CFD Assessment of Steady-State Heat Loss during the Normal Operating Condition for the Advanced SMRs

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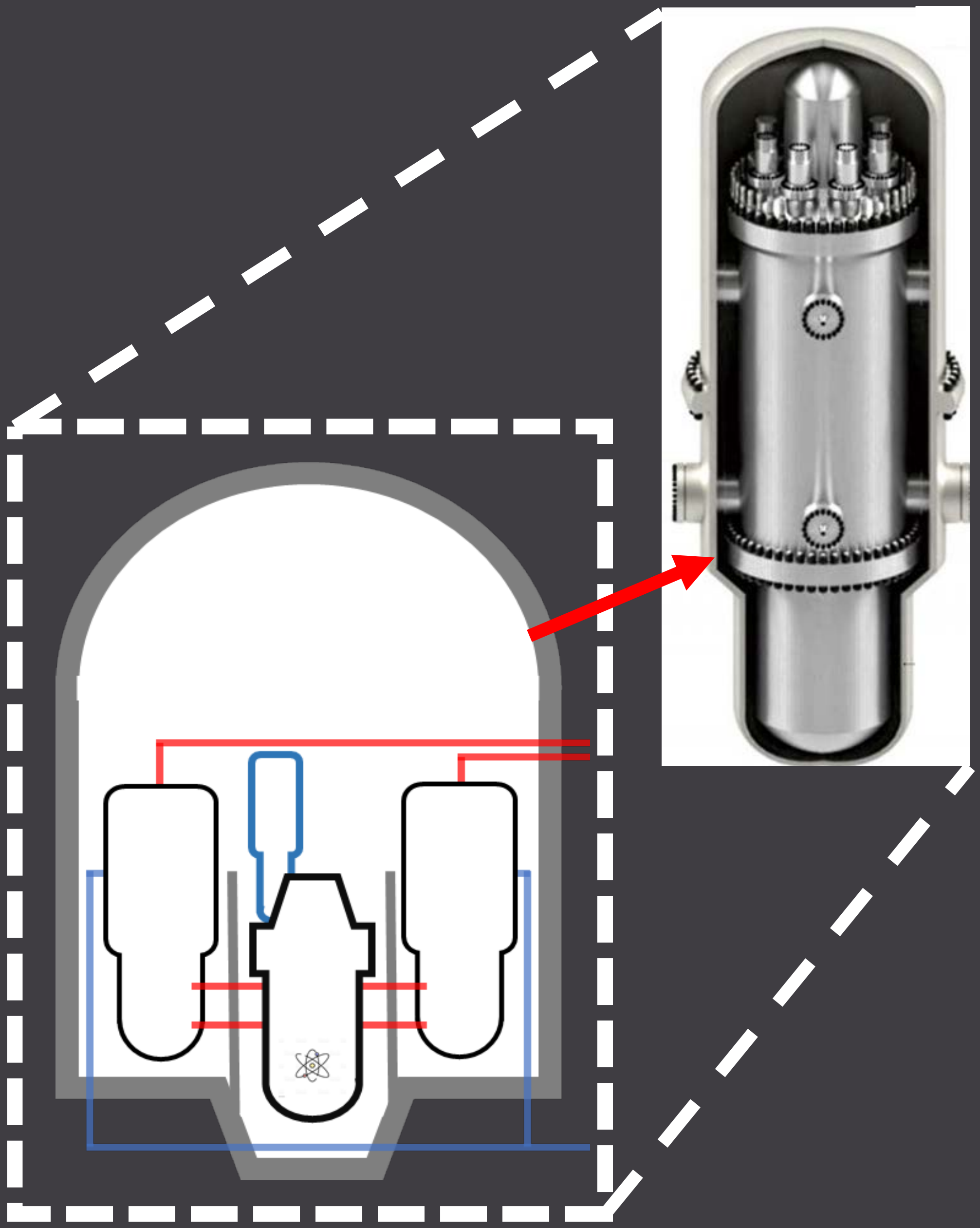
2021. 10. 21

2021, KNS, Autumn



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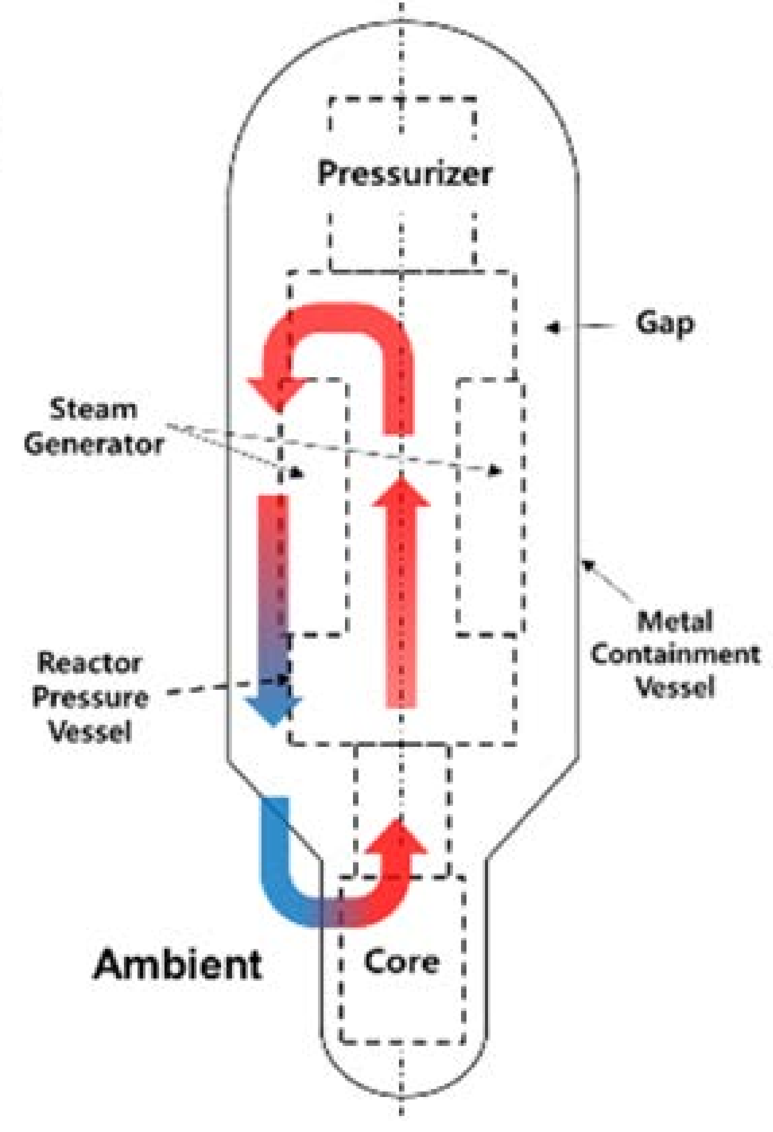

Backgrounds & Motivation

Small Modular Reactor

IAEA
International Atomic Energy Agency

Small Modular Reactor (SMR)
An advanced reactor that produces electrical power up to 300 MWe.

Characteristics

Safety

- CDF $<10^{-9}$/RY
- LRF $< 10^{-10}$/RY
- Simple design
- Passive Safety System

Utilizations

- Seawater desalination
- Local generation
- With renewable energy

Economic

- Capital cost ↓
- Construction period ↓
- Factory-modularization

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1) https://www.iaea.org/topics/small-modular-reactors/smr-regulators-forum

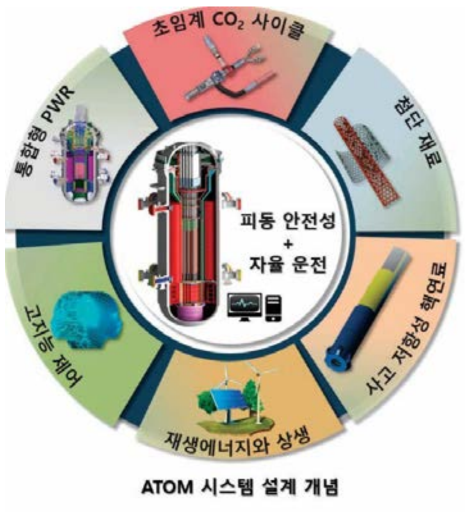
Backgrounds & Motivation

Double Vessel Structure

❖ Advanced SMRs

NuScale

i-SMR

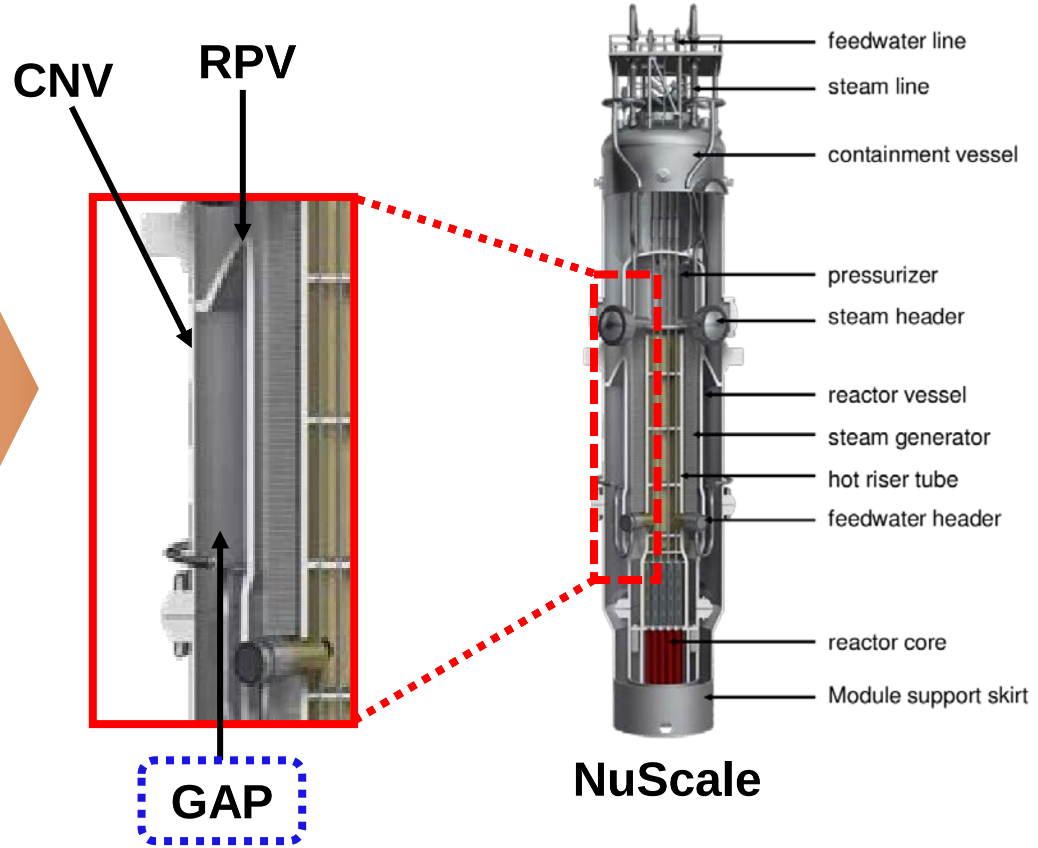


ATOM

Characteristic structure

Double Vessel Structure

Reactor Pressure Vessel & Metal Containment Vessel



NuScale

1. To retain unwanted loss of coolant and FP
2. **Acts as an insulator**

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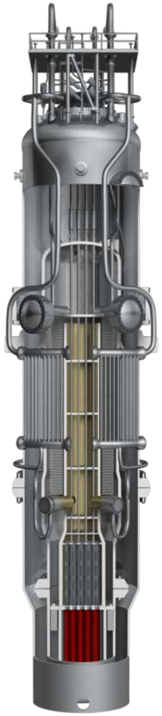
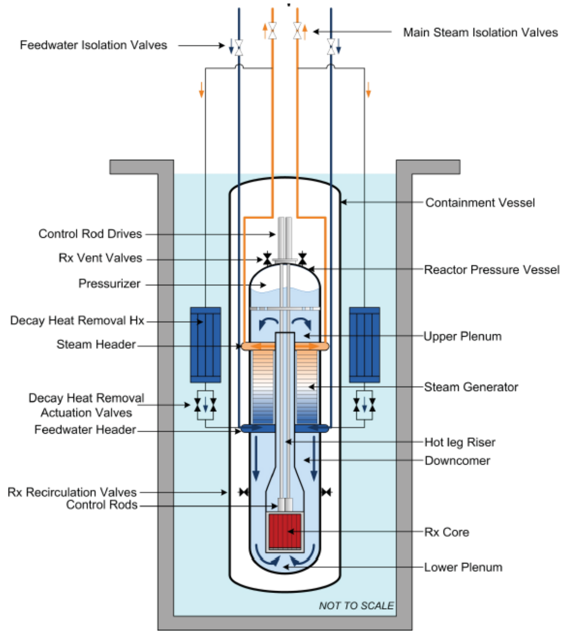
1) https://www.nuscalepower.com/technology/design-innovations

Backgrounds & Motivation

Double Vessel Structure

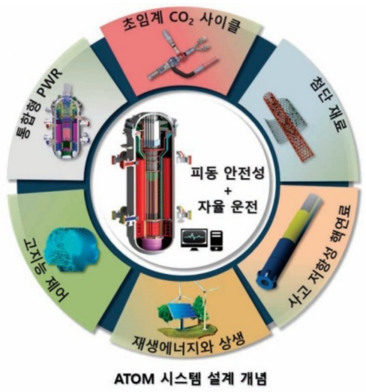
❖ Thermal condition during the normal operating condition



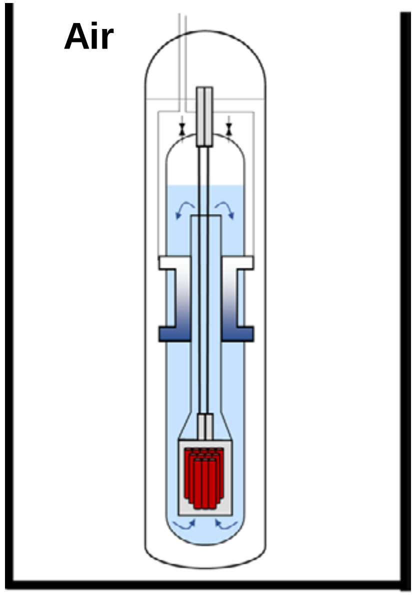


NuScale

1. **Submerged** containment vessel
2. Maintaining **vacuumed** containment



ATOM 시스템 설계 개념



ATOM and i-SMR

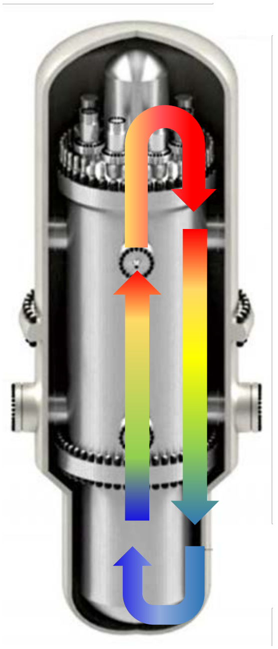
1. **Dry** containment vessel
2. Filling the gap **with gas material**

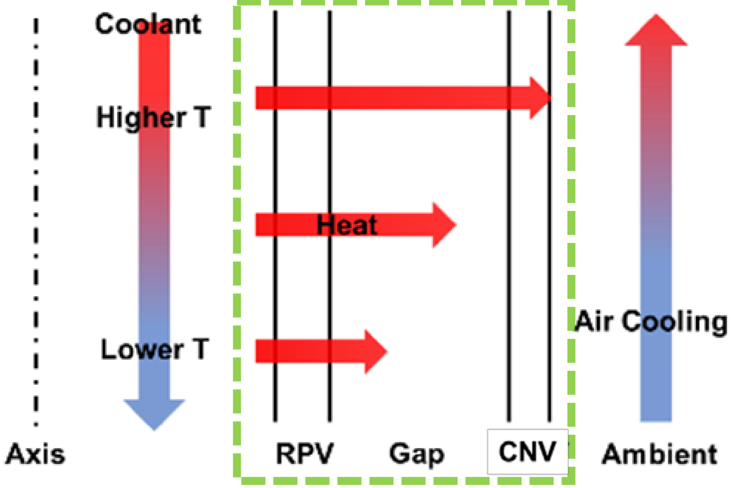
1) https://www.nuscalepower.com/technology/design-innovations

Backgrounds & Motivation

Overview

Heat transfer mechanism of the i-SMR





Inside gap space

1. Vacuum

- Only radiation heat transfer (Ideally)

2. Gas-type filler

- Convection and Radiation
- Candidates: *Air*, *Argon*, *Xenon*, *Carbon dioxide*

Purposes

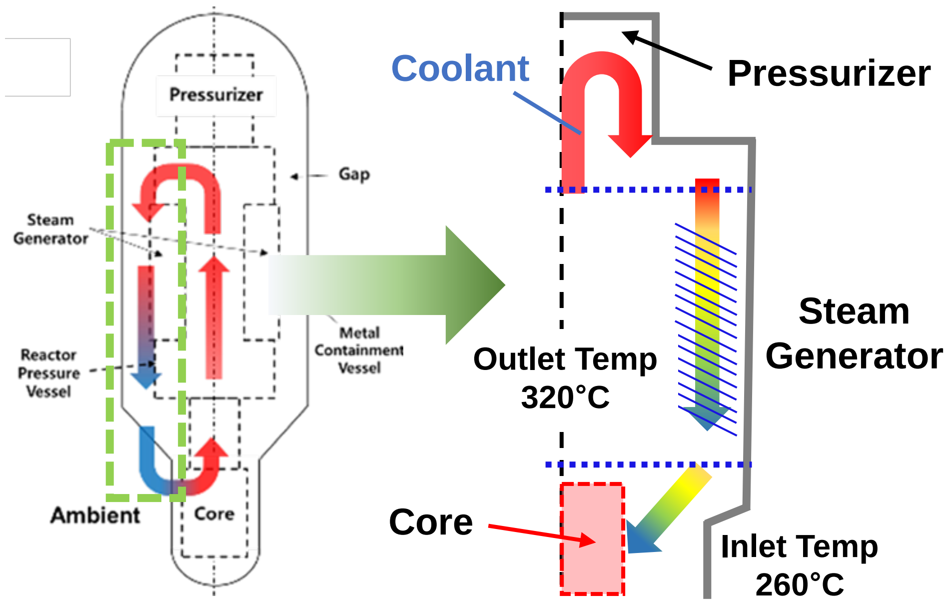
1. To understand the heat transfer mechanism of the ATOM
2. To make a quantitative comparison of heat loss according to gap conditions.
3. To identify the possibility of replacing the vacuum condition with the gas filler

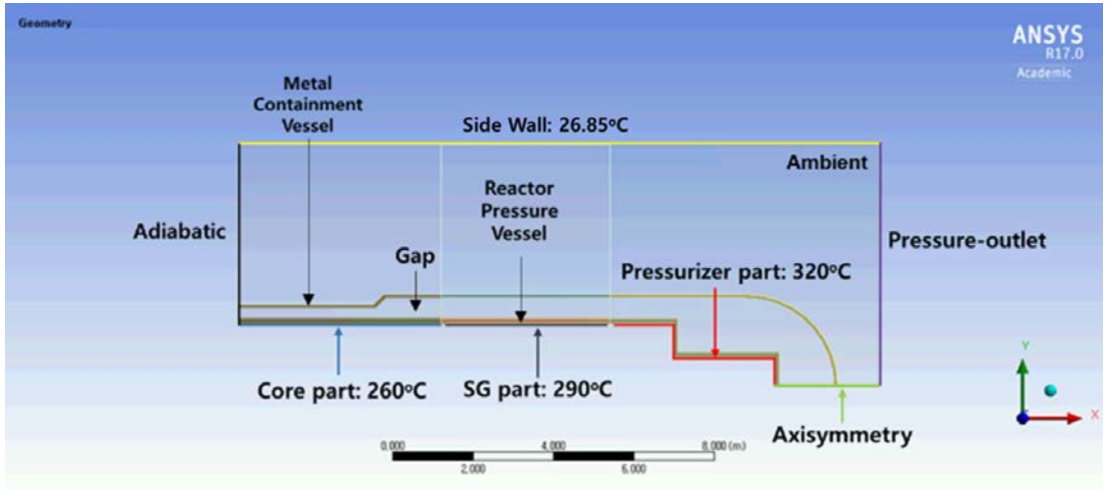
CFD simulation
Ansys Fluent

Methodology

Geometry and Boundary Condition

❖ Geometry and Boundary Condition





Variable [m]	Size	Variable [m]	Size
CNV height	14.886	RPV height	13.440
CNV outer radius	2.022-2.273	RPV outer radius	0.84-1.68
CNV thickness	0.09	PRV thickness	0.13

	Density (ρ) $[kg/m^3]$	Specific Heat (Cp) [J/(kg·K)]	Thermal Cond. (k) [W/(m·K)]	Emissivity (ε) [-]
Carbon steel (RPV)	7,833	465	54	0.7
Stainless steel 316 (CNV)	7,870	490	13	0.4

RPV Temperature B.C

Steady-State, Constant coolant temperature

Divided into 3 parts: Pressurizer, SG, Core

Area: 56.78 m^2, 84 m^2, 70m^2 (respectively)

Methodology

Fluent Solver Setting and Convergence Criteria

❖ Solver Setting

Viscous Model		**k-epsilon Realizable**
Density Model		**Boussinesq approximation**
Radiation Model		**DO Model (Gray-radiation)**
Spatial Discretization	Gradient	Least Squares Cell Based
	Pressure	**Body Force Weighted**
	Momentum	2nd Order Upwind
	Energy	2nd Order Upwind
Pressure-Velocity Coupling		**Coupled**
Flow Courant Number		**1**

Buoyancy effect

1. Boussinesq approximation

$$\rho = \rho_0 - \beta\rho_0(T - T_0)$$

Assume that the density change is linear

2. Body Force Weighted

Radiation effect

Discrete Ordinates (DO) Model

gray-radiation: emissivity is constant depending on wavelength

❖ Convergence Criteria

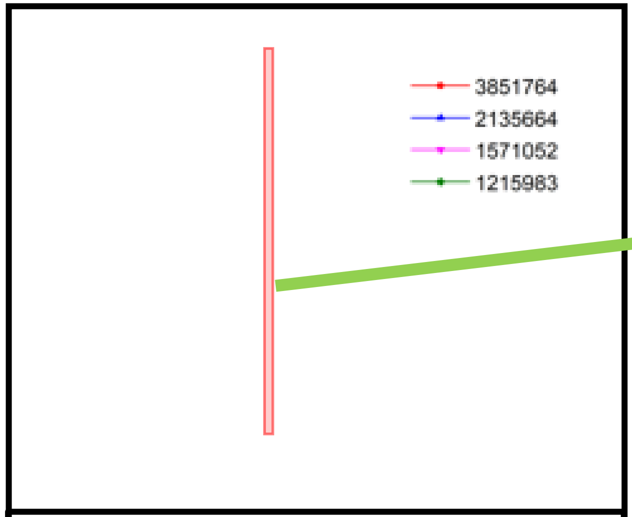
Residual of continuity, k and epsilon: **below 10^{-3}** Residual of energy: **below 10^{-8}**

Methodology

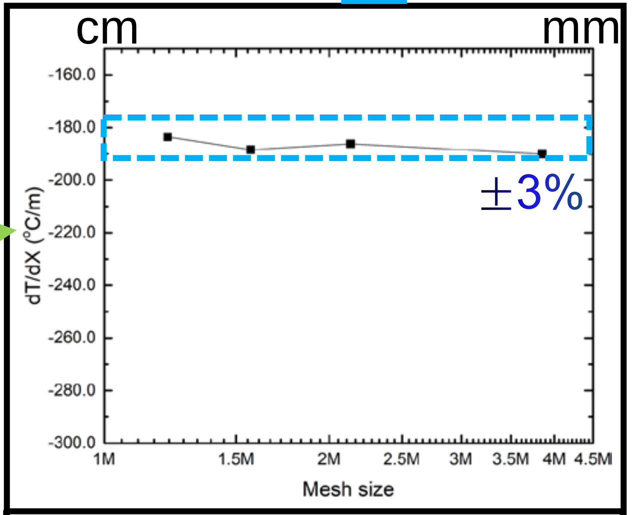
Mesh Sensitivity

❖ Mesh sensitivity

$$Fourier's\ law:\ q'' = -k\boxed{\frac{dT}{dx}}\ (k_{MCV} = 13\ W/m\cdot K)$$

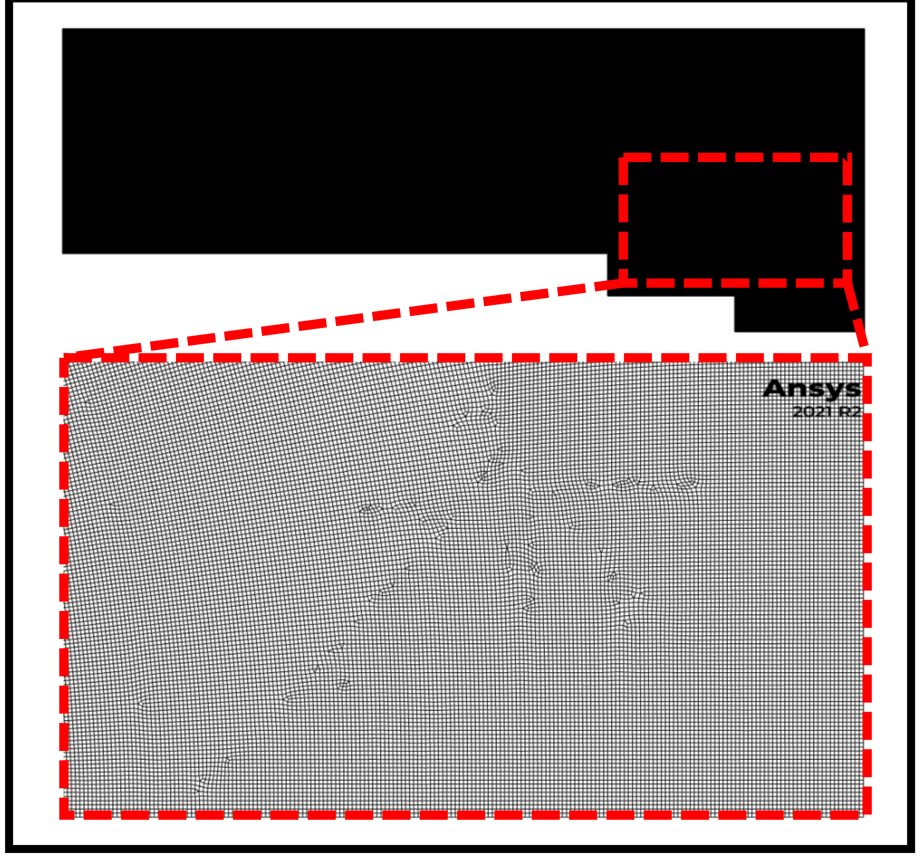


Temperature distribution



Temperature gradient

Generated mesh (2,135,664#)



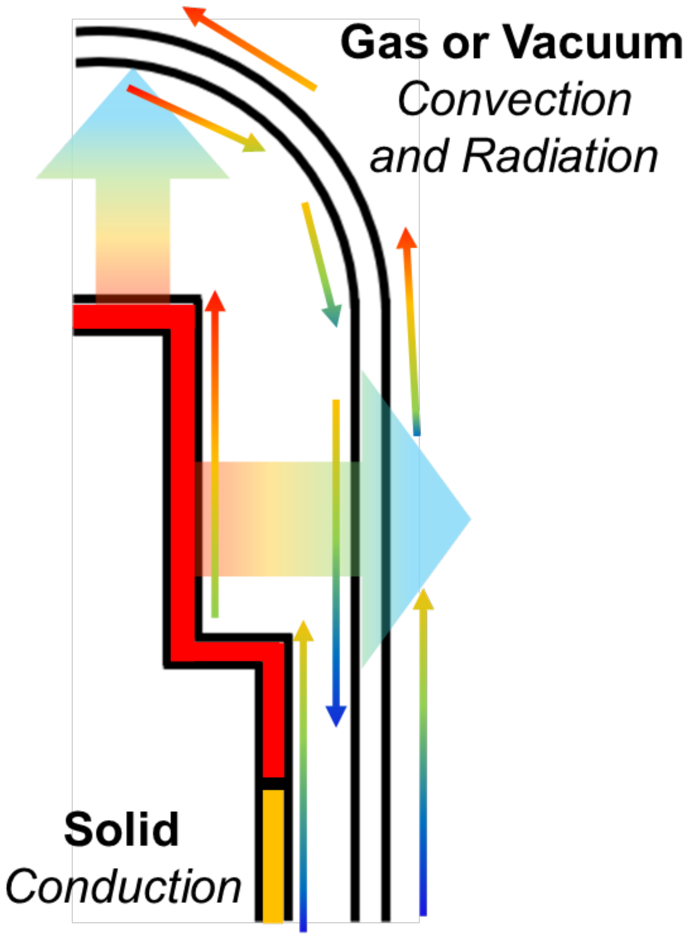
The difference in the results according to the mesh size is not large.

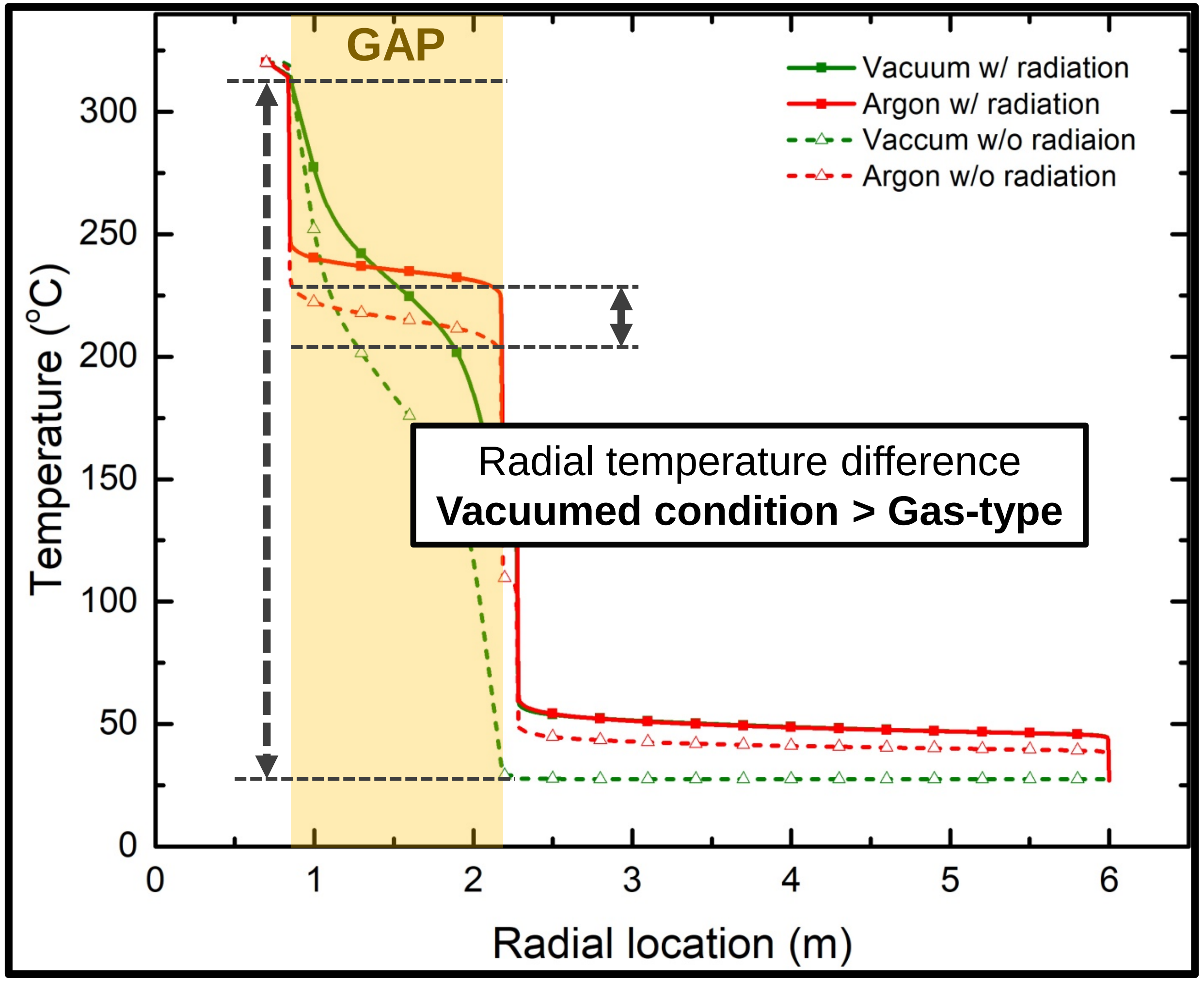
In this study, **mesh size: 2,135,664#**

Results and Discussion

Results and Discussion

❖ Heat transfer Mechanism





Radial temperature difference

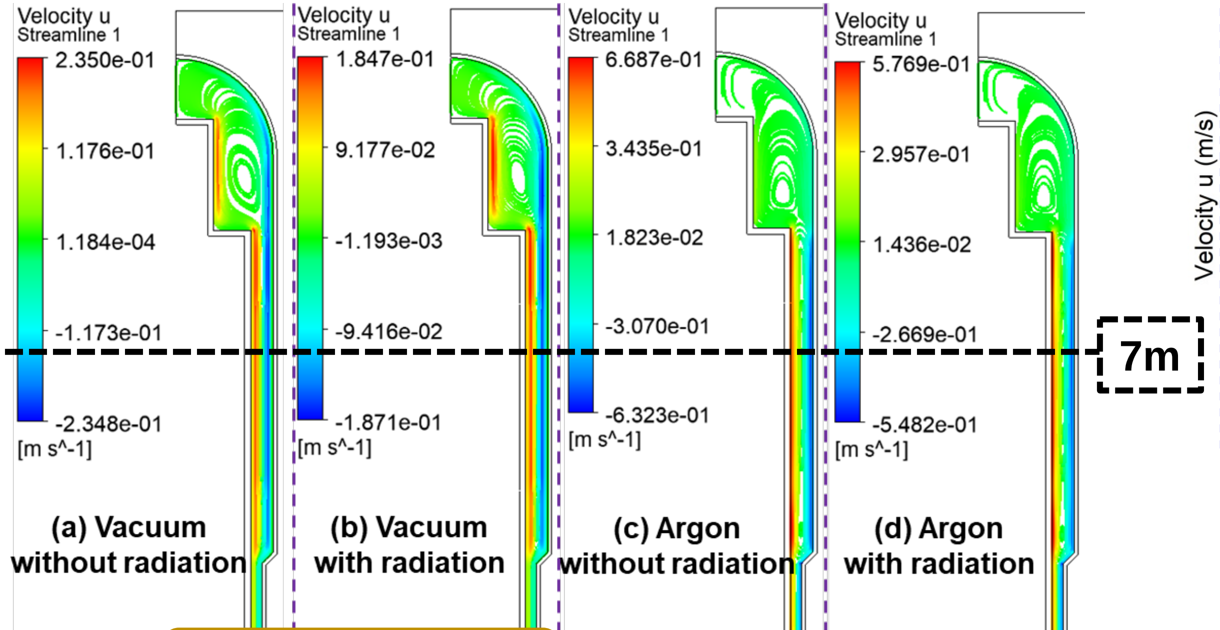
Vacuumed condition > Gas-type

HANYANG
UNIVERSITY

Results and Discussion

Results and Discussion

❖ Natural Circulation

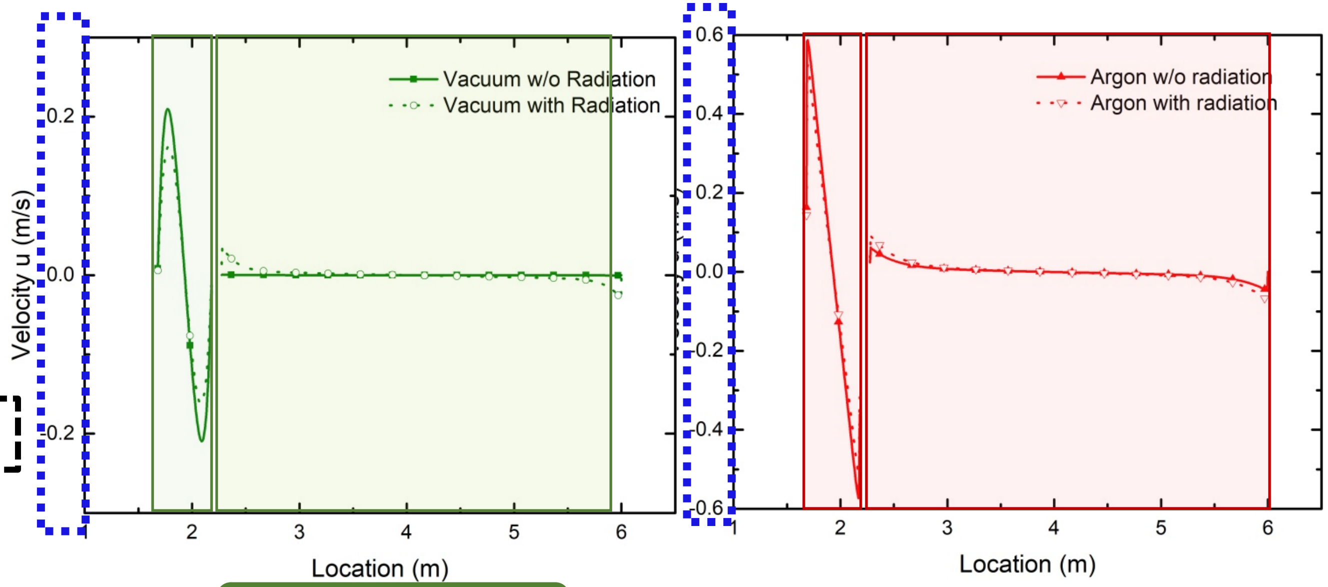


(a) Vacuum without radiation

(b) Vacuum with radiation

(c) Argon without radiation

(d) Argon with radiation



Flow direction

RPV/CNV outer wall

- The gas rises along the wall

CNV inner wall

- The gas descends along the wall

Flow velocity

Vacuumed condition

Very low density → viscosity dominant

Flow is slower than in a gas-filled condition.

Without Radiation (vs with radiation)

Less energy is transferred to the CNV→

Flow is faster than with radiation case

Results and Discussion

Results and Discussion

❖ The total heat loss

To reflect the different RPV temperatures

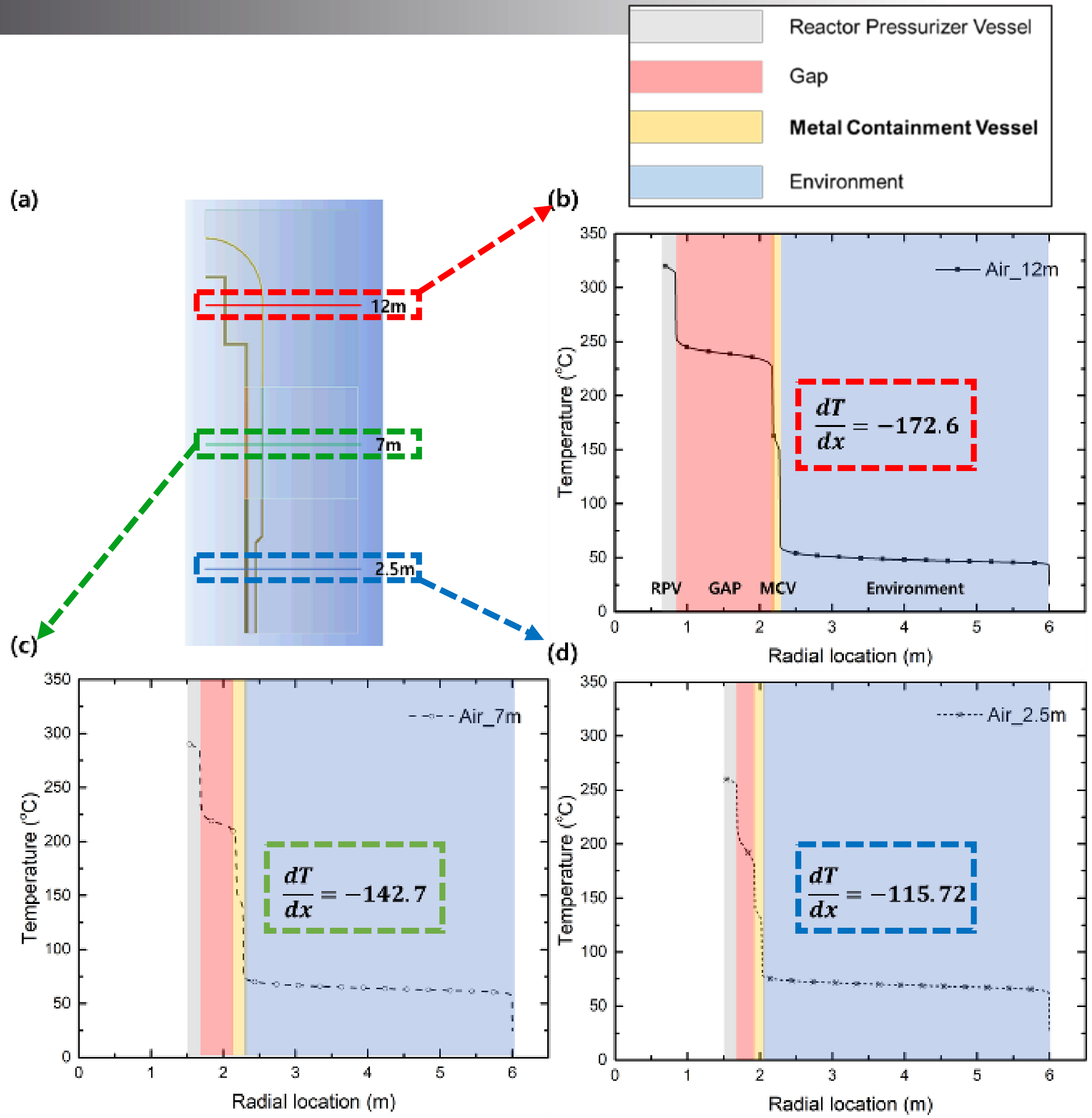
Calculate the representative heat flux for each

The heights: 12m, 7m, and 2.5m.

CNV Temperature gradient

$$Fourier's\ law:\ q'' = -k\boxed{\frac{dT}{dx}}\ (k_{MCV} = 13\ W/m\cdot K)$$

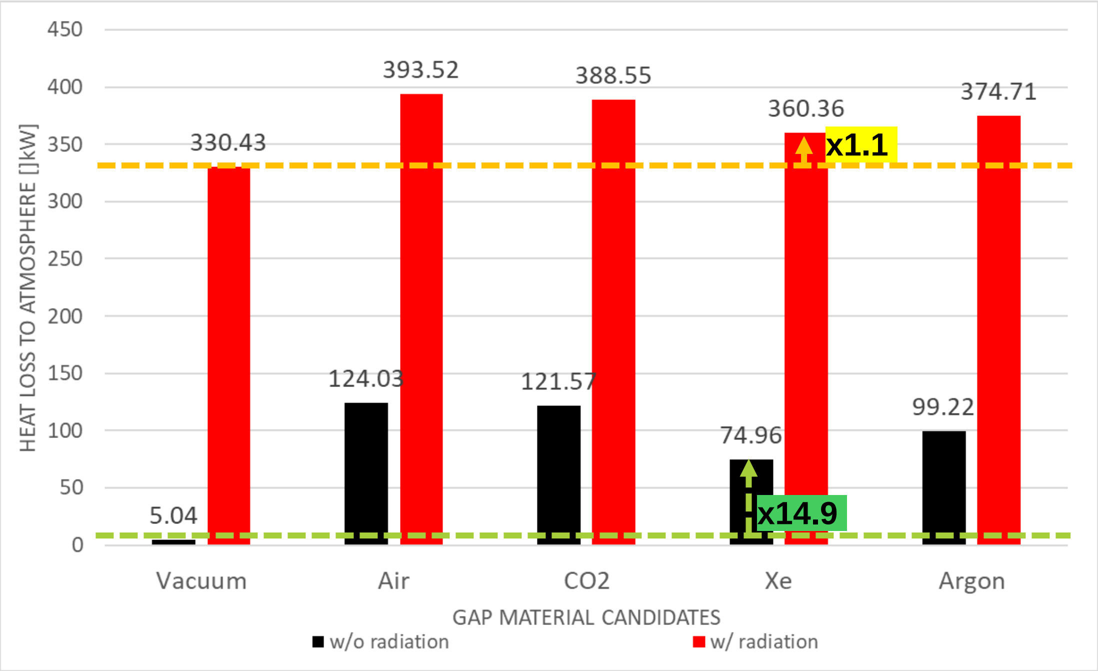
$$\boldsymbol{Total\ heat\ loss = q''_p A_p + q''_{sg} A_{sg} + q''_c A_c}$$



Results and Discussion

Results and Discussion

❖ The total heat loss



without Radiation

Air > CO_2 > Ar > Xe (x 14.9) >> Vacuum

In the case of vacuum, relatively little heat loss occurs.

Vacuum Very low density → Reach the maximum temperature in a short rise → Convection are difficult to occur

Gas fillers According to the properties forementioned (h_{nature})

with Radiation

Air > CO_2 > Ar > Xe (x 1.1) > Vacuum

The difference with gas fillers is reduced to a level of 10-20%.

Vacuum Most of the heat loss is due to radiation.

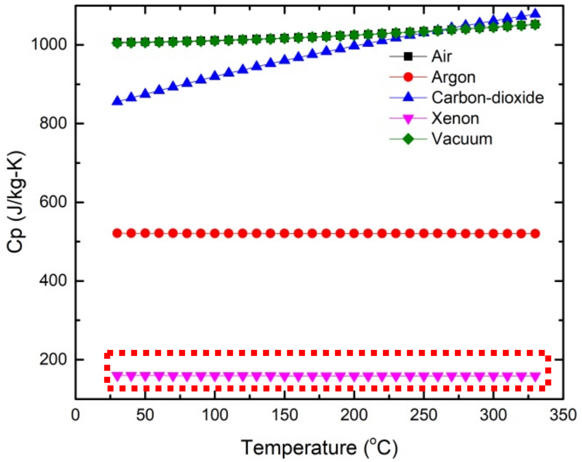
→ Radiation heat transfer: dominant heat loss mechanism

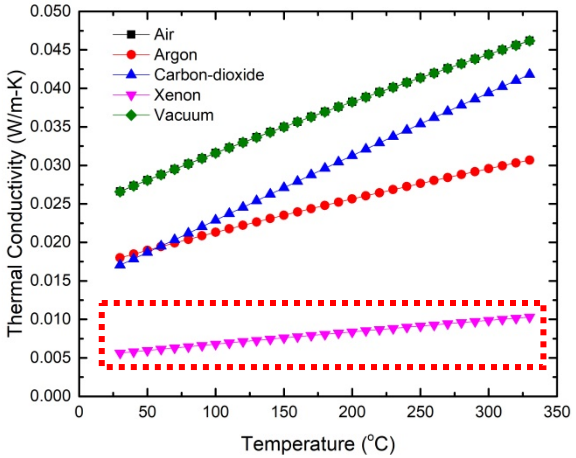
Xenon The best gas-type filler among the candidates

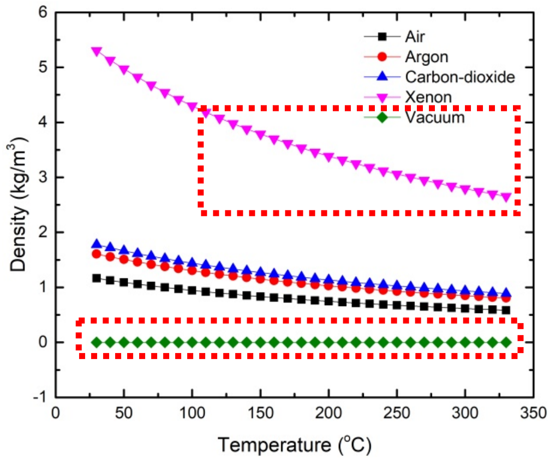
Results and Discussion

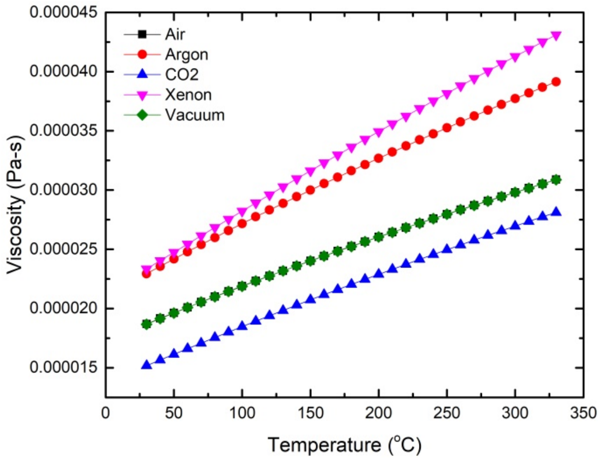
Results and Discussion

❖ Comparison of the thermo-physical properties









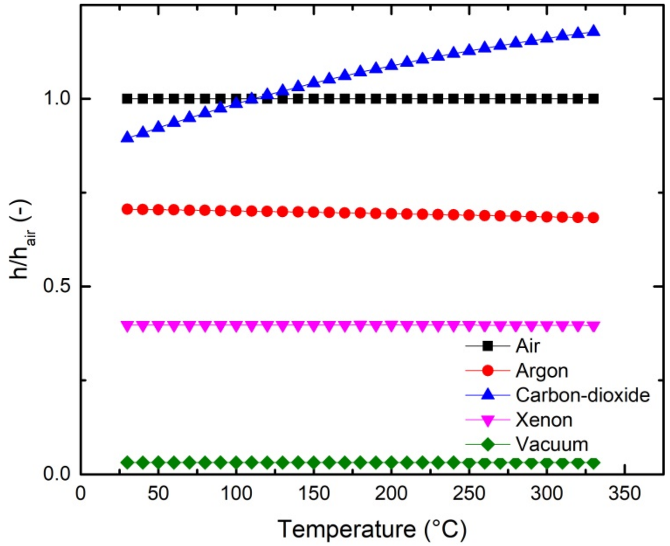
❖ Vacuum condition

1 mbar, Air (NuScale Operating Temperature: 37°C)

❖ Natural convection $Ra=Gr\cdot Pr \propto C_p\cdot\rho^2/k^{-1}\cdot\mu^{-1}$

✓ **Gap:** Enclosed space, natural convection

➢ $Nu=h\cdot L/k \sim Ra^{1/4} \rightarrow h_{natural} \propto k^{3/4}, C_p^{1/4}, \rho^{1/2}, \mu^{-1/4}$



h_{natual}: Air ≃ CO_2 > Ar > Xe > Vacuum

Conclusion and Future Works

Conclusion

Summary

Natural convection

Heat transfer Mechanism

Total heat loss

Conclusion

Purposes

1. The heat transfer mechanism
2. A quantitative comparison of heat loss
3. The possibility of replacing the vacuum condition with the gas filler

The possibility of replacing

1. Radiation heat transfer the dominant heat loss mechanism
2. The total heat loss: Air > Carbon dioxide > Argon > Xenon (best insulation performance)
3. Xenon Difference in heat loss: within 10%→ enough possible

Future Works

Compare the cost of
a. Maintaining the vacuum condition
b. due to increased heat loss in the gas filler

Radiation shielding
Reduce the radiation heat loss

Thank you for your attention

E-mail: ghlee9605@hanyang.ac.kr

Conclusion and Future Works

Conclusion

Conclusion

Natural convection

✓ Flow velocity
a. **Gas-type filler** is faster than vacuumed condition
b. **Without radiation case** is faster than with radiation case

Heat transfer Mechanism

✓ **Radiation heat transfer**
Considering the vacuumed condition, the dominant heat loss mechanism

Total heat loss

✓ with/without radiation model
Air > Carbon dioxide > Argon > **Xenon (Best gas-type filler)**

The possibility of replacing

✓ Xenon (Best gap filler)
Difference in heat loss: within 10%→ enough possible

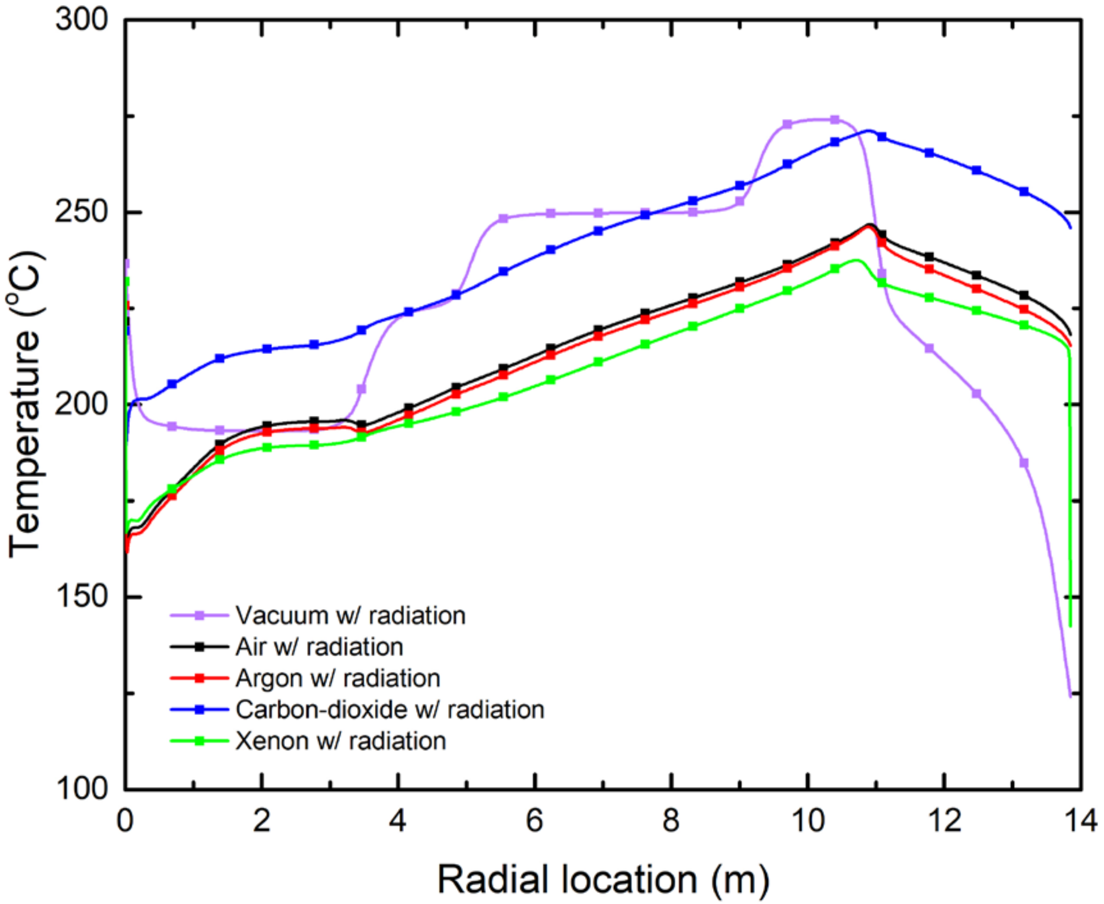
Future Works

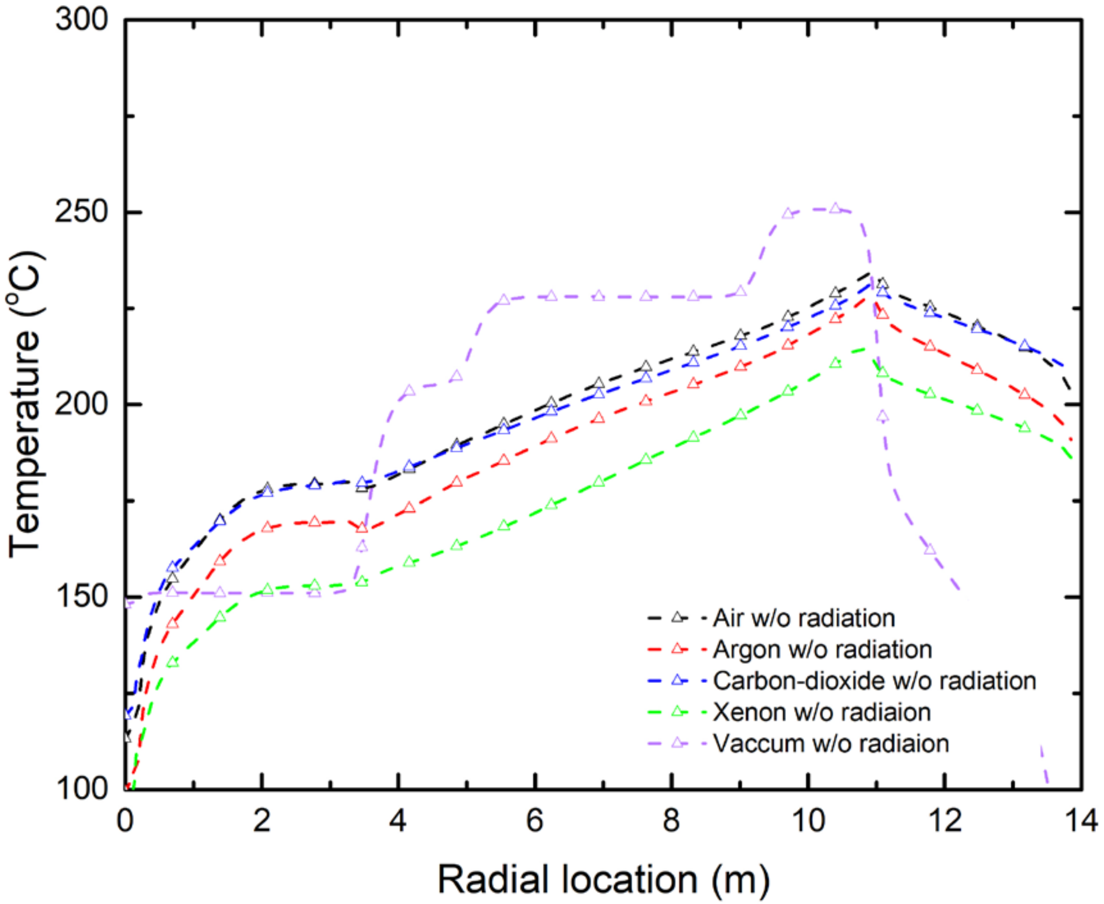
Compare the cost of
a. Maintaining the vacuum condition
b. due to increased heat loss in the gas filler

Radiation shielding
Reduce the radiation heat loss

Appendix

ATHENA



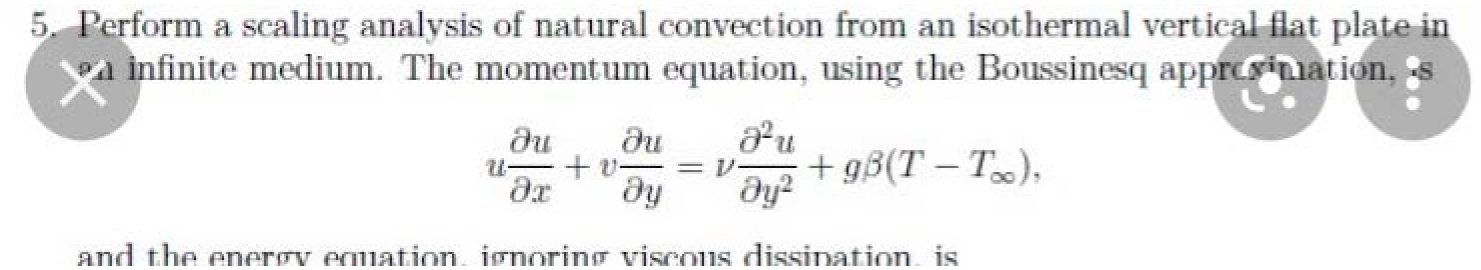


Appendix

$$\underbrace{\rho\frac{\partial U_j}{\partial t}}_{I}+\underbrace{\rho U_i\frac{\partial U_j}{\partial x_i}}_{II}=-\underbrace{\frac{\partial P}{\partial x_j}}_{III}-\underbrace{\frac{\partial \tau_{ij}}{\partial x_i}}_{IV}+\underbrace{\rho g_j}_{V}$$

I: Local change with time
II: Momentum convection
III: Surface force
IV: Molecular-dependent momentum exchange (diffusion)
V: Mass force

$$\tau_{ij}=-\mu\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)+\frac{2}{3}\delta_{ij}\mu\frac{\partial U_k}{\partial x_k}$$

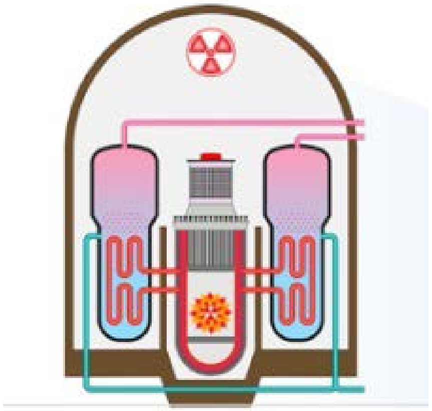


5. Perform a scaling analysis of natural convection from an isothermal vertical flat plate in an infinite medium. The momentum equation, using the Boussinesq approximation, is

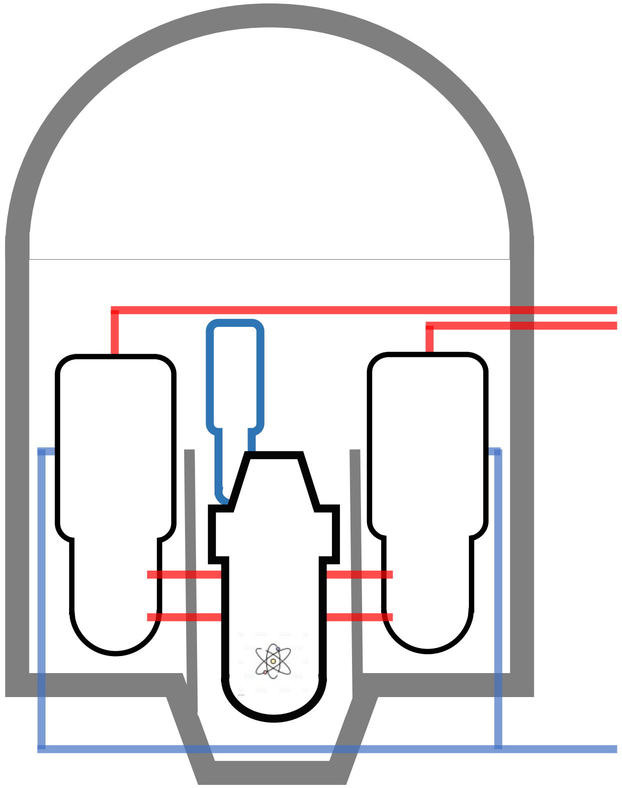
$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty),$$

and the energy equation, ignoring viscous dissipation, is

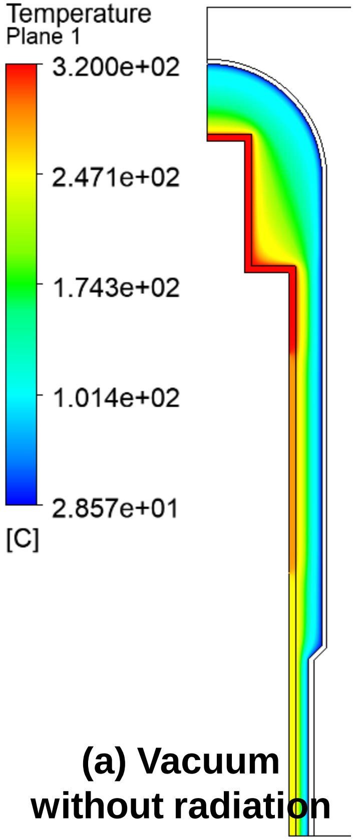
$$\rho\frac{\partial U_j}{\partial t}+\rho U_i\frac{\partial U_j}{\partial x_i}=-\frac{\partial P}{\partial x_j}-\mu\frac{\partial^2 U_j}{\partial x_i^2}+\rho g_j$$



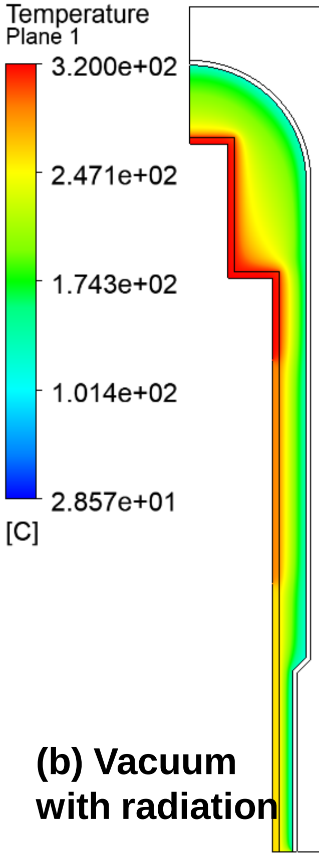
대형 원전 주기기 및
격납 건물



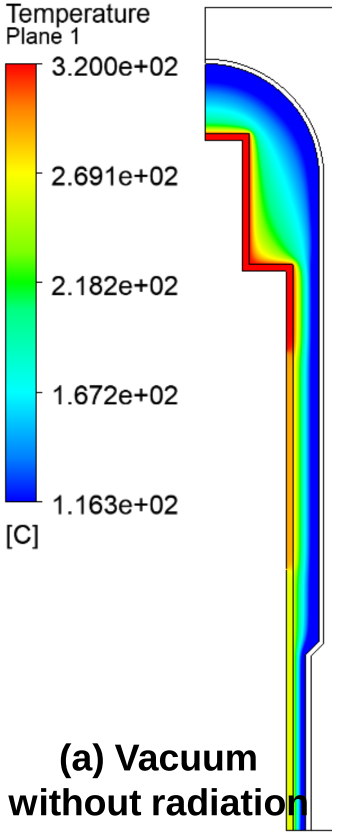
Appendix



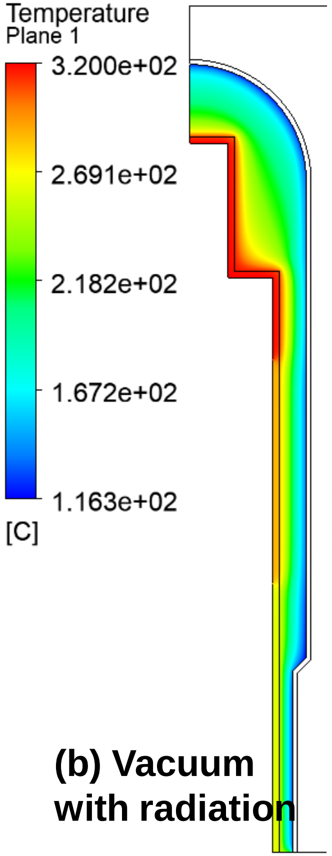
(a) Vacuum without radiation



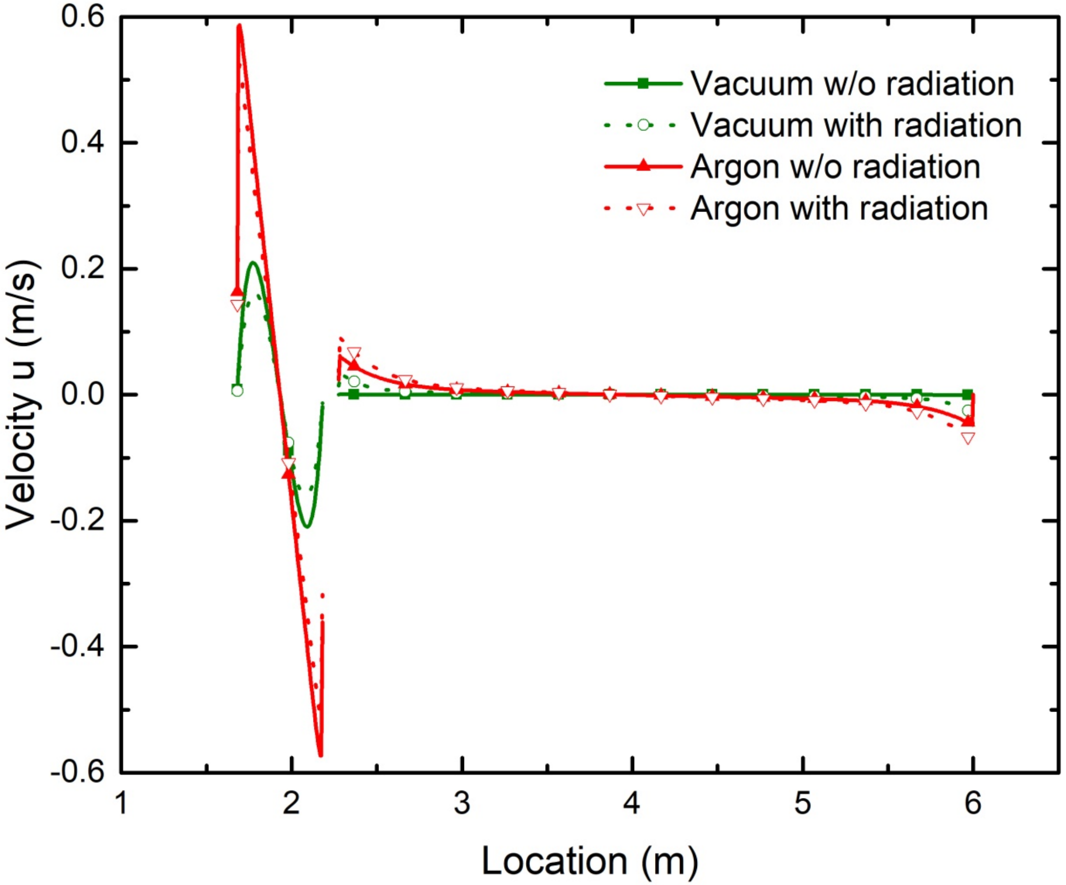
(b) Vacuum with radiation



(a) Vacuum without radiation



(b) Vacuum with radiation



Backgrounds & Motivation

Double Vessel Structure

❖ NuScale (USA)

Design and Manufacturer: NuScalepower

- 77 MWe/module, 12 modules, 924MWe

Innovative characteristics

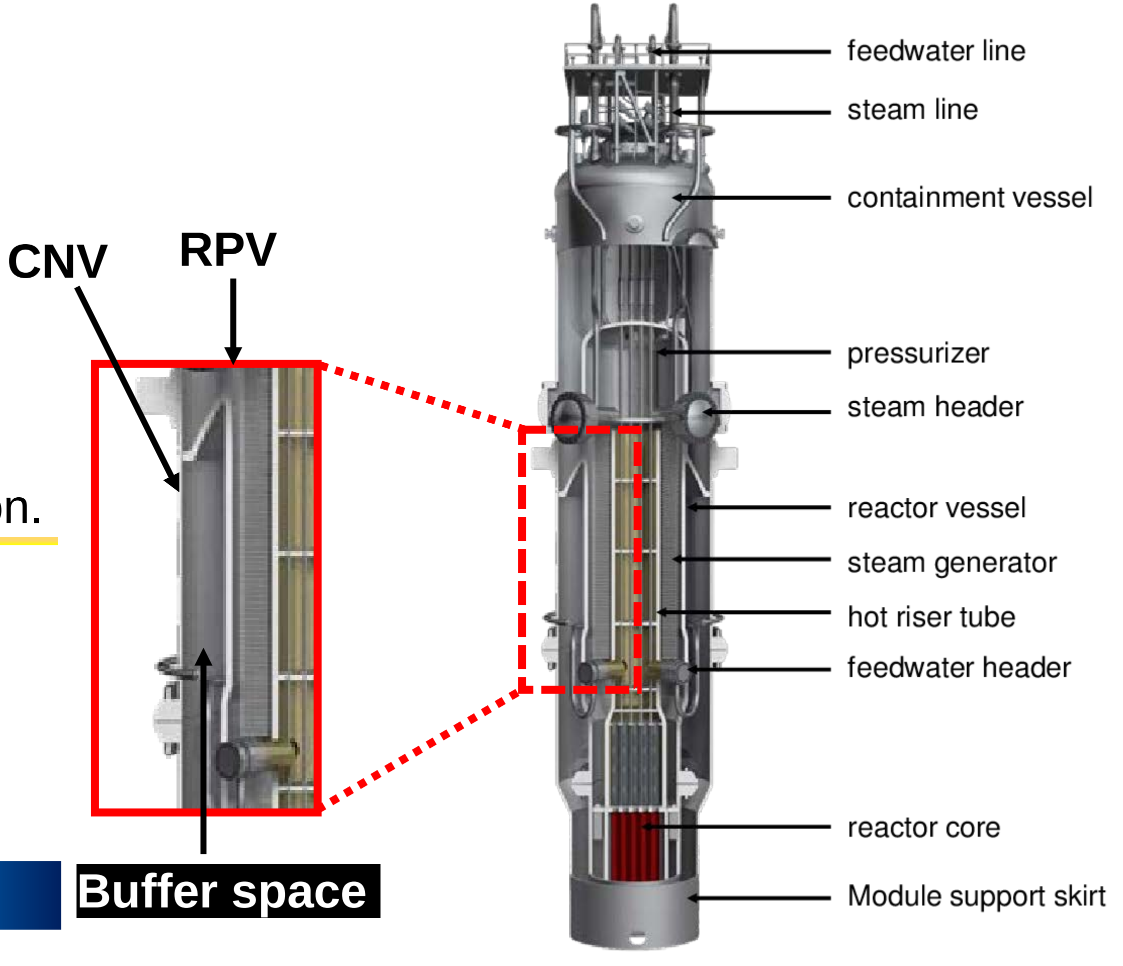
1. No pump to circulate water (natural circulation)
2. Helical Coil Steam Generators (HCSG)
3. Immersed containment vessel
4. Maintaining vacuumed containment during normal operation.

Double Vessel

Reactor Pressure Vessel & Metal Containment Vessel

Buffer space (gap): **Vacuumed condition**

1. Minimizes reactor vessel heat loss
2. Prevent component corrosion
3. Not require reactor vessel insulation
4. Not require H_2 recombiner



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NuScale

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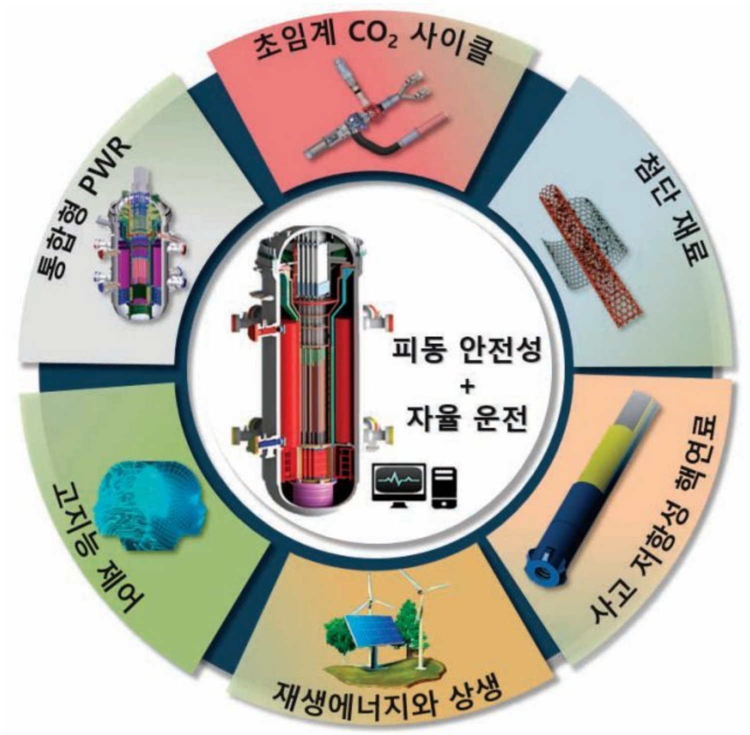
1) https://www.nuscalepower.com/technology/design-innovations

Backgrounds & Motivation

Double Vessel Structure

Autonomous Transportable On-Demand Reactor Module (Korea)



ATOM 시스템 설계 개념

Design: Multi-university research team centered through the KAIST

- conceptual design reactor
- ~150MWe (450MWth)

Design Characteristics

1. *supercritical-CO_2 cycle system (with air-cooling system)*
2. *Autonomous operation*
3. *Soluble boron-free coolant system*
4. *Nano-material and ATF*

+ Double vessel structure

Gap material: **Inert gas, stagnant**

- ✓ Not require vacuum maintenance cost
- ✓ Generating additional heat loss

Need to confirm!