Coupling of thermal-mechanics and thermal-hydraulics codes for the hot channel analysis of RIA events

First steps in AEKI toward „multiphysics”

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- Introduction: the relation of the presented activity to the final targets of the safety analysis
- Why the multi-physics treatment can be useful or even necessary? Arguments for using thermal-mechanical codes and coupling them to thermal hydraulic sub-channel codes for the hot channel analysis.
- The method of coupling the FRAPTRAN fuel behavior and the TRABCO hot channel thermal hydraulic codes
- Demonstration: results for a Control Rod Ejection event
- Conclusions

Introduction

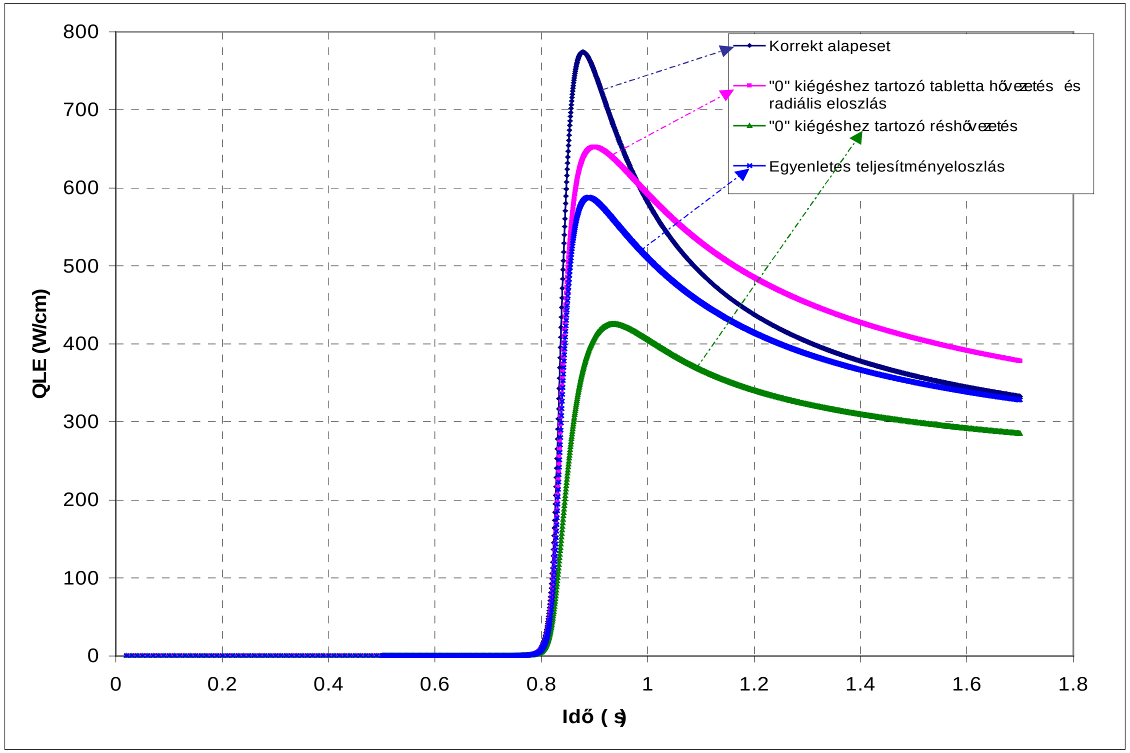
The hot channel calculation is an important final stage of the safety analysis for checking the acceptance criteria fulfillment or/and for counting up the failed fuel rods, necessary for the activity release evaluation.

Quantifying the uncertainties of the final results – originating from the hot channel analysis – is an essential condition for the applicability of the methods and codes for the safety analyses.

For quantifying the uncertainties a best estimate calculation method is necessary, while the present hot channel calculation methods are usually comprise essential assumptions, expected conservative, concerning the gap conductance and the coolant mixing.

Importance of the correct fuel state modeling in a CRE event

Time dependence of the heat transferred to the coolant



Black: Base case (without approximation)

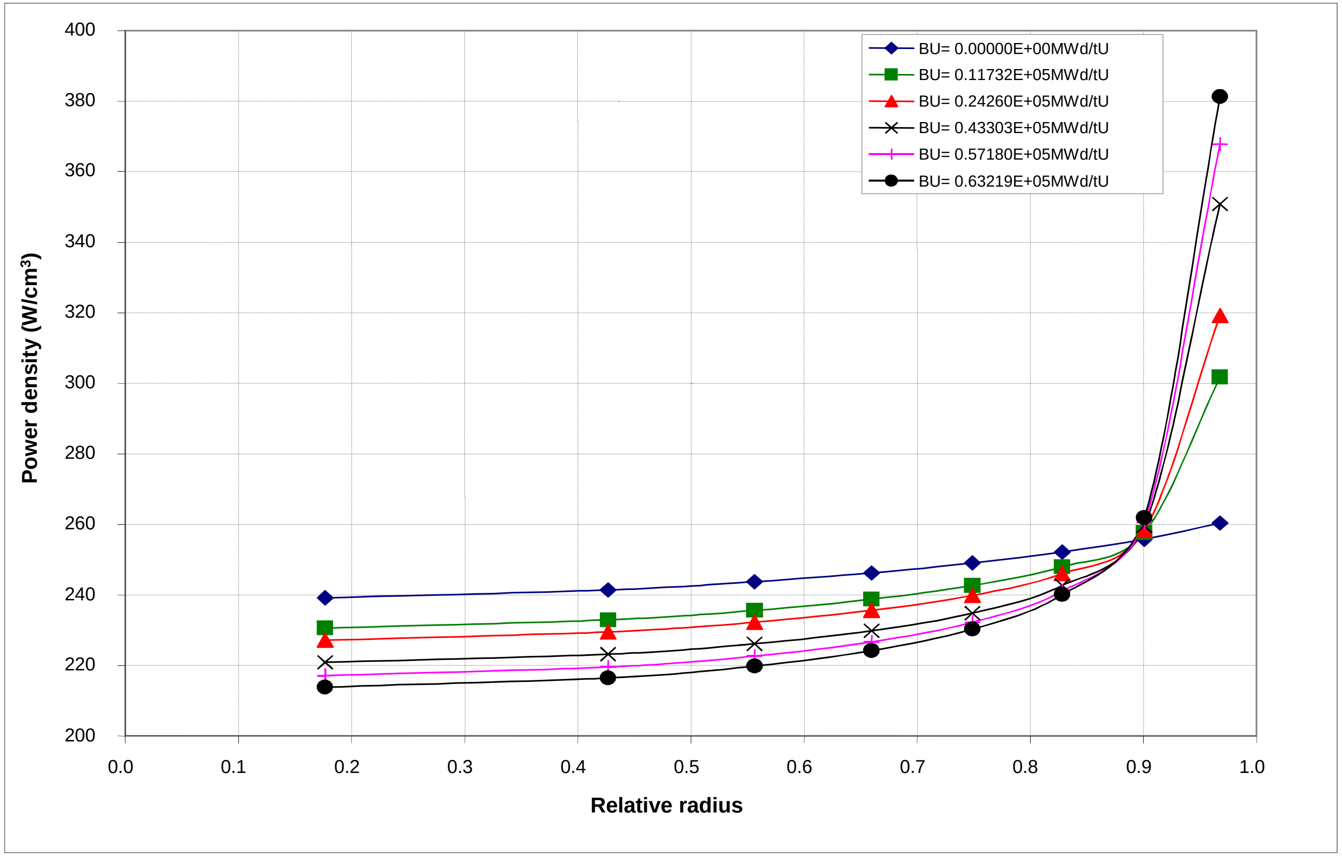
Violet: Pellet heat conductance and power distribution according zero burnup

Blue: Flat power distribution

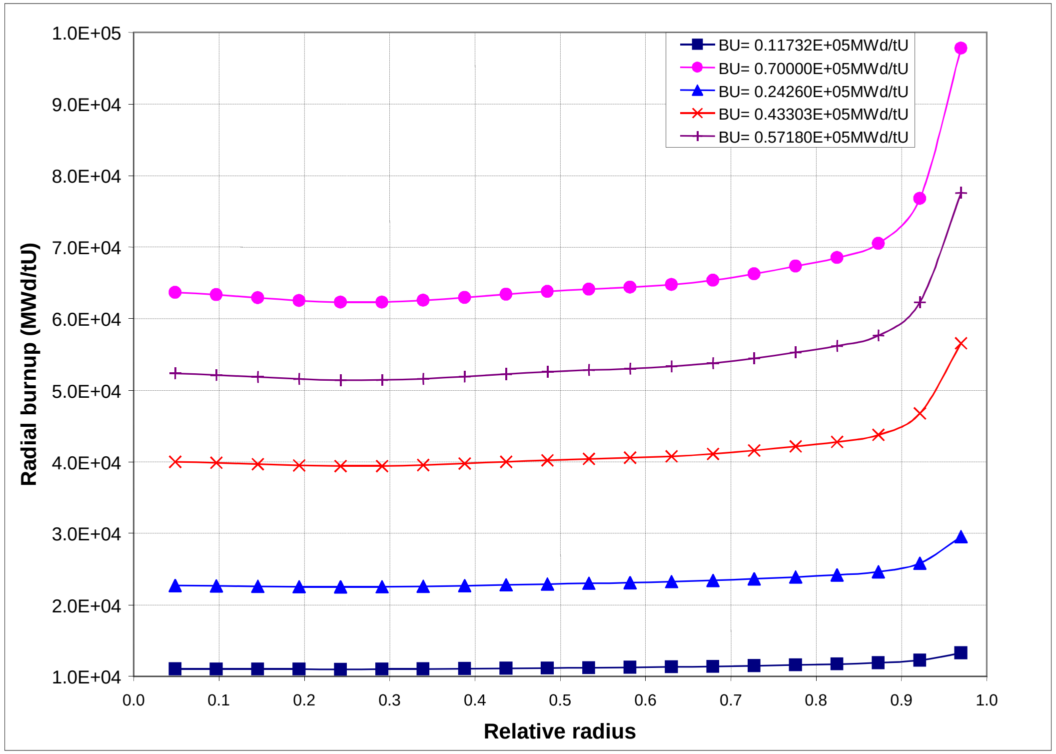
Green: Gap conductance according to zero burnup

Power density radial distribution in the pellet at various pellet average burnup values

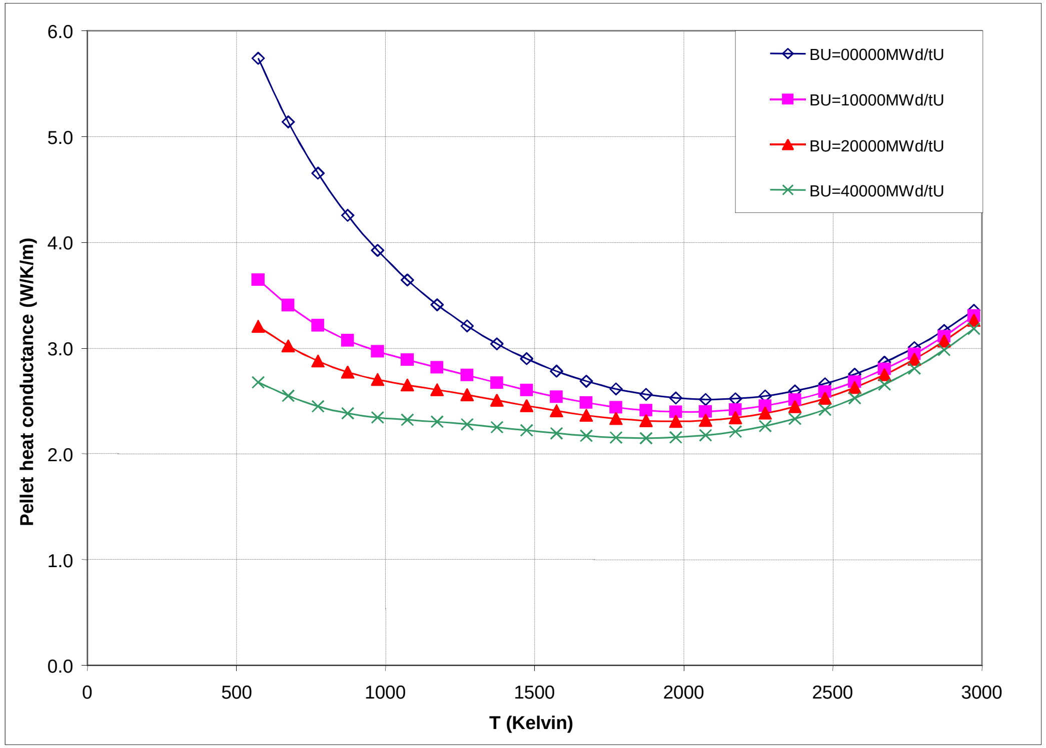
Plutonium build up at the pellet edge, due to the U-238 strong resonance absorption cross section



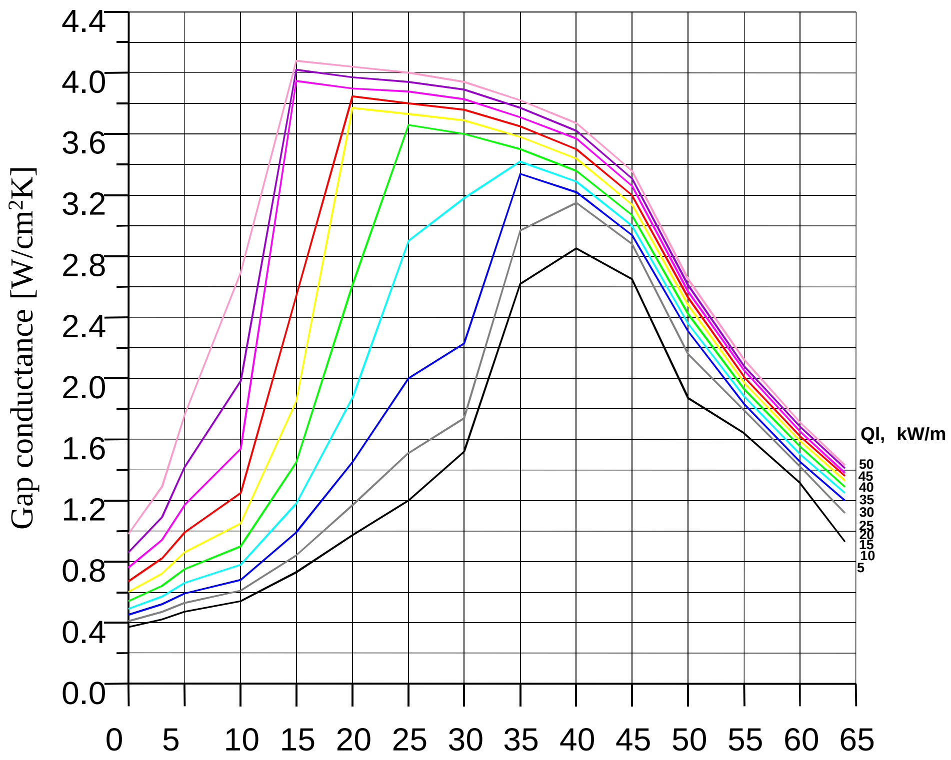
Local burnup radial distribution in the pellet at various pellet average burnup values.



Pellet heat conductivity coefficients depending on the temperature at various local burnup values



Gap conductance depending on the pellet average burnup at various linear heat rate values. Obtained from long term fuel behavior calculations.



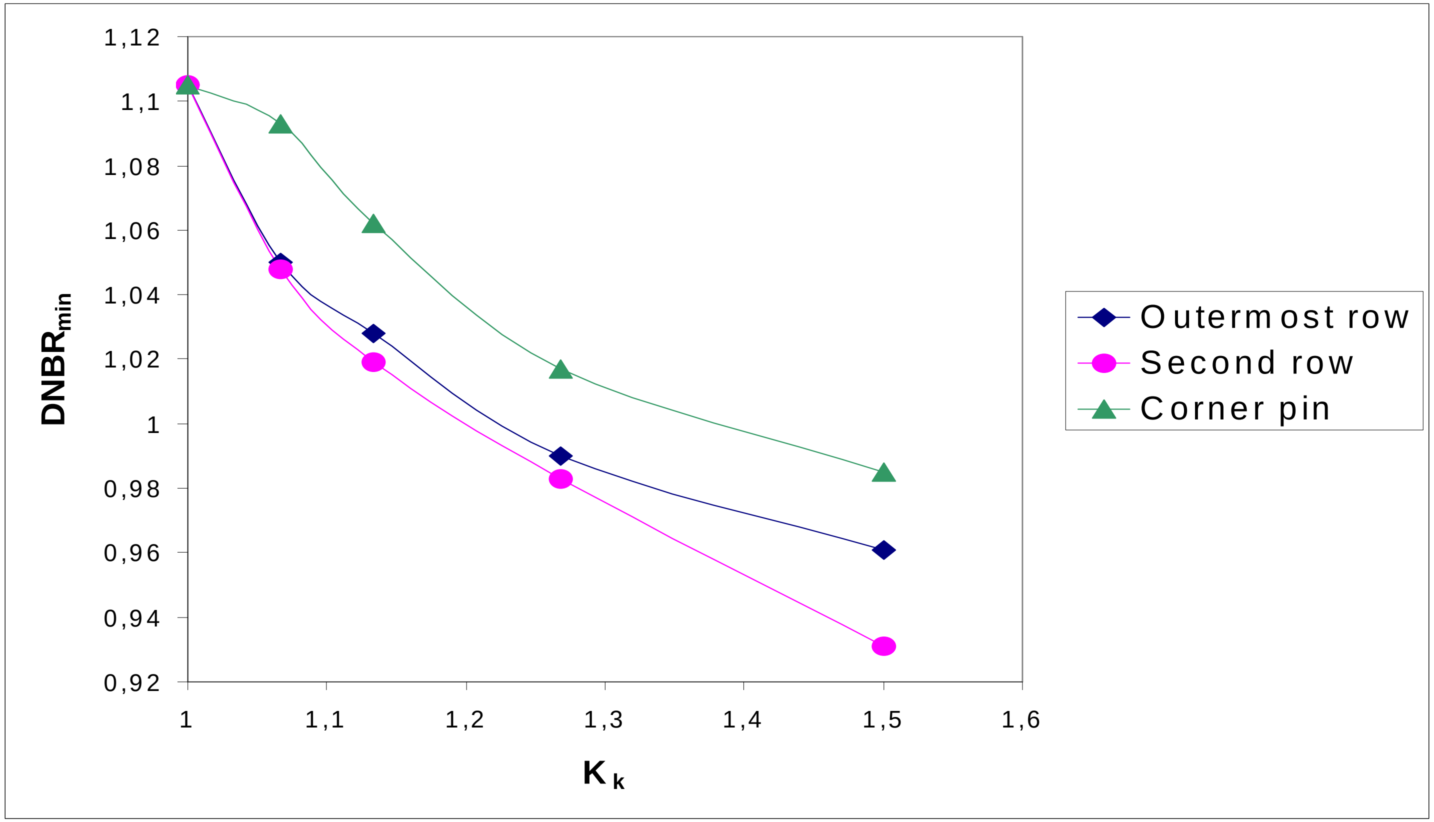
Hot channel calculations of the safety analysis considering the pin-wise power distributions inside the assembly

Phenomena influencing the coolant state:

1. Intensive cooling from coolant MIXING from the not heated wall region and from the less heated adjacent channels
2. Increased resistance or blockage of the hot channel due to the temperature increase or even the void, REDISTRIBUTION of the flow map, the flow can have a tendency avoid the hottest point

DNBR minimum of the CRW ATWS event for different relative pin power distribution in the assembly.

The sub-channel outlet temperature and the linear heat rate is limited in the Normal Operation



Necessity of the multi physics approach including thermal mechanical and thermal hydraulic calculations

The gap conductance – gap size and pressure - play essential role in case of fast transients. Both the initial and time dependent values, the latter ones changing during the transient, is important.

The mixing effects play also essential role, because the heat transfer regime, cladding temperature depend on the coolant state.

Some acceptance criteria are of mechanical character: strains and stresses are to be determined. There is a recent tendency to define acceptance criteria, which are closer to the real reasons of the fuel failure and can be less conservative.

PHENOMENA LEADING TO FUEL FAILURE AND ACTIVITY RELEASE

Hoop strain

Stress corrosion cracking of the cladding

Reaching ultimate strain or stress of cladding
Fuel rod collapse

Cladding fatigue

Large deformations
- Cladding diameter reduction
- Cladding elongation

Fuel rod internal pressure

Corrosion (oxidation)

The two codes used in the calculations

TRABCO: Thermal hydraulic hot channel code, single channel, 1D, 4-equation model

Without thermal mechanics, geometrical changes can be followed only in an implicit way: parameterized – conservative - gap heat conductance is to be applied.

FRAPTRAN: Transient fuel behavior code, single channel thermal hydraulics, frequently not used (cladding outer surface temperature is prescribed), no mixing with the adjacent channels

Computational method of the on-line coupling

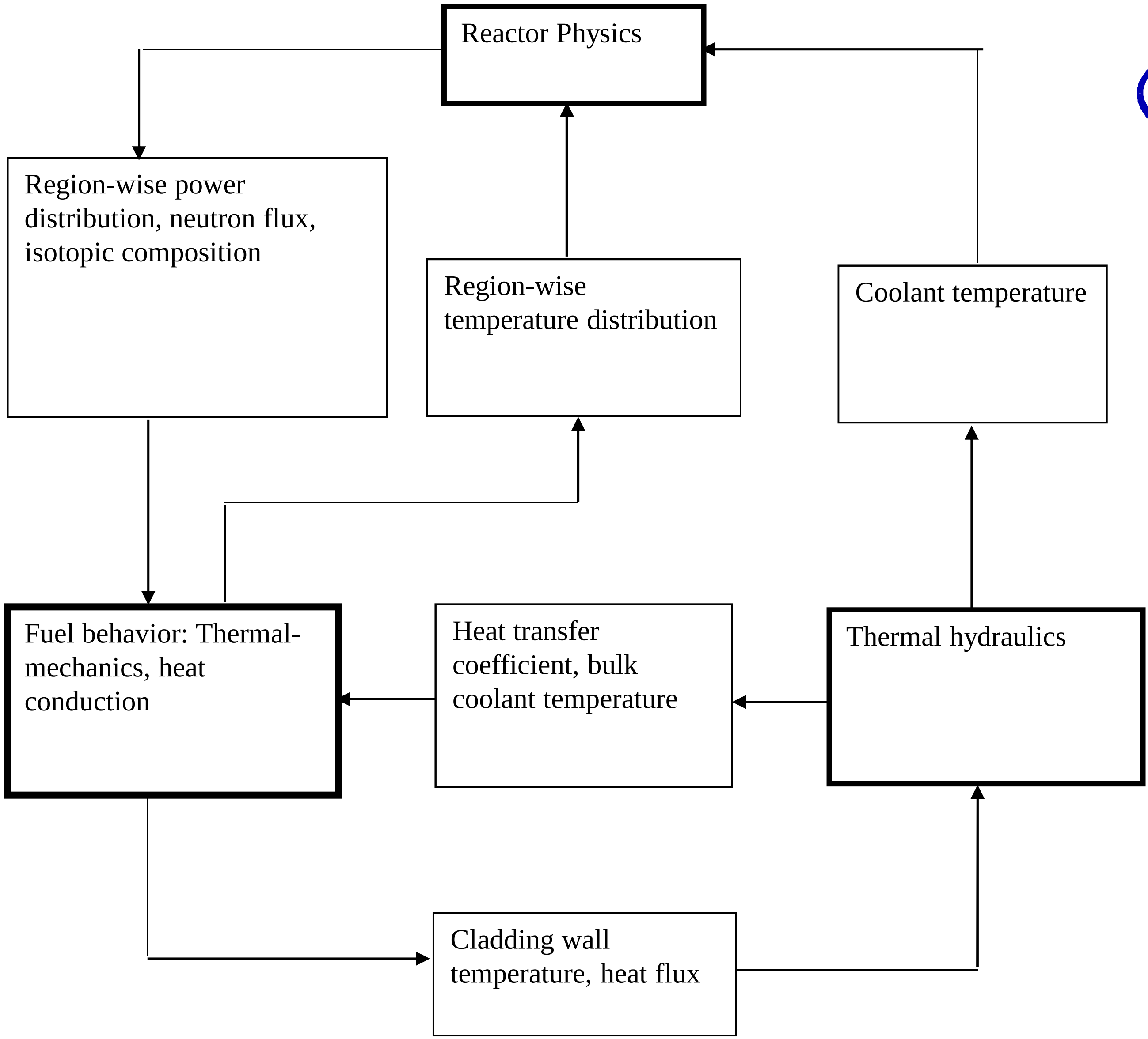
INTEL FORTRAN service function „USE DFWIN" for sharing selected memory parts between separately parallel running processes

Possibility to develop our own FORTRAN subroutines for assuring synchronization

Minimizing the necessary modifications in the standalone codes

Only few control points for the data transfer and synchronization had to be built in

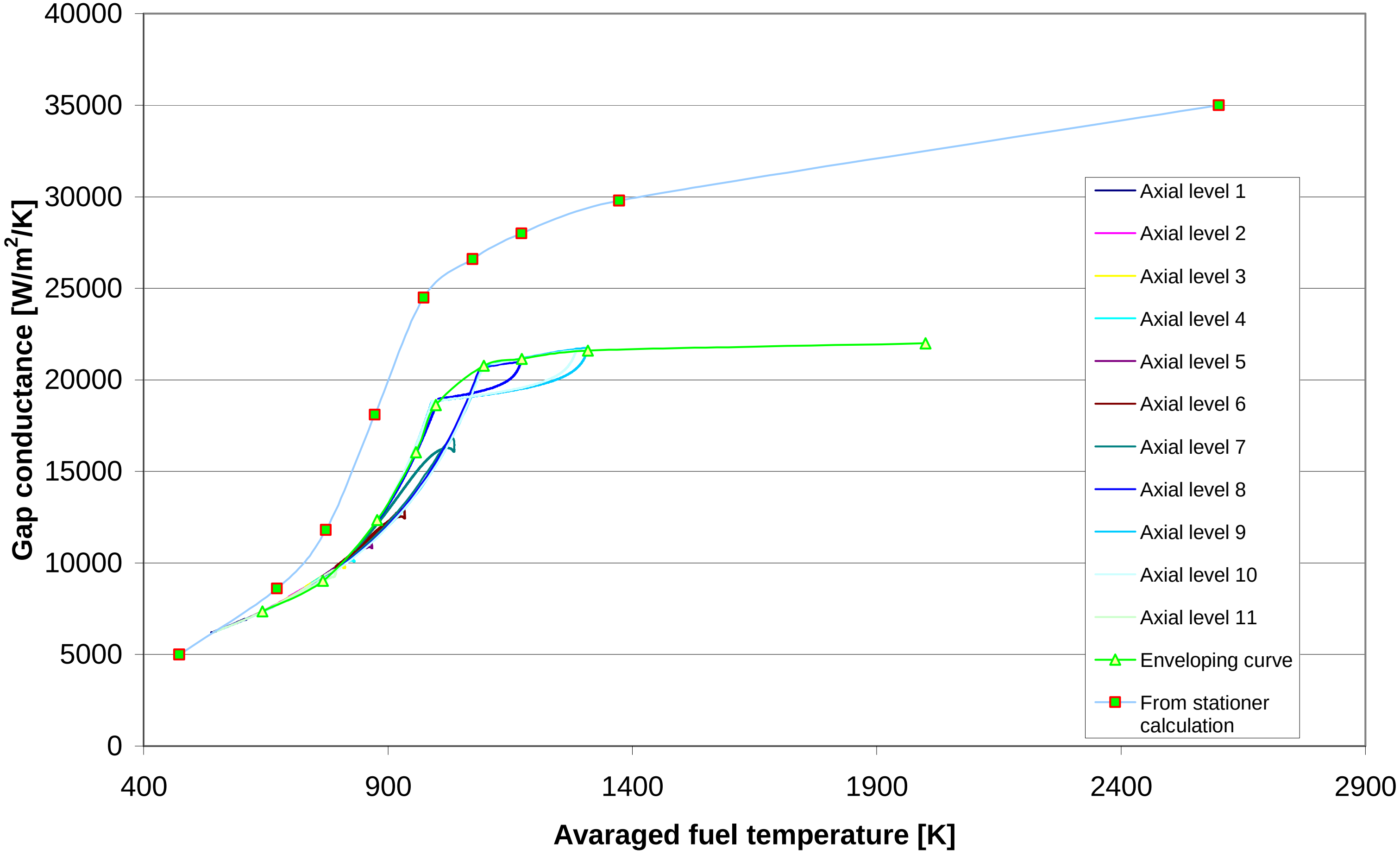
- for using its own separated memory of each separate parallel task,
- and at the same time to define the shared part of the memory for the communication between them.


Reactor Physics
Region-wise power distribution, neutron flux, isotopic composition
Region-wise temperature distribution
Coolant temperature
Fuel behavior: Thermal-mechanics, heat conduction
Heat transfer coefficient, bulk coolant temperature
Thermal hydraulics
Cladding wall temperature, heat flux

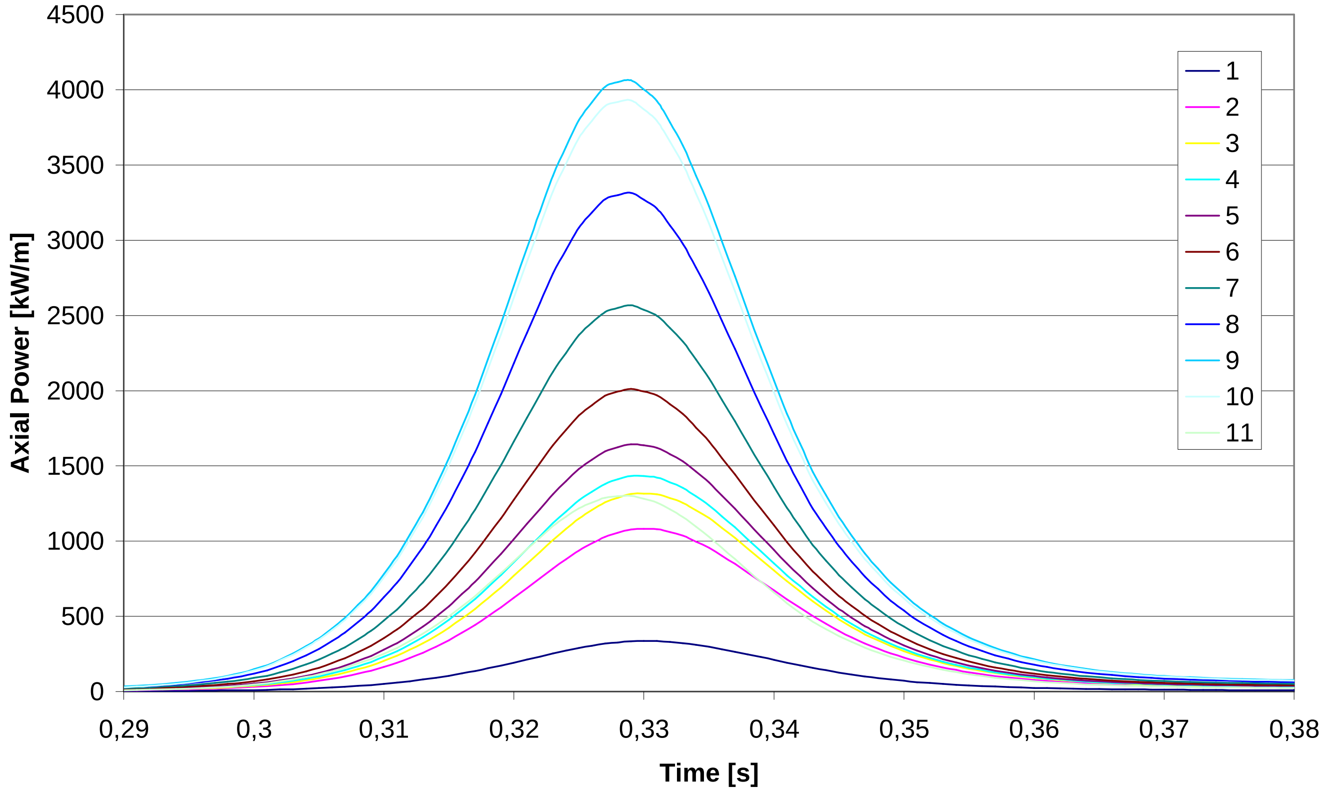
The three investigated ways of the hot channel calculation

- Standalone TRABCO calculation with parameterized conservative „enveloping” gap heat conductance according to the preceding long term “stationary” fuel behavior calculations results. Beside the pellet burnup, which is constant in these investigations, the average pellet temperature was selected for the parameterization. Two sub-cases: “Method 1.a” no DNB, “Method 1.b” for methodical reasons, DNB is supposed conservatively.
- Similarly to “Method 1”, standalone TRABCO calculation with parameterized conservative „enveloping” gap heat conductance, but the gap conductance to be parameterized is taken from the FRAPTRAN results of the coupled calculation.
- On-line coupling of the TRABCO and FRAPTRAN codes. At the end of each time step data exchange.

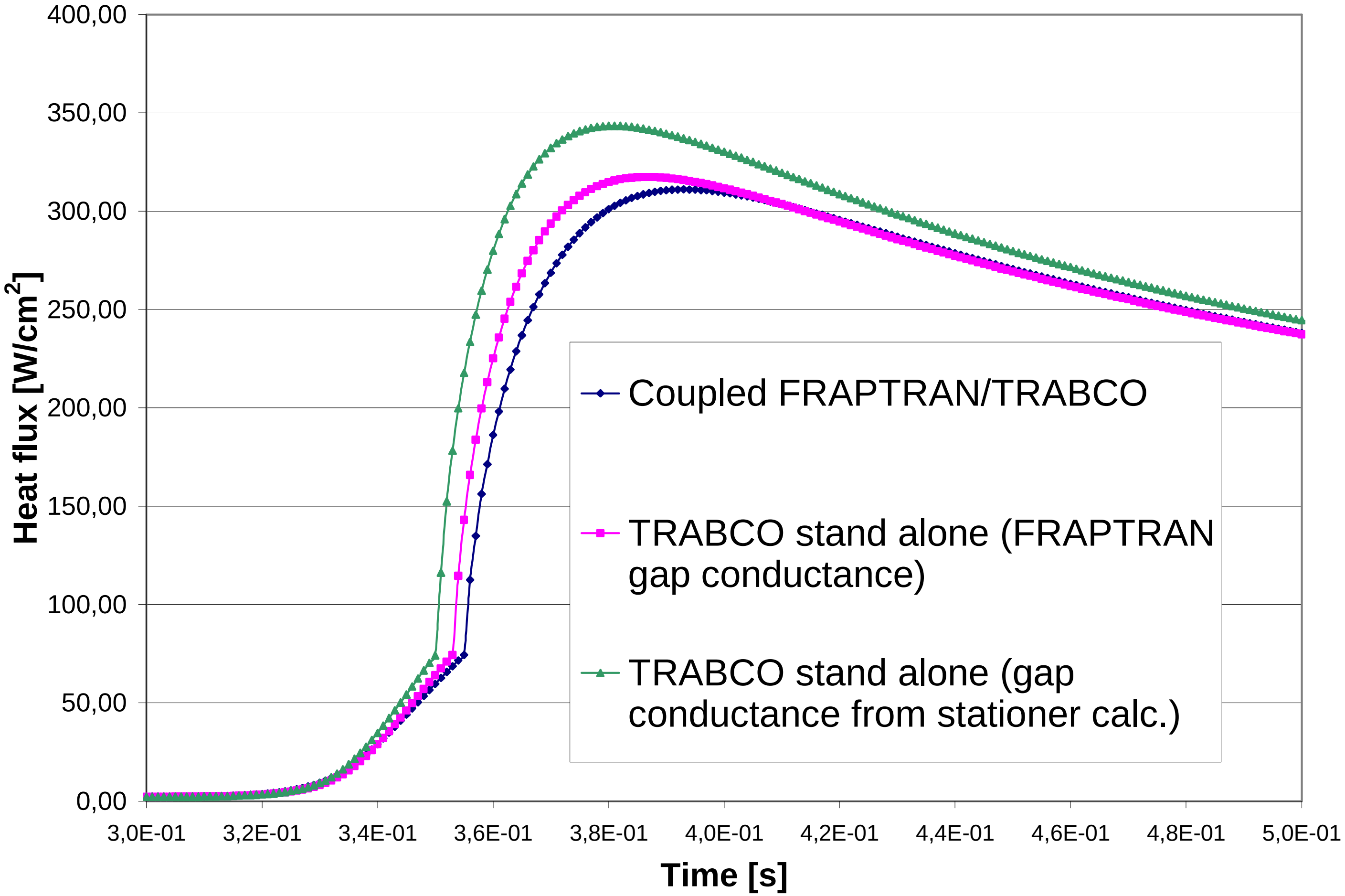
Gap heat transfer coefficients from the preceding stat. calc. or from the FRAPTRAN



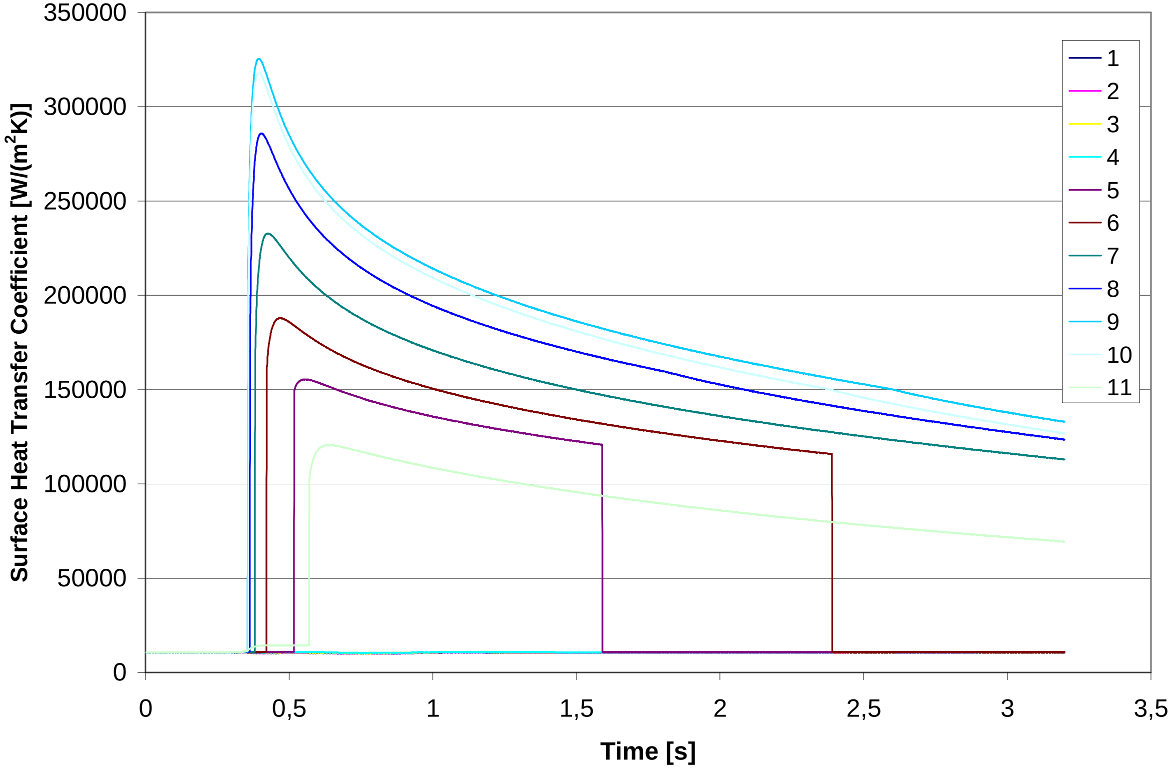
Fission power for the CRE event starting from HZP state



Surface heat flux for the three cases, no DNB

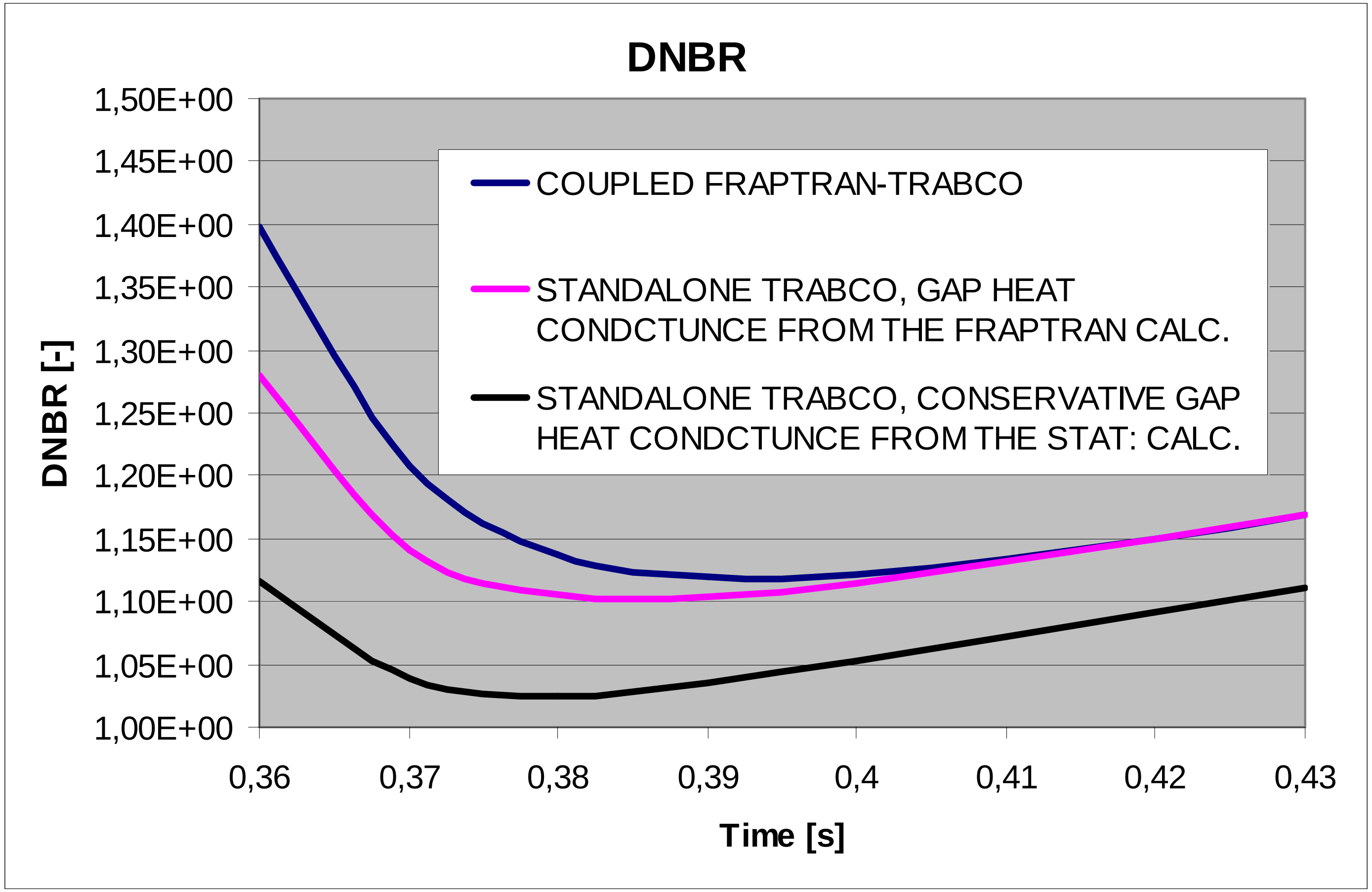


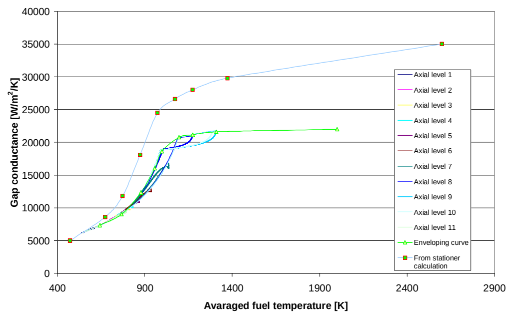
Heat transfer coefficients to coolant, no DNB



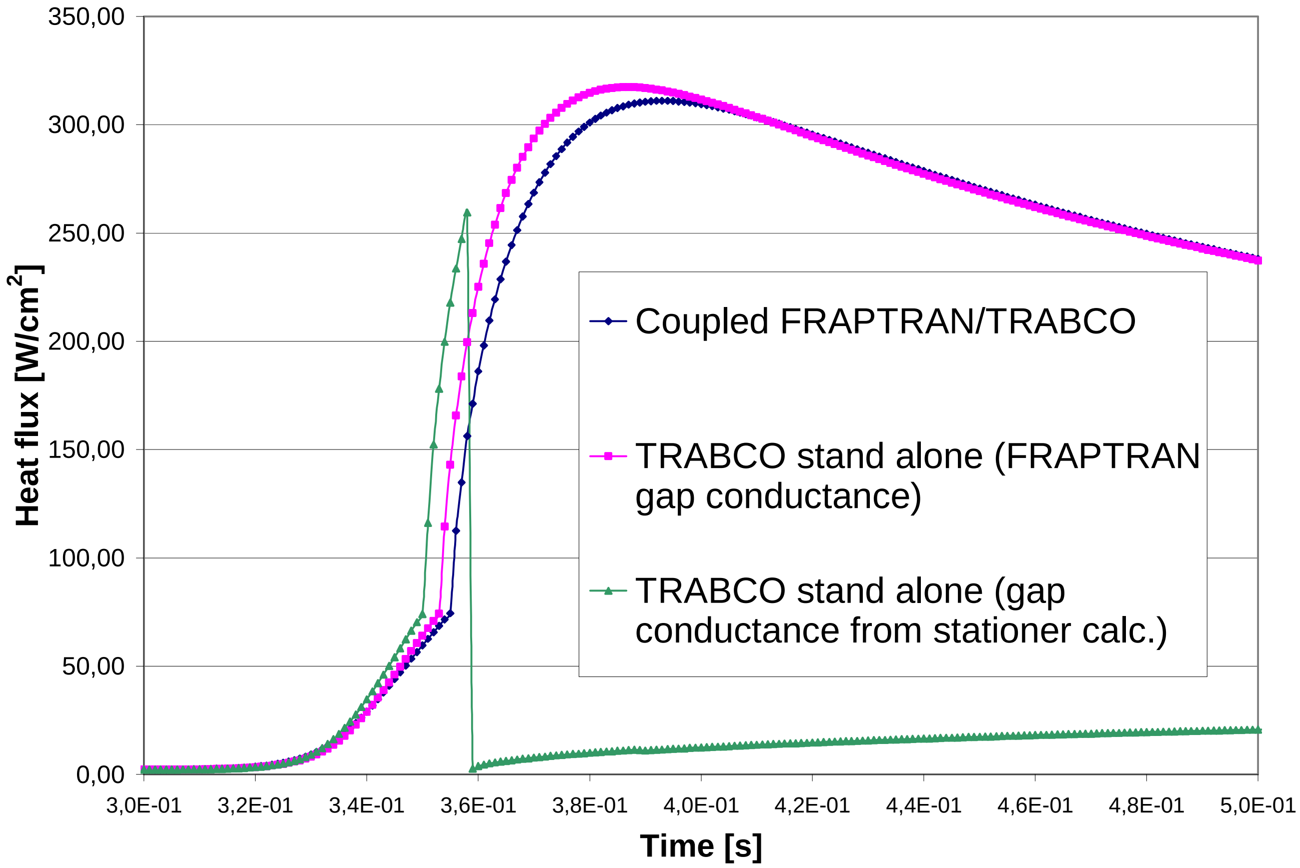
Switching between the different heat transfer regimes: convective heat transfer („Dittus-Boelter”), sub-cooled boiling („Thom”)

DNBR for the three cases

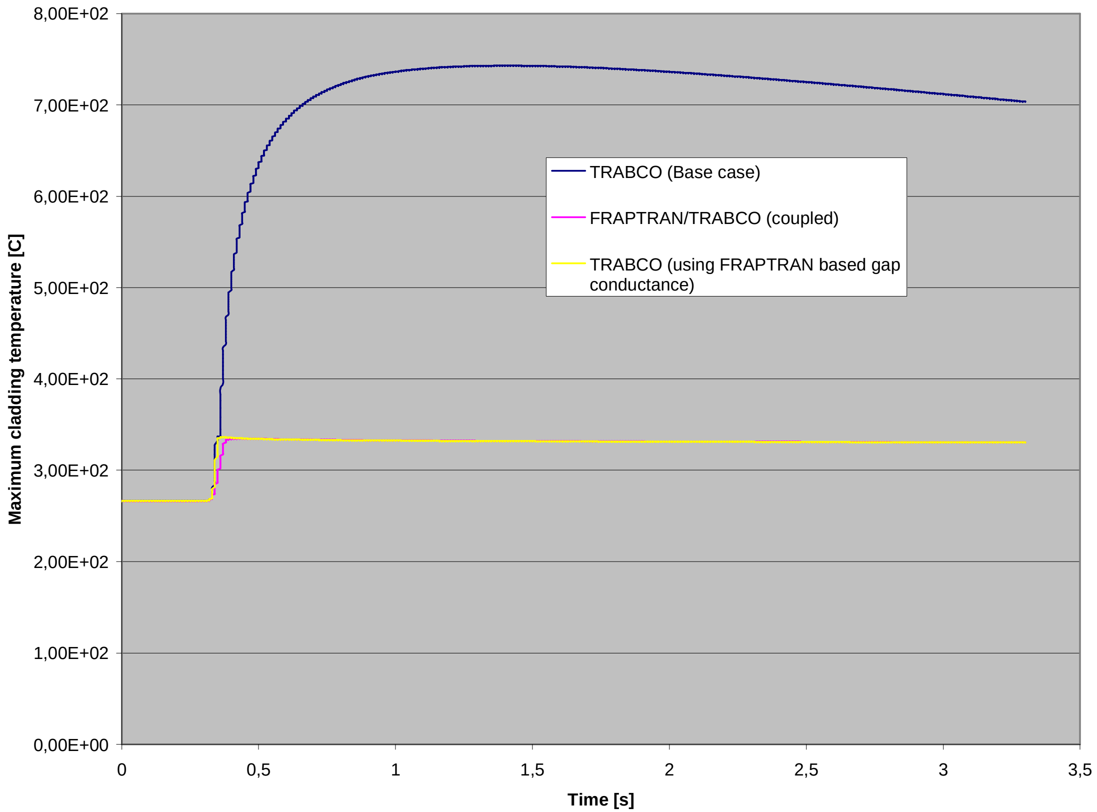




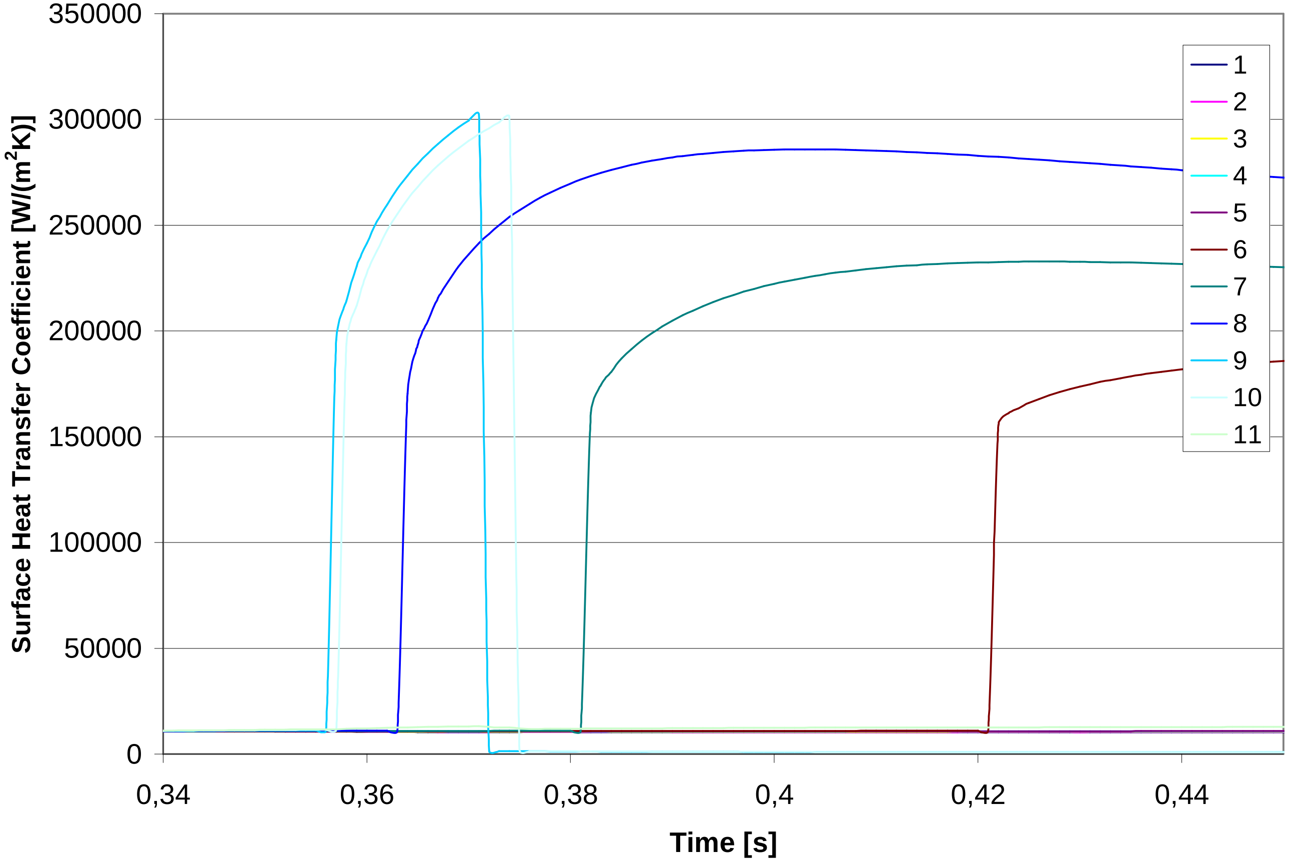
Surface heat flux for the three cases, DNB in the worst case



Maximum cladding temperatures for the three cases, DNB in the worst case

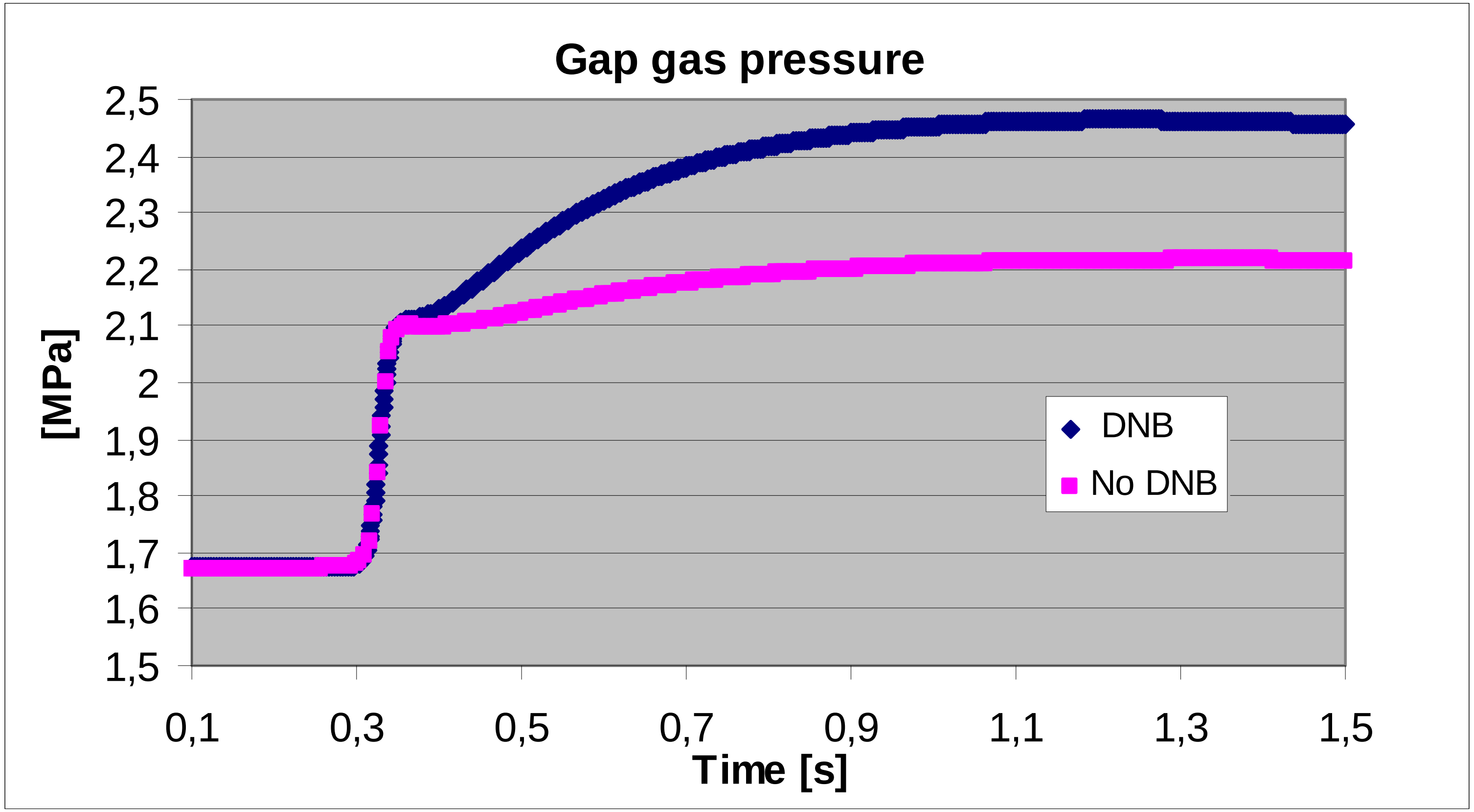


Heat transfer coefficients to coolant, DNB in the worst case

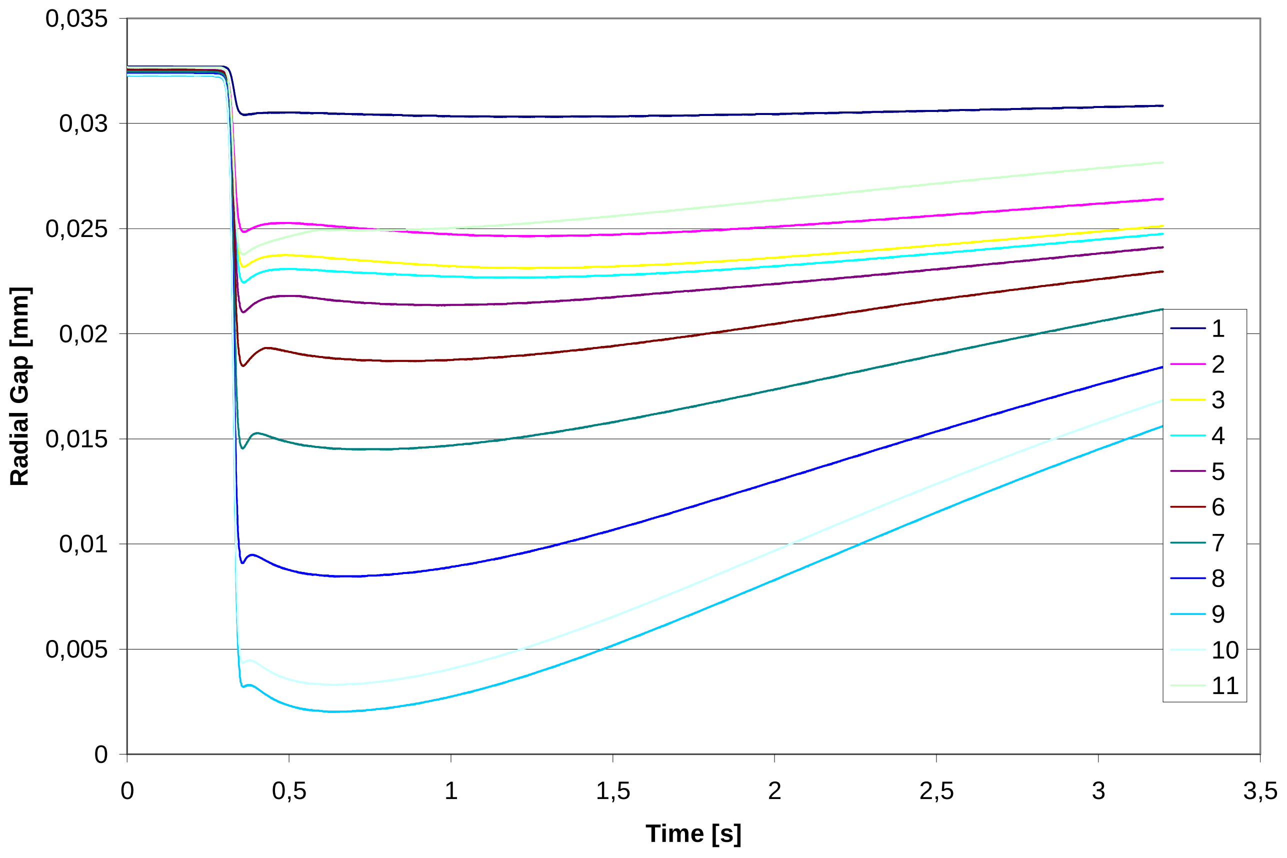


Switching between the different heat transfer regimes: convective heat transfer („Dittus-Boelter”), sub-cooled boiling („Thom”), transition boiling

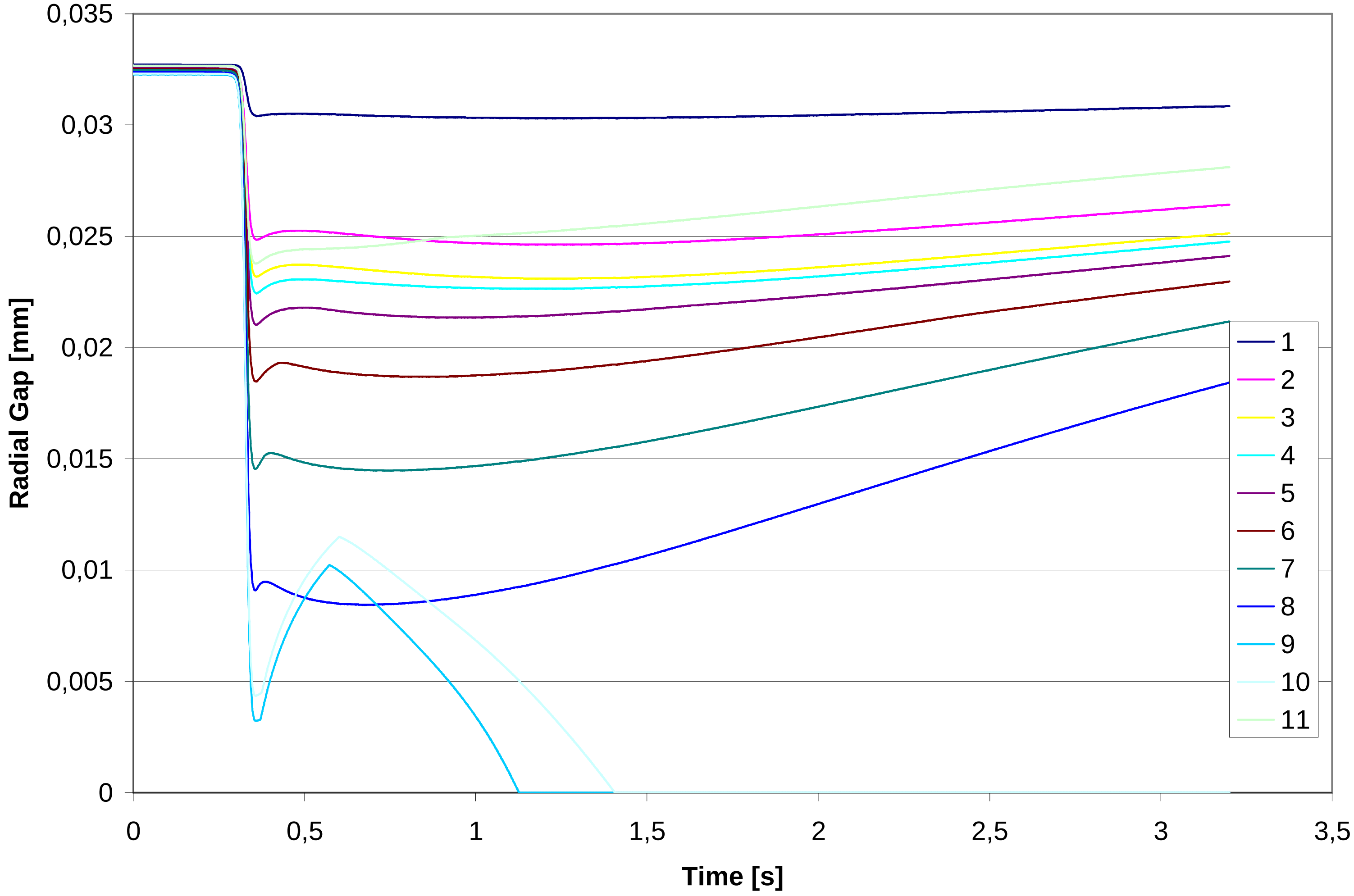
Gap gas pressure



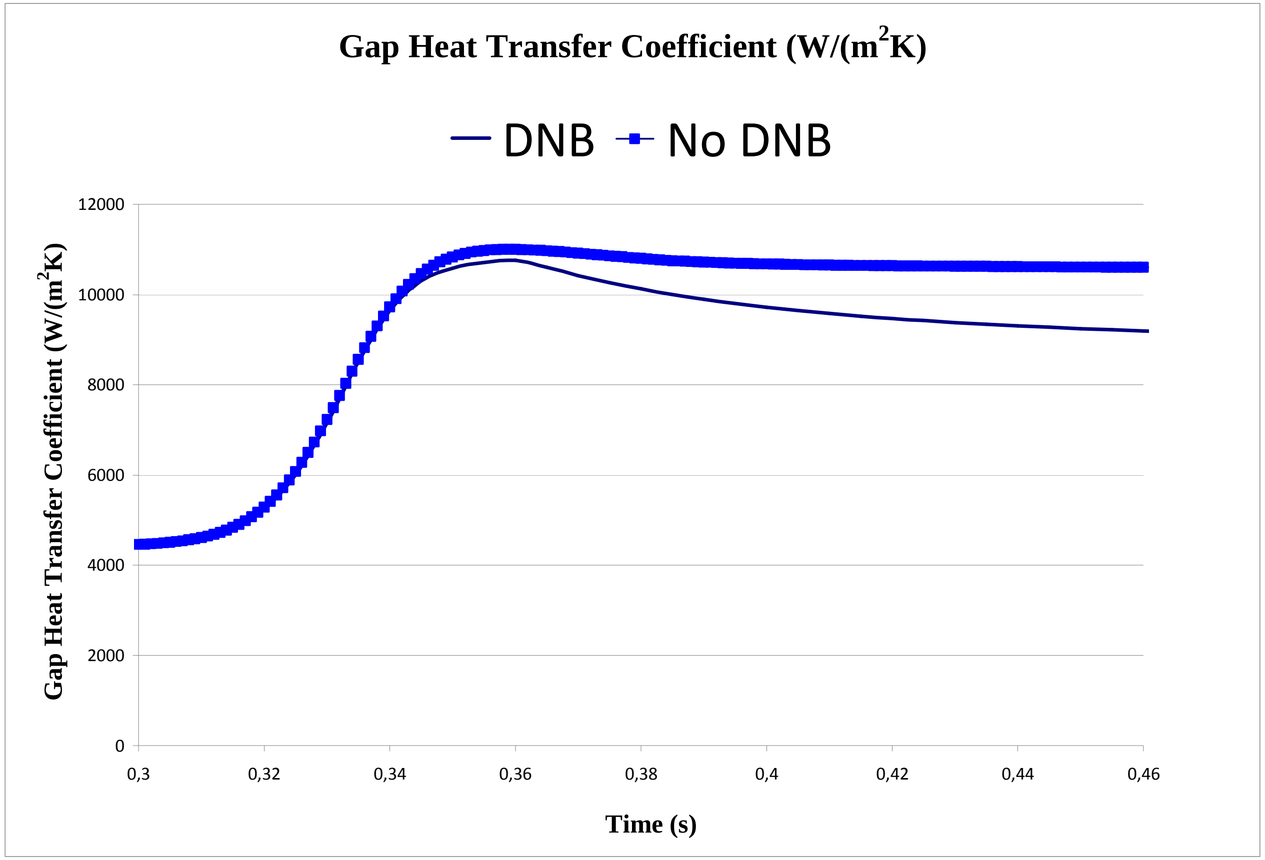
Thermal mechanical processes, gap size, no DNB



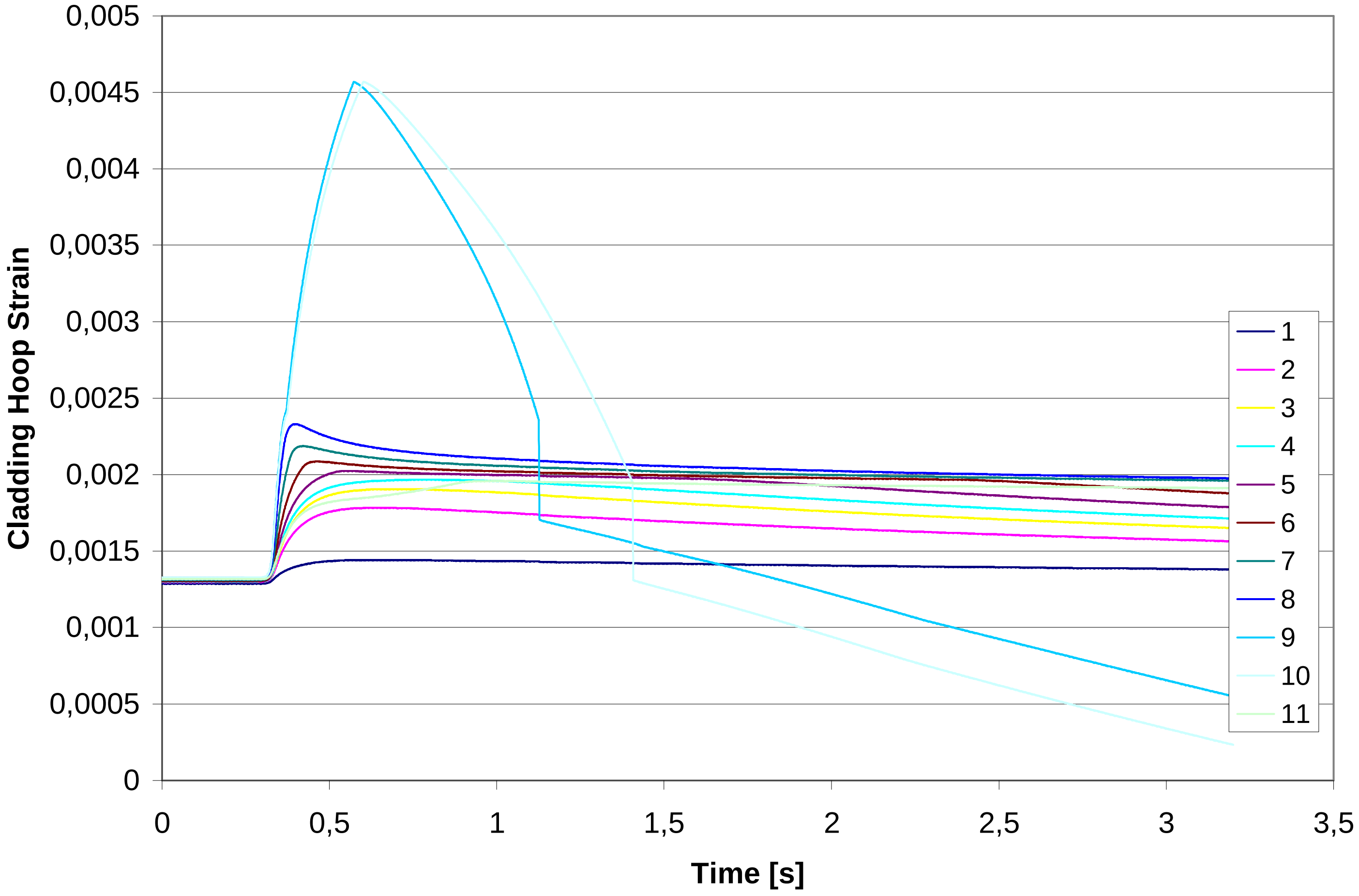
Thermal mechanical processes, gap size, DNB in the worst case



Gap heat transfer coefficient



Cladding hoop strain at different axial levels in case of DNB
No fuel failure can be expected!



Summary

• **The gap conductance, gap size and pressure play essential role in case of fast reactivity transients. Both the initial and the time dependent values, the latter ones changing during the transient, are important.**

•**In case of fast RIA transients, a thermal mechanical code has to be connected on-line to the thermal hydraulics for the best estimate calculation – the latter approach necessary for uncertainty analysis -, or even only for justifying a method, expected conservative.**

• **A not negligible reserve, concerning our earlier conservative method, could be explored by the on-line coupling the TRABCO and FRAPTRAN codes.**