Study on Application of Phase Change Material for passive containment cooling

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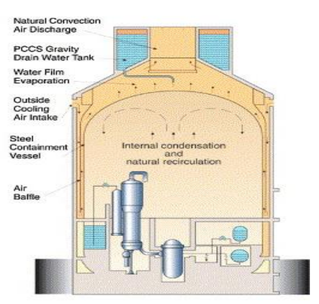
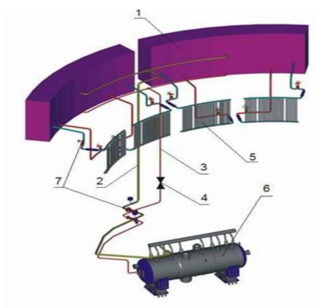
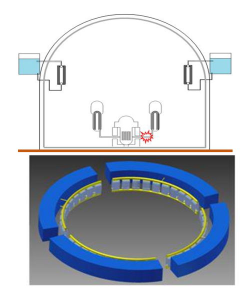
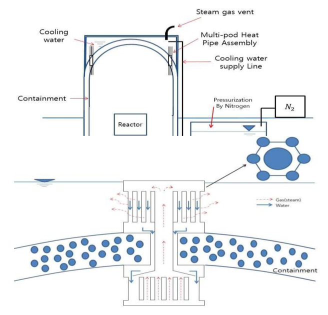
Introduction

▣ After the Fukushima accident, the importance of passive system is increased.

AP1000 (USA)	VVER-1200 (Russia)	APR 1400, APR + (Korean)	
Designed by Westinghouse and under construction	Under construction	Developing	
Steel containment, Spray	Heat exchanger modules	Heat exchanger modules	Thermosiphon
			
- Not applicable to domestic plants - New containment building design is required	- Penetration - Only for new nuclear power plants - Boiling of coolant → It cannot ensure its cooling capability		

▲ Features of existing technologies related to PCCS

▣ Authors propose additional passive containment cooling method using **Phase Change Material (PCM)** to increase the efficiency of passive cooling. PCM has a good potential because it stores heat energy as a form of latent heat during phase change

▣ This study suggests a preliminary study of applying PCM for containment passive cooling.

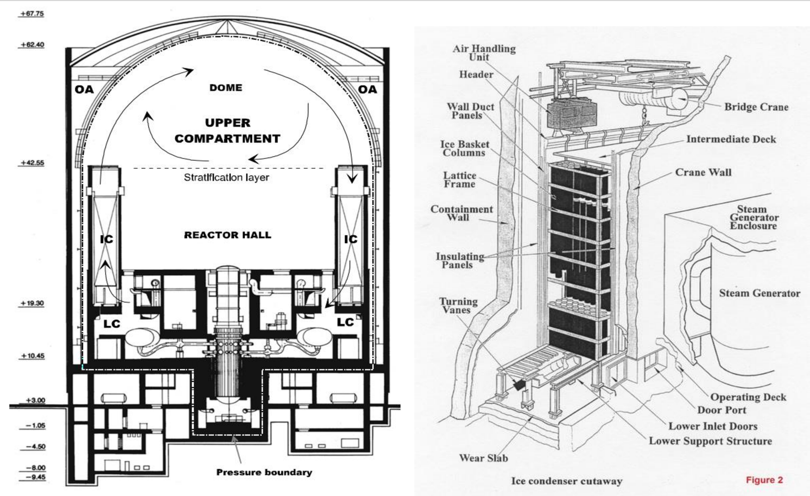
Passive containment cooling system using PCMs

▣ Existing concept: Ice condenser

➢ It is designed by Westinghouse in the late 1970s and early 1980s.

- In the United States (DC Cook(AEP), McGuire(Duke), Catawba(Duke), Sequoyah(TVA), and Watts Bar(TVA)), Finland (the Loviisa plant), and Japan (Ohi plant)

➢ The ice is maintained in a refrigerated compartment surrounding the reactor coolant system. The steam is condensed by the ice and decreases the potential pressure rise in the containment



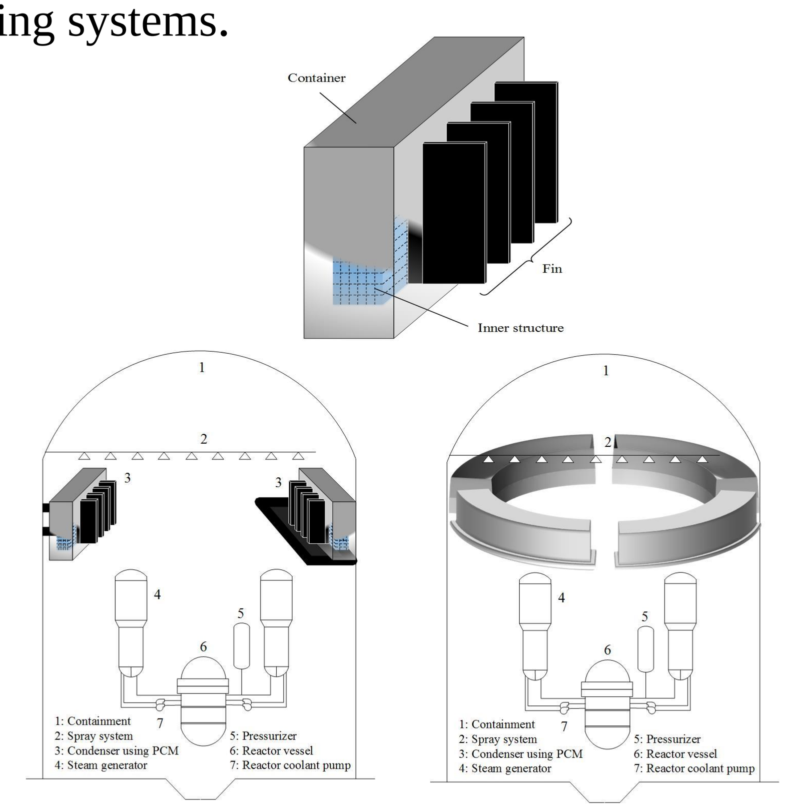
▲ (a) The Loviisa NPP containment (in Finland) (b) Ice condenser cutaway

▣ PCM condenser

➢ PCM is a substance with a high heat of fusion as latent heat. Thermal energy storage by means of latent heat can be a promising alternative to conventional active cooling systems.

Characteristic	Drawback	Advantage of PCM condenser
Much smaller containment building	Maintenance cost to keep the cool containment (-13~-6 °C)	Using the PCM with melting point between 49~80°C
Chiller	Removing the ice from the condenser walls	Maintenance free
In accidents condition, the ice condenser inlet doors open due to pressure rise in the lower compartment	Foreign material clog the lower inlet drains or the sumps	Completely passive system
Borated ice is stored in cylindrical baskets	Checking for an even amount of ice through the condenser	Easy replacement
Weighing and re-filling the empty ice basket		

▲ Comparison of Ice Condenser and PCM condenser



▲ (a) Configuration of condenser using PCM (top) (b) Installation type (down)

Selection of PCM candidates

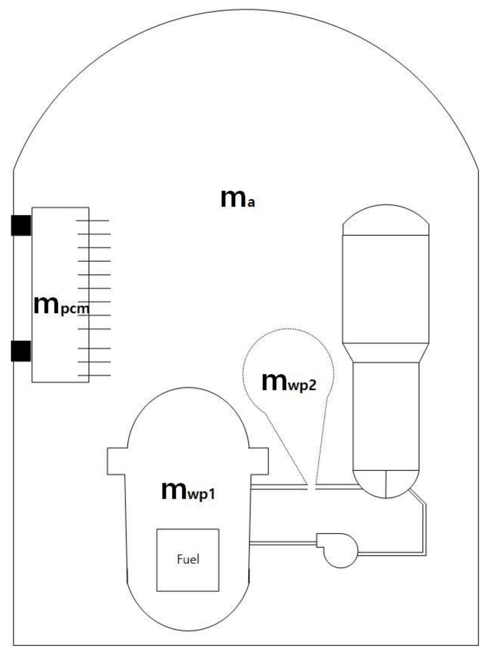
▣ PCMs for containment passive cooling are classified by the following criteria.

Criteria	Remark
Thermal properties	• Phase change temperature near 49~80ºC (accident condition) • High change of enthalpy near 49~80ºC • High thermal conductivity
Physical properties	• High density
Chemical properties	• Stability • Non-toxic, non-flammable, non-polluting
Economic properties	• Cheap and abundant

▲ Criteria for PCM to apply to the containment

Thermodynamic Calculation for the amount of PCMs

▣ **The minimum mass and volume of PCM** required for PCM condenser is calculated. The reference reactor is APR1400.



▲ Schematic diagram of thermodynamic system in PWR

▣ The Assumptions

➢ Final conditions are the state **after the completion of the blowdown process**

➢ Final conditions are defined as the state of **pressure equilibrium** between the contents of the containment vessel and the primary system.

▣ Decay heat

➢ PCCS safety analysis standard

- The total heat output for the PCCS is set as **the decay heat after 5 min of shutdown.**
- The integrity of the containment should be maintained for at least **72hrs after 5 min of shutdown.**

▣ Calculation method

➢ Energy conservation

$$m_w(u_{wp2}-u_{wp1}) + m_a C_{va}(T_2 - T_1) + m_{pcm}\Delta u_{pcm} = Q_{decay}$$

➢ Final temperature calculation

$$P_2 = P_{w2} + P_{a2} = P_{sat}(T_2) + \frac{m_a R_a T_2}{V_c} = 0.4MPa$$

Conditions	
Decay energy	625×10⁹ MJ
Initial containment pressure	1.013×10⁵ Pa
Initial containment temperature	27°C
Primary system pressure	15.5 MPa
Final containment pressure	0.4 MPa

▲ Initial and final conditions for the calculation

➢ The difference of internal energy of PCM (Heat absorbed per unit mass of PCM)

$$\Delta u_{pcm} = C_{pcm,s}(T_m - T_{pcm,1}) + u_{fus} + C_{pcm}(T_{pcm,2} - T_m)$$

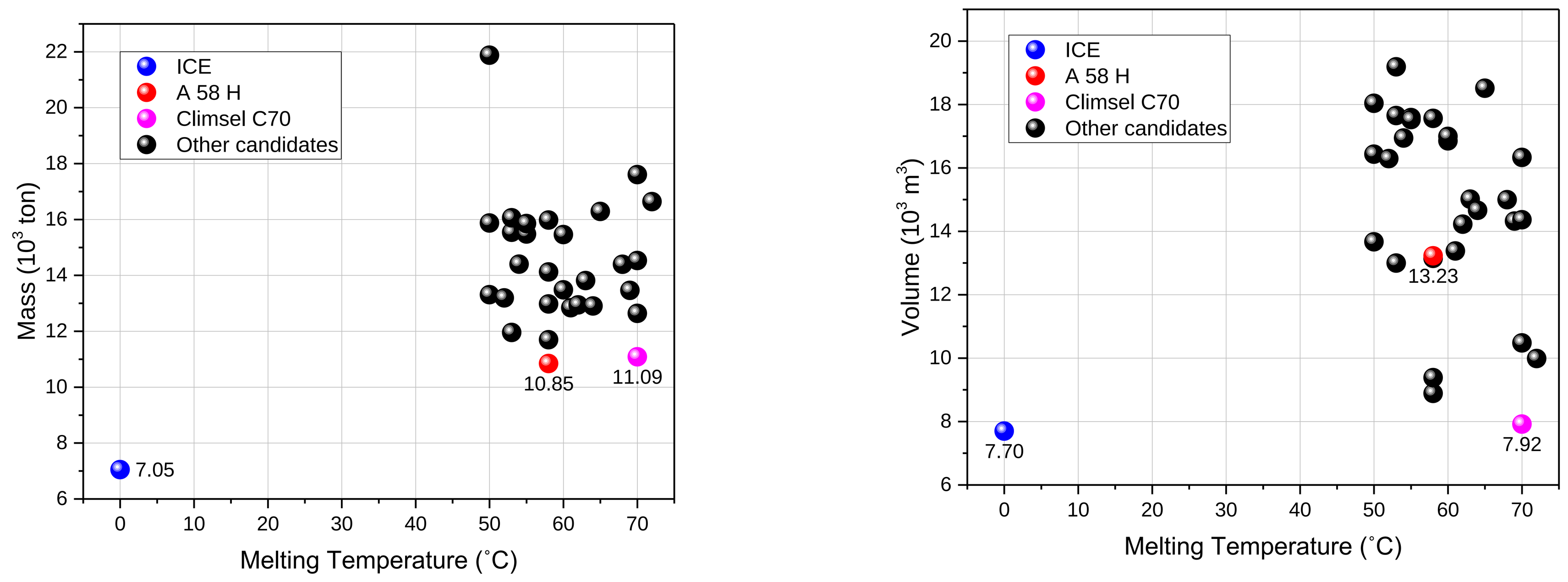
➢ The mass of PCM

$$m_{pcm} = \frac{Q_{decay} - m_{wp}(u_{wp2}-u_{wp1}) - m_a C_{va}(T_2 - T_1)}{\Delta u_{pcm}}, \quad V_{pcm} = \frac{m_{pcm}}{\rho_{pcm}}, \quad V_{c,iter} = V_c - V_{pcm}$$

▣ Results

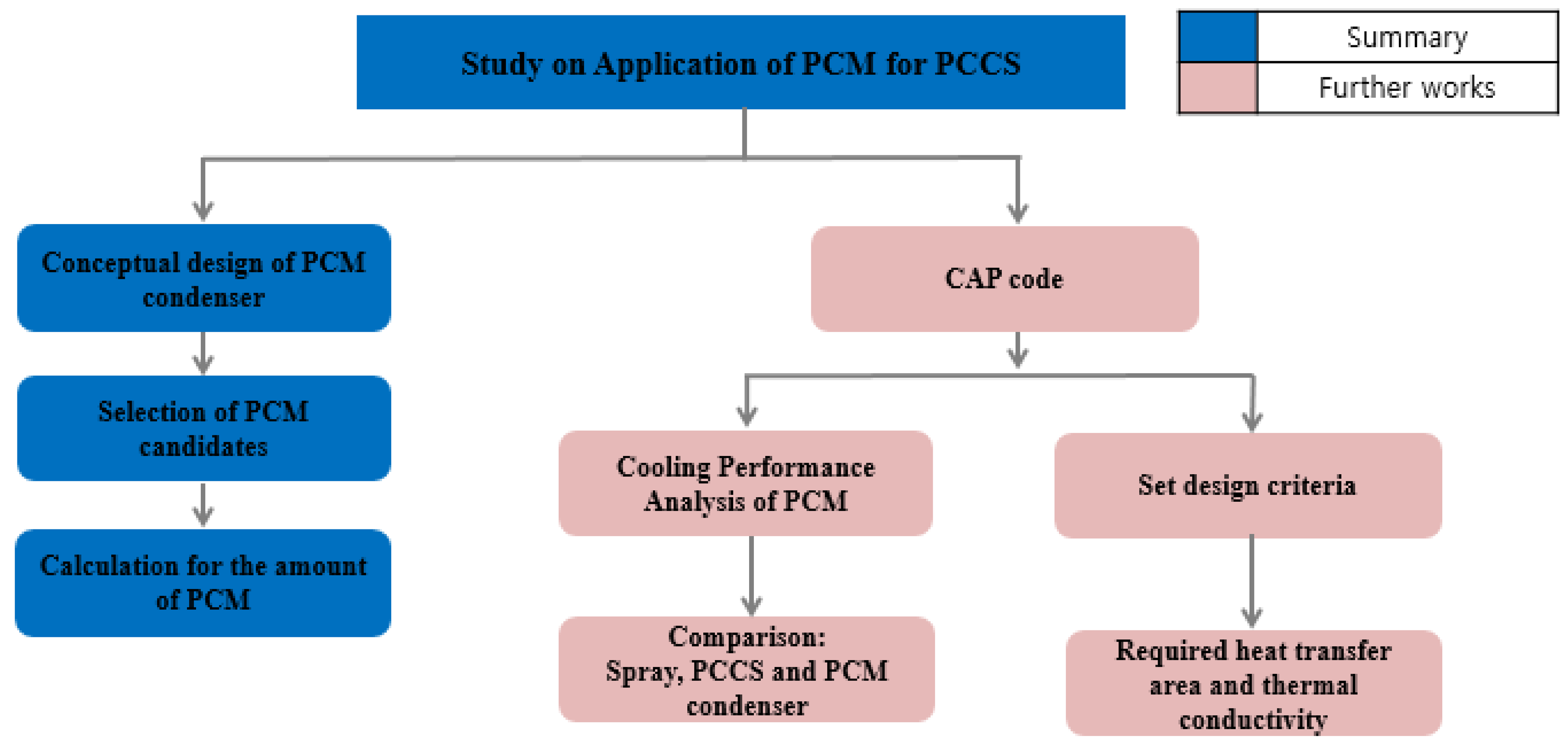
➢ In terms of safety, It is important to have more free volume to minimize the pressure and temperature of containment

➢ **Climsel C70** is considered as the most suitable material for the PCM condenser.



▲ Thermodynamic calculation results for mass and volume of PCMs

Summary & Further works



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