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Results of experimental and numerical studies of light gas mixing processes for NNP accident management tasks within ERCOSAM-SAMARA projects

M.A. Kamnev, A.M. Khizbullin, O.V. Tyurikov,
E.P. Potekhin, M.A. Antonenkov
JSC "Afrikantov OKBM",
Nizhny Novgorod, Russia

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ERCOSAM – SAMARA Projects

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ROSATOM

EU-Russian cooperation

EURATOM

The State contract

Containment thermal-hydraulics of current and future LWRs for severe accident management - ERCOSAM-SAMARA

Agreement

SAMARA:
IBRAE RAN (Moscow)– coordinator
SSC RF-IPPE (Obninsk)
+ JSC "Afrikantov OKBM" (N.Novgorod)

Coordination of ERCOSAM and SAMARA Projects Project Coordination Agreement

ERCOSAM
PSI (Switzerland) – coordinator,
IRSN (France),
CEA (France),
KIT (Germany),
NRG (The Netherlands),
AECL (Canada)
+ ***FZJ*** (Germany),
+ ***NRC*** (USA)

ERCOSAM-SAMARA objectives

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Goal&Activities

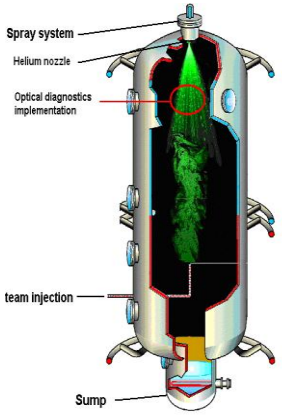
Creation of an experimental database on the physical phenomena occurring in the containment of light water reactors during postulated accident sequences involving core damage and demonstrate the maturity of the main computer programs developed for containment thermal-hydraulic analysis

Objectives

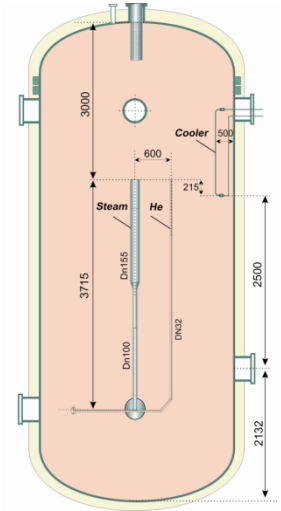
- to establish, for a severe accident sequence chosen from existing plant calculations and representative the strength of hydrogen stratification that can be established into the containment
- to determine whether this stratification, once established, can be broken down by the operation of SAM devices: sprays, coolers and PARs

Testing of containment thermal-hydraulics response

- 5 facilities (16 tests)
- one scenario of tests
- initial and boundary conditions
- 3 Severe Accident Management systems (SAMs); sprays, coolers and Recombiners
- Scaling factor
- Effect of Complexity of the Geometry



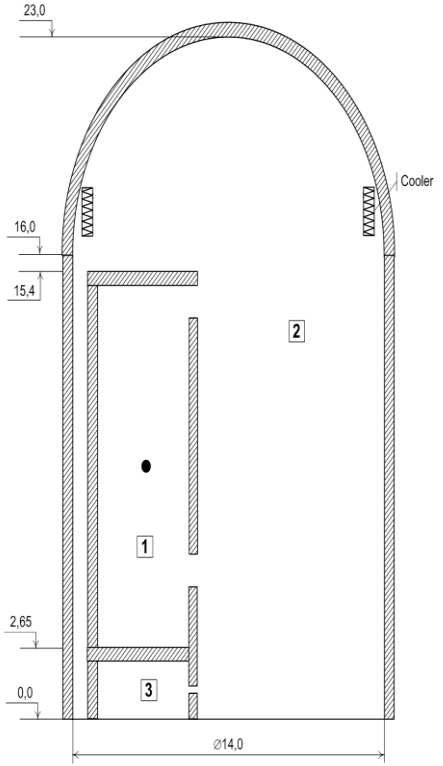
3 tests TOSQAN (FR), 7м3



2 tests SPOT (RU), 59m3

4 tests MISTRA (FR), 100м3

5 tests PANDA (CH), 2x90 м3



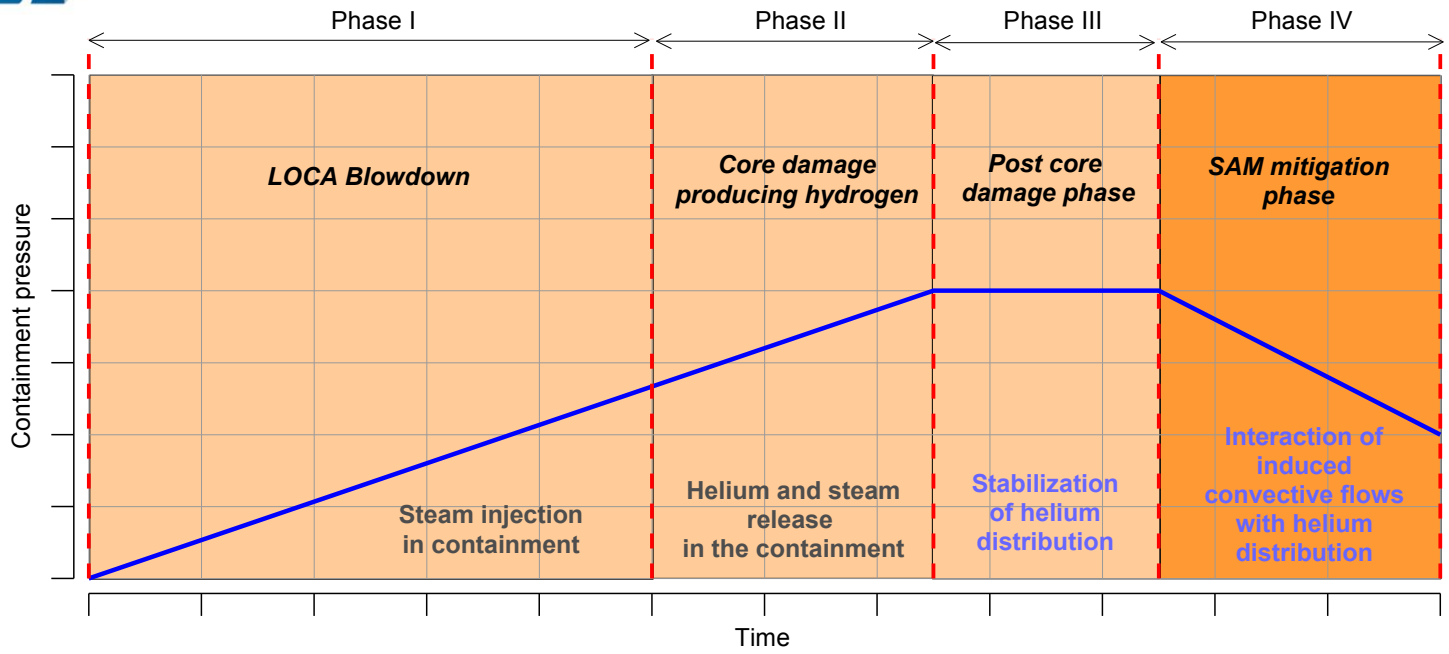
Code benchmarking using the concept "nearly prototypical scale" facility HYMIX (RU), 3181м^3

Analytical program

Organization			PSI	IRSN	CEA	NRG	KIT	AECL	JUELICH	IBRAE RAN	SSC RF-IPPE	JSC "Afrikantov OKBM"	USNRC
			GOTHIC/ FLUENT	ASTEC TONUS	TONUS	FLUENT-6 CFD	GASFLOW	GOTHIC/ FLUENT	[a]CFX-13 [b]COCOSYS	SOCRAT (plant calc.) OpenFOAM/FLUENT	KUPOL	KUPOL - MT	FLUENT
TOSQAN	T1	Spray		PL, PO		PT,PO	PO	PO (Fluent)	-	PT, PO	PO	PO	PO
	T2	Spray	PT,PO	PL, PO		PT,PO	PO	PO(Fluent)	-	PO	PO		PT, PO
	T3	Spray	PT,PO	PL, PO		PO	PO	PO(Fluent)	-	PO	PO		
MISTRA	M1	Spray				PO	PO		-	PO	PT, PO		
	M2	Cooler					PO		[a]PT, [a]PO	PT, PO	PT, PO	PT, PO	
	M3	PAR			PL, PO	PO	PO		[a]PO	PT, PO	PO	PT, PO	
	M4	2 PARs			PL, PO		PO		[a]PT, [a]PO	PO	PO	PO	
PANDA	P1	Spray	PL, PT, PO	PO		PT,PO	PL, PO	PL, PT, PO	-	PT, PO	PT, PO		
	P2	Spray	PL, PT, PO	PO		PO	PO	PL, PT, PO	-	PO	PT, PO		PT, PO
	P3	Cooler	PL, PT, PO			PO	PO	PL, PT, PO	[b]PT, [b]PO	PT, PO	PT, PO	PO	PO
	P4	PAR	PL, PT, PO	PO		PT,PO	PO		[b]PT, [b]PO, [a]PO	PT, PO	PO	PO	PO
	P5	Cooler	PL, PT, PO				PL, PO	PL, PT, PO	[b]PT, [b]PO	PO	PT, PO	PT, PO	
HYMIX	K1	Spray [2]		PT/PO					-	PT	PT, PO		
	K2	Cooler [3]	PT				PT, PO	PT[6]	[b]PT, [b]PO	PT	PT, PO		
SPOT	S1	Cooler [4]	PO				PT, PO		[b]PT, [b]PO	PT, PO	PO	PL, PT, PO	
	S2	Cooler [5]					PT, PO		[b]PT, [b]PO	PT, PO	PO	PL, PT, PO	

PL: planning analysis, PT: pre-test analysis, PO: Post-test analysis

Original test scenario

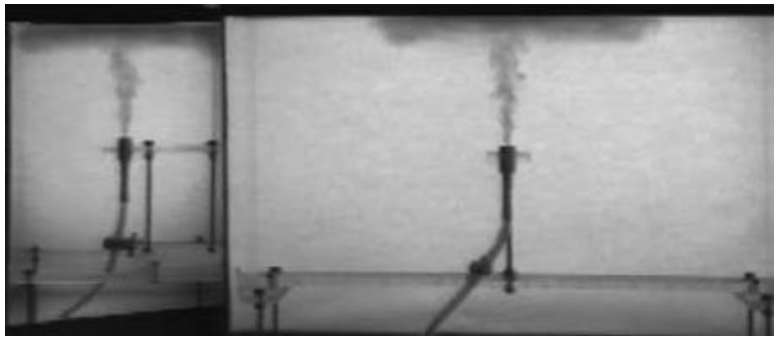


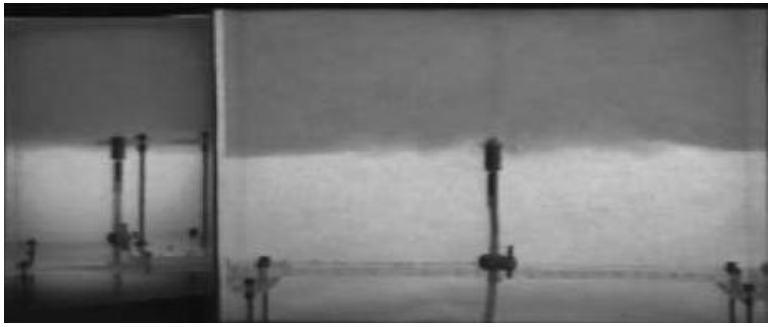
The following target conditions should be obtained:

- approximately homogeneous steam&air distribution inside the vessel at the end of the Phase I with steam molar fraction 60 % above the injection point;
- pressure in the containment at the end of the helium injection phase is 2.5 bar;
- He =10% (vol.) above the injection point at the end of the He injection.

Scaling down & stratification criteria

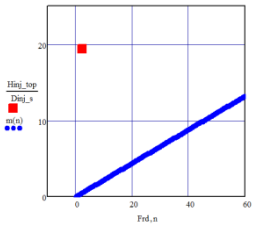
	phase 1_steam, g/s	phase 2_He, g/s	volume, m3
GC	8000	61	20000
SPOT	24	0,18*	59





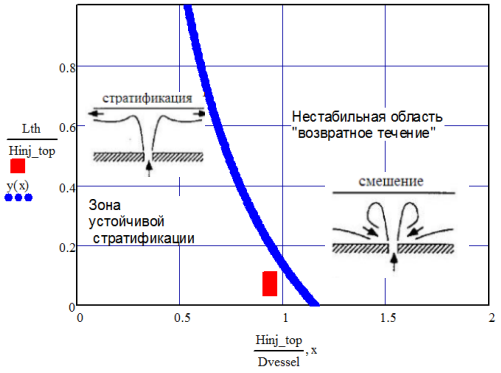
Jirka criterion determine the conditions of stratification in the propagation of lower density jet in an unlimited vertical extent [1]

$$\frac{H_{инж}}{D_{инж}} > 0.22 Fr^{1/2}$$



Hunt criterion determine the conditions of stratification of buoyant jet subject with consideration of vessel walls [2]

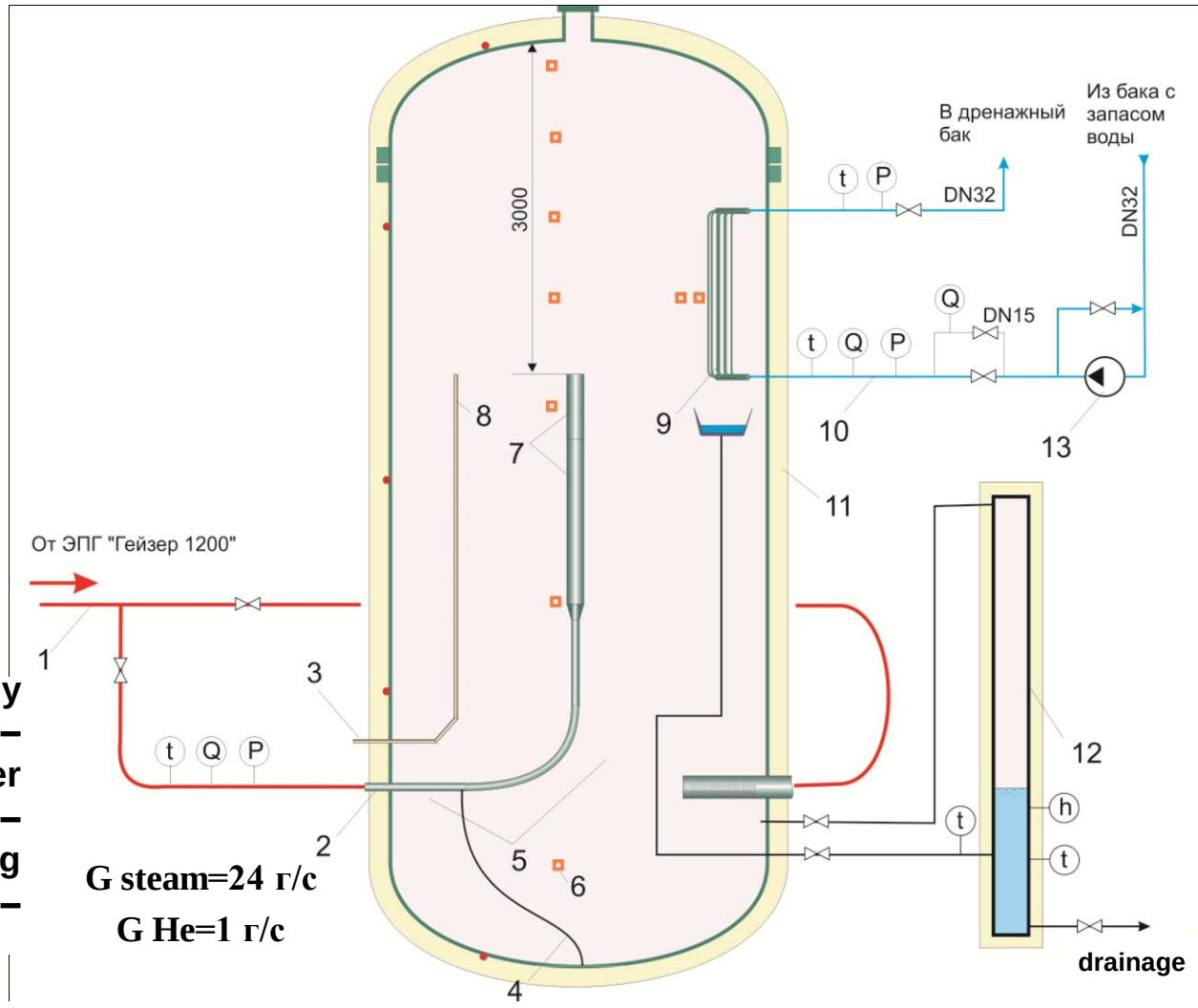
$$\left(\frac{L_{струи}}{H_{инж}}\right)_{крит} = \frac{1}{G}\left[\frac{1}{3\cdot\alpha^{1/2}}\left(\frac{2\cdot H_{инж}}{D_{ЗО}}\right)^{-1} - 1\right]$$



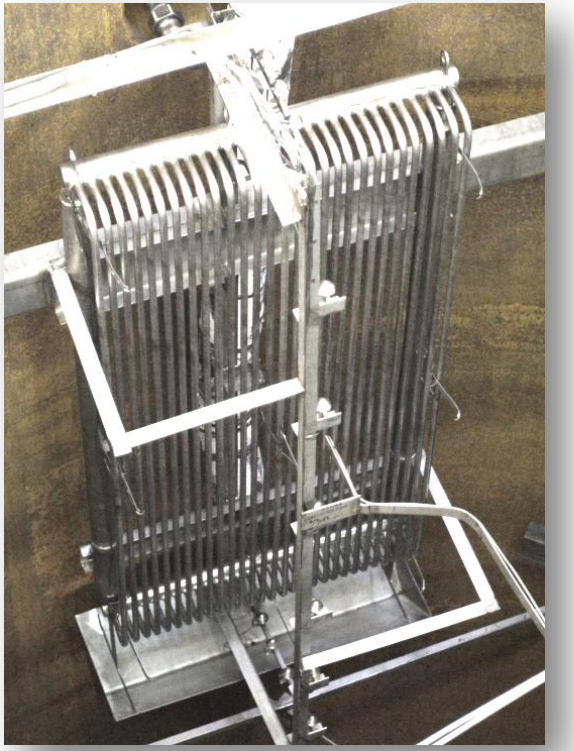
In view of stratification criteria implementation, steam and helium injection diameter and height were determined

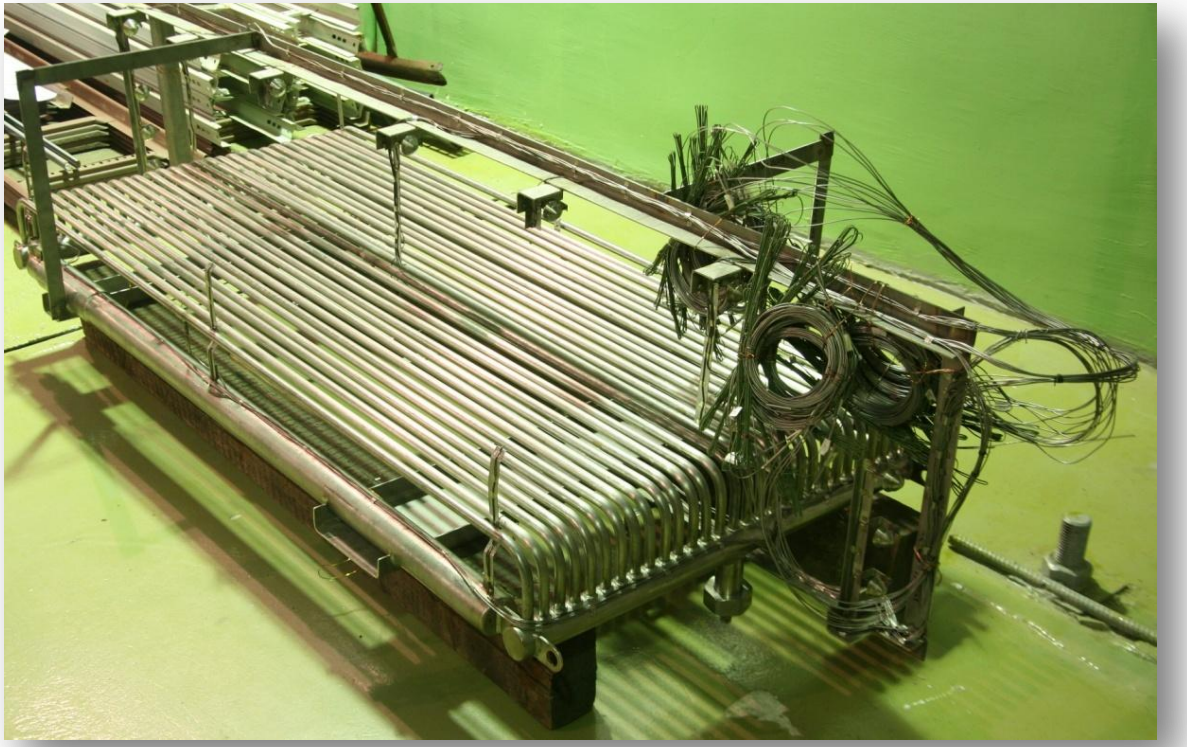
Scheme of the SPOT updated

1 – heating circuit; 2 – steam supply pipeline; 3 – helium supply pipeline; 4 – drainage pipeline; 5 – thermal transducer racks; 6 – sampling points; 7,8 – removable inserts; 9 – cooler; 10 – cooling circuit; 11 – containment model; 12 – condensate tank; 13 –pump



Cooler

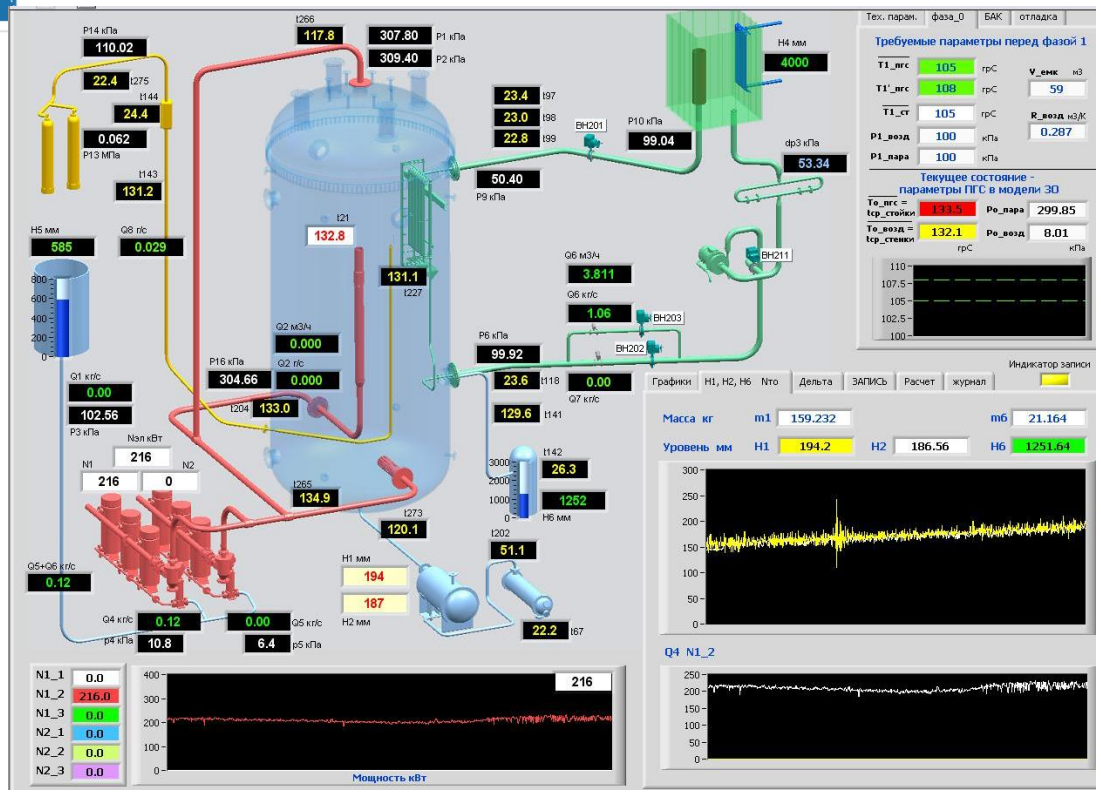




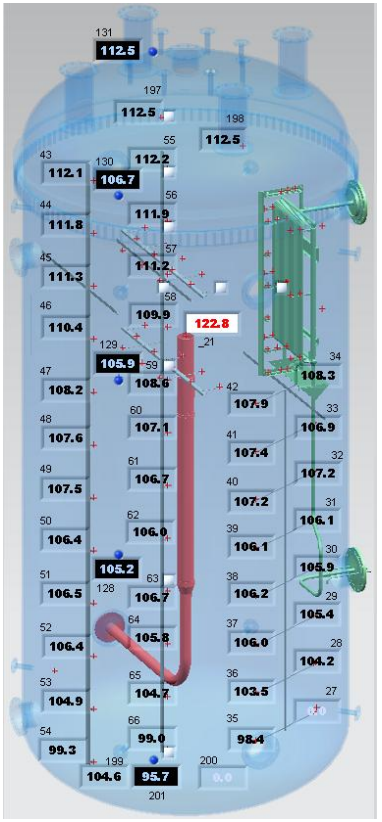
Cooler capacity of SPOT test facility is determined based on maximum capacity of air coolers for CANDU 6 NPP heat removal system (containment volume is 50,000 m^3), which is 0.74 kW/m^3. For containment model volume of 59 m^3, SPOT cooler capacity is 44 kW.

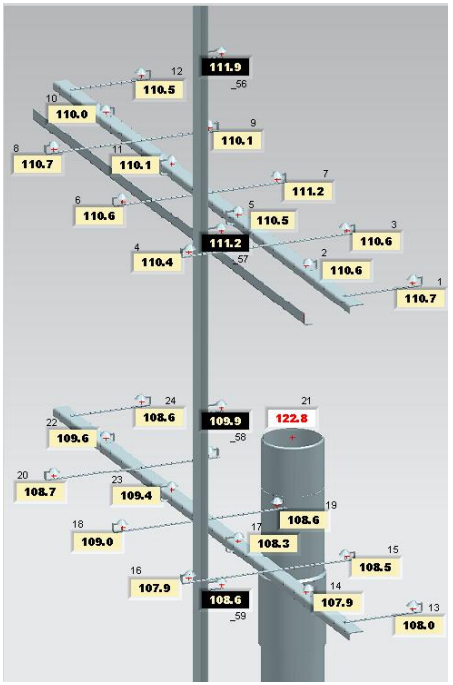
Information and measurement system

Operating window



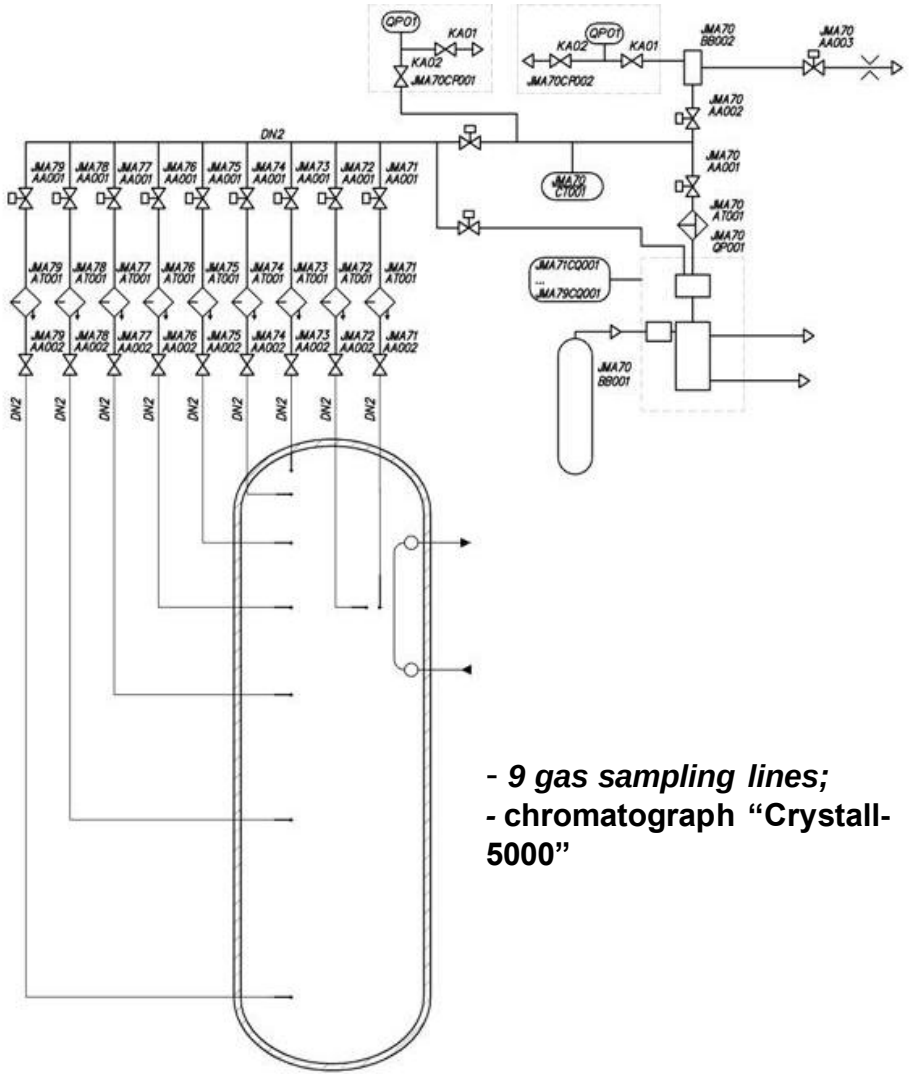
thermocouples location in the vessel

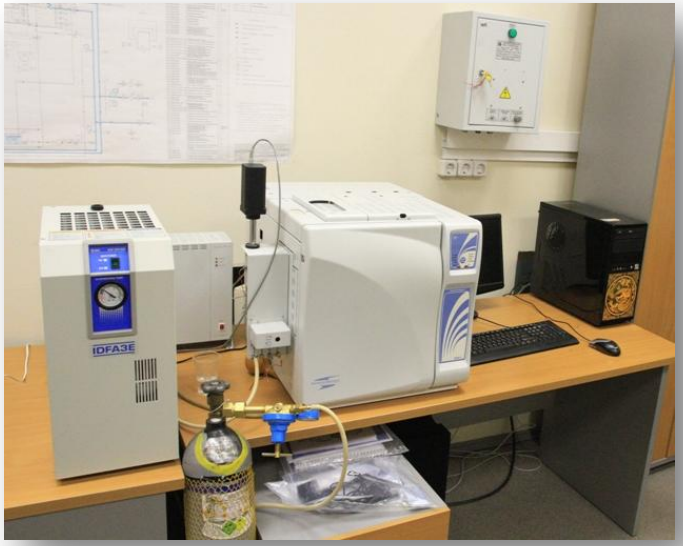


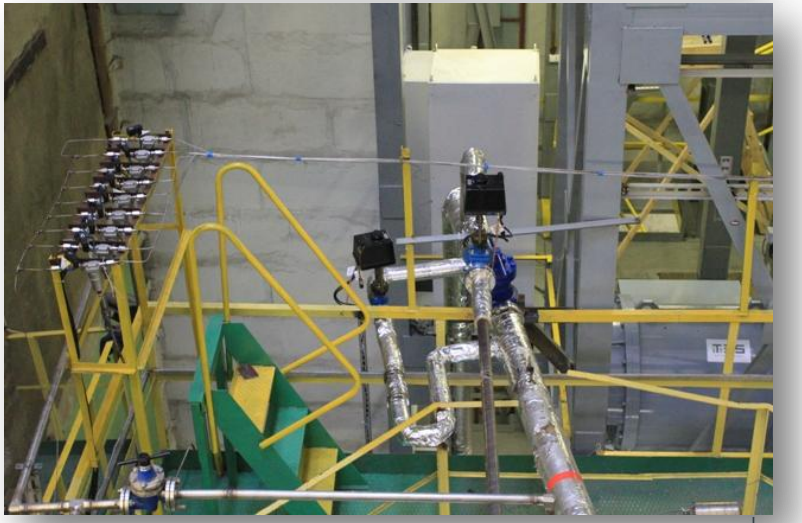


Thermocouples	***95***
Type	***K***
Measuring range	***0-180 °C***

Gas concentration measurement system







- *9 gas sampling lines;*
- **chromatograph "Crystall-5000"**

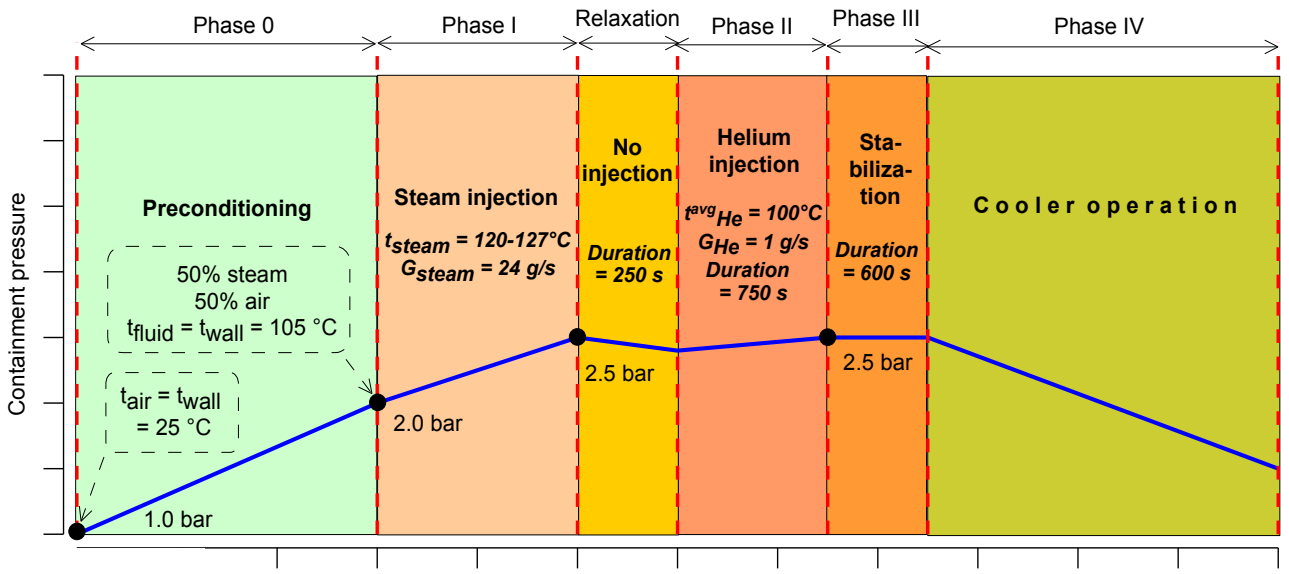
S1 test procedure

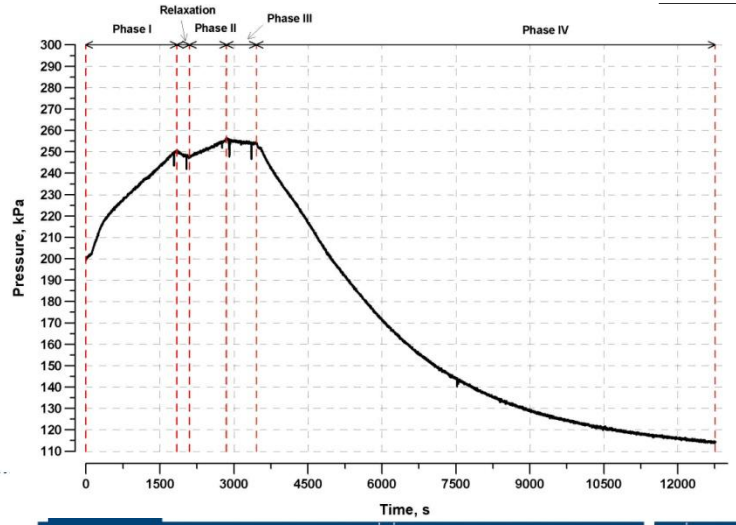
Phase 0 – preconditioning phase;

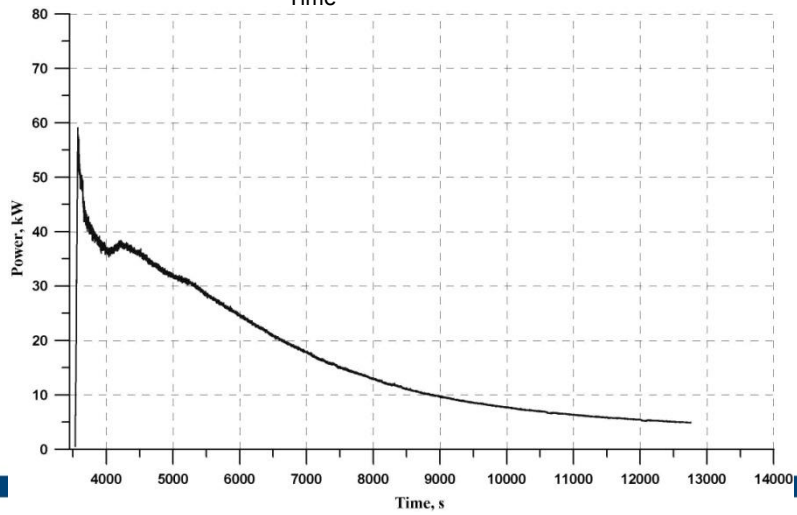
Phase I –LOCA blowdown;

Phase II – He injection;

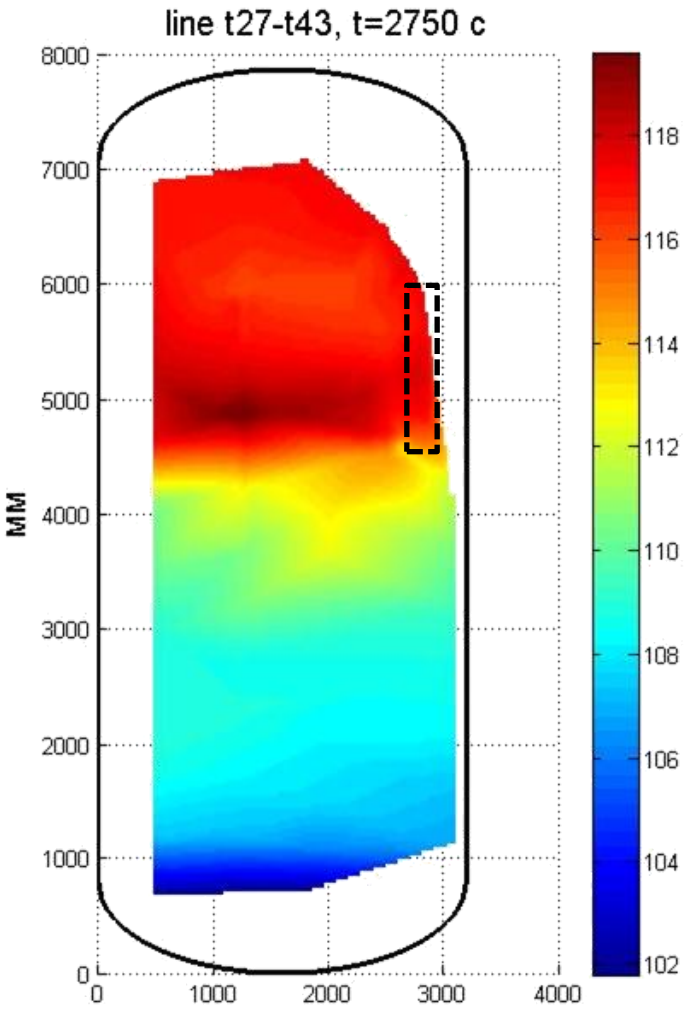
Phase IV – cooler activation



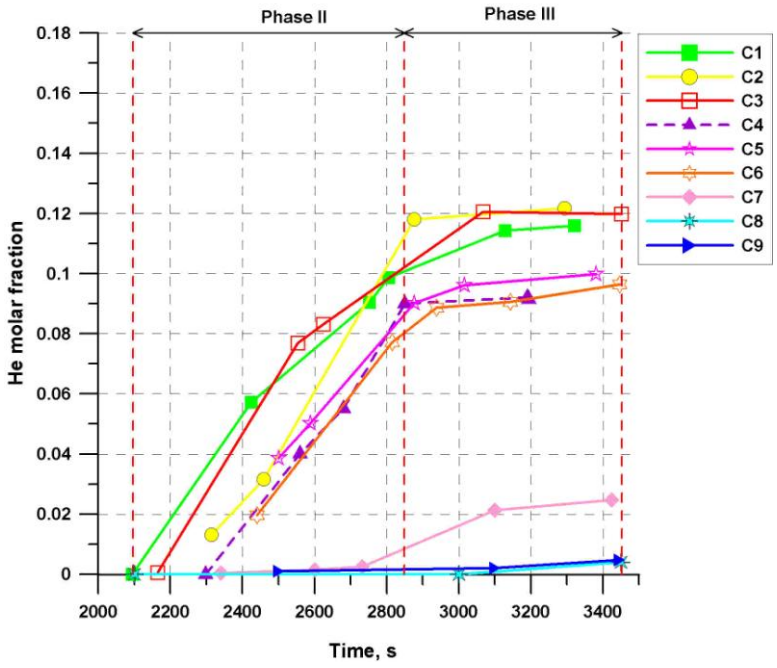


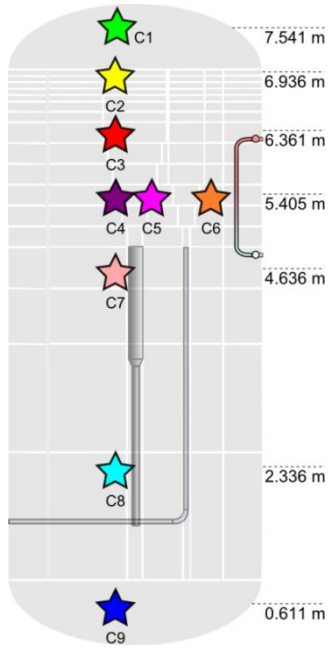


Condition before cooler activation



Temperature distribution before He injection





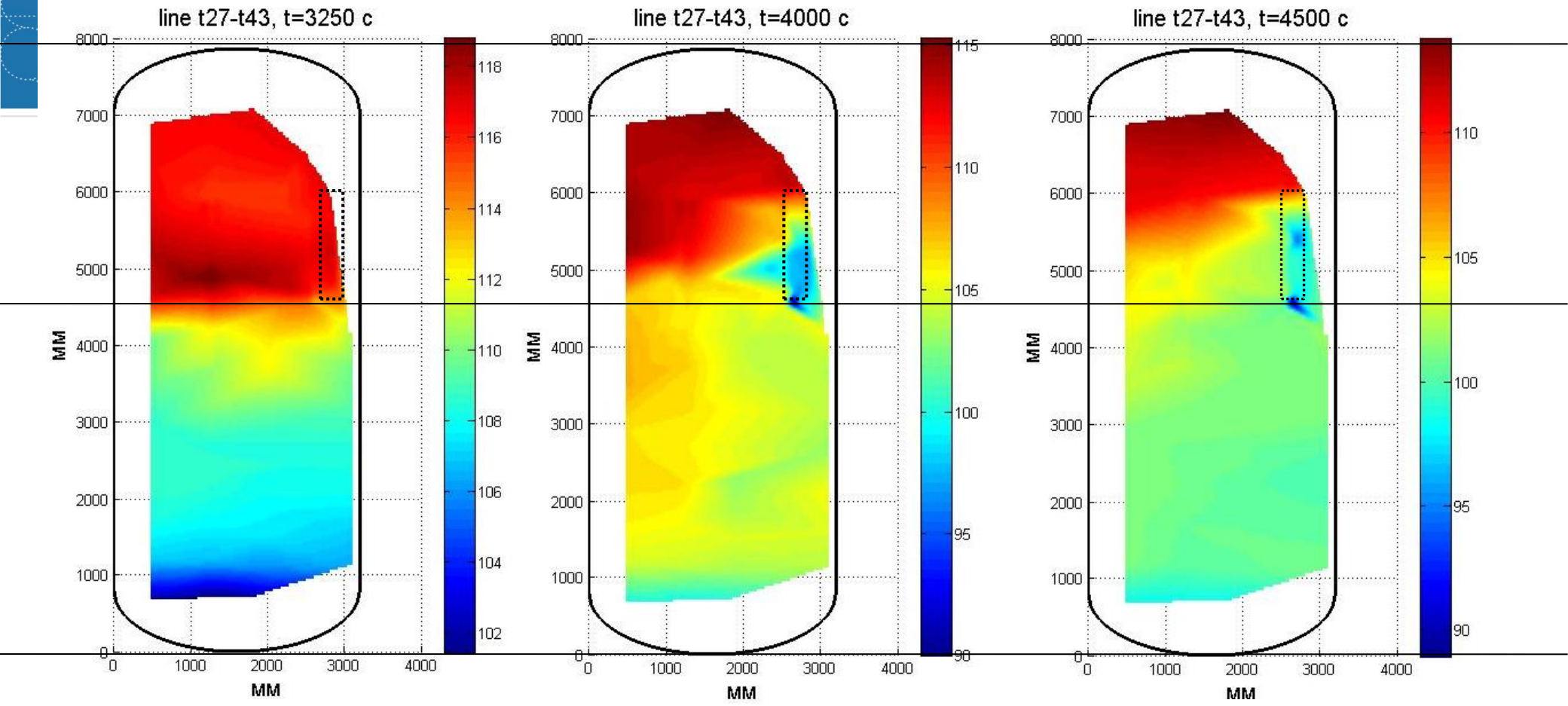
Before cooler activation the He stratified layer above the injection point is observed

10% -helium; 70% - steam; 20% - air

Below the injection point

50% - air and 50% - steam

S1: Phase IV – Temperature contour maps



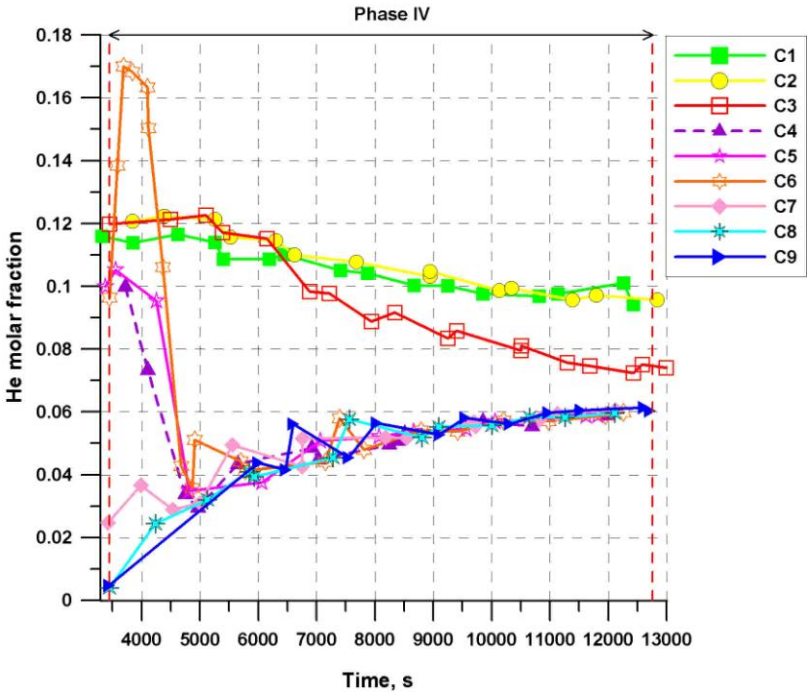
Temperature stratification above the injection points before Phase IV

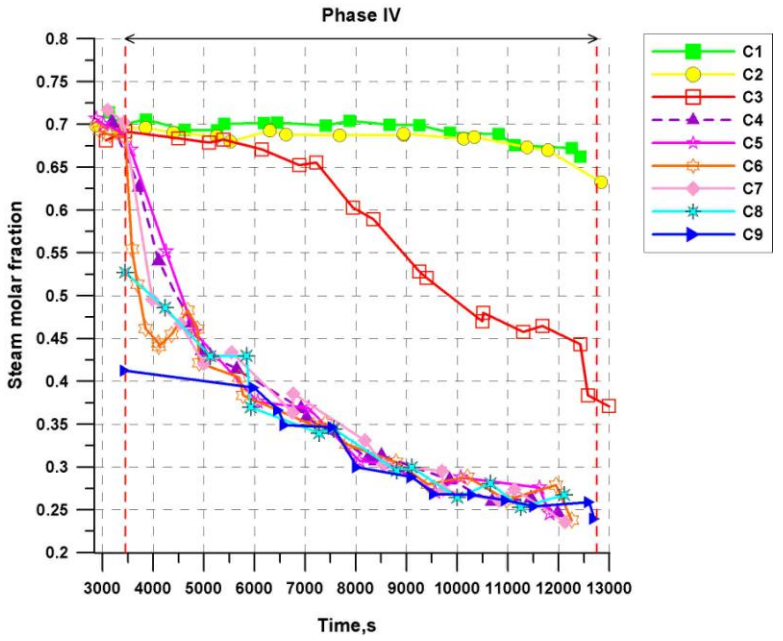
"cold" gas-steam mixture surrounding the cooler

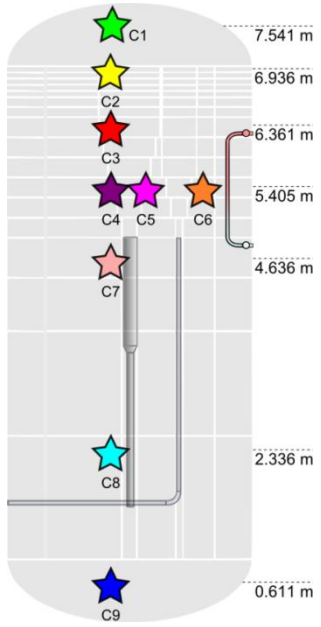
-Below the cooler and opposite it temperature becomes uniformly

- above the cooler the gas temperature remains constant

He and steam molar fraction at cooler activation (test S1)



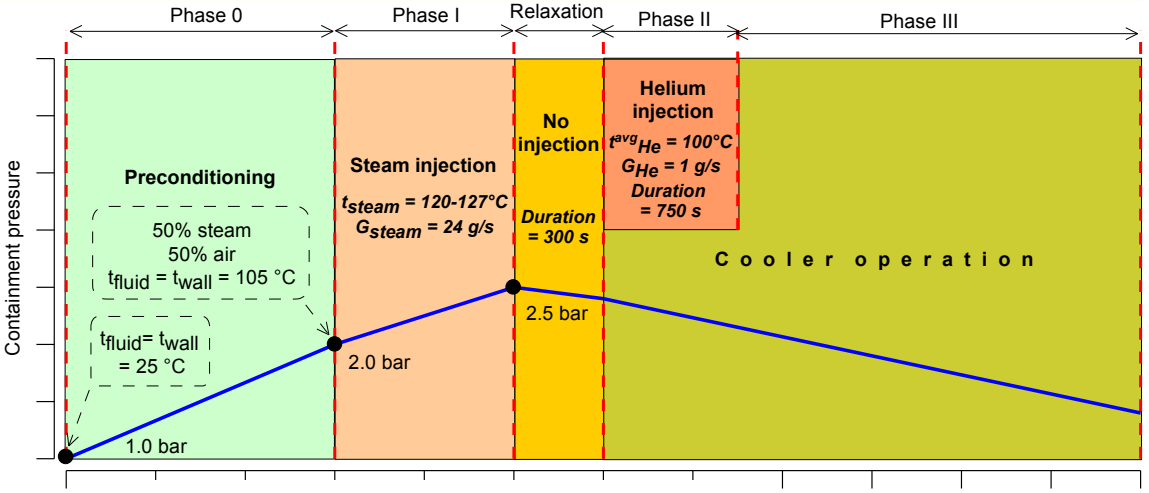


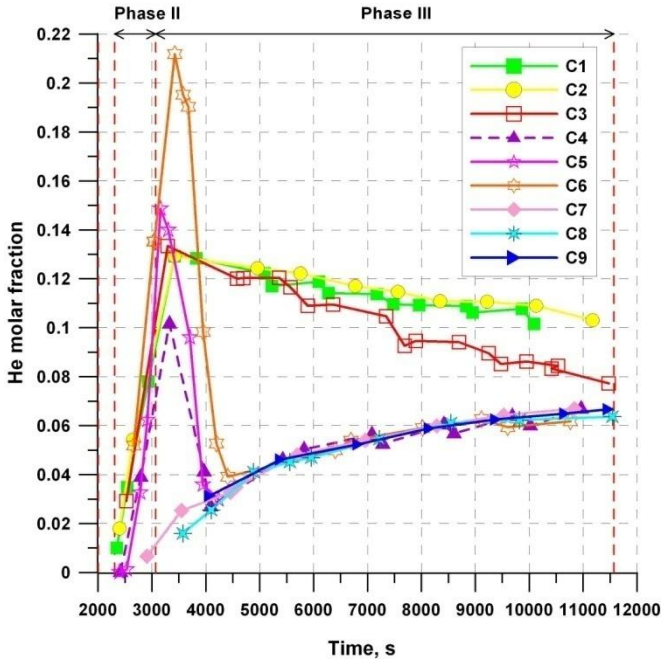


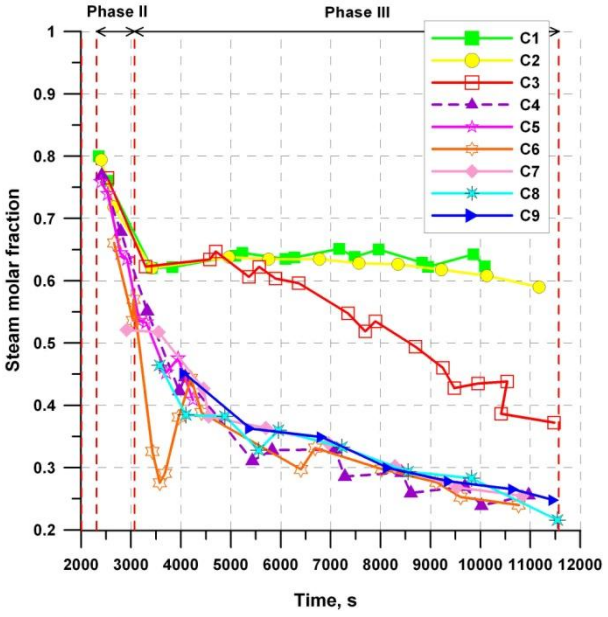
In Phase IV the stratified layer above the cooler is retained

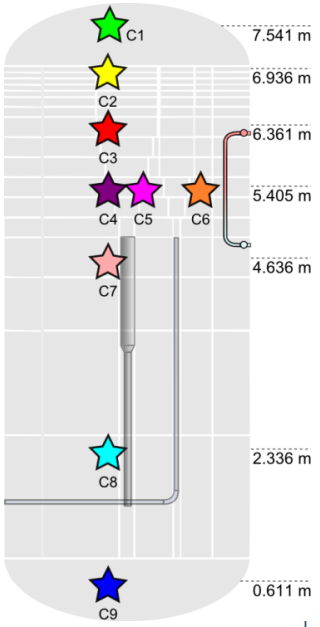
Test S2 & He and steam molar fraction at cooler activation

Test S2 is performed to estimate the cooler effect on helium distribution in vessel. The cooler is put into operation at the second phase together with helium supply to the vessel

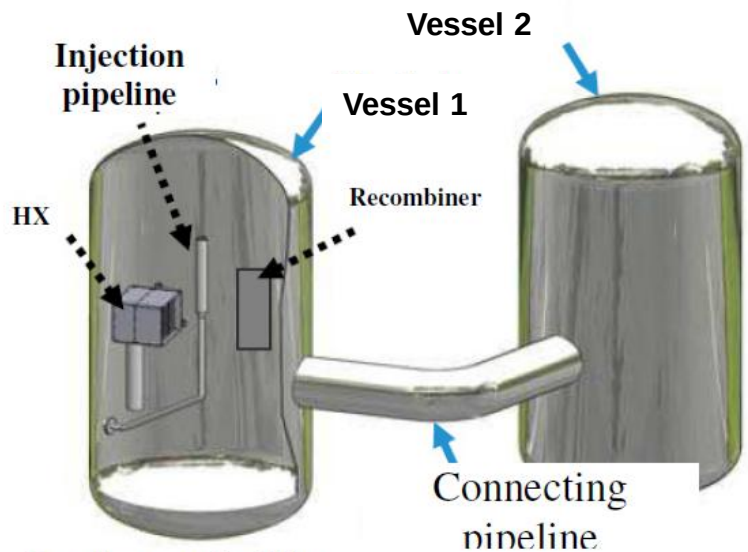








PANDA test facility and calculation model



Panda test facility

- Total free volume ~183 m^3
- Tank height ~8 m, diameter ~4 m

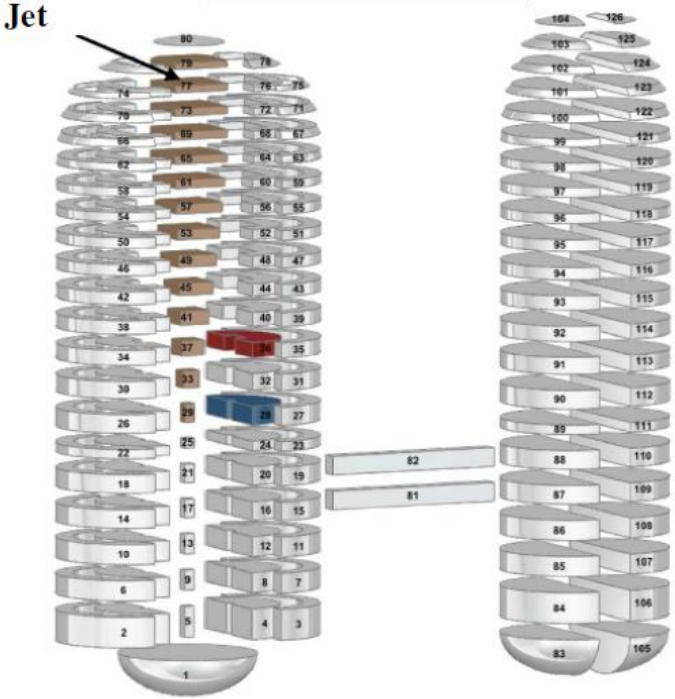
Recombiner

Height ~1 m, flow area ~00.6 m^2

N_{el}^{max} = 10 kW

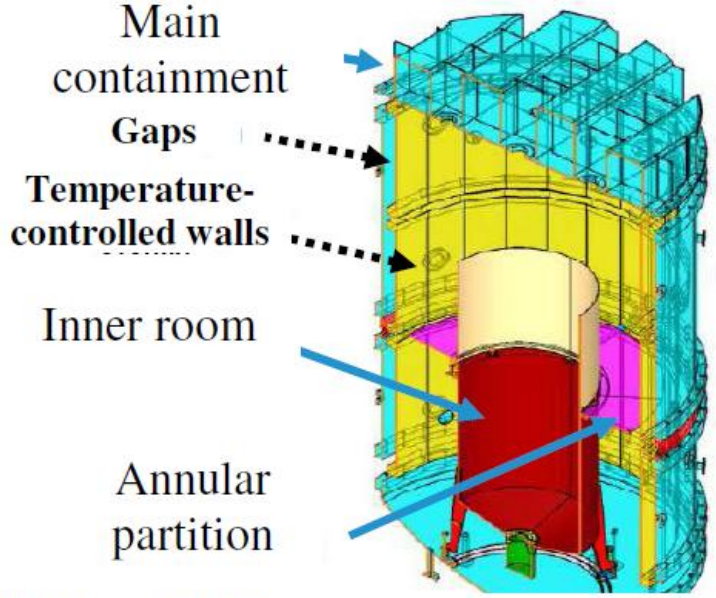
Heat exchanger

- U-tubes -224
- Tubing system ~12m^2



- 126 calculation elements
- 259 gas bonds
- 157 water bonds
- Steam and helium jet simulation
- Recombiner jet simulation

MISTRA test facility and calculation model



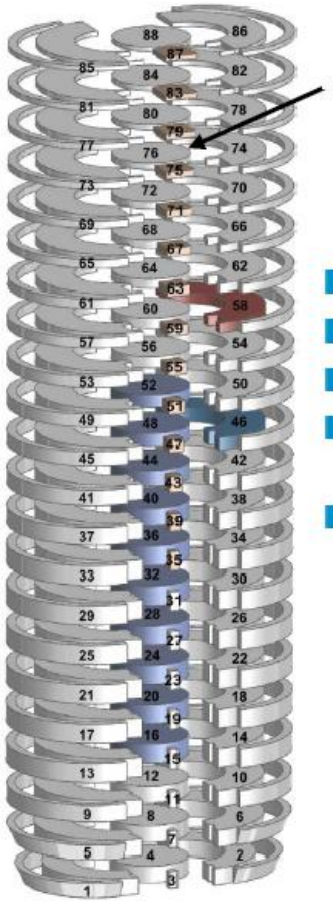
MISTRA test facility
- Free volume ~98 m^3
- Containment height ~7.5 m, diameter ~4.3 m

Recombiner

Height ~1 m, flow area ~0.035 m^2

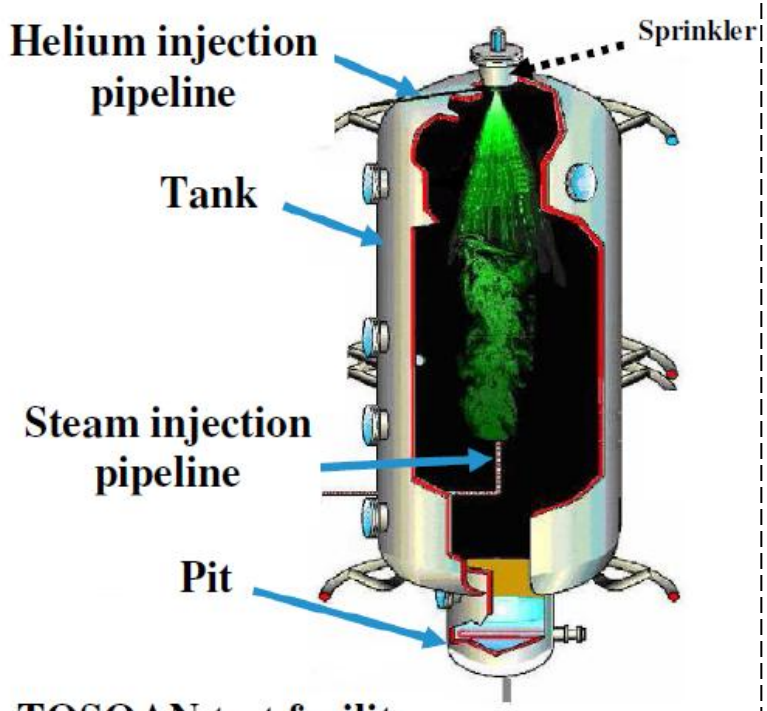
Heat exchanger
- Cooled wall
- Surface area ~22 m^2

Calculation model



- 95 calculation elements
- 132 gas bonds
- 87 water bonds
- Steam and helium jet simulation
- Recombiner jet simulation

TOSQAN test facility and calculation model



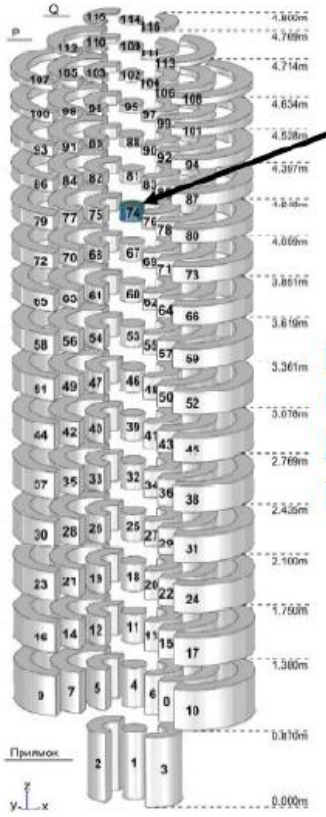
TOSQAN test facility

- Free volume ~7 m^3
- Containment height ~5 m, diameter ~1.5m

Sprinkler

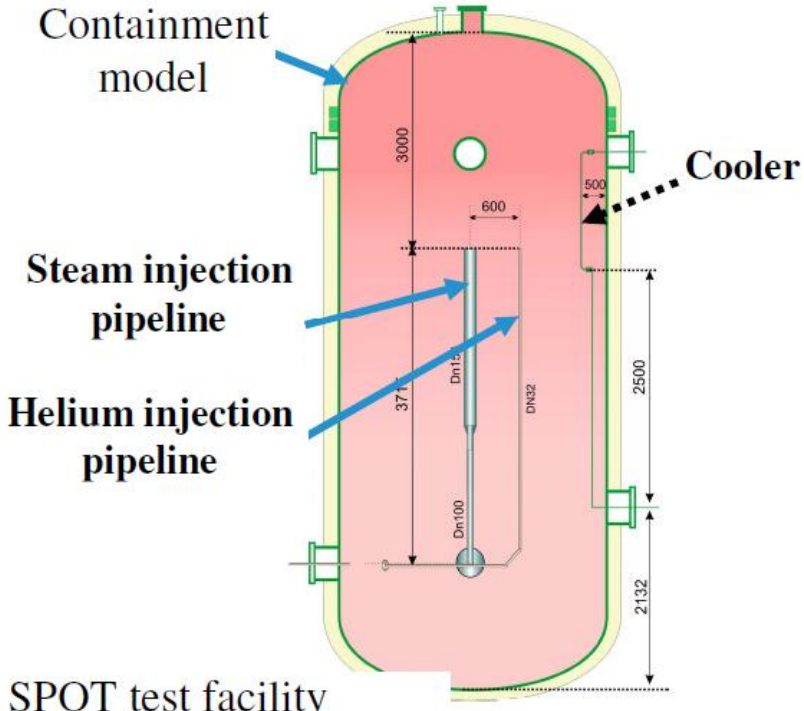
- Hollow torch cone

Calculation model



- 116 calculation elements
- 207 gas bonds
- 80 water bonds
- 24 water bonds for sprinkler jets

SPOT test facility and calculation model

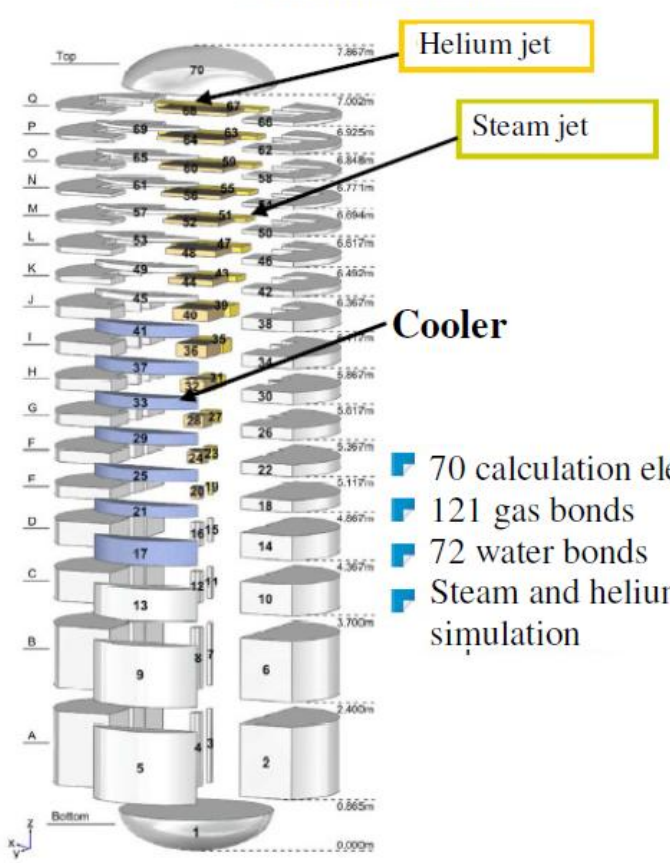


SPOT test facility

- Free volume ~7 m^3
- Containment height ~7.9 m, diameter ~3.2 m

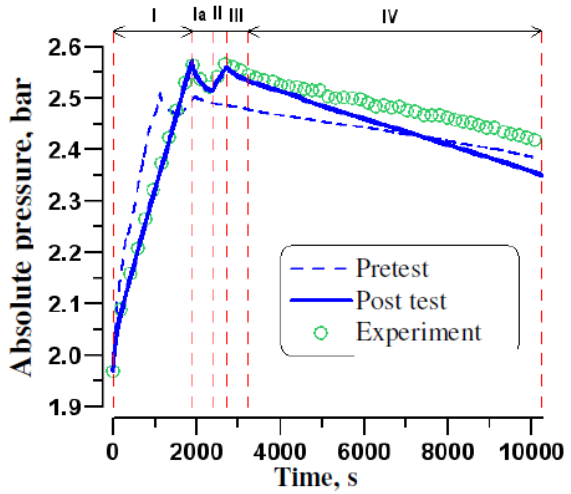
Heat exchanger

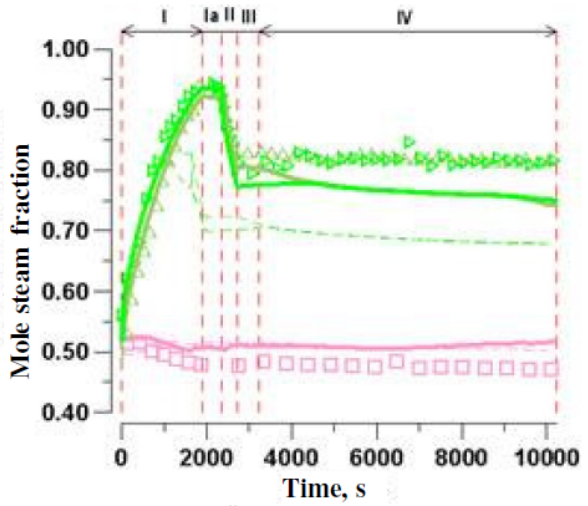
- Cooled wall
- Surface area ~22 m^2

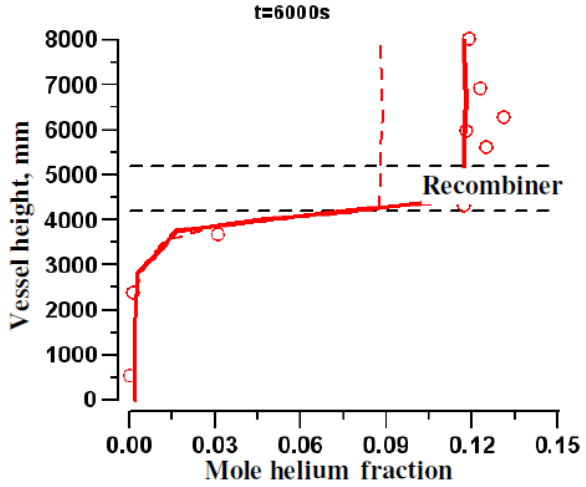


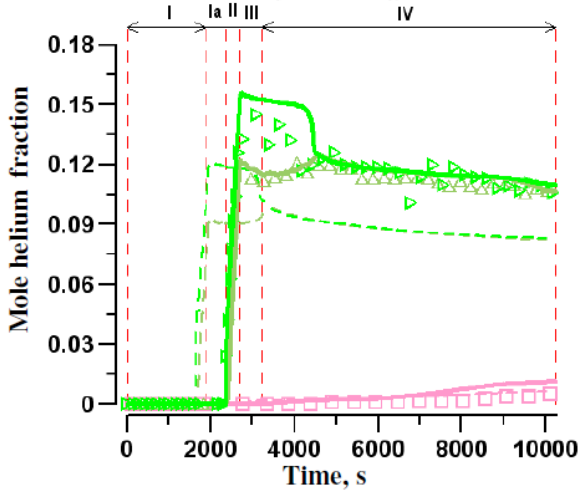
- 70 calculation elements
- 121 gas bonds
- 72 water bonds
- Steam and helium jet simulation

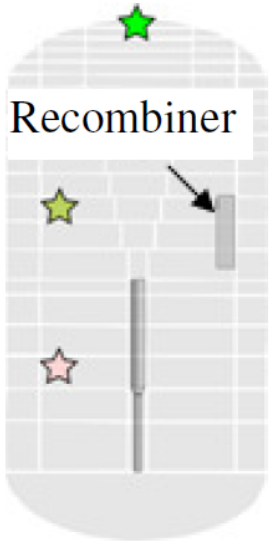
Calculation results for the experiment with recombiner at PANDA test facility







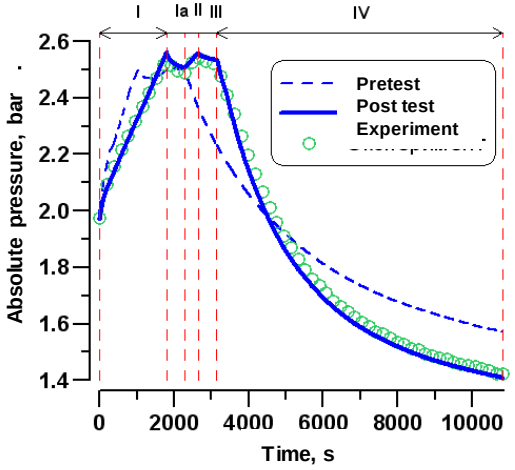


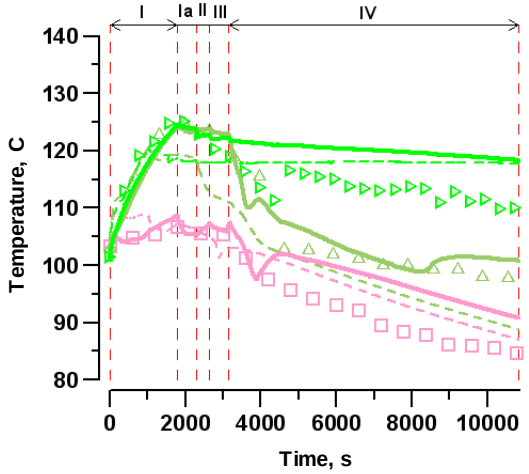


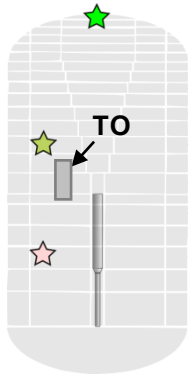
Max. deviations

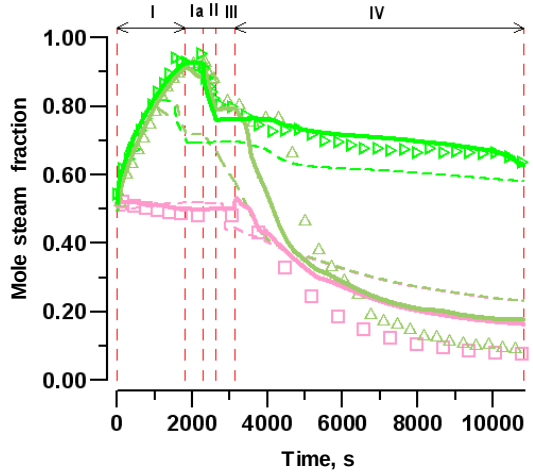
- **δP = 2 % (± 3,5…7 %)**
- **δT = 8 % (± 7…20 %)**
- **δn(He) = 5 % (16 %)**
- **δn(пар) = 10 % (16 %**

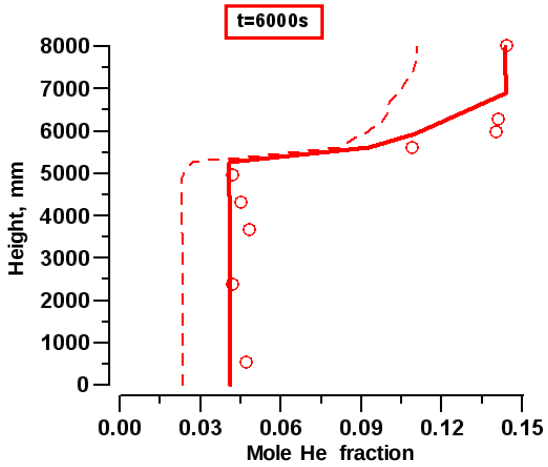
Calculation results for the experiment with cooler at PANDA

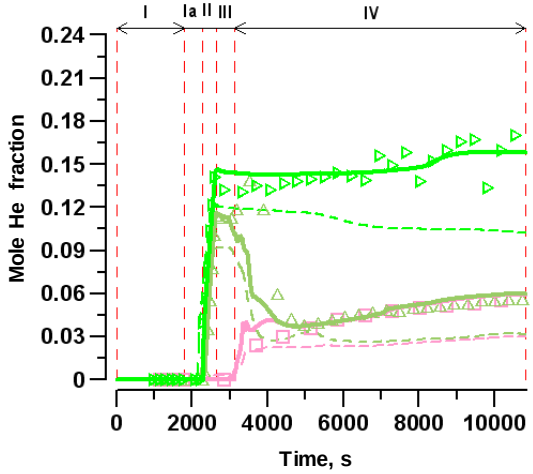








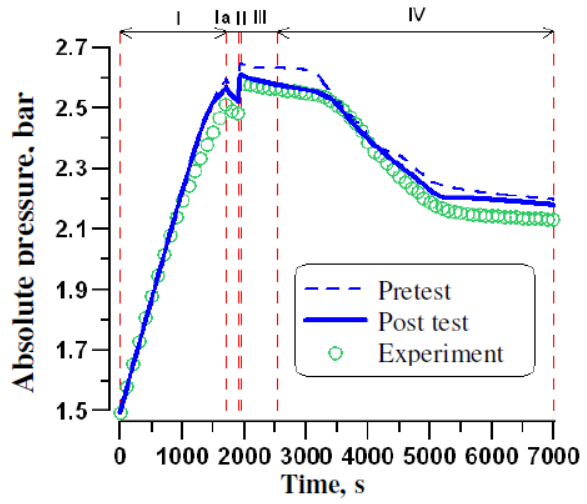


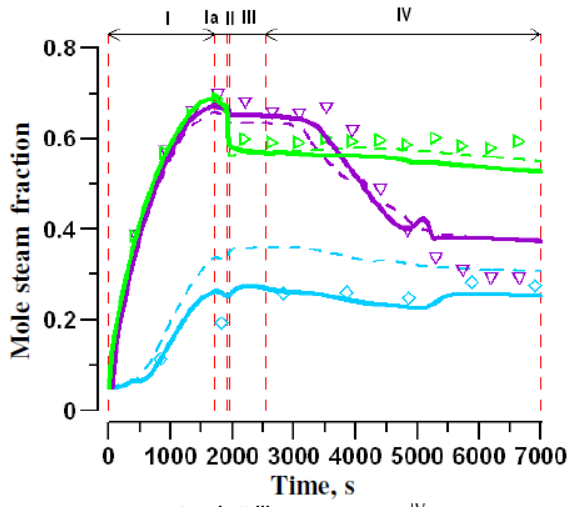


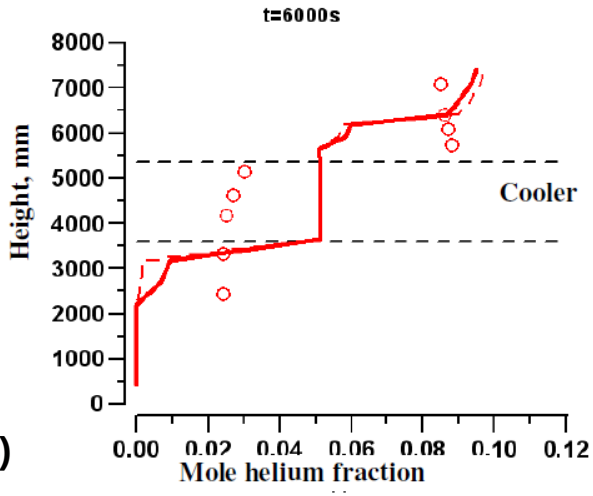
Max. deviations

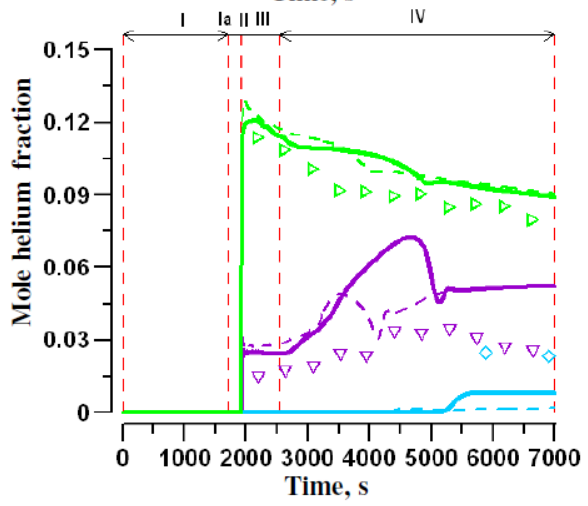
- δP = 4 % (± 3,5…7 %)
- δT = 11 % (± 20 %)
- δn(He) = 8 % (16 %)
- δn(пар) = 10 % (16 %)

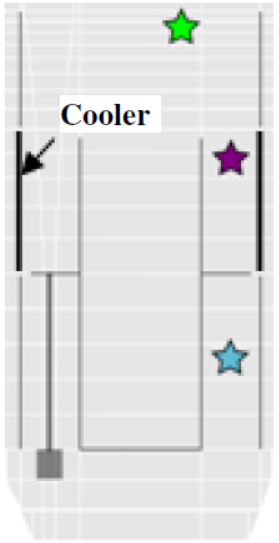
Calculation results for the experiment with cooler at MISTRA test facility







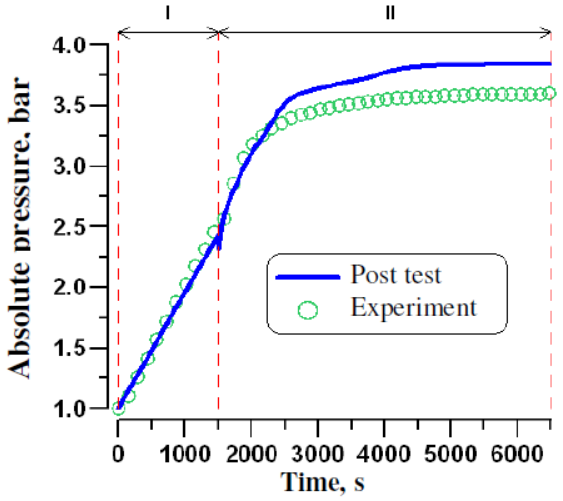


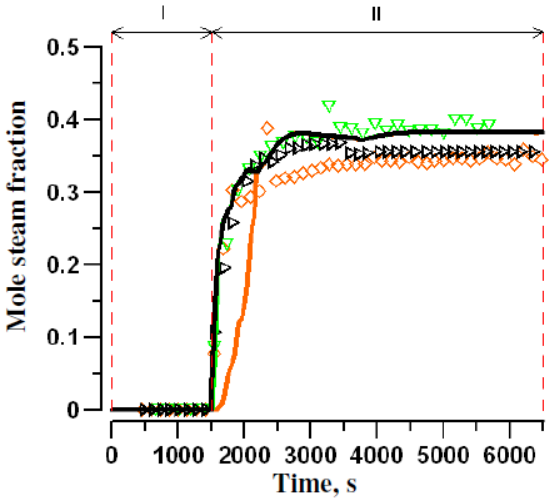


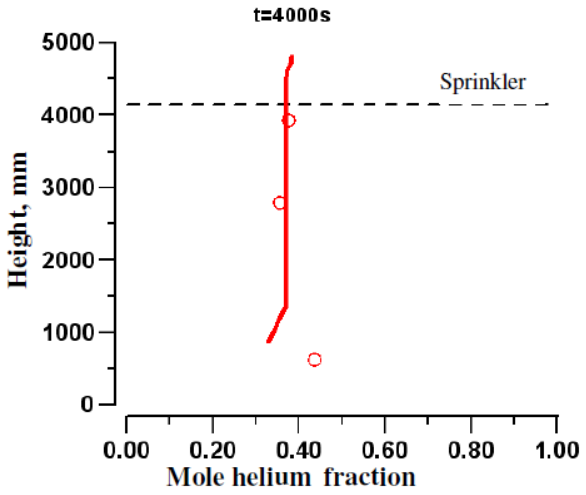
Max. deviations

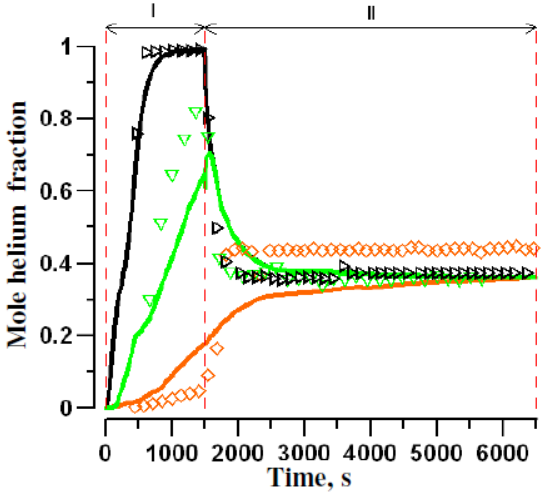
- **δP = 5 % (± 7…14 %)**
- **δT = 15 % (± 20 %)**
- **δn(He) = 3 % (16 %)**
- **δn(пар) = 15 % (16 %)**

Calculation results for the experiment with spray at TOSQAN





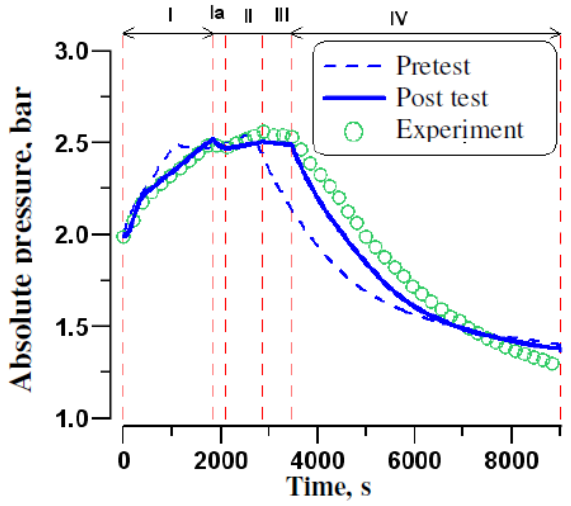


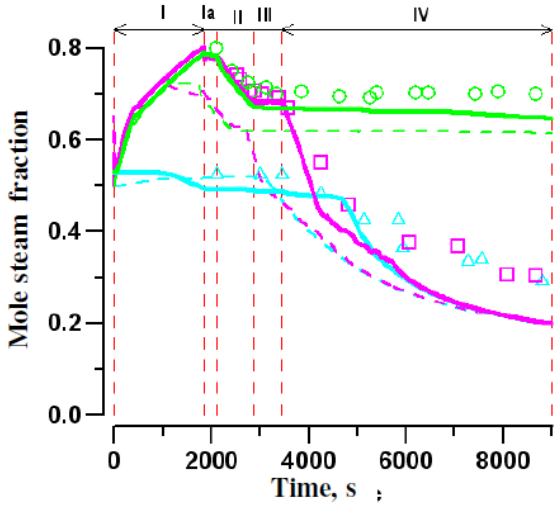


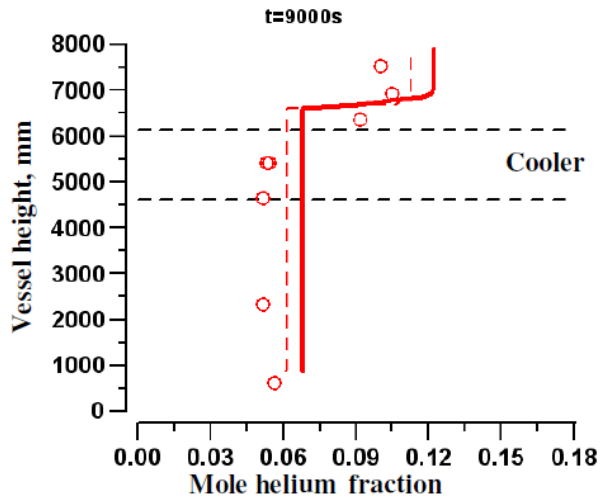
Max. deviations

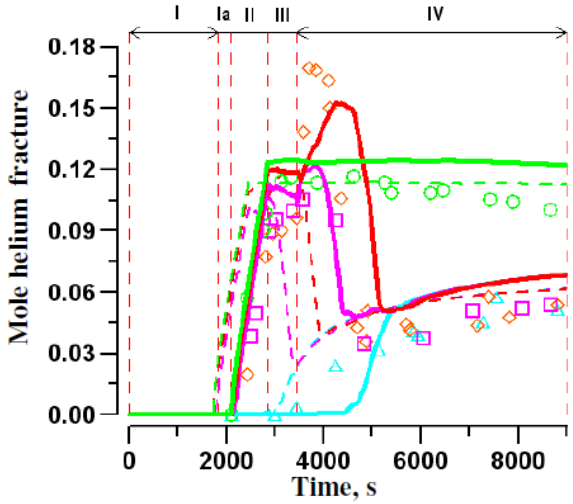
- **δP = 14 % (± 7…14 %)**
- **δT = 9 % (± 20 %)**
- **δn(He) = 15 % (16 %)**
- **δn(пар) = 25 % (16 %)**

Calculation results for the experiment with cooler at SPOT facility









Max. deviations

- **δP = 9 % (± 7…14 %)**
- **δT = 16 % (± 20 %)**
- **δn(He) = 4 % (16 %)**
- **δn(пар) = 10 % (16 %)**

Conclusions

1. Within ERCOSAM-SAMARA projects stratification of light gas and cooler operation effect on stratification were studied by experiment at SPOT test facility

2. According to the results of studies, stable stratification of steam-gas mixture through containment model height before cooler putting into operation was obtained. At that, cooler operation does hot ensure complete atmosphere homogenization through the entire height of containment model volume.

3. Numeric simulation of experiments at SPOT, PANDA, MISTRA, and TOSQAN was performed using KUPOL-MT code with lumped parameters. The results of numeric analysis show that HX and recombiner operation does not result in complete homogenization of atmosphere in the containment models; the sprinkler system ensures stratified layer destroying that is confirmed by the results of experiments.

4. The experiments within ERCOSAM-SAMARA project are the benchmarks and are important verification material, which can be used for verification of lumped parameter code (LP-code) and space codes on computational fluid dynamics (CFD-code).

5. It is necessary to perform the additional calculation and experimental studies aimed at elimination of high-concentration hydrogen generation in the containment volume. Investigation of joint recombiners and coolers operation can be one of the ways of further studies**.**

Thank you for attention!

References

- J. H. Lee, G.H. Jirka. “Stability and mixing of a vertical round buoyant jet in shallow water”, Energy Laboratory Report No. MIT-EL 74-014, 1974.
- G.R. Hunt, P. Cooper, P.F. Linden, “Thermal stratification produced by plumes and jets in enclosed spaces”, Building and Environment 36 (2001), 871-882.