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Study of Light Transmission and Noise Attenuation Properties of Light Active Glass Materials

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Lighting and noise belong to important environmental factors that have an influence on human psyche, concentration, labour protection, sleep quality and so on. This paper is focused on study of light transmission and noise attenuation properties of light active glass materials, which are applied as window and door panels in residential buildings. The light transmission through tested materials was evaluated by means of the transmission coefficient from the illuminance ratio method. The material ability to dampen noise was determined based on the sound pressure level attenuation during sound propagation through the light active glass materials. Different factors, which have an influence on the propagation of light and noise through the investigated glass materials, were evaluated in this work. Finally, the effect of the light transmission through the tested light active glass materials on the daylight quality in a living room was mathematically simulated using Wdls 5.0 software.

Keywords: Light Active Glass Material, Light Transmission, Noise Attenuation, Sound Pressure Level, Wdls 5.0 Software.

1 Introduction

Global warming and protection of environment are increasingly common topics in the modern society [1]. There are different environmental factors that affect the health of living organisms such as water, air and land pollutions, noise, mechanical vibration, lighting, temperature, relative humidity, and atomic irradiation [2-5]. These factors have also a significant influence on manufacture accuracy, work safety, production efficiency, worker´s comfort etc. For these reasons, it is necessary to consider these environmental factors in the design of various buildings, houses, apartments, construction of roads and railways, in the manufacture of means of transport, industrial production etc.

The purpose of this work is to investigate light transmission and noise attenuation properties of light active glass materials that are applied in practice as window and door panels in residential buildings. Different factors, which influence the light transmission and noise attenuation through the tested materials, are evaluated in this paper.

Sound is generated by any mechanical movement and is propagated as a motion wave through different environments (i.e.; fluids and solids) [6]. Noise is typically defined as an undesired sound or a combination of sounds that have negative effects on health of living organisms. It can be accompanied by physiologic damage or psychological harm [7]. Therefore, it is desirable to dampen noise with appropriate measures. For example, it is possible to remove undesirable noise sources, reduce mechanical friction and use highly sound-absorbing materials and soundproof partitions [8].

Visible light is defined as electromagnetic radiation detectable by the human eye in the wavelength range from 380 to 780 nm. It is the transition region between ultraviolet light (at shorter wavelengths) and infrared light (at longer wavelengths) [9-11]. Optical properties of light active materials are generally influenced by different factors, namely by their colour, thickness, structure, surface shape, pollution, light wavelength, angle of light incidence and application of thin films [12].

2 Methodology

2.1 Materials

In this study, a total of 12 light active glass samples differing in thickness, surface shape, number of glasses, etc. were evaluated. Examples of the glass samples examined are depicted in Fig. 1. Their designation, description, total thickness, and number of individual glasses in the given glazing units are shown in Tab. 1.

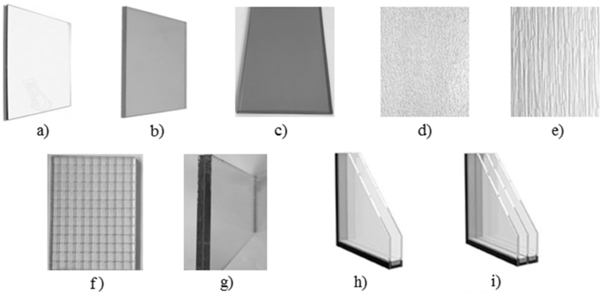

Fig. 1 *Investigated glass samples: Basic clear glass (a), silver coated glass (b), reflective bronze coated glass (c), ornamental decorative glasses with clear chinchilla (d) and clear crust (e) textures, wire glass (f), laminated glass (g), double (h) and triple (i) glazing units [13]*

Tab. 1 *Specification of the investigated glass samples*

Sample designation	Sample description	Thickness (mm)	Number of glasses (–)
S1	Basic flat clear glass "Float"	4.0	1
S2	Basic flat clear glass "Float"	6.0	1
S3	Silver coated (LowE) glass	3.8	1
S4	Reflective bronze coated glass "Stopsol"	3.8	1
S5	Reflective bronze coated glass "Stopsol"	5.9	1
S6	Ornamental decorative glass with texture of clear chinchilla	3.8	1
S7	Ornamental decorative glass with texture of clear crust	4.0	1
S8	Wire glass	6.0	1
S9	Laminated safety glass VSG 33.1	6.1	1
S10	Laminated safety glass VSG 33.2	6.6	1
S11	Double glazing unit	24.0	2
S12	Triple glazing unit	40.0	3

2.2 Glass manufacturing process

The investigated glass samples, which are summarized in Tab. 1, were produced by different manufacturing technologies [14].

The basic flat clear glasses S1 and S2 were made by continuous casting of molten glass on the surface of tin melt. During this process, glass sheets of the required format are created and subsequently intended primarily for further processing. The low emissivity (LowE) glass sample S3 is characterized by high thermal insulation properties. It is coated on one side, which is deposited using magnetron sputtering equipment. In this process, a layer of silver atoms and metal oxides is deposited by cathodic sputtering on the glass surface in a vacuum environment. The monolithic glasses S4 and S5 consist of a pyrolytically deposited transparent layer of metal elements in the form of a thin dioxide tin-film on their surface. The pyrolytic coating is deposited during the flat glass production by the float process. The obtained metal layer is very resistant to mechanical damage and climatic influences. The function of these glasses is based on the principle of the visible light reflection in combination with the light absorption, which is caused by glass coloring during the melting process. Therefore, these glasses are used to protect against sunlight, especially in summer. The ornamental glasses S6 and S7 are made by casting molten glass between two cylinders. Their decors are created by the impression of the cylinder surface into the glass surface. The chinchilla textured glass is one of the finest decors. Contrarily, the texture of the clear crust is one of the roughest decors on the glass market. The wire glass S8 is a safety glass that does not crumble and remains inside the glass. It is made by pressing a wire insert in the form of a rectangular square grid between two cylinders during the casting of molten glass. The laminated safety glasses S9 and S10 consist of two glass sheets joined by a tough elastic intermediate layer in the form of a highly tear-resistant polyvinyl butyral foil. The double glazing unit (S11) consists of two plane glass sheets whose distance is defined by a spacer frame. The first glass sheet is made of the clear glass (S1) measuring 4 mm in thickness. The second glass sheet is made of the low emissivity glass (S3). The triple glazing unit (S12) consists of three plane glass sheets separated by two spacer frames. The first two glass sheets are made of the clear glass (S1) measuring 4 mm in thickness. The third glass sheet is made of the low emissivity glass (S3).

2.3 Measurement methods

The sound pressure level L_p, which is frequently used to characterize the noise intensity, is defined by the formula [15-17]:

$$L_p = 20 \cdot log \frac{p}{p_0} \ [\mathrm{dB}], \quad (1)$$

Where:

p…Root mean square sound pressure [Pa],

p_0…Reference sound pressure (20 μPa in air) [Pa].

The measurement principle of sound insulation properties of the investigated light active materials is shown in Fig. 2. The experimental measurements were performed in a room where a noise source (NS) is located. In this case, the Concept vacuum cleaner type VC-2022 (VP model 9133) with a maximum electrical power of 1400 W was used as the noise source. Furthermore, one of the walls of the room is provided with a hole for inserting the tested soundproof glass samples.

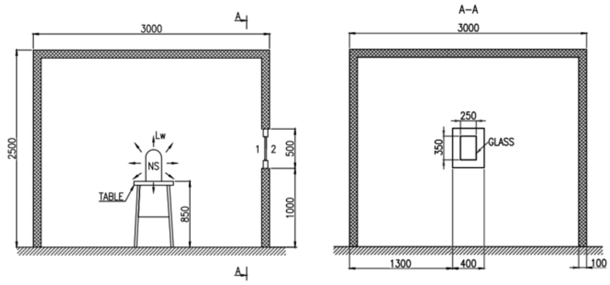

Fig. 2 *Measurement principle of sound insulation properties of soundproof glasses*

Sound insulation properties of the investigated light active materials were evaluated based on the A-weighted [18] sound pressure level attenuation ΔL_{pA} that is expressed as follows:

$$\Delta \boldsymbol{L_{pA}} = \boldsymbol{L_{pA1}} - \boldsymbol{L_{pA2}}\ [\mathbf{dB}], \tag{2}$$

Where:

L_{pA1}…A-weighted sound pressure level measured at point 1 in front of the glass sample tested [dB],

L_{pA2}… A-weighted sound pressure level measured at point 2 behind the glass sample tested [dB].

Experimental measurements of sound insulation properties of the tested soundproof glasses were performed at night (in this case between 1:00 am and 4:00 am) in a quiet and secluded location in order to eliminate external disturbing noise sources. Measurements of the A-weighted sound pressure level attenuation ΔL_{pA} were realized using a Voltcraft sound level meter SL-400 (Conrad Electronic SE, Hirschau, Germany). Each type of the tested soundproof glass was measured 10 times at an ambient temperature of (17 ± 1) °C. Subsequently, arithmetic means and standard deviations of the A-weighted sound pressure level attenuation were determined.

Light transmission properties of light active materials are expressed by the light transmission coefficient τ that is defined by the ratio [19]:

$$\boldsymbol{\tau} = \frac{\boldsymbol{\phi_t}}{\boldsymbol{\phi_i}}\ [-], \tag{3}$$

Where:

ϕ_t…Total transmitted luminous flux [W],

ϕ_i…Incident luminous flux [W].

The light transmission coefficient of the investigated window and door glass panels was determined according ČSN 36 0011-2 standard [20] by means of the illuminance ratio method as follows:

$$\boldsymbol{\tau} = \frac{\boldsymbol{E_\tau}}{\boldsymbol{E_i}}\ [-], \tag{4}$$

Where:

E_τ…Light intensity (or illuminance) measured with the inserted glass sample [lx],

E_i… Incident light intensity measured without the inserted glass sample [lx].

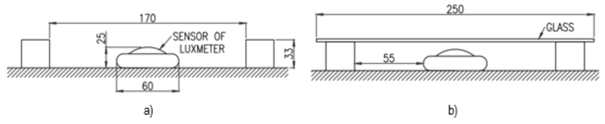

Fig. 3 *Measurement principle of light transmission properties of light active materials based on measurement of the incident light intensity (a) and the light intensity behind the tested glass sample (b)*

The measurement principle of the light transmission coefficient is shown in Fig. 3. Experimental measurements of light transmission properties of the tested window and door glass panels were performed during the propagation of diffuse daylight through the tested clean glass samples using a Voltcraft MS-1300 luxmeter (Voltcraft, Hirschau, Germany). In order to obtain the most accurate values of the light transmission coefficient, the measurements were taken in the shade under clear skies (i.e.; without clouds) in the summer months around noon. Each measurement was repeated 10 times at an ambient temperature of (28 ± 2) °C. Arithmetic means and standard deviations of the light transmission coefficient were subsequently evaluated.

3 Measured results and discussion

3.1 Sound insulation properties

The experimentally measured values of the sound pressure level attenuation (ΔL_{pA}) of the tested glass samples, including their standard deviations, are summarized in Tab. 2. These values were determined according to the equation (2) from the measured values of the A-weighted sound pressure levels at measuring points 1 and 2 (see Fig. 2), whose mean values (i.e.; L_{pA1m} and L_{pA2m}) are also shown in Tab. 2.

It is obvious from Tab. 2 that the glass type has a significant effect on the the sound pressure level attenuation. The lowest values of the sound pressure level attenuation (i.e.; from 7.2 to 7.6 dB) were generally found for thin glass samples measuring about 4 mm in thickness. This phenomenon was caused by low internal friction during propagation of acoustic waves through these glass structures and was accompanied by a relatively low transformation of acoustic energy into heat. Higher sound damping properties (i.e.; $\Delta L_{pA} \cong 10$ dB) exhibited the glass samples measuring about 6 mm in thickness (i.e.; samples S2, S5, S8, S9 and S10), which was accompanied by higher internal friction when propagating acoustic waves through these samples compared to the thinnest glass samples. As shown in Tab. 2, the highest sound pressure level attenuation (i.e.; over 20 dB) were found for multi-pane glazing units (i.e.; samples S11 and S12), which are made of several separate sheets of glass. As acoustic waves propagate through these samples, there are multiple reflections of the acoustic waves between the individual glasses, which results in a higher conversion of acoustic energy into heat. Therefore, the double and triple glazing units exhibited the highest values of the sound pressure level attenuation due to their more complex constructions compared to the investigated single glazing units. In the case of the double glazing unit tested, the noise level was reduced by approximately 26%. The maximum reduction in noise level (approximately 30%) was obtained for the triple glazing unit tested.

Tab. 2 *Sound insulation properties of the investigated glass samples*

Sample type	L_{pA1m} (dB)	L_{pA2m} (dB)	ΔL_{pA} (dB)
S1	81.2	73.6	7.6 ± 0.1
S2	81.2	71.2	10.0 ± 0.1
S3	80.6	73.4	7.2 ± 0.2
S4	79.4	72.2	7.2 ± 0.1
S5	80.5	70.6	9.9 ± 0.1
S6	79.4	72.2	7.2 ± 0.1
S7	80.7	73.1	7.5 ± 0.2
S8	81.0	71.1	9.9 ± 0.1
S9	80.3	70.2	10.1 ± 0.2
S10	81.1	70.6	10.5 ± 0.2
S11	81.9	60.5	21.4 ± 0.1
S12	82.1	57.9	24.2 ± 0.1

It can be concluded that the lowest sound pressure level attenuation (ΔL_{pA}) was observed for the thinnest clear glass samples. These glass samples are characterized by low internal friction during the propagation of acoustic waves through their structures. The sound attenuation generally increased with the increasing glass thickness, number of multilayer glass sheets and separate sheets of glass. The highest acoustic sound pressure level attenuation was found for the triple glazing unit due to multiple reflections of acoustic waves inside the complex construction measuring 40 mm in thickness. For this reason, the triple glazing units are applied as door or windows panels in various buildings in order to significantly improve the acoustic comfort inside these buildings. However, the triple glazing units are more expensive compared to the other investigated glass samples.

3.2 Light transmission properties

The experimentally obtained values of the light transmission coefficient (τ) for the tested glass samples, including their standard deviations, are summarized in Tab. 3. These values were determined according to the equation (4) from the measured values of the light intensities E_τ and E_i, whose average values (i.e., $E_{\tau m}$ and E_{im}) are also shown in Tab. 3.

Tab. 3 *Light transmission properties of the investigated glass samples*

Sample type	$E_{\tau m}$ (lx)	E_{im} (lx)	τ (–)
S1	382.4	455.3	0.840 ± 0.001
S2	380.2	461.9	0.823 ± 0.002
S3	346.8	455.3	0.762 ± 0.001
S4	112.3	471.8	0.238 ± 0.001
S5	86.9	469.6	0.185 ± 0.001
S6	373.9	470.8	0.794 ± 0.001
S7	393.5	492.1	0.800 ± 0.001
S8	328.6	445.1	0.738 ± 0.002
S9	356.4	439.8	0.810 ± 0.002
S10	381.2	474.0	0.804 ± 0.001
S11	320.8	480.4	0.668 ± 0.001
S12	268.1	479.1	0.560 ± 0.001

The highest light transmission ability (i.e.; $\tau = 0.84$) was found for the basic clear glass measuring 4 mm in thickness (i.e.; sample S1). For this reason, this glass sample is characterized by low light reflection and light absorption properties. If the thickness of the clear glass is increased to 6 mm (i.e.; sample S2), the light transmission is reduced by approximately 2%. Thus, the increasing glass thickness generally leads to higher light absorption and thus lower light transmission when light propagates through thicker glass samples. Relatively high light transmission properties (i.e.; $\tau \cong 0.8$) were also detected for the ornamental decorative (i.e.; samples S6 and S7) and laminated safety (i.e.; samples S9 and S10) glass specimens. Therefore, the glasses produced with ornamental decorative and safety elements reduce the light transmission only slightly compared to the basic clear glasses. The wire (i.e.; sample S8) and silver coated (i.e.; sample S3) glasses exhibited a reduction of approx. 25% in light transmission (see Tab. 3). Lower values of the light transmission coefficient were observed for the tested multi-pane glazing units. Its value decreased with the increasing number of separate sheets of glass in the multi-pane glazing units, namely from 0.668 (i.e.; sample S11) to 0.56 (i.e.; sample S12). This phenomenon was caused by multiple light reflections between separate glass panels inside the multi-pane glazing units, which is reflected in higher light absorption and thus higher conversion of light energy into heat during the propagation of light through these units. The lowest light transmission properties (i.e.; $\tau \cong 0.2$) were found for the reflective bronze coated glass specimens (i.e.; S4 and S5) due to a thin dioxide tin-film on their surface. Therefore, the coated and tinted glasses absorb and reflect most of the incident light energy and are applied to protect against sunlight, mainly during the summer season.

It can be concluded that the best light transmission properties were found for the thinnest clear glass sample. Thicker glasses, ornamental decorative and safety elements, coloured and metallized layers, wire-glass structure and multi-pane glazing systems generally led to a reduction in light transmission through the glass samples examined.

4 Mathematical simulation of daylighting quality

The light transmission coefficient of window or door panels has generally a big influence on the daylighting quality in buildings, means of transport and so on. The daylight factor *DF* is the most common quantity to evaluate the annual daylight in interiors and is defined by the equation [21,22]:

$$\boldsymbol{DF} = \frac{\boldsymbol{E_x}}{\boldsymbol{E_h}} \cdot \mathbf{100}\ [\%], \quad (5)$$

Where:

E_x…Indoor illuminance measured in a point x on tested working surface [lx],

E_h… Outdoor diffuse illuminance measured on horizontal surface [lx].

Higher daylight quality in a given place is generally achieved at higher values of the daylight factor. For example, the minimum and average values of the daylight factor for classrooms are defined as 1.5% and 5%, respectively [22,23].

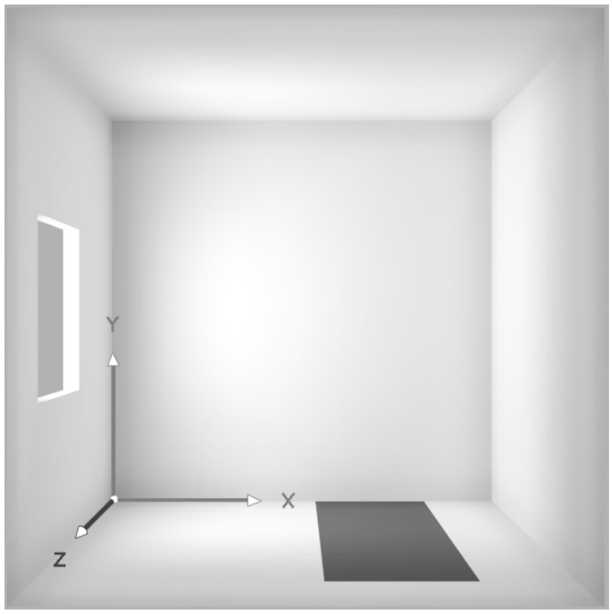

Fig. 4 *View of the reference room for mathematical simulations of the daylight factor*

Mathematical simulations of the daylight factor were performed using Wdls 5.0 software (Astra 92 a. s. Zlín, Czech Republic) based on multiple light reflections in a reference room (see Fig. 4), which has dimensions of 2.8 m × 2.8 m × 2.4 m (length × width × height) as in the case of measuring the sound insulation properties of the tested glass samples (see Fig. 2). The room is equipped with a door measuring 0.8 m × 2.0 m (width × height) and a glass window measuring 1.0 m × 0.9 m (width × height). As shown in Fig. 4, the glass window is located above the floor of the reference room, in this case at a height of 1 m.

The daylight propagation in the reference room is also affected by light reflections from the room surfaces. The ability of a material to reflect light is characterized by the light reflectance ρ as follows [24]:

$$\boldsymbol{\rho} = \frac{\phi_r}{\phi_i}\ [–], \quad (6)$$

Where:

ϕ_r…Reflected luminous flux [W].

The values of the light reflectance of the surfaces in the reference room are shown in Table 4.

Tab. 4 *Light reflectance ρ of individual surfaces in the reference room*

Surface	Walls	Ceiling	Floor	Door
ρ (–)	0.91	0.91	0.72	0.14

The effect of the light transmission coefficient of the glass windows on the daylight factor distribution in the reference room on the working plane, which is at a height of 0.85 m above the room floor, is shown in Figs. 5 and 6. It is evident (see Fig. 5a) that the highest values of the daylight factor, and thus the best daylight quality inside the reference room, were found for the thinnest clear glass (i.e.; sample S1) that is characterized by the maximum value of the light transmission coefficient (i.e.; $\tau = 0.84$) and low light reflection and light absorption properties. It is also visible from Figs. 5 and 6 that the values of the daylight factor in the given place generally decreased with the decreasing light transmission coefficient. The worst daylight conditions were observed for the reflective bronze coated glass (i.e.; sample S5), which is characterized by the minimum value of the light transmission coefficient (i.e.; $\tau = 0.185$), as shown in Fig. 6b. Therefore, this glass type is mainly used to protect against solar radiation.

The above conclusions are consistent with minimum (DF_{min}), mean (DF_m) and maximum (DF_{max}) values of the daylight factor that were obtained by the mathematical simulations and are summarized for the investigated glass specimens in Tab. 5.

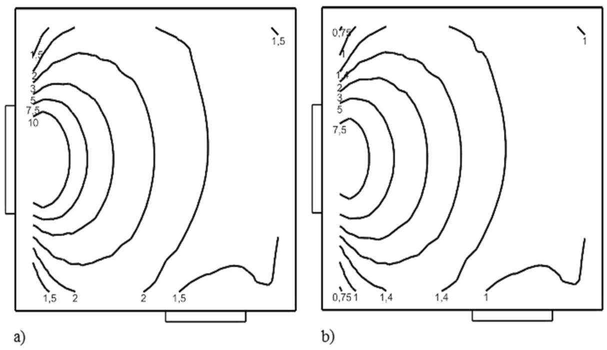

Fig. 5 *Daylight factor distribution at a height of 0.85 m above the room floor for the light transmission coefficient $\tau = 0.84$ (a) and $\tau = 0.56$ (b) of the glass windows*

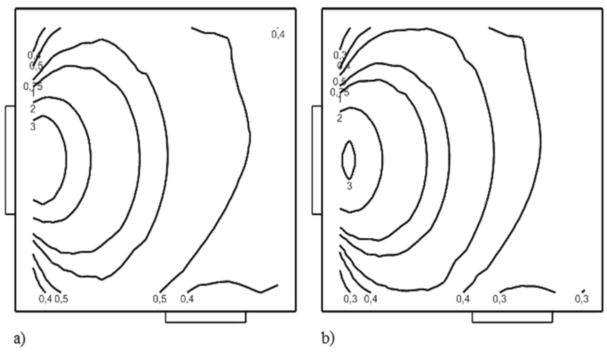

Fig. 6 *Daylight factor distribution at a height of 0.85 m above the room floor for the light transmission coefficient $\tau = 0.238$ (a) and $\tau = 0.185$ (b) of the glass windows*

Tab. 5 *Mathematically simulated values of the daylight factor of the tested glass samples*

Sample type	DF_{min} (%)	DF_m (%)	DF_{max} (%)
S1	1.1	3.3	14.3
S2	1.0	3.2	14.0
S3	1.0	3.0	13.0
S4	0.3	0.9	4.1
S5	0.2	0.7	3.2
S6	1.0	3.1	13.5
S7	1.0	3.1	13.6
S8	0.9	2.9	12.6
S9	1.0	3.2	13.8
S10	1.0	3.2	13.7
S11	0.8	2.6	11.4
S12	0.7	2.2	9.5

5 Conclusion

Nowadays, there are many factors that affect working conditions, the human psyche, concentration, relaxation etc. The aim of this work was to investigate the light transmission and noise attenuation properties of various light active glass materials that are applied as window and door panels in residential buildings. It was found in this study that the light transmission and noise damping properties of the investigated glass samples were contradictory in many cases. For example, thin clear glasses were characterized by high light transmission and low noise attenuation properties. In general, the noise attenuation increased with the increasing glass thickness, number of multilayer glass sheets and separate sheets of glass. Similarly, thicker glasses, ornamental decorative and safety elements, coloured and metallized layers, wire-glass structures and multi-pane glazing systems decreased the light transmittance of the investigated glass samples. It was also confirmed based on mathematical simulations of the daylighting quality using Wdls 5.0 software that lower light transmission properties of the investigated glasses were accompanied by lower values of the daylight factor, which led to a reduction in the quality of daylighting in the simulated residential room. For the above reasons, it is necessary to consider a suitable type of window and door panels in residential buildings in the given environment, not only in terms of the light transmission and noise attenuation, but also in terms of their price, thermal insulation and mechanical properties, etc.

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