

Post-VERCORS needs for analytical experiments on fission-product release

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- The status of the VERCORS programme
- Remaining needs
- Plans at IRSN for further experiments
- Conclusion

VERCORS status

- Test series

- **HEVA: 8 tests, release of volatile FPs**

re-irradiation for 4 tests

$$1900 \leq T_{max} \leq 2370K$$

- **VERCORS: 6 tests, release of volatile + low volatility FPs**

re-irradiation for all tests

$$2070 \leq T_{max} \leq 2620K$$

- **VERCORS HT: 3 tests, release of volatile + low volatility FPs + transport**

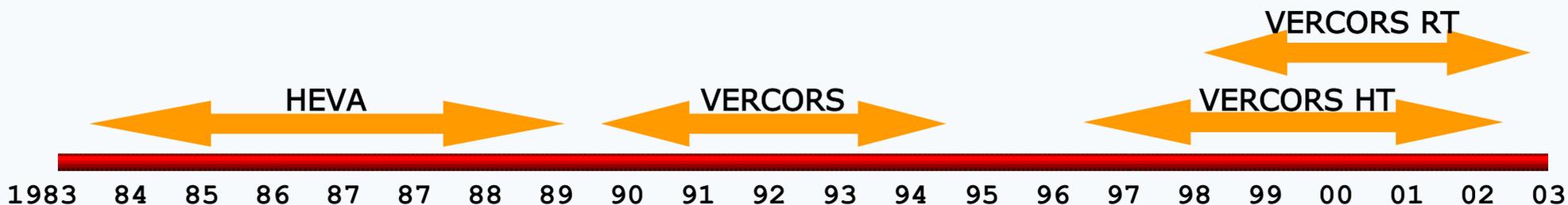
re-irradiation for all tests

$$2600 \leq T_{max} \leq 2900K$$

- **VERCORS RT: 8 tests, release of low volatility (priority) + volatile FPs**

re-irradiation for 5 tests

$$2400 \leq T_{max} \leq 3000K$$



VERCORS status

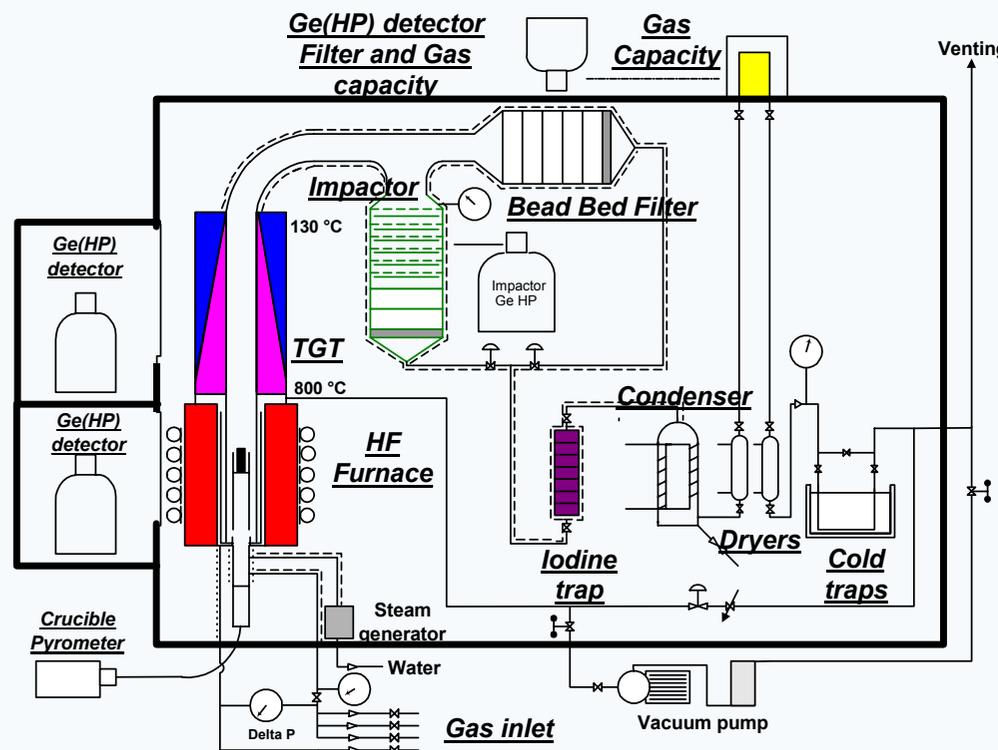
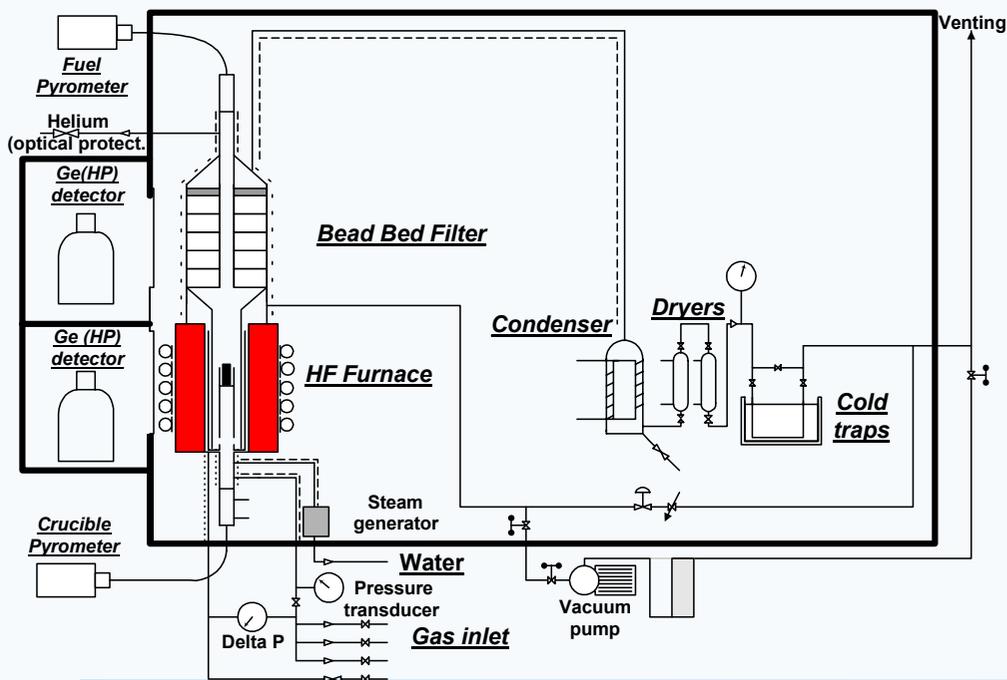
- Test apparatus

- RT series:

- release of low-volatility FPs (priority)
- release of volatile FPs

- HT series:

- release of volatile FPs
- release of low-volatility FPs
- FP transport (incl. Ag, In, Cd, B)



VERCORS status

- **VERCORS RT series: final test matrix**

RT	1	2	3	4	5	6	7	8
date of test	03/1998	04/1998	11/1999	06/1999	12/1998	09/2002	04/2000	11/2002
burn-up GWd/t _U	4 cycles 47	3 cycles 46	3 cycles 38	3 cycles 33	5 cycles 60	6 cycles 70	3 cycles 43	6 cycles 70
re-irradiation	no	no	yes	no	yes	yes	yes	yes
fuel	UO ₂	MOX-AUC	UO ₂	UO ₂	UO ₂	UO ₂	MOX-AUC	UO ₂
atmosphere at high temperature	H ₂ O/H ₂	H ₂ O/H ₂	H ₂ /H ₂ O	H ₂ O/H ₂	H ₂ [∅]	H ₂ O/H ₂	He/H ₂	H ₂ O/H ₂ , He, He/air
temperature ramp rate, K.s ⁻¹	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
max. T _{fuel} K	2570	2440	~3000	2500	2600	2470	2890	2670
other	clad fuel	clad fuel	UO ₂ debris	UO ₂ debris+ oxidized Zrly	clad fuel	clad fuel	clad fuel	clad fuel

VERCORS status

- **VERCORS HT series: final test matrix**

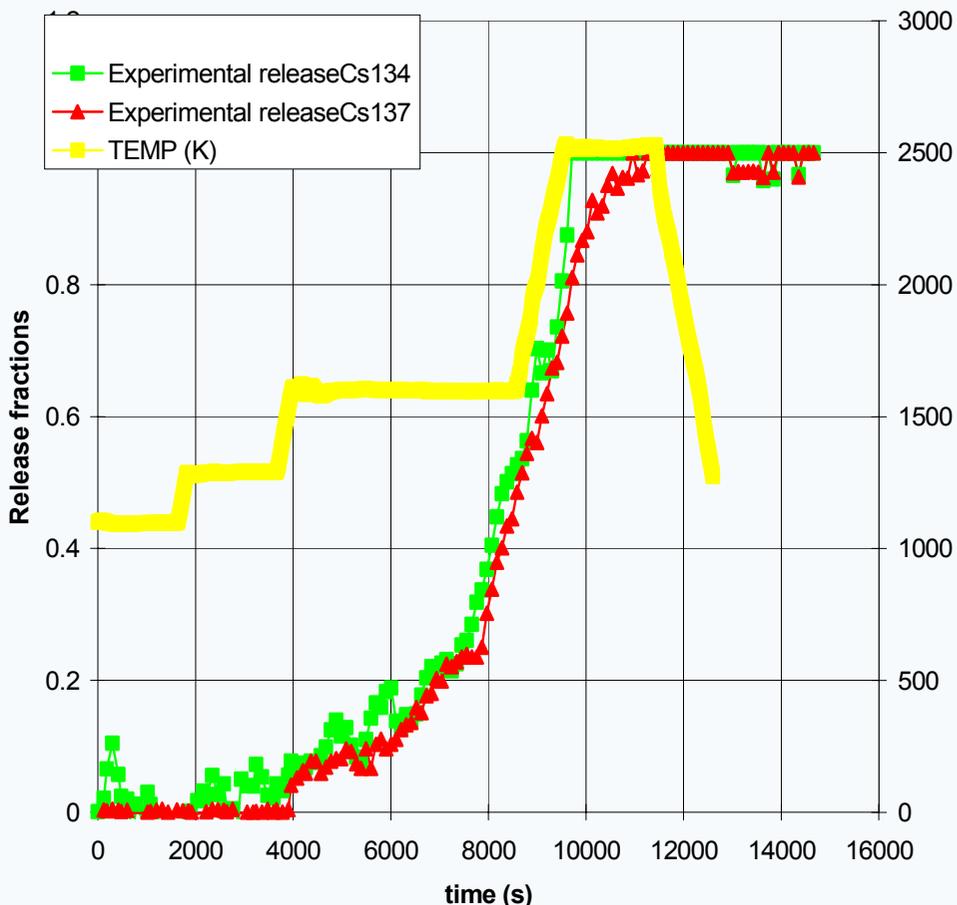
HT	1	2	3
date of test	06/1996	04/2002	06/2001
burn-up GWd/t _U	4 cycles 49	4 cycles ~50	4 cycles 49
re-irradiation	yes	yes	yes
fuel	UO ₂	UO ₂	UO ₂
atmosphere at high temperature	He/H ₂	H ₂ O/H ₂	He/H ₂
temperature ramp rate, K.s ⁻¹	0.5	0.2	0.2
max. T _{fuel} K	2900	liquefaction	2680
other	clad fuel	clad fuel; boric oxide + SIC	clad fuel; boric oxide + SIC ^Ψ

- All tests started with a H₂O/H₂ phase that fully oxidized cladding
- HT2 + HT3: absorber materials introduced at intermediate temperature to explore effect on transport, i.e., phase without then phase with.
- Ag, In and Cd activated for better measurement.

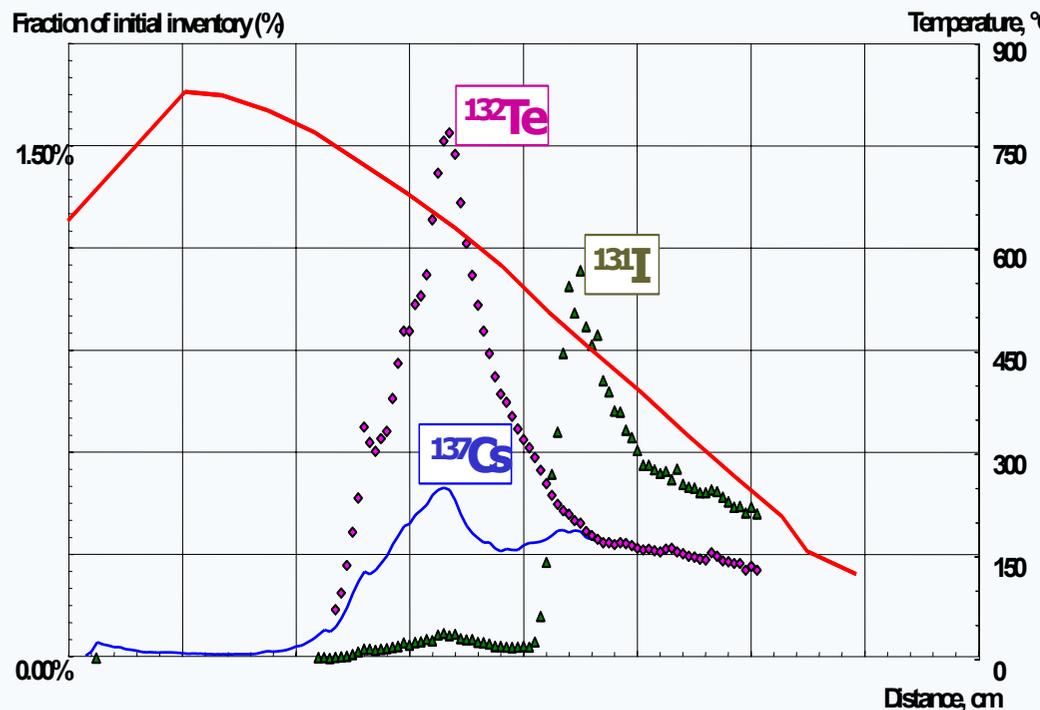
VERCORS status

- Two examples of results

- Test VERCORS 5, release: Cs kinetics



- Test HT1, transport: I, Cs, Te post-test deposition profile along TGT



Remaining needs

- **Evolution of fuel in France**

- **UO₂**

- average burn-up per assembly, current: 47 GWd/tU (52 max. in assembly)
- average burn-up planned by 2008-10: 62 GWd/tU

- **MOX**

- average burn-up per assembly, current: 39 (41 max. in assembly)
- average burn-up planned by 2008-10: 49-53
- a new manufacturing process for MOX around 2007

- **Gadolinium-doped UO₂**

- used in CYCLADES and GEMMES fuel-management cycles (higher ²³⁵U enrichment, longer cycles)

Remaining needs

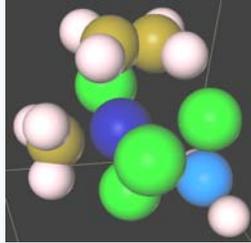
- **Evolution of safety issues at IRSN (recent internal action)**
 - **PSA level 2**
 - desirable to reduce uncertainties and over-conservatism
 - **Modelling needs**
 - confirm current interpretation where data on FP location & chemical species (e.g., Cs in solid solution, uranate, molybdate, iodide?) are lacking
 - detailed-modelling capability (MFPR code) → exploratory FP-release tool
 - **Air ingress**
 - increased awareness of potential consequences
 - inadequate data on release (and transport) especially with respect to Ru
 - **Gadolinium-doped UO₂**
 - very few data relevant to impact on source term
 - **MOX**
 - few data relevant to impact on source term, i.e.,
2 VERCORS tests (also 2 VEGA tests) for AUC, nothing for TU2

Remaining needs: further analytical experiments (ideally)

- **Micro-characterization**

- **Knowledge/modelling needs**

- as a function of temperature and oxidation, require data on FP location and chemical speciation
- analyses (SEM, TEM, EPMA, XRD,...) before and after annealing
- atmosphere either inert, oxidizing or reducing, $1200 \leq T \leq 2500\text{K}$



- **FP release (rate and amount)**

- **Air ingress**

- require more data on release (and transport) especially with respect to Ru

- **MOX**

- TU2

- **Design-basis LOCA**

- high burn-up UO_2
- MOX

Remaining needs: further analytical experiments

- **Context: the Source Term Programme**

- **IRSN-CEA-EDF joint-research programme**

- open to and being proposed to other partners, e.g., CEC
- based on separate-effect experiments
- four axes of research:
 1. iodine
 2. boron-carbide
 3. air-ingress
 4. fission-product release
- programme duration: 2005 – 2010, 6 years

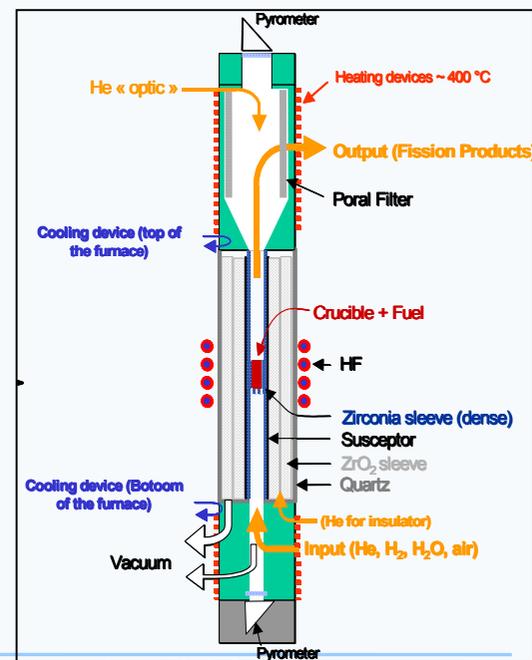
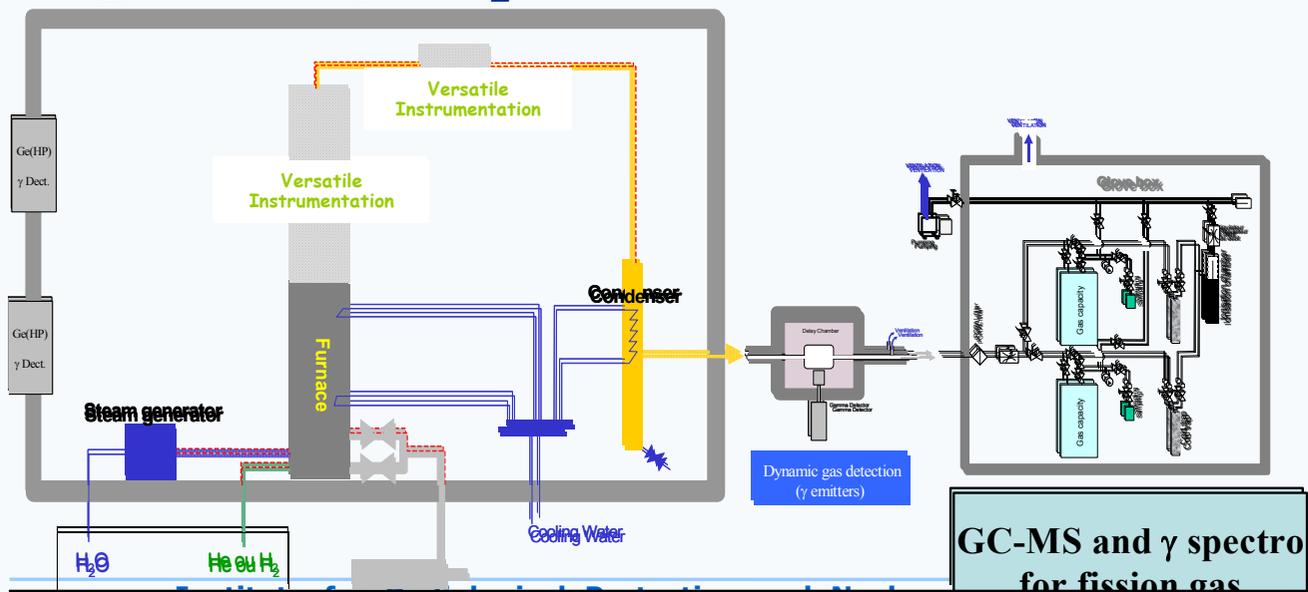
Remaining needs: priority experiments

- **Micro-characterization**

- **Knowledge/modelling needs:** analyses (SEM, EPMA,...) of VERCORS samples including pellets from source rods (covers initial and final state)

- **FP release : VERDON facility (CEA/Cadarache)**

- **Air ingress:** one test including transport aspects in 2008-09
 - **MOX:** two tests on TU2 in different oxidizing atmospheres in 2008-09
 - **High burn-up UO₂:** one test in 2008-09



Conclusions

- **VERCORS very successful**
 - **rich database on FP release and, to a lesser extent, transport**
 - wide range of burn-ups, reducing/oxidizing conditions & final temperatures
 - fuel types and physical configurations explored to some extent
- **Require now...**
 - **Knowledge of microscopic evolution of FPs in fuel**
 - confirm IRSN's understanding of FP behaviour in fuel and release process
 - creation of an IRSN tool for exploratory analyses, i.e., predictive capability
 - **More data on current, outstanding issues**
 - air ingress
 - high burn-up UO₂
 - MOX
- **Much to be gained from Source Term Programme**

Acknowledgements

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- VERCORS test conditions were specified by IRSN in consultation with CEA and EDF.