Development of a 3D Neutron Kinetic-Thermal-hydraulic Model for an RBMK Reactor by RELAP5-3D© Code

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- Thermal-hydraulic modeling
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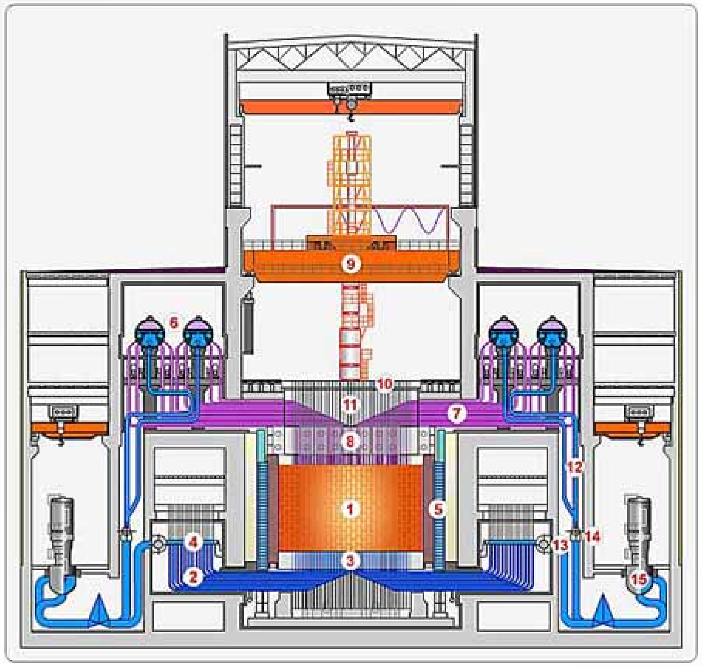
- RBMK peculiarities and 3D NK modeling
  - Qualification
  - Transients Results
- Conclusions

Framework of the activities

- 12 units still in operation
- 1 unit under construction (Kursk 5)
- Development of Plants life extension (50 yrs)

NEEDS TO INCREASE & IMPROVE KNOWLEDGE FOR THIS TECHNOLOGY



1)	Core
2)	Water pipe
3)	Reactor bottom plate
4)	Group Distribution Header
5)	Shield
6)	Steam Drum
7)	Steam Water Pipe
8)	Reactor top plate
9)	Refuelling machine
10)	Reactor lid structure
11)	Top reactor channel
12)	Downcomers
13)	Pressure Header
14)	Suction header
15)	Main Coolant Pump

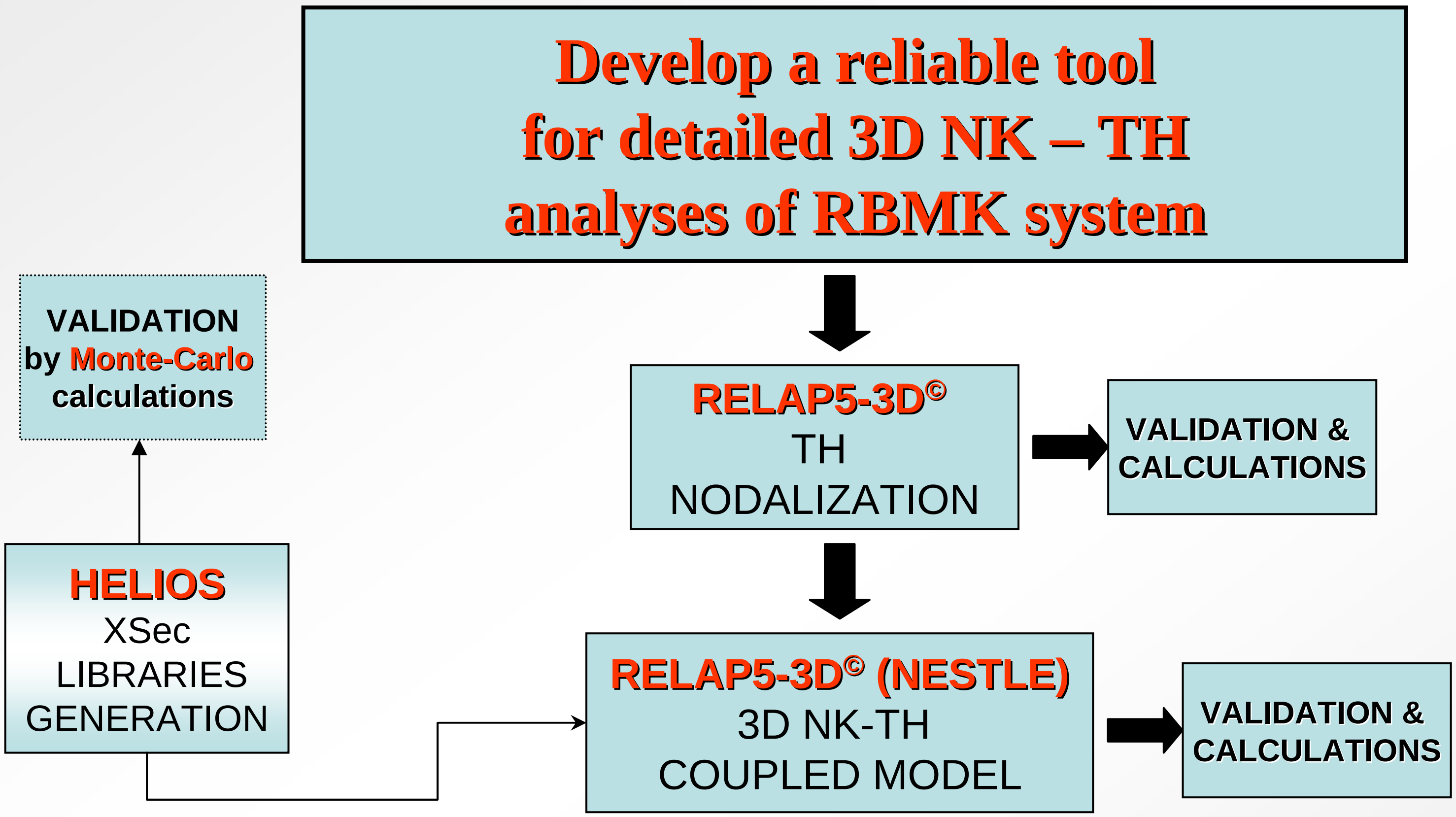
RBMK Sketch

TACIS Project R2.03/97 part B

Tacis

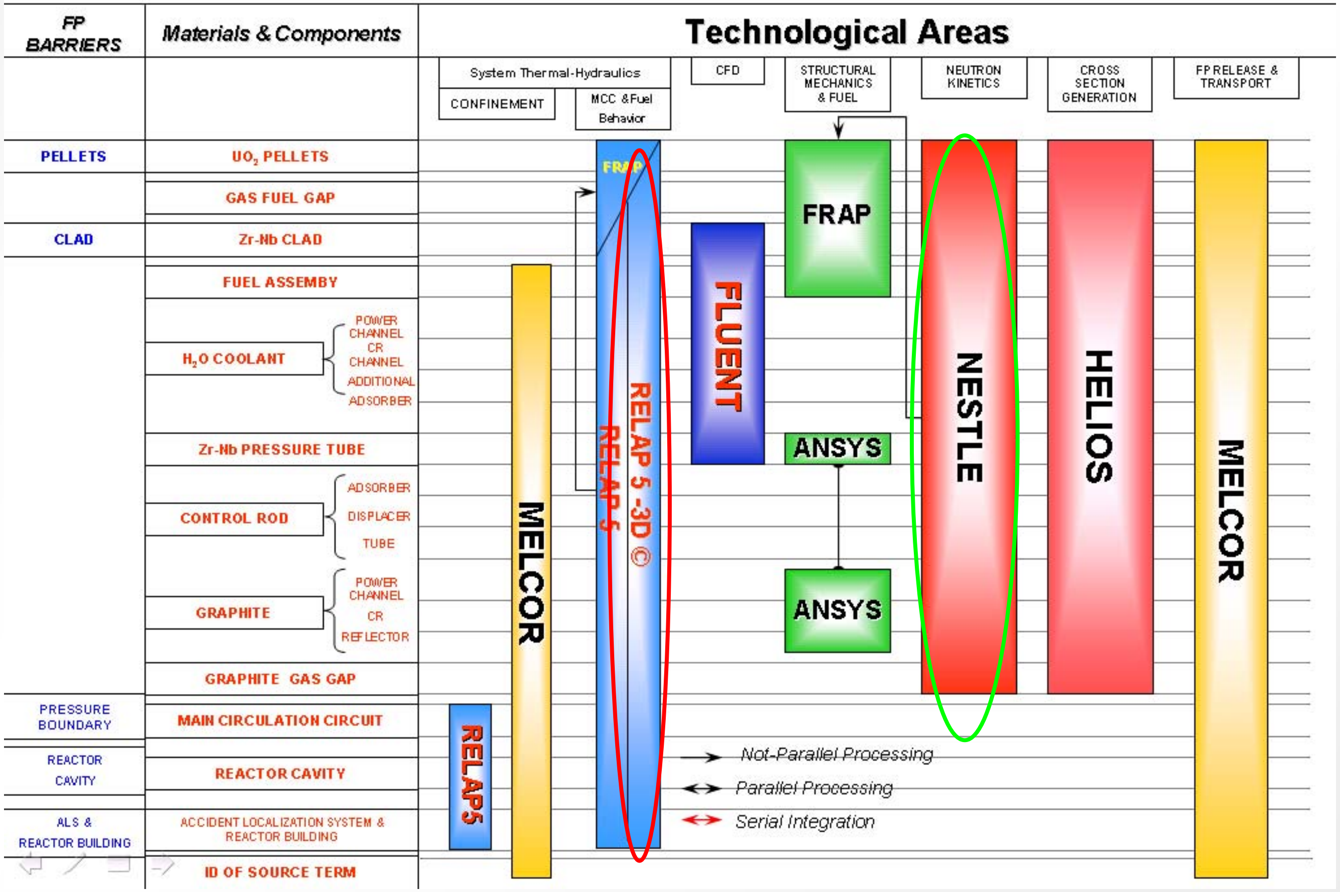
A project funded by the European Union

Main Goal & Steps 1/2



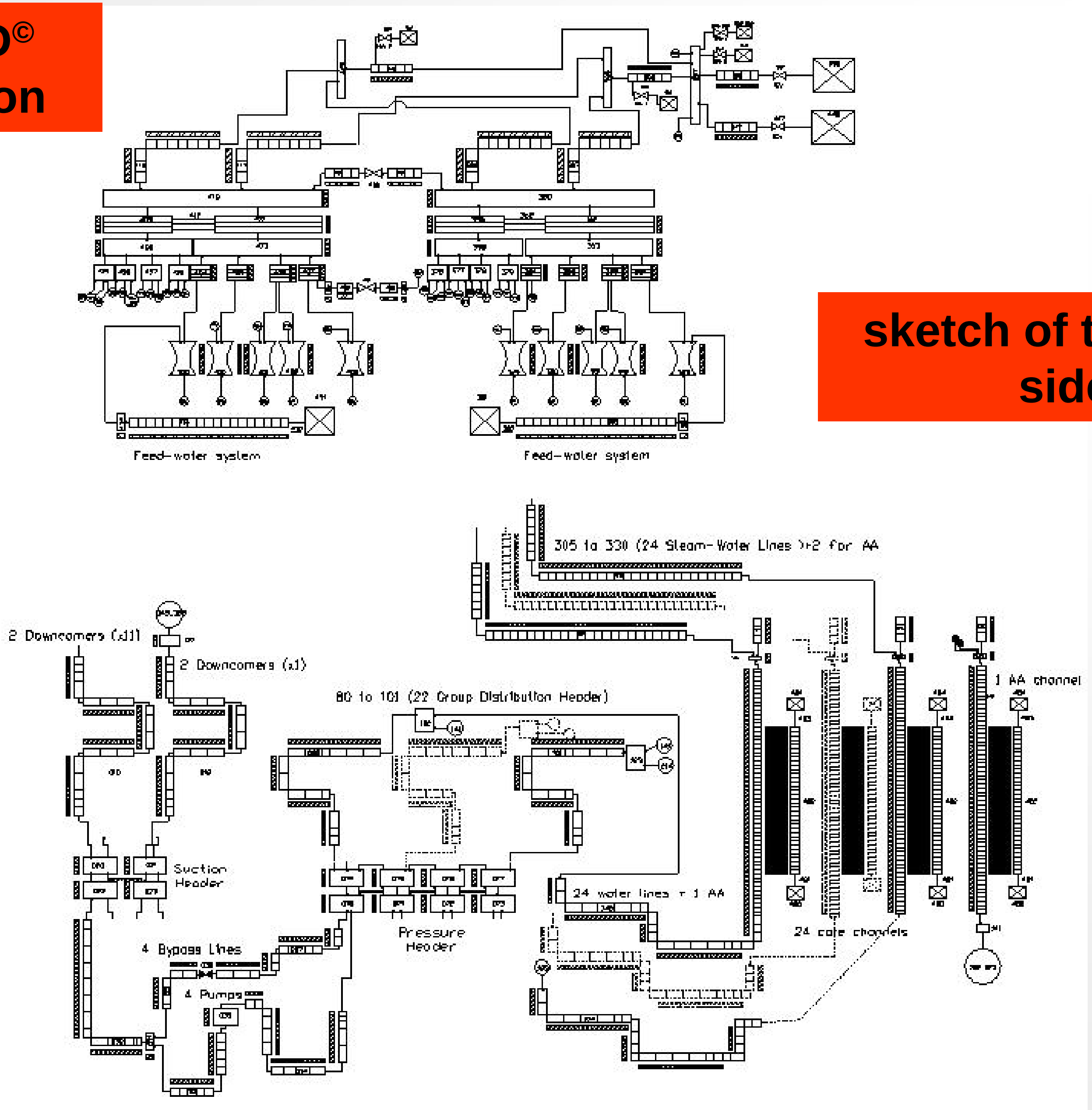
Main Goal & Steps 2/2

- **RELAP5-3D© had a central role in the assembled Chain of Codes for RBMK severe accidents analyses**



TH modeling 1/5

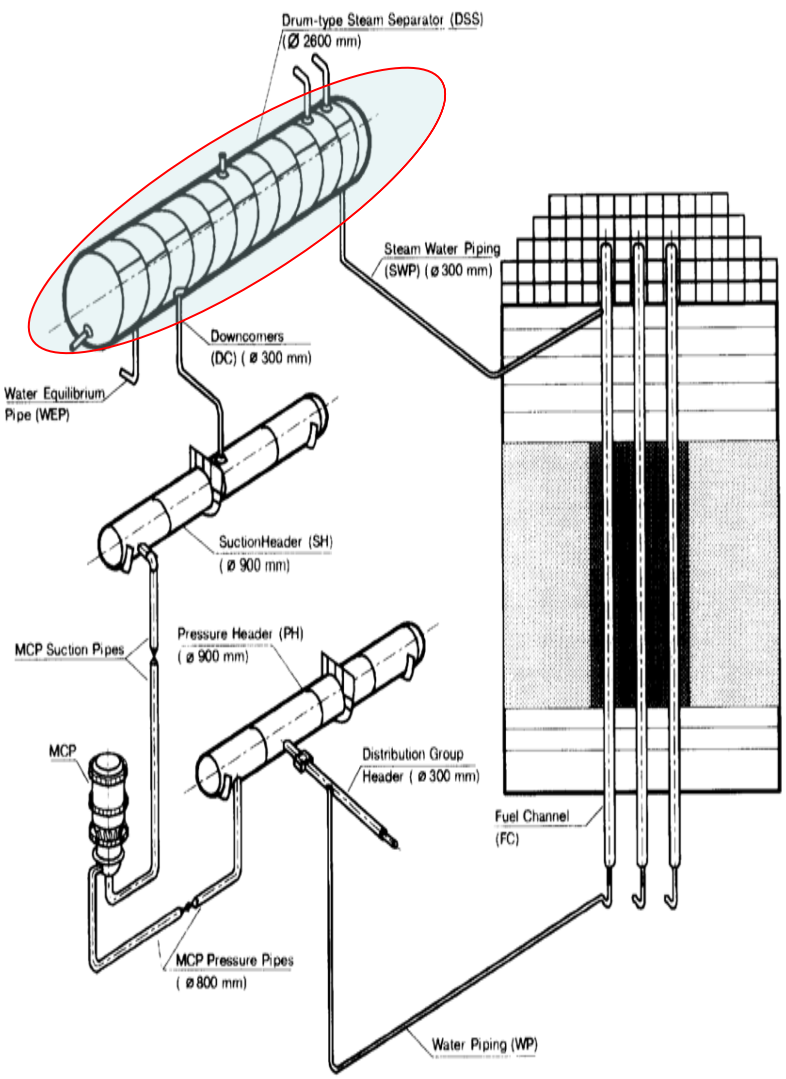
Relap5-3D© nodalisation

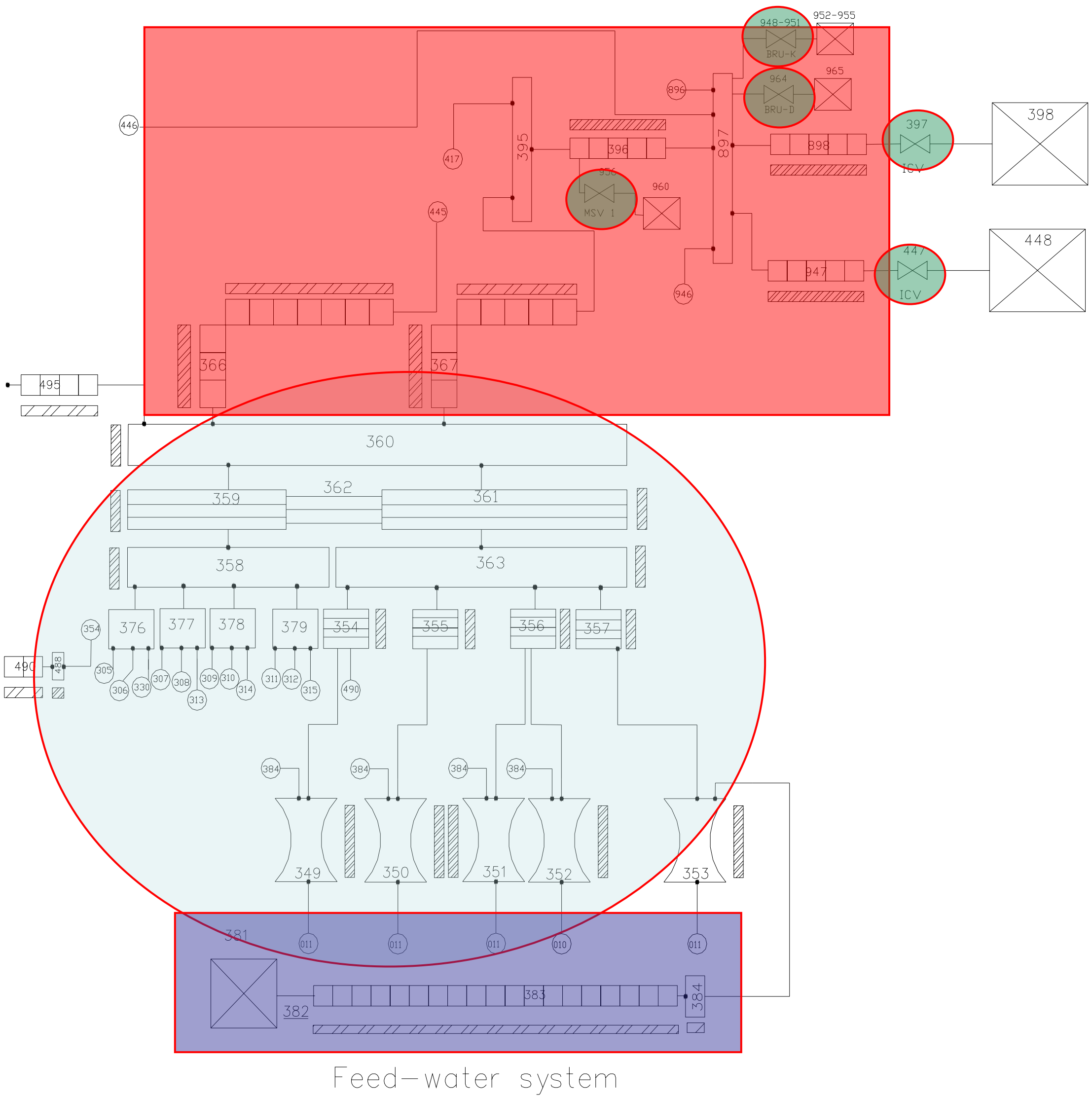


sketch of the right side

TH modeling 2/5

Steam Drum | **FW** | **Steam Line** | **ICV, MSV, BRU-K, BRU-D**

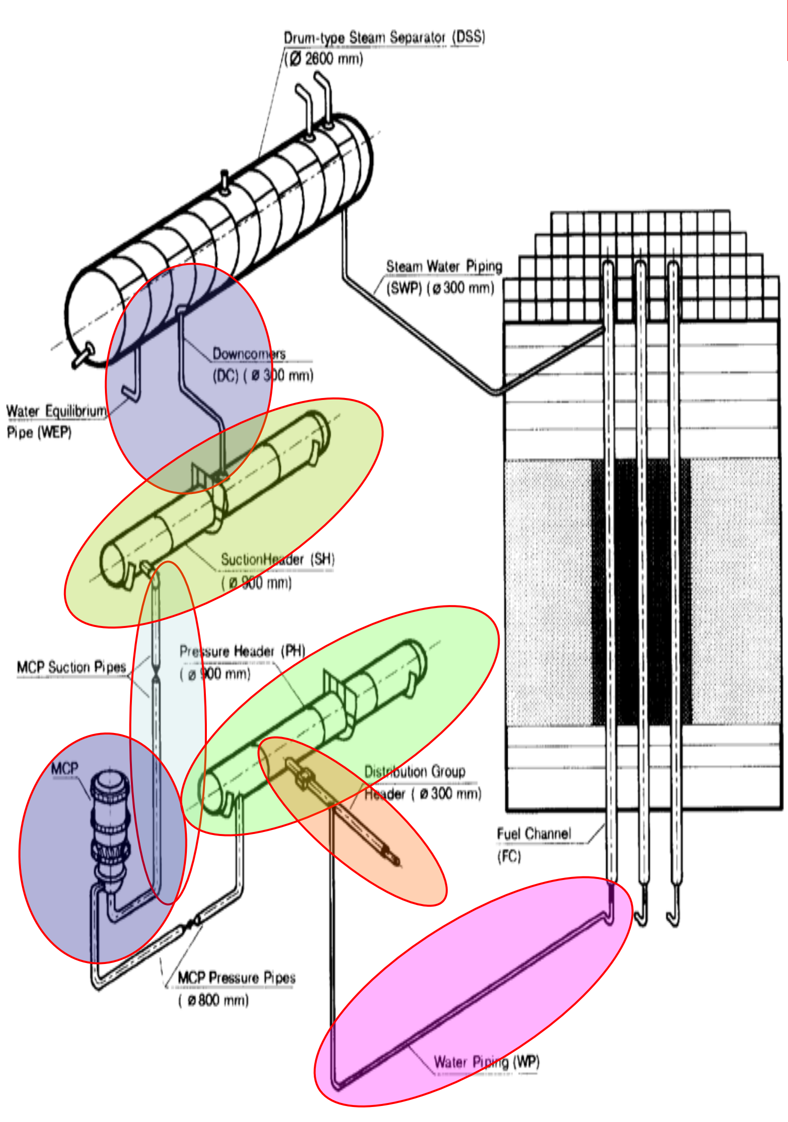


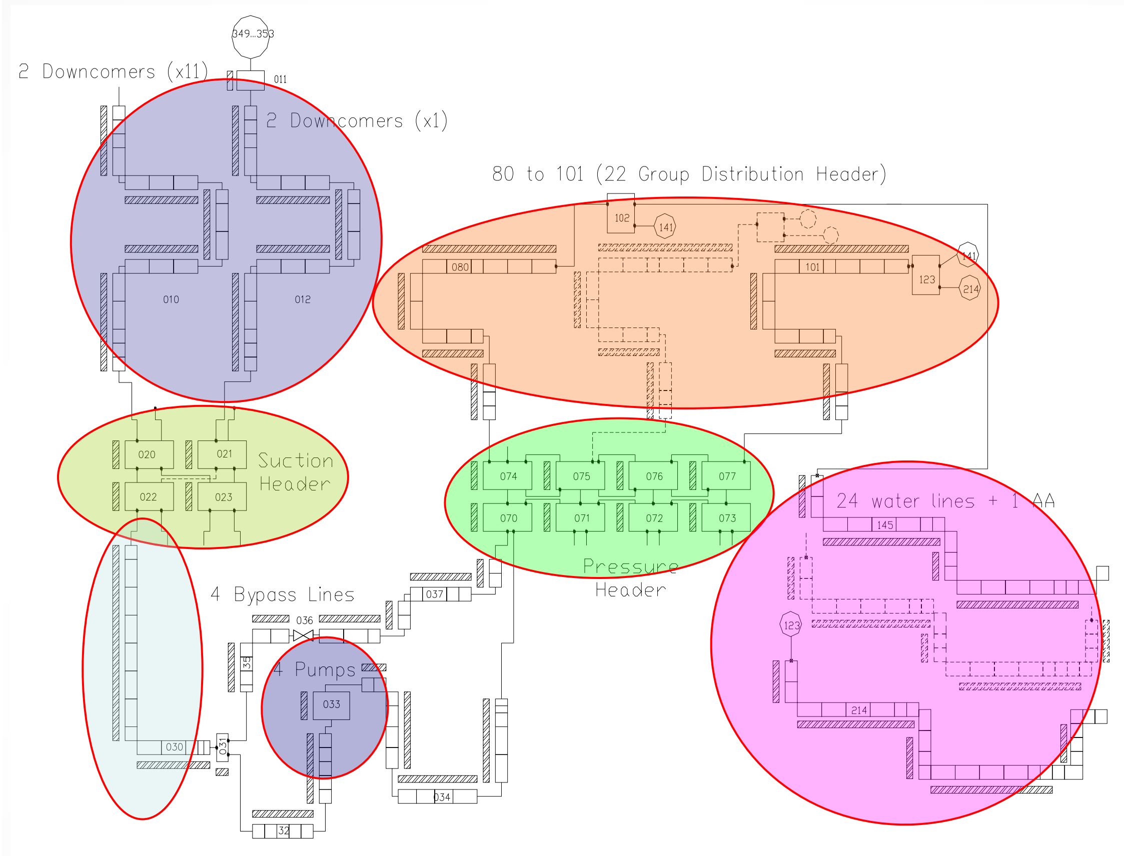


TH modeling 3/5

Downcomers | **Suction Header** | **Suction pipes** | **Pumps** | **Pressure Header**

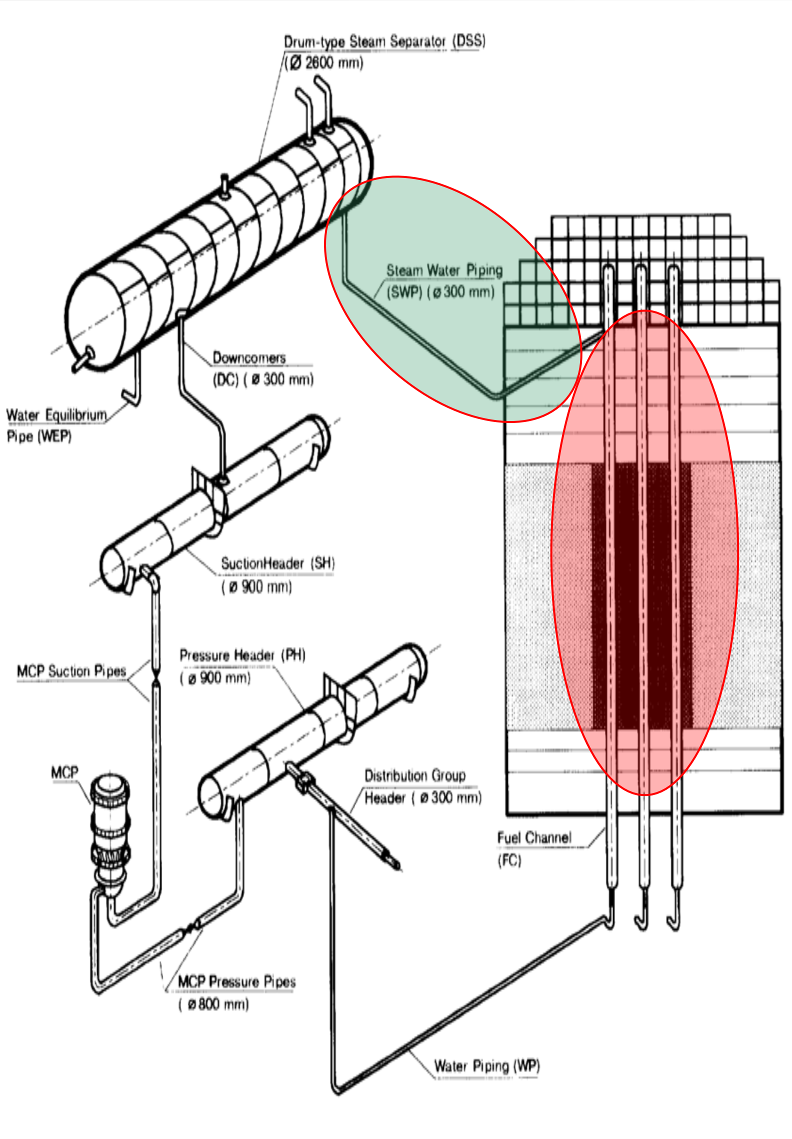
Group Distribution Header | **Water lines**

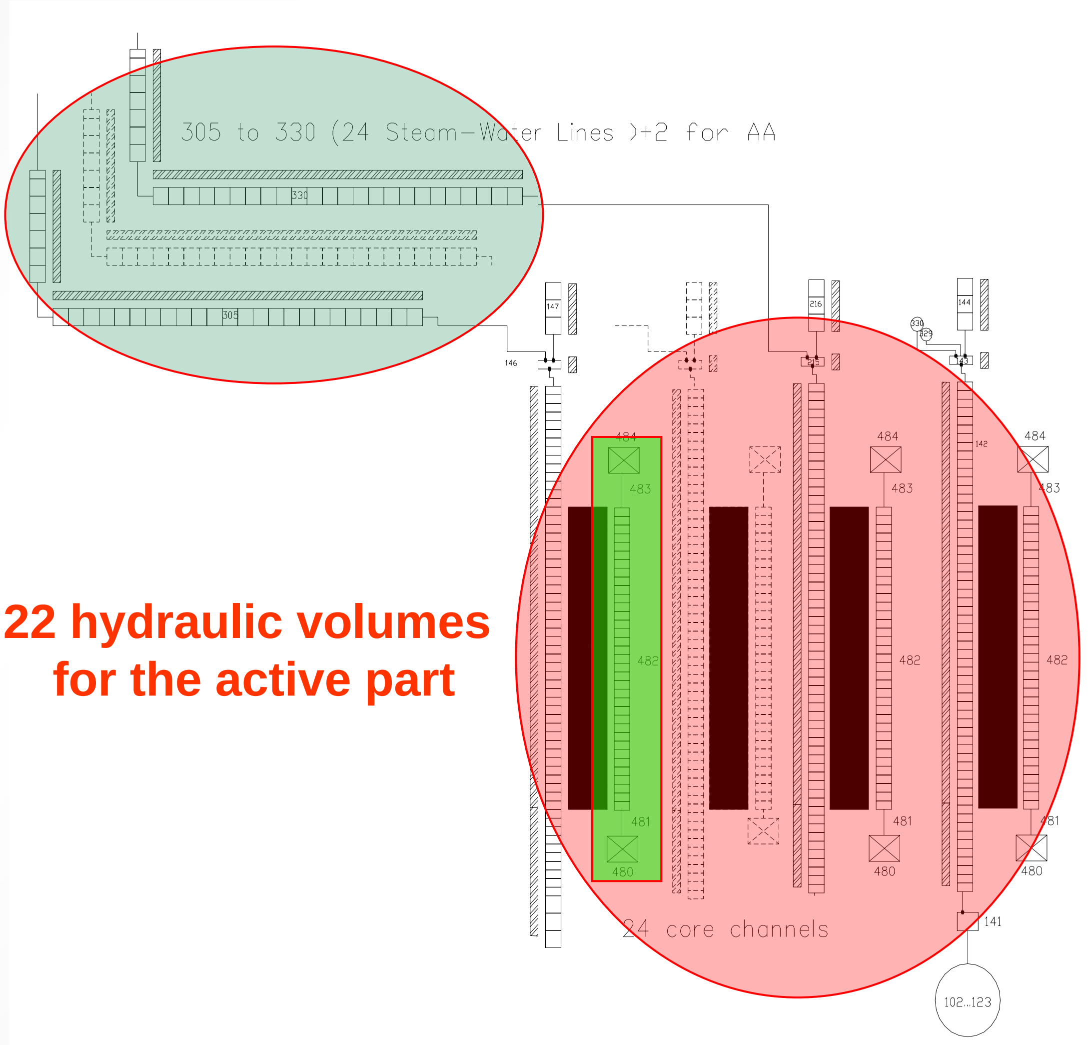




TH modeling 4/5

Core & Graphite stack | **Graphite Gap** | **Steam water lines**





22 hydraulic volumes for the active part

TH modeling 5/5

Main modelled subsystems	Right side	Left side
Number of GDH	22	1
Number of Core channels	24	7
Number of Steam Drums	2	2
Number of Additional Absorber channels	1	1
Number of Pumps	4	4
Number of Bypass lines	4	4

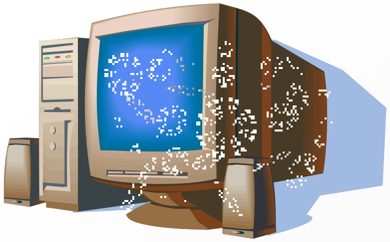
Adopted code resources

Number of Nodes	4272
Number of Junctions	4411
Number of Heat structures	4561
Number of Mesh Points	32590
Number of active structures (fuel + graphite)	64

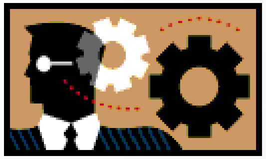
Qualification Process

Basic condition for TH system codes use:

- ✓ **Frozen code version**
- ✓ **User qualification**

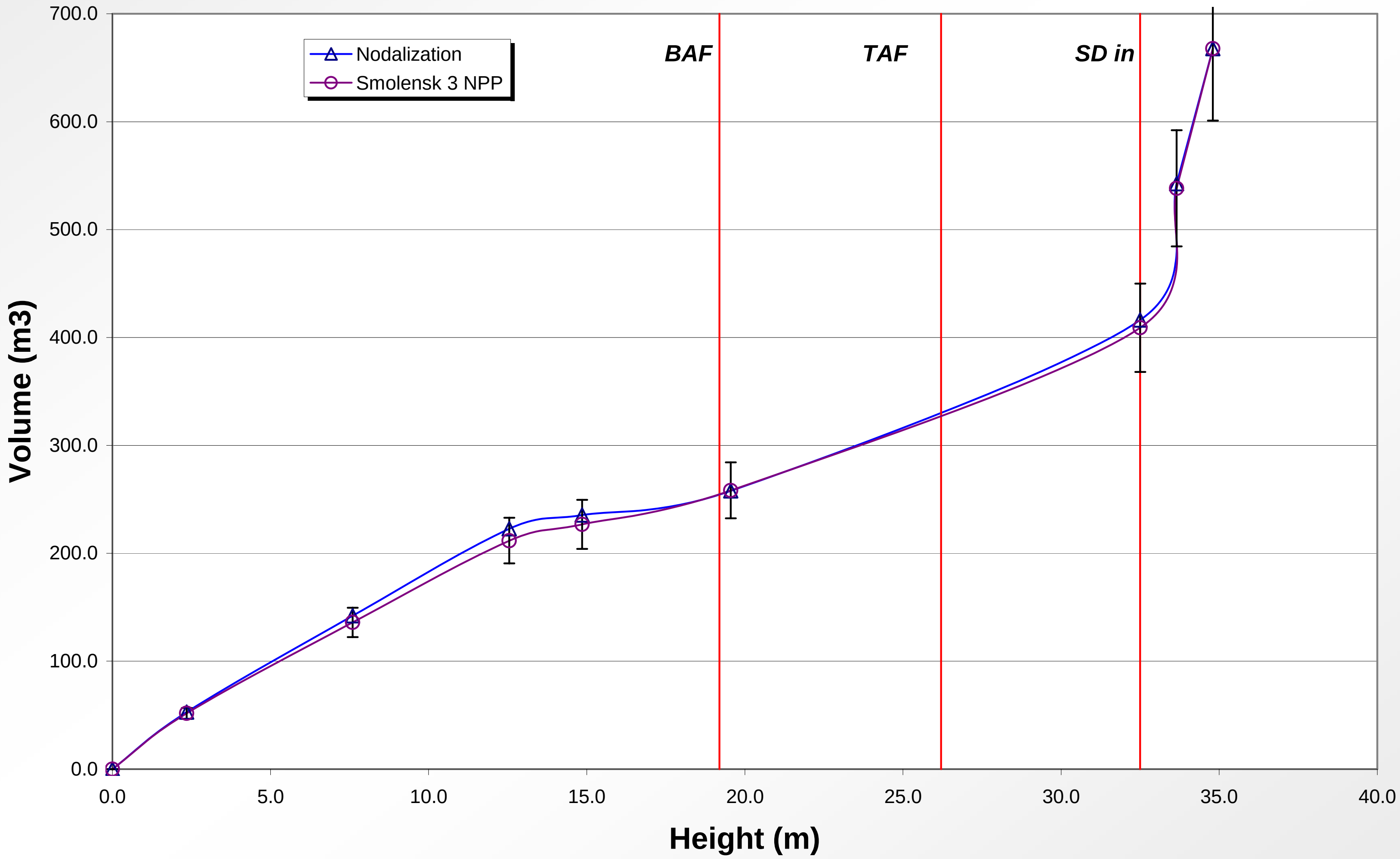


- ✓ **Nod. qualification process**
    - ✓ **Steady state**
    - ✓ **On transient**



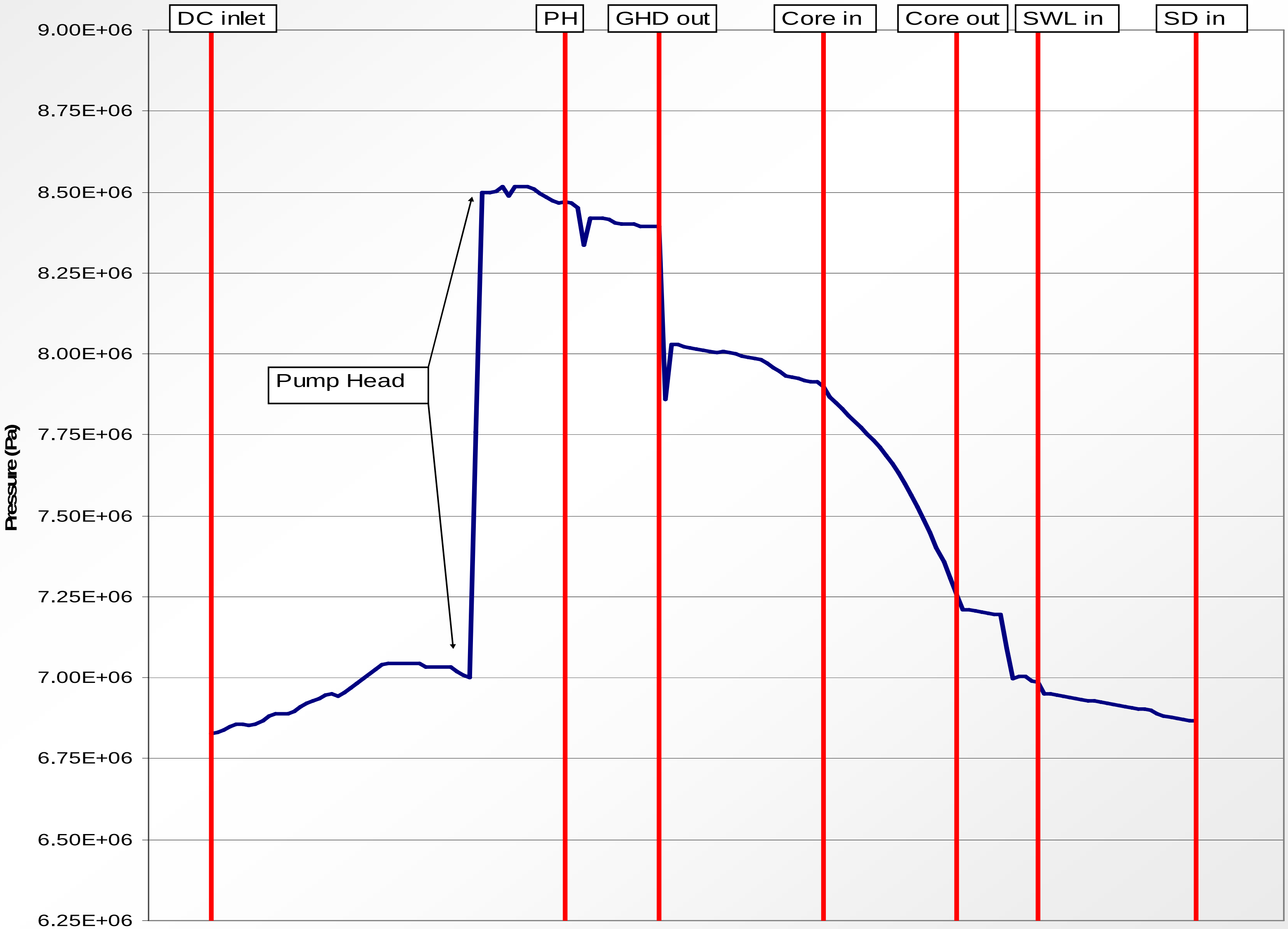
Qualification Process

Steady State level – Volume vs. Height



Qualification Process

Steady State level- DP vs. Length



Qualification Process - SS level

Nodalisation geometrical check

No	QUANTITY	Unit	Design	RELAP5 right side / left side	Acceptable Error (°)	Error	Notes
1	Circuit volume	m^3	667.67	667.78	1%	0.01%	For right side
3	Active structures heat transfer area (overall)	m^2	5919.4 (fuel & PT) / 6712.0 (Graphite-Gap)	5919.6 / 5906.5	0.1%	0.03% / -12%	Error on Graphite-Gap surface due to different geometry
5	Active structures heat transfer volume (overall)	m^3	14.423 / 378.7	14.427 / 408.44	0.2%	0.02% / 7.8%	Error on Graphite-Gap surface due to different geometry
6	Volume vs. height curve	m^3	--	--	10%	5%	Max error

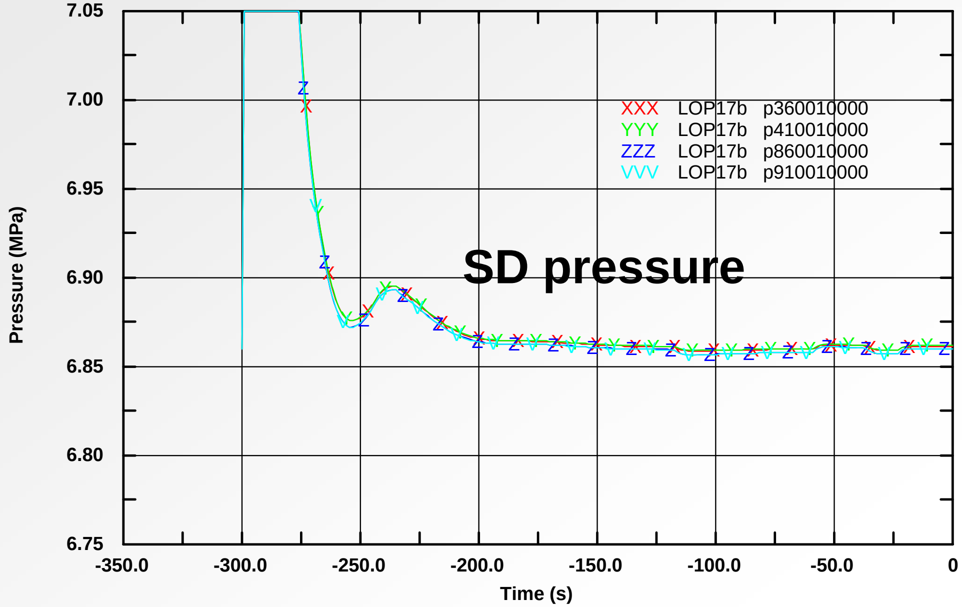
Qualification Process - SS level

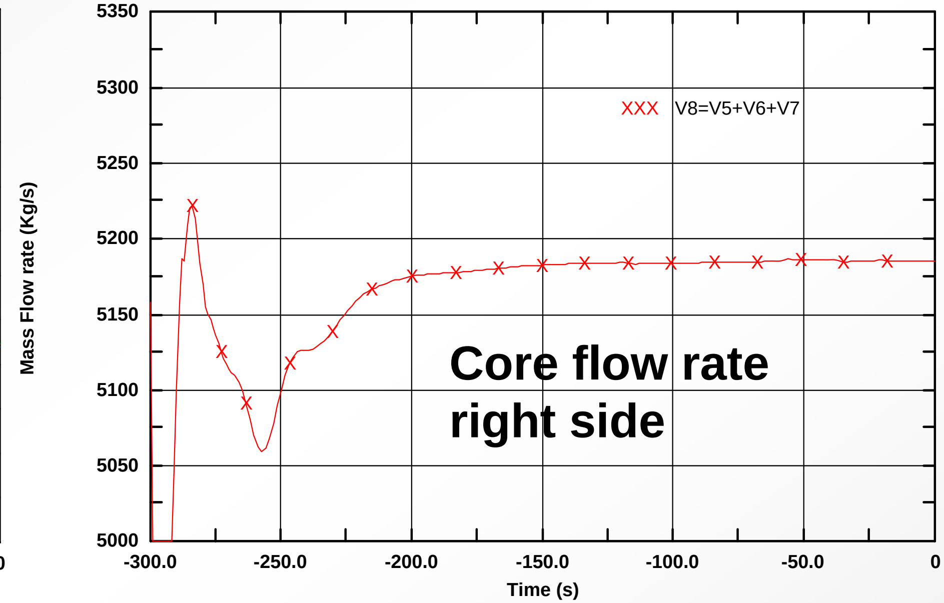
Steady State demonstration:

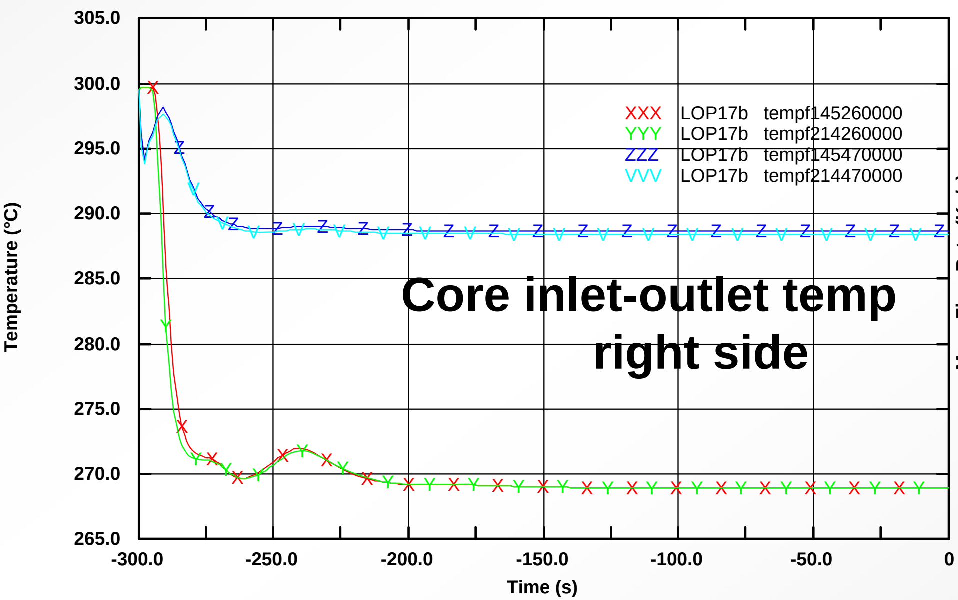
20 selected parameters

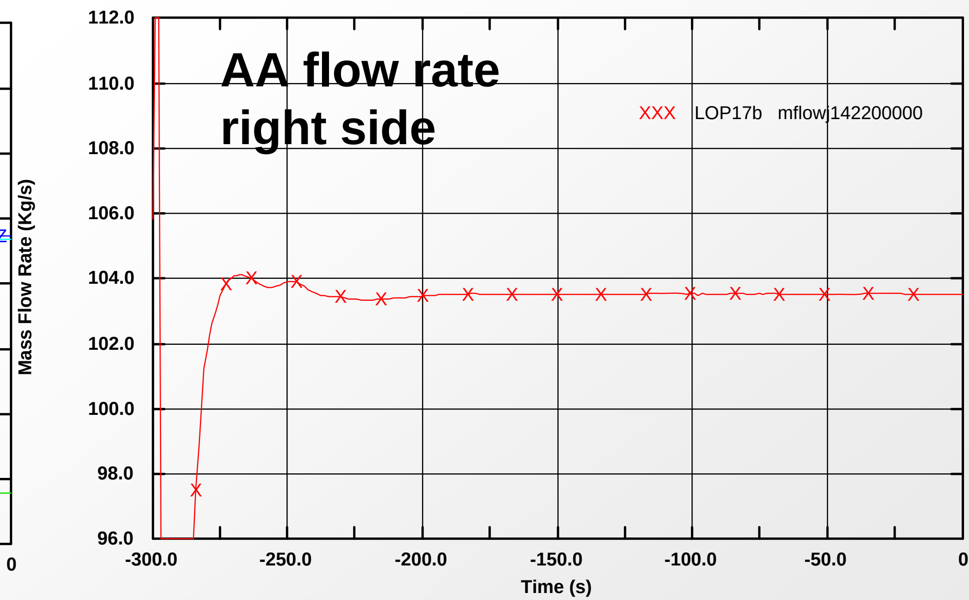
N.	Quantity	Unit	Design	RELAP5 right side / left side		Acceptable Error (°)	Error		Notes
1	Thermal power	MW	1629	1628.1		2%	0.05%		
			1583	1588.1			-0.3%		
2	DS pressure	MPa	6.86	6.861	6.862	0.1%	-0.01%	-0.03%	On all SD dome
				6.859	6.859		0.01%	0.01%	
3	Core inlet temperature	°C	270	269		0.5%	0.37%		
				269			0.37%		
4	DS inlet temperature	°C	284	284.5		0.5%	0.1%		
				284.5			0.1%		
5	Average quality in the core exit	%	14.5	15.5		?			
				15.3					
6	DS feed water temperature	°C	165	165		0.5%	0.0%		Imposed Value
7	Maximum fuel rod temperature surface	°C	?	298		10			
8	MCP speed	rad/s	104.2	104.7		1%	0.4%		Imposed Value
				104.7			0.4%		
9	Pressure drop on the water line	MPa	0.5	0.496 ÷ 0.51		10%	0.8% ÷ - 2%		For 2.049 MW channel
				0.491 ÷ 0.497			1.8% ÷ 0.6%		
10	Pressure drop on the core		0.657	0.64÷0.658			2.5%÷ -0.15%		
				0.654÷0.658			0.46%÷ -0.15%		
11	Pressure drop on the steam-water line		0.392	0.376÷0.387			4%÷1.3%		
				0.366÷0.369			6.6%÷5.9%		
12	Total pressure drop on the TC	MPa	1.549			10%			
13	MCP head	MPa	1.51	1.512		10%	-0.13%		For all pumps
14	PS total mass inventory	tons	?	801		2%			
15	DS mass inventory	m^3	85±?	89.5	91.4	2%	-5%	-7%	Liquid Fraction Volume
				86.8	87.8		-2%	-3%	
16	Total loop coolant flow rate	Kg/s	5157.9	5185.2		2%	-0.5%		
			5103.9	5106			-0.04%		
18	Additional absorber flow rate	Kg/s	105.82	103.5		10%	2%		
			105	92.5			12%		
19	Balance between feed water and steam mass flow rate	%	0.0	0.6%		?			
				0.7%					
20	Average graphite temperature	°C	?	485		?			
				484					

Qualification Process - SS level

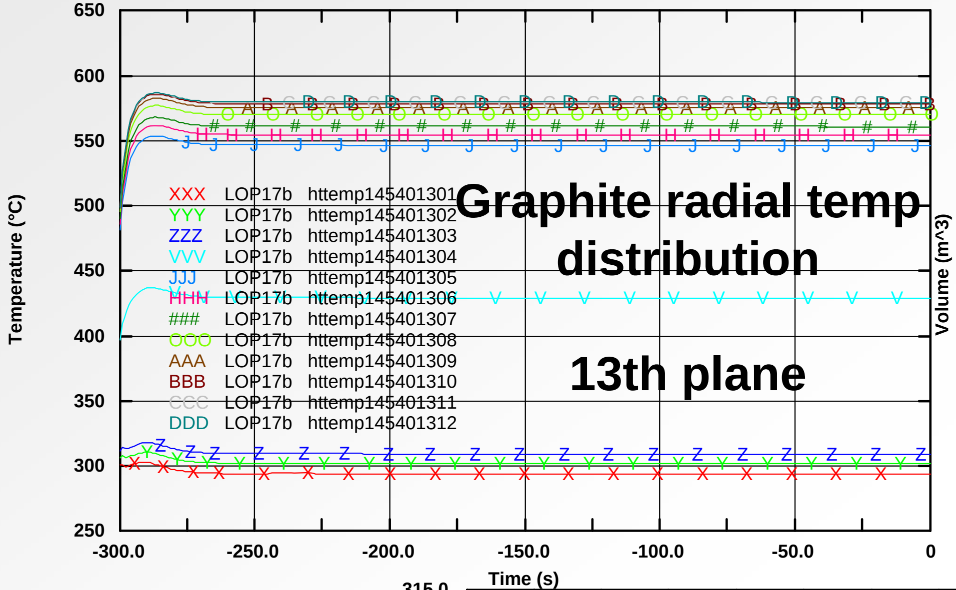


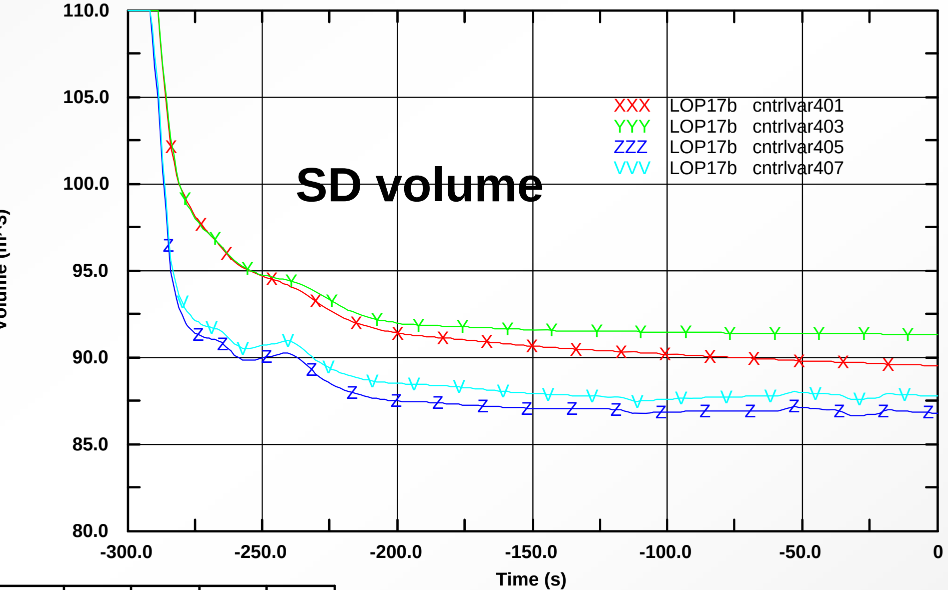


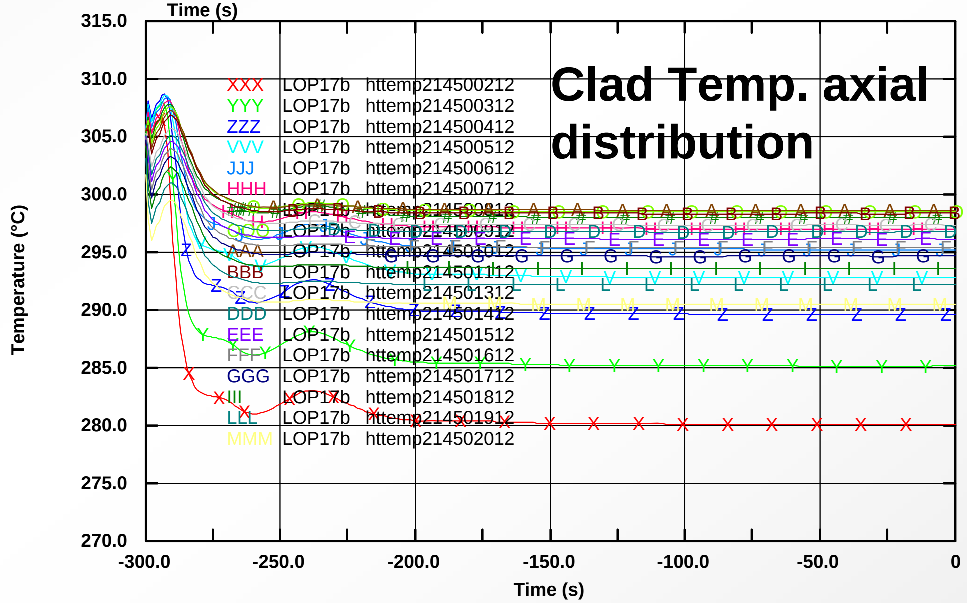




Qualification Process - SS level







Qualification Process

On Transient level

REPLICATION OF A SELECTED TEST

Qualitative evaluation

Accuracy quantification

LOSS of POWER

Comparison
with exp. data

~~FFTBM~~

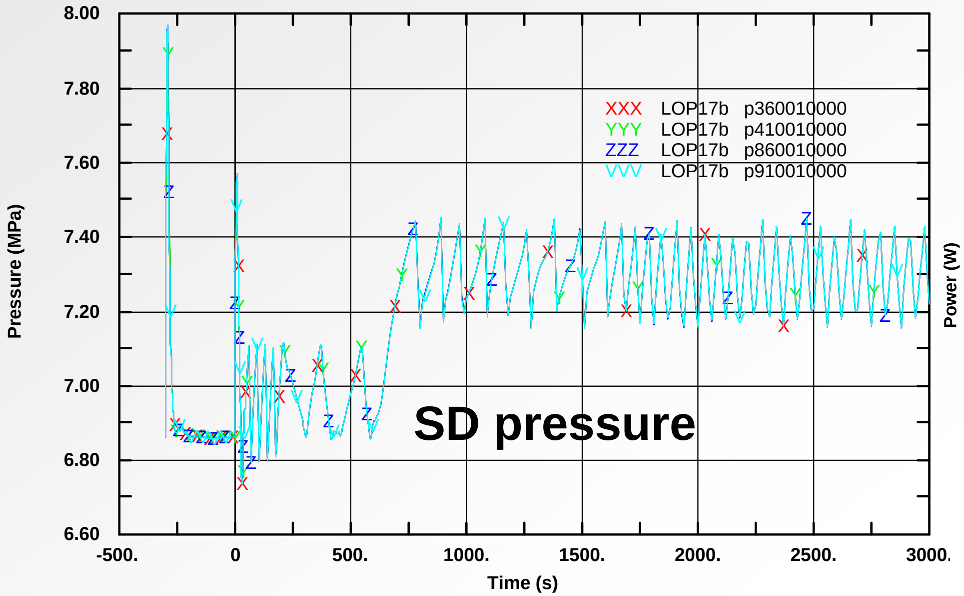
Comparison with
Russian results

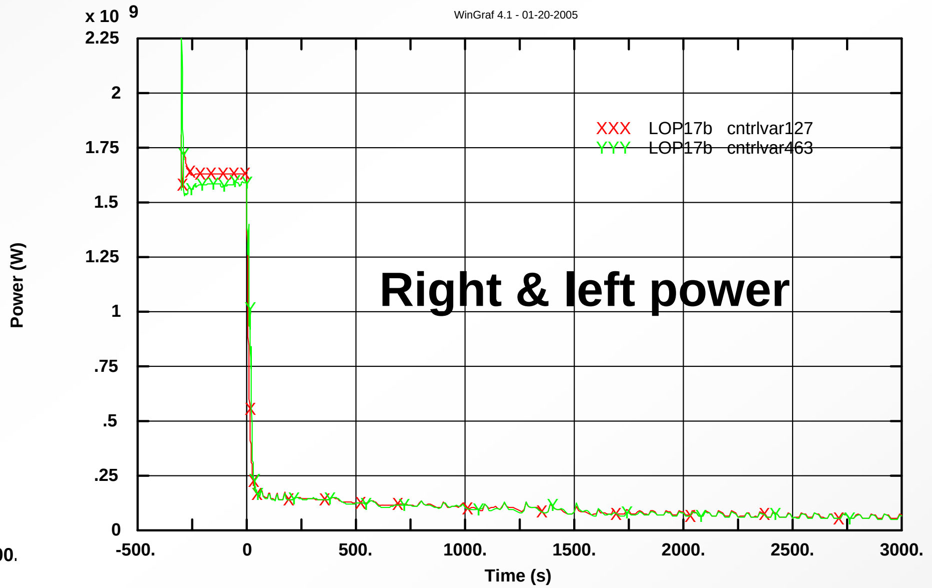
Qualification Process – On Transient

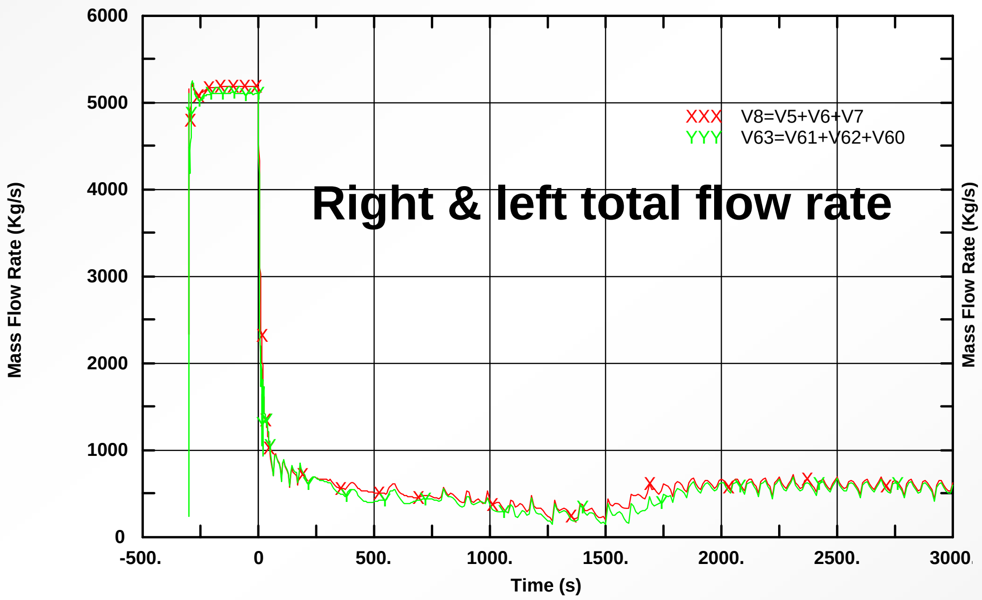
Time sequence of main events

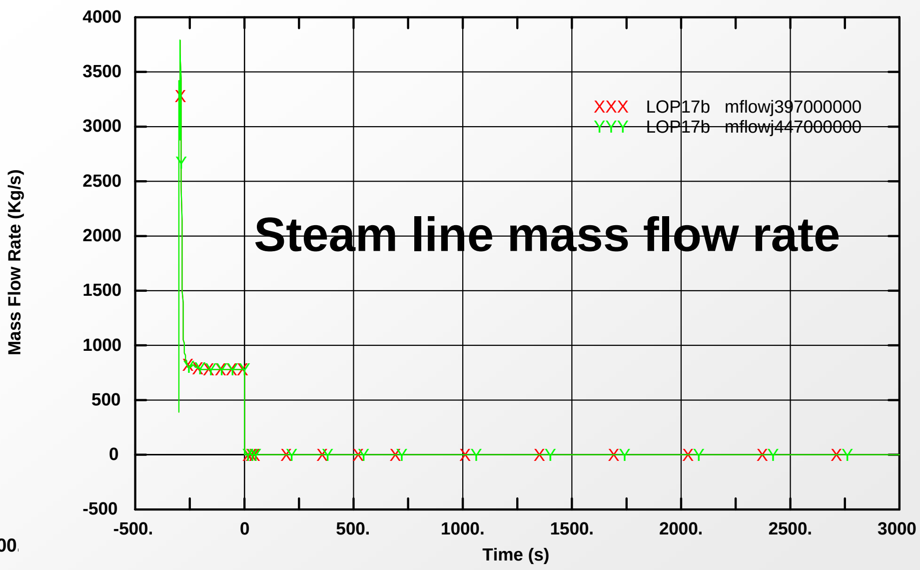
Unipi Time (s)	Event	Russian Time (s)
0.	Loss of preferred AC power supply. Diesel generators start.	0.
0.4	Turbine isolation and regulation valves fully closed.	0.4
1.0	1st AZ-5 command issued by CPS upon EPPS reading that turbine valve has closed. This signal is neglected in the simulation.	1.0
1.0	2nd AZ-5 command issued as a result of pressure downstream turbine valve falling to 12 bar. This signal is credited in the simulation. Power begins to reduce. CPS rods start moving.	1.0
1.0	BRU-K valves start to open due to over-pressure. BRU-K operate as pressure controller with opening and closure set-points equal to 7.11 MPa and 6.86 MPa respectively	1.0
3.0	First group of MSV start to open.	226.
15.0	Diesel generators reach nominal loading.	15.0
55.0	2 EFWP starts.	55.0
180.	BRU-K valves are fully closed.	180.0
600.	BRU-D valves are closed.	600.
1090.	The operator switch off EFWP on level signal.	1211.
3000.	Final problem time	3000.

Qualification Process – On Transient

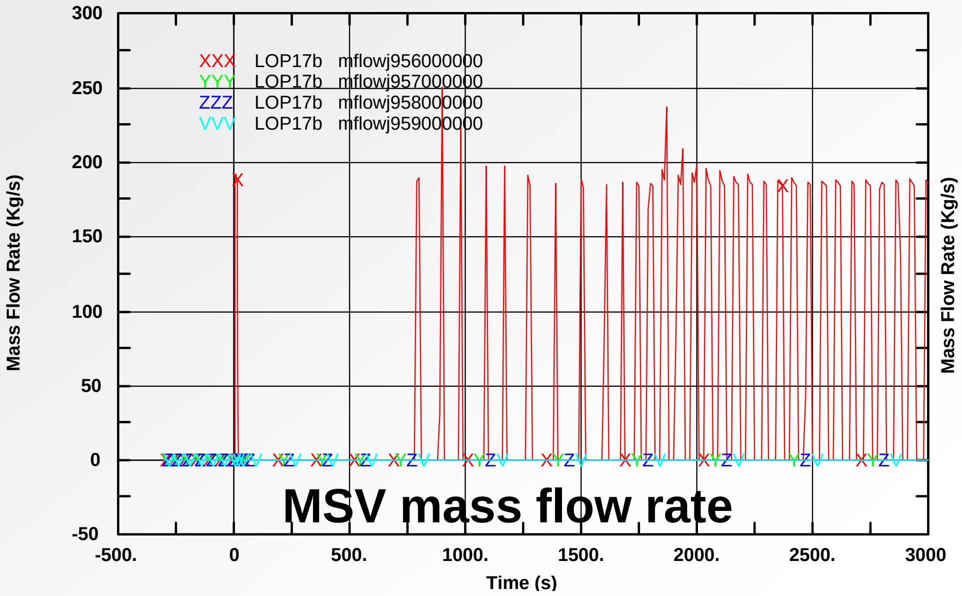


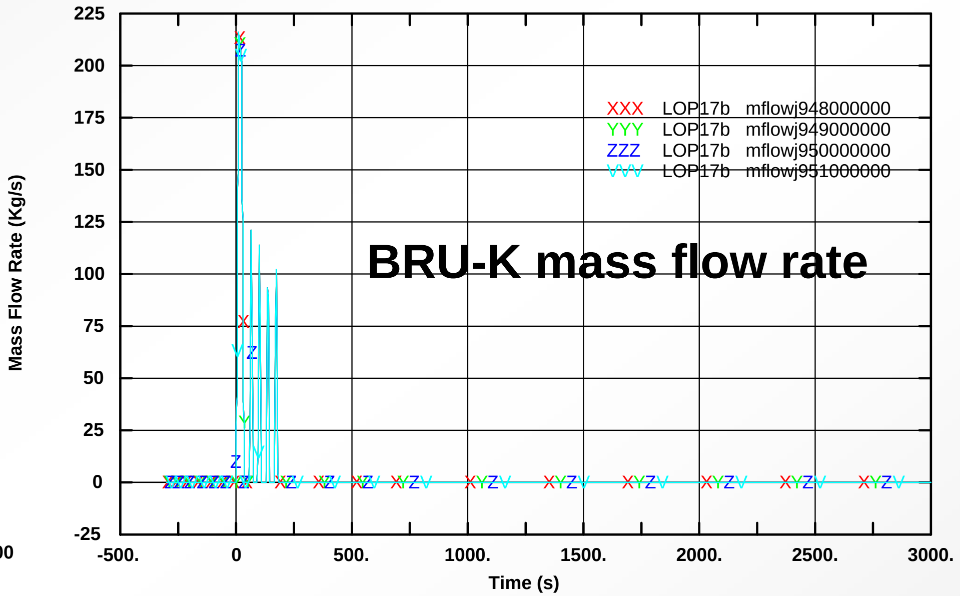


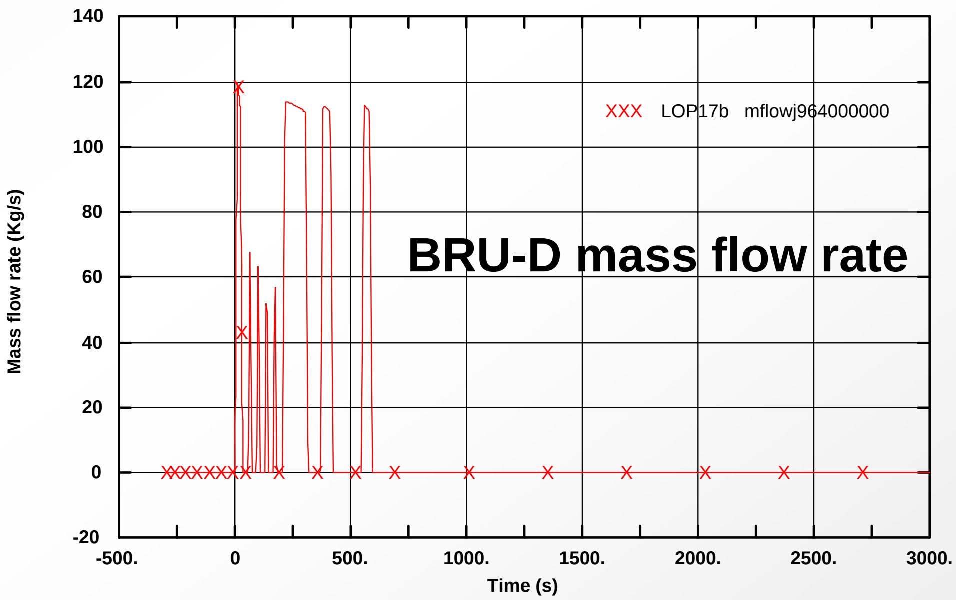




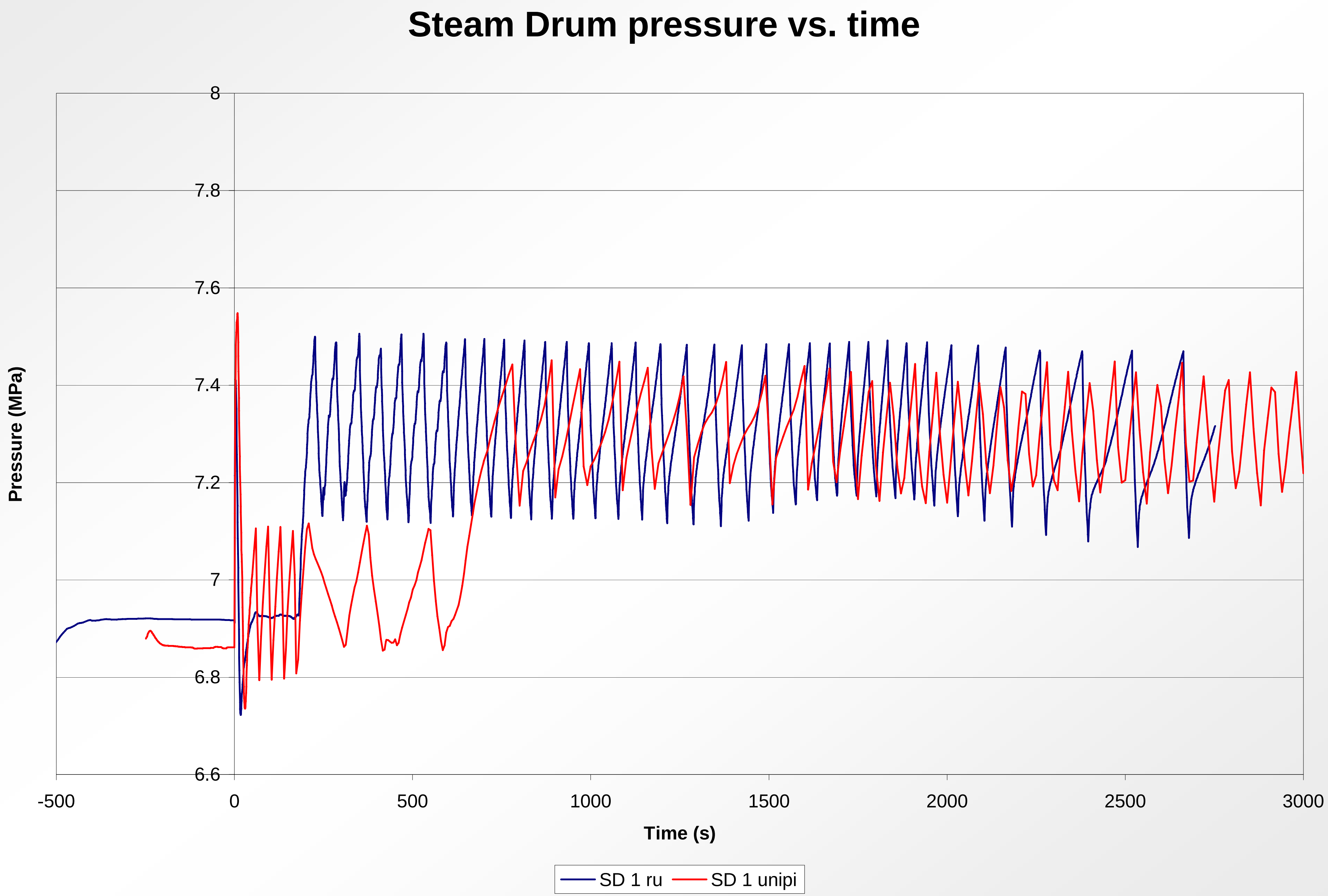
Qualification Process – On Transient



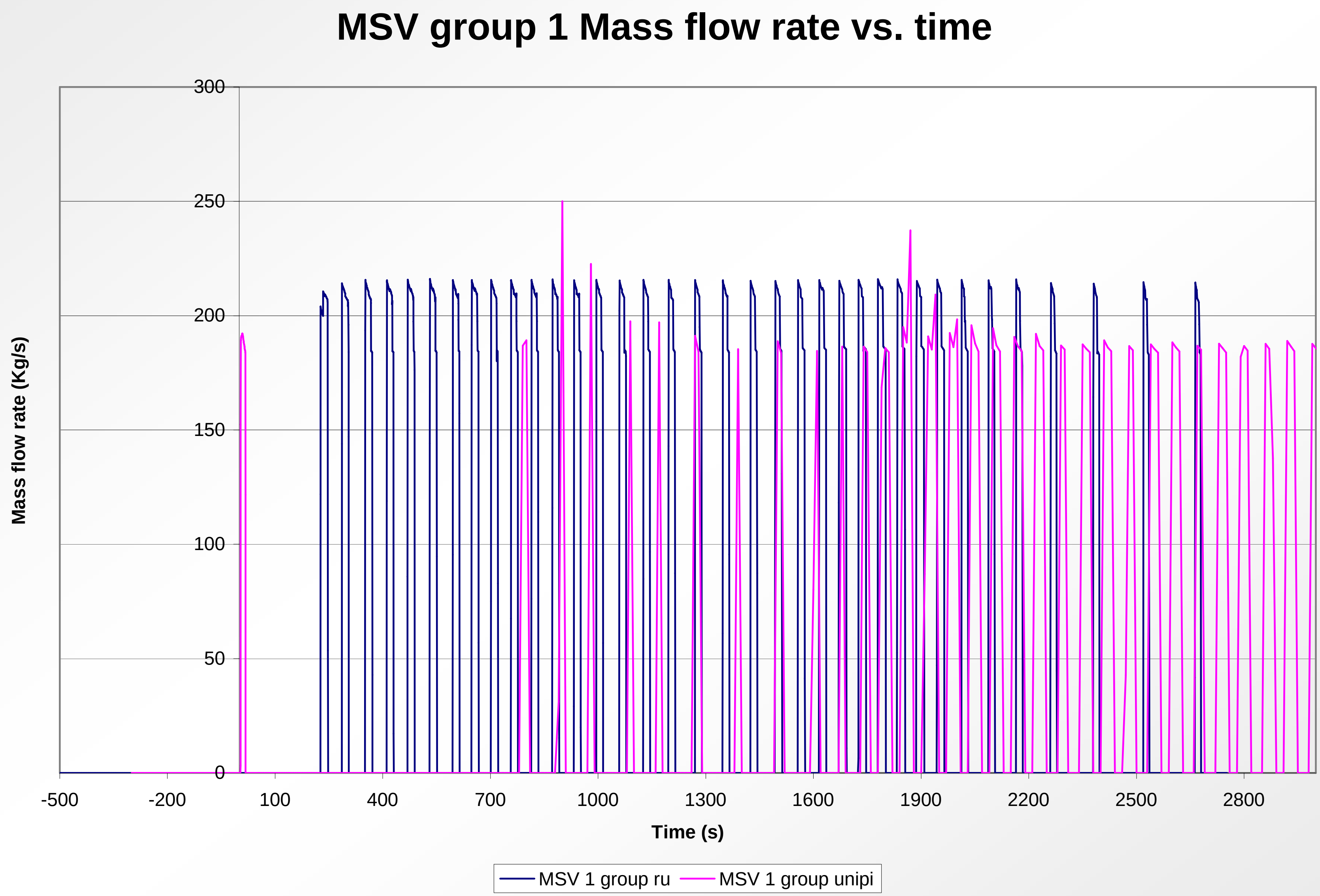




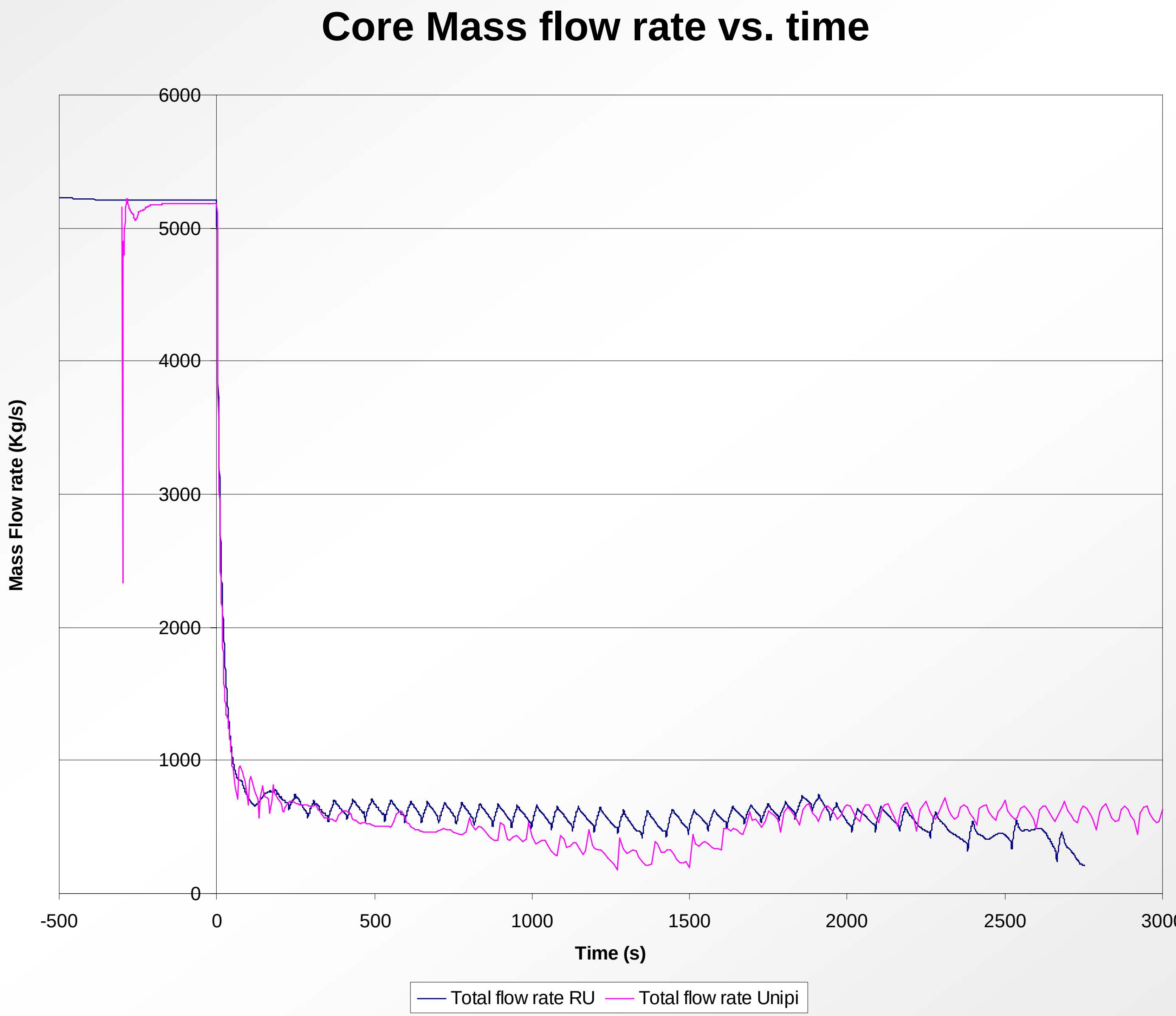
Qualification Process – On Transient



Qualification Process – On Transient



Qualification Process – On Transient



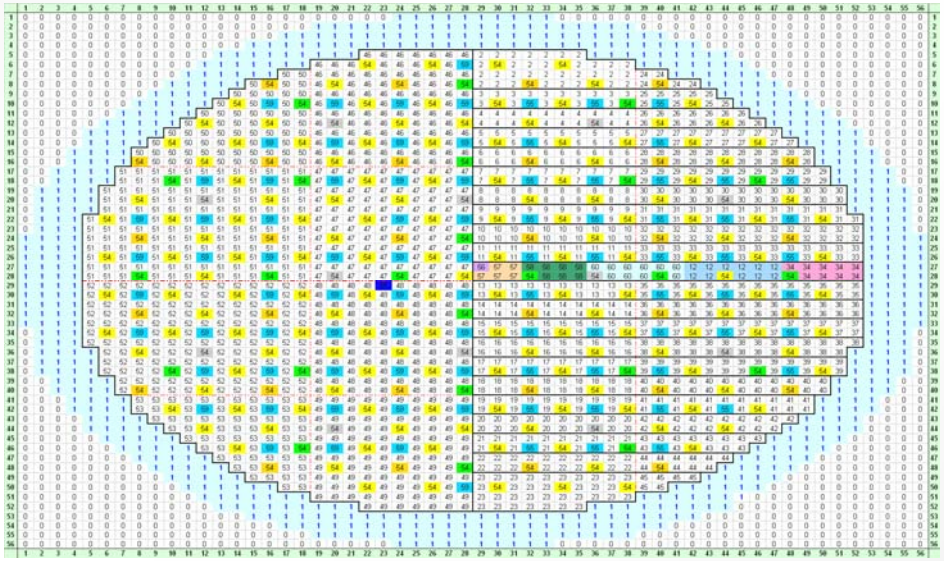
Considerations on TH model

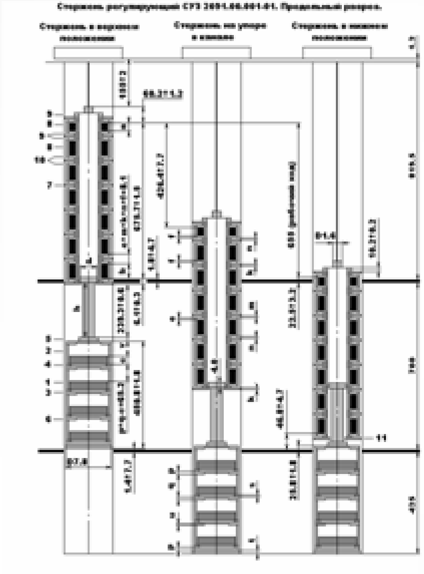
- The pioneering study (for UNIPI) of the RBMK reactor type gave the following results:
  - Steady State level: all the limits regarding the geometrical fidelity have been fulfilled; precision of few parameters should be improved (i.e. SD mass inventory)
  - On transient level: a qualitative comparison between Russian and UNIPI results shows some discrepancies (e.g. MSV timing)
- The same phenomena are predicted from both calculations (SD pressure trend)
- Lacking of measured values does not permit the application of the FFT-BM to quantify the accuracy of the obtained results
- The nodalisation is capable to reproduce the selected transient – LOOP – even though some improvements are necessary

Successive step → development of 3D NK model

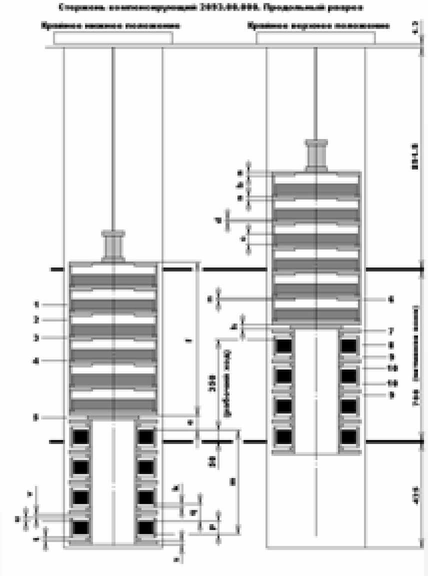
RBMK 3D NK Peculiarities

- RBMK peculiarities:
  - Loosely coupled core
  - Large number of nodes (30000)
  - 2488 channels (*1570 FC, 314 non-FC (AA, Axial detectors,..), and 604 Reflector Channels*)
  - Complex neutron XSecs structure (graphite & fuel temp, water density, Xenon conc,.. feedbacks)
  - Different CR arrangements & type:
    - Up & Bottom Inserted
    - Manual CR, Shortened CR, Fast Acting Scram CR

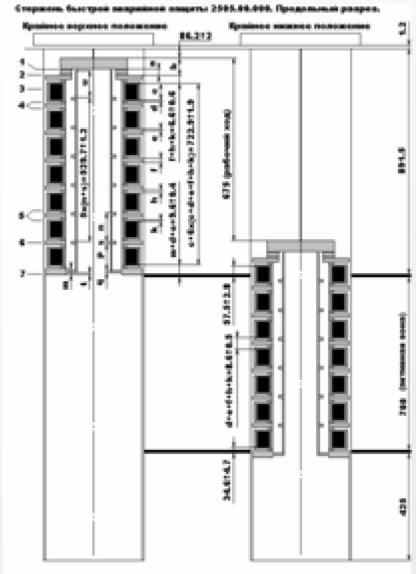




Manual CR



Shortened CR

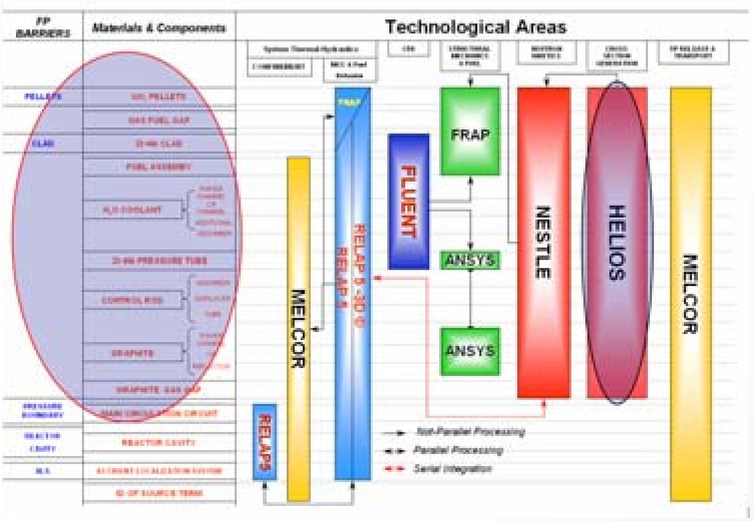


Fast CR

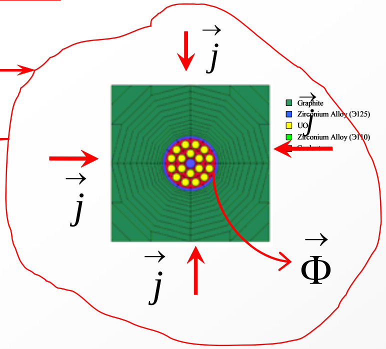
Neutron Database - Code

HELIOS:

- 1D- 2D neutron-gamma transport code for lattice burnup
- complete geometric flexibility
- Generate Few-Groups <u>Macroscopic XSecs Libraries</u>



ENDF/B-VI → NJOY → MultiG XSec → HELIOS



1D – 2D Transport Calculations

```
*  NEM-Cross Section Table Input
*
*   T Fuel      T Mod.      Rho Cool.    CXe
        3           4           6           0
*
*******         X-Section set #      1
*
*     Group No.  1
*
***************           Diffusion Coefficient Table
*
 .5570000E+03  .8500000E+03  .1030000E+04  .5570000E+03  .7000000E+03
 .8560000E+03  .1060000E+04  .1000000E+02  .1000000E+03  .3000000E+03
 .5000000E+03  .7440000E+03  .9980000E+03  .1161020E+01  .1161020E+01
 .1161000E+01  .1161440E+01  .1161430E+01  .1161420E+01  .1160100E+01
 .1160100E+01  .1160090E+01  .1157710E+01  .1157680E+01  .1157680E+01
 .1159020E+01  .1159020E+01  .1159010E+01  .1159440E+01  .1159420E+01
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 .1155650E+01  .1155640E+01  .1153360E+01  .1153330E+01  .1153300E+01
 .1153740E+01  .1153710E+01  .1153700E+01  .1152390E+01  .1152360E+01
 .1152340E+01  .1149940E+01  .1149910E+01  .1149890E+01  .1146530E+01
 .1146480E+01  .1146460E+01  .1146920E+01  .1146850E+01  .1146830E+01
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 .1142980E+01  .1137150E+01  .1137100E+01  .1137090E+01  .1137520E+01
 .1137460E+01  .1137460E+01  .1136130E+01  .1136080E+01  .1136050E+01
 .1133630E+01  .1133580E+01  .1133550E+01  .1126540E+01  .1126500E+01
 .1126480E+01  .1126880E+01  .1126840E+01  .1126800E+01  .1125490E+01
 .1125440E+01  .1125400E+01  .1122970E+01  .1122890E+01  .1122850E+01
*
***************      Total Absorption X-Section Table
```

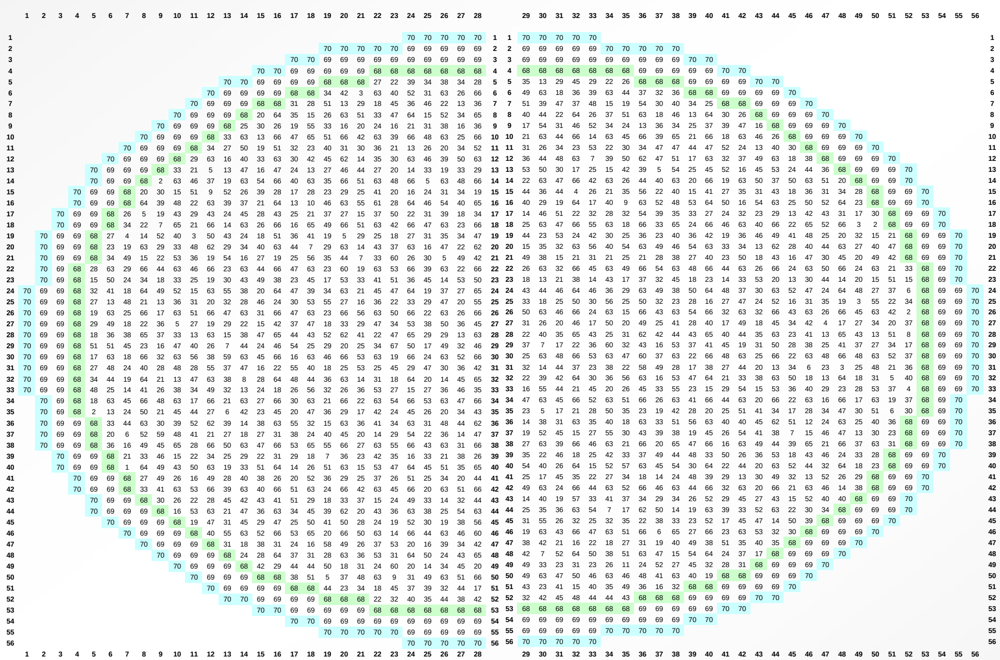
XSecs Libraries

- Database function of:
  - ✓ Exposure
  - ✓ Fuel temperature
  - ✓ Graphite temperature
  - ✓ Coolant density

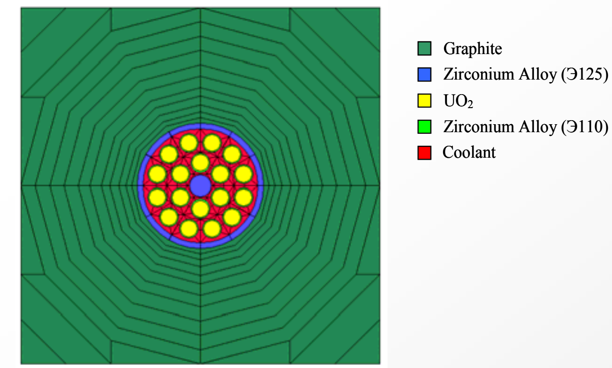
- 675 Compositions
  - for fuel cells: 610
  - for non-fuel cells: 65

Neutron Database Generation 2/2

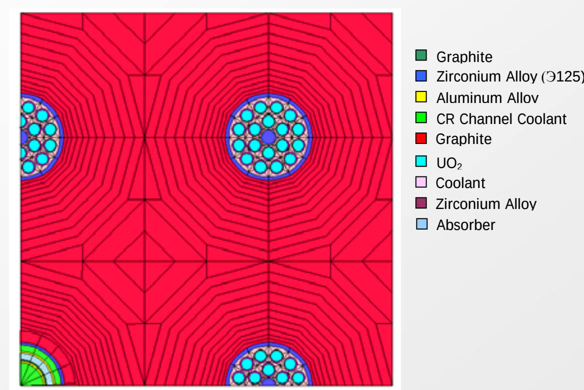
- Operational data obtained with radial & axial in-core detectors
- Reactor core divided axially into 10 layers with a height of 70.0 cm
- Upper and lower axial reflectors have a thickness of 30 cm
- All non-fuel cell type considered
- Validation of the **Neutron Cross Sections Database** by precise **Monte Carlo calculations**



Smolensk-3 NPP status at 16.10.1996

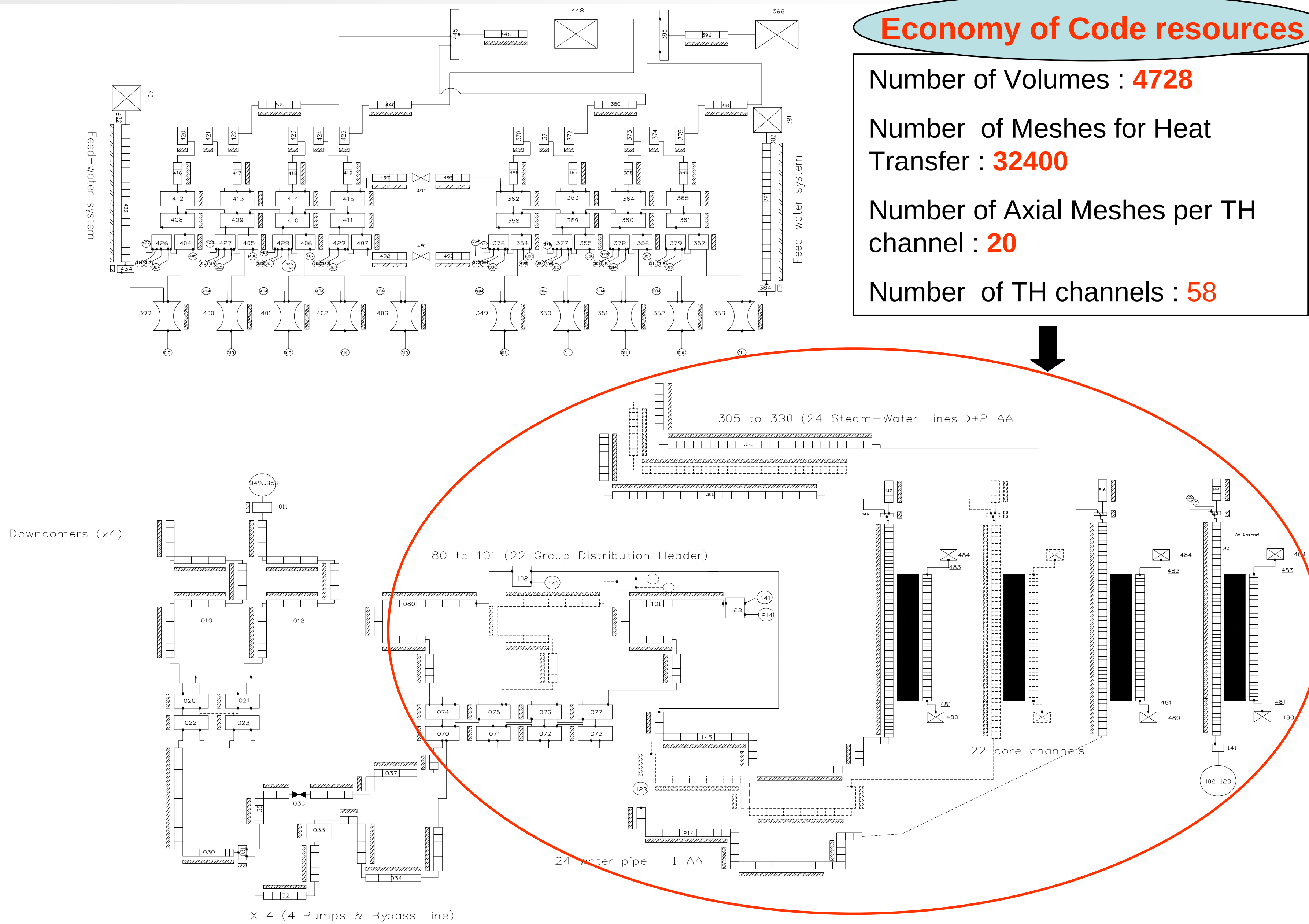


FC cell



MCR cell

RBMK TH/3D NK Model Developed



Economy of Code resources

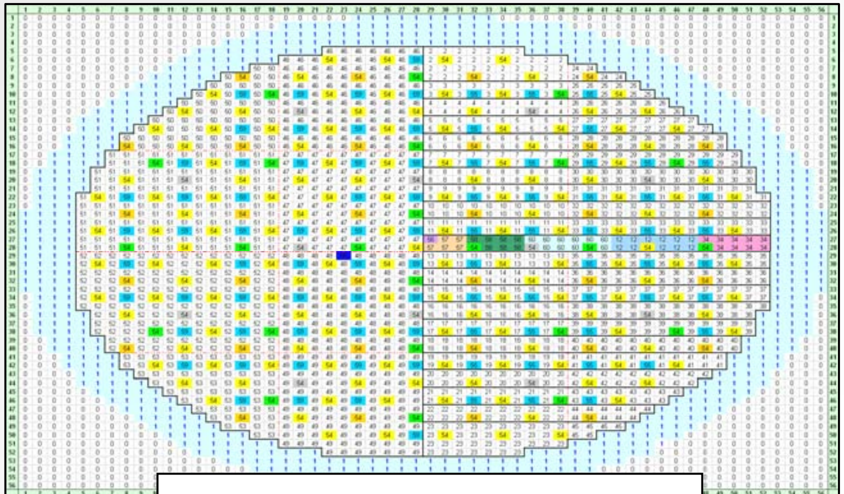
Number of Volumes : **4728**

Number of Meshes for Heat Transfer : **32400**

Number of Axial Meshes per TH channel : **20**

Number of TH channels : 58

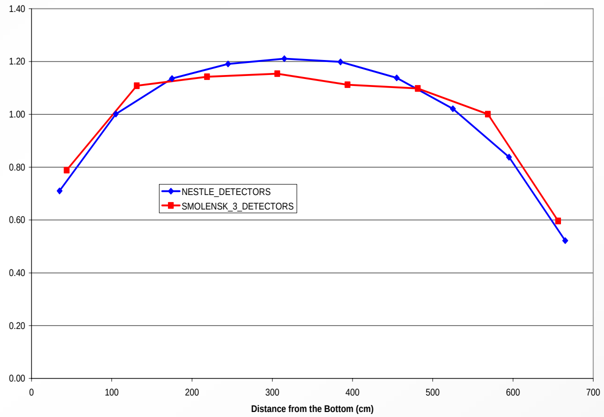
3D NK Core Modeling & Qualification



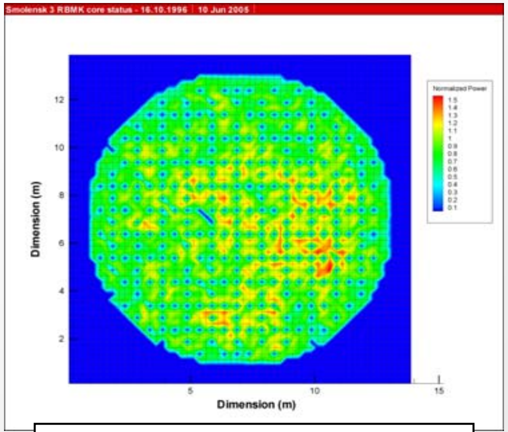
NESTLE 3D NK model

- **29856** Neutron Kinetic Nodes
- All CR Types (Manual, Shortened, Safety), Axial Detectors & Additional Absorbers **Simulated**
- Bottom, Top and Radial Graphite **Reflector** Modelled

- **Radial power peaking factor – 1.62**
- **Radial power distribution: RMS from 130 radial detectors – 7%**
- **Axial power distribution: RMS from 12 axial detectors – 8%**



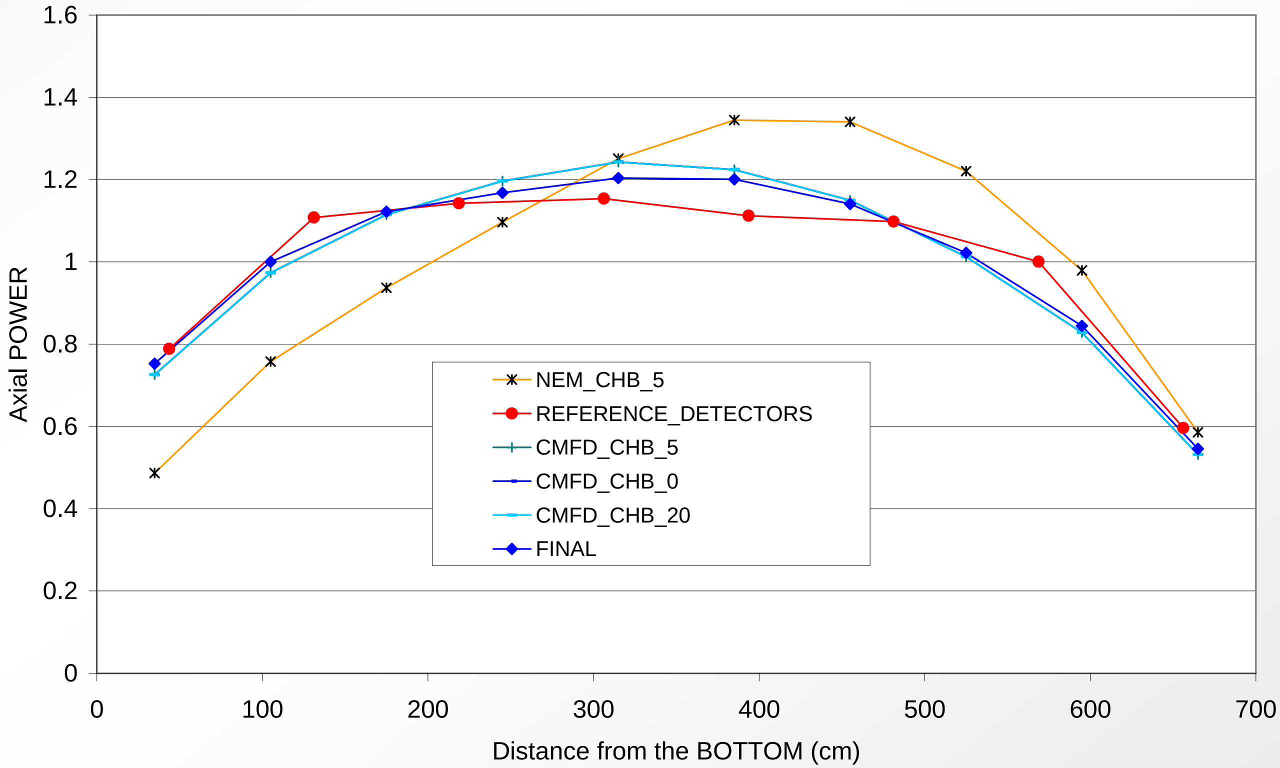
Axial Core Peaking Factor



2D Core Power

3D NK Sensitivity Analysis

- Several tests performed for axial power distribution changing NESTLE numerical methods
- Pure CMFD method resulted more robust than NEM for this core configuration



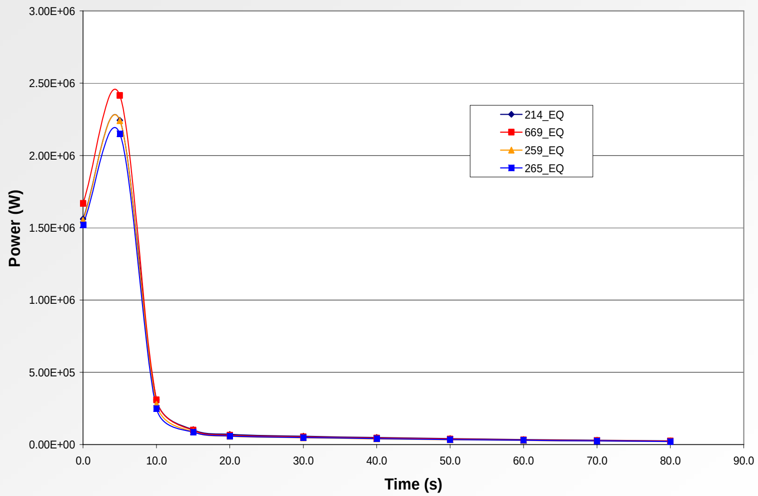
RBMK Transient Analyses

- Several Plant transients were proposed and analyzed in order to check the codes capabilities in modeling RBMK phenomena:

  - CR Withdrawal *
  - CR Bank Withdrawal *
  - GDH Rupture
  - Flow Blockage in GDH *
  - Flow Blockage in FC *
  - CPS cooling LOCA

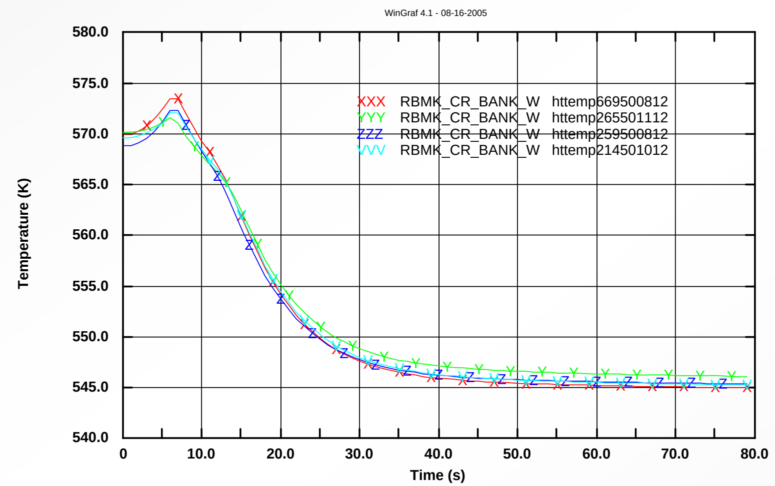
  * = sample results given in next slides

Sample Results 1/3



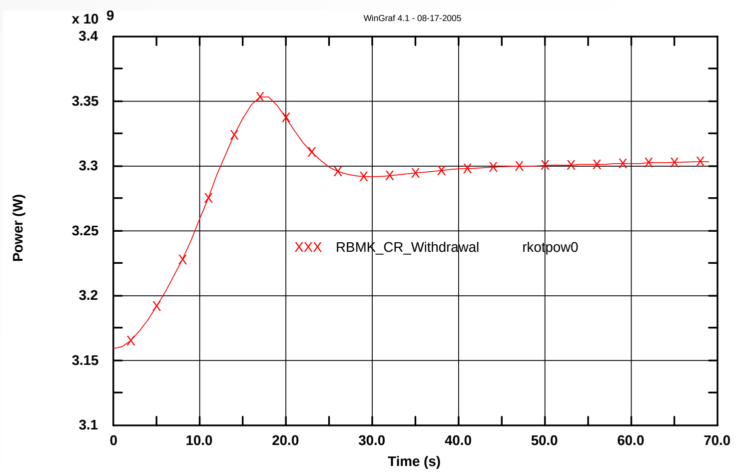
RELAP5-3D© CR Bank Withdrawal

Local power



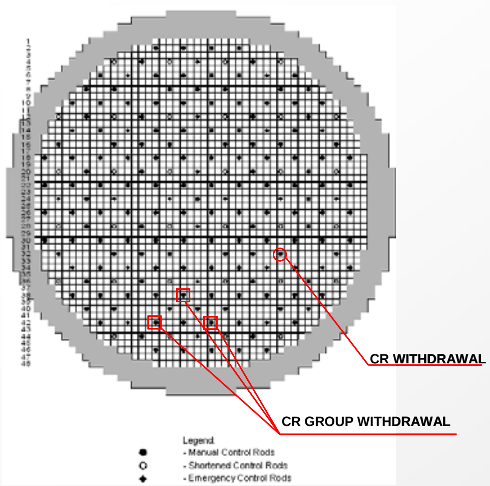
RELAP5-3D© CR Bank Withdrawal

Clad Temperature for affected zone



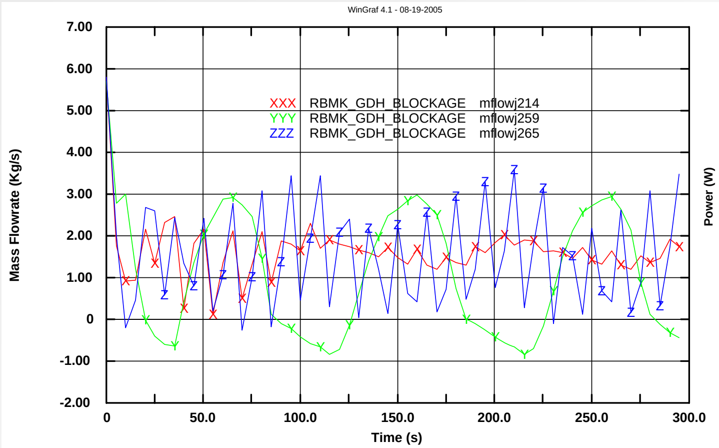
RELAP5-3D© CR Withdrawal

Total power



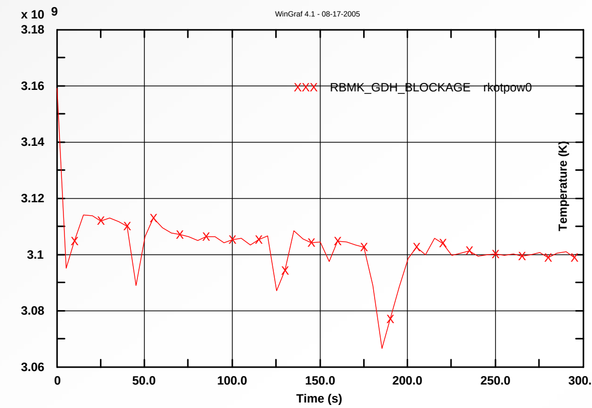
- CR system (CPS) operating at low pressure → CR / CR bank withdrawal at 0.4 m/s
- CR Bank withdrawal generated scram signal (Reactor Power 106% of Nominal Power)

Sample Results 2/3



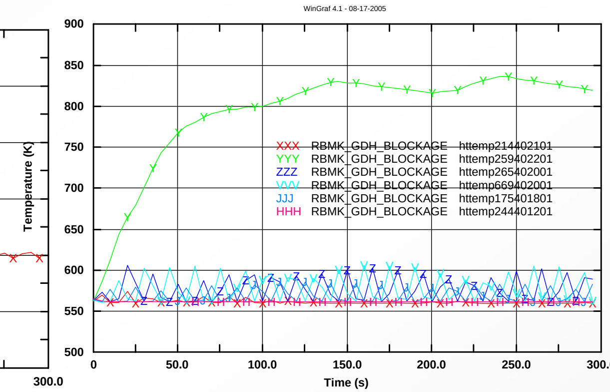
RELAP5-3D© GDH Blockage

Flow oscillations in blocked FC



RELAP5-3D© GDH Blockage

Total Reactor Power

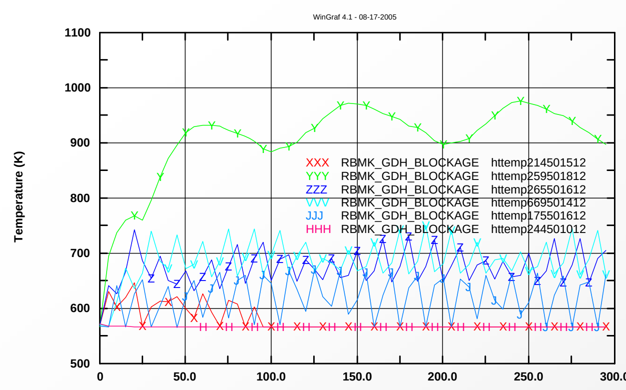


RELAP5-3D© GDH Blockage

Pressure Tubes temperature in affected FCs

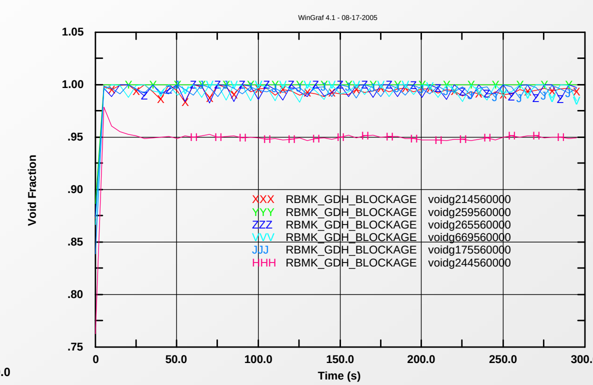
Time trend of the main events:

- **0.0 sec.** – onset of the GDH Blockage; coolant flowrate by the ECCS by-pass line
- **5.0 secs.** – onset of mass flow oscillations in the affected FCs
- **140 secs.** – Pressure tube reaches maximum temperature



RELAP5-3D© GDH Blockage

Clad temperatures in hot-FC

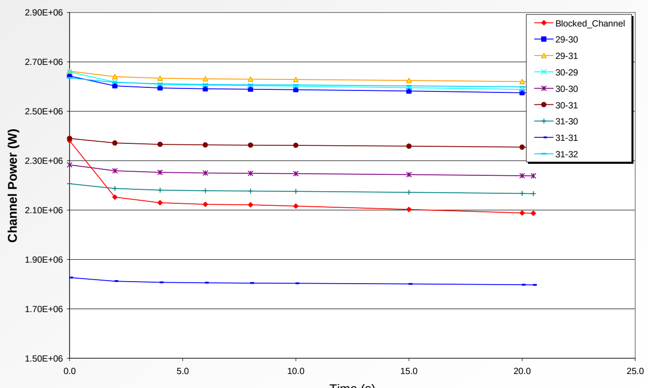


RELAP5-3D© GDH Blockage

Void fraction in affected FCs

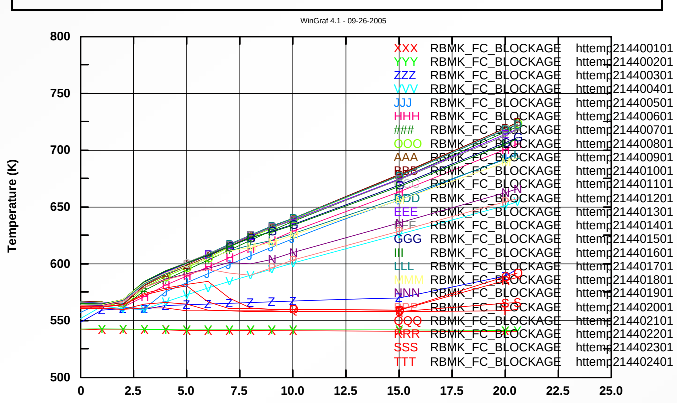
Sample Results 3/3

- Fuel Channel blockage → <u>reference transient</u> for the TACIS Project → demonstration that Pressure Tube Rupture does not propagate → what happens to FC power?



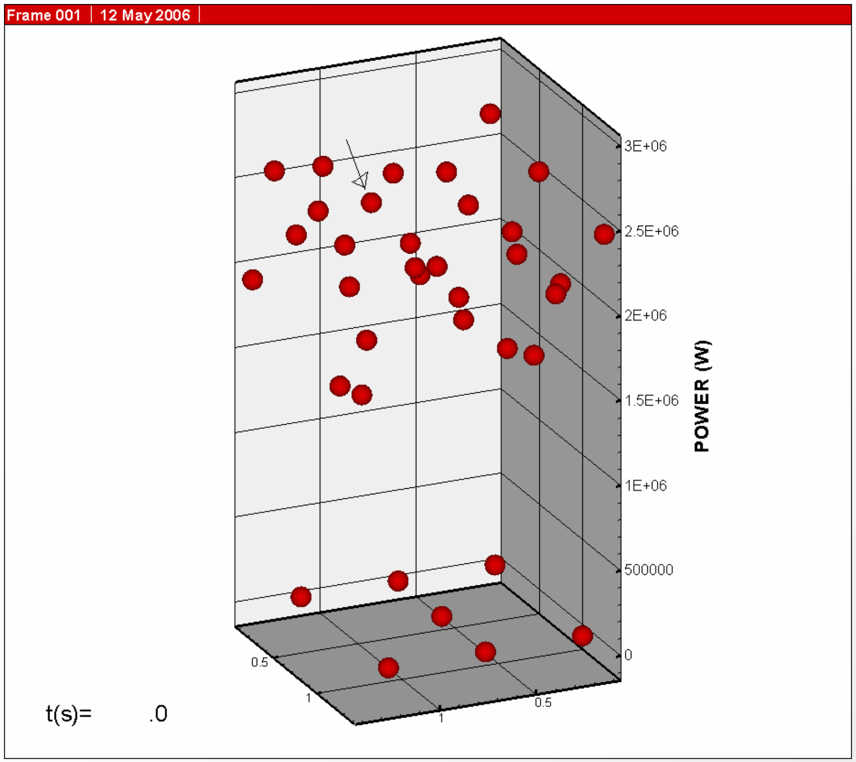
RELAP5-3D© FC Blockage

Power in blocked FC and neighbor FCs



RELAP5-3D© FC Blockage

Pressure Tube temp. in blocked FC



RELAP5-3D© FC Blockage

Power in blocked FC and neighbor FCs

Conclusions

- A detailed **TH RBMK NPP nodalization** was developed
- **RELAP5-3D©** demonstrated capabilities in reproducing all TH phenomena of RBMK
- **3D NK model** was able to reproduce all reactor core peculiarities → good agreement with in-core plant data
- **RELAP5-3D© (NESTLE) - HELIOS** constitutes an **independent and valid alternative** to Russian system codes KORSAR-BARS-UNK (comparison executed)
- Future works in the framework of a PhD thesis: reproduction of transients at low power (e.g., Chernobyl accident)