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THE IMPORTANCE OF ETHYLENE-TETRAFLUOROETHYLENE FOR BUILDING DAYLIGHTING

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Abstract. *Nowadays, it is possible to implement and realize solutions that once seemed inconceivable. Namely, the development of novel technologies allows the implementation of creative ideas, as well as new approach to building design. The use of the state of the art technology offers the application of functional high-tech coatings and building claddings. Hence, a new generation of plastic - ethylene tetrafluoroethylene (ETFE) is increasingly used in buildings and architectural structures. The use of ETFE is increased due to its very low weight, high transparency potential and possibility to control the utilization of daylight in buildings, as well as due to self-sufficient performances and low environmental load. Therefore, it is necessary to overcome a lack of information on some advantages of this environmentally friendly material. In this paper, the properties and possibilities of applications of ETFE are presented. It increasingly replaces traditional glazing and enables the implementation of creative solutions due to its performance and possibility of advancing sustainable construction. This could contribute to sustainable development and to the prevention of the negative influence to climate change.*

Key words: *Daylighting, self-sufficient performances, environmentally friendly, novel materials, ETFE foil cushions, sustainable construction*

1. INTRODUCTION AND HISTORICAL DEVELOPMENT OF ETFE

Ethylene tetrafluoroethylene-ETFE ($C_4H_4F_4$) is a fluorocarbon based polymer, a new kind of plastic generation. It is important to mention that considerable research has been carried out through the world, providing a large volume of useful data and important findings on the possible application. Namely, investigation of fluoropolymers paved the way for the development of products such as ETFE. Although ETFE was first developed in 1938 at DuPont, the foils of this material were commercially applied by American chemical

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company DuPont and German chemical company Hoechst in the early 70's of the previous century [1, 2]. This novel material was recognized for architectural application due to good properties, such as low weight, excellent light transparency, high tensile strength, resistance to tearing and low flammability, but building cladding was not possible until the discovery of the drop bar welding technique that was capable of welding large sheets. This has enabled application of this new generation material for cladding of swimming pools, botanical gardens, zoological gardens, sport facilities and exhibitions.

Membrane structures with ETFE-foils have been used in building constructions in the last several decades and every year approximately 30 new famous ETFE-foils constructions are designed. It should be noted that the first structure clad by ETFE was done at Burgers Zoo in 1982, (Fig. 1) and that although it has been fully functional for 35 years and the applied material has not shown visible signs of deterioration.

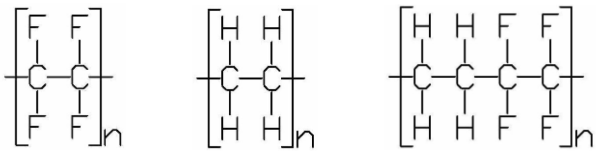
Fig. 1. The first structure clad by ETFE single layer at Burgers Zoo [3]

In this privately owned zoo, in the forest near Arnhem in Netherlands, exotic animals are housed in large enclosures that attempt to replicate their natural habitats. At the same time, by using ETFE, the animals are protected from the influence of weather conditions. Also, visitors can enjoy an outdoor feeling, because ETFE foils are highly transparent for visible light. Further that, this type of foils transmits ultraviolet UV-A radiation. Namely, a single layer used foil of 100 µm transmits more than 90% of light (ranging 380-780 nm) and 80% of UV-A rays, which is important because of so-called bactericidal effect [3].

2. Manufacturing and Chemistry

The raw materials for ETFE manufacturing are fluorspar CaF_2, sulphuric acid H_2SO_4 and trichloromethane $CHCl_3$, that make chlorodifluoromethane (CHF_2Cl) and then tetrafluoroethylene-TFE (C_2F_4). It should be noted that chlorodifluoromethane is a II class substance (according to the Montreal Protocol on ozone depleting substances) i.e. does not contribute to global warming [4]. Following process is pyrolysis which produces tetrafluoroethylene $CF_2 = CF_2$. In the manufacturing ETFE the by-products are calcium sulfate $CaSO_4$, hydrogen chloride HCl and hydrogen fluoride HF [1, 4]. The by-products $CaSO_4$ and HF are reused to make more fluorspar which can be used again as an input into the manufacturing process and the other waste products are incinerated.

In the manufacturing, the polymerization process is used to create long molecular chains, i.e. ETFE (25% ethylene and 75% TFE) [5]. Polymerization is a chemical reaction that constructs a long molecular chain using small basic molecules, so ethylene and tetrafluoroethylene monomers alternately form *n* identical units (Fig. 2). The process is carried out at approximately 125 °C. The result of the manufacturing process is an ETFE powder. The next step is the creation of ETFE granules in the process of granularization by heating up the powder. Further, granules can be formed into many different products including a sheet, rod, and film. Obtained ETFE material can be extruded into large thin sheets (foils or films) which can be used in single or multi-layer cladding applications. The thickness of films in production ranges from 50 mm to 300 mm, while wide ranges from 150-220 cm.



(a) (b) (c)

Fig. 2 (a) tetrafluoroethylen; (b) ethylen; (c) ethylen - tetrafluoroethylen [5]

ETFE is a semi-crystalline polymer (there are crystalline regions, which are impeded in the amorphous matrix) with a degree of crystallinity of about 33% [6, 7]. Amorphous properties increase the flex life of a material, as well as the number of fatigue cycles until failure, while crystalline properties decrease a material's resistance to fatigue. The presence of the hydrogen atom is also very important, because it increases the hardness and toughness of the produced material and reduces susceptibility to creep, but decreases its thermal stability.

Regarding the environmental impact, it is important that the whole process is water based and does not involve any solvents or additives (to enhance ETFE service performance). Also, they are environmentally friendly as they can be recycled by heating and require ten times less energy per square meter than glass for their production.

3. Properties of ETFE Material

3.1. Basic physical properties

It is important to note that ETFE has excellent chemical, thermal and electrical properties, as well as superior resistance to abrasion and cut-through. Another important advantage is its ductility and flexibility. Namely, the material is able to elongate between 250-650% and to maintain its tension and stability despite large deflections. A stress-strain curve for a typical uniaxial test of ETFE, which illustrates qualitatively how ETFE strains under loads [7] is presented in Fig. 3. It could be seen that the first substantial change in stiffness occurs at the point called Elastic Limit, although the elongation is negligible. At the next important point called Yield Point, the material momentarily loses all of its stiffness and becomes highly nonlinear (at elongation less than 20%). This point is followed by the large plastic region, where the material is in a stage of strain hardening in which (before Break Point) it can elongate its own length almost 650%.

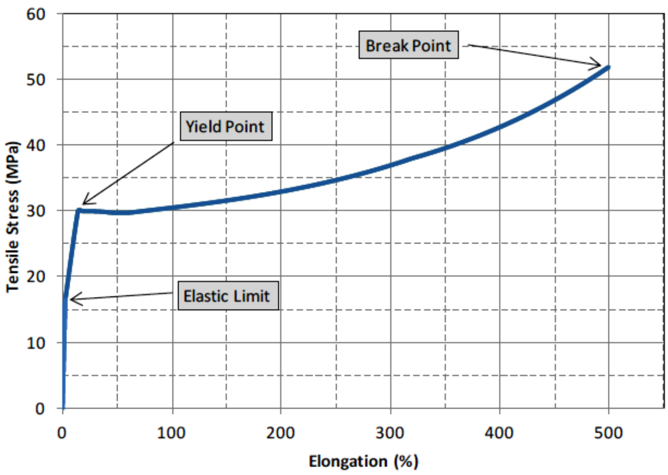


Fig. 3 Stress-Strain Curve for Uniaxial Tested ETFE Foil [7]

Besides significant ductility and flexibility, the most important advantage of ETFE is its light weight. Namely, one foil layer weights only 1% of the weight of glass. Even with the addition of the extra foil layers (to produce an inflated cushion), aluminum extruded flashings, and an inflation tubing system, the roof weight is significantly lower (10-50%) in comparison to glass roof [6]. The mass values of glass and ETFE foil are presented in Tab. 1. [8]

Table 1 Specific masses of glass and ETFE foil.

	ETFE			GLASS	
	single layer	double layer	triple layer	single layer	double layer
	200 μm	200 μm + A300 + 200 μm	200 μm + A300+200 μm + A300+200 μm	6mm	6 mm+A12+ 6 mm
Specific Mass (kg/m^2)	**0.35**	**0.7**	**1.05**	**15**	**30**

3.2. Thermal insulation properties

Originally, ETFE was developed as wire insulation for extreme temperature environments, so it is reasonable that it surpasses the insulation ability of glass. Values of overall heat transfer coefficient *U* (the measure of the heat transmission through a building part, such as a wall or window) for glass and ETFE foil are presented in Tab. 2 [8]. Lower *U*-value shows better insulating ability. Insulation ability is increased with the introduction of the air pocket (creating cushions) which acts similarly to double or triple pane glass. In addition, it is possible to adjust their insulation value by decreasing or increasing the pressure in the cushions. The insulation characteristics of ETFE cushion system can be multiply improved by adding more layers of ETFE film. The additional (middle) layer of a typical ETFE film cushion is added just for insulation purposes. This film layer creates two divided air cavities, which vastly improves the thermal capacity of the ETFE pillow. The *U*-value is reported to vary from 2.94 to 1.18 W/(m^2 K) for 2–5 layers ETFE cushions [1, 6].

Table 2 Overall heat transfer coefficient *U* of glass and ETFE foil.

	ETFE			GLASS	
	single layer	double layer	triple layer	single layer	double layer
	200 μm	200 μm + A300 + 200 μm	200 μm + A300+200 μm+ A300+200 μm	6mm	6 mm+A12+ 6 mm
***U* (W/m^{2}K)**	**5.8**	**2.6**	**1.7**	**5.9**	**2.9**

Insulating properties of ETFE cushions could be improved by using coatings developed especially for fluoropolymers, so that low-energy coat applied onto the film increases insulating capacity.

3.3. Acoustic properties

Probably one of the most important disadvantages of ETFE is the acoustic transparency, because cushions made of ETFE transmit almost all sound from the outside and create additional noise from the impact on the surface such as in the case of raindrops. Also, the sound generated by building occupants passes through the ETFE foil and is not reflected back into the space below. A measure of acoustic insulation is the coefficient of fading or the R_w value, which measures a material's capacity of acoustic insulation. Even three-layer ETFE foil cushion has an R_w value of 8 dB, while R_w value of glass double glazing is 42 dB [9]. This drawback of the cushions made of ETFE material can be mitigated by including acoustic insulation.

Noise produced by rain can be easily minimized by installing a patented Texlon® RS rain suppression mesh, which is made from fluoropolymer monofilament fibers or fabrics with a weave diameter typically measuring 20 mm to 40 mm. The mesh is held under tension across the external surface of each panel and reduces both sound generation and transmission. This mesh decreases noise levels by 9.7 dB which equates to a 50% noise reduction to the human ear [10]. However, the use of the rain suppression mesh will result in a small reduction in light transmission by 5%-10%.

3.4. Light transmittance

One of the most important advantages of ETFE is the light transmittance. Namely, ETFE foils are more transparent than glass in every wavelength of visible light, and have a significantly higher level of transparency in the UV spectra, that can be seen in Fig. 4. This property makes ETFE foils attractive for atria and especially for greenhouses (as well as for already mentioned structures like Burgers Zoo) since plants use the entire spectrum of light for photosynthesis [11].

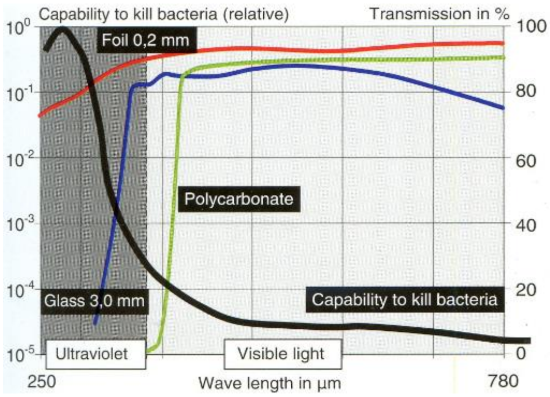


Fig. 4 Light Transmittance of ETFE and Other Glazing Materials [6]

Values of light transmittance for glass and ETFE foil are presented in Tab. 3 [8].

Table 3 Light transmittance of ETFE foil.

	ETFE			GLASS	
	single layer	double layer	triple layer	single layer	double layer
	200 µm	200 µm + A300 + 200 µm	200 µm + A300+200 µm+ A300+200 µm	6mm	6 mm+A12+ 6 mm
Visible (%)	**90.5**	**82.4**	**75.4**	**88.9**	**79.6**
UV (%)	**83.5**	**71.5**	**62.3**	**61.4**	**45.5**

Because ETFE transmit most ultraviolet light, it is resistant to UV degradation and discoloration, which is a common problem with other architectural glasses. On the other hand, high value of transmittance has adverse effects on solar heat gain in buildings. In order to reduce this effect, foils can be printed with an infinite variety of shading patterns that can block out light at varying amounts throughout the day.

3.5. Fire performance and chemical resistance

Another very important property of ETFE is self-extinguishing, as well as unique property of self-venting the products of combustion to the atmosphere [6]. Under fire conditions, the cushions self vent as the hot plume causes the foil to shrink back from the source of the fire (the film will shrink away from the flame), thus allowing the fire to vent to atmosphere. In the case of fire any hot gases impinging on the cushions at a temperature above 200°C will cause the foil to soften and lose strength. It is important that the quantity of material in the roof is insignificant in fire terms and molten drips of foil do not appear, so according international standards, ETFE is very good (see Table 4 [8,12]). In addition to its good fire performance, ETFE has excellent chemical resistance to acid, base and salt, what is presented in Table 5. In comparison to other commonly used polymeric materials, such as polyvinyl chloride, polyvinyl fluoride and polypropylene, ETFE has superior properties.

Table 4 Fire resistance of 250 μm ETFE foil according international standards.

Standards	Class
UL 94VTM	V -0
EN 13501-1	B-s1-d0
ASTM E84	A
ASTM E108	A
JIS A 1322	1
DIN 4102	B-1

Table 5 Chemical resistance of ETFE foil, PVC, PVF and PP material [13].

	ETFE	PVC	PVF	PP
Acid	excellent	good	low	good
Base	excellent	good	good	good
Salt	excellent	low	low	low

However, some chemicals are not compatible with ETFE, such as oleum, chlorosulfonic acid (HSO_3Cl), nitric acid (HNO_3), acid brine ($NaHCO_3$, $NaHPO_4$), potassium permanganate ($KMnO_4$), sodium permanganate ($NaMnO_4$) [14].

3.6. Recycling and embodied energy

It is anticipated that the life span (life time) of ETF film may be 50-100 years. At the end of life, the ETFE film can be recycled. For this recycling process an additive is not required, since it is necessary to have only ETFE material and heat. It is enough that an old, torn, misshapen cushion is simply removed from the structure, cleaned and heated to melting temperature. Melting should be done along with virgin ETFE granules, and such obtained material could be extruded again to create more ETFE film. Besides that, low melting temperature shown in Table 6 [15] (more than three times lower than melting temperature of glass) makes the process of recycling energy-efficient [9].

Table 6 Melting temperature of different polymer products.

	ETFE	PTFE	FEP	PFA
Melting point [^{o}C]	220-280	327	260	306

Table 7 Embodied energy of ETFE foil and 6 mm float glass [16].

		ETFE foil	6 mm float glass
EE	[GJ/t]	26.5	20
EE per m^2	[MJ/m^2]	27	300

Embodied energy is the measure of required energy to produce a certain material (including raw material extraction, manufacturing, and transportation). Embodied energy values of ETFE foil and 6 mm float glass [9] are presented in Tab. 7. It could be noticed that embodied energy for ETFE is an order of magnitude less than that of 6 mm glass due to the thinness of the material. The amount of material required to clad a building with ETFE cushions is extremely low (mass of a typical foil for the roof is 450 g/m^2).

4. TYPE OF ETFE FOR BUILDINGS OR CONSTRUCTIONS

The ETFE product that is predominantly used in buildings or constructions is ETFE film. This film could be utilized as a single layer stretched between two supports or in a form of many air-trapping layers to create a foil cushion (pillow). In both cases, the ETFE material requires a pre-tensioning process so the film transfers imposed loads through tension only without folding. In the case of the single layer ETFE film membranes it is important to perform the mechanical pre-stressing in order to transfer loads to the primary structure. On the other hand, in the case of the multi-layer ETFE cushions the air is used to pre-stress the film layers and to carry applied loads.

4.1. Single layer ETFE film panels

Single layer ETFE film panels are supported by a primary structure, stretched to the frame edges and fastened (Fig. 5a). The single layer ETFE membrane takes advantage of double counter curved surface increasing its capacity of load by using two way action of the material. The size of each membrane panel is limited by load capacity of the ETFE material (a factor of surface and thickness). Usually, the maximum size of mechanically inflated film panel is approximately 1.5 m and they could be used to cover small surfaces.

(a) (b)

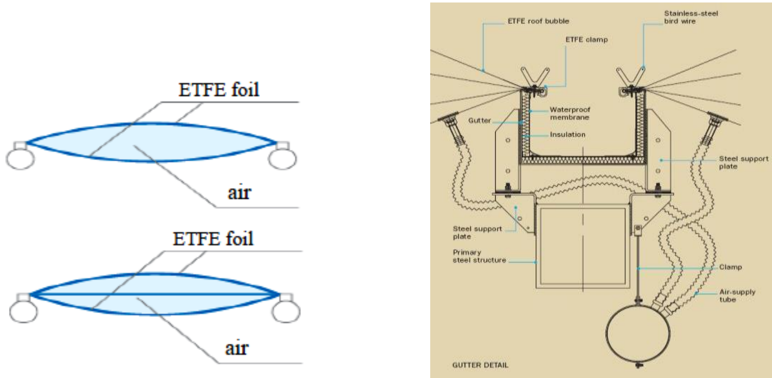
Fig. 5 a) Cross section of single layer ETFE film panel; b) Gaislachkogl gondola [17];

The mechanically pre-stressed panels are much smaller than pneumatically controlled ones because the ETFE supports the load with only its material strength. Besides that, due to lower insulating values than that of cushions single layer films could be used for objects which do not have to be heated.

While in the past high-altitude buildings could be made only as solid structures, all the roofs of the Gaislachkogl cable car stations have been built with sculpted foil -ETFE which is highly tear resistant (produced by 3M Dyneon®) [17]. The Gaislachkogl project is the first time that foil architecture has been used in high mountain locations where extreme conditions come with the territory. The cover of the mountain station is designed for wind loads of up to 300 km/h. The Gaislachkogl cable car is opened in 2010 year, in the Austrian municipality of Sölden.

4.2. ETFE foil cushions

ETFE cushions are of the great interest for application in structural engineering and architecture. There are several different methods of creating the foil cushion. Generally, pillows are created by connecting two or more (3-5) layers of ETFE foil shaped together around their perimeter (Fig. 6a). The cushion consists of layers of ETFE foil and pressurized air which stabilizes the pillow and pre-stresses the system to take the load. Such a pneumatic system achieves adequate thermal properties, structural stability and resist to external forces due to the difference between external and internal pressure. The pressure (provided by air supply) is usually between 200 Pa and 1000 Pa, which is enough to resist most external loads such as wind and snow. In the case of failure of air supply system, the pressure in cushions is maintained during the next 3-6 hours due to use of non-return valves [18].



(a) (b)

Fig. 6 a) Cross section of two-layer and three-layer ETFE cushions; b) *detail* of the air supply for the formation of cushions [24]

Once the air hose is attached to the cushion it is inflated using a central air pump system (Fig. 6 b) that monitors the cushion's internal pressure, temperature, and humidity. By using cushion sensors the central air pump system also monitors external factors caused by weather such as snow loading, wind pressures and directions, temperature, humidity, and dew point. Using the control system and central pump the cushion's pressure can be adjusted to adapt to a number of external stimuli [18]. It should be mentioned that the pump system is meant to maintain pressure and not to produce airflow. A single inflation unit consists of two backward air foil blowers powered by electric motors and can pressurize about 1000 m^2 of ETFE cushions.

ETFE foil cushions systems are produced in various shapes and sizes. It is important to note that maximum glass panel spans from 2 m to 4 m, while ETFE can span much larger distances. Namely, hexagonal cushions as large as 11 m across (Eden Project, England [19]) and 17 m rhombuses (Allianz Arena, Germany [20]) have been constructed for buildings in Europe. The larger ETFE cushion spans reduce the length of flashing at the edges of cushion, which improves the insulation value of the entire roof and provides fewer points of entry for water leakage and outside air. Thermal insulation properties with the cushion-like system can be changed by employing a variety of film with a certain texture.

5. Maintenance of the Structures

Maintaining an ETFE roof is less expensive than maintaining a glass roof. The foil cushions can be either prefabricated or assembled on site. The cushions could be easily replaced or mended and do not require access from inside of the structure. Maintenance can be performed from the outside of the structure by mending a cushion onsite or removing it from the frame and replacing it.

ETFE is resistant to weathering due to environmental causes (ultraviolet light and pollution) and when it is exposed to the elements, it experiences no chemical or physical degradation and also maintains its strength. These advantages, as well as light weight, have led the selection of this material for biome domes at the Eden Project in England (Fig. 7a). Inside the two biomes (that consist of hundreds of hexagonal and pentagonal cells supported by steel frames) [19] are plants that are collected from many diverse climates and environments.

The anti-adhesive nature of ETFE allows that self-cleaning properties could be pronounced. Dust or mineral deposits from snow or rainwater remain unattached to the very smooth surface of ETFE and are immediately washed off during the next rain. Furthermore, this non-stick property prevents the creation of algae or dirt collection on the cushion surface. Considering that ETFE is one of the smoothest known substances, the need for regular cleaning services is reduced. This leads to a reduction in the cost to the owner of the building. Also, this leads to a reduction in the use of detergents and water to maintain the building that is very important regarding the influence on the environment. On the other side, the inside face of the cushions could not be cleaned by occasional rain so the internal surface of the pillows may be cleaned (if necessary) every 5 - 10 years [9, 11].

It is interesting that according to a report provided by the Department of the Environment Transport and the Regions, Westminster Hospital (Fig. 7b) only £30500 was calculated to be spent for cleaning of their ETFE atrium during the 60 year lifespan of the building, as opposed to £104700 for a glass atrium [21].

(a)

(b)

Fig. 7 a) Eden Project, Cornwall (England); b) Westminster Hospital, London

Although the ETFE could not be broken like glass, it can be punctured by a knife or by birds or other sharp objects. It is interesting that ETFE film cushions are vulnerable to direct penetration, however, the film has considerable tear propagation resistance. A puncture will penetrate the layer of foil but will not continue to its perimeter. For tears, less than 100 mm, a patch of ETFE tape can be heat welded into place. In this way, the need to replace entire panel if any cracks occur is not necessary, in contrary with a glass panel. However, if it is eventually necessary to replace the entire panel, the ETFE is so light weight that it can be easily replaced without the need of scaffolding or lifting equipment. Also, servicing the roof with workers is not problematic since the cushions could easily handle the weight of foot traffic.

6. DESIGN AND SOLAR CONTROL

It is known that daylighting techniques can both reduce electric energy demand for lighting as well as minimize loads on the cooling equipment due to overheating. Consequently, daylighting design has to be carried out with great care. In order to obtain diverse visual effects, ETFE Foil can be treated in a number of different ways. Namely, light transmission properties could be manipulated by printing, tinting, surface treatments, radiation and adding layers.

Printing (fritting) means that the surface of the foil is covered with a variety of patterns in order to reduce solar gain while retaining translucency. In this way, the energy transmission can be altered by varying the percentage of coverage and density of the ink. The foil can be over printed with a number of treatments to affect transmission. Tinted, coloured foils can be used alongside clear foil to incorporate branding and large scale imagery. Also, white ETFE foil can be used to reduce glare keeping the light transmission and insulation properties. Surface treatments undertaken during the manufacturing process can vary the properties of the foil and allow light transmission manipulation. These treatments render the foil matt in appearance and therefore provide a good projection surface for light shows and images. The foil could be conditioned with a range of radiation treatments which can reduce the levels of infrared and ultraviolet rays transmitting through the membrane skin. Insertion of additional ETFE foil layers to a cushion also allows light transmission and solar gain to be controlled.

Solar gain (solar heat gain or passive solar gain) refers to the increase in temperature (heat gain) in object or structure that results from solar radiation. The amount of solar gain increases with the strength of the sunlight, and with the ability of the material to transmit or resist the radiation. To measure the solar energy transmittance of glass a g-value is commonly used (a Solar Factor). The g-value of an installation represents the fraction of solar energy transmittance through glazing. This factor is usually expressed as a percentage (0% - 100%) or a value ranging 0 to 1, where 1.0 or 100% represents the maximum amount of solar energy passing through the surface. It could be observed that on some window literature value is very often 0.53 (standard glass is approx 0.88 whereas some specially treated glass may be as low as 0.46). On the other hand, the g-value of an ETFE roof can be reduced to 0.48 for a 2 layer system with a fritted top surface and to approximately 0.35 by using a 3 layer system. It has to be noted that the g-value of any ETFE installation is very dependent on aspect and location and should be estimated taking project elements into account.

An additional design aspect is that companies can have their logos printed onto the ETFE building brand equity along with controlling the light and heat transmission.

Depending on application and design of the structure, various types of ETFE foil could be chosen. In Fig. 8 common used foils are presented **Error! Reference source not found.**. The corresponding transmittances are shown in Tab. 8.

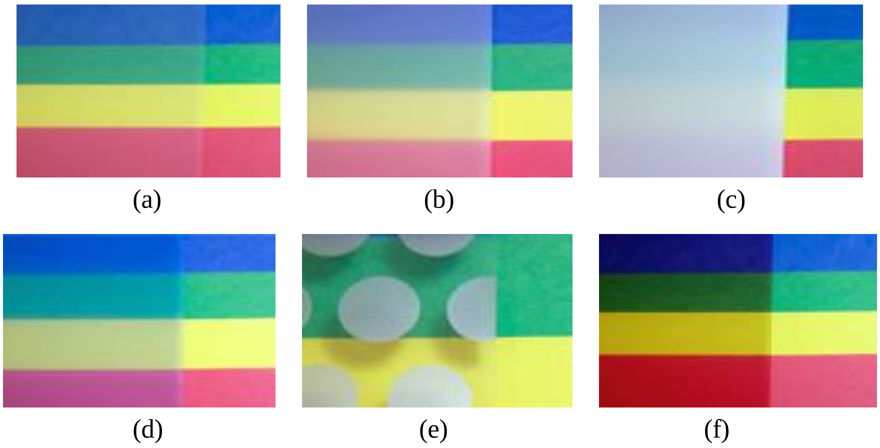


Fig. 8 Types of ETFE film: (a) Transparent (NJ), (b) Matte (HJ), (c) White (WT), (d) Blue (TB), (e) Print (PT), (f) UVC

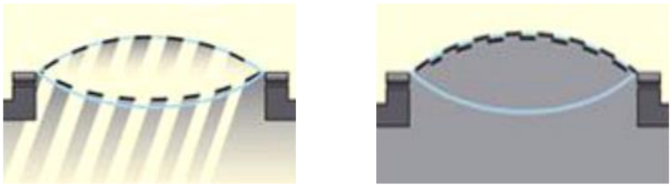
The Transparent (Fig. 8a) transmits over 90% of sunlight; the Matte (Fig. 8b) diffuses light giving it a natural glow and has a privacy aspect as because it cannot be seen through it with clarity; the White (Fig. 8c) diffuses the light letting up to 40% through to light up the area, reducing the need for electric lighting (provides a great shaded area as well with less than 1% UV filtering through); the blue (Fig. 8d) was chosen as the coloured ETFE film pioneer to be developed as needed; the Print (Fig. 8e) has silver patterns (dots or squares) printed with special ink (to reduce fading), specially designed to control light and heat transmission; specially developed film UV reflection cut (Fig. 8f) allows for high light transmission yet reduces the UV transmission to the inside.

Table 8 The values of transmittance (in different parts of spectrum) for presented types of ETFE film (200 μm thickness) [8].

Type of foil		NJ	HJ	PT	WT	BT	UVC
Visible light (380-780 nm)	%	90.5	91.7	63.2	40.5	80.3	87.3
Ultraviolet (300-380 nm)	%	83.5	88.2	58.2	1.0	75.4	36.9
Sunlight (300-2100 nm)	%	91.9	90.4	63.7	50.1	86.9	88.9

Combining the different types of film, UV protection and/or light control to the inside could be created. For example, by combining one translucent and two printed ETFE films into a three layer design and moving the middle layer up and down, the amount of light that is transmitted to the inside can be controlled.

Multi-layer cushions could be constructed to incorporate movable layers and intelligent (offset) printing. By alternatively pressurizing individual chambers within the cushion, maximum shading or reduced shading could be achieved as and when it is required. Practically, this means that it is possible to create a building skin which is reactive to the environment through changes in climate.



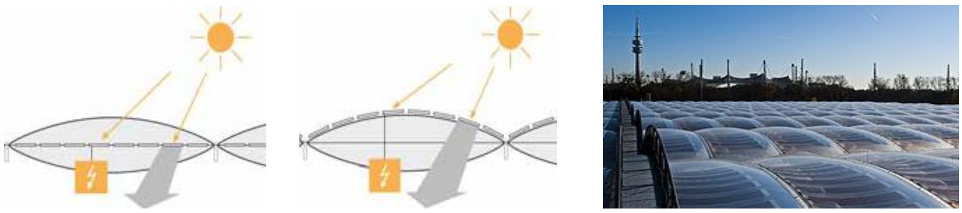
(a) (b)

Fig. 9 Lighting control system of cushions by using two printed foils and one transparent ETFE film: (a) middle layer (supplementary print) down and (b) middle layer up **Error! Reference source not found.**

It should be emphasized that principles of sustainable development criteria and the preservation of environmental quality in the function of preventing the negative consequences of climate change could be achieved by integration of photovoltaic cells into the membrane structures. In addition, it is important that using flexible solar cells could contribute to solar control [23].

In general, integration of photovoltaics (PV) in buildings offers a lot of potential in future. Namely, in an appropriate application in transparent or translucent parts of surface it might also provide necessary shading which reduces the solar heat gains in the building (or structures) and thereby helps to minimize cooling loads and energy demand in summer. Practically, this synergy effect is of great importance because it principally helps to reduce the balance of system cost for the PV application. From an aesthetic point of view (which is very important especially for building design in urban areas), an integrated solution offers significantly more potential than any other application. Such, extremely flexible, amorphous thin-film solar cells embedded in ETFE cushions can follow the most complicated form of the roof construction. In this way, architecture has received a completely new dimension [24]. Also, the PV does not require an additional substructure as it is an integrated part of the building envelope.

The PV can be integrated into pneumatic constructions such as ETFE foil cushions as presented in Fig. 10. When PV is applied in the middle layer (Fig. 10a) it will be protected, but the power output will be limited due to refraction effects (of the top layer foil) and also due to the heating of the absorptive middle layer which will not be reduced by convection effects of the outside air. Consequently, the integration on the outer top layer of the cushion (Fig. 10b) will be more efficient [23].



(a) (b) (c)

Fig. 10 ETFE cushions roof with integrated photovoltaic cells a) on the middle layer [23]; b) on the top layer [23]; and c) Munich's municipal waste management department **Error! Reference source not found.**

In Fig. 10 c the new roof of the Munich's municipal waste management department with its integrated photovoltaic cells is presented. This roof constructed in 2011 fulfils all the requirements which can rightfully be expected of a functionally and ecologically advanced structure [25].

Another attractive possibility is an application of various lighting effects that can be achieved through LED lighting or image projection used at night for the best results. During the last decade in many attractive buildings ETFE foil was combined with LED lighting.

7. The Most Famous ETFE Projects

Advantages of using ETFE enabled application of this material for many famous structures which are located all over the world. The use of ETFE allowed completely new approach to the architecture. Especially, light sources incorporation and final visual performance make this novel material useful for creation of advanced structures. Each of these structures are modern and innovative. Several examples of ETFE application are presented below.

Donau Shopping Center [26] is the biggest shopping mall in Vienna and second largest shopping centre in Austria (Fig. 11). The impressive air-cushion facade of this mall is made of partially transparent and partially printed ETFE foil. LED lights are arranged in a polygon behind the air cushions, while the outer foil is printed in white using screen printing.

Fig. 11 Donau Shopping Center

The facade made of air-cushions (printed ETFE foil) gives the centre its unique visual charm. Such facade enables that, during the day, the light passes directly through the cushion and provides a bright feel-good atmosphere, while, when night falls, the LED lights draw attention to the spectacular facade.

Baku National Stadium [27] in Azerbaijan is the six-story, 65.7 m structure near the Boyukshor Lake (Fig. 12). Construction of the 225.000 m^2 stadium on a 650,000 m^2 site was completed in 2015. This multi-function stadium is set on land fill site of petroleum production. During the construction, it was difficult to determine the height of the appropriate ground level because the groundwater was high due to the adjacent lake. To maximize design flexibility, the structure was designed using piled raft foundations, a system more typical of high-rise buildings than stadiums. During the building process, an advanced modelling approach was applied. An automated design routine to check beam and column reinforcement was developed. Precast reinforced concrete, main and secondary steel structures were all modelled using Tekla Structures 19.0 and full fabrication drawings were delivered to the contractor's fabrication facility. In addition, the ETFE facade and roof systems were applied.

Fig. 12 Baku National Stadium

The stadium is equipped with an innovative lighting solution, including an HDTV-compliant floodlighting system. The outstanding lighting could create different visual effects.

Water Cube National Swimming Centre [28] in Beijing, China is a multifunctional aquatic centre, which required extensive use of digital technology, energy-reduction and water-saving methods, as well as the incorporation of new construction materials (Fig. 13).

The unique design of this 31 m high centre played on the geometry of water bubbles within a square form. The structure's shape was specifically designed to work in harmony with water games and functional requirements.

There are two parts to the structural framework – internal and external. The external structure forms the actual roof, ceiling and walls and comprises a flat web of rectangular boxed sections. These sections are clad with the transparent ETFE. More than 22.000 stainless steel members create the sides of the bubbles, which are welded at the joints to more than 12.000 spherical steel nodes. The advantage of using this frame design, as well as resembling water bubbles, is ideally suited to the seismic conditions found in Beijing.

This swimming centre is built in 2008 (for the Beijing Olympics), and its envelope surface is covered by 100 000 m² of ETFE (4000 cushions), making it the largest ETFE structure in the world. One of the challenges encountered by the designers was to convince the authorities about the advantage of ETFE and that the design allows 140 000 t of recycled water to be saved a year. The ETFE cladding lets in solar heat, reducing energy costs by up to 30%. A stringent temperature and humidity control system, and a recycled hot water system were incorporated into the design, helping to air-condition the public area and the swimming pool. These indoor and outdoor air recycling systems, solar energy systems and deck ventilation systems maintain a comfortable climate and humidity of 50%-60% in the venue. Also, the designers had to prevent dewdrop from the ceiling, which could affect the swimmers in the pool or divers on the springboard. The ETFE and air conditioning systems have partially helped in preventing of dew dropping. Moreover, the building's air supply, return inlets and exhaust outlets improve the ventilation in the upper spaces of the building.

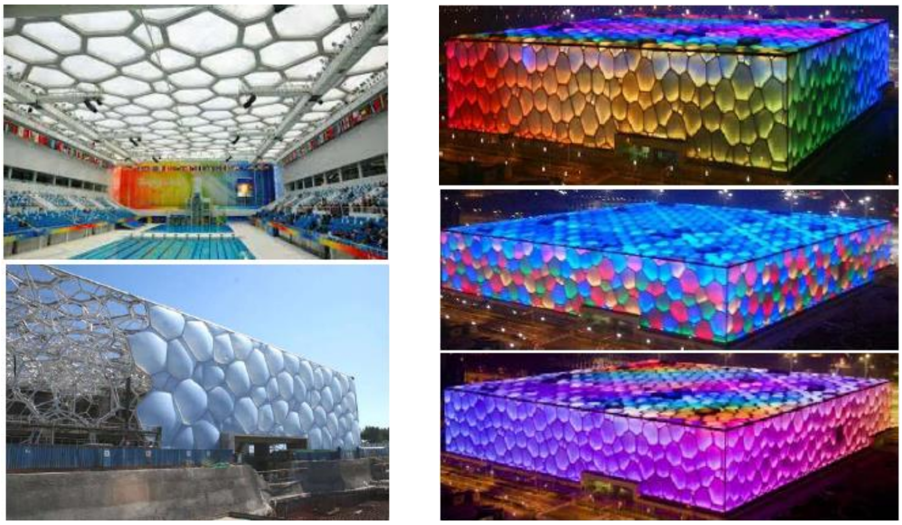


Fig. 13 Water Cube - National Aquatic Centre in Beijing, China

The Water Cube is lighted by LED light sources, which are produced by novel technology. It is possible to use the cube's lighting to simulate an extremely low-resolution screen. Dynamic lighting allows incredible lighting effects. More than 450 000 LEDs are embedded throughout the structure. LED lighting fixtures illuminate the bubble designs from inside the structure’s translucent walls, allowing the entire building to glow with extraordinary colour changing LED light. In addition, spectacular lighting effects are enabled by using remarkable, world-renowned lighting installation. Also, it is important that it is possible to create dramatic effects while consuming as little energy as possible.

The bubble like “skin” of the massive five-story building is illuminated each night with a light display that is designed to reflect traditional and contemporary aspects of Chinese life. The colours and movement patterns are based on the ancient Chinese philosophical system, and on the daily mood of the Chinese people as expressed through social media. The resulting display of light, colour and movement is visible every evening from dusk to 10 p.m. on the surfaces of the building.

Khan Shatyr Entertainment Center [29] in Astana, the new capital of Kazakhstan was built in 2010. Although the city lies in an austere eastern landscape with an inhospitable climate that can generate temperatures of -35 ^{o}C in winter and +35 ^{o}C in summer, Center is designed to provide a comfortable microclimate all year round, whatever the weather. The building's tented structure has great resonance in Kazakh history as the tent is a traditional nomadic building form, and Khan Shatyr means the Tent of the Khan.

Fig. 14 Khan Shatyr Entertainment Center, Astana **Error! Reference source not found.**

The structure soars 150 m from a 200 m x 195 m elliptical base to form one of the highest peaks on the Astana skyline. Enclosing an area in excess of 100 000 m^2 it comprises an urban-scaled park, with a wide variety of shopping and leisure facilities. The tubular-steel tripod structure supports a suspended net of steel, which is clad with a three-layer ETFE envelope, formed as 3.5 x 30 m cushions. Specific areas are air conditioned, but the open circulation areas are environmentally tempered, with target temperatures of +14 ^oC in winter and +29 ^oC in summer. Preventing ice forming on the inside of the envelope is achieved by a combination of temperature control and directing warm air currents up the inner fabric surface, a strategy that also prevents downdraughts.

The new Unilever headquarter building [30] for Germany, Austria and Switzerland is located in Hamburg near the river Elbe (Fig. 15). It was built in 2009 and marks the end of the route out of the town centre to the cruise ship terminal and the promenade on Strandkai. The central element is the generous atrium, flooded by daylight, which gives passersby the opportunity to get to know the company better while browsing in the shop stocked with Unilever products, sitting in the cafe or relaxing in the spa. Also, the atrium is the central place for people to meet and communicate.

The building follows the principles of sustainable architecture. Although technologies that help the saving of resources are implemented, the energy concept adheres to the principle of avoiding technical solutions wherever possible. A single-layer ETFE film, placed in front of the building insulation glazing, protects the daylight optimized blinds from strong wind and other weather influences.

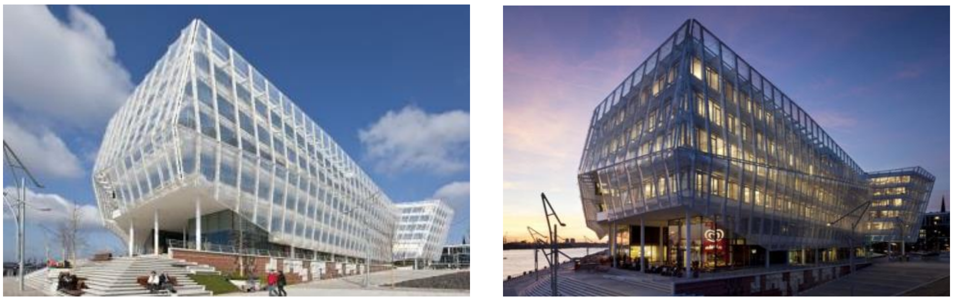


Fig. 15 Unilever headquarter building

A newly developed SMD-LED system has been applied for the building's general lighting and for workplace lighting. It is very important that this system is up to 70% more efficient than conventional halogen or metal halide lighting. This building received the newly established HafenCity EcoLabel in gold.

Allianz Arena [20], a football stadium located in Munich, in Germany is widely known for its exterior of inflated ETFE panels (Fig. 16). It is the first stadium in the world with a full colour changing the exterior, officially opened on May 30, 2005. Total steel used during stadium construction is 22 000 t, while for the parking garage was used another 14 000 t. The roof of the stadium has built-in roller blinds, which may be drawn back and forth during games to provide protection from the sun.

Fig. 16 Allianz Arena stadium

The arena facade is constructed of 2 874 rhomb designed ETFE foil cushions (air panels) that are kept inflated with dry air to a differential pressure of 3.5 Pa and can be effectively illuminated from the inside.

Each panel could be independently lit with red, blue or white light. Usually, the panels are lit for each game with the colours of the respective home team (red for Bayern, blue for TSV and white for the national team). Other colours or multicolour or interchanging lighting schemes are theoretically possible, but police insist on uni-colour only due to several car accidents on the nearby road when drivers have been distracted by the changing lights. It is interesting that in clear nights the stadium can easily be spotted even from Austrian mountain tops, e.g. from a distance of 80 km.

Innovative stadium-facade lighting concept of Allianz Arena has been subsequently adopted in other newly built venues.

8. Conclusion

Physical properties and possibilities of ETFE application have been presented, considering that it could contribute to sustainable construction in our region also. Firstly, the production of this recyclable material requires significantly less energy per square meter than glass. In addition, superior characteristics of this kind of plastic allow a huge range of potential applications and enable creativity, practically without boundaries.

A single layer ETFE foils can be transparent, translucent, coloured or printed with a graphical design. Also, between two and five layers of foil could be used to form air pressure stabilized cladding panels. The number of layers depends on project specific requirements for structural and thermal performance, so that wide range and combination of visual transparency, solar control and thermal resistance could be achieved. Each layer of cladding panel is made up of smaller elements cut from the foil rolls to a predetermined design by a computer controlled plotting machine and welded together to form sheet, which is usually supported by steel frames. In addition, incorporating light sources into the envelope and possibility that building or construction could be lighted "from the inside" significantly contribute to achieving the visual performance and appearance, while the application of amorphous thin-film solar cells embedded in ETFE cushions could contribute to providing energy and to controlling solar gains.

It is obvious that applications of this environmentally friendly, lightweight material (which offers a wide range of attractive options) could further contribute to the development of architectural design and new dimension of architecture.

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ZNAČAJ PRIMENE ETILEN-TETRAFLUOROETILENA ZA UVOĐENJE DNEVNE SVETLOSTI U GRAĐEVINSKO - ARHITEKTONSKE OBJEKTE

Razvoj visokih tehnologija materijala omogućava realizaciju kreativnih rešenja i ideja. Savremene tehnologije i materijali, uz sasvim nov pristup načinu projektovanja, pružaju realizaciju nečega što je nekada izgledalo nezamislivo da se može izvesti. Jedan od takvih materijala, novije generacije jeste etilen – tetrafluoroetilen (ETFE). Ovaj materijal koji se sve više koristi u građevinsko-arhitektonskim objektima, stekao je svoju popularnost zbog izrazito male težine, velike mogućnosti propuštanja i kontrole uvođenja dnevne svetlosti u objekte. Inovativni materijal - ETFE se kod prekrivanja objekata koristi u vidu folija koje se u cilju postizanja toplotne izolacije povezuju na ivicama i pune vazduhom uz pomoć kompresora formirajući oblogu koja podseća na naduvane jastuke. U ovom radu prikazane su osobine i mogućnosti primene ETFE koji zbog svojih performansi održive gradnje sve više zamenjuje tradicionalno stakleno oblaganje i omogućava realizaciju kreativnih rešenja

Ključne reči: *dnevna svetlost, inovativni materijali, ETFE folije, ETFE jastuci, održiva gradnja*