MAIN OUTCOMES OF THE PATRICIA PROGRAM

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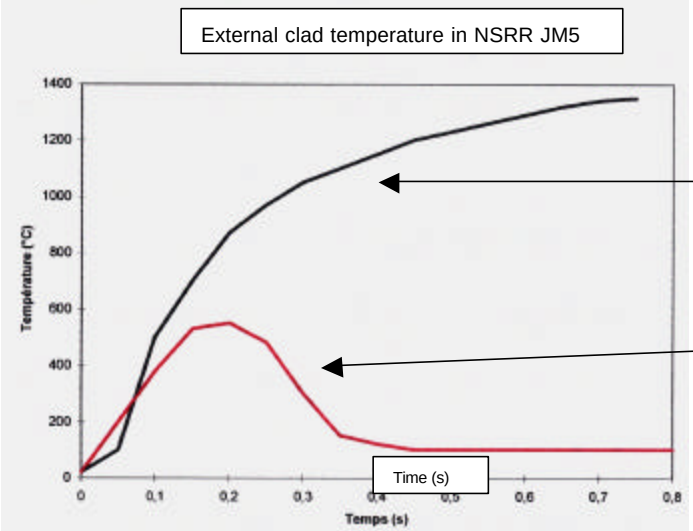
Outline

- *Origin and aim of the program*
- *Experimental procedures*
- *Experimental matrix*
- *Steady-state experiments*
- *Transient experiments*
- *Physical analysis and recommended correlations*
- *Applications with the SCANAIR code*
- *Conclusion*

Origin and aim of the program

Starting point : NSRR - JM5 calculation with usual correlations



SCANAIR
(film boiling:
Bromley correlation)

Experiment

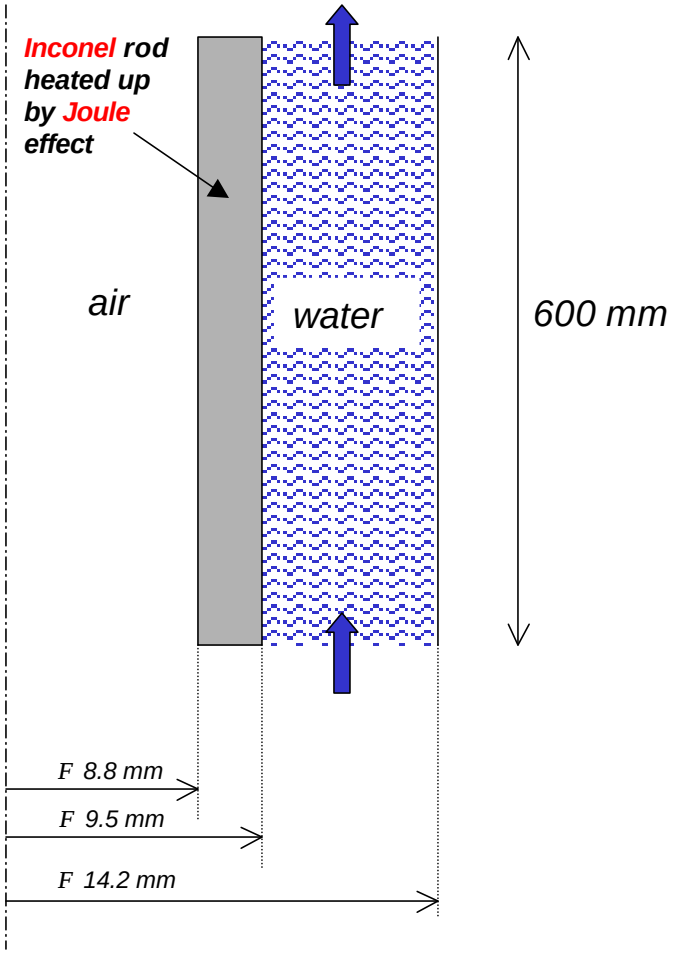
=> usual film boiling correlation in pool boiling: strong underestimation of clad-to-coolant heat-transfer

Presence of kinetic effects ?
Transposition to PWR conditions ?

1995 : IRSN and EDF set up the PATRICIA program in the PATRICIA loop (CEA/Grenoble)

PATRICIA facility

Water loop operating around PWR conditions (15 MPa, 4m/s, 280°C)
or NSRR conditions (stagnant water, atmospheric pressure, 20°C)



Comparison with PWR case :

- *conservation of the most important parameters for clad-to-coolant heat transfer:*
  - *flow cross section S=88.1 mm²*
  - *heated perimeter c_{heated}=11.7 mm (=4 cross section/heated perimeter)*

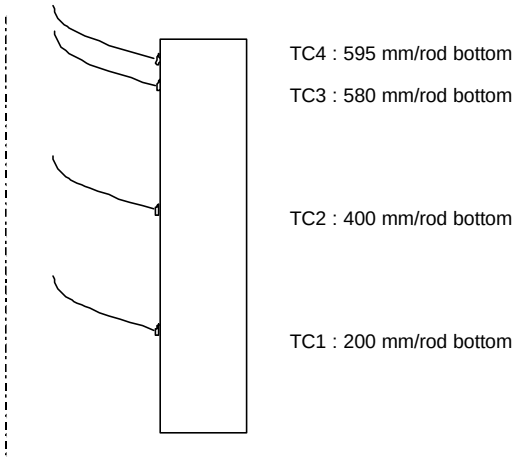
- *non conservation of hydraulic perimeter (no influence)*
  $c_{hydraulic}$=4.7 mm instead of 11.7 mm

IRSN

Experimental procedure (2/2)

Instrumentation

4 thermocouples welded on the clad inner surface



TC inner clad temperature

↓ *deconvolution*

« Real » inner clad temperature

↓ *Inverse conduction calculation*

Temperature field in the rod ($T_{outer}=f(t)$, heat-flux$=-\lambda\,(dT/dr)_{r=router}$)

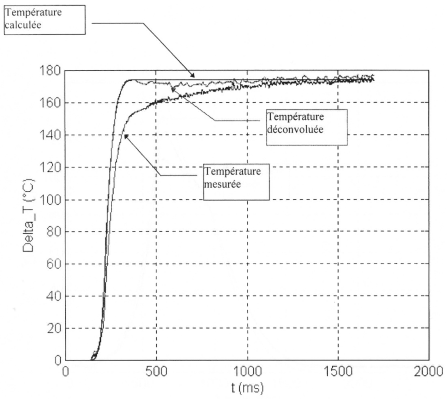
Uncertainty analysis

Heat-flux : ± 25 %

Clad outer surface temperature : ± 30°C

Deconvolution

Transfer function previously determined with tests in air (« adiabatic »)

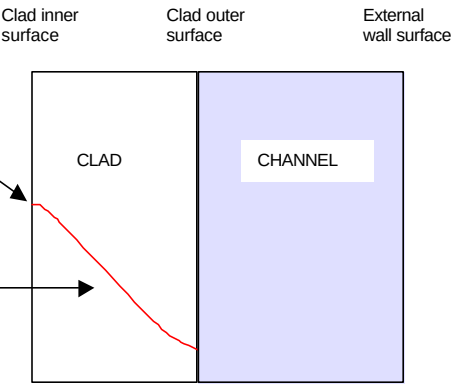


Inverse conduction calculation

$$T_{(r=r\,\mathrm{int},t)} = T\,\mathrm{int}\,deconvoluted\,(t)$$

$$\left.\frac{\partial T}{\partial r}\right|_{(r=r\,\mathrm{int},t)} = 0$$

$$mCp\frac{\partial T}{\partial t} - \lambda\,\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = p$$



Experimental matrix

Inlet conditions: PWR (15 MPa, 280°C, 4 m/s) *=> saturation temperature ~ 345°C*

Heating kinetics

- steady-state experiments

=> link with existing data-base and usual correlations

+ setting a reference for transient experiments to check the possible presence of kinetic effects

- transient-experiments :

=> correspondence with neutronic pulses (estimated with SCANAIR)

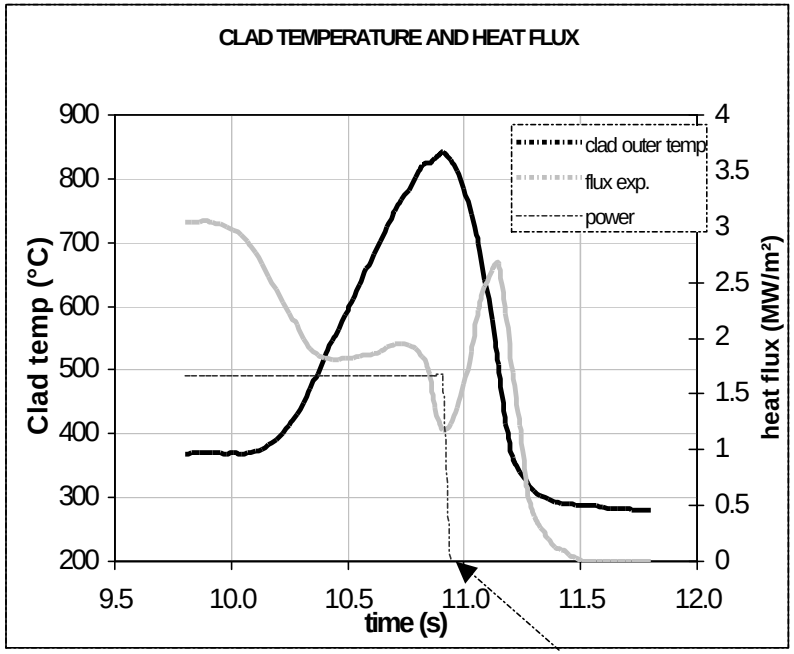
	Neutronic pulse half-width	Clad heating transient half-width	PATRICIA experiments
"Slow" transient	300 ms	250 ms	750
"Fast" transient	30 ms	60 ms	150 and 112
"Ultra-fast" transient	10 ms	20-30 ms	065

Representative of RIA

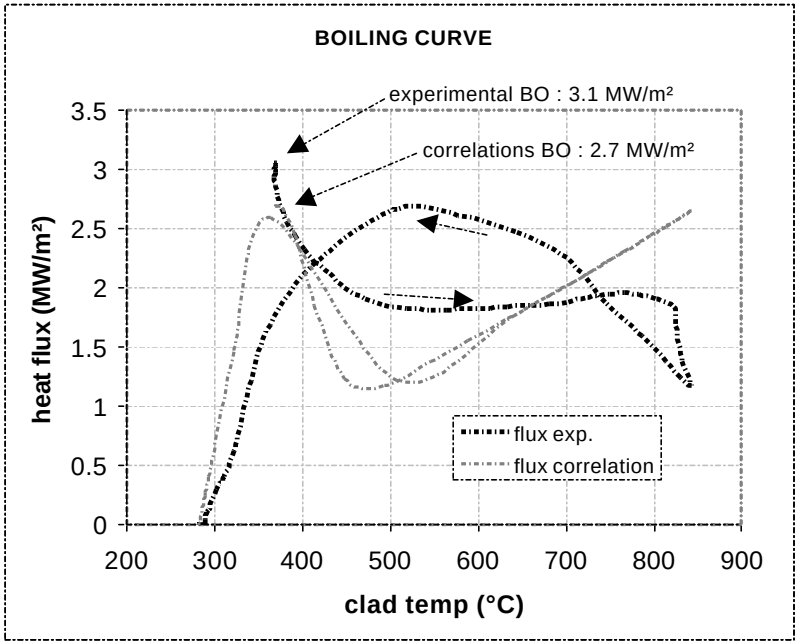
Name	P (bars)	Te (°C)	Q (g/s)	Injected energy in the clad	Massic injected energy in the clad (J/g clad)	BOILING CRISIS
150.049	145.9	280	262	10183	201	
150.050	145.9	280	262	12078	238	✓
150.051	145.8	280	289	12480	246	✓
150.052	145.8	278	289	11911	235	✓
150.061	154.9	280	262	12529	247	✓
150.065	145.8	280	289	16784	331	✓
150.069	145	282	262	13315	263	✓
150.070	145	323	289	880	17	
150.072	145	325	289	3805	75	
150.074	145	324	289	13947	275	✓
750.055	145.6	320	289	3844	76	
750.058	145.5	280	289	18464	365	
750.059	145.5	280	262	18268	361	
750.060	156	280	262	15998	316	
750.063	146.1	280	289	27553	544	
750.064	146.1	280	289	25871	511	
750.067	145.1	282	289	18990	375	
750.068	145	282	262	19816	391	

Steady-state experiments

Objective : setting a reference for transient experiments to check the possible presence of kinetic effects.



Power switched-off



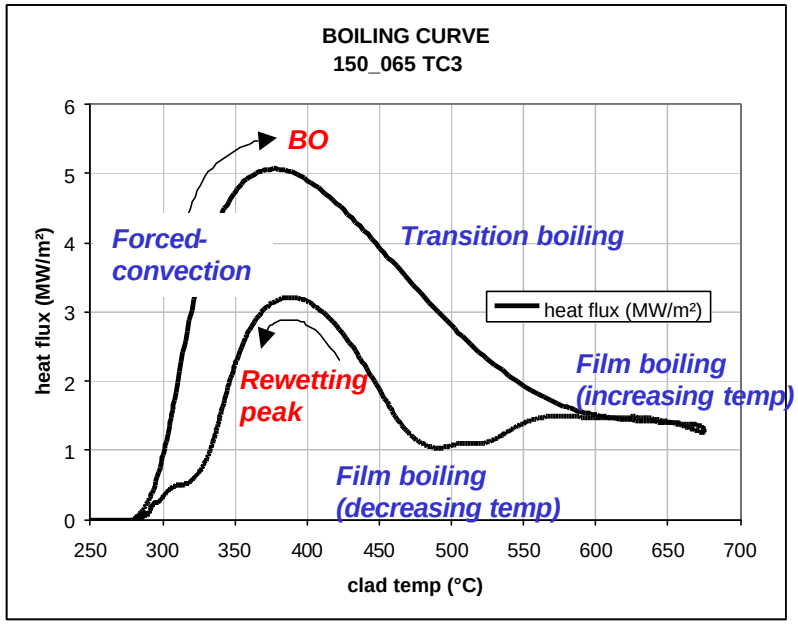
Possible correlations :

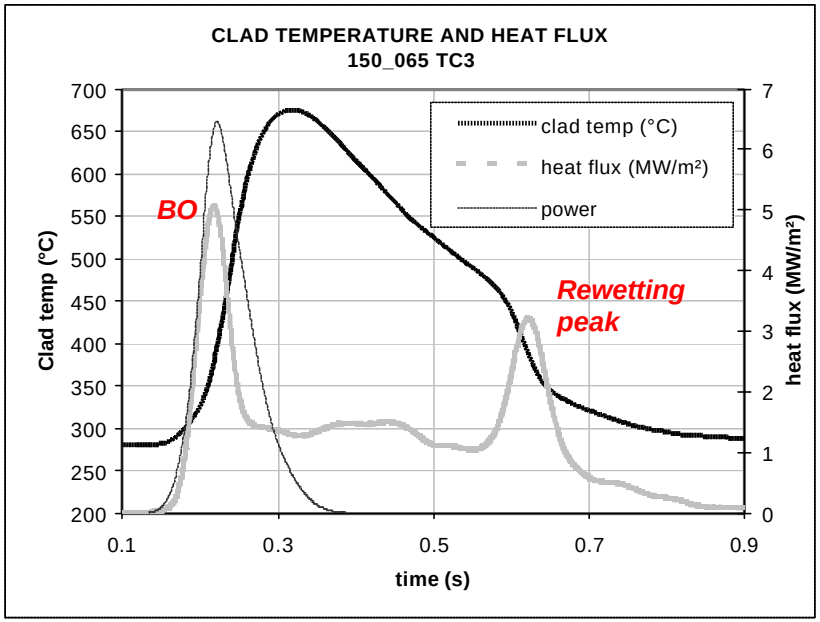
- *forced-convection : Dittus-Boelter*
- *critical-heat flux : Babcock and Wilcox*
- *transition boiling : exponential fitting*
- *film boiling : Bishop Sandberg Tong (BST)*

=> steady-state experiments do not exhibit any significant discrepancy compared to existing data base and correlations.

Transient experiments (1/2)

Typical boiling curves





4 heat-transfer regimes

- *forced-convection*
- *transition boiling*
- *film boiling (increasing temp)*
- *film boiling (cooling down)*

2 peaks of heat-flux

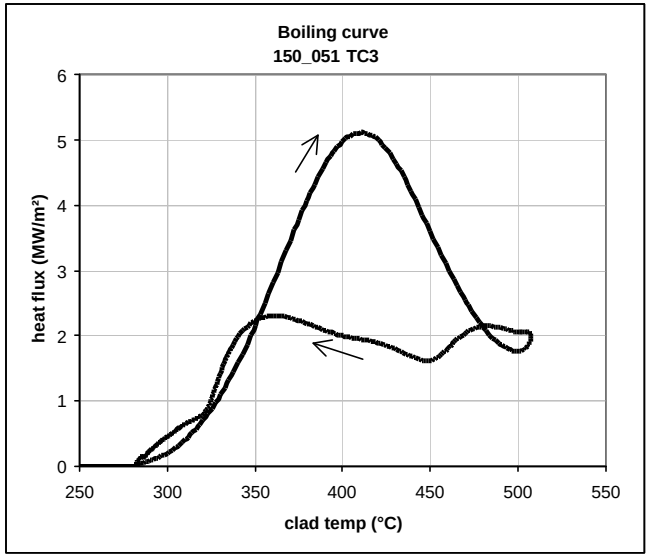
- *Burn-Out or « Boiling Crisis »*

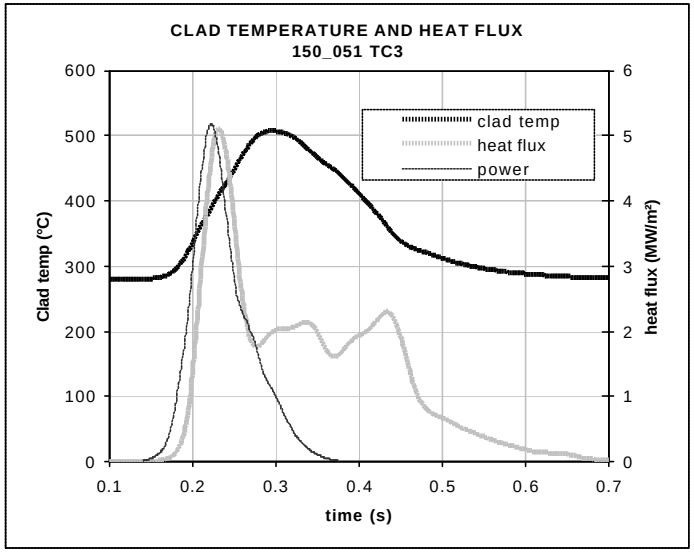
  (or DNB in case of nucleate boiling only),

- *rewetting peak*

Transient experiments (2/2)

Typical boiling curves (cont 'd)

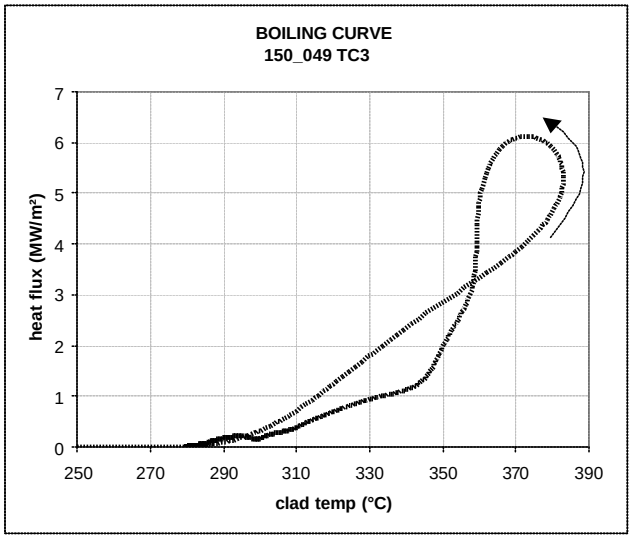


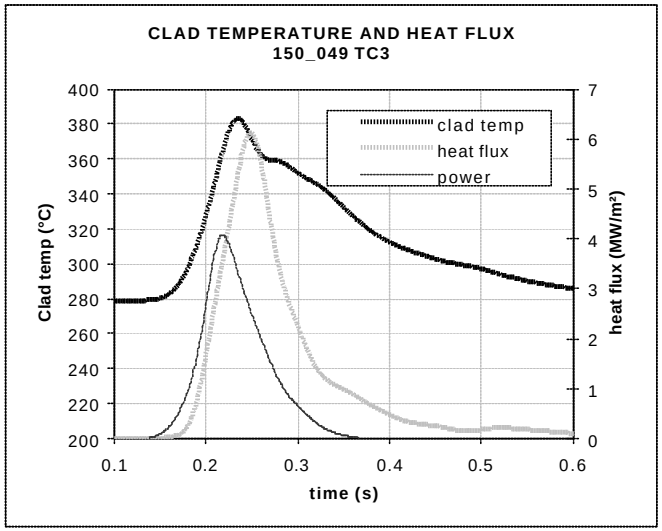


Other transients

(lower injected energy => no film boiling phase)

Experiments with too low injected energy do not break through the boiling crisis:





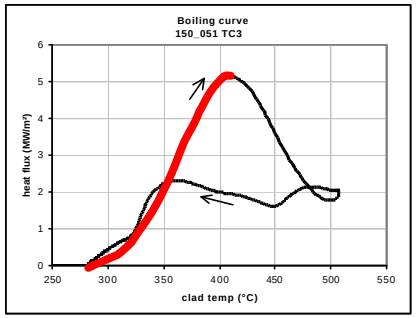
No heat-flux peak

No transition boiling

Only forced-convection is described.

Physical analysis and recommended correlations (1/4)

Single phase forced-convection



Simultaneous increase of temperature and heat-flux up to the BO

No steep increase of the slope while overpassing the saturation temperature Tsat
=> no clear evidence of nucleate boiling

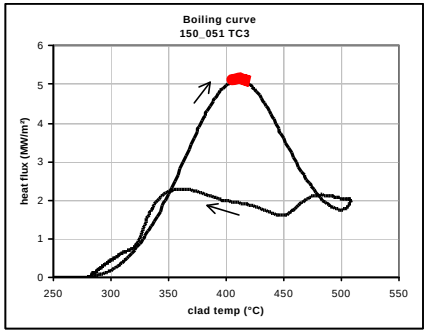
Duration of the phase [T_{sat}, T_{BO}] ~ 20 ms (bubble nucleation-detachment time : dozen of milliseconds)

*=> **not enough time to have a fully established nucleate boiling regime***

Orders of magnitude :

- *heat-flux : 0 to 5-6 MW/m²*
- *heat-transfer coefficient : 20 000-50 000 W/m²/K*

Burn-Out point



Seems to be reached in single-phase conditions
*=> **« flash boiling » of a superheated water layer***
(steady-state: fully established nucleate boiling, ie. two-phase conditions)

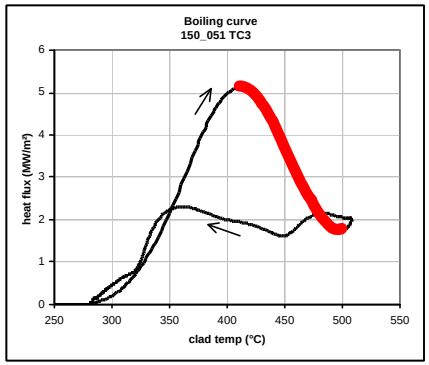
Fast transient => steep thermal gradients in the fluid at the wall => high heat-fluxes

Orders of magnitude :

- *BO temperature ~ Tsat + 50°C*
  (steady-state : Tsat + 15°C)
- *Critical Heat Flux (CHF) : 5-6 MW/m²*
  (steady-state : ~3 MW/m²)

Physical analysis and recommended correlations (2/4)

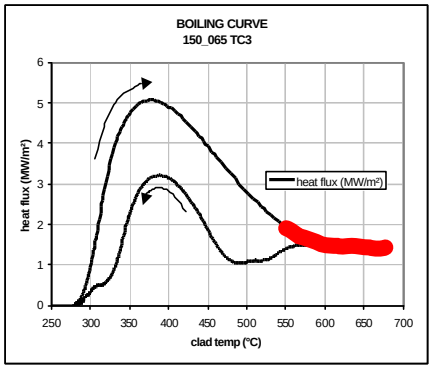
Transition boiling



Increase of temperature with decrease of heat-flux (up-to ~ 500°C)
=> degradation of the heat-transfer because of the creation of a vapor film that insulates the clad from the liquid.

Duration : 20-30 ms

Film boiling



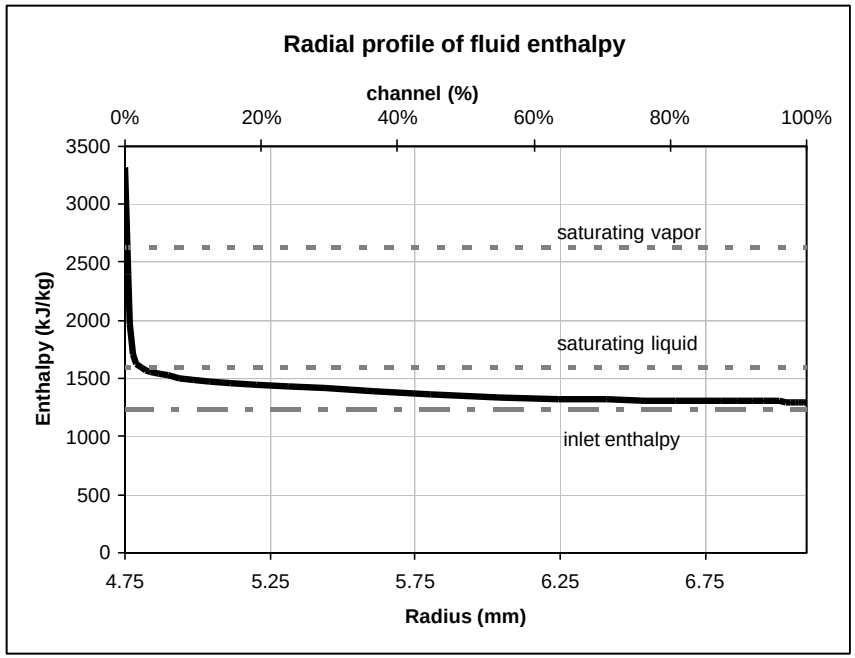
Stabilization of the heat-flux
(+ increase for higher temperatures)

Orders of magnitude :

- *heat-flux : 1-2 MW/m²*
  (steady-state : ~ 2 MW/m²)
- *heat-transfer coefficient : 3 000 - 5 000 W/m²/K*
  (steady-state : 5 000 - 6 000 W/m²/K)

Physical analysis and recommended correlations (3/4)

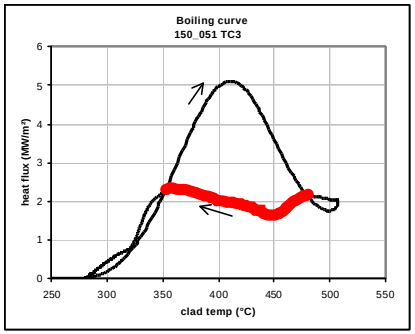
Film boiling (cont'd)



TH2D calculations (2D, 2-phase code developed in a IRSN / Kurchatov Institute collaboration)

Strong undersaturation (inlet :280°C / saturation:345°C)
=> only a small layer of fluid is affected by the clad heating
(thickness of vapor film £ 5% of the channel)

Cooling down and rewetting



The cooling down does not follow the reverse path
=> lower heat-transfer (may be linked to the stabilization of the vapor film)

Rewetting peak around the Minimum Stable Film temperature (Tmsf ~ 385°C) with fluxes typical of forced-convection heat-transfer

Physical analysis and recommended correlations (4/4)

Single-phase:

- *Dittus-Boelter up to the saturation temperature*
- *linear interpolation up to the Burn-Out point*

Burn-Out:

- *Critical Heat Flux: Babcock & Wilcox*
- *Temperature of BO : $T_{BO}=T_{sat}$ + 50°C*

Transition boiling:

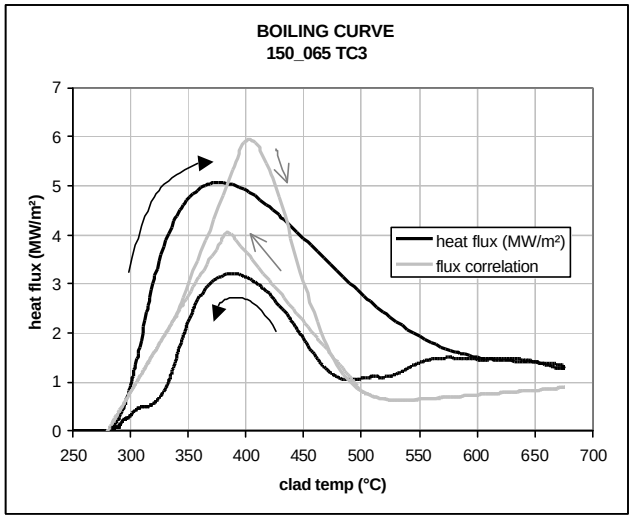
- *exponential fitting tending towards a film boiling correlation for high temperatures (T>500°C)*

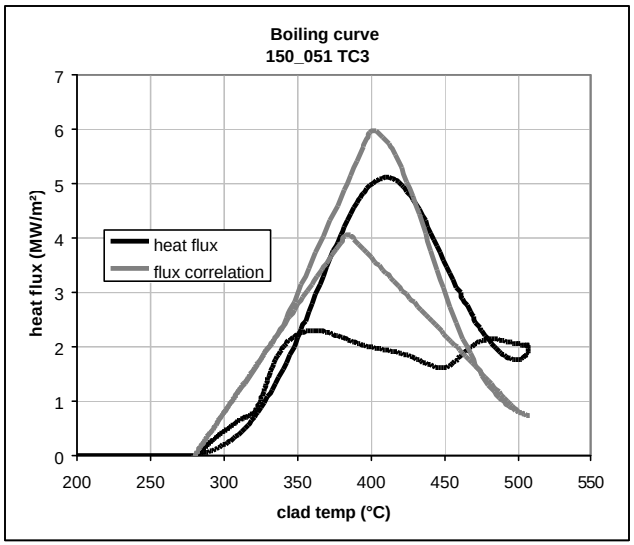
Film boiling (increasing temp):

- *Bishop Sandberg Tong (BST)*

Film boiling (cooling down):

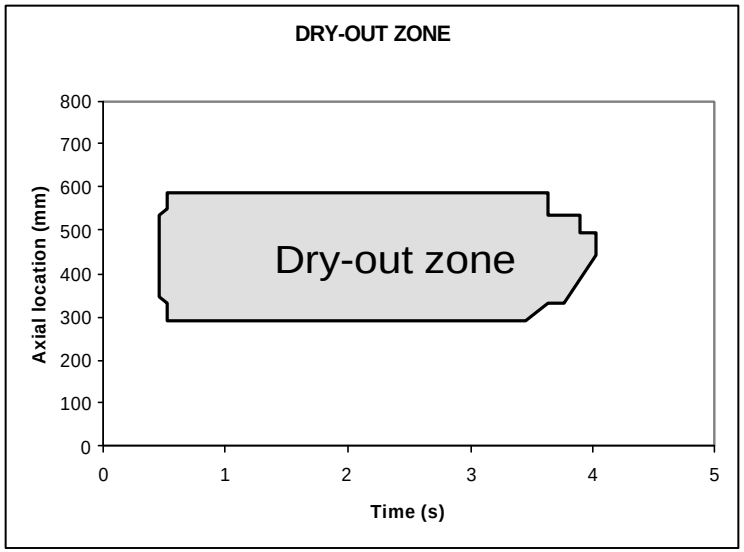
- *BST down to 500°C,*
- *linear interpolation to forced-convection at minimum stable film temperature (Tmsf) below 500°C.*

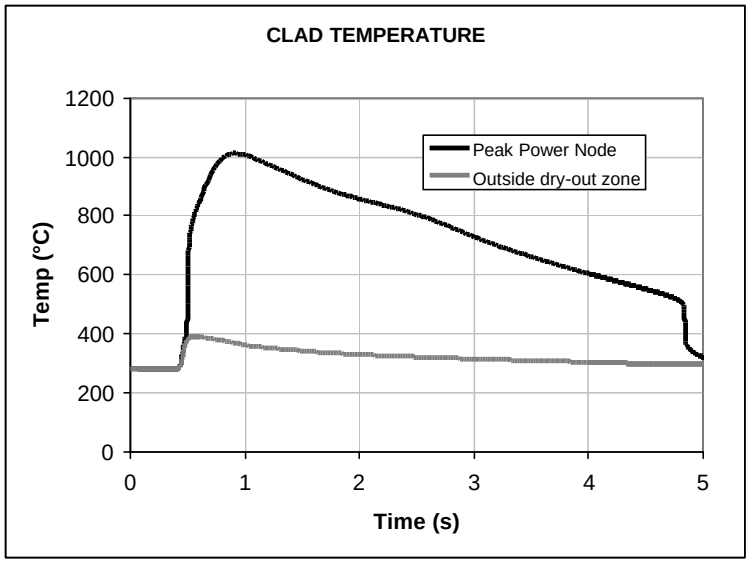




These correlations and parameters have been implemented in the SCANAIR code

Case : 4-cycle UO2 rod (ZrO_2 : 50µm, no transient spalling simulated), 800 mm long
Injected energy : 586 J/g (140 cal/g) with the REP-Na10 power pulse





Considerable dry-out zone (300 mm long), centered on the Peak Power Node because of the shape of the CABRI power profile.

High temperatures (around 1000°C) are reached in the dry-out zone.

The post-BO phase lasts about 4s.

The BO is reached first at the Peak Power Node at a fuel enthalpy of about 470 J/g (113 cal/g).
NB: this value strongly depends on the zirconia thickness and on the fuel-clad heat-transfer modelling
=> no zirconia (simulation of transient spalling) + solid-solid fuel-clad heat-transfer : H_{BO}~85 cal/g

Thermal conditions adequate for clad ballooning provided the rod internal pressure is high enough.

CONCLUSION

The PATRICIA program allowed to highlight the following characterisitic of clad-to-coolant heat-transfer during a RIA in PWR conditions:

- *kinetic effects take place in fast clad heating transients representative of RIAs,*

- *the boiling crisis is mainly governed by the flash boiling of a superheated water layer (not enough time to have a fully established nucleate boiling),*

- *critical heat-flux around 5-6 MW/m² (~3 MW/m² in steady-state) at $T_{BO} \sim T_{sat}$ + 50°C (T_{sat} + 15°C in steady-state),*

- *the fast crossing of transition boiling is followed by film boiling, heat-flux around 1-2 MW/m² (2 MW/m² in steady-state),*

- *only a small fraction of the fluid at the very vicinity of the clad is affected by the clad heating.*

Recommended correlations implemented in the SCANAIR code.

These results are intensively used for the definition of future experiments of the CABRI Water Loop Program.

Possible additional work :

- *study of very-fast transients (representative of 10ms neutronic pulses),*
- *study of the influence of the clad surface roughness.*