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Wir schaffen Wissen – heute für morgen

Paul Scherrer Institute

Investigations of Gas stratification break-up in Containment for reactor safety issues

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Presented by Jon Birchley

Third EMUG Meeting
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Outline

- Introduction and motivation of the OECD/SETH-2 project
- Investigations carried out in the PANDA facility
- Results from selected PANDA series
- Follow-up activities
- Conclusions

Introduction

In a nuclear power plant the containment is the last barrier for avoiding the release of any radiological material to the environment, therefore **the safety systems should always ensure containment integrity**

Analysis of thermal-hydraulic process as occurring in a LWR containment building under accident conditions (DBA, BDBA) is very **complex**, due to the large number of inter-related parameters/proceses:

- **BWR and PWR** have differences in the **safety systems**
- **Performance of** active (e.g. spray, cooler, etc.) or passive **safety systems** (e.g. recombiner, rupture foils, PCC, etc.) **varies during the evolution of a postulated accident**
- **Modeling of Physical phenomena**: e.g. jet, plume (positively or negatively buoyant), diffuse flow, transport, mixing, stratification, condensation, re-evaporation, etc.

Introduction…contd.

Advanced Lumped Parameter (LP) and Computational Fluid Dynamic (CFD) codes are **the only tools** for the analysis of DBA and BDBA in real reactors:

- At the present the Assessment and Validation (A&V) of the codes is one limiting factor in their **reliable application**.
- One of the hindrance in the A&V is the **lack of experimental data** for the representation of a broad range of phenomena and scenarios with safety relevance for LWRs

The experimental data should be obtained:

- In large-scale, multi-compartment facilities to **minimize distortion effects** due to scaling considerations.
- **With instrumentation** having temporal and spatial resolution adequate to validate both advanced LP and CFD codes.

A PIRT-Type Exercise on NRS items requiring CFD

Overall Priority Ranking (Single-Phase)

Item No.	Short Description	Score /36
1	PTS	31
2	**Hydrogen mixing and combustion in containments**	**31**
3	Flows in complex geometries	29
4	Boron dilution	28
5	Sump strainer clogging	26
6	Aerosol deposition in containments	26
7	Thermal fatigue	23
8	MSLB (leading to asymmetric flow)	22
9	Hot-leg heterogeneities	21
10	HTGR lower plenum mixing	16
11	HTGR core heat transfer	15
12	HTGR reactor cavity cooling heat transfer	13
13	VHTR heat transfer issues	12
14	Flow behind blockages in LMFRs	9
15	Flow-induced vibrations in LMFRs	8
16	Core barrel vibration in APWRs	6

Overall Priority Ranking (Multi-Phase)

Item No.	Topic	Score /36
1	Reflooding following LB-LOCA (including UPI and EPR)	28
2	PTS	27
3	CHF	26
4	Condensation-induced water hammer	26
5	Sub-cooled boiling in PWRs	23
6	Steam condensation in pools	19
7	Induced break	16
8	Gas entrainment in LMFRs	9
9	Special issues for CANDU reactors	3

H/M/L were assigned the numerical values 3/2/1, respectively, and N/A the value zero. The numbers from the 12 participants were then summed to give a total priority value (max. 36).

B. Smith, *ICONE17, 2009*

Severe Accident Research Priorities (SARP)

EUROSAFE (5th FWP EC): Identification of areas of needed research in the domain of severe accident in nuclear power plant

- **Outcome**: identification of 21 research issues with recommendation for experimental programs and code developments

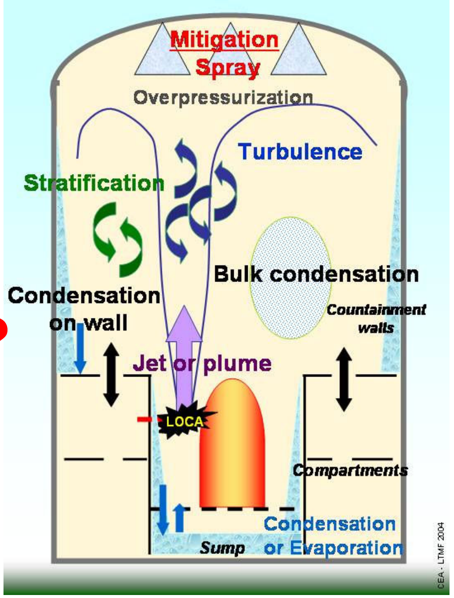
SARP is one of the work-packages of SARNET: reviewing and reassigning priorities by ranking research issues (4 ranking grades: closed issue, low priority, medium priority, high priority)

- Containment atmosphere mixing and hydrogen combustion/detonation- **High priority**

Progress in Nuclear Energy 52 (2010) 11-18

Containment reactor safety issues

Hydrogen released into the reactor containment during the course of a severe accident



- **Homogeneous distribution or stratification ?**
- **How long a stable stratification would be maintained ?**
  - ✓ *Erosion of the stratified layers by mass or heat sources and heat sinks*

The first question was investigated during OECD/SETH, EU/ECORA projects

The second question is the subject of the OECD/SETH-2 project

OECD SETH-2 Project

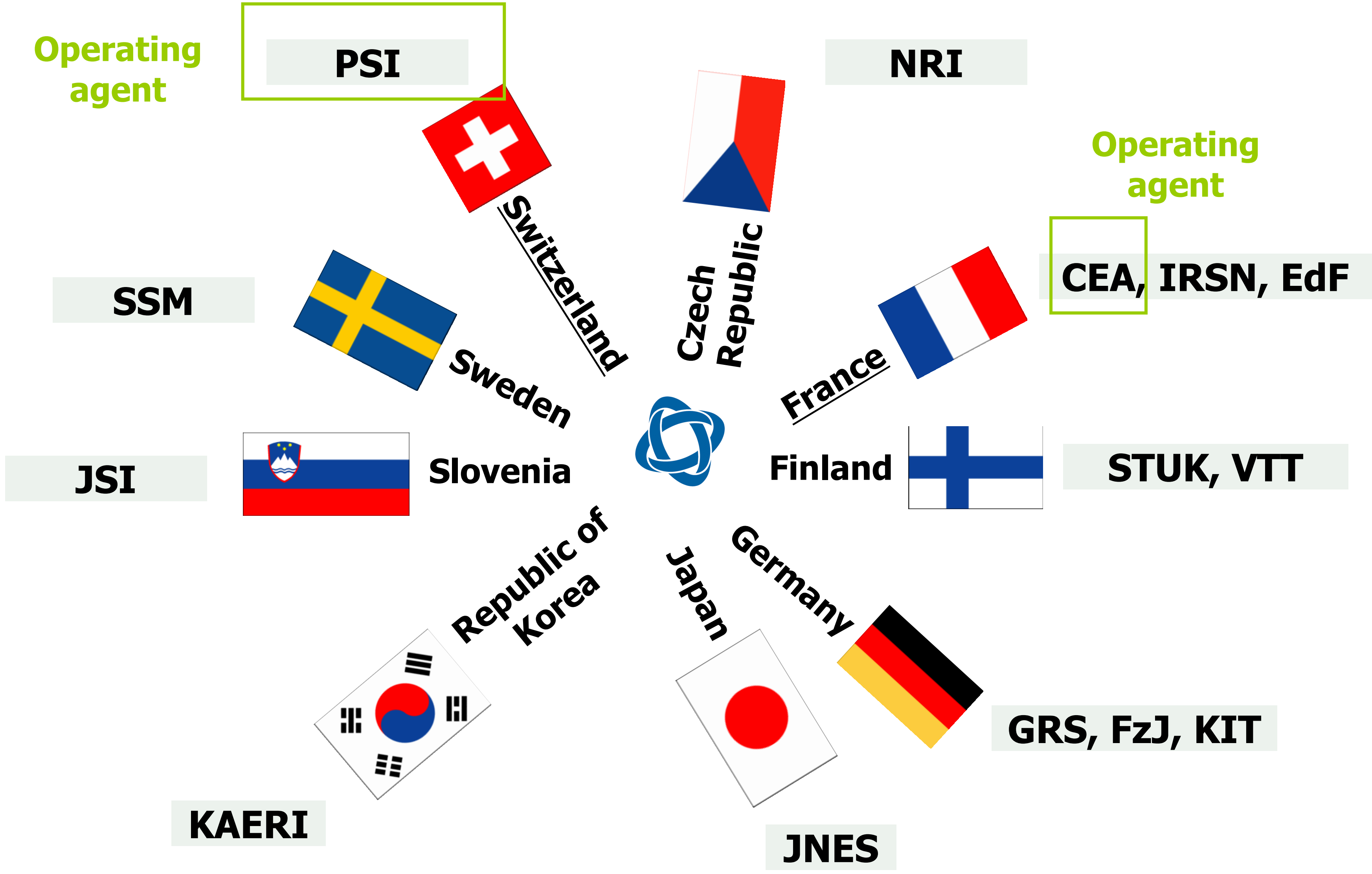
Subject: Investigating of key safety issues for LWR containment Thermal-hydraulics which are not covered by reliable simulations

Focus: Destabilization and mixing of hydrogen stratification and large scale containment integral tests

Objectives: Generation of experimental database for Advanced Lumped Parameter codes and CFD codes.
Assessment/validation related to investigation of **gas stratification break-up by:**

- Horizontal or vertical, negatively buoyant jet or plume
- Flow induced by safety system or component activation, e.g. spray, containment cooler, heat source simulating recombiner
- Sudden opening of hatches separating two large volumes

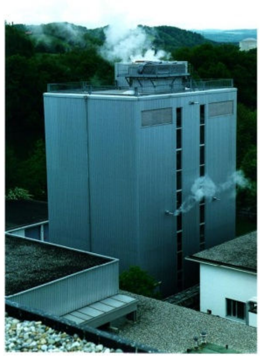
Participants to the OECD SETH-2 Project

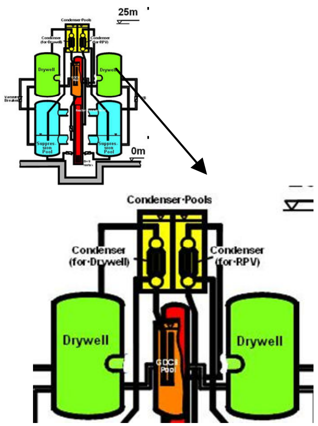


March 2007 – December 2010

Facilities used in SETH-2

PANDA





PANDA Drywell

Volume = 2 x 90m^3

Diameter = 4m

Height = 8 m

Free volume with

Interconnecting line diameter ~ 1m

Scaling :

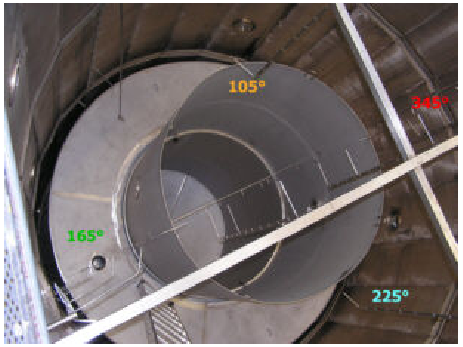
Simplified Boiling Water Reactor (SBWR).

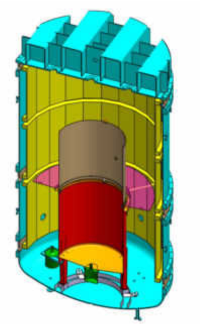
Height = 1:1

Volume = 1:25

Specified: 24 PANDA tests

MISTRA





MISTRA

Volume = 97.6m^3

Diameter = 3.8m

Height = 7.4 m

Compartmented volume

Scaling :

Pressure Water Reactor (French PWR).

Height-Diameter ~ 1:10

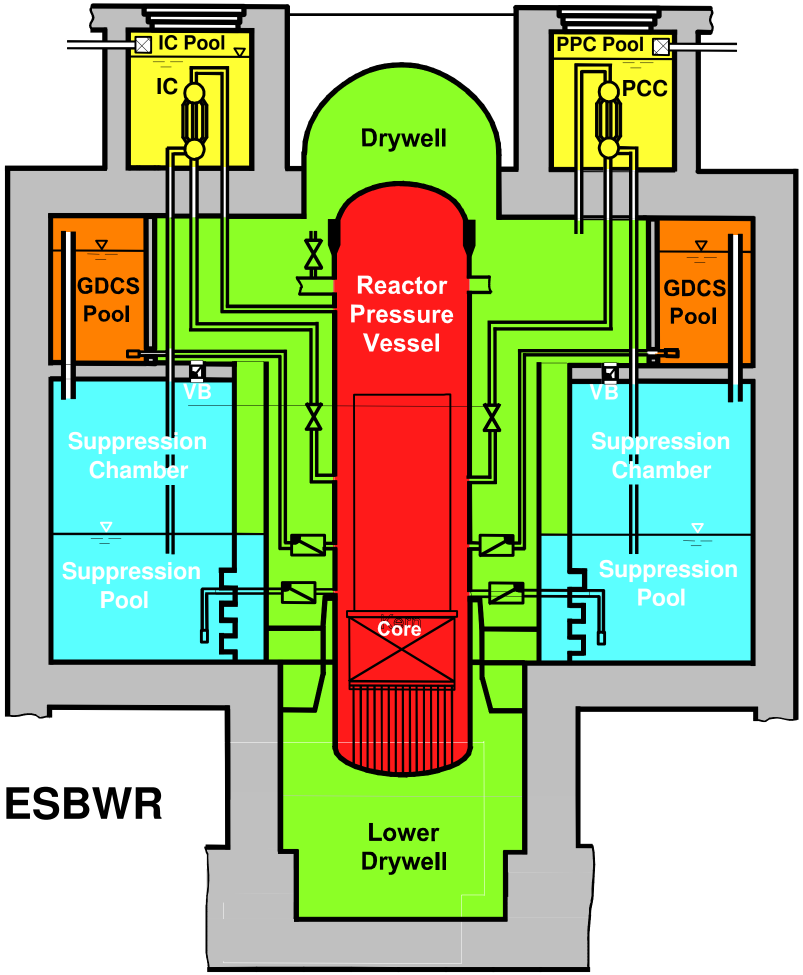
Volume = 1:700

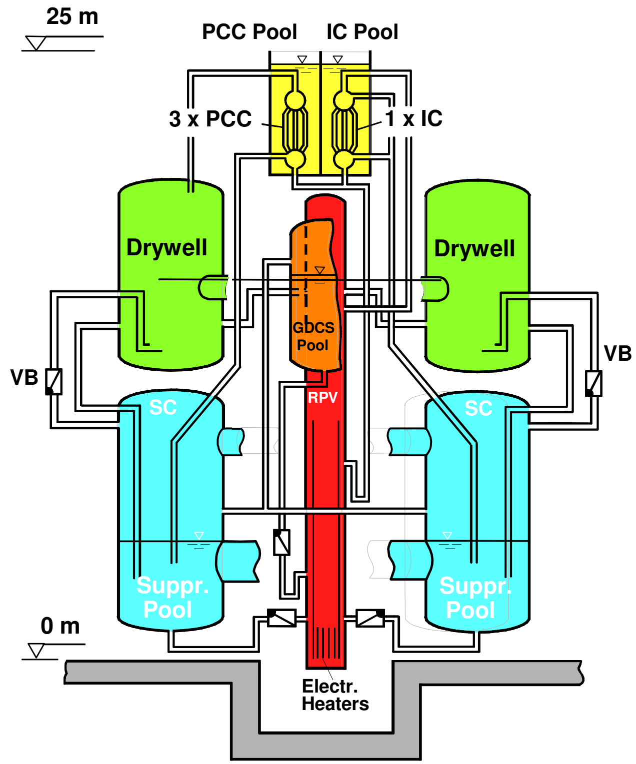
Specified: 6 MISTRA tests

PSI contribution to OECD/SETH-2

Project manager:	
Dr. Domenico Paladino	Leader of the Experimental Group
Logistic and meeting organization:	
Renate van Doesburg	LTH Secretary
PANDA test performance, documentation, test analysis and code simulations:	
Dr. Michele Andreani	Analysis and modeling Group. *GOTHIC Simulations*
Dr. Medhat Sharabi	Analysis and modeling Group. *FLUENT Simulations*
Wilhelm Martin Bissels	Experimental Group
Dr. Nejdet Erkan	Experimental Group
Max Fehlmann	Experimental Group
Klaus Kaiser	Experimental Group
Dr. Ralf Kapulla	Experimental Group
Dr. Guillaume Mignot	Experimental Group
Martin Ritterath	ETHZ-IET-PSI, PhD student
Chantal Wellauer	Experimental Group
Dr. Robert Zboray	Experimental Group
Dr. Jörg Dreier	NES-LTH, Scientific support and project deliverables
Mechanical, Electrical, Electronic, Control, etc.	PSI LOG- Various Groups
Members in the Programme Review Group (PRG) and Management Board (MB):	
Dr Jörg Dreier	NES-LTH
Prof. Horst Michael Prasser	LTH Head

ESBWR versus PANDA





Scaling:

Height ~ 1 : 1
Volume ~ 1 : 40
Power ~ 1 : 40

PANDA Major Test Programs

- **1991-1995** *EPRI/GE:* Investigation of passive decay heat removal systems for SBWR
- **1996-1998** *EU-4th FWP:* Passive decay heat removal system tests for: **-** SWR1000 *(IPPS);* ESBWR *(TEPSS)*
- **1999-2004** *EU-5th FWP:* Effect of Hydrogen distribution on passive systems *(TEMPEST);* Investigation of BWR-natural circulation stability *(NACUSP)*
- **2002-2006** *OECD/NEA:* Gas mixing and distribution in LWR containments *(SETH)*

- **2007-2010** *OECD/NEA:* Resolving LWR containment key computational issues *(SETH-2)*

- **2010-2013** *EU-7th FWP*: Containment thermal-hydraulics of current and future LWRs for severe accident management (ERCOSAM-SAMARA)
- **2012-2015** *OECD/NEA:* Primary circuit-Containment response to DBA and BDBA for various ABWR and PWR (e.g. EPR, AP1000, APR1400, VVER) (EDARS proposal)

PANDA Vessels *(Construction Phase)*

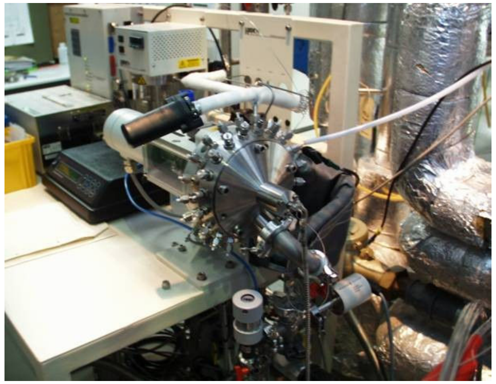
PANDA facility instrumentation

Extensive basic instrumentation

Temperature sensors	~1000
Pressure transducers	49
Flow meters	20
Electrical power meters	7

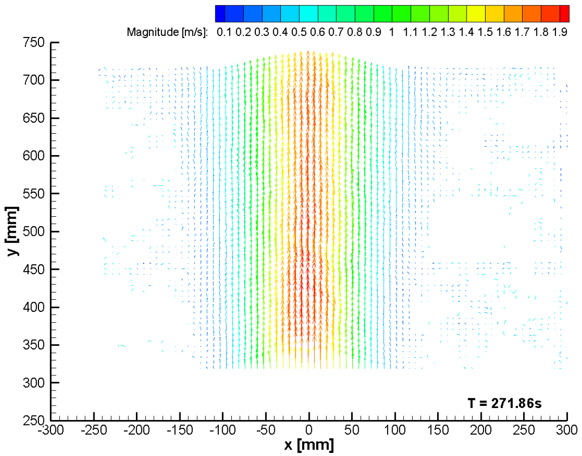
Gas concentration measurement system

Gas (He/air/steam) concentration distri-bution measured by **Mass spectrometry**



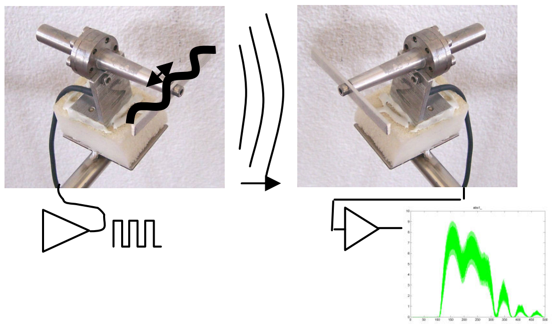
Gas velocity-field measurement

2D Particle Image Velocimetry **(PIV)** system

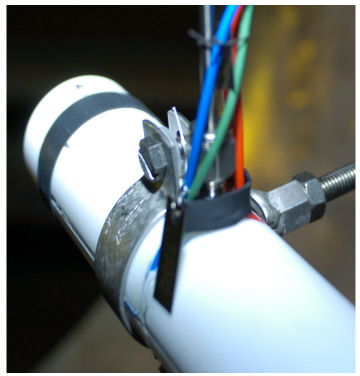


Novel, alternative measurement methods

Ultrasonic sensor system (speed of sound sensors)



Thermocouple Tube (1D gas velocity sensor)



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SETH-2 PANDA test campaign

Series	Investigation	Performed	Specified
Series ST1	Low momentum vertical steam release at various positions:	15 tests	9
Series ST2	Low momentum horizontal jet:	4	4
Series ST3	Containment spray:	4	3
Series ST4	Containment cooler:	6	4
Series ST5	Heat source simulating Recombiner:	6	3
Series ST6	Sudden opening of hatches separating two volumes:	3	1
Series ST7	Long-term cooling system test (s): Substituted with a test of ST3 type	1	-
Heat losses characterization of Vessels 1-2		1	-
Diffusion tests: He-air, He-steam		2	-
Total number of tests:		41	24

Specified: test cases each with different test conditions.

Performed: specified + selected repetitions (test repeatability, instrumentation) + few cases initially not specified

OECD/SETH-2 PANDA Project challenges

- PANDA tests addressing phenomena challenging for the codes

- Implementation in PANDA of new components and related systems

- Obtaining the PANDA test specified conditions

- Obtaining CFD grade experimental data

- Project Schedules

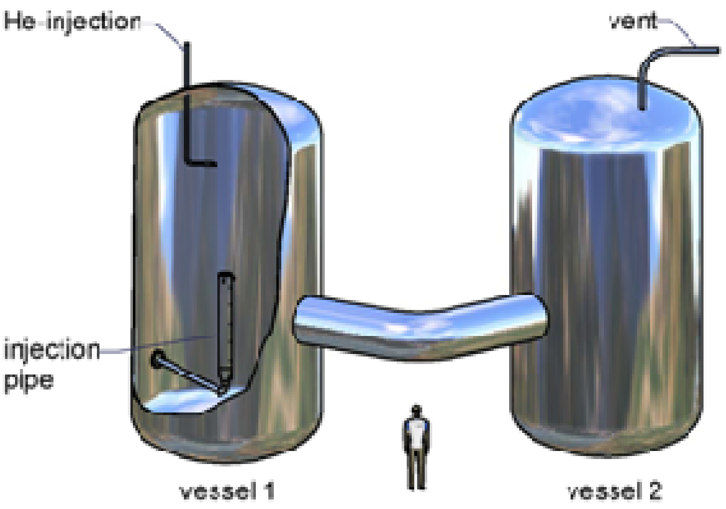
Low momentum vertical fluid release (ST1)

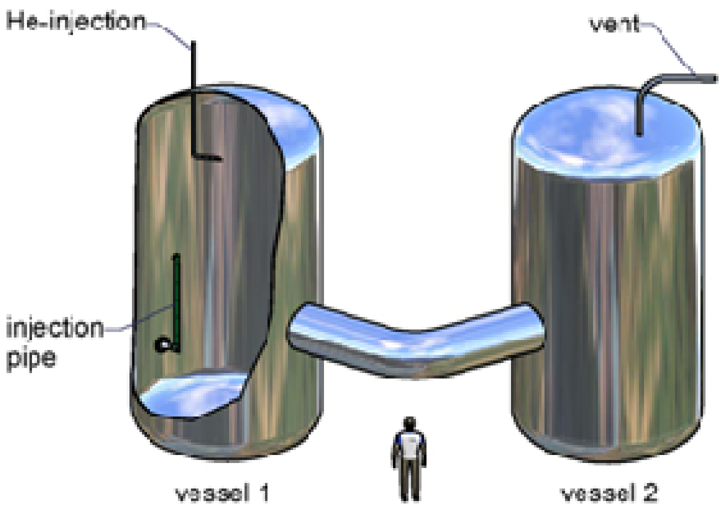
Issues:

The hydrogen which would be released in a postulated severe accident would mix with the original containment gas (air or nitrogen) and steam and may lead to a stratified gas atmosphere. Hydrogen stratification break- up by negatively buoyant plumes and jets.

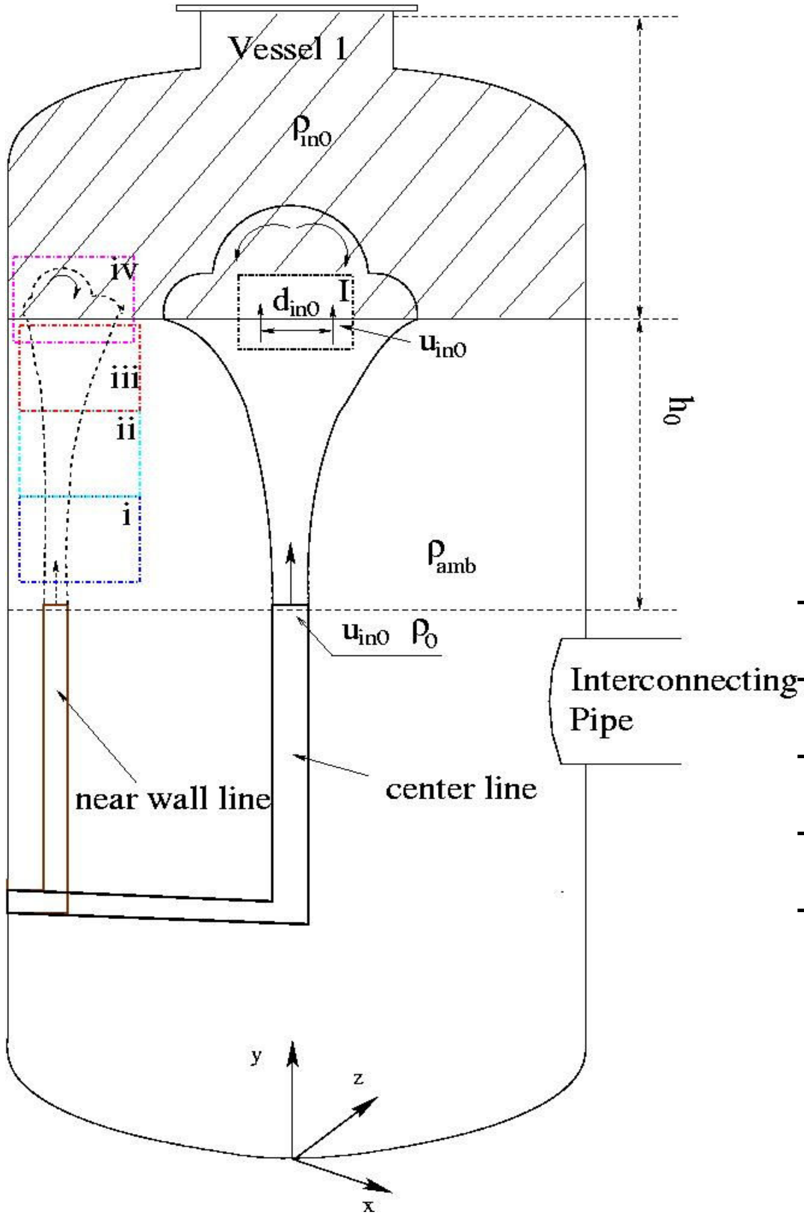
Main objectives:

- Parametric investigation of gas stratification break up by vertical fluid release
- Characterization of erosion and diffusion effects
- “Facility-related” effect on the evolution of stratification break-up (MISTRA LOWMA-PANDA ST1_7, ST1_7_2 counterpart test)





ST1: Experiment Description



$$Fr_0^{\ 2} = \frac{u_0^{\ 2}}{g\frac{(\rho_{amb} - \rho_0)}{\rho_0} d_0}$$

$$Fr_{in}^{\ 2} = \frac{u_{in0}^{\ 2}}{g\frac{(\rho_0 - \rho_{in0})}{\rho_0} d_{in0}}$$

$$\frac{\text{inertia}}{\text{buoyancy}}$$

-2 geometry: centered and near wall injection

-Variation of d_0 , initial momentum flux

-Variation of u_{in0} , initial momentum flux

-Variation of ρ_{in0} , initial helium concentration

-Variation of ρ_{amb}, ambient fluid (steam of air)

Large parametric test matrix

ST1: Parametric Test Matrix

Test	Ambient Fluid	Re	Fr_0	Fr_{in}	He %	Geometry
ST1_4	Steam	10000	2.3	0.5	Low	Center
ST1_1	Steam	14000	3.1	0.7	Low	Center
ST1_2	Steam	28000	6.2	1.4	Low	Center
ST1_3	Steam	42000	9.3	2.1	Low	Center
ST1_5	Steam	14000	3.1	0.5	High	Center
ST1_6	Steam	39000	8.7	1.5	High	Center
ST1_7	Air	14000	-	0.6	High	Wall
ST1_8	Steam	9000	3.2	0.5	Low	Wall
ST1_9	Steam	27000	9.3	1.5	Low	Wall

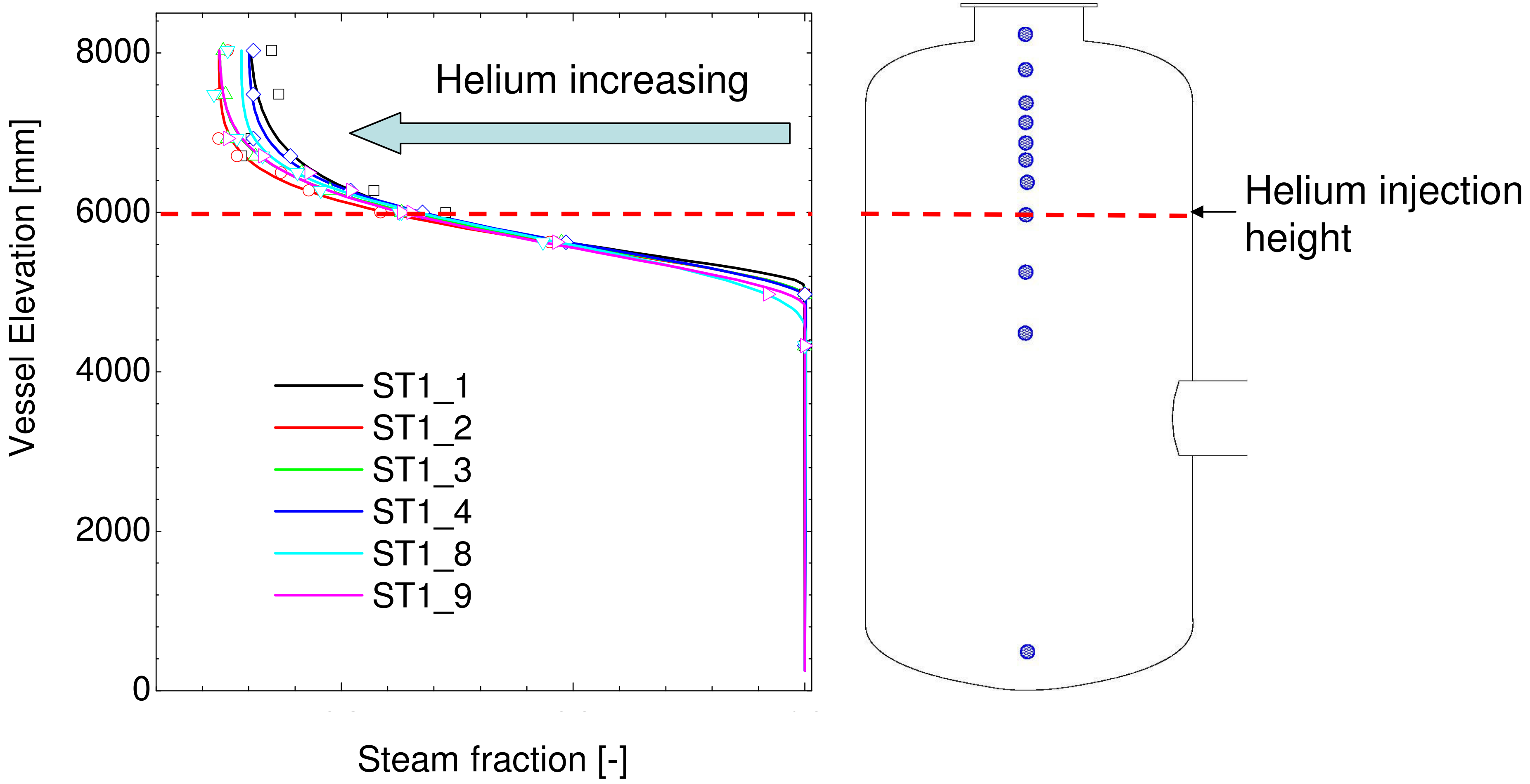
Variation of initial momentum (green)

Variation of injection location (red)

Variation of fluid (magenta)

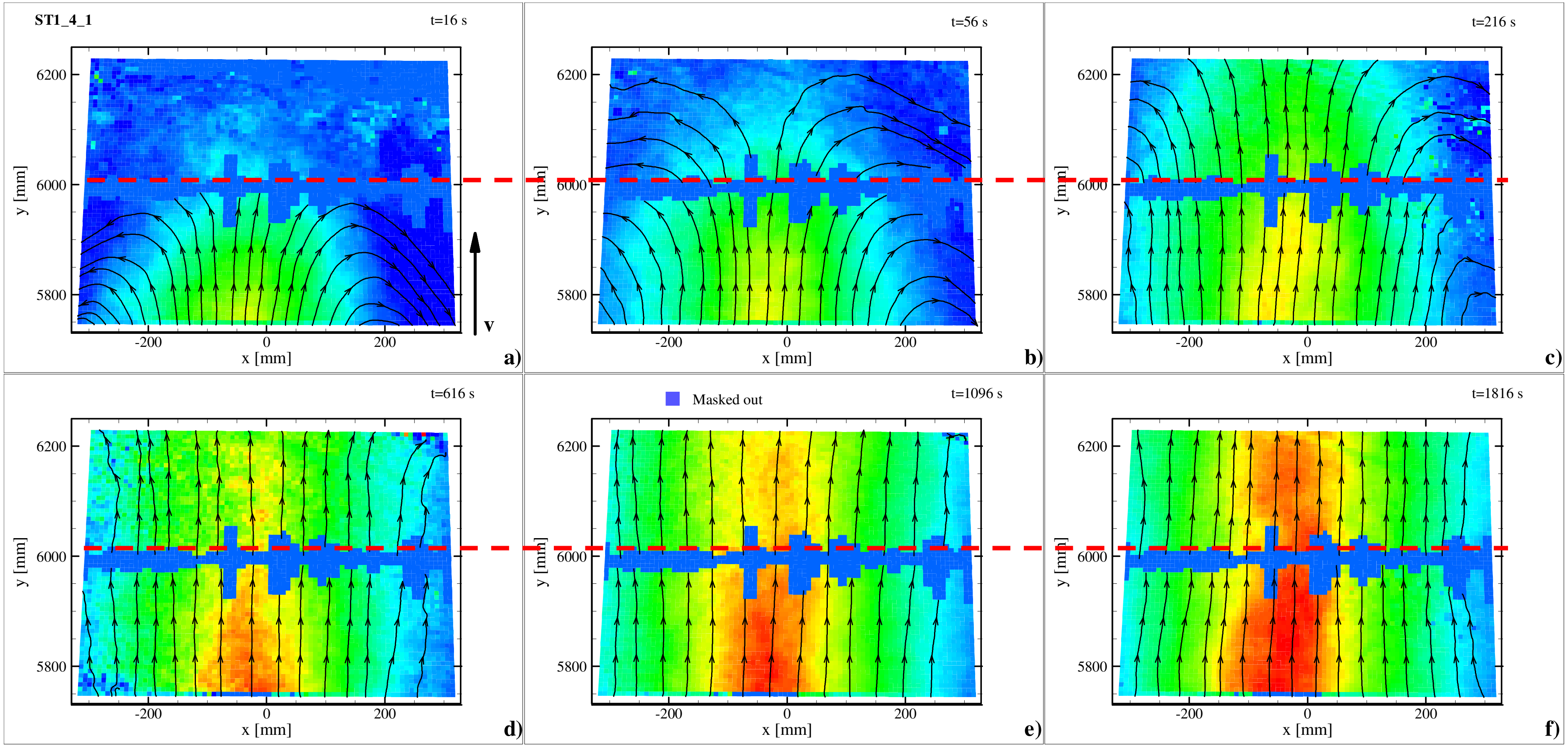
Variation of initial helium concentration (blue)

ST1: Initial Conditions



Good reproducibility of the initial helium layer concentration profile.

ST1: Velocity measurements with PIV

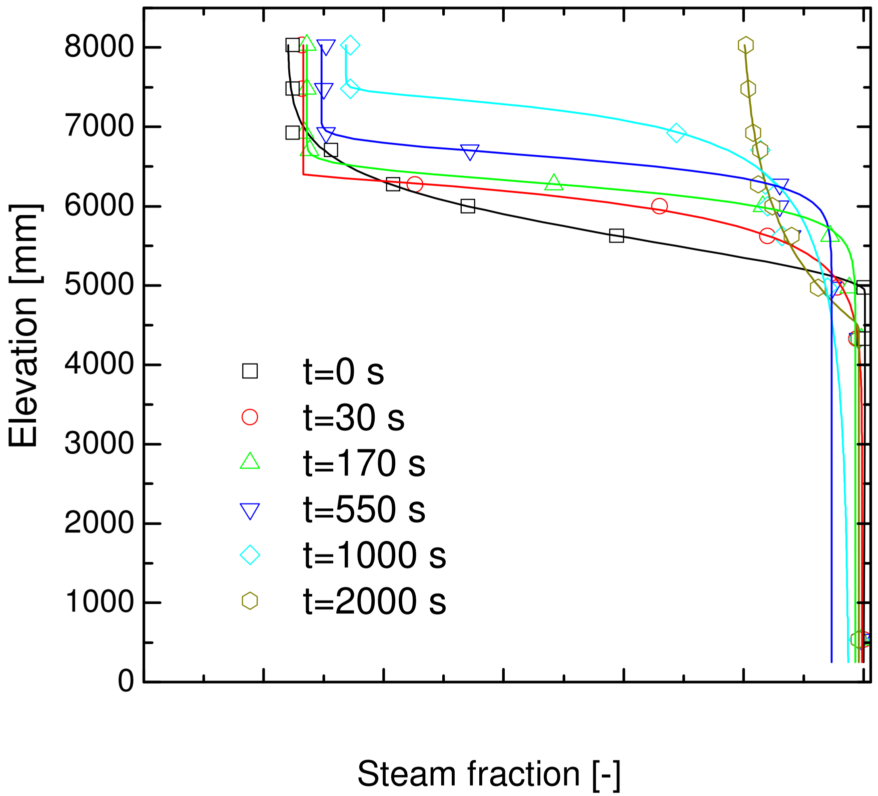


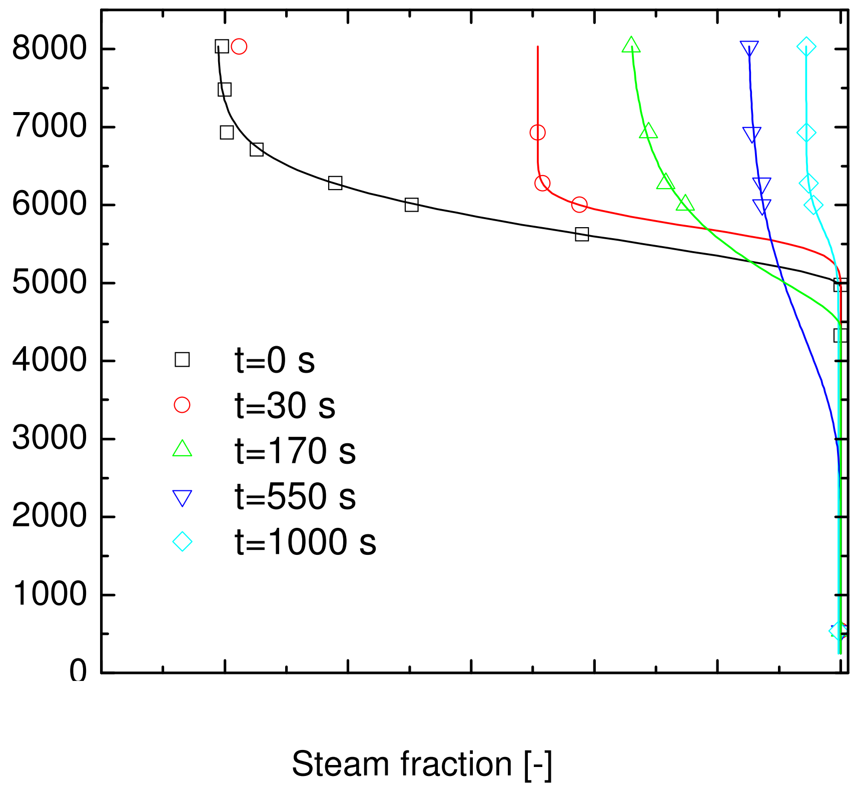
- The helium-rich layer is initially located in Vessel 1 in the upper region: ~6-8 m
- The PIV investigation area is around the initial “interface” between steam and steam/helium regions

ST1: Momentum Effect - I

ST1_4 : 22 g/s Steam

ST1_3 : 90 g/s Steam



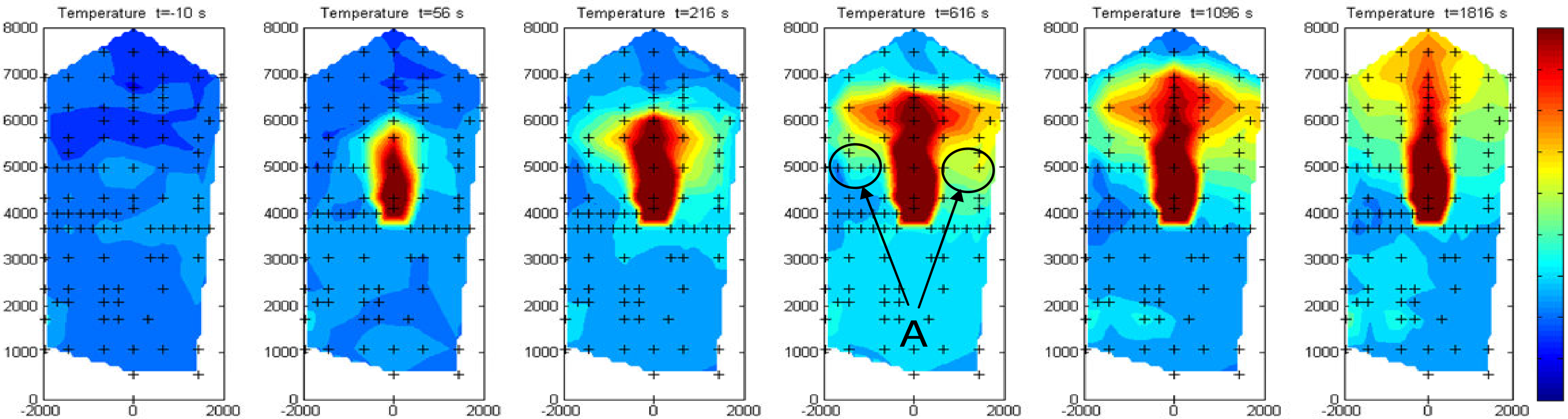


Erosion rate increases with increasing mass flow rate

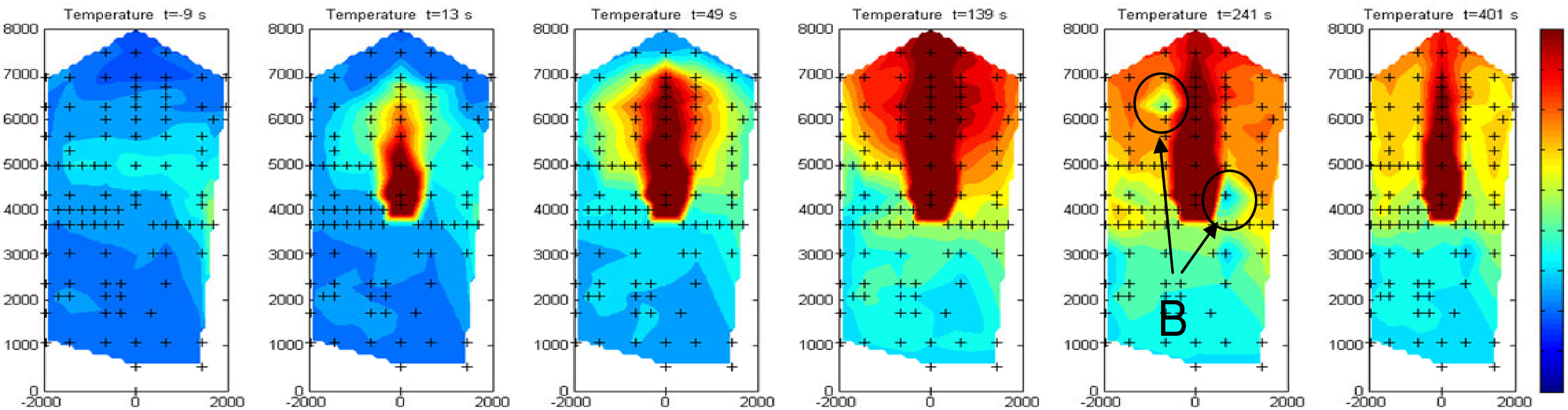
at constant initial helium concentration

ST1: Momentum Effect - II

ST1_4



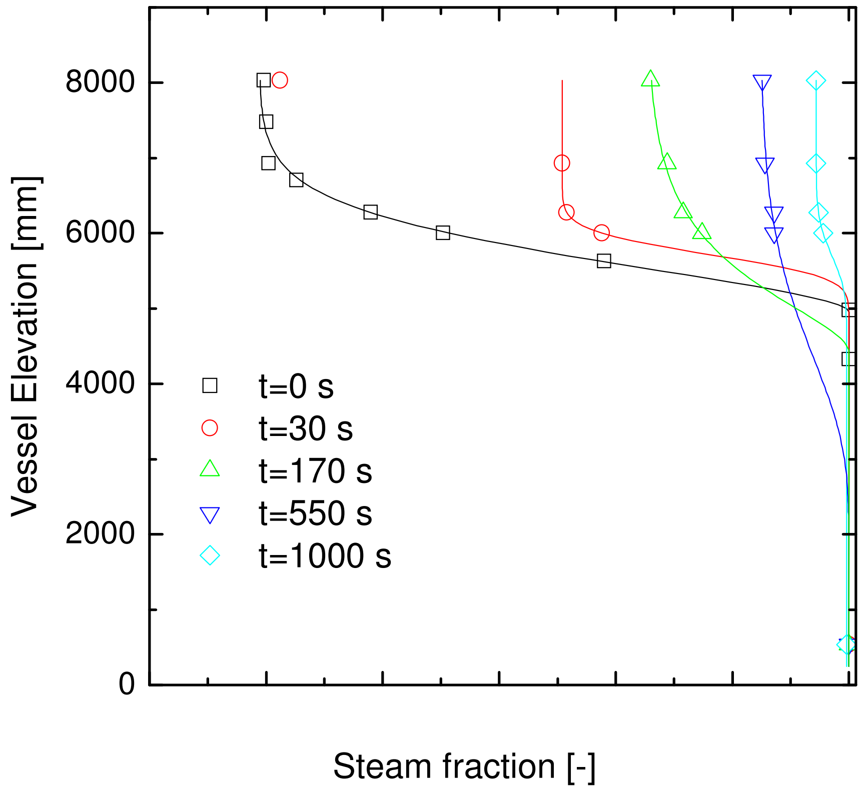
ST1_3

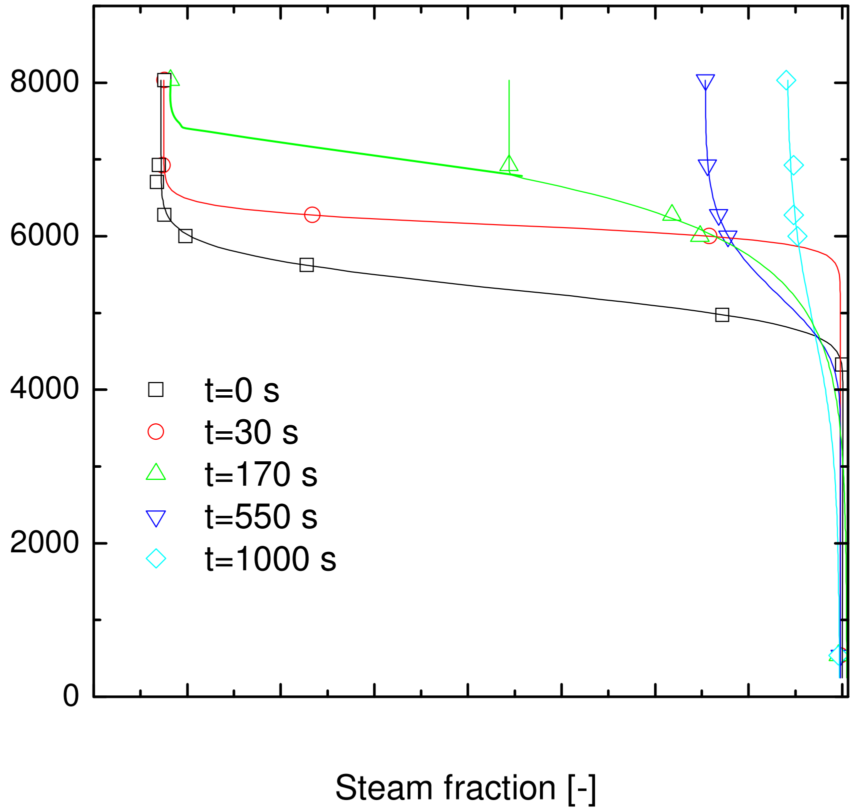


ST1: Concentration Effect - I

ST1_3: Re = 42000 , Fr_{in}= 2.1
~25 % helium

ST1_6: Re= 39000, Fr_{in}= 1.5
~38 % helium





Erosion rate increases with decreasing initial He-concentration

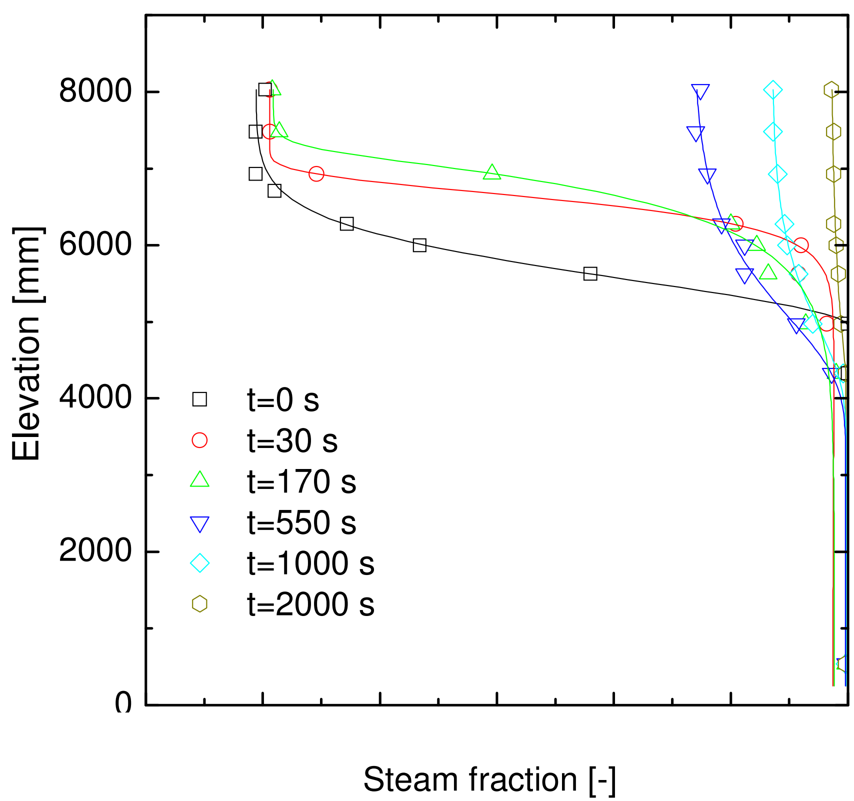
ST1: Concentration Effect - II

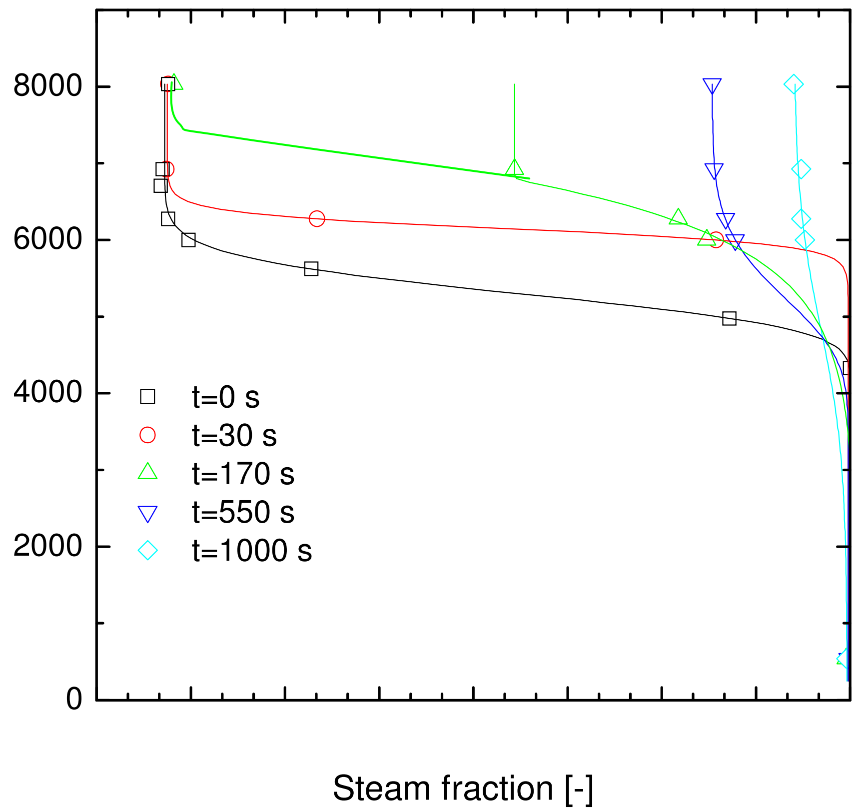
ST1_2 : Re = 28000 , Fr_{in}= 1.4

~25 % helium

ST1_6: Re = 39000, Fr_{in}= 1.5

~38 % helium

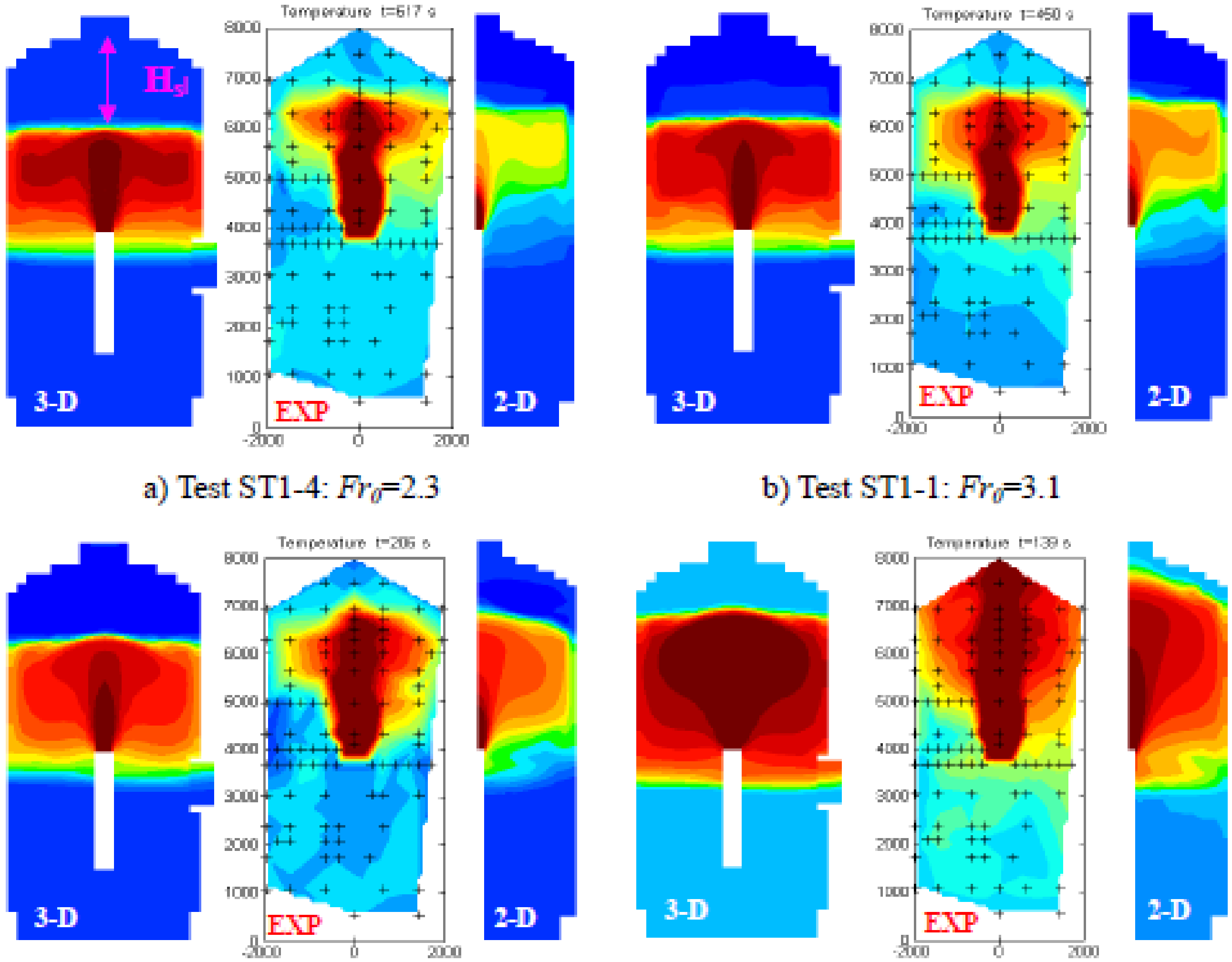




Similar erosion rate for different Re-number

ST1: analysis with GOTHIC

Example



a) Test ST1-4: Fr_0=2.3

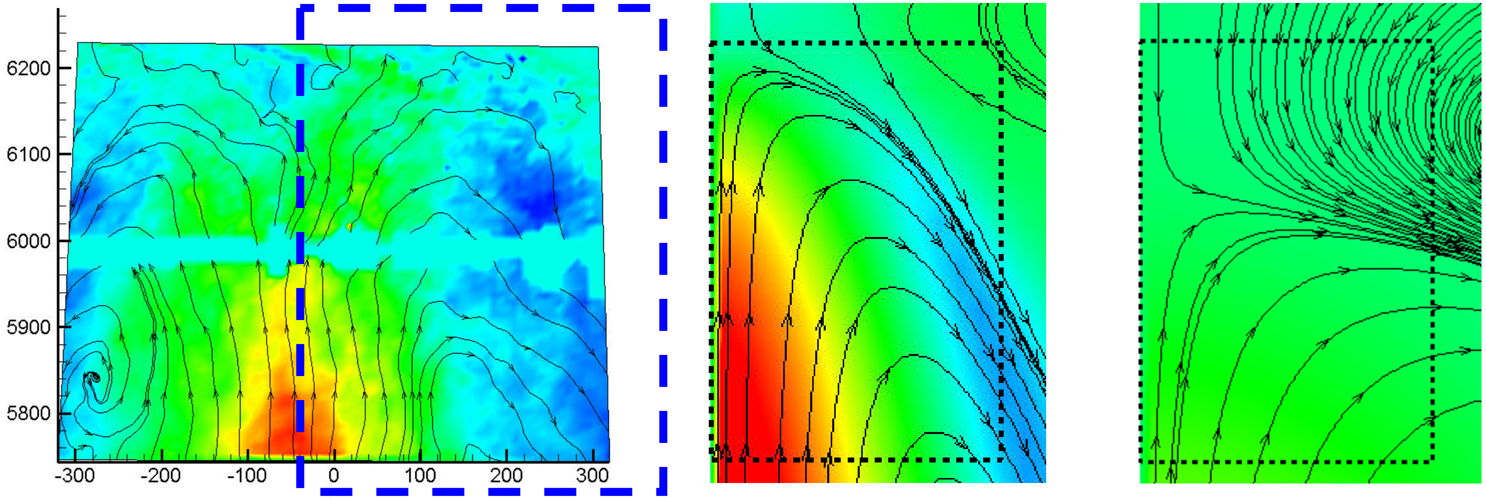
b) Test ST1-1: Fr_0=3.1

c) Test ST1-2: Fr_0=6.2

d) Test ST1-3: Fr_0=9.3

- 3-D (coarse mesh) model underpredicts the penetration of the jet. No further result is shown
- 2-D model with finer mesh better represents the erosion of the initial stratification

ST1: analysis with GOTHIC…contd.



Exp. ST1-1 | 2-D, Mixing Length | 2-D, k-ε

• The velocity field measured with the PIV (contours show the vertical component of velocity) in the region of the density interface shows that the jet is still narrow and streamlines are strongly curved. This shows the existence of a “fountain” flow

• The k-ε model predicts a broader jet and nearly horizontal streamlines. This leads for some conditions to inaccurate prediction of jet upwards penetration and stratification erosion

• The results with the Mixing Length model (with optimized value of the ML) shows that the correct velocity field can be obtained for certain cases

The correct modeling of turbulence has a strong effect in the jet-layer interaction region

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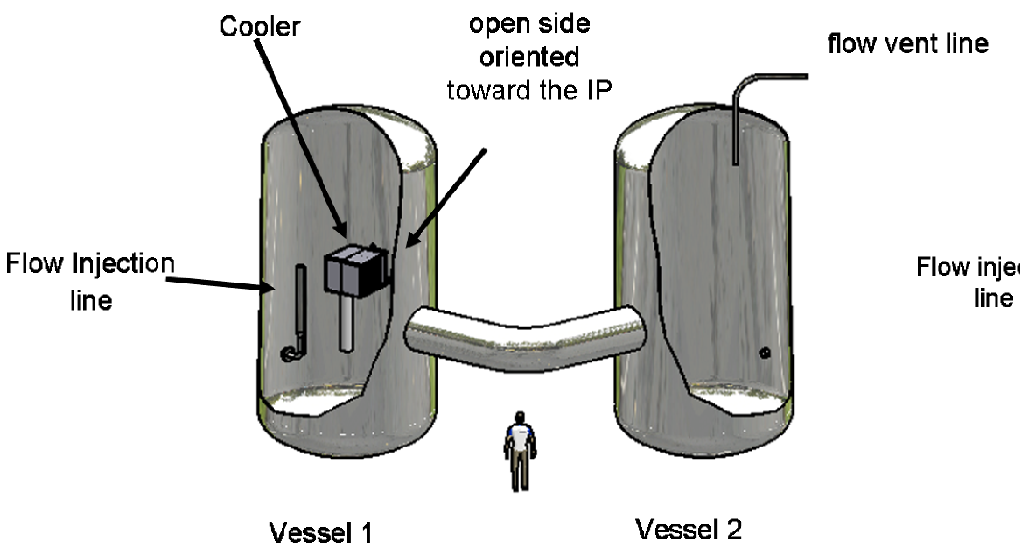
ST4: Containment cooler

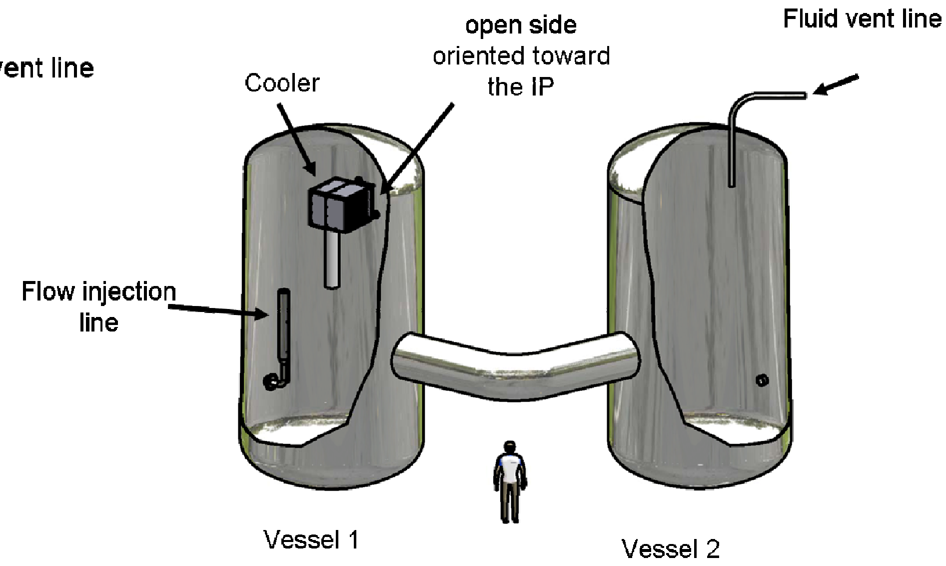
Issues:

In case of severe accident, with release of hydrogen, the condensation induced by the cooler activation as well as the flow induced by the cooler will have an effect on the hydrogen distribution in the containment

Main objectives:

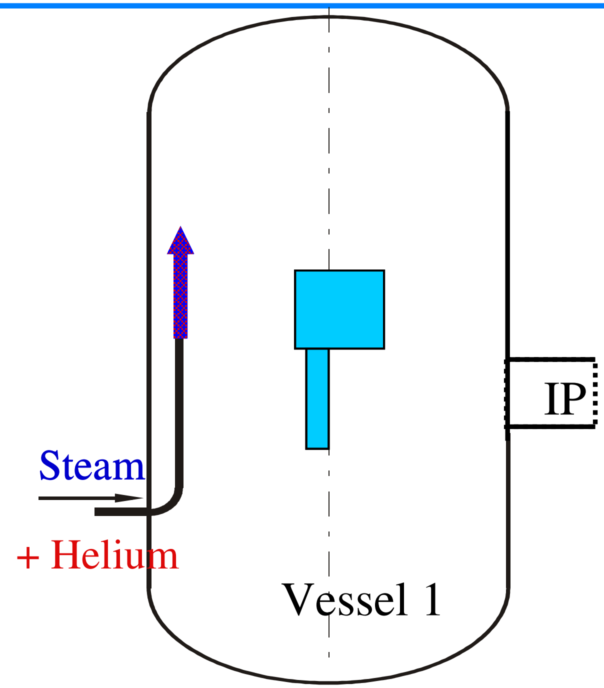
To investigate the effect of cooler on the gas transport in the containment, in particular whether a local increase of helium concentration may be mitigated (i.e. break-up) with the cooler in operation





ST4: configurations

- **PHASE I:**
  Steam is injected for 3600 s at 40 g/s
- **PHASE II:**
  Steam is injected for 1800 s at 40 g/s + Helium at 2 g/s
- **PHASE III:**
  Steam is injected for 3600 s at 40 g/s
- **ST4_2, ST4_3 and ST4_4:**
  →Constant pressure (1.3 bar)
- **ST4_1: no venting :**
  → **PRESSURIZATION**



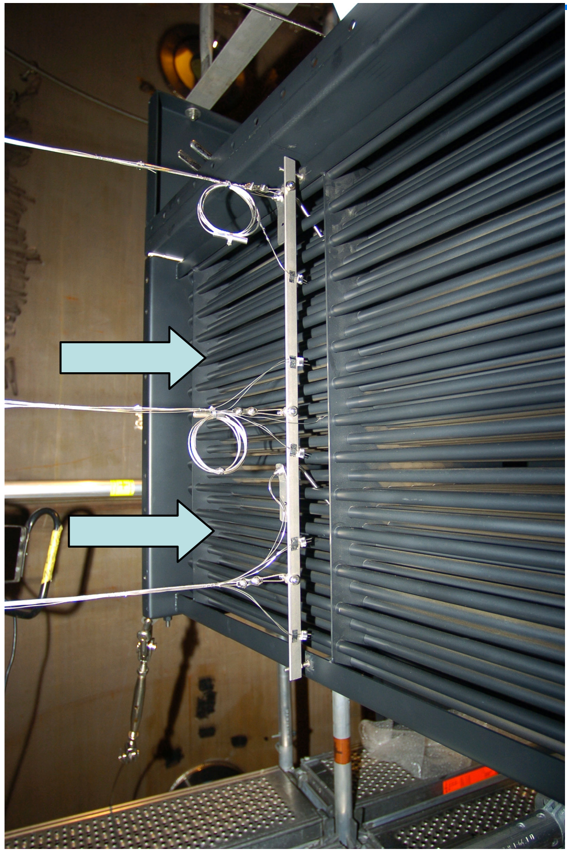
ST4_1, ST4_2, ST4_3

→ **Same gas injection scenario for all 4 tests**

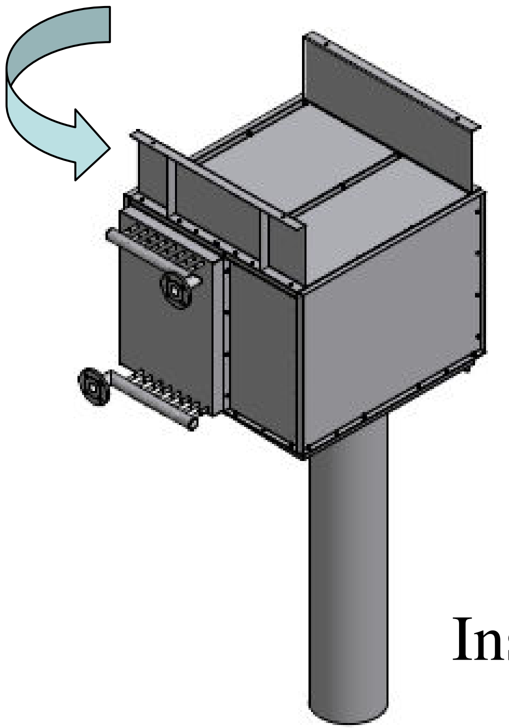
→ **Duct, cooler location, pressurization (venting) vary**

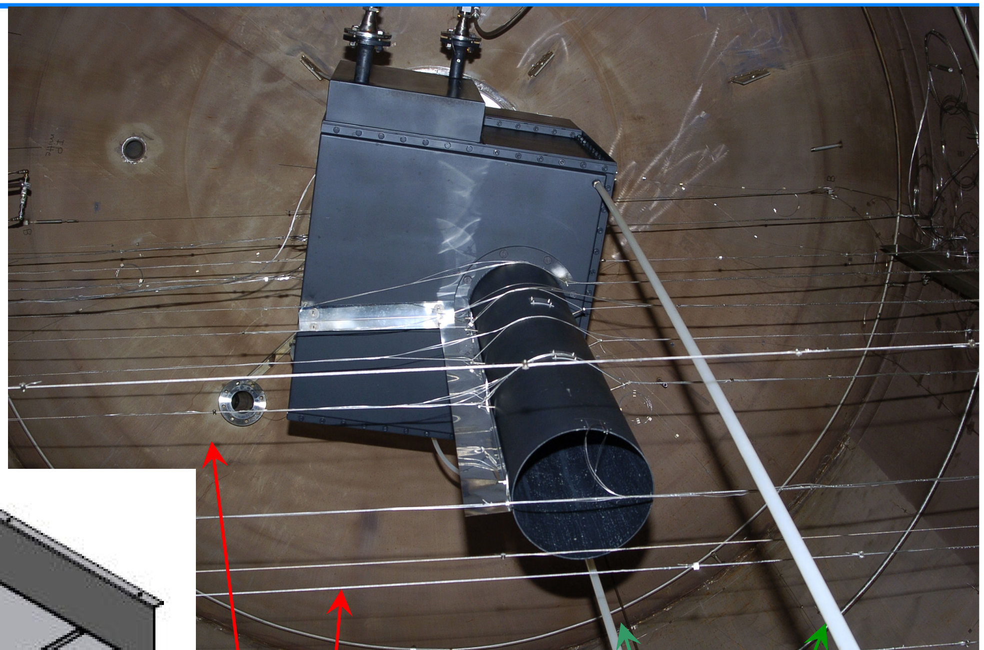
	ST4_1	ST4_2	ST4_3	ST4_4
Location	4 m	4 m	4 m	6 m
Duct	Yes	Yes	No	Yes
Venting	No	Yes	Yes	Yes

ST4: PANDA Cooler



Open Face

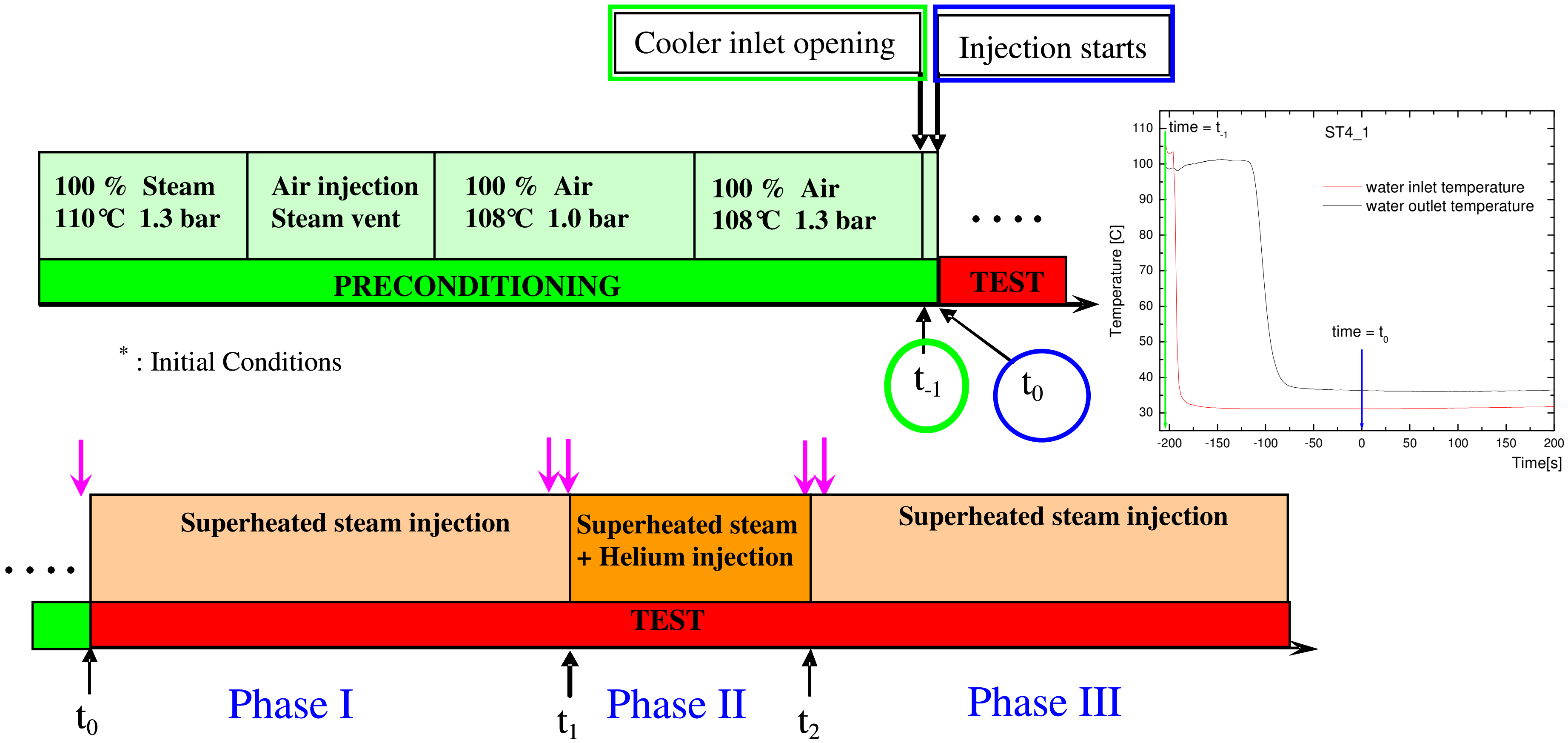




Condensate drain

Instrumentation support wires

ST4: schematic of test procedure



Time at which initial conditions are given

Start of mass spectrometer sequence

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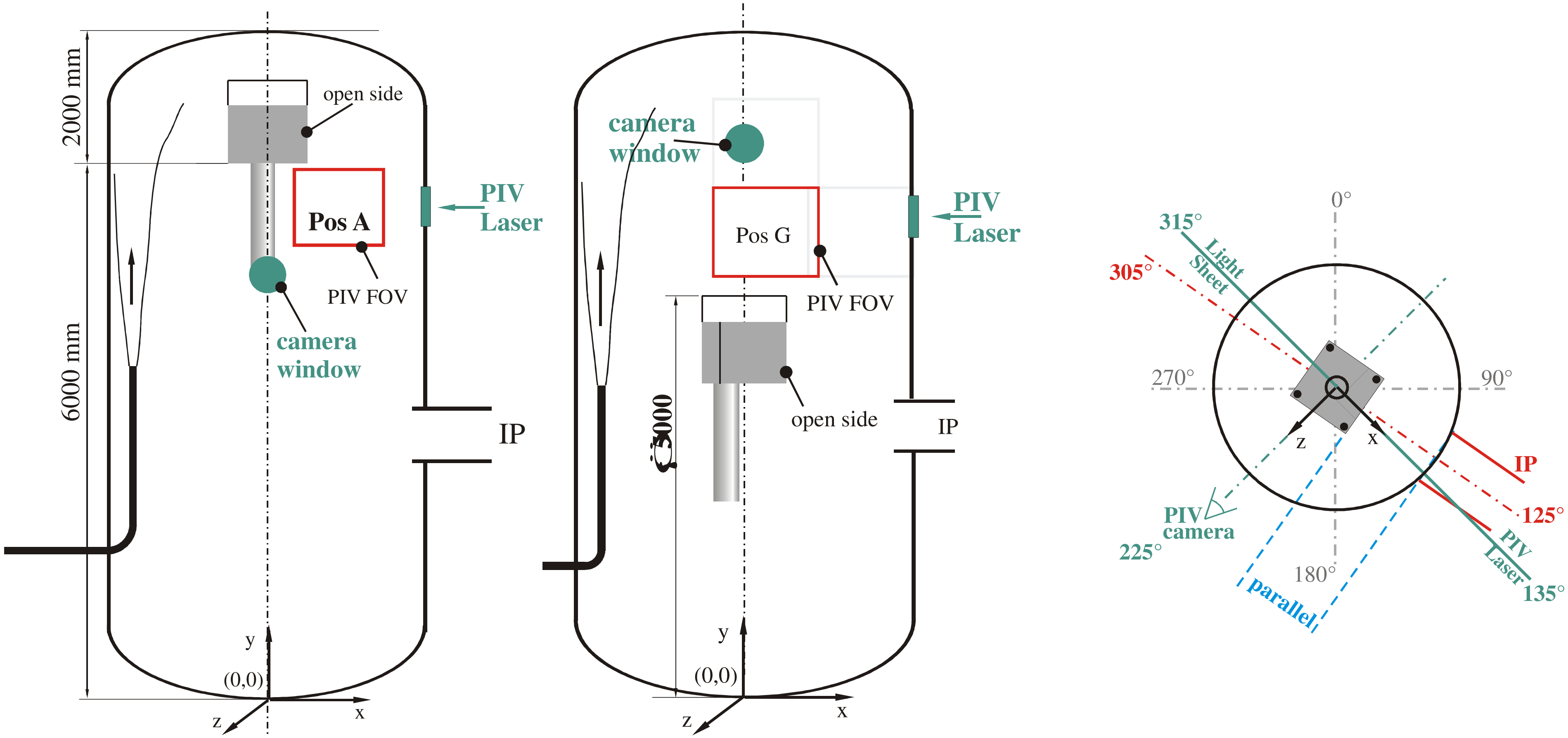
ST4: location of PIV windows

Instrumentation Implementation- Cooler -PIV

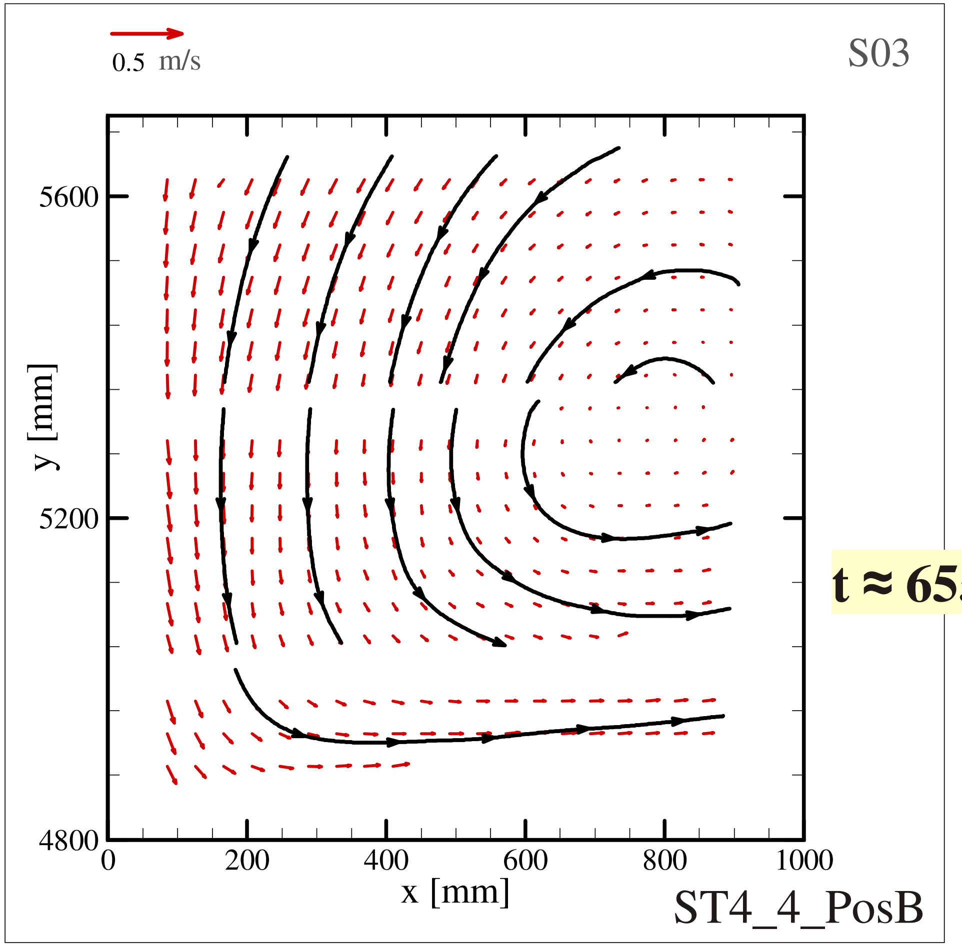


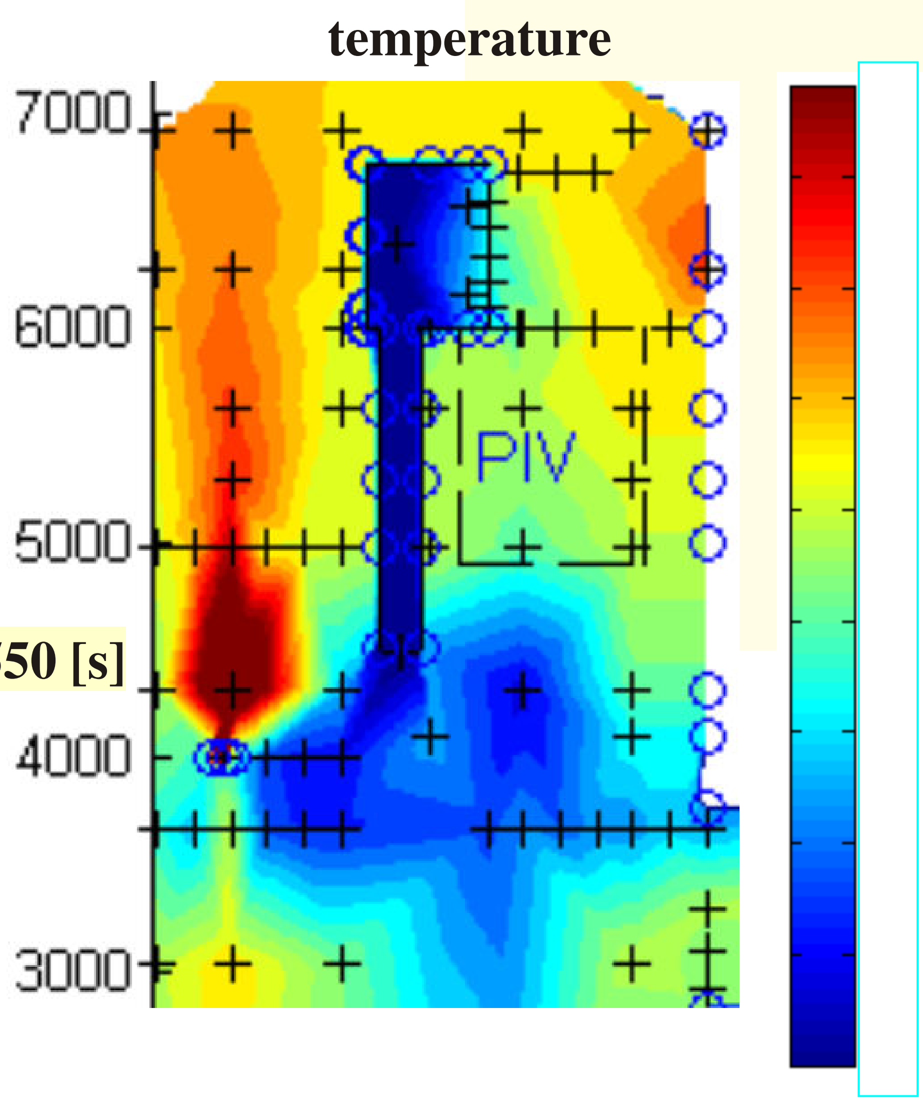
Upper position

Middle Position

ST4: flow patterns

Mean velocity – S03 – Phase III





t ≈ 6550 [s]

Upper Position + Pressurization: PIV Observation

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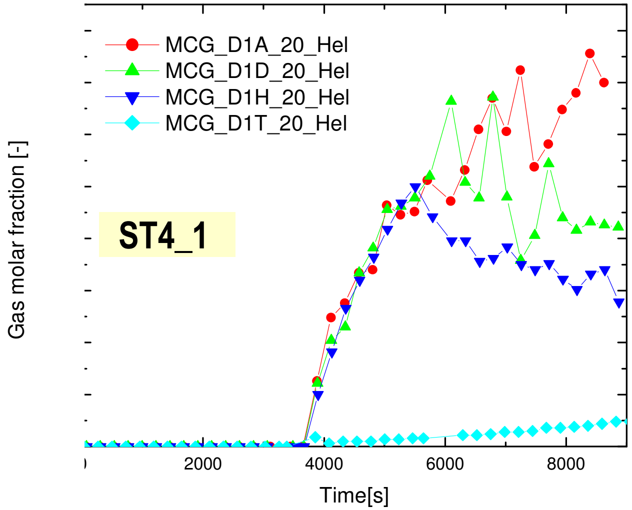
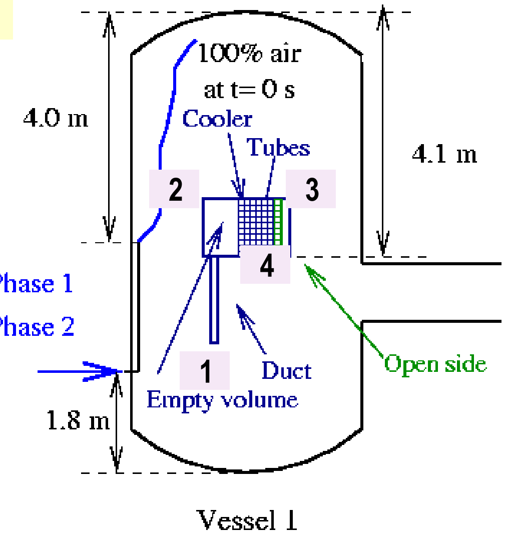
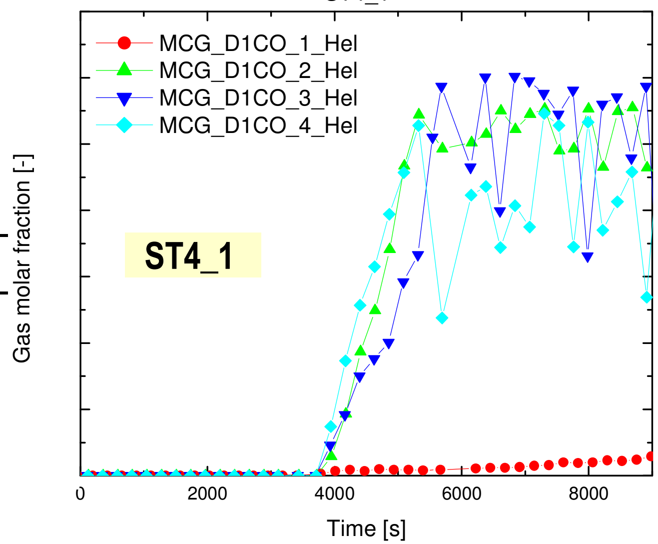
ST4: helium concentration results

Stratification build-up in the upper dome

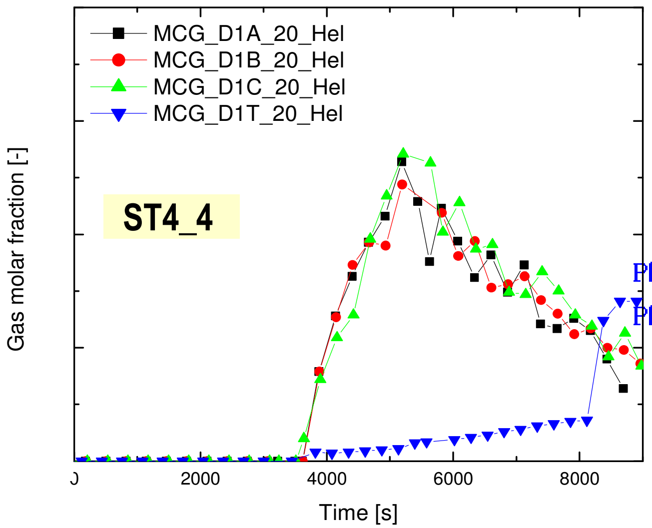


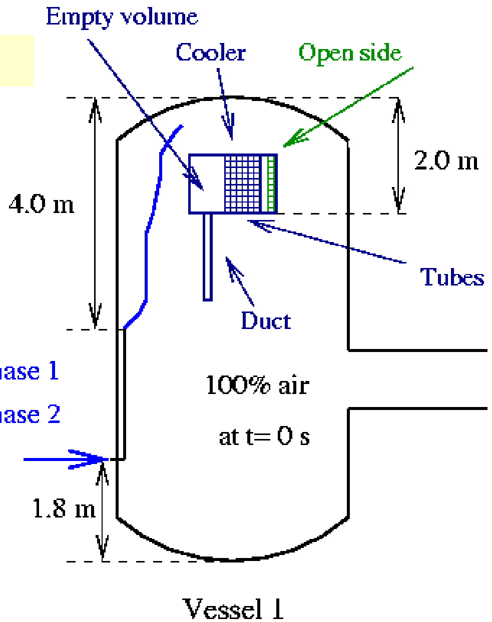


High He concentration inside the cooler

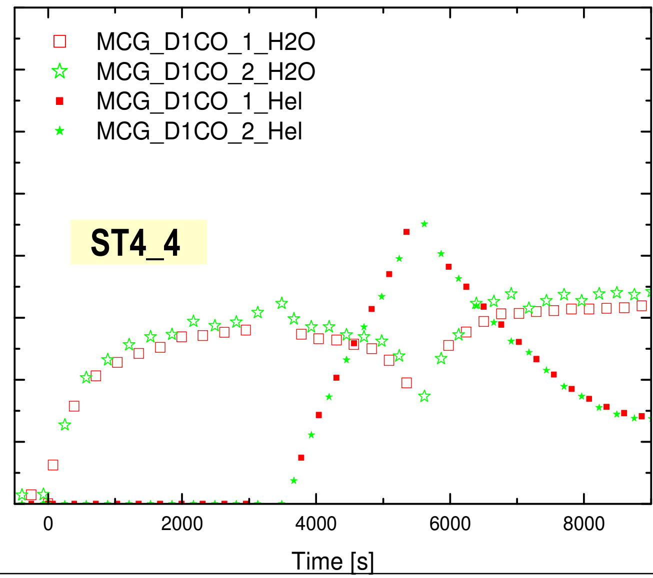


Stratification erosion in the upper dome





Low He concentration inside the cooler



OECD/SETH-2 PANDA highlights

- PANDA test campaign consisting of 41 tests has been concluded according project schedule
- Facilities upgrading e.g. auxiliary systems, mitigation tools (spray, recombiners-heat source, cooler), enabled us to obtain tests with well controlled initial and boundary conditions and with an **excellent repeatability**
- Efforts done to improve the various measurement systems (temperature, gas concentration, PIV, novel instrumentation, etc.) allowed for obtaining, high quality data also for the most challenging tests (e.g. cooler-condensation, spray, rupture disk, etc.)
- **The PANDA test results contributed to an improvement of the knowledge on phenomena which have a high relevance for LWR containment safety issues**
- The relevance and **applicability to plants** of PANDA tests will be further discussed in the forthcoming **OECD/SET-2 analytical workshop**

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Analysis of SETH (1-2) PANDA tests

Organization (18)	Code (10 + 1?)	Country (13)
CEA	TONUS	France
ISRN	TONUS, ASTEC	France
EdF	NEPTUNE	France
FZK	GASFLOW	Germany
FZJ	CFX	Germany
GRS	CFX, COCOSYS	Germany
JNES	FLUENT	Japan
KAERI	MARS	Korea
JRC	CFX	The Netherlands
NRG	FLUENT-CFX6	The Netherlands
KFKI	FLUENT	Hungary
NRI	FLUENT, MELCOR?	Czech Republic
PSI	GOTHIC, CFX, FLUENT, MELCOR?	Switzerland
US NRC	FLUENT, MELCOR?	USA
Vattenfall	FLUENT	Sweden
VTT	FLUENT	Finland
AECL	GOTHIC	Canada
IBRAE	FLUENT	Russland

Analysis of SETH (1-2) PANDA tests…

Approach used in the analysis:

- In-kind contribution by individual Groups
- Various EU and OECD analytical workshops
- Systematic approach in the EU 5FWP ECORA Project in applying BPG

Analytical workshop on OECD SETH and SETH-2 experimental data

OECD/NEA, Paris, France, 13-14 September 2011

Attached benchmark on PANDA ST1_7 and MISTRA LOWMA

Investigations in the PANDA programs

PANDA	SETH 2002-2006	SETH-2 2007-2010	EDARS 2012-2015
Basic Phenomena	One-phase Plumes –jets Stratification build-up	One-phase Plumes-jets De-stratification	One / two -phases Plumes-jets Flow- obstructions
Safety components rupture foils		Spray, cooler, heat source	Combination of 2 components: e.g. spray+ cooler, etc.
Gen II-III+ Systems			Combination of compartments, and components, i.e. system

PANDA	EU-ROSATOM ERCOSAM-SAMARA (2010-2013)
Safety components	Accident scenarios from real plants scaled to different facilities

ERCOSAM-SAMARA project

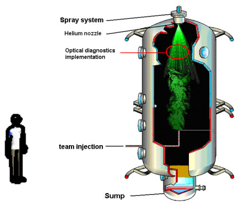
Objectives:

- investigate characteristic of hydrogen (helium) stratification build-up, in test sequence representative of a severe accident in a LWR, well chosen from existing plant calculations
  - Operation of Severe Accident Management systems (SAMs); sprays, coolers and Passive Auto-catalytic Recombiners (PARs).

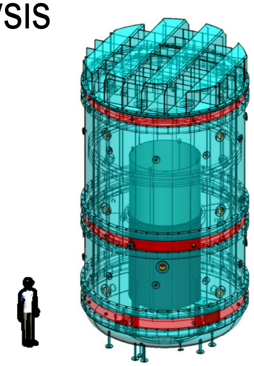
Approach:

- experiments at four different scales
- scaled down prototypical accident conditions in real plants
- Pre- and post- test analysis

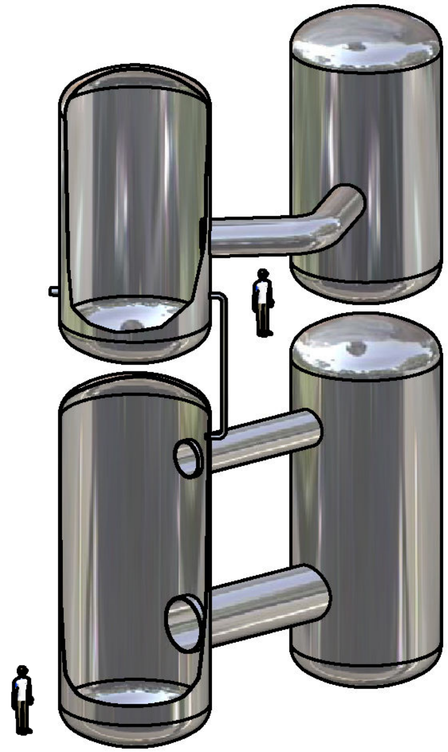
with various codes



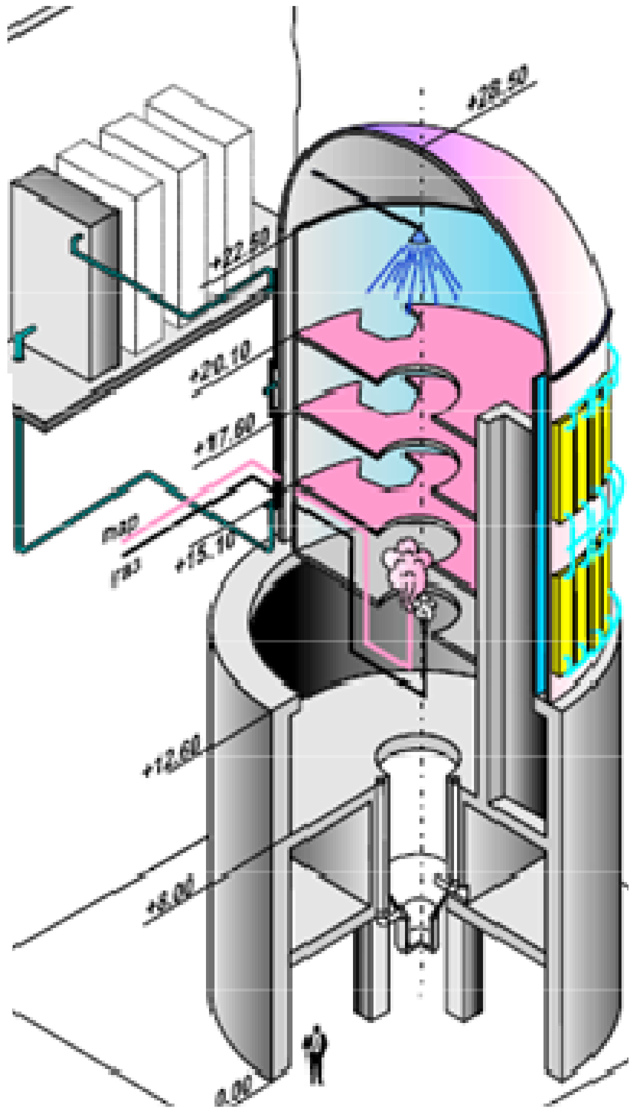
TOSQAN, IRSN ~7 m³



MISTRA, CEA ~100 m³



PANDA, PSI ~ 415 m³



KMS (NITI-RUSSIA) ~1920 m3

EDARS Project in the OECD frame (proposal)

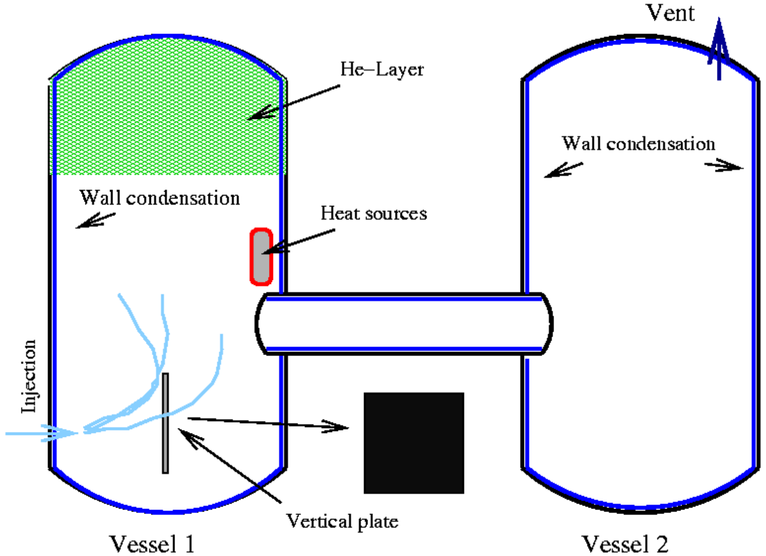
- **Basic phenomena**: containment stratification break-up by **diffuse flow source**, created by impinging of jet (**one phase), two-phase flashing jets,** use of horizontal or vertical flow obstructions

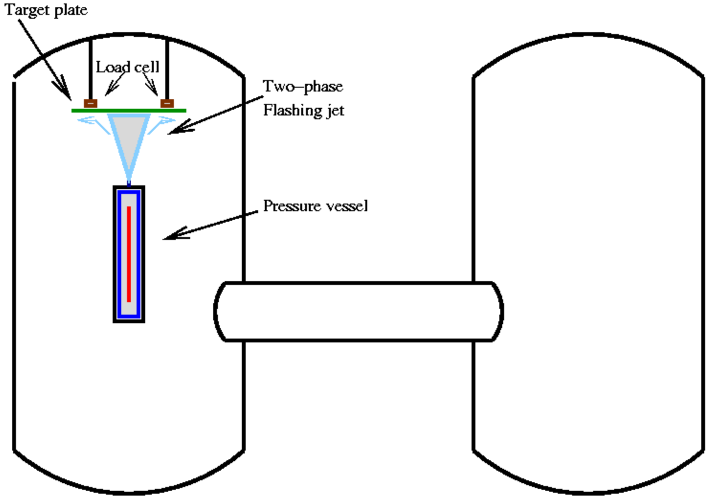
- **Complex flow pattern:** interaction of two LWR safety systems: e.g. combination of **spray and cooler** or **two heat sources**

- **LWR system response:**
  - BWR system thermal stratification in wetwell pool, effect of spray and cooler activation, interaction of primary circuit and passive containment cooling system
  - PWR system: overall natural circulation flow in the containment for effect of rupture foils opening and activation of safety systems.

EDARS: selected PANDA series

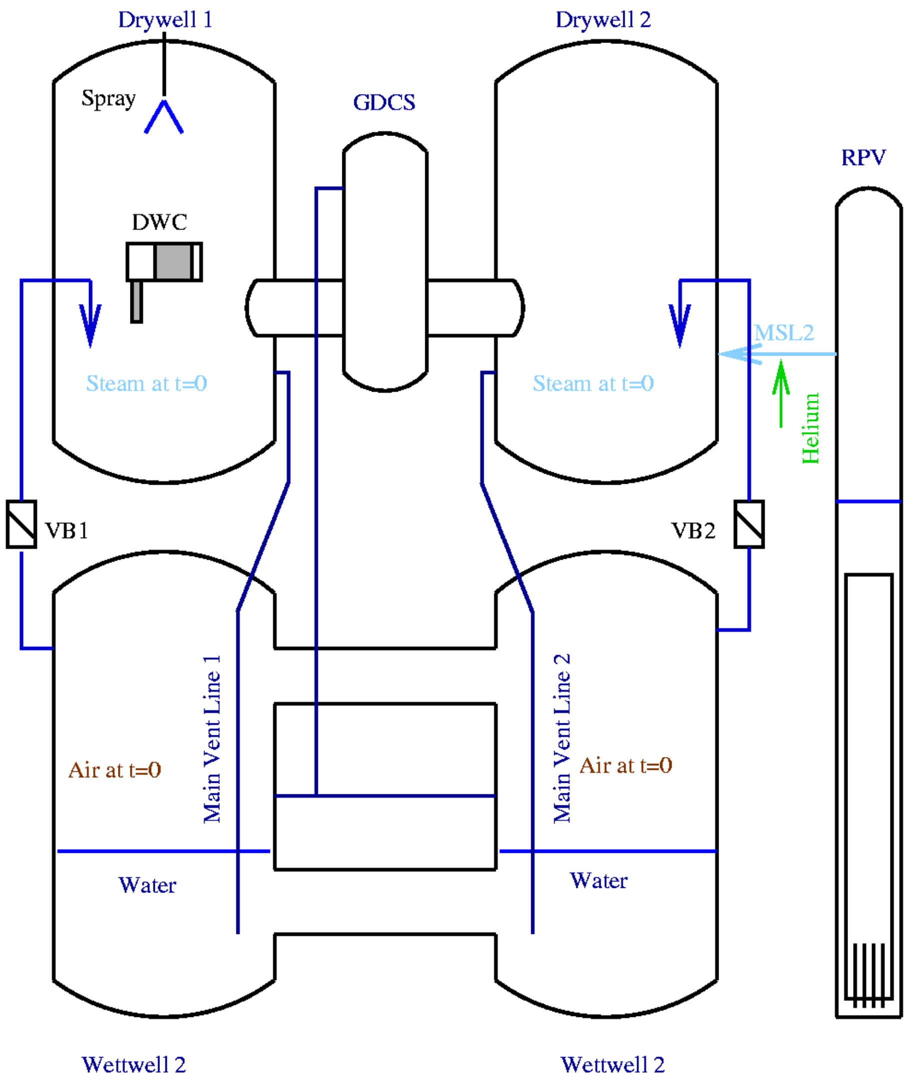
Flow obstruction and heat source





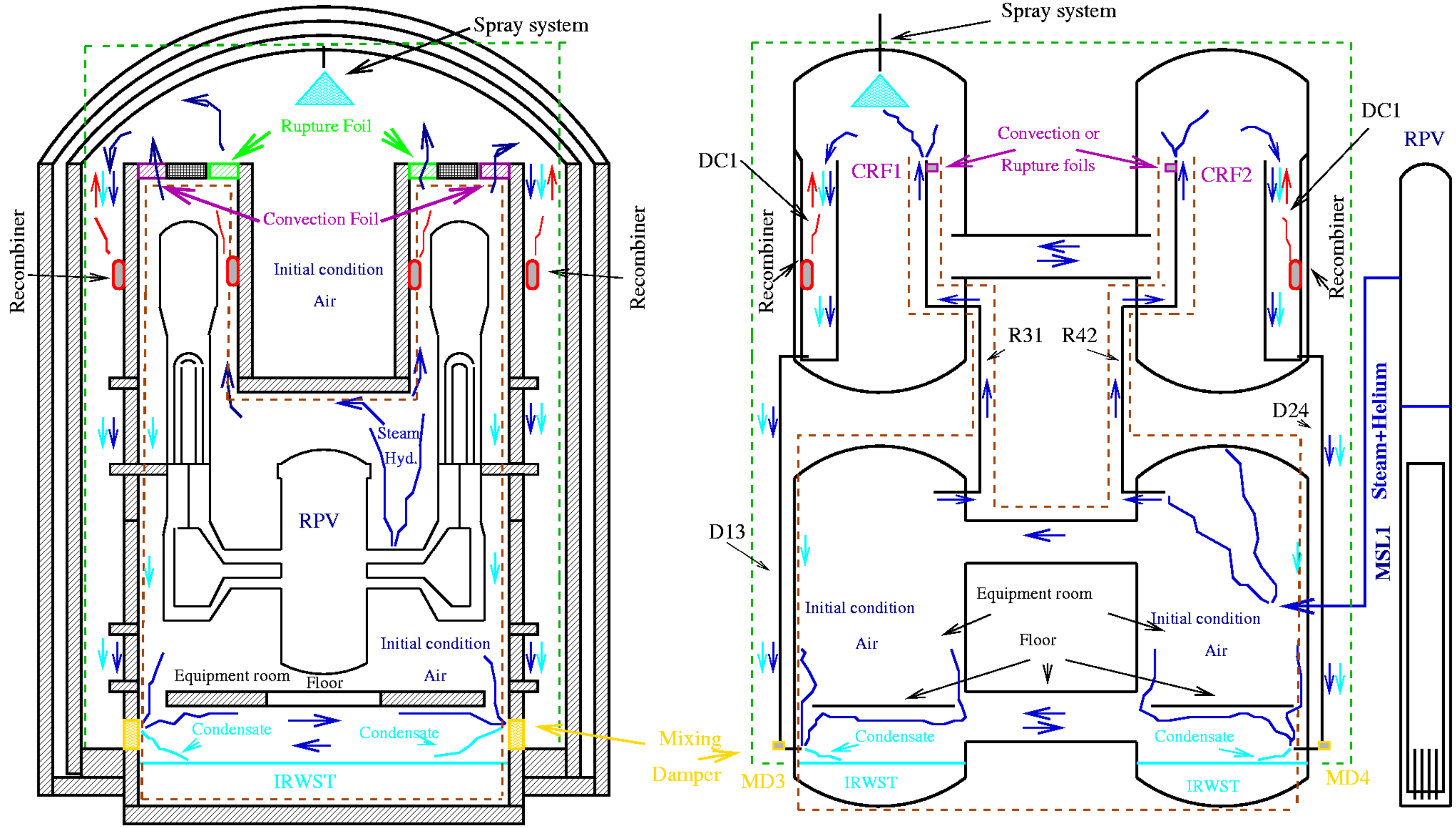
Vertical jet and horizontal flow obstruction

Cooler or spray activated



EDARS: selected PANDA series…contd.

Convection flow in the containment (internal/external compartments)



The tests produce an experimental database on complex natural circulation flow between containment compartments for a wide range of geometrical and thermal-hydraulic parameters

Overview of proposed series (1/2)

n		C_n	C_n*n_{Pn} (PANDA)
	Separate effects/flow obstruction		
1)	Low momentum horizontal (or vertical) with vertical (or horizontal) flow obstruction	1	C_1*n_{P1}
2)	Two-phase flashing jets (horizontal and/or vertical)	2	C_2*n_{P2}
	Safety components		
	Safety component/flow obstruction		
3)	Heat source with vertical (or horizontal) flow obstruction	1	C_3*n_{P3}
	Safety component interactions		
4)	Two Heat sources with and without cooler	2	C_4*n_{P4}
5)	Heat sources with and heat sink (cooler)	2	C_5*n_{P5}
6)	Spray and heat source	2	C_6*n_{P6}
7)	Spray and containment cooler	2	C_7*n_{P7}

Overview of proposed series (2/2)

	Systems		
	BWR systems		
8)	Thermal stratification in pools	2	$C_8 * n_{P8}$
9)	Cooler and spray, Drywell to Wetwell venting, and VB opening	3	$C_9 * n_{P9}$
10)	Primary + containment	4	$C_{10} * n_{P10}$
	PWR systems		
11)	Opening of foil and dampers	4	$C_{11} * n_{P11}$
12)	Opening of foil and dampers + spray	5	$C_{12} * n_{P12}$
13)	Opening of foil and dampers + spray + heat source	5	$C_{13} * n_{P13}$
14)	Opening of foil and dampers+ 2 heat sources	5	$C_{14} * n_{P14}$
15)	Opening of foil and dampers +spray + 2 heat sources	5	$C_{15} * n_{P15}$
			$\sum_{n=1}^{15} C_n \bullet n_{pn} \leq 32$

Recommendations for code validation

For the sake of identifying the tests most suitable for their validation, it is useful to divide the codes in five categories:

- A: Lumped-parameter containment codes (e.g., MELCOR, ASTEC)
- B: System codes (e.g., TRACE, MELCOR, CATHARE, MARS)
- C: Lumped-parameter containment and integral codes used on a 3-D mesh (e.g., COCOSYS, ASTEC)
- D: System and Containment codes with 3D capabilities (e.g., GOTHIC, GASFLOW, TONUS, MARS)
- E: General purpose (commercial) CFD codes

EXT: extended version, i.e. modification is needed

n	A	B	C	D	E
1)				+	STD
2)				+	STD and EXT
3)				+	STD
4)				+	STD
5)			+	+	STD
6)	+	+	+	+	EXT
7)		+	+	+	EXT
8)		+	+	+	STD and EXT
9)	+	+	+	+	EXT(*)
10)	+(*)	+	+(*)	+(*)	EXT(*)
11)	+	+	+	+	
12)	+	+	+	+	
13)	+	+	+	+	
14)	+	+	+	+	
15)	+	+	+	+	

* Coupling with a system code is required

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Conclusions

- The OECD/NEA/SETH-2 project has been carried out with the support of 9 countries to generate an experimental data base on **LWR containment phenomena for safety issues**
- The PANDA investigation addressed **gas stratification and stratification break-up by heat and mass source** as well as consequence of activation of safety systems
- The interpretation of the PANDA test results is still on going
- **Analytical activities** accompanied the SETH-2 projects and others are on going in view of an **OECD/NEA workshop and benchmark,** which will be held in Paris in September 2011
- Needs identified within and beyond the SETH-2 project are currently investigated in the **EU-Russian ERCOSAM-SAMARA project** and the proposed **SETH-2 follow-up (EDARS project)**