SEARCH-MAXSIMA International Workshop 2014

Uncertainty and Sensitivity safety analysis of the MYRRHA reactor

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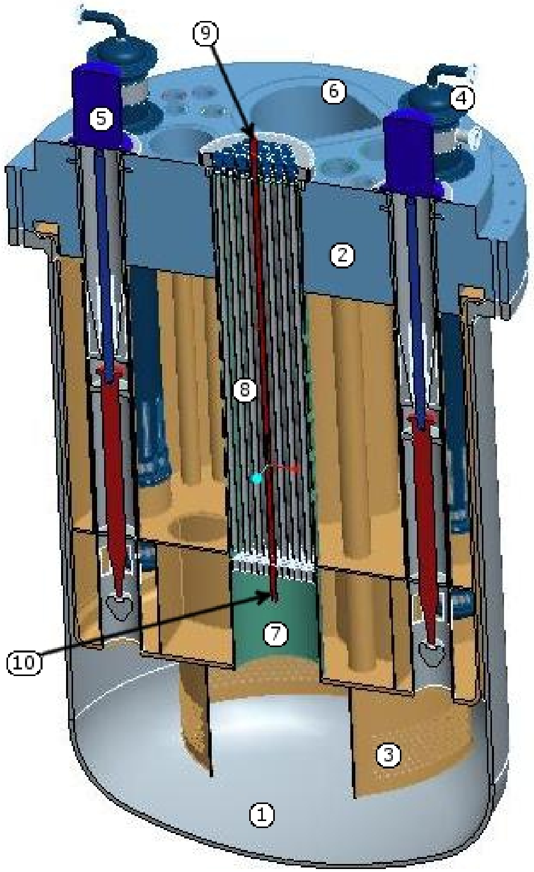
  - Output parameters for U + S analysis
  - Result description by all Task 2.2 participants
- Task 2.2 future activities and interfaces with other Tasks and Work Packages

MYRRHA plant: purposes and general design

- MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications
- Pool-type Accelerator Driven System (ADS) with ability to operate also as critical reactor
- Liquid Lead-Bismuth Eutectic (LBE) as primary coolant
- Main purposes:
  - Flexible irradiation facility
  - Minor Actinides (MAs) transmutation demonstration in support of R&D on a "closed fuel cycle" (Generation IV requirement)
  - ADS demonstrator
  - Lead Fast Reactor demonstrator
  - (Pre-) Gen IV plant
- MYRRHA project recognized as high priority infrastructure for nuclear research in Europe

MYRRHA plant: purposes and general design

- MYRRHA primary system design current status (design revision 1.6):



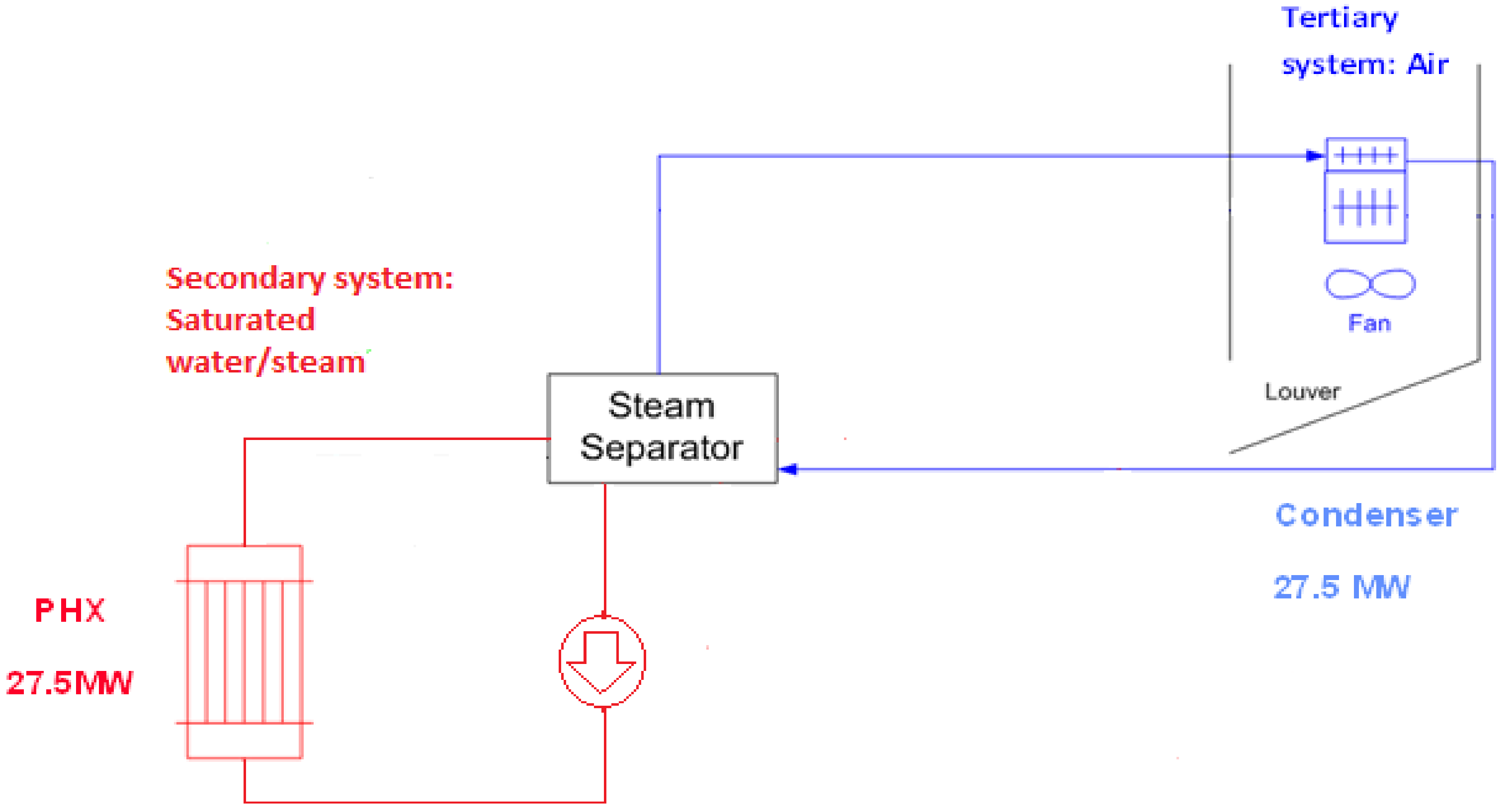
1. Reactor vessel
2. Reactor cover
3. Diaphragm
4. Primary heat exchanger
5. Pump
6. In-Vessel Fuel Handling Machine
7. Core barrel
8. Above Core Structure
9. Core plug
10. Spallation window

MYRRHA plant: purposes and general design

- Primary system:
  - Completely enclosed in primary vessel (pool-type)
  - Primary LBE flow path:
    - Lower plenum (270 °C)
    - Core (100 MW)
    - Upper plenum (~325 °C)
    - 4 Primary Heat eXchanger (PHX) units
    - 2 Primary Pumps (PPs)
    - Lower plenum
  - Cold plenum separated from hot plenum by Diaphragm supporting core barrel and components' penetrations
  - Above LBE free surface: Nitrogen layer

MYRRHA plant: purposes and general design

- MYRRHA secondary system (one loop out of four) design state of the art (developed in FP7 Central Design Team project):



MYRRHA plant: purposes and general design

- Secondary system:
  - Four independent secondary loops (linked through PHXs)
  - Operated with forced flow two-phase water mixture (16 bar, 200 °C)
  - Secondary water flow path:
    - PHX inlet (~saturated conditions)
    - PHX outlet ($x \sim 0.3$, $\alpha \sim 0.9$)
    - Moisture separated in steam drum
  - In normal operation, secondary water temperature kept constant by control system (primary LBE temperature changing as a function of core loading)
- Tertiary system: dissipating heat to external environment through air condensers (forced circulation air fans)
- Condensed steam recirculated into steam drum

MYRRHA plant: purposes and general design

- MYRRHA plant designed for 110 MW as nominal power:
  - 100 MW → core power
  - 10 MW → additional heat sources:
    - In Vessel Storage Tank (IVST)
    - Po decay heat
    - Pump power
    - γ heating
    - Spallation target power
- Normal operation → all three cooling systems designed to operate in forced circulation
- Accidental conditions → DHR in full natural circulation (three cooling loops operating in passive mode)
- Two systems to remove decay heat power:
  - DHR-1: secondary and tertiary systems operating in passive mode
  - DHR-2: Reactor Vessel Auxiliary Cooling System (RVACS)

Task 2.2: main targets

- FP7-MAXSIMA Work Package 2: Safety analysis in support of MYRRHA
  - Task 2.2: Transient analyses using system codes
- Main Task 2.2 targets:
  - Study of steady state and transient behavior of MYRRHA reactor under several operational and accidental events using system codes
  - Application of Uncertainty + Sensitivity methodology to MYRRHA transient analysis through sensitivity analysis tools

Task 2.2: updated activities summary and main plan

- Phase 1:
  - Deliverable 2.3 release
    - List of transients to be studied within the Task 2.2 activities
  - 1st Technical Database release
    - Technical description of the complete MYRRHA reactor (from core to tertiary) to be used for first phase models
    - Very similar to latest design version released from CDT project (March 2012)
  - Steady state comparison
    - Steady state comparison between all the participants actively involved in system code modelling
  - Deterministic ULOF and PLOF transients comparison
  - Uncertainty and sensitivity analysis on ULOF and PLOF transients
  - Phase 1 summary report (part of D2.4) to be finalized and approved

Task 2.2: updated activities summary and main plan

- Phase 2:
  - 2^{nd} Technical Database release:
    - Task 2.1 activities finalization → new core characterization
    - MYRRHA Design Revision 1.6 release → frozen MAXSIMA design
  - Agreement on an updated U + S parameters set:
    - Input and output parameter lists
    - Input parameters range
  - Uncertainty and sensitivity analysis on the selected transients (according to participant's commitment) in sub-critical and critical mode → providing a single enveloping case for safety authority interface
  - Final contributions from each participants → Deliverable 2.4 finalization

Phase 1 activities description

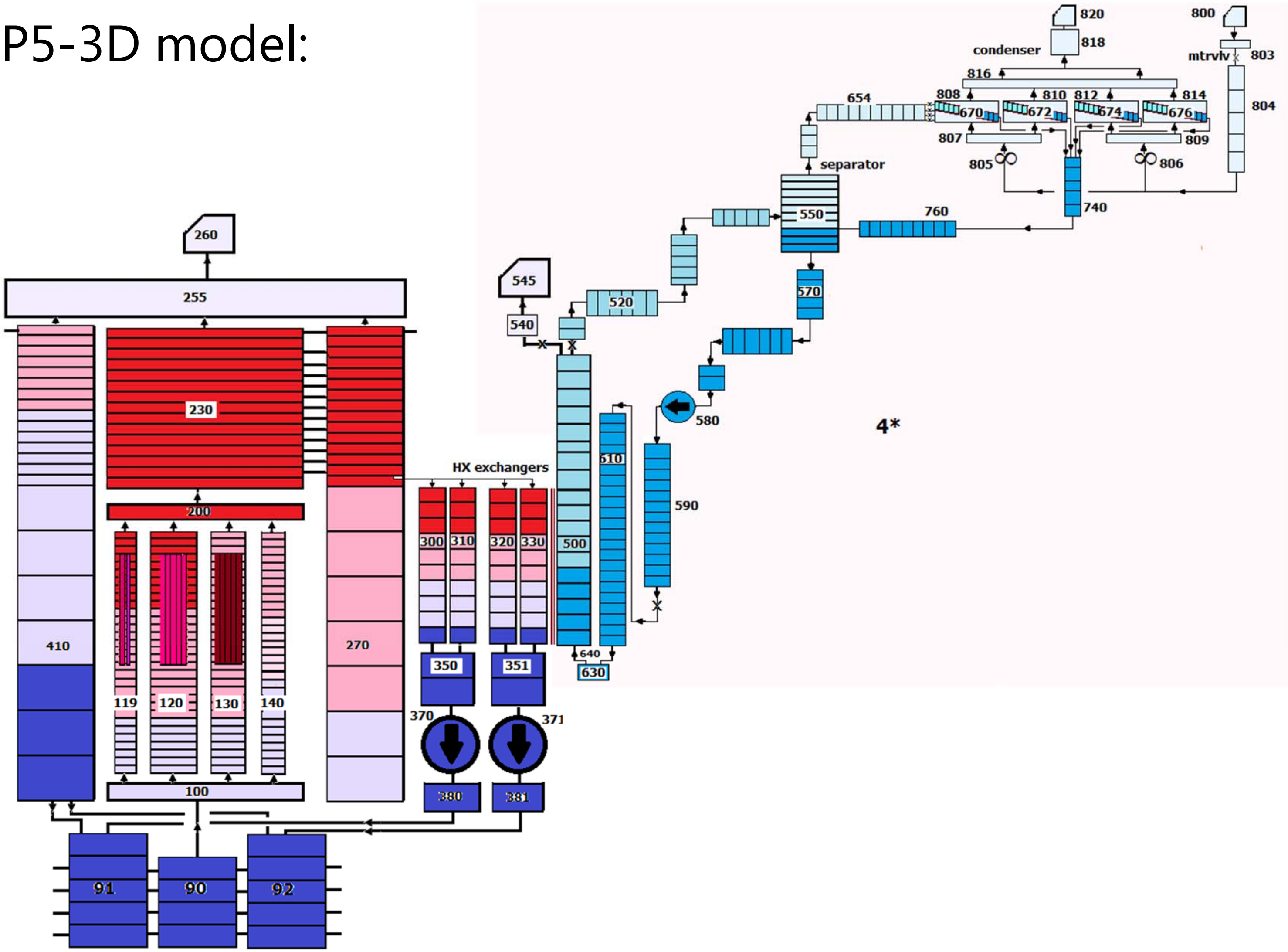
- Phase 1 main features and objectives:
  - Analysis based on MYRRHA design version 1.4 by three Task 2.2 participants (SCK•CEN, KIT, ENEA)
  - Steady state simulation and comparison
  - Deterministic analysis of two transients in sub-critical and critical mode:
    - Unprotected Loss of Flow (ULOF)
    - Protected Loss of Flow (PLOF)
  - Transients used as benchmark for the Uncertainty + Sensitivity methodology to be extensively applied in Phase 2

Deterministic transient analysis - evolution

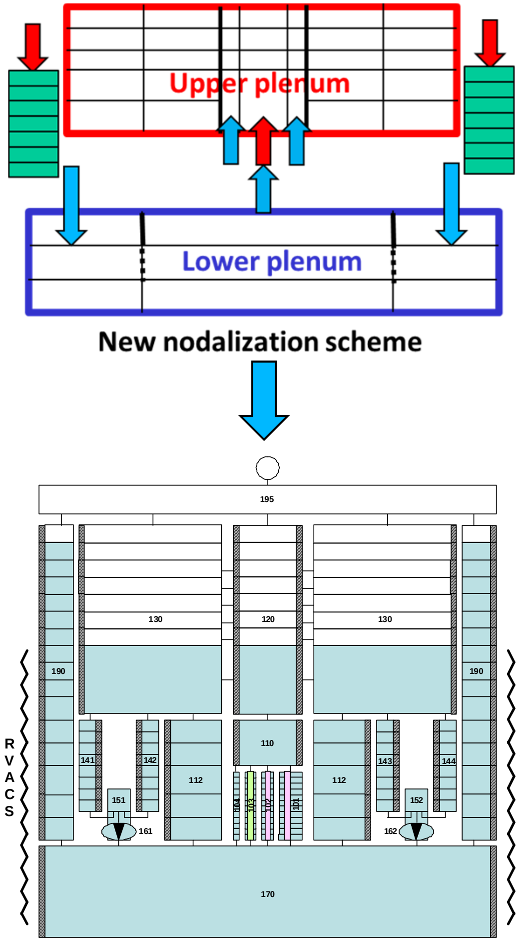
- ULOF transient evolution:
  - Primary pumps trip at time 0
  - Flow reversal through PPs and PHXs → NC onset
  - No scram → new steady state defined by reactivity feedbacks coefficients
- PLOF transient evolution:
  - Primary pumps trip at time 0
  - Flow reversal through PPs and PHXs → NC onset
  - Scram triggered by 2^{nd} signal (core outlet temperature > 20%) after ~ 6 s
  - System evolving towards a safe shutdown condition

SCK•CEN – RELAP5-3D MYRRHA design revision 1.4 model

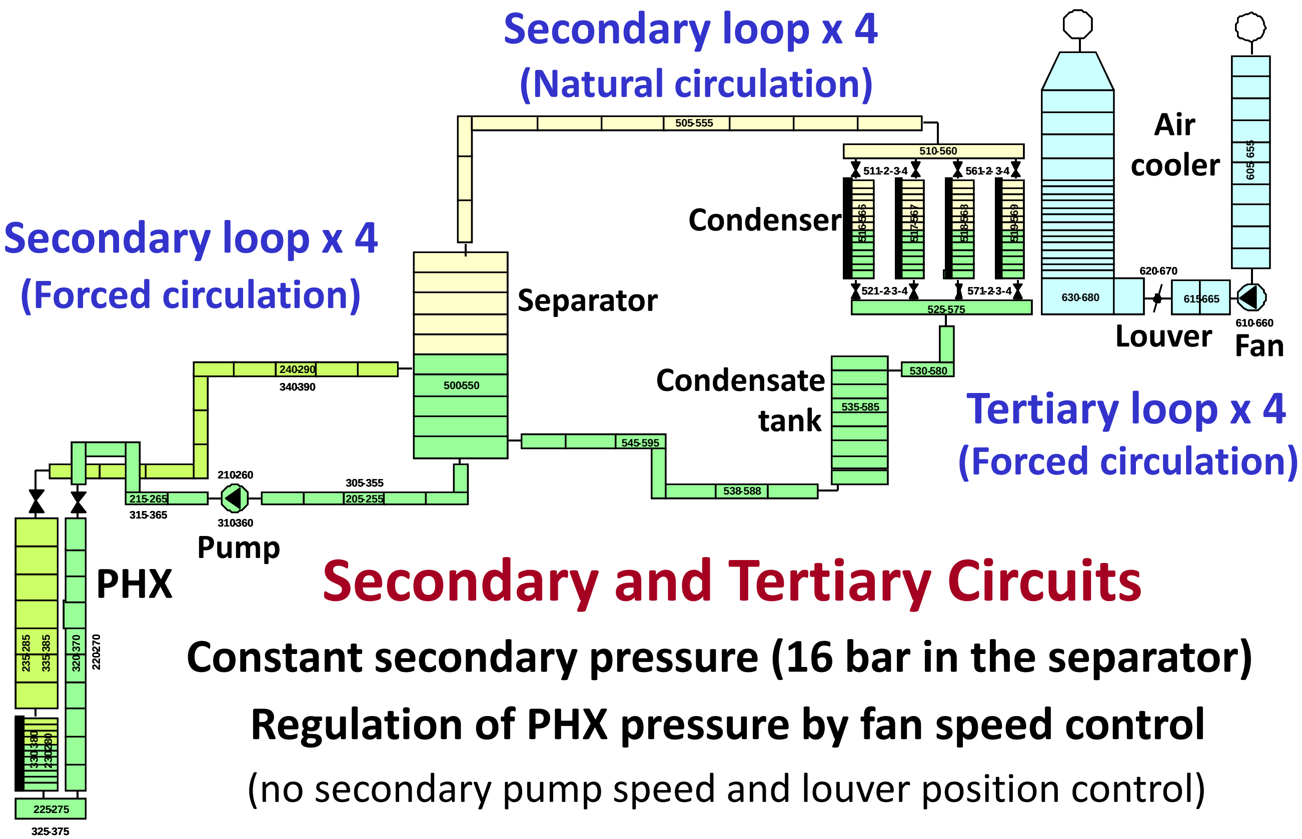
- RELAP5-3D model:



ENEA – RELAP5 mod 3.3 MYRRHA design revision 1.4 model



Primary System



Secondary and Tertiary Circuits

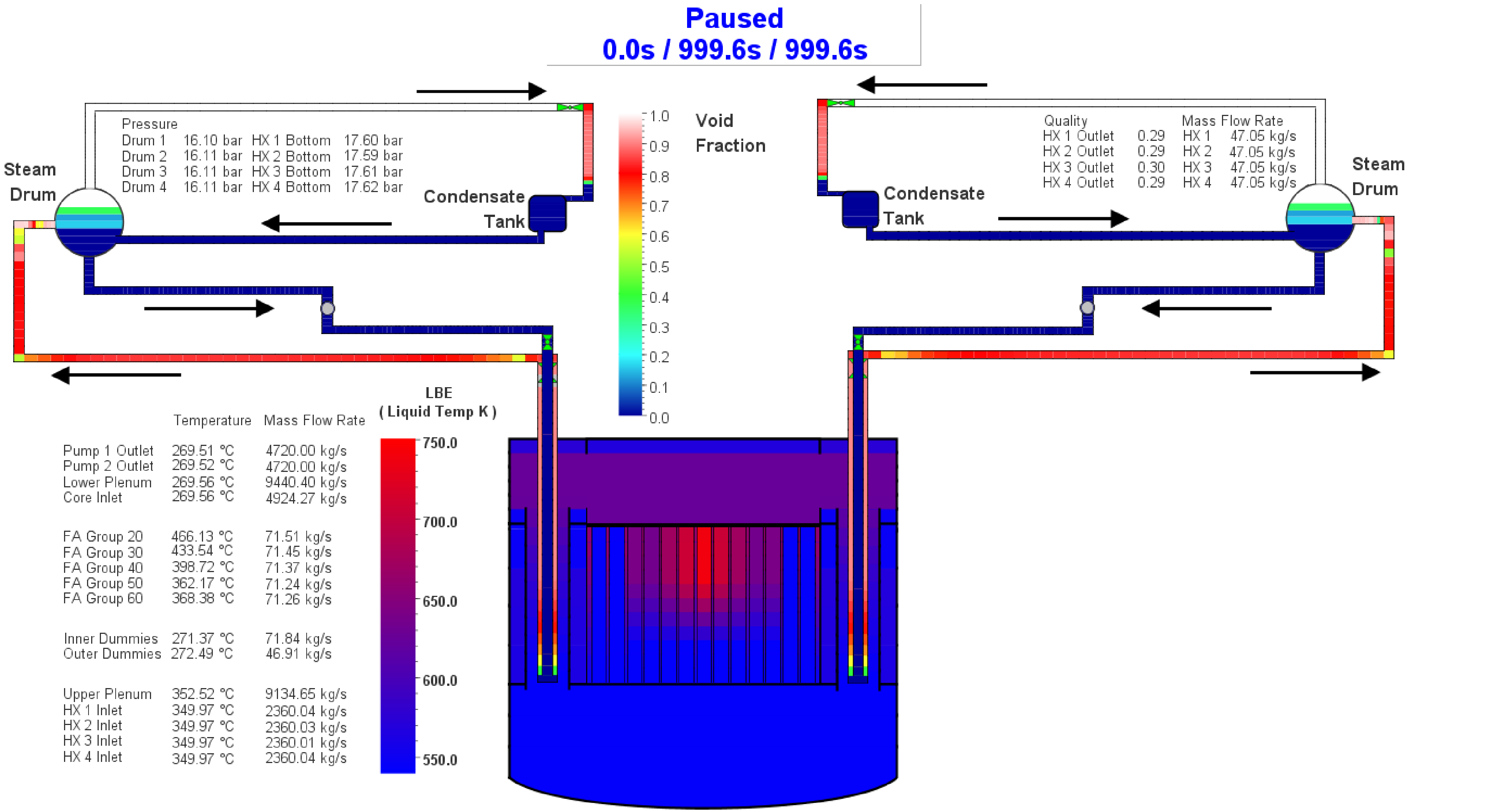
Constant secondary pressure (16 bar in the separator)

Regulation of PHX pressure by fan speed control

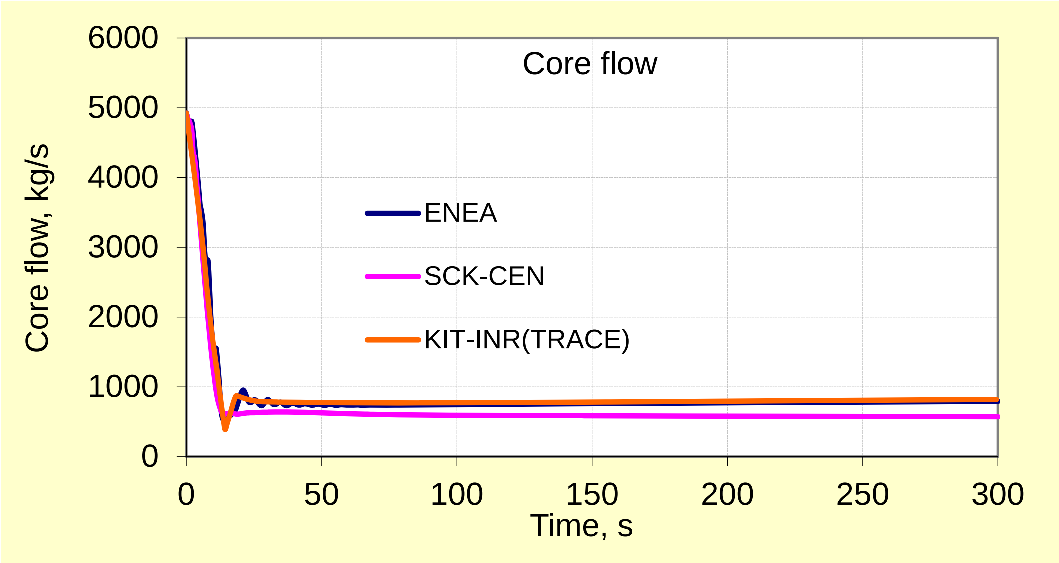
(no secondary pump speed and louver position control)

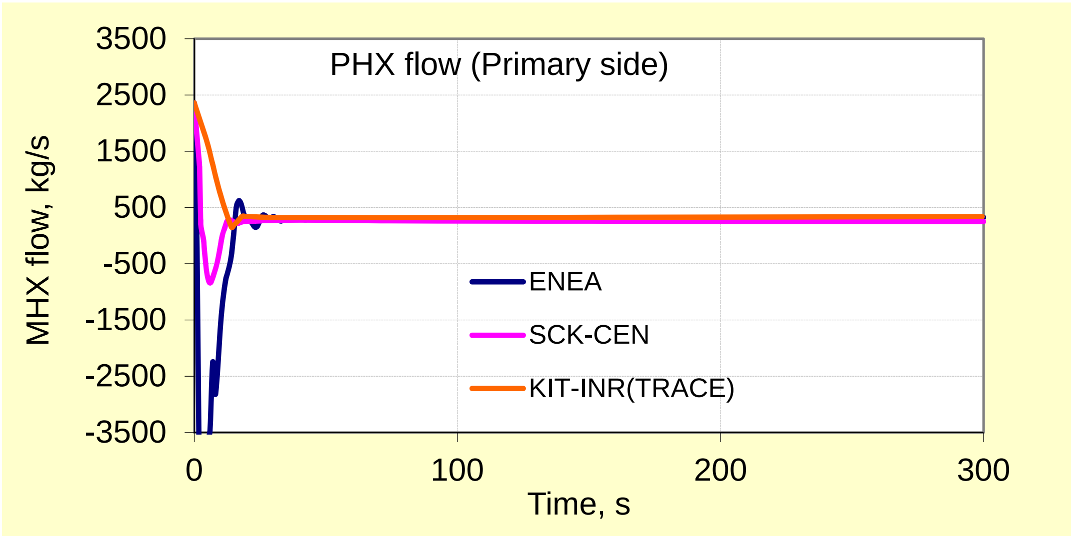
RELAP5 Nodalization Scheme of MYRRHA

KIT – TRACE MYRRHA design revision 1.4 model

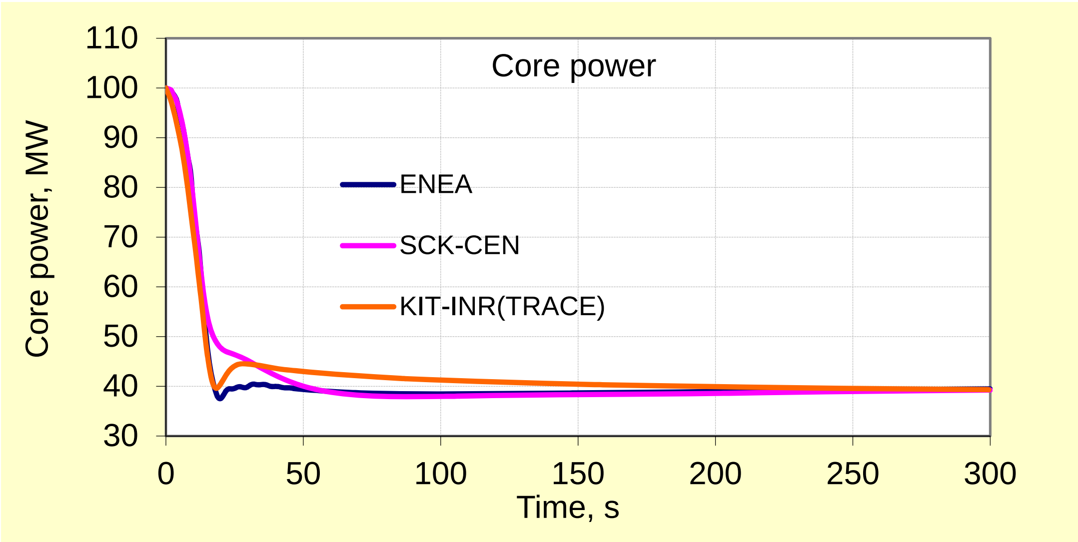


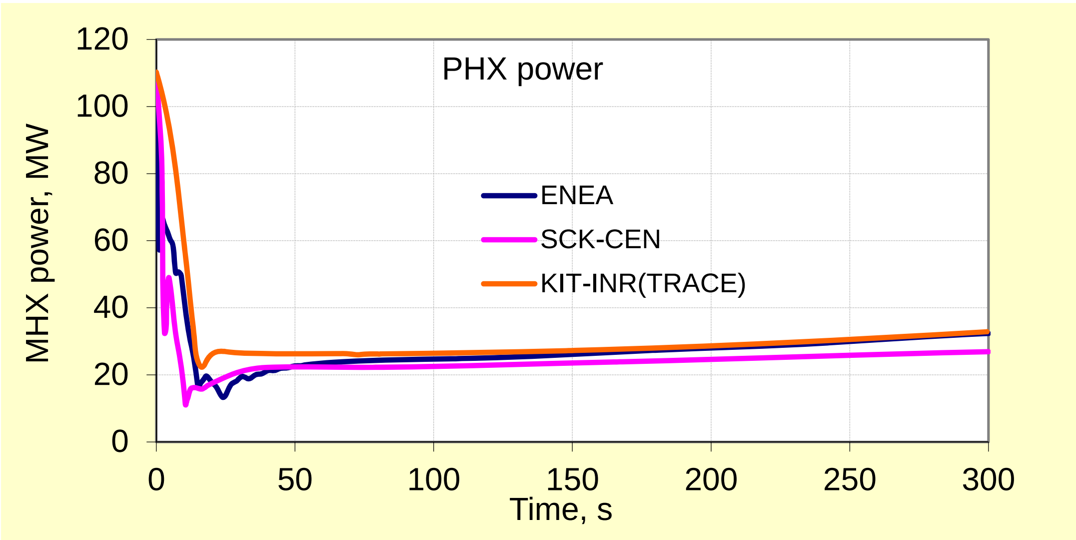
Transient analysis – ULOF comparison



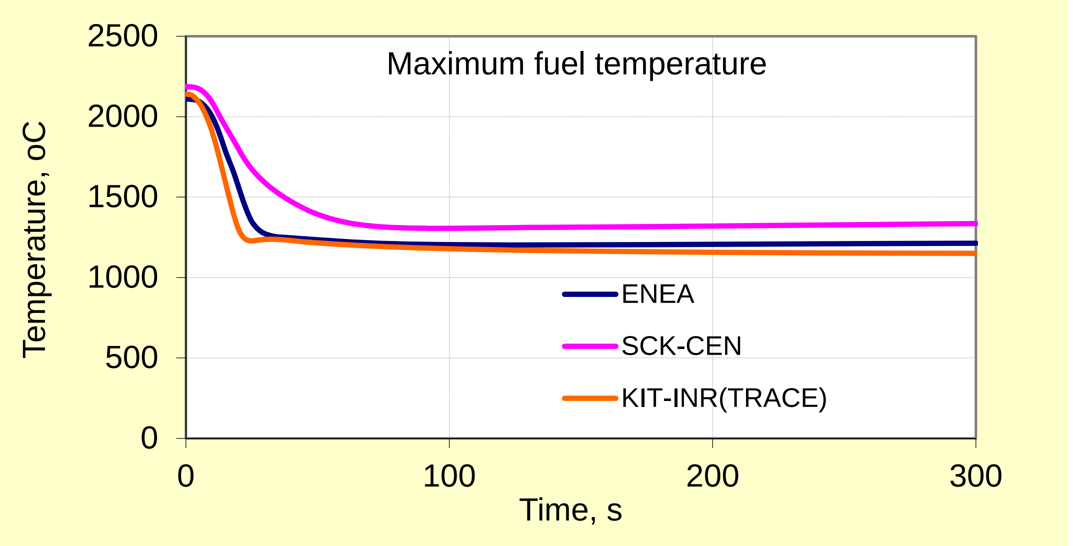


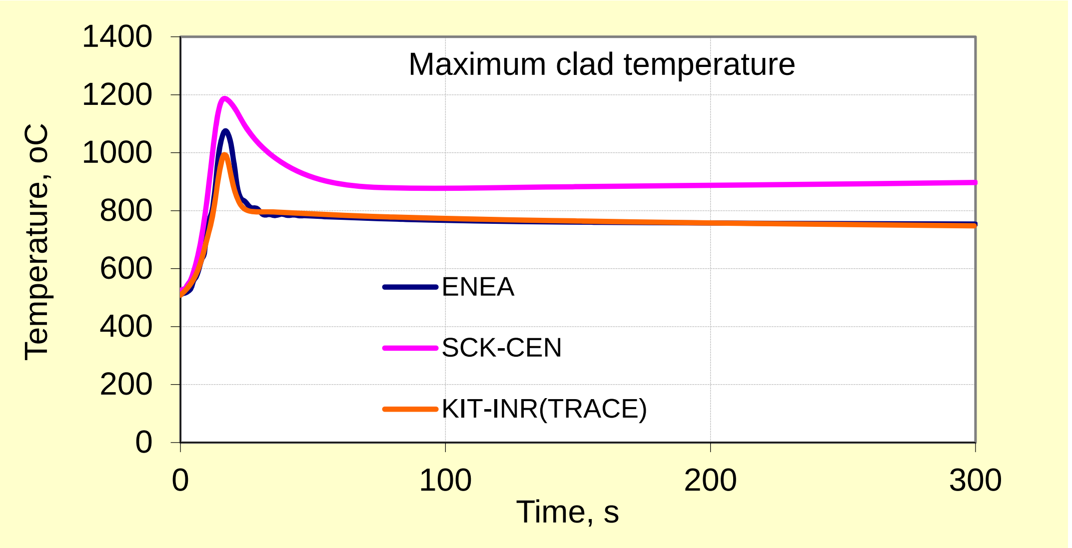
Transient analysis – ULOF comparison





Transient analysis – ULOF comparison





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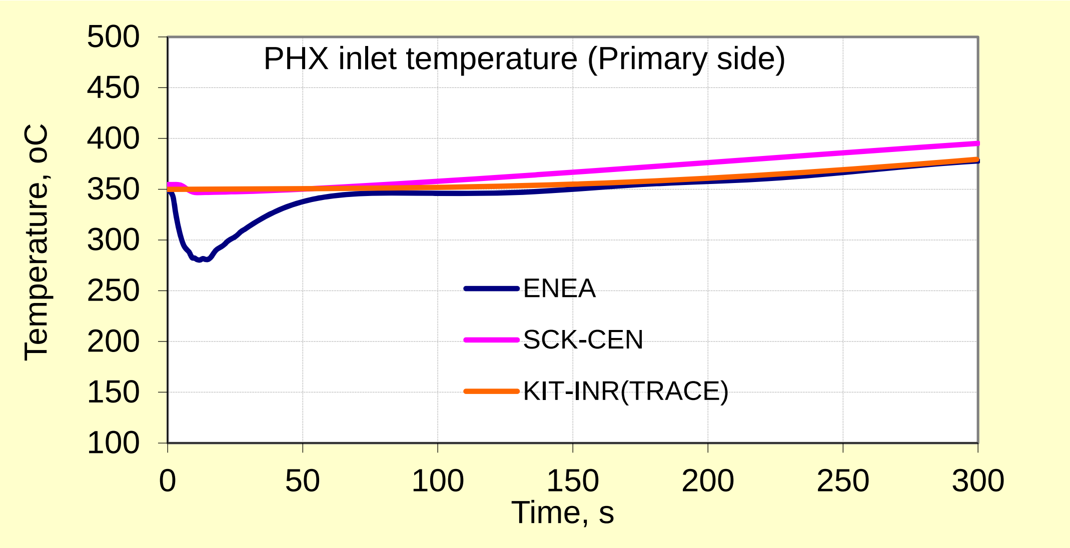

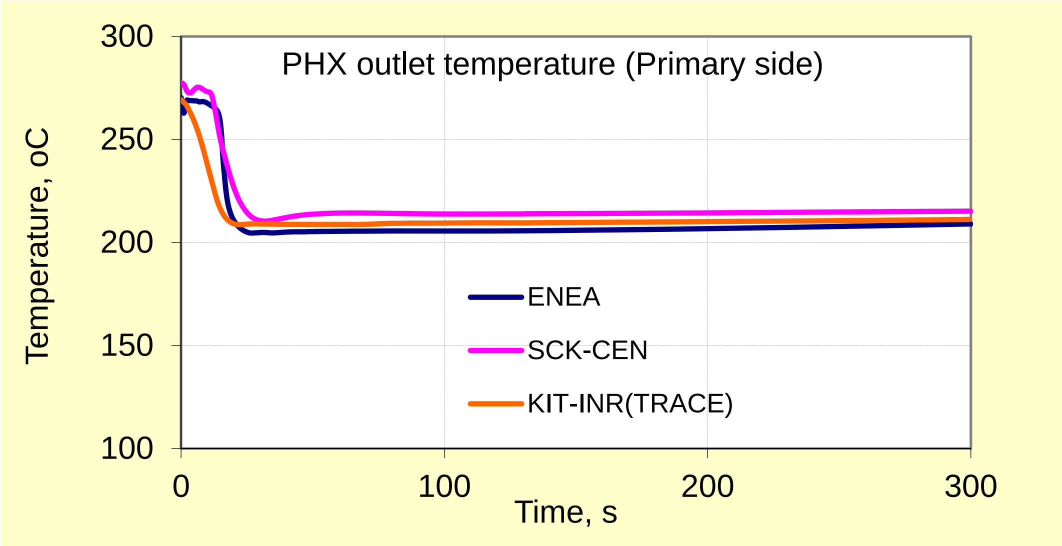

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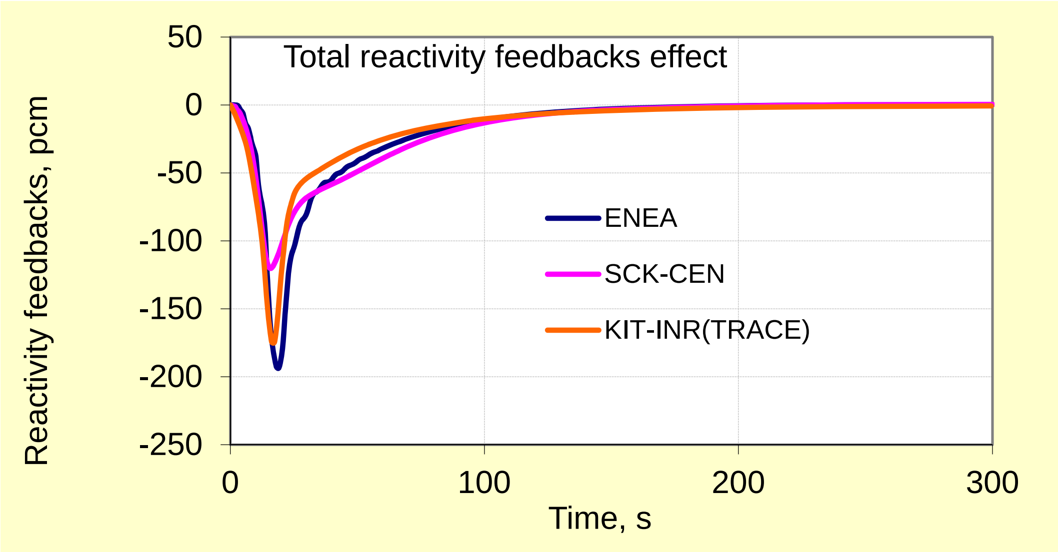
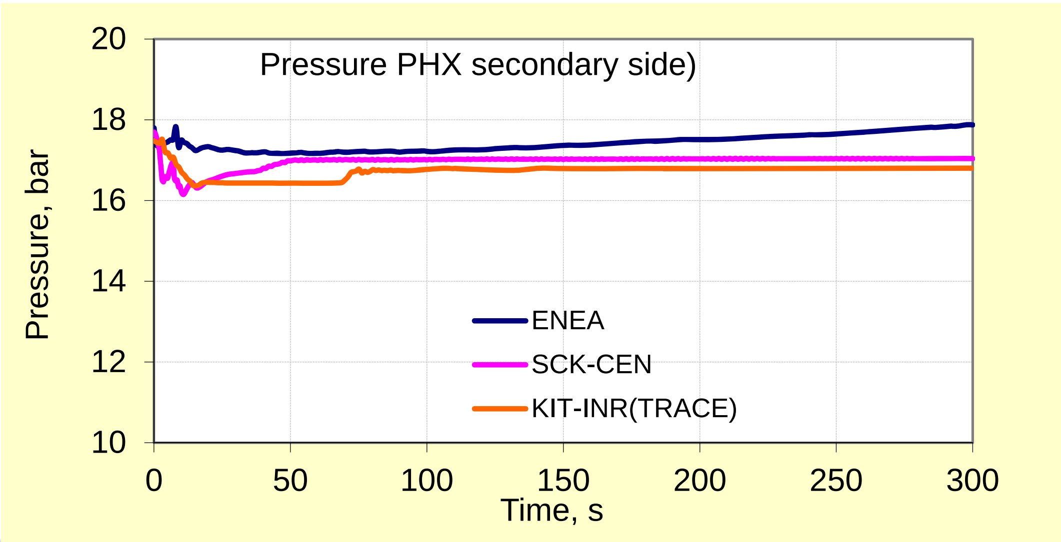
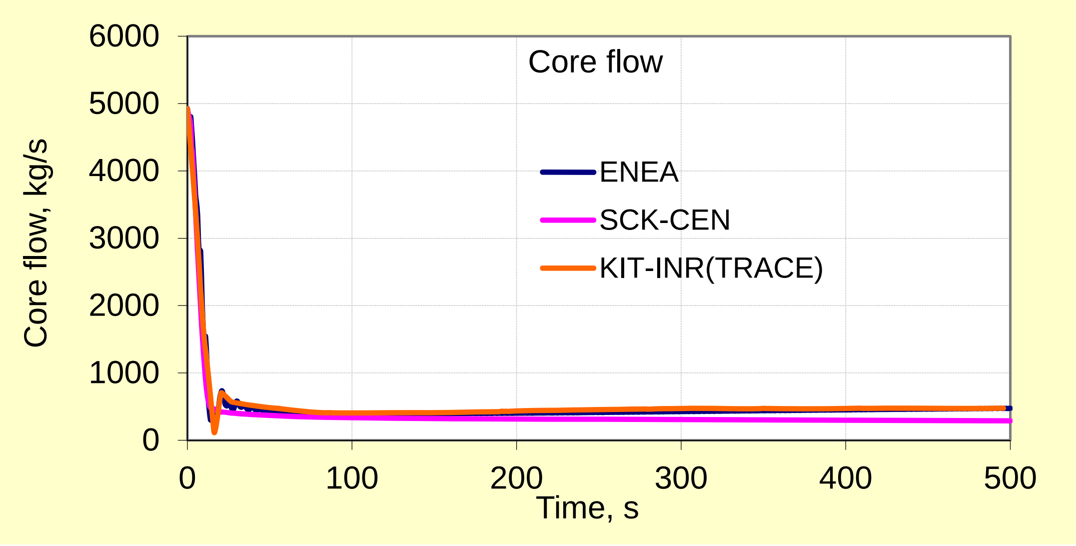
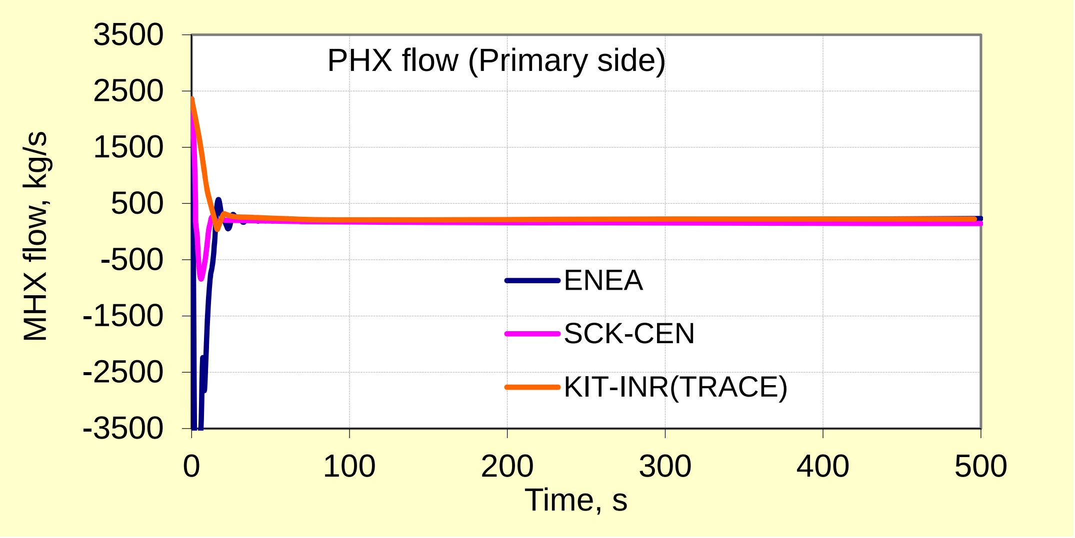




Transient analysis – PLOF comparison





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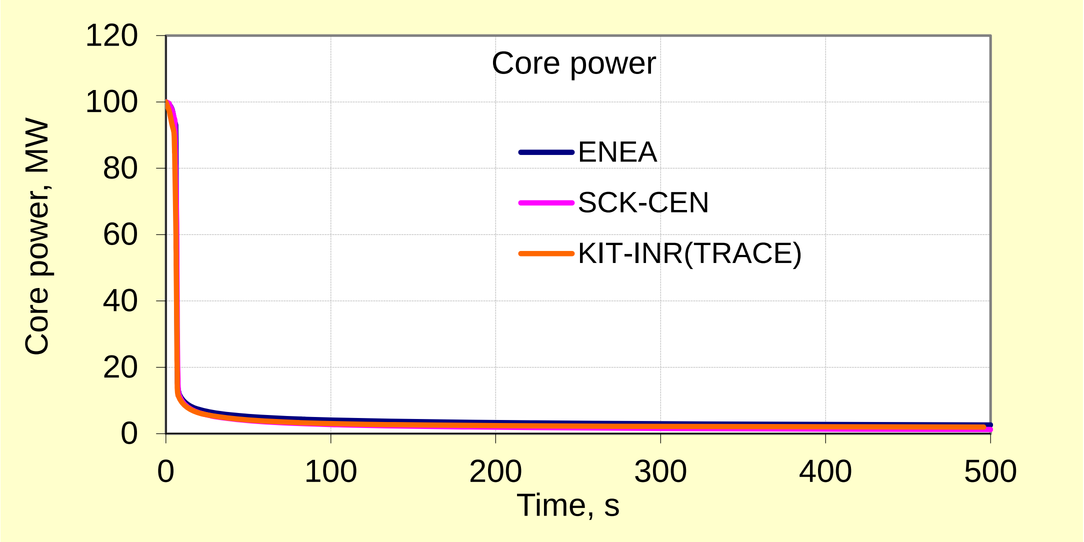

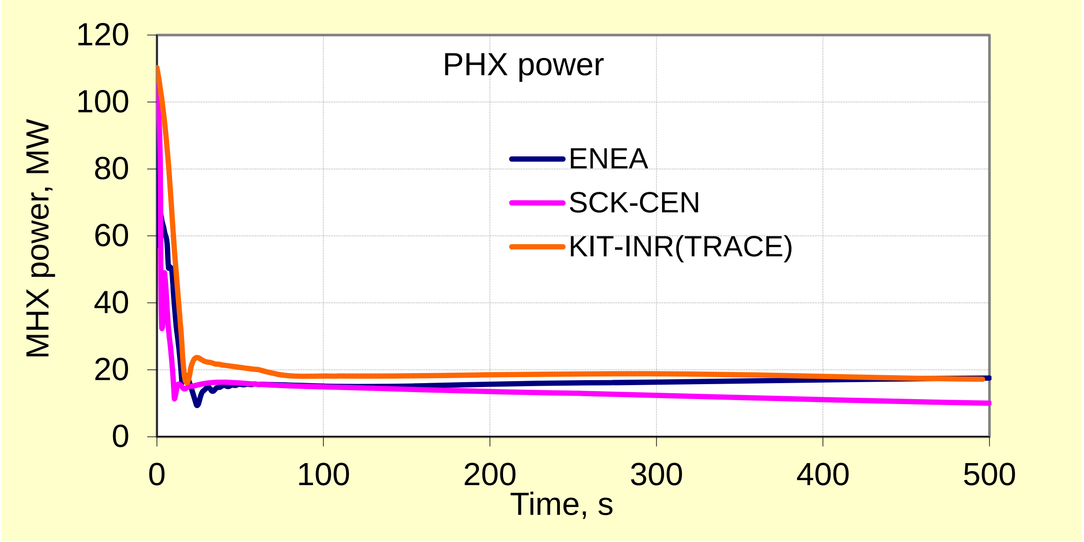

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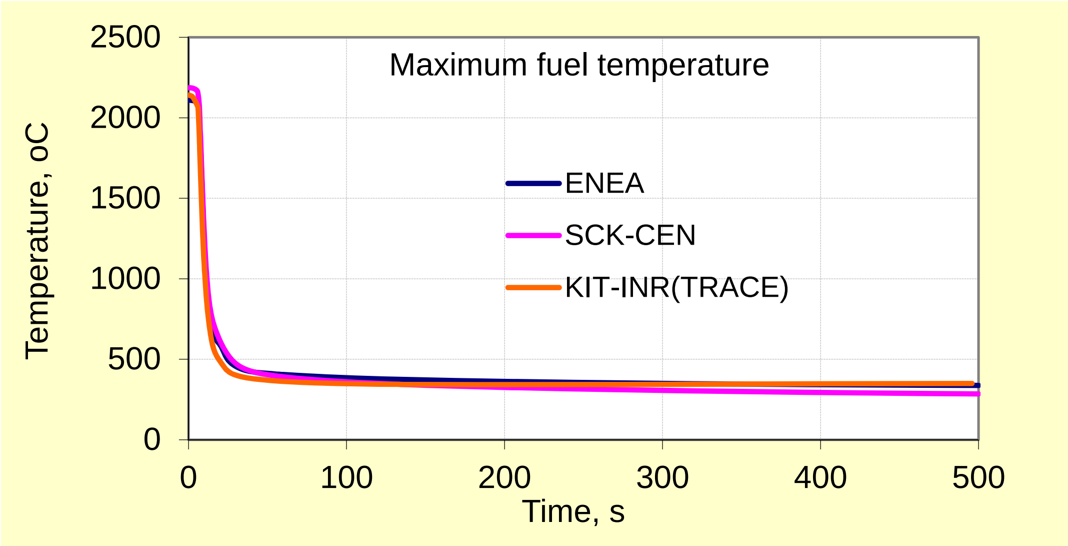

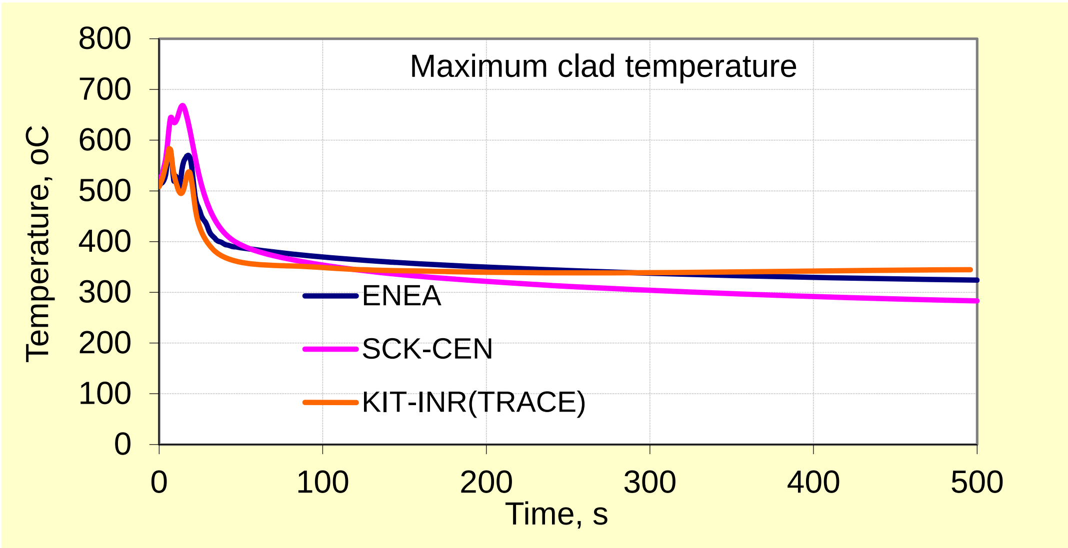

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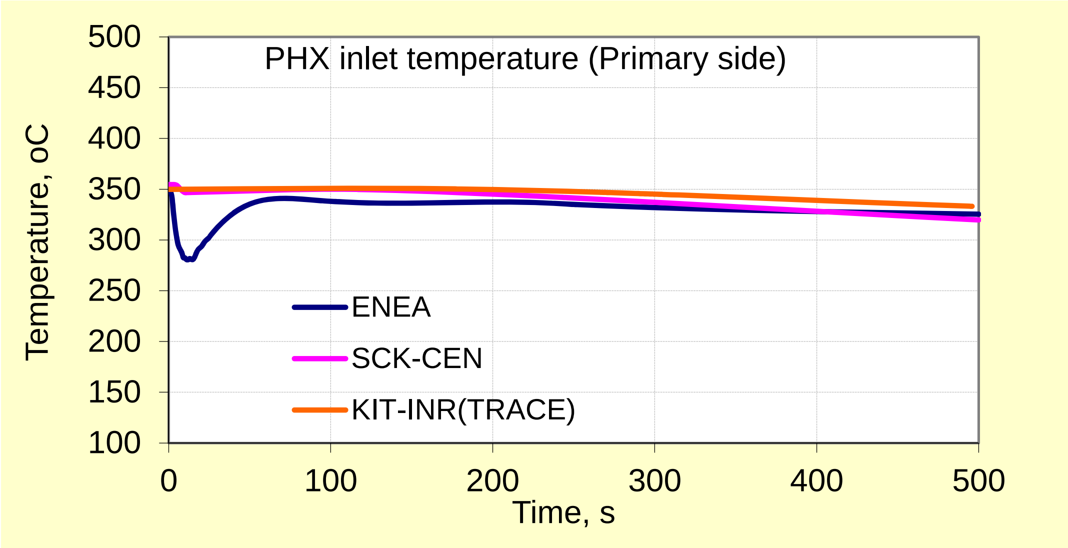

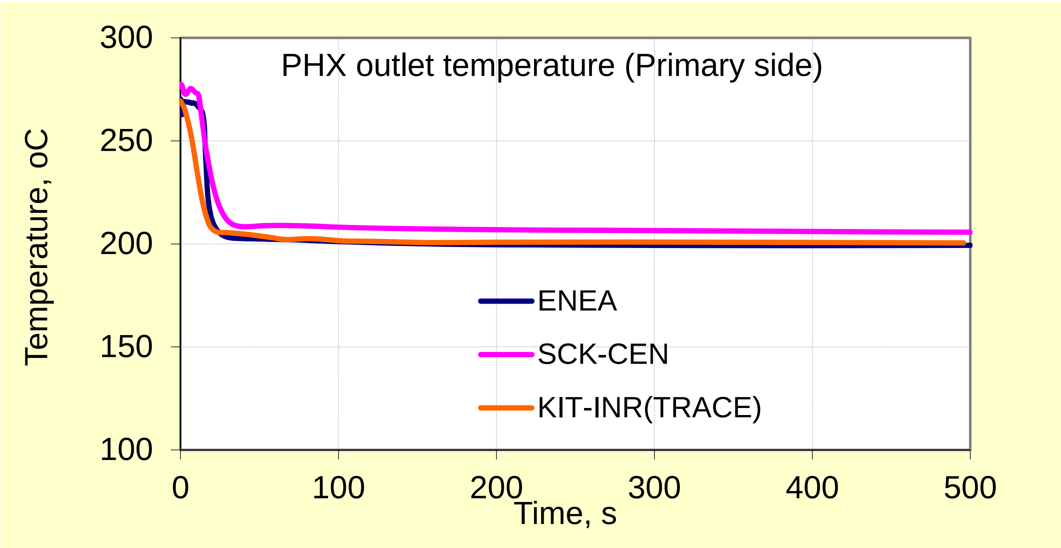

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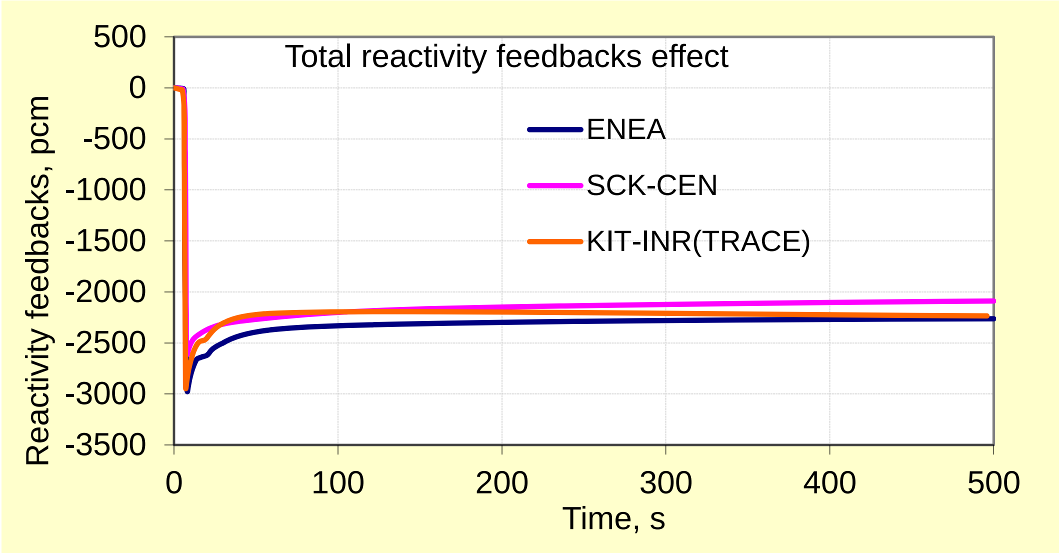
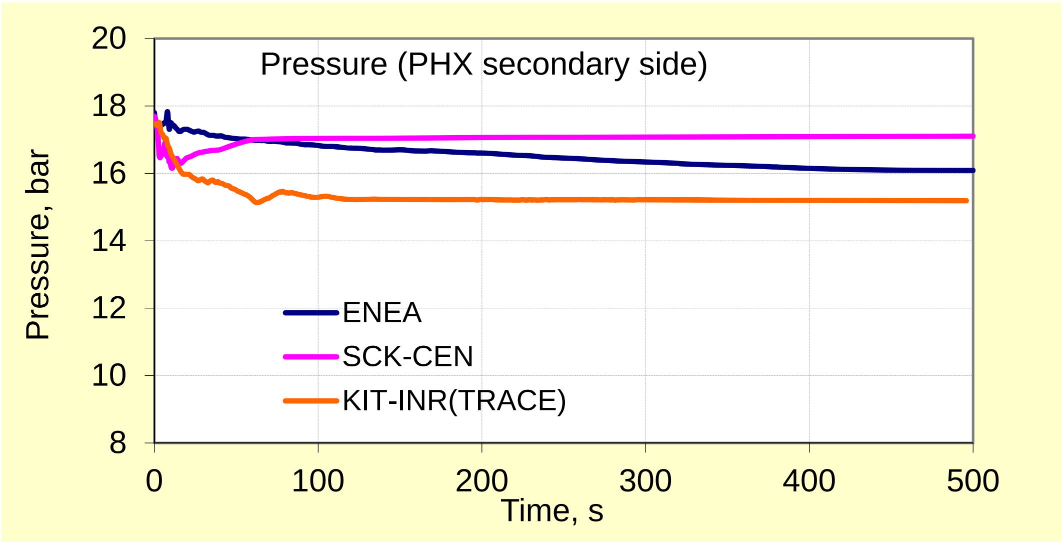




Deterministic analysis - Conclusions

- ULOF and PLOF deterministic analysis in good agreement
- Main differences:
  - Different natural circulation mass flow rate → different hot channel (LBE and clad) temperatures
  - Different pump characteristics → different reverse mass flow rate in pump + PHX volumes
  - Different HTC in core and in PHX (Kazimi-Carelli correlation vs. Ushakov correlation)
  - Different free surface modeling
  - Different secondary system conditions (little impact)

Uncertainty + Sensitivity analysis – Input parameters

- U + S analysis purpose: to identify the influence of selected input parameters variations on selected output parameters
  - Statistical-based analysis aiming at evaluating, through multiple system code runs, the variation of a certain output parameter caused by a certain input variation
  - *E.g.: How does the fuel conductivity influence the PCT?*
- A final input parameter list for Phase 1 activities agreed between SCK-CEN, ENEA, KIT and GRS
- Factors considered:
  - Parameters usable by all involved participants
  - No source code manipulation required
- Same transients considered for the deterministic comparison
  - Unprotected Loss Of Flow (ULOF)
  - Protected Loss Of Flow (PLOF)

Uncertainty + Sensitivity analysis – Input parameters

- Every parameter identified through:
  - Reference values (BE value from MAXSIMA Phase 1 Technical Database and/or from discussion between participants)
  - Suitable variation range estimated on the basis of engineering judgement
- Gaussian distribution (+/- 3σ) centred on the reference value for each variation range considered
  - Variation expressed in percentage or in absolute values
- 100 input decks for each transient studied (ULOF and PLOF) in order to achieve a 95%/95% statistical accuracy
  - Same model used for the deterministic comparison (MYRRHA revision 1.4)

Uncertainty + Sensitivity analysis – Input parameters

Parameter	Placeholder	Unit	Value	Variation	Note
Average clad oxide layer thickness	#*01R	μm	5.0	± 2	
Hot clad oxide layer thickness	#*02R	μm	10.0	± 2	
Clad oxide layer conductivity	#*03R	W/(m*K)	1.0	± 10%	
Peak pin gap conductivity	#*04R	W/(m*K)	0.067	± 0.02	Hot pin
Peak pin gap width	#*05R	mm	0.012	± 8%	Hot pin
Fuel conductivity	#*06R	W/(m*K)	1.0	± 10%	*
Fuel heat capacity	#*07R	J/(m³*K)	1.0	± 10%	*
PHX LBE side oxide layer thickness	#*08R	μm	40.0	± 2	
PHX water side oxide layer thickness	#*09R	μm	10.0	± 2	
PHX oxide layer conductivity	#*10R	W/(m*K)	1.0	± 10%	Both PHX tubes sides
Core inlet pressure drop form factors	#*11R	-	1.0	± 20%	*
Secondary pressure setup	#*12R	bar	16.0	± 1	
Scram set-point (DT core)	#*13R	°C	168.0	± 5%	Second scram signal
Control rods insertion delay	#*14R	s	1.0	0 ÷ 1	

* Value multiplying all table entries

- Parameters #13 and #14 only used for PLOF analysis (scram-related input data)

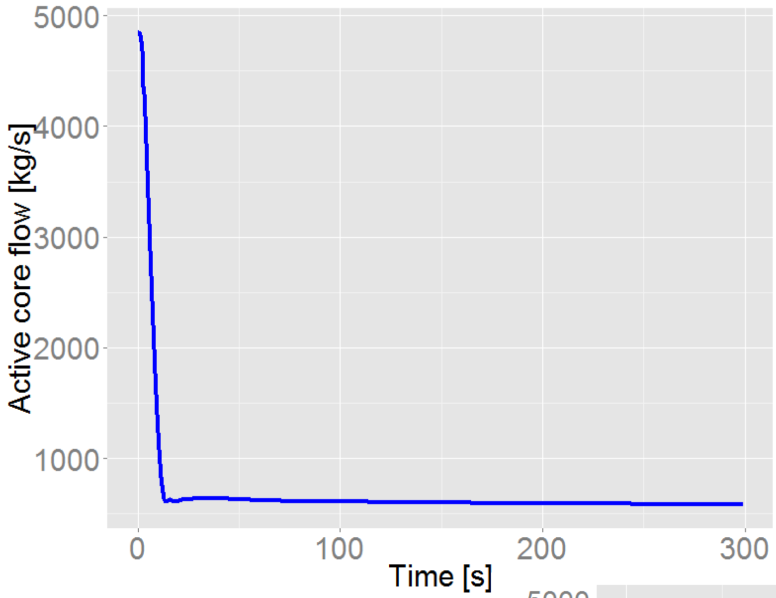
Uncertainty + Sensitivity analysis – Output parameters

- A list of relevant output parameters has been agreed between participants
- Output parameters chosen on the basis of the comparison made in the deterministic analysis
- System code models set up to easily provide the output parameters required, limiting the post-processing at minimum
- The 100 outputs (→ 100 different transient evolutions) have provided, through statistical elaboration, two different kind of information:
  - Mean values and standard deviation associated to each output parameter considered
  - Spearman Rank Correlation Coefficients (SRCC) for all input parameters in function of time (< 0.2 → statistically negligible)

Uncertainty + Sensitivity analysis – Output parameters

Parameter	Label	Unit	Note
Active core flow	#Out1	kg/s	Hot channel + Average channel
Active core power	#Out2	MW	Hot channel + Average channel
PHX LBE flow	#Out3	kg/s	Single PHX unit
PHX water flow	#Out4	kg/s	Single PHX unit
PHX power	#Out5	MW	Single PHX unit
Core coolant inlet temperature	#Out6	°C	
Maximum core coolant outlet temperature	#Out7	°C	Hot channel
Hot plenum temperature	#Out8	°C	
Cold plenum temperature	#Out9	°C	
Maximum fuel temperature	#Out10	°C	Hot pin
Maximum clad temperature	#Out11	°C	Hot pin
PHX LBE inlet temperature	#Out12	°C	
PHX LBE outlet temperature	#Out13	°C	
PHX water inlet temperature	#Out14	°C	
PHX water outlet temperature	#Out15	°C	
Steam drum pressure	#Out16	bar	
Total reactivity feedback effect	#Out17	pcm	

Uncertainty ULOF analysis: Active core flow



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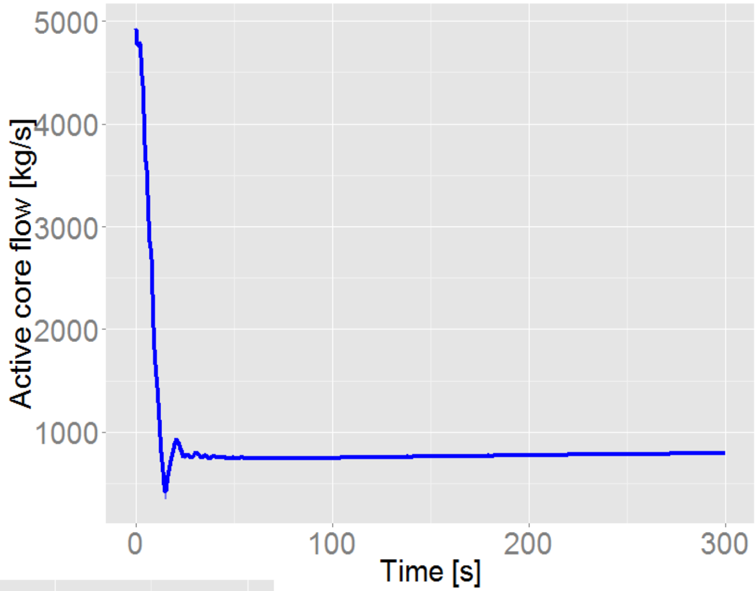
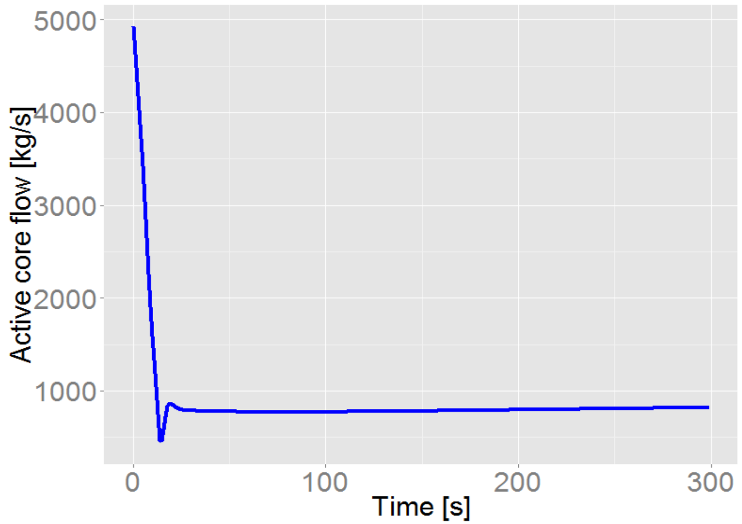
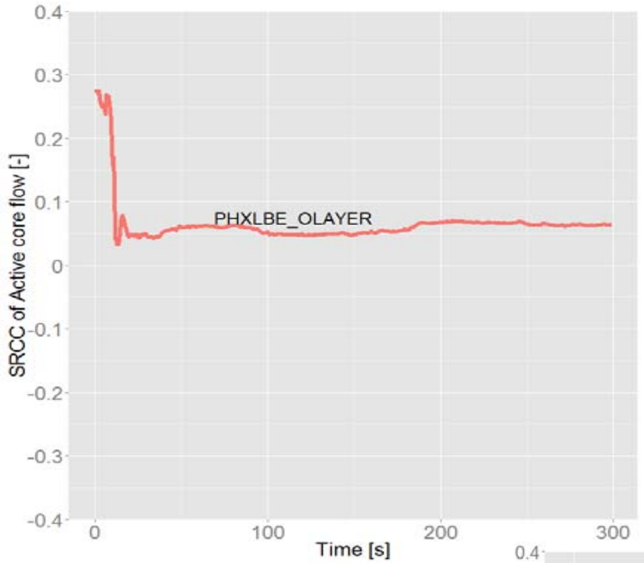


ENEA



KIT

Sensitivity ULOF analysis: Active core flow



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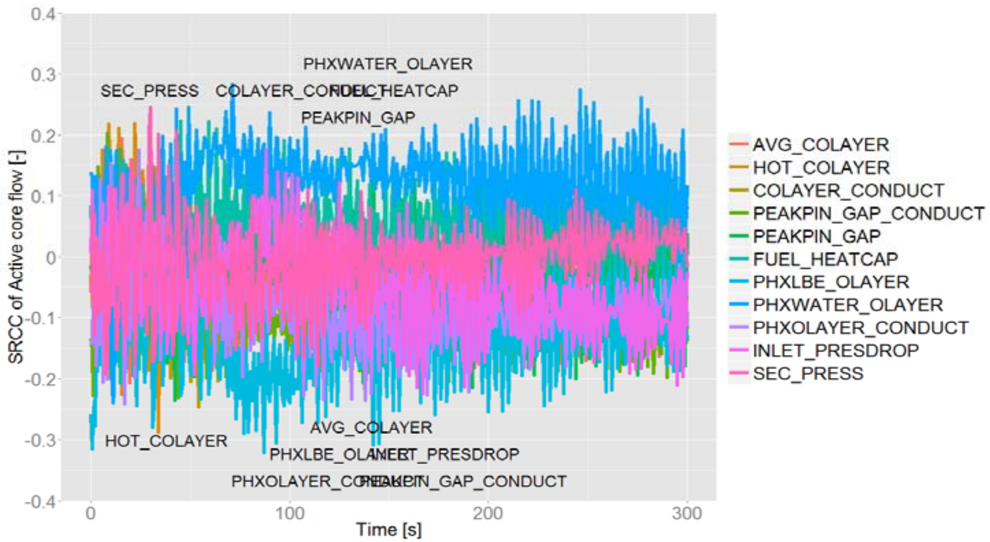

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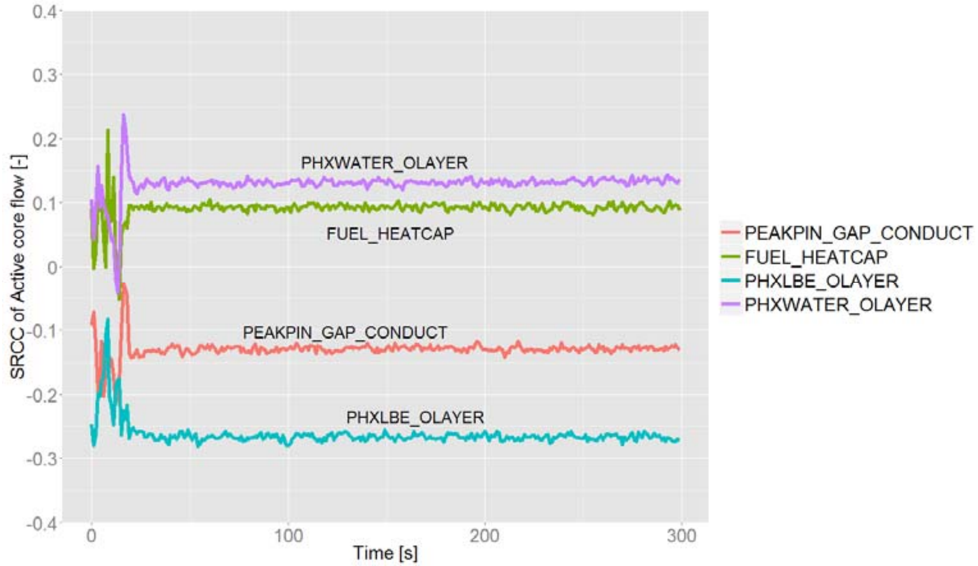
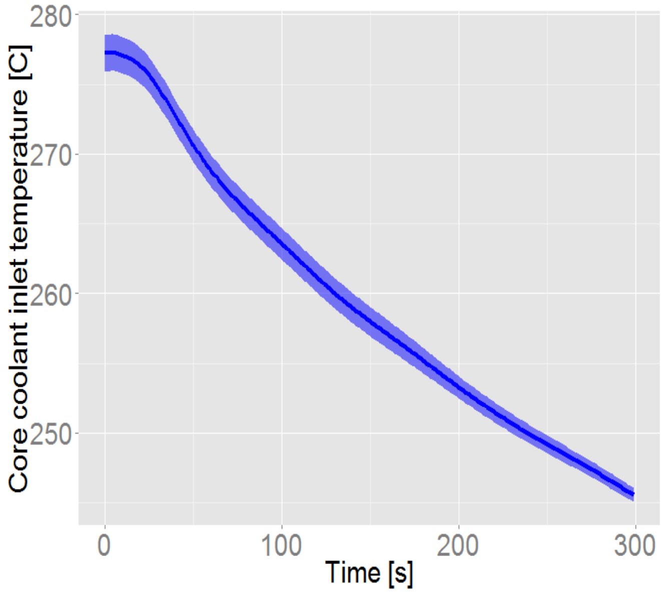
KIT



Uncertainty ULOF analysis: Core inlet temperature



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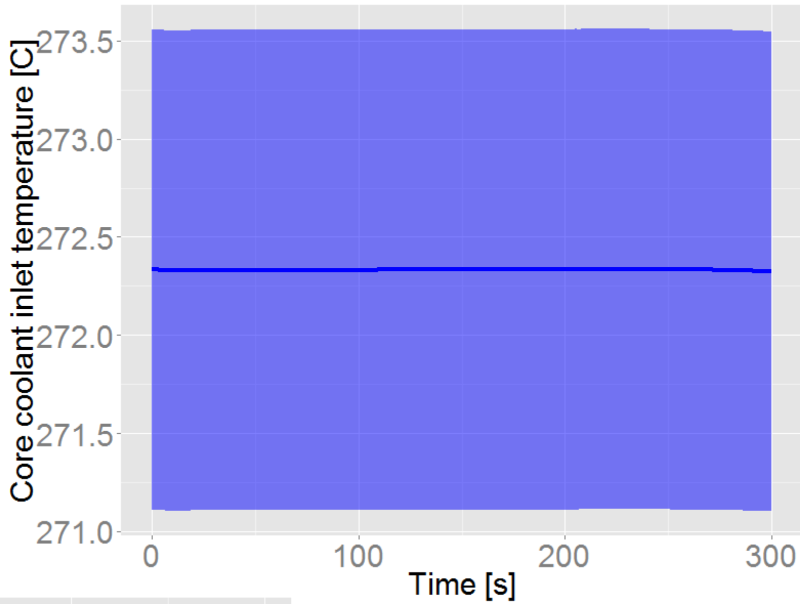

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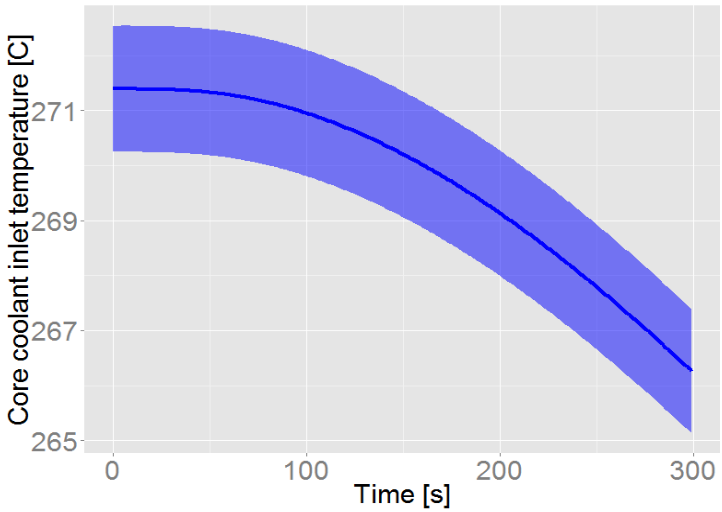
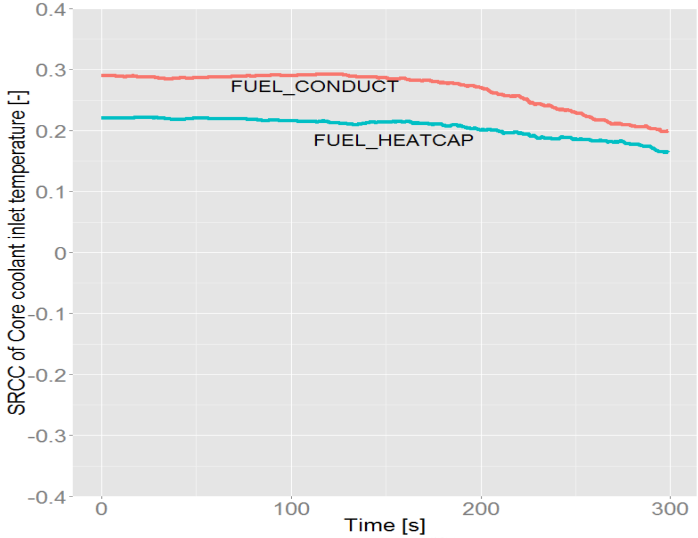


Sensitivity ULOF analysis: Core inlet temperature



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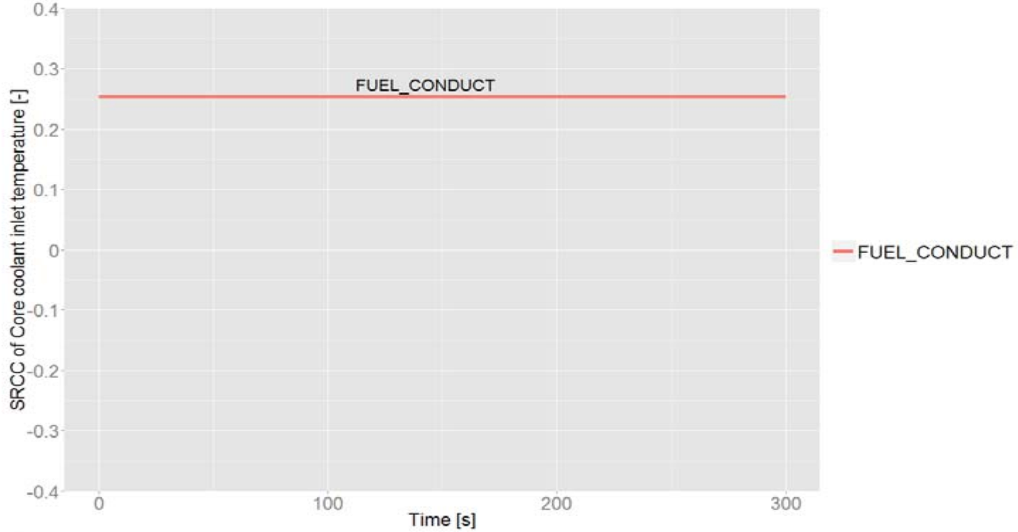

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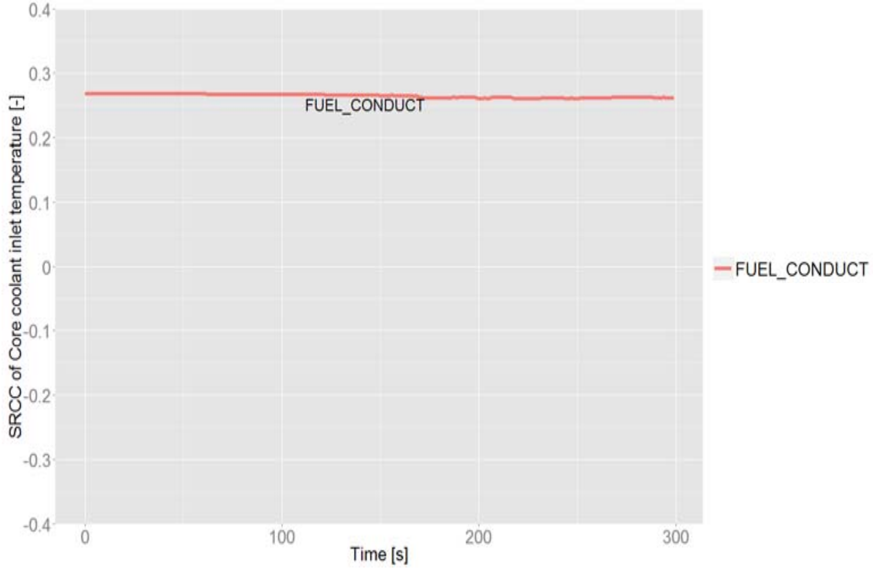
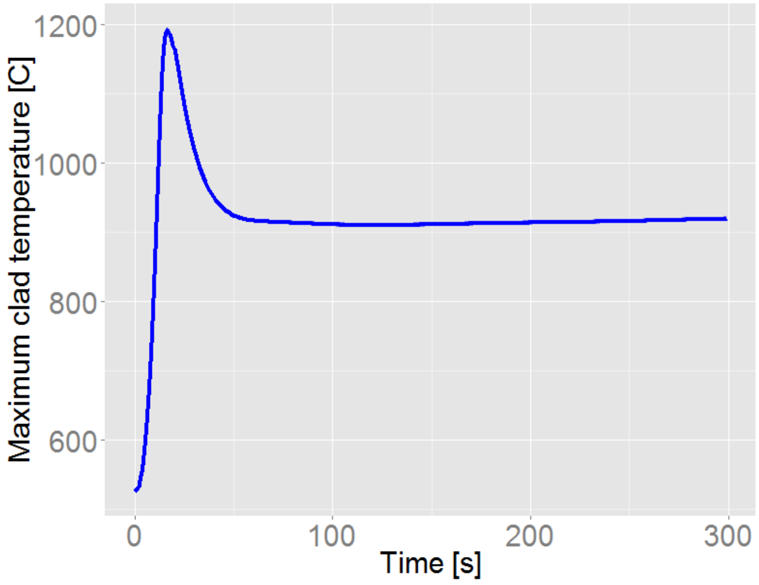
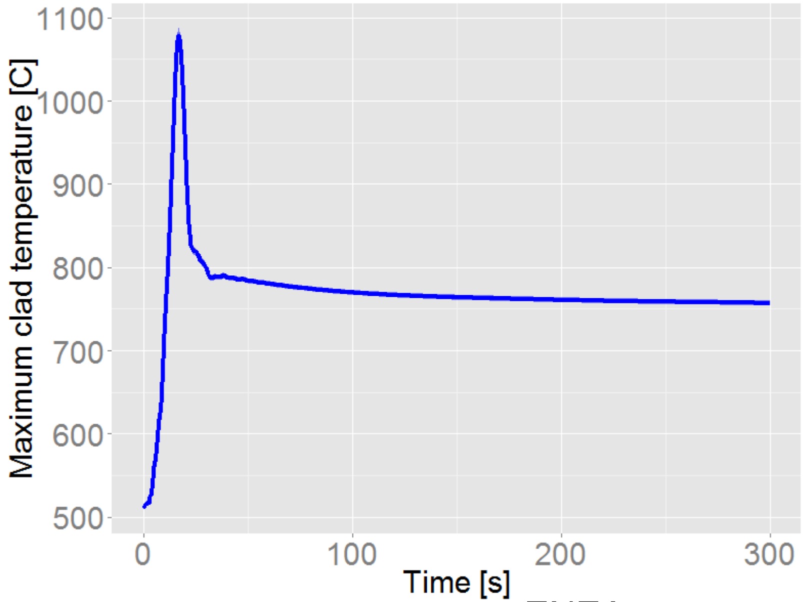


KIT

Uncertainty ULOF analysis: Peak clad temperature



SCK•CEN



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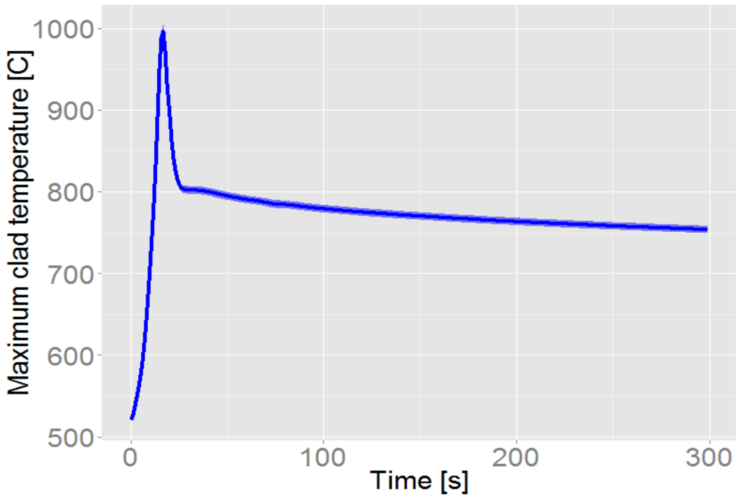

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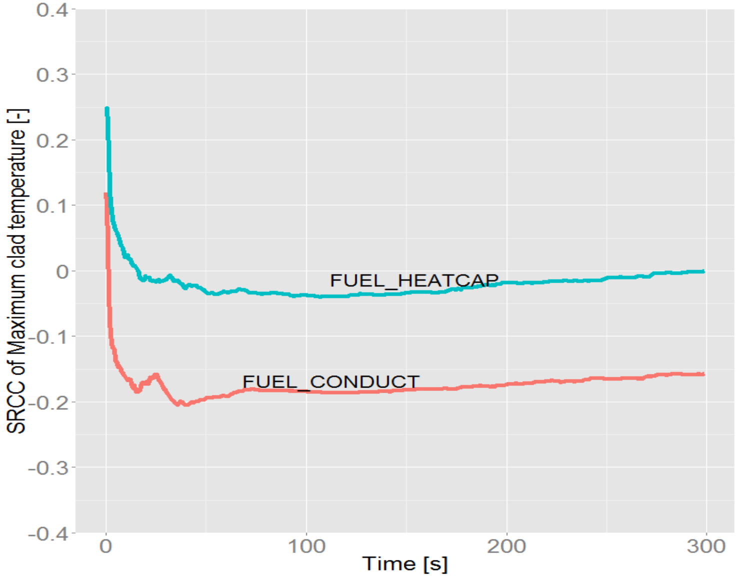
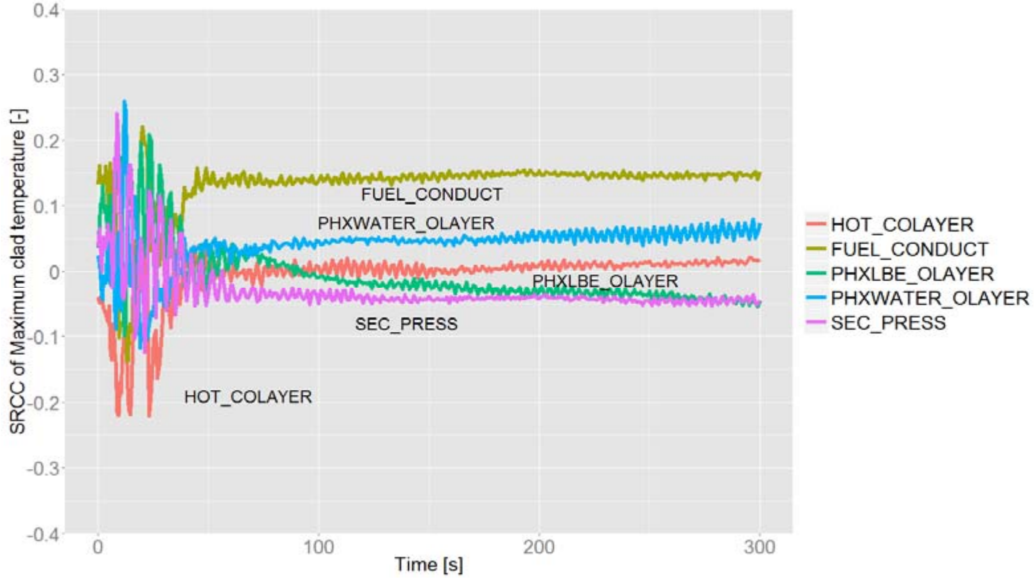
Sensitivity ULOF analysis: Peak clad temperature





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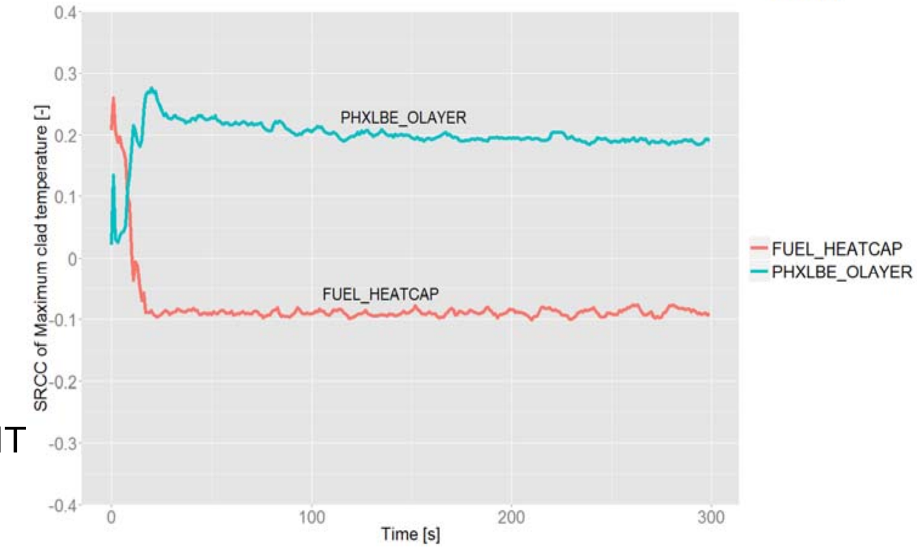

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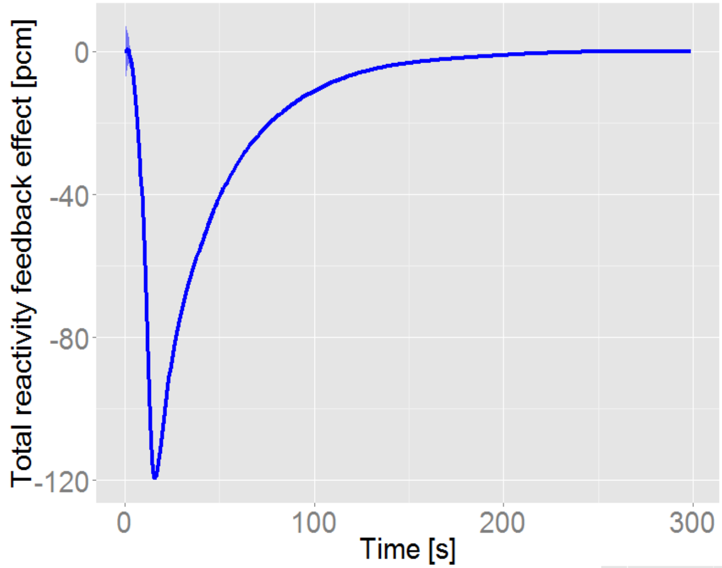
Uncertainty ULOF analysis: Total reactivity feedback



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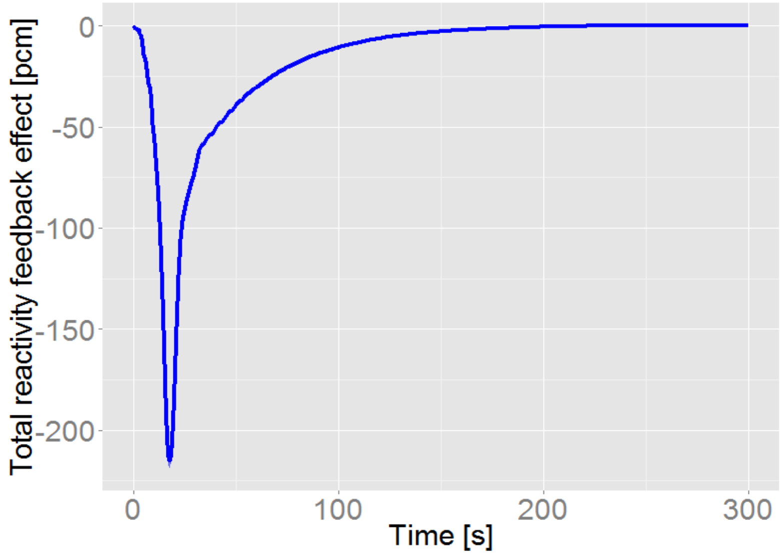

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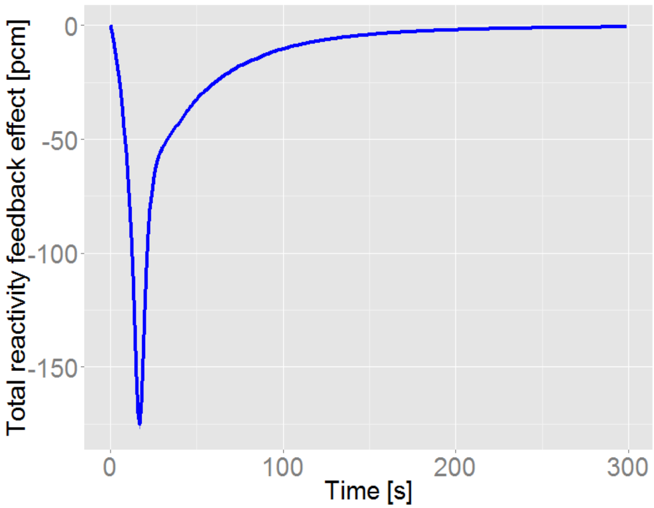

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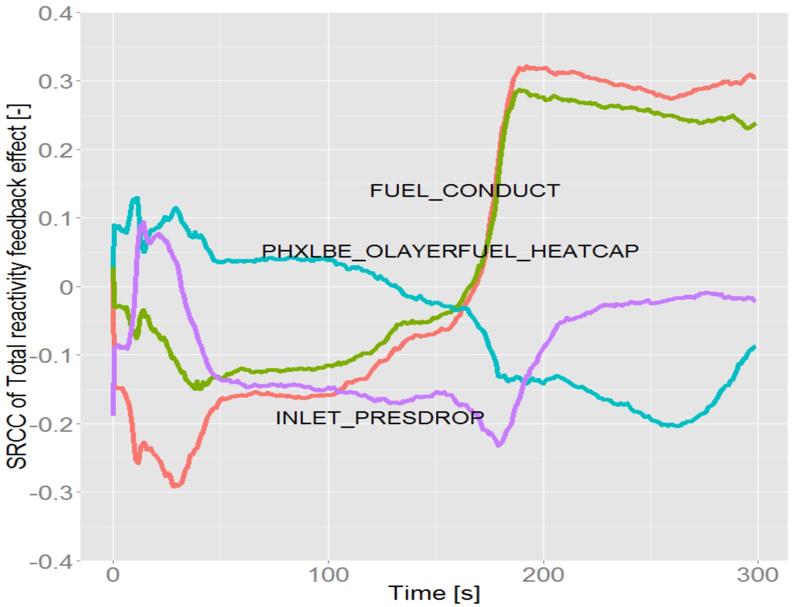
Sensitivity ULOF analysis: Total reactivity feedback



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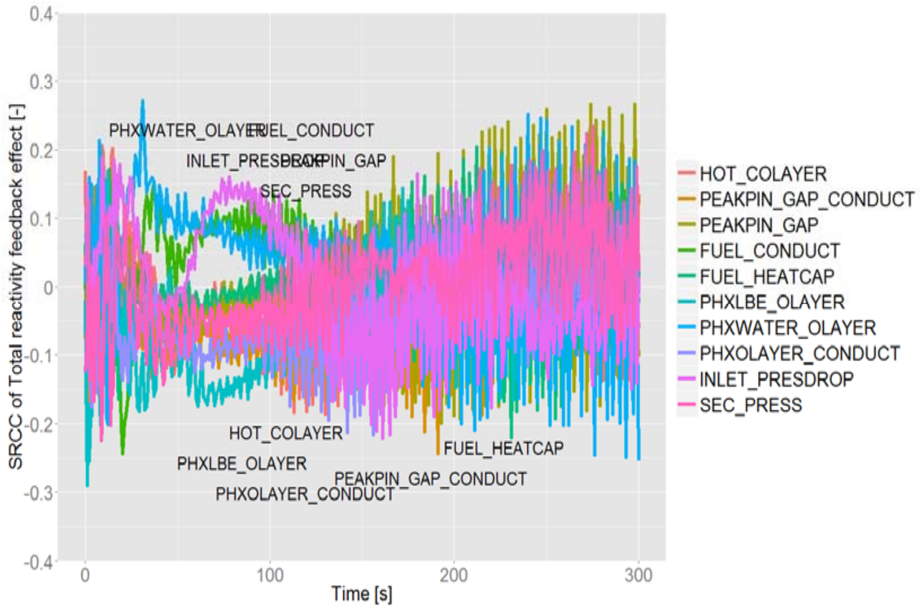

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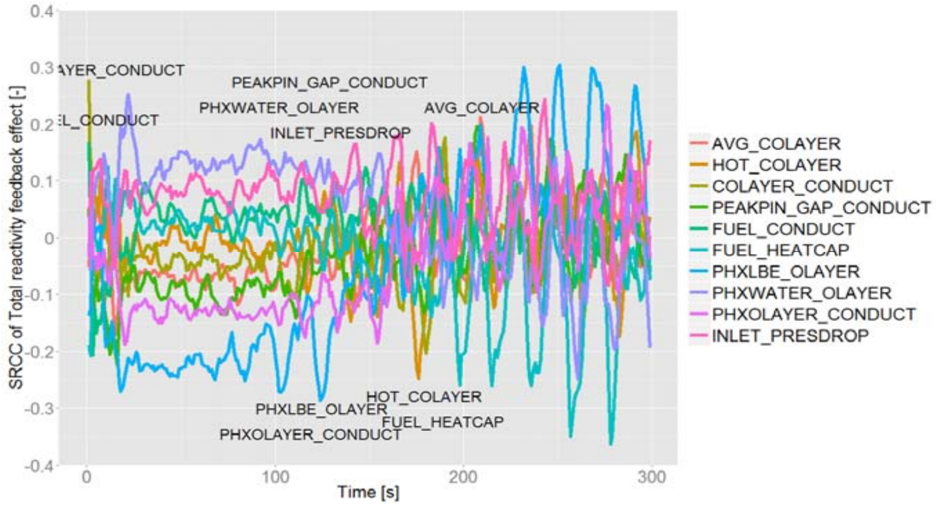
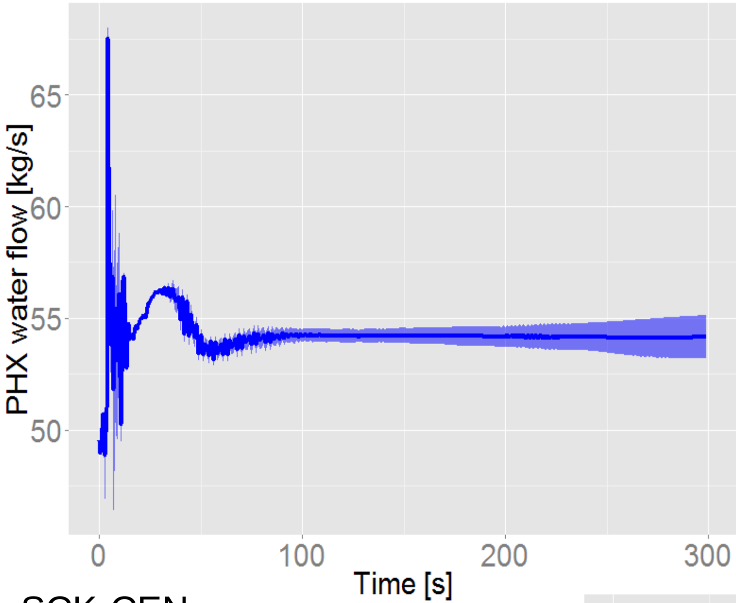


Uncertainty ULOF analysis: PHX water flow



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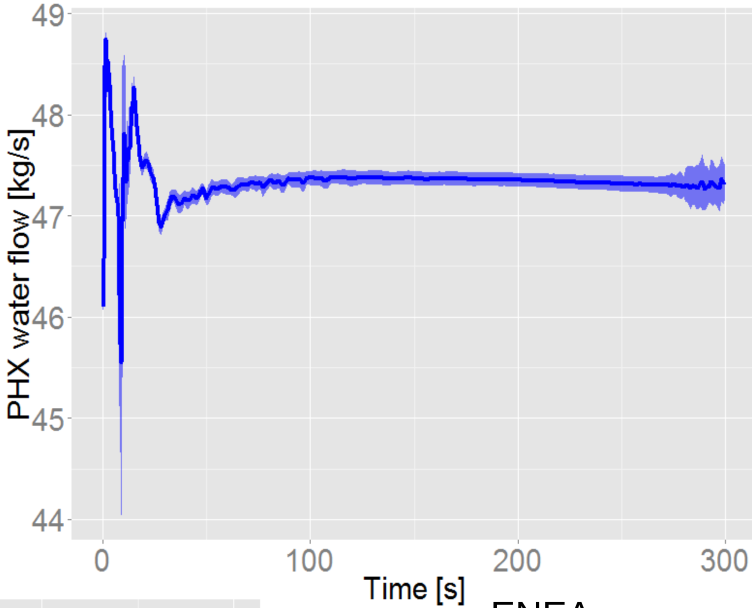

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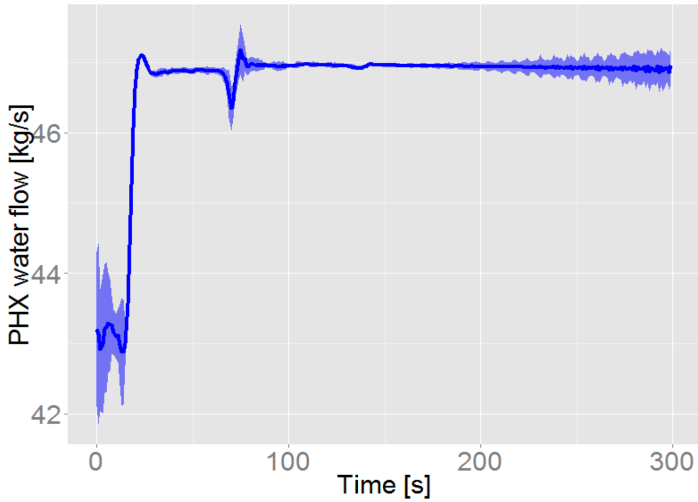
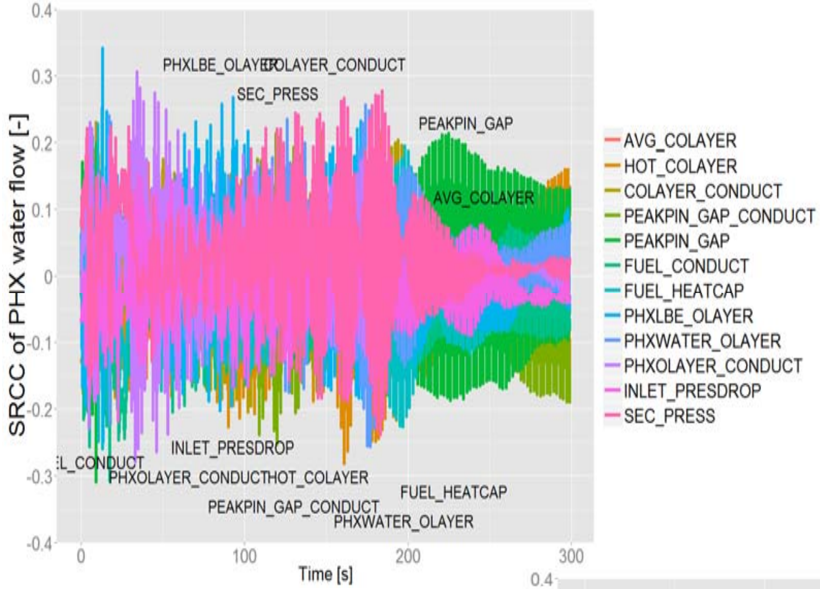


Sensitivity ULOF analysis: PHX water flow



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All Spearman Rank Correlation Coefficients (SRCC) absolute values are < 0.2

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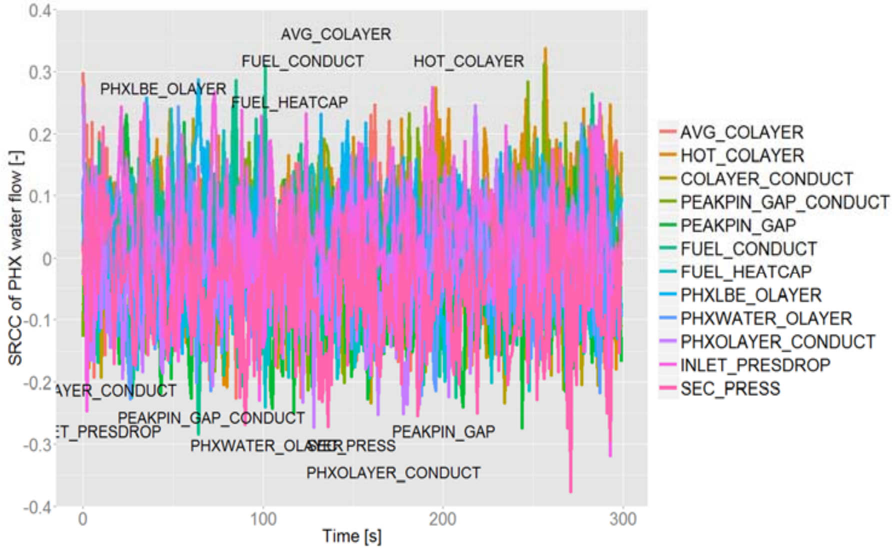

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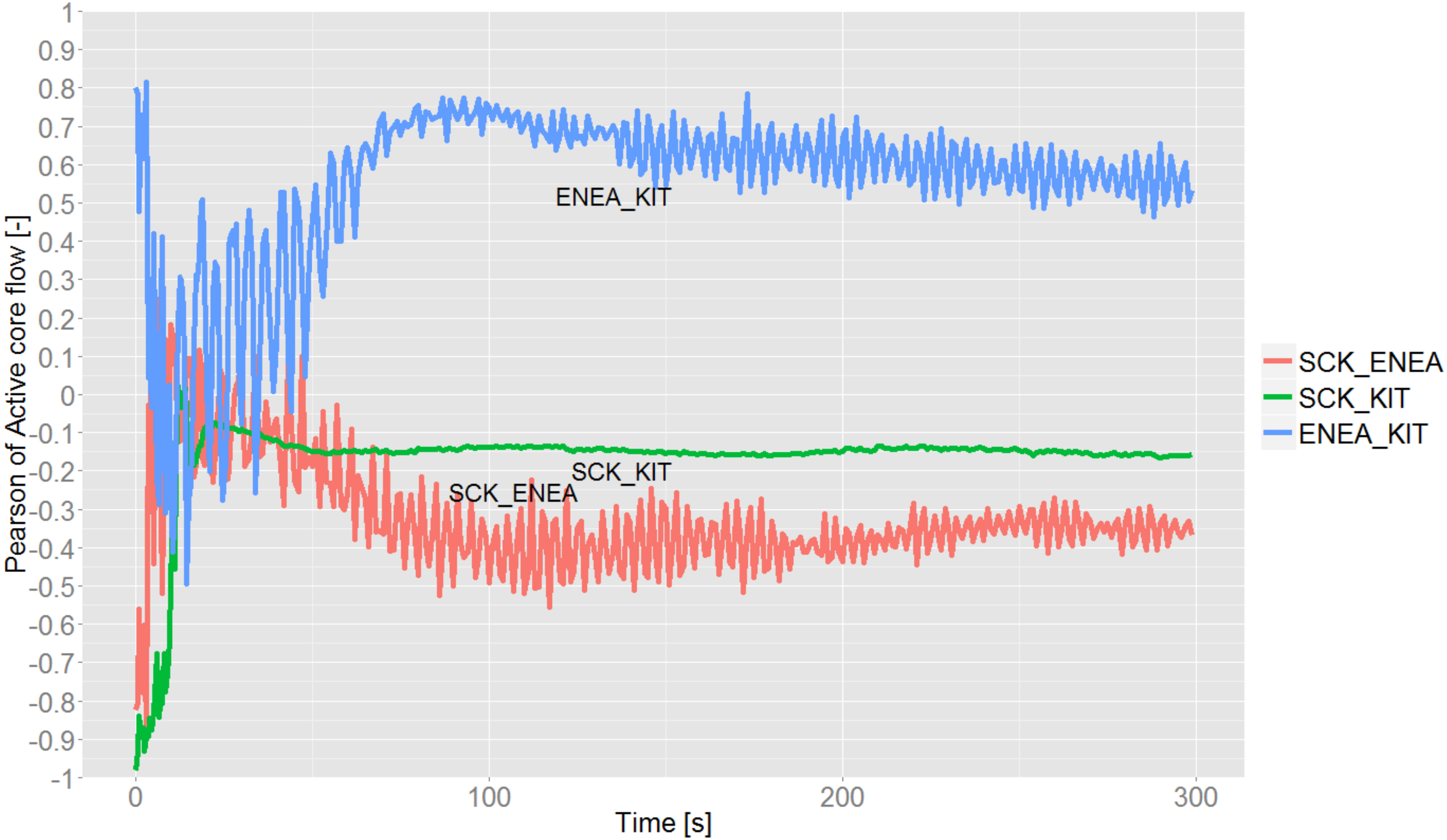
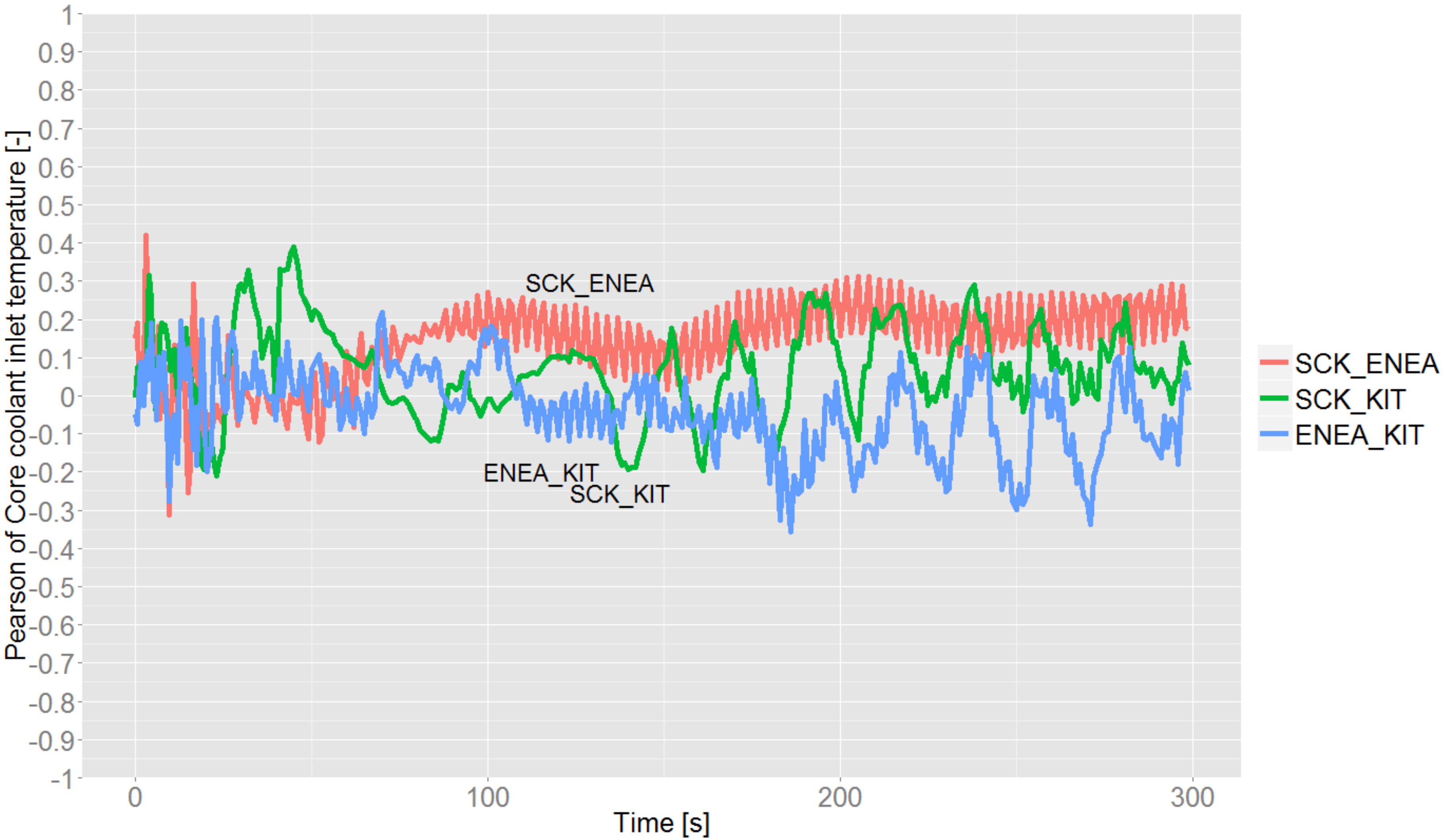
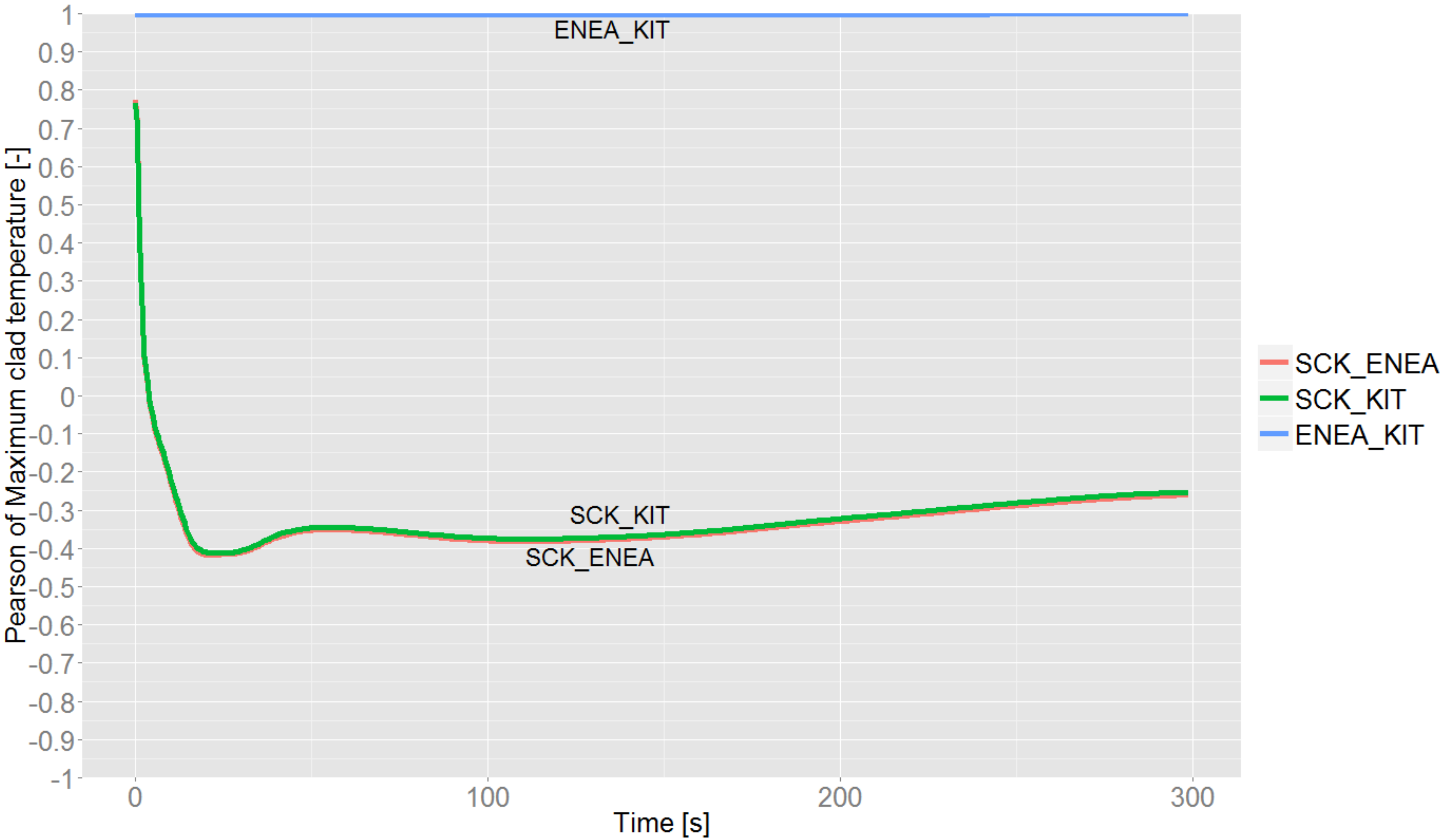
Pearson coefficients for ULOF: Active core flow



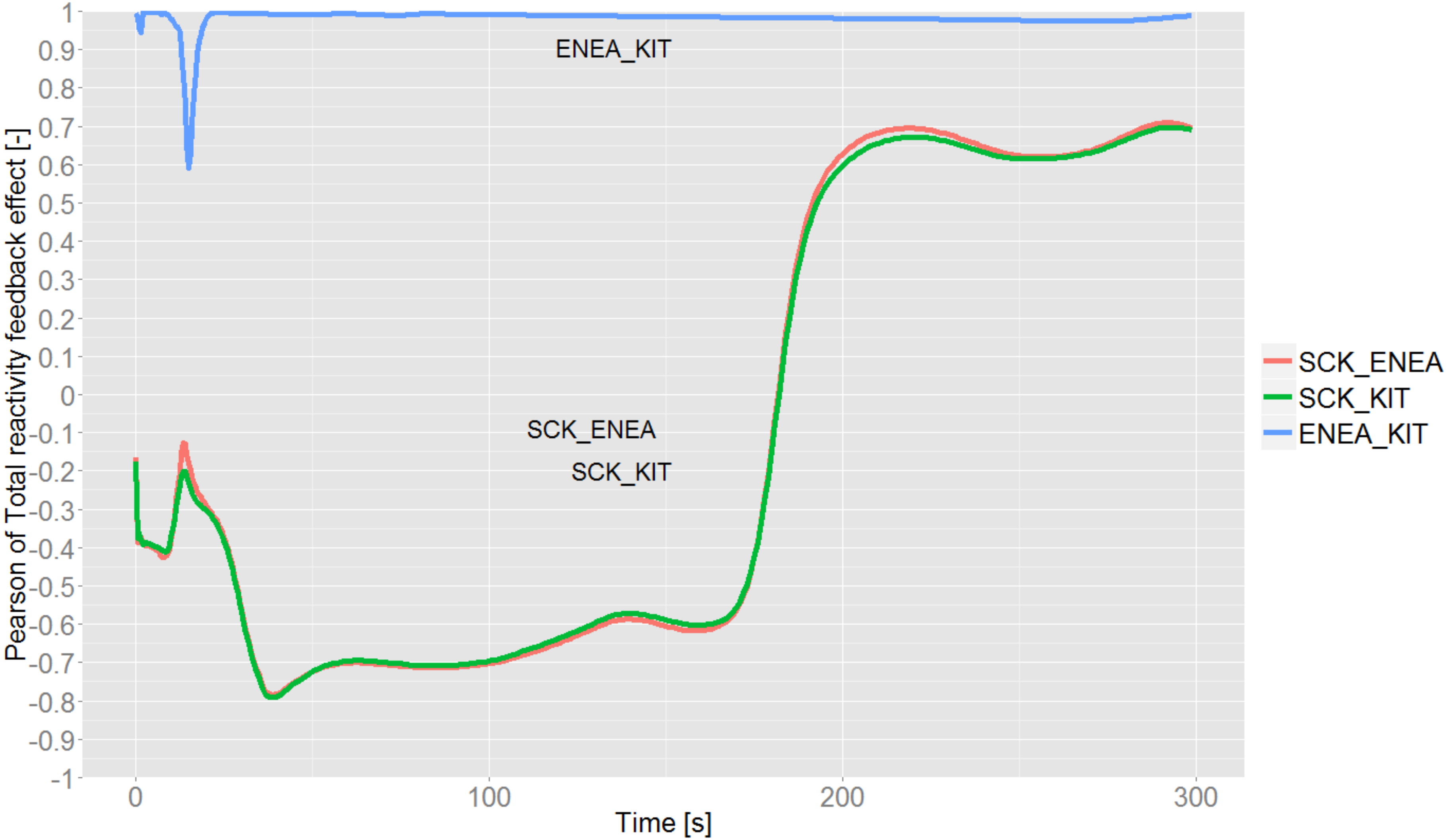
Pearson coefficients for ULOF: Core inlet temperature



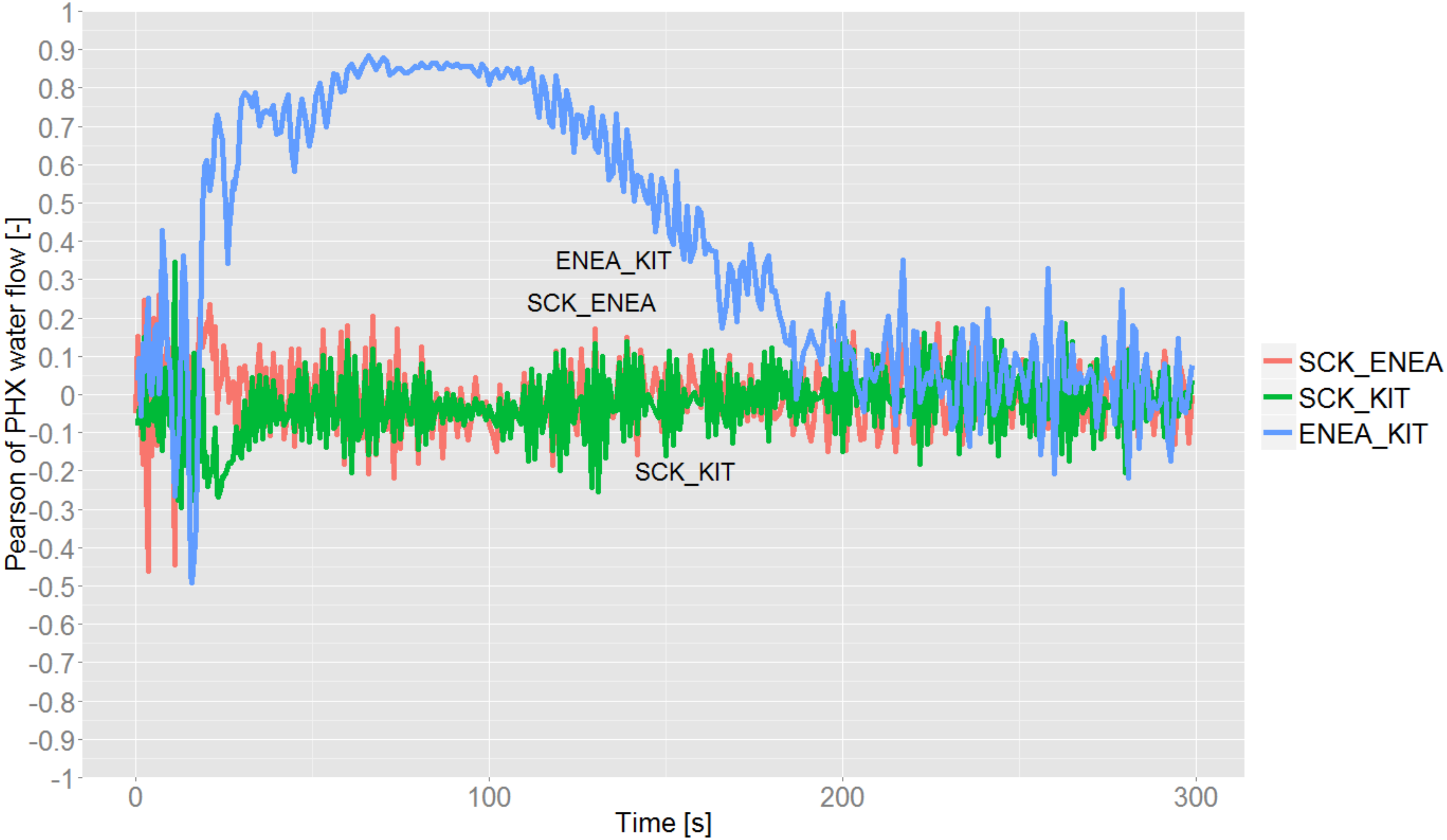
Pearson coefficients for ULOF: Peak clad temperature



Pearson coefficients for ULOF: Total reactivity feedback



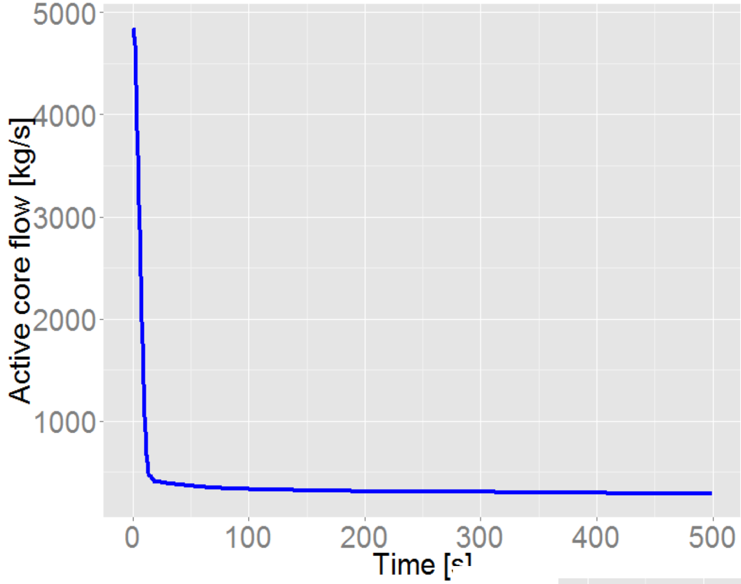
Pearson coefficients for ULOF: PHX water flow



U + S ULOF analysis: conclusions

- Variation range relatively not wide for primary system parameters
- In general, ULOF transient shows limited sensitivity to the considered parameters (SRCC almost always < 0.2)
- Fuel conductivity, fuel heat capacity and oxide layer thickness appear to be the most influent parameters over the transient duration
- PCT also mildly influenced by core pressure losses and PHX heat transfer (deviation within +/- 20 °C)
- Reactivity feedbacks show strongly variable input parameters influence over transient evolution
- Little importance coming from secondary system (low feed-back)

Uncertainty PLOF analysis: Active core flow



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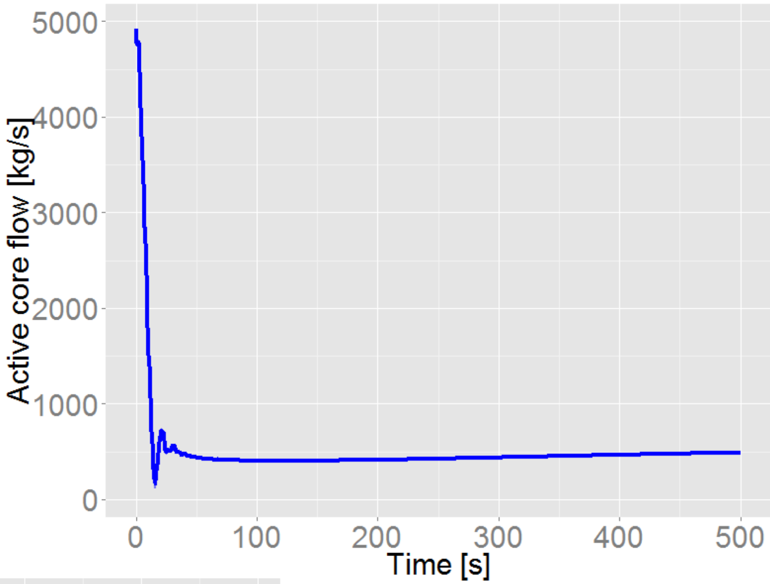

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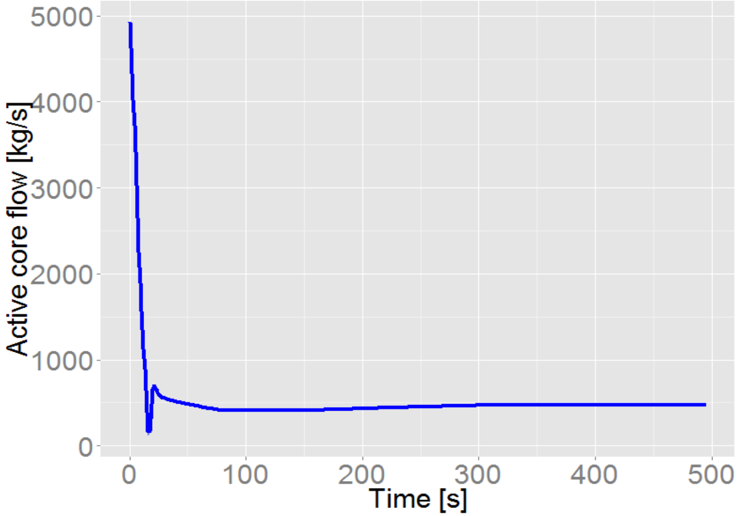

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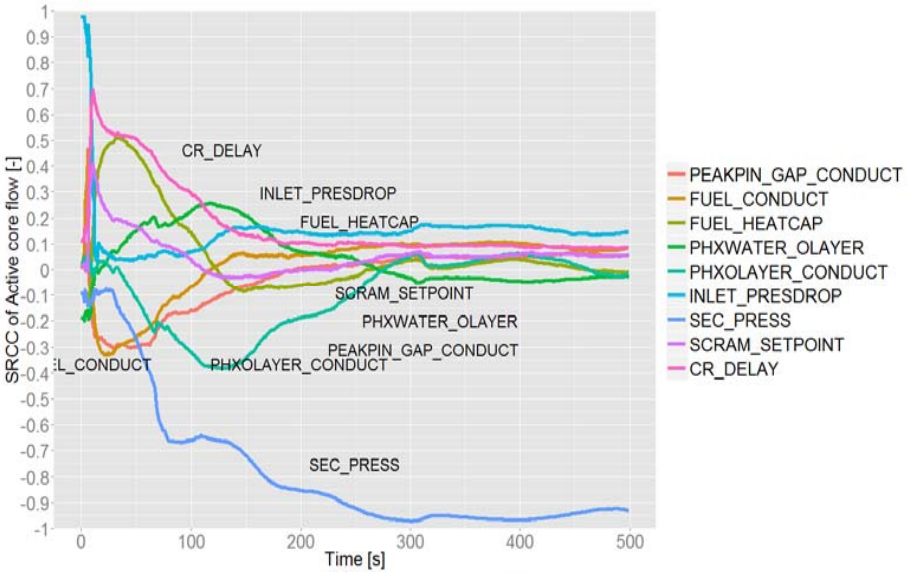
Sensitivity PLOF analysis: Active core flow



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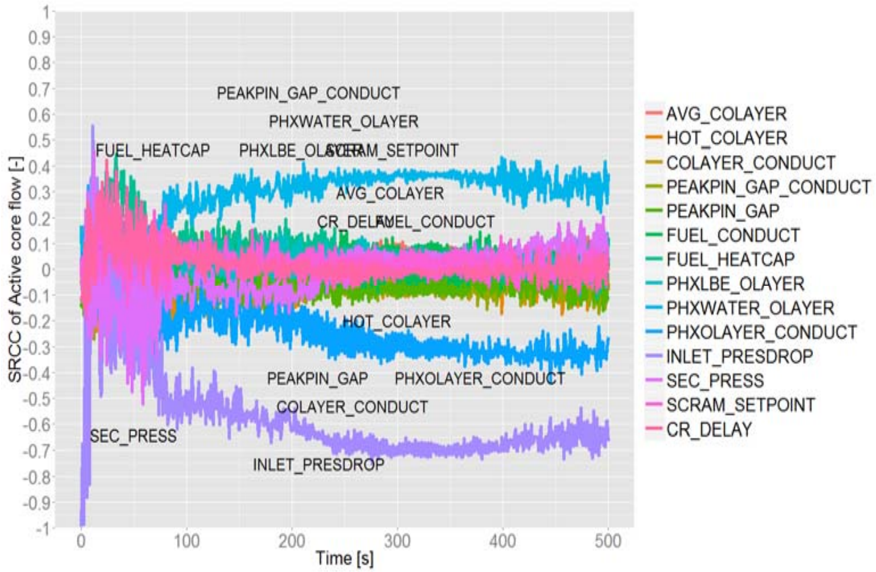

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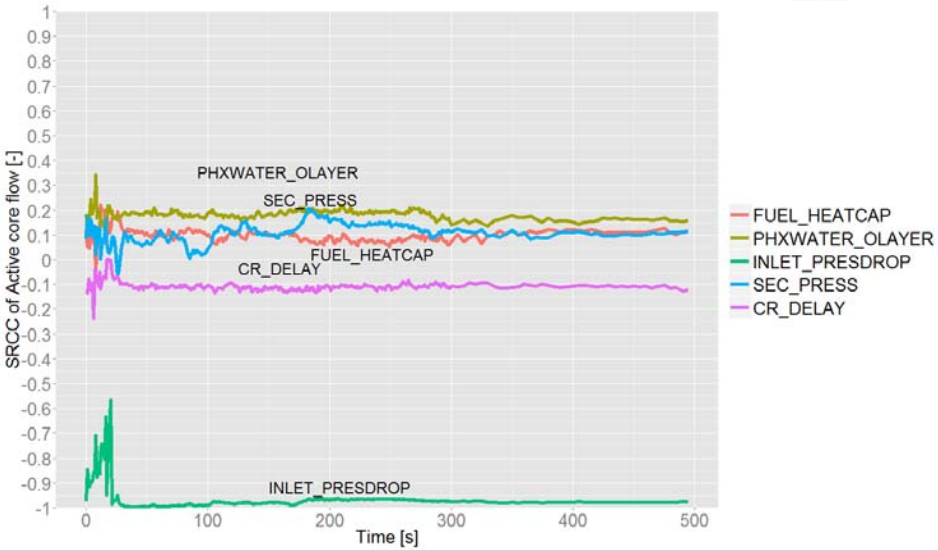

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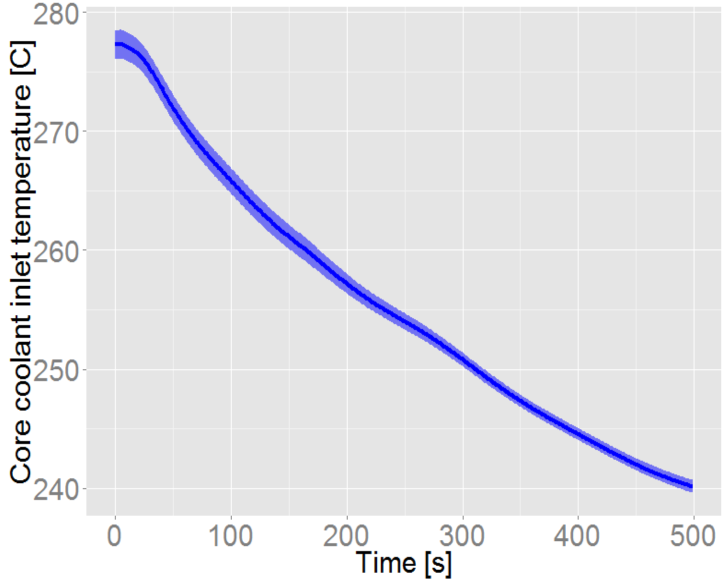
Uncertainty PLOF analysis: Core inlet temperature



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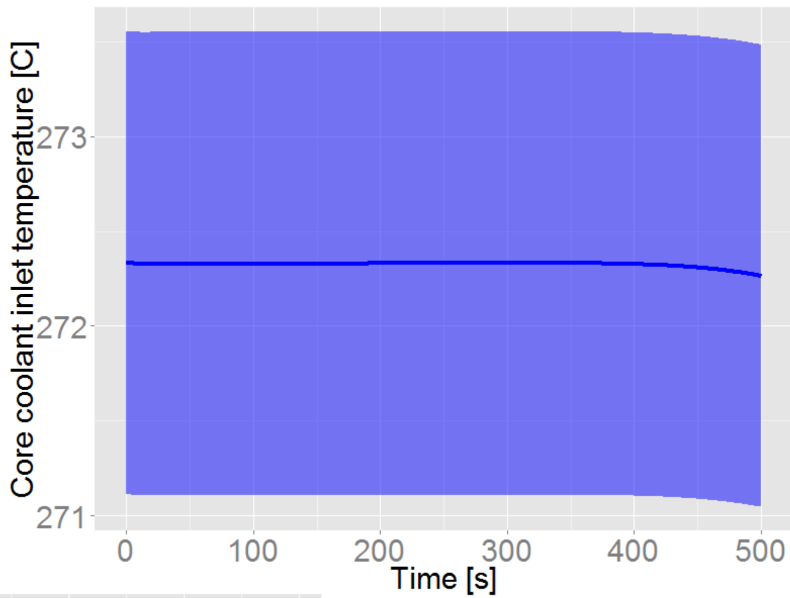

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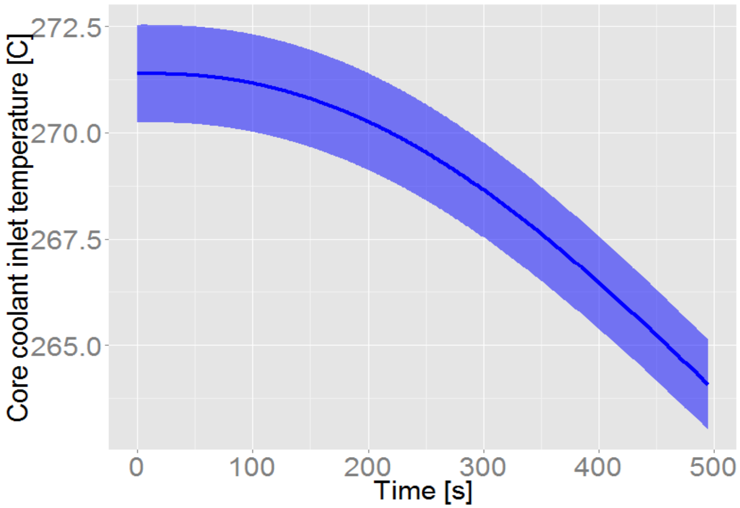

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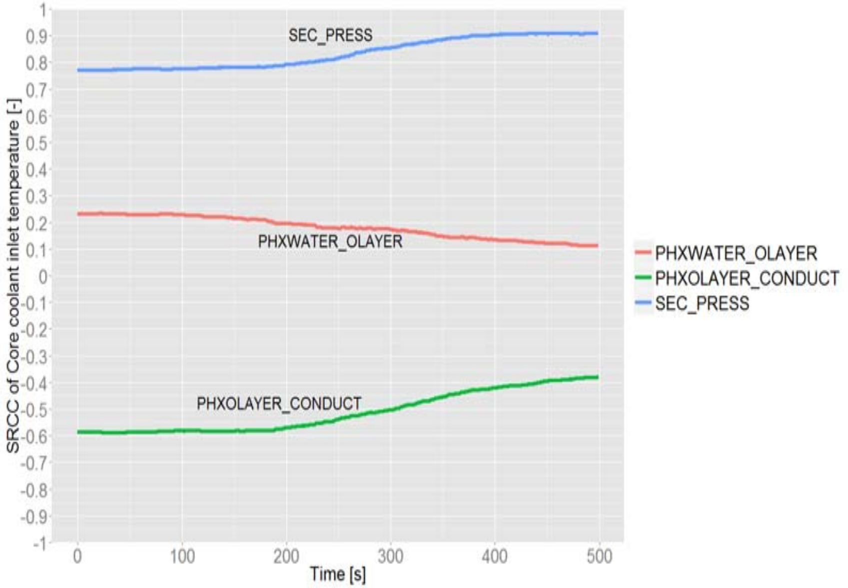
Sensitivity PLOF analysis: Core inlet temperature



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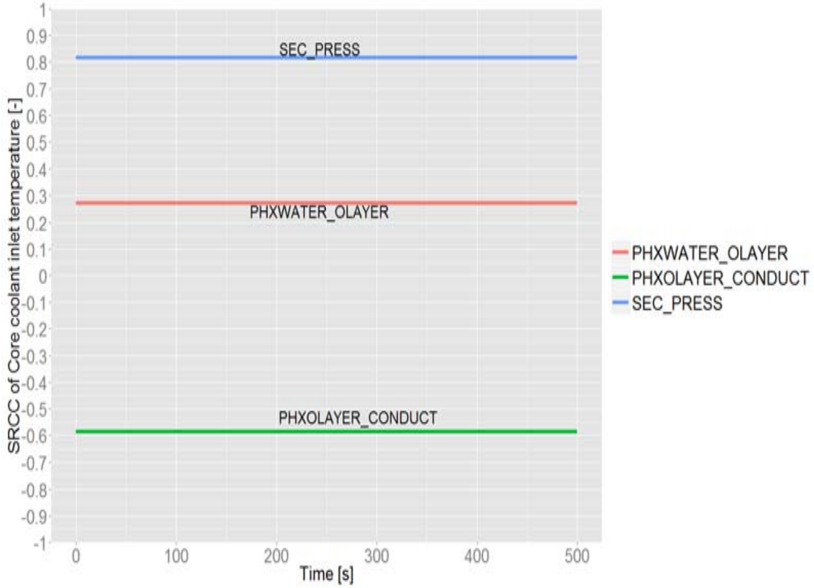

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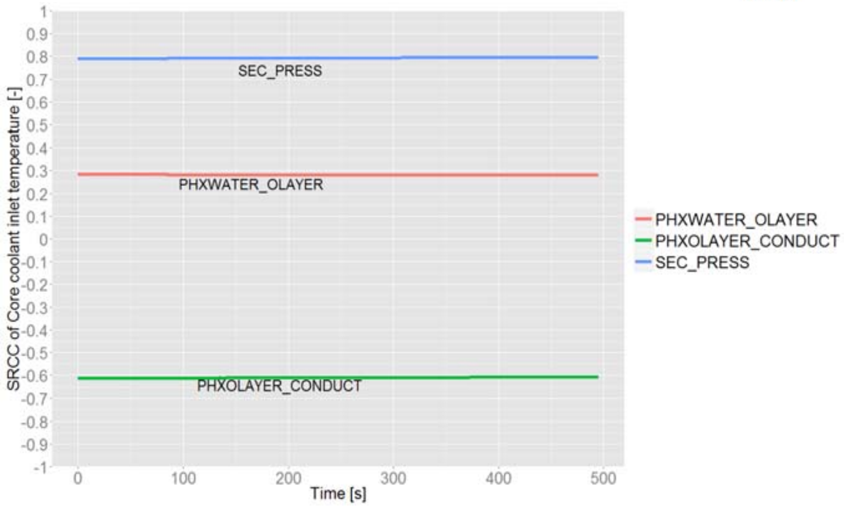

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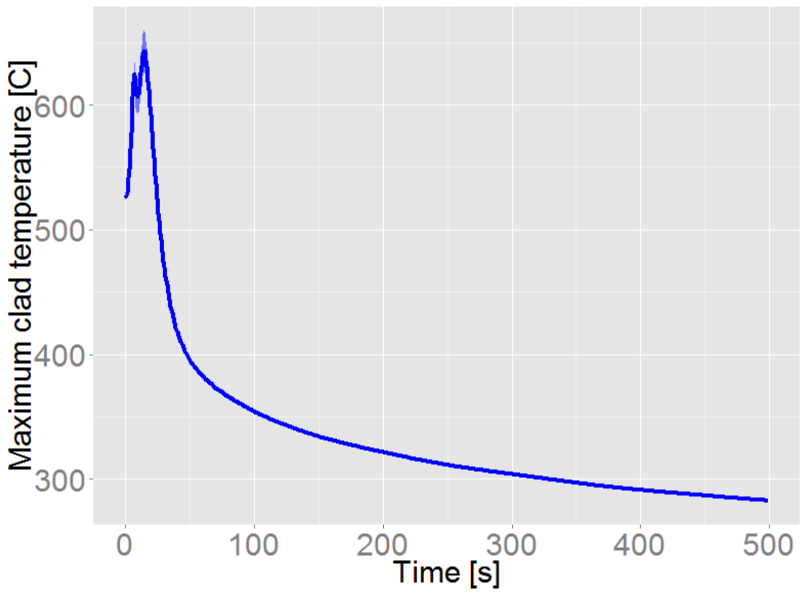
Uncertainty PLOF analysis: Peak clad temperature



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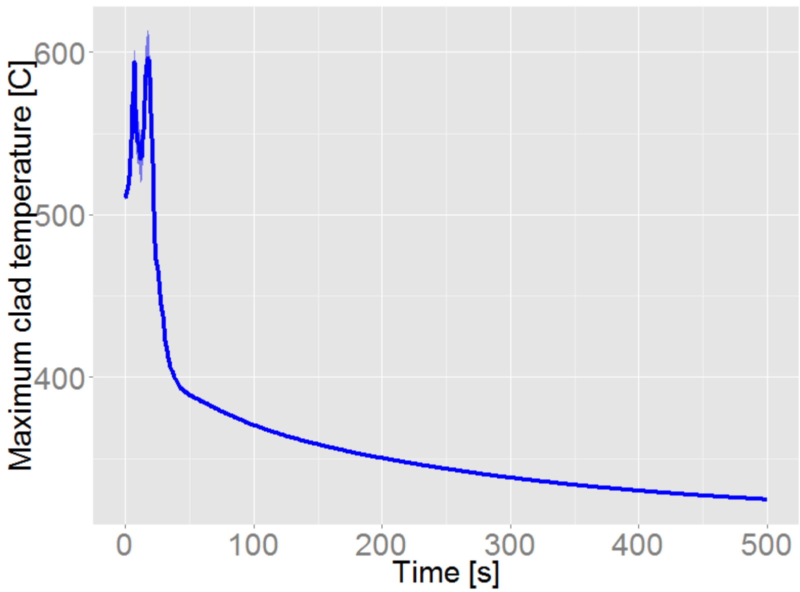

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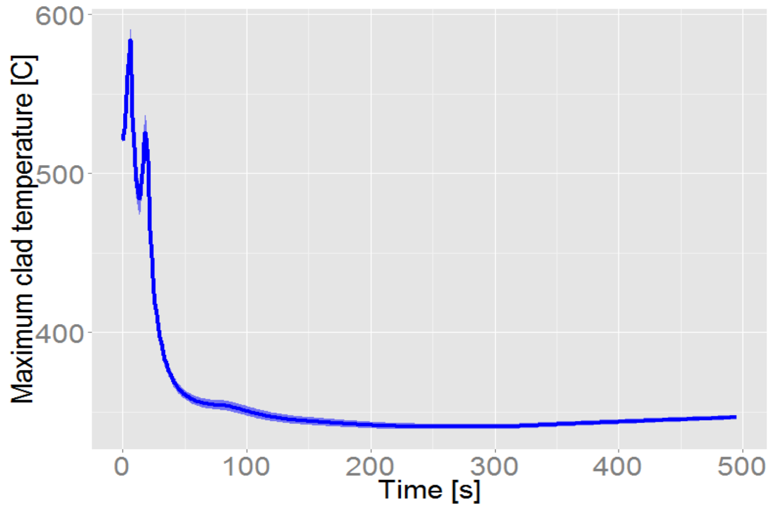
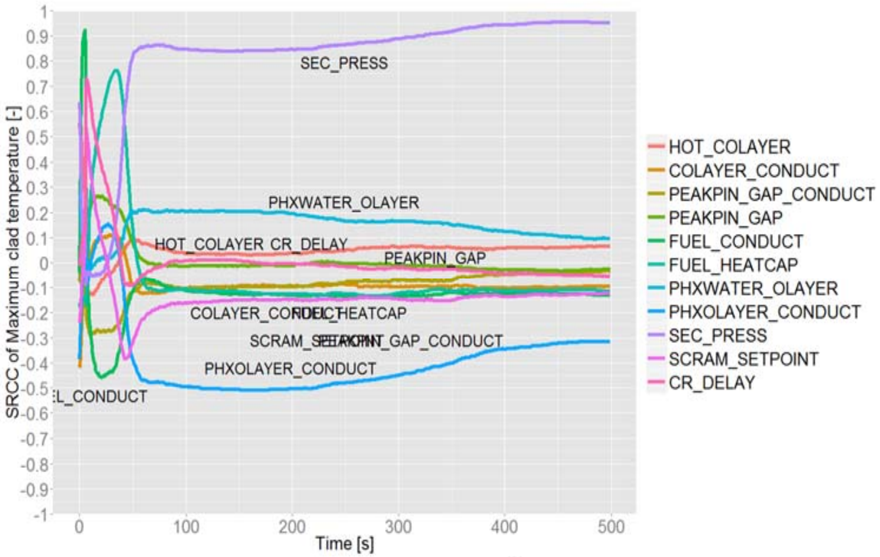


Sensitivity PLOF analysis: Peak clad temperature



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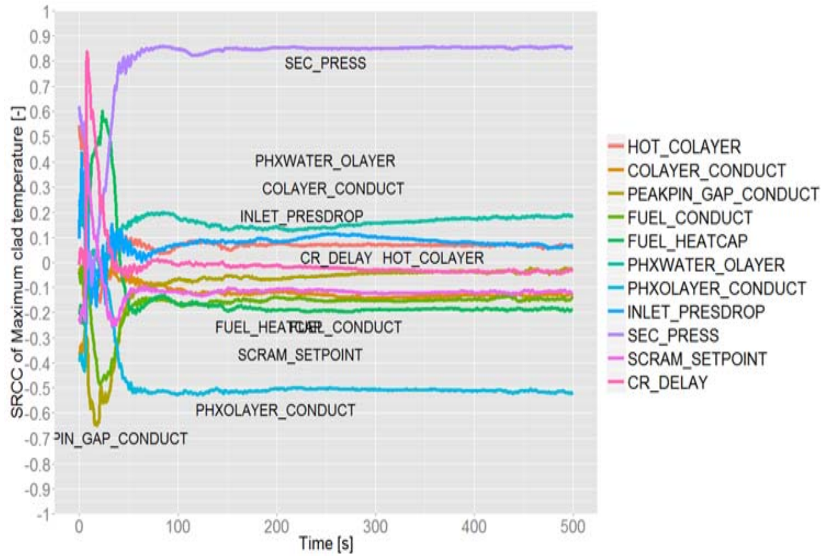

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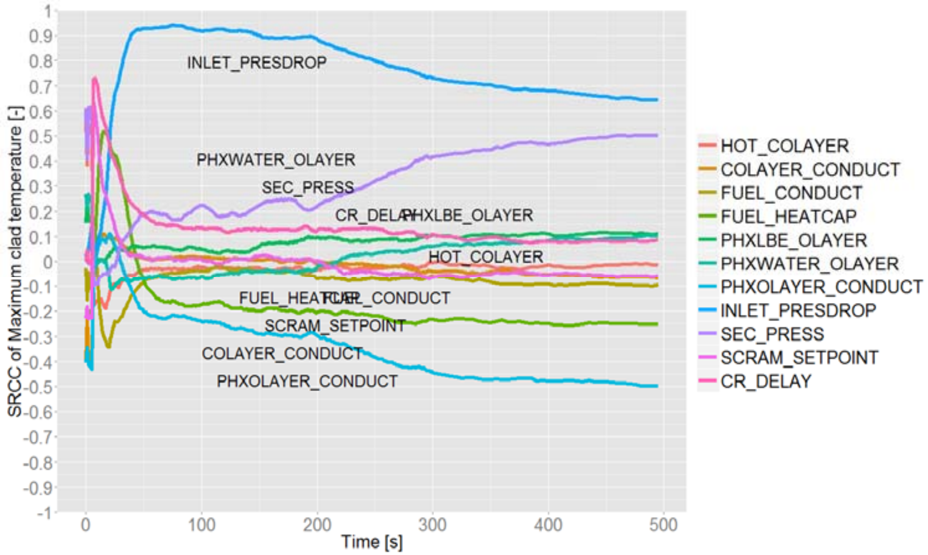

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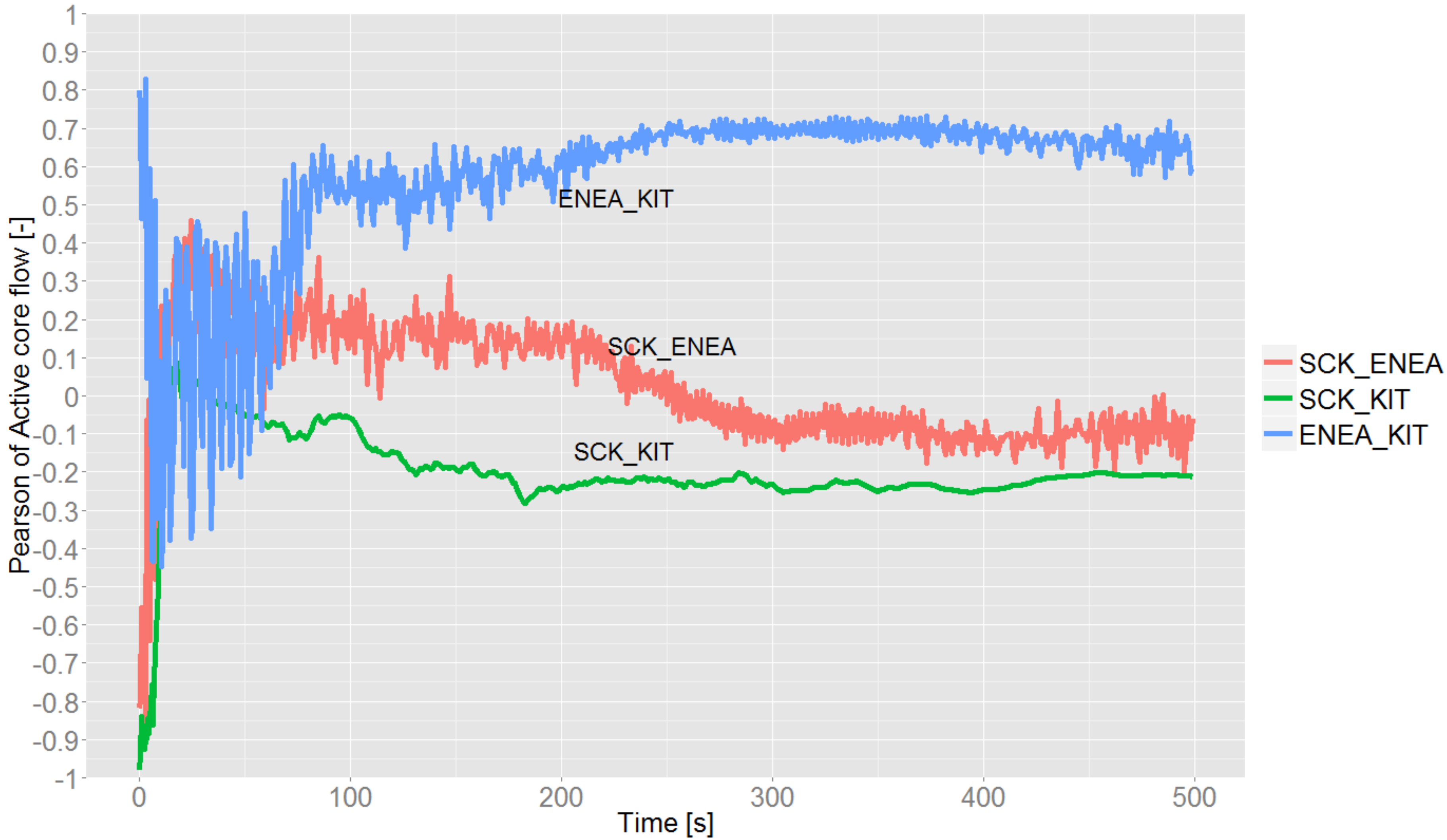
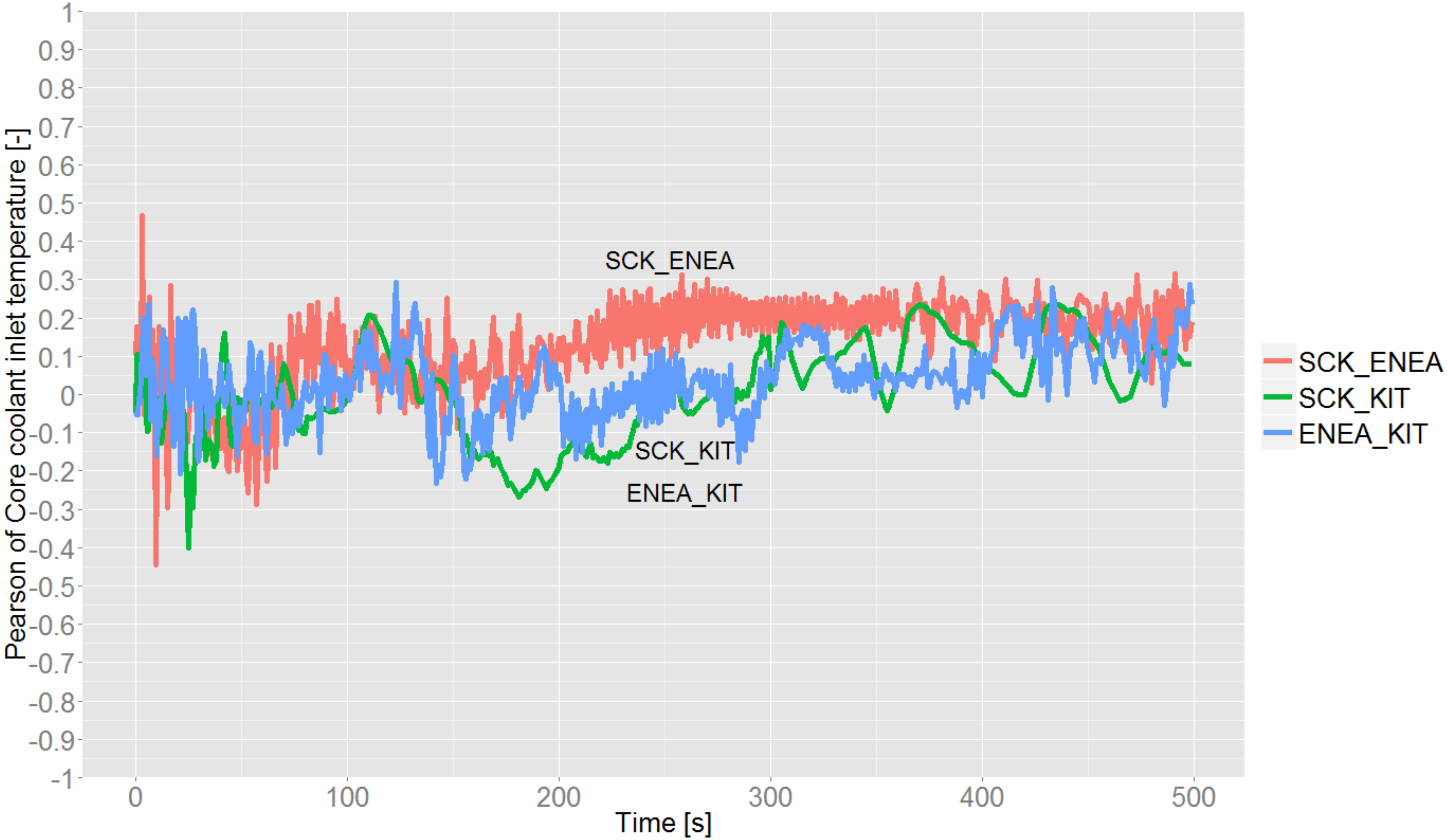
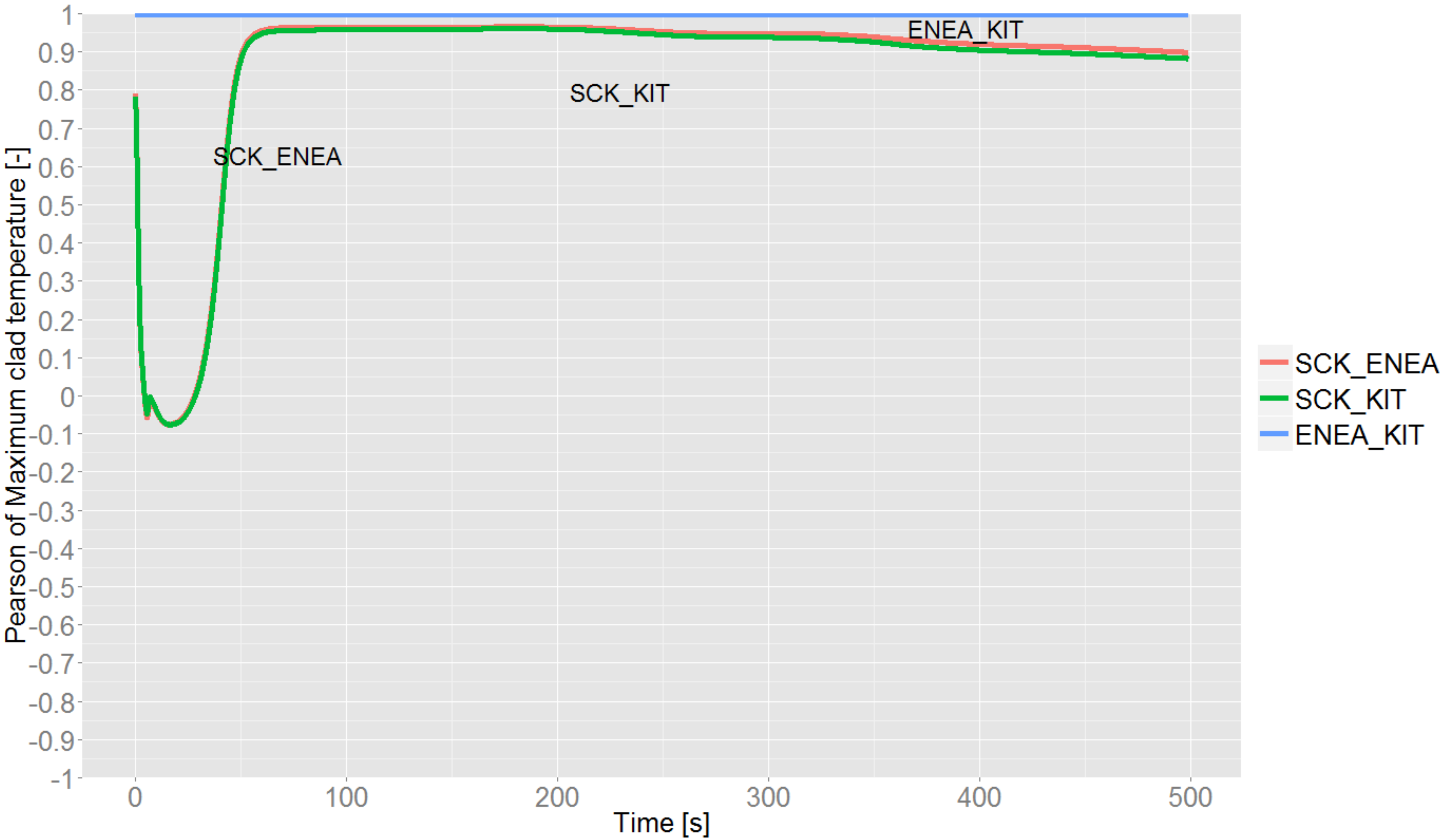
Pearson coefficients for PLOF: Active core flow



Pearson coefficients for PLOF: Core inlet temperature



Pearson coefficients for PLOF: Peak clad temperature



U + S PLOF analysis: conclusions

- Variation range relatively not wide for primary system parameters
- PLOF transient shows greater sensitivity (compared to ULOF) to the considered parameters
- Scram-related uncertainties have great influence over the beginning of transient evolution
- PCT influenced by fuel properties and core pressure losses in the first phase, while PHX heat transfer conditions (oxide layer properties) and secondary system parameters are more important in safe shutdown
- Secondary system related parameters have great influence over the transient, especially after the NC onset

U + S analysis general conclusions and proposed refinement

- Interesting conclusions provided by first U + S evaluations applied on MYRRHA safety analysis
- Good consistency between the three participants' results found in U + S results
- Majority of output parameters uncertainty not greatly affected by input parameters variation (uncertainty band almost not visible in most cases, PCT variation +/- 20°C)
- No real important parameter identified for ULOF sensitivity (SRCC coefficients almost always below 0.2) → ULOF transient not sensible to the variation of the considered input
- PLOF sensitivity more affected by chosen parameters:
  - Secondary system related parameters showing greater influence (especially in later stages)
  - Scram-related properties affecting early transient evolution

U + S analysis general conclusions and proposed refinement

- Comparative analysis of participants' U + S results shown through Pearson Correlation Coefficient.
- Comparative results coherent with the deterministic and the U + S analysis
- Possible improvement for Phase 2:
  - Most relevant parameter needed
    - Pump inertia
    - Reactivity coefficients
  - Variation range increase
  - Statistical distribution change (from Gaussian to uniform)

Interfaces with other Tasks/Work Packages

- Task 2.2 will interface with other Tasks in the MAXSIMA project:
  - Task 2.1: evaluation of MYRRHA new core (design revision 1.6) with the complete set of related parameters (peak factors, reactivity coefficients, etc…)
  - Task 2.3: comparison of reactivity insertion analysis performed with SIMMER-III code with results obtained through system codes
  - WP6: new DHR solutions proposals analysis with potential interest for MYRRHA safety systems design
- Task 2.2 future activities development:
  - Second iteration of U + S analysis with refinement of parameters range and distributions
    - Compatible with man-months availability?
  - Finalization of Phase 1
  - Preparation of databases and technical notes for Phase 2 (delayed because of design activities)

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Belgian Nuclear Research Centre

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