CATHARE-TRIO_U Coupled Calculation of the Phénix Reactor Natural Circulation Test

R. BAVIERE, N. TAUVERON, D. PIALLA, F. PERDU, D. TENCHINE, E. GARRE, S. LI

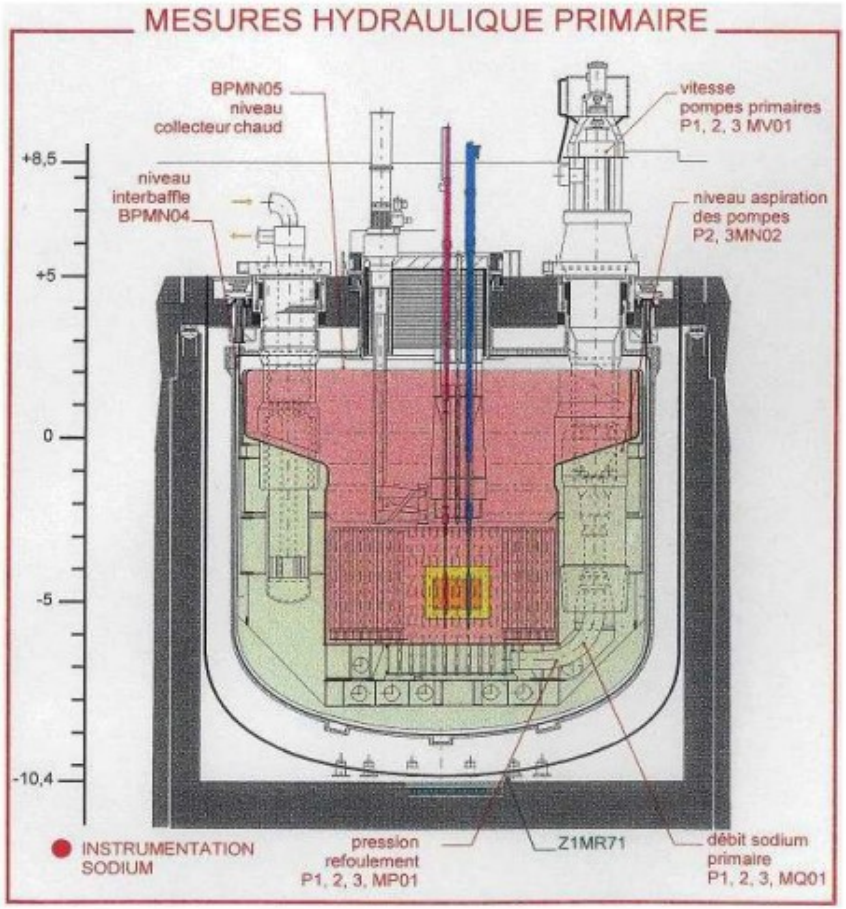
CEA, FRANCE

Outline

- Phenix Reactor
- Natural Convection Test
- Coupling Methodology
- No Mixing Model
- Calculation
- Sensivity Analysis
- Iso Thermal Calculation
- Refined Model
- Conclusions and Perspectives

Phenix Reactor

- PHENIX = French SFR (1973-2009)



- Prototype + research
  - 560 MWth then 350 MWth since 1993
- Suspended reactor block – Pool type
  - main vessel 11,8 m in diameter
  - ~ 800 tons of primary sodium
  - vessel cooling system
- Hexagonal fuel assemblies in core
  - 4.3 m in height - 217 pins each
  - inner-core, outer-core, annular fertile zone, steel reflectors and lateral neutron shielding rods
- 2 pairs of IHX (since 1993)
- 3 primary pumps

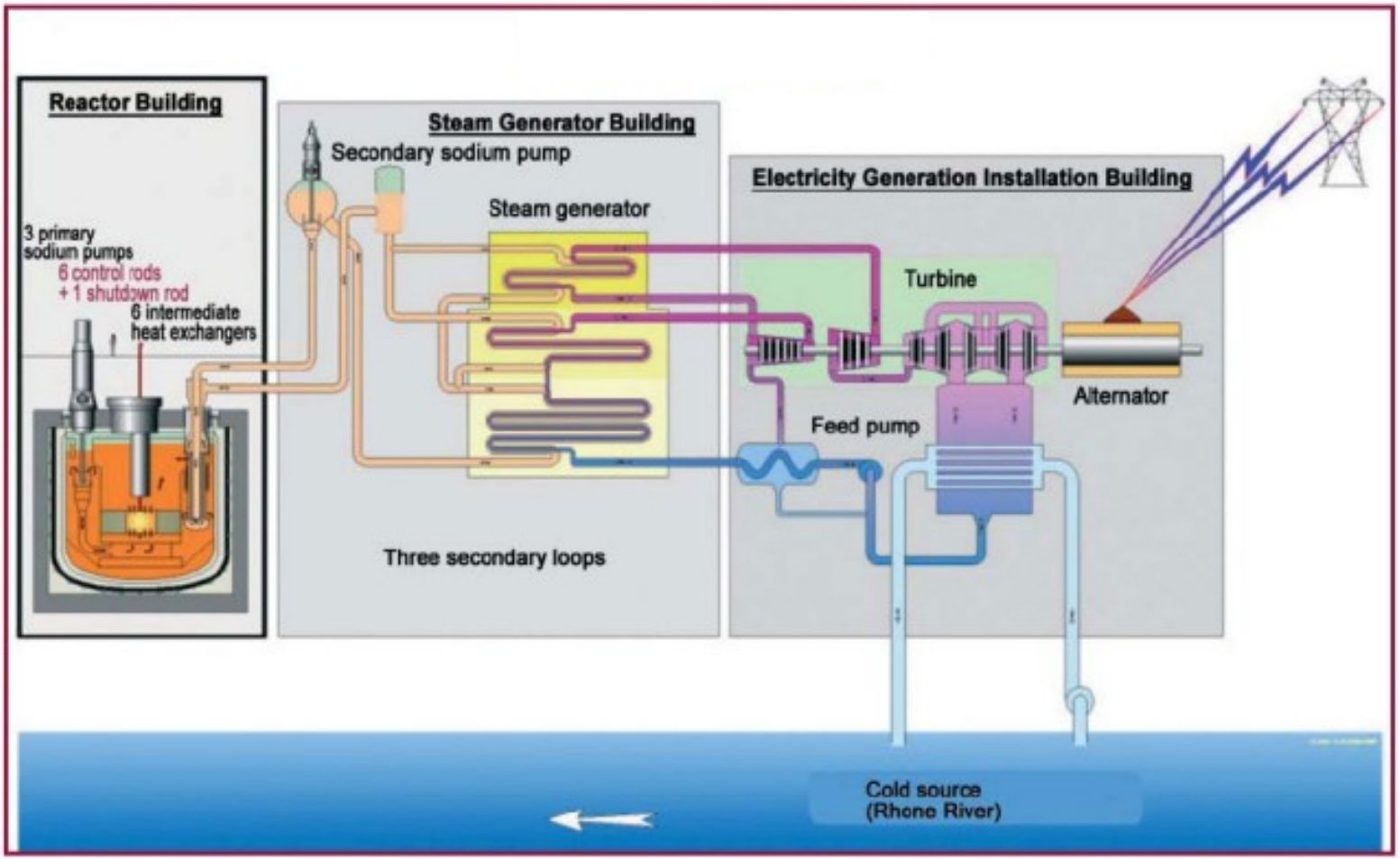
Natural Convection Test

Time line

t-

Initial State :

Decrease from 350 to 120 MWth
3 Pumps
2 Secondary Loops



Natural Convection Test

Time line

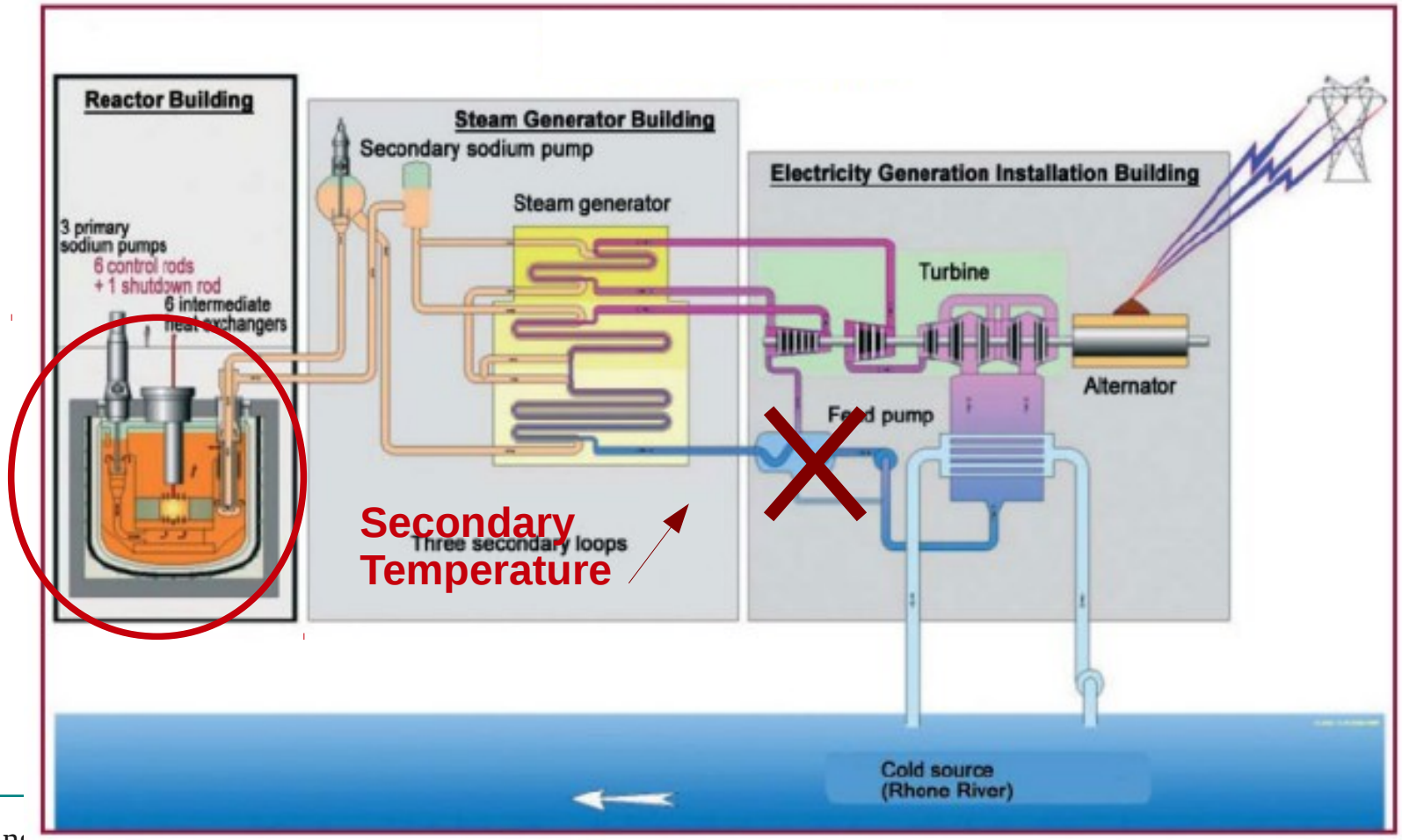
t- t0

SG feedwater system is switched off

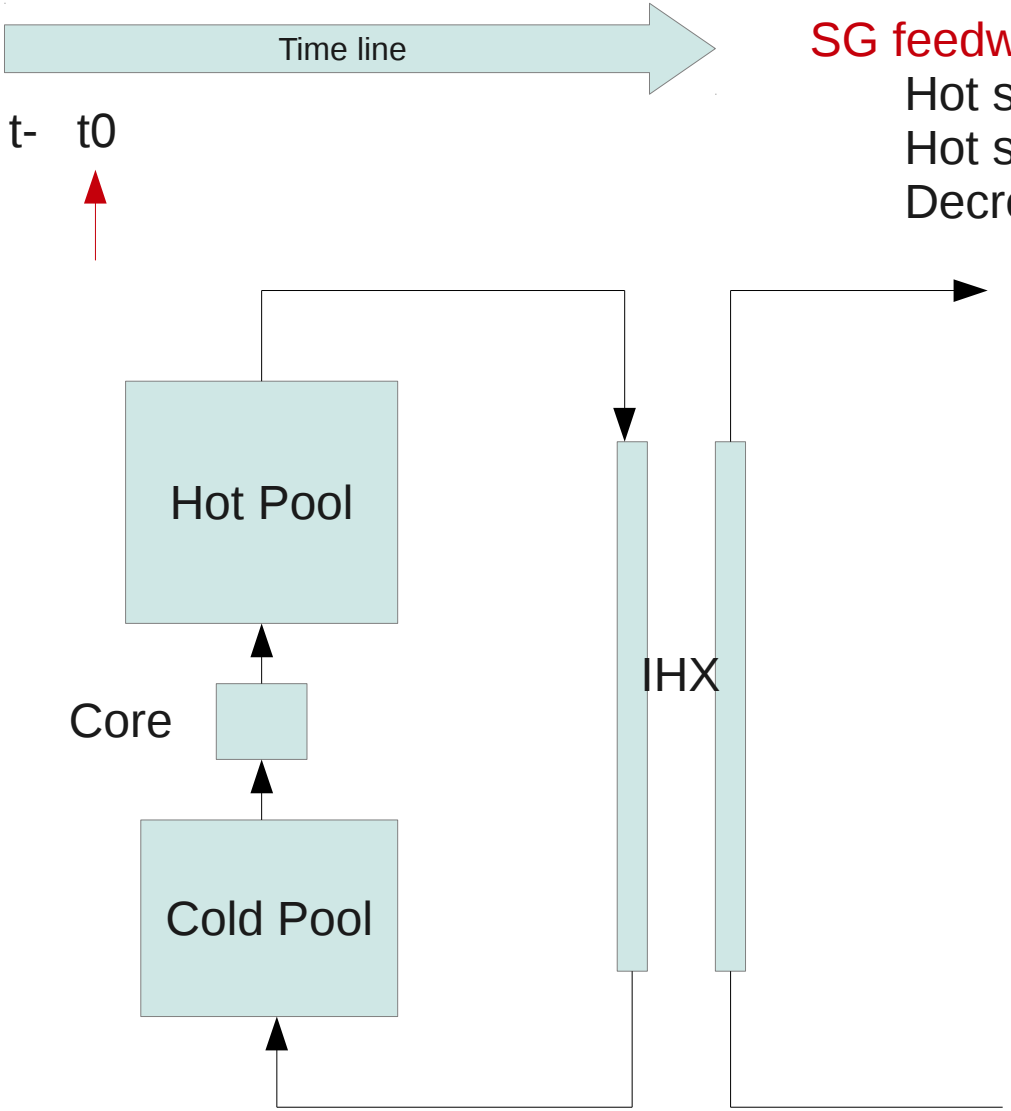
Hot shock at primary IHX

Hot shock at core inlet

Decrease of core power



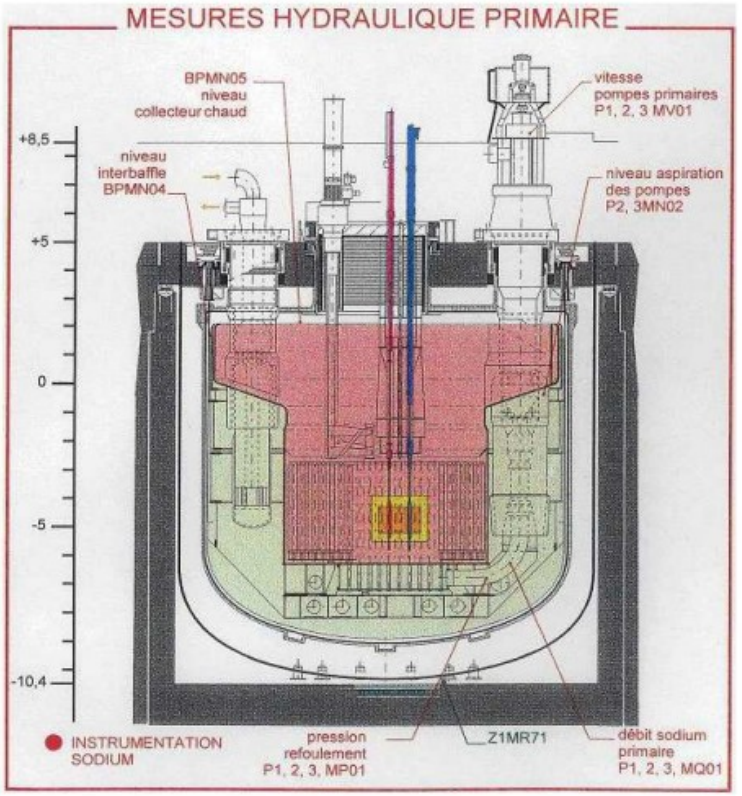
Natural Convection Test



SG feedwater system is switched off

- Hot shock at primary IHX
- Hot shock at core inlet
- Decrease of core power

Unprotected Forced Circulation



Natural Convection Test

Time line

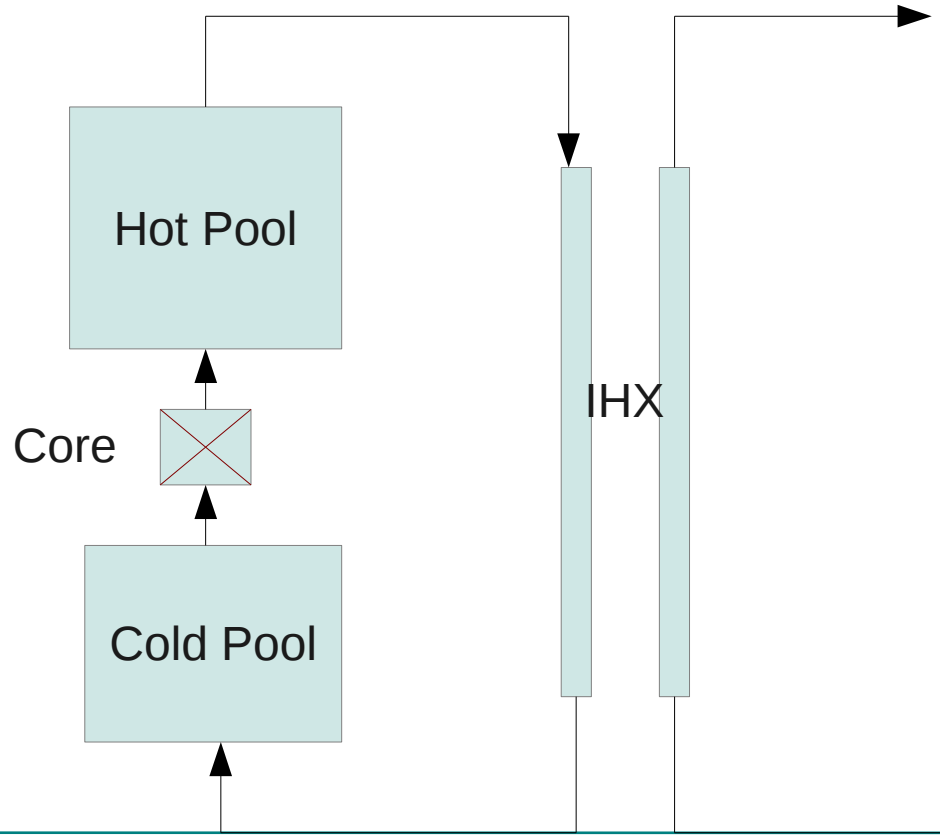
t- t0 t1
= t0+458

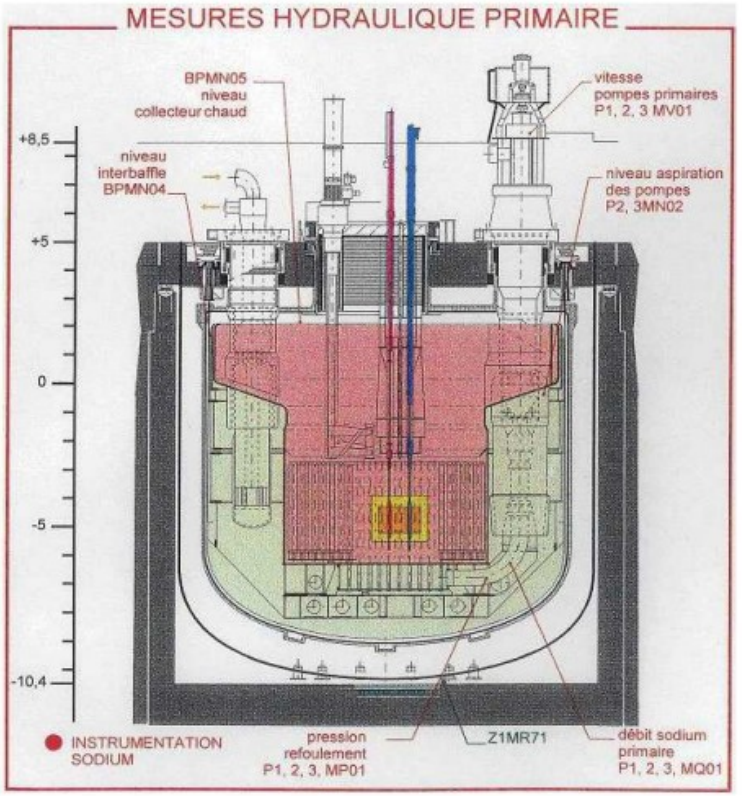
Reactor Scram
+ Secondary Pump Trip
+ Primary Pump Trip

Thermal loss
~ 1 MWth

Cold shock
followed by hot shock in Hot pool

Natural Circulation





Natural Convection Test

Time line

t- t0 t1 t2
= t1+9 982s

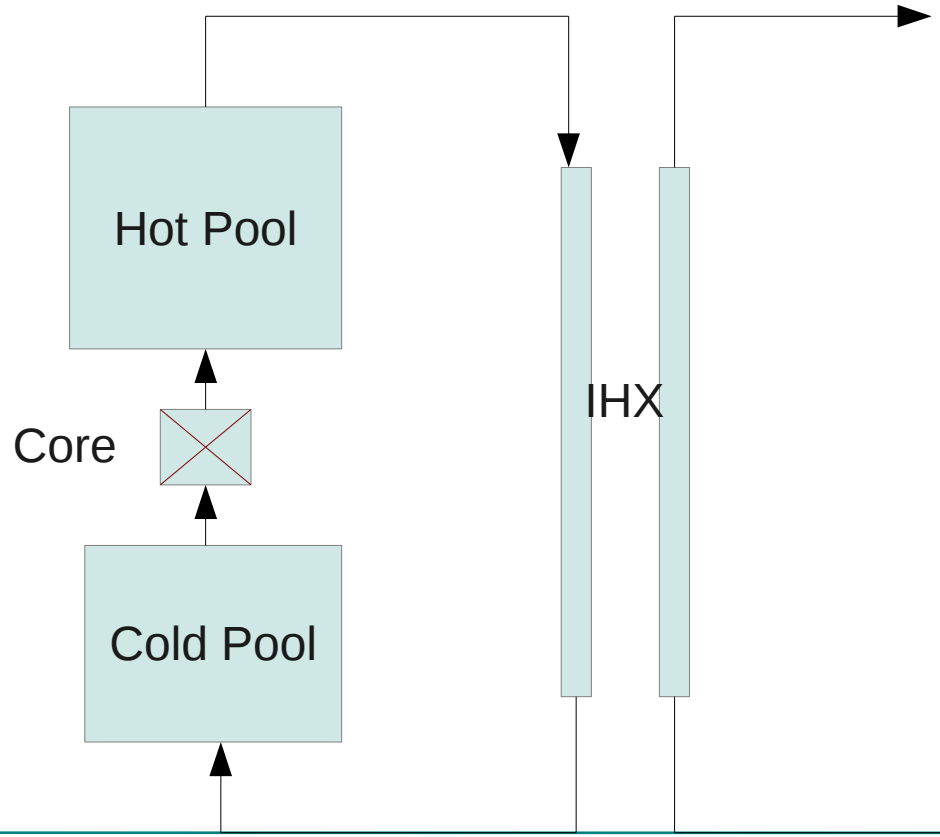
Opening of SG casing

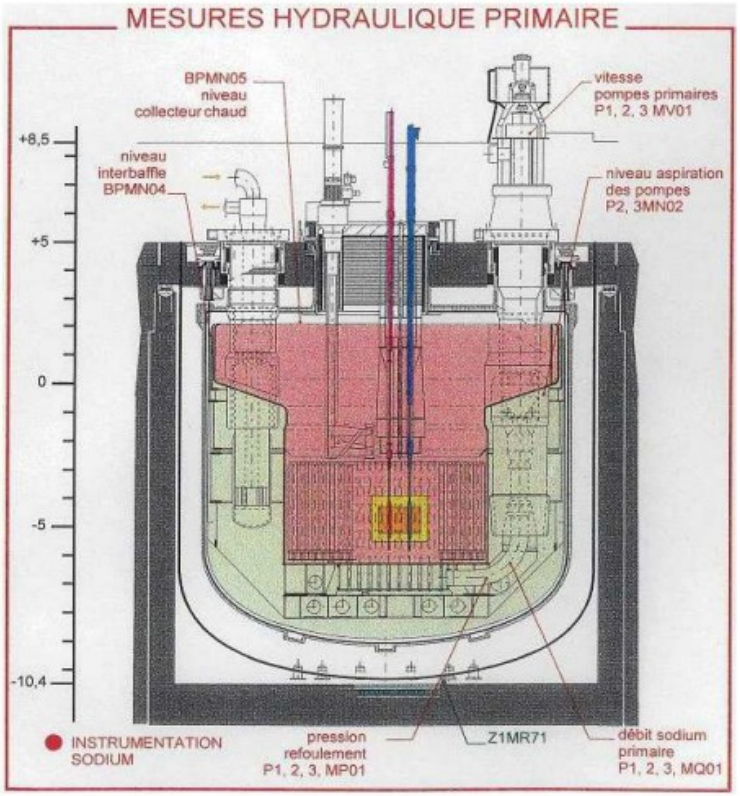
Thermal loss
> 3 MWth

Decrease of primary average temperature

Protected Natural Circulation

End of test = t2 + 13 560s





Coupling

- System codes
  - Represent the whole reactor or facility
  - Low resource consumption
  - Coarse representation
  - Not well suited for big 3D volumes

- CFD codes
  - Fine mesh of a local volume
  - Fine phenomena can be represented : mixing, stratification, turbulence,...
  - High resource consumption
  - Not suited for large scale systems

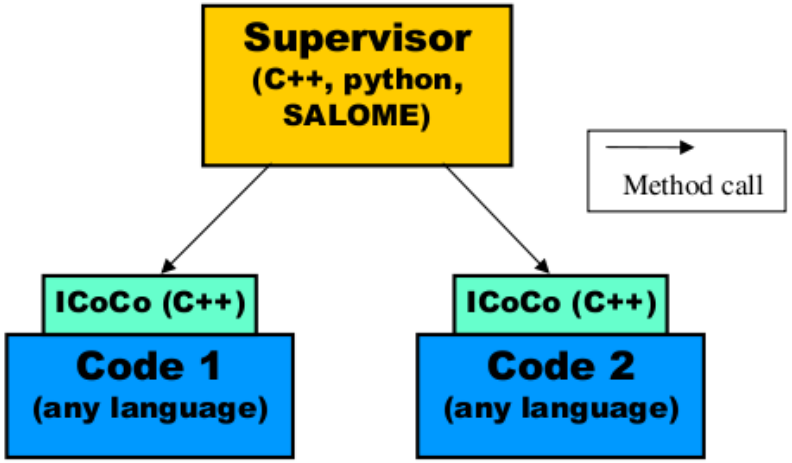
- System-CFD coupling
  - Uses CFD fine description where necessary, with feedback to the system.
  - Computes the rest of the loop with system code, giving smart boundary conditions to CFD.
  - Optimizes the use of computer resources by concentrating them where 3D phenomena are important

Computer Architecture

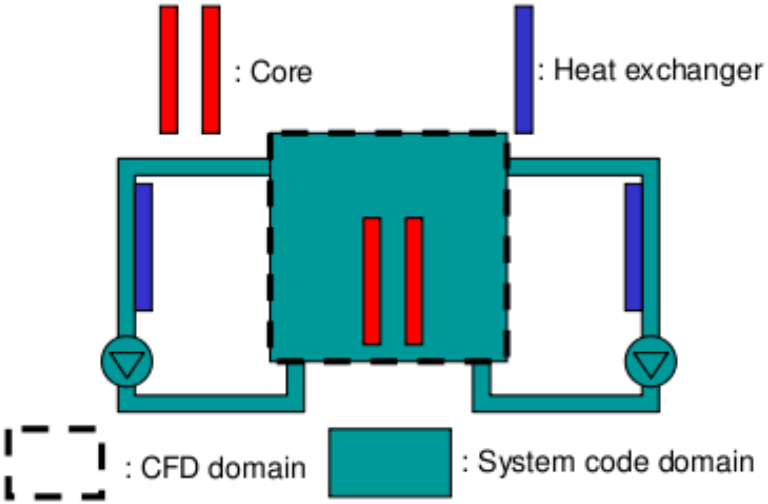
- Computer architecture based on a common API called IcoCo:
  - Flexible solution
  - Algorithm outside the codes : easy to read, modify, reuse
  - Interpolation and data manipulation outside the codes

- ICoCo "Interface for Code Coupling"
  - Defines a C++ mother class with standardized methods
  - For the codes : specifies WHAT the methods should do
  - For the supervisor : specifies WHEN the methods can be called

- Methods define
  - Time-marching (including iterations)
  - Field exchange
  - Save / restore
  - Compatible with parallel computing, and parallel interpolation



Numerical Considerations



Domain decomposition

System code does not calculate CFD part

Overlapping

System code includes CFD part

Same system data deck
Easy & progressive approach
Flexible
Numerical stability

Boundary conditions for CFD

- Mass flow-rate imposed at every boundary
- Enthalpies imposed at every boundary

Coupling Methodology

Feedbacks on system code

Energy Feedback

System energy equation is replaced at each boundary point by the CFD feedback value.

Momentum Feedback

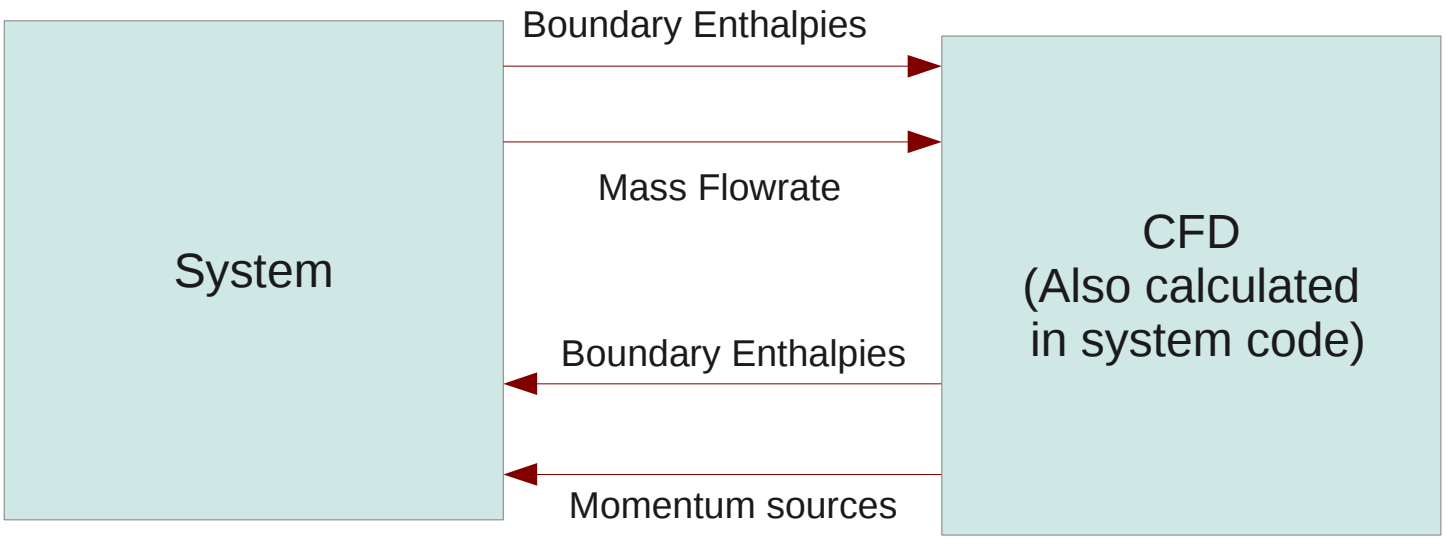
Needed to correct the system head loss (or gain) through the CFD domain

$$[P_0 - P_{boundary}]_{system} = [P_0 - P_{boundary}]_{CFD}$$

Reconstruction of free levels (density variations)

Non compressible flow with Boussinesq approximation

Coupling Methodology



Validation on simple analytical test cases and on Cathare-Cathare transients (NCT)

One Cathare module plays the CFD role

No Mixing Model

Big volumes
System = 0D model
not enough

Where should CFD be used ?

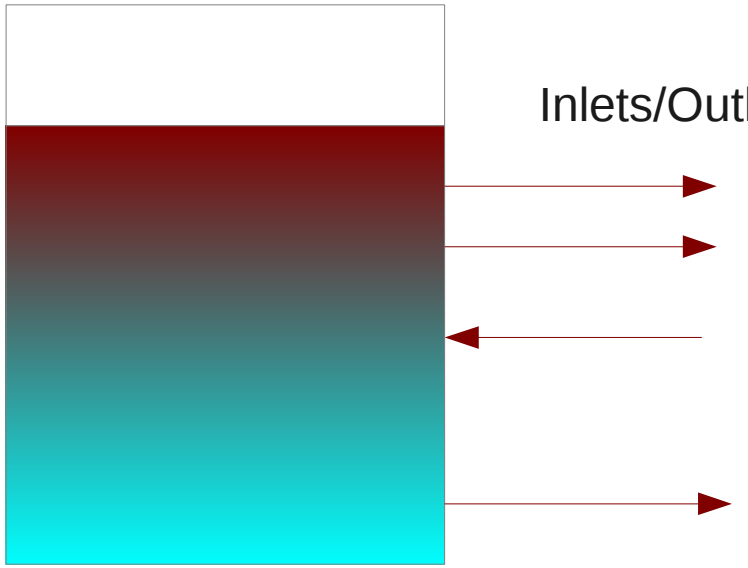
Where local phenomena occur

Where system code's behaviour is highly sensible to the model

No Mixing Model

1D non-compressible thermalhydraulic problem with free surface but no flow mixing

Maximum
layer number
can be fixed

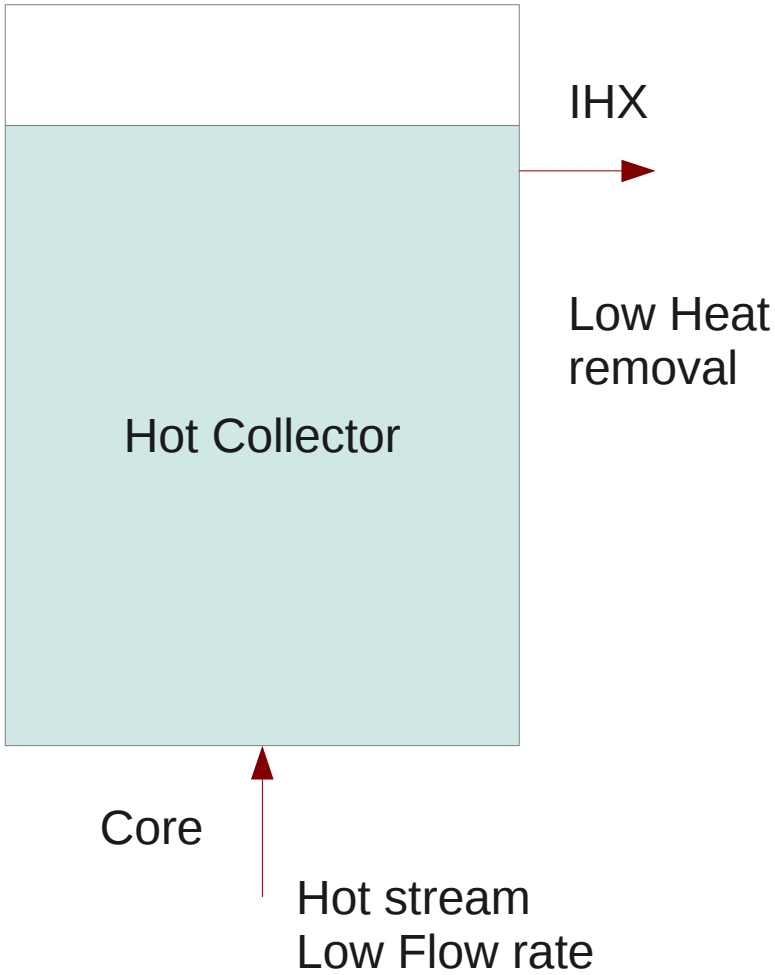


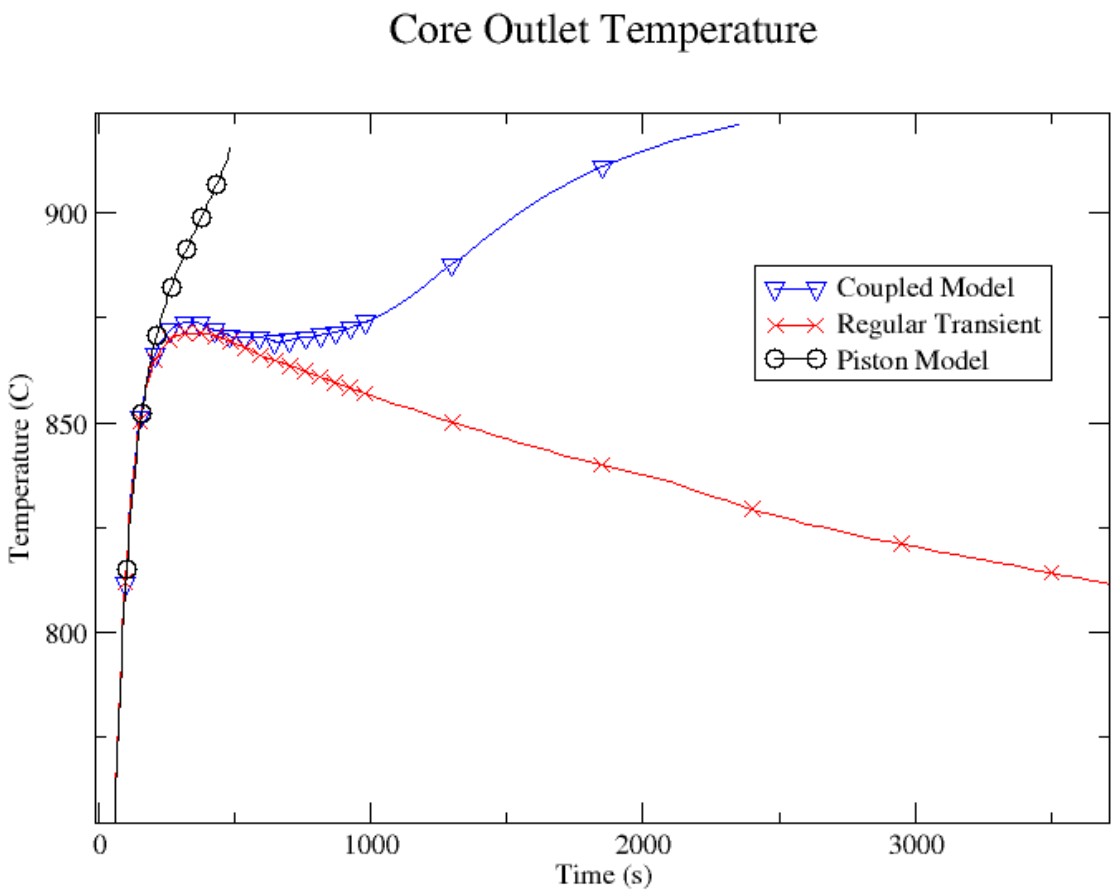
Inlets/Outlets at fixed elevations

Temperature
Density
Mass Flowrate

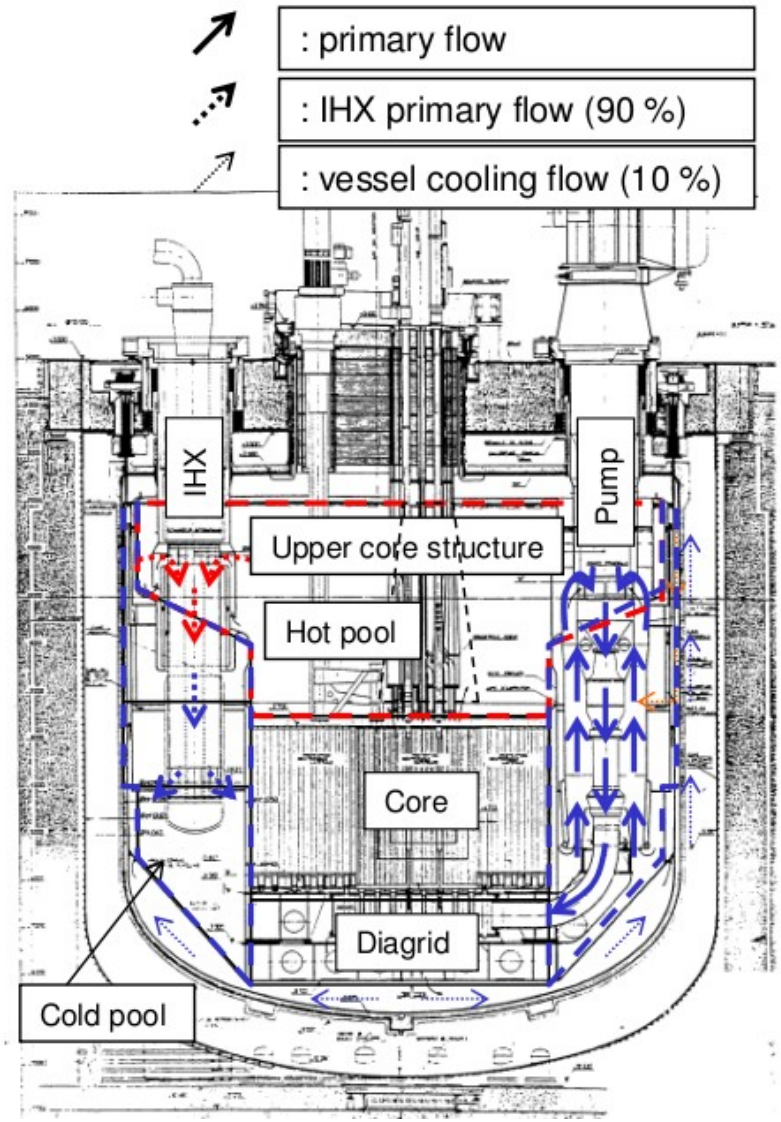
No Mixing Model

Example on Astrid Reactor





Calculation



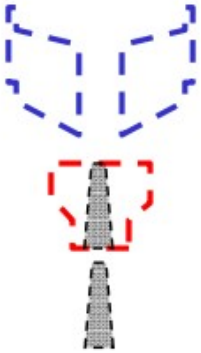
System part :

- Primary circuit
- Secondary loop = input data

CFD part :

- Upper Core Structure (solid)
  - 50 000 mesh
- Hot collector (fluid)
  - 350 000 mesh
- Cold Collector (fluid)
  - 880 00 mesh

CFD SCALE:



: CFD domain for cold pool (fluid)

: CFD domain for hot pool (fluid)

: CFD domain for the upper core structure (solid)

Calculation Porting

Calculation ported to new versions of codes :

- Cathare v25_3 mod 2.1
- Trio_U v1.6.6

And ported onto new cluster

- ERIS (CEA)

More processors were added :

- Total of 50 procs instead of 20

Good agreement = Robust models and codes

Calculation time reduced

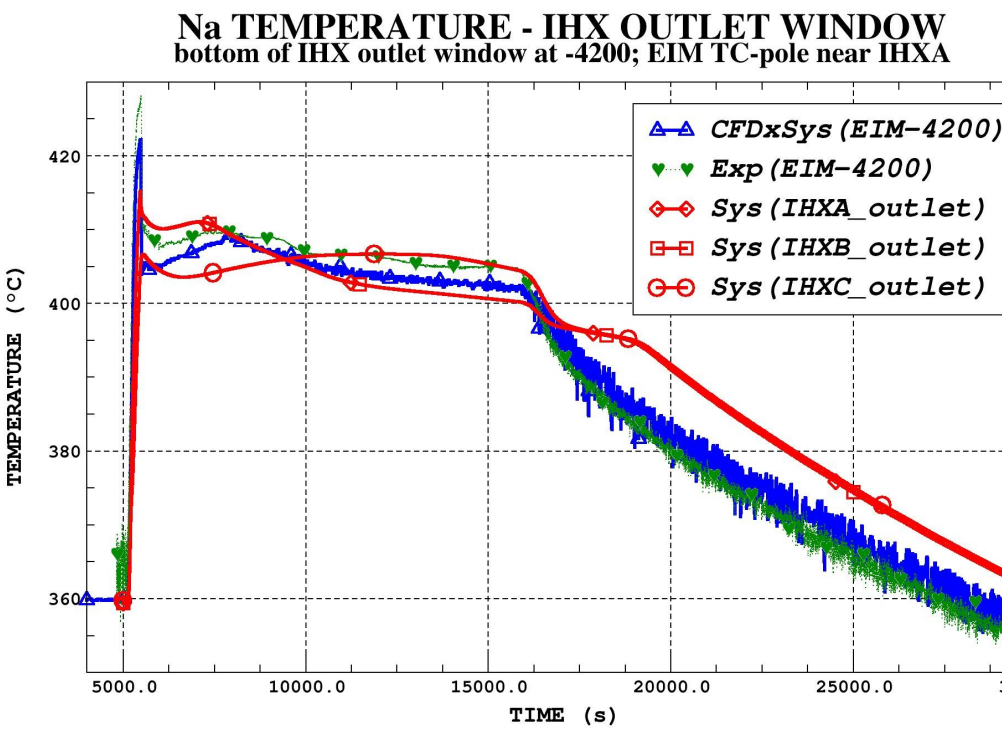
- 3 days intead of 8 days

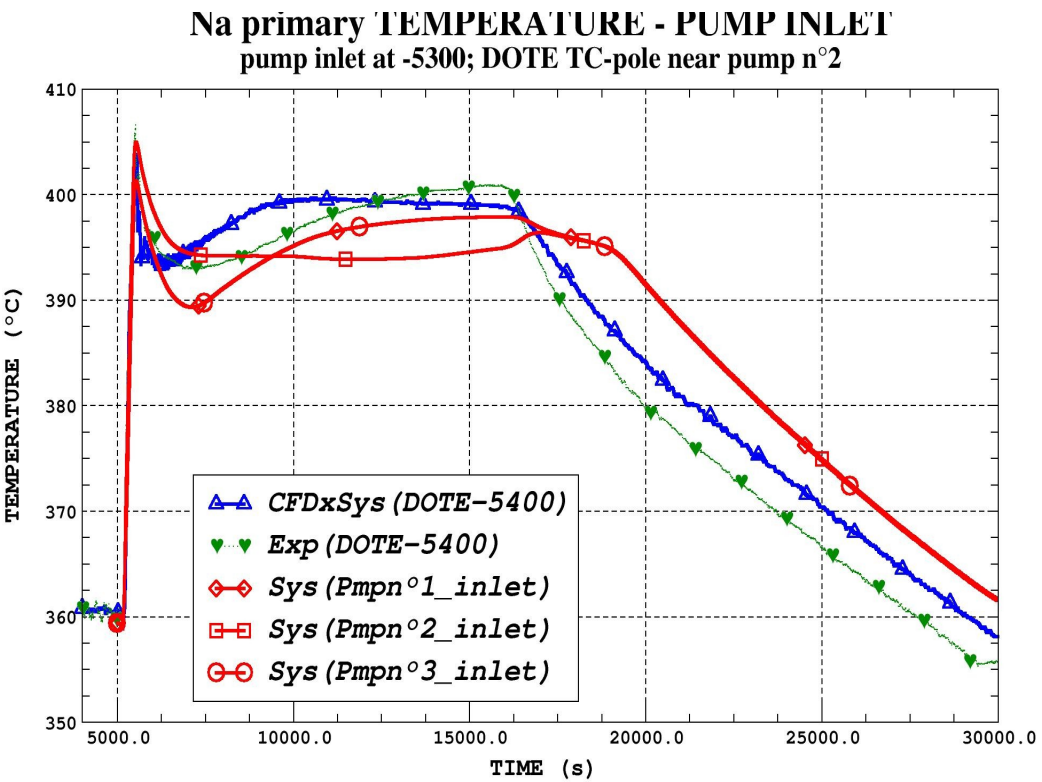
Calculation

THINS February 2013 - Stockholm

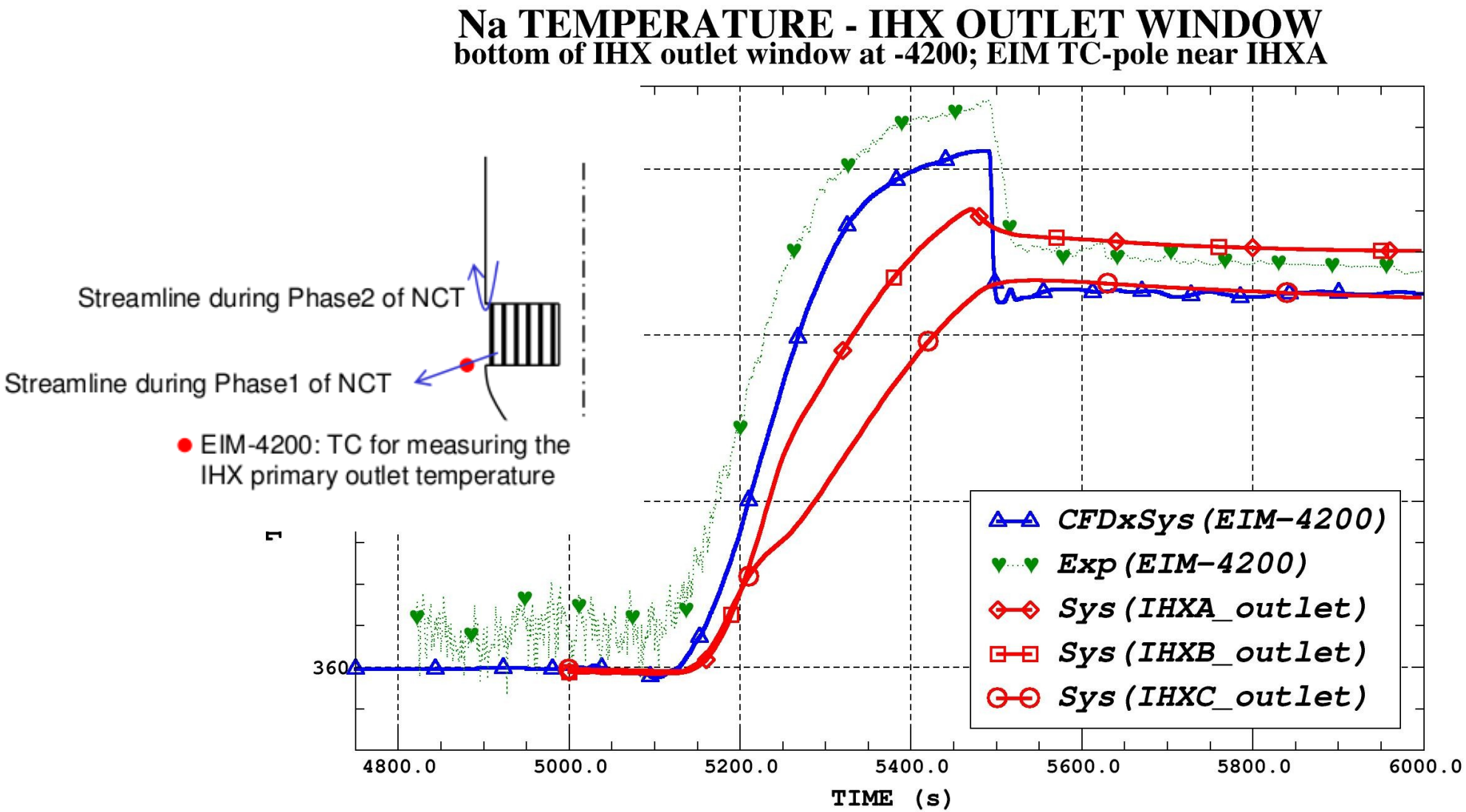
See movie

Good agreements between Numerical and Experimental results

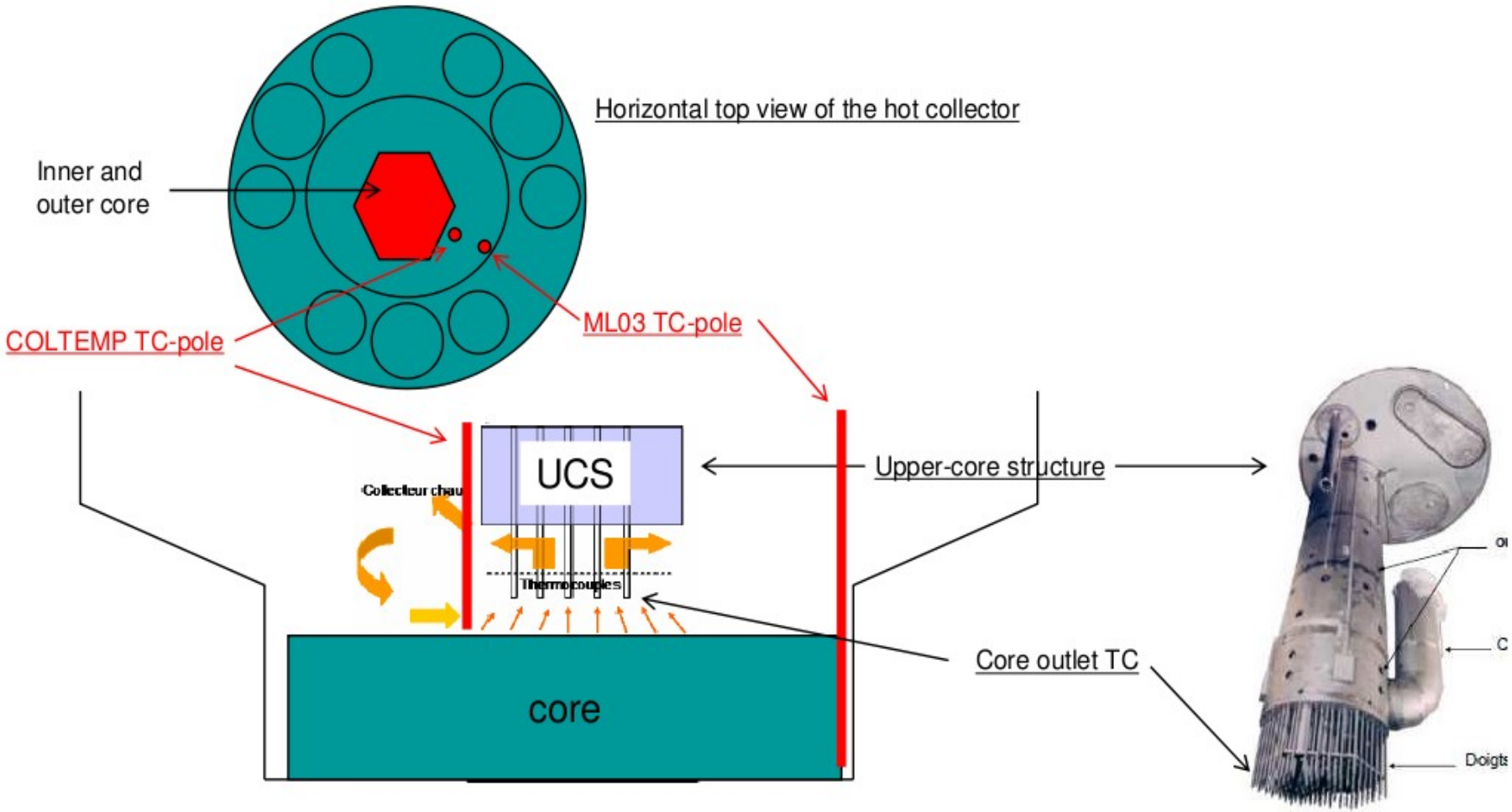




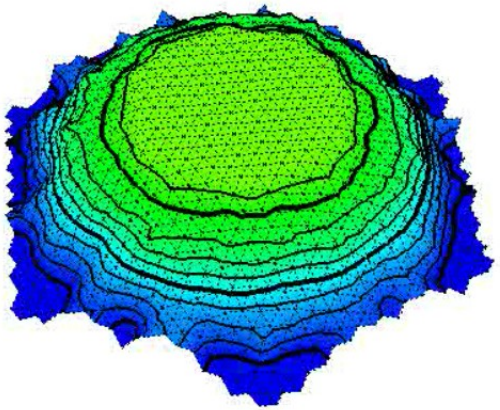
Calculation

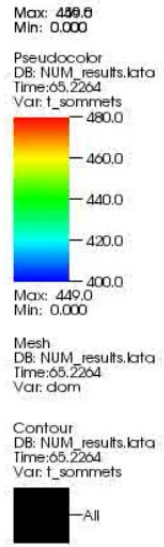


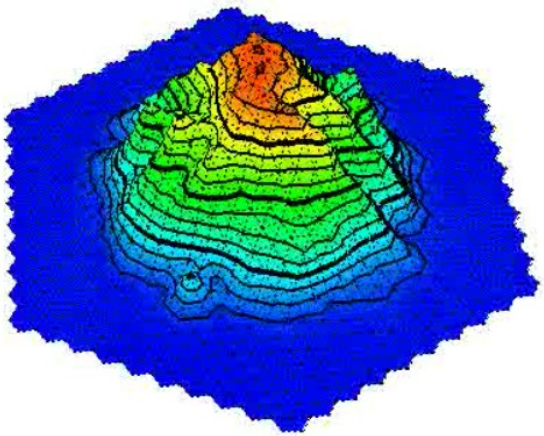
Calculation

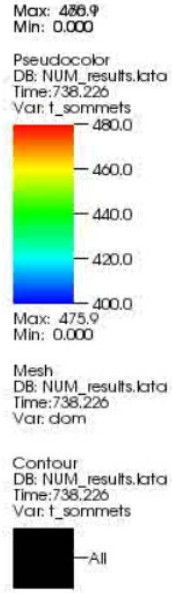


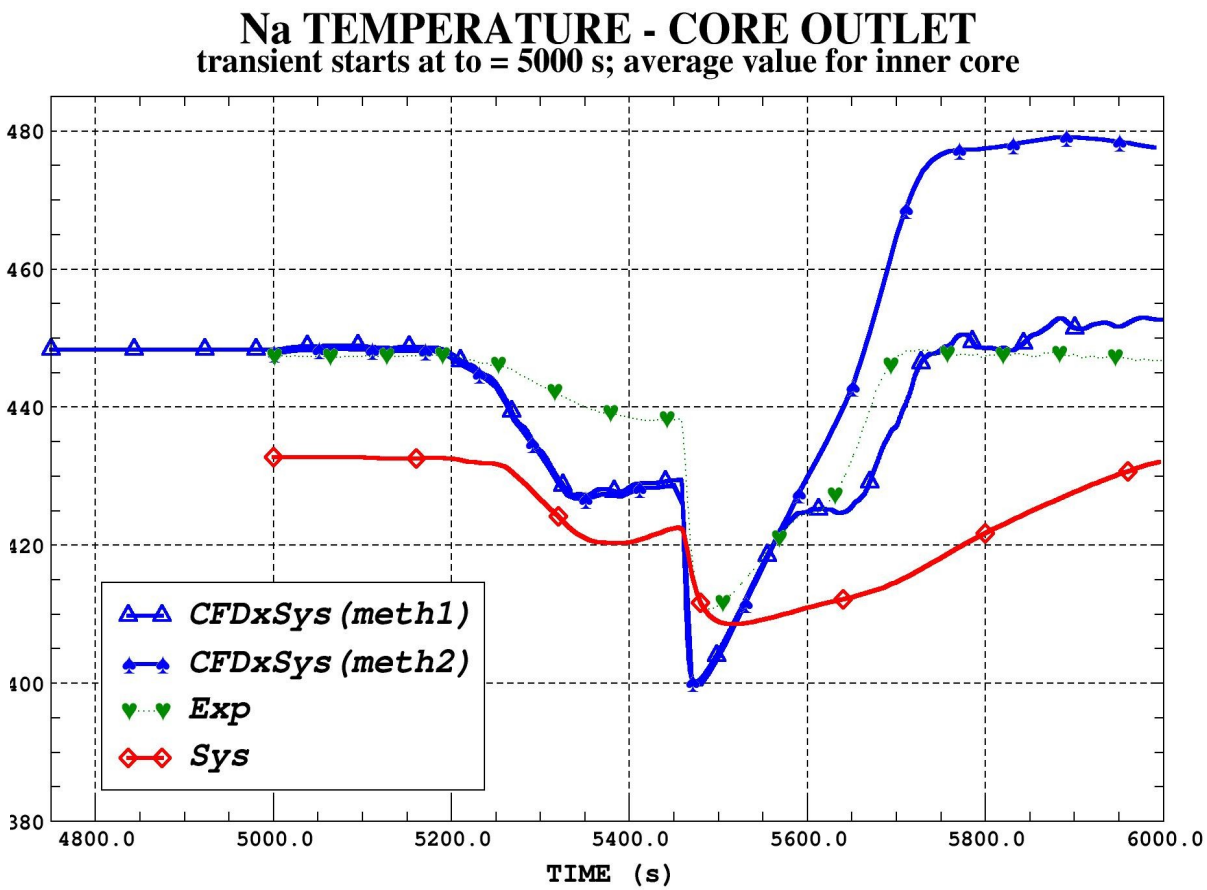
Calculation





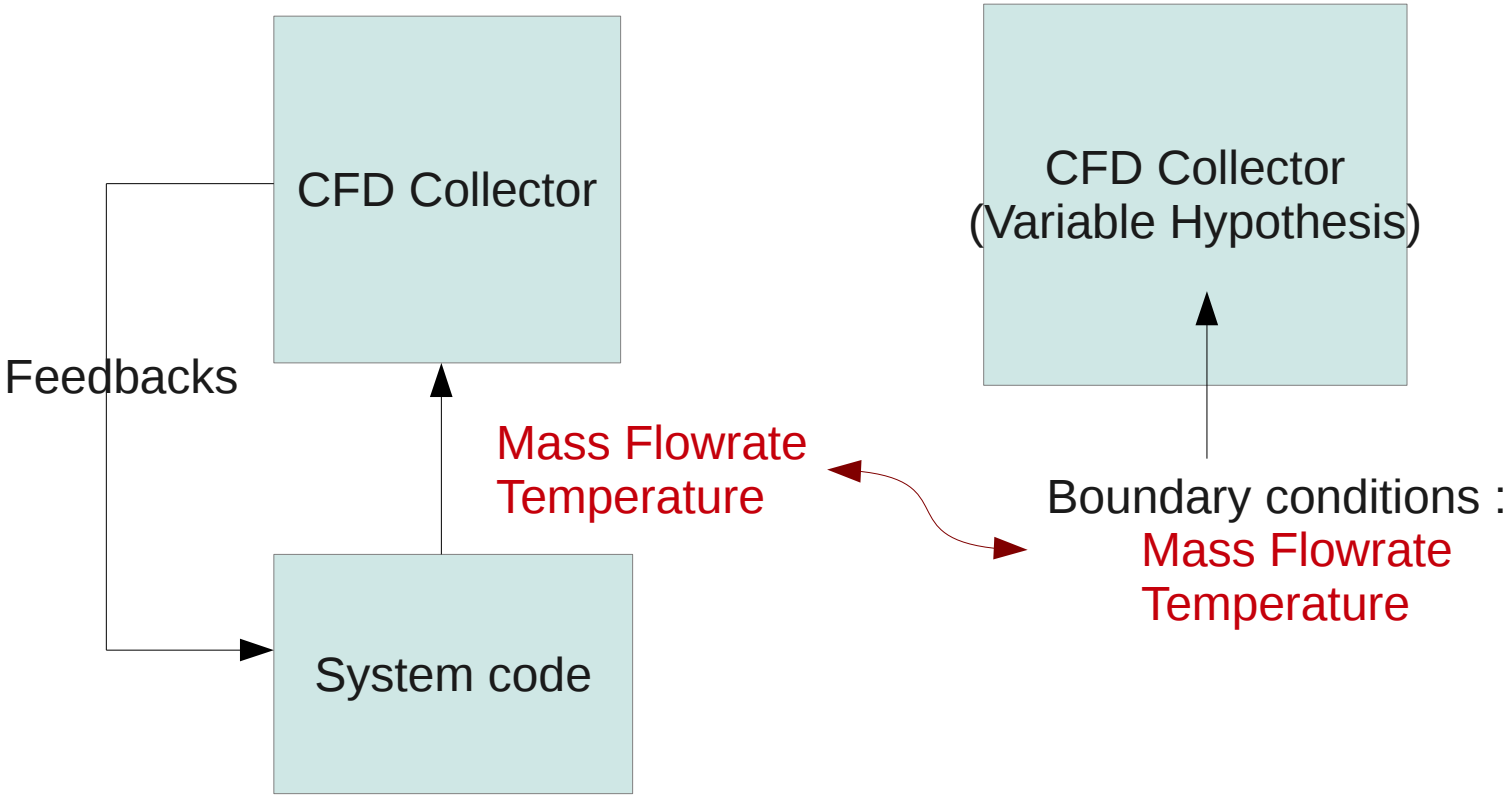






Sensivity analysis

Methodology



Reference Coupled calculation

Sensivity Analysis

Good agreement with reference
Fast computation

Sensivity Analysis

Turbulence Model

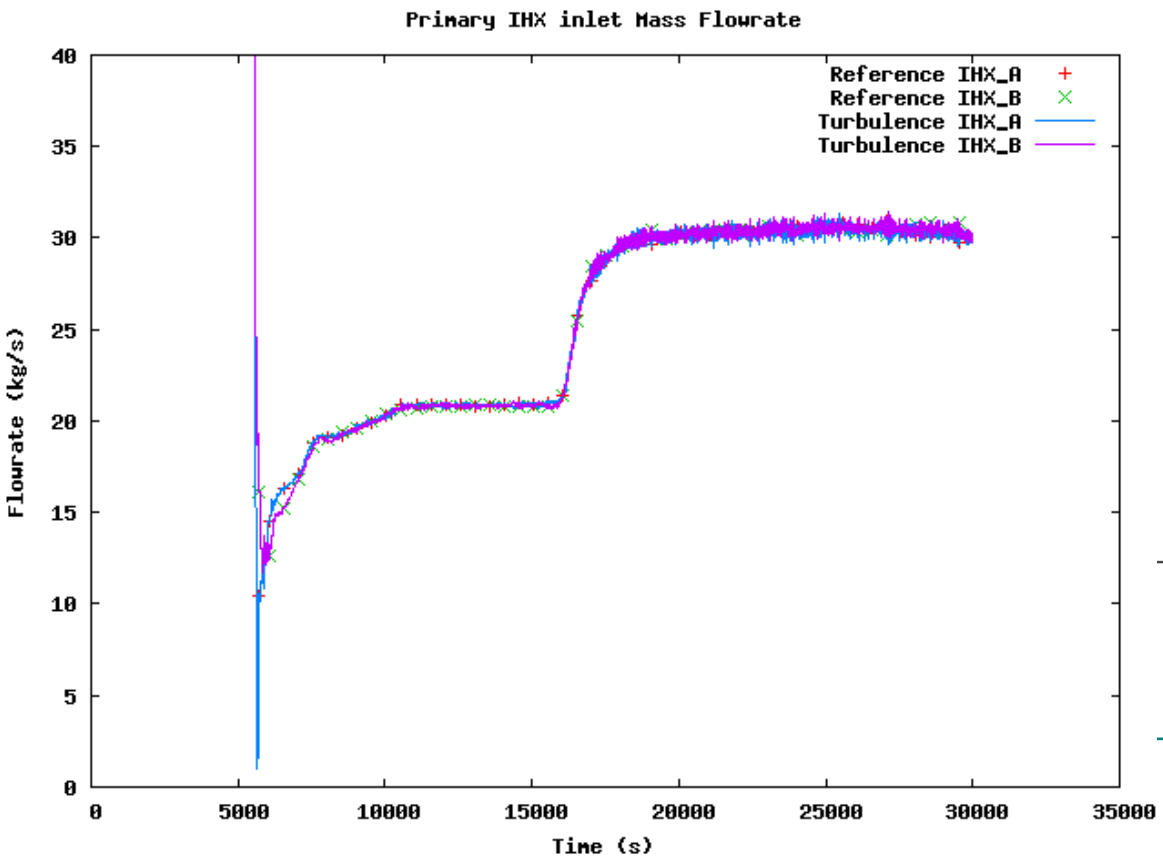
Smagorinsky sub-grid model

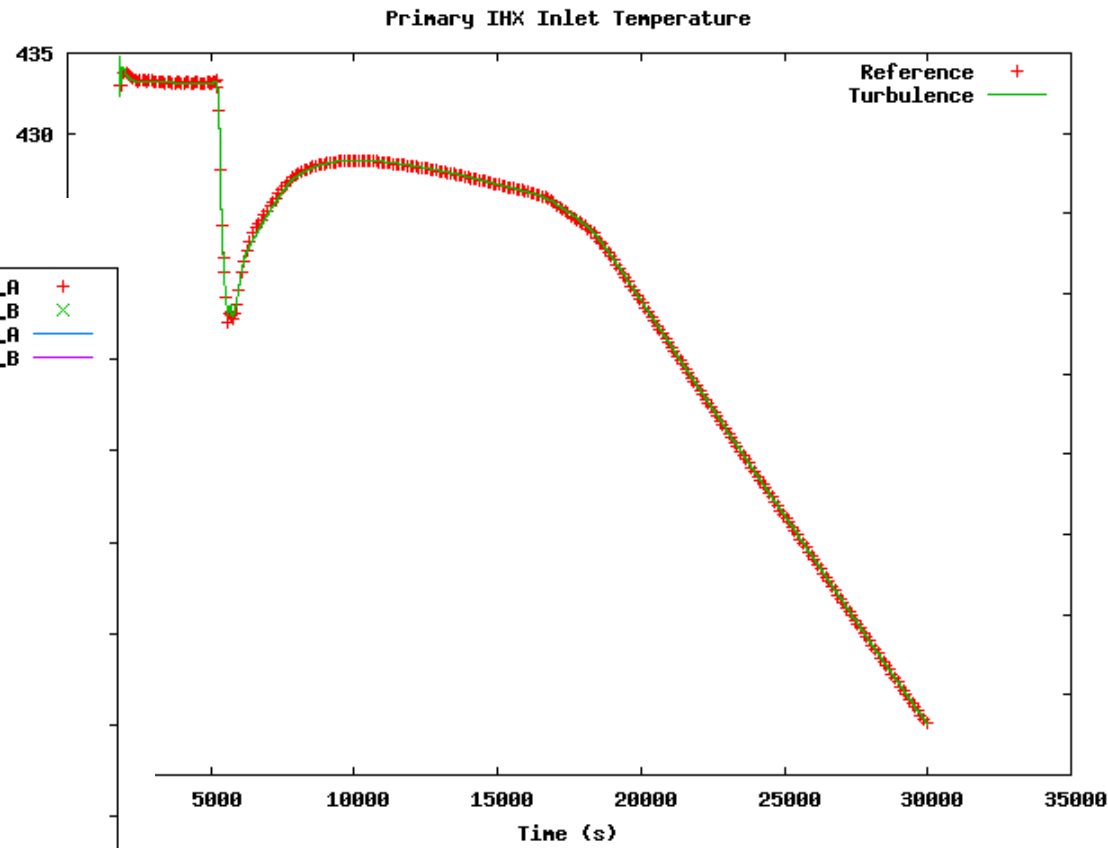
Cs = 0,1 to 2,5

No Impact on results

Low Re number

Diffusive scheme

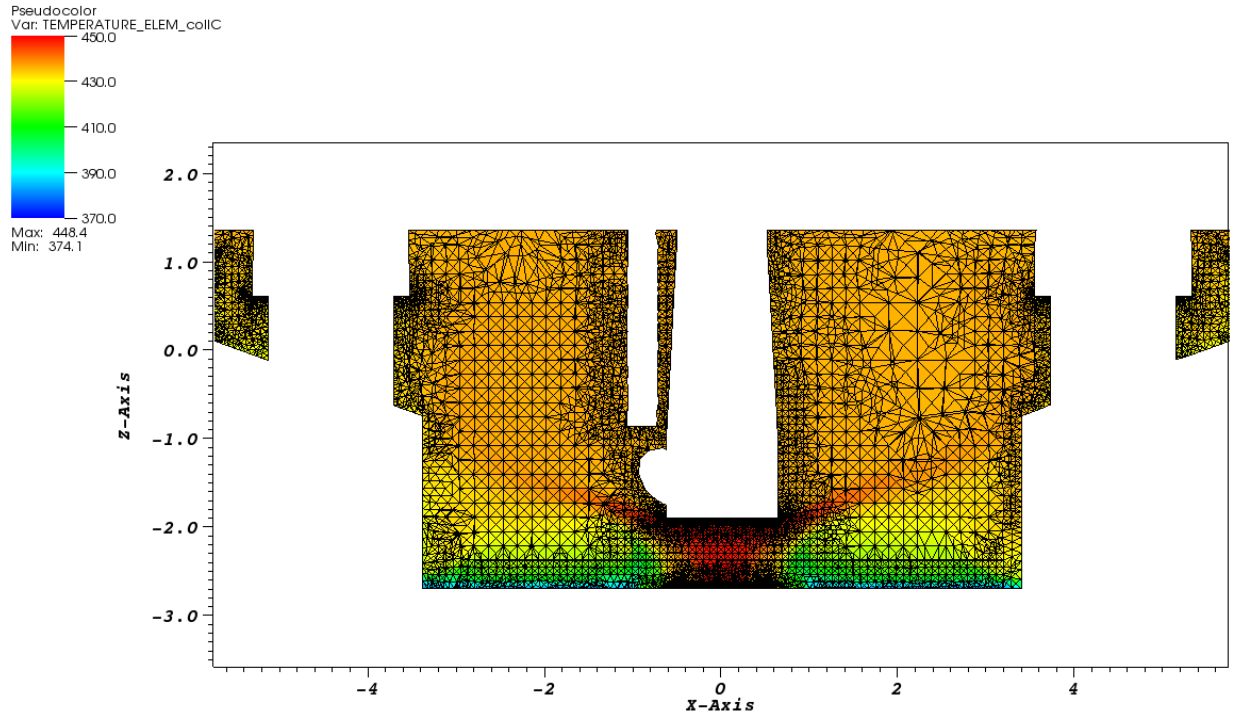




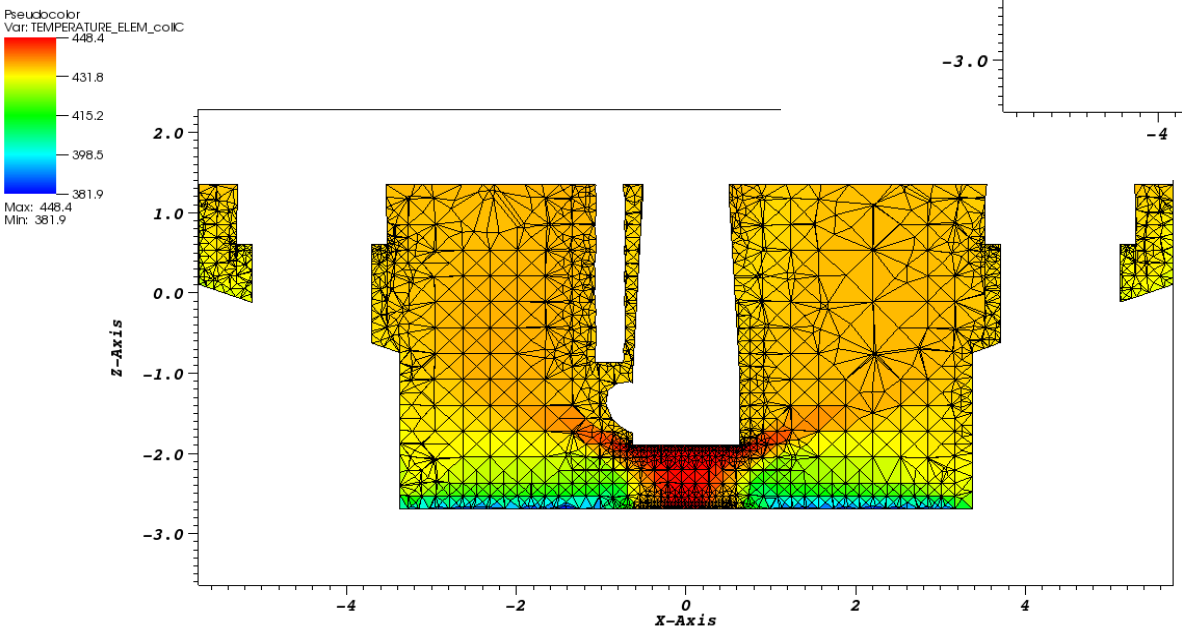
Sensivity Analysis

Mesh refinement

Isotropic and uniform x8



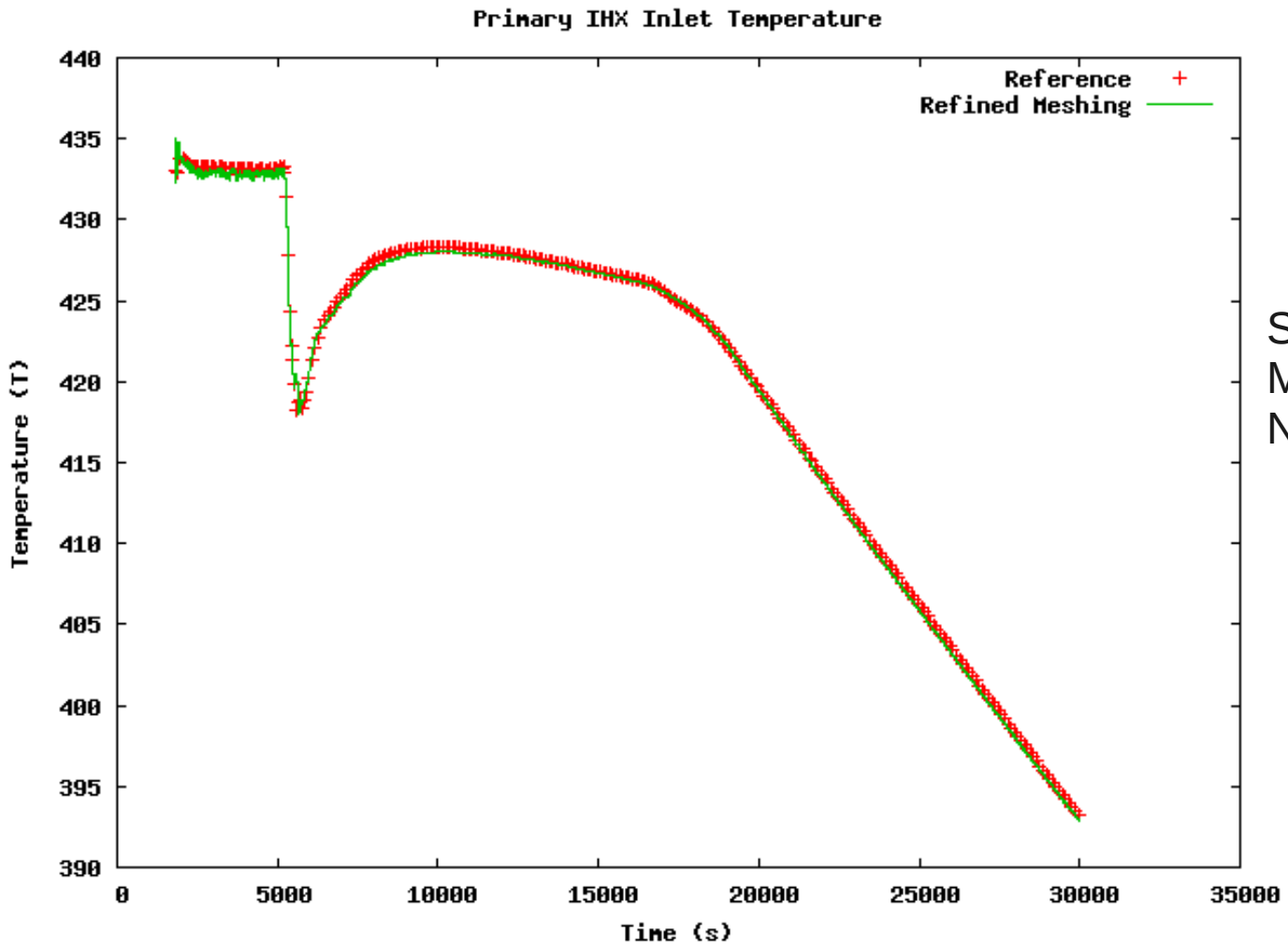
350 000 meshes



2 800 000 meshes
4 weeks calculation

user: fperdu
Thu Sep 5 18:24:40 2013

Sensivity Analysis



Sodium stream is the same
More mesh = less diffusive
No effect on macroscopic values

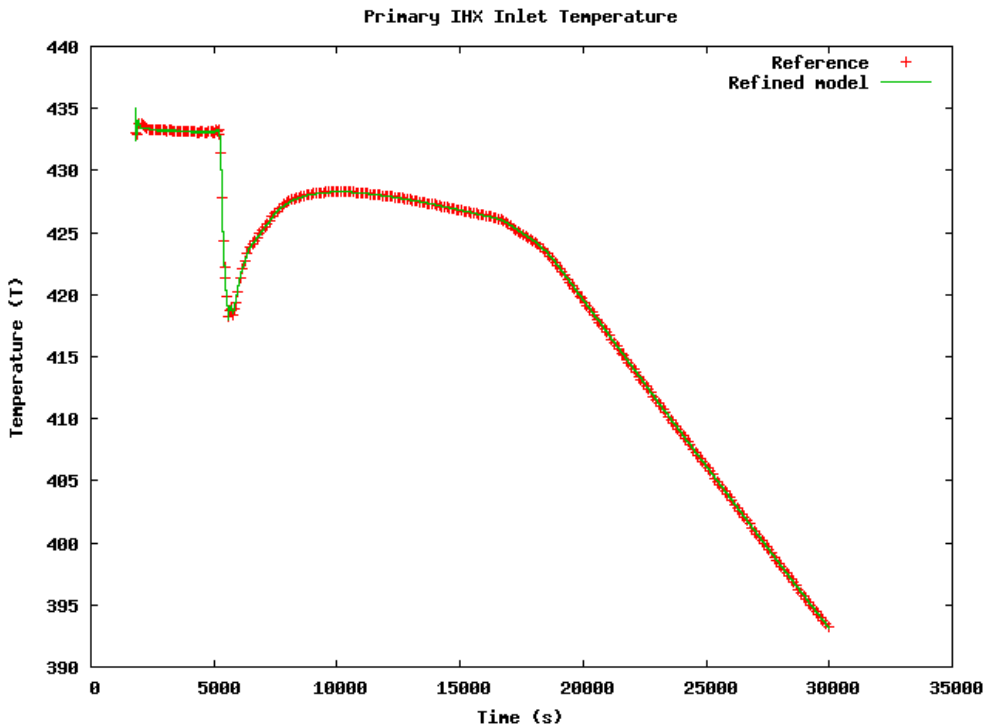
Sensivity Analysis

Upper Core Structure

- Solid in model
- Fluid with obstructed areas in reality (control rods, grids, instrumentation...)

Internal Flow => Thermal Diffusivity

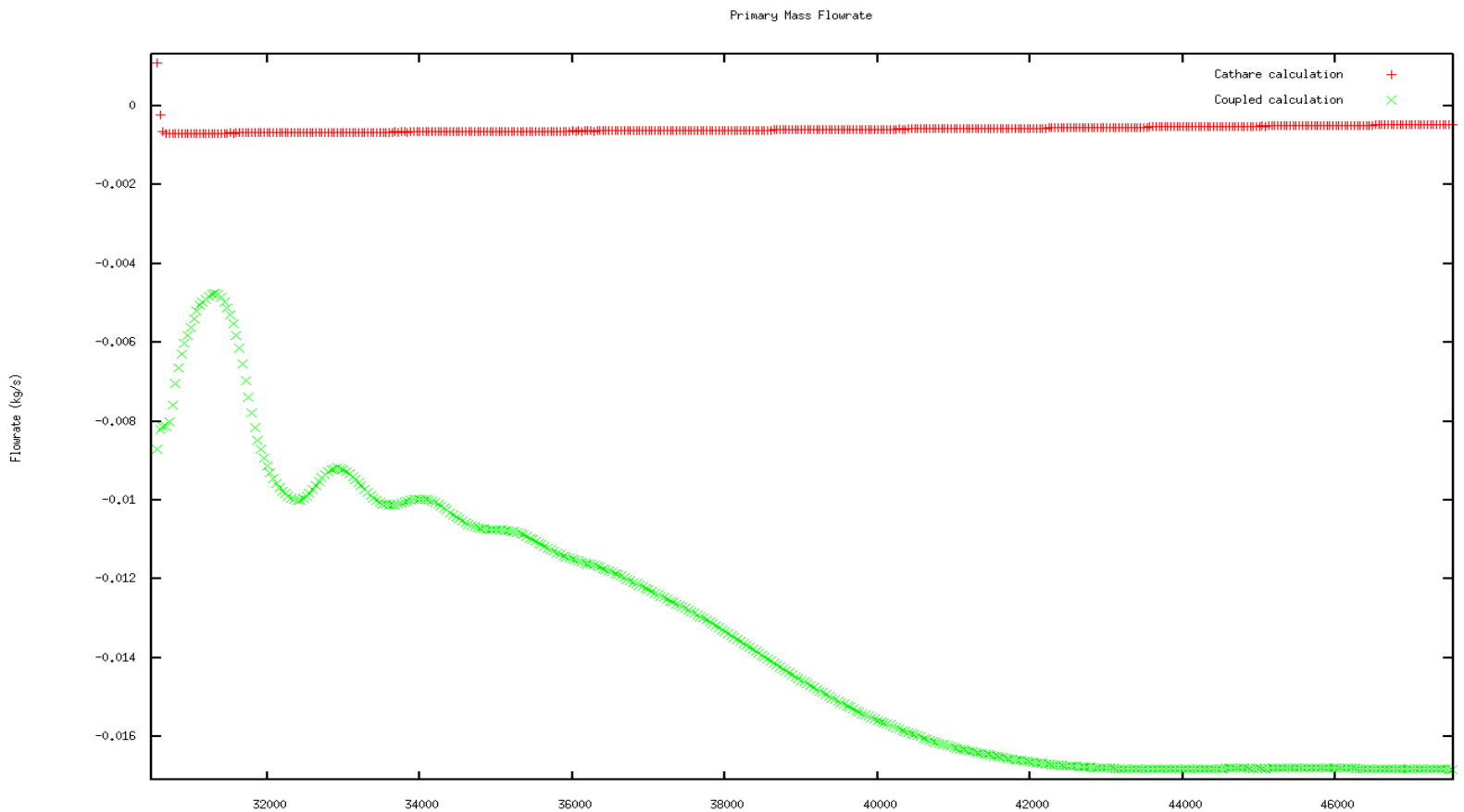
- Modeled with equivalent conductivity
- Because of Boyancy effect, conduction may be under estimated
- Lambda x10



Iso Thermal Calculation

Full Coupled Calculation
- Scram Reactor
- Isothermal secondary loop
- Primary pump stop

Objective :
- Lead to an Iso Thermal state with pump tripped
- Control primary flow rate
- No parasite momentum source



Iso Thermal Calculation

Cathare :

Flow rate ~ 0,004 kg/s and tends to 0

Coupled calculation :

Flow rate ~ 0,017kg/s and stabilizes

Bias effect / Parasite momentum effect ?

Neutronic activation of structure => generate power

Density differencies between CFD and System

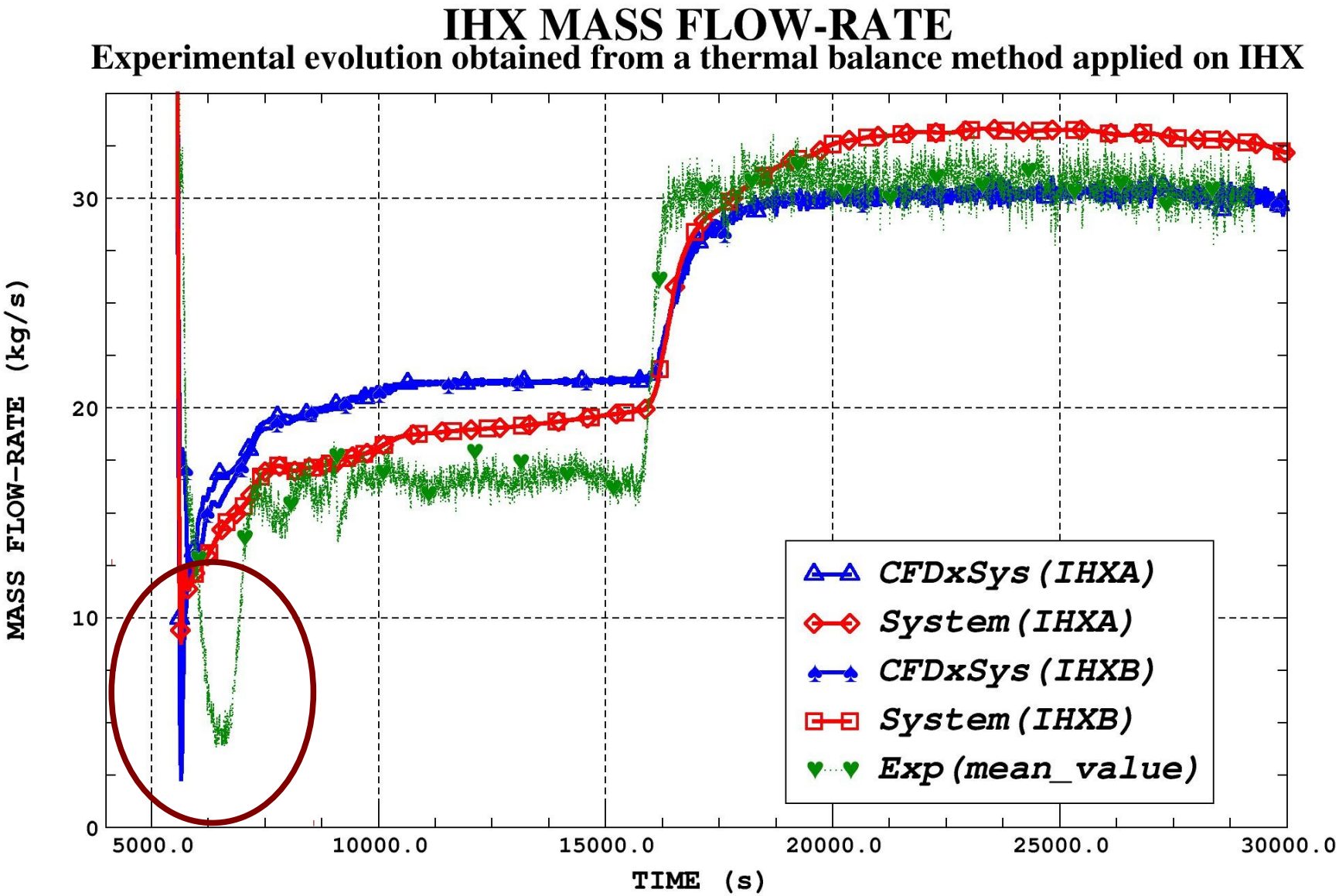
Flow rate are much lower than natural convection

0,017kg/s VS 30kg/s

No parasite momentum effect

Calculation

Object of concern



Into Refined Model

Uncertainties :

Secondary boundary conditions => calculation with shifted time values has been done

Steel Reflector and Diagrid Leaks

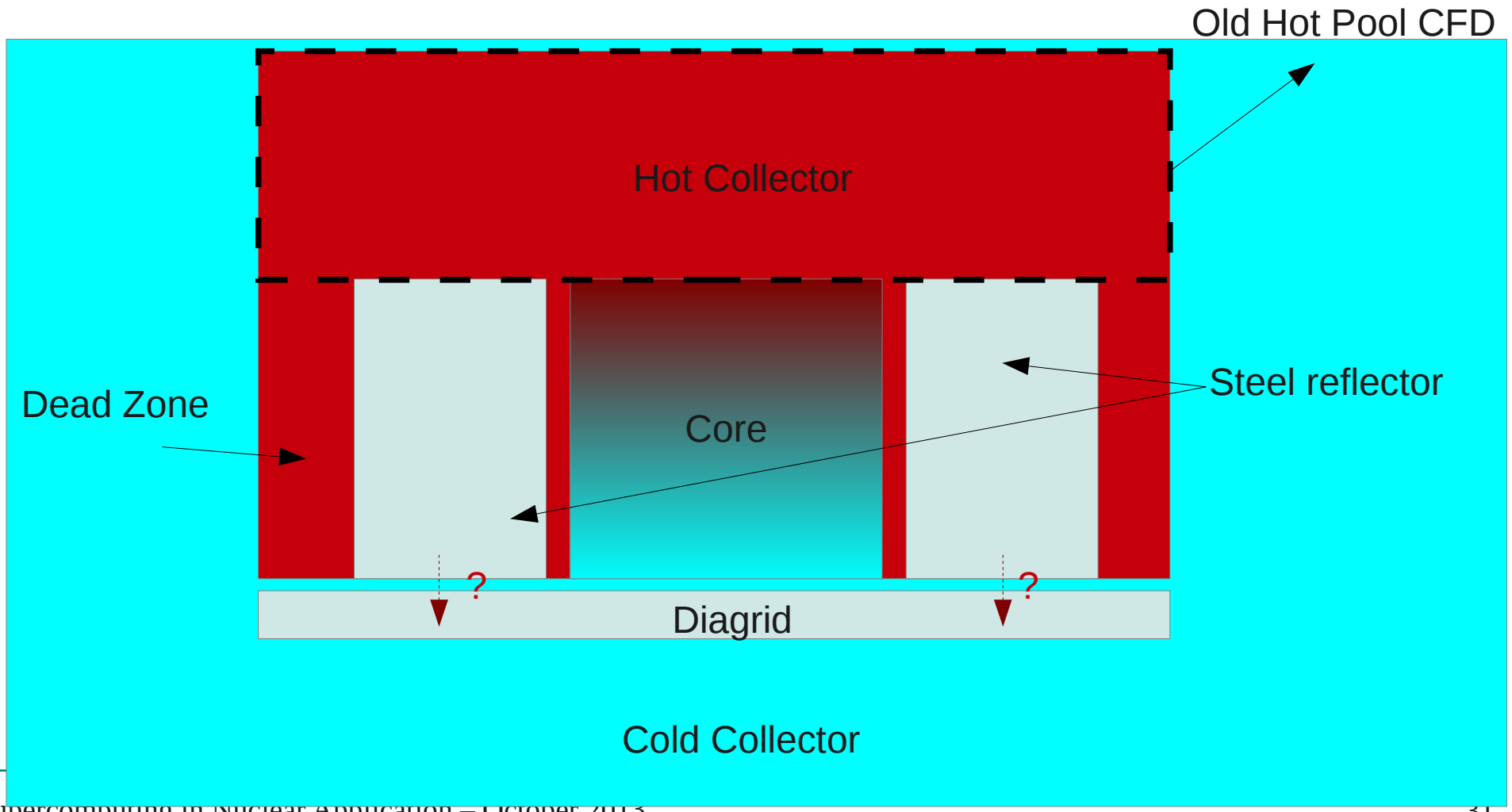
IHX inlet flow rate and core outlet flow rate don't have the same variation scheme

Re circulation in core ?

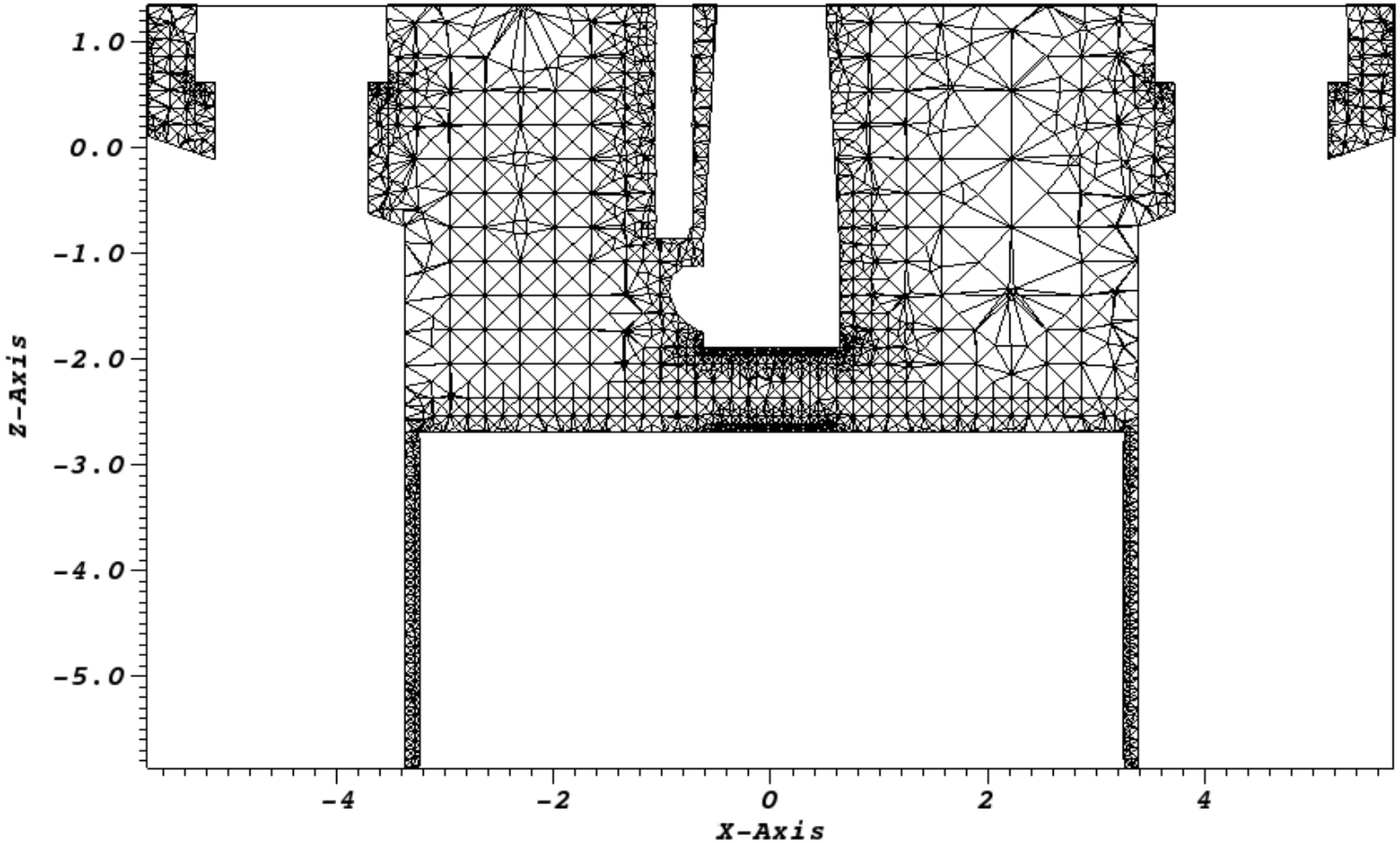
We know that our inner wrapper are not fully modeled (1D VS 3D)

Refined Model

Observed discrepancies may be due to heat exchanges between the steel reflector zone and the cold collector

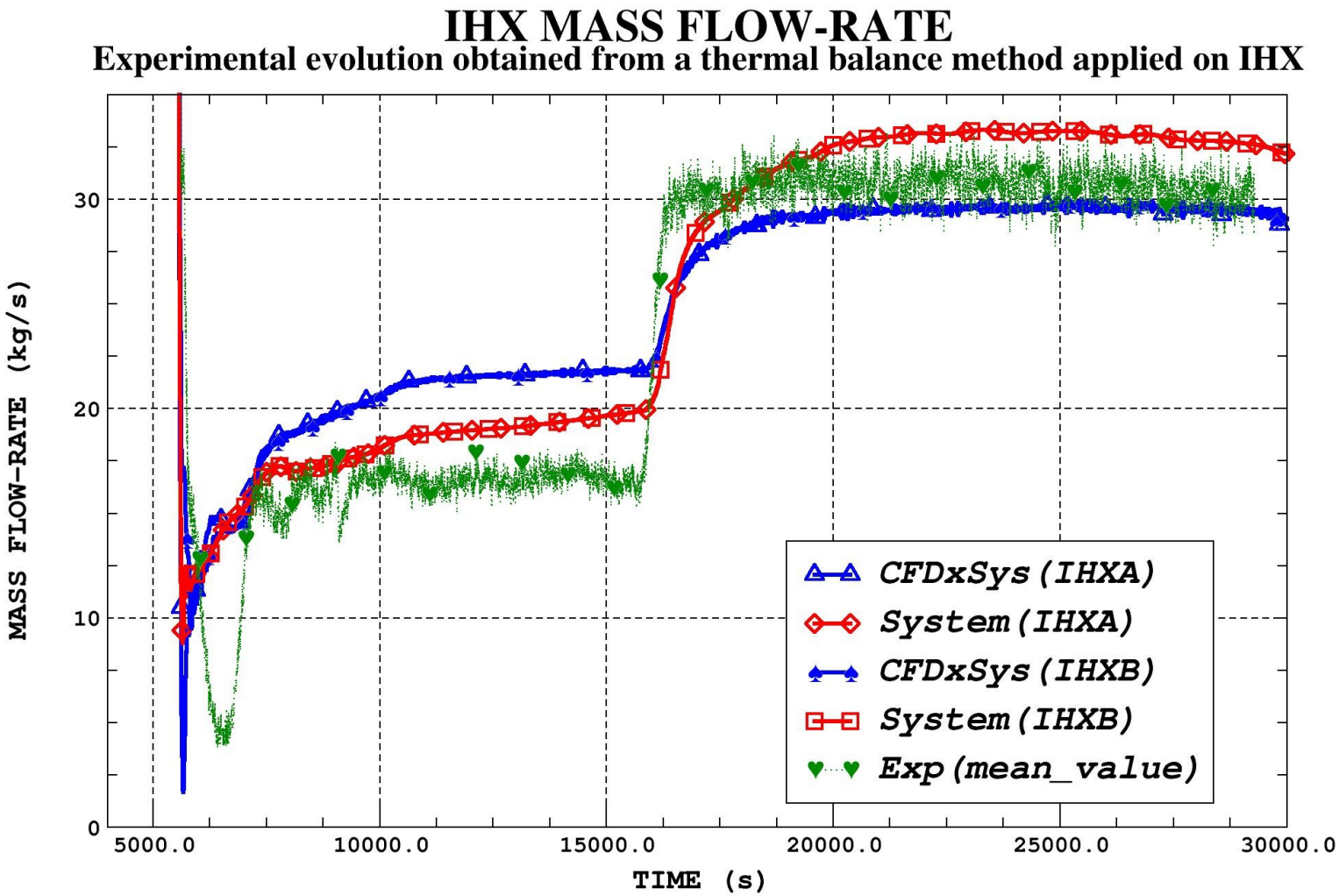


Refined Model



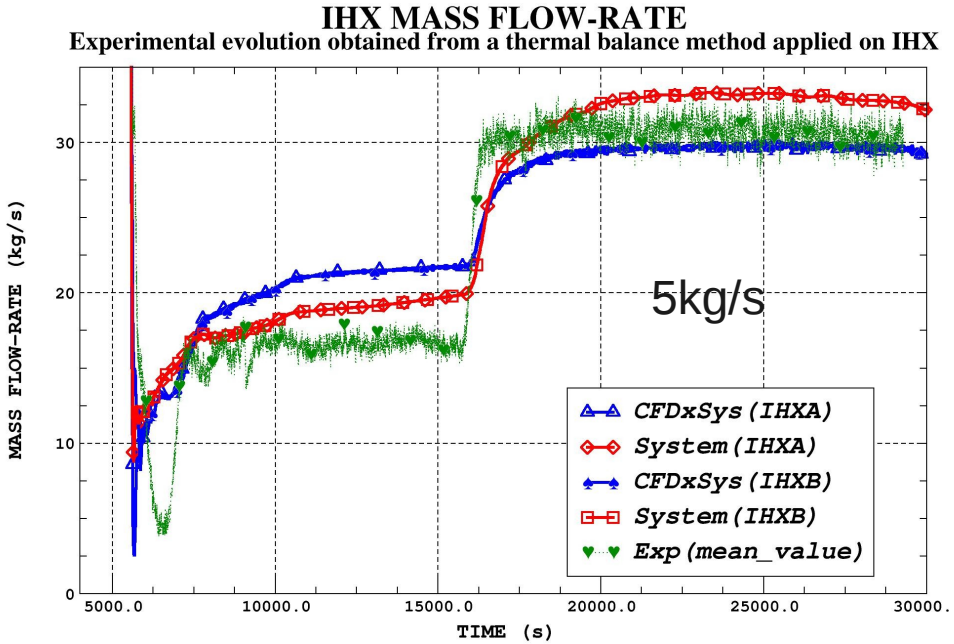
Add Dead Zone in CFD Hot Collector
Rework Cathare Modelisation
Add heat exchange with Cold Collector

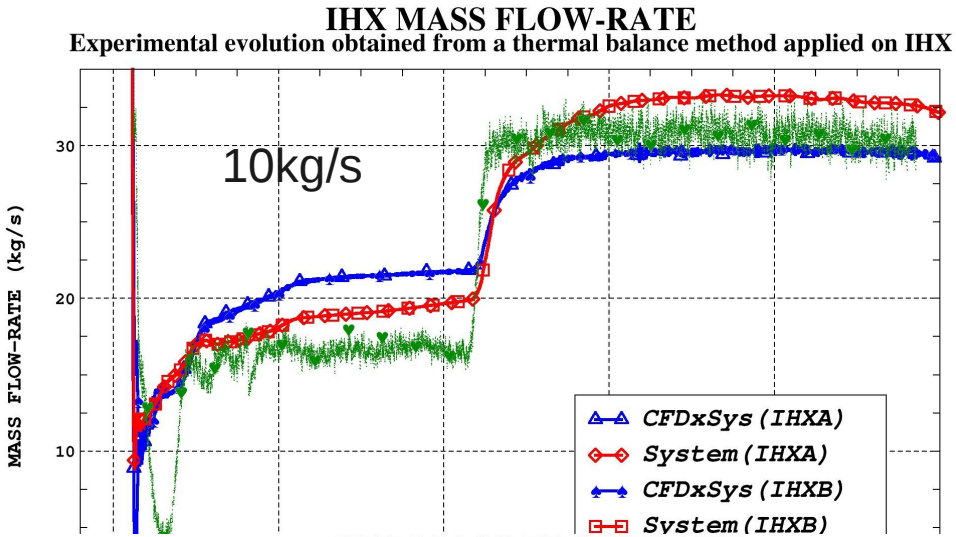
Refined Model

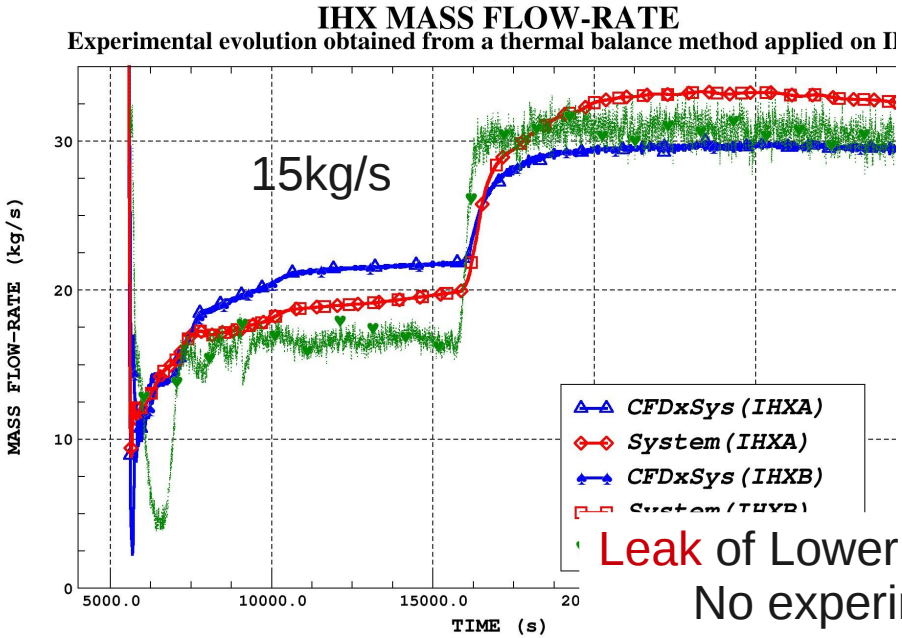


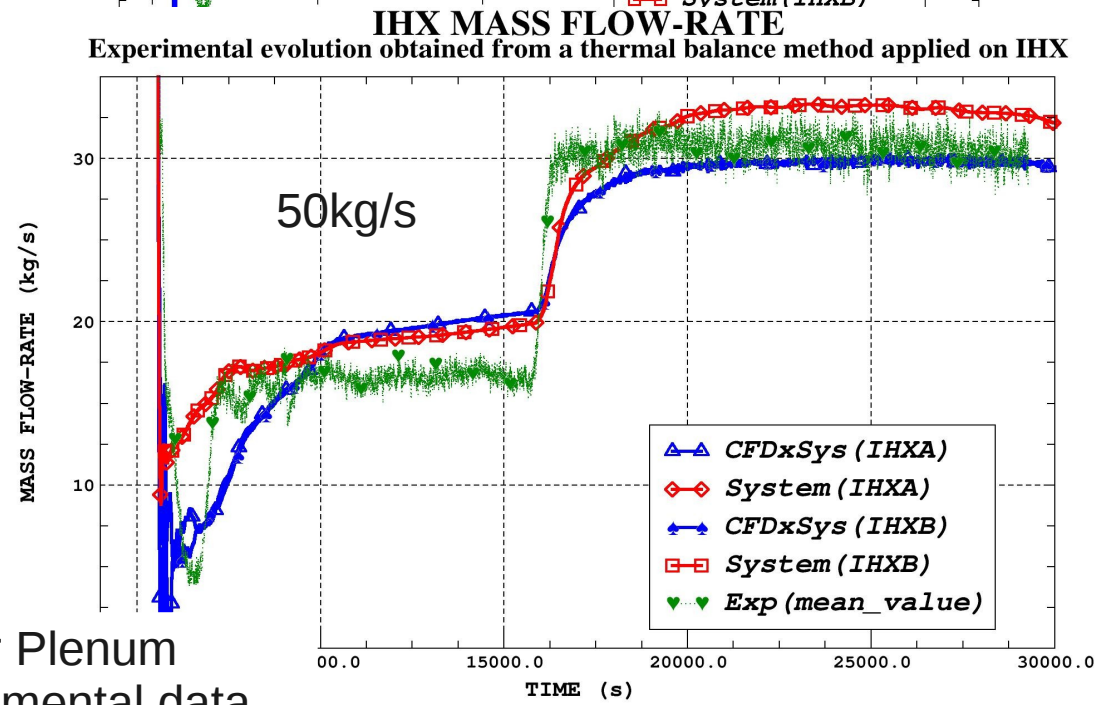
Without Leaks
No significant improvement

Refined Model









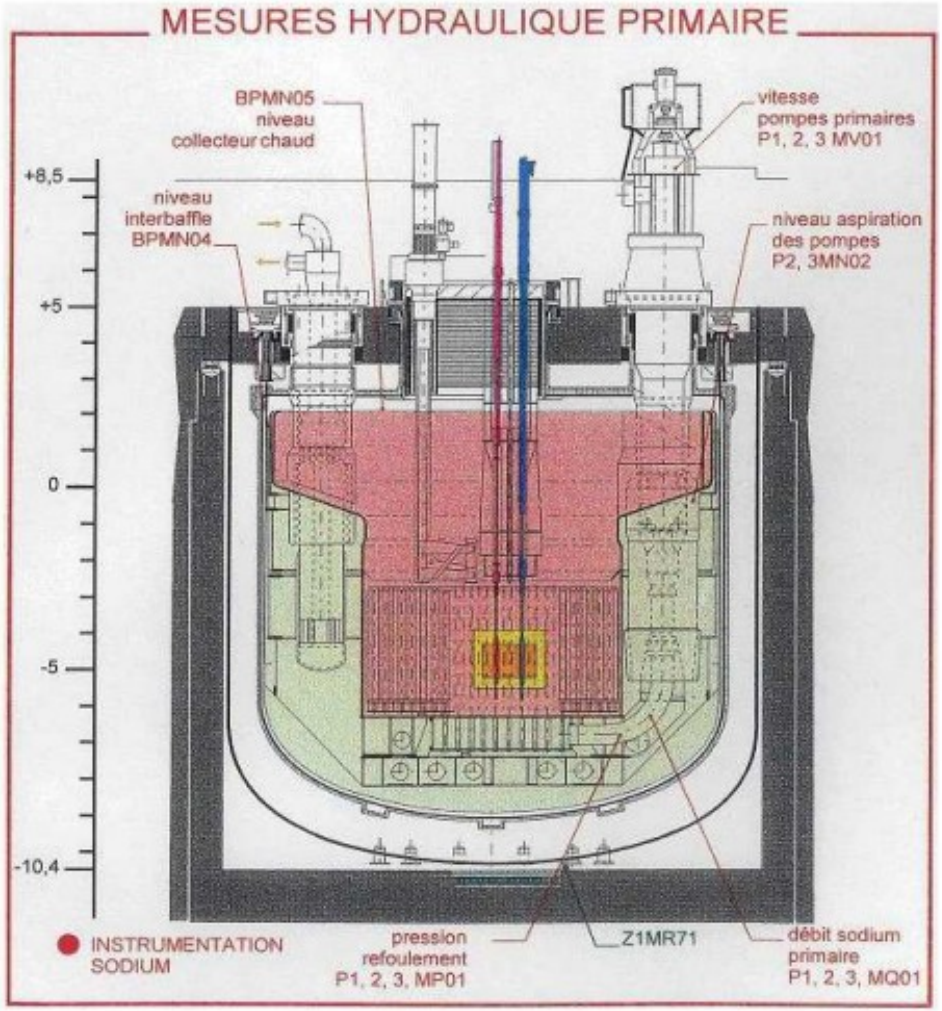
Leak of Lower Plenum

No experimental data

Refined Model

Calculations are not mature enough to be reliable
The steel reflector has not been modeled
Intermediate simulation
Leak sensivity analysis show us some clues

Still work and reflexion to do
- How to model the steel reflector ?
- How to model inner wrapper flow ?



Conclusion

- Phénix NCT :
  - Very rich test from the Thermal-hydraulic point of view
  - Forced ← → natural circulation transitions in both collectors
  - Mixing ← → thermally stratified transitions in both collectors
  - Complexity due to the reactor environment: uncertainties on boundary conditions, lack of sensors …
- Coupled Calculations :
  - Coupling methodology has been verified
  - The results of the coupled calculation have been extensively post-processed and verified
  - The validation of the coupled model against available experimental data shows a reasonable agreement → the model has reached a good level of maturity.
  - Developments are foreseen to further improve the model (will be continued beyond THINS project)
  - Use the results to help the validation of the system alone calculation

Still work to do for prediction calculations

Perspective

- Comparaison with KIT coupled calculations
- Steel reflector + Core : reflexion on new 3D model
  - TRIO MC2 model ?
- Best Practice Guideline
- For methodology validation :
  - Phenix Dissymetric Test

THANK YOU FOR YOUR ATTENTION