



IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÉCRÉTÉ NUCLÉAIRE

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**Progress on B₄C modelling in Severe Accident Codes
in the frame of SARNET network of excellence
Applications to Phebus and Quench experiments**

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OUTLINE

Introuduction

Review of the Separate Effect Tests and codes modelling

Applications to Integral Quench and Phebus experiments

Conclusion



Introduction

Boron carbide (B₄C) is used as absorber material in Western (BWRs, some PWRs, EPR) and Russian (VVER) nuclear power plants

Investigation of the physical processes of B₄C impact on core degradation has been carried out through **Separate-Effect and Integral tests**

This presentation is focused on the progress on the B₄C control rod **modelling in Severe Accident codes** (SA), like ATHLET-CD, ICARE2, MELCOR and MAAP, performed in the frame of the Network of Excellence SARNET during the five year activity of the Work Package 9.2, : early phase and B₄C effects

The modelling has been applied to the **interpretation of experiments** involving a B₄C control rod, such as Phebus FPT3 in pile experiment, as well as out of pile experiments Quench-07 and -09

Part I

Brief review of the experiments and codes modelling activities

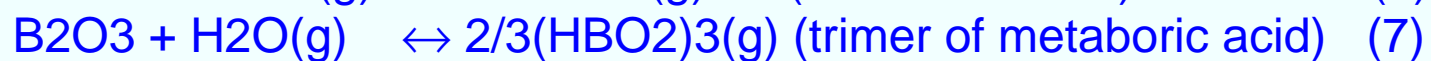
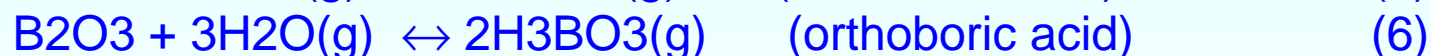
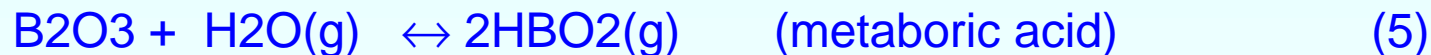


The modelling is mainly focused on the solid B₄C oxidation phenomenon : with the following complex chemical reaction compared with the simple Zircaloy oxidation in steam

Oxidation of boron Carbide



Reaction of boron oxide with water (B₂O₃ reduction)

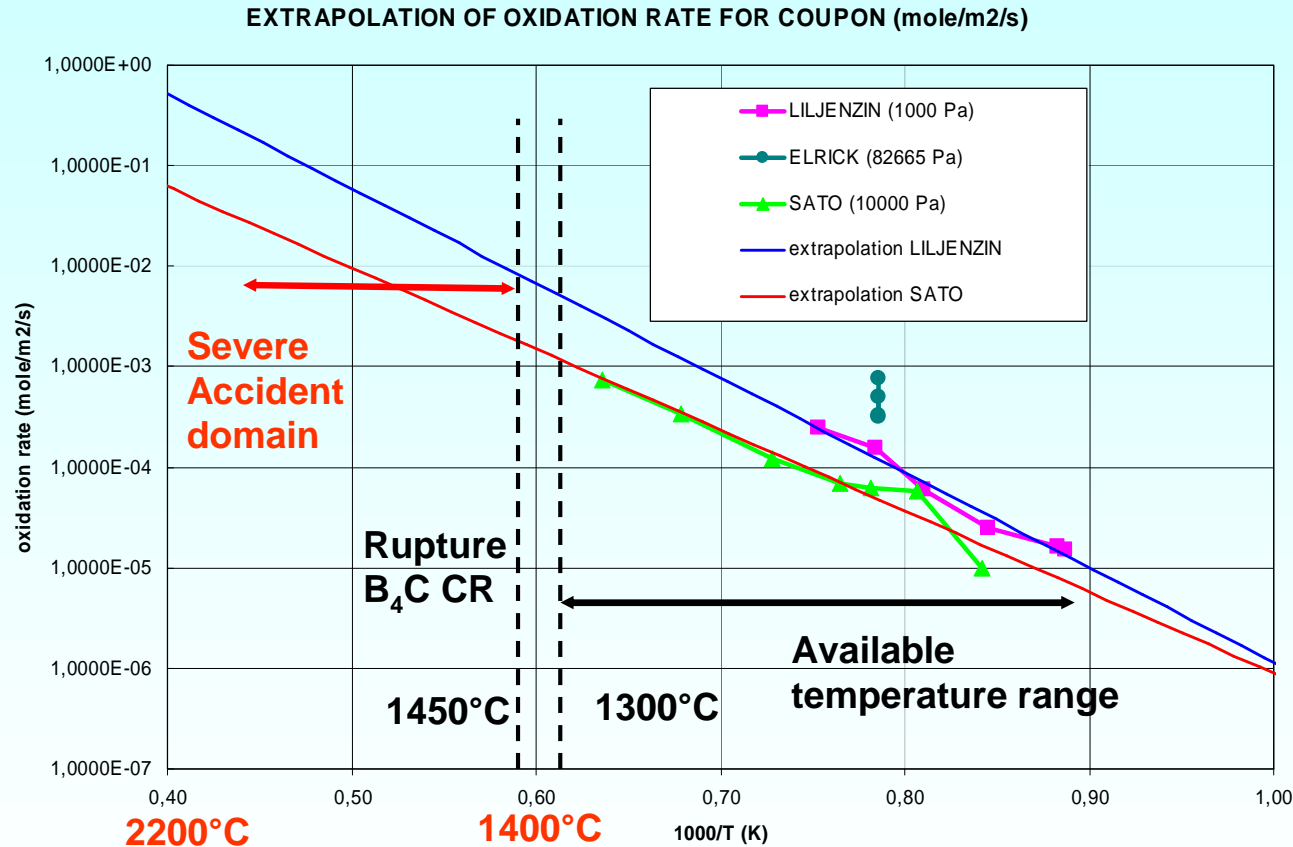


Reaction in gas phase



Available B₄C oxidation experiments

Before the COLOSS and the current SARNET projects, experimental database on this phenomenon was very limited especially at high temperatures ($T \geq 1600$ K).



→ VERDI 1200 to 1800°C (IRSN)
 → BOX 800 to 1400°C (FzK)

were performed during the COLOSS and the following SARNET project

Preliminary B₄C oxidation modelling

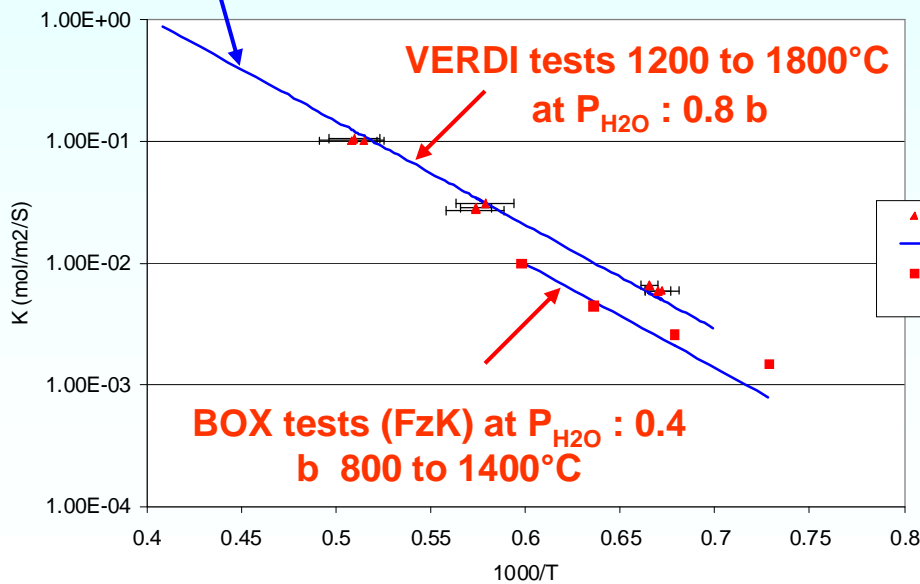
à Simple model implemented in ICARE/CATHARE

à Arrhenius Law type (dn/dt)

$$k = k_0 e^{\frac{-E_a}{RT}} P_{H_2O}^{1.18} P_{Tot}^{-0.78} \quad (\text{mol/m}^2/\text{s}) \quad \text{with } R=8,314472, \quad k_0 = 34,17$$

↑ Steam partial pressure
 ↑ Total pressure
 Predicted against measured kinetics

kinetics



Ø Validated on first VERDI / BOX tests proposed in COLOSS project

Ø Improvement and validation of the kinetic parameters in the frame of Source Term program (BECARRE – I)

Recall of B₄C oxidation experiments

Experiments	Liljenzin, Litz, Sato	BOX (FzK)	VERDI (IRSN)
	1963-1990	2000-2003	2001-2005
Number of tests used for modelling	21	~40 (29 used for IRSN modelling)	69 tests
Type of sample	Pellets and powders	Framatome, Codex, ESK	Framatome
Type of measurement	Mass balance	H ₂ release	Mass balance
P _{tot} (atm)	10 ⁻² – 1	1	1
P _{steam} (atm)	10 ⁻² – 10 ⁻¹	0.43 - 0.07(8) - 0.6(1)	0.2 - 0.4 - 0.8 0.9
Temperature (K)	1127-1573	1073-1673	1473-2073
Q _{tot} (g/min)			2.5 - 10
Velocity (m/s)			1 - 5

Old data base

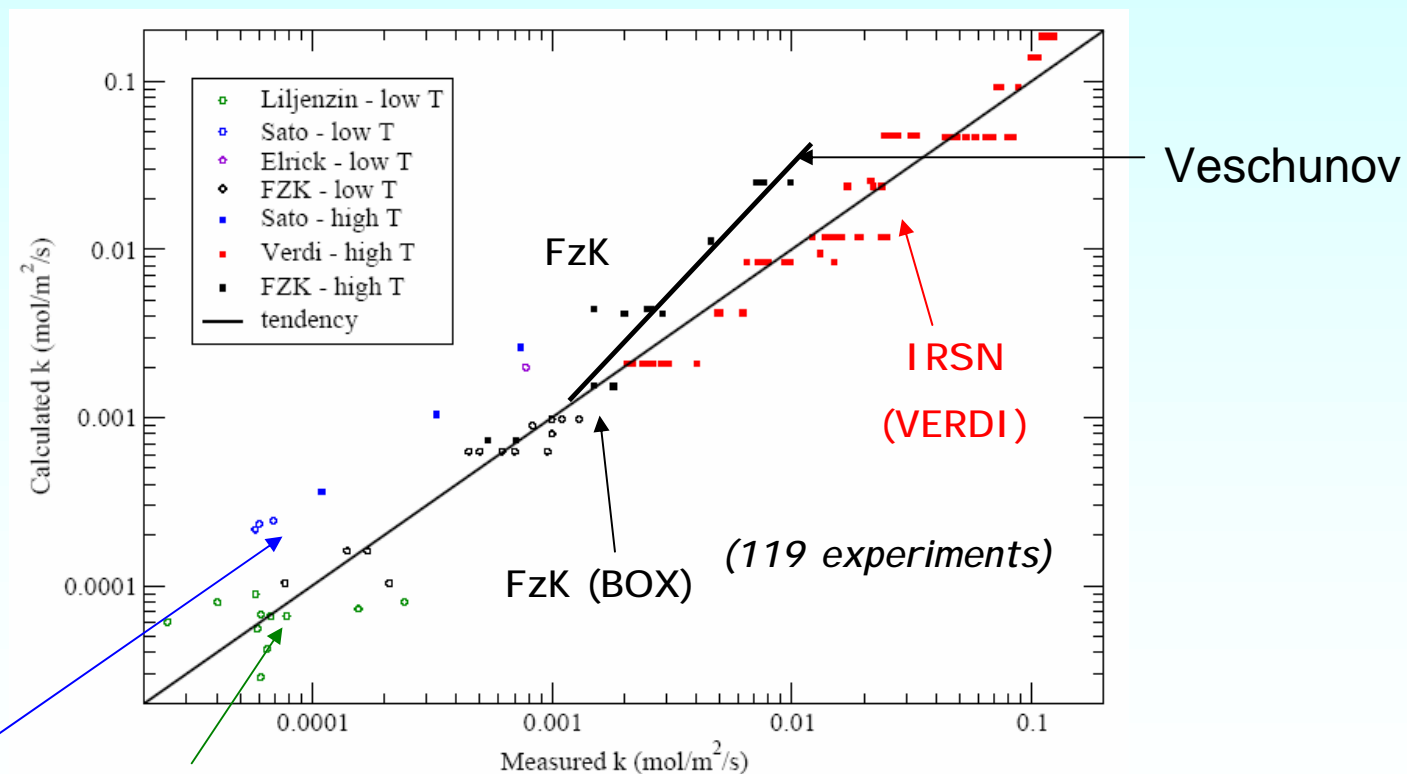
COLOSS project

COLOSS and SARNET projects

Modelling options : B₄C oxidation ICARE 2 (1/4)

For ICARE2 (IRSN code), the kinetics of solid B₄C oxidation based on IRSN (VERDI) and FZK (BOX) experiments, as well as all the previous data

$$k = k_0 e^{\frac{-E_a}{RT}} P_{H_2O}^a P_{Tot}^b \quad (\text{mole/m}^2/\text{s}) \quad \text{with } R=8,314472$$



SATO (1988 Japan) , LILJENZIN (1990)

MAAP has adopted the same kinetics as that of ICARE2 (EDF-IRSN cooperation)

Modelling options : B₄C oxidation (ATHLET-CD) (2/4)

For ATHLET-CD, the kinetics are also based on Arrhenius equations:

$$k = k_0 \cdot \exp(-E_a / R_{gas} / T) \cdot g(p_{H_2O}) \cdot f(p) + C \quad (\text{moles of B}_4\text{C or B}_2\text{O}_3 / \text{m}^2/\text{s})$$

$$g(p_{H_2O}) = (10 - (15 - 6x)x)x^3$$

$$\text{with } x = p_{H_2O} / p_{total} / x_{lim} \leq 1.0$$

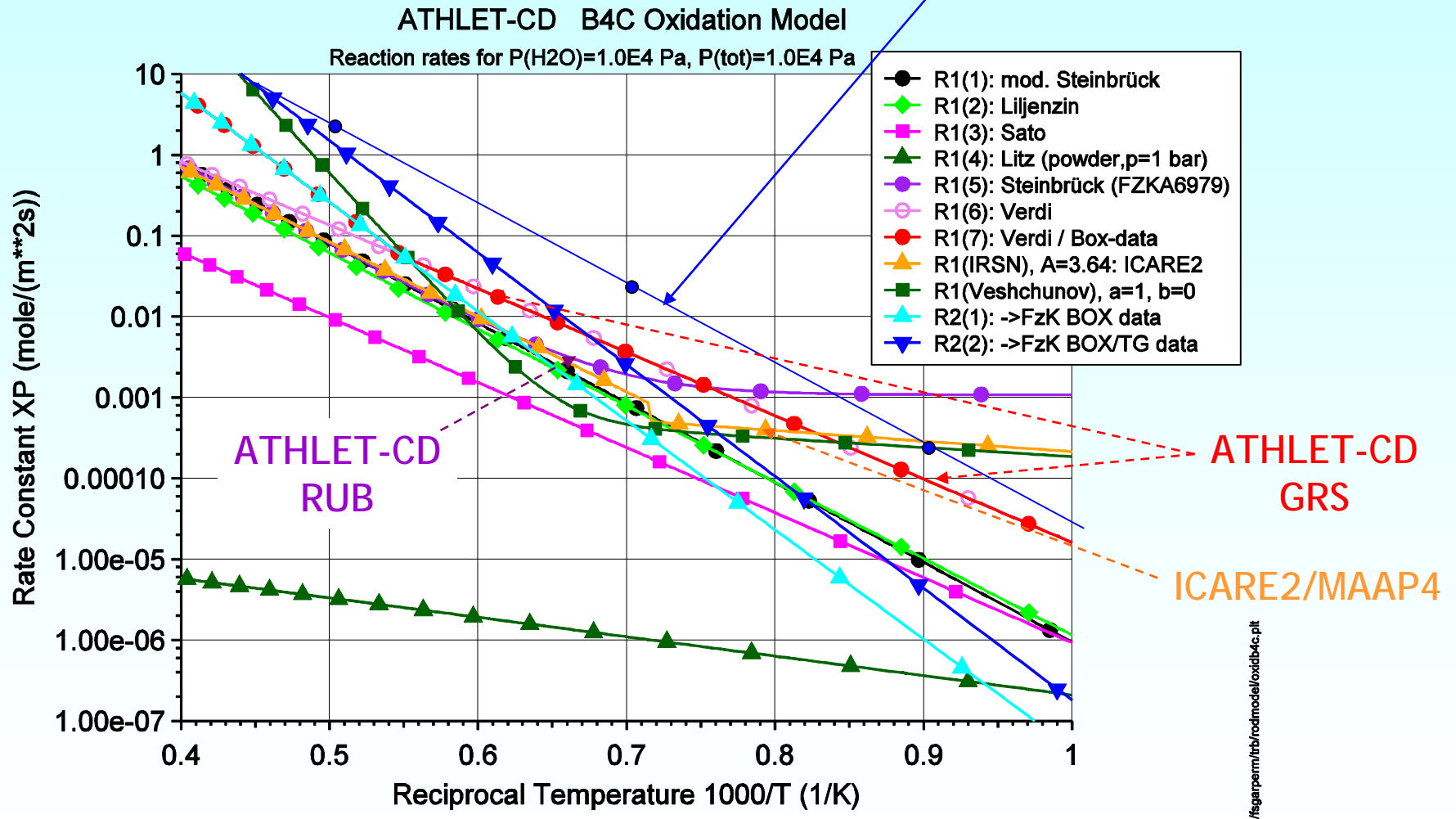
$$f(p) = (p_{H_2O} / p_R)^a \cdot (p_{tot} / p_R)^b$$

$$\text{with } p_R = 1.0 \text{ Pa}$$

with functions (f and g) to consider fluid pressure and steam availability
the steam availability is considered by a separate steam starvation function

Modelling options : B₄C oxidation (ATHLET-CD) (3/4)

MELCOR (for BWR)
coming from powder experiments



Modelling options : B₄C oxidation (4/4)

$k = k_0 e^{\frac{-E_a}{RT}} P_{H_2O}^a P_{Tot}^b$	T(K)	K ₀ (mol B ₄ C/m ² /s)	Ea (10 ⁵ J/mol)	α	β
Liljenzin		3.29 10 ⁺³	1.81	0	0
Litz		5.29 10 ⁻⁹	0.46	1	0
Sato		1.03 10 ⁺²	1.54	0	0
IRSN (2002)		34.17	1.6334	1.18	-0.78
IRSN (2004)		263.32	1.8587	1.18	-0.75
BOX data (FzK 6979)		6.81 10 ⁺³	1.887	0	0
GRS (VERDI data)		1.143 10 ⁺³	1.503	0	0
GRS (VERDI BOX data)	< 1800	1.143 10 ⁺³	1.503	0	0
ATHLET-CD	> 1800	1.471 10 ⁺⁶	2.586	0	0
FzK (BOX data) *		1.471 10 ⁺⁶	2.586	0	0
FzK (BOX/TG data) *		1.250 10 ⁺⁶	2.650	0	0
Veshchunov (2005) approach (R_j + R_{j+1})	R _j	2.5 10 ⁻⁷	0.216	1	0
	R _{j+1}	6.0 10 ⁺⁵	3.829	1	0
IRSN (2006)	< 1400	4.33 10 ⁻⁶	0.25	1	-0.25
MAAP4	> 1400	3.64	1.775	1	-0.25
MELCOR correlation **		1.662167 10 ⁺⁵	1.88299	0	0

* for B₂O₃ reduction

** developed for BWR control blades

Part II

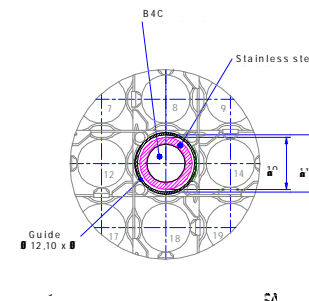
Applications to Quench and Phebus tests



Numerous simulations were performed with different codes and organisations in the frame of the SARNET CORIUM WP 9.2

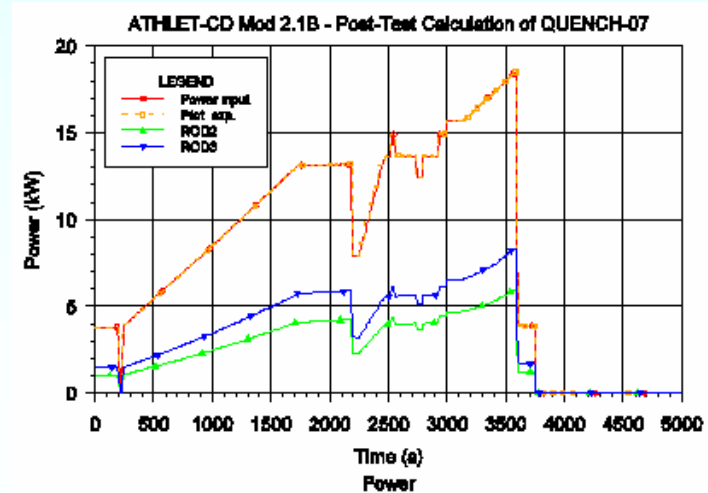
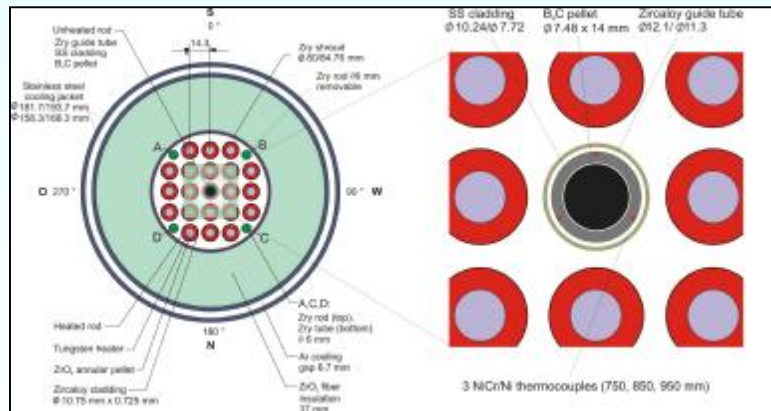
- Quench 07 /09 tests (FzK)
- Phebus FPT3 (IRSN)

including the same B₄C control rod



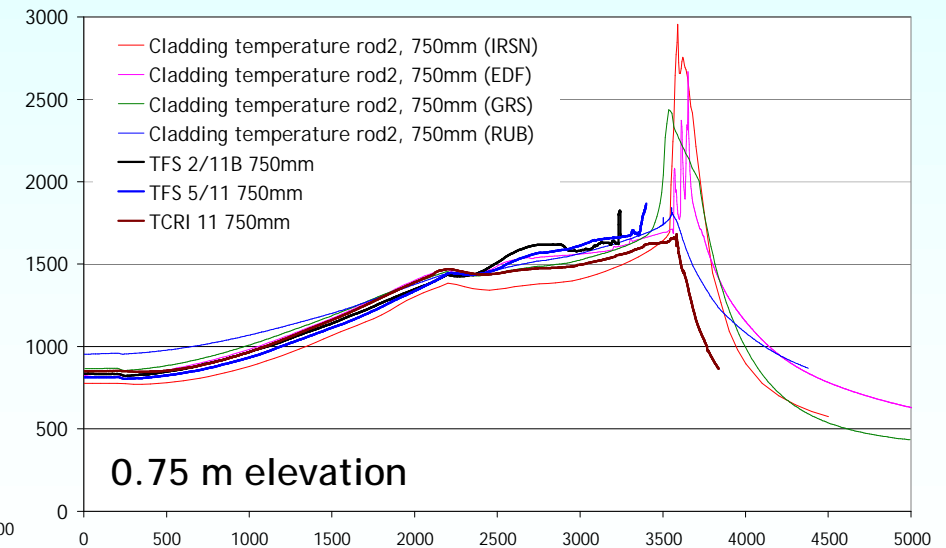
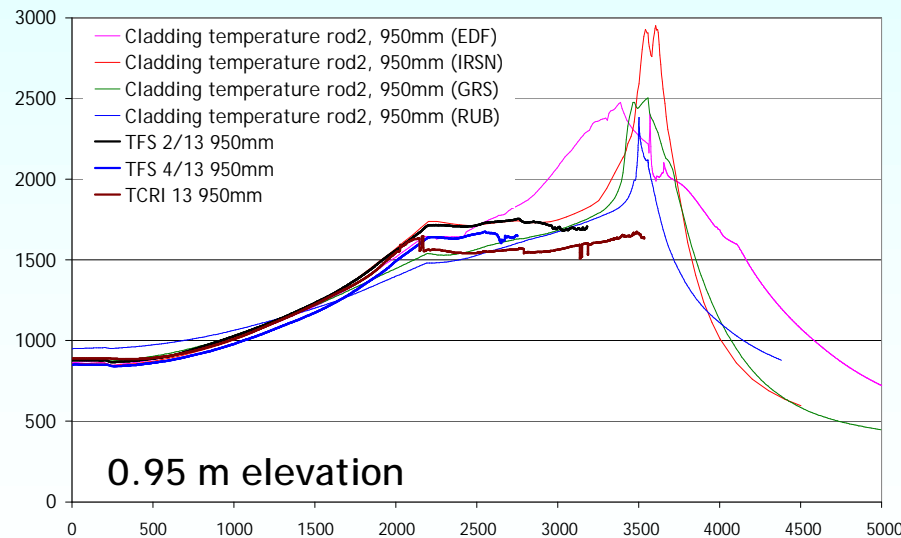
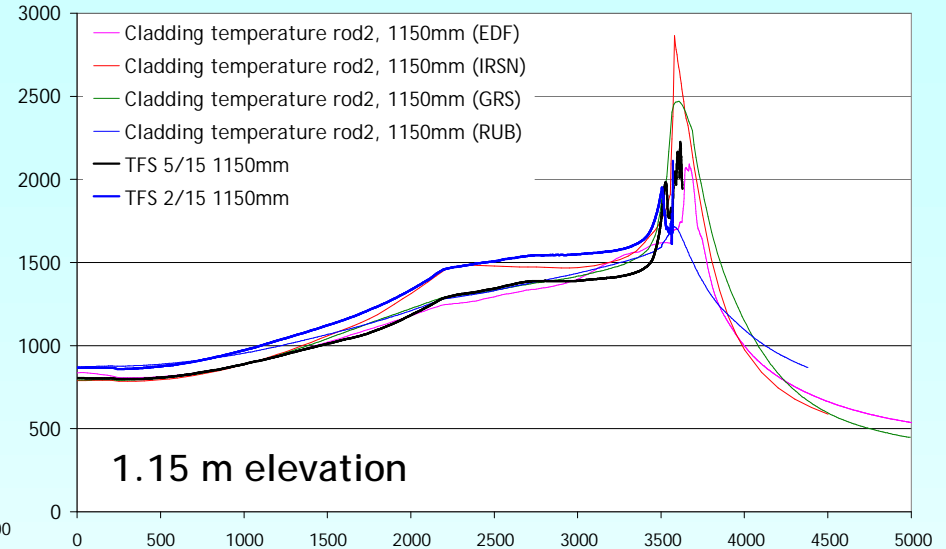
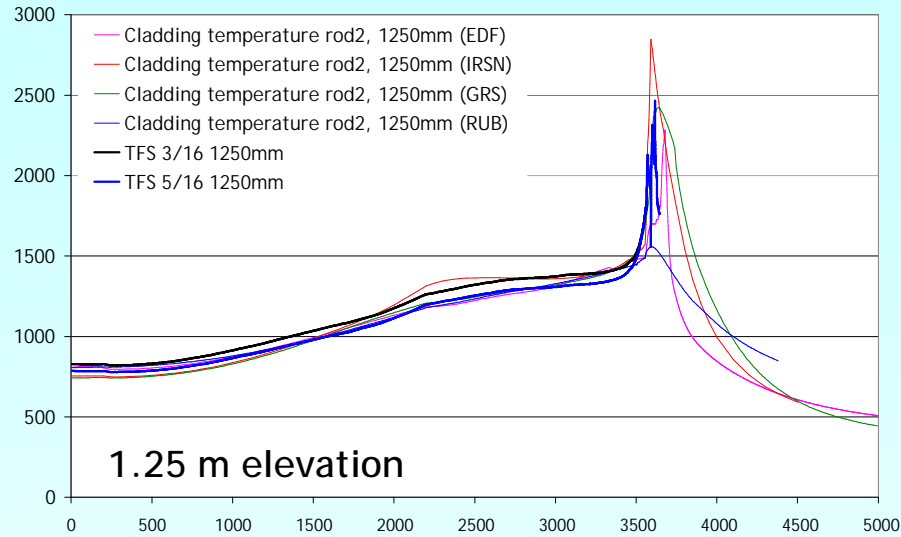
Applications to Quench 07 test

1. **IRSN** (ICARE2)
2. **GRS** | (ATHLET-CD)
3. **RUB** |
4. **EDF** (MAAP4)



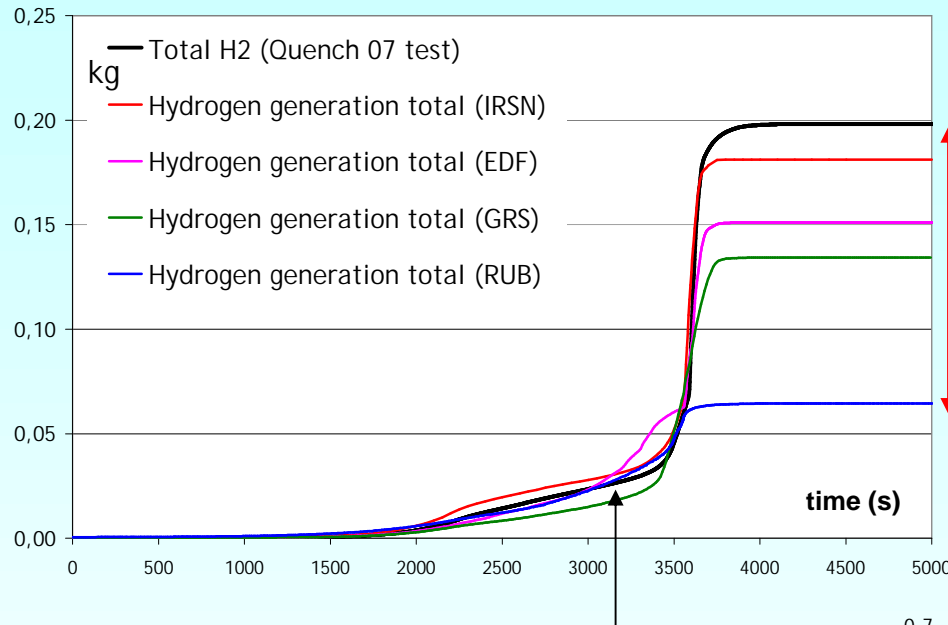
Transient : heated by electrical power increase

Thermal results : temperatures evolution (Quench 07)



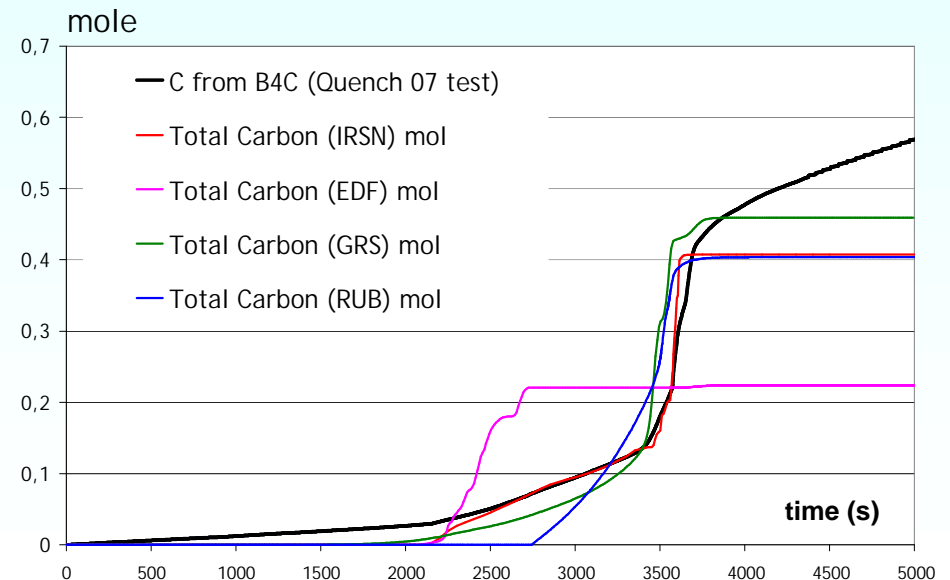
All the simulations gave rather good results except for the end of the transient very sensitive to the Zircaloy escalation

Gas releases : Hydrogen and carbon species



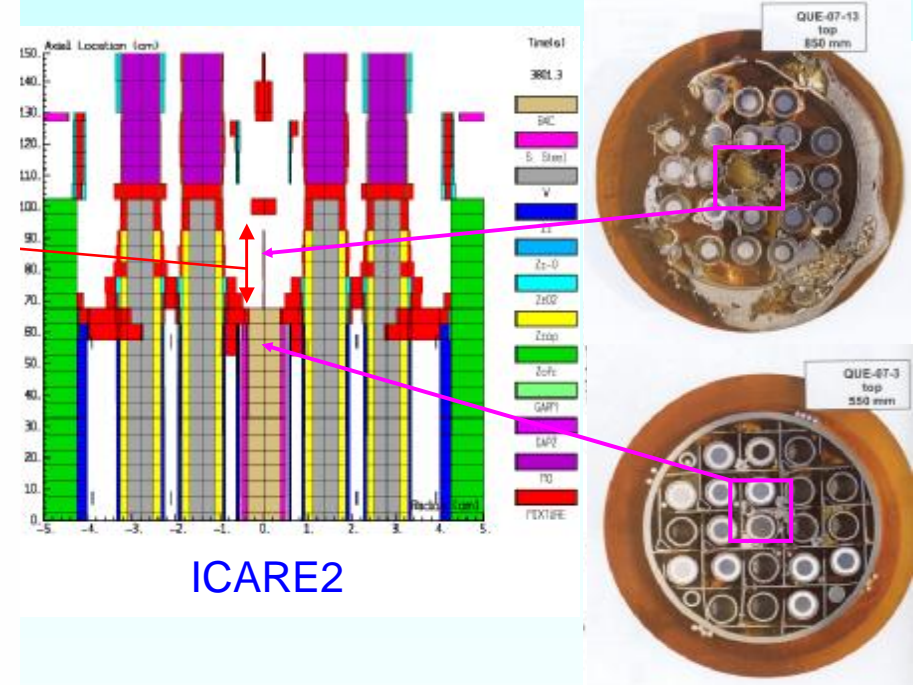
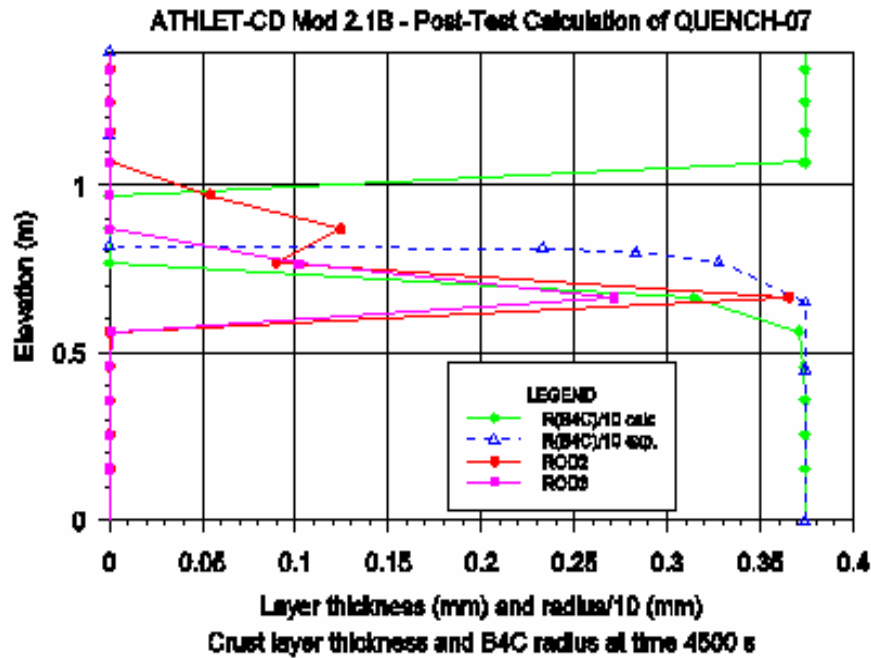
The H₂ generation is rather well reproduced by both the simulations

The total H₂ produced (very sensitive to the escalation during the quench phase) has to be improved for some contributions, nevertheless, the total carbon release obtained for most of the simulations gave satisfactory results except that of one case (which have to be checked)



B₄C oxidation and degradation

QUENCH-07

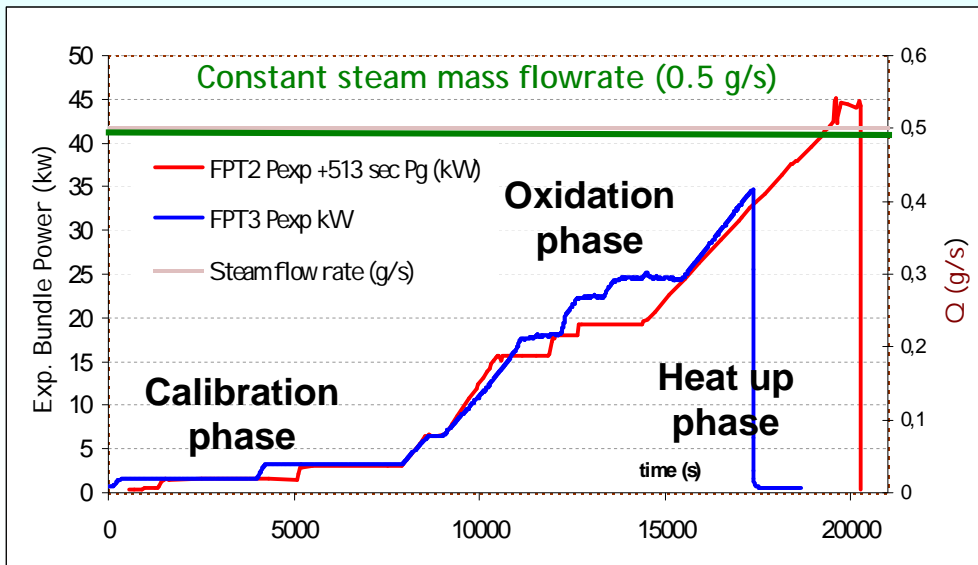


Experimental amount probably overestimated due to gaseous measures defects

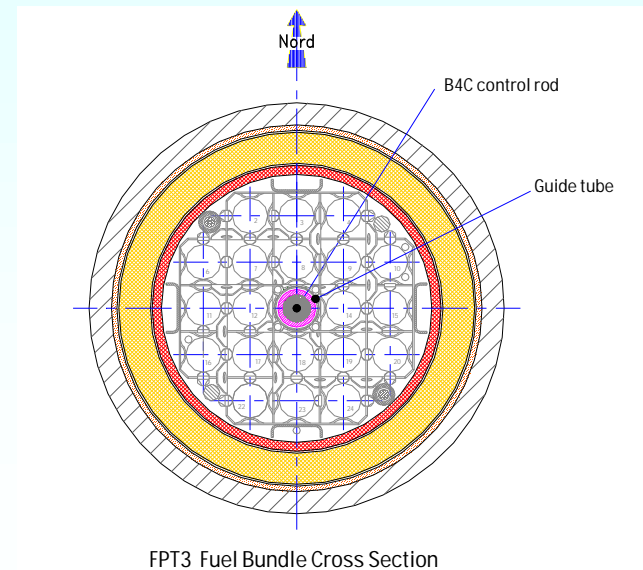
- new kinetic ~ 22.4 g / old kinetic ~ 18.2 g
- 6.6 g of H₂ produced from B₄C/ 8 g (exp)

Applications to Phebus FPT3

1. **IRSN** (ICARE2)
2. **GRS** (ATHLET-CD)
3. **RUB**
4. **PSI** (MELCOR)

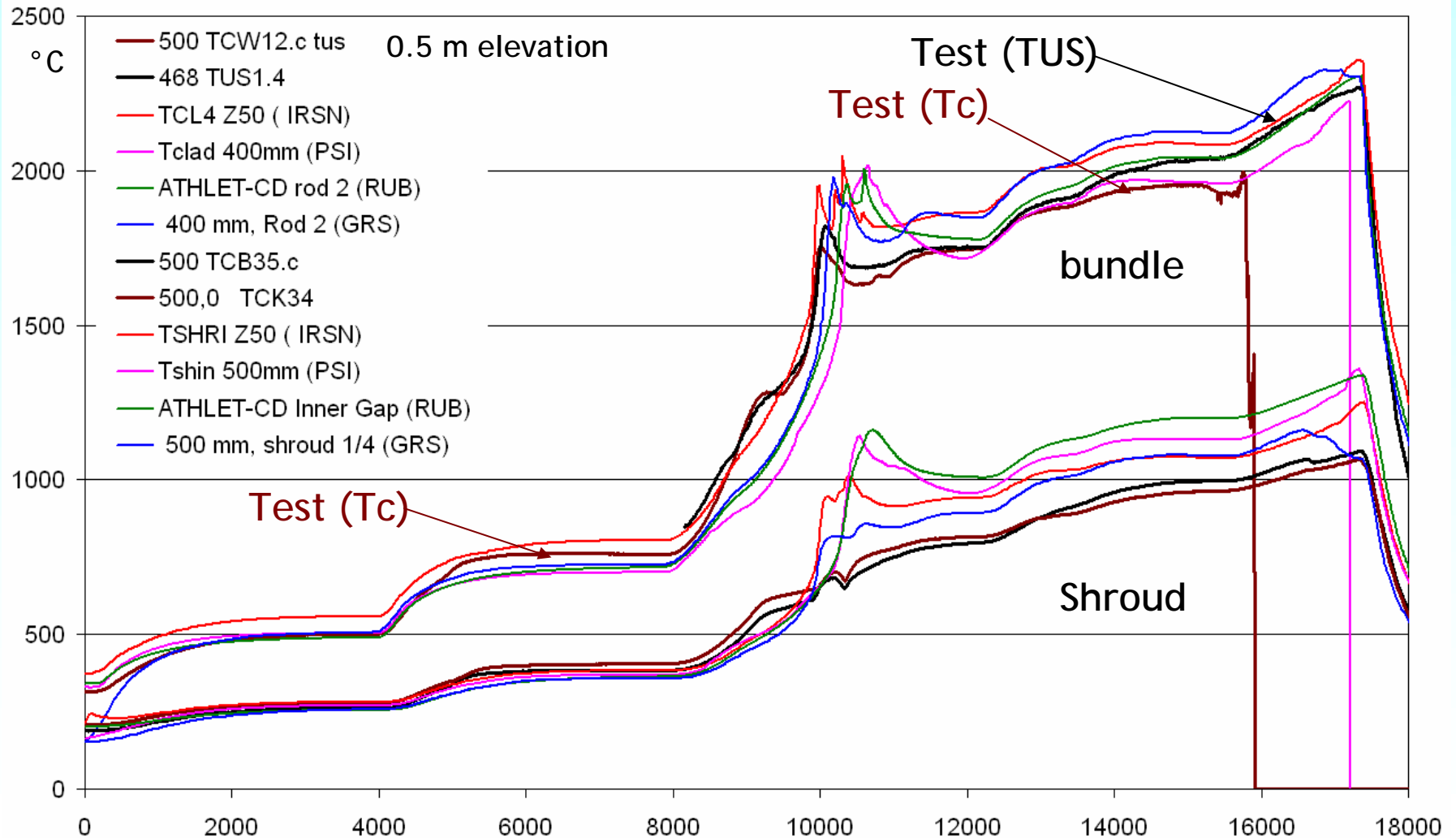


Transient : nuclear power increase by steps



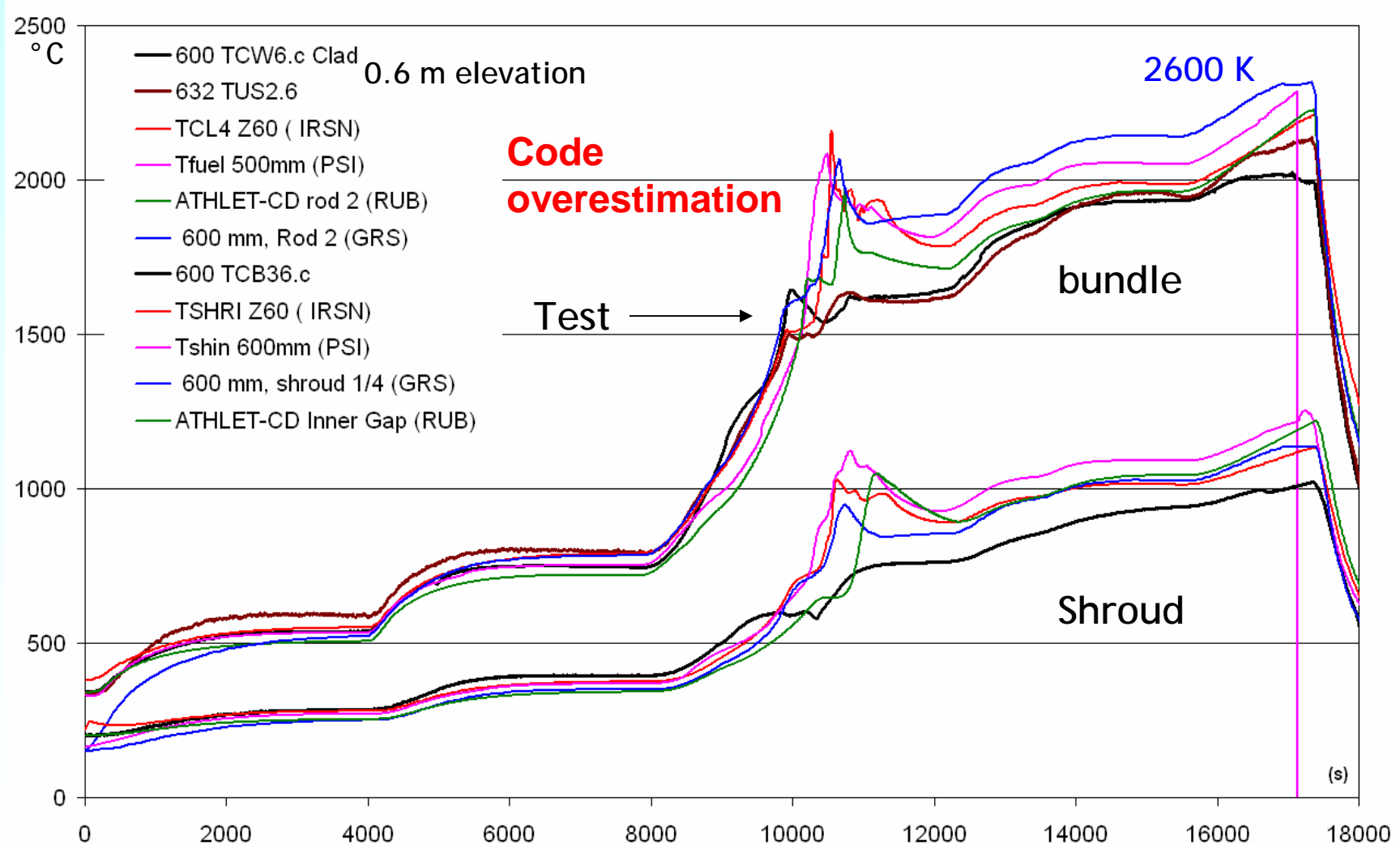
FPT3 thermal results : temperatures evolution (1/2)

Assuming bundle power adjustments, rather good thermal results were obtained up to the end of the transient

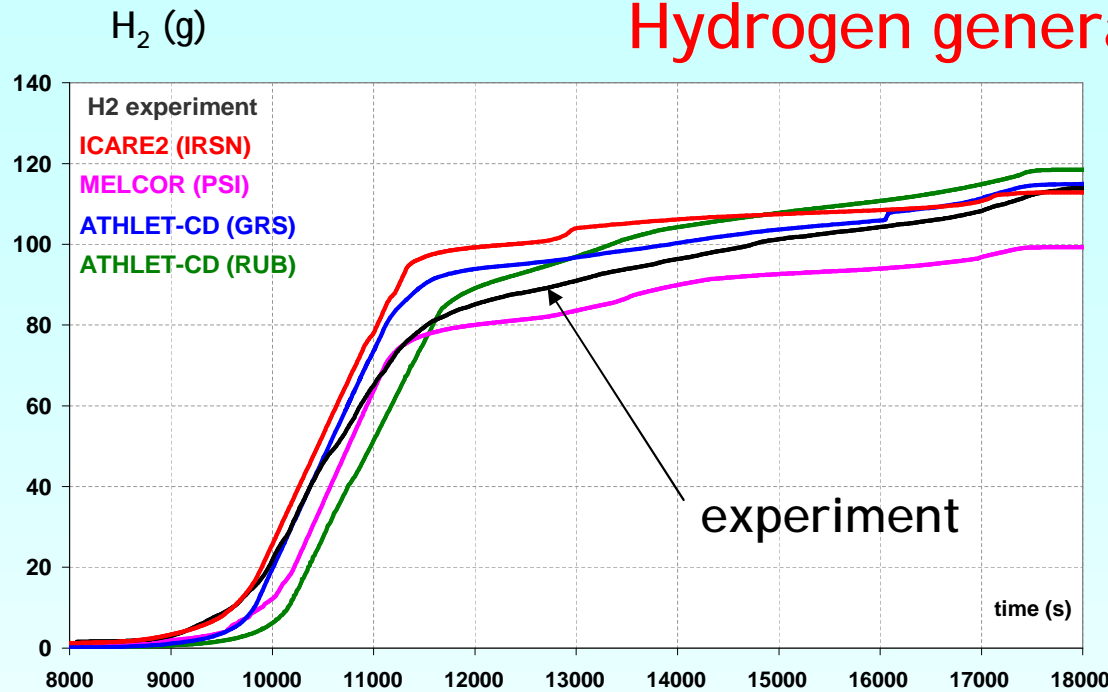


FPT3 thermal results : temperatures evolution (2/2)

Rather good thermal results with however **overestimation** of temperature during oxidation which seems to be linked to overestimation of the steam starvation duration given by the codes



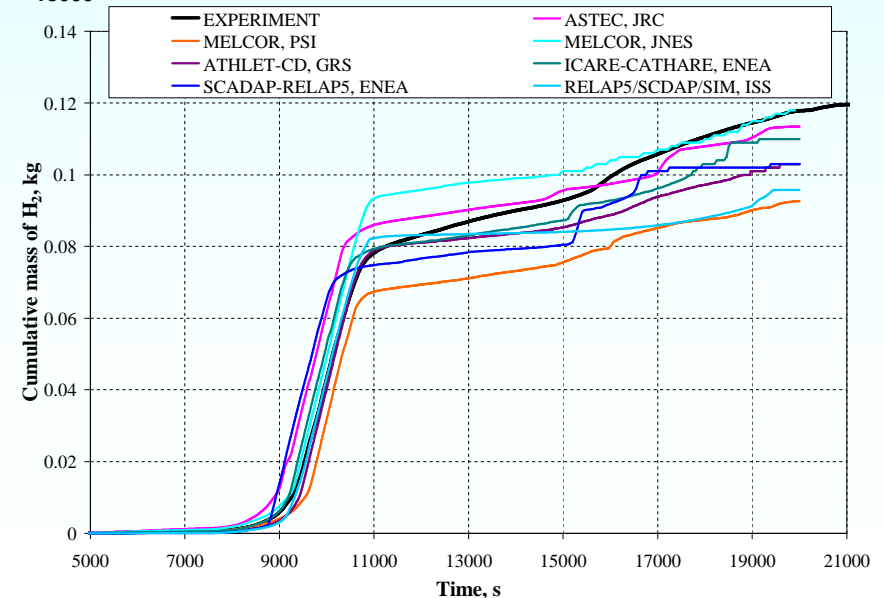
Hydrogen generation (1/2)



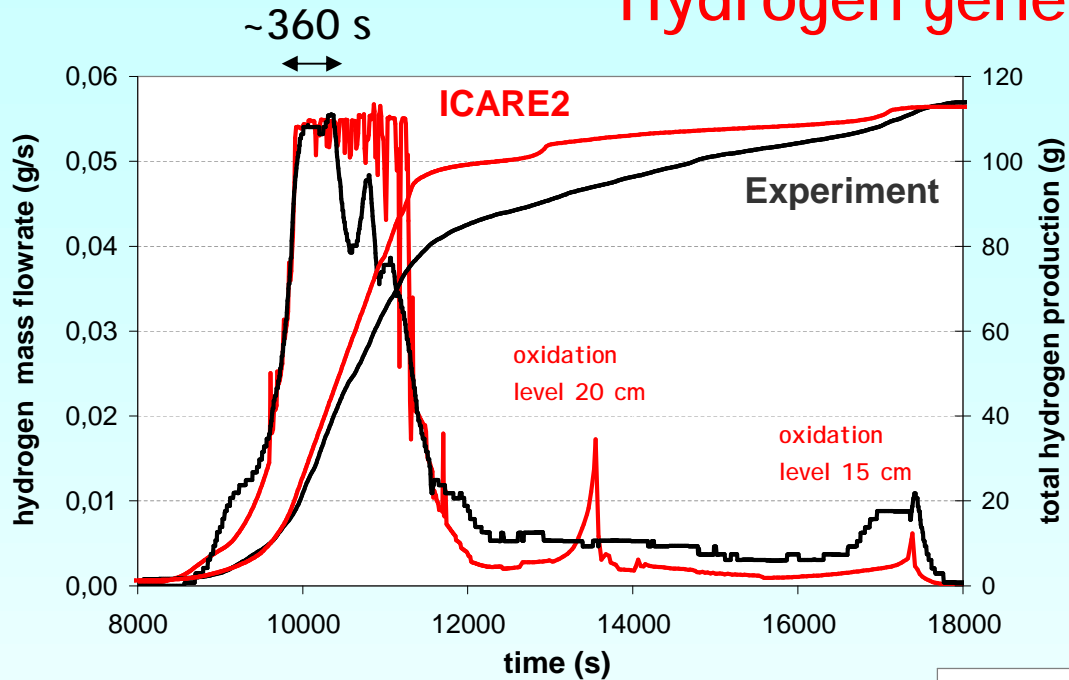
Rather good results obtained with both code simulations regarding **the total hydrogen generation**

The lower value produced with MELCOR is due to the under-estimation of the H₂ during the main oxidation period (mainly coming from B₄C)

This trend was also observed during FPT2 post test calculations

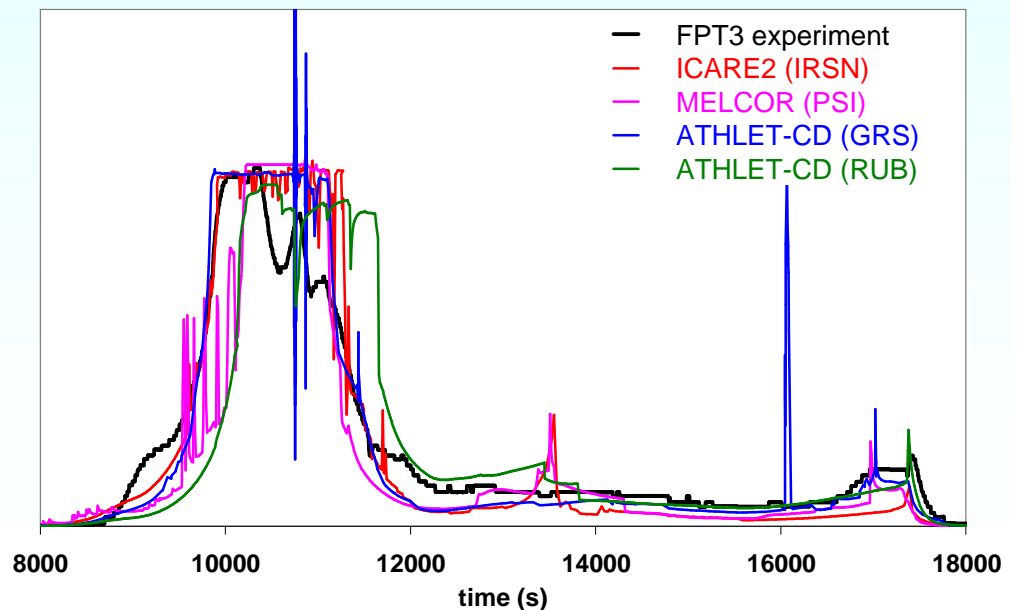


Hydrogen generation (2/2)



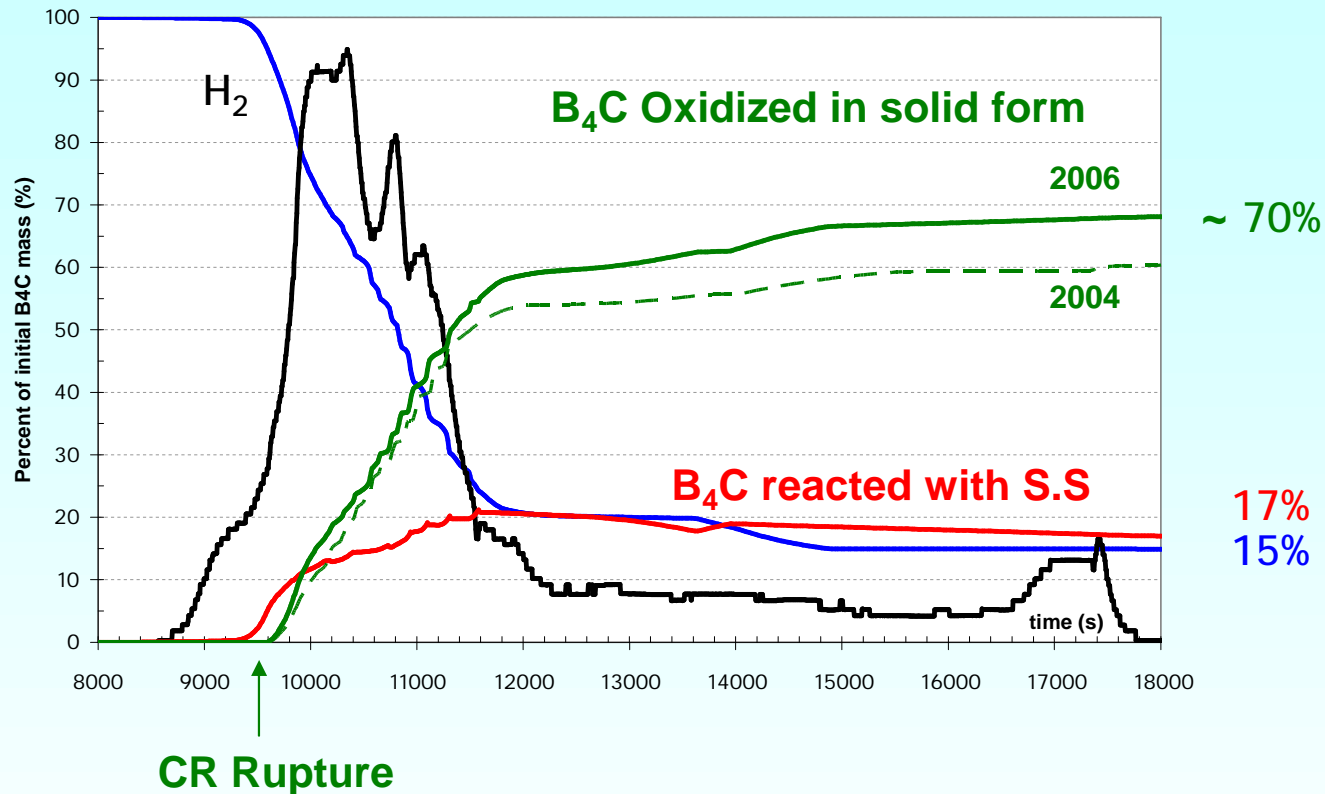
The total H₂ produced is correct
 Nevertheless, the rather **short starvation** period observed in the experiment **is not simulated** by both codes

à the pure starvation period during the test was confirmed to be shorter than what was foreseen by pre-calculations (**1200 +/- 200 s**)



B₄C oxidation and Hydrogen generation

Initial solid
B₄C (77 g)

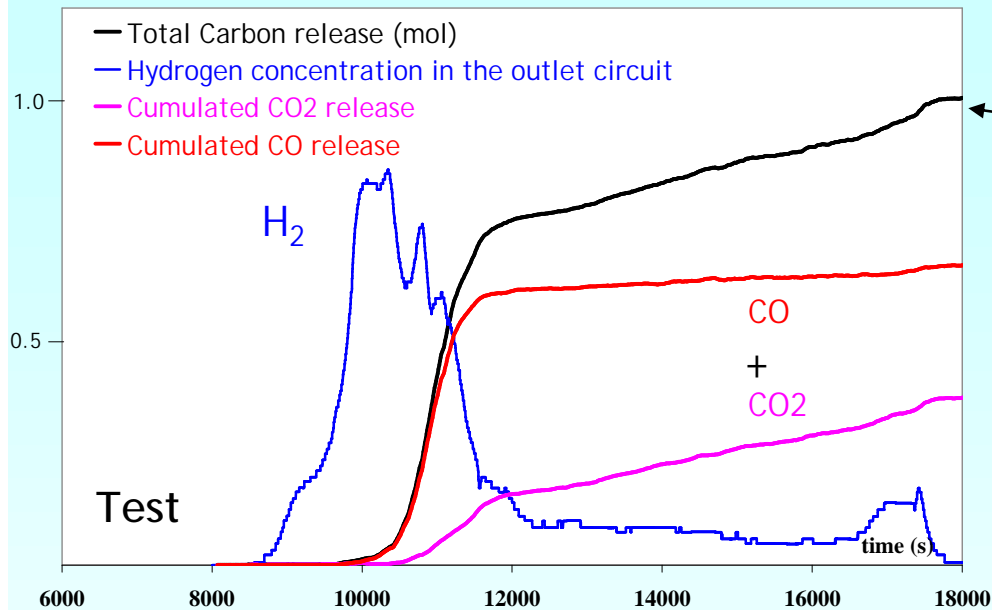


As an example, the results given by ICARE2 code lead to **oxidation of 68%** of the initial inventory in solid form whereas **17% was dissolved by S.S** and do not participate to the oxidation process.

About 15 % solid B₄C remained intact, which is consistent with the test

Gas release coming from B₄C oxidation (test results)

Carbonaceous species

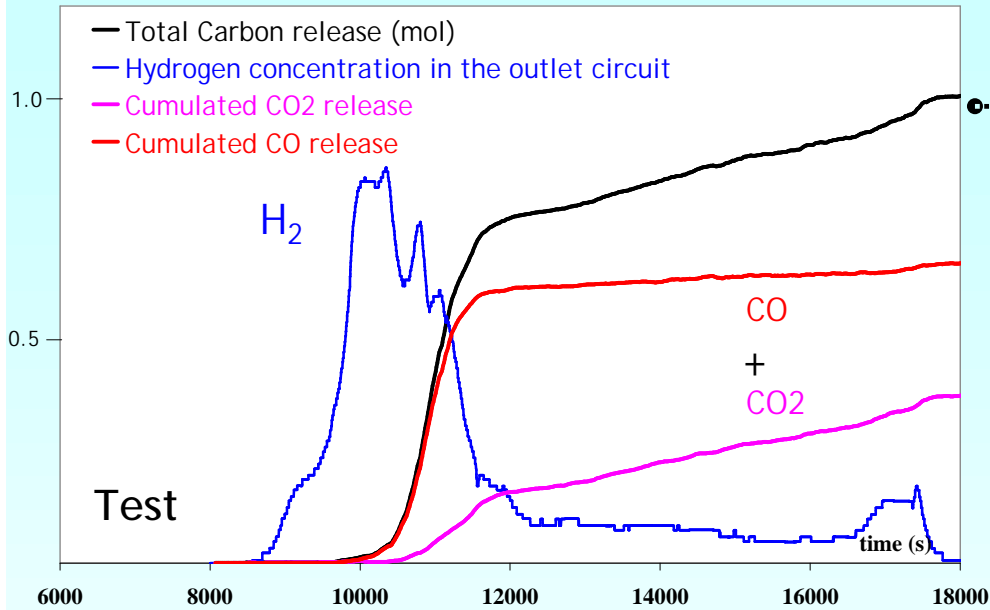


1 mole of Carbon was released

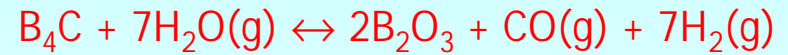
0.64 mole of CO
mainly during the starvation phase

0.37 mole of CO₂
most of the release during
the heat up phase
at low H₂ concentration

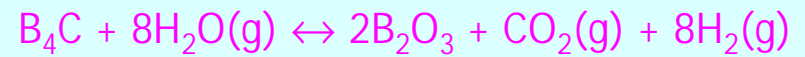
Gas release : Comparison with the code simulations (1/2)



Taking into account the most probable reaction :



1 mole of B₄C gives 1 mole of CO

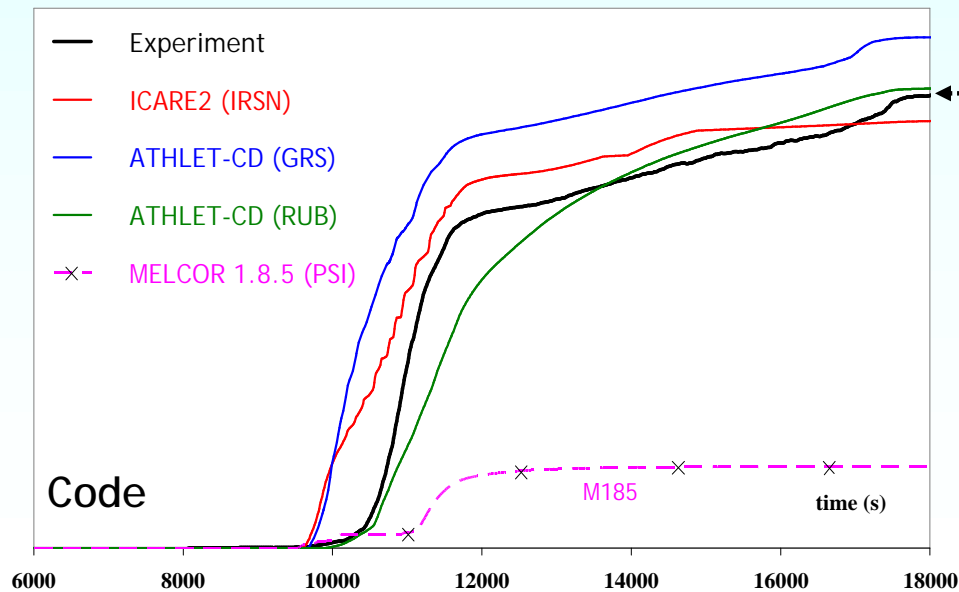


1 mole of B₄C gives 1 mole of CO₂

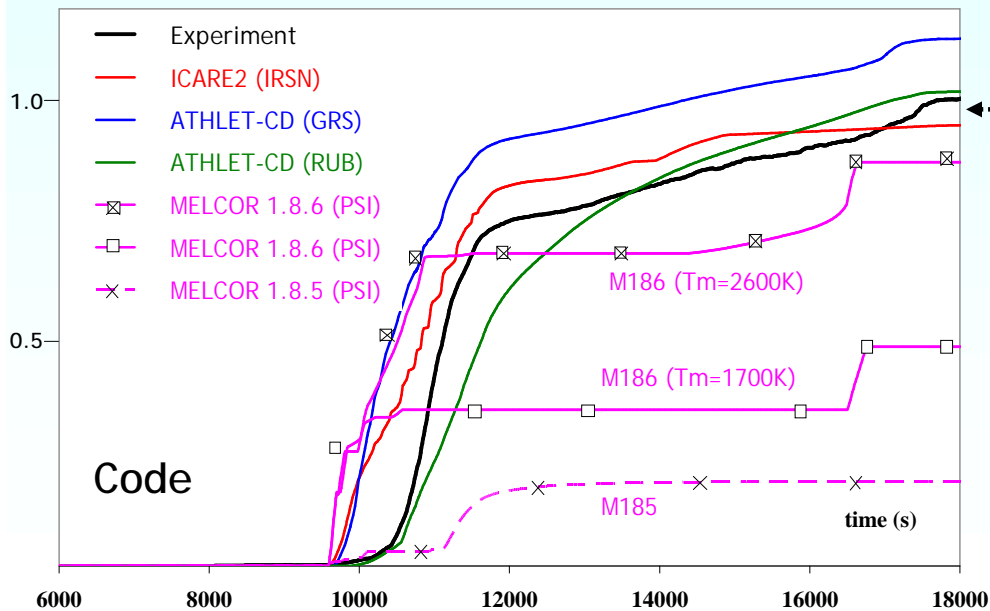
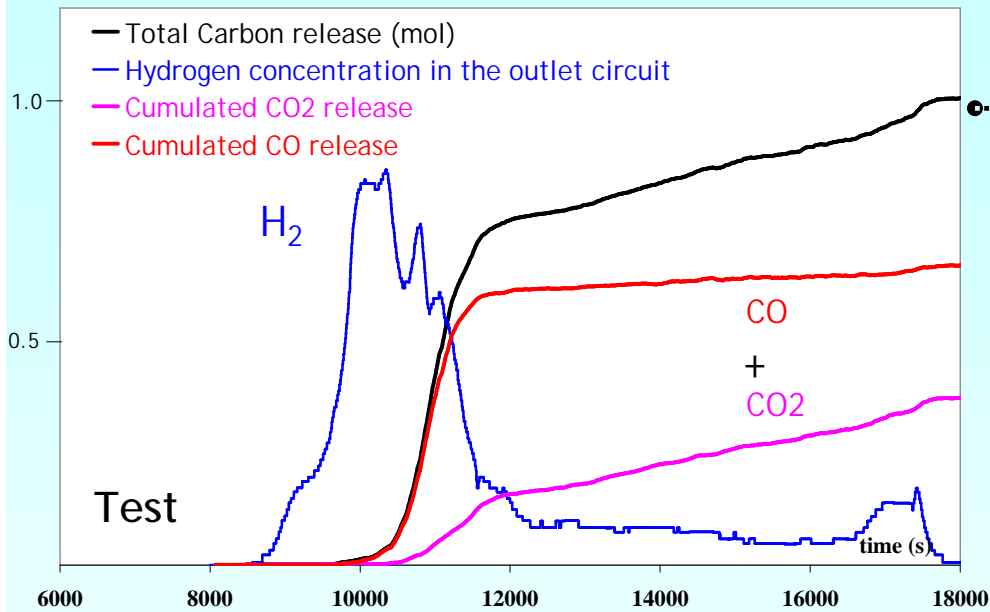
1 mole of Carbon produced during the experiment should come from 1 mole of oxidised B₄C

At the end of the test, carbon releases by codes (0,95 to 1.15 mole) are consistent with the test result (roughly 1 mole)

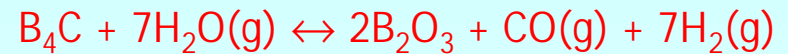
MELCOR 1.8.5 produces only 0.2 g of CO (part of the reacted B₄C lead to elemental carbon not account for in the curve)
MELCOR model was more adapted to BWR control blade



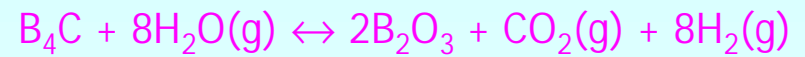
Gas release : Comparison with the code simulations (2/2)



Taking into account the most probable reaction :



1 mole of B₄C gives 1 mole of CO



1 mole of B₄C gives 1 mole of CO₂

1 mole of Carbon produced during the experiment should come from 1 mole of oxidised B₄C

At the end of the test, carbon releases by codes (0,95 to 1.15 mole) are consistent with the test result (roughly 1 mole) : nevertheless, kinetics have to be slightly improved

The results have been improved with new modelling in the MELCOR 1.8.6 version
The best results have been obtained with the increase of temperature level for the B₄C relocation

General conclusion

The works which have been performed in the SARNET produced significant improvement regarding the control rod behaviour, mainly for the solid B₄C oxidation process.

The Severe Accident Code capabilities to simulate the control rod behaviour during the course of Severe Accident on PWR have been demonstrated, nevertheless, some progress in degradation processes are needed.

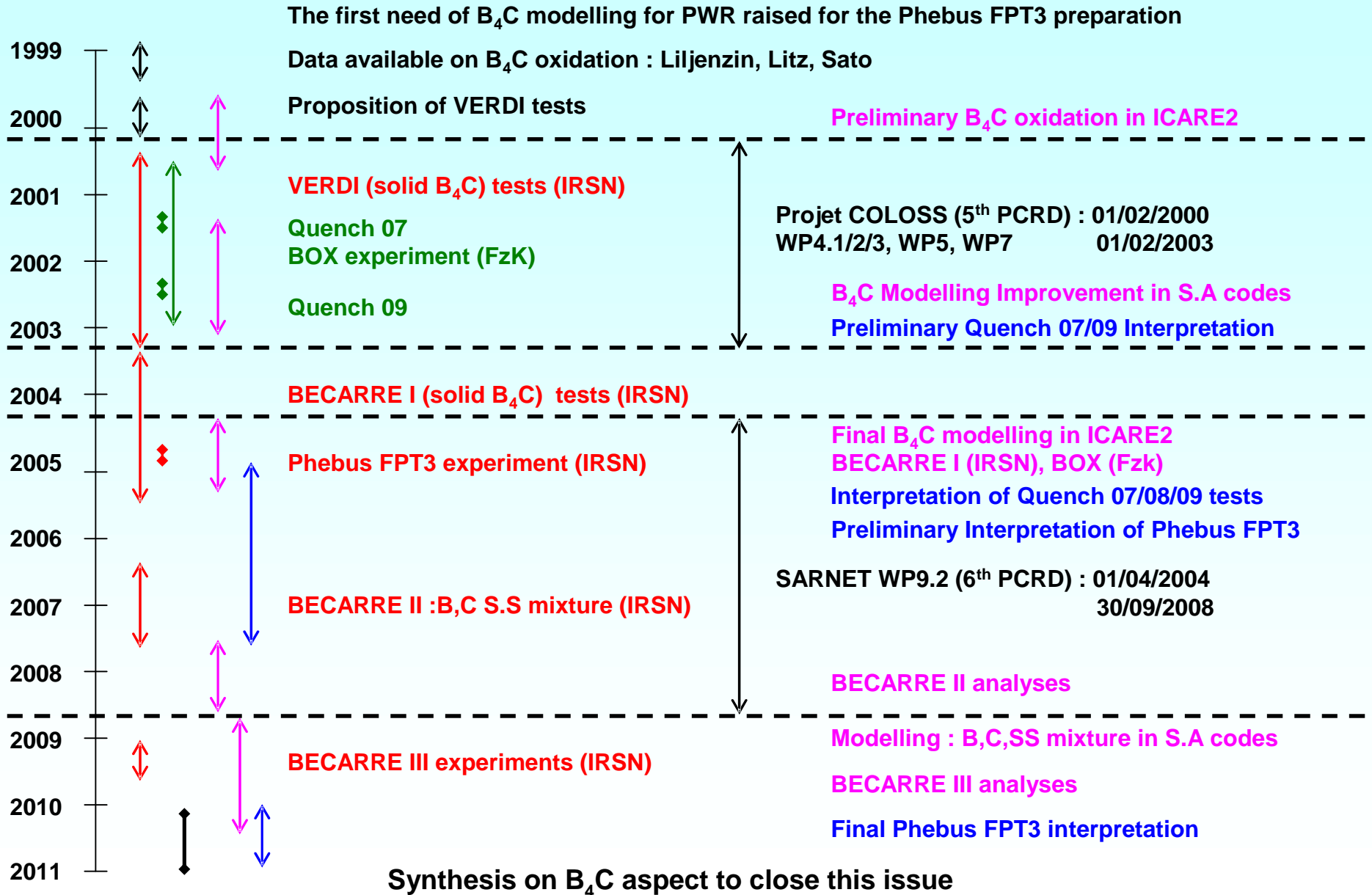
There are still some difficulties to reproduce the final degradation of the bundle using codes (which is out of the scope of this paper). Codes do not recognise the interactions between the molten (B₄C/SS) and neighbouring fuel rods

The need for further code developments of the early phase of core degradation is recognized for the absorber rod material behaviour, mainly on oxidation of mixture (more important for BWR) by analysing BECARRE II tests.

BEARRE III experiments, foreseen to be conducted in 2009, in the framework of the International Source Term Program should help us in the understanding and improving the modelling.

Out of the scope of the following SARNET 2, a synthesis of the B₄C aspect is foreseen in 2010 to close this specific issue.

Summary of B₄C activities (exp., modelling, interpretation)





Thank you for your attention

