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Description of the TMI-2 Accident: OECD-Benchmark final results with ASTEC

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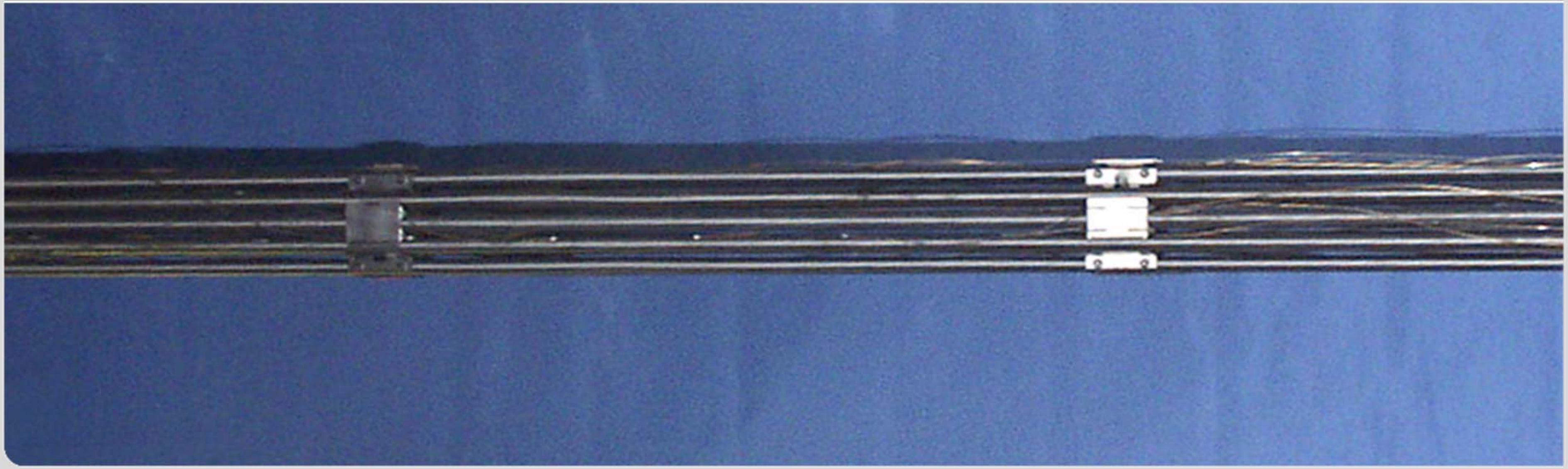


Outline of the Benchmark Exercise

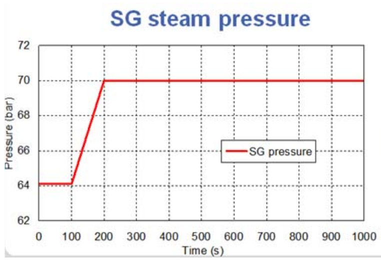
- BCs, Core degradation parameters
- Nominal TMI-2 steady state
- Chronology of main events
- code to code comparison of some results

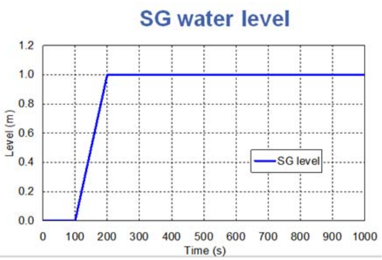
Participant	Country	Code
GRS	Germany	ATHLET-CD
ENEA	Italy	ASTEC
IKE	Germany	ATHLET-CD
IRSN	France	ICA/CAT
IVS	Slovakia	ASTEC
KIT*	Germany	ASTEC, MELCOR
Tractebel	Belgium	MELCOR
RUB	Germany	ATHLET-CD
BARC	India	ASTEC
IBRAE-RAS	Russia	SOCRAT
INRNE	Bulgaria	ASTEC

Parameter	KIT_ASTEC
Zry-4 ox kinetics	**Cathcart-Pawel** (low temp. range) **Prater-Courtright** (high temp. range)
Cladding failure criteria (T = clad temperature) (ε = ZrO_2 layer thickness)	T > 2300 K and ε < 0.3 mm; T > 2500 K and ε > 0.3 mm
T_m of oxide (UO_2 and ZrO_2)	**2550 K**
Debris formation criteria	***2300 - 2500 K***
Debris porosity and particle diameter	***Porosity = 40%, D = 3 mm***

- SG **Steam** pressure **= 70 bar** after **t = 200 s**
- **Water level = 1 m after t = 200 s,**

controlled by auxiliary feed water injection





CSNI/CAPS: justification, safety significance

- info on the capability of code/models to predict the key phenomena during the SA
- of interest by comparing results from several codes
- Since codes extended their range of applicability to the late phase, it is necessary to challenge them to the full extent of their capabilities, even if they are less reliable
- research is focused on degraded core *reflooding/ coolability*, consistent with that: the BE involves late phase degradation
- Δp & level control on SG secondary side:
  - ❑*Const. value of steam Δp = 70 bar after 200 s*
  - ❑*Const. value of water level = 1 m after t = 200 s by AFW injection*
- No letdown
- Const. value of **make-up** flow rate **= 3 kg/s** over the whole transient
- the approx. prediction of core degradation and the effects of SA measures to stop or delay the progression of an SA are of high safety significance; uncertainties remain on the limits to **in-vessel *coolability*** (threats to containment integrity)
- TG decided to launch a 1st transient calc. starting from a seq close to the one calc in the previous TMI BE, but without HPI in the late phase, and thus until v f: →nomination of the two participants by KIT
- The aim of the transient calc. was mainly:
  - ❑To achieve a better harmonization of different code IDs regarding geometry, initial s-s and BC
  - ❑To choose the timing of HPI/LPI for different core degradation *reflooding* seq-s and identify potential low Δp scenarios, also by opening of the PORV

Introduction

- The objectives/ scope of the BE on TMI2 were outlined: radial/axial core power
- profiles according to specification OECD MSLB BE Report (1999) as well as ATMI geometry
- 3 SA seq-s: to investigate core reflood - / in the lower head until vf different degree of **in-vessel** core degradation /melt progression: (incl. molten corium relocation -slumping into LP)
- 1st transient calc. started from a seq close to the one of the **A**TMI Benchmark, but w/o HPI in the late phase, and thus until **vessel failure (vf)**
- identifying low Δp scenarios: timely opening of the PORV etc
- **SCENARIO Nr.1: INIT EVENT -** small break of 20 cm^2 in the hot leg A, with contemporary loss of main feed water (t = 0 s)
- Reactor scram on high pressurizer Δp signal
- AFW startup at 100 s
- Primary pump shutdown when primary mass < 85 t
- Neither HPI nor LPI system actuation
- Free evolution of the transient until vf
- 2nd/3rd BE scenario (SBO+ surge-line DEGB 387cm^2): flow rates 28 kg/s vs. 360 kg/s

SBLOCA sequence			SBO sequence			SBO 3rd seq.	
Base case	Reflood 10 t	Reflood 45 t	Base case	Reflood 10 t	Reflood 45 t	Reflood 10 t	Reflood 45 t

TMI-2 isometric schematic drawing

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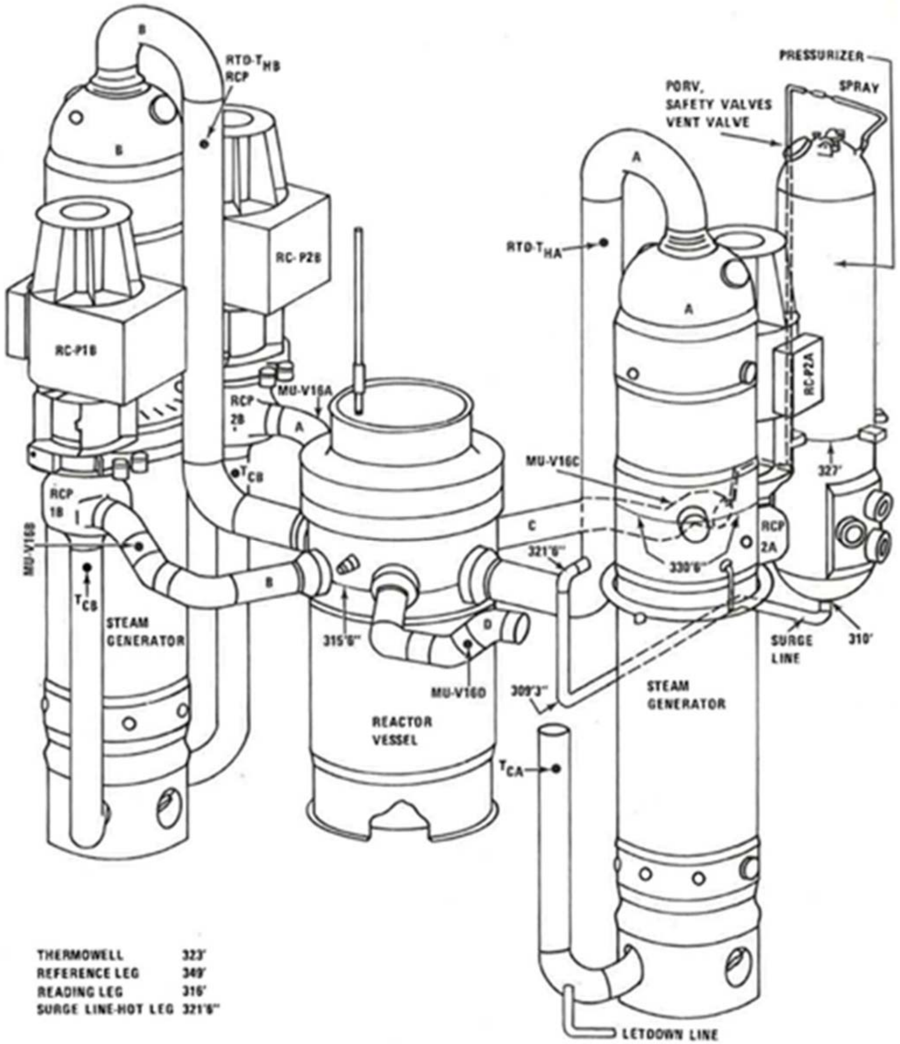
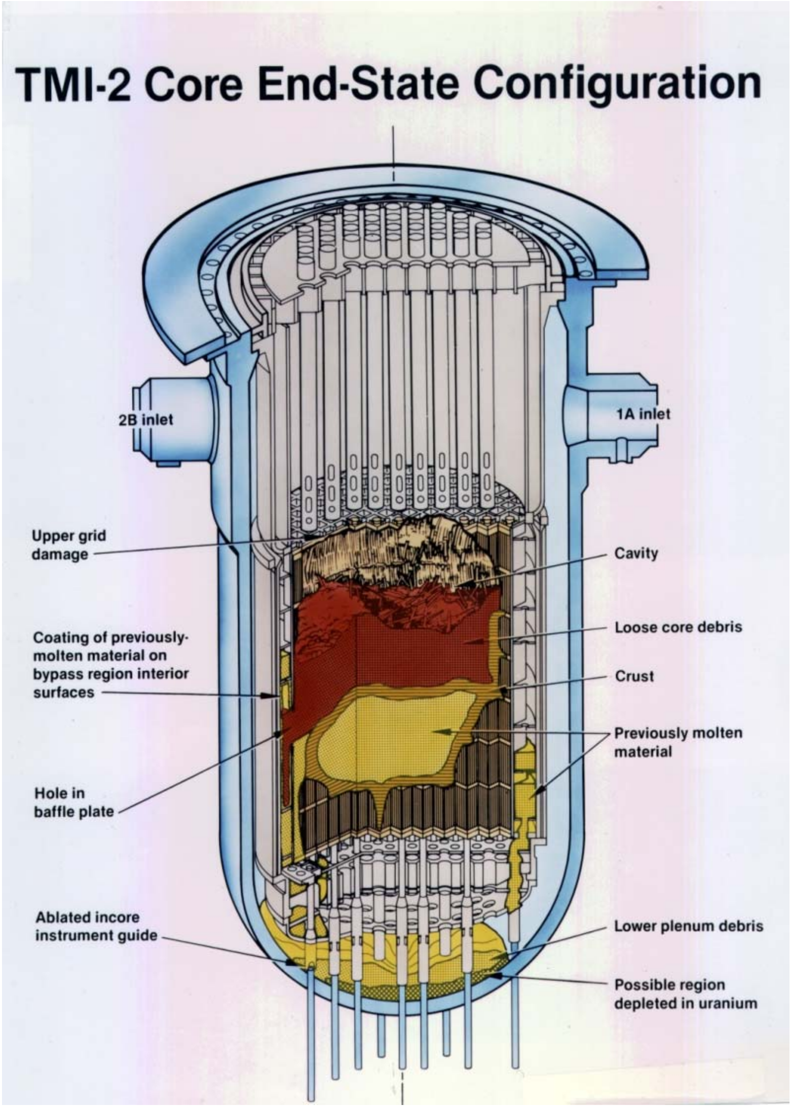


FIGURE II-23. TMI-2 Isometric Schematic Drawing



Nodalisation: primary/secondary system- *courtesy: Barnak, IVS Trnava*

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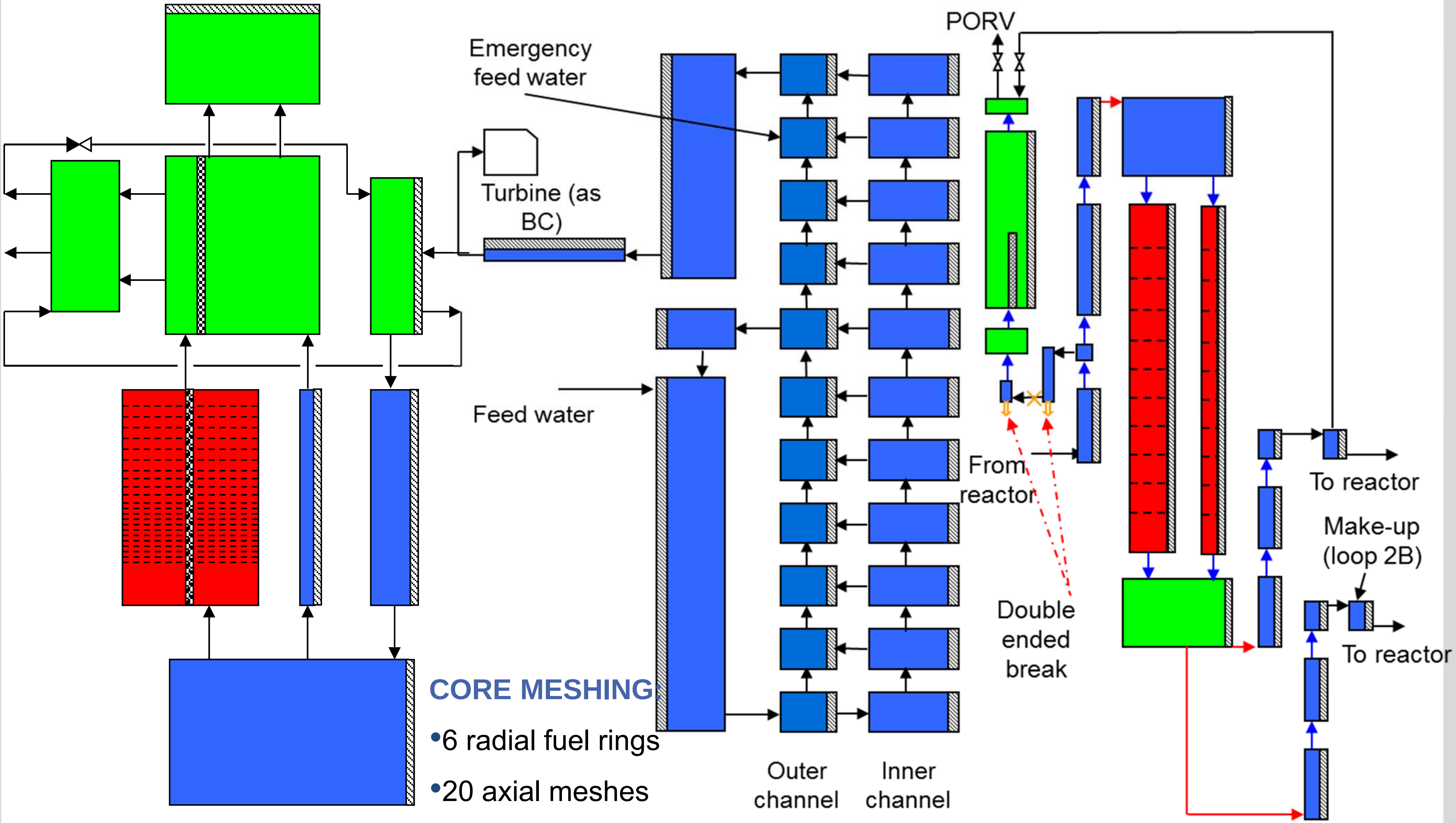

CORE MESHING:

- 6 radial fuel rings
- 20 axial meshes
- Inconel grids added

TMI-2 nominal steady state: KIT-ASTEC modeling results

Parameter	Unit	ASTEC KIT	TMI-2
Reactor core power	MW	2772	2772
Pressurizer pressure	MPa	14.9	14.96
Temp hot leg A	K	591	591.15
Temp hot leg B	K	591	591.15
Temp cold leg A	K	564	564.15
Temp cold leg B	K	564	564.15
Mass flow rate loop A	kg/s	8820	8800
Mass flow rate loop B	kg/s	8800	8800
Pressurizer collapsed level	m	5.59	5.588
Pressurizer water mass	kg	14600	13710
Total primary mass	kg	222400	222808
Steam Δp SG A	MPa	6.41	6.41
Steam Δp SG B	MPa	6.41	6.41
Steam temp SG A	K	567.0	572.15
Steam temp SG B	K	567.0	572.15
Riser collapsed level SG A	m	3.21	-
Riser collapsed level SG B	m	3.21	-
Downcomer collapsed level SG A	m	4.52	-
Downcomer collapsed level SG B	m	4.52	-
Liq mass SG A	kg	16800	-
Liq mass SG B	kg	16800	-
Feedwater flow rate SG A	kg/s	772	761.1
Feedwater flow rate SG B	kg/s	772	761.1
Feed water temp SG A & B	K	511	511.15

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- ASTEC KIT s-s in good agreement with new TMI2 specifications
- Main deviations are:
  - Pressurizer water mass *(may depend on reference elevation for level measurement)*
  - SG steam temp. is under-predicted by 5 °C, with consequent over-estimation of the feed water flow rate to match the right SG power removal

Some ASTEC ATMI-2 transient results (SB LOCA)

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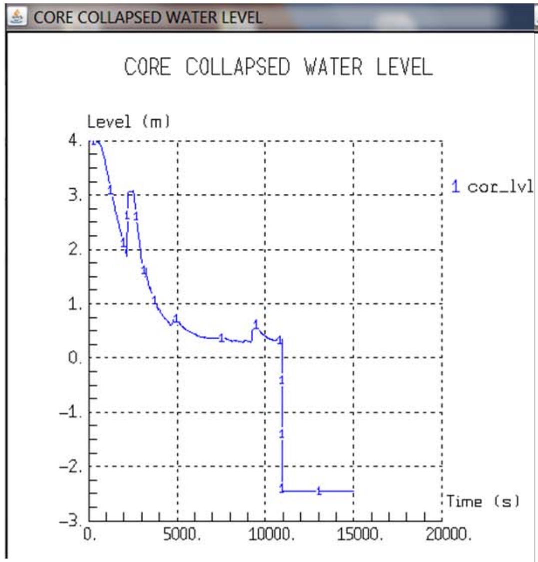
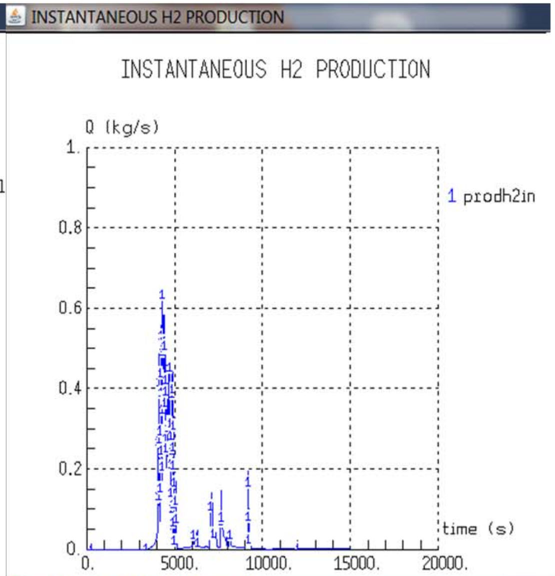
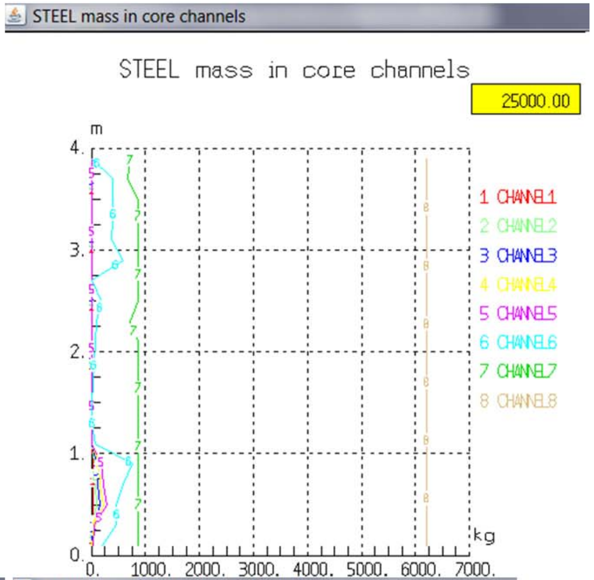
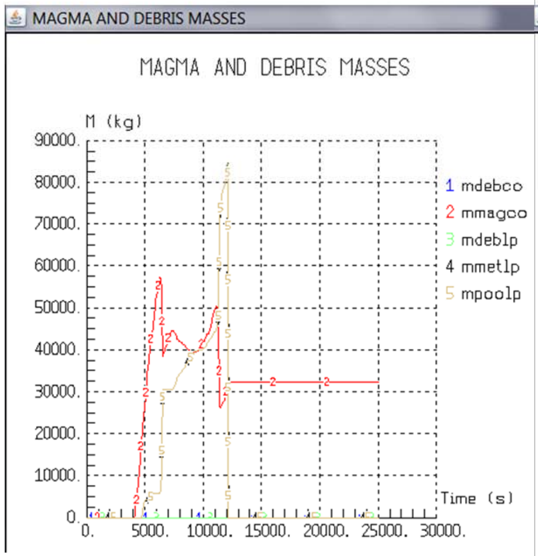
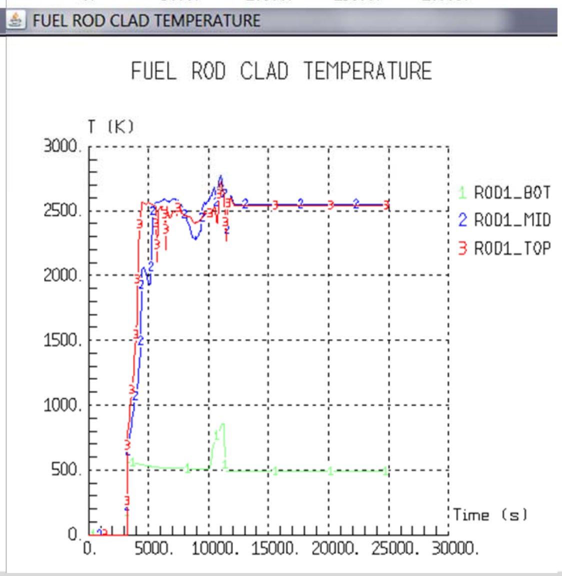
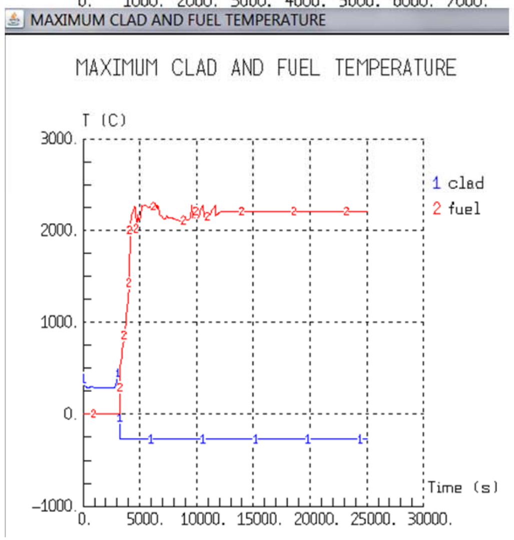




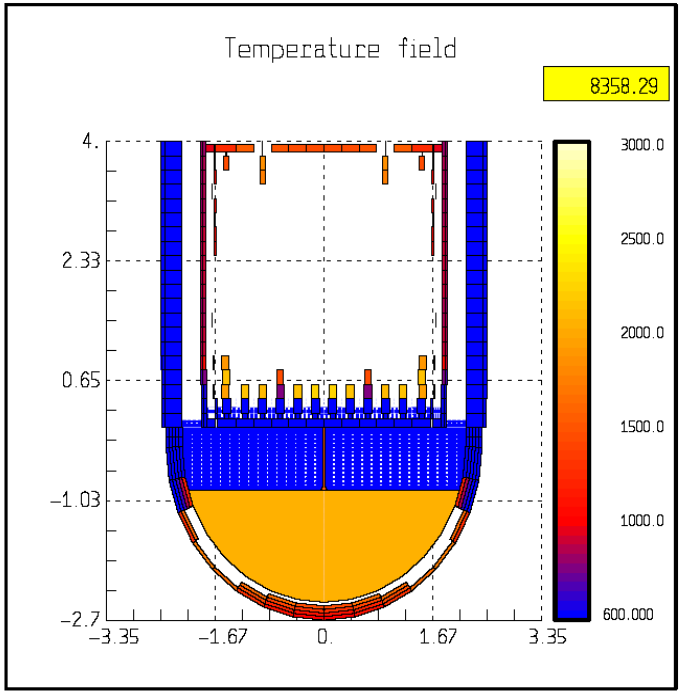








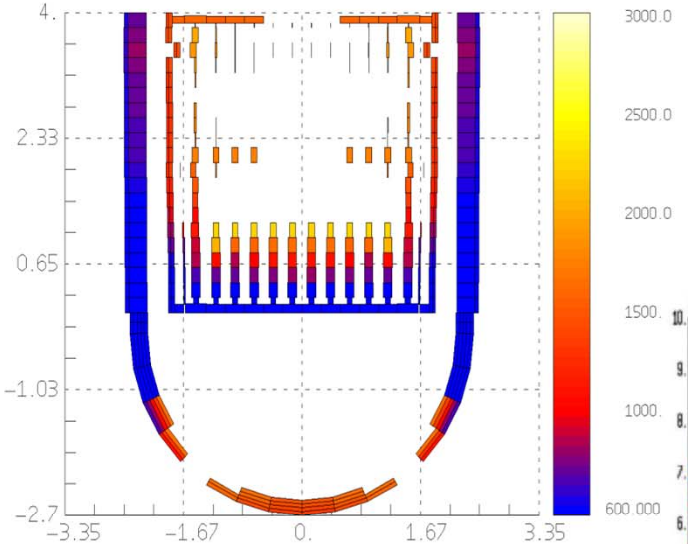
In-vessel core degradation –comparative temp. mapping



ASTEC (ENEA)

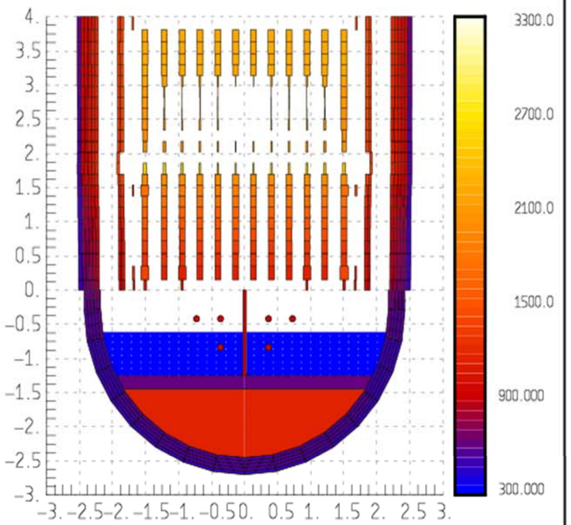
Just before vessel failure

(No molten jet fragmentation during core slumping)



ASTEC (KIT)

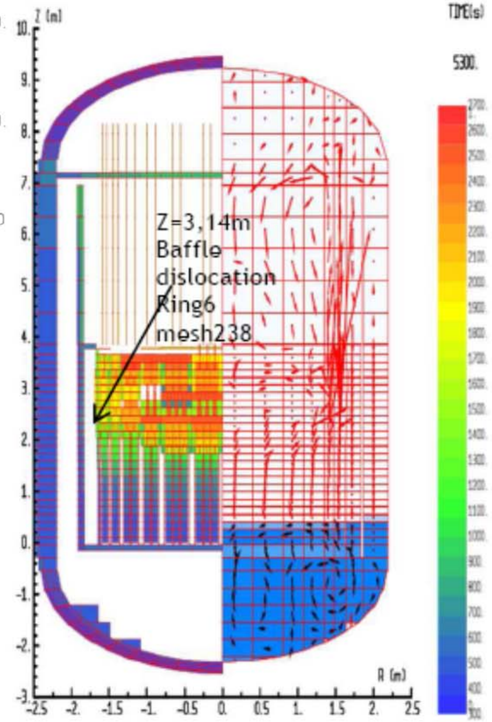
After vessel failure



ASTEC (IVS)

No vessel failure

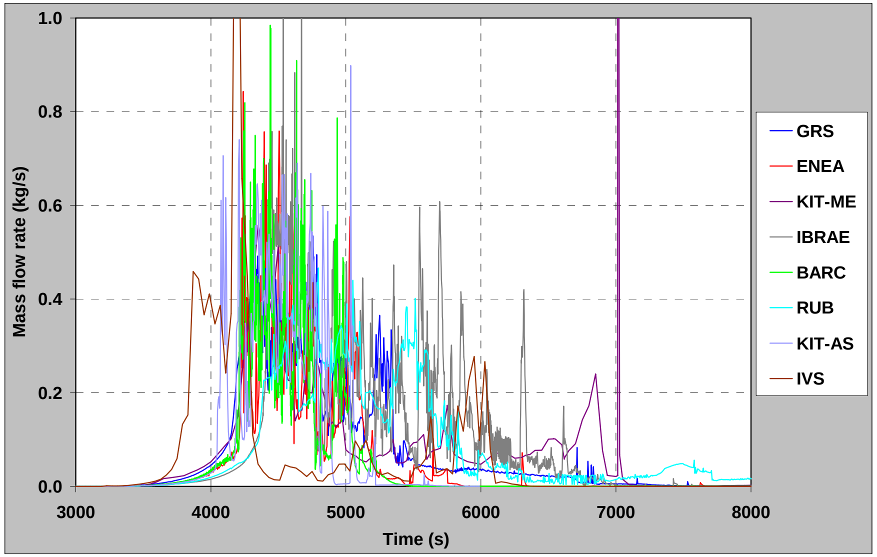
(Molten jet fragmentation during core slumping)

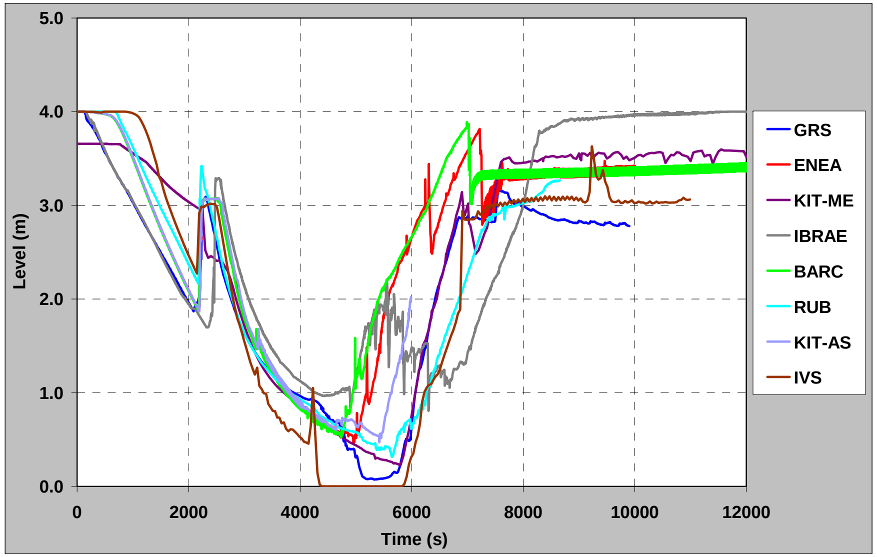


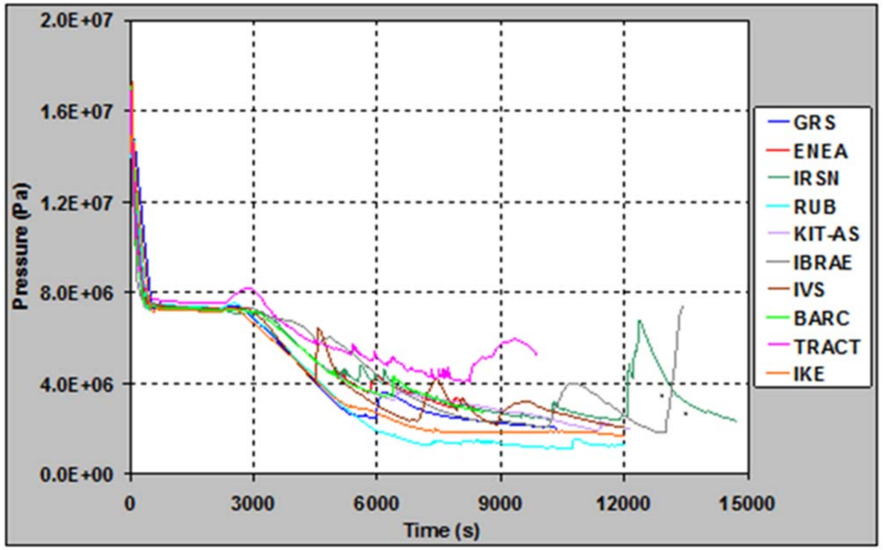
ICARE/CATHARE (IRSN)

Onset of core slumping

Comparison of some code results: *Reflooding* starts at m = 45t
Instantaneous H_2 prod *(le)*; PRZ Δp; core collapsed water level, 45t







Break mass flow rate
Total primary mass
Loop A/B mass flow rate
Pressurizer level / pressure
SG A pressure
SG A level
Power exchange with SG A/B
Core power
Core collapsed water level
Mass of water in the core
Fuel rod clad temp. at core top
Hot leg A-1 /A-2 temp.
Cold leg A temp.
Instantaneous /cumulated H2 production
Total mass of molten metal
Total mass of molten material in the L. P.
TMI-2 plant data according to OECD MSLB Benchmark Report – 1999)

Chronology of main events- a quick look table (*LOCA Stage 1*)

EVENT	Time (s)/ ASTEC KIT
Break opening & main feed water loss	0
Pressurizer PORV opens	17.1
Reactor scram	21.8
Pressurizer PORV closes	25.3
Full SG dry out	27.0
Startup of AFW	100.3
Pressurizer is empty	128
Stop of primary pumps	2177
1st fuel rod clad perforation/burst	3737
1st clad melting & dislocation	4040
1stceramic melting & dislocation	-
First molten mat slumping into LP	4681
Vessel failure	10937

- 1st fuel rod perforation occurs at t = 3737 s due to Zry clad dissolution by Inconel grids
- Molten mat. slumping into the LP through the core by-pass after baffle melting
- 1st mat. slumping at t = 4681s followed by further massive molten material slumping
- VF at t = 10937 s by rupture criteria

Discussion points

Key-role for ASTEC models at the current State of the Art NPP performance (evidence given)

U-H vs. best fit (Schanz` recommendation) kinetics of Zry ox by steam

Coupling with SUNSET for sensitivity studies (propagation of uncertainties) related study: GRS, SUSA- approach of 1992 for “code to code” data set comparisons /final report

Analysis of base case results regarding transient th_H of the TMI-2 accident: 3 different hypothetical, but plausible alternative SA-scenarios

Ref ID adopted, ENEA & an IRSN
Majority of captured trends -consistent with the (intuitive) expectation
Results dependent on the imposed BC, IC…changing the max Δt influences the results

the output is satisfactory
Tables, fig-s , spread sheets were submitted to the BE-chair, G. Bandini, ENEA
results were presented 6 times at WGAMA/ OECD Meetings in Paris;

2nd and 3rd stage (new ASTEC-runs) for TMI-2 BE purposes (ref. ID): upgraded transients
´ obtained/ actual outcomes: sent to the chairman in time
Actions foreseen for the 2nd and 3rd stage: main requirements (runs) are fulfilled, work nearly completed: Report, recommendations and suggestions will follow till 28th of Feb. 2014

Further discussion at this stage of ASTEC TMI-2 simulations

SBO + line break scenario runs performed many times, (**redundant runs**) to get more experience further discussion needed (on the basis of ***.lst** files)

For both *reflood* cases M_{TCO} = 10t (Trigger value 1) M_{TCO} = 45t (Trigger value2)
only M from **magma corium**, / **Differences at the $\Delta\tau$, when CESAR stops and ICARE starts**
Short time in-between: a linear interpolation suggested;
SBO+ surge line break scenario modeled; runs with the same parameters done
redundant runs: to get experience, how ASTEC works here, further discussions (on the basis of ***.lst** files)
SBO-sensitivity (parameter studies) still to be performed,
Mandatory post processing – further work still to be continued on :
· **early** phase modeling (HT, mechanical behavior, movement of mat)
· **late** phase modeling (idem)

M_{TCO} = 10t (Trigger value 1) 1765sek till 2765 sek *(3rd stage of our BE)*
M_{TCO} = 45t (Trigger value 2) 2176sek till 3176 sek *(3rd stage)*

I will get the opportunity to obtain a second PC under a LINUX platform, (or a part of a cluster) exclusively for ASTEC runs.

Conclusions

• ASTEC has the potential to simulate real NPP performance (some evidence given here)
Many ISPs were already calculated using ASTEC *(P. Chatelard, 15y*)

• Dynamic behavior (time dependences; evolution)/ profiles developed can be visualized online …
• New skills developed / some insight into stru-s, philo behind ASTEC…

• Captured NPP TMI- (overall) trends are consistent with the (intuitive) expectation

• Results /outputs/ satisfactory to me being presented / discussed at 6 WGAMA/ OECD/NEA-Meetings in Paris;

• Tables, fig-s ,spread sheets upgraded transients were submitted to the BE-chairman in time

• Up till now main requirements are fulfilled, work completed in time (partially done) following recommendations

• **-->Presentation at the 17th QWS** Karlsruhe **given**

• An ERMSAR paper and an NURETH paper were prepared with G. Bandini, ENEA et al. (published)

• **Actual outcomes: new** EXCEL **plots (transients) –** delivered shortly to ENEA, Bologna

Ref. ID adopted being developed by ENEA; clarification was needed only at some particular points Specifications (3rd seq) selected **: 2nd SBO + surge-line DEGB** with an increased total HPI *reflood* rate of **360 kg/s** for **1000s** starting **at 10t/45t of degraded** core. Objectives & scope outlined:
3rd SBO-SA -*"no more than a sensitivity case of the 2nd SBO reflood-case*" (citation, GB**)**

submission of my **EXCEL charts** (= modified ASTEC *.plot files) needed for the global **revised results comparison file**.

Numbers are given in the ERMSAR paper

TMI-2 BE Outlook

- Sensitivity analysis to key parameters is ongoing to investigate the influence of the : ox kinetics, fuel rod melting point on core coolability and H_2 production

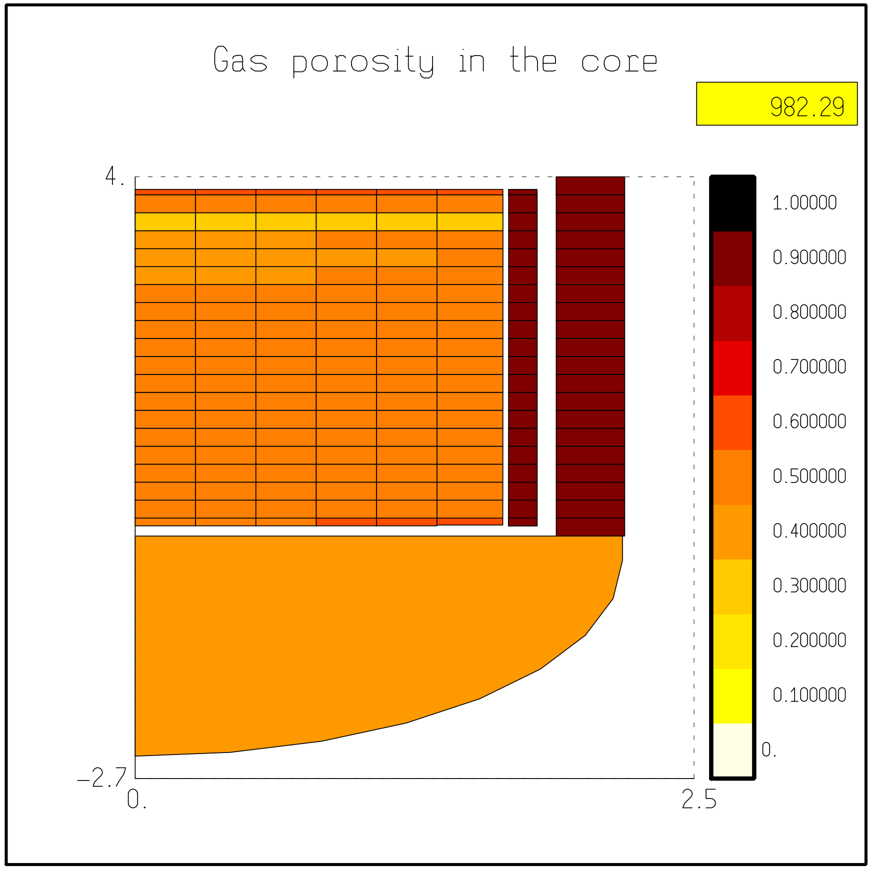
  actual outcomes: analyses to be conducted until **vf**

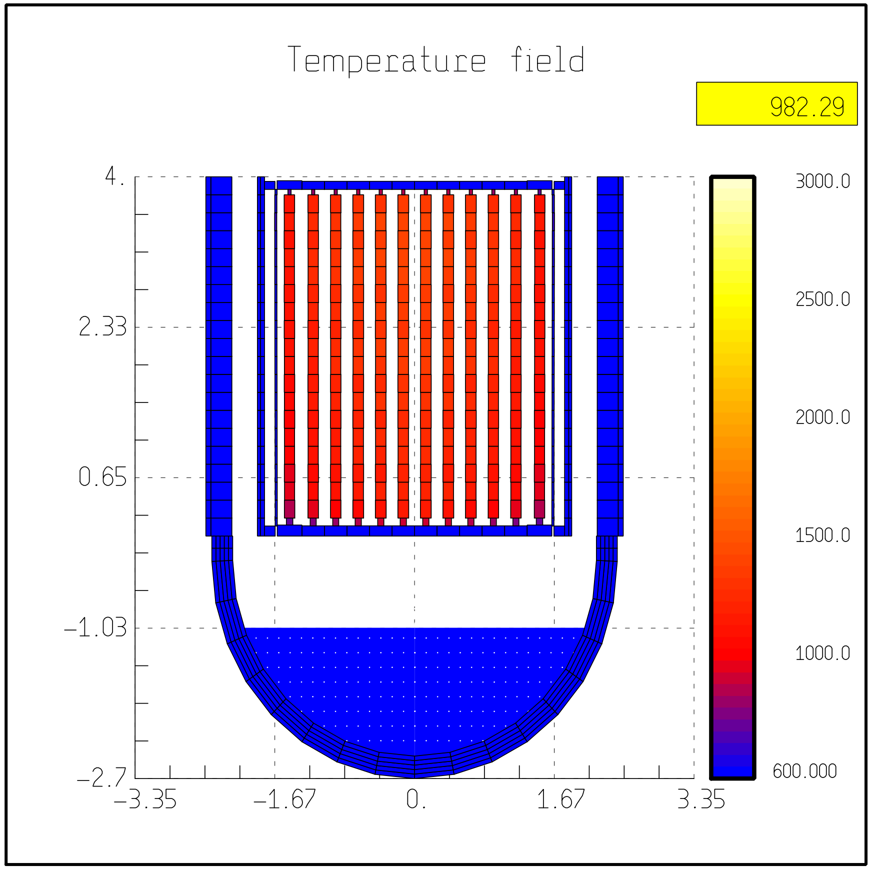
- concerning the obtained numbers : a kind of “*semi quantitative time-series analysis*” has to be continued

- Contribution for the 3rd SBO-SA seq. as indicated in the OECD summary record
- 3rd SBO-SA -*“no more than a sensitivity case of the 2nd SBO reflood-case”* (citation, GB)

- Further EXCEL charts (= modified ASTEC *.plot files) needed for the global revised results comparison files. Regarding the status, “We need to finalize the large amount of work already done and discuss the contents of the Final Report that is due by the beginning of the next year”. (G. Bandini, cited),
- additional Uncertainty Analysis with SUNSET or SUSA / GRS, done by GRS, partly done by KIT
- presentation of comparison files by G. Bandini at WGAMA/ CSNI/ PRG, 2014
- Mandatory post processing – further work still to be continued on:
- →Writing a 25 pages report, waiting for an external independent review

Addendum: mid-term transients, SBO, 2nd case 45t, color coded





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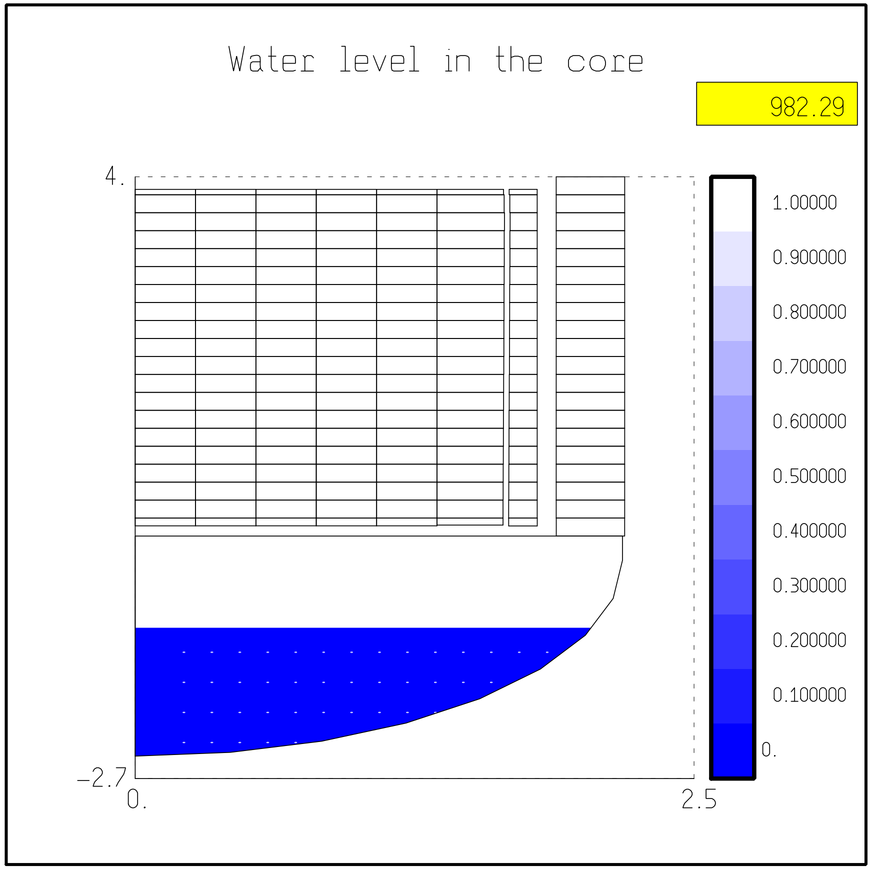
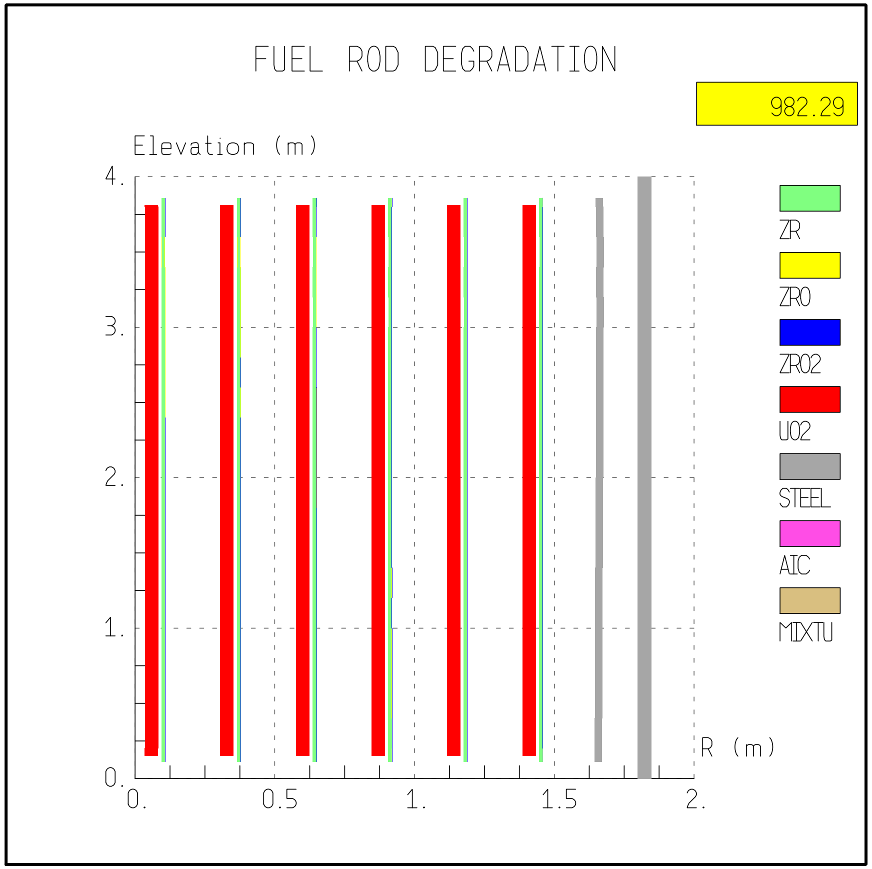
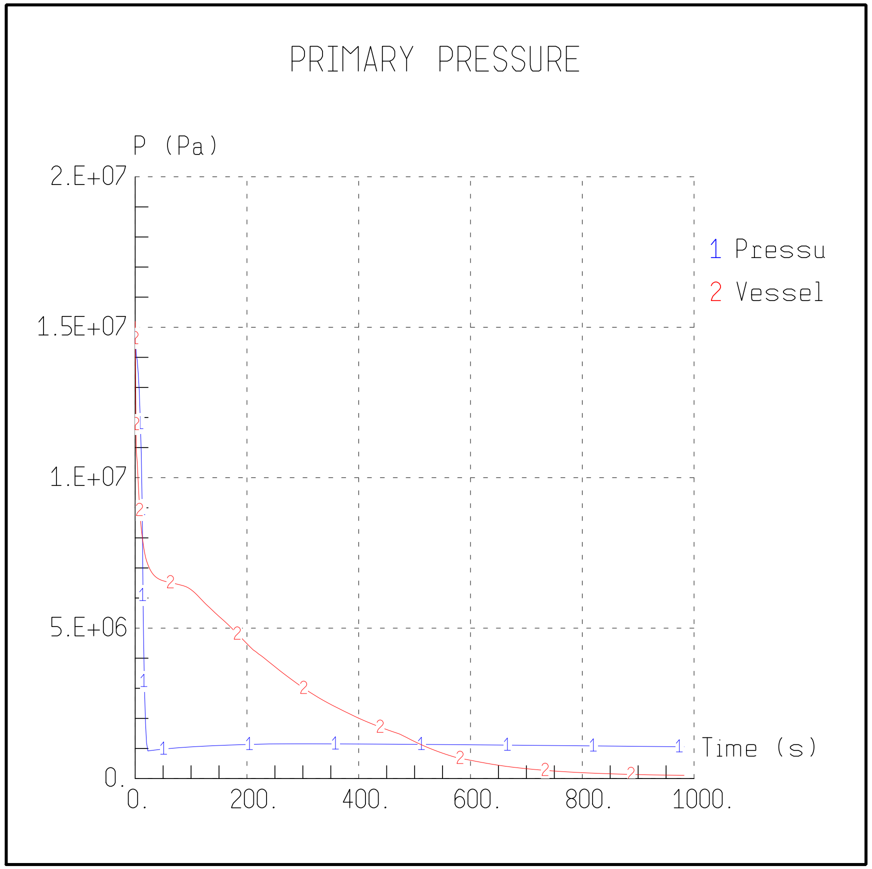
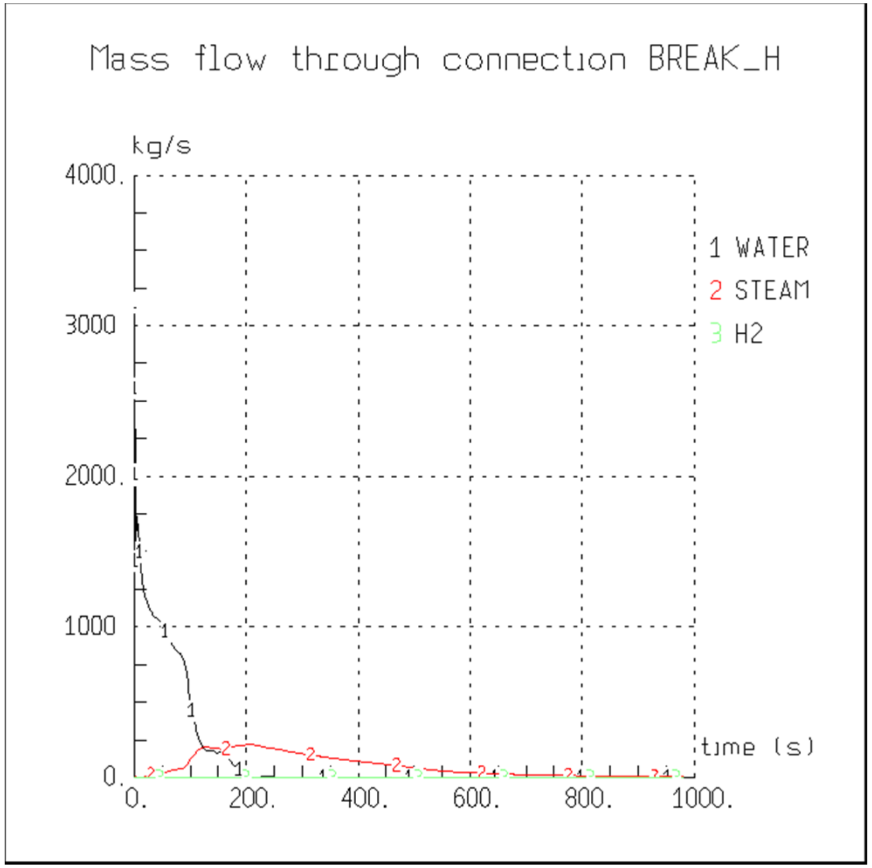




Addendum: mid-term transients, SBO, 2nd case 45t, *schematic*





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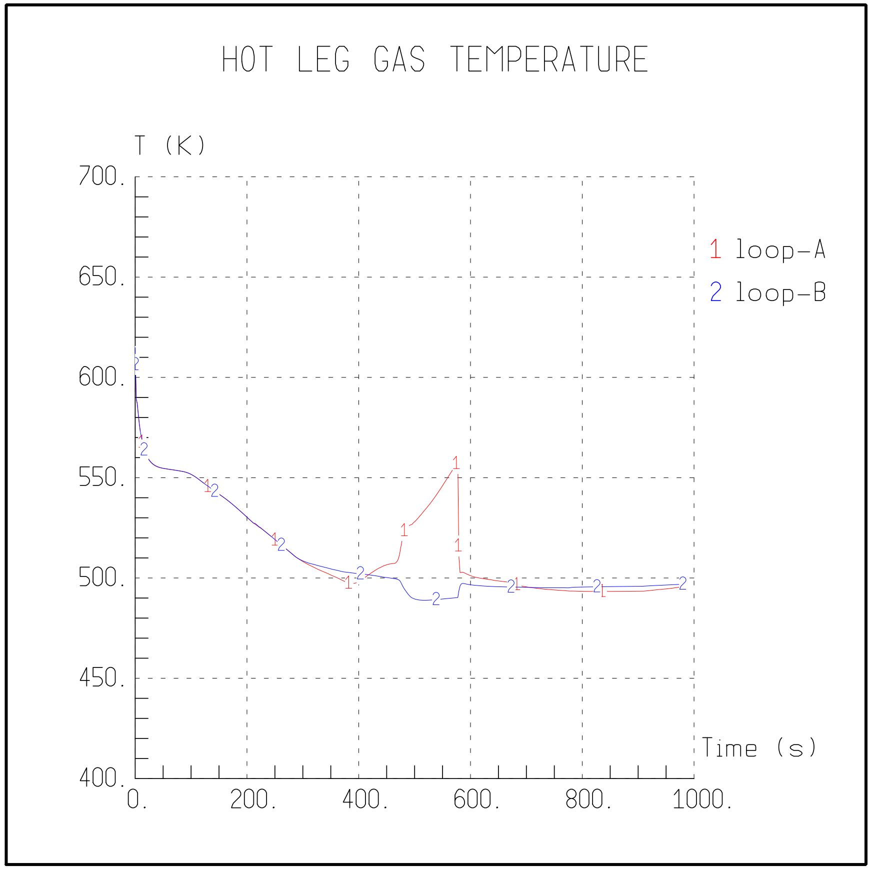

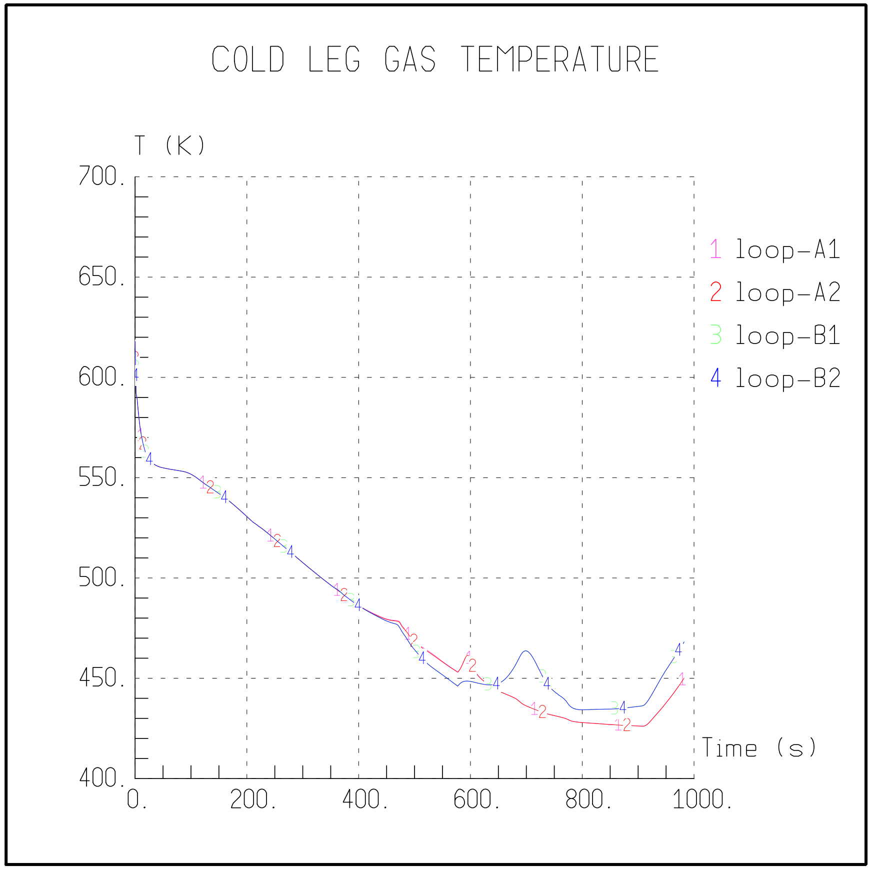

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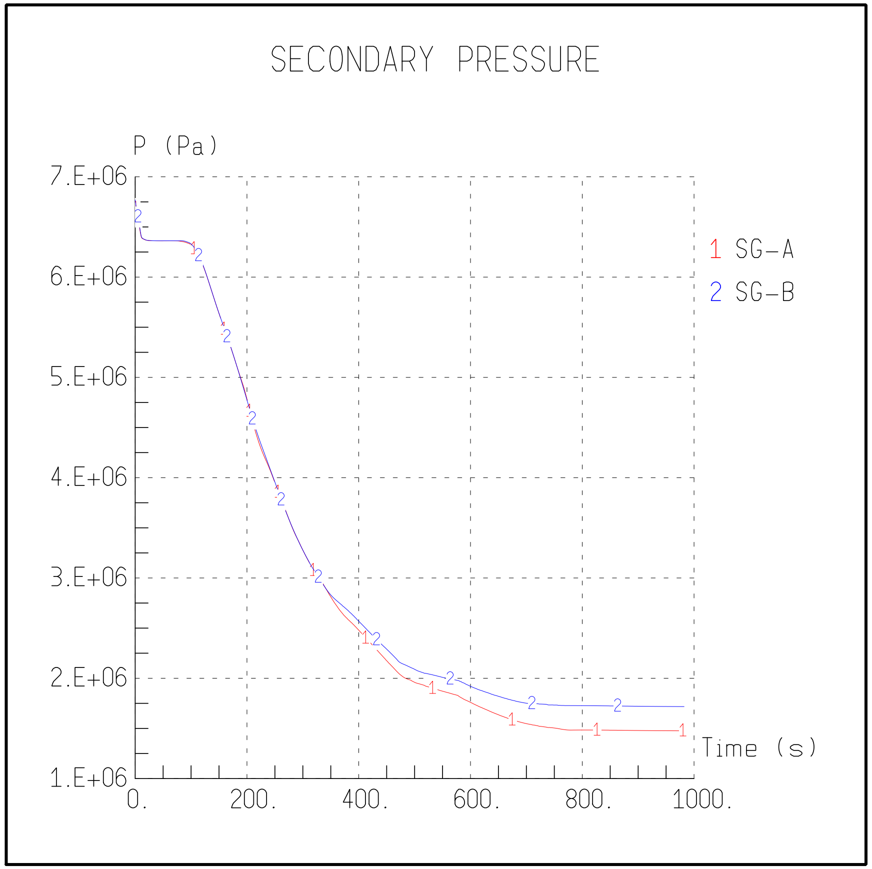

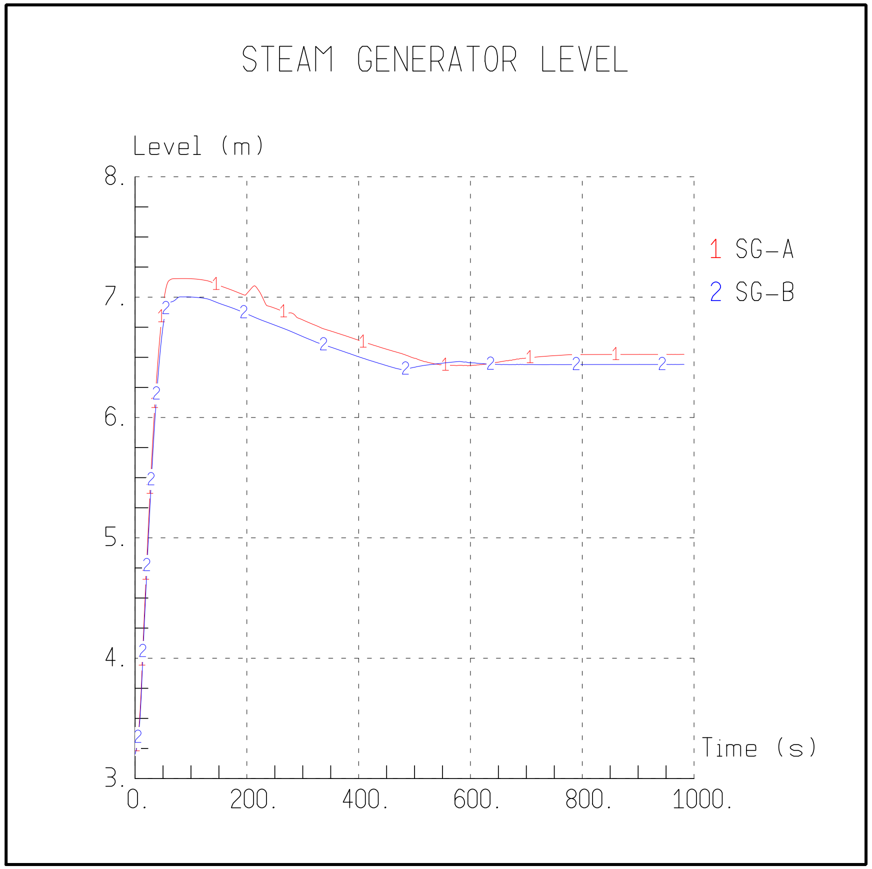

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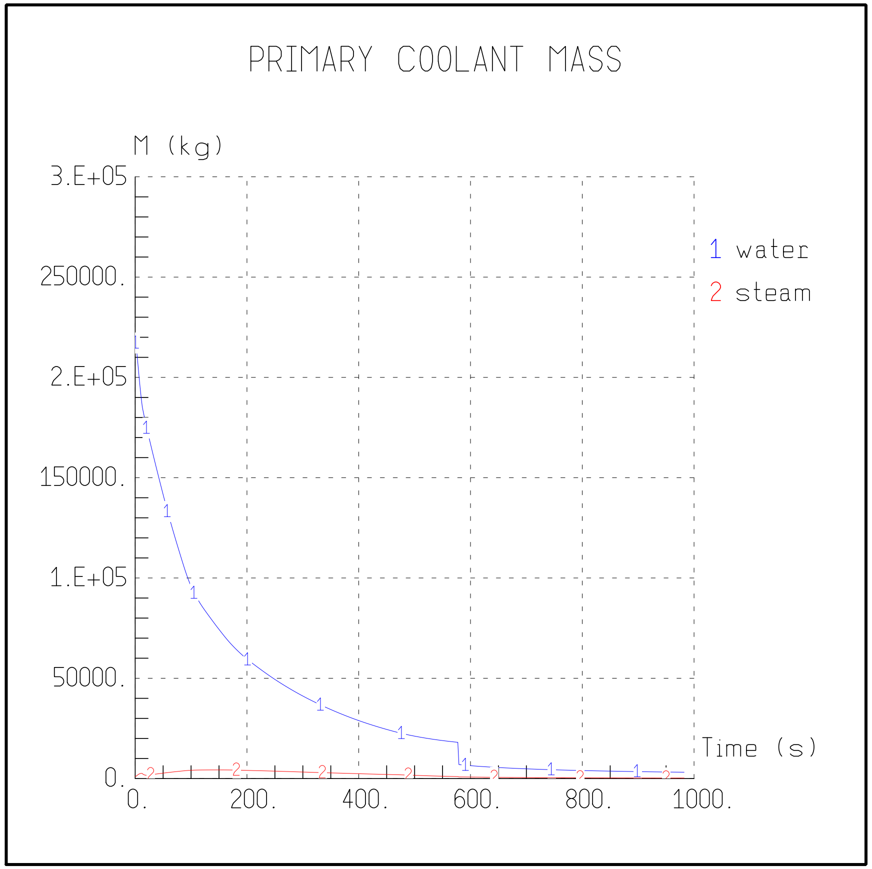

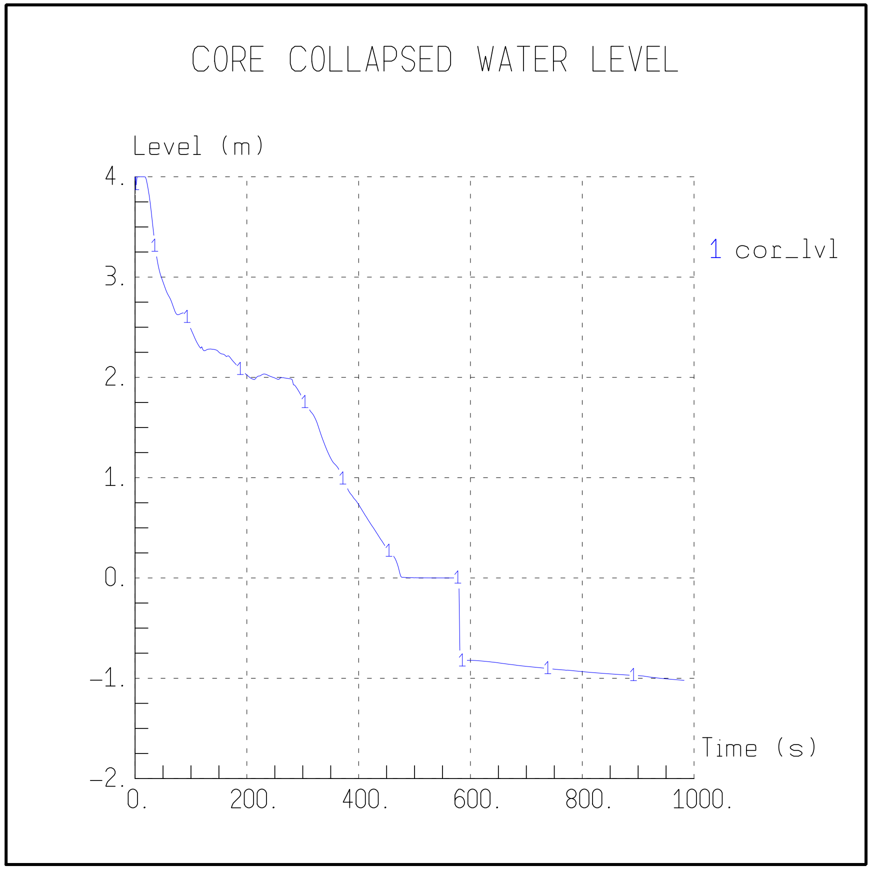

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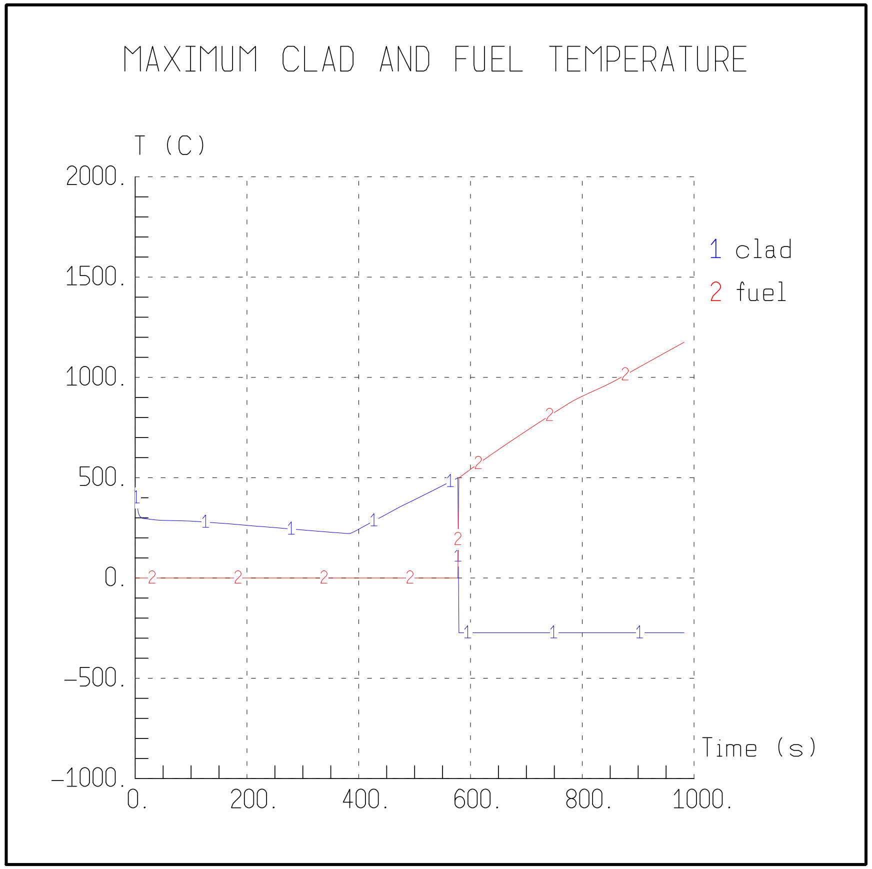

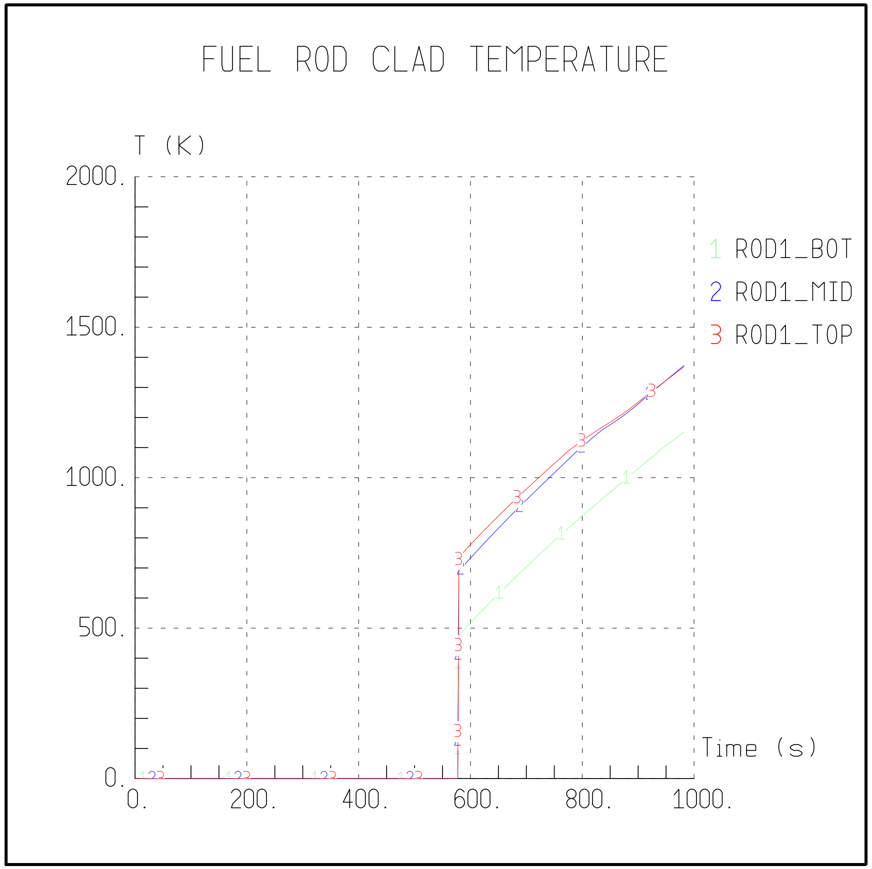

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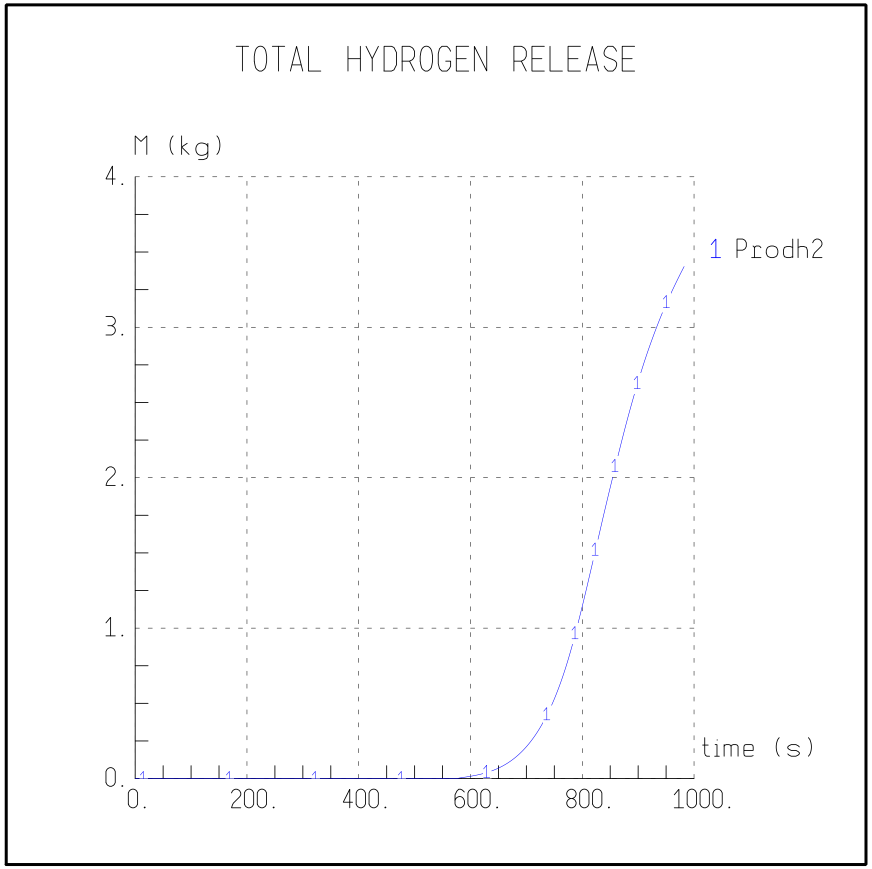
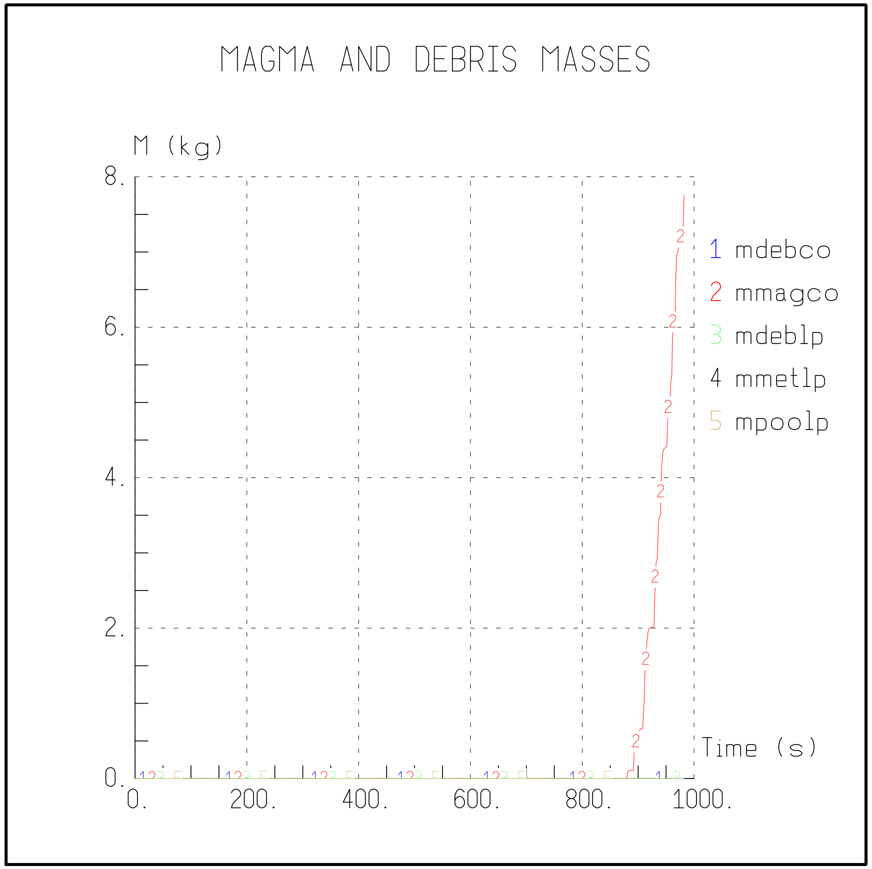
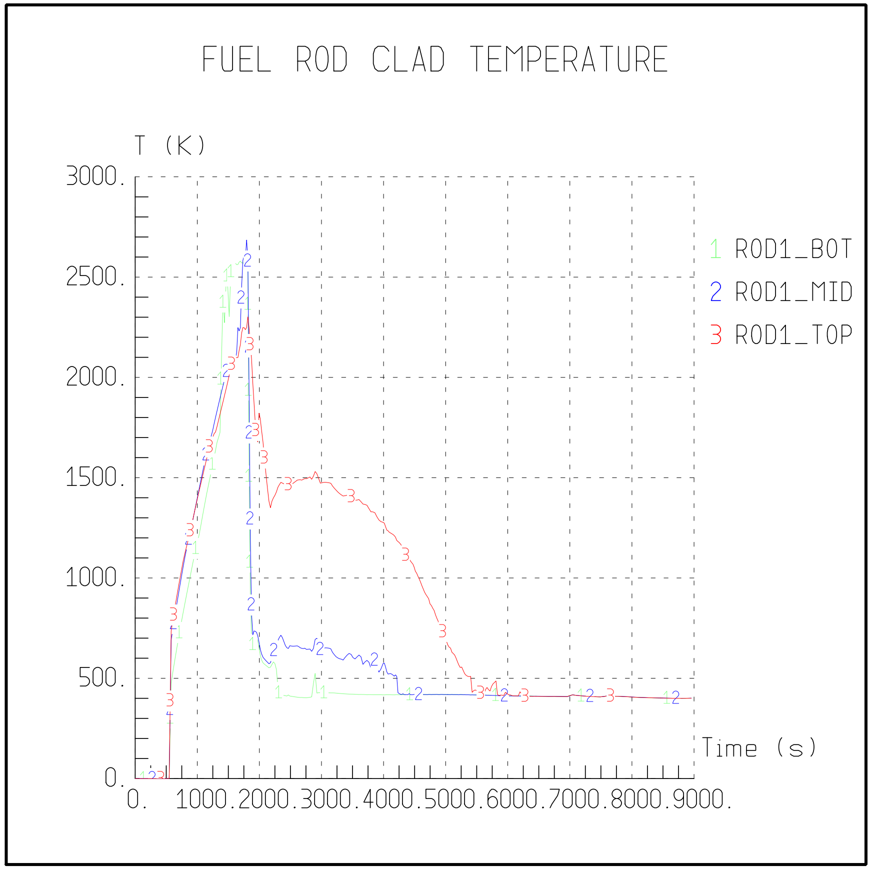
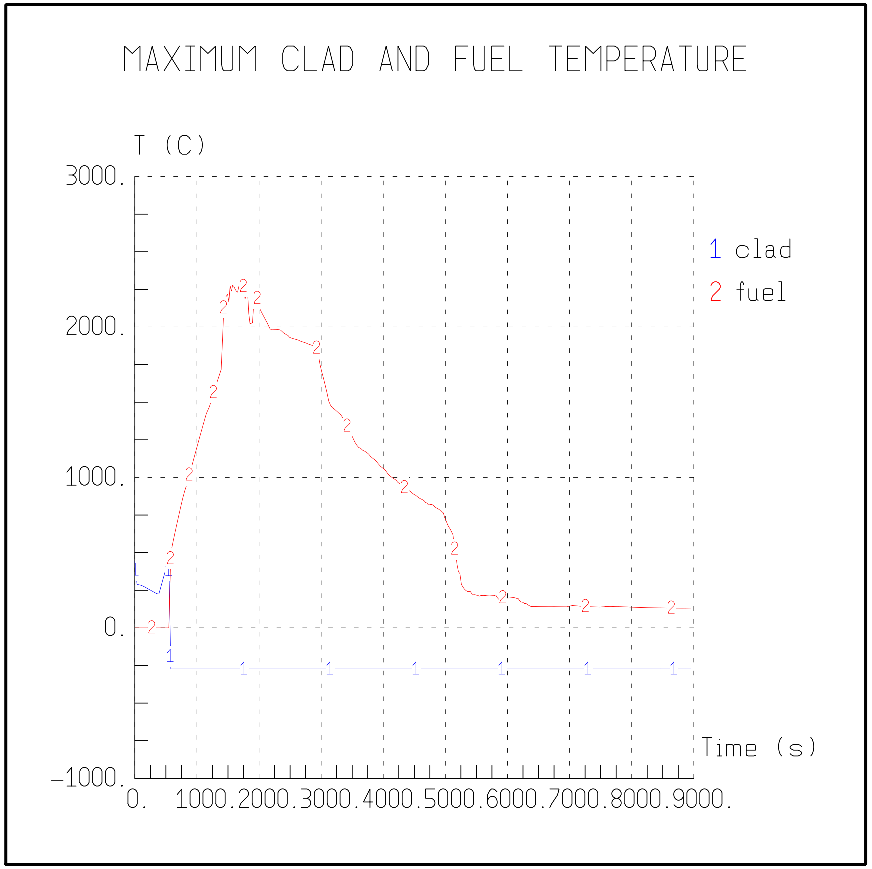




Addendum: long-term transients, SBO, 2nd case 45t, *schematic*





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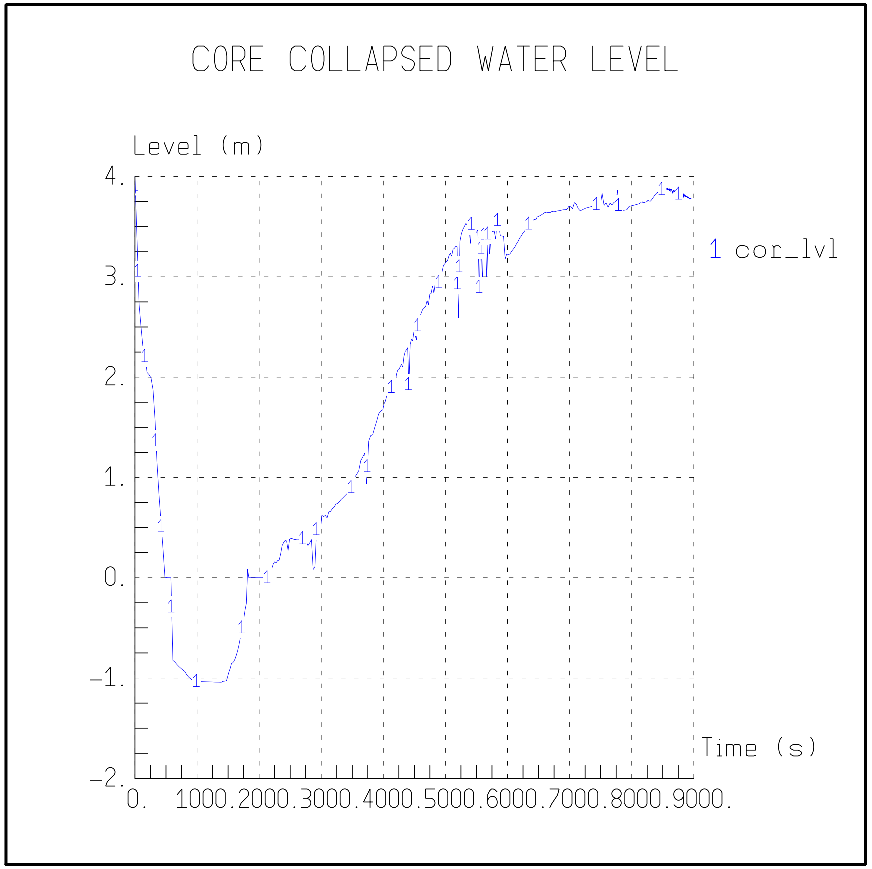
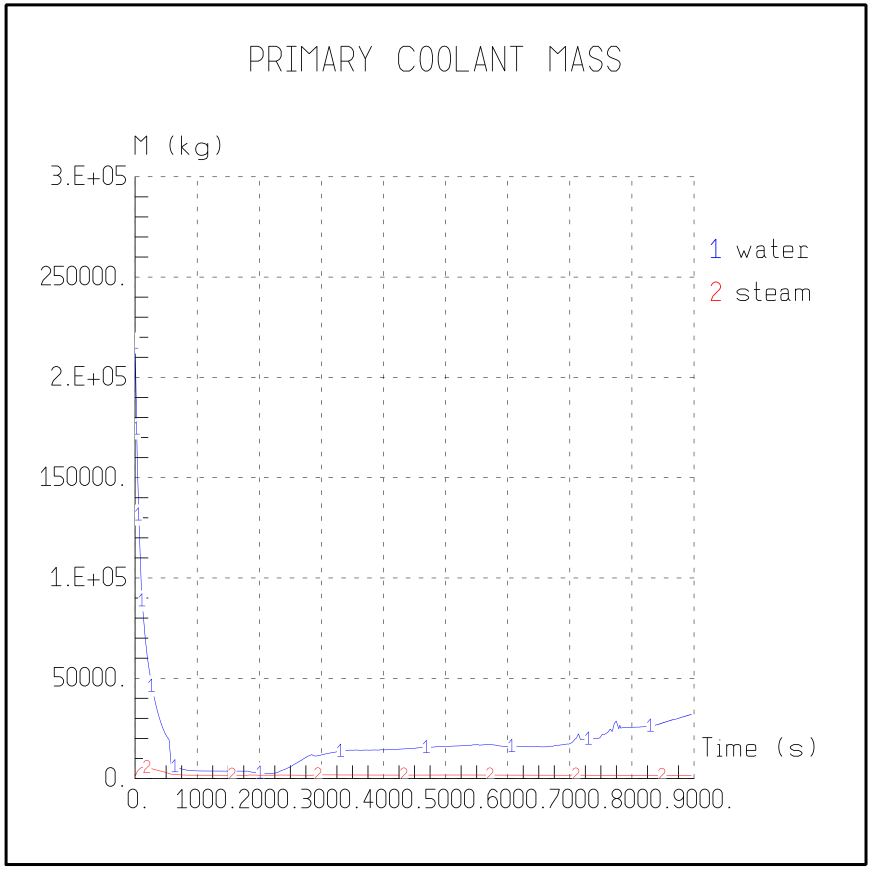
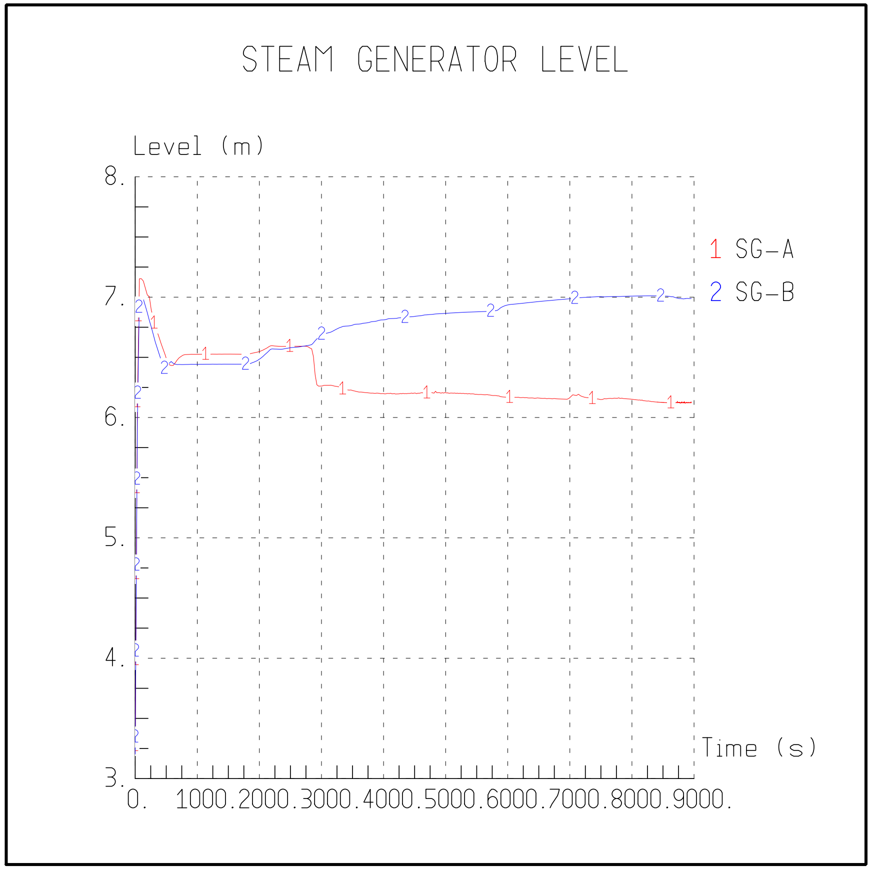
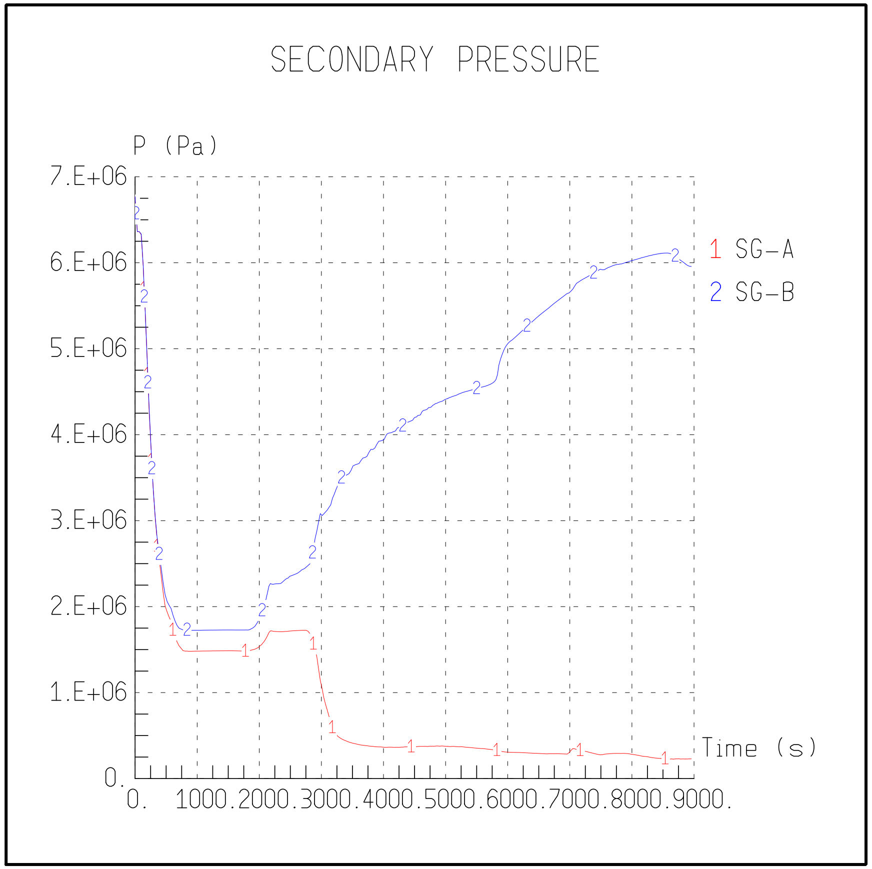


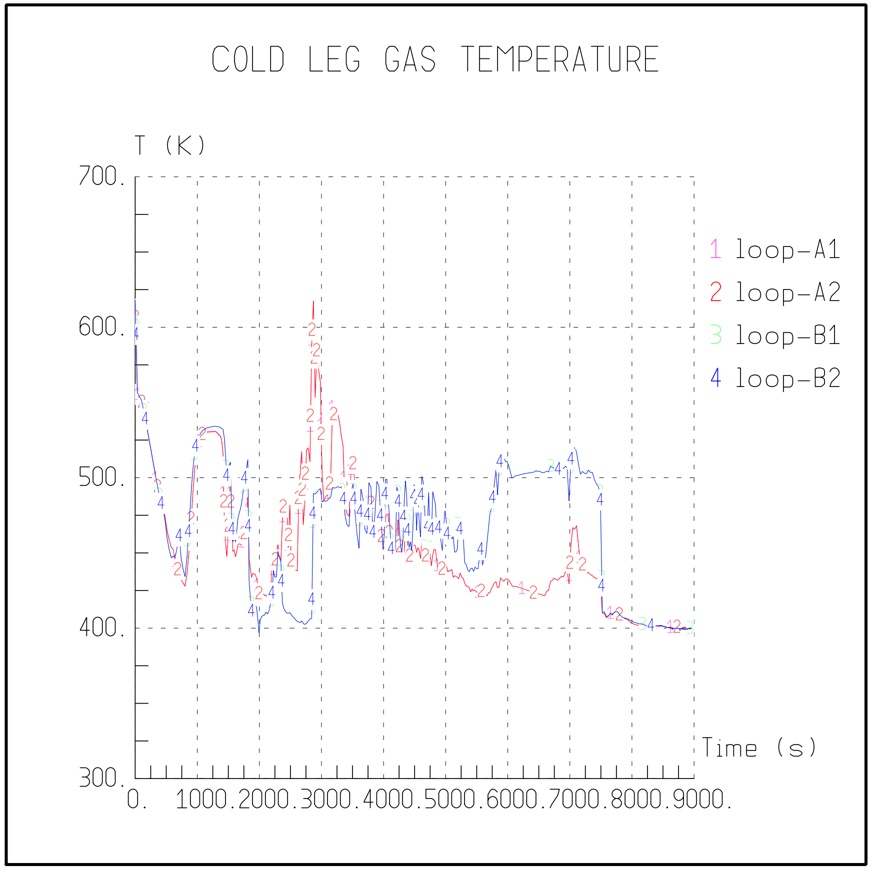


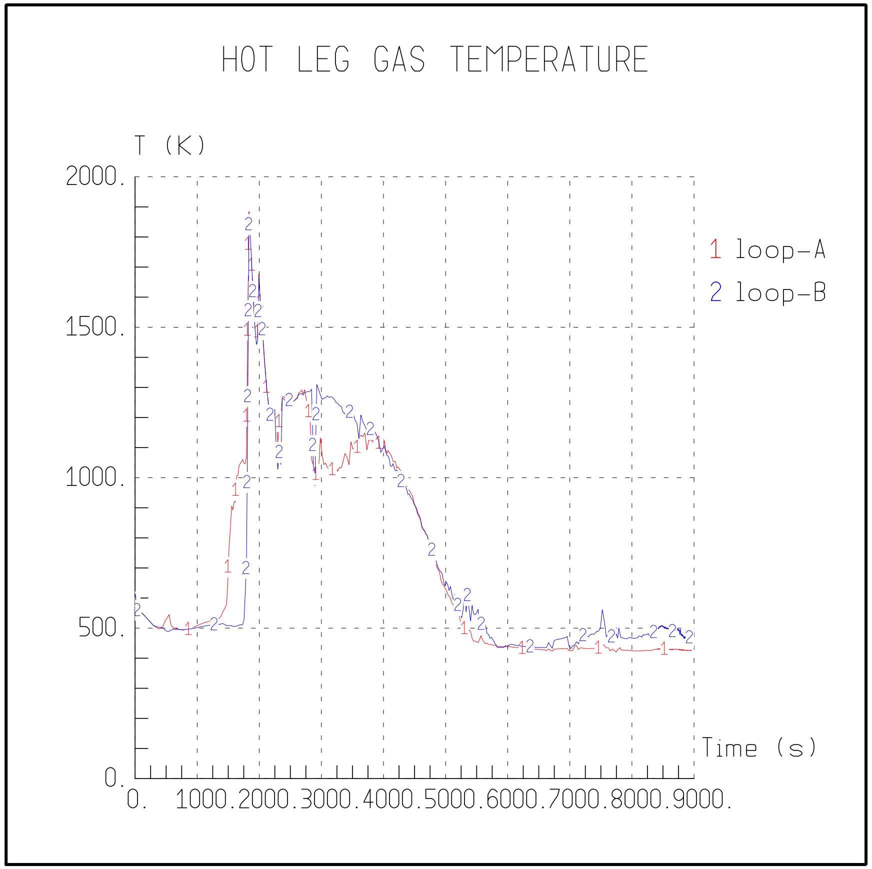
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*





Addendum: long-term transients, SBO, 2nd case 45t, *schematic*





Addendum: long-term transients, SBO, 2nd case 45t, *schematic*

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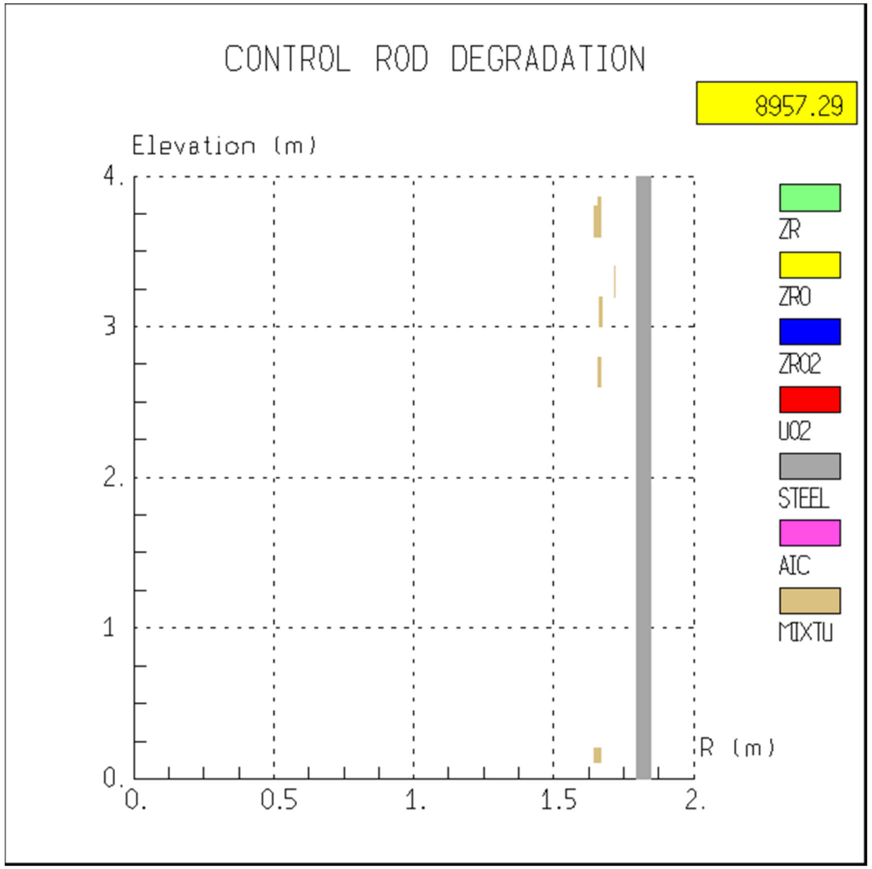
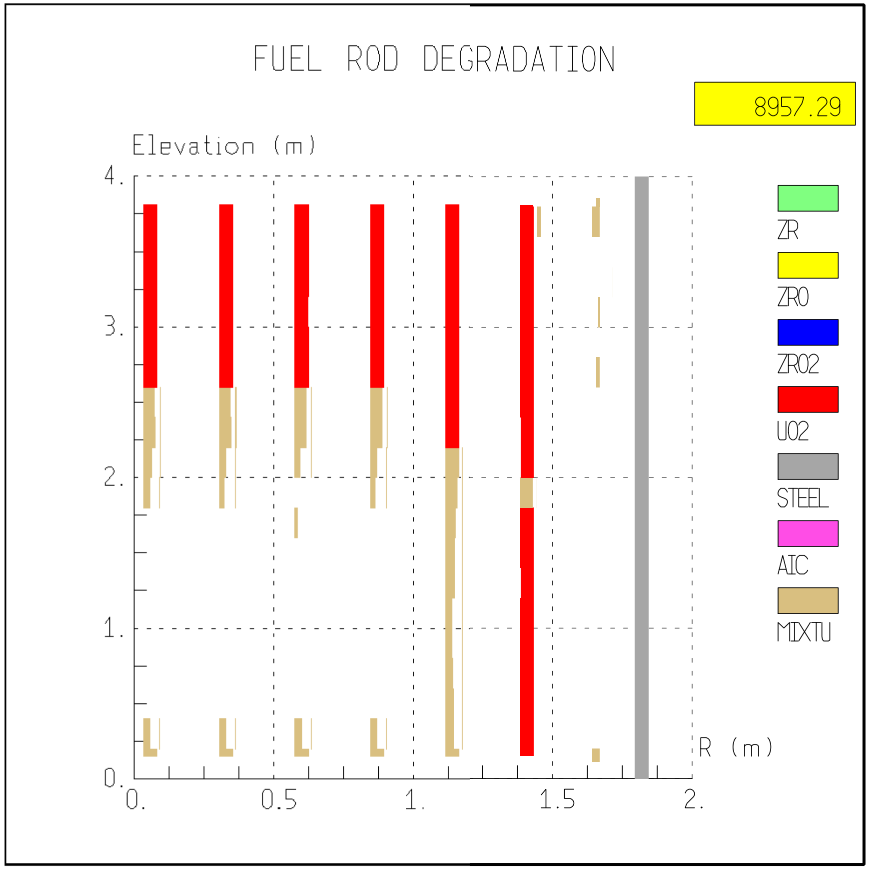
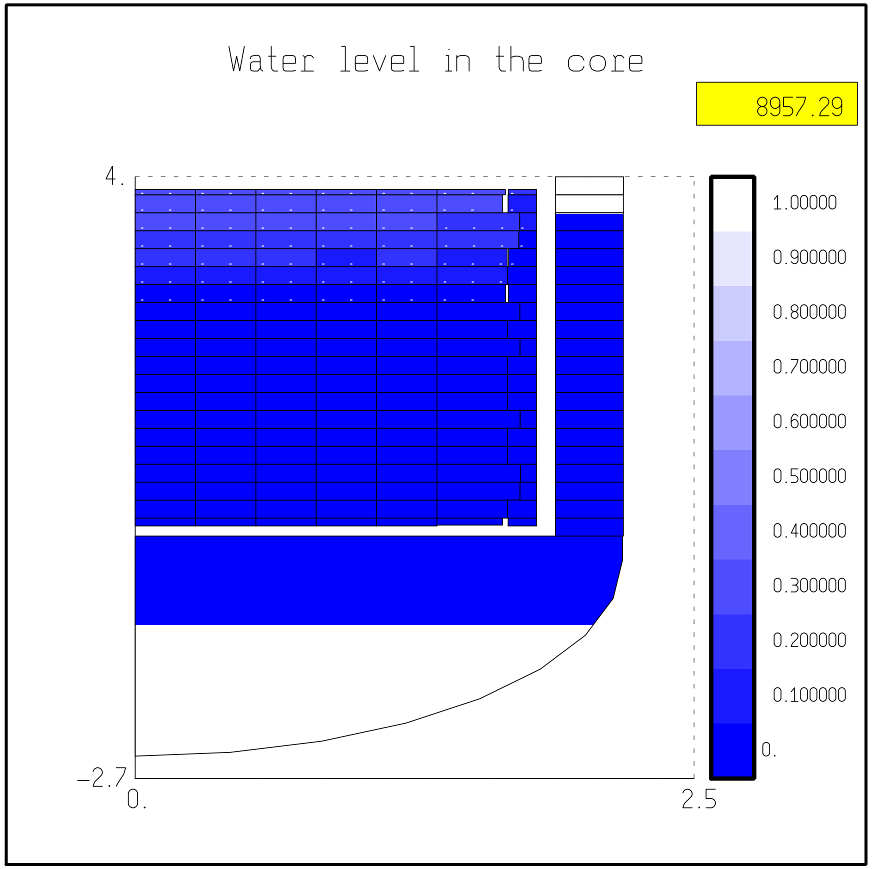
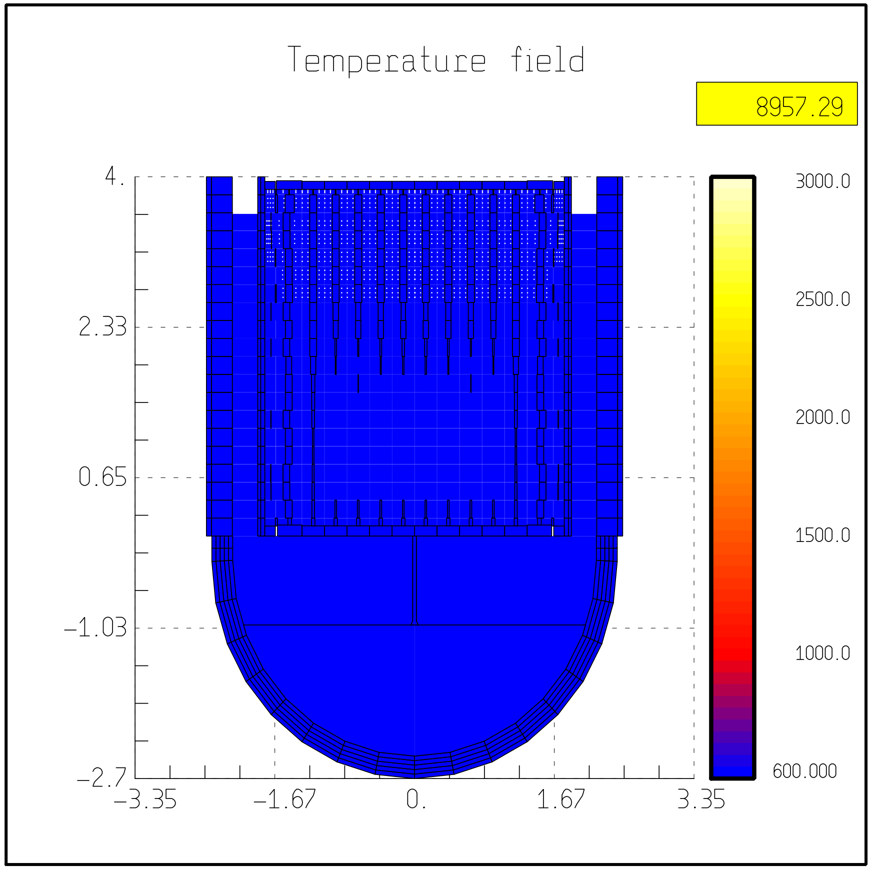




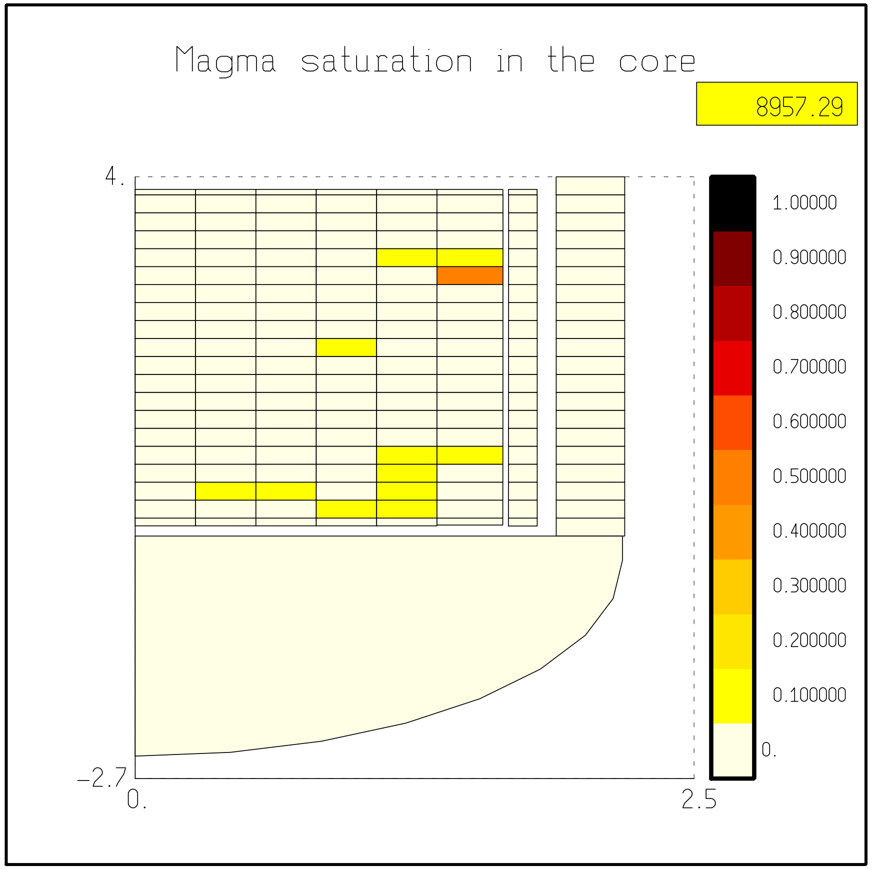
explanation of the degradation phenomena given in ASTEC manuals

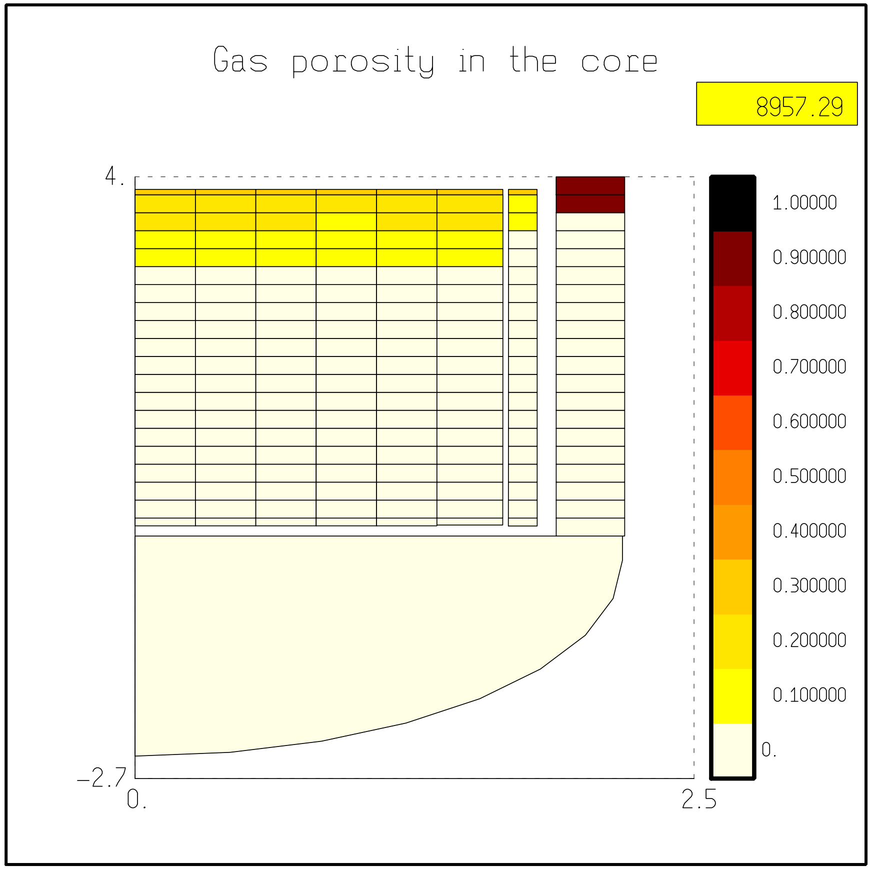
Addendum: long-term transient, SBO, 2nd case 45t, colour coded water field



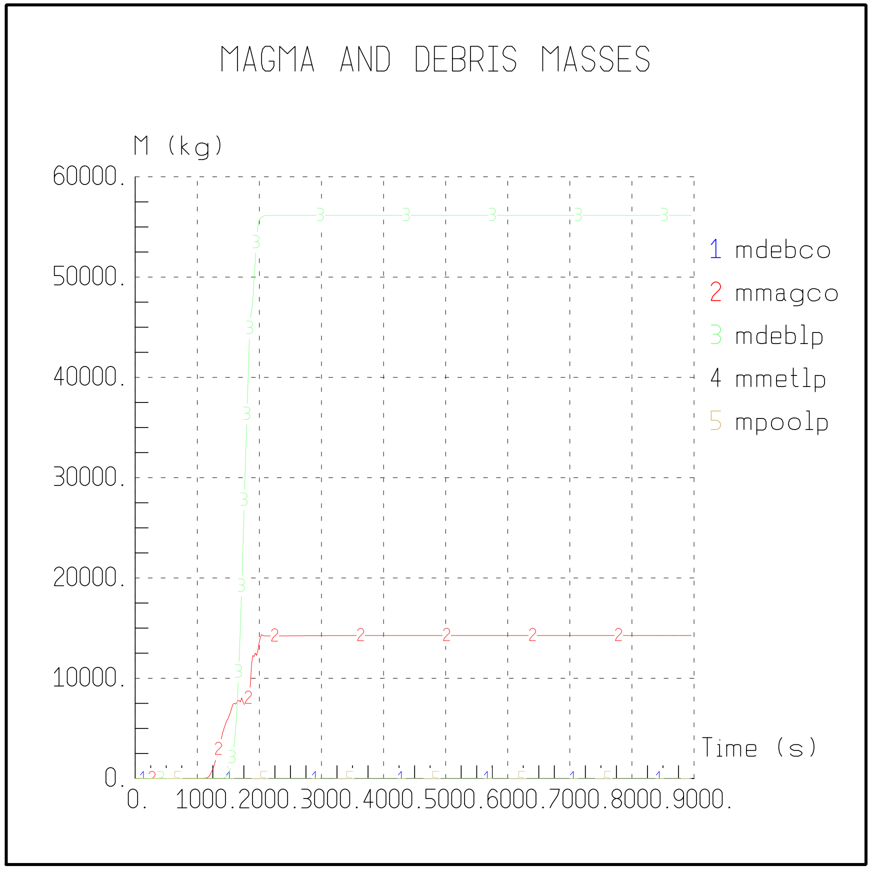


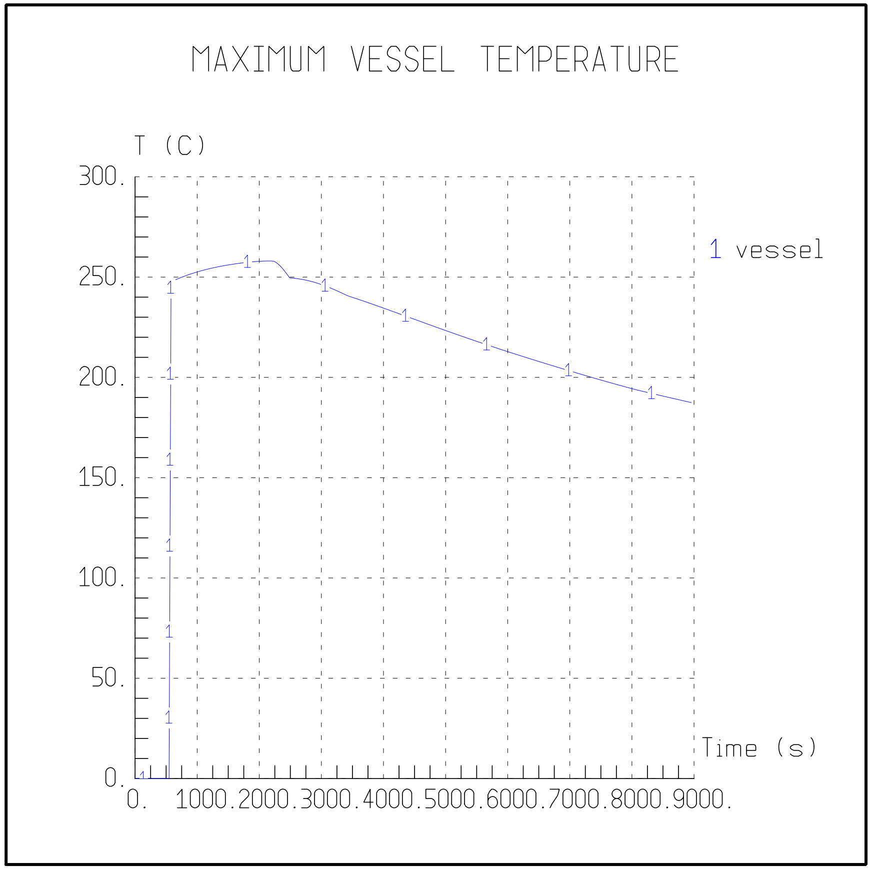
Addendum: long-term transients, SBO, 2nd case 45t, colour coded maps



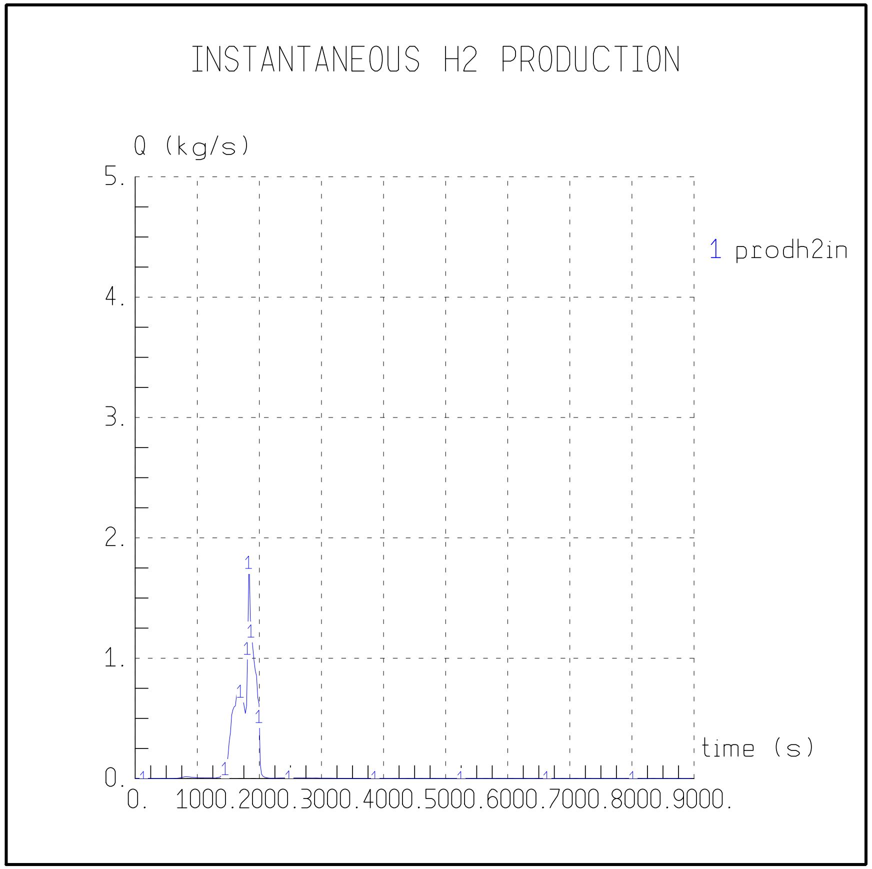


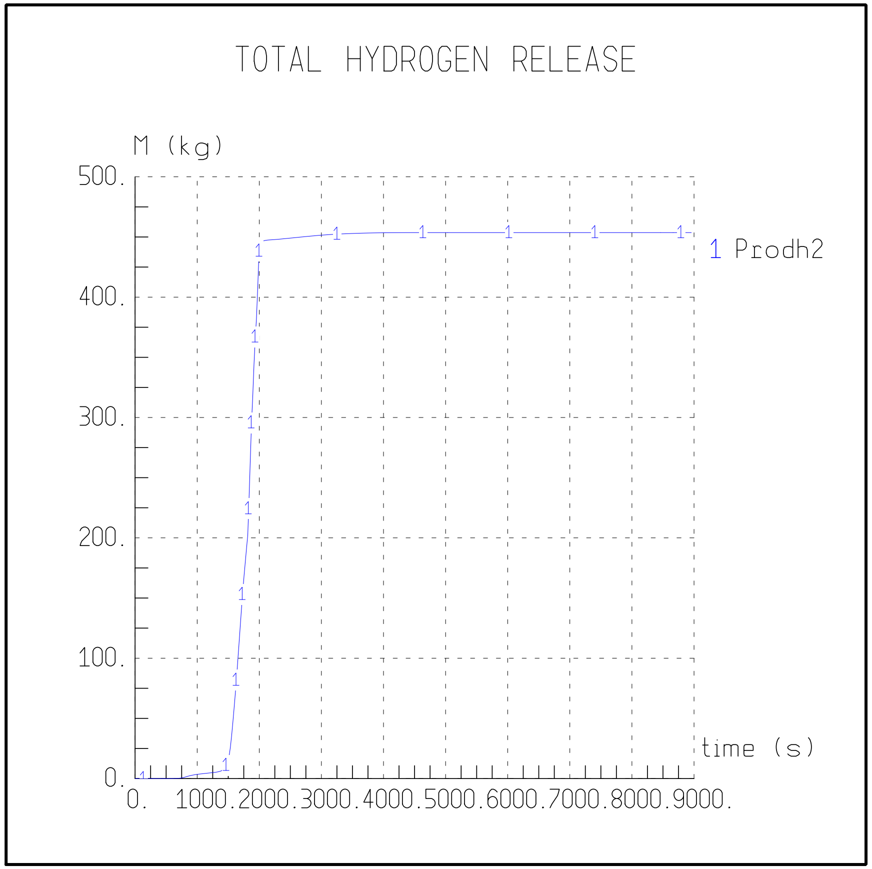
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*



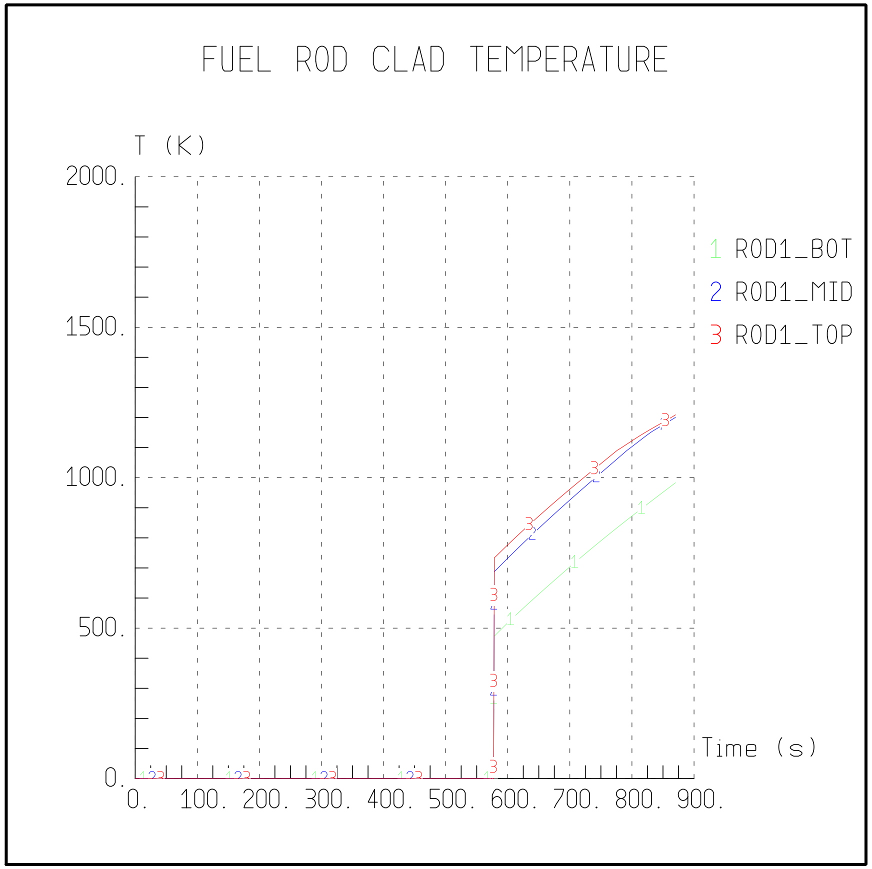


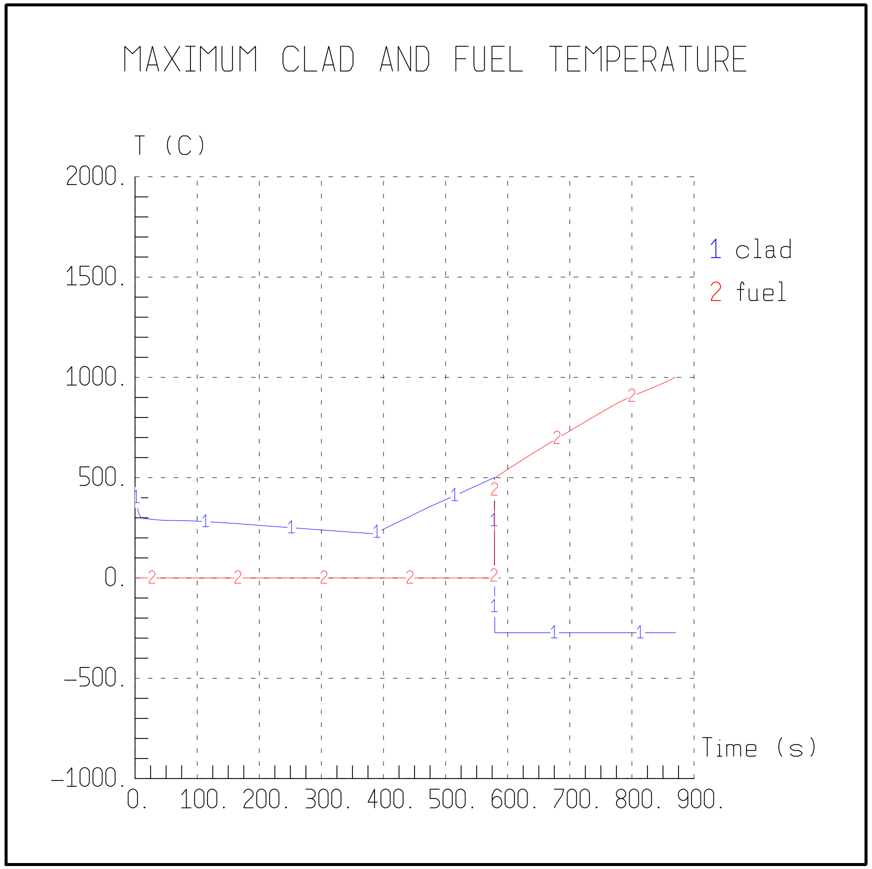
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*



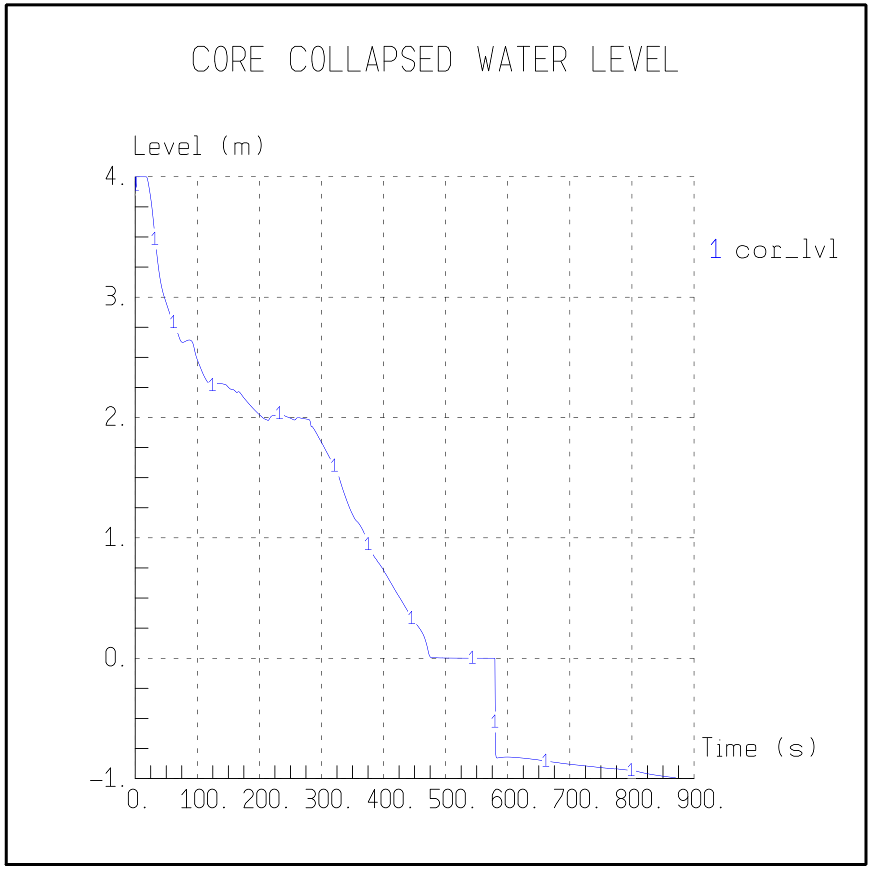


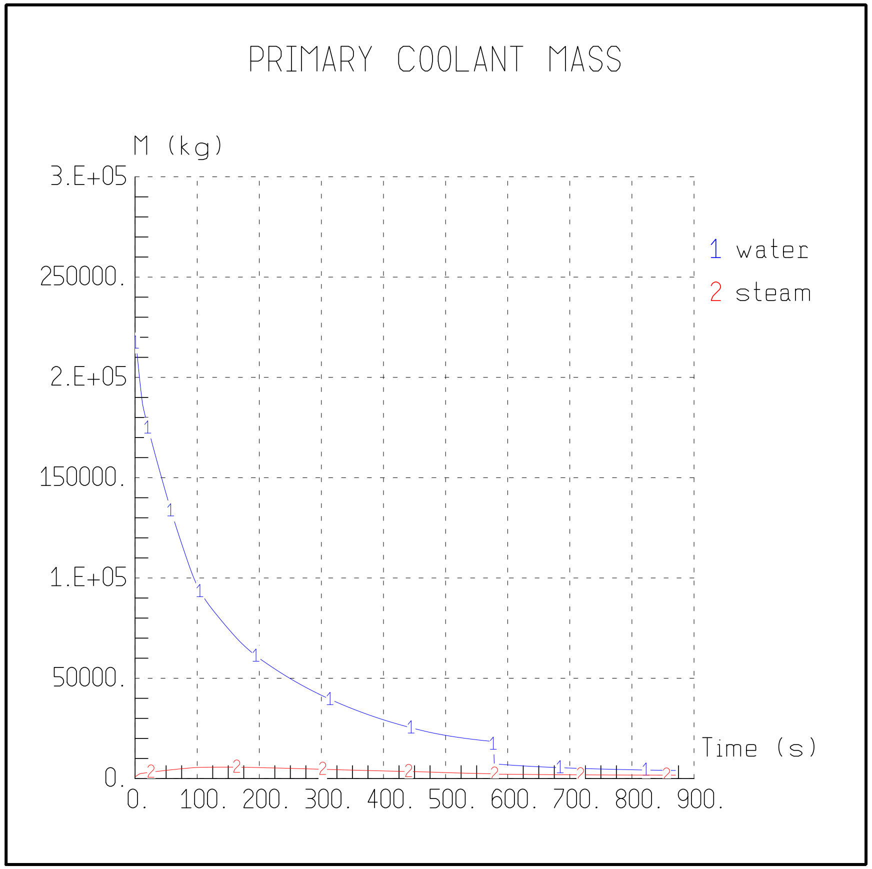
Addendum: mid-term transients, SBO, 2nd case 45t, *schematic*



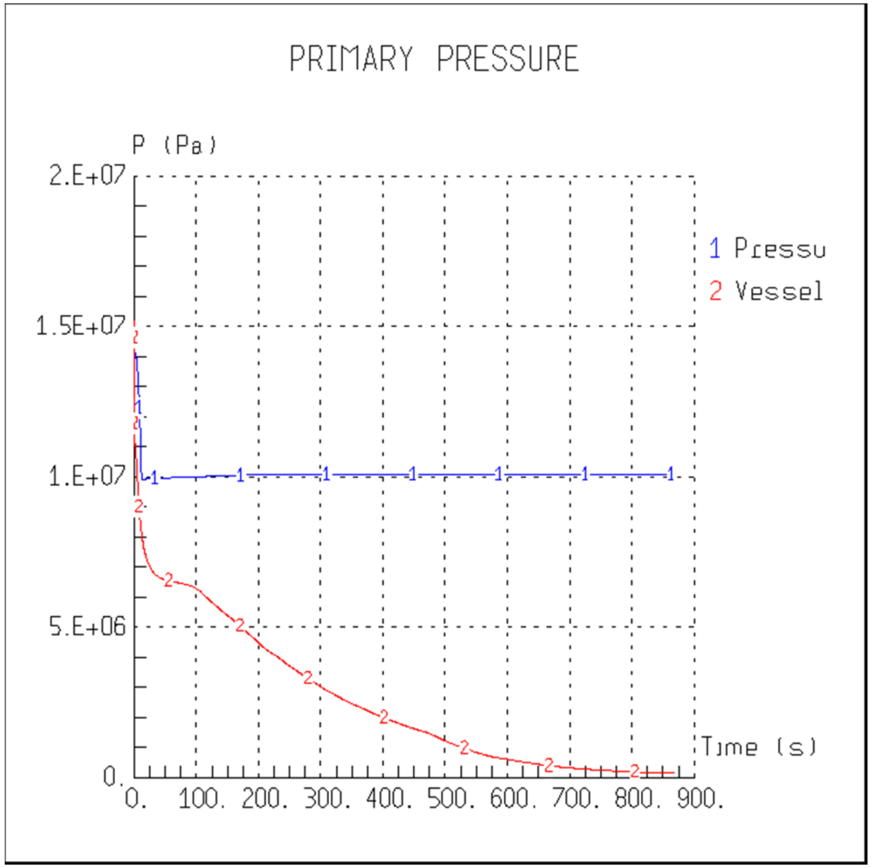


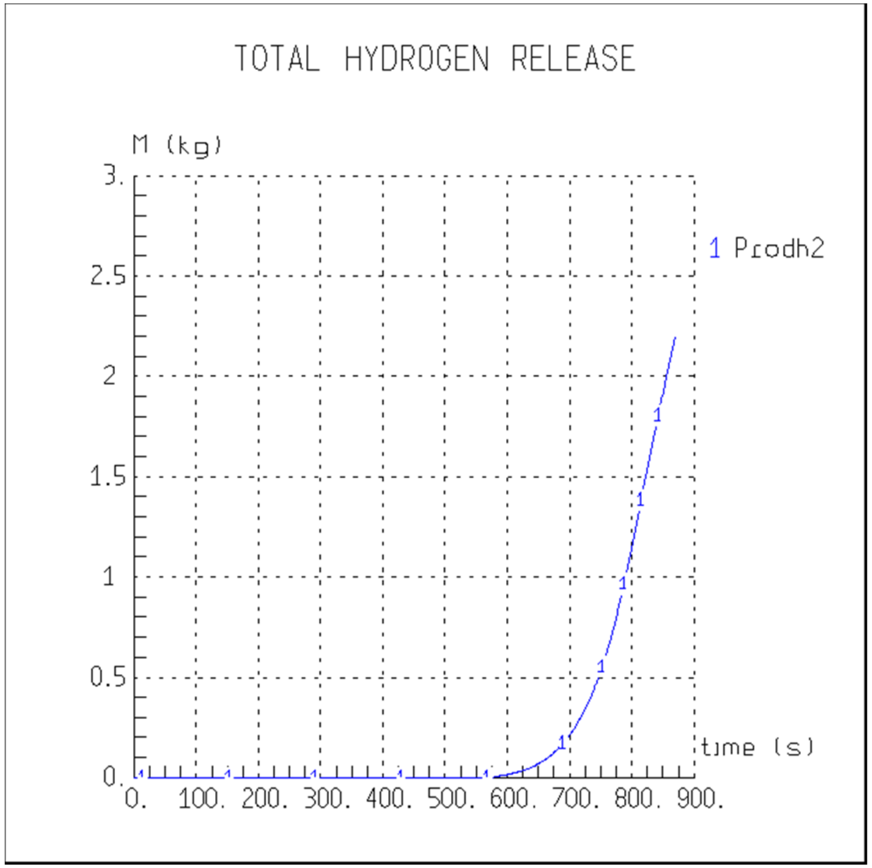
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*



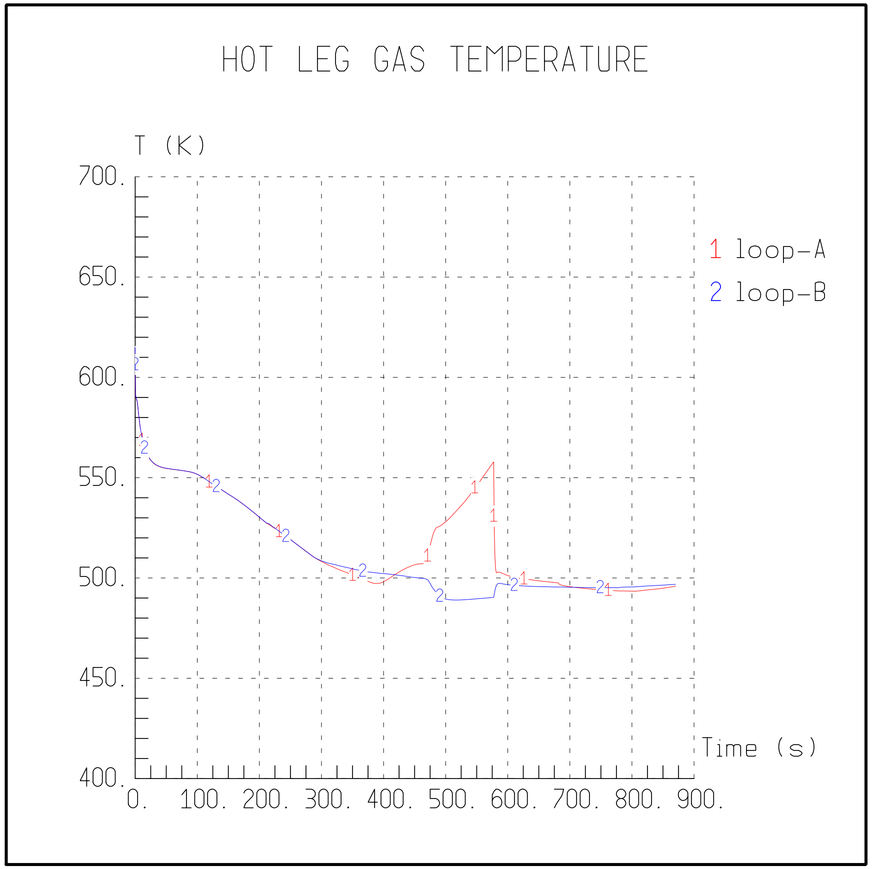


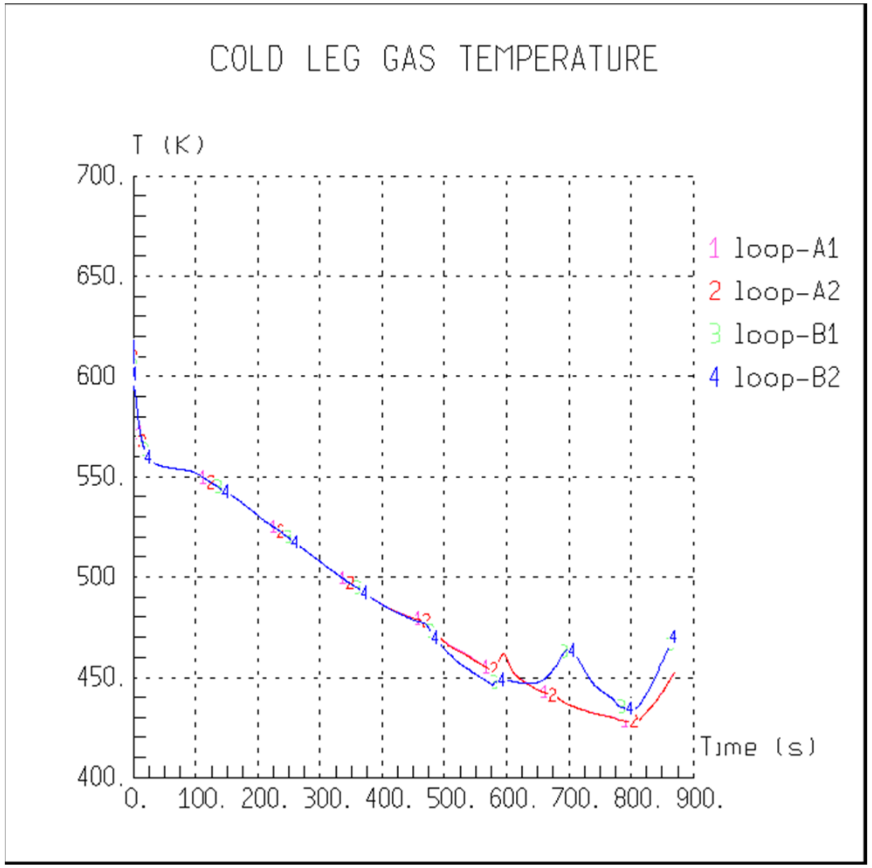
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*



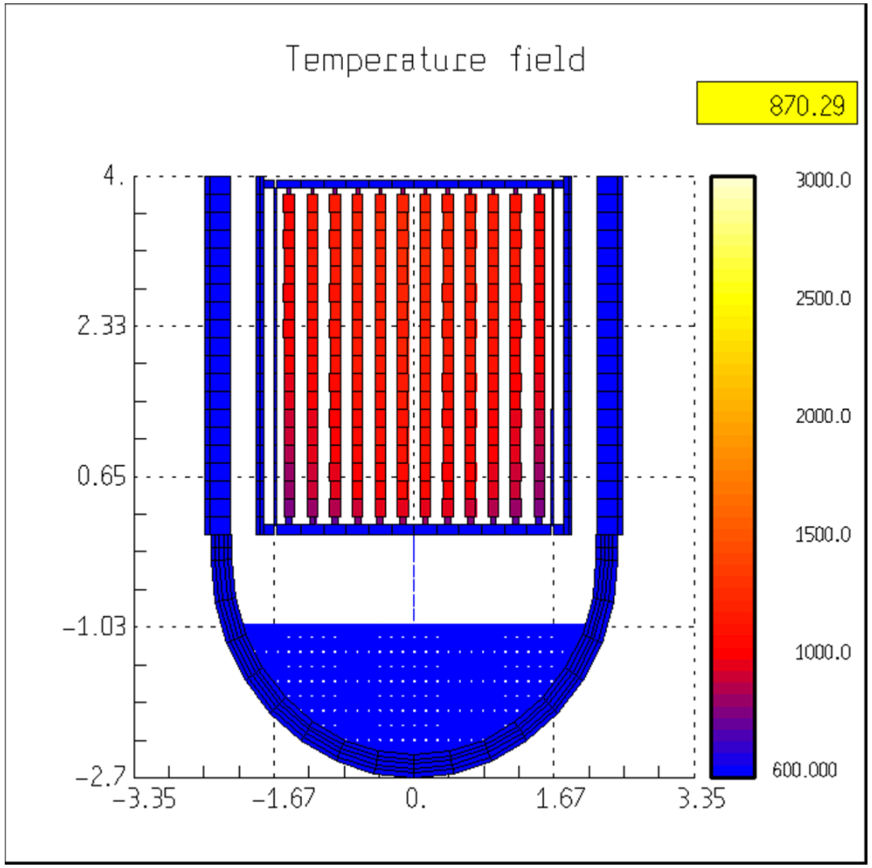


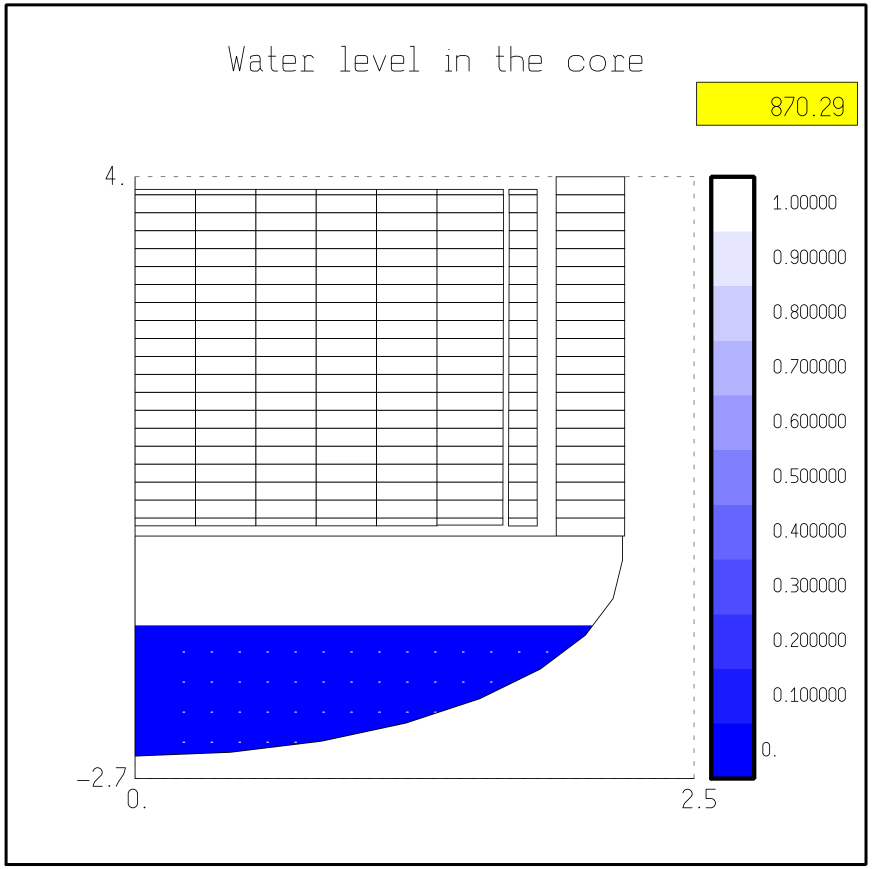
Addendum: long-term transients, SBO, 2nd case 45t, *schematic*



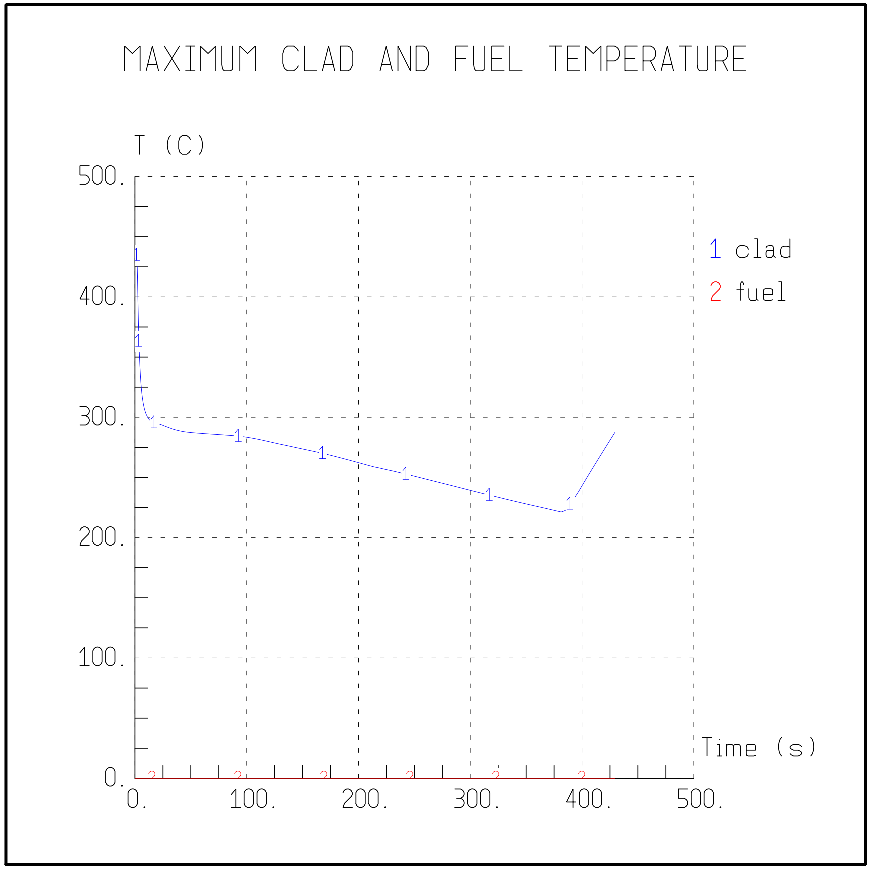


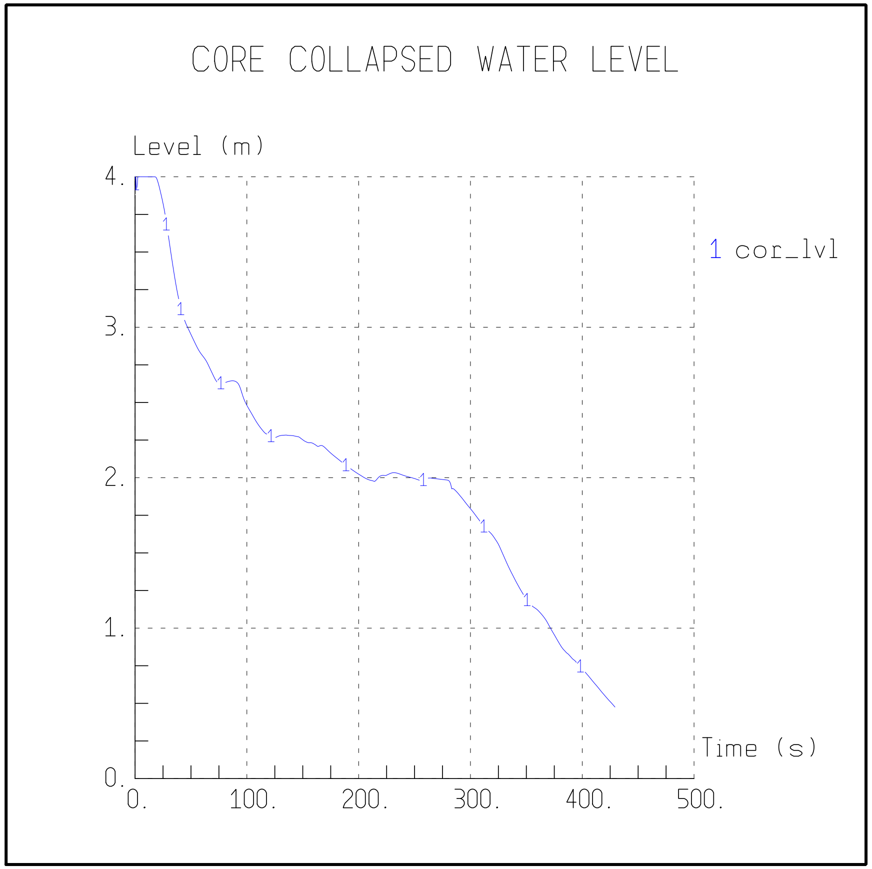
Addendum: mid-term transients, SBO *schematic/ revisited*



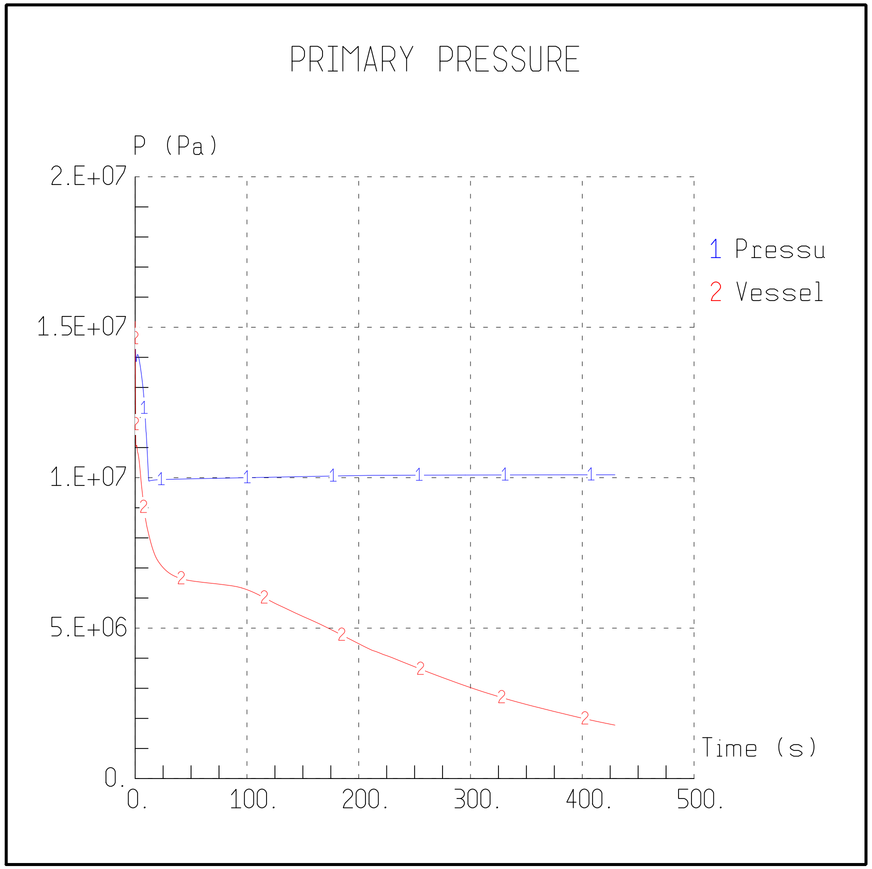


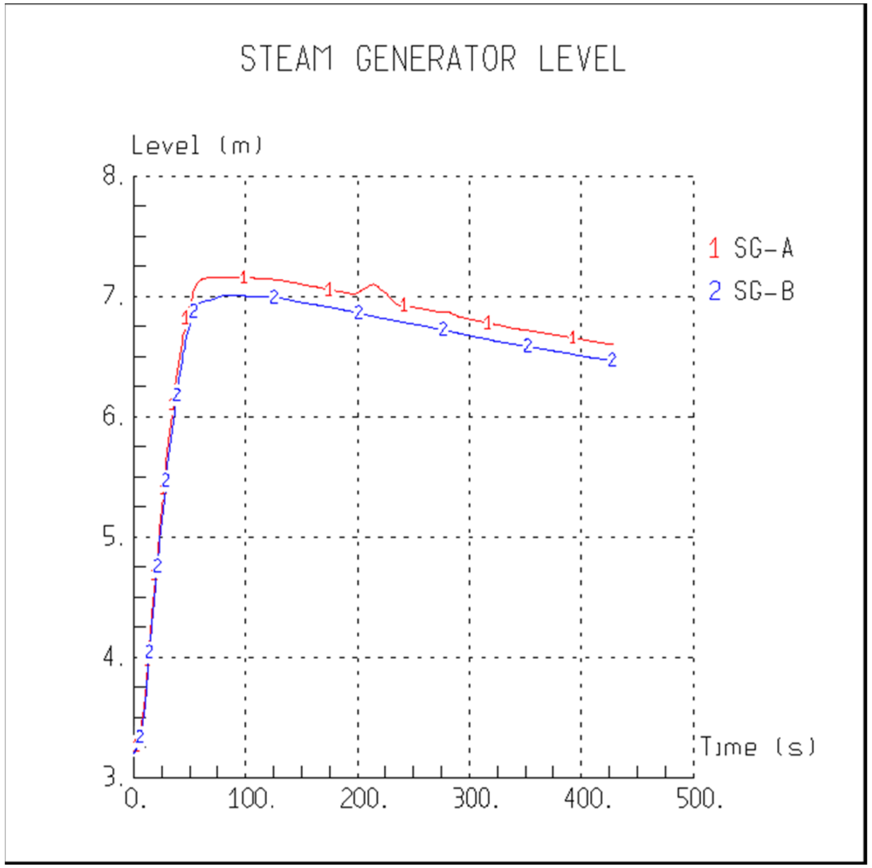
Addendum: short-term transients, SBO, 2nd case SBO 45t, *schematic*





Addendum: short-term transients, SBO, 2nd case SBO 45t, *schematic*





Addendum: short-term transients, SBO, 2nd case SBO 45t, schematic

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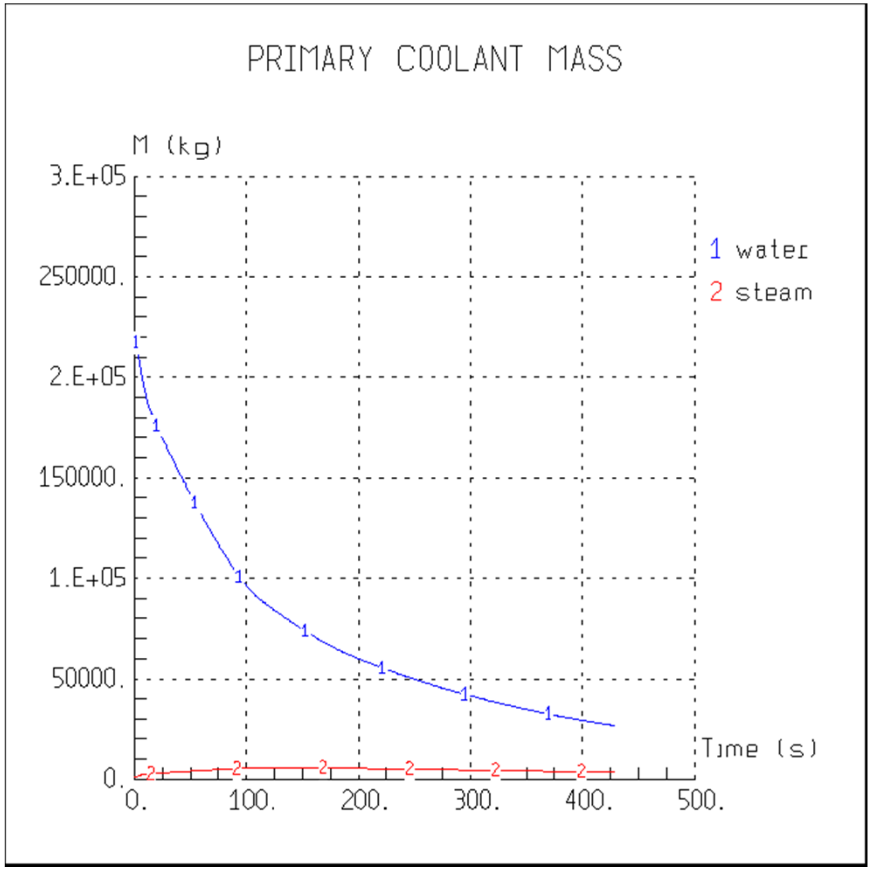
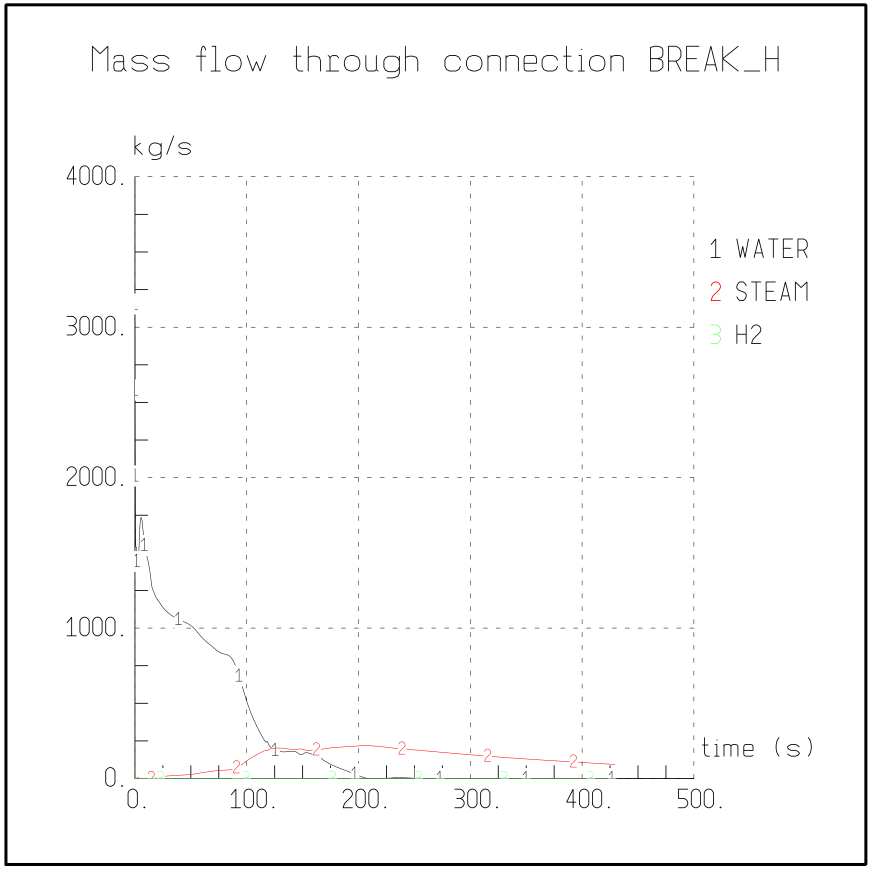
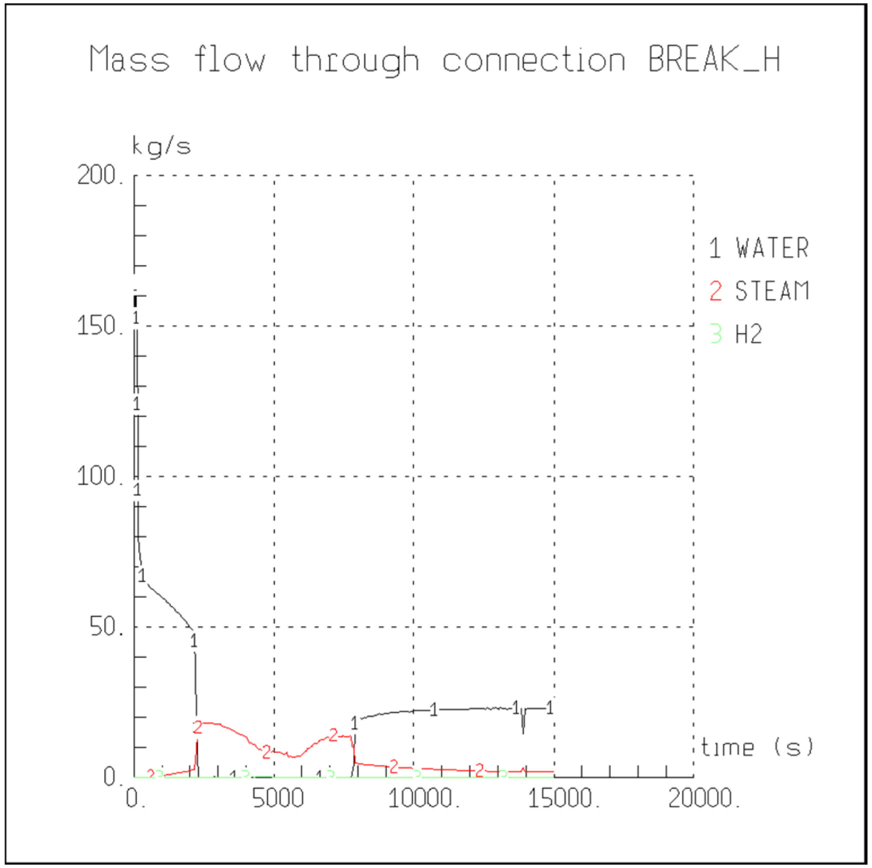
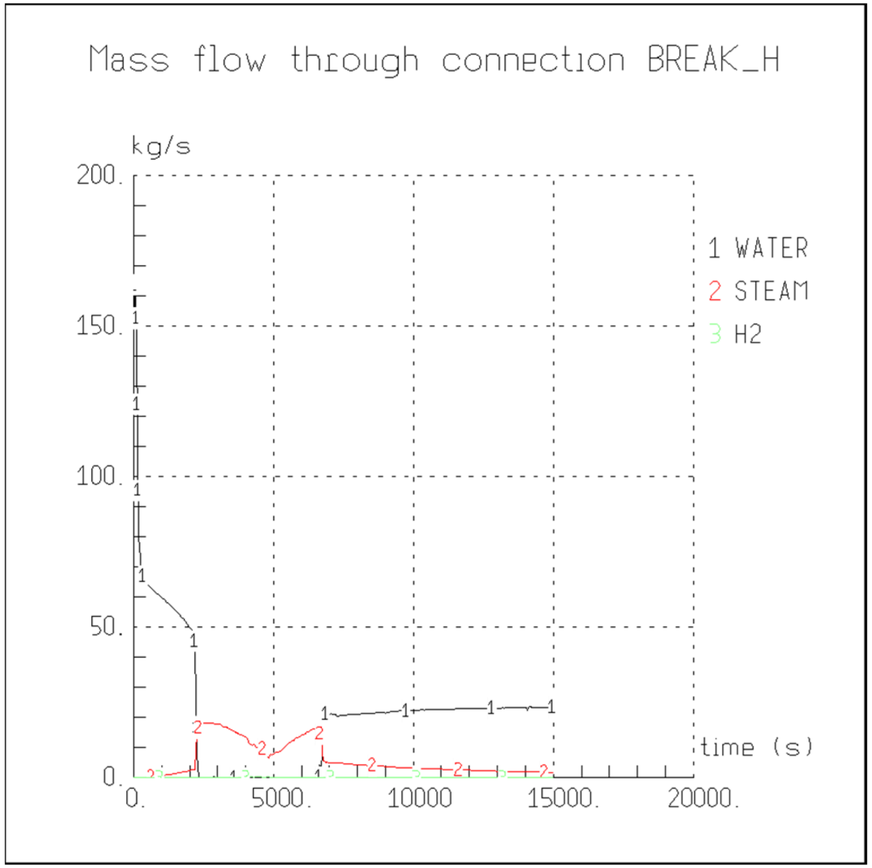




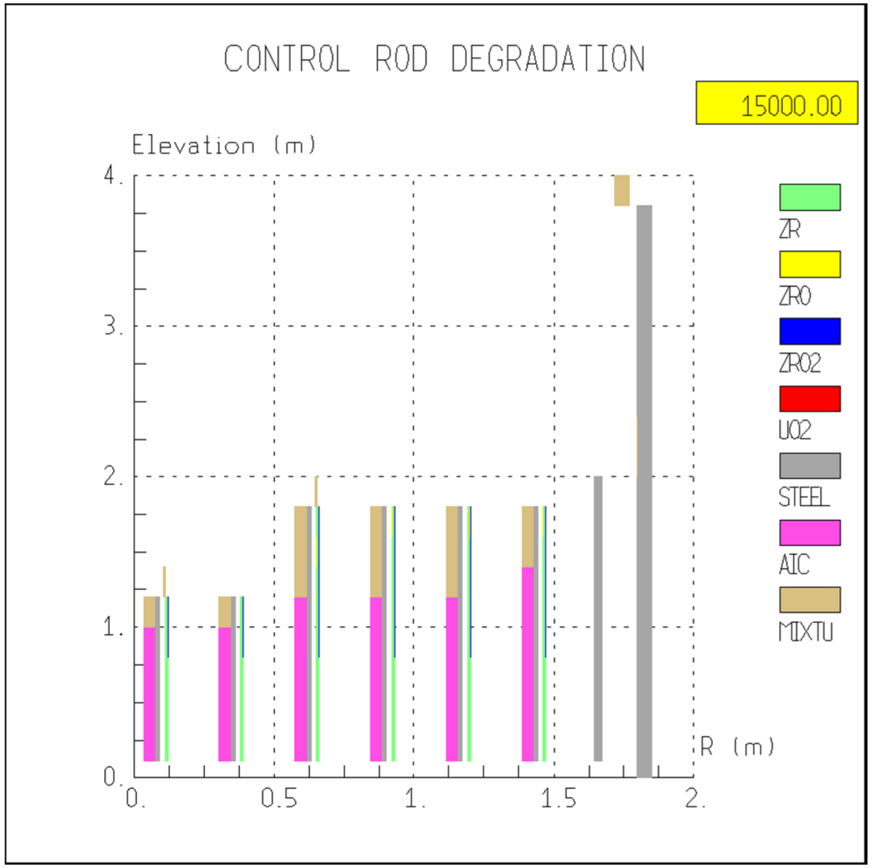
M=45 t/ right vs. M=10 t/ left (*reflooding* cases, 2nd stage)

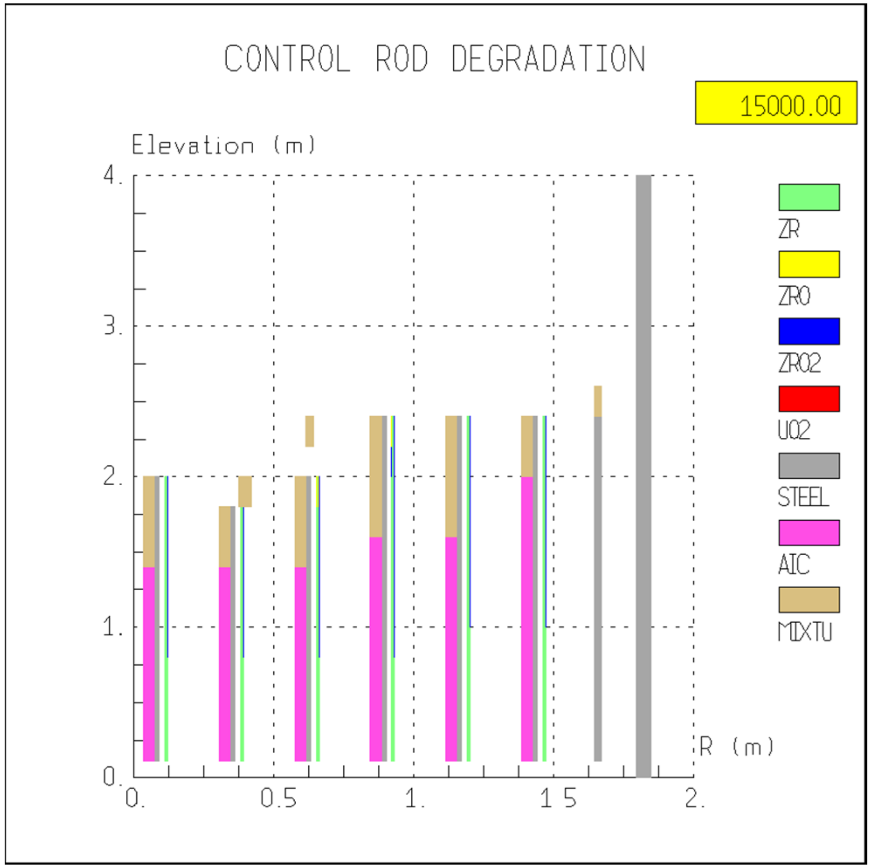
A LOCA seq. with the start of core reflood triggered by the total degraded mass of M = 10t/ 45t , respectively; Base case calc.-s repeated, outputs → to the Chair



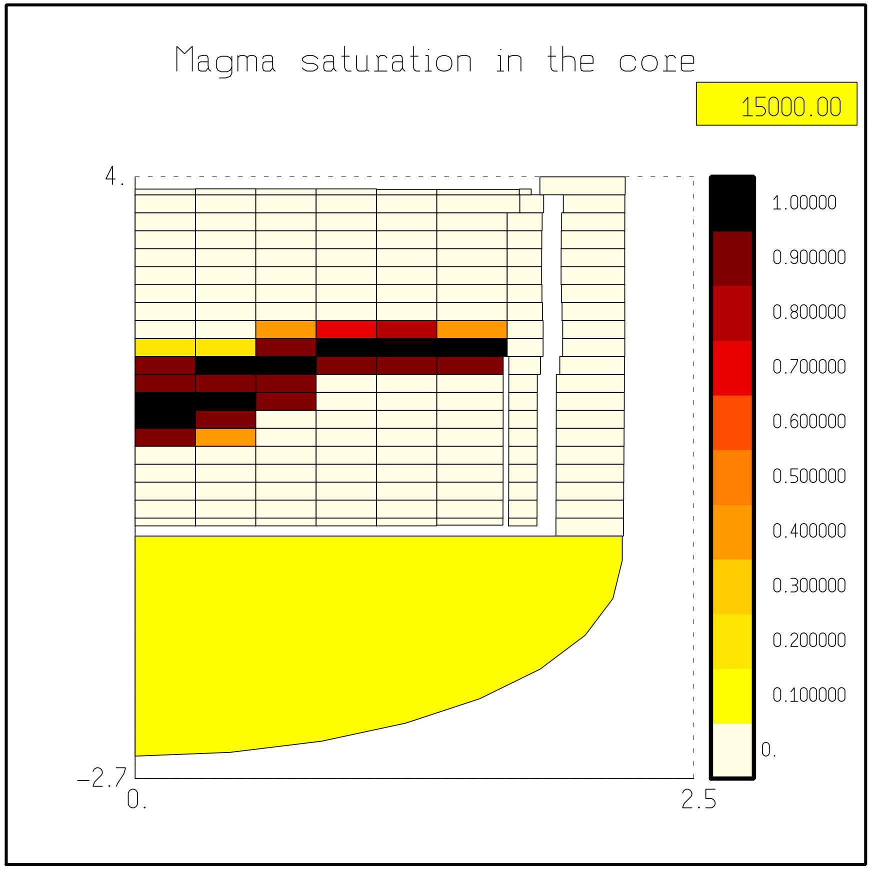


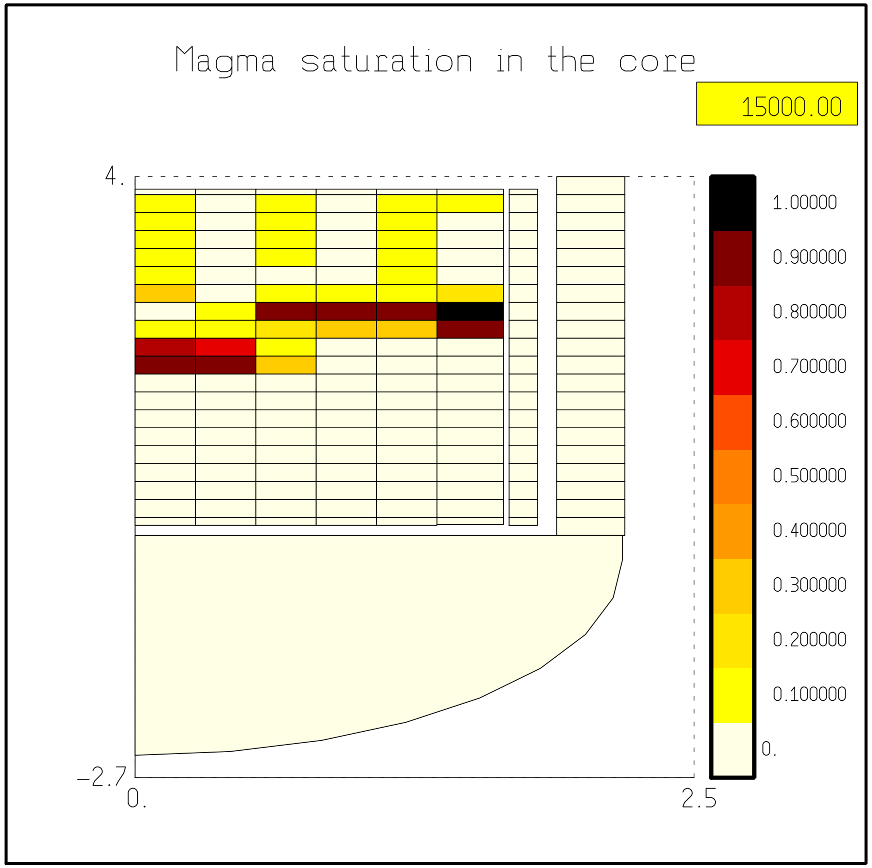
M= 45 t/*right* vs.M=10 t/ *left* (*reflooding* cases, *forwarded*)



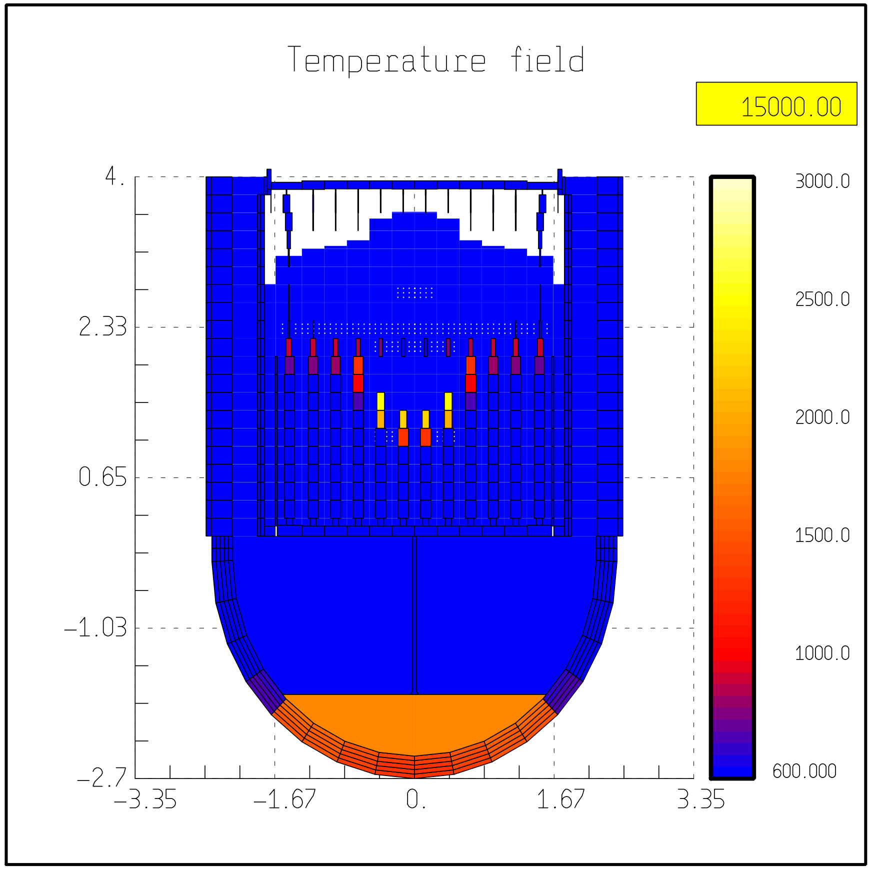


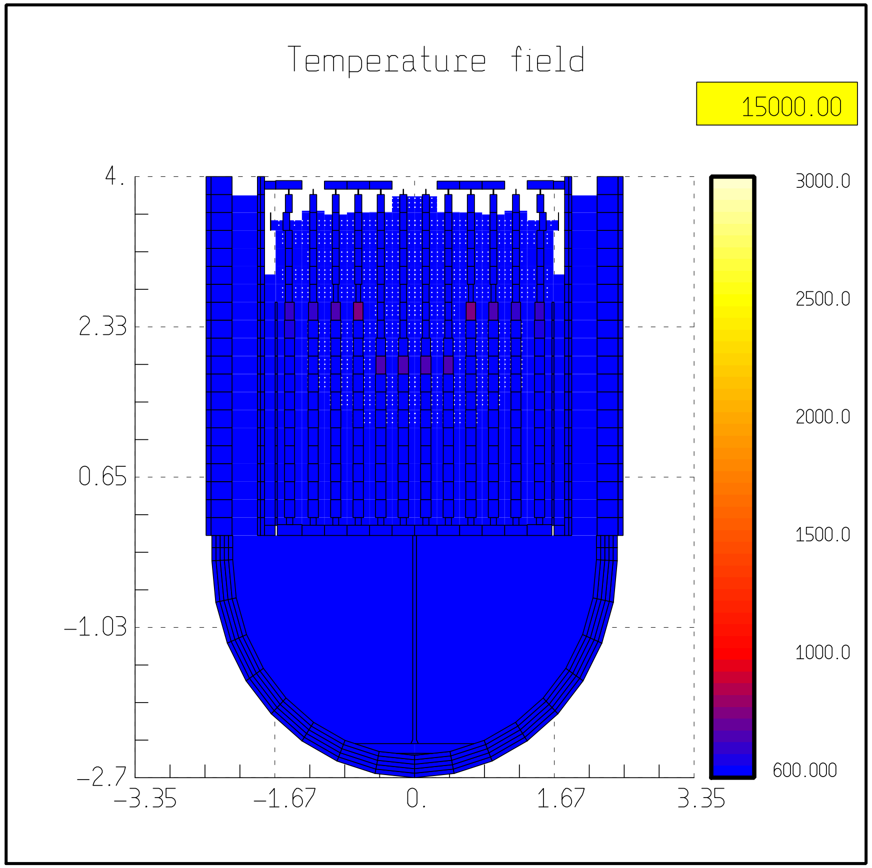
45 t/right vs.10 t/left (*reflooding* cases)



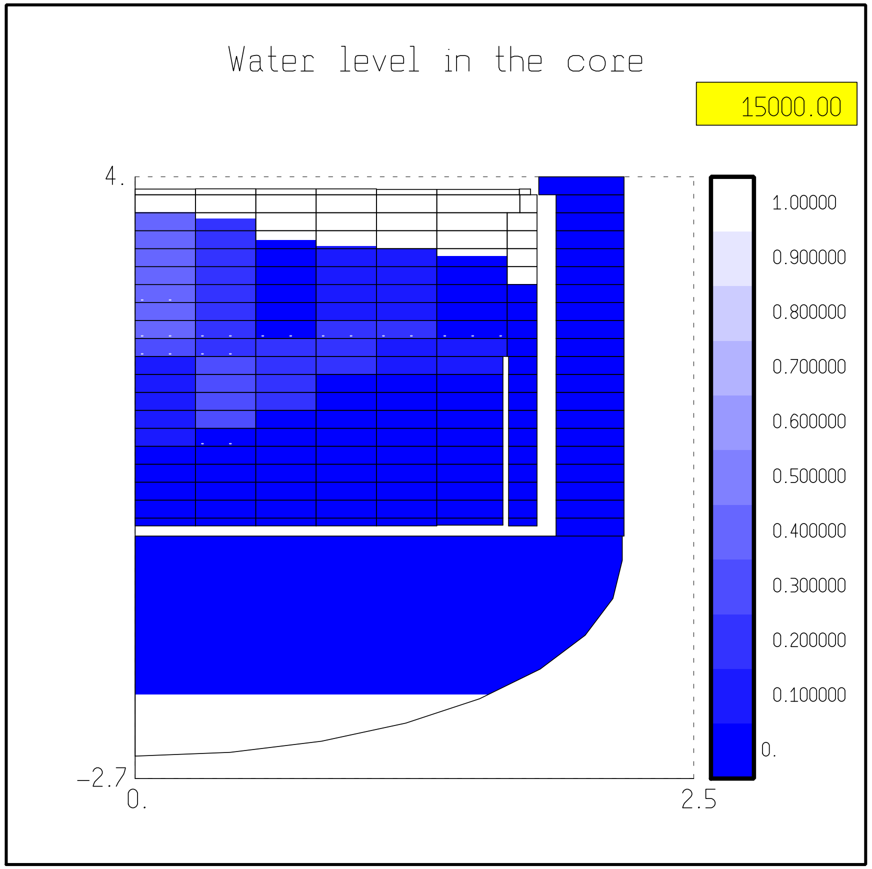


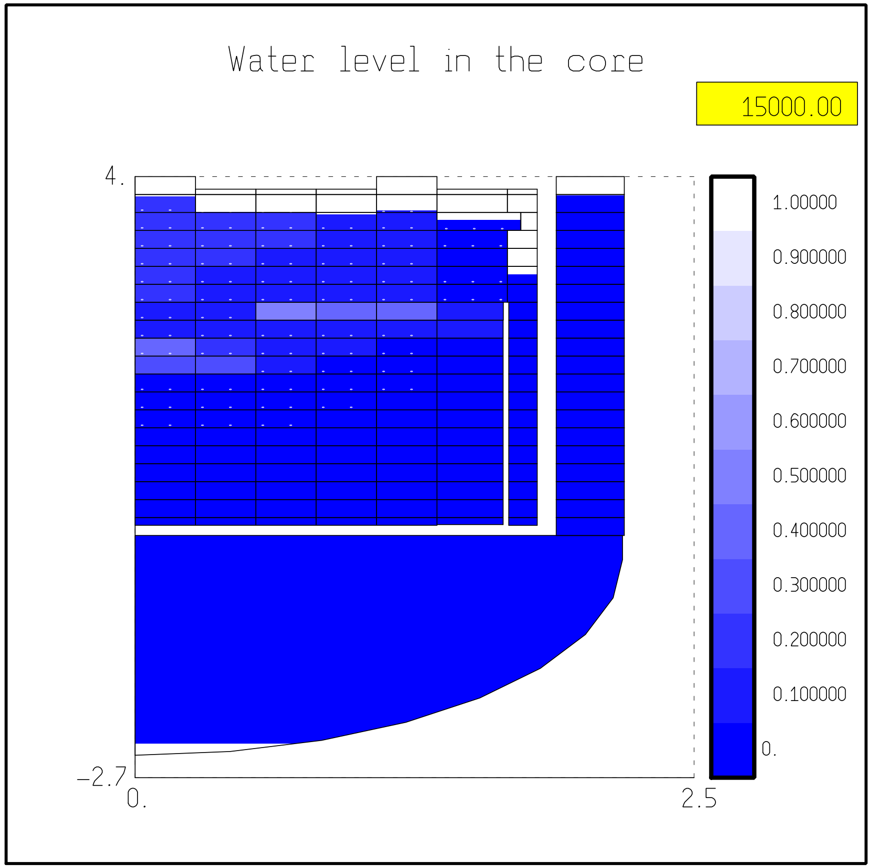
45 t vs.10 t (*reflooding* cases)- corresponding T-fields



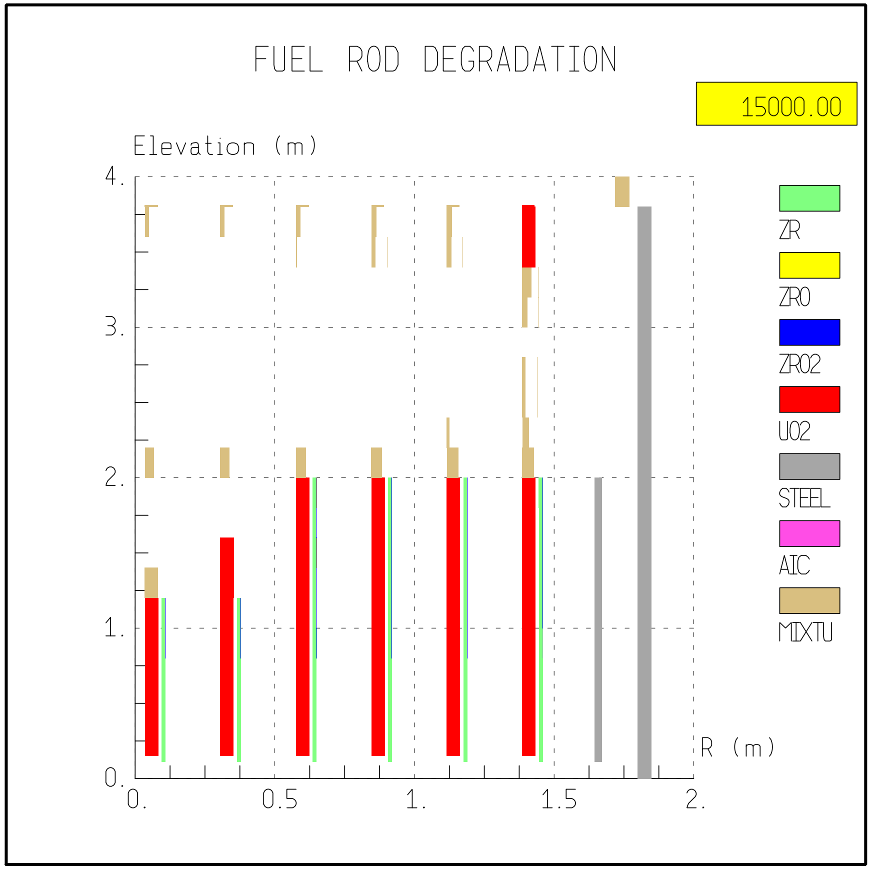


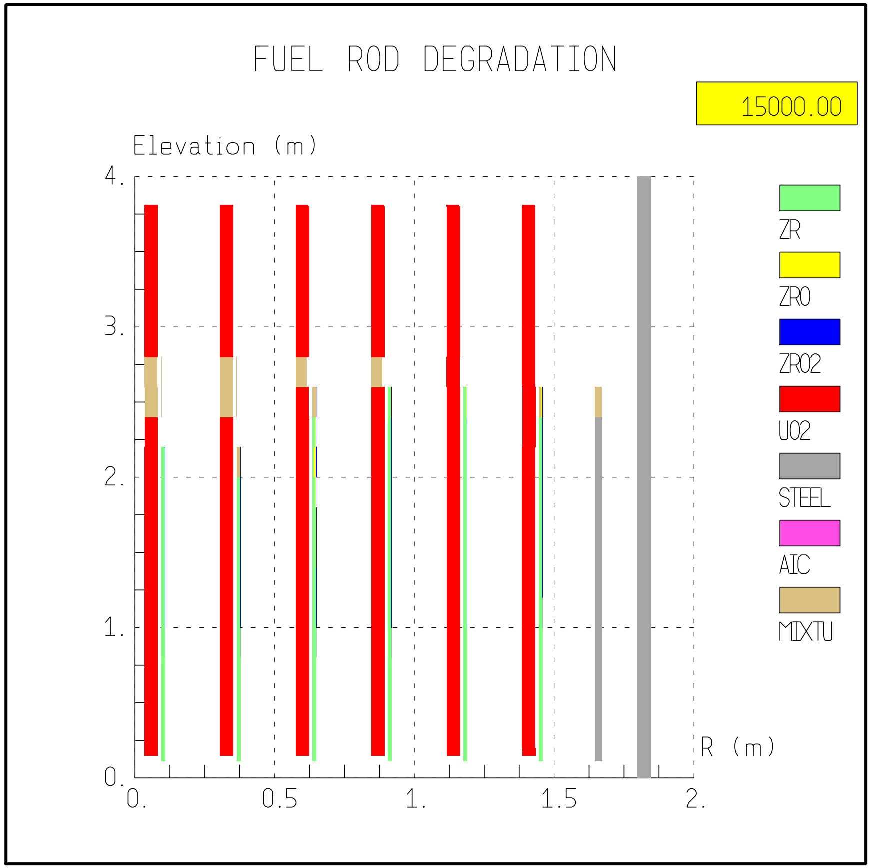
Water level fields: for M= 45 t vs.10 t (*reflooding* cases)- *preliminary* results



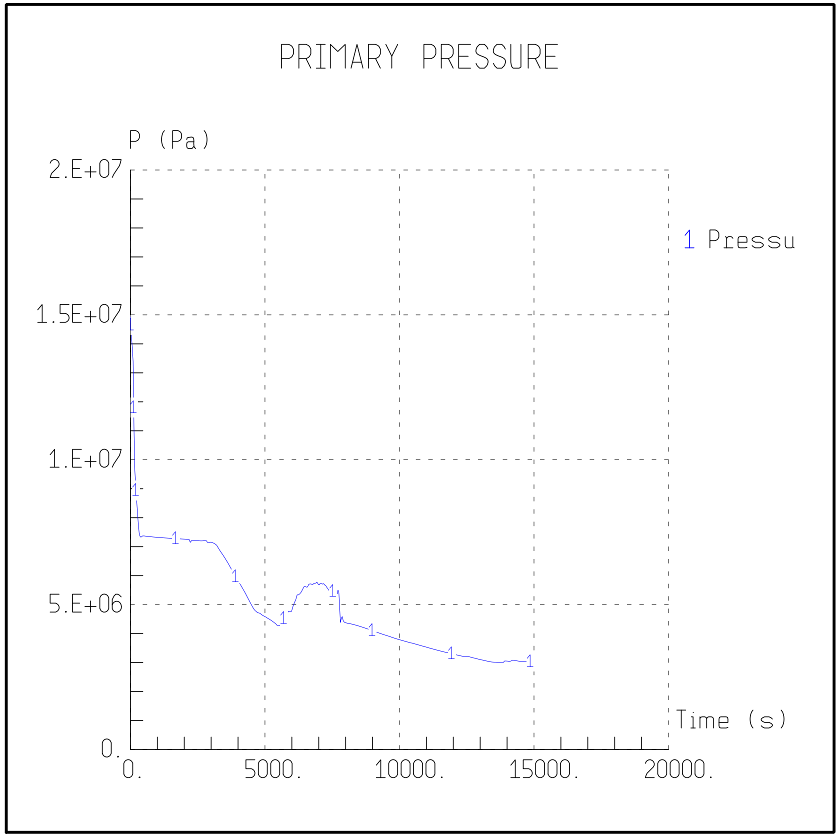


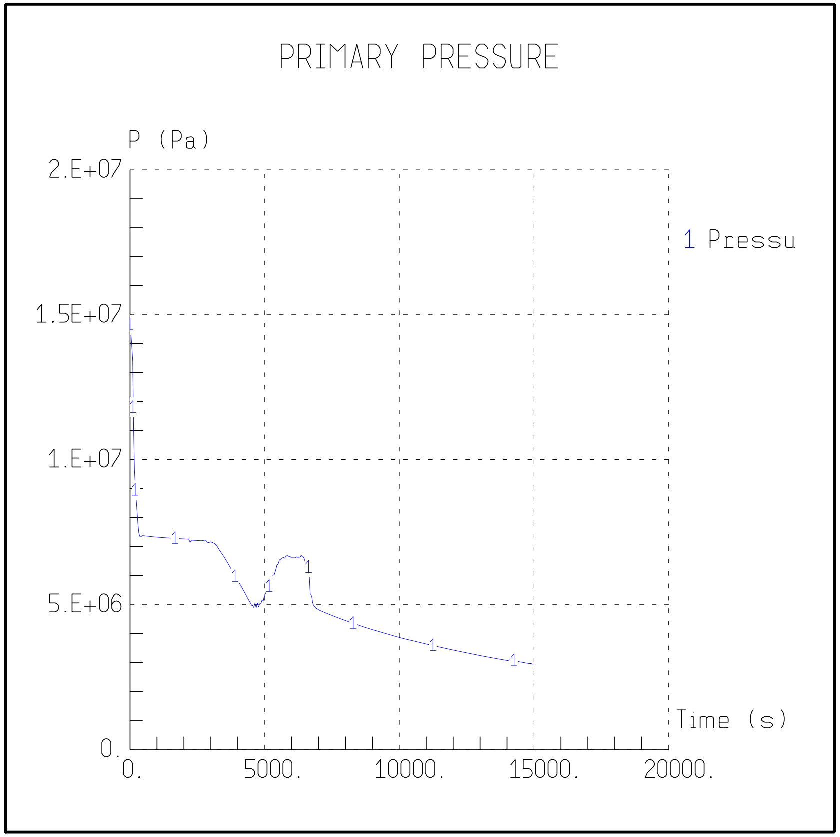
Trigger values M= 45 t vs.10 t (*reflooding* cases)



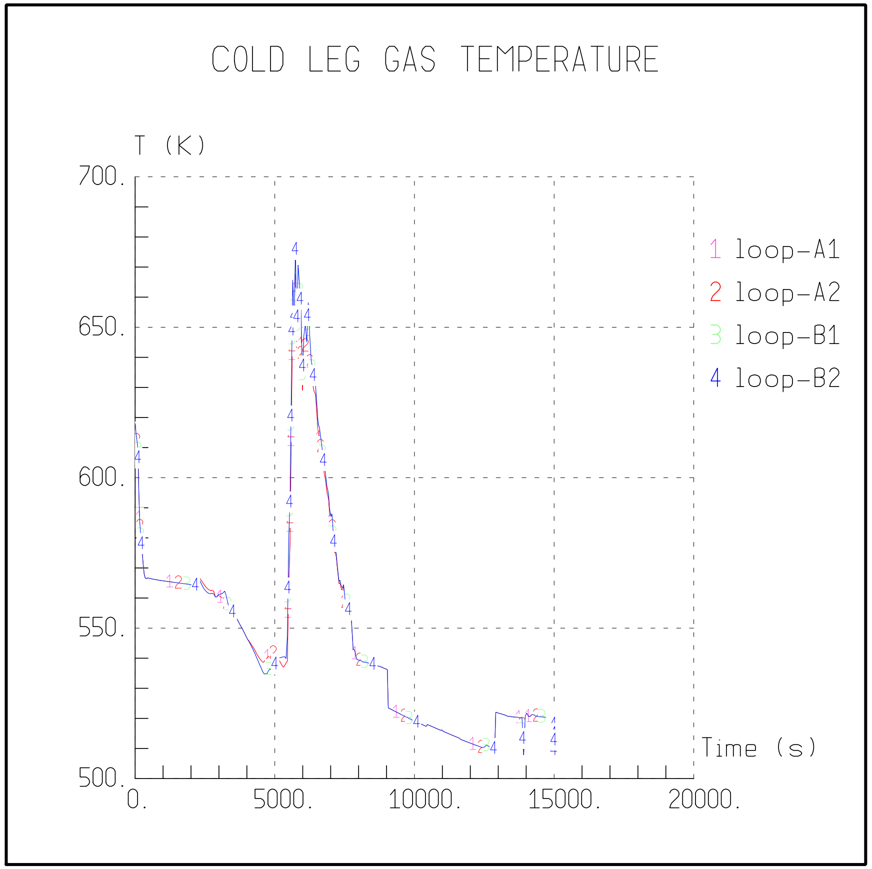


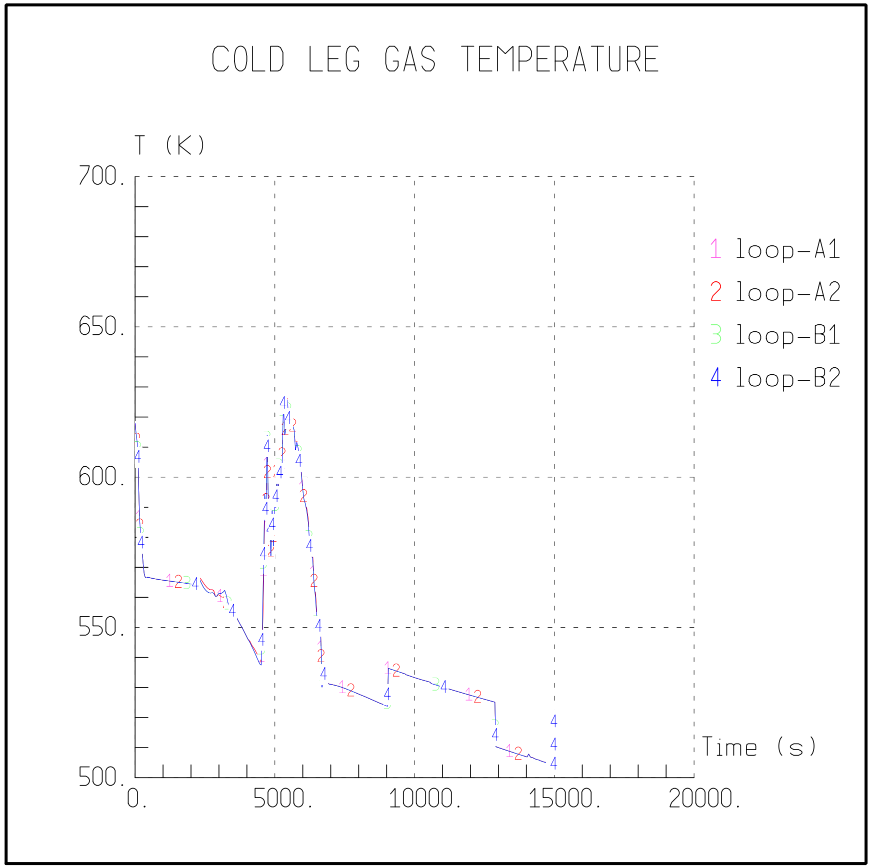
Trigger: 45 t vs.10 t (*reflooding* cases)



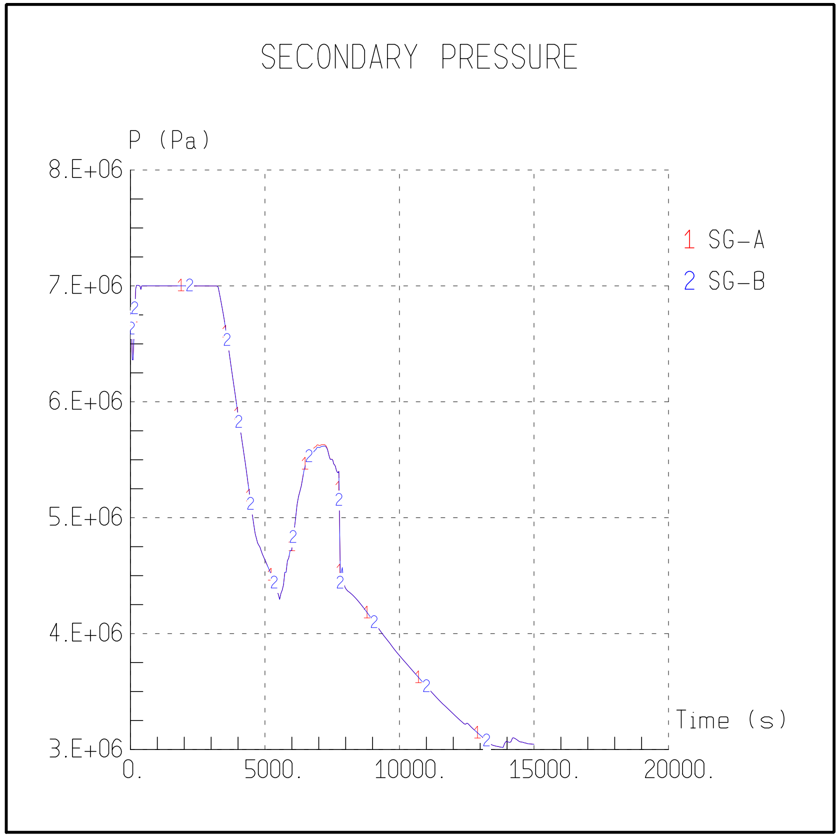


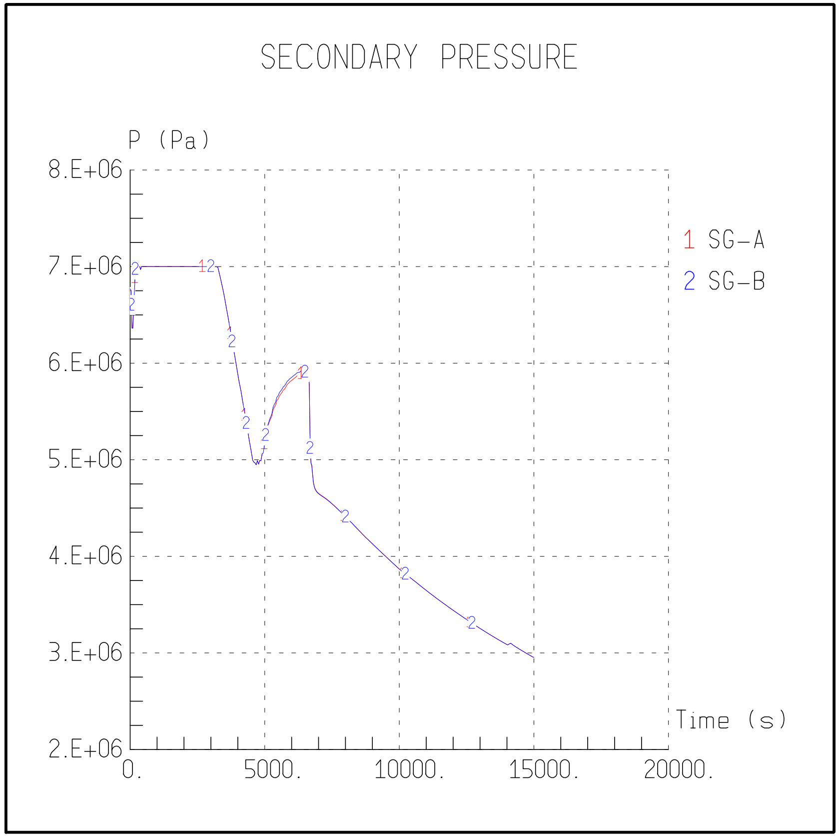
Trigger value : 45 t vs.10 t (*reflooding* cases)



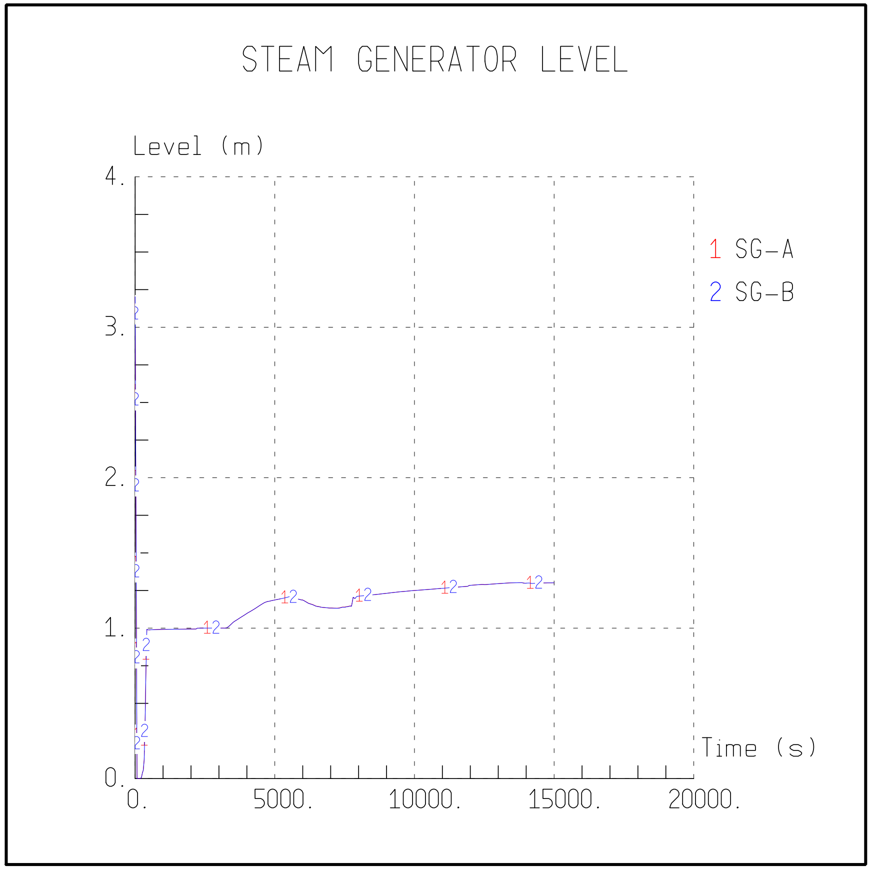


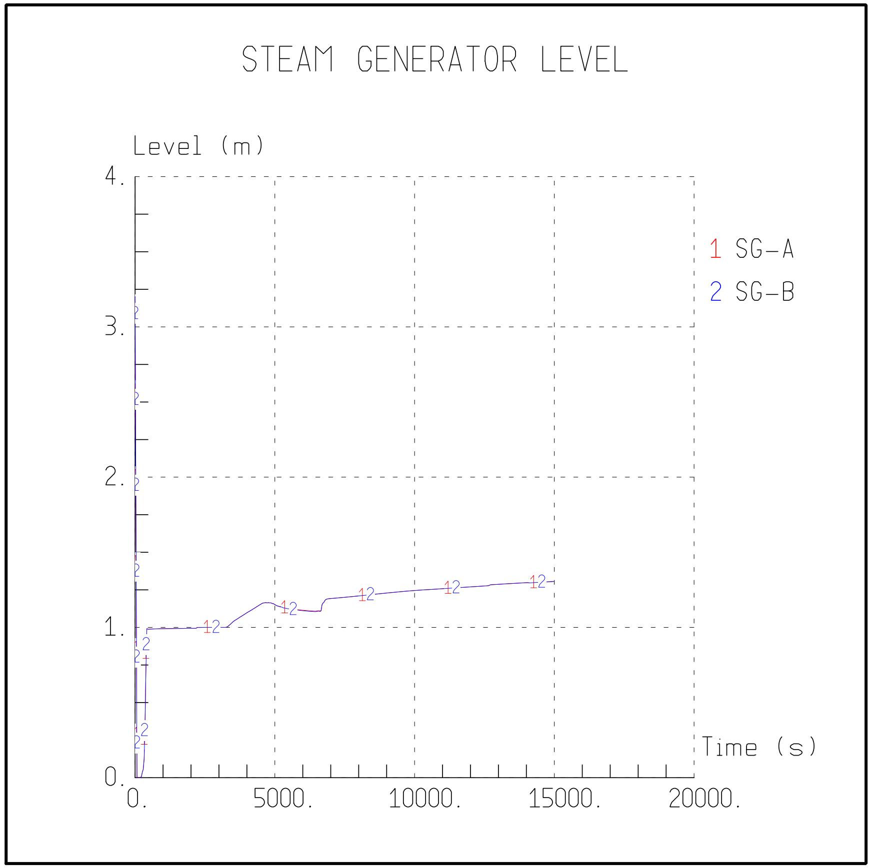
Trigger 45t vs.10t (*reflooding* cases)



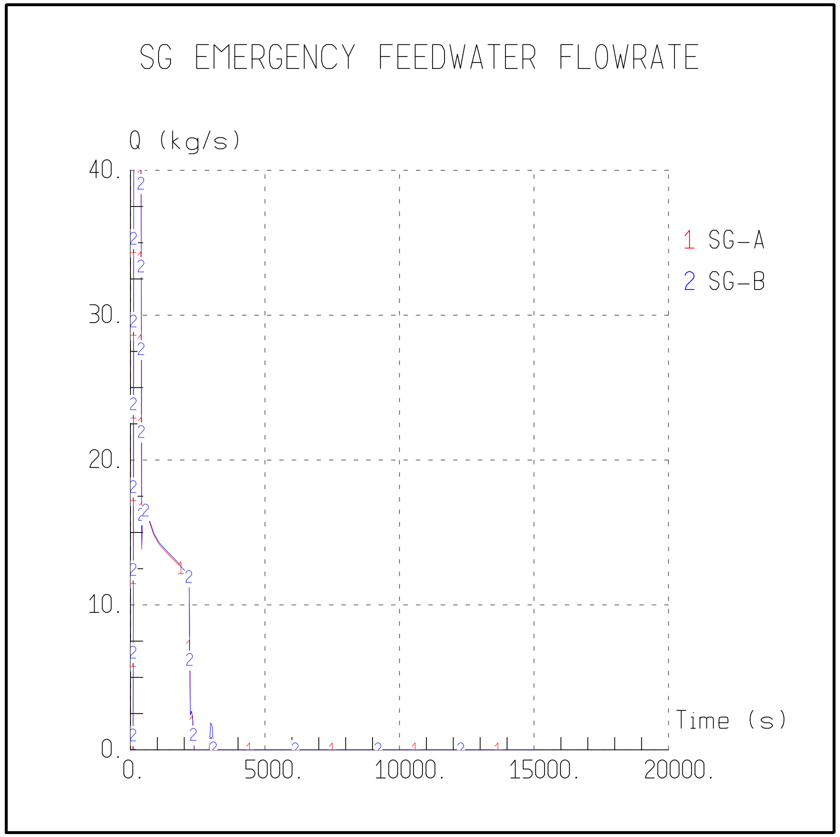


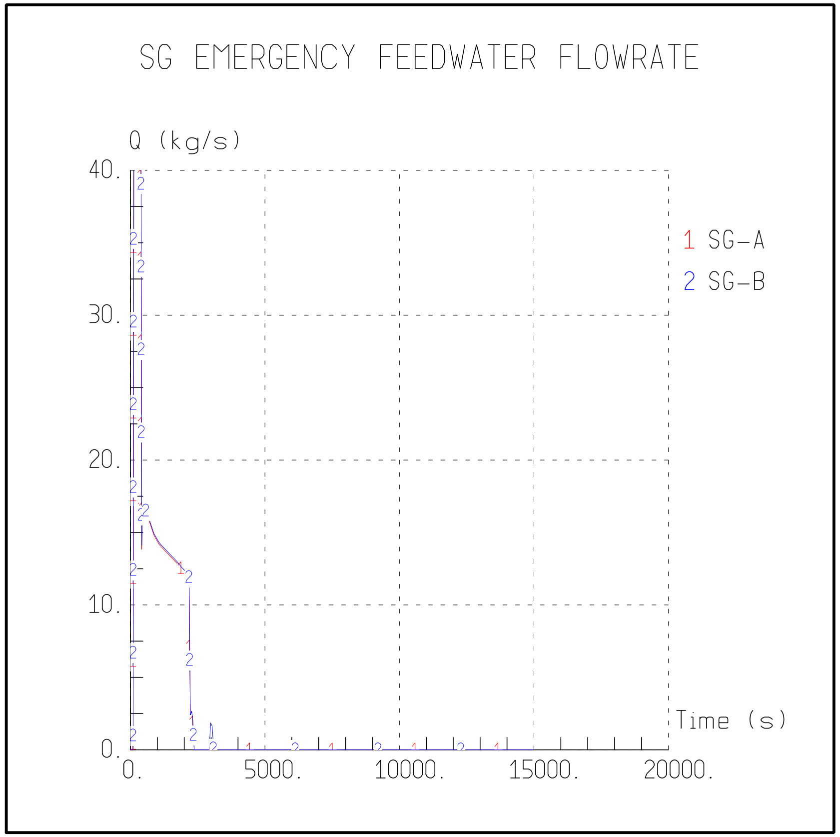
Trigger 45 t vs.10 t (*reflooding* cases)



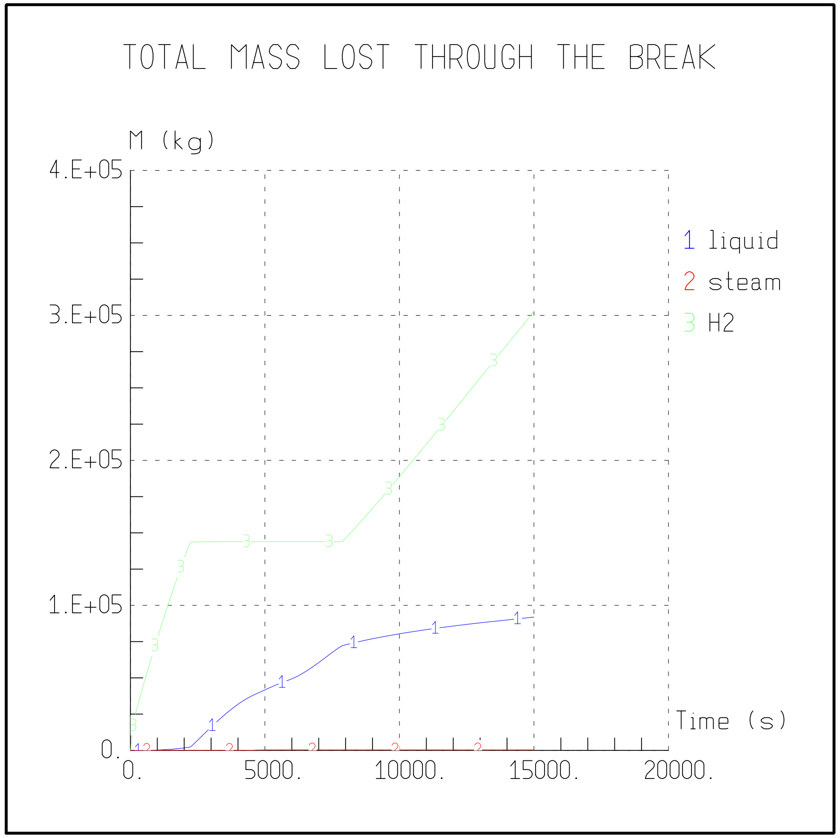


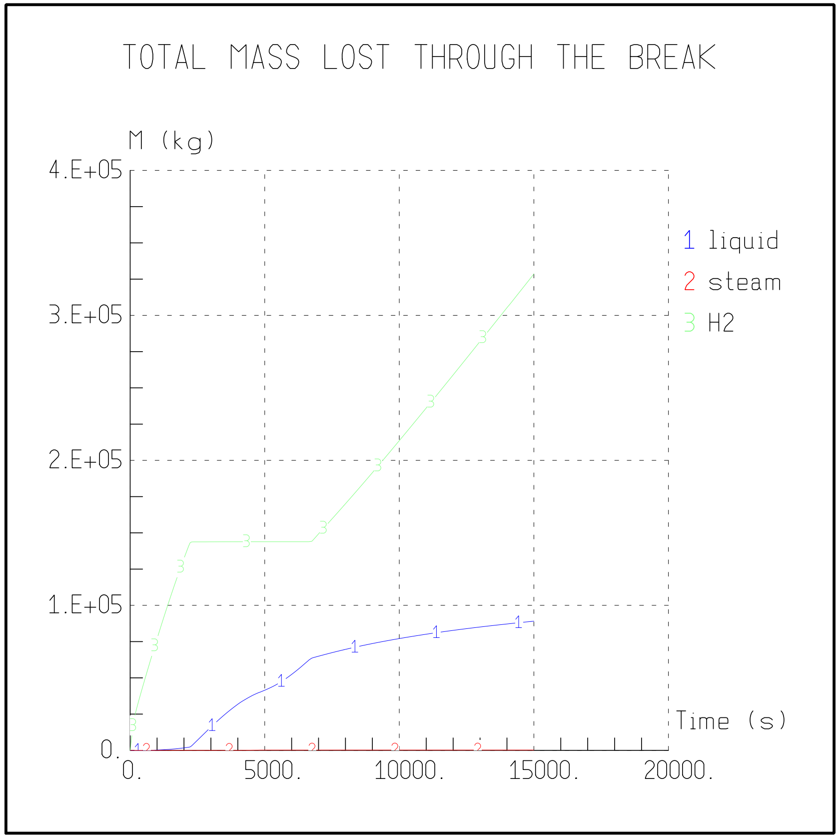
Trigger: 45 t vs.10 t *(reflooding* cases)



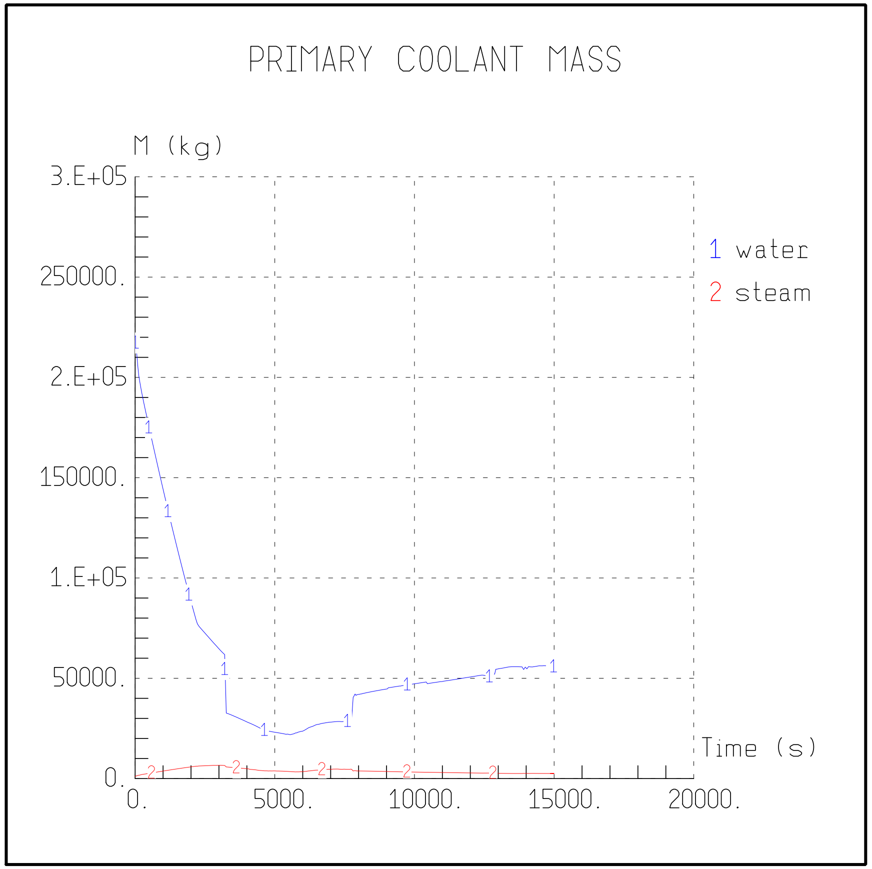


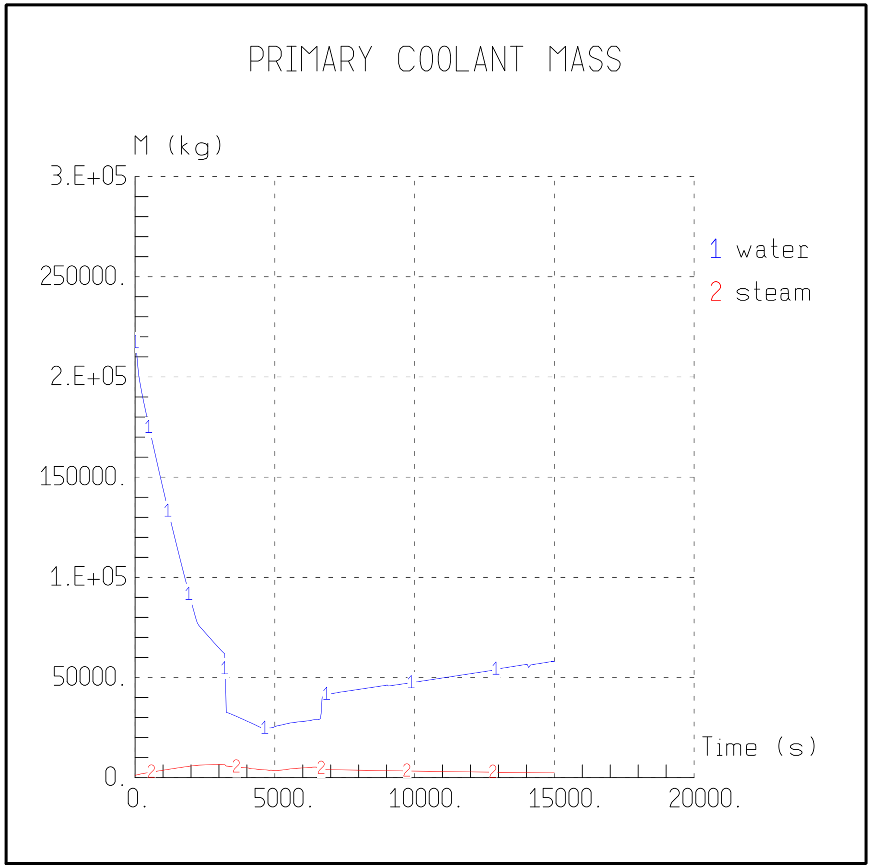
Trigger 45 t vs.10 t (*reflooding* cases)



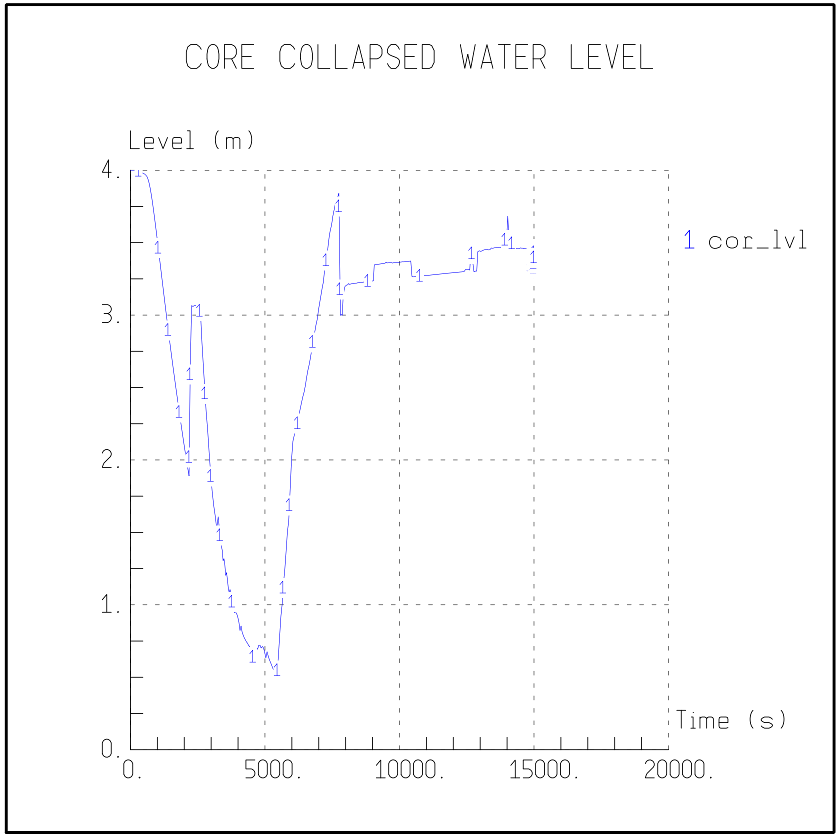


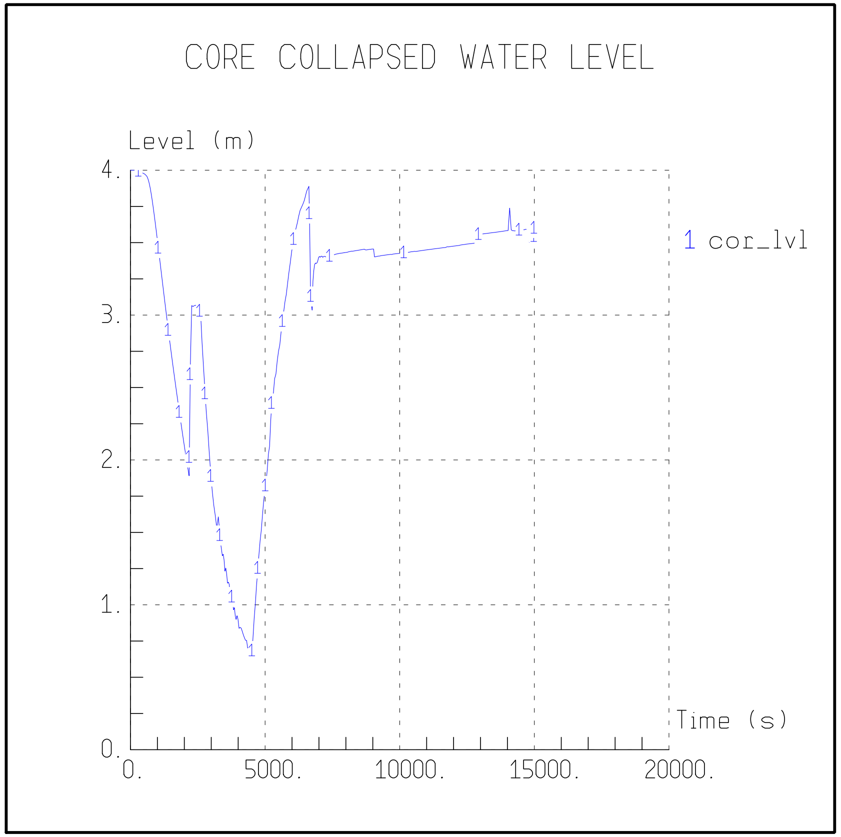
Trigger 45 t vs.10 t (*reflooding* cases)



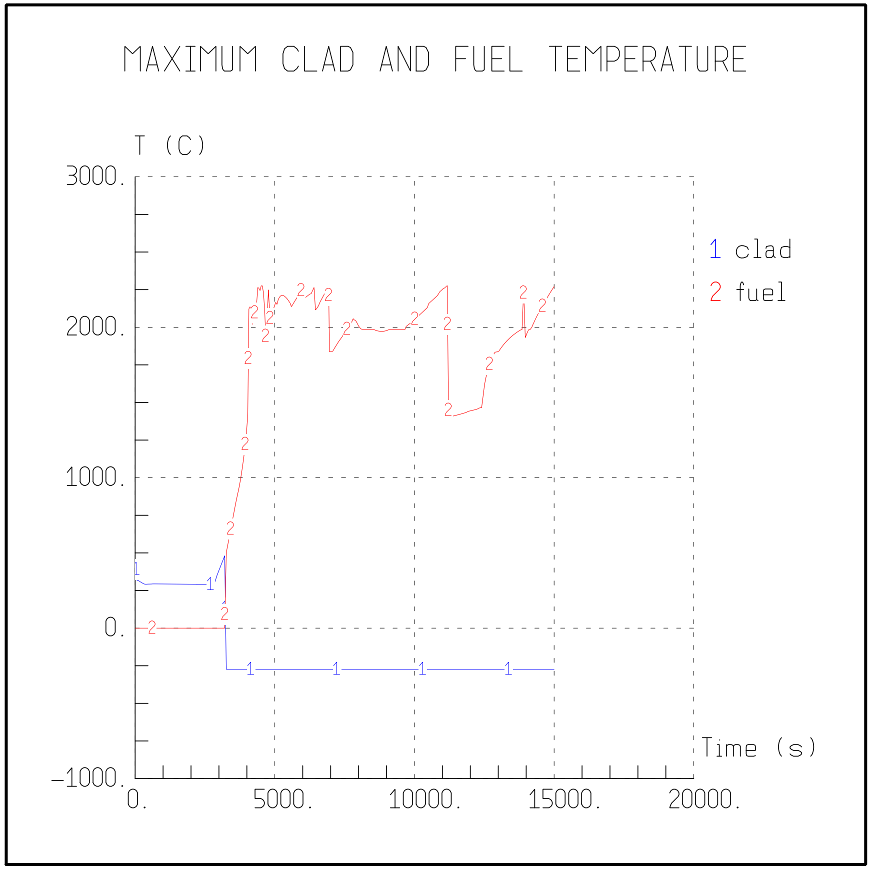


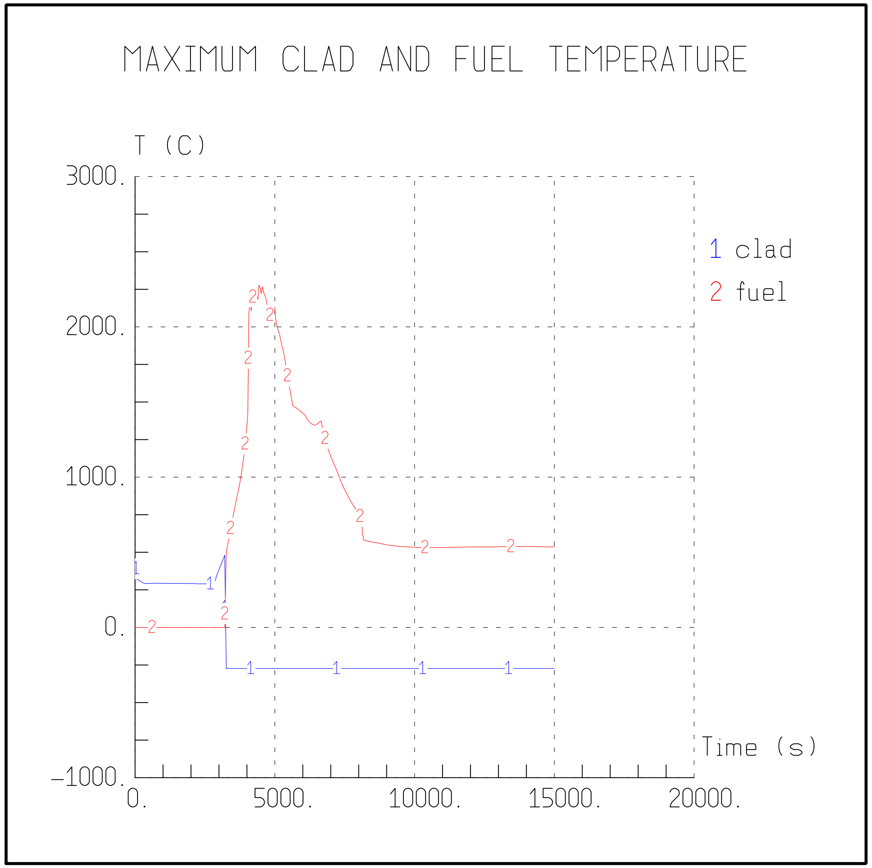
Trigger: 45 t vs.10 t (*reflooding* cases)



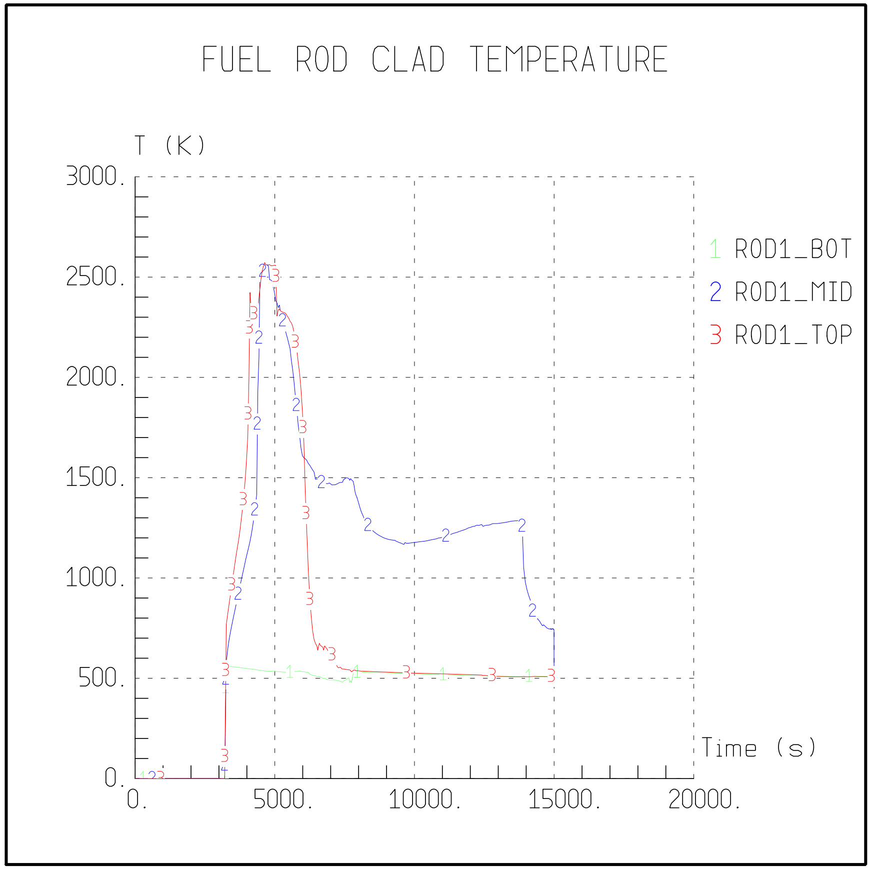


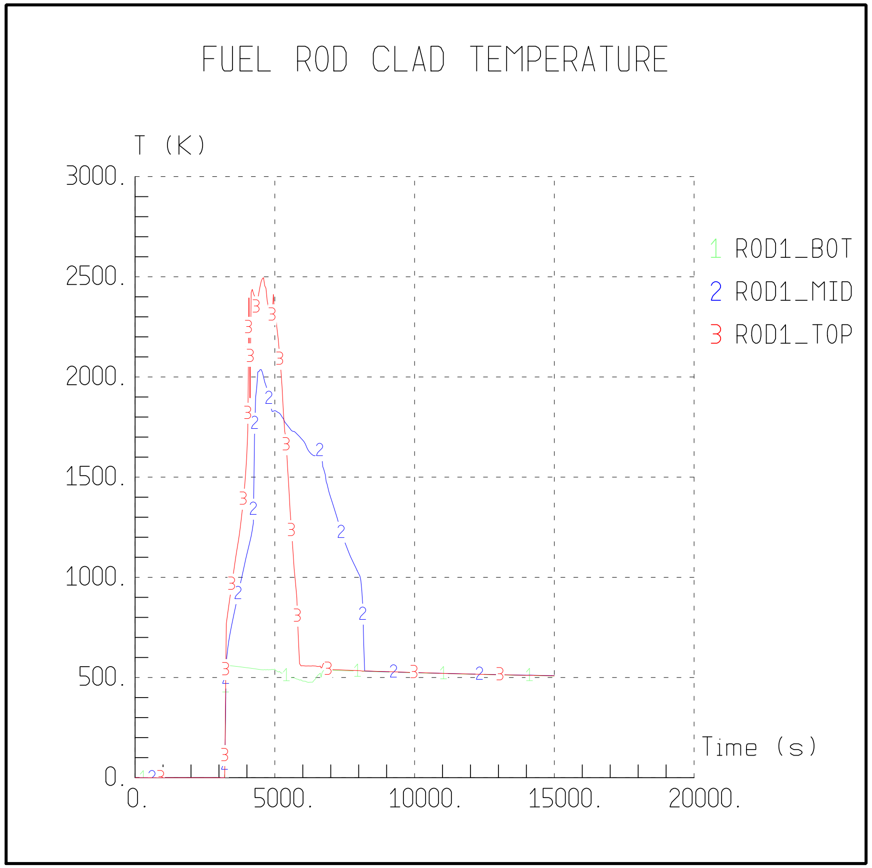
Trigger 45t vs.10t (*reflooding* cases)



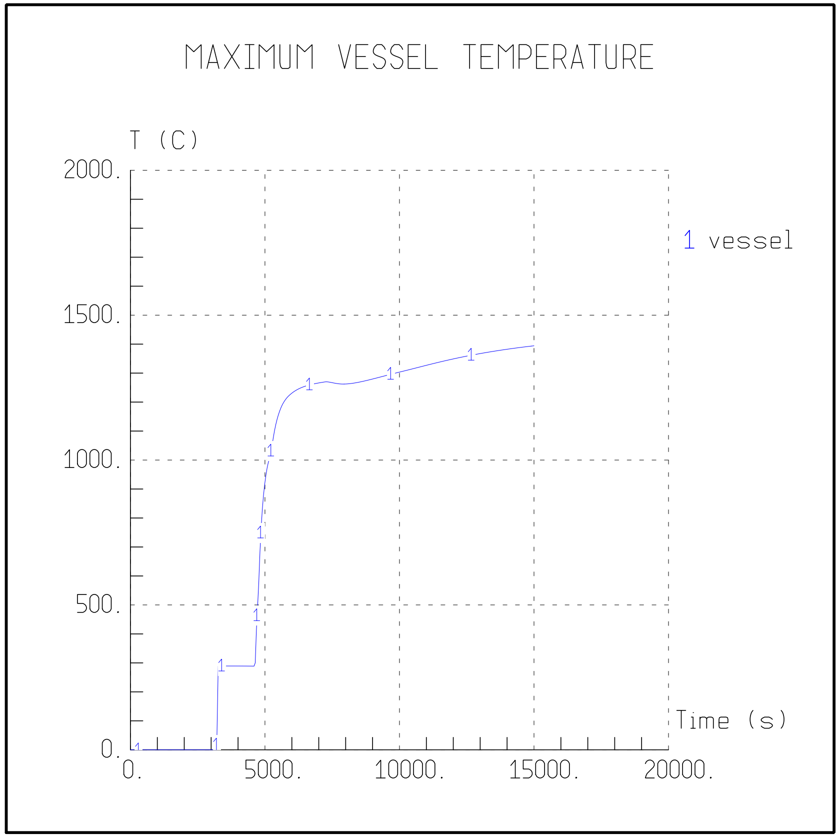


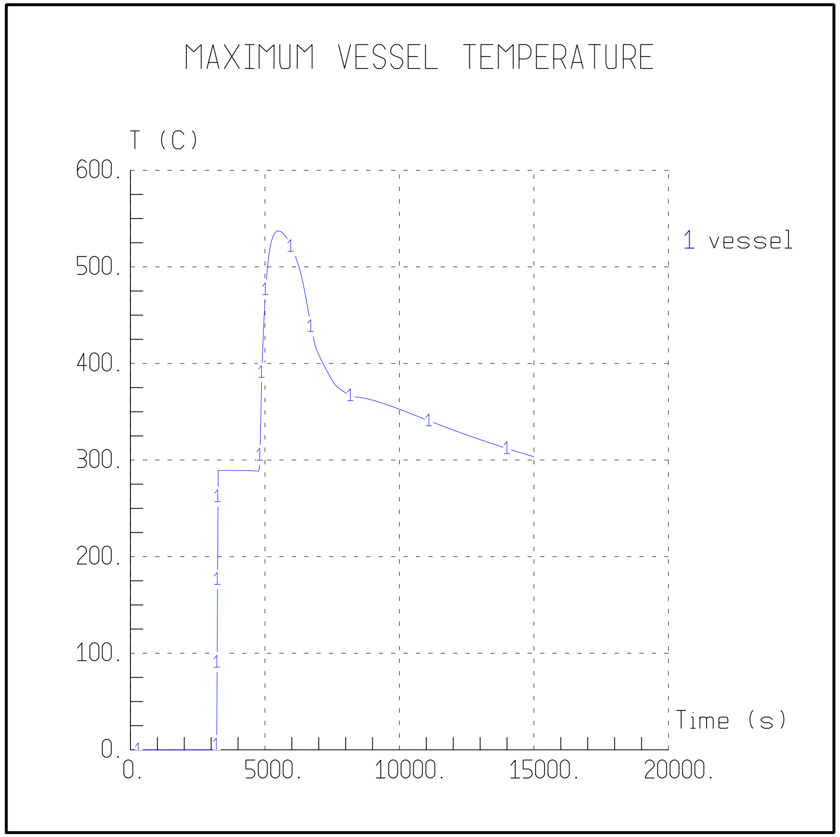
Trigger 45 t vs.10 t (*reflooding* cases)



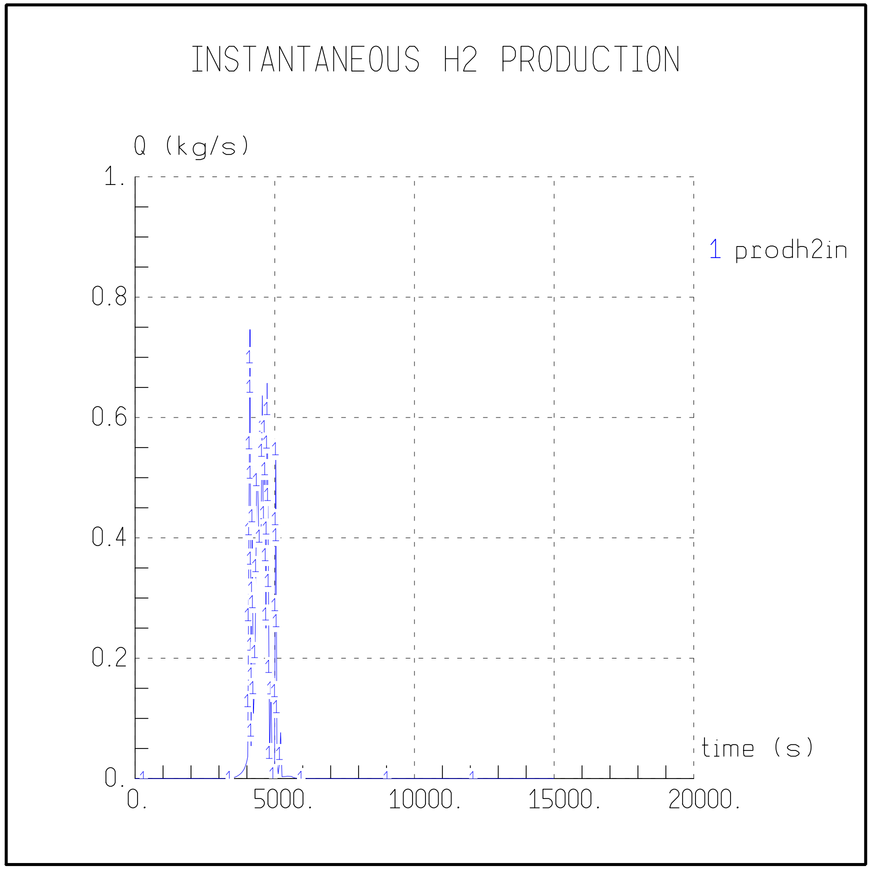


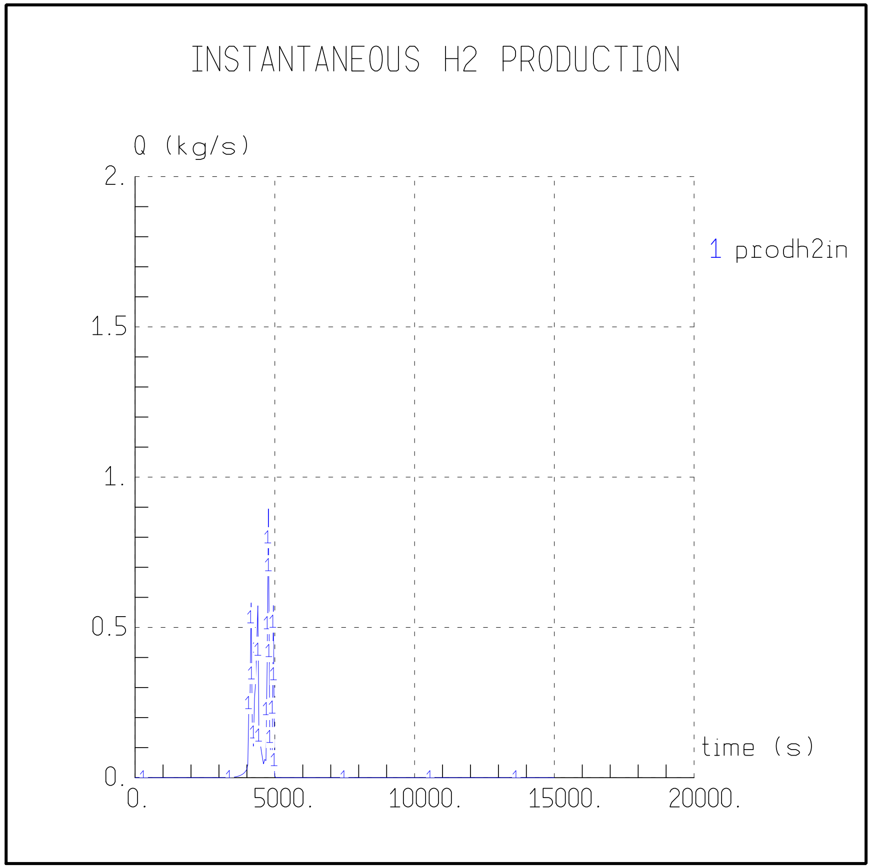
Trigger 45 t vs.10 t (*reflooding* cases)



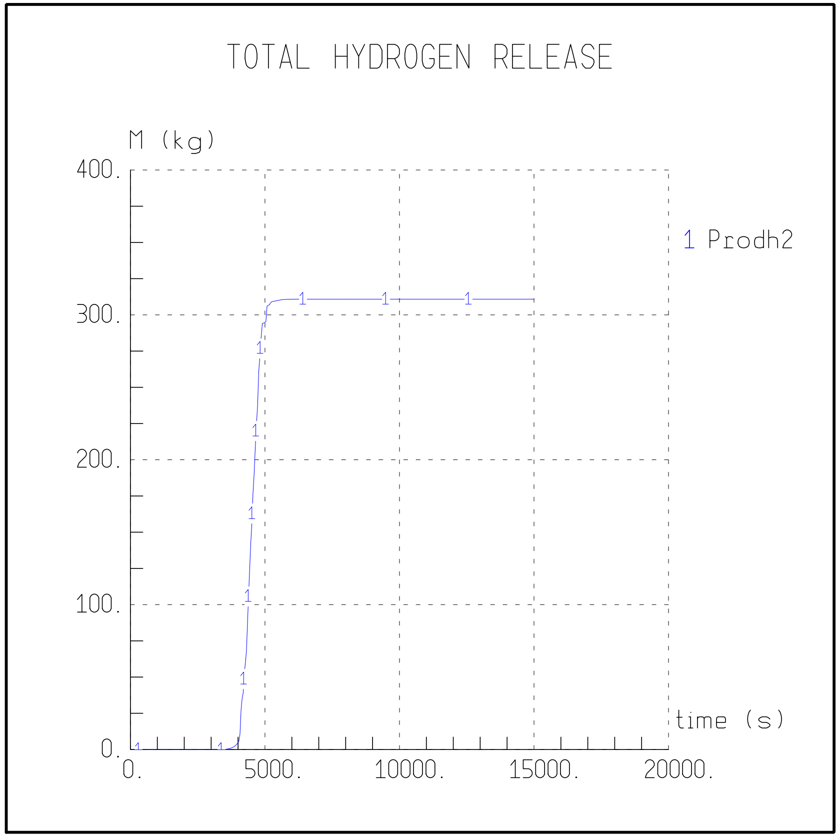


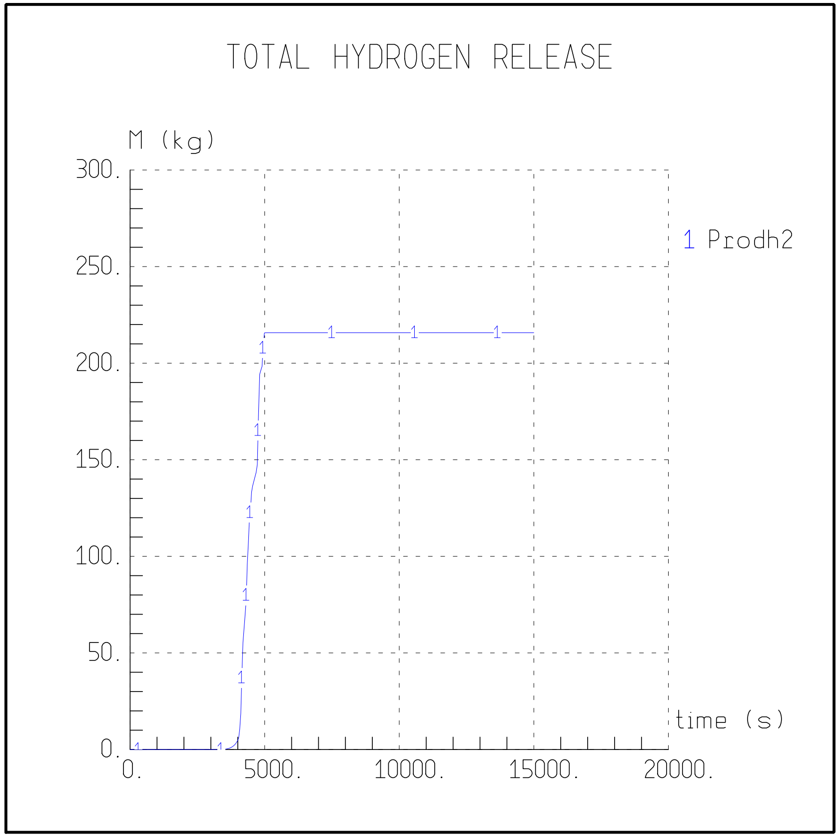
Trigger: 45 t vs.10 t *(reflooding cases)*



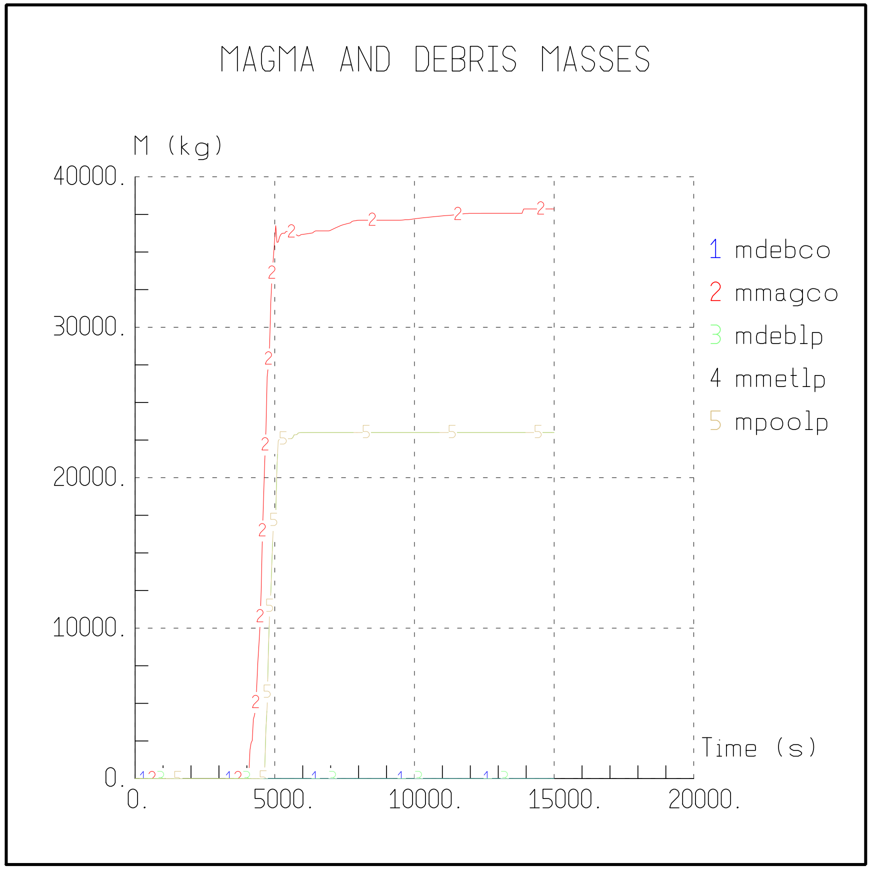


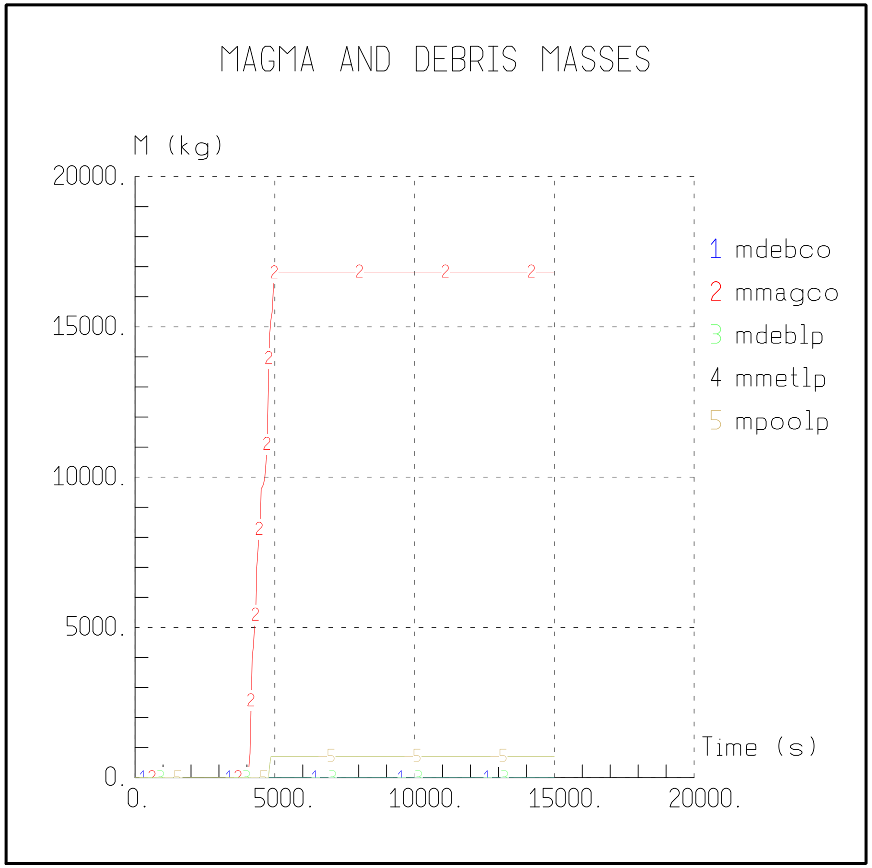
Trigger: 45 t vs.10 t *(reflooding cases)*



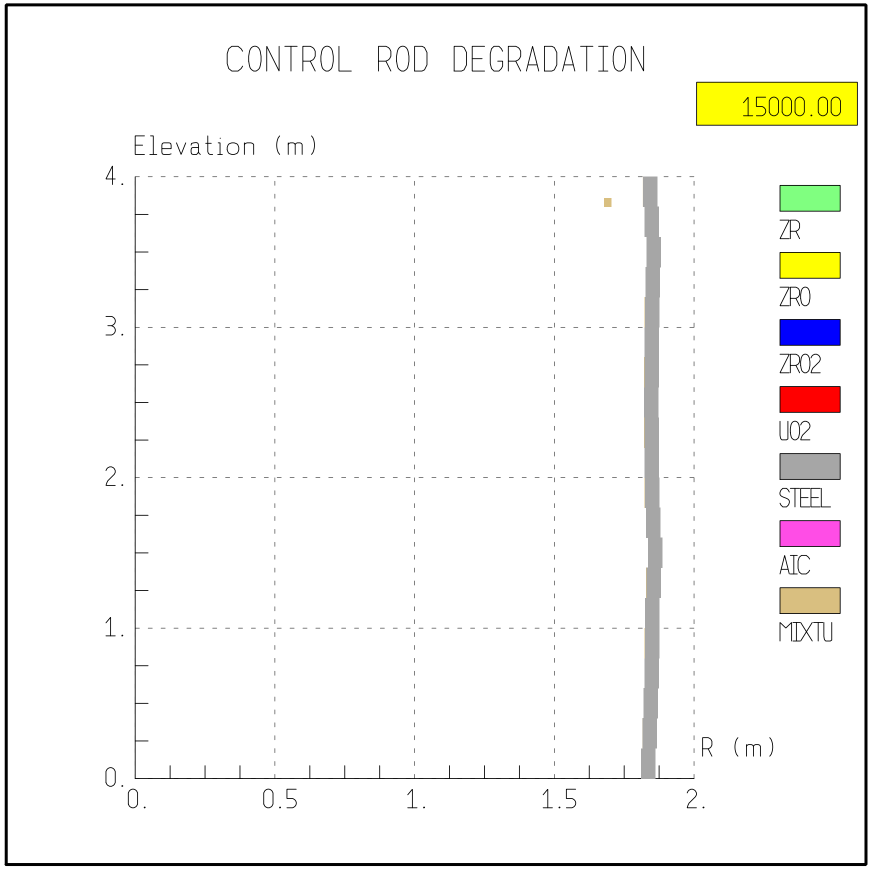


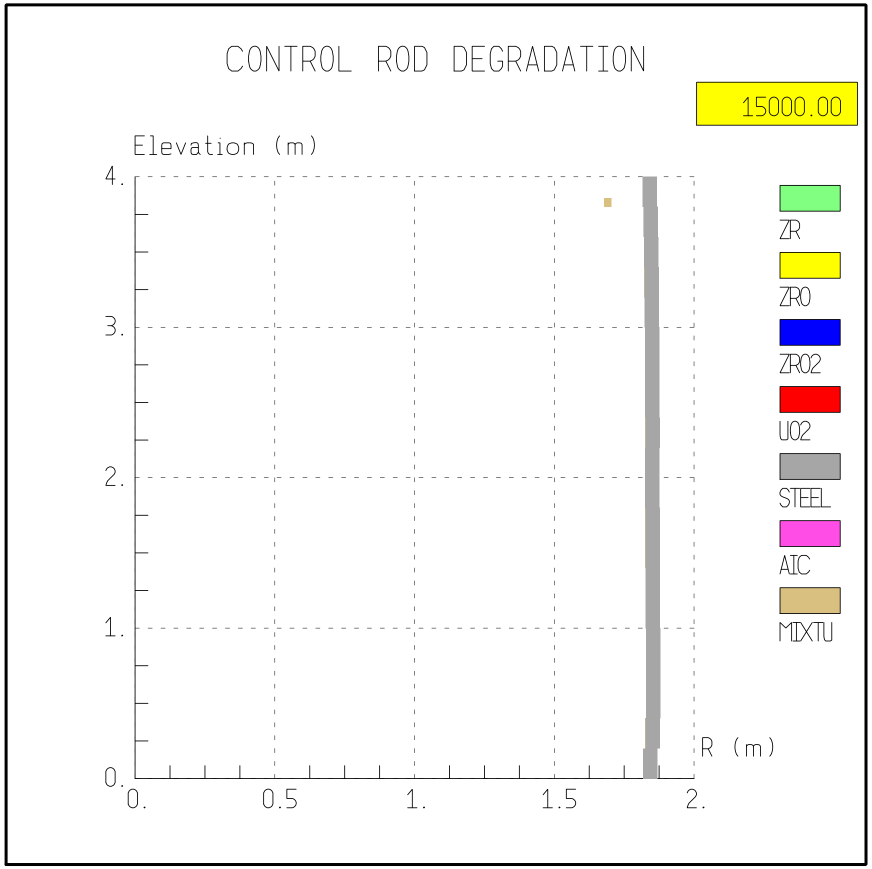
Trigger: 45 t vs.10 t *(reflooding* cases)



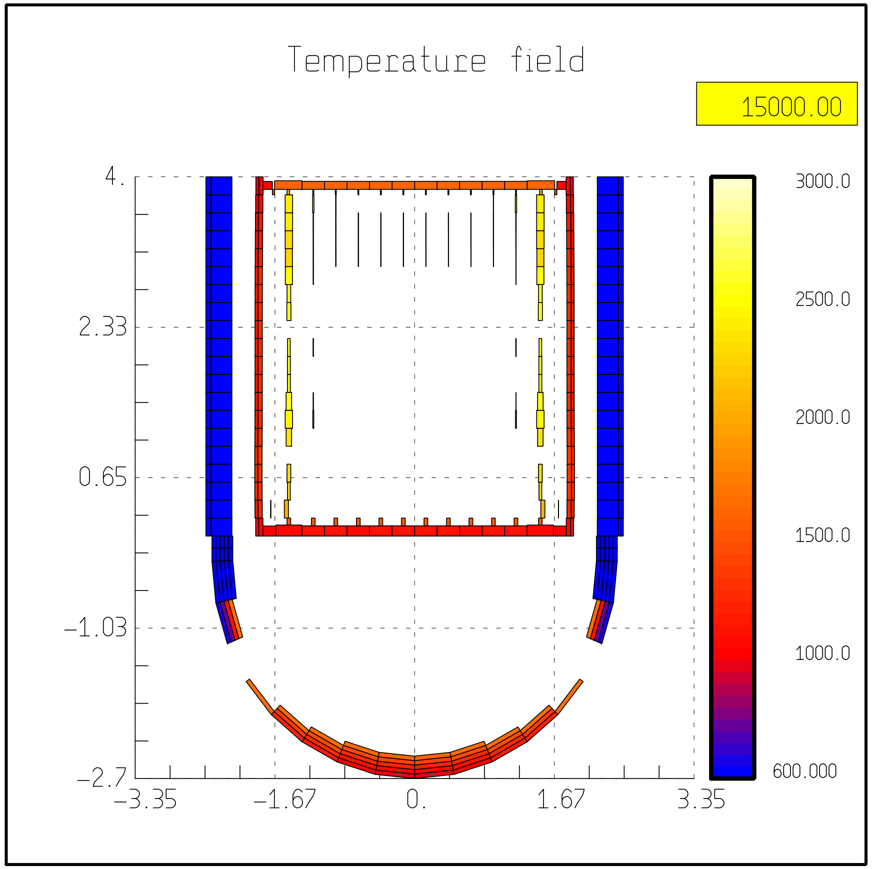


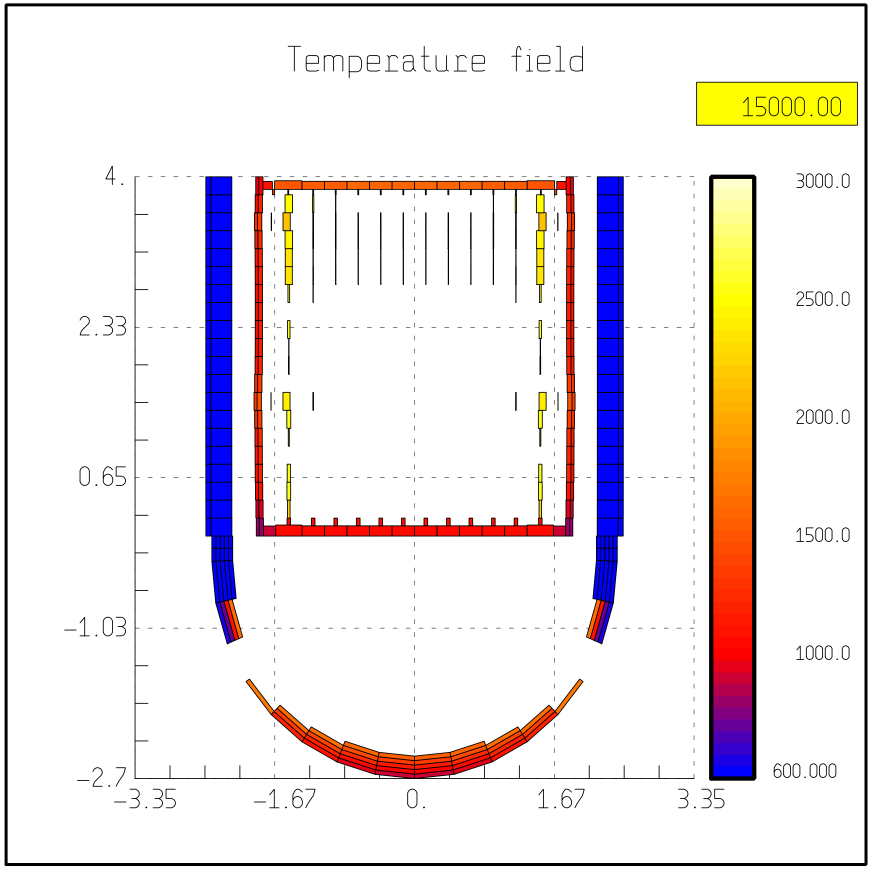
SBO base case/ *two simulations*, compared



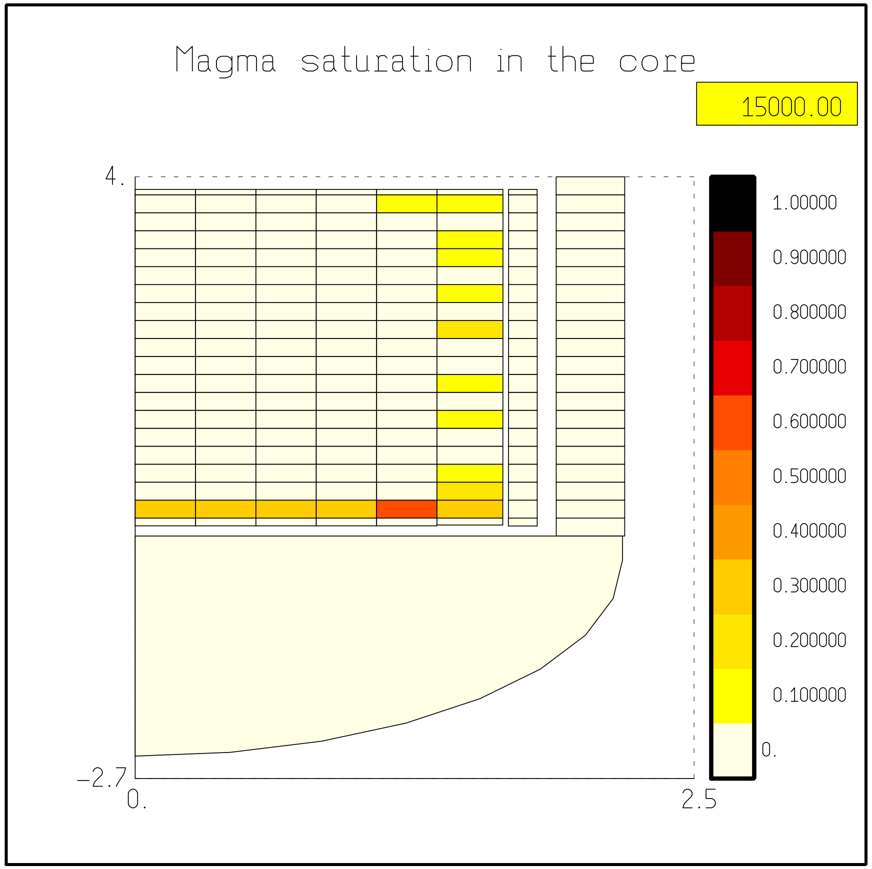


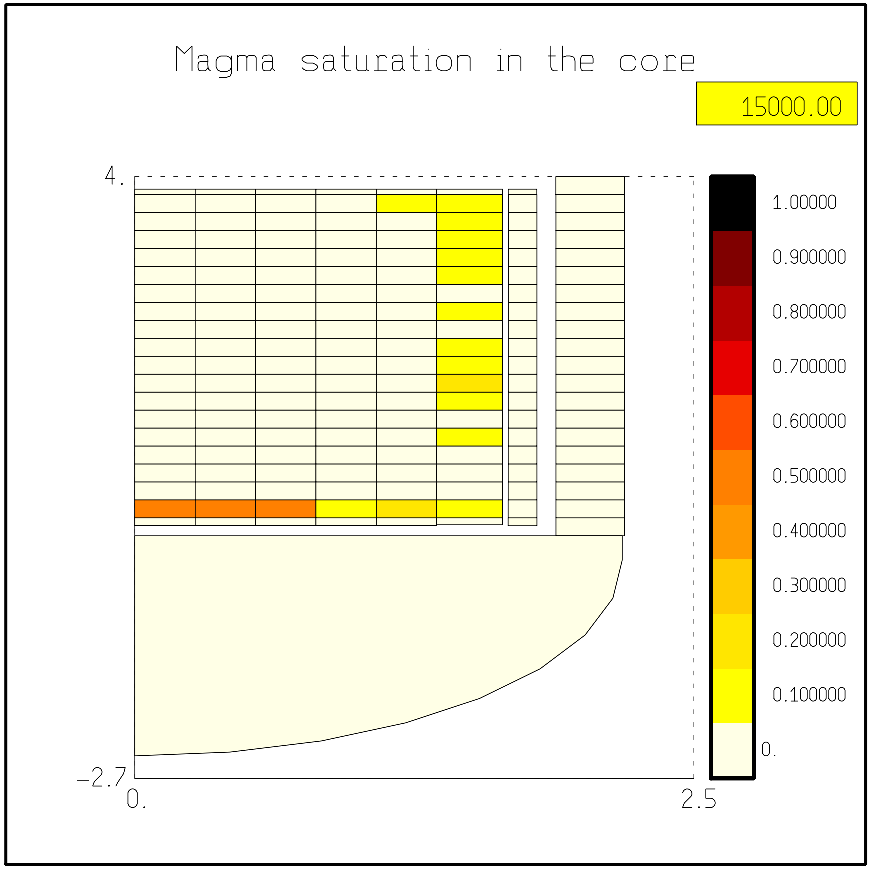
SBO base case/ *two redundant simulations, forwarded*





SBO base case/ *two simulations,ff*





SBO base case/ *two simulations,ff*