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Platform for Improvements in Nuclear Industry and Utility Safety

(PLINIUS)

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Final report

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Project coordinator

Christophe Journeau, CEA Cadarache (FR)

Infrastructure web address

http://www-cadarache.cea.fr/fr/DEPTS/DTN/Fr/Plateformes/Plinius/Plinius.htm

1. *Executive summary (database report)*

This project is aimed at providing support for European research to conduct experiments with prototypic corium in the PLINIUS experimental facility. This large infrastructure at CEA Cadarache is dedicated to the experimental study of molten mixtures containing depleted UO_2. It is mainly directed towards severe accident R&D and comprises the following facilities:

VULCANO: a 300 kW plasma arc furnace able to reach 3000 K and to melt and pour 50-100 kg of prototypic corium. Spreading test sections and crucible for sustained heating have been used in VULCANO. Molten Core Concrete Interaction is currently the major activity in VULCANO. Specific instrumentation including high temperature thermometers and up to 8 video and infrared cameras follow the corium evolution. A test has been successfully performed for a German user to validate the COMET core-catcher concept with prototypic corium and sustained heating

COLIMA: a smaller scale facility in which a few kilogram of corium can be molten by induction (150 kW available). The crucible is installed in an instrumented enclosure with a temperature-controlled wall capable of representing accidental containment configuration. It is devoted to aerosol and material interaction studies as well as to the determination of some physical properties. A series of tests dedicated to the aerosol release above a VVER440 oxidic corium in reducing atmosphere have been conducted in 2003 for a Bulgarian user group. The Post Test Examinations have been successfully compared to Fission Product release calculations using GEMINI2 and ELSA

KROTOS: devoted to steam explosions, this facility in which a few kilograms of prototypic corium are poured into water has been developed and operated by the Joint Research Centre. It has been reinstalled in a new building extension of the PLINIUS platform. A Slovenian user group has been selected to study material effects (presence of non-volatile FPs and steel oxides in the corium melt) on fuel coolant interaction. This test has been performed in May 2006. It concluded this project.

2. *Description of the publicity concerning the new opportunities for access*

To publicise the opportunities to access PLINIUS a website has been published by CEA and a leaflet has been distributed. Participants from eligible countries to several corium related European projects, to the FISA 2001 conference have been informed by email of the PLINIUS Transnational Access project.

A poster has been displayed at the FISA 2001 conference where 10 scientists manifested their interest by depositing their business card. They were evidently contacted to participate. A poster and a communication at FISA 2003 (Journeau, 2003) where used to publicize the last call for proposals.

Leaflets were distributed during meetings of European projects and major conferences (as e.g. ICONE in the US or Nuclear Energy New Europe in Slovenia) and the transnational access schema was presented during scientific communications (such as Piluso, 2002, 2005).

Copies of the leaflet and of major website pages are provided in Annex 1.

After the last call for proposal has been closed, the publicity efforts were devoted to the presentation of the PLINIUS selected accesses in conference communications. At least one communication has been made for each of the accesses. A complete listing of these communications can be found in Annex 3.

3. *Description of the selection procedure*

Seven proposals (see Annex 4) have been received for the three PLINIUS Calls for Proposals. These proposals dealt with the following issues: radioactive releases during severe accidents, corium mechanical properties, UO_2 corium cooling by bottom flooding, steam explosions with a focus on materials effects and the hydrogen generation due to metallic fragmentation during a rapid quench.

The candidates had filled a proposal form that was first analysed by the PLINIUS team, then by the Selection Panel (see Annex 2). Three Selection Panel meetings have been held, one after each call deadline.

It must be noted that there has been a better outcome in terms of interesting proposals in the third call compared to the first two calls, showing that the knowledge on this TALI scheme is increasing within the European severe accident scientific community.

The selection criteria, listed in the PLINIUS contract, have been used to analyse the proposals:

- Safety of proposed experiment
- Scientific merit
- Compliance with interests of the Community
- Relevance to end users
- Technical feasibility
- Fluency of visitors in languages understood by PLINIUS team.

- Priority will be given to research teams who have not previously used the infrastructure[1] and who are working in regions of the Community where few such research infrastructures exist.

[1] Actually all the selected users were first-time users of the PLINIUS facility and had no operating corium facility in their country capable of running the proposed experiments.

From the analysis of these proposals, the selection panel has chosen the following proposals for accesses regarding:

- A COLIMA test on the aerosol release above a VVER440 corium molten pool. This access was awarded jointly to two teams who merged, one led by the Technical University of Sofia and one from the NPP Kozloduy, also in Bulgaria.
- A VULCANO test to validate with prototypic corium the COMET bottom flooding core-catcher concept, performed with Forschungszentrum Karlsruhe (Germany).
- A KROTOS Steam explosion experiment focused on the role of additives as Fission Products and Steel oxides, which had been proposed by a team from the J. Stefan Institute (Slovenia).

A joint British-Bulgarian proposal, dedicated to metal-water interaction, was the panel second-choice in the users short-list on the last call and it has been proposed to keep it for future calls if transnational access to PLINIUS is to be pursued within FP6[2].

A total of 9 scientific users (see Annex 5) were granted access to the PLINIUS infrastructure for stays varying from 1 day to 4 weeks (the length of the stays mainly depended on the user requests). One user (B. Fluhrer) had to cancel her stay for health reasons.

The Selection Panel strongly recommended that students participate to the accesses. As a consequence 3 students have been granted accesses. Moreover another student (Polina Tusheva, T.U. Sofia, Bulgaria) is currently using the result of the COLIMA test as part of her PhD thesis work.

[2] A proposal for “PLINIUS FP6” has been sent by CEA and is under negotiation with the EC.

4. Scientific output of the users at the facility

4.1 COLIMA tests for the Bulgarian user group

The Bulgarian user group (I. Ivanov, P. Grudev, I. Mladenov, S. Kalchev) visited the COLIMA facility in January 2003 to perform two tests on the aerosol release and transport from a VVER440 corium. Due to experimental difficulties with these first two tests, I. Ivanov had to make a second visit in May 2003 when the test CA-U3 was finally performed.

The objectives of these tests are the quantification of the increase of the gaseous radioactive products in severe accidents of nuclear water reactor through a simulation in the PLINIUS Platform in behalf of the Environmental Impact Assessment of the VVER440 plants at NPP Kozloduy. Its aims are to measure and then compute the quantity of the additional gaseous radioactive products by the corium melt, in the hypothetical scenario of a severe accident. Low-volatile fission products have been considered for a burn-up of 35 MWd/kgU, 24 hours after shutdown and were inserted in the load as oxides of natural isotopic composition (except for uranium which was depleted).

Definition of the tests and experimental set-up

The final composition for the COLIMA CA-U1 experiment has been chosen after a common agreement between the Bulgarian team and the PLINIUS team. This composition has finally only oxides fission products without any metallic components. The too low amount of fission products (about a few 100 ppm) has been eliminated because it would not have been possible to detect them as regards of the total load. The experimental load of the first test (CA-U1) is presented in Table I. The COLIMA facility uses the hot crucible technique. The corium load (depleted uranium dioxide pellet and powders for the other oxides – representing oxidized cladding and steel as well as fission products) has been installed in a tungsten crucible (Fig. 1).

Raw materials	Experimental mass (g)	Colour
Fe2O3	31.603	red
Cr2O3	0.852	green
MoO2	12.068	black
ZrO2 pure	320.01	white
Nb2O5	4.184	white
UO2 pure	1923.357	black
SrO 97 %	2.784	white
BaO 9 % carbonated BaCO3	4.539	white
RuO hydrated	11.414	black
TeO2 include Sb simulation	1.75	white
Nd2O3 to simulation Eu	12.74	green
CeZrO4	14.468	yellow
Pr2O3	3.831	green + pieces
Y2O3	1.556	white
Rh2O3	1.429	black
La2O3	3.847	white
Ratio UO/ZrO	6.010302803	
Total mass	2350.432	

Table I: Experimental composition of the COLIMA CA-U1 experiment

Fig. 1: Corium load in the COLIMA crucible

The general principle of hot crucible heating is to use a medium frequency generator (about a few kHz) and an inductor in order to heat the susceptor (tungsten crucible), as visible in Fig. 2. Then, the susceptor transmits the heat to the total load (about a few kilogrammes) till it reaches the liquidus temperature of the load. The temperature of the pool is estimated thanks to a radiative pyrometer. For the COLIMA CA-U1 experiment, a specific instrumentation has been developed, especially in order to characterize the fission products release. It comprises a thermal gradient tube (Fig. 3) made of steel and of tungsten in its lowermost part, three lines of filters (Fig. 4) and an impactor. **Fig. 5** presents the experimental set-up.

Fig. 2: COLIMA inductor and furnace

Fig. 3: COLIMA thermal gradient tube + thermo couples

Fig. 4: COLIMA aerosol filter lines

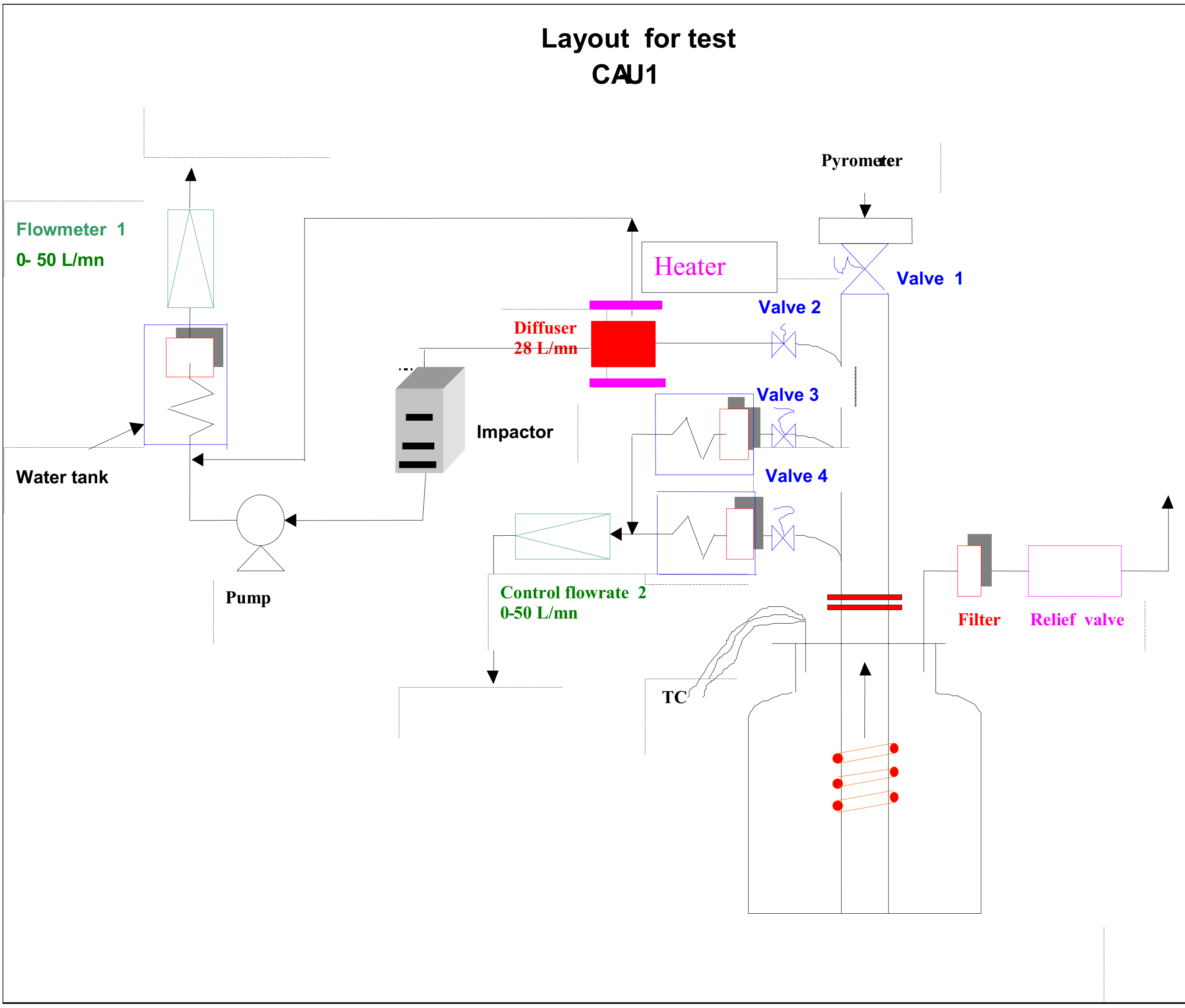

Fig. 5: Experimental set-up

After a corium preheating test (CA-U1.1), a first test (CA-U1.2) has been conducted on January 21, 2003 with the participation of the Bulgarian user group. It failed due to the formation of a leak in the inductor coil. On January 23, 2003, a new inductor had been installed and a second test (CA-U1.3) was performed. It stopped due to the piercing of the crucible sidewall after the inductor pierced again. Post-mortem analyses showed the formation of metallic balls (Fig. 6) in the molten corium pool (Piluso, 2003).

After these two failures, it has been decided to modify the set-up by

- Changing the gas from hydrogenated argon to hydrogenated helium to limit the risks of electric arcs;
- Replacing the graphite supporting tube by an electrically-insulating support

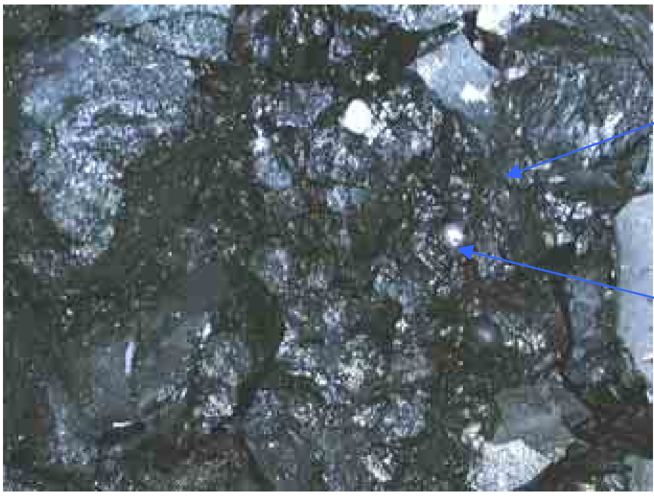

Fig. 6: CA-U1.3 corium melt sample

A second series of tests have been performed in May 2003 with the presence of Pr. Ivanov from the Technical University of Sofia (the user group leader).

Following the crucible failure in the first test attempts, it was decided to withdraw from the load composition Ru, Mo, Mn that were reduced and could have reacted with the tungsten crucible (Piluso, 2004). The final corium composition (taking into account the fact that a few pellets did not melt) was the following:

Chemical formula	**Molten pool (g)**	**Molten pool (wt %)**	**Molten pool (mol %)**
Fe_2O_3	21.02	1.2%	3.3%
Cr_2O_3	0.57	0.03%	0.09%
ZrO_2	260.00	14.7%	26.5%
Nb_2O_5	2.78	0.16%	0.3%
UO_2	1 485.55	83.9%	68.0%
SrO 97%	1.85	0.10%	0.2%
BaO	3.01	0.17%	0.2%
TeO_2	1.19	0.07%	0.1%
Nd_2O_3	6.17	0.35%	0.5%
$CeZrO_4$	9.64	0.54%	0.4%
Pr_2O_3	2.34	0.13%	0.2%
Y_2O_3	1.06	0.06%	0.1%
Rh_2O_3	0.96	0.05%	0.1%
La_2O_3	2.56	0.14%	0.2%
ratio UO_2/ZrO_2	5.71		
Total mass	**1 798.70**		

Table II: Corium molten pool initial species composition for COLIMA CA-U3

CA-U3 test description

On 5 May 2003, corium melting was achieved but the crucible pierced after the final power increased. After this incident, it has been decided to withdraw ruthenium and molybdenum oxides from the corium composition since they were suspected to reduce to metallic balls that could form eutectics with the tungsten crucible.

Finally, on 16 May 2003, a long high temperature plateau was maintained allowing for aerosol sampling. Fig. 7 presents the evolution of the temperature recorded on various pyrometers and of the induction power control level (defined as a percentage of maximum voltage, plotted in red on Fig. 7). Temperatures of 2760 °C were maintained for more than 50 minutes.

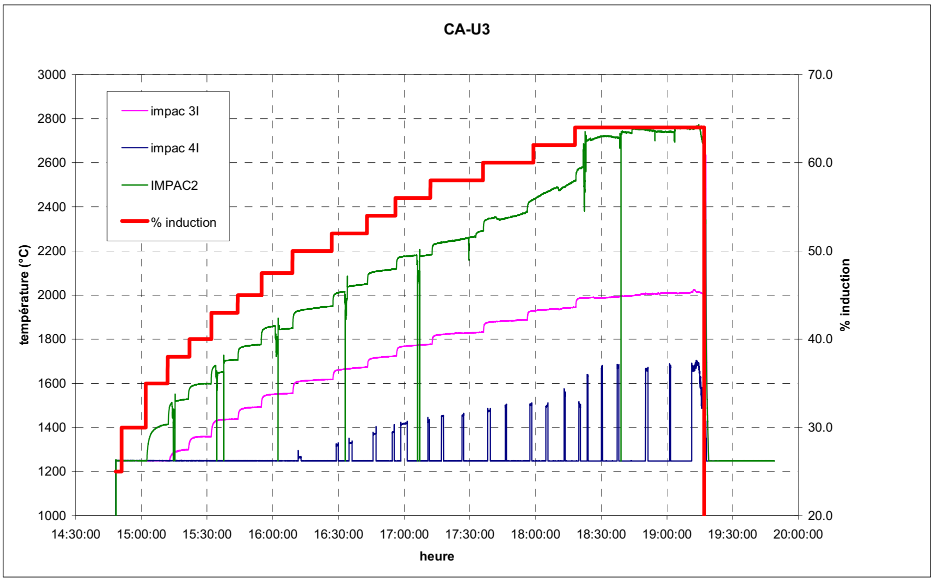

Fig. 7: Evolution of pyrometric measurements and of induction power

Fig. 8 presents the temperature measured in the tungsten tube. TC W3 broke after 16:30; measurement were obtained after this event but are not validated. The maximum temperature was around 750 °C, i.e. much lower than the StarCD pretest calculations (Conte, 2003). This discrepancy is attributed to the lower crucible temperature and to the effect of very thick aerosols on radiation. There is a more than 300 °C difference between the upper and lower parts of the tungsten tube.

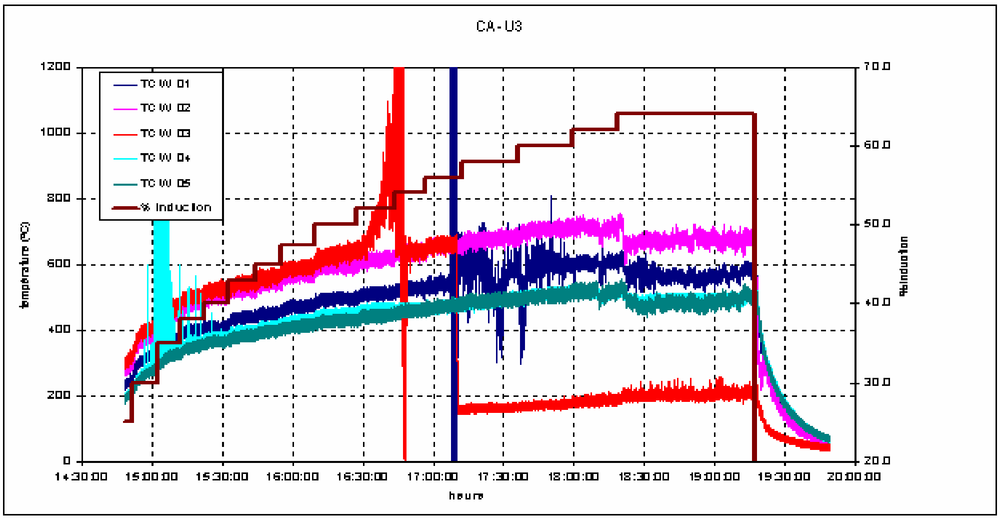

Fig. 8: Tungsten Thermal Gradient Tube temperatures

Fig. 9 presents the thermograms recorded on the steel thermal gradient tube (K01 is at the lowest position and K10 at the topmost position). The temperature ranged from 250 to 165 °C during the highest temperature plateau.

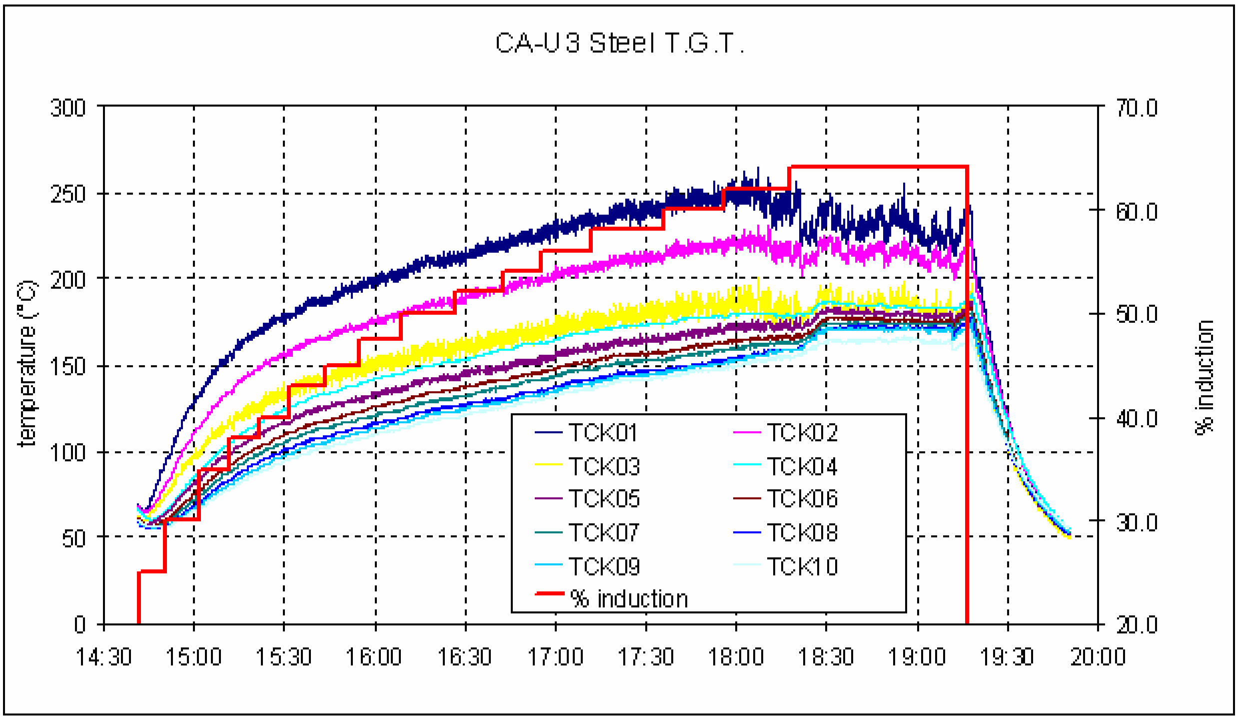

Fig. 9: Evolution of temperatures along the steel Thermal Gradient Tube

Temperature recorded at the gas outlet was always below 140 °C and remained in general below 70 °C. The valve temperature remained below 40 °C. The diffuser in the impactor line has thus been controlled at a temperature of 90 °C to avoid thermophoresis.

A constant 3 bar gauge pressure was maintained throughout the experiment. A gas flow rate of 8 to 11 l/minute was maintained during the test, except for the impactor phase with a flow rate around 25 l/min in the impactor line. It must be noted that fluid-dynamic precalculation indicated that more than 90 % of the gas flow goes directly in the thermal gradient tube without flowing at the corium pool surface.

During the heating phase, until 18h25, the aerosols were collected on filter 2. From 18h25 to 19h11, the aerosols produced at the high temperature plateau were collected on filter 3. At 19h11, they had been directed to the impactor line. At 19h17, a hole appeared in the tungsten crucible, required to terminate the test.

Post-test analyses

The steel thermal gradient tube has been cut into 6 zones. The aerosols deposited on each section of the tube have been collected by wiping a cloth over the surface, using the standard procedure used for labile contamination measurements. The cloth and aerosols have then been dissolved and the solution has been analyzed by X-ray fluorimetry.

Due to the collection technique, it is unfortunately impossible to obtain absolute values but only relative values (from one sample to the other and from one element to the other) of the deposited aerosol masses. Only iron, chromium, nickel and tellurium deposits have been observed (Fig. 10). In particular, no uranium has been detected and no other fission product either.

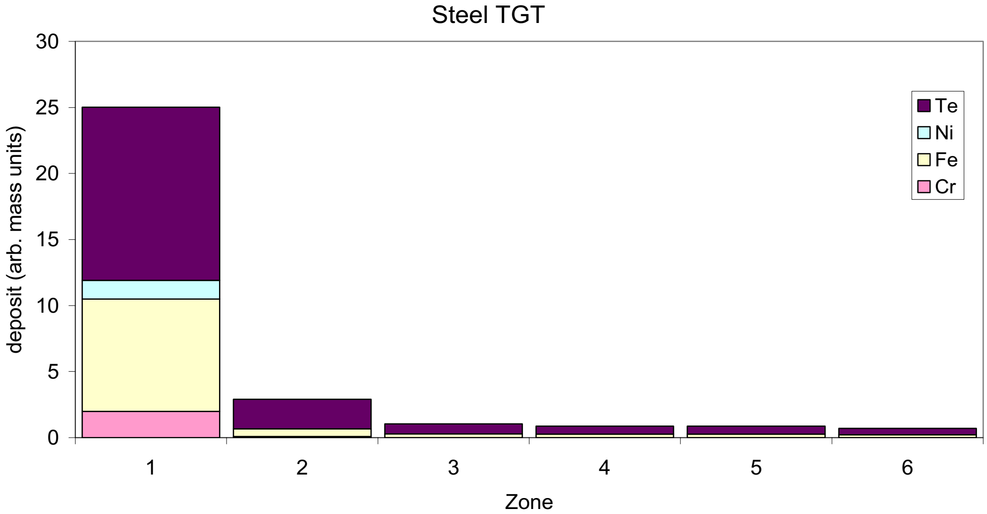

Fig. 10: Aerosol deposited on the steel TGT (cumulated linear scale)

Synthesis

Table III synthesises the observation for each of the elements of the load (excluding oxygen) in comparison with the published assessment of FP releases by Ducros (Baichi, 2001).

Element	**Ducros's assessment of releases** (Baichi, 2001)	**Remaining in corium**	**Tungsten TGT**	**Steel TGT**	**Filter 2 Heat-up**	**Filter 3 45' Plateau**	**Impactor 5' Plateau**
Ba	10-50%	>90%				Traces	+ 1.3µm
Ce	10%	>90%			Traces	Traces	Traces
Cr		0	+	+		Traces	Traces
Fe		50%	+++ hot side	++	Trace	+++	+++
La	10%	>90%					Traces
Nb	10%	>90%					
Nd	1%	>90%			Traces	Traces	Traces
Pr	10%	Traces	-	-		Traces	
Rh	30%	0			Traces	Traces	Traces
Sr	10%	Traces	0	0	0	0	++ 0.3µm
Te	100%	0		1st zone (230°C)	+++	++	+ 2 µm
U	10%	>95%	+++				1.5µm
Y	1%	>90%				Traces	
Zr	1%	~100%					

Table III: Synthesis on aerosol element behaviour during CA-U3

- Among the fission products, only niobium and zirconium have not been in any of the collection devices. These are definitely non-volatiles in the reducing atmosphere of this test.
- Traces of yttrium have been collected during the plateau phase, in coherency with the 1% release value.
- Traces of neodymium, in coherency with the 1% release value, have also been collected but during all phases of the test.
- Traces of lanthanum have been observed in the impactor (with a peak geometric diameter around 0.8 µm). It seems that lanthanum volatility was lower than the expected 10% from Ducros' assessment (Baichi, 2001).
- Traces of cerium have been found in filters and impactors from all phases of the test. This is compatible with the assessed value of 10% released.
- Barium releases were quite low (1-10%) and appeared mainly during the last phase (the impactor indicates a peak geometric size around 1.3 µm). This low value is consistent with the observations (Dubourg, 2001) of Phebus FPT0 whereas analytical tests (ORNL and VERCORS) gave larger release. Dubourg and Taylor (2001) explained this by the solubility of barium in uranium oxides that has been observed in the melt.
- The results of praseodymium are more difficult to interpret, since only traces remained in the melt but only small deposits (traces in the plateau filter) have been collected. An hypothesis might be that the praseodymium aerosols were out of the range of the analyzed impactor stages.
- Most of the strontium has been released from the melt (contrary to the assessed value of 10%). This release must have occurred during the last phase of the test. Very small aerosols (geometric diameter around 0.3µm) have been collected in the impactor. The discrepancy between this high release rate and the lower rate observed during FPT1 (Dubourg, 2006) highlights the role of molybdates (Mo was absent of CA-U3) in stabilizing strontium oxides.
- Some uranium was released from the melt. Although it is a small relative value, it must have made an important part of the aerosol population, due to the important proportion of uranium in the load. Some uranium deposited in the tungsten tube (peak around a temperature of 550°C). The remaining aerosols have only been observed in the impactor (peak geometric size around 1.5 µm).
- About half of the iron has been volatized. It has been observed in all collecting devices and deposited more on the hot sides of the TGTs.
- Rhodium has been totally released in contrary to the limited volatility (30%) given by Ducros. Traces of rhodium have been collected during all three phases of the test.
- All chromium has been released. It has been collected on the TGTs (mainly the hotter tungsten tube).
- Tellurium has been totally released as expected. Its release was mainly during the first phase (heat-up) but some was still released during the 50 minutes of plateaux. Important deposits in the bottom of the steel tube (around 230 °C) have been observed.

Modelling

A thermodynamic modelling of the release has been made with GEMINI2 with the NUCLAiv051 database (Journeau, 2002, 2006). Post test calculations are reported in Fig. 11 for two cases considering that the pool was in contact with 5 % of the gas flow (fraction estimated by CFD calculations before the test; Conte, 2003) or with all the gas flow, for equilibrium calculations at 3033 K. Except for Strontium, all the tendencies for the elements in the database (Ag represents Te, La represents all the lanthanides) are satisfactorily fitted. Effect of pool temperature uncertainties has been verified not to modify qualitatively the calculation results. For steel components (Fe, Cr), the high release rates seem to indicate that, assuming correct modelling, most of the gas flow was in thermodynamic equilibrium with the corium pool.

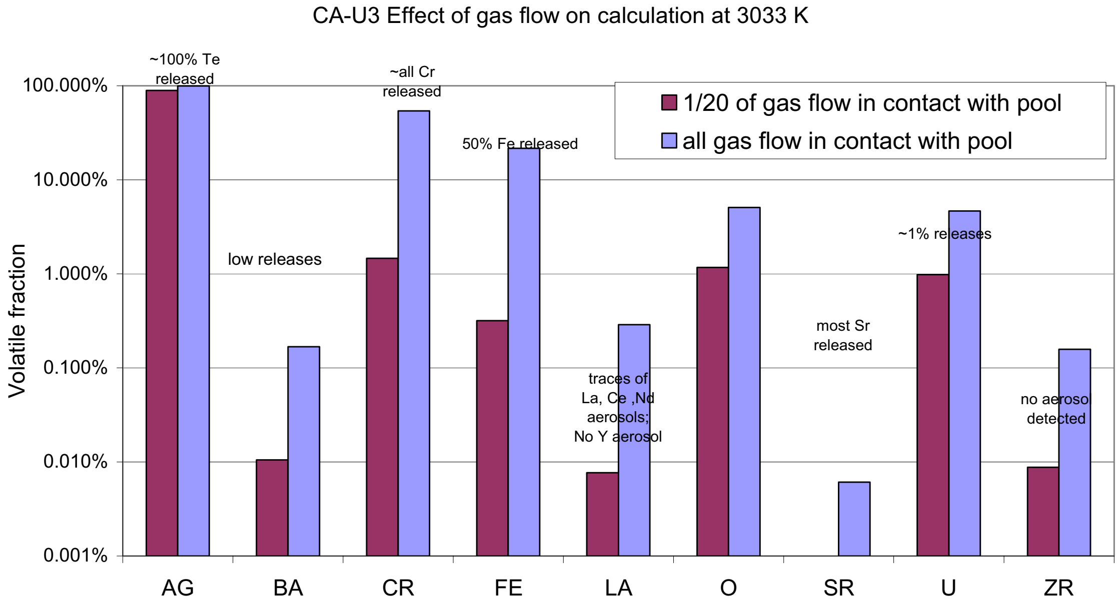

Fig. 11: GEMINI2 post test calculations

The results from this test were also compared to ELSA calculations (Godin-Jacqmin, 2005, 2006). Fig. 12 presents the cumulative releases of tellurium, barium and strontium during the test: In accordance to the experimental results, most of the tellurium release has been calculated to occur during the heat-up phase. On the contrary, no significant Ba and Sr have been detected in the heat-up filter although calculations indicate an early release. Deposition calculations are required to determine whether the absence of collection on the filter during the heat-up phase can be due to deposition on the thermal gradient tubes.

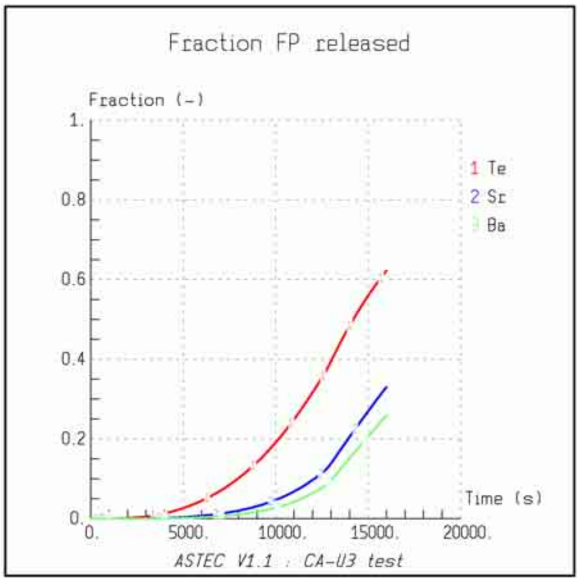

Fig. 12: ELSA calculation of the Te, Sr and Ba releases

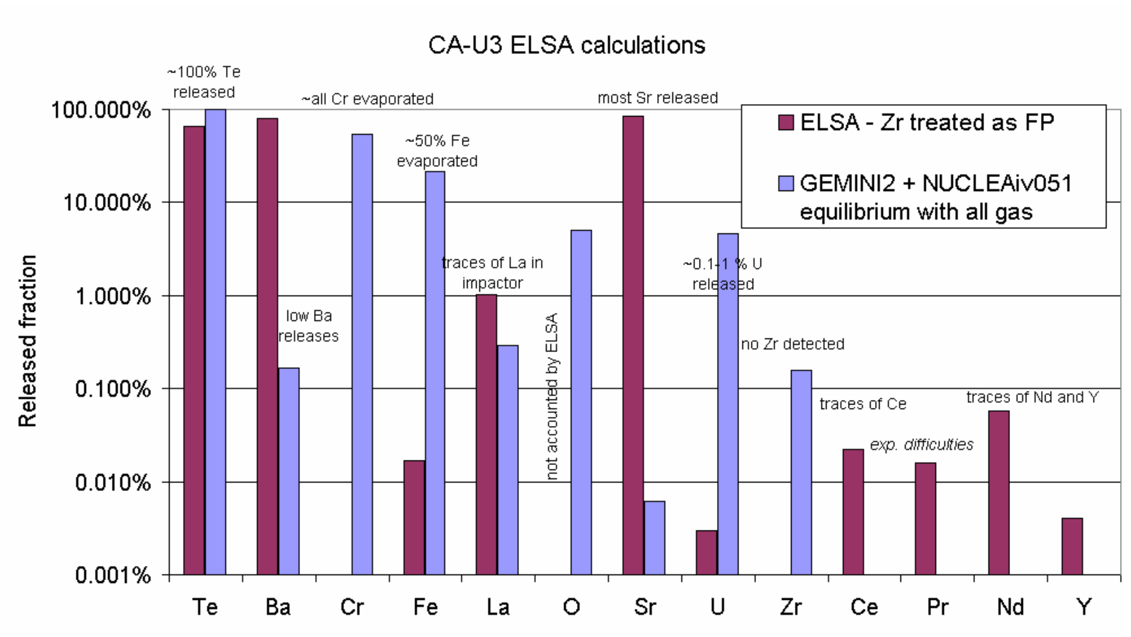

Fig. 13: Comparison of GEMINI2 and ELSA calculations

Fig. 13 compares the total release fractions estimated by ELSA and GEMINI2. It occurs that:

- The tellurium almost total release is well calculated by both codes.
- The low barium releases are well calculated by GEMINI2 + NUCLEAiv051 but not by ELSA.
- The steel oxides are not (well) modelled by ELSA but are satisfactorily estimated by GEMINI2.
- The high Strontium release is on the opposite well predicted by ELSA and is not well modelled in the NUCLEAiv051 database.
- ELSA computes a much too low level of uranium volatilisation.

Nevertheless, each of the elements is well modelled by at least one of the two codes, which tends to indicate that satisfactory models are available for improvements.

4.2 VULCANO test of the COMET concept for the German user group

The COMET concept is developed to cool an ex-vessel corium melt, in case of a hypothetical severe accident leading to vessel melt-through, by passive injection of coolant water to the bottom of the melt. An advanced version of this concept (COMET PCA) uses a porous concrete layer from which the water is supplied to the melt predominantly through a group of porous channels. The concept was designed to be largely independent of different accident scenarios. It could be applied to both current and future reactors. FZK has successfully performed in Germany a series of large-scale experiments with simulant corium melts (Alsmeyer, 2004).

The VULCANO VW-U1 experiment has been performed at CEA Cadarache, providing Hans Alsmeyer (FZ Karlsruhe, Germany) with an access to the PLINIUS platform, in order to validate this concept with prototypic corium and simulated decay heat. After describing the COMET core catcher concept, the test section in the VULCANO facility is presented. Finally the experiment is described and its main results are shown.

The COMET core-catcher concept

The COMET core catcher (Alsmeyer, 1994, 2005) is designed to reach rapidly complete melt quenching and solidification by bottom flooding. Two variants are proposed which use passive bottom water injection either through flow channels or from a layer of porous, water filled concrete (Fig. 14). Experiments have demonstrated the high efficiency of melt fragmentation driven by the fast evaporation of the injected water, and complete quenching and long term coolabilty was achieved in a series of large scale experiments.

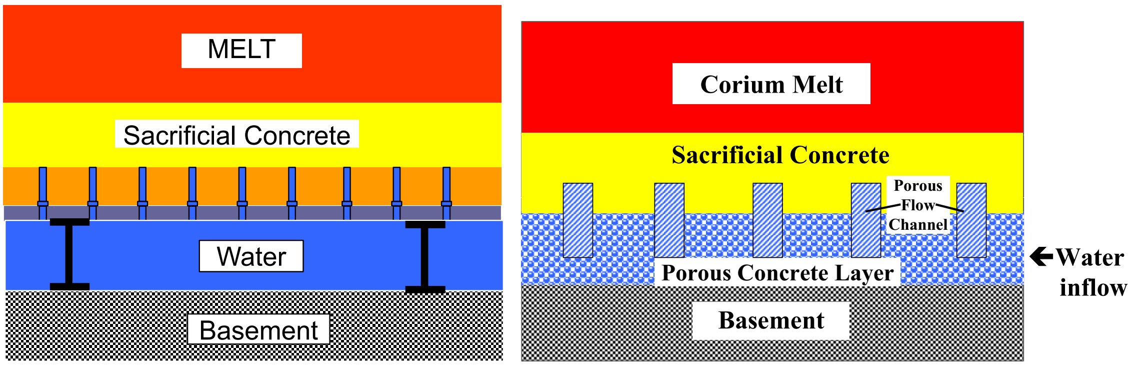

Fig. 14: The COMET bottom-flooding concept:

Water injection through channels (left)   or from porous concrete layer (right)

The principle of the cooling concept is as follows: after erosion of a sacrificial concrete layer, the melt is passively flooded from the bottom by injection of coolant water from an elevated water reservoir. The water is forced up through the melt, the resulting evaporation process of the coolant water breaks up the melt, and creates a porously solidified structure from which the heat is easily removed. The porous melt is expected to solidify within less than one hour from onset of flooding, and continuous boiling removes the decay heat from the permanently flooded corium bed.

The advantages of this concept are the fast cool-down and complete solidification of the melt within one hour typical. This stops further release of fission products from the corium. The solidification of a porous melt is the basis for safe, permanent long term cooling. The structures in the lower containment and the basement remain cold and intact. A drawback may be the fast release of steam during the quenching process, which results in a steam pressurization of the containment, although condensation would subsequently reduce the steam pressure.

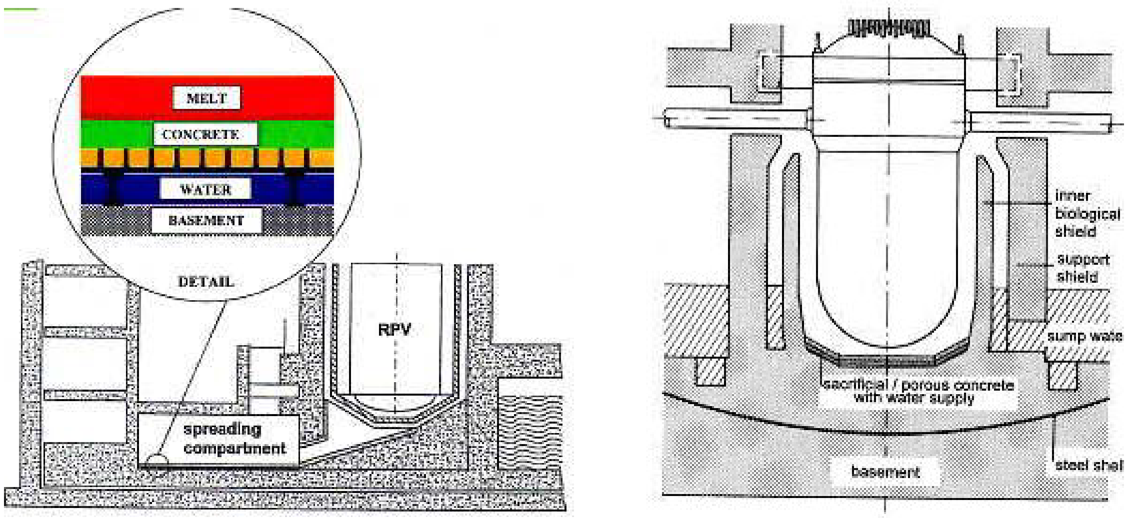

Fig. 15: Localisations of the COMET cooling device sideways of or in the reactor pit

Two different solutions are envisaged for the location of the coolant device in the containment (Fig. 15):

- The cooling device is located sideways of the reactor pit. This is done in order to pre-collect melt in the pit over a prolonged time period, allowing collection of late melt releases, and further to enable a better controlled spreading onto the cooling device. This arrangement was designed as a back-up design concept for the EPR. Application of the COMET bottom-flooding concept in the spreading area can replace the EPR retention concept designed for this area.
- The cooling device is located in the reactor pit, which may be enlarged laterally to reduce the height of the melt. For this variant, the spreading requirements are less demanding, but the time available for melt accumulation is smaller, only limited by the erosion time for the available sacrificial concrete layer. Optionally, the coolant water level which starts to build up after onset of cooling may be designed to rise to a sufficiently high level, in order to cool residual core debris directly in the RPV, thus reducing and possibly eliminating further melt releases. This variant may in principle be applicable to existing plants

Independent of its localization, two variants of the COMET design are presented for the basic processes of passive flooding and cooling, and have been evaluated by experiments:

- The first variant uses an array of plastic tubes, embedded in a horizontal concrete layer (Fig. 14 left). Connected to a water reservoir and pressurized by static overhead, water is fed into the melt through the plastic tubes after the melt has eroded the sacrificial concrete layer on top.
- The second variant uses a layer of porous, water filled concrete (CometPCA = COMET Porous Concrete Advanced) from which flow channels protrude into the layer of sacrificial concrete (Fig. 15 right). The porosity of the concrete and the flow

resistance of the flow channels are adjusted to yield an appropriate coolant water flow into the melt. This modified concept combines the advantages of the original COMET concept with flow channels and the high resistance of a water-filled porous concrete layer against downward melt attack.

The time span between start of melt release and passive onset of flooding is defined by the thickness of the sacrificial concrete layer, which may be from 10 to 20 cm typical in a real plant application. The sacrificial concrete may be fabricated with aggregates from boron silicate glass to exclude nuclear re-critically.

The COMET concept has already been thoroughly validated thanks to large scale experiments with up to 1.3 t of high temperature steel and oxide simulant melt, at FZK Karlsruhe, comprising transient and sustained induction heating experiments. They have been complemented by transient tests with UO_2 based melts at Argonne National Laboratory and lower temperature analytical experiments at KTH Stockholm.

This experimental database has now been completed with an experiment with prototypic corium and sustained heating aimed at validating the COMET-PCA Concept.

Experimental set-up

On Monday 17th and Tuesday 18th October 2005, the COMET core-catcher concept was tested with prototypic corium in the VULCANO facility.

A unit cell of the cooling device (Fig. 16) was used in the VULCANO facility in a 20 cm Ø, 60 cm high zirconia crucible with about 40 kg corium melt. It consists, from bottom to top in

- a layer of structural concrete,
- a 30-mm layer of porous concrete which is connected to the water piping system, and is filled with water,
- a 20-mm layer of "sacrificial" concrete ensuring leak tightness,
- two porous concrete tubes connecting the porous concrete to an intermediate level of the sacrificial concrete.

This test is thus almost scale 1 in the vertical direction and represents the behaviour of a Ø 20 cm cylinder from the large core-catcher. The thickness of the sacrificial concrete layer, however, is reduced to allow adequate decay heat simulation by inductive heating. It must also be stressed that the COMET device is quite thin (10 cm excluding the sacrificial concrete layer) so that only a 20-30 cm height would be requested to install this system in a reactor pit.

A dedicated test section has been constructed for this test. An inductor coil was installed around the zirconia cylinder, which was surrounded in a concrete cylinder, inside a fibre-reinforced resin shell. This cylindrical test vessel (Fig. 17) is topped by a metallic shell connected to the off-gas line. This gas line is connected to a steam condenser (Fig. 18) and a gas analysis circuit leading to a mass spectrometer.

The test insert is connected to a 90 l water tank installed at a height of 2 m above the floor level. This defines the static overhead of 0.2 bar, so that water can flow passively into the corium melt as soon as the sacrificial concrete is eroded.

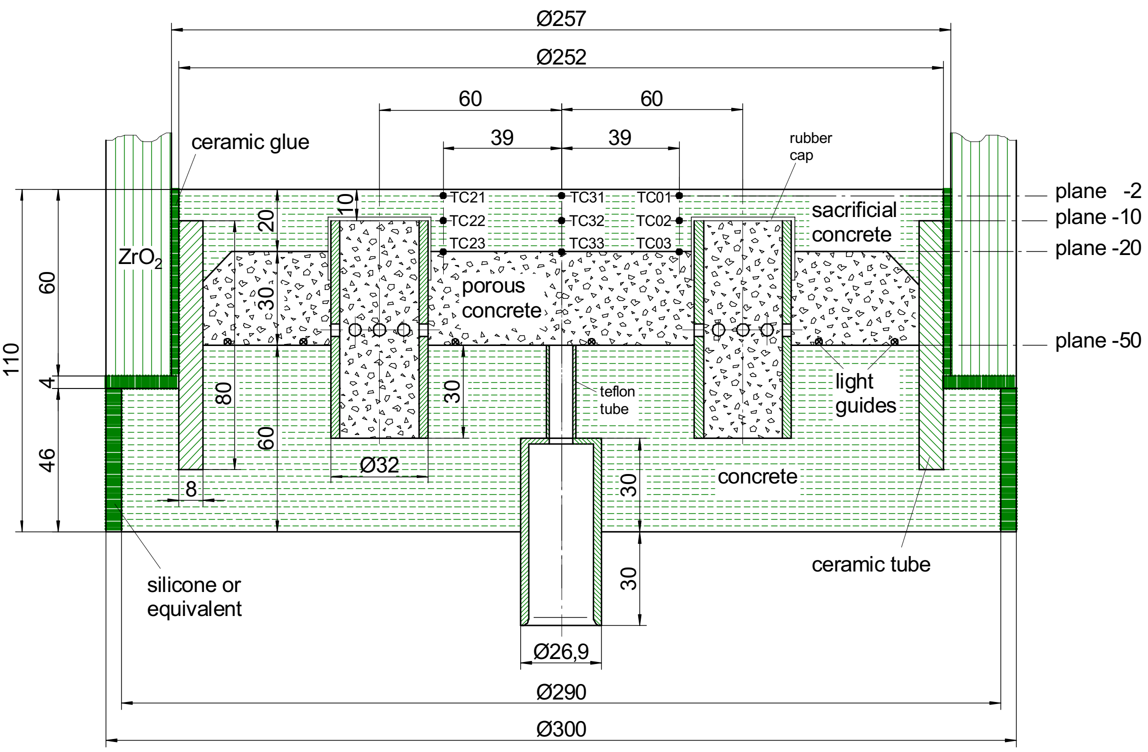

Fig. 16: The COMET test insert installed in the VULCANO test section

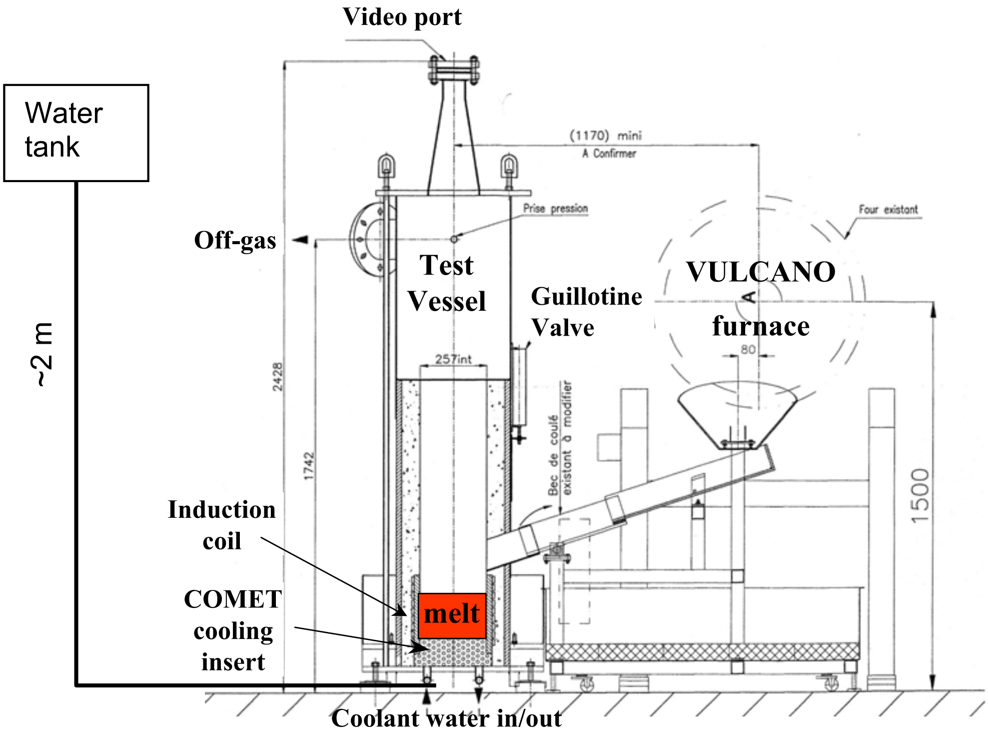

Fig. 17: Drawing of the test vessel

The VW-U1 experiment

The melt has been generated and poured from the VULCANO plasma arc furnace into the COMET cooling device at an initial temperature above 2000 K (Fig. 19). The corium load (45 wt % UO_2, 19.3 % ZrO_2, 19.6 % SiO_2, 15.3 % FeO_x, 0.7 % CaO, 0.1 % Al_2O_3) is characteristic of the mixture of a corium with a part of a ferro-siliceous sacrificial concrete. Its liquidus temperature has been estimated to be around 1900 °C.

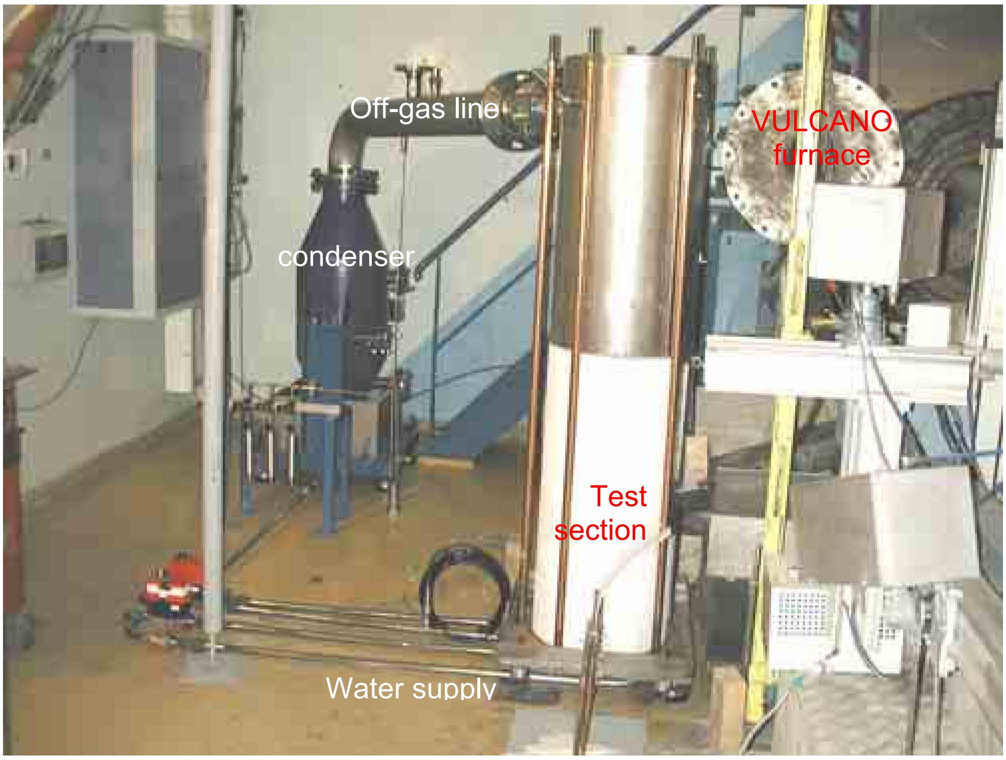

Fig. 18: General view of the COMET test section and the VULCANO plasma-arc furnace

Fig. 19: Corium pouring out of the VULCANO furnace above 2000 K towards the COMET test section

In the test section, the melt was internally heated by sustained induction power over the first 22 minutes of the test (varying between 10 and 30 kW). Upon melt pour, the corium melt started to erode the sacrificial concrete. This established the initial condition for onset of passive flooding, when the first layer of sacrificial siliceous concrete was removed and the passive water injection started, 57 seconds after melt arrival on the test insert. It must be reminded that only the last centimetre of sacrificial concrete layer above the porous channels is represented in this experimental set-up.

The next important process was the inherent generation of a permeable porous oxide melt layer by fast evaporation of the injected coolant water, allowing a good contact with the steam/water flow from below (Fig. 20).

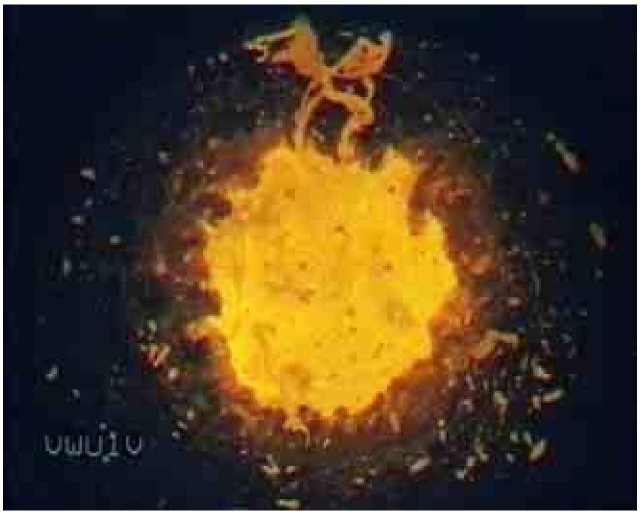

Fig. 20: Corium pool agitated by the steam flow from bottom flooding in the COMET cooling device

Fig. 21 shows the progression of concrete erosion, as measured from thermocouples embedded in the concrete. The thermo couple at the – 10 mm level detect arrival of the melt at 70 seconds in good agreement with the onset of bottom flooding at 57 s. The thermo couple at – 20 mm, i.e. 10 mm below the porous channel outlet, were rapidly quenched to levels below 100 °C as coolant started.

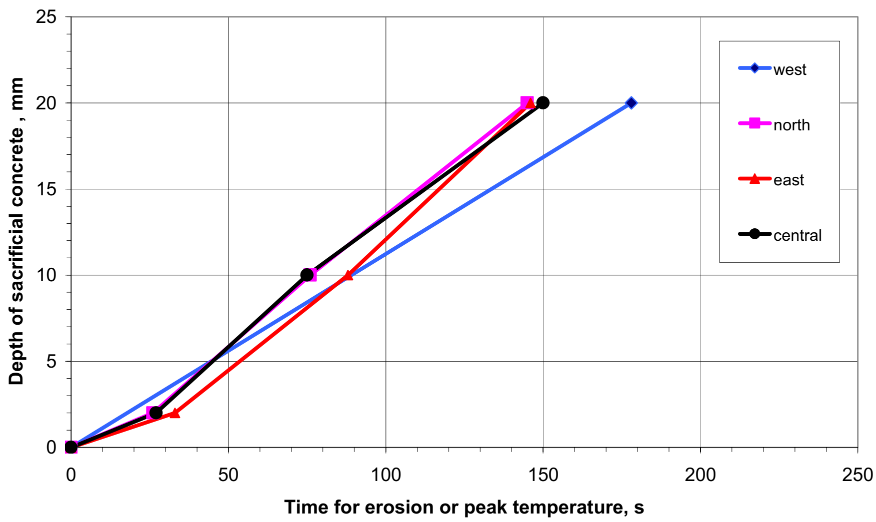

Fig. 21: Erosion time (or peak temperature time) for the thermocouples inside the sacrificial concrete

The thermocouples at 2 and 10 mm below the initial sacrificial concrete surface failed, whereas those at 20 mm at the porous concrete interface remained intact as efficiently cooled by water. This is shown in Fig. 22, which gives the thermocouple readings together with the inflow of the coolant water. After the initial fast quenching, the temperature reached 100 °C only when the water flow was manually stopped (to prevent the risk of water overflow), leading to the boiling of the stagnant coolant water. The low temperatures illuminate the high stability of the porous concrete layer, which remains permanently cooled by the water inflow and thus represents a safe barrier.

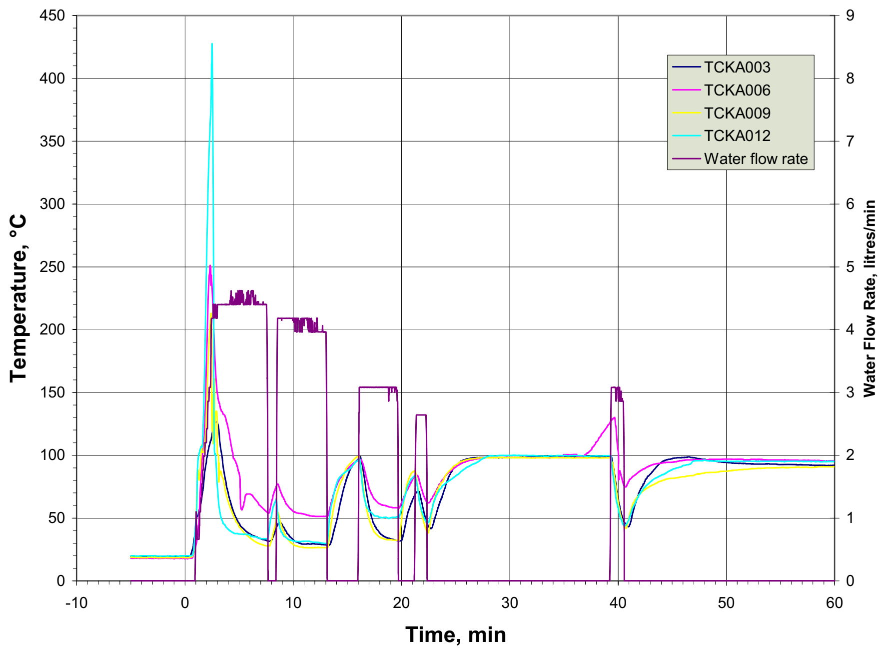

Fig. 22: Temperatures in the 20 mm plane (at the porous concrete interface) and water flow rate in the COMET device

The water flow rate in Fig. 22 reaches a value of 4.5 litres per min, or 75 g/s after about 3 min. Some reduction of the flow rate during the further course of the test is due to the rising water level in the test vessel, which reduces the effective overpressure of the coolant water.

The gas temperature in the upper test vessel land in the off-gas line increased to values in the order of 500 °C with peaks in the order of 800-1200 °C (Fig. 23). Long term cooling brings the gas temperature to 200 °C and below.

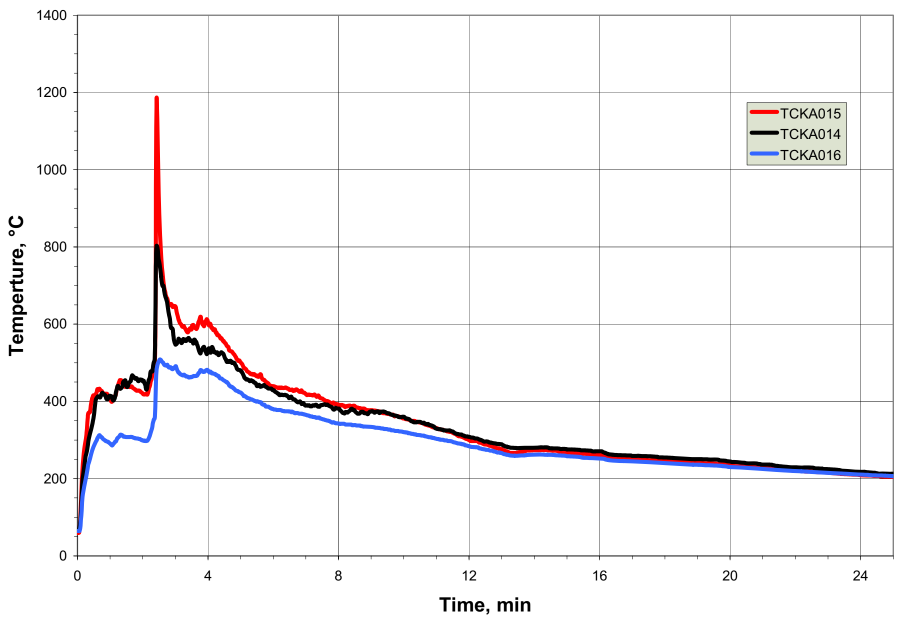

Fig. 23: Gas temperature measured in the dome of the vessel (black), and in the entrance (red) and the middle (blue) of the gas line

The composition of the non-condensable gases has been analyzed with a Balzers quadrupole mass spectrometer, after removal of the steam content by condensation. A constant argon cover gas flow of 120 l/min (STP) was injected into the test vessel throughout the test, which enables the estimation of the released gas species in relation to the known Ar flow rate (Fig. 24). During the initial phase of concrete erosion, up to one third of CO_2 (from the dissociation of concrete carbonates) has been detected in the gas. When the water flow started, there was the release of hydrogen (due to the reduction of steam by the slightly hypostoichiometric corium). The hydrogen peaks correspond to about 8 g/min. The clear decrease of the CO_2 and H_2 release during the first 4 or 7 min indicate the end of concrete erosion and the successful quenching of the corium melt, respectively.

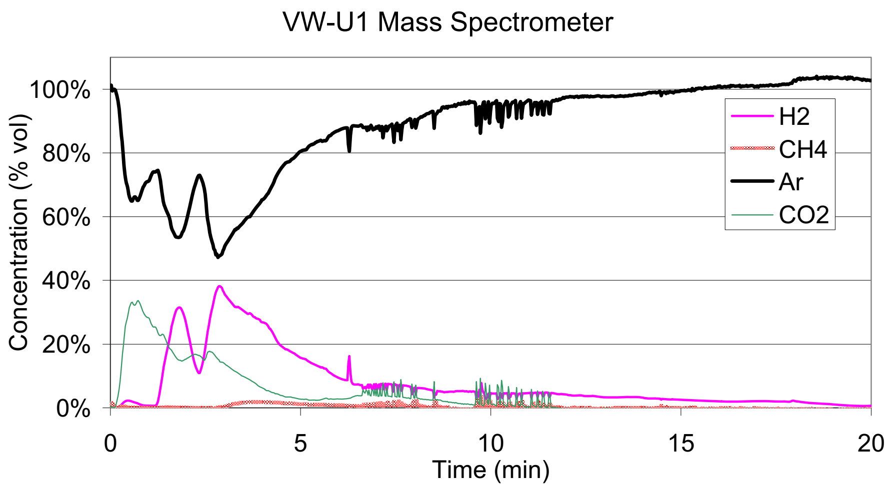

Fig. 24: Off-gas analysed after steam has been condensed

The off-gas flow rate was measured by a Pitot tube and by a turbine flowmeter – which was not inserted during the first phase of flooding to prevent deposition of particles or overheating. The total flow rate is always much larger than that of incondensable gases (maximum rates respectively of 4 and 75 l/s); so we have assumed that the gas was composed of steam only to estimate the mass flows (Fig. 25). The maximum steam rate (30 g/s is less than half the coolant water inflow rate of 75 g/s). Actually during the initial phase of flooding, although both Pitot and turbine readings were perturbed, it seems that the water in and outflows were roughly of the same magnitude. This lasted less than one minute after which a significant part of the water remained liquid.

The total integrated amount of steam (16 kg, blue curve) is almost the amount of water found in the condenser after the test.

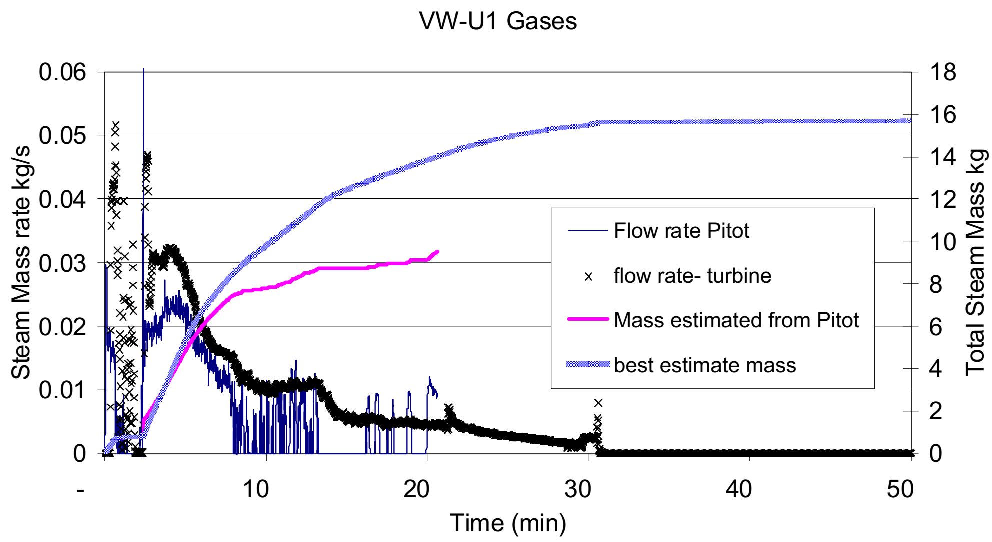

Fig. 25: Steam mass flow rate estimated from Pitot tube and turbines. The accumulated steam mass has been integrated from Pitot tube (pink) and from a best estimate (blue) using Pitot data for the first instant and turbine when it has been inserted in the flow

The extracted heat flux, estimated from the steam flow and the enthalpy difference between the steam temperature and the water inlet temperature, reaches a typical value of 75 kW (corresponding to an averaged heat flux of 1.5 MW/m²) in the early quenching phase until about 5 min (Fig. 26). This is much higher than the induction heating power (between 10 and 20 kW). In the last part of the test, although the extracted heat was below the total injected power, cooling was indeed achieved because some heat was lost to the crucible.

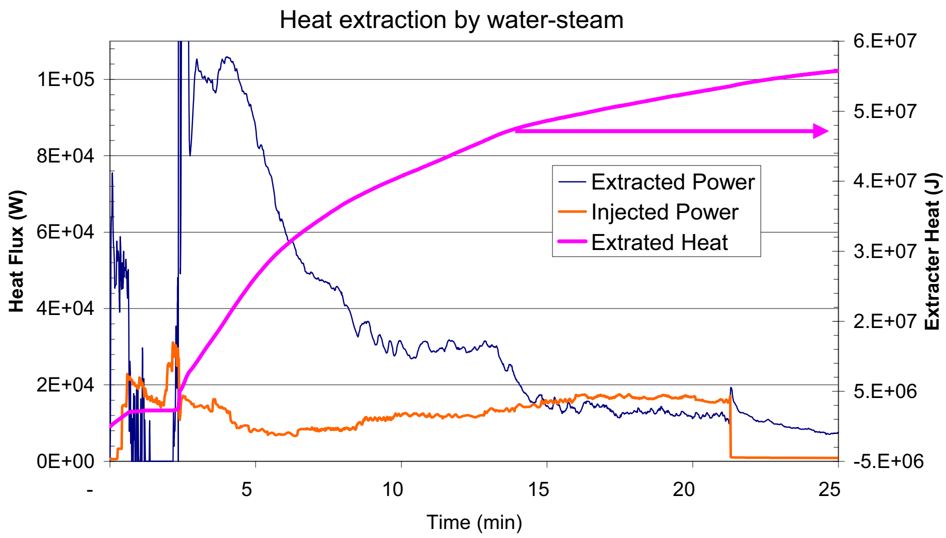

Fig. 26: Heat generated in the melt by induction heating and extracted by evaporation of the injected coolant water

Subsequently, the evaporated heat decreases as the melt cools down and eventually reaches the level of the simulated decay power. Fig. 26 also shows the power input during the test until end of heating at 21.3 min, when the operator switches off the power supply, as the melt seems completely quenched.

This shows the ability of the bottom-cooling concept to arrest the prototypic corium pool within a period of less than 20 minutes until complete cooling was achieved.

It is important to note that in spite of addition of water to the bottom of the melt, no energetic event occurred that would produce a fast pressure spike or mechanical loads by an “exploding” melt. This is in agreement with the safety analysis (Boccaccio, 2005) based on the observations in the previous COMET experiments at Forschungszentrum Karlsruhe and on the fact that water injection through the prepared flow channels is moderate with the consequence that no major water volumes exist in the melt that could undergo a strong interaction.

Dismounting and post-test examination

The COMET Test section has been dismounted (Journeau, 2006b). It appeared that a large amount of corium (accounting to 1/3 of the corium mass) have been projected to the wall sides. Although this is an artifact due to the small test section size, compared to the reactor scale, it implies that a significant fraction of the melt will be ejected. Even if most of it may fall back into the pool, this phenomenon will affect the cooling process. Then, the lower part of the resin and concrete shells has been sawn (Fig. 27). The copper coils have then been disassembled, leaving the zirconia crucible, the COMET PCA device and the corium pool. The copper coils and the zirconia crucible have been found without any damage and no corium leak has been observed, confirming the good retention of corium by the COMET PCA core-catcher.

Fig. 27: After sawing half of the concrete shell

The crucible and the pool have been disassembled from the COMET core-catcher, which is shown on Fig. 28. The ablation of the sacrificial concrete layer has been strongly limited and reached about 1 cm in average. The maximum ablation (< 2 cm) has been observed at the centre, i.e. far from the water channels, whereas some millimeters of sacrificial concrete remained above the water channel, although it must have been fractured enough to allow water to flow. No corium leaks were observed. A (roughly 5 mm thick) greenish layer (maybe a U_3O_8 containing glass) was visible on the core-catcher surface.

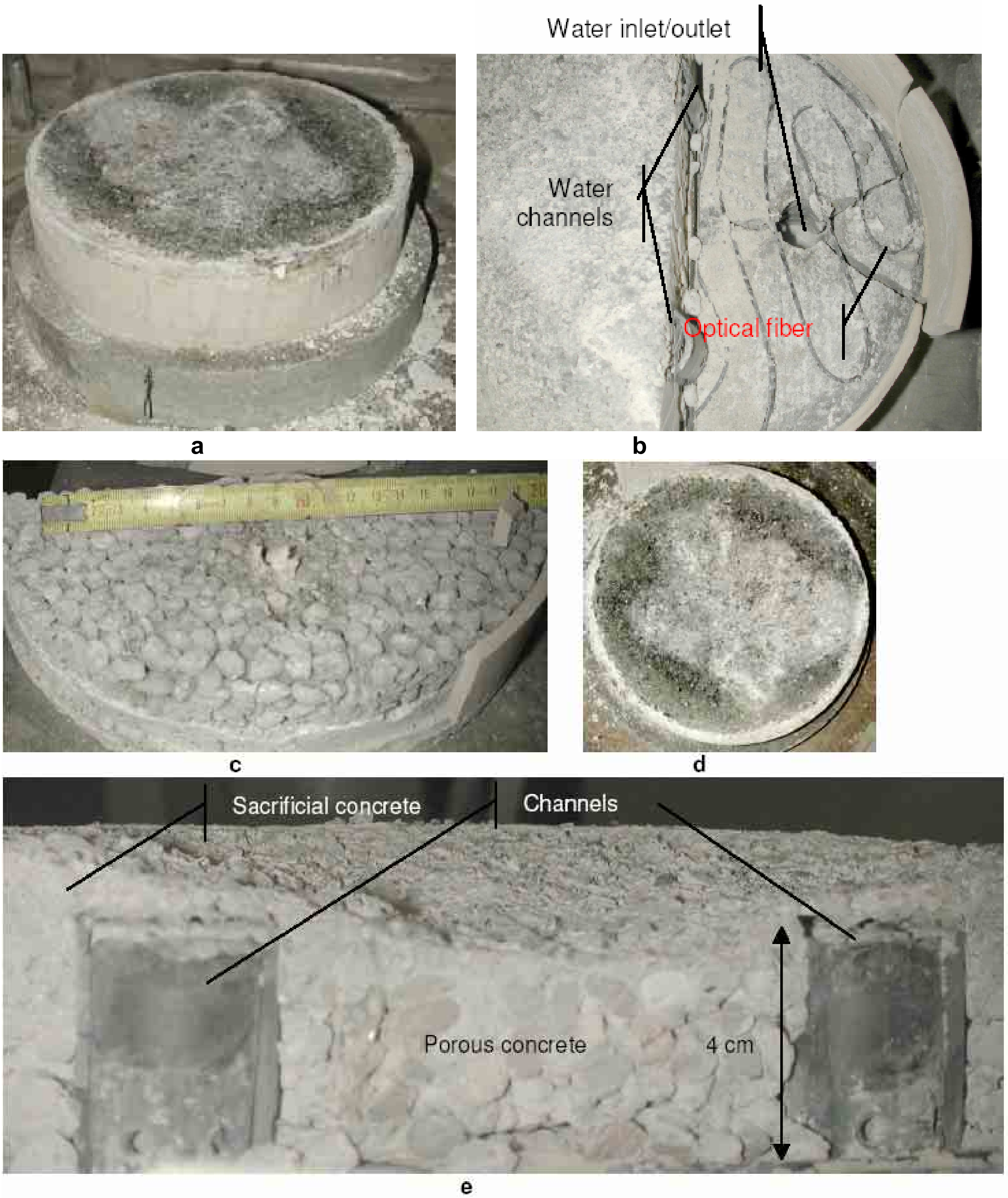

Fig. 28: COMET PCA core catcher after the test

a: View of the core-catcher before cutting   b: Top view with one half removed
c: Bottom view of removed porous concrete   d: Zoomed top view showing greenish layer
e: Cut view of the core catcher

Fig. 29 presents a top view of the zirconia crucible and of the corium pool while Fig. 30 presents a view of the corium pool from the corium. Crevices are visible on both sides. Some decomposed concrete (in grey) is attached to the central part of the corium pool lower surface. On the external part of Fig. 30, a glassy material is visible.

Fig. 29: Top view of the corium pool in the zirconia crucible

Fig. 30: Bottom view of the corium pool after the zirconia crucible has been removed from the COMET core-catcher

It appears that the 20 mm thick crucible has not been significantly ablated during the test, another proof of the rapid cooling of the corium melt. The corium pool was 85-100 mm high (after ejection corium). Up to 30 mm thick of projections are found on the upper inert part of the crucible.

Chimneys have been observed in the lower part of the corium pool (Fig. 31). It has not been possible to observe the paths between the lower and upper surfaces. The only post-test verification has been to reopen the water supply and to verify that water could go through the solidified pool and exited through the crevices. Cavities have also been found in the solidified corium pool.

Fig. 31: Chimneys observed at the lower part of the corium pool

From the weighing of the various corium samples, it is estimated that about 60 kg of corium have been poured out of the VULCANO furnace. On these 60 kg, 50 kg reached the test section. After the test, 2/3 (33 kg) were found as a pool (27 kg) and debris (6 kg). 17 kg had been projected on the walls.

Summary

The COMET PCA core catcher concept has been satisfactorily validated with prototypic corium and sustained heating in the VULCANO facility, allowing a transposition to reactor scale applications.

After a short corium-concrete interaction phase, the bottom flooding passively started leading to efficient heat removal by evaporation form the bulk of the melt. A maximum power of 75 kW was initially extracted through the generated steam, which was more than 3 times of the injected power, ensuring fast cool-down and solidification of the melt. In the long term, coolability of the corium was characterized by continuous removal of the simulated decay heat.

The temperatures measured at the interface of the porous concrete layer (1 centimetre below the water channel outlets) remained around 100 °C or below. The presence of coolant water in the porous concrete layer keeps the concrete cold, thus providing a safe barrier against the corium that was continuously heated.

Apart from its demonstrative result, this experiment will provide inputs for the further validation of the WABE code (Widmann, 2004) – within the SARNET joint programme of activities on corium coolability – to achieve further insight into the essential processes of porosity formation, melt cooling and quenching, so that these results can be transferred to the reactor scale. This will conclude the present research and development actions devoted to the qualification of this cooling concept (Journeau, 2006d).

4.3 KROTOS K-101 test performed for Slovenian users

The KROTOS facility had been operating at JRC Ispra. After termination of JRC programme, it has been purchased by CEA In 2005, the KROTOS building has been achieved and the KROTOS facility has been transferred to this building extension. Reinstallation finished in early 2006 (Fig. 32). The Slovenian users came in May 2006 to have access to a KROTOS experiment.

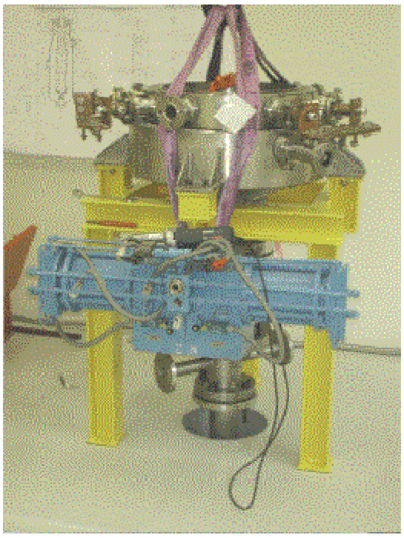

Fig. 32: KROTOS installation in the PLINIUS building extension

Left: Furnace lower head **Right: Test section and transfer tube**

The aim of the experiment that had been proposed by the Josef Stefan Institute is to study the material effect in steam explosion. The idea is to lower the liquidus temperature thanks to the adjunction of iron oxide and oxidic fission product prototypes to the melt, while all the other parameters would be kept similar to KROTOS K-58. The load composition is based on the Krško NPP (Westinghouse design) inventory in which all the zirconium and 30 % of the lower head steel has been oxidized. Some of the fission products that can form metallic species (e.g. Ru) may be discarded to prevent any risk of interaction with the crucible, as well as nickel oxide (for health reasons). It has been discussed between CEA and IJS. The target composition is shown in Table IV:

Phases	K-101 load (g)	K-101 load (%)
UO2	2628.2	73
ZrO2	733.8	20.38
FeO1,5	146.7	4.07
CrO1,5	45.8	1.27
BaO	10.7	0.30
LaO1,5	27.9	0.77
SrO	7.0	0.19
Total	3600	100

Table IV: K-101 load composition

Some products in the initial load are in excess with respect to the target values to take into account partial evaporation during the melting process. Actual final composition will be verified by appropriate post-test analyses.

The target load liquidus and solidus temperatures have been calculated by using GEMINI-2 (Gibbs Energy minimizer) and NUCLEA-06 iv database (in-vessel)

- Liquidus temperature: 2670 K
- Solidus temperature: 1640 K

A preliminary test has been made in the COLIMA facility to verify the high temperature compatibility between the proposed load and the KROTOS tungsten crucible.

The test experimental conditions (Table V) have been selected, in collaboration between IJS and CEA, to mimic as closely as possible those of test K-53 (performed in ISPRA with an 80 wt % UO_2 – 20 % ZrO_2 melt composition).

Melt mass	3.6 kg
Melt temperature	2850 °C
Melt jet diameter	30 mm
Free fall in gas[3]	0.25 m
Water column height	1.05 m
Water mass	34 kg
Water column diameter	0.2 m
Water temperature	295 K
Free board gas	He
Free board gas volume	0.330 m^3
Free board gas pressure	0.36 MPa
Free board gas temperature	295 K
Trigger gas	N_2
Trigger gas volume	15 cm^3
Trigger gas pressure	15 MPa

Table V: Definition of K-101 experimental conditions

Pre-calculations have been realised by IJS (Leskovar, 2006).

The K-101 experiment

On May 30, 2006, the first KROTOS Fuel-Coolant Interaction (FCI) test was performed on the PLINIUS platform with the Slovenian user group. One researcher and three students from IJS participated to this test. This corium composition (Table IV) was also tested for the first time in a FCI facility. The load has been prepared using powder metallurgy technique to increase its density.

The corium load molten and heated up to 2760 °C in 4 h, following the test procedure. Fig. 34 presents the evolution of the tension and intensity in the 3 phases of the furnace resistance heater (Fig. 33). A final temperature of 2732 °C (above liquidus) has been measured by bi-chromatic pyrometer (Fig. 35).

[3] It is not possible to respect strictly K-53 values for both the free fall and the water height (0.44 and 1.10 m in K-53, respectively).

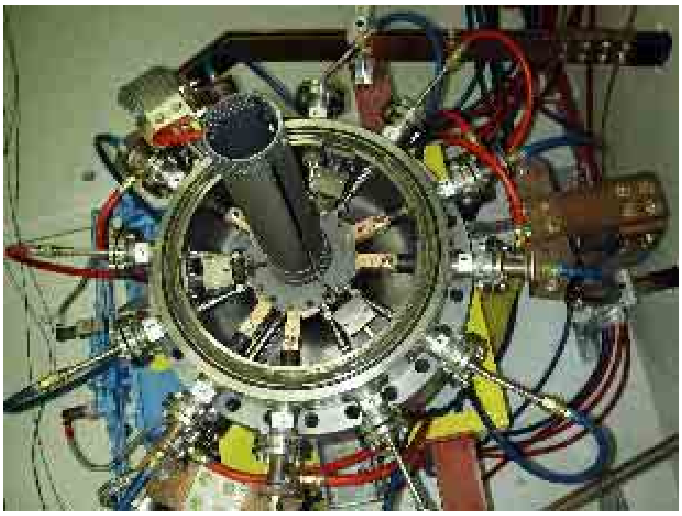

Fig. 33: KROTOS furnace heating elements

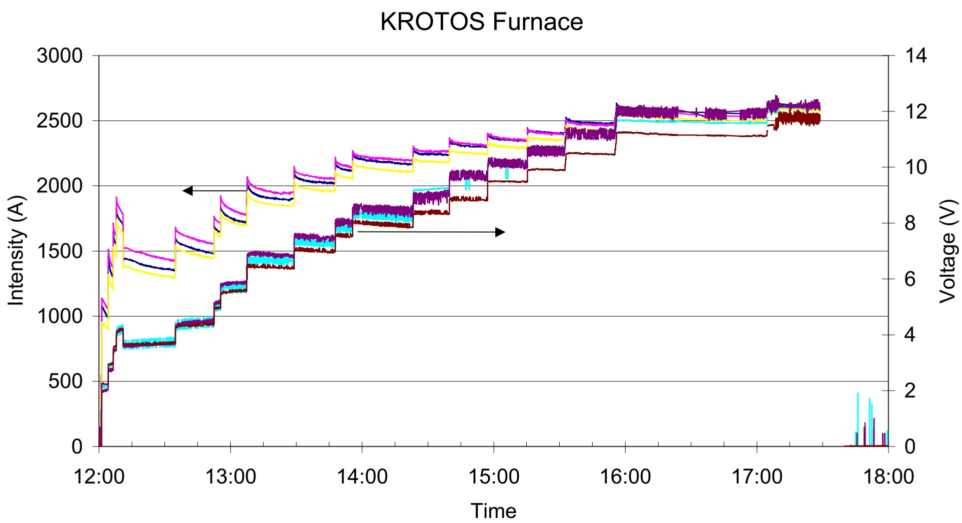

Fig. 34: Furnace electrical measurement for the 3-phases

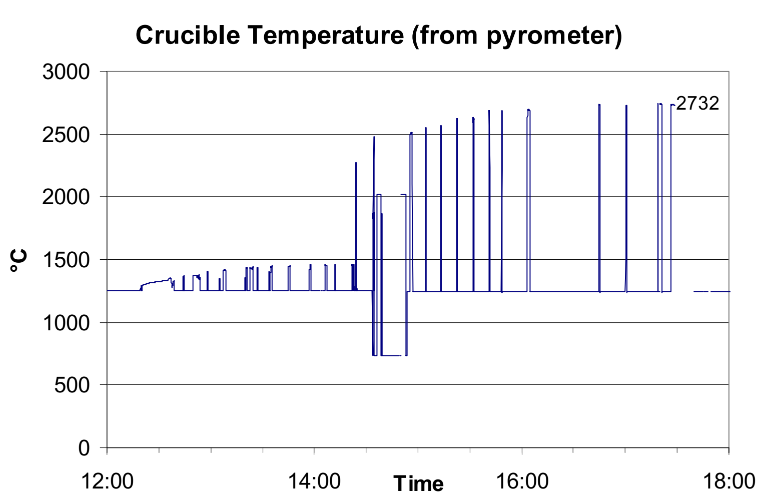

Fig. 35: Evolution of pyrometric readings
Crucible temperature is measured only at discrete instants when the view port is opened

The crucible was correctly released in the KROTOS test section (Fig. 36). The facility's good technological operation validated the recommissioning of KROTOS and the transfer of know-how from Ispra to Cadarache.

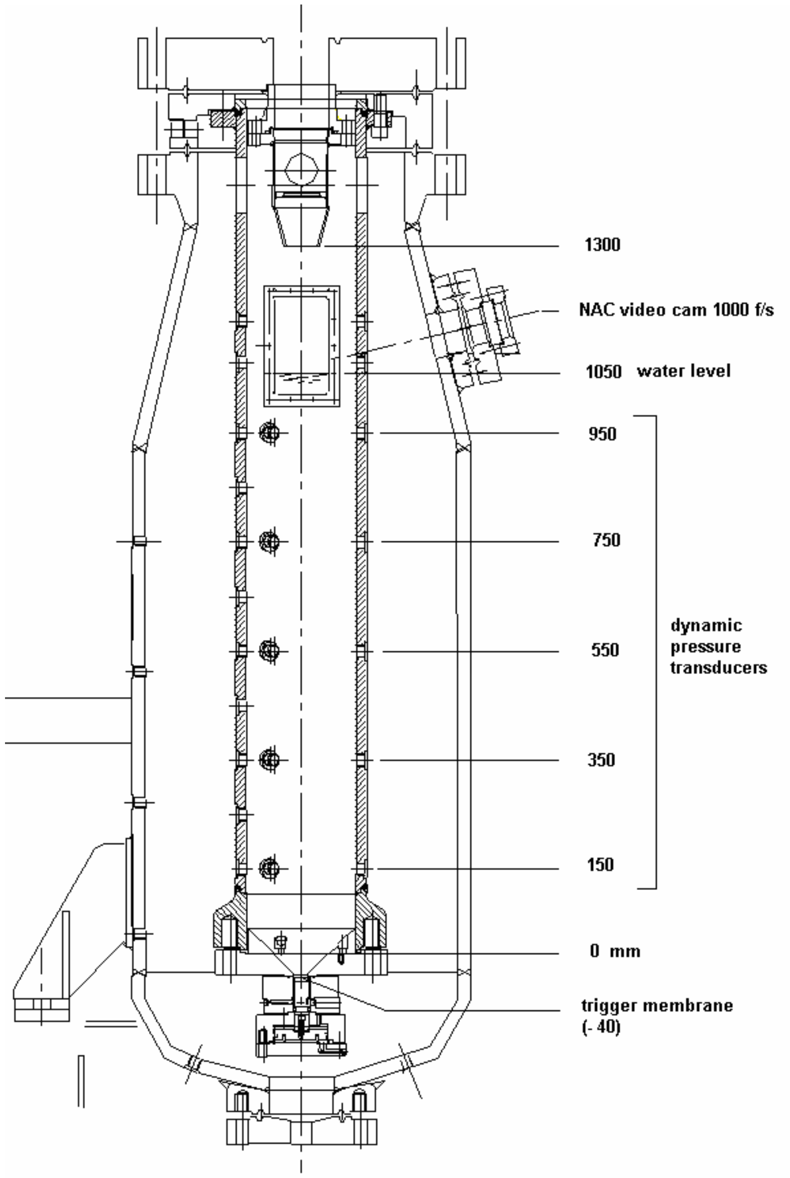

Fig. 36: Sketch of the KROTOS test section

The expected explosion was not observed. After dismounting the facility, it happened that the crucible had been correctly pierced by the release device but that only 300 g (out of a 3.6 kg load) of corium had poured in the test section. Fig. 37 shows the bottom of the test section on which corium debris have been dispersed. The red colour has been attributed to the iron oxides present in the melt.

The trigger has not been actuated and no spontaneous steam explosion has been observed during this test. Actually, due to the small mass of melt, neither the pressure nor the temperature transducer did exhibit any significant signal during the interaction.

Fig. 37: Post-test examination of the test section (after drainage of the water)

Even if this first test did not succeed in observing a violent interaction between corium and water, our Slovene partners have expressed their satisfaction of having discovered the PLINIUS infrastructure and of having learned about the challenges of experiments dealing with high-temperature prototypic materials at very high temperatures as well as for the thorough scientific exchanges between experimentalists and code users (see Annex 6). CEA will invite them again to attend a next experiment (outside the PLINIUS TALI contract) and let them use its results for their current research.

5. Management issues

Due to the above-mentioned delays in the KROTOS building, a time extension of the contract has been requested by CEA, supported by the International panel and finally accepted by the European Commission.

This project was the first *Transnational Access to Large Infrastructures* (TALI) awarded under the Euratom Framework Programme. Thus, some time has been necessary to gain experience on the way this instrument functioned. It appeared that there was an uncompressible delay of one year between the call for proposal and the performance of a test, due to the delays for the call, for its analysis and for the preparation of accesses, which always led to modifications of the facilities. This has been accounted for in the schedule associated with the PLINIUS FP6 project currently under negotiation with the European Commission.

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Annex 1 – Text of the announcements

Text of the leaflet (to be presented folded in three)

The PLINIUS platform is located at Cadarache in Southern France

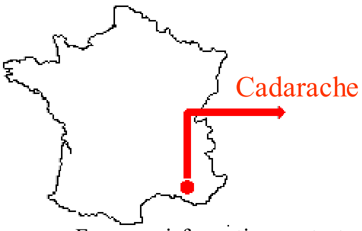
•70 km North East from Marseille

•70 km from Marseille-Provence International Airport

•40 km from Aix en Provence at the confluent of Durance and Verdon rivers

CEA / Cadarache hosts experimental reactors, specialized laboratories, workshops and experimental halls for nuclear energy research. 450 buildings are devoted to R&D.

Cadarache is the largest CEA site outside Paris region, both in term of staff (5000 persons, mainly researchers, engineers and technicians) and of budget (380 M€).



For more information contact

Christophe JOURNEAU

E-mail : plinius@cea.fr

http://www.cad.cea.fr/plinius/Plinius_Frame1.htm

Next calls for proposals deadline:

1 December 2002

31 December 2003

Only individual researchers or Research teams (Company, university, research lab,....) conducting their research in the Member States (except France) and the Associated States will be eligible to benefit to access to PLINIUS. Research teams must be entitled to disseminate or arrange dissemination of (e.g. through open publication) of the knowledge they have generated under the access to the PLINIUS infrastructure. An exception may be made in the case of 1st time access by a Small or Medium Enterprise.

These access grants are offered either for students (Master or PhD thesis, post-docs,…) or for more experienced scientists and engineers working on severe accidents or any other field for which access to our platform would be fruitful.

European Union Member States
(except France)

AUSTRIA, BELGIUM, DENMARK FINLAND, GERMANY, GREECE, ITALY, IRELAND, LUXEMBOURG, NETHERLANDS, PORTUGAL, SPAIN, SWEDEN, UNITED KINGDOM.

Associated States (Nuclear Fusion):

BULGARIA, CZECH REPUBLIC, HUNGARY, LATVIA, ROMANIA, SLOVAKIA, SLOVENIA

Access for users from other countries could be negotiated with CEA on a bilateral basis

EU-sponsored
Free Transnational Access
to the PLINIUS
Corium Platform

Commissariat à l'Energie Atomique
Direction de l'Energie Nucléaire
Severe Accident Mastering Laboratory
CEA / Cadarache
F13108 St Paul lez Durance

EUROPEAN COMMISSION
RESEARCH DIRECTORATE-GENERAL
Directorate J –Preserving the Ecosystem-
Research Actions for Energy

Do you want to perform **free of charge** severe-accident experiments with prototypic corium at CEA Cadarache (France)?

Access for visiting scientists from EU (*except France)* and Associated Countries

The EU will pay all facility costs + travel and expenses. You pay only your salary(ies) .

•Submission of Proposals by potential visitors

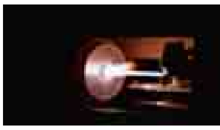
•Selection by International Panel

•Visit by 1-3 scientist(s) during ~1 month for the performance of experiment(s) with our scientific and technical team.

•You may bring specific apparatus to install in our facility.

•Visitors must disseminate results in the open literature.

PLINIUS is CEA experimental platform for prototypic corium.
It is staffed with an experienced scientific and technical team.
Access to the following prototypic corium facilities will be offered.
Prototypic corium = high temperature melts with depleted UO_2



VULCANO
•Transferred arc plasma torch furnace
•200 kW
•35-70 kg of molten corium up to 3000°C

•Crucible tests with induction sustained heating

•Spreading tests

•Molten Core Concrete Interaction ….

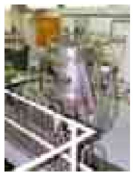
VITI
•Viscosity & Surface Tension of molten corium
•Aerodynamic levitation technique
•Induction heating of droplet (few millilitres)

Droplet at rest

Compressed droplet

COLIMA
•Induction heating (150 kW)
•Few kg of corium
•1.5 m³ enclosure (5bars, 150°C)
•Temperature controlled walls
• Material interactions
• Corium Physical Properties
• Aerosols

KROTOS
•Fuel Coolant Interaction (steam explosion) facility
•Electric Resistance heating of 4.5 kg corium
•Release in water filled test tube.



Excerpts from the web pages

[General Information] – [Corium – Severe Accidents] – [The Facilities : VULCANO ; KROTOS ; COLIMA ; VITI] – [Eligibility] – [How to Apply] – [Deadlines] – [Evaluation] – [Remuneration] – [Applications should be sent to] – [Application Form] – [Location of the Facility]
Links to EU Access to Research Infrastructures page , the Euratom Research and Training Programme and CEA Cadarache

PLINIUS
(Platform for Improvements in Nuclear Industry and Utility Safety)

Experimental platform for corium severe accident mastering laboratory

CEA Cadarache, France

EC supported Transnational Access to Large Infrastructures
(Contract FIR1-CT-2001-40152)

The EC can sponsor your visit to perform a prototypic corium experiment in our PLINIUS platform (VULCANO, KROTOS, COLIMA and VITI corium facilities) at CEA/Cadarache. Experimental costs + travel and subsistence can be fully paid. This applies to research teams in the EU (except France) and Associated States. For more information, consult our pages.

The deadline for the 2nd call for proposals has been set to 1 December 2002.

How does a PLINIUS visit looks like in practice?

At first, you send a summary of your experience plan with the objectives and the background of your visit. You fill in the application form with your address, the name of your company, the number of days and of visiting researchers you estimate for the tests (*typically 4 weeks for 2 researchers*), and the wished dates of your trip. (This programme operates from autumn 2001 to autumn 2004).

Only scientists (researchers, professors, engineers, students, etc.) from Member or Associated States who are entitled to disseminate, or arrange to disseminate, the knowledge they have generated during the project are eligible to benefit from access to the PLINIUS platform.

The deadline for the 2nd call for proposals is 1 December 2002.

Then an expert panel selects and retains the most relevant and interesting proposals. Priority will be given to research teams who have not previously used the infrastructure.

Selection of projects will be on the basis of scientific merit taking into account the interests of the Community.

The experiments presented in this site are only those corresponding to the ideas we have had in our team. One of the interests of the Transnational Access to Large Infrastructures programme is to have external scientists proposing NEW ideas and applications for existing applications. So be creative! Please contact us to discuss in advance your proposal. We will try to find a technical solution to have it fit with the capabilities of our facilities.

If your proposal is accepted, you will receive a mail encouraging you to take contact with us to prepare your trip. We will consider the dates you propose and try to organise the entire visit as well as possible. A contract will be established between CEA and you and your personal data will be requested for CEA regulatory checking. After discussing the experience plan and the test details with you (you may be asked some pre-test calculations for experiment dimensioning, especially concerning safety), the second step of your trip will begin.

Typically, we reserve and pay for your lodging at Aix-en-Provence or Cadarache, at your convenience. You reserve yourself the travel (use 2nd class rail fare or APEX air fare) and pay your ticket in advance. We will reimburse you it *(don't forget to keep any bills you paid for your travel).* In the same time, we will reimburse you the subsistence rate to an amount of 32.62 Euro per day.

In Cadarache, you will have a place to work and a computer with an Internet access and an e-mail account. The time of work is 7h55 to 16h35. The first day, the experience plan is discussed and explained more in details with the team who will perform the tests with you. You can also bring some specific apparatus to our facility. During your trip, we will ask you to present your works and your company or institution to the severe-accident mastering laboratory.

At the end of the trip, you will receive a digital copy of the data acquired during the experiment and, if required, the debris for post-test analysis (if nuclear material transport permits are OK).

You will be asked write the data report (CEA writes a brief technical report of the experiment – without interpretation) and to disseminate the results by writing a publicly available paper. A summary of your work will be inserted in the PLINIUS final report.

In practice, a visitor must come from a European Union or Associated Country institution (company, university, laboratory, small or medium enterprise, etc.). However, the applicant can be a student during a training programme in such an institution, typically at the end of his/her education (engineer, master, PhD, post-doctorate). Thus we encourage any students as well as any researchers to organise an experience plan in response to real and innovative objectives for a real problem solving approach.

Please note:

All publications resulting from work carried out at the facility must acknowledge the support of the European Community – Nuclear Energy Programme (contract FIR1-CT-2001-40152) and be submitted to CEA.

The PLINIUS platform

PLINIUS is the only European experimental platform dedicated to the study of severe accidents using large masses of prototypic corium (i.e. high temperature molten mixtures containing depleted uranium oxides prototypic of the melt that could arise during hypothetical severe accidents). It has been dedicated to C. Plinius Caecilius Secundus (Pliny the Younger) who wrote the scientific description of AD 79 Vesuvius eruption.

Paper describing the PLINIUS platform (1.68 MB)

It consists of four facilities:

VULCANO

A 50-100 kg corium melting facility operated for spreading or crucible experiments (possibility of sustained induction heating)

KROTOS

A Corium-Water Interaction facility in which up to 5 kg corium is molten and dropped into water. Energetic steam explosions can be triggered and studied.

COLIMA

A small scale (few kg) facility with induction heating (up to 170 kW) and a thermostatic 1.5 m^3 enclosure.

© J. Moneris, CEA, 1999

VITI

A levitating droplet facility to measure corium viscosity and surface tension.

It is operated by a staff of 12 engineers and technicians (operation, heating, instrumentation, materials, corium physics, radioactive waste, health and safety specialists).

Post-mortem analyses can be performed with prototypic corium at our site.

Calculation tools have been developed at CEA to analyse corium behaviour.

(Pre- and post-test calculations by CEA are not included in our proposal for access but could be discussed on another basis.)

1st PLINIUS Call for Proposals

Deadline: 18 March 2002

The 1st PLINIUS Call for Proposals concerns the access to the COLIMA and VITI facilities for research teams from EU (except France) and Associated Countries.

Researchers wishing to access (access charges and travel + subsistence paid by the EC) these facilities must submit their experimental programme using the following Application form.

It is planned that the proposed accesses will take place between June 2002 and June 2003.

A second call (including VULCANO and KROTOS) should be opened in early 2003.

2nd PLINIUS Call for Proposals

Deadline: 1 December 2002

The 2nd PLINIUS Call for Proposals concerns the access to any of the PLINIUS facilities (VULCANO, COLIMA, KROTOS and VITI facilities for research teams from EU (except France) and Associated Countries.

Researchers wishing to access (access charges and travel + subsistence paid by the EC) these facilities must submit their experimental programme using the following application form.

It is planned that the proposed accesses will take place between June 2003 and November 2004.

3rd PLINIUS Call for Proposals

Deadline: 31 December 2003

The 3rd PLINIUS Call for Proposals concerns the access to the KROTOS facility of the PLINIUS platform for researchers or research teams from EU (except France) and Associated Countries.

Researchers wishing to access (access charges and travel + subsistence paid by the EC) these facilities must submit their experimental programme using the following Application form.

It is planned that the proposed accesses will take place between September 2004 and November 2004, or in 2005 (in case of prolongation of the PLINIUS contract).

This is the final call for proposals within this contract.

Annex 2 – Composition of the Users Selection Panel

The Selection Panel membership has been slightly modified to prevent potential conflict of interest (H. Almeyer who submitted a proposal was replaced by Risto Sairanen).

- Michel GIOT, Université Catholique de Louvain, Belgium
- Christophe JOURNEAU, Commissariat à l'Energie Atomique, France
- Daniel MAGALLON, Joint Research Centre, Netherlands
- Hans ALSMEYER, FZK, Germany (1st Meeting)
- Risto SAIRANEN, VTT then STUK, Finland (2nd and 3rd meetings)

Gérard COGNET (CEA Saclay) also attended the Selection Panel meeting as an observer. Alejandro ZURITA (EC Brussels) participated as project scientific manager to the 2nd meeting held in Brussels.

The following table summarises the dates and place of the Selection Panel Meetings

	Date	**Place**
1st Meeting	April 25th, 2002	Cadarache
2nd Meeting	May 21st, 2003	Brussels
3rd Meeting	March 8th, 2004	Cadarache

Annex 3 – List of publications

- P. Piluso, C. Journeau, E. Boccaccio, J.-M. Bonnet, P.I Fouquart, J.-F. Haquet, C. Jégou, D. Magallon, Corium Behaviour Research at CEA Cadarache: The PLINIUS prototypic corium experimental platform; International Conference Nuclear Energy for New Europe 2002, Kranjska Gora, Slovenia (2002).
- C. Journeau, P. Piluso, L. Godin-Jacqmin, I. Ivanov, I. Mladenov, P. Grudev, S. Kalchev, H. Alsmeyer, B. Eppinger, Transnational Access to the PLINIUS Prototypic Corium Experimental Platform, Symposium FISA 2003, EU Research in Reactor Safety, Luxembourg (2003).
- 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 Protypic corium Platform, Int. Congr. Advances nuclear Power plants (ICAPP'05), Seoul, Korea (2005).
- P. Piluso, E. Boccaccio, J.-M. Bonnet, C. Journeau, P. Fouquart, D. Magallon, I. Ivanov, I. Mladenov, S. Kalchev, P. Grudev, H. Alsmeyer, B. Fluhrer, M. Leskovar, Severe Accident Experiments on PLINIUS Platform - Results of First Experiments on COLIMA Facility Related to VVER-440 - Presentation of Planned VULCANO and KROTOS Tests, International Conference Nuclear Energy for New Europe 2005, Bled, Slovenia (2005).
- C. Journeau, "PLINIUS" Transnational Access to the corium research infrastructure, FISA 2006, EU Research and Training in Reactor Systems, Luxembourg (2006).
- C. Journeau, H. Alsmeyer, Validation of the COMET Bottom-Flooding Core-Catcher with Prototypic corium, Int. Congr. Advances nuclear Power plants (ICAPP06), Reno, NV (2006).
- L. Godin-Jacqmin, C. Journeau, P. Piluso: Analysis of the COLIMA CA-U3 test using the ELSA module of ASTEC, International Conference Nuclear Energy for New Europe 2006, Bled, Slovenia (2006).
- M. Leskovar, Precalculation of PLINIUS/KROTOS Steam Explosion Experiment with MC3D, International Conference Nuclear Energy for New Europe 2006, Bled, Slovenia (2006).

Annex 4 – List of received projects

Project number	Title	Status[4]	Country	Number of CAU	Facility	Year of activity
1	Quantification of the increase of the gaseous radioactive products in severe accidents of nuclear water reactors through a simulation at the PLINIUS Platform on behalf of the Environmental Impact Assessment of the NPP (VVER440)	C	Bulgaria	**3**	COLIMA	2
2	H_2 and radioactive releases in case of severe accidents	C (merged with Project 1)	Bulgaria	3	COLIMA	2
3	Tests of mechanical properties and non-destructive testing of corium	R	Bulgaria	2	COLIMA	
4	Cooling of UO_2 corium melt by bottom flooding	C	Germany	**6**	VULCANO	3-4
5	Quantification of the H_2 release in severe accidents of VVER-1000 and the probability for an excess of the ignition or explosive concentrations with a view of the management of the accidents and prevention of the environment impact	R	Bulgaria	2	KROTOS	
6	Composition effects (addition of FP in melt) on steam explosion energetics	C	Slovenia	**2**	KROTOS	5
7	Interaction of molten metal with water	R	United Kingdom	2	KROTOS	

[4] C = completed, O = ongoing (i.e. started, but not yet completed), A = approved, R = rejected, and NE = not yet evaluated. **Bold** numbers correspond to the actually offered CAUs.

Annex 5 – List of users

User ID	Users	Year of visit	Number of visits	Project number	First access to PLINIUS (Y/N)	Time spent by user at PLINIUS	User category[5]	User institution	Institution type[6]	T/R reimbursed
1	Ivan IVANOV	2003	2 (for 1 access)	1	Y	4 weeks	EXP	Technical University of Sofia	UNI	Yes
2	Pavlin GRUDEV	2003	1	1	Y	3 weeks	EXP	INRNE, Bulgarian academy of Science	PUB	Yes
3	Ivan MLADENOV	2003	1	1	Y	3 weeks	PGR	Energy Institute	PRI	Yes
4	Stoyan KALCHEV	2003	1	1(2)	Y	3 weeks	EXP	NPP Kozloduy	IND	Yes
5	Hans ALSMEYER	2005	1	4	Y[7]	3 days	EXP	FZK	PUB	Yes
6	Beatrix FLUHRER	2005	1 planned	4	Y[7]	Cancelled for health reasons	EXP	FZK	PUB	No
7	Matjaz LESKOVAR	2006	1	6	Y	3 weeks	EXP	Josef Stefan Institute	PUB	Yes
8	Janez GADE	2006	1	6	Y	1 day	PGR	Josef Stefan Institute	PUB	Yes
9	Miroslav BABIC	2006	1	6	Y	1 day	PGR	Josef Stefan Institute	PUB	Yes

[5] UND = Undergraduate, PGR = Post-graduate (student with a first university degree or equivalent), PDOC = Post-doctoral researcher, TEC = Technician, EXP = Experienced researcher (professional researcher).
[6] UNI = University, PUB = Public Research Organisation, PRI = Private Research Organisation, non-profit, IND = Industrial or Commercial enterprise.
[7] Not counting short tours during meeting at Cadarache.

Annex 6 – Opinions from a PLINIUS user

Matjaz Leskovar, lead user from Slovenia, has been requested to state his impressions after having completed his access to the PLINIUS/KROTOS facility:

I stayed at CEA, Cadarache from 11.5 to 31.5.2006. The KROTOS/PLINIUS experiment was performed on 30.5.2006. So I was able to get an insight in the activities before the experiment (i.e. experiment preparation), during the experiment (i.e. experiment performance) and after the experiment (i.e. first analysis of experiment).

Before my visit at CEA, I had no experience in performing scientific tests on experimental facilities. I performed only some simple training experiments during my studies. I am involved in the research of severe reactor accidents – especially the research of steam explosions – for more than 10 years. During all this time I was involved only in the modeling part of the severe accidents research and got information about the accompanying experimental programmes mainly from literature. By only reading articles, conference papers, reports, etc. about the experimental programmes, it is not possible to get a real impression how experimental research looks like. And without this insight and knowledge it is difficult to estimate what data can be provided by an experimental programme. A model developer knows what experimental data he would need to be able to develop an appropriate model or validate it. But is it feasible to perform such an experiment, which would provide the model developer the requested information? That is a question which can be answered only by an experimentalist. On the other hand, an experimentalist knows what kinds of experiments are feasible and what experimental data can be obtained. But will this experimental data be of great significance for the model developer? This is a question which can be answered only by a model developer. Due to these facts it is of utmost importance that the model developers and the experimentalists work closely together.

During my stay at CEA I got the opportunity to be nearly one month in direct contact with the experimentalists and got an insight in the activities before, during and after the performance of the KROTOS/PLINIUS experiment. It was very interesting already seeing the experimental facility, observing the technicians during their work and becoming familiar with the safety procedures during the different activities. But the greatest benefit was the close contact with the experimentalists, leading to numerous interesting and dynamic discussions. In the beginning it looked like we came from different planets, not understanding each other's way of thinking well, but during our discussions we came closer and closer together and at the end of my stay we already spoke the same "language". Now I understand better where the experiments have their limits and why a complex experiment cannot provide all the detailed information, which would make model development more straightforward. I realised that experimental work is not a fairy tale, where everything is ideal, but real life, where things are mostly not ideal. At experimental work we therefore have to focus on seeking the optimal feasible solution in a given situation, since an ideal solution, which in the given situation is not feasible, is useless.

Beside this direct benefit of getting more familiar with experimental work, which is very useful for model developers since it makes the joint research more efficient, there is also an important indirect benefit. Due to my long stay at CEA, a number of new personal contacts were established and the existing personal contacts were refreshed and strengthened, which is a good basis for a fruitful cooperation in the future.

Similar impressions were expressed (orally) by other users. It shows that besides the scientific benefits of transnational access to research infrastructures, there are other benefits in terms of experimental training, networking of researchers, and of in-depth communication between researchers from different backgrounds.