

10

CEA COMMISSARIAT À L'ÉNERGIE ATOMIQUE
DIRECTION DES REACTEURS NUCLEAIRES DEC-SECC

The VERCORS HT facility for studies up to molten PWR fuel conditions

*P.P. Malgouyres¹, G. Ducros¹, M.P. Ferroud-Plattet¹,
M. Prouve¹, D. Boulaud²*

**Performed by : CEA Grenoble
Supported by : IPSN and EDF**

1 : C.E.A. Centre de Grenoble, DEC-SECC, 17 rue des Martyrs, 38054 Grenoble Cédex 9, France
e-mail "ducros@dtp.cea.fr"
2 : Institut de Protection et de Sécurité Nucléaire, Centre de Saclay, DPEA-SERAC, 91191 Gif sur Yvette, FRANCE

THE ATOM, FROM RESEARCH TO INDUSTRY

European working group "Hot laboratories and remote handling" meeting, Windscale, 21-23/09/98 1

severe PWR accidents

Gerald Ducros Grenoble

ABSTRACT

The first objective of the Vercors Program is to improve the data base of fission products release and behaviour after an extensive fuel temperature increase and loss of integrity of the fuel elements that occurs in case of severe PWR accident.

For these tests, industrial fuel from French PWR reactor plants is used. In order to rebuild the short lived fission product inventory, a reirradiation is performed in an experimental reactor, prior to the test.

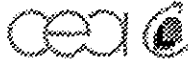
Eight tests were conducted in the frame of the Heva Program up to 2370 K in the 1983-1988 period. The main outcomes of these studies are linked to the volatile and some semi volatile fission product release. This program was extended by the Vercors one with higher fuel temperature (2600 K) and improved instrumentation. The knowledge of the behaviour of low volatile fission products has been significantly improved with the six Vercors tests.

Since 1996, a new facility is available for studies up to 3100K. Because of the high temperature level, a specifically designed thoria furnace is used. In complete configuration, the loop is instrumented with a thermal gradient tube devoted to the study of chemical species characterised by deposition temperature, a cascade impactor, an aerosol filter and a specific iodine filter aimed to separate chemical forms of iodine. This loop allows kinetic release measurements by using four gamma spectrometry units. One test was performed in 1996 with this loop up to 3100 K. In reduced configuration, the loop is instrumented with the thoria furnace and a total filter that allows balance studies. This loop is devoted to non volatile and transuranic element release studies. Three tests are scheduled in 1998 with this loop. The first one was conducted in march 98.

Since the Heva program, gamma spectrometry, gamma emission tomography, metallography, scanning electron microscopy, energy dispersive X-ray analysis, X-ray diffraction, ICP spectrometry are some of the experimental techniques used for on-line and post-test characterisation.

The use of MOX fuel, the interaction between fission product aerosols and control rod materials (Ag-In-Cd) and the influence of the fuel fragmentation on fission product releases are the next steps of the experimental program.

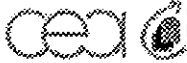
The program is co-funded by the French Nuclear Protection and Safety Institute (IPSN) and Electricité de France (EdF). The experiments are conducted in a shielded cell of the French Grenoble Nuclear Centre in the LAMA facility.



PLAN

- Objectives of the VERCORS program
- Description of the new VERCORS HT and RT facilities
- On line instrumentation and PTA techniques
- Some results

fin. prod. laiettes



Objectives of the VERCORS program

- Objectives
 - *Improve and validate models used in accidental codes (ESCADRE/ASTEC)*
 - *Create a realistic data bank for computing FP behaviour*
- Measurements
 - *Release kinetics and total release of FP and structural materials*
 - *Aerosol source, distribution size*
 - *FP chemical forms*

source term calculation



Experimental VERCORS program

- 8 HEVA tests from 1983 to 1988
 - Temperature between 1900 K and 2370 K
 - Volatile FP release
- 6 VERCORS tests from 1989 to 1994
 - Temperature between 2070 K and 2620 K
 - Volatile and low volatile FP release
- VERCORS HT and RT test from 1996 on
 - Up to molten fuel conditions *
 - HT1 performed on june 1996
 - RT1 and RT2 performed on march and april 1998

I, Cs, Te

max. temp. before
fuel collapse
+ ... Mo

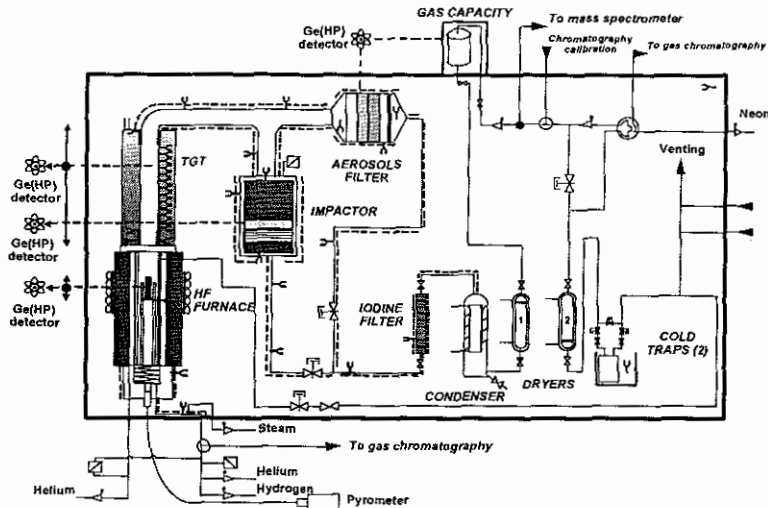
non-volatile FP
release
at melting

The experimental program began in 1983 with the HEVA program. **8 HEVA tests** were performed in this range of temperature around 2000 K and slightly above. The most important results were obtained for volatile FP, iodine, caesium and tellurium.

Then **6 VERCORS tests** were performed in an upper range of temperature ; 2600K represented the maximum temperature before fuel collapse. Volatile FP release were well quantified and some low volatile FP, as molybdenum, antimony and barium have completed the data bank.

Now **VERCORS HT and RT tests** have begun in 1996 and are still going on. The aim of these tests is focused on the release of non volatile FP and transuranic elements when the temperature reaches the melting.

VERCORS HT loop



European working group "Hot laboratories and remote handling" meeting, Windscale, 21-23/09/98

5

Thermal
Gradient
Tube

Impactor

aerosol
distribution
cell

The HT loop is located in a shielded hot cell. The cell is made of steel, 25 cm thick ; the dimensions are 1,25x2,5x1,7 m (lxlxH).

The **fuel** is heated to high temperature by induction furnace in a fluid flow constituted of steam and hydrogen, in order to represent the conditions of a nuclear accident. The **furnace**, specially designed for these very high temperature conditions, is made of thoria crucible and thoria insulators. A **pyrometer** measures the temperature of the crucible supporting the fuel.

Just above this furnace, a **thermal gradient tube** is designed to separate FP chemical species and to study their deposits on an inconel tube, representative of a steam generator tube.

An **impactor** is located on a derived line, in order to have a good measurement of the aerosol size during a well known temperature window, and to avoid any blockage of the loop during the test.

A specific iodine filter is intended to separate chemical forms of this particularly volatile FP.

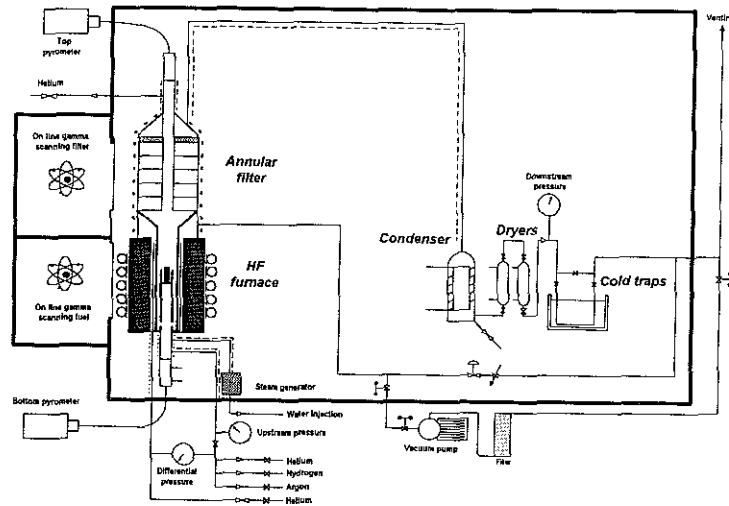
At last, charcoal traps, cooled by liquid nitrogen, stop the active gas before venting.

Because of freshly irradiated fuel use, iodine filters located within the venting, are in operation during the test.

During the test, gamma spectrometers measure on line the FP, emitted by the fuel, deposited on the TGT, on the impactor, and on the total aerosol filter. The active gas are also measured on line when going through this specific capacity.



VERCORS RT loop



European working group "Hot laboratories and remote handling" meeting, Windscale, 21-23/09/98

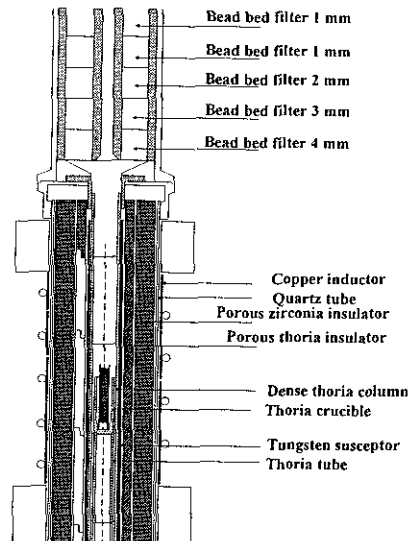
6

The RT version of the loop is more compact. The furnace is similar than the HT furnace, but it is more easily remote handling ; so it enables to increase the frequency of the tests. In this configuration, all FP and transuranic elements are trapped as near as possible from the emission point in a total filter. The release quantification of transuranic elements and pure β FP is obtained by post test chemical analyses.

A second pyrometer is viewing the top of the fuel through a channel in the total filter.



VERCORS RT furnace



This is a zoom of the VERCORS RT furnace. The **fuel** is constituted of three pellets of enriched UO_2 in their original cladding irradiated in a PWR reactor. Two half pellets of depleted UO_2 are placed on each side of the test sample. For most tests, this total sample is irradiated again during one week at low power in an experimental reactor just before the test in order to recreate the short half-life FP.

The fuel is set down on a thoria crucible, which is maintained on a thoria tube. A dense thoria column separates :

- the main channel, where steam and hydrogen is injected,
- and the inductor channel, where the tungsten susceptor is protected from steam oxidation by a small helium flow.

Outside of the tungsten susceptor, two thermal insulators are placed, the first made of porous thoria and the second made of porous zirconia.

All thoria pieces are manufactured in our own laboratory.



HT or RT facility ?

■ HT loop

- *Non volatile fission products*
- *Kinetics measurements : 4 on line γ spectrometers*
- *Chemical aspects : TGT, Maypack*
- *Physical aspects : Impactor*

High Temp.
of

- non volatile FP

■ RT loop

- *Transuranic elements*
- *Fuel collapse detection*
 - 2 pyrometers
 - fuel on line γ spectrometer
- *Remote handling furnace*
 - one month delay between 2 tests

Transuranic
release

- transuranic
elements
non measurable by
 γ spectrometry

Why two configurations HT and RT loops ?

At the beginning HT, which means "High Temperature" was focused to the quantification of non volatile FP with measurements of short half life FP by gamma spectrometry, and RT, which means "Transuranic Release", was focused to the quantification of transuranic elements release, which are not measured by gamma spectrometry. So the reirradiation was not necessary and the collection of the aerosols as near as possible from the emission source was very important for release quantification.

At present, the differences have slightly evolved, because we intend to reirradiate the fuel samples for some RT tests. Nevertheless :

- HT loop remains better adapted for non volatile FP measurements and particularly kinetics measurements with the 4 on line γ spectrometers, chemical characterisation with the TGT and the Maypack for iodine chemical forms, and physical characterisation with the impactor,
- RT loop remains better adapted for transuranic elements and pure β FP measurements ; it is also well adapted for fuel collapse detection with the two complementary pyrometers and the fuel on line γ spectrometer. Finally, the special remote handling furnace is very efficient and the last RT1 and RT2 tests were performed within only one month delay.



Estimated VERCORS HT/RT grid

VERCORS tests	HT1	RT1	RT2	RT5	RT4	RT3	RT6	HT3
Date	June 18 th 1996	March 17 th 1998	April 15 th 1998	December 1998	February 1999	April 1999	December 1999	2000
Fuel	UO2	UO2	MOX	UO2	UO2	UO2	UO2	UO2
Burnup (GWd/tU)	47	47	41	60	33	33	12	?
2 nd irradiation	SLOE	No	No	OSIRIS	No	OSIRIS	OSIRIS	OSIRIS
Max fuel temperature (K)	> 3100	2570	2440	Fuel collapse	Fuel collapse	Fuel melting	Fuel collapse	Fuel collapse
H ₂ (mg/s)	0,2	0,45	0,45	0,45	0,4	1,25	0,45	0,45
H ₂ O (mg/s)	0	25	25	25	14,6	1,25	25	25
He (mg/s)	8	0	0	0	0	0	0	0
Main objective	H ₂ atm., high temperature	RT reference test	MOX	High Burnup	Debris bed oxid. atm.	Debris bed equ. atm.	Low Burnup	SIC injection

This is the main parameters of the HT/RT grid, as defined today. The experimental conditions or the order of the tests can change slightly.

HT1 was performed in June 96 in a reducing atmosphere. The fuel heated up to 3100 K collapsed early during the last heating phase at around 2600 K.

So RT1 and RT2 performed in March and April 98 without reirradiation of the fuel, were aimed at measuring with a good precision the temperature of fuel collapse ; RT1 was performed with UO2 fuel, as RT2 was performed with MOX fuel.

RT5 and RT6 will be performed with a reirradiated fuel, RT5 with high BU fuel (60 GWd/tU) and RT6 with a low BU (12 GWd/tU).

* RT3 and RT4 will be performed with a configuration of debris bed, in support of the PHEBUS FPT4 test.

Finally HT3, planned in 2000, will be the first test with additional injection of silver, indium and cadmium aerosols within the fluid steam and hydrogen flow.



VERCORS Post Test Analyses

■ γ spectrometry

- *FP balance*
 - Fuel measurement before the test
 - All the elements of the loop after dismantling
- *Fuel γ tomography*

■ Radiography and Ceramography of the fuel

■ SEM/EDS (WDS) of aerosols (impactor plates)

■ Cooperation with other laboratories

- *AEA Technology (Winfrith) : SEM/EDS and WDS - XRD - XPS*
- ♦ *TUI Karlsruhe : ICP spectrometry*
 - Transuranic elements
 - pure β emitters FP (^{90}Sr)

Several complementary techniques are used to quantify the release of FP and transuranic elements.

Firstly **gamma spectrometry** is the best adapted technique for the FP characterization, which are, nearly all of them, gamma emitters. We used it :

- on line for the kinetics measurements, previously described,
- before the test, for FP initial inventory inside the fuel,
- and after the test, on all the elements of the loop, in order to quantify the balance before and after the test, and also to study the FP transport and deposition.

The main quantitative results come from this technique.

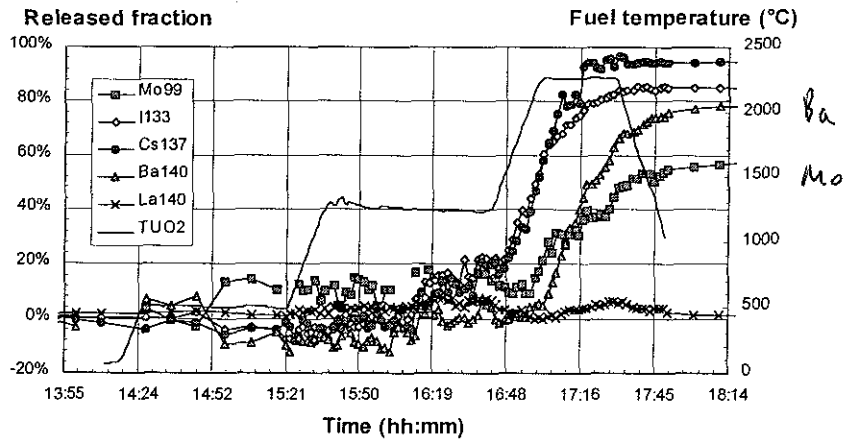
After the test, we also used to perform **radiography** and **ceramography** of the fuel sample in our hot laboratories.

Aerosol samples, coming generally from impactor plates, are examined par **SEM** and elemental chemical forms are determined by secondary X ray analyses.

A strong cooperation is in place with **AEA technology** for a long time : they perform numerous chemical analyses on powders taken on impactor plates : SEM and secondary X ray analyses, X ray diffraction, and X ray photo electron spectroscopy. Recently a new cooperation is going to take place with the **Transuranium Institute of Karlsruhe**, in order to quantify by ICP-MS the transuranic elements and pure β emitters FP trapped in the total filters of RT loops.



FP release kinetics (VERCORS 4 example)

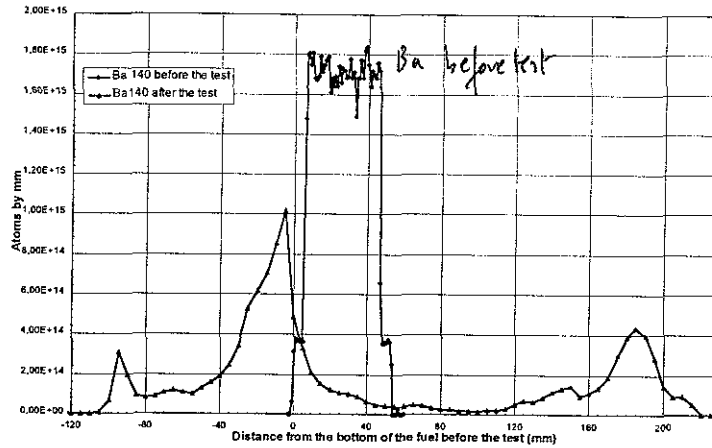


Now, some examples of results to illustrate these techniques.

This graph gives the release kinetics, measured by the gamma spectrometer in sight of the fuel during VERCORS 4 test. For instance, volatile species (Cs and I) have the same kinetics, their release beginning during the clad oxidising plateau and being nearly complete at the end of the high temperature plateau. The release of semi-volatile species (Mo and Ba) is slightly delayed and occurs at the beginning of the high temperature plateau. Finally, you can see the total lack of release from lanthanum, daughter of barium.



FP balance (^{140}Ba on VERCORS HT1)



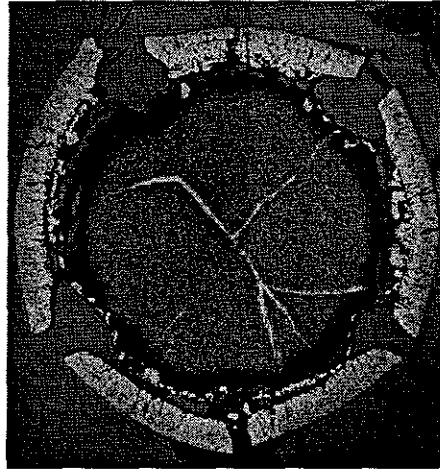
This graph illustrates, for VERCORS HT1 test, the distribution of ^{140}Ba inside the fuel sample before the test, and along the furnace after the test :

- in blue, before the test : distribution within the original irradiated pellets, and within the depleted half pellets,

- in red, after the test : main part of the melted fuel has flown down under the crucible. About 50% of ^{140}Ba initial inventory is located in this corium, and about 25% is deposited along the thoria tube, where no corium is present.



Fuel ceramography (VERCORS 5 example)



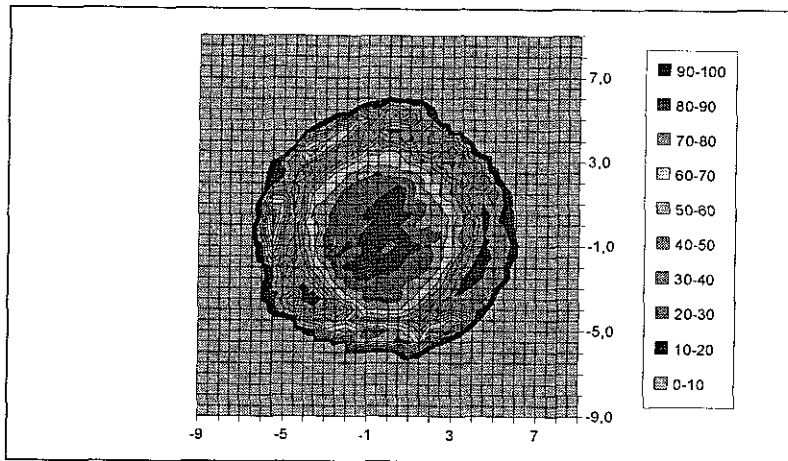
This graph illustrates a fuel ceramography, performed after VERCORS 5 test.

The fuel has kept its integrity, but the clad is broken in many parts. You can see a strong interaction between the clad and the fuel.

The fuel is very porous (swelling effect) with closed porosity inside, and a ring of nearly 1 mm thick at the periphery, constituted of large opened porosity.



γ emission tomography (^{140}Ba on VERCORS 5)



18 projections, symmetrical model, 30 iterations (LST)

Sometimes, we perform gamma emission tomography of the fuel sample after the test. This graph gives you the radial distribution of ^{140}Ba in VERCORS 5 test, which reveals two concentric zones :

- the first, located in the inner zone of the fuel, where the porosity is closed,
- the second is a ring of about 1 mm thick, located in the clad, which has trapped a large amount of ^{140}Ba .



Outcomes

■ Instrumentation improvements

- *An optical camera, beside the top pyrometer, will equip the RT loop for next tests*
- *A SIC injection system is in study for HT3 test*

■ FP release modelling studies performed by IPSN

- *ELSA : simplified model for implementation in ESCADRE/ASTEC system code*
- *MFPR : "Mechanistic FP Release" code, developed in cooperation with IBRAE institute (Russia)*

*

In conclusion, I'd like to tell you some words about instrumentation improvements and modelling studies.

Concerning the instrumentation, we intend to install soon an optical camera, beside the top pyrometer on the VERCORS RT configuration. Later an injection system of silver, indium and cadmium aerosols will be necessary for the VERCORS HT3 test. The study of this new system will be done next year.

Concerning FP release modelling studies, they are performed by IPSN, which develops two kinds of models :

- ELSA is a simplified model describing the release of volatile and non volatile FP, as well as the uranium release by oxidation of UO_2 in UO_3 . This model is intended to be implemented in the ESCADRE/ASTEC scenario code describing all the aspects of a nuclear accident.

- MFPR is a mechanistic and more complicated code, describing all the physical phenomena occurring within the fuel in case of nuclear accident. It is under development in cooperation with IBRAE institute in Russia.