# An Experimental Study on the Insulation Effect of Thermal Radiation Shielding within a Metal Containment Vessel of Small Modular Reactors

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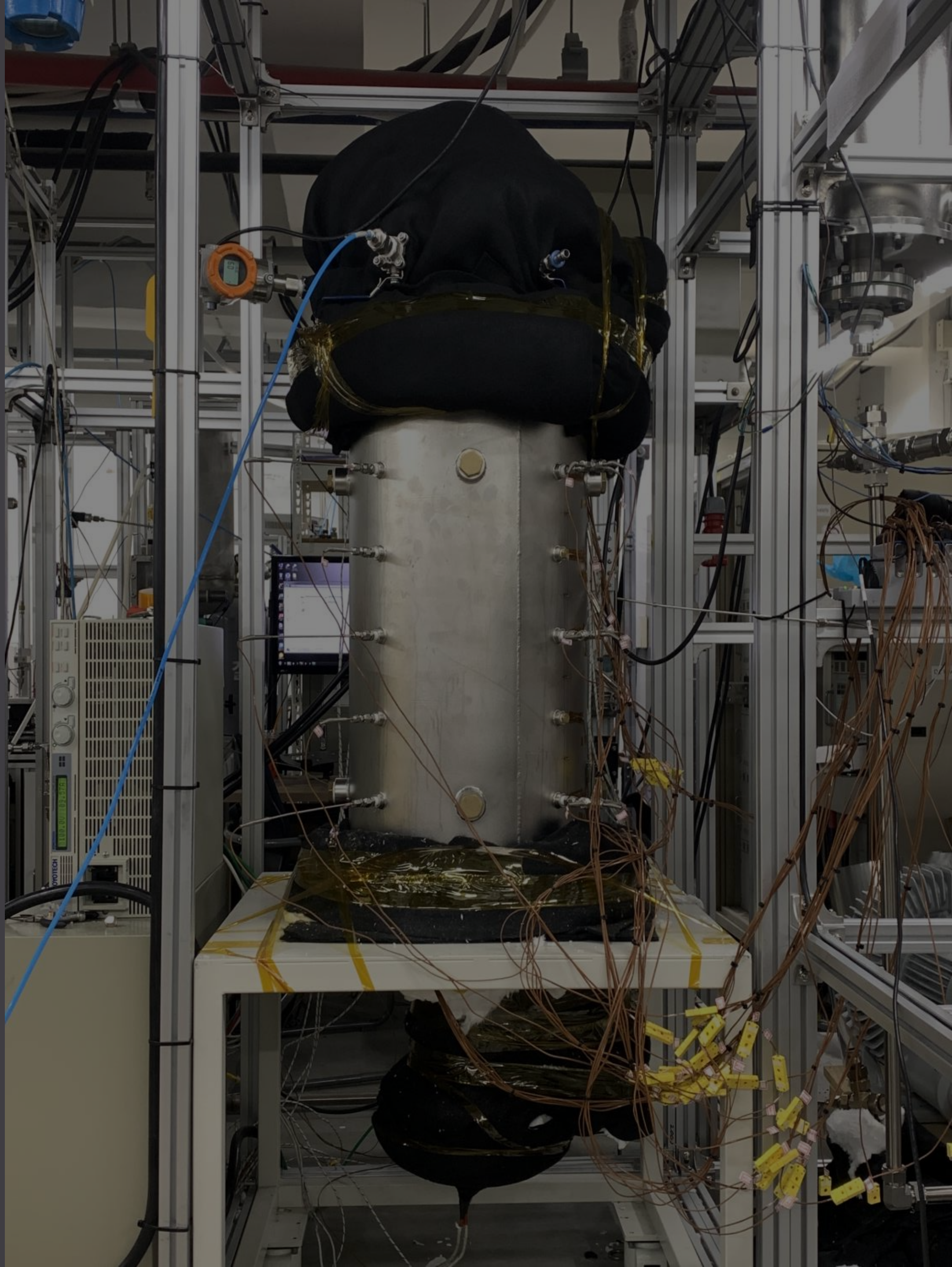

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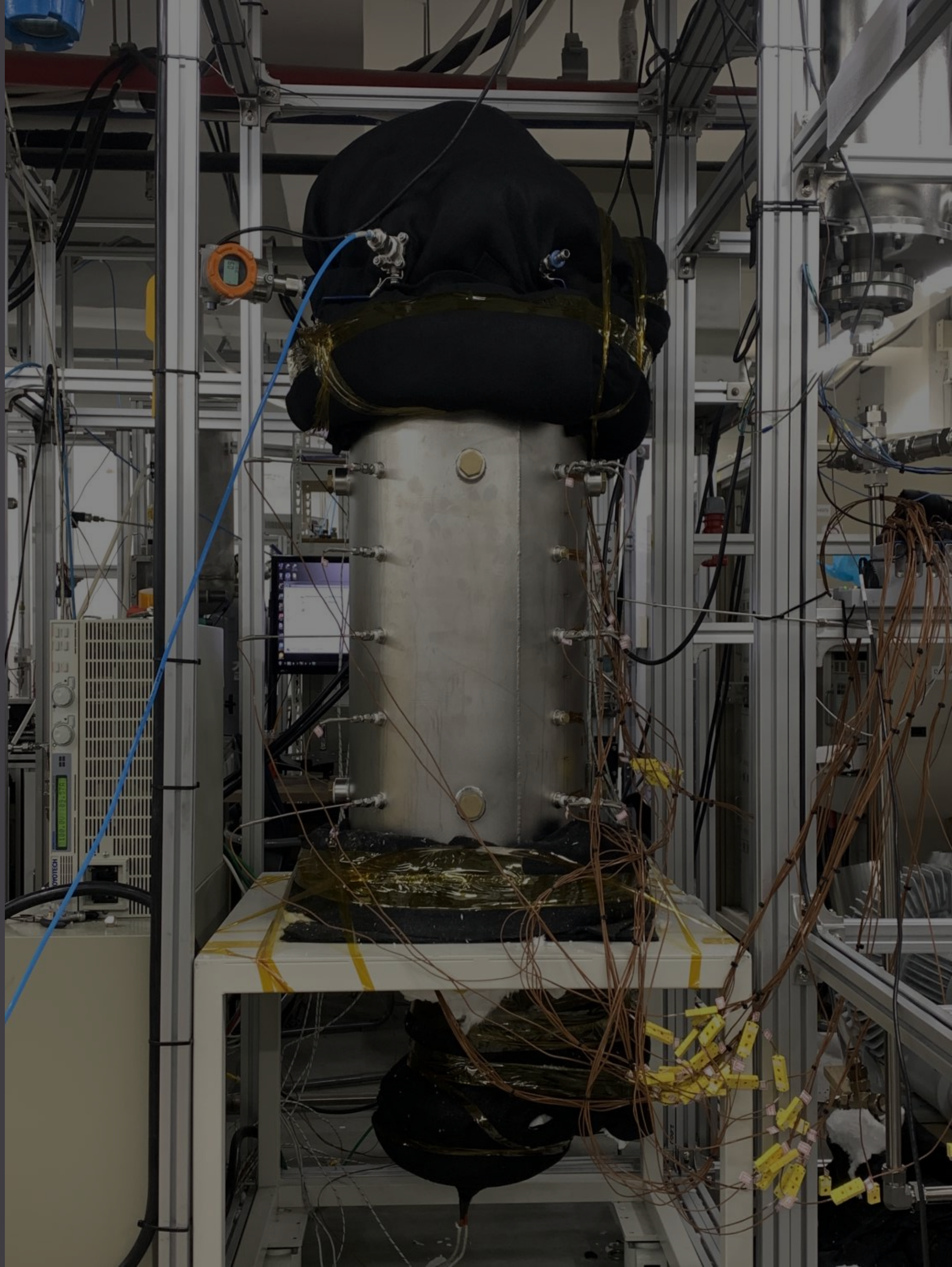
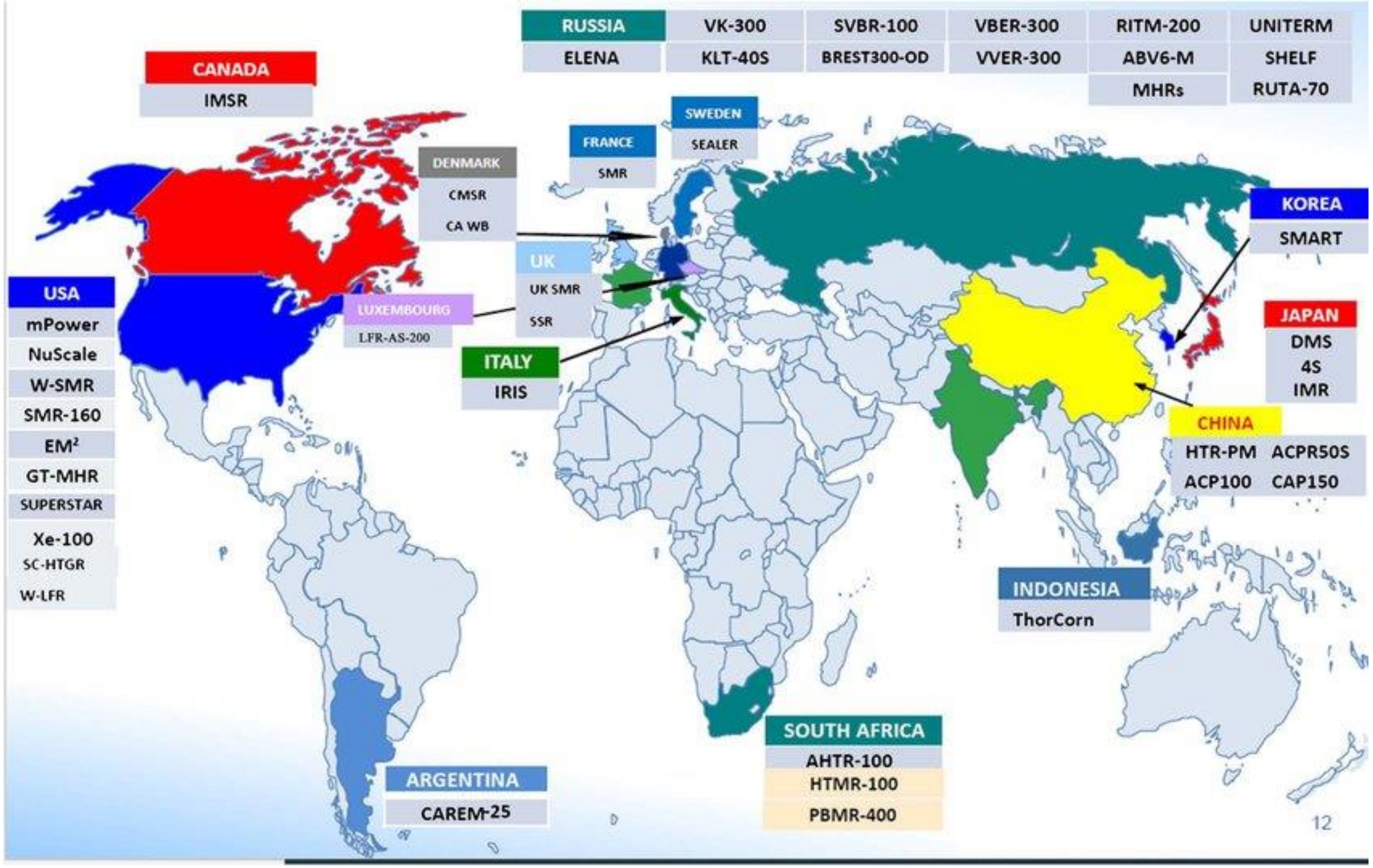


# Introduction

## SMR: definition & features

- **SMR**: Advanced Reactors to produce up to **300 MWe.**

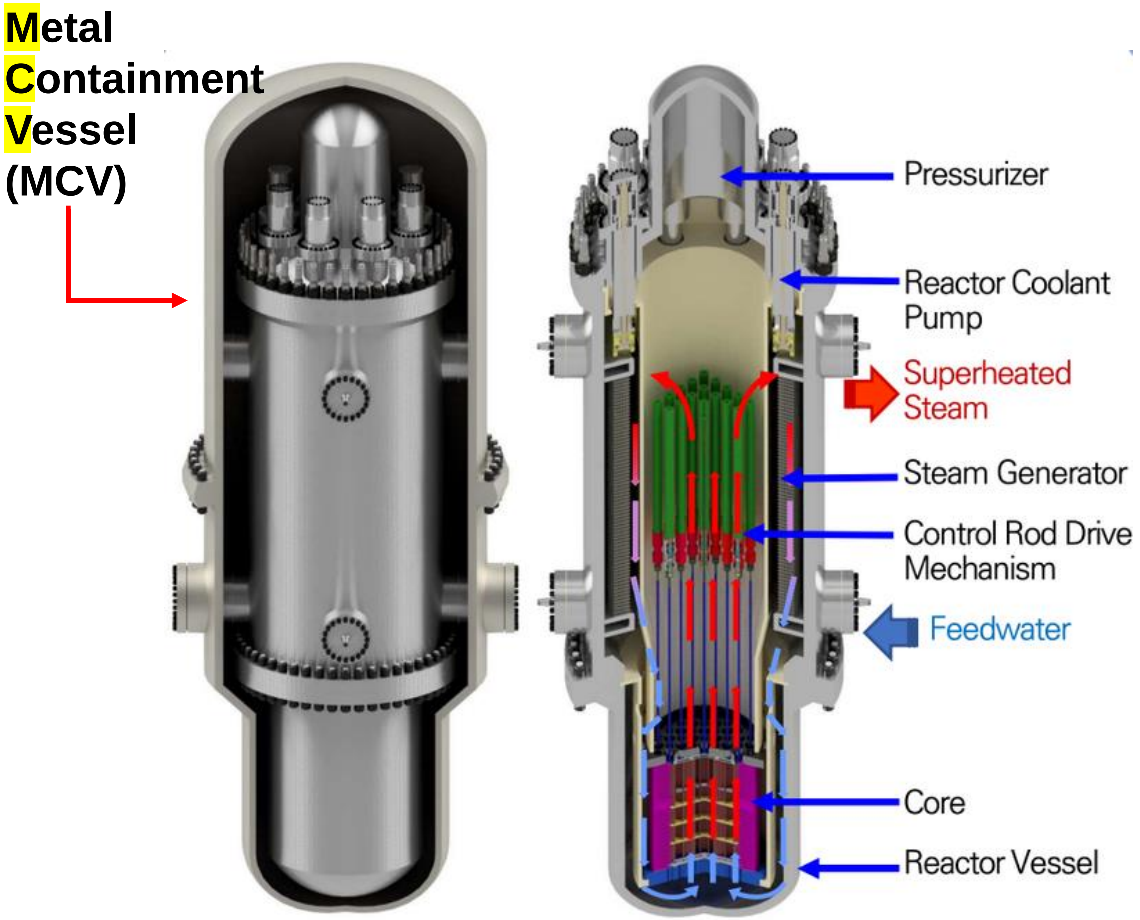



- Features of SMR
  - High safety
  - Operational resilience
  - Modular operation
  - Site selection flexibility
  - Reduced construction time

- Developing i-SMR in Korea (170 MWe)
  - Standard design in progress (2024~)

# Introduction

## Background of study on heat transfer behavior in the MCV




**innovative-SMR (Korea)**

- ❑ Enhance passive safety
- ❑ Defense in depth strategy barriers
- ❑ Acting as a heat sink in an accident

  → Reducing the likelihood of serious accidents

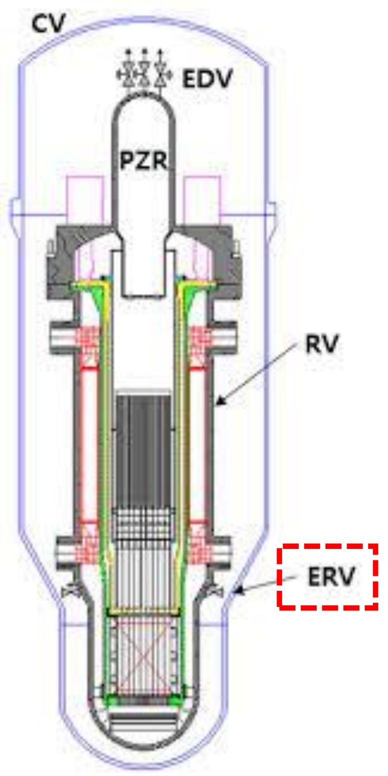


1) https://kienews.com/news/newsview.php?ncode=1065586959498329
2) https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

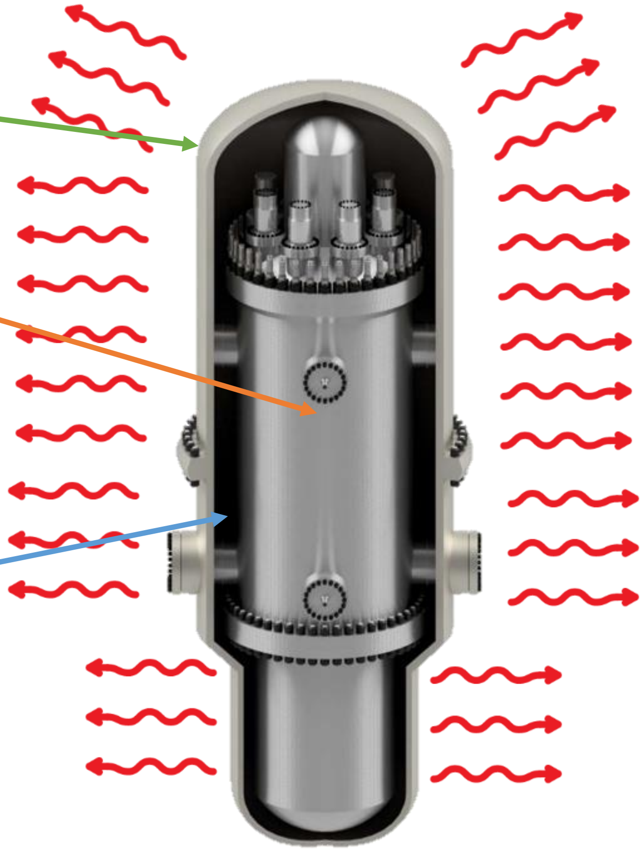
# Introduction

## Background of study on heat transfer behavior in the MCV

**Absence of insulation for smooth recirculation**




**Increase heat-loss in normal operation**




- ❑ Absence of insulation can **reduce reactor efficiency**
- ❑ **Apply a vacuum** to the gap to limit heat loss due to convection
- ❑ Need to assess for heat loss **due to radiation**

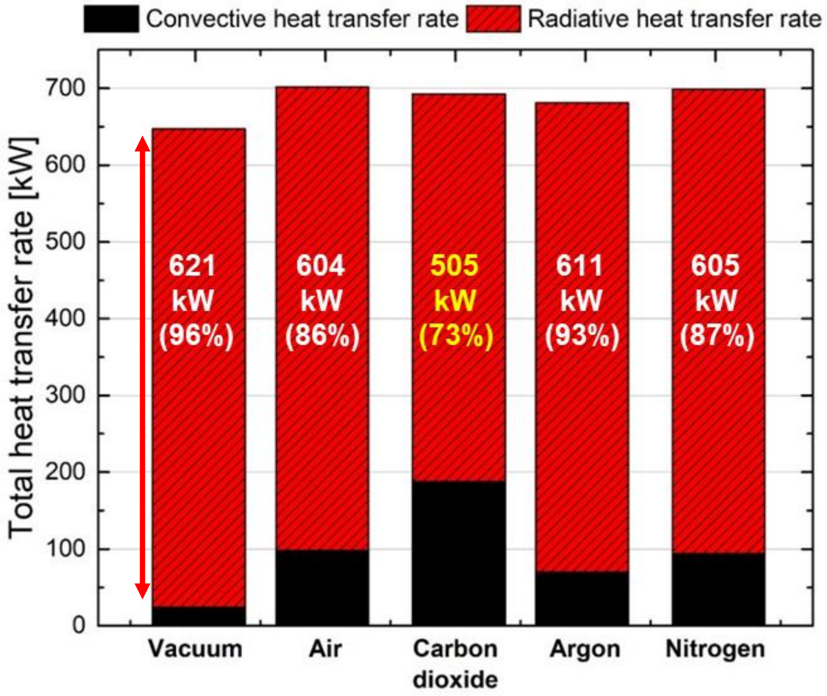


1) https://kienews.com/news/newsview.php?ncode=1065586959498329
2) https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

# Introduction

## Motivation

### Heat loss of i-SMR in normal operation




(CFD) Heat transfer mechanism

Max radiative heat transfer in vacuum

### How to reduce radiative heat loss?

Experimental apparatus in literature research,


(a) cylindrical enclosure (b) radiation shielding

**Thermal radiation is dominant → Solution: Thermal Radiation shielding**



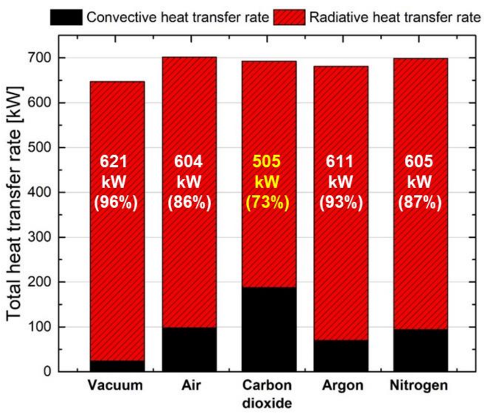

1) Chang Hyun Song, Geon Hyeong Lee, Sung Joong Kim, "CFD ANALYSIS OF RADIATIVE HEAT TRANSFER BETWEEN REACTOR PRESSURE VESSEL AND METAL CONTAINMENT VESSEL", 2023 International Congress on Advances in Nuclear Power Plants in conjunction with 38th Korea Atomic Power Annual Conference, Gyeongju, South Korea, April 23–27, 2023

2) Mohammad Sadegh Motaghedi Barforoush, Seyfolah Saedodin, Heat transfer reduction between two finite concentric cylinders using radiation shields; Experimental and numerical studies, International Communications in Heat and Mass Transfer, Volume 65, 2015, Pages 94-103, ISSN 0735-1933

# Introduction

## Objectives

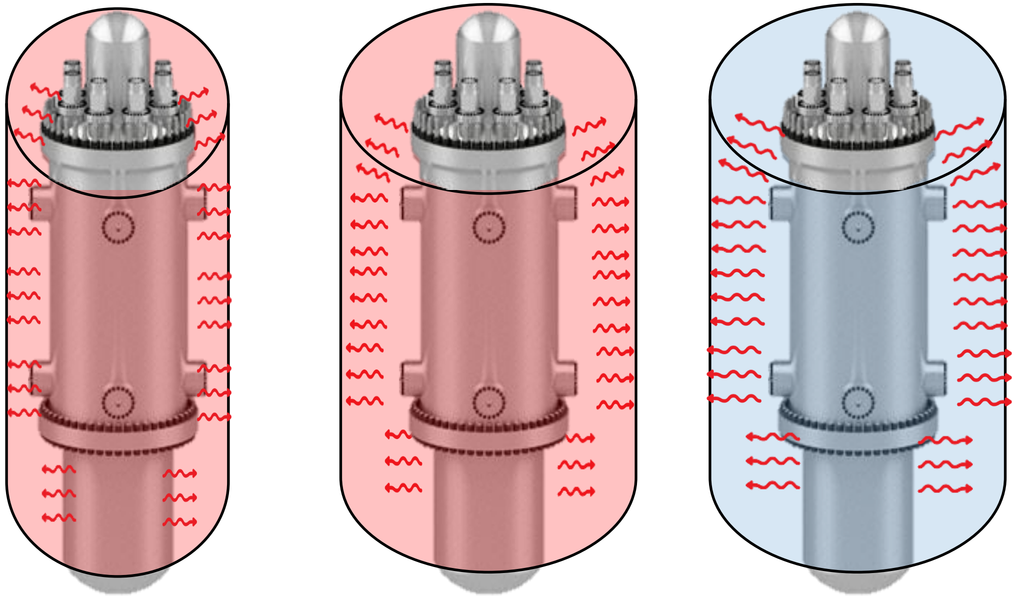
### 1. Heat transfer mechanism




**Validate by experiment**

### 2. Effect of thermal radiation shielding


### 3. Effective variables of thermal radiation shielding



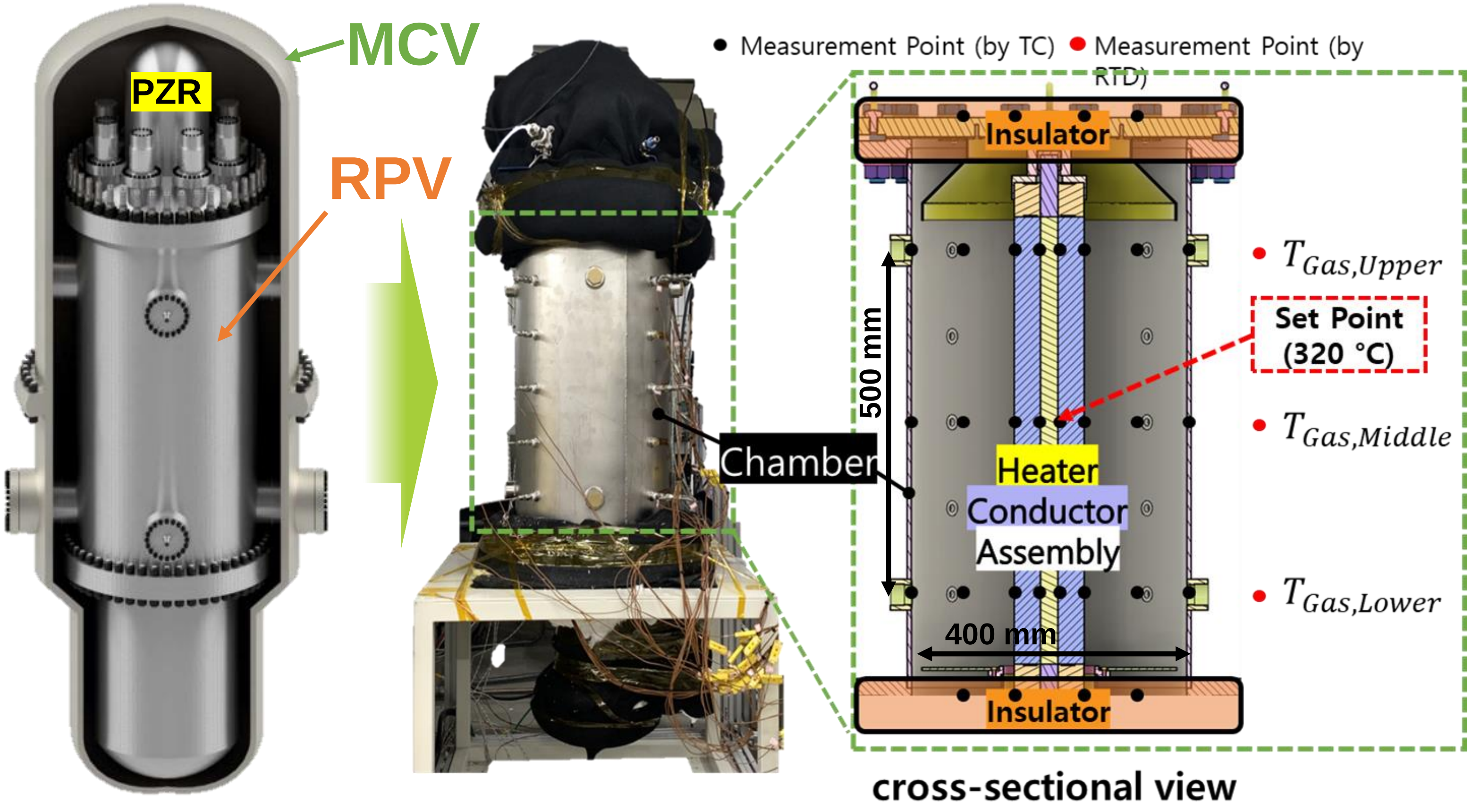

**Different diameter (heat transfer area)**

**Different material (emissivity)**

# Methodology

## Experimental setup

**Design of i-SMR to Experimental setup**



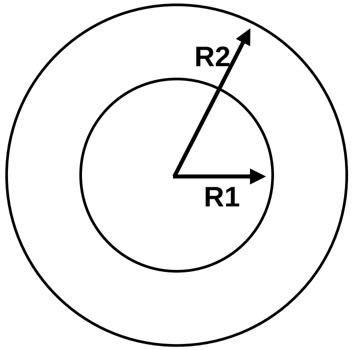

- ❑ **Region of interest**
  - → **Pressurizer**
- ❑ **Reactor Pressure Vessel**
  - → Cartridge heater-Al conductor
- ❑ **Metal Containment Vessel**
  - → Chamber
- ❑ **Tightly sealed by flanges**
  - → For vacuum experiment
- ❑ **Heat loss of chamber wall**

# Methodology

## Experimental setup

### Design factor

**View factor: The proportion of the radiation which leaves surface 1 that strikes surface 2.**




**[ Ratio scale of the experimental setup ]**

| | Height | Diameter | View factor (i−SMR) |
|---|---|---|---|
| Ratio scale | 1/40 | [illegible] | 0.273 |

| | Heater temperature | Operating pressure |
|---|---|---|
| Ratio scale | 1 | 1 |

**Radiative heat transfer considering the view factor**

$$\dot{Q}_{1\rightarrow 2} = A_2 F_{2\rightarrow 1}\sigma({T_1}^4 - {T_2}^4)$$

**View factor calculation for two cylinders**

$$F_{2\rightarrow 1} = \frac{R_1}{R_2}$$

$F_{21}: view\ factor$

# Methodology

## Experimental setup

### Design of the thermal radiation shielding

**Material (emissivity)**

**Al-400**

**Al shielding (ε:0.04)**

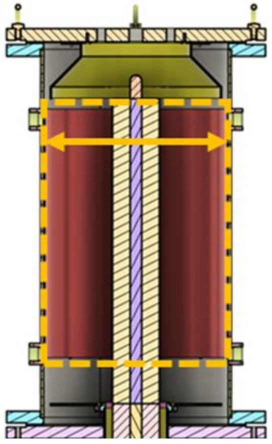
**SS304-400**

**SS304 shielding (ε: 0.1)**

**Diameter (heat transfer area)**

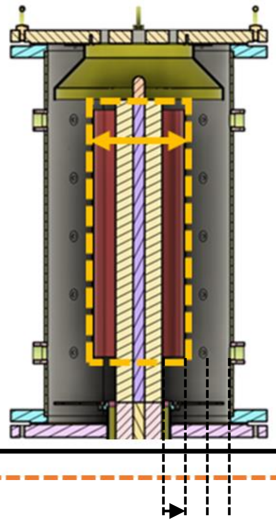
**Al-400**

**Diameter: 400 mm**



**Al-200**

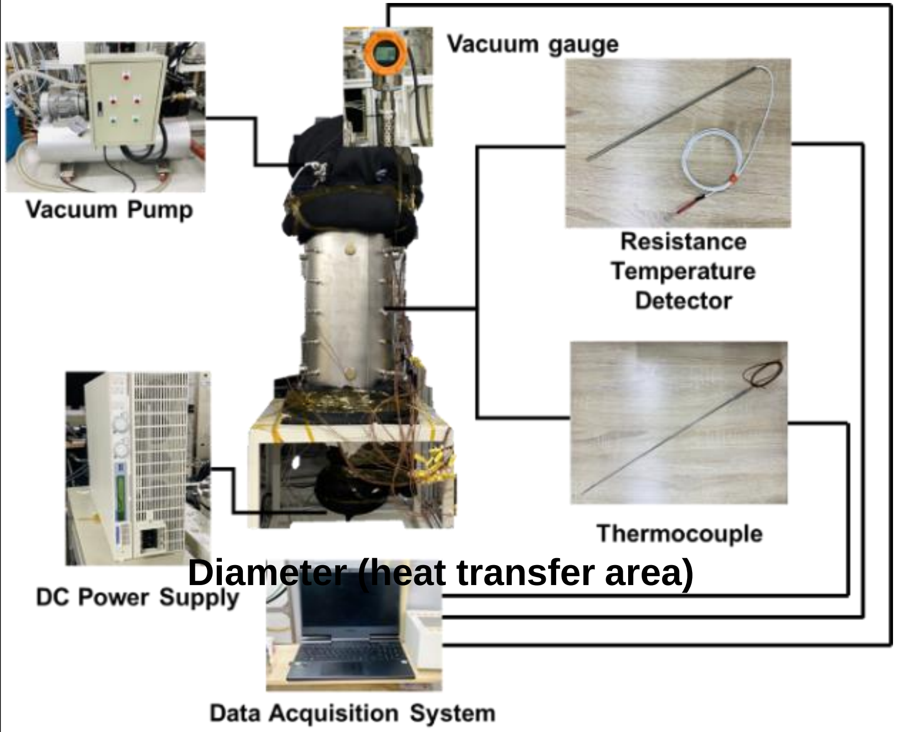
**Diameter: 200 mm**



**1/3**

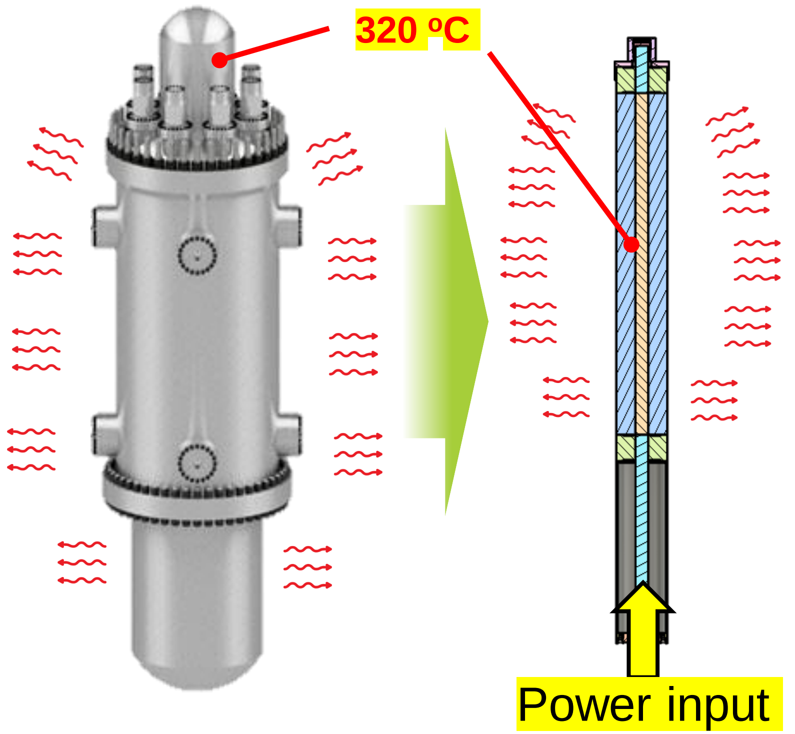
Thickness: 0.2~0.3 mm
Height: 520 mm

### Schematic of experimental setup



# Methodology
## Test matrix

### Experimental method




**Mimicking a temperature of the pressurizer part by heater assembly**

### Test matrix

| Test Name | Heater Temperature | Ambient Temperature | Pressure | Gap condition | Shielding diameter | Shielding material |
|---|---|---|---|---|---|---|
| **Background conduction case** | 320 °C | 18 °C | 0.07 bar | Insulator+Vacuum | - | - |
| **Base case** | | | | Vacuum | - | - |
| **Al-200** | | | | | **200 mm** | **Al** |
| **Al-400** | | | | | **400 mm** | **Al** |
| **SS304-400** | | | | | **400 mm** | **SS304** |

- **Steady state experiment**
- **Repeat 3 times each**
- **Evaluate heat loss by heater input**

# Methodology

## Test matrix

Expe

**Background conduction case**

**Only Conduction**

**Base case**

**Cond. + Rad.**

[ Mim ... embly ]

- ✓ Constant
- ✓ Steady-st
- ✓ Evaluate the he ... ater input power (W)

**Test matrix**

**Heater T : 320 °C**
**Ambient T : 18 °C**
**Chamber P : 0.07 bar**

| Test Name | Gap condition | Shielding diameter | Shielding material |
|---|---|---|---|
| **Background conduction case** | Insulator+Vacuum | - | - |
| **Base case** | Vacuum | - | - |
| Al-200 | Vacuum | 200 mm | Al |
| Al-400 | Vacuum | 400 mm | Al |
| SS304-400 | Vacuum | 400 mm | SS304 |

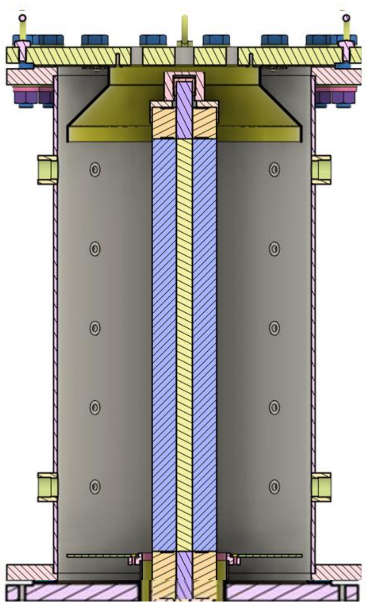
- ➢ Preliminary experiment
- ➢ Shielding effect experiment
- ➢ Shielding variables experiment
  - ▪ Material
  - ▪ Diameter

**Is radiation dominant?**

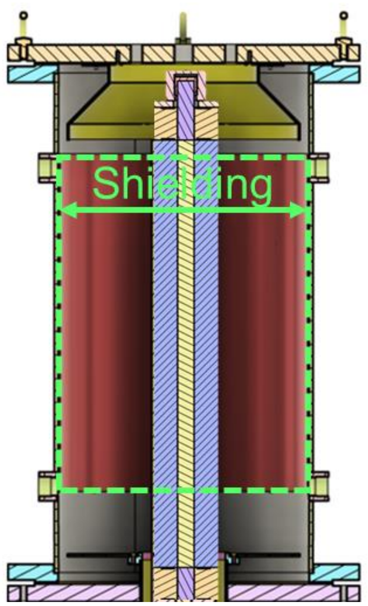
## Test matrix

Base case | Al-400

w/o shielding



w/ shielding




✓ Constant heater temperature
✓ Steady-state for all measurement
✓ Evaluate the heat loss by heater input power (W)

### Test matrix

Heater T : 320 °C
Ambient T : 18 °C
Chamber P : 0.07 bar

| Test Name | Gap condition | Shielding diameter | Shielding material |
|---|---|---|---|
| Background conduction case | Insulator+Vacuum | - | - |
| Base case | Vacuum | - | - |
| Al-200 | Vacuum | 200 mm | Al |
| Al-400 | Vacuum | 400 mm | Al |
| SS304-400 | Vacuum | 400 mm | SS304 |

- Preliminary experiment
- Shielding effect experiment
- Shielding variables experiment
  - Material
  - Diameter

**w/ shielding vs w/o shielding**

# Methodology

## Test matrix

AI-400

SS304-400

**Al shielding (ε:0.04)**

**SS304 shielding (ε: 0.1)**

- ✓ Steady-state for all measurement
- ✓ Evaluate the heat loss by heater input power (W)

### Test matrix

**Heater T : 320 °C**
**Ambient T : 18 °C**
**Chamber P : 0.07 bar**

| Test Name | Gap condition | Shielding diameter | Shielding material |
|---|---|---|---|
| Background conduction case | Insulator+Vacuum | - | - |
| Base case | Vacuum | - | - |
| Al-200 | Vacuum | 200 mm | Al |
| **Al-400** | Vacuum | **400 mm** | **Al** |
| **SS304-400** | Vacuum | **400 mm** | **SS304** |

- ➢ Preliminary experiment
- ➢ Shielding effect experiment
- ➢ Shielding variables experiment → **Emissivity**
  - Material
  - Diameter

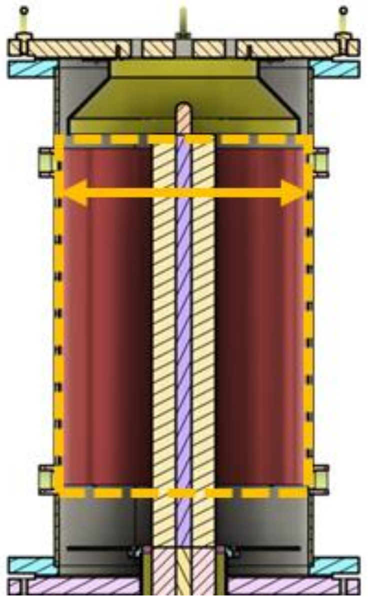
# Methodology

## Test matrix

ATHENA

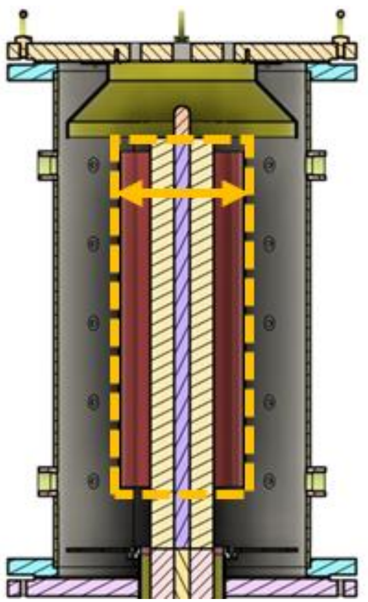
Al-400

Diameter: 400 mm



Al-200

Diameter: 200 mm



- ✓ Constant heater temperature
- ✓ Steady-state for all measurement
- ✓ Evaluate the heat loss by heater input power (W)

**Test matrix**

**Heater T : 320 °C**
**Ambient T : 18 °C**
**Chamber P : 0.07 bar**

| Test Name | Gap condition | Shielding diameter | Shielding material |
|---|---|---|---|
| Background conduction case | Insulator+Vacuum | - | - |
| Base case | Vacuum | - | - |
| Al-200 | Vacuum | 200 mm | Al |
| Al-400 | Vacuum | 400 mm | Al |
| SS304-400 | Vacuum | 400 mm | SS304 |

- ➢ Preliminary experiment
- ➢ Shielding effect experiment
- ➢ Shielding variables experiment
  - ▪ Material
  - ▪ Diameter

**Heat transfer area**



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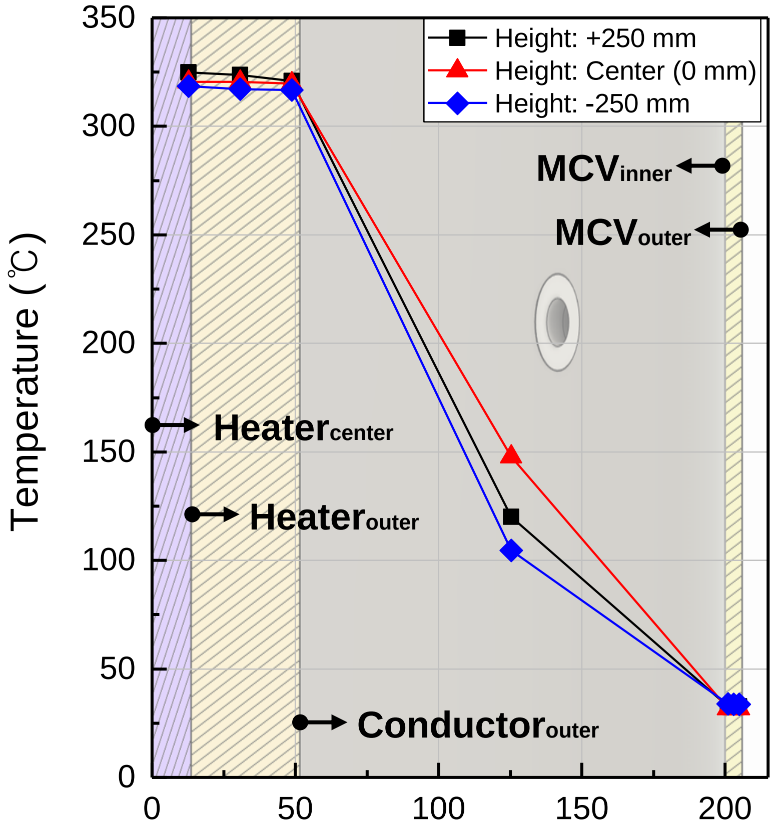
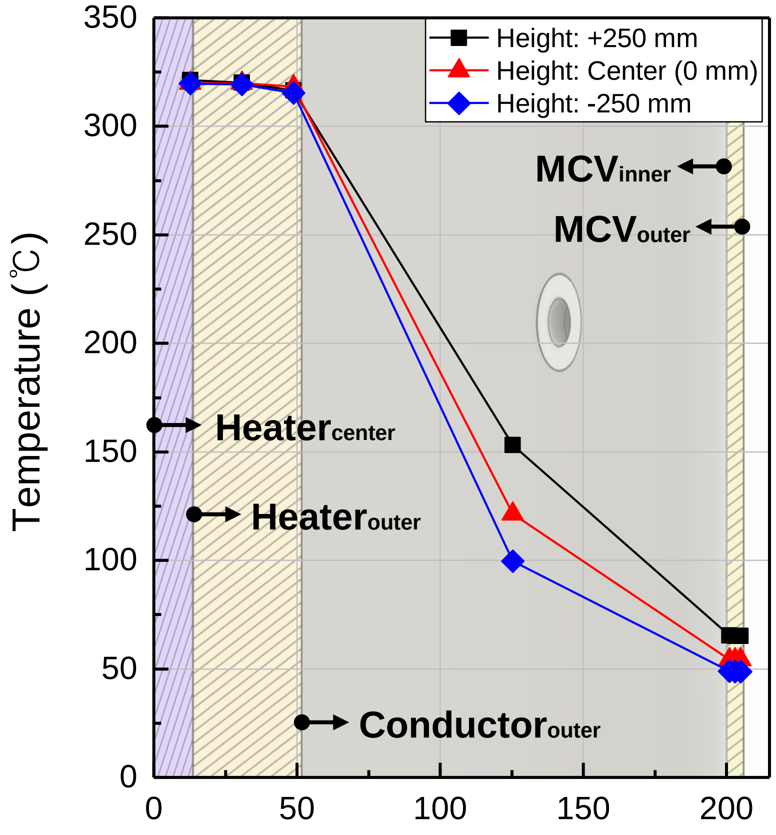
# Results and discussions

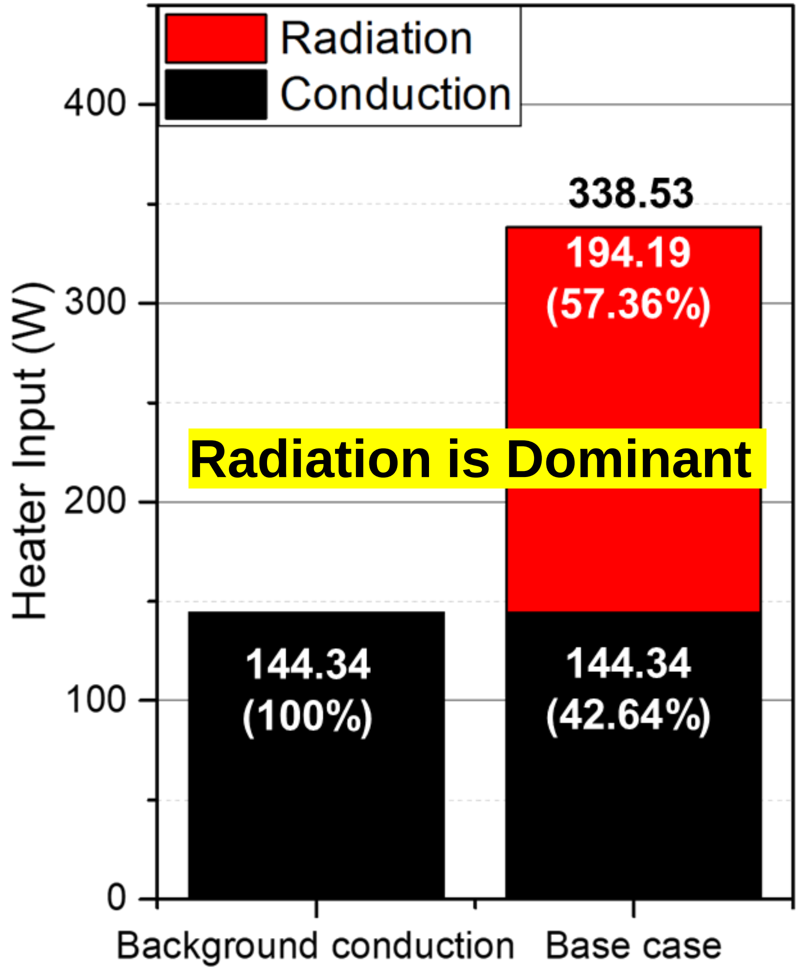
## Preliminary experiments: Heat transfer mechanism



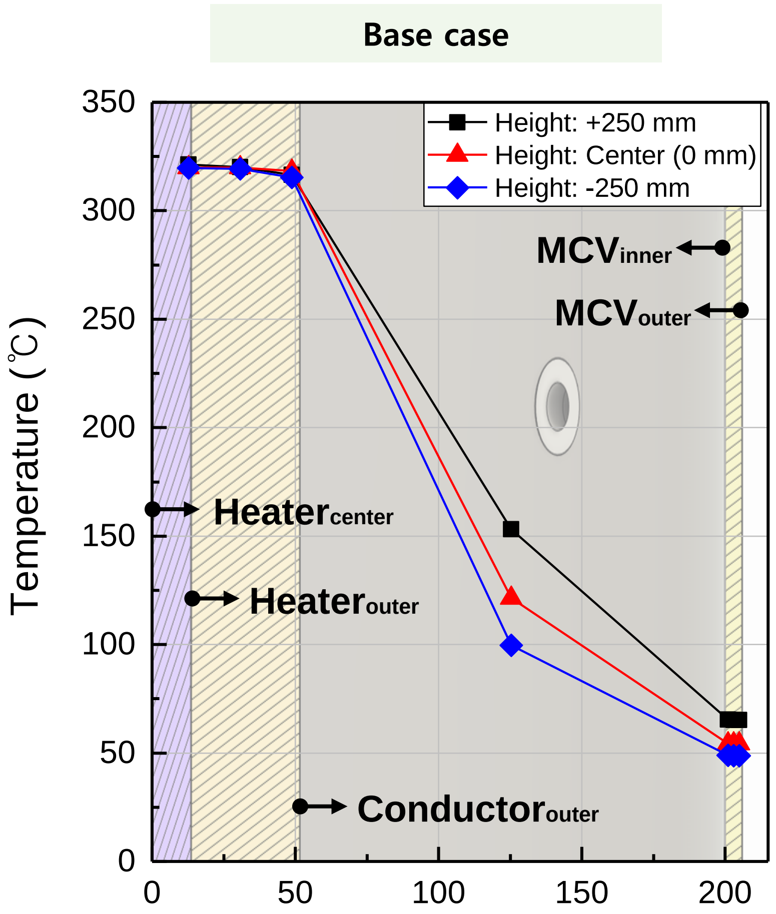

[ Temperature according to distance from the center ]

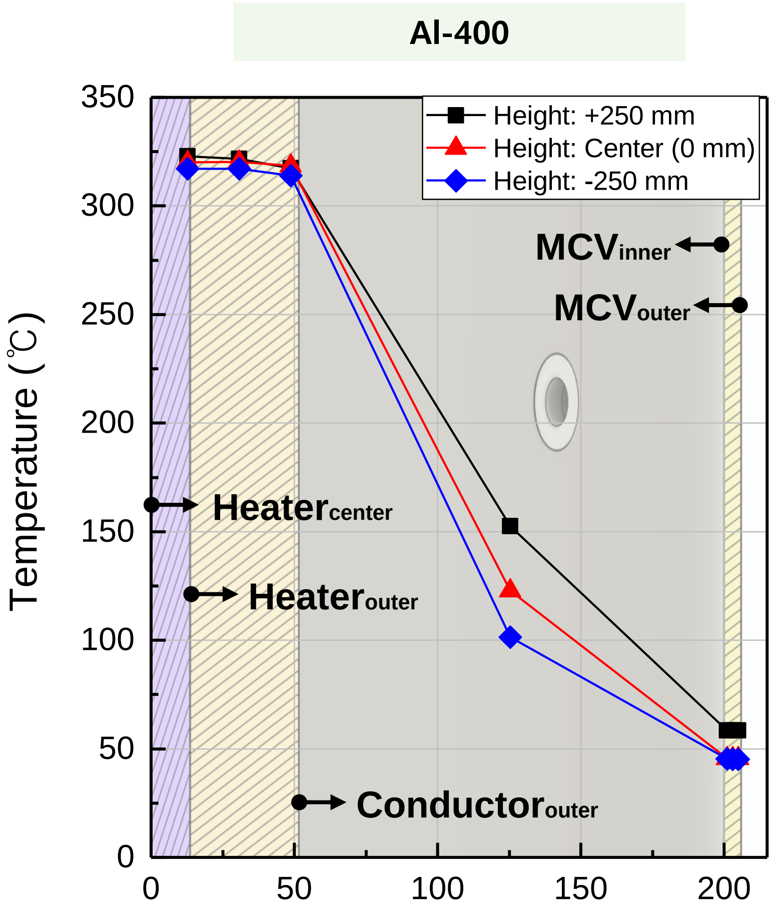
[ Heat loss of Background conduction and Base cas



# Results and discussions

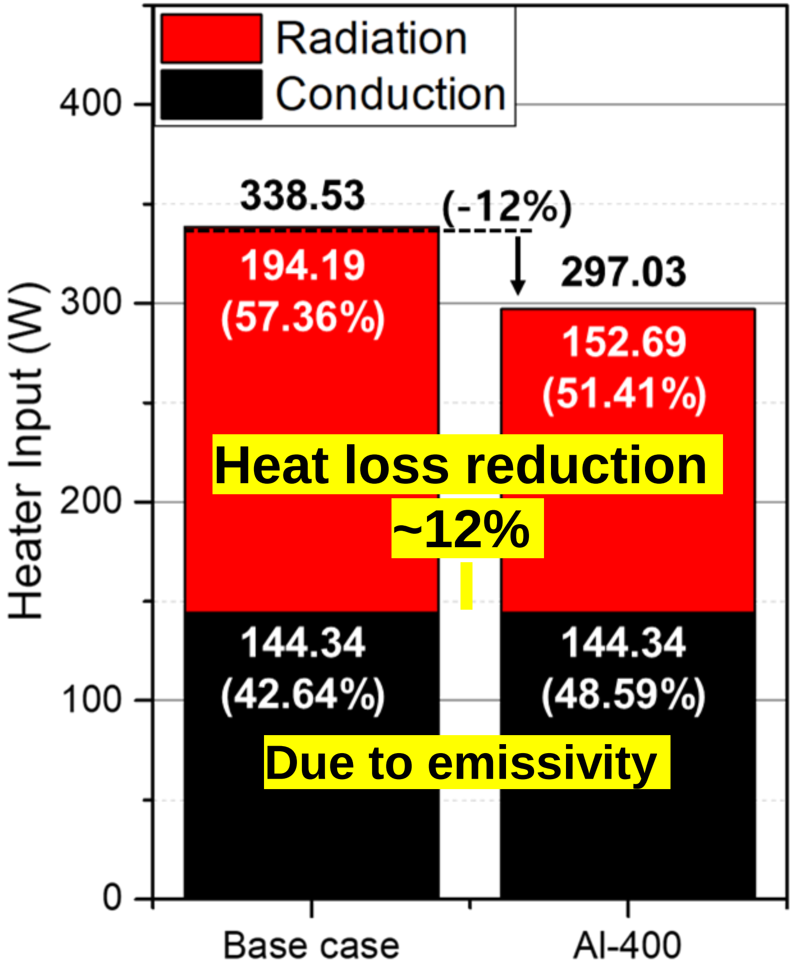
## Experimental results: Thermal radiation shielding effect




[ Temperature according to distance from the center ]

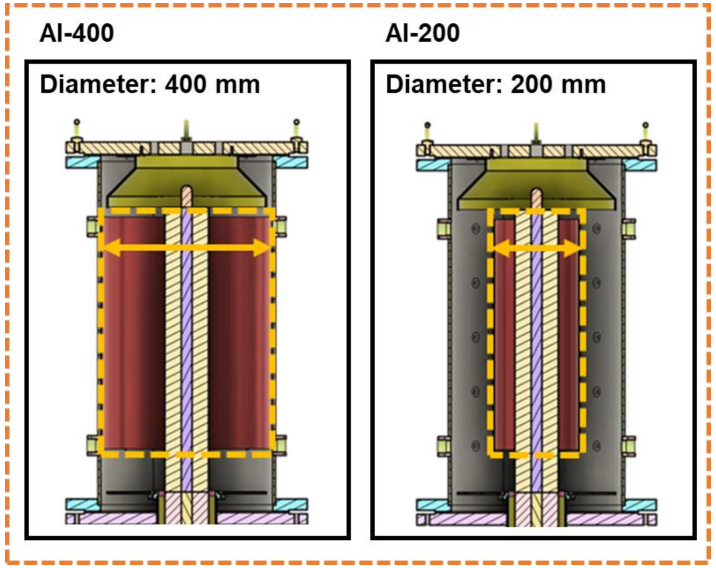
[ Heat loss of Base case and Al-400 ]



# Results and discussions

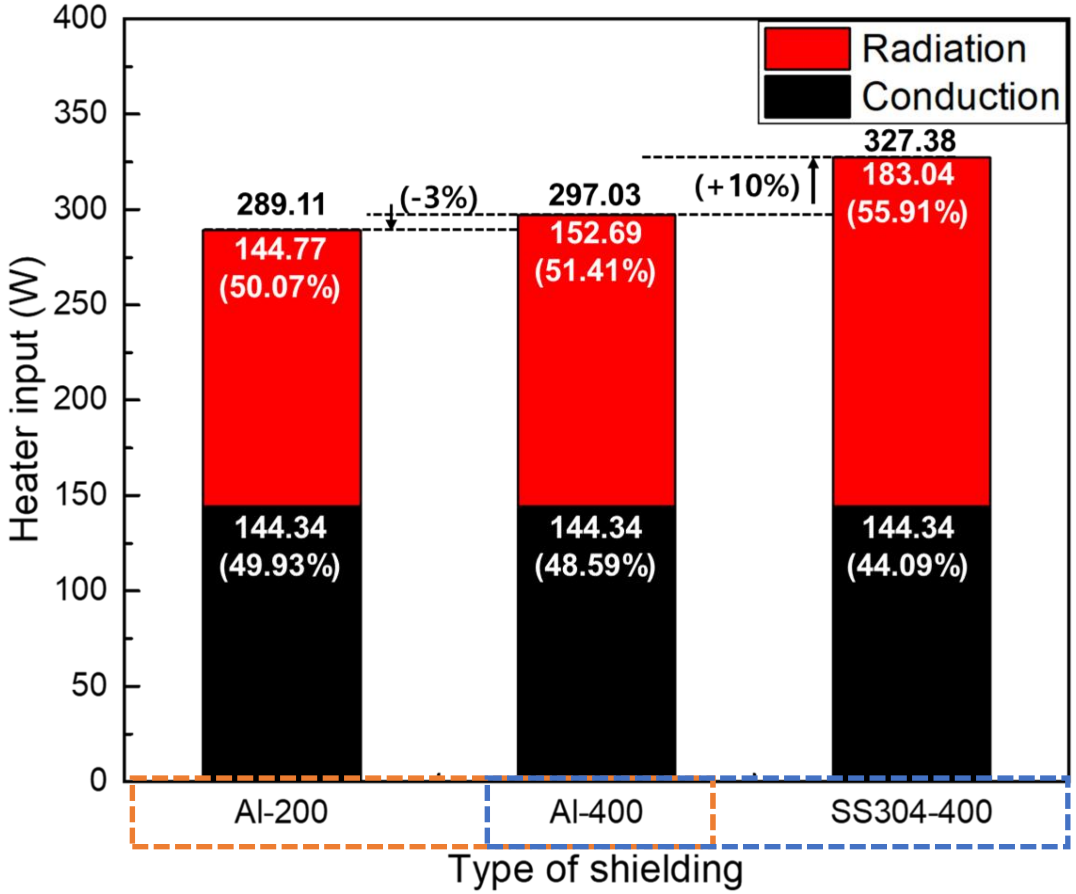
## Experimental results: Depending on the shielding variables

### Heat loss reduction ~3%

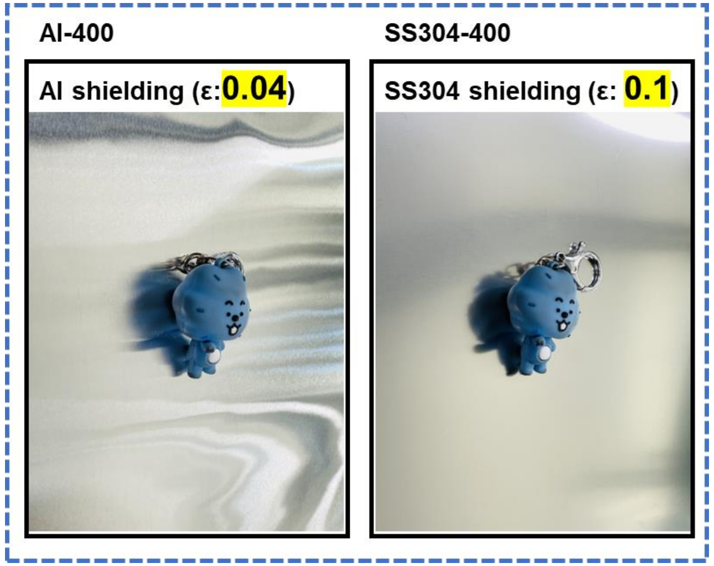



**Due to heat transfer area**

[ Heat loss according to type of shielding]




### Heat loss increase ~10%



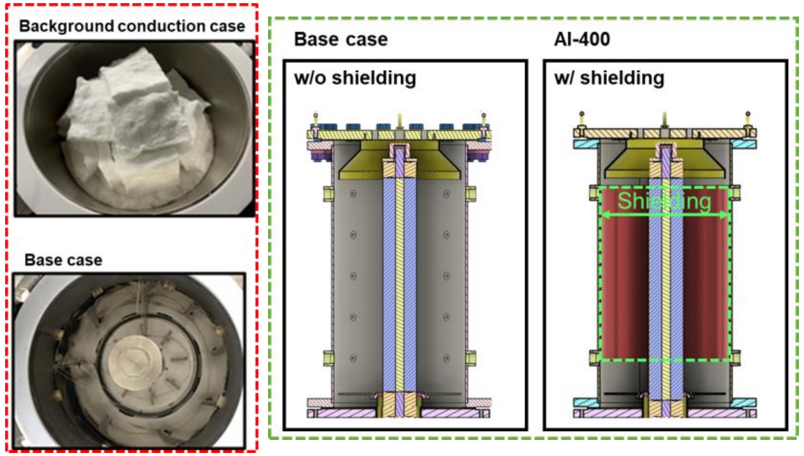

**Due to emissivity**

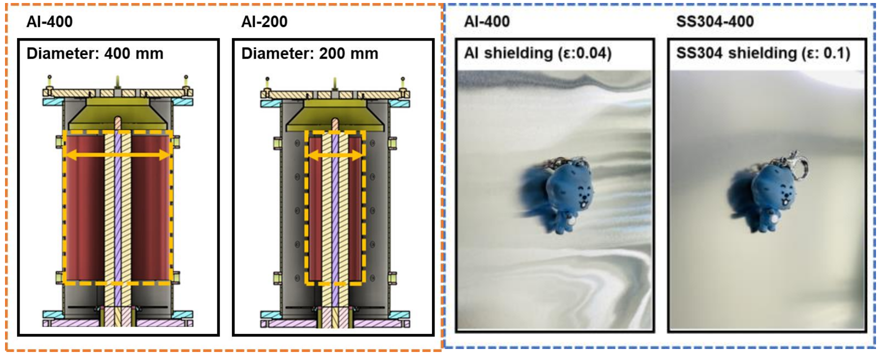
# Conclusion

## Summary and conclusion

ATHENA

- **Summary**
  - **Preliminary experiment**
    → "**Radiation is dominant**"
  - **Effect of radiation shielding experiment**
    → Shielding **reduced heat loss** about **12%**.
  - **Effective variables of radiation shielding experiment**
    → Heat loss of **Al shielding** is **10%** lower than **SS304 shielding.**
    → **200 mm shielding** is **3%** lower than **400 mm shielding.**




- **Conclusion**
  - Suggest applying thermal radiation shielding for the efficient SMR
  - Reducing emissivity using **surface modification** methods is also worth considering

# Thank you for your attention

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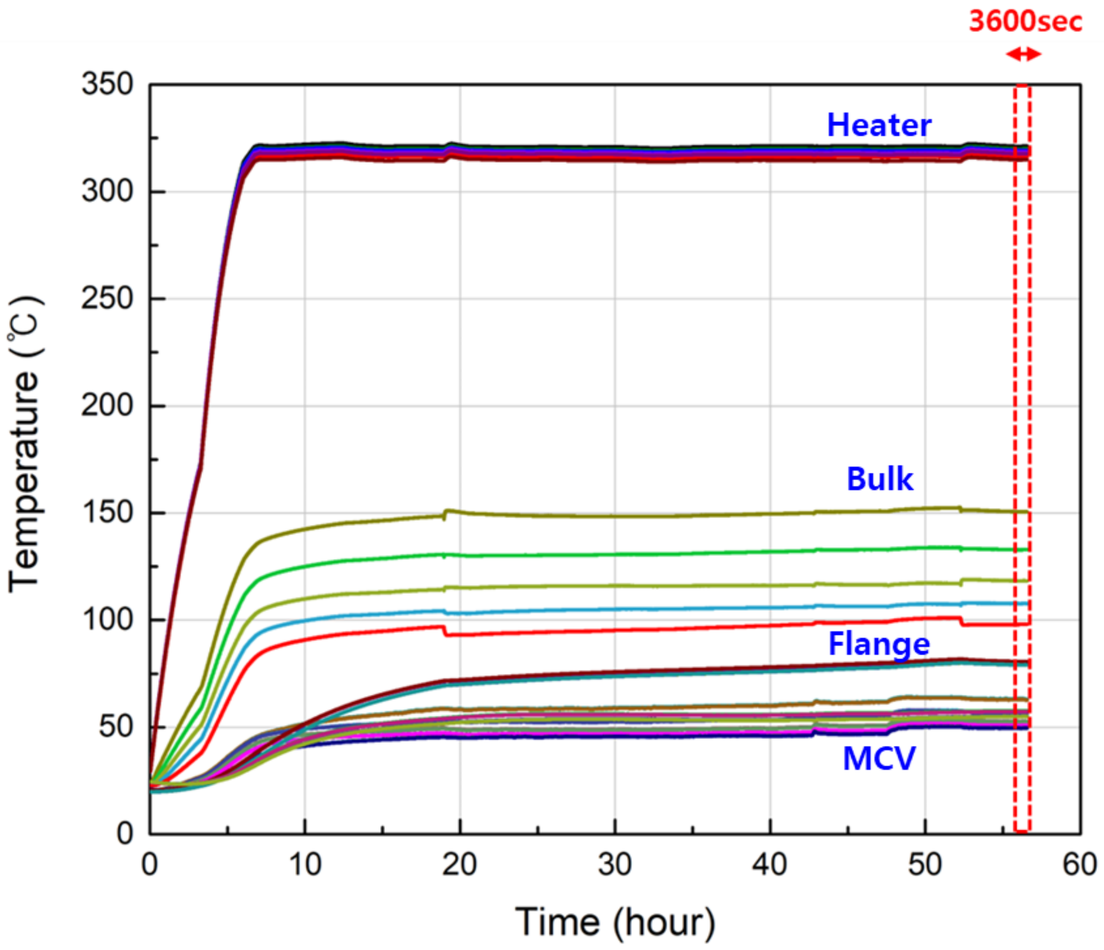
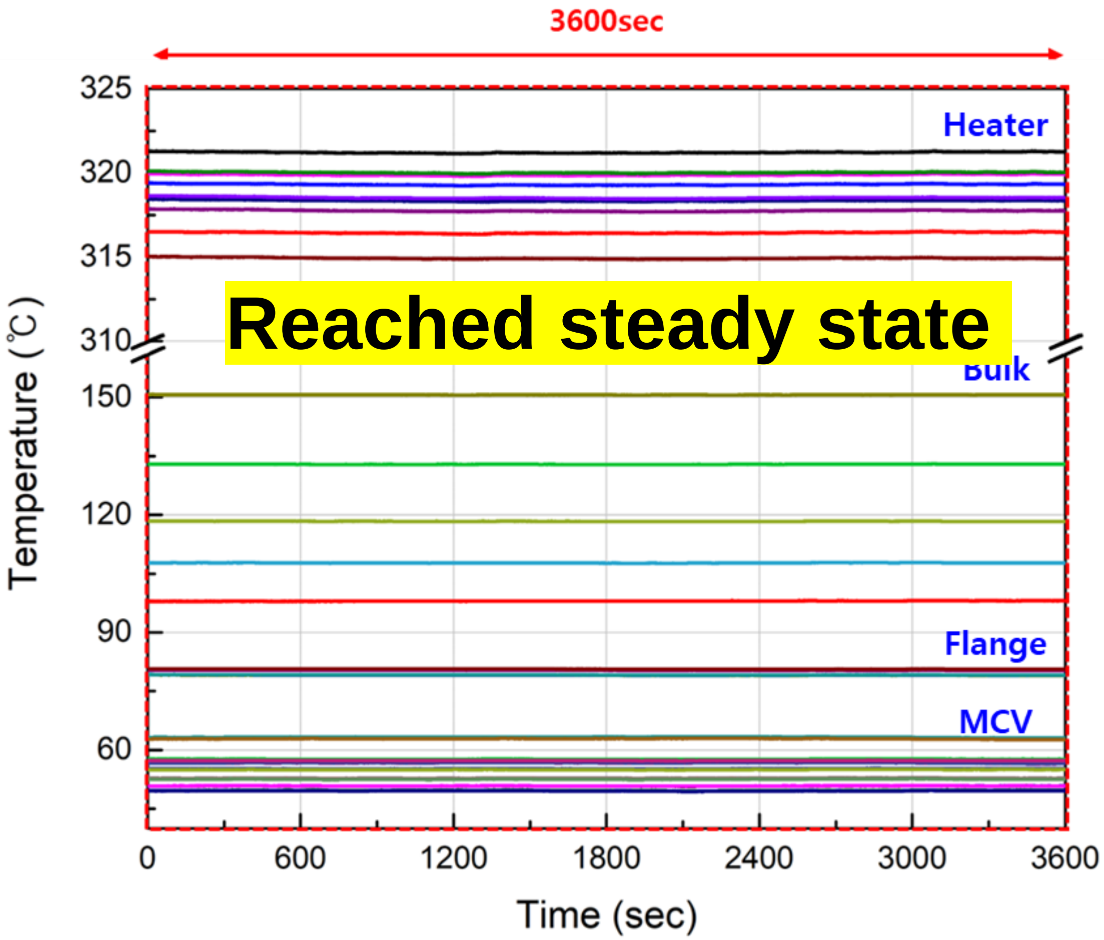
# Appendix

## Steady state experiment




[Measurements over the entire experiment time]




[Steady state for 3600 seconds]: Max-Min < 0.5 ℃