the emulsionned pool at  $t=30$  s]

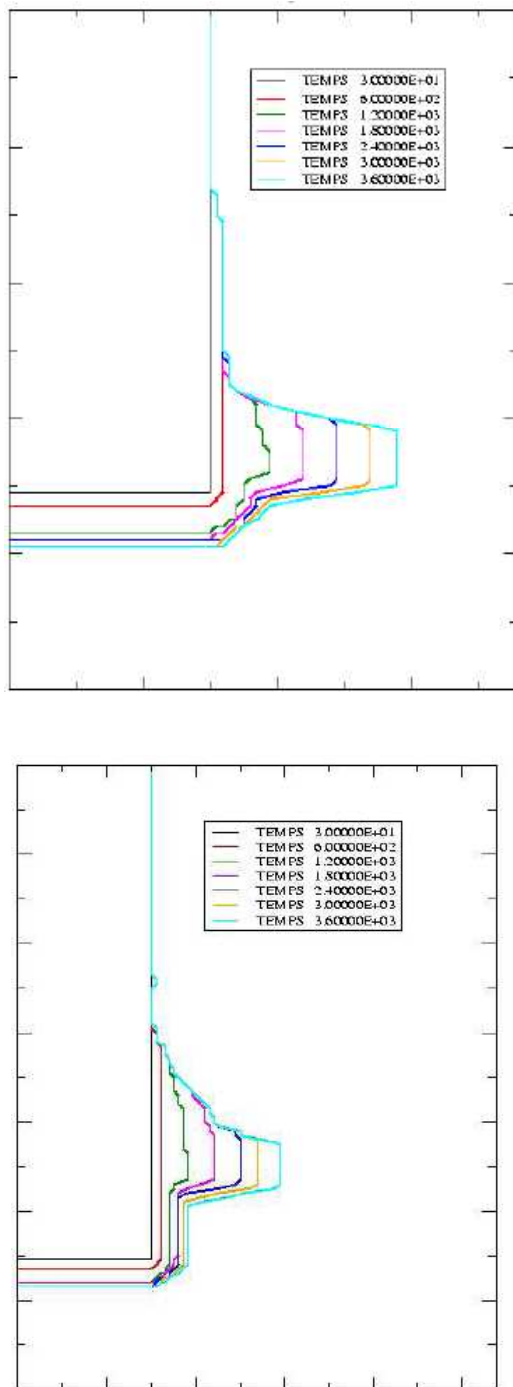


Fig. 6. Estimated ablations profiles at 30, 600, 1200, 1800, 2400, 3000 and 3600 s for anisotropic heat transfer coefficients. Top: 20% metal – Bottom 50% metal

On the opposite, the effect of convective heat transfer anisotropies is very important. Fig. 6 presents the evolution of ablations profiles for both compositions in the case Blottner<sup>20</sup> correlations are used on both horizontal and

vertical boundaries implying a large anisotropy in the oxidic pool heat transfer coefficients, and Greene<sup>21</sup> correlations for the oxide-metal interface.

TOLBIAC-ICB being coupled with a Gibbs energy minimizer, the composition of each phase is determined from the thermodynamic equilibrium and the oxidation energy is an output from the thermodynamic calculation. The oxidation power can reach 20 kW in the first 5 minutes. This power is of the same order of magnitude than that of the sustained heating. Fig. 7 presents the evolution of the masses of iron oxides and metallic iron throughout the test. It appears that about 4% of the iron is oxidized in the emulsionned stage, and about 1–2% after 1 hour. The results are of similar orders of magnitudes for equilibrium and out of equilibrium cases. This oxidation by the flow of steam and carbon dioxide leads to the formation of hydrogen and carbon monoxide. Both will burn when it enters atmosphere at high temperature. About 100-150 g/hr of hydrogen are expected, which is acceptable in the VULCANO containment, in which the atmosphere is renewed every two and half minutes.

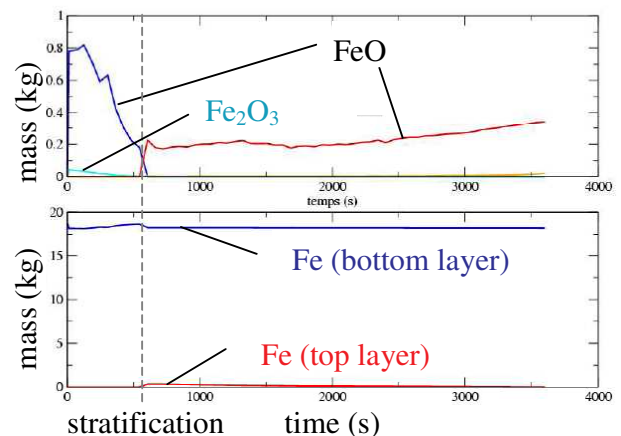


Fig. 7. Evolution of the masses of iron and iron oxides (50% metal)

#### IV. The VULCANO VBS-U1 Test

The VULCANO VBS-U1 has been performed at the PLINIUS Platform on the 20<sup>th</sup> and 21<sup>st</sup> September 2006. The corium load was made of about 15 kg stainless steel and about 35 kg oxides (70 mass% UO<sub>2</sub>, 16 % ZrO<sub>2</sub> and 14% concrete decomposition products). The oxides have been transferred in the limestone-rich concrete test section at a temperature around 2000°C, simultaneously with the molten steel at about 1700°C. Induction heating has been sustained for 4 hours at about 32 kW in order to study the interaction process.

The oxidic part of the corium melt was similar to the load used for the VULCANO VB-U6 test<sup>17</sup> (with purely oxide melt). The concrete composition was also similar to that of the VB-U6 test.

During the interaction, a continuous flow of gases (Fig. 8) was observed at the pool surface as well as large flames (presumably due to the combustion in air of hydrogen and carbon monoxide). This gas flow led to the ejection of corium particles. It must be noted that a crust with "volcanoes" formed at the pool surface and that the pool level frequently rose above the volcano altitude leading to small flows. This shows that the whole cavity was often filled by the multiphase mixture during the test.

22 to 33 minutes after the start of the experiment, the melt pool equivalent impedance varied significantly. This has been interpreted as an effect of metallic phase stratification, which changed the melt properties in between of the two series of shielding coils. This time is of the same order of magnitude than the calculated values, and the differences can be attributed to the uncertainty on the precise composition (and thus density) of the corium flowing out of the furnace, or on the correlation.



Fig. 8. Pool surface during the interaction

Concrete ablation has been monitored by the in-concrete thermocouples. During the first hour, ablation is anisotropic and is more efficient radially than axially. Then, the ablation has progressed roughly isotropically for the next three hours. Fig. 9 presents the ablation shape estimated from the thermocouples ruptures and the temperature field in the remaining.

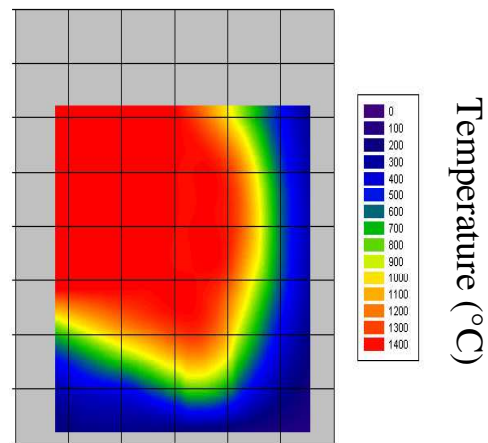


Fig. 9. Final view of the ablated cavity and of the temperature profiles in the concrete test section (arbitrary scale)

After the end of the test, six volcanoes (Fig. 10) have been found on the pool surface. These volcanoes were made of quite thin corium shells and a large cavity occupying more than half of the space that used to be filled with the corium pool has been found when the upper crust – including the volcanoes – has been dismantled.



Fig. 10. One of the volcanoes found on the corium surface.

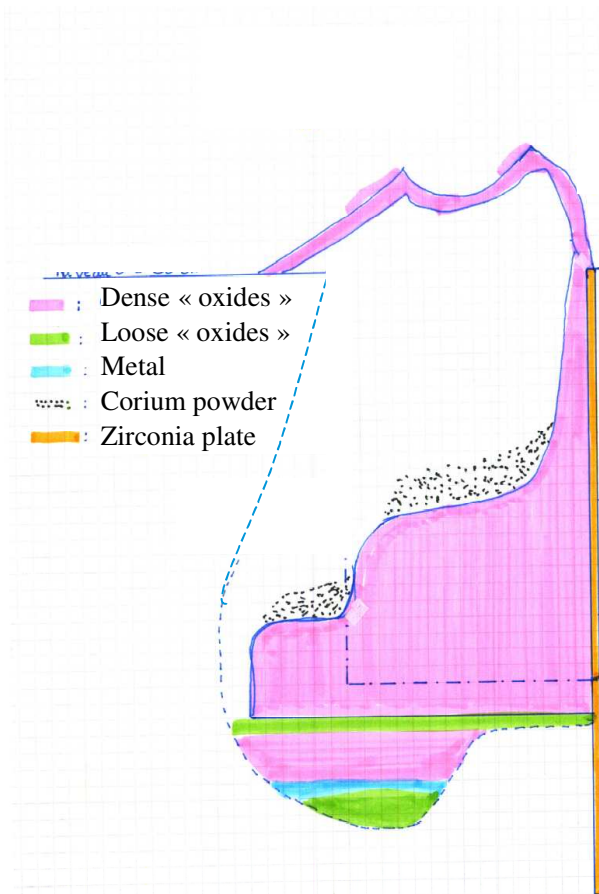


Fig. 11. Sketch of the corium layered found during dismantling

Below this cavity, a dense layer of presumably oxidic corium has been found. The most surprising finding was that only 1.2 kg of metal (Fig. 12) was present, showing a very extensive oxidation of more than 10 kg of stainless steel, which is much larger than the calculated values. A simple thermodynamic calculation at thermodynamic equilibrium indicates that all the oxidizing gases from the molten concrete as well as from the solid concrete above the 100°C threshold for the free water, 350°C isotherm for the bound water and 750°C isotherm for the carbon dioxide must be considered to oxidize such a mass. Current MCCI codes consider only the gases that are volatilized from the ablated concrete (above isotherm 1600°C). On the other hand, only part of the produced gases will get in direct contact with the metal, so further comprehension of the phenomena is necessary.

It must also be noted that seven distinct layers have been observed in the posttest analyses but have not yet been interpreted.

Several samples have been taken that will be analyzed in the coming months. Material analyses and posttest calculations should provide precious insights into the comprehension of the MCCI phenomena. In particular, determination of the metal initial oxidation state, of the iron, chromium and nickel fraction in the oxides and of the metal final compositions is necessary to interpret the observed metallic oxidation.

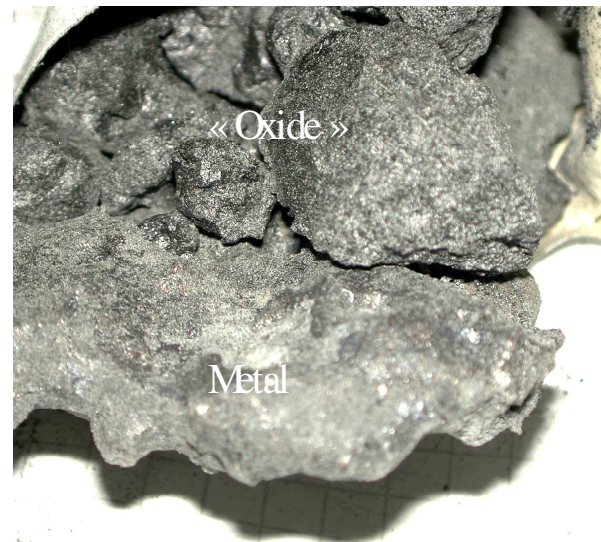


Fig. 12. Oxide and metal samples

#### IV. CONCLUSIONS

A first experiment studying the interaction of prototypic oxide and metal corium with concrete has been performed in the VULCANO facility after several upgrades have been provided to the test facility. The objective of this test was to study the effect of the presence of a molten steel layer on the MCCI processes. Preliminary results indicate that the ablation profiles are roughly similar to those observed with oxidic corium in the same conditions: anisotropic during the first hour and then isotropic ablation.

The major difference between the tests with and without metal is the presence of a very large void fraction (above 50 %). The most surprising finding of this experiment is the fact that more than 10 kg of metal have been oxidized during the test. Therefore, it is difficult to make direct comparisons with the precalculations. Post calculations are thus underway.

The next test in this series will be devoted to the study of the interaction of the same oxide-metal mixture with a silica-rich concrete.

## ACKNOWLEDGMENTS

This work has been done within a financial and technical collaboration between CEA, Electricité de France (EDF) and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). The TOLBIAC-ICB code has been developed under a CEA-EDF agreement.

The Metal furnaces have been developed with the Ecole Centrale de Lille Foundry Pole (M. Tissier) and ATYS induction heating consulting (Th. Bréville).

## REFERENCES

1. H. Alsmeyer, et al., *Molten corium/concrete interaction and corium coolability—a state of the art report*, Report EUR 16649, European Commission (1995).
2. D.H. Thompson, M.T. Farmer, J.K. Fink, D.R. Armstrong, B.W. Spencer, *Compilation, analysis and interaction of ACE Phase C and MACE experimental data*, Report ACEX TR-C-14, Argonne National Laboratory, Chicago, IL, USA (1997).
3. E.R. Copus, *Sustained Uranium dioxide Concrete interaction tests: The SURC test series*, 2<sup>nd</sup> OECD (NEA) Spec. Mtg. on Molten Core Debris –Concrete Interactions, Karlsruhe, Germany (1992).
4. R. E. Blose, D. A. Powers, E. R. Copus, J. E. Brockmann, R. B. Simpson, D. A. Lucero, *Core-Concrete Interactions with Overlying Water Pools - The WETCOR-1 Test*, Sandia Nat. Lab. Report NUREG/CR-5907, SAND92-1563 (1993).
5. M. T. Farmer, B. W. Spencer, D. J. Kilsdonk, R. W. Aeschlimann, *Status of large scale MACE Core Coolability experiments*, OECD Workshop on Ex-Vessel Debris Coolability, Karlsruhe, Germany (1999).
6. K-Y. Shin, S.-B. Kim, J.-H. Kim, M; Chung, P.-S. Jung, “Thermophysical properties and transient heat transfer of concrete at elevated temperatures”, *Nucl. Eng. Des.*, **212**, 233-241 (2002).
7. Y. Maruyama, Y. Kojima, M. Tahara, H. Nagasaka, M. Kato, A.A. Kolodeshnikov, V.S. Zhdanov, Yu.S. Vassiliev, “A study on concrete degradation during molten core/concrete interactions”, *Nucl. Eng. Des.*, **236**, 2237-244 (2006).
8. M.T. Farmer, S. W. Lomperski, S. Basu, “The results of the CCI-2 reactor material experiment investigating 2-D core-concrete interaction and debris coolability”, *Proc. 11<sup>th</sup> International topical meeting on nuclear reactor thermal hydraulics (NURETH 11)* Avignon, France (2005).
9. M.T. Farmer, S.W Lomperski, S. Basu, “The Results of the CCI-3 Reactor Material Experiment Investigating 2-D Core-Concrete Interaction and Debris Coolability with a Siliceous Concrete Crucible”, *Proc. Int. Cong. Advances nuclear Power Plants (ICAPP’06)*, Reno, NV (2006).
10. C. Journeau, E. Boccaccio, J.M. Bonnet, P. Fouquart, L. Godin-Jacqmin, J.F. Haquet, D. Magallon, S. Malaval, K. Mwamba, P. Piluso, V. Saldo, “Severe Accident Research at the PLINIUS Prototypic Corium Platform”, *Proc Int. Conf. Advances nuclear Power Plants (ICAPP’05)*, Seoul, Korea (2005).
11. C. Journeau, P. Piluso, J.F. Haquet, “Behaviour of nuclear reactor pit concretes under severe accident conditions”, *Proc. CONSEC ’07, Concrete under Severe Conditions*, Tours, France (2007).
12. M. Nie, *Temporary Melt Retention in the Reactor Pit of the European Pressurized Water Reactor (EPR)*, Doctoral Thesis, University of Stuttgart, Germany (2005).
13. B. Spindler, B. Tourniaire, J.M. Seiler, “Simulation of MCCI with the TOLBIAC-ICB code based on the phase segregation model”, *Nucl. Eng. Des.*, **236**, 2264-2270.
14. C. Journeau, E. Boccaccio, J.M. Bonnet, P. Fouquart, L. Godin-Jacqmin, J.F. Haquet, D. Magallon, S. Malaval, K. Mwamba, P. Piluso, V. Saldo, “Severe Accident Research at the PLINIUS Prototypic Corium Platform”, *Proc. ICAPP’05*, Paper 5209, Seoul, Korea.
15. G. Cognet, G. Laffont, C. Jegou, J. Pierre, C. Journeau, M. Cranga and F. Sudreau, “The VULCANO Ex-Vessel Programme”, *Wiss. Ber. FZKA*, **6475**, 156 – 168 (2000).
16. C. Jégou, G. Cognet, A. Roubaud, J.M. Gatt, G. Laffont and F. Kassabji, “Plasma transferred arc rotary furnace for corium melting”, *J. High Temp Mater. Proc.*, **1**, 409-420 (1998).
17. C. Journeau, P. Piluso, J.F. Haquet, L. Brissonneau, V. Aubert-Saldo, “Behaviour of nuclear reactor pit concretes under severe accident conditions”, *Proc. CONSEC ’07, Concrete under Severe Conditions*, Tours, France (2007).
18. B. Tourniaire, J.M. Bonnet, „Study of the mixing of immiscible liquids by sparging gas; results of the BALISE experiments”, *Proceedings 10th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH 10)*, Seoul, Korea (2003).
19. J.M. Seiler, A. Fouquet, K. Froment, F. Defoort, „Theoretical analysis for corium pool with miscibility gap”. *Nuclear Technol.* **141**, 233–243 (2002).
20. F.G. Blottner, *Hydrodynamics and heat transfer characteristics of liquid pools with bubble agitation*, NUREG/CR-0944 Report (1979).
21. G.A. Greene, *Experimental modeling of Heat and Mass Transfer in a Two-Fluid Bubbling Pool with Application to Molten Core-Concrete Interaction*, Report NUREG/CR-5875, Brookhaven National Lab.