KNS Autumn Meeting,

A Conceptual Study of a system combines FS-MSR and ESS

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Contents

Topic Introduction

- Development of clean energy system technology
  - Without pollutant & supply of electricity stays constant the day
  - Distributed power ➔ high inherent safety

- Fast Spectrum Molten Salt Reactor (**FS-MSR**) + Liquid Air Energy Storage System (**LAES**)
  - FS-MSR is new generation reactor which have long life time(50years) without online-refueling
  - Target FS-MSR is 100MW_{th} power
  - LAES has large energy storage capacity
  - LAES collects carbon dioxide and fine dust during energy conversion and supplies clean air.

Topic Introduction

- Passive residual heat removal system(PRHRS) for Fast-Spectrum Molten Salt Reactor(FS-MSR).
  - RVACS: Reactor Vessel Auxiliary Cooling System
  - Passive safety system which air cooled by natural circulation
  - Prevent the core temperature increasing after reactor shutdown.

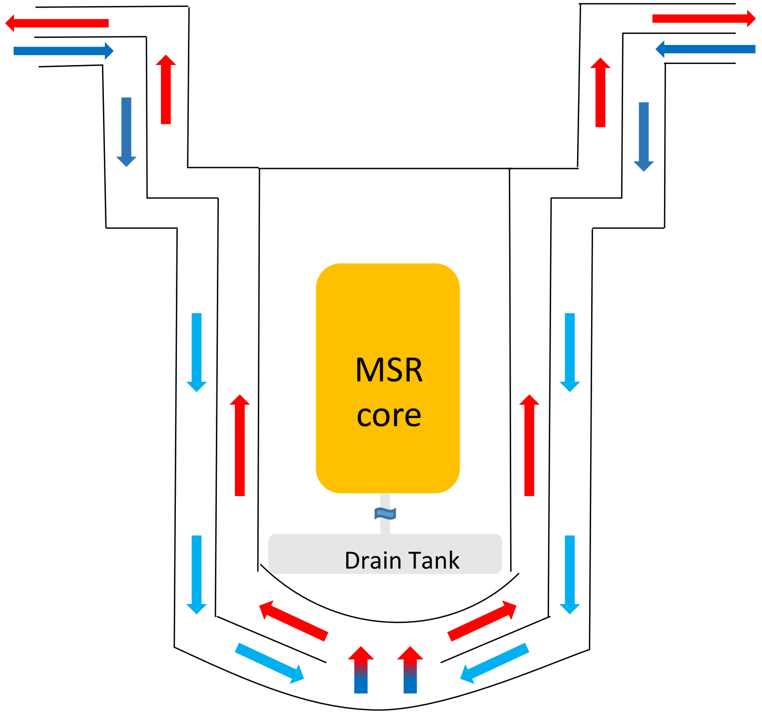


Fig1. RVACS System

- Find out the feasibility of RVACS
  - Simple evaluated by MATLAB calculation
  - Optimizing design parameters for $100MW_{th}$ FS-MSR

Background Study -core

- Fuel efficiency : online-refueling problem
- Low waste production: fast neutron < thermal neutron

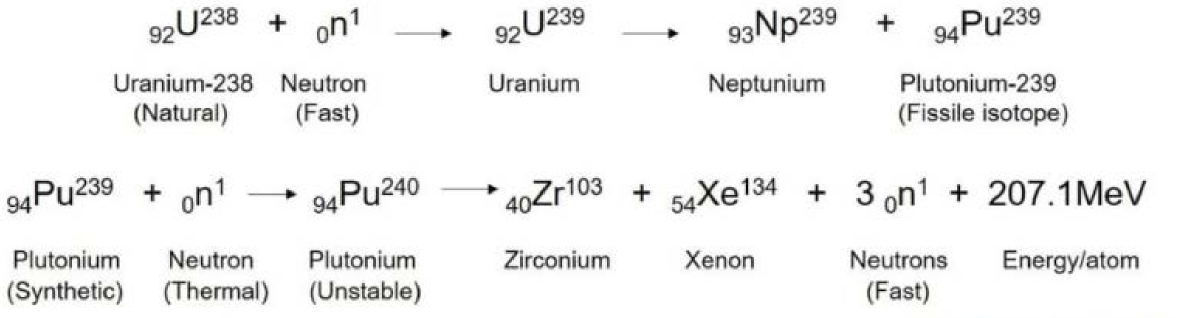


Fig2. U-238 reaction in Fast reactor

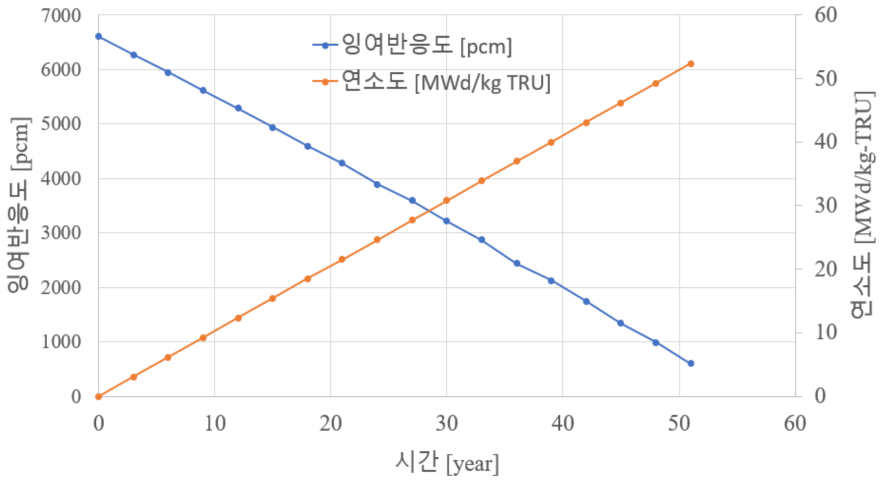
- Chloride based salt
  - Moderator effect: Fluoride based salt > Chloride based salt
  - Viscosity: Fluoride based salt > Chloride based slat ➔ high power density by pump

Molten salt	Viscosity (kg/m*s)
LiF-NaF-KF (46.5-11.5-42)	6.3e-3
LiF-NaF-ZrF_4 (26-37-37)	16.6e-3
LiCl-KCl (59.5-40.5)	1.8e-3
NaCl-KCl-$MgCl_2$ (30-20-50)	2.1e-3

Background Study -core

- Target reactor core design parameters
  - Eutectic point : mole fraction 54%
  - Fuel salt: 46KCl-54UCl_3
  - Cl enrichment: 99 a/o
  - U235 enrichment: 19.75 w/o
  - Core temperature : 650℃
  - Core diameter(height): 218cm
  - Initial heavy metal inventory: 35,576kg
  - Initial excess reactivity: 6608 ± 15 pcm

- Helium bubbling ➔ remove noble metal
- Off-gas system ➔ gaseous fission products



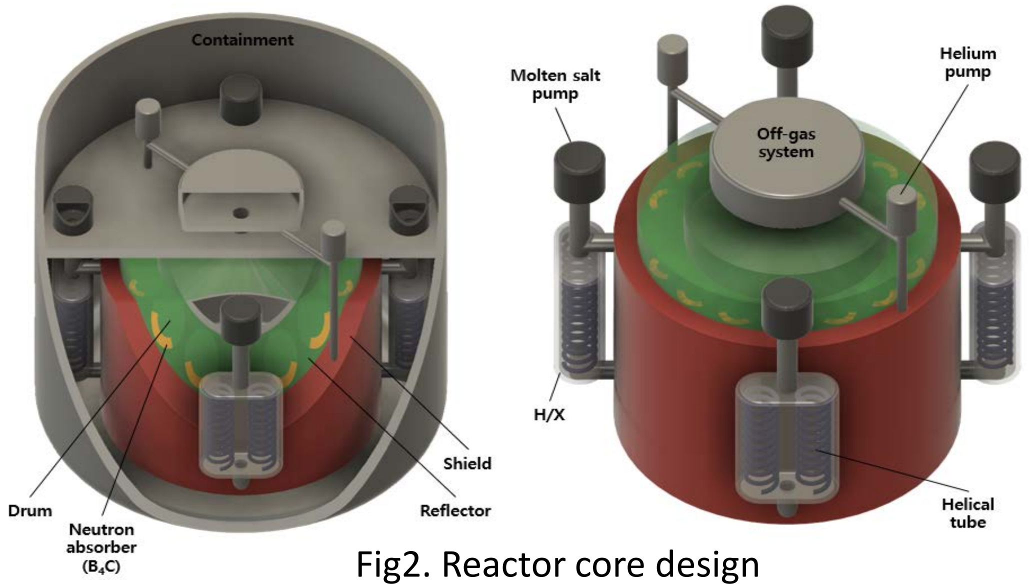


Fig2. Reactor core design

Background Study -ESS

- Electricity consumption rate by hour in july
  - 34.7% higher at noon to midnight ➔ need a energy storage

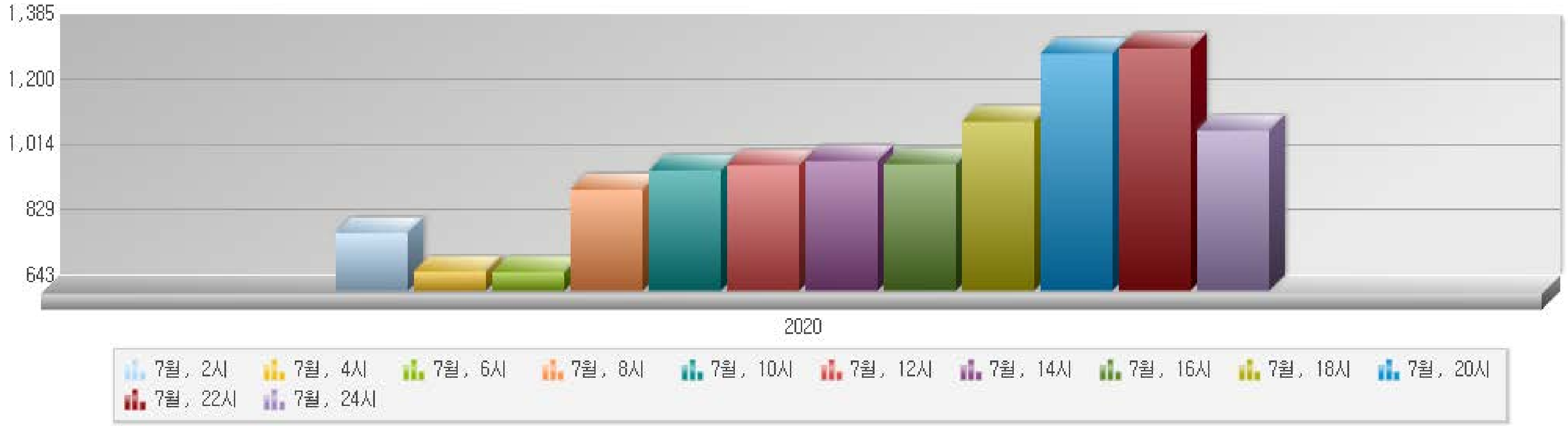


Fig3. power consumption(July, 2020)

- ESS type: Liquid air energy storage (LAES)
  - LAES should have a capacity to store at least 14.8% of power generation
  - 4.44MWe/53.28MWh capacity energy storage system is needed.

Background Study -ESS

- A supercritical CO_2 power conversion system applied
  - High temperature Brayton cycle, high efficiency than rankine cycle (< 5%)
  - Carbon dioxide capture mechanism
  - High density fluid make system simplify
  - Propose system optimum turbomachinery speed is 10,000RPM, 40cm, type is radial multi stage.

- Thermal energy storage (TES) to store heat transferred without temperature decrease
  - Control the reactivity (temperature control)
  - Hot & Cold insulated tank
  - ex) Crescent Dunes (USA), Andasol (Spain), Aurora (Australi)

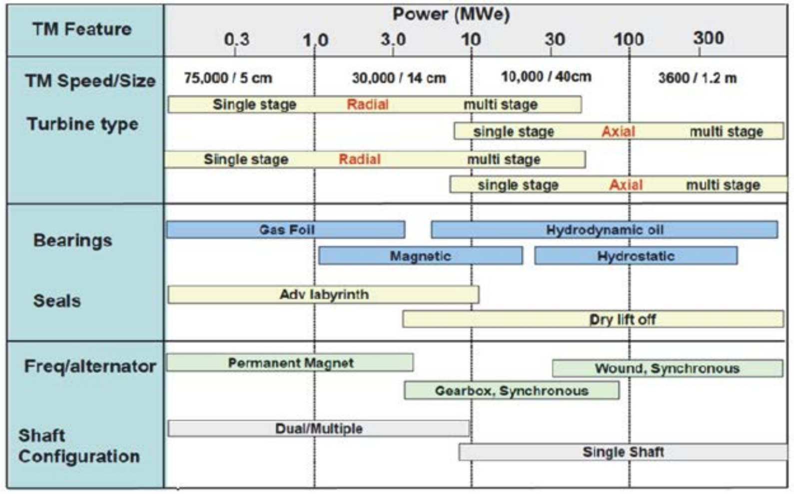


Fig4. sCO_2 optimum

Background Study -ESS

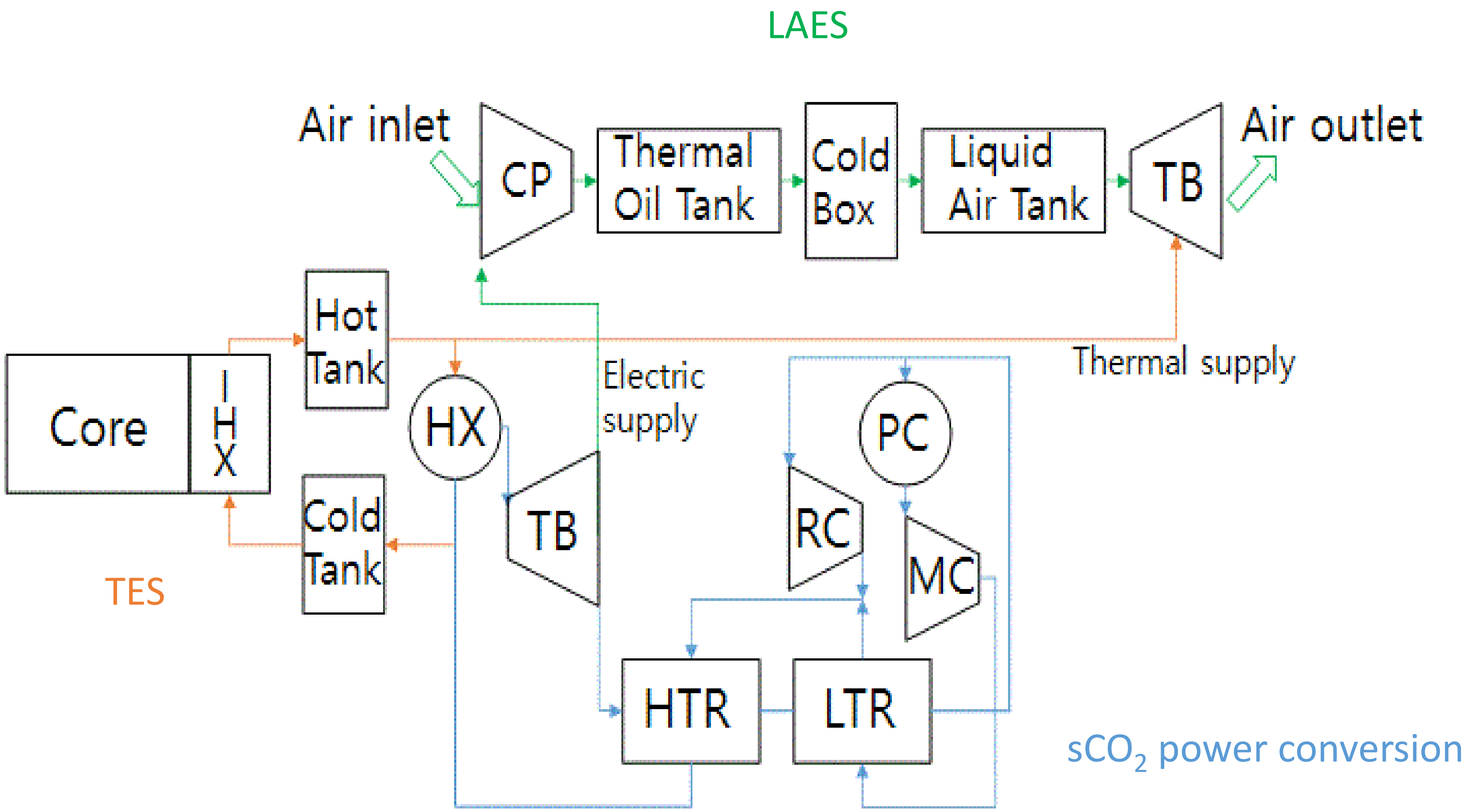
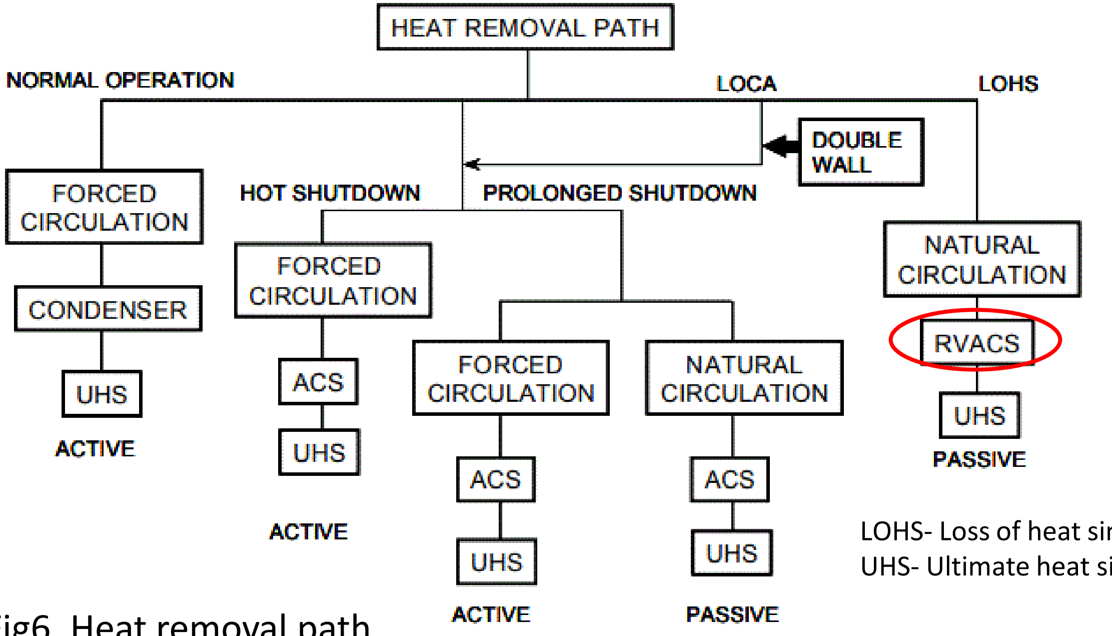


Fig5. Combines System

Background Study -RVACS

- There are no previous study about RVACS application for FS-MSR.
  - Direct reactor auxiliary cooling system(DRACS), Primary reactor auxiliary cooling system(PRACS) exists
  - The RVACS heat removal capacity was investigated for similar types of reactor
  - The existing models were compared, and satisfactory heat removal criteria were determined

- IRACS fails completely, RVACS is able to remove shutdown heat as a fully passive system of air convection.



LOHS- Loss of heat sink
UHS- Ultimate heat sink

Fig6. Heat removal path

Background Study - RVACS

- PRISM reactor has RVACS that heat removal capacity was 0.7% of full power using the air. Also, SAFR reactor has 0.6% heat removal capacity and Phenix reactor has 0.7%.
- These reactors have different characteristics from FS-MSR, because neutron leakage rate and temperature distribution are totally different. However these reactor was designed heat removal capacity is about 0.6~0.7 % of full power. Therefore, it is applicable if the target heat removal of FS-MSR satisfies under 0.6%

Reactor	Power (MWth)	Coolant	RVACS method	Heat remove (% full power)	mechanism
PRISM	840	Sodium	RVACS with air	0.7	Natural
SAFR	900	Sodium	RVACS with air	0.6	Natural
IMSR	400	Molten Salt	RVACS with Nitrogen	unknown	Natural
Phenix	840	Sodium	RVACS with water	0.7	Forced
CLEAR-I	45	Lead	RVACS with air tubes	0.2	Natural

Table3. RVACS application reactor features [3]

Research Question

- Find out the feasibility of Reactor Vessel Auxiliary Cooling System (RVACS)
  - The exist RVACS's target feature ability is 0.2 ~ 0.7%
  - RVACS target for FS-MSR is remove 0.6% of full power (600kW_{th})
- Optimizing design parameters for our target reactor
  - CV outer wall temperature affects heat removal ability
  - Total heat removal capacity
  - Stack height
  - Air path thickness

RVACS test methods

- Using MATLAB code calculation (natural circulation)
  - Simplified geometry (overflow x)
  - Considering : pressure drop, Convection & Radiation heat transfer
  - Changing values: Air patch thickness, mass flow rate

Design parameter	value
Air inlet Temperature	50 ℃
CV temperature	600 ℃
CV diameter	3 m
Air path thickness	3 – 7 cm
Air mass flow rate	1 – 3 kg/s

Table1. RVACS design parameter

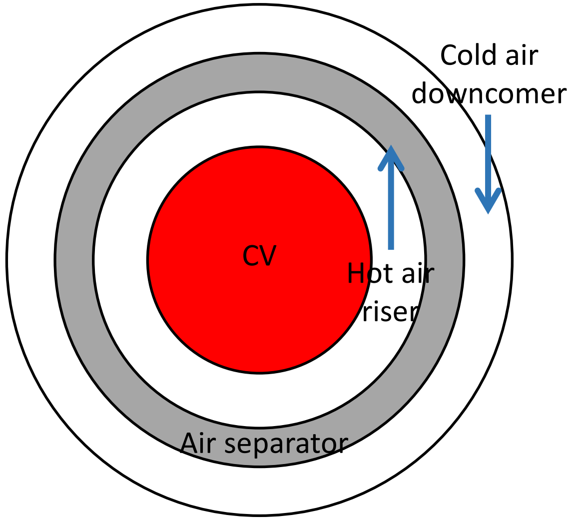


Fig7. RVACS cross section

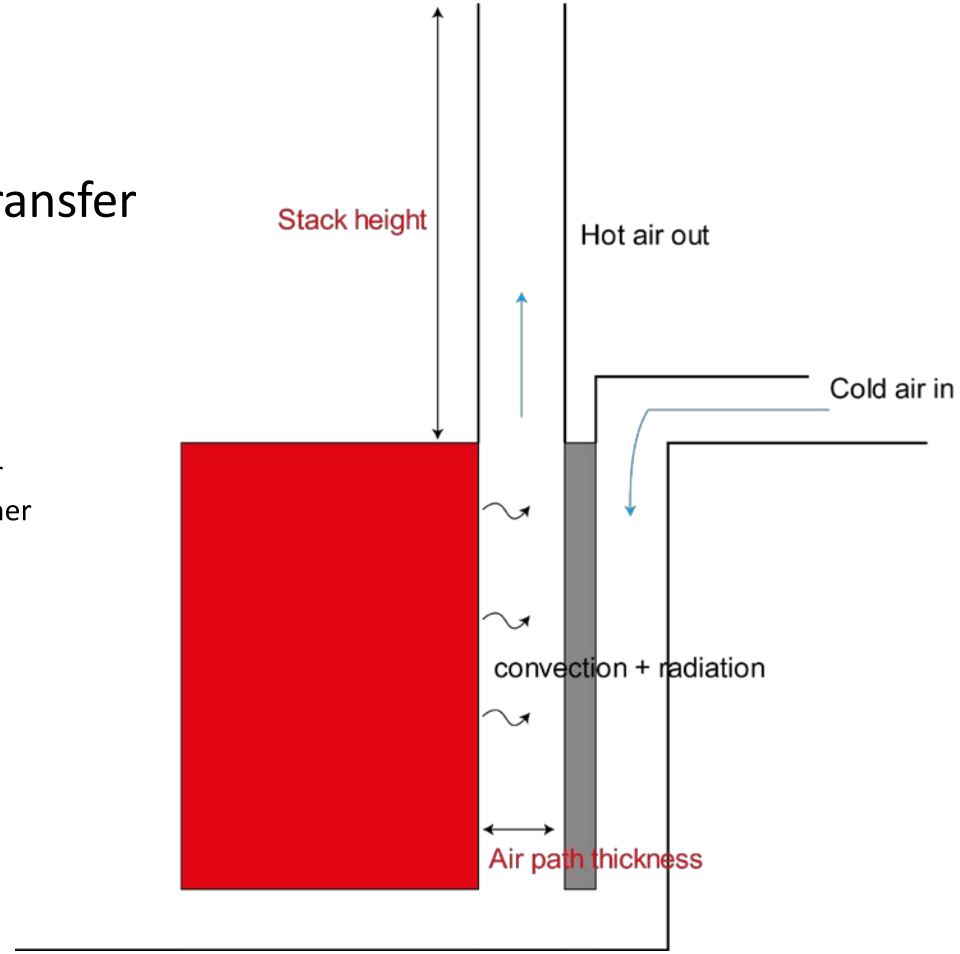


Fig8. RVACS side view drawing

RVACS test results

- Target of heat removal capacity is 0.6% of the full power.
  - $100MW_{th}$ reactor using, so $600kW_{th}$ decay heat removal capacity design
  - Case3 is optimization design (stack height is acceptable(<15m) and high heat removal)

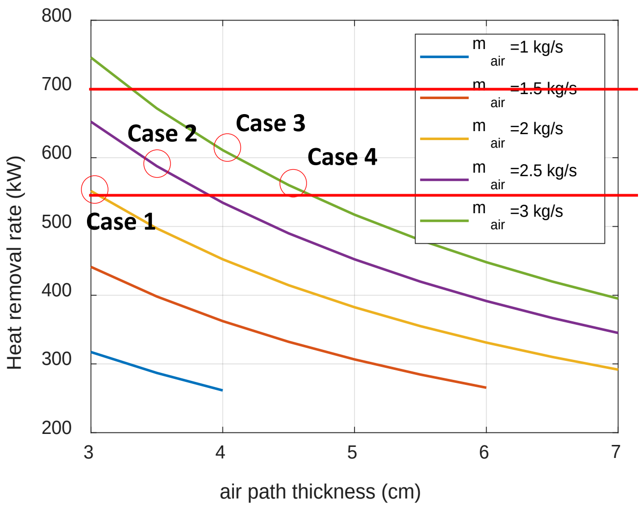


Fig9. Heat removal rate

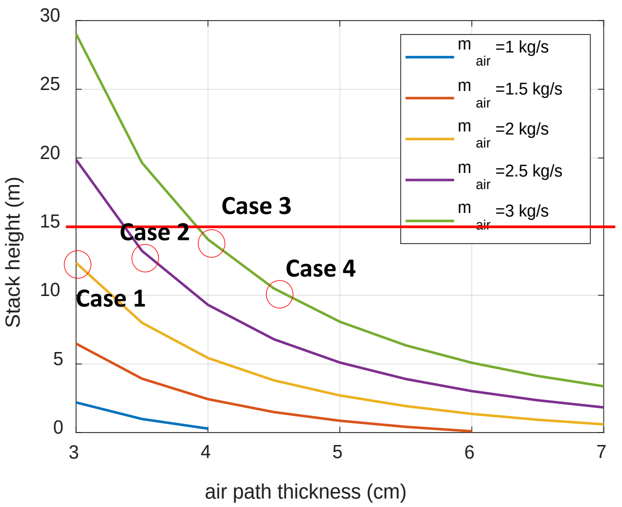


Fig10. Stack height

Case	Case 1	Case 2	Case 3	Case 4
Air path thickness	3cm	3.5cm	4cm	4.5cm
Air mass flow rate	2kg/s	2.5kg/s	3kg/s	3kg/s
Stack height	12.4m	13.2m	14.0m	10.5m
Heat remove	552.0kW	588.0kW	611.0kW	560.0kW
Air outlet temperature	317.3℃	278.5℃	248.4℃	232.1℃
Air heat transfer coefficient	27.6W/m2K	27.7W/m2K	27.6W/m2K	24.4W/m2K

Table2. Code calculation results

RVACS test results

- The percent of convection decay heat removal is 55%.
- If containment vessel wall temperature increase
  - Heat removal capacity is increase.
  - Necessary stack height is decrease.

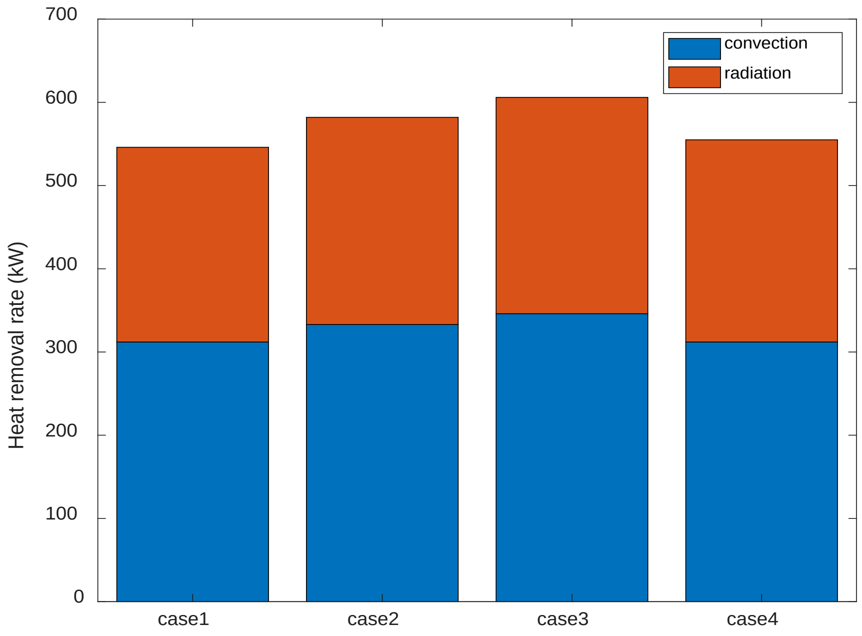


Fig11. The ratio of convection to radiation heat removal

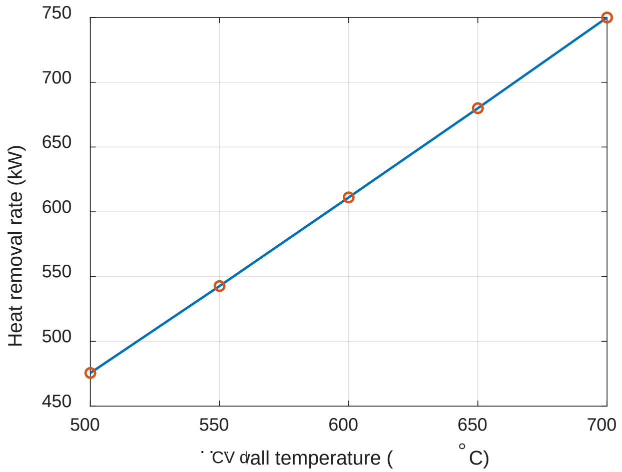


Fig12. Heat removal

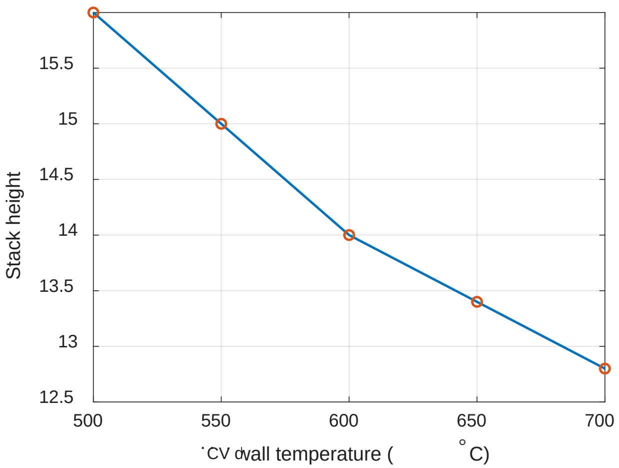


Fig13. Stack height

RVACS test results

- Evaluate the applicability to higher reactor power(200, 300MW_{th})
  - Air path thickness is 4 cm fixed
  - CV diameter, stack height are variables
- Increase CV diameter is essential to improve RVACS performance

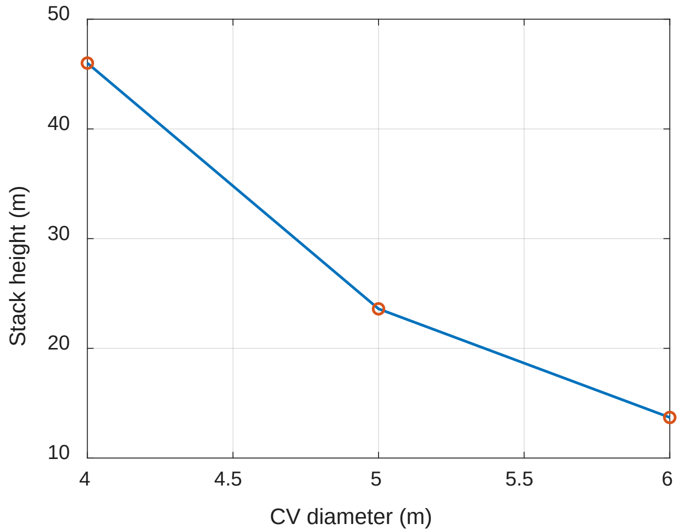


Fig14. Stack height (200MWth)

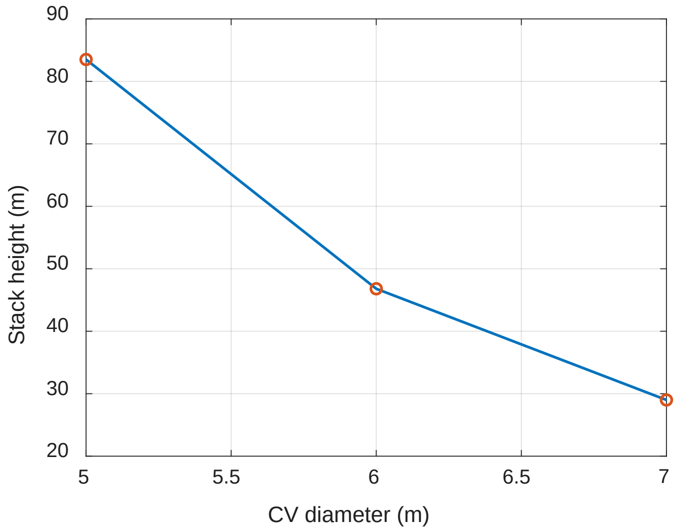


Fig15. Stack height (300MWth)

Limitation of Study & Future work

- This is preliminary conceptual study about RVACS application for FS-MSR
  - There many assumptions (especially concrete silo temperature was unapplied)
  - It is difficult to obtain the CV outer wall temperature distribution (viscosity, heat conductivity coefficient)
  - The placement of Internal Heat Exchanger(IHX) and internal structure of reactor vessel also need to considered

- Ar41 is produced from irradiation of air due to neutron leakage
  - Looking for a solution to prevent air pollution
  - Closed circuit geometry (valve or damper)
  - Compare heat loss in normal operation and mechanical operation

Conclusion

- Combination system
  - Fast spectrum Molten salt reactor
  - TES + LAES + sCO_2 power conversion
  - RVACS, residual heat removal
- The feasibility of RVACS evaluation result is enough to decay heat removal after 100MWth reactor shutdown.
- Optimized design for $611kW_{th}$ decay heat removal using RVACS
  - Air path thickness is 4cm, air mass flow rate is 3kg/s
  - The required stack height is 14m
  - Air heat transfer coefficient is 27.6 $W/m^2 K$

References

General Electric, PRISM, Preliminary Safety Information Document, prepared for U.S Department of Energy Under Contract No.DE-AC03085NE37937, December. 1987. Volume 2

CHENG, Lap-Yan. *Phenomena Important in Liquid Metal Reactor Simulations*. Brookhaven National Lab.(BNL), Upton, NY (United States), 2018.

LISOWSKI, Darius, et al. Technical Letter Report: An Overview of Non-LWR Vessel Cooling Systems for Passive Decay Heat Removal. 2021.

BOARDMAN, C. E.; HUNSBEDT, A. *Performance of ALMR passive decay heat removal system*. 1991.

Eoh, Jae-Hyuk, et al. "Feasibility study of a passive DHR system with heat transfer enhancement mechanism in a lead-cooled fast reactor." *Nuclear technology* 160.2 (2007): 216-232.

HUNSBEDT, A. *Experiments and analyses in support of the US ALMR thermal-hydraulic design*. 1993.

Thank you