

# Main Outcomes from the Phebus FP Programme

B. Clément, M. Schwarz

Institut de Radioprotection et de Sûreté Nucléaire

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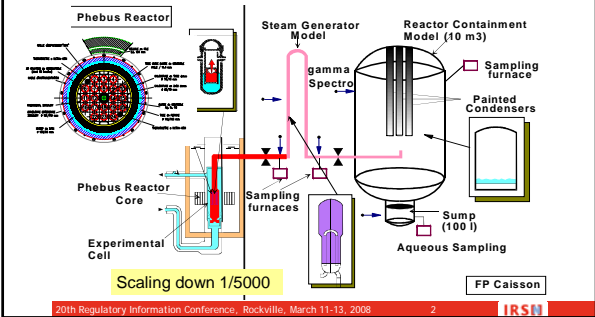
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## PHEBUS FP FACILITY

Experimental simulation of Reactor Core, Cooling System and Containment Building




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## PHEBUS FP TEST MATRIX

No.	Type of fuel	Fuel bundle	Primary circuit	Containment vessel	Date
FPT-0	Fresh fuel, 1 AgInCd rod, 9 d. pre-irrad.	Melt progression & FP release in steam rich environment	FP chemistry and deposits in non condensing steam generator.	Aerosol deposition. Iodine radiochemistry at pH 5.	Dec. 2, 1993
FPT-1	BR3 fuel -23GWd/U, 1 AgInCd rod, re-irrad.	As FPT-0 with irradiated fuel.	As FPT-0	As FPT-0.	July 26, 1996
FPT-2	As FPT-1, with BR3 fuel 32 GWd/U	As FPT-1 under steam poor conditions.	As FPT-1 with effect of boric acid.	pH9, evaporating sump.	October 12, 2000
FPT-3	As FPT-1, with B4C instead of AgInCd, BR3 fuel 24 GWd/U	As FPT-2	As FPT-0	pH5, evaporating sump, H <sub>2</sub> recombiner coupons	November 18 2004
FPT-4	EdF fuel -38GWd/U, No re-irrad.	Low volatile FP & actinide release from UO <sub>2</sub> , ZrO <sub>2</sub> debris bed, up to melting.	Integral filters in test device Post-test studies on samples		July 22, 1999

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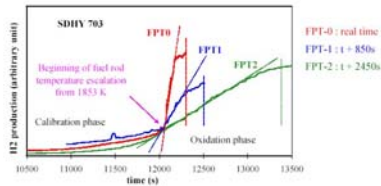
## MAIN OUTCOMES: FUEL DEGRADATION

### Cladding oxidation

More violent than expected cladding oxidation runaway in first test FPT-0

Need to revise correlations for "cladding dislocation criteria" based on temperature and oxide scale thickness

New correct predictions of cladding oxidation and hydrogen production in FPT-0, FPT-1, FPT-2 in different conditions



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## MAIN OUTCOMES: FUEL DEGRADATION

### Fuel relocation

Fuel liquefaction and transition from rod-like geometry to molten pool at temperatures ( $2600 \pm 200$  K) far below actual melting point of pure  $UO_2$  (3100 K)

Recent detailed analysis of FPT-0 and FPT-1 PIE show that:

According to oxidation measurements and thermodynamic calculations, a deviation from stoichiometry of  $x = 0.15$  must be taken into account for ceramic phase  $(U_{1-y}Zr_y)O_{2+x}$

According to recent measurements (Manara JRC/TUI) this composition due to interactions between oxidised cladding and fuel can reduce the fuel collapse temperature to 2500-2600 K

In the mean time calculation codes can reproduce final state of degradation given suitable reduction of bulk fuel relocation temperature

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## FP AND STRUCTURE MATERIAL RELEASE

### FP Releases

Volatile generally well calculated even if CORSOR approach tends to overestimate kinetics at the beginning of the transient

Semi empirical models, though not describing all processes, able to do well for volatiles using consistent set of parameters for Phebus and separate-effect experiments

Situation more contrasted for less volatiles for which chemistry plays an important role

Insights gained from mechanistic codes describing repartition of fission products in different phases of the fuel and their changes with temperature and stoichiometry

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## FP AND STRUCTURE MATERIAL RELEASE

### Coupling with fuel degradation

In FPT-0 using 9-days irradiated fuel, early release of volatiles can only be explained by fuel dissolution during cladding oxidation phase

Barium release much smaller in Phébus than in separate-effect experiments - difference attributed to interactions of fuel with cladding material and maybe iron reducing barium volatility

Low release from molten pool

### Release from silver-indium-cadmium control rod

Governing phenomena well understood but modelling effort still needed especially for coupling with degradation processes

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## FP AND AEROSOL TRANSPORT IN RCS

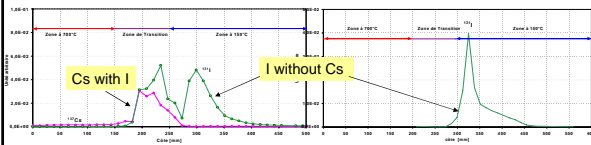
### FP and structural material speciation

In the hot leg, iodine and cadmium were the only non condensed elements for FPT-0 and FPT-1 - CsOH was not dominant for caesium transport

Codes calculating chemical speciation can reproduce caesium volatility and indicate the formation of caesium molybdate

Iodine is transported partly as a gas and partly as metal-iodides

Caesium iodide is not the only species for iodine transport as vapour and/or aerosol (see deposition profiles in FPT-2)



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## FP AND AEROSOL TRANSPORT IN RCS

### Deposition

High deposition on the hot leg vertical section above the bundle where temperature drops down to 700°C underestimated by codes (factor about 2)

Can be accounted for by the effect of developing flow characterised by much higher mass transfer coefficients of vapours to the walls than for developed flow

Deposition of aerosols by thermophoresis in the steam generator overestimated by codes (factor about 2)

Recent detailed studies (PSI) taking into account the interaction between turbulence and aerosol particles give promising results

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## T/H AND AEROSOL IN CONTAINMENT

### Thermal-hydraulics

Governed by the balance between incoming steam and condensation - generally well calculated

### Aerosol depletion

Mainly by gravitational settling and diffusiophoresis - generally well calculated

Significant deposition on outer walls cannot be explained by Brownian diffusion - a model accounting for turbulence damping in the boundary layer can reproduce the results satisfactorily

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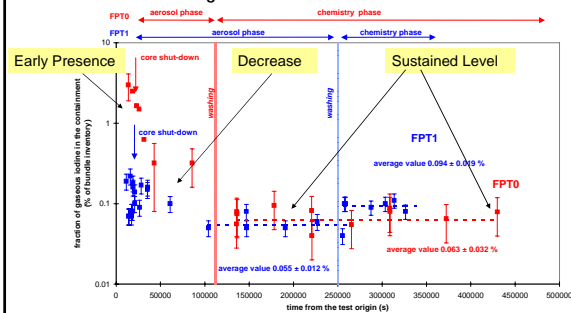
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## IODINE CHEMISTRY

### General evolution of gaseous iodine in containment FPT-0/1



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## IODINE CHEMISTRY

### Early presence of gaseous iodine in containment

Likely to have been formed in the primary circuit

Probably linked to non equilibrium chemical effects

Assumption supported by existence of sharp and large temperature gradients in the circuit especially at the bundle exit and the steam generator inlet

Fully compatible with higher fraction in FPT-0 with lower concentrations as compared with FPT-1

Much higher fraction in FPT-3 - due to the absence of Ag-In-Cd? - due to the presence of boron carbide degradation products?

⇒ Studied in CHIP (International Source Term Programme)

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## IODINE CHEMISTRY

### Liquid phase chemistry

Sump water does not contribute much to production of gaseous iodine in Phebus tests

For FPT-0 and FPT-1, due to reaction with silver to form non soluble species and inhibiting gaseous iodine production by radiolysis processes despite acidic pH

For FPT-2, due to alkaline pH

For FPT-3, due to an excess of iodates  $\text{IO}_3^-$  as compared with iodides  $\text{I}^-$  - iodates come from the radiolytic oxidation of  $\text{I}_2$  and  $\text{RI}$  in gas phase (interpretation)

Note that efficient trapping of iodine by silver requires an excess of silver as compared with iodine ( $\text{AgI}$  decomposes under radiation)

Some additional tests in EPICUR (ISTP)

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## IODINE CHEMISTRY

### Gas phase chemistry

Volatile iodine concentration mostly determined by gas phase chemistry

Importance of gaseous iodine injection from RCS

Equilibrium between iodine formation/destruction processes and/or reversibility of iodine adsorption/desorption processes yield a steady-state concentration in the long term

In FPT-0 and FPT-1 most of gaseous iodine organic in the long term

Previous conclusion does not apply to FPT-2 and FPT-3

Role of homogeneous gas phase radiolysis reactions determining speciation and evolution of iodine (formation of iodine oxides)

Gas phase chemistry studied in EPICUR (ISTP)

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## STATUS OF KNOWLEDGE AND IMPLICATIONS

A number of unexpected and/or badly quantified phenomena have been identified by previous and ongoing research programmes, especially Phebus FP, e.g.

Fraction of iodine entering the containment as a gas and not as an aerosol

Fp release and transport, cladding oxidation in air ingress conditions...

The associated uncertainties have an impact on the results of Source Term assessment studies, e.g. for IRSN

S3 reference source term (corresponding to a delayed filtered release of fission product outside of the containment) used for checking the adequacy of Emergency Planning

PSA level 2 studies

The International Source Term Programme (ISTP) aims at reducing the uncertainties on Source Term assessment

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## GENERAL OBJECTIVES OF ISTP (2006-2010)

Provide a set of data allowing the improvement or elaboration of models (to be) implemented in Severe Accident codes

Priorities were given in accordance with the outcomes of EURSAFE European Project as revised within the SARNET Network of Excellence (items with high safety significance and important lack of knowledge)

Set of separate-effect experiments dealing with

- Iodine behaviour in RCS and containment building

- Impact of boron carbide on the progression of a severe accident

- Air ingress situations

- Fission products release from fuel

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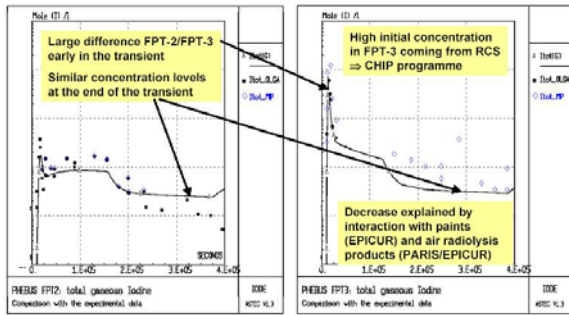
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## CONCLUDING REMARK

An example of link between ISTP and Phebus tests



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