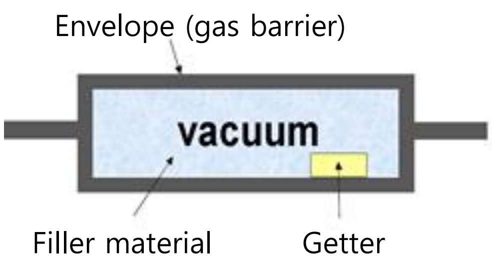
「Pillar-supported core structure for vacuum insulation panel」

Bongsu Choi

VACUUM INSULATION PANEL

- VIP samples -

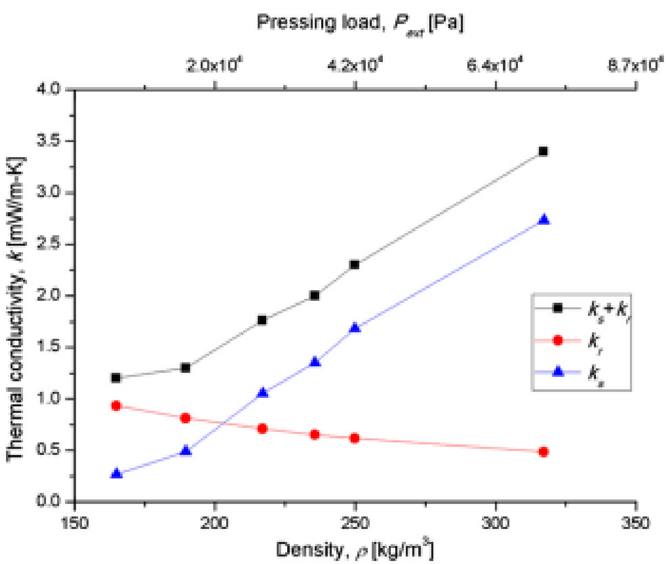


- Structure of VIP -

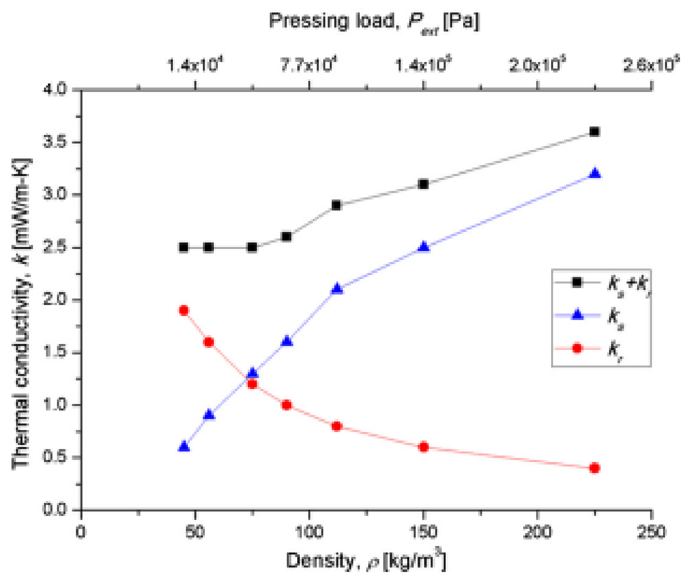
- Heat transfer of VIPs
  - Filler material
    - Gas conduction, k_g
    - Solid conduction, k_s
    - Radiation, k_r
  - Envelope
    - Edge conduction, k_{edge}

$$k_{eff} = k_g + k_s + k_r + k_{edge}$$

FILLER MATERIAL



- Glass wool [1] -

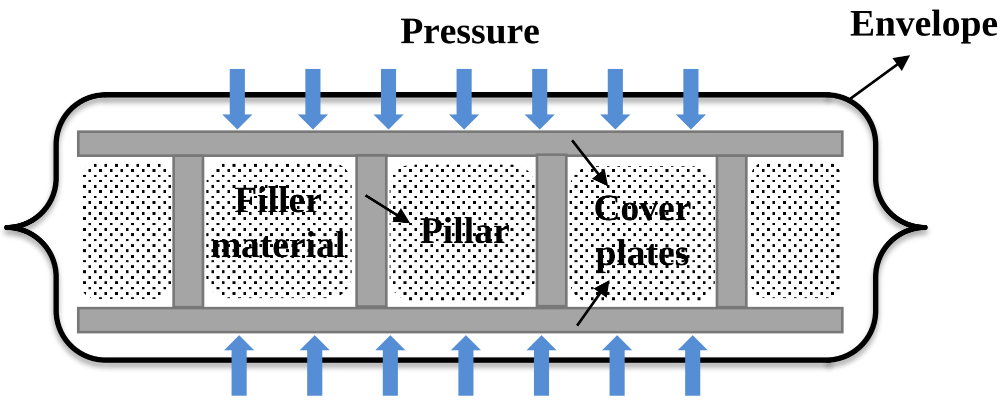


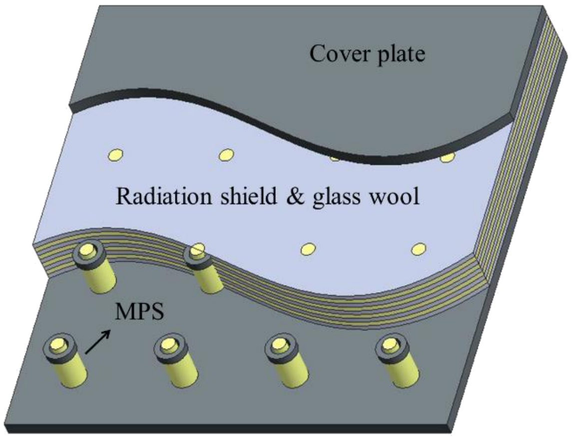
- Fumed silica [1] -

k_s+k_r can be reduced by releasing the external pressure

[1] J. Kim, T.H. Song, Vacuum insulation properties of glass wool and opacified fumed silica under variable pressing load and vacuum level, Int. J. Heat and Mass Transfer 64 (2013), 783-791

PILLAR-SUPPORTED VIP

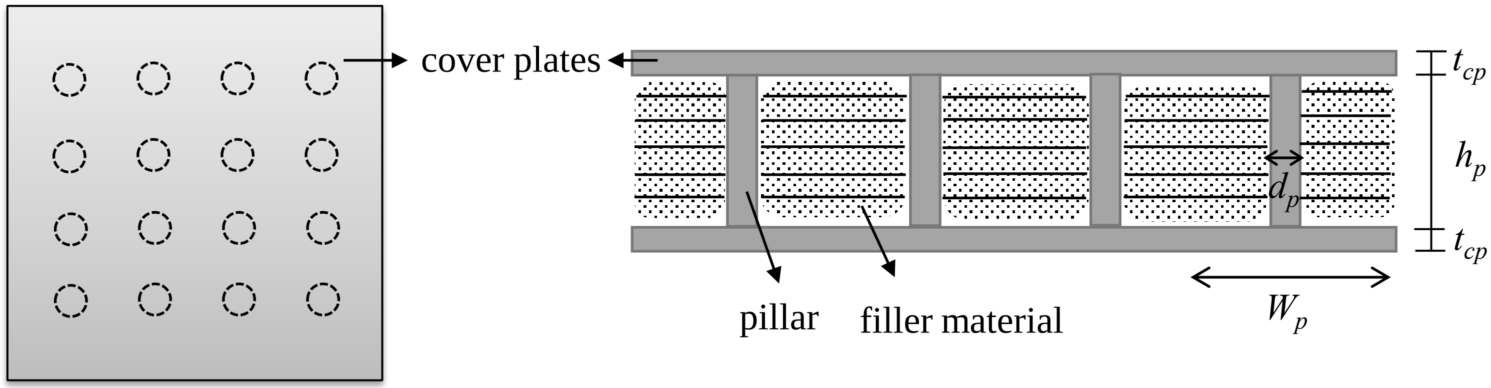




- **Support structure**
  - Top and bottom cover plate & pillars
  - Design considerations : structural stability & heat transfer
  - Simple cylindrical pillar & multi-pass support

- **Filler material**
  - Glass wool & radiation shield layers

SUPPORT STRUCTURE



-Top view -

-Side view -

- **Structural stability**
  - Deflection of cover plate

$$\delta_{\max} = 0.00581 \frac{P_{atm} W_p^4}{\gamma}, \ \gamma = \frac{E_{cp} t_{cp}^3}{12(1-\nu_{cp}^2)}$$

  - Compression of pillar

$$P_{atm} W_p^2 < \sigma_{YS} \frac{\pi d_p^4}{4}$$

- **Thermal conductivity**

$$R_{tot} = R_{cp} + \left(\frac{1}{R_p} + \frac{1}{R_{fm}} \right)^{-1} + R_{cp}$$

$$k_{tot} = h_p + 2t_{cp} \left(\frac{k_{fm}}{h_p} + \frac{k_p (\pi/4 \, d_p^2)}{h_p W_p^2} \right)$$

$$k_{tot} \geq \frac{h_p + 2t_{cp}}{h_p} \left(k_{fm} + \frac{k_p P_{atm}}{\sigma_{YS}} \right)$$

SUPPORT STRUCTURE

- **Material selection**

$$k_{tot} \geq \frac{h_p + 2t_{cp}}{h_p}\left(k_{fm} + \frac{k_p P_{atm}}{\sigma_{YS}}\right)$$

- Figure of merit : $Z \equiv \frac{\sigma_{YS}}{k_p}$

Material	k_p (W/m·K)	σ_{YS} (Mpa)	Z (10^6 s·K/m^2)
1040 steel	51	415	8
STS 410	25	1225	49
Polycarbonate	0.20	65	325
Polyimide	0.24	118	492

- Large Z leads to outstanding insulation performance

- **Specification of pillar-supported VIP (280 × 280 × 15 mm^3)**

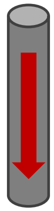
Pillar	Material	Polycarbonate
	Diameter d_p	3.5 mm
	Height h_p	12.6 mm
Cover plate	Material	STS 304
	Thickness t_{cp}	1.2 mm
	Total width W_{VIP}	280 mm
	Span W_p	70 mm
	Maximum deflection	0.5 mm
Thermal conductivity of support structure		0.47 mW/m·K

SUPPORT STRUCTURE

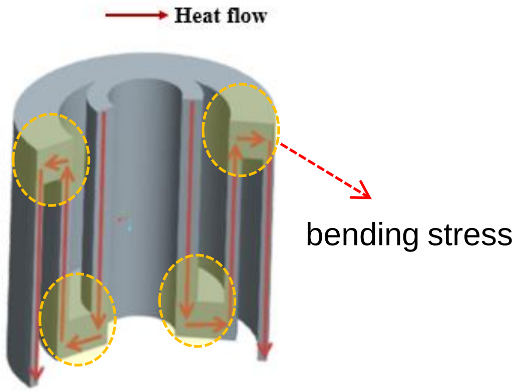
- **Multi-pass support**

$$k_{tot} \geq \frac{h_p + 2t_{cp}}{h_p}\left(k_{fm} + \frac{k_p P_{atm}}{\sigma_{YS}}\right)$$

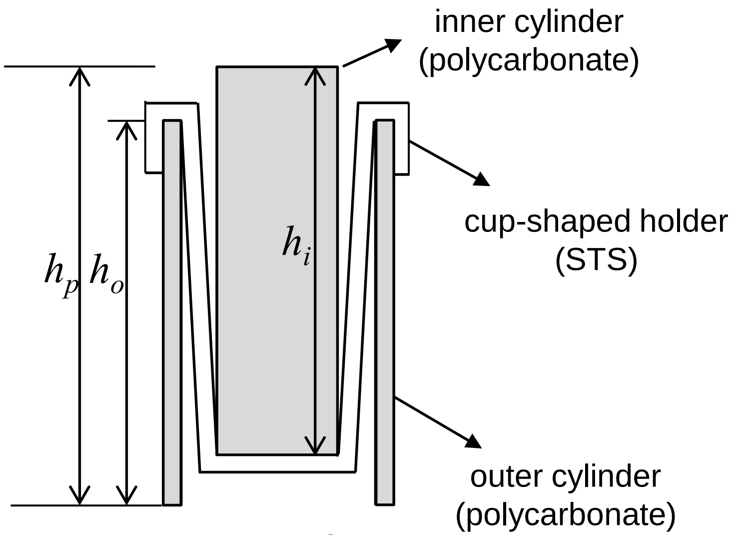
heat transfer path of pillar



- cylindrical pillar -



- multi-pass support (MPS) -



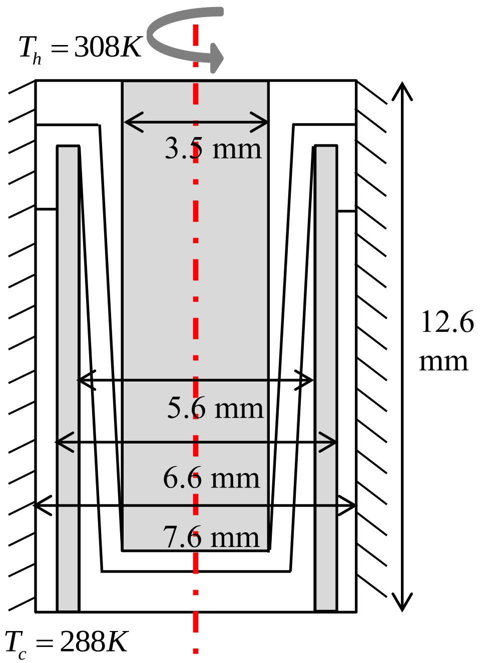
- Structure of MPS -

$$R_{MPS} = \frac{h_i}{k_p A_p} + R_h + \frac{h_o}{k_p A_p} \cong \frac{h_{eff\_MPS}}{k_p A_p}$$

$$\Rightarrow k_{tot} \geq \frac{h_p + 2t_{cp}}{h_p}\left(k_{fm} + \frac{k_p P_{atm}}{\sigma_{YS}} \times \frac{h_p}{h_{eff\_MPS}}\right)$$

SUPPORT STRUCTURE

- **Multi-pass support – numerical analysis**



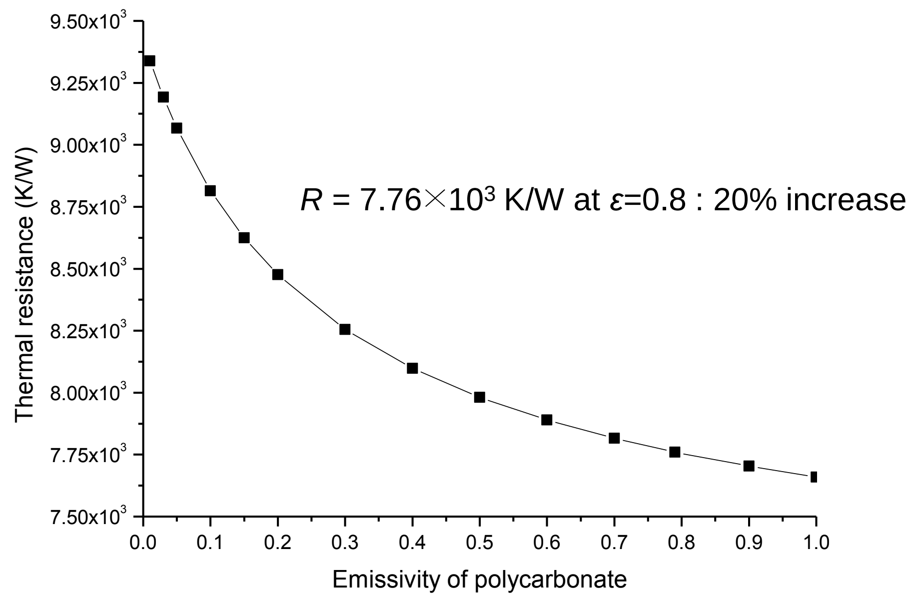
$$\begin{pmatrix} \varepsilon_{SUS} = 0.242 \\ k_{SUS} = 14.9 \mathrm{W/m \cdot K} \\ k_{PC} = 0.2 \ \mathrm{W/m \cdot K} \\ k_{vac} = 1.0 \times 10^{-10} \ \mathrm{W/m \cdot K} \end{pmatrix}$$

- Conduction only

	Simple cylindrical pillar	MPS (conduction only)
R (K/W)	6.55×10^3	1.10×10^4

Maximum 70% increase of *R*

- Conduction & radiation (DOM)



FILLER MATERIAL

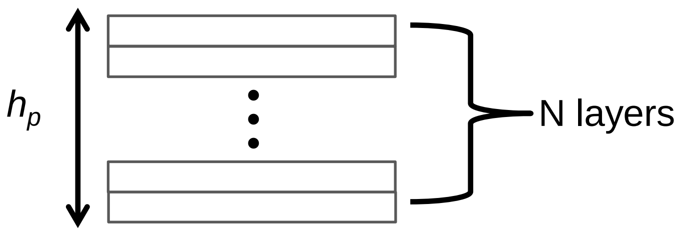
- **Multi-layered filler material**

$$k_{tot} \geq \frac{h_p + 2t_{cp}}{h_p}\left({\color{red}k_{fm}} + \frac{k_p P_{atm}}{\sigma_{YS}} \right)$$

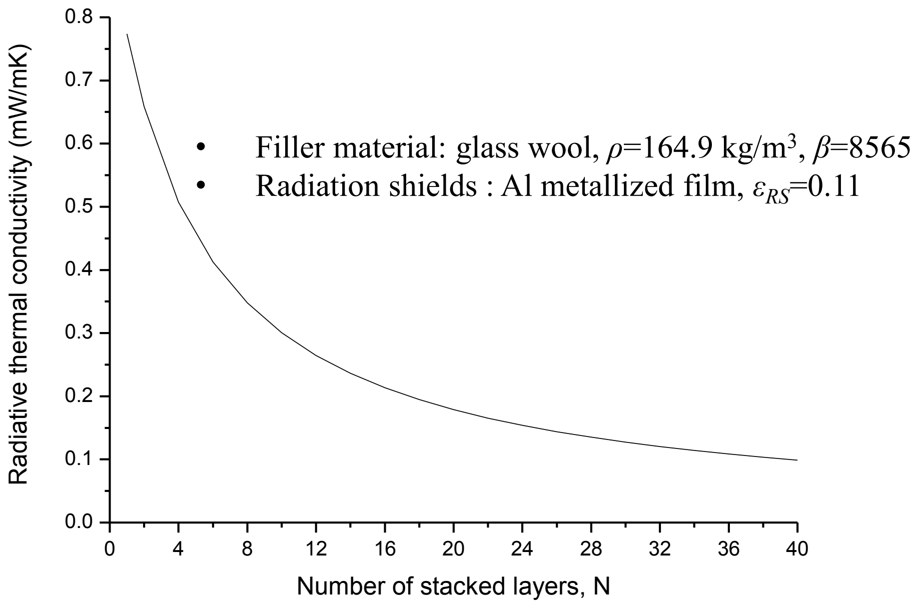
$$k_{fm} \rightarrow k_{fm,r} + k_{fm,s}$$

- No filler material -

short lifetime
large $k_{fm,r}$

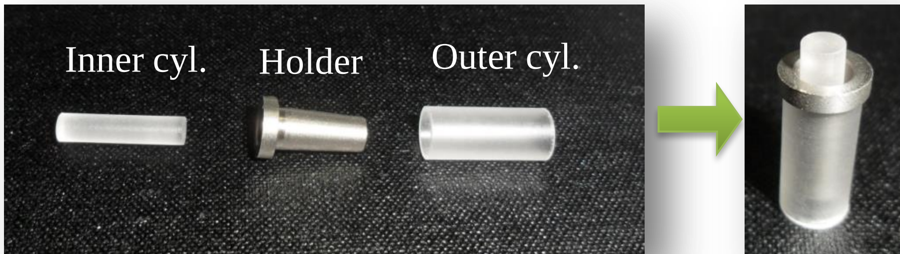


$$k_r = \frac{4\sigma T_m^4 h_p}{3\beta h_p/4 + N\left(2/\varepsilon_{RS} - 1 \right)}$$



SAMPLE

- **MPS**

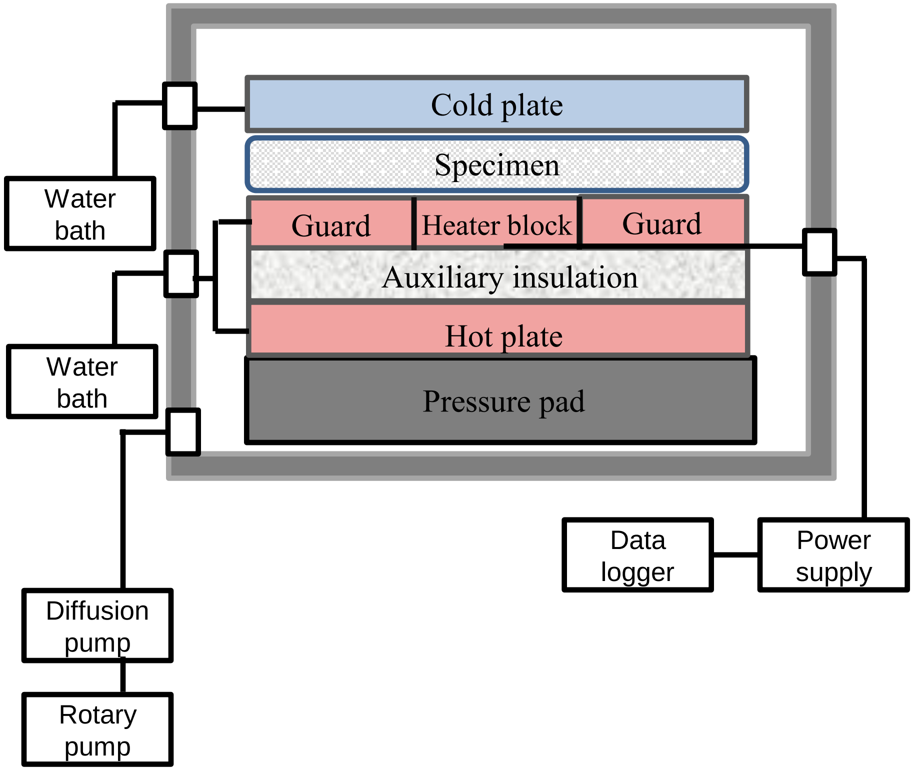


- **Pillar-supported VIP**

MPS	Material	Polycarbonate + Stainless steel
	Arrangement	4 X 4
	Height h_p	12.6 mm
Cover plate	Material	Stainless steel
	Thickness t_{cp}	1.2 mm
	Area	280 X 280 mm^2
	Span W_p	70 mm
	Maximum deflection	0.5 mm
Filler material	Glass wool + Al metallized film	16 layers

APPARATUS

- **Vacuum guarded hot plate (VGHP)**



- Thermal conductivity

$$k_{eff} = \frac{q_{heater} \cdot H}{A_{eff} \cdot \Delta T}$$

H: thickness of specimen
A_{eff}: effective surface area of specimen
ΔT: temperature difference

$$q_{heater} = q_{spec.} + q_{guard} + q_{h.plate}$$

$$= q_{spec.} \text{ when } T_{heater}=T_{guard}=T_{h.plate}$$

- Mean temperature : 298 K
- Vacuum level : 1.01×10^5 kPa to 10^{-2} Pa

- Uncertainty analysis

$$\frac{dk_{eff}}{k_{eff}} = \sqrt{\left(\frac{\partial k_{eff}}{\partial A_{eff}}\frac{dA_{eff}}{k_{eff}}\right)^2 + \left(\frac{\partial k_{eff}}{\partial(\Delta T)}\frac{d(\Delta T)}{k_{eff}}\right)^2 + \left(\frac{\partial k_{eff}}{\partial H}\frac{dH}{k_{eff}}\right)^2 + \left(\frac{\partial k_{eff}}{\partial q_{heater}}\frac{dq_{heater}}{k_{eff}}\right)^2}$$

$\Rightarrow 8\%$

RESULTS

- **Support structure**

Support structure with simple cylindrical pillar (estimated)	Support structure with MPS (estimated)
0.47 mW/m·K	0.39 mW/m·K

- **Filler material (glass wool & radiation shield 16 layers)**

$k_{fm,s}$	$k_{fm,r}$ (estimated)	$k_{fm,s}+k_{fm,r}$
0.31 mW/m·K	0.30 mW/m·K	0.61 mW/m·K

- **Pillar supported VIP**

Thermal conductivity of pillar supported VIP (with MPS)	
Estimated	Measured
1.00 mW/m·K	1.18±0.09 mW/m·K

CONCLUSION

- **Pillar-supported VIP**
  - Thermal conductivity of the filler material is increased with external pressure.
  - Support structure is designed to sustain the atmospheric pressure.
  - MPS has better insulation performance due to its long heat transfer path length.
  - Filler material is multi-layered with glass wool and radiation shields.
  - Insulation performance is increased by 76% compared with glass wool based VIP.

- **Improvement of insulation performance**
  - Surface coating of polycarbonate used in MPS.
  - More stacked layers of filler material.
  - Small $(h_p+2t_{cp})/h_p$ considering the allowable insulation thickness

「Thank you」