PSI Center for Nuclear Engineering and Sciences

Scaling aspects in PANDA experiments

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EASI-SMR Workshop 1 on scaling issues

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Outline

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- Scaling relevance and challenges
- SBWR/ESBWR versus PANDA
- PANDA facility modularity
- Multi-step planning calculations to define tests
- EASI-SMR PANDA tests
- Conclusions

Scaling relevance and Challenges

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- *"Scaling is a reference 'key-word' in engineering and in physics. The origin of the scaling-issue, i.e. the impossibility to get access to measured data in case of accident in nuclear reactors".* F. D'Auria, G.M. Galassi, **Scaling in nuclear reactor system thermal-hydraulics**, Nuclear Engineering and Design, 240 (2010)

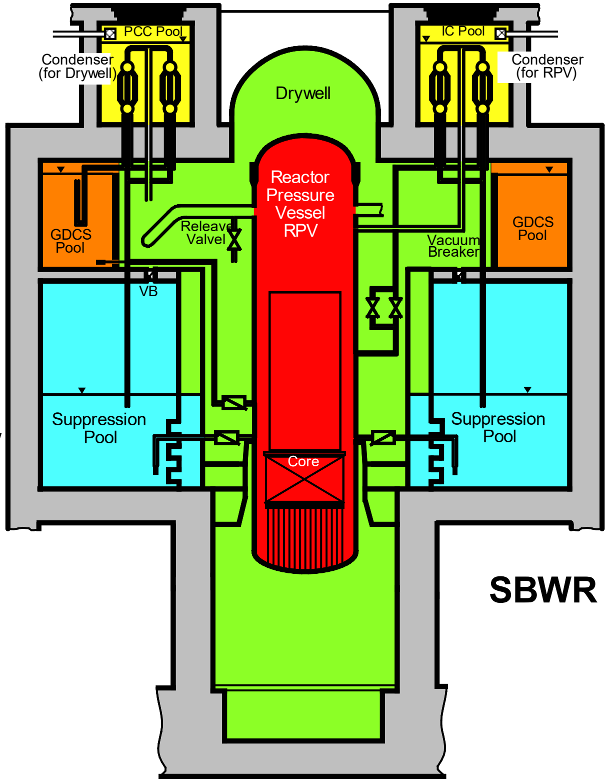
- *"The assessment of reactor prototype computer model against meaningful experimental data is essential in a reactor design. Scaling analysis includes the process to design a scaled test facility from the prototype to reproduce physical phenomena of interest expected in the prototype design. It also includes distortion analysis to gauge the amount of distortion resulted from scaling".* P. -H. Lien, U. -S. Rohatgi**, Scaling challenges in small modular reactor** Nuclear Engineering and Design, 407 (2023)

- **Challenges:**
  - Different scaling methodologies
    - ✓ Hierarchical Two-Tiered Scaling (H2TS),
    - ✓ Ishii Three-Level Scaling (TLS),
    - ✓ Fractional Scaling Analysis (FSA),
    - ✓ Dynamical System Scaling (DSS),
    - ✓ etc.
  - Impossibility to scale all the phenomena
  - Multi-scale phenomena affecting the evolution of postulated scenarios
  - Costs and compromises associated to the facility, instrumentation, simulations, etc.

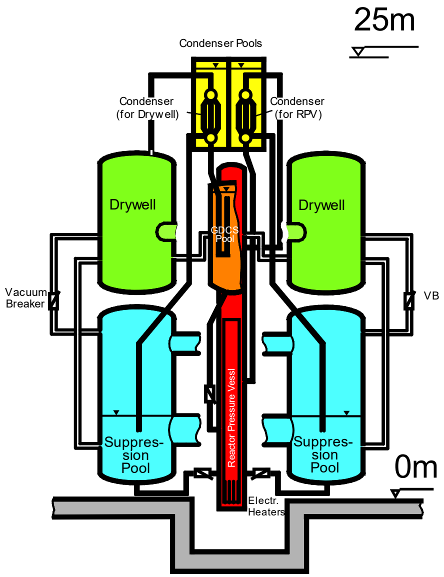
SBWR/ESBWR versus PANDA

PANDA is based on the Simplified Boiling Water Reactor (SBWR, 670 MWe) and Economic SBWR (ESBWR, 1200 MWe)

- ❑ Modular structure gives flexibility:
  - Drywell and Wetwell are both subdivided into two inter-connected vessels
  - Connecting lines between vessels allow for broad variety of test configurations
- ❑ Scaling:
  - Height 1:1
  - Volume 1:25 (SBWR)
  - Power 1:40 (ESBWR)
  - Same fluids *(water, steam, gas)*
  - Same operating conditions *(P, T)*
- ❑ Main parameters:
  - Volume : 515 m^3, Power : 1.5 MW
  - 0 - 10 bar; up to 200 °C

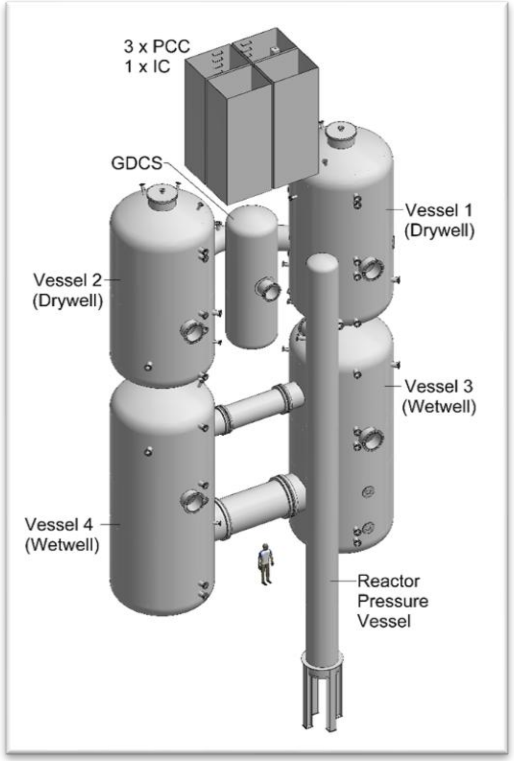


SBWR



PANDA

Scaling:
Height 1:1
Volume 1:25
Power 1:25



SBWR containment and passive decay heat removal system are represented in PANDA
Identical colors indicate volumes with identical functions

Yadigaroglu, G., 1993. **Scaling of the SBWR Related Tests.** GE, NEDO-32258.

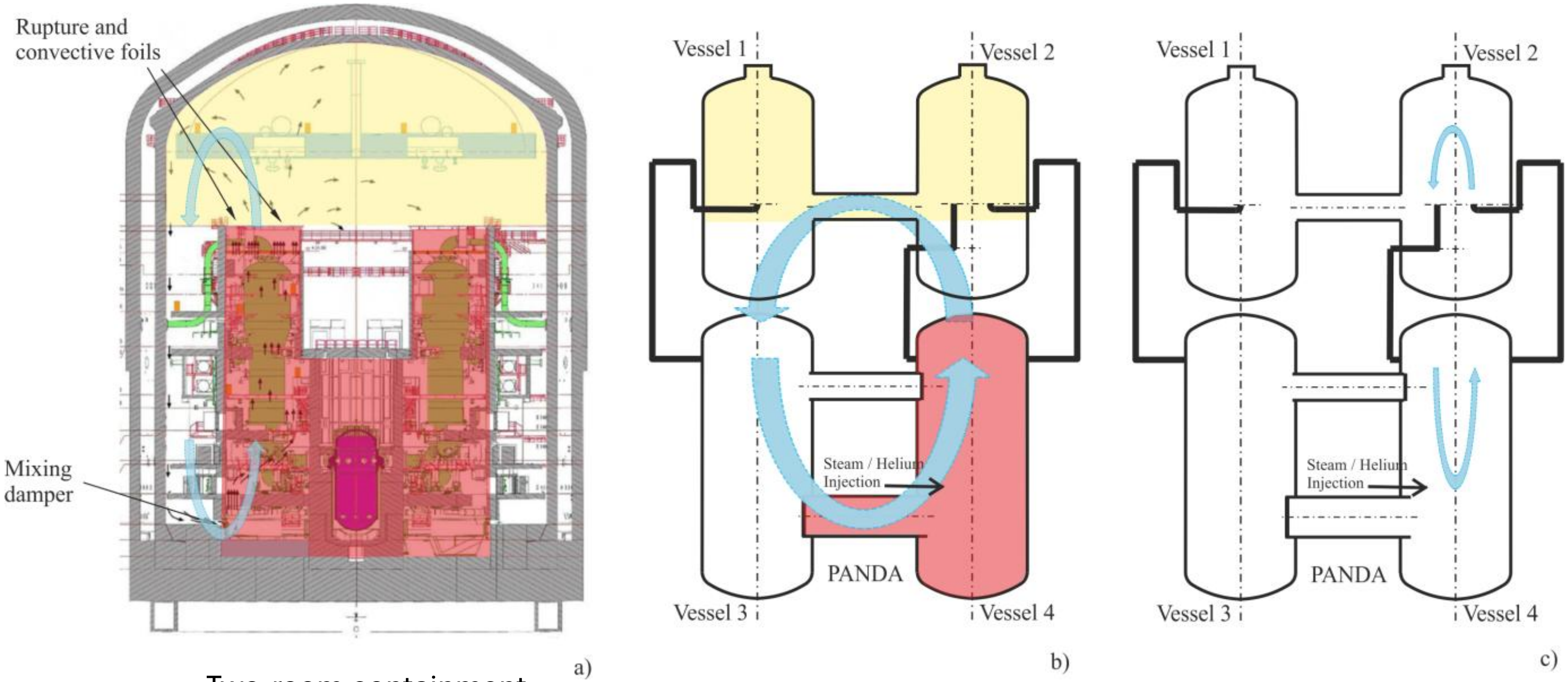
Multi-step planning calculations to define test… PSI

- Over the years, PANDA was operated in for investigations including a variety of reactor designs.
- However, since PANDA was designed for specific geometries and accident conditions, global scaling criteria are of limited use for designing new experiments addressing 3-D phenomena in different geometries and for different scenarios.
- PANDA Tests addressing specific reactor safety features specific were defined applying a multi-steps methodology based on planning calculations with computational tools. Examples include the PANDA series HP2, HP3, HP6 (OECD/NEA HYMERES project).
- The HP6 series) was defined to address “Natural circulation flow induced by opening hatches and effect on safety systems”, (KONVOI-EPR reactors).
- The multi-step methodology include the following:
  - Modeling first a generic NPP containment
  - Identify the key-phenomena characterizing the postulated accident
  - Analyze the postulated accident considering a variety of potential PANDA modifications
  - Identify the modifications needed in PANDA to reproduce the key-phenomena with “acceptable distortions” with respect to the generic NPP

D. Paladino, R. Kapulla, S. Paranjape, S. Suter, C. Hug, M.-S. Chae , M. Andreani, **PANDA experimental database and further needs for containment analyses**, Nuclear Engineering and Design, Volume 404, 1 April 2023, 112173.

Multi-step planning calculations to define tests... PSI

PANDA HP6 - Natural circulation flow induced by opening hatches and effect on safety systems



Two-room containment

PANDA HP6_1 test (EPR type)

PANDA HP6_2 test (KONVOI type)

M. Andreani, D. Paladino, D. Papini, **Multi-Step Planning Calculations with the GOTHIC Code Used for the Design of Complex Experiments in the PANDA Facility**, Nuclear Engineering and Design, Volume 339, Pages 116-125, 2018.

EASI/SMR PANDA tests

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Key phenomena

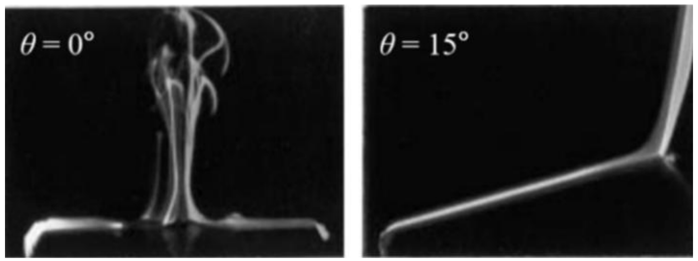
B. Thermal stratification

✓ Identification of thermal evolution on the pool over the vertical elevation

F. Condensation

E. Water surface evaporation

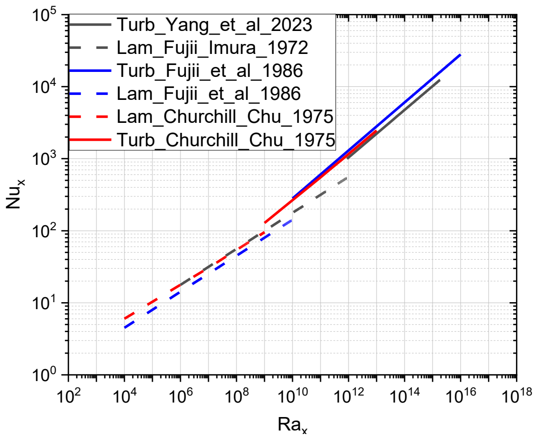
D. Detached boundary layer on the top

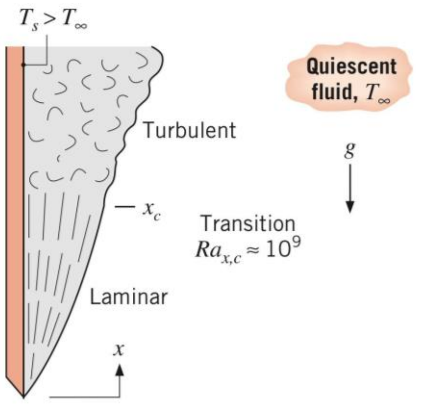


[Kimura et al., 2002]

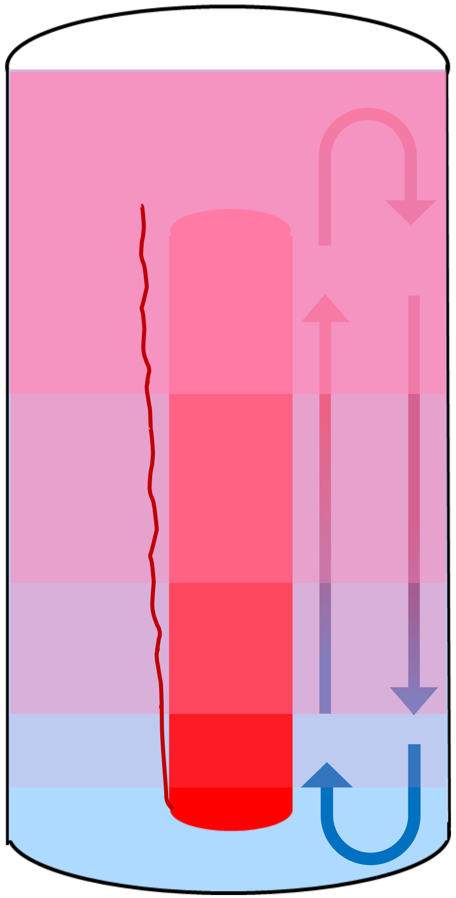
C. Laminar-to-turbulent transition

✓ Transition to turbulent regime → $Ra_x \sim 10^9$





[Fundamentals of Heat and Mass Ttransfer, Incropera, p.602]

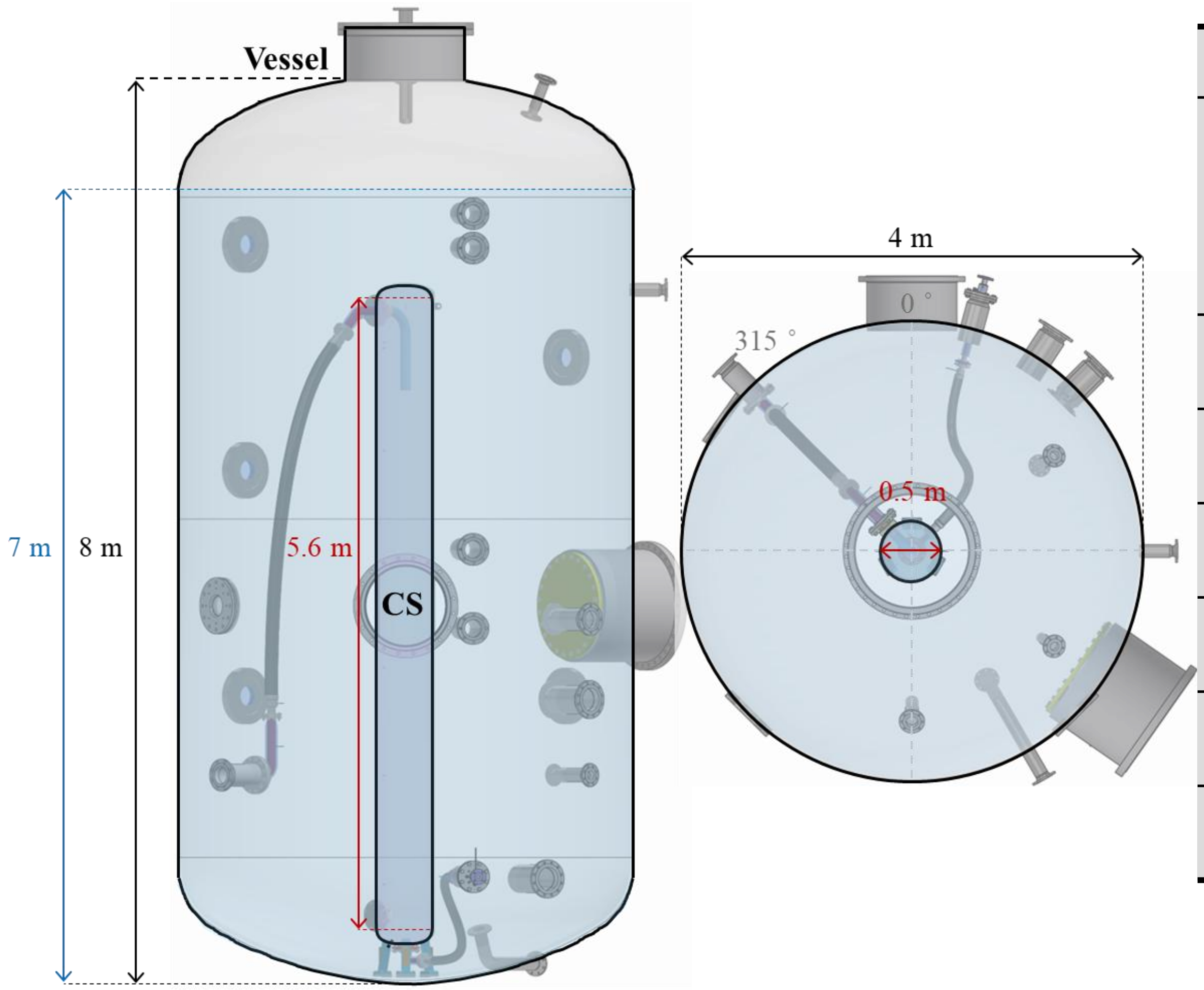


A. Turbulent natural convection

✓ Main heat transfer mechanism, characterized by Ra_H

✓ $H = 5.6\ m$ → $Ra_H \sim 10^{15}$

EASI/SMR PANDA tests…contd.



Parameters	CS	Vessel
H (m)	5.600 (excludes the upper and lower domes) 5.842 (total inner), 5.850 (total outer)	8.000 (without manhole) 7.000 (water level)
D (m)	0.490 (inner), 0.508 (outer)	3.961 (inner) 4.000 (outer)
Thickness (m)	0.0098	0.02
Area (m^2)	9.000 (inner), 9.340 (outer)	108.49 (total area) 90.67 (wetted area)
Volume (m^3)	1.085	89.91 (total volume) 79.98 (water volume)
D_{CS}/D_{Vessel}	Diameter of Vessel / Diameter of CS ~ 8	
V_{CS}/V_{Vessel}	Volume of Vessel / Volume of CS ~ 73	

※ The dimension was set based on scoping analysis by EDF using CFD codes in OECD/NEA PANDA P1A5 project.

Morente (EDF), J. Uribe (EDF), S. Benhammadouche (EDF), P. Rotach (EDF), M. Montout (EDF) J.-L. Vacher (EDF), D. Paladino (PSI), M. S. Chae (PSI) **New Experiments for Natural Convection at High Rayleigh Numbers: Definition, Sizing and Analysis using CFD** *Proceeding of NURETH-21, 2025*

Morente, A.; Uribe, J.; Benhamadouche, S.; Rotach, P.; Vacher, J.-L.; Chae, M.S.; Paladino, D, **Scoping Analyses for the Definition of New Experiments for Natural Convection at High Rayleigh Numbers** Proceedings of Advances in Thermal Hydraulics, ATH 2024

EASI/SMR PANDA tests...contd.

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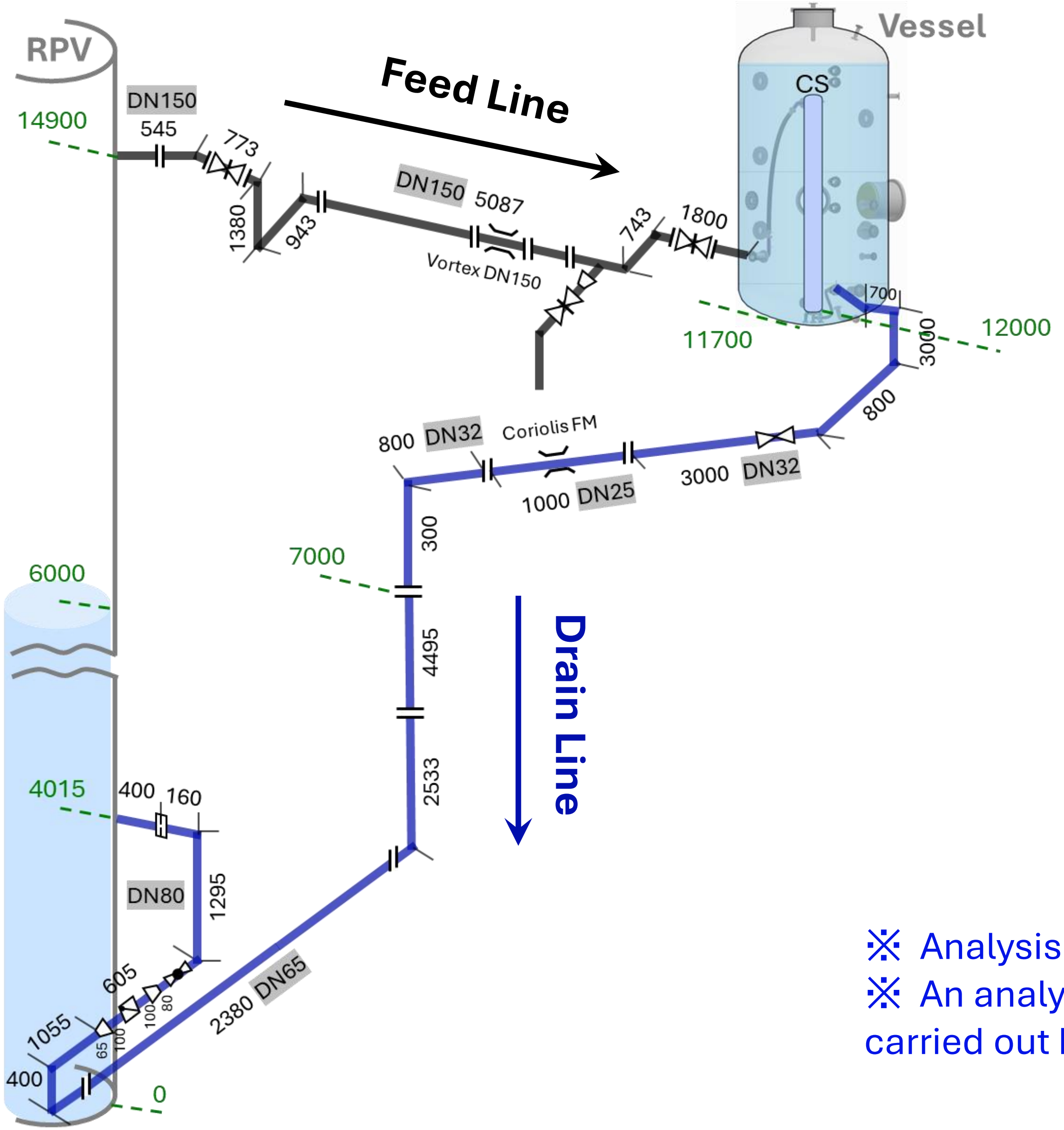


Feed Line

- Saturated steam injection from RPV
- Flow rate : 100 g/s – 380 g/s
- Injection pipe inside the vessel to be insulated as a double-wall pipe

Drain Line

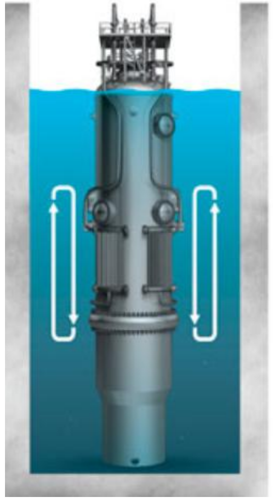
- Condensation inside CS flows back to RPV
- Flow is driven by differential head between the condensate level (CS) and water level (RPV)
- Drainpipe inside the vessel to be insulated as a double-wall pipe

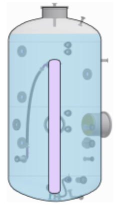
※ Analysis of the drain line using TRACE was performed by Nikitin Konstantin (PSI).
※ An analysis of the natural circulation between the Feed and Drain lines is being carried out by Farah Alsafadi, (PSI) with APROS.

EASI/SMR PANDA tests...contd.

Scaling prototype versus PANDA-CS

Parameters	SMRs [1 - 3]	PANDA-CS
Volumetric ratio (V_{SMR}/V_{water})	0.200 - 0.608	0.012
Diameter ratio (D_{SMR}/D_{water})	0.500 - 0.738	0.125
Height-to-diameter ratio	0.196 - 0.333	0.089
Power (MW)	~ 10	~ 0.9
Heat flux (W/m²·K)	~ 100,000	~ 98,000
Pressure (bar)	~ 60	~ 8
Characteristic length, H (m)	12 - 23	5.6
Ra_H	**10^{15} - 10^{16}**	**10^{14} - 10^{15}**
Pr	**~ 7**	**~ 7**





$$Ra_H = \frac{g\beta(T_w - T_b)H^3}{\alpha v} \qquad Pr = \frac{v}{\alpha}$$

α : Thermal diffusivity
β : Thermal expansion coefficient
ν : Kinematic viscosity
H : Height of the CS
Physical properties at T_c, where $T_c = \frac{T_{wall} + T_{bulk}}{2}$

1. **NuScale** Small Modular Reactor Integration for Hydrogen and Ammonia Production, WP-178373, Rev 2, Office of Technology, 2025.02.25
2. **LDR-50** District Heating Reactor Technology SYP2022, Jaakko Leppanen, 2022.11.02.
3. Design characteristics of nuclear steam supply system and passive safety system for Innovative Small Modular Reactor (**i-SMR**), Nuclear Engineering and Technology Vol. 57, No. 10, 103697 (2025)

EASI/SMR PANDA tests...contd.

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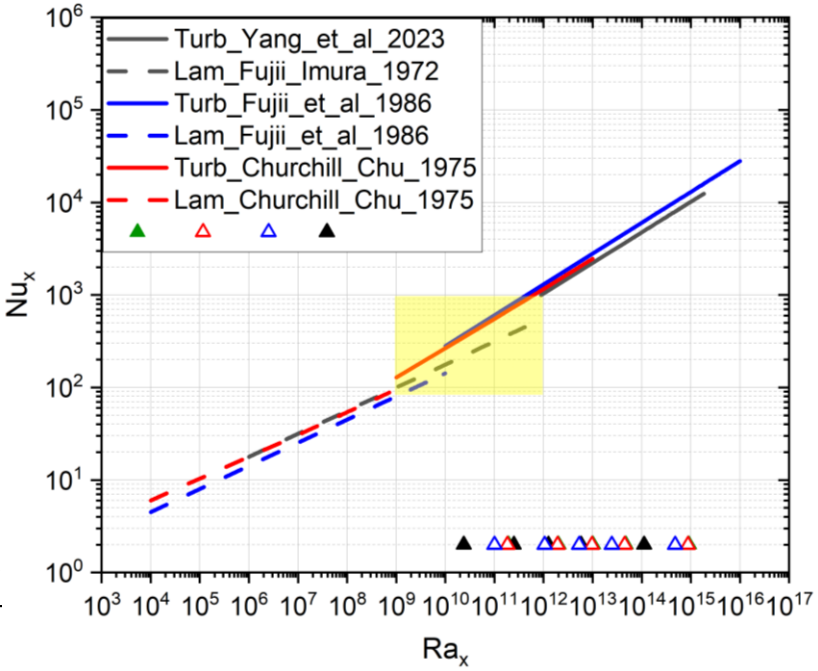
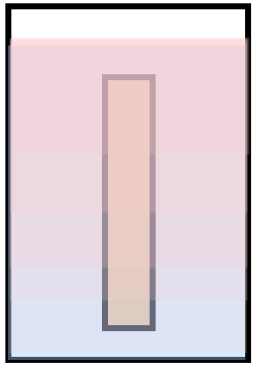
Scaling issue

- The dominant parameter in natural convective heat transfer is the **buoyancy force** generated by $T_w - T_b$.
- Dimensionless number of this effect is **Rayleigh number (Ra).**
- The graph of $\boldsymbol{Ra_H}$ **-** $\boldsymbol{Nu}$



$$Nu = \frac{hH}{k}$$

- In order to realistically represent a prototype SMR, multiple phenomena need to be taken account
  - **Coupling** between the natural convection on the heated wall and thermal stratification in the pool
  - **Geometric effect** : the magnitude of volume surrounding containment of SMR
  - **Geometric effect** : aspect ratio effect (such as *H/D*, *D/H* etc.)



$$Ra_H = \frac{g\beta(T_{wall} - T_{bulk})H^3}{\alpha v} = Gr_H \cdot Pr$$

$$f(x) = \{Ra_H, \frac{H}{D}, \frac{D_{SMR}}{D_{total}}\ etc.\}$$

→ Scaling between the prototype and the PANDA facility, including **geometric effects**, **thermal stratification effects** etc. based on Ra_H.

Conclusions

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- Objectives of scale analysis are to:
  - Preserve the key physical phenomena observed in the prototype
  - Ensure similarity between the prototype and the experimental facility

- However, it is difficult to simulate all specific phenomena taking place in the facilities with those expected in a real plant. Moreover, large scale facilities are typically operated for years and for a variety of reactor designs, and accident scenarios and therefore global scaling criteria are of limited use to define the needed facility modifications and the new test conditions.
  - Need to characterize the governing parameter on certain phenomena
  - Consider the Figure of Merit (FOM) : quantitatively assess how well a scaled experimental facility reproduces the thermal-hydraulic behavior of the prototype system

- Multi-steps planning calculations, in which analyses of postulated accident scenarios are carried out modeling prototypal reactor :

  i) to improve the understanding on the phenomena, **ii)** to define the needed facility modification, instrumentation and experimental conditions, **iii)** to assess the phenomena distortions, **iv)** to improve the computational tools, **v)** to train the code user, etc.

Thank you!