Inflatable Pillow System as a Glass Substitute In Terms of Building Envelope

By

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ABSTRACT

In the line with the increasing energy demand, there have been many investigations related with the conservation of energy used in buildings. The systems and materials used in buildings have an important role in consumption of energy. Transparent materials and the systems occupies transparent materials contributes this consumption in positive and negative way due to their design and properties. Nevertheless, the transparent materials used in buildings as glazing have importance in order to increase comfort, decrease cost and environmental harm.

This study aims to investigate a contemporary construction system; ETFE foil pillow system, which is also known as, Inflatable Pillow System made of ETFE Foil. In the scope of the study, pneumatic pillow system investigated in detail and its performance evaluated due to environmental control criteria, which can be compared with other conventional glass glazing products. The study also involves cost analysis and brief knowledge about contemporary cases that have been completely or partially constructed with this system. The increase in the amount of transparent surfaces in contemporary buildings, pointed out that the conventional glazing system are no more appropriate. Therefore, in specific cases, usage of conventional glass glazing systems results as a cost increase and loss of comfort. The alternatives of the conventional glazing systems don't have appropriate performance or don't meet the need of the consumer. Inflatable ETFE foil pillows have better optical properties than glass glazing systems. Generally, thermal properties of this system equal to the advanced double-glazing. Light and heat transmission values vary by changing the foil type and number of layer. Low sound reduction index can be an obstacle or a chance for designers that should be given attention in design phase. The pillow system that relatively provides fire and earthquake protection is also lightweight and flexible. Thus, includes many criteria that are expected in contemporary constructions. The inflatable pillow system made of ETFE foil can be considered as a safe construction method due to mechanical properties of the system and the membrane material that is used as pillows. System reduces operational and maintenance cost for the building. Considerable amount of expenses for lighting and heating can also be reduced by the usage of the pillow system.

The lightweight nature of the pillow system affects the construction of the whole building, which also results as a cost reduction.

Pillow system is commonly used for greenhouses and botanical gardens and also used for sports and leisure halls as well as institutions ands museums. Addition to its usage as a skylight or façade cover, pillow system can be used as a total envelope that covers the whole construction underneath.

As a result, this study investigates ETFE foil pillows and their environmental control properties against conventional glass glazing systems. The results are evaluated in the line with the information gained. The advantages and disadvantages of the system as a glazing are given in detail. Although it's not expected that ETFE pillow system totally be replaced with the conventional glass glazing system, it constitutes an alternative glazing system in specific cases.

Keywords: pillow system, pneumatic membrane, glazing, ETFE foil, glass, fluoropolymer, environmental control criteria

ÖZ

Günümüzde, artan enerji ihtiyacına paralel olarak, binalarda kullanılan enerjinin korunumu konusunda çeşitli araştırmalar yapılmaktadır. Yapının pencere ve benzeri açıklıkları, kullanılan enerji miktarında önemli bir rol oynamaktadır. Şeffaf malzemelerle oluşturulan bu yüzeyler, tasarımlarına ve özelliklerine bağlı olarak harcanan enerji miktarına olumlu veya olumsuz yönde katkı yapmaktadır. Dolayısı ile yapılarda camlama olarak kullanılan şeffaf malzemelerin ve bunların oluşturdukları sistemlerin incelenmesi, yapının konfor şartlarının iyileştirilmesi, maliyetin düşürülmesi ve çevreye verilen zararın azaltılması bakımından oldukça önemlidir.

Bu çalışma, bir fluoropolymer membran olan ETFE folyo ile yapılan camlama sistemlerinin incelenmesini konu alır. Şişirilebilen yastık sistemi olarak adlandırılan sistemin, performansının çevresel kontrol kriterleri açısından incelenmesi ve maliyet analizinin yapılması amaçlanmıştır. Bu pnömatik sistemle yapılan yada sistemi içeren çağdaş örneklerin irdelenmesi çalışma kapsamındadır. Çağdaş tasarımlarda şeffaf yüzeylerin artmasıyla, konvansyonel camlama sistemleri konfor açısından yeterli olamamaya ve yapıya maliyet açısında daha fazla yük getirmeye başlamıştır. Alternatif camlama malzemeleri de bu ihtiyacı tam anlamıyla karşılayamamışlardır. Genel olarak, ETFE folyo ile yapılan hava destekli yastık sistemler optik özellikleri dolayısı ile camdan yüksek ışık geçirim değerine sahiptirler. Sistemin termal özelliğinin ise yaklaşık olarak çift cama eşdeğer olduğu söylenilebilir. Katman sayısı ve folyo özellikleri değiştirilerek ışık ve ısı geçirim değerleri değiştirilebilmektedir. Akustik ses redüksiyon katsayısı oldukça düşük olmasına rağmen tasarımda kullanıma bağlı olarak yarar sağlayabilmektedir. Göreceli olarak yangın ve deprem güvenliği sağlayan sistem, hafif ve esnek olması ile de çağdaş mimaride istenen bir çok kriteri bünyesinde bulundurmaktadır. Bunun yanı sıra, sistemin ve membran malzemenin mekanik özellikleri ve güvenlik performansı araştırılmıştır. Isı ve ışık giderlerinde önemli oranlarda indirim sağladığı gibi işletim ve bakım giderlerini de oldukça düşürmüştür. Ayrıca kullanım şekli ve ölçeğe bağlı olarak yapının taşıyıcı sistemine, dolayısı ile maliyete katkıda bulunmaktadır.

Yastık sistem, genellikle sera ve botanik bahçeleri ile spor ve eğlence amaçlı yapılar başta olmak üzere eğitim amaçlı yapılarda, müze ve çeşitli kurumlarda da kullanım olanağı bulmuştur. Çatıda ve cephede kullanımının yanı sıra yapıyı tamamen örten bir kabuk gibi kullanıldığı uygulamalar bulunmaktadır.

Sonuç olarak bu çalışmada, binalarda kullanılan konvansyonel camlama sistemleri ile ETFE folyo ile yapılan şişirilebilen yastık sistemleri çevresel kontrol kriterleri açısından karşılaştırılarak, elde edilen bilgiler ışığında kullanım alanı ve olanakları değerlendirilmiştir. Sistemin camlama olarak kullanımın sağladığı yüksek maliyet avantajı detaylı olarak belirtilmiştir. Tüm bu özellikleri ile hava destekli çok katmanlı membran sistem, tamamen yerini alması beklenmese de konvansyonel camlama sistemlerine alternatif oluşturmakta oldukları söylenebilir.

Anahtar kelimeler: yastık sistem, pnömatik membran, camlama, ETFE folyo, cam, fluoropolymer, çevresel kontrol kriterleri

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Chapter 1

INTRODUCTION

1.1. The Definition Of The Problem

The present study aims to determine inflatable pillow structure, which is a new generation construction technique as a building envelope, and explain its possible use now and in near future. In the line with this, comparison will be made with glass and other relevant materials and conventional construction techniques. In present research the Inflatable Pillow System will be discussed as a glazing system rather than membrane systems. A brief explanation will be made in comparison with the performances of the glazing systems and other membrane materials.

The building shell, which separates indoor and outdoor, altered in the parallel of development on material technology and new construction systems. It is been always expected from the building shell much more than to be just a skin or a total coverage of the structure inside, where this building envelope can help to get more efficient environments in terms of quality and energy. Concept of shelter has changed and developed during centuries from the basic tent to the intelligent skins. In addition to that, today there are continuous comprehensive researches for better building envelopes to develop spatial quality in buildings. Not only in façade systems, but also investigations made about roof claddings in order to reach the appropriate solution for users. There have been made several building envelope performance tests to monitor results, which directly affect quality and energy. These studies form the building regulations and standards for better environments. Besides that, result of energy crisis after 70's that affected studies around energy efficient systems and energy efficient cladding technologies to find sustainable, environmentally responsive, low energy materials and systems.

Glass is the traditional material for glazing. Glass is commonly preferred as a glazing material to protect the building against environmental effects. The reason for using a transparent material is to get high light transmittance through the material into the building. In addition, transparent glazing also saves a visual link between inside and outside. Traditional glazing material: *"glass"* has been used for centuries without any alternative in the market. Besides free form opportunity membranes are used for their translucent property. Improvements in polymer technology: new plastics and their properties exploited in building construction. Ethylene Tetra-Fluoro-Ethylene is a copolymer that is adapted to the construction in sheets. Therefore, this new plastic foil found an appropriate place in architecture as a part of the building skin, mostly as glazing.

The "*Inflated Pillow System*" which can be understood from the name given, is an inflated structure, used for various glazing purposes with high performance than its alternatives. However, because of the existence of a primary load bearing structure the self-supporting nature of the inflatable structures can partially be seen in Inflatable Pillow Structures.

IPS involves two different structures; primary (supporting) and secondary structures (pillow). Pillow structure, which occupies the self-supporting nature on itself is made of foil. The primary structure, which holds the pillows, can change according to the architectural choice, but the pillow structure will be still same in concept. IPS is consists of at least two membrane layers, with intermediate space inflated to a slight excess pressure to provide stability. It is possible to use system in multilayer with changing options that will be discussed soon after. Therefore this cladding system is also called as "*Pneumatically Supported Multi-layer Membrane System"* and *"Inflated Cladding And Roofing System"*. Furthermore IPS has adaptability to change for outdoor conditions, takes part in intelligent facade systems. According to design, the variable shading system, which can be defined to obtain climatically responsiveness by the click of a switch or by more sophisticated building automation systems can be applied with the usage of at least three-layer systems.

Inflated Cushion System can also be classified according to glazing materials' technical and physical characteristics as in other facade systems. In this respect, explanations and analysis for the usage of the system depends on the material. Besides the cladding construction, used in applications, glazing material has the primary importance in the performance of the system. Instead of various textile fabrics and coatings used in membrane systems like PTFE, PVC, PES etc.; an isotropic film ETFE folio (ethylene-tetrafluoroethylene) is commonly preferred in pneumatic supported multi-layer membrane system applications. Because of the nature of the glazing material, the system mostly applied by worldwide membrane constructors in accordance with polymer film manufacturers rather than local cladding companies.

Inflated Pillow System that is fabricated with ETFE folio has better values for several properties in comparison to other alternates. This study aims to determine the system in comparison to glazing systems, (which were constructed with glass or similar transparent/translucent materials) by the way of investigation of the ETFE applications in architecture. In the line with this, there will be a comparison between ETFE and glass. Thermal, optical, physical, acoustical properties as well as ecological attitudes will be compared with its cladding/glazing substitutes. The expected result of this comparison is, to analyse the environmental performance and cost of system. The system reduces total weight of the building and it also makes construction much more slender. Naturally pillows save the double curvature forms on the envelope where it's used. It could be used in its limited load bearing strength, as an elongated form, a radial form or a grid-structure in buildings for various cladding -or as said in respect of the study: glazing- applications. This study will search the advantages and disadvantages of this system comparing with conventional systems.

Briefly, in the scope of this study, the applications of Inflated Cushion System as a highly energy efficient cladding system will be investigated. In addition to that, present research determines the potential of the system, and information about the types of applications that will be allowed by using Inflatable Pillow System in the future uses.

1.2. The Domain Of The Study

The present research is objected to clarify the development of Inflatable Pillow System as a building envelope construction type while investigating traditional uses and applications on relevant subjects. History of inflatable structures and contemporary usages will be included to the investigation in order to get basic knowledge about inflation. Besides this, the conventional membrane materials will be explained in limits, in order to make comparison with the glazing, which is considered as a non-woven membrane sheeting or film.

Building envelopes like; curtain wall systems and roof lights consist of glass and similar claddings will be used in comparison and will be determined as conventional types of recent applications in buildings.

1.3. The Method Of The Study

This study aims to investigate by comparing the subject with a common alternative in construction sector and discussing results upon environmental control criteria of the systems that are important in terms of glazing. In the scope of the thesis, related with the problem determined, the study investigated mainly in four chapters supported with general overviews and specific examples. Due to lack of manufacture, technical information and application of ETFE film in Turkey, data is obtained from abroad, from those who have been previously involved in application of this system.

Construction of inflatable pillow system and glazing material is investigated by the literature survey. A through literature survey has been conducted on subject and relevant topics. Technical information about ETFE foil directly maintained from international manufacturers and polymer producers. Further information about construction, detailing and usage get from the worldwide membrane constructors and contractors as well as from several architectural and engineering firms that are participated to the projects. In some parts, knowledge that depends on personal communication with specialists is given as reference or valuable data.

The first chapter is the introduction chapter, which describes the qualities of the study. In the subtitles of the study aim, domain, and the method of the study are determined in brief.

The second chapter is a complementary of chapter one where building envelope and glazing is determined and evaluation of the current trends and debates are discussed. The need for new design alternatives for glazing in order to conserve energy is underlined. Therefore the most common glazing material, glass and its architectural types are determined in order to understand the materials properties.

The third chapter aims to create a reference for those who use inflatable pillow system as a glass substitute. This section gives the designer information about performance and usage. The foil and the structure are described briefly which are used to form the whole system. This chapter also gives information about evolution of inflatable structures.

The fourth chapter determines the state-of-the-art applications of the IPS. Structural information is described upon examples, which were constructed after 90s in Europe. These applications are classified in three groups; greenhouses and zoos, institutes, and sport and leisure facilities. The applications are selected to show various types of usage of IPS.

The fifth chapter provides a comparison between various glass types and IPS types. This comparison made by the environmental control criteria of the glazing materials. Optical, thermal, and acoustical control performances discussed as well as safety and security and many other properties.

At the end of this study, conclusion are interpreted in the concept of this study, findings are presented.

Chapter 2

CONVENTIONAL GLASS GLAZING SYSTEMS IN TERMS OF BUILDING ENVELOPE

2.1. The Role of Building Envelope, Building Fenestration and Glazing

In the 20th century architecture, there have seen a change from the buildings with thick, solid walls with windows, to buildings with thin, completely transparent skins which have a completely sealed separation between the inside of the building and the outside. Brookes (1990) describes the building envelope as often the most critical element of building construction in so much that it affects its exterior appearance and keeps the weather out.

The critical aspects of building envelope are; minimizing air infiltration and allowing ventilation with outdoor air when it is desirable. In other words; it provides a barrier between the internal building environment and the outdoor environment. This could only be achieved by voids in the envelope. All building void design order defined as fenestration. These include doors and windows, which are the connections between indoor and outdoor. They establish a physical connection as well as visual connection through transparent components.

Behling (1999) explains that, the shift toward timesaving standardization, prefabrication and modular construction for the exterior skin are greatly accepted by the designers. In addition to that, the façade has changed in function from passive wall on the building's interior to an active building envelope in terms of fenestration. In the line with that, traditional and conventional construction techniques evolved until middle of the 20th century when the awareness raised about usage of fossil fuels. Today, building envelope construction is the subject of the debate in terms of energy and quality.

Improvements for the building envelope typically provide the first line of defence in energy-efficient design strategies. The major turning point of the century can be considered to be the energy crisis of 1973 -1974 and 1979, which led to a realization that there was an essential need to conserve energy. According to Brookes (1990), before the breakthrough event of the 70’s, the building envelope was representing the function given like being just a partition between or on the supporting members. As a reaction of the oil crises, there was an increased interest in energy savings and environmental protection. Thus the thermal and optical performance of the building envelope become much more important, and this, in turn led to a greater concern for insulation and insulated skin.

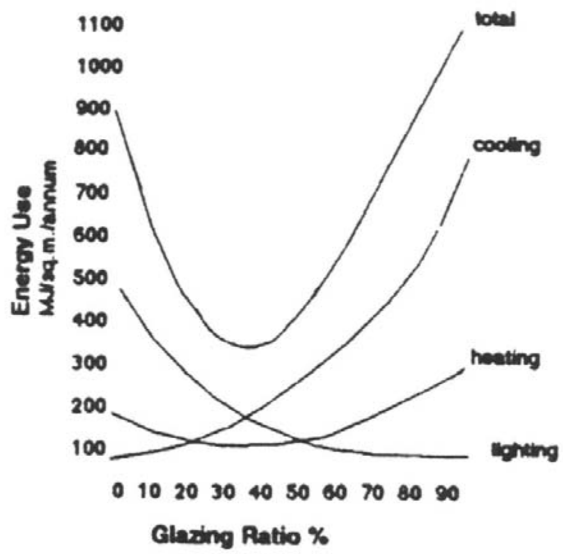
Factor	**Positive Aspect**	**Negative Aspect**
Ventilation	Air movement Draught	(Potentially Major Heat Loss)
Daylighting	View + Light	Glare
Thermal Performance	Solar Gains	Thermal Transmission
(Noise Insulation)		
(Security)		

Table 2.1. Glazing Factor That Affects Indoor Comfort And Energy Use
Source: Wooley and Kimmins (2000)

As a result of energy conscious environment, the current demands and debates are commonly made upon the ecological and sustainable products, and energy efficient products. Green architecture and intelligent architecture are the other outcomes of the market related with these issues. The architectural trend, based on the treaties of Montreal (1992) and Kyoto (1997), has influenced the building envelope design with other emerging concepts. The results of the ecological experiments carried out by the alternative energy groups and dome builders of the 60s can now be combined with the innovations of the electronics industry to create solid-state mechanism for dealing with climatic control and building energy management (Detail, 1998-3).

Efficiency in building design or awareness in consumption of the sources radically influences the way of architecture. According to U.S Environmental Protection Agency, unwanted heat gain or loss could be reduced by adopting sun shading, appropriate insulation, a tight building envelope that limits infiltration and thermal bridging, and high performance glass (EPA, 2001). Many developed countries of the industrialized world tied themselves up with these acts in terms of saving habitat and living in better environments.

The issue of energy is important to architecture for it represents about 50% of the total energy used throughout the world. Grey (1997) determines that 25% of the world is using 75% of the energy. Therefore the use of energy has to be controlled, monitored and designed much more carefully than previous years. Architects have to take the case a very thorough, and have to look analytically at the way in which energy used. According to Oesterle et.al. (2001), constraints of building physics and aspects of comfort limit the architectural applicability. Lack of the environmental awareness led in many cases to buildings with a high-energy consumption and correspondingly great emissions of pollutants.



Energy Use: Glazing Ratio (Temperate Climate)
(Robertson, 6., 1992)

Fig.2.1. Energy Use And Glazing Ratio
Source: Yeang K. (1997), Dimensions Of Sustainability

Internal walls, ceilings and floors with high thermal capacitances can provide thermal storage that reduces energy use by storing solar energy. Wooley (2002) explains that, windows typically account for %15 to %30 of the total heat loss, and for overheating in the summer. As such, glazing can cause energy and comfort problems, but through good design large areas of glass can save energy and improve comfort in both homes and commercial buildings through passive solar heat gain and natural day lighting.

In the line with the development in material technology, new achievements gained for better cladding, window frames and glazing products. By using active involvement with the energy efficient industry and energy efficient products, the fenestration and glazing industry will have an effective force in the future of architecture. Although the total impact and thermal energy balance depends on the glazing, the window frames also have an important effect on the issue. Therefore, a right frame choice contributes to the efficiency.

The limitation of the present study is made upon the fenestrations and the glazing. For that reason the glazing systems are investigated in order to make comparison with “Inflatable Pillow Systems” while discussing glass and its properties.

2.2. Definition of Glass Glazing System

Definition of conventional glass glazing systems can be determined as transparent systems with one and more panes of glass, which can be modified with films and gases. In other words; glazing is a transparent infill between frames. Glass glazing is an extremely broad issue, fundamental not only to energy use for heating, cooling and lighting, but also aesthetics, indoor comfort, health and connection with the outside world. Glass as glazing material is used for hundreds of years as a transparent glazing product for fenestrations. The transparency have replaced by some other determining factors to be used as a glazing material in terms of energy.

Various types and systems are developed in order to widen architectural applicability of glass. There are also new transparent materials are invented such as polycarbonate panes and foils. These new glazing products are used instead of glass and have succeeded their role in particular applications.

Krewinkel (1998) explains the basic properties of glass are; transparency, weatherproof quality, environmental sustainability, fire protection, sound insulation measures, surface printing with ceramic substances, the use of various intermediate layers, and light deflection systems. It is not possible to meet the goals unless designer perceives the properties of glass correctly and use it in an appropriate way.

2.3. Components of Glass Glazing System

Basically the glass glazing system consists of two main parts: “glass and frame”. There are so many glass types that are preferred according to function and expected performance of building. The frame material is also depends on these factors and structural necessities. For instance, while wood frames can be used in low height buildings; there should be used steel or aluminium frames for curtain wall applications in multi storey buildings whilst wood also can be used for according to the design. The architectural approach is also so important in these decisions.

The structural glass and other curtain walling systems, like bolted assembly, are not in limits of the study. Therefore it is not explained in the respect of the thesis.

2.3.1. Glazing

The glass types have to be known to perceive how glass technology inclines the application ways of it. The variety of glass products has been increased with the latest technological improvements and there are several types of glass in market. Glass types are not limited only to the industrial products. Many advanced glasses have been manufacturing to extent the usage of glass in architectural applications for the future. These high-tech glasses are not commercially available or the market price of these products is so high and generally the industrial glasses are preferred in contemporary glazing systems.

There are two different classifications. According to Krewinkel (1998), five main technologies have contributed to glass material’s present state of development. In this classification, only the industrial glasses are taken into consideration and they are classified according to form and application type:

- The pioneering of laminated safety glass;
- The prestressing of glass to form single-layer safety glasss;
- The edge sealing of glass to create multiple-layer insulated glazing;
- The float glass process; and
- The coating of glass to reduce its emissive properties (thermal and solar screening)

Another classification is made by the Corning Museum of Glass (www.cmog.org). According to CMOG, nearly all commercial glasses fall into one of six basic categories or types, which are based on chemical composition: “soda-lime glass, lead glass, borosilicate glass, aluminosilicate glass, ninety-six percent silica glass and fused silica glass”.

A. Soda-lime glass: This type of glass is the most common (90% of glass made), and least expensive form of glass. It usually contains 60-75% silica, 12-18% soda, 5 - 12% lime. Resistance to high temperatures and sudden changes of temperature are not good and resistance to corrosive chemicals is only fair.

B. Lead glass: This type of glass has a high percentage of lead oxide (at least 20% of the batch). It is relatively soft, and its refractive index gives a brilliance that may be exploited by cutting. It is somewhat more expensive than soda-lime glass and is favored for electrical applications because of its excellent electrical insulating properties. Thermometer tubing and art glass are also made from lead-alkali glass, commonly called lead glass. This glass will not withstand high temperatures or sudden changes in temperature.

C. Borosilicate glass: This type of glass is any silicate glass having at least 5% of boric oxide in its composition. It has high resistance to temperature change and chemical corrosion. Not quite as convenient to fabricate as either lime or lead glass, and not as low in cost as lime, borosilicate's cost is moderate when measured against its usefulness. Pipelines, light bulbs, photochromic glasses, sealed-beam headlights, laboratory ware, and bake ware are examples of borosilicate products.

D. Aluminosilicate glass: This type of glass has aluminum oxide in its composition. It is similar to borosilicate glass but it has greater chemical durability and can withstand higher operating temperatures. Compared to borosilicate, aluminosilicates are more difficult to fabricate. When coated with an electrically conductive film, aluminosilicate glass is used as resistors for electronic circuitry.

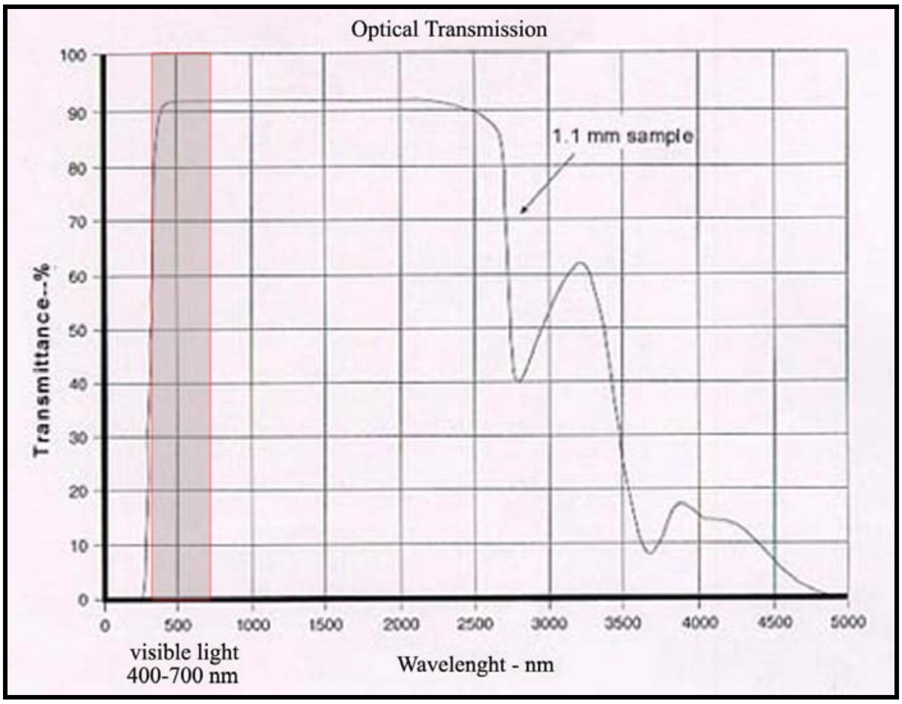


Fig. 2 2 Soda Lime Glass Light Transmission Chart A
Source: www.cmog.org

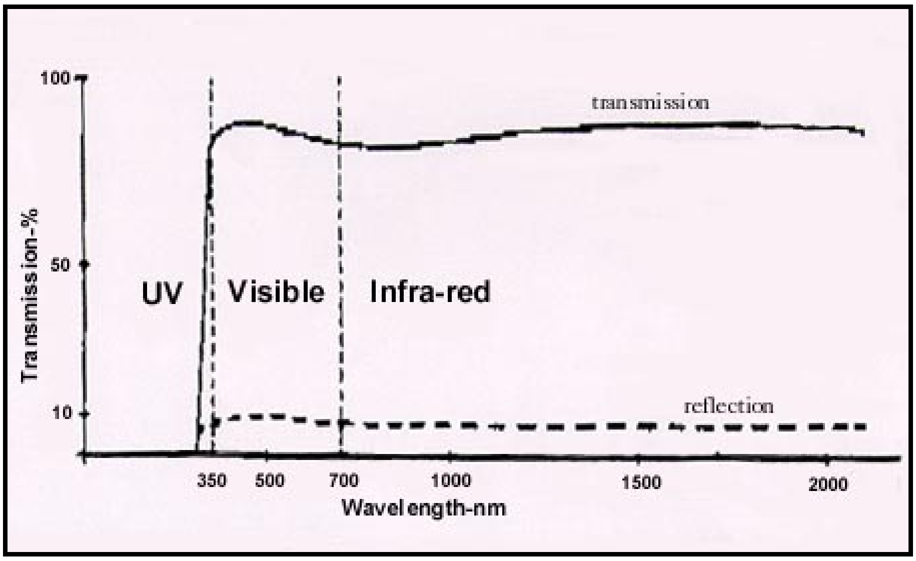


Fig. 2.3.Soda Lime Glass Light Transmission Chart B
Source: www.cmog.org

E. Ninety-six percent silica glass: This type of glass is a borosilicate glass, melted and formed by conventional means, then processed to remove almost all the non-silicate elements from the piece. By reheating to 1200°C the resulting pores are consolidated. This glass is resistant to heat shock up to 900°C.

F. Fused silica glass: This type of glass is pure silicon dioxide in the non-crystalline state. It is very difficult to fabricate, so it is the most expensive of all glasses. It can sustain operating temperatures up to 1200°C for short periods.

2.3.2. Structure

Other than the basic frame usage which is formed by an assembly of frame unit around the perimeter of glazing, the most commonly used and industrialized glass glazing type is that glass curtain walls. Curtain walling is a form of vertical building enclosure, which supports no load other than its own weight, that of ancillary components and the environmental forces which act upon it. The classification of types of curtain walling varies but the following terms are commonly used: “Stick, Unitised, Panellised, Spandrel panel ribbon glazing, Structural sealant glazing and Structural glazing”.

2.4. Classification of Glass Glazing System Types

Glass glazing system types classified as according to their “number of layers, their form and their function”.

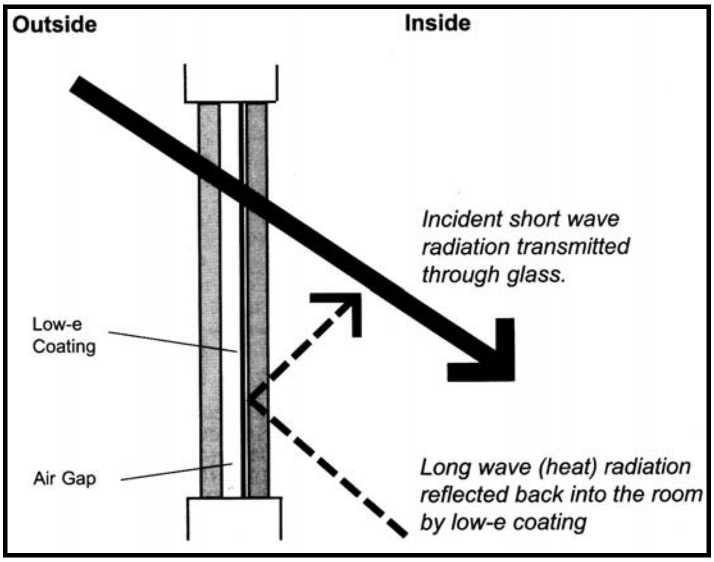
2.4.1. Classification According to the Number of Layers

A glazing system affects a number of factors essential to the comfort of the user. Therefore design must take into account the building user. Common glazing material; glass has developed its properties, varied in size and type. Common types of glazing systems used can be listed as:

- single layer,
- double glazing,
- triple glazing,

- double glazing with low-e coating,
- double with inert gases.

Traditional single pane glazing used for years to provide light and ensure transparency in order to make a connection between two sides of the pane. Relative to all other glazing options, single-glazed with clear glass allows the highest transfer of energy (i.e. heat loss or heat gain depending on local climate conditions) while permitting the highest daylight transmission. It's important to note that the frame choice can drastically affect performance.



2.4. Heat Loss Control With Low Emissivity (Low-e) Glass
Source: Wooley and Kimmins, 2002

Double and triple glazing systems evolved to conserve energy in buildings. Double-glazing, introduced by 1940s, compared to single glazing, cuts heat loss in half due to the insulating air space between the glass layers. This thermal buffer zone reduces heat losses and facilities passive heat gains from solar energy. Where the intermediate space is linked with the outside air, the windows in the inner skin can be opened even in buildings exposed to strong winds. This ensures a natural form of ventilation and nighttime cooling of the building (Detail, 1998-3).

According to British Research Establishment tests, which are made by an initiative for profiling the material database, show that heat losses are significantly reduced by double-glazing, compared to single glazing. Triple glazing effects a greater reduction in losses, and low emissive glazing gives further reductions in heat loss, with low-e coated double glazing being equivalent to triple glazing (Wooley and Kimmins, 2002). Besides the technological advances in multiple glazing systems, coatings for various aims used between double-glazing and inert gases used in cavity, to improve their efficiency For instance, Argon and Krypton are both inert gases and they are heavier than air, resulting in a reduction of convective heat transfer between panes of glass.

Glazing system			Thermal transmittance U-value		
			Sheltered	Normal	Severe
Single			5.0	5.6	6.7
Double	Air space	3mm	3.6	4.0	4.4
		6mm	3.2	3.4	3.8
		12mm	2.8	3.0	3.3
		20mm (or more)	2.8	2.9	3.2
		12mm low-E	1.7	1.8	1.9
Triple	Air space	3mm	2.8	3.0	3.3
		6mm	2.3	2.5	2.6
		12mm	2.0	2.1	2.2
		20mm (or more)	1.9	2.0	2.1

Table. 2.3.Thermal Performance (U-value) in (W/m^2K) Of Various Glazing Types
Source: Wooley and Kimmins, 2002

In order to understand glazing and ensure its benefits in a project, designer has to know properties of glazing materials in brief. Glass has certain properties, which affect its performance in the spectrum of solar radiation. The solar radiation energy, which strikes to the surface of the glass, shows three types of behaviour; some goes straight through, some is reflected outside and some is absorbed by glass. Almost all the solar heat is carried by visible (%53) and infrared (%46) wavelengths of radiation. Absorbed radiation includes the longer wavelengths infrared that cause the glass to heat up, while shorter infrared wavelengths pass through into the building and strike objects, warming them up. Therefore long wavelengths of solar radiation (IR) transforms to shorter wavelengths (UV) after hit a surface inside.

Saving energy through out windows, which is partly succeeded by glazing, is an important issue. Thus, energy efficient glazing should allow solar heating in winter when overall heating demand is positive, and also should prevent unwanted heating in summer, when excessive solar gain may need mechanical cooling with consequent energy problems.

The measure of success in energy efficiency will change due to design in every building. For the buildings with complex energy management systems, it is impossible to assign every savings to windows, which make up one part of an integrated system.

2.4.2. Classification According to the Form

Glasses classify as "flat glass, bent glass and block glass" according to their form. Flat glass is the group that is used the most widely in architectural applications. It includes sheet glass, plate glass, float glass and rolled glass. All kinds of industrial flat glasses are obtained with two main glass production methods, which are float and rolled.

According to Türkseven (1996), the common glass type that is used today is the float glass. This high quality type of glass is produced by floating the melted glass on a tin solution. By using this method, the amount of energy required reduces. Besides that, this type of glass has put an end to all other flat glass manufacturing methods. Float glass can be evaluated in two groups: "clear float glasses and coloured float glasses".

Clear float glass is used in areas where the criterion of high light transmission and visual quality are important. The important advantages of float glass are its high optical quality and admittance of 90% of the visible light. Thus, it decreases the artificial lighting costs by an important ratio (Lof Glass, 1990). In contrast with clear float glass, coloured float glass is used in areas where high light transmission is not very important but the control of solar heat gain and the emphasize of colour on the building as an aesthetic element is necessary (Akçakoca, 1996). Coloured or clear float glasses can be used for different purpose in buildings by using bending, coating and tempering processes.

2.4.3. Classification According to the Function

Türkseven (1996) classifies glasses according to their functions as “glasses for sun and climate control, glasses for building safety and security and decorative glasses”.

2.4.3.1. Glasses for sun and climate control

As Türkseven (1996) explained; the solar control for a building must be considered together with the window area, orientation, shading devices and the selection of the appropriate glass. The solar control glasses can be classified in four main headlines: “body tinted glasses, coated glasses, insulating glass units and spandrel glasses”.

A. Body tinted glasses: Body tinted glasses are obtained by adding colour-giving materials to the glass mixture. These types of glasses decrease the amount of visible light as it is absorbing the sunlight. The colour darkens as the thickness of glass increases. In this respect, glasses have to be used at the same thickness over the entire façade to ensure a homogeneous appearance. Body tinted glass is less reflective but more absorbent than clear float glass. Beside this, heat-treating process has to be applied on to the body-tinted glass to prevent its breakage due to thermal shocks, while clear glass does not require such an extra treatment.

B. Coated glasses: These types of glasses control sun by reflecting a considerable amount of sunbeam with their coating. Solar control performance of these glasses is better than the body tinted glasses. When coated and body tinted glasses combined with each other the variety and performance can be increase. Coated glasses can be examined in two main headlines as “reflective and low-E” coated glasses.

a) Reflective coated glasses: Reflective coated glasses are obtained by applying of metal-alloyed reflective coating on one side of clear or body-tinted glass. If it is coated during the float process, then it is called “on line”. In another way, if it is coated after the process, it is called “off-line” coated glass. It is important to protect the coated surfaces against direct sunlight. The reflective glasses have higher solar control performance and larger product and colour variety in comparison to body-tinted glasses.

They reflect back some of the incident sunlight and reduces the cooling costs of inner spaces. However, these glasses decrease the amount of visible light as they beams that strike the glazed surface. In addition to that, it is not good to use reflective glass in cold climates under these because reflecting back the light increases the heating expenses.

b) Low-E coated glasses: These types of glasses are one of the most recent developments of solar control and energy conservation. Low-Emissivity glasses are obtained by the application of a very thin metal coating directly either on glass surface or on plastic film. The most important characteristics of this kind of glass are to provide sun and climate control while admitting most of the visible light in. According to Mays (1989), Low-E coatings may be divided into two categories as “soft and hard”. While soft coating is obtained by sputtering of a thin layer of silver or metal oxide on glass surface; hard coating of this kind is obtained by the application of reflective and ultraviolet resistant film between two layers of glass during production.

Low-E coated glasses decrease the amount of heat transfer and they increase the R-value of glazed units. They reflect rather more but absorb more solar energy, half of which tends to be reflected back into the internal space thus causing more efficient warming. Such coatings reduce heat loss; by reflecting back the heat, which had turned to longwave after hit an indoor element. Low-E coated glasses let in a reasonable amount of solar gain, and are suitable for climates with both heating and cooling concerns. Low solar gain Low-E glazing is ideal for buildings located in cooling-dominated climates (www.efficientwindows.com). Therefore designer should be careful about the usage in hot climates and south facing buildings.

According to Fisher (1985), Low-E coatings do not only transmit or reflect different wavelengths in the solar spectrum. Manufacturers can tune the coatings to transmit different amounts of a given wavelength. For instance, Low-E coating will admit some shortwave infrared heat along with the visible light in cold climate residential buildings where heat gain is desired. However, in office buildings or in structures in warm climates where heat gain is undesirable a thicker coating will reflect most of the shortwave heat although at the expense of some of the visible light.

C. Insulating glass units: The standard insulating glazed units were consisting of two or more glass pane with an air space between, isolated from humidity in the assembly phase. However, today it is possible to manufacture insulating glazed units with three or more plates that some of them modified with Low-E coatings. These plates combined with either air or gas filled spaces and this increases the thermal performance of insulating glass greatly. According to Lof (1986), in an insulating unit, the thermal heat transfer through the units occurs in three forms: "conducted energy, convected energy and radiated energy". In other words; solar heat transferred by conduction, convection and radiation. Heat transfer by conduction between glass panes is commonly prevented by a surrounding component. Poli Vinyl Butinal (PVB) thermally breaks the heat transfer, therefore prevents heat loss.

Thermal efficiency of an insulating unit depends on the width of the airspace between glass panes, the property of the used glass and also the properties of the gases filling up this space. The airspace between panes of glass is called as cavity. The argon and krypton gases, which are used in cavity, provide better insulating than air infill. Because these gases that are inert, decrease the thermal heat losses of the glazing units, increase their R-value. They are also more intensive. While argon is especially preferred, because of its cheap cost; some companies try krypton or sulfur hexafluoride because of its effectiveness.

Insulating glass units also give successful results in sound control by the way of leaving a space between the glass panes to dampen the sound. The effective parameters in sound insulation are the thickness of used glass and the width of the space left between them (cavity).

D. Opaque glasses (spandrel glass): Opaque glasses use to ensure a colour unity in front of the parapets of the buildings and also to control the undesired effects of short wave ultraviolet rays and the excessive heat gain created by radiation. The glasses can be classified as "furnace-painted glasses, silicon based coated glasses, polyethylene or polyester film coated glasses" (Akyürek, 1993).

2.4.3.2. Glasses for building safety and security

Ordinary glasses are not resistant to thermal tensions and strikes, they can be easily broken and they have no fire safety. Today glass can be brought to a more secure condition against many effects with the under various processes of current technology. Glasses for building safety and security can be classified as "heat treated glass, tempered glass, laminated glass, wired glass, alarm glass and fire resistant glass".

A. Heat-treated glass: Solar control glasses absorb a considerable amount of energy and then they warm. If glass cannot receive the solar energy to the some parts of it then there will be a tension difference between the lighted and shaded parts on the same glass surface. This may cause glass to break into pieces which is used widely on the exterior walls of the buildings. So that, "heat strengthening" method has to be applied on glass to prevent this hazardous problem. This process is based on applying a pre-tension to glass surface by cooling it with blowing fans after it reached a certain temperature. Heat strengthened glass also gain resistance against thermal tensions and decrease the breakage risk. In another words, this method increases glass resistance almost twice. However these glasses are irresistant to the strong effects and break into sharp and large pieces so that, these glasses are not accepted as ideal safety glasses.

B. Tempered glass: The principle of obtaining tempered glass is same with heat-strengthened glass except the fast cooling of tempered glasses. Tempering process provides glass four or five times more resistance and glass become resistant to the stroke effects or thermal tensions and fall apart into very small pieces, which are remain in the frame and do not harm anybody. Tempering process provides the glass a waved surface. Once the glass is tempered, it is impossible to cut or make changes in size.

C. Laminated glass: This type of glass is obtained by uniting two or more glass panes with plastic based transparent layers in between them under a certain temperature. If laminated glass is composed of two layers of glass and one layer of plastic sheet between them, it can be used as "safety glass" against breakage. The resistance of laminated glass unit increases as the numbers of glass and plastic layers increase. As Krewinkel (1998) explained, the laminated safety glasses retain an adequate residual structural strength and dampen the noise acting as an acoustical barrier as a result of the strong elastic bonding of the PVB film. However the amount of light transmission property is not very different from the ordinary glass. In addition to that, while laminated glass is resistant to spot effective breakages, tempered glass is more successful to meet the surface effective strokes.

D. Wired glass: Wired glass is produced by sandwiching steel wire between two glass layers and obtained by the rolling process. Wired glass is resistant to stroke, fire and pressure effects. It breaks into the pieces against the effects of stroke and heat, but does not spread out because of the wire net in it.

E. Alarm glass: Alarm glass is an improved version of wired glass and used against attacks. This type of glasses obtained by placing 0.1 mm thickness of wires in glass to form an electrical circuit. This circuit is broken setting of an alarm when the glass is broken.

F. Fire resistant glasses: Fire resistant glass has 60 and 90 minute fire rating. It encapsulates a transparent polymer gel between two layers of tempered glass. As Fisher (1985) explained, when the temperature in a room reaches about 700^0 F, the gel separates from the glass surface exposed to the fire; at about 800^0 F to 900^0 F. The tempered glass shatters and the gel turns opaque and its water content evaporate a process that absorbs a great deal of heat and thus protects the other layer of tempered glass.

2.4.3.3. Decorative glasses: Glasses can also be used as a decorative element by the help of its aesthetical appearance. Decorative glasses can be classified as “mirror glass, obscured glass and glass blocks”. Obscured glass is also obtained by methods of “patterning, surface treating and printing” application way. The desired texture can be given to them with these methods.

2.5. Environmental Control Criteria Of Glass Glazing Systems

Glass is the most practical and common used material among its alternatives because of its work performance and maximum use of area on the buildings. The application of glass as a building skin increases the inner space utilization because of providing economy on climatization, which is an important management expense. Energy efficient houses with glass annexes are good examples of this kind of usage.

The properties of glass can be varied and regulated by modifying the composition and production techniques as explained in previous chapters. Glass coverage has to carry the responsibilities of building; to make the buildings sheltered for every environmental effect and to control the effects of light, vision, solar heat, wind, physical and chemical corrosion, noise, robbery beyond its traditional use as window. In the further sections, glass performance assessed by four basic environmental control criteria in terms of constructional physics: optical, thermal, acoustic, and safety.

2.5.1. Light Transmission Control

Light and vision control are important criteria for glass glazing that is used on building skin. While low light transmission cause insufficient interior illumination and thus, require artificial lighting even in the daytime; the high light transmission cause excessive brightness and it destroys the homogeneous appearance of glazed building. The selected glass should balance the negative effects with the optimum desired light amount. Glass can also change colour and modify the transmission of light; and with the use of liquid crystals, it can be made transparent or translucent.

	Heat Transmission Coefficient			**Day Light Transmission**	**Solar Energy Transmission**
PRODUCTS / cavity	6mm	9mm	12mm		
Isıcam Standard	3,3	3	2,8	78%	70%
Isıcam Comfort	2,5	2	1,7	70%	46%

Table 2.4. Heat Transmission Coefficients And Day Light And Solar Energy Rates Of Glasses
Source: www.yasasan.com

When a beam of light falls on the surface of glass pane, some of the light is reflected from the glass surface, some of the light passes through the glass, and some is absorbed in the glass. While the measure of the proportion of light reflected light from the surface is called “reflectance”, the measure of the proportion absorbed is the "absorptance" and the measure of the proportion transmitted is the" transmittance". Each quality is expressed as a fraction of the total quantity of light in the beam. If the intensity of the beam is represented by the numerical 1, reflectance by R, absorptance by A and transmittance by T, intensity may be expressed as follows: $R + A + T = 1$ (www.cmog.org)

Reflectance from a glass surface can be regulated by coatings applied to the surface. A metallic coating will produce the maximum reflectance. Other coatings show selective reflectance, such as the heat-shielding glass that reflects a high proportion of infrared but transmits a high proportion of visible light. Still other coatings eliminate reflectance almost completely such non-reflective coatings are commonly used on lenses (www.cmog.org).

Optical properties are concerned with the behaviour of glass toward light, the visible spectrum that extends like the rainbow from violet on one end to red on the other. However optical refers also to behaviour towards the infrared and ultraviolet regions of spectrum. The greatest physical difference between these bands of energy spectrum is in the wavelength. Ultraviolet waves are shorter than visible waves and visible waves are shorter than infrared. All of them are so short that extremely small units are used in measuring them (www.cmog.org).

2.5.2. Thermal transmission control

Solar energy control is another responsibility expected from glass. An efficient glass should prevent excessive heat gain as admits the maximum amount of light in. According to Demetri, (1996), significant energy savings are more likely to come from new glazing technology, and the use of ventilated cavities within triple glazed systems, and improvements to framing systems. With the improvements in glazing technology and the decrease of loss to minimum through connection points make glass to reach an ideal performance.

As it is known, the solar energy strike to the glass surface is reflected back, admitted it, or is converted into heat as being absorbed by glass. Low-E coatings may keep the longwave radiation after transmitted through glass, thus may protect heat loss.

Commercially available insulating glass glazing units' thermal transmission coefficient chance between 1.7 / 3.2 W/m^2K depending on the temperature (Isıcam). As Türkseven (1996) explained, the light transmission and solar heat transmission are not directly proportional with each other. Light transmission rates of the glass panes are given for the visible light spectrum, where the solar heat gain is calculated from the whole spectrum. The wavelengths of visible light and infrared light, which are both responsible for the heating, are different from each other in the solar spectrum. As the ratio of the light transmission coefficient rises, the success of the solar control glass increases along with it.

Glass is the leading element in insulation and energy conservation. Developments on photochromic, thermochromic and electrochromic glass plates showed that, improved glass can adapt itself according to the climate and air conditions like a chameleon. Photochromic glass is used in solar panels for the conversion of sunlight into electricity. Electrochromic glass can be made to change from clear to coloured (and also opaque) when a mild electric current is applied to it. It provides all kinds of insulation perfectly and presents the best comfort to the user at optimum (Demetri, 1996).

2.5.3. Acoustical control

Light structures, such as glass glazing systems, let sound to pass easily through building when compared to the heavy and load bearing walls. So that acoustical insulation is another responsibility that glass has to provide as a building skin. There should be precautions not only taken by glass but also taken by frames and installation elements. The practical precautions that can be taken by glass can be listed as below:

- to leave a space between the glass panes to dampen the sound and to coat the sides in between by sound absorbing material.
- to use insulating glass units and laminated glasses combined with special resins
- to increase the thickness of glass, by using multilayered insulation glass and pvb combined laminated glass (Lof, 1987).

The thickness of glass used and the width of the space left between them are effective parameters in sound insulation. As these parameters increase the sound insulation value also increases, up to a definite value. Approximately 20cm cavity between panes of 6mm ordinary glass provides up to 41dB reduction, which saves the best reduction performance. Addition to the list of improvements given above, particular gases (SP6) can be useful to dampen sound as an infill. In section 5.1.3. acoustical performance of glass types (sound reduction index) are given as a table.

2.5.4. Safety and security control

Glass takes the responsibility of providing a safety and security line for the buildings. Safety and security properties deal with the action of forces on a material and the effects that these forces produce within the material. There are three types of forces to be considered: “a tensile force exerts a pull on the material”, “a compressive force acts to squeeze the material” and “a shear force acts on the material in a manner similar to a pair of shears to slide one part of the material in one direction and another in the opposite direction”. Tensile forces, which are the most important in glass, give rise to tensile strain within the glass and glass breaks only from tensile tension. (www.cmog.org).

Mechanical hardness of glass is a complex phenomenon that is not completely understood. It can be measured by three methods: “scratch, penetration and abrasion”. Strength of glass is only slightly affected by composition but is highly dependent on this surface condition. Strength is measured in the laboratory by applying a bending load to a bar of glass until the bar breaks. The break originates in the lower surface since glass always fails from tension. (www.cmog.org).

Especially tempered and laminated glasses resistances against strokes and thermal tensions are high. If laminated glass is composed of two layers of glass and one layer of plastic sheet between them, it can be used as safety glass against breakage. The resistance of laminated glass depends on the numbers of glass and plastic layers. Fire resistance of glass is also important in terms of security. Especially wired glass and glass block have been used for years for fire resistance. But the choices have been increased along with the improved technology.

Glass can also be strengthened by several ways of chemical means. One of the most commonly used requires an exchange of ions in the glass surface and another method is laminate strengthening process. In the first method, the glass is immersed in a molten salt both and large ions migrate into the surface, replacing smaller ions. This action crowds the surface and produces compression. In laminate strengthening method, the product is made of a sandwich glasses and the inner glass shrinks more on cooling, causing the outer layer to be put into compression (www.cmog.org).

Pre-stressing process of the glass is often done by thermal tempering, which causes a wavy appearance on the surface of the plate. It is possible to temper the plate partially. But semi tempered glasses are out of the security glass list, because of the big plates obtained that can be harmful when broken. In the tempering process, first the glass is heated to the point of almost sagging under its own weight, and then it is chilled suddenly. A large temperature difference exists between the surfaces and interior because of low thermal conductivity. When pre-stress is applied there will be an equal amount of tension somewhere to maintain the balance. This tension is buried in the middle of the glass where it is safe from damage protected by the outer skin of compressed glass (www.cmog.org).

Products	Day Light		Solar Energy					Thermal Transmission Coefficient (K veya U)			Relative Heat Gain (W/m^2)
	Transmittence %	Reflectance Outdoors %	Reflectance Outdoors %	Absorbition %	Direct Transmittence %	Total Transmittence	Shading Coefficient	ISO 9050 W/m^{2}K	ASHARE (W/m^{2}K)		
									Winter	Summer	
ISIcam	78	14	11	29	60	,69	,81	2,8	2,8	3,2	533
ISIcam S	73	11	17	38	45	,54	,63	1,8	1,8	1,9	414
ISIcam ULTRA	38	9	8	62	30	,42	,49	2,8	2,7	3,2	332
ISIcam ULTRA S	36	9	10	67	23	,34	,40	1,8	1,8	2,0	268
ISIcam konfor	70	13	24	36	40	,46	,54	1,7	1,7	1,8	355

Table.2.5. The Comparative Performance Values Of Isıcam Samples, 2003
Source: www.yasasan.com

Chapter 3

INVESTIGATION OF THE INFLATABLE PILLOW SYSTEMS

Glazing which has been discussed in previous chapter is one of the major components of the buildings. Traditional glazing commonly depends on the use of glass and its properties. In order to upgrade its environmental properties glazing systems are evaluated. However contemporary architecture exploits existing or new materials with increased performances. Plastics, architectural fabrics and their combinations are developed in terms of cladding that can be determined also glazing in specific cases.

Plastics which consist of a combination of various polymer types, did gain an increasing importance as a building material in contemporary architecture. They have found a wider application area than before. Technological improvements and new processes in industry upgraded plastics, in terms of their properties and performance. They have reached to the surface qualities of glass. Form free and lightweight natures of the plastics are two basic advantages against traditional glazing (Detail, 2002/12). But, true potential of the plastics is seldom exploited in architectural applications. Since the 1980's, transparent and diaphanous plastic semi-finished sheet products have been used for the skins of many buildings, allowing light to enter by day and to radiate out at night.

Architectural fabrics used also as a cladding solution in specific buildings. Architectural fabrics and membranes are produced in various types with special coatings to provide better environmental control properties. Coated fabrics have inherent strength sufficient for them to be used as self-supporting, pre-tensioned roof membranes.

The basic need for a membrane application is the need of high light gain into the structure. The need of light transformed membrane cladding to glazing in many cases. However, light transmission values achieved with fabrics are very low. Therefore, in terms of a better light transmittance the ideal solution would be a clear foil without fabric support. Furthermore, due to low thermal performance of membrane structures, multilayered systems are formed with inflated structures. As Watts (2001) explains that air supported fabric roofs are used to cover large areas that require a degree of transparency together with high thermal insulation. Development of pneumatic systems and other structural systems has improved the inflatable applications. Festo Seminar Hall in figure 3.1. , is a new generation inflatable structure where the human analogy is made by extrapolating tendons and muscles and where intelligent pneumatics are used. In the line with these developments, inflatable systems are still the subject of researches with the awareness of the performance of inflated structures depends on the usage, material property and number of layers.

Today Ethylene Tetrafluoroethylene (ETFE), which is a polymer, assumed a major importance in membrane and inflatable constructions. It can be translucent or transparent and it can also be coated. Because ETFE foils have no inner fabric layer to give them strength, they are not capable of covering large areas unsupported. Therefore, to form large spanning areas, the foil must be supported by a sub-structure of arches, beams or cables, which divides the foil into panels. Inflating multilayered ETFE membranes are relatively new solution in terms of glazing.

Fig. 3.1. Festo Group Inflated Seminar Hall Designed with Human Analogy
Source: www. festo.com

3.1. Definition Of Inflatable Pillow System

The Inflatable Pillow System (IPS) developed for the roofing and cladding applications. It is a glazing solution for those claddings that have been used for a decade in architectural applications. Instead of other glazing systems like curtain walls and rooflights that are made of glass and glass glazing systems, this chapter is objected to investigate inflatable pillow systems and its potential. Inflatable Pillow Systems are principally pneumatic structures taking name from their pillow form. IPS can be defined as *"Pneumatically Supported Multilayer Membrane Systems"* made of a modified co-polymer called ethylene-tetra-fluoro-ethylene (ETFE). Robinson- Gayle et.al. describes the ETFE pillows as; it is a multilayered system that consists of several layers of ETFE foil which is heat-sealed and clamped in a frame in order to top up with a small pump intermittently.

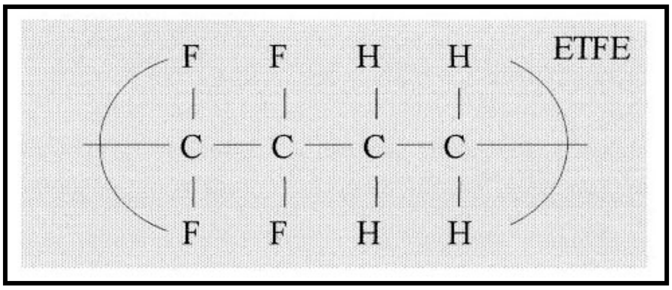


Fig. 3.2. ETFE Chemical Formula – (ethylene- tetra fluoro ethylene)
Source: www.texlon.ch

IPS inherits the common characteristics of the inflatable systems, which is a part of pneumatic systems. Besides this, because of the glazing material is a membrane it has the properties of membrane structure. Because of the lightweight nature of the foil, this system can be defined as among other lightweight systems. Furthermore, this system has been determined as an energy efficient cladding technology or as the climatic envelope according to its environmental properties.

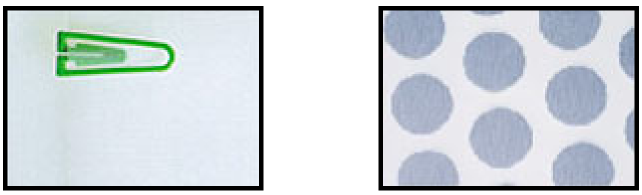


Fig. 3.3. Transparent and Dotted ETFE Sheets
Source: www.covertex.com

ETFE foil that is preferred for pillow construction is a synthetic sheeting or film; a new generation membrane. Isotropic film or sheeting exhibits a tension-stretching behaviour that is virtually equal in all directions. Of the many kinds of synthetic sheeting that are available, two groups of thermoplastic materials are of special importance in membrane construction: fluoropolymer sheeting (mainly ETFE and THV) and polyvinyl-chloride sheeting (PVC) (www.covertex.com).

Thin fabrics generally don't provide adequate thermal and sound insulation. But multilayer systems can make it possible. In other words fabric systems that have appropriate thermal insulation and light transmittance, could be possible with only pneumatically supported multilayer membrane systems, made of ETFE. However these pillow systems could be assembled with another type of ethylene foil, PTFE that have been previously used for several applications in architecture. PTFE is generally known as Teflon trademark. It has been also used as a topcoat on architectural fabrics.

Among many synthetic sheeting ETFE foil has better biaxial tensile properties. It is an almost isotropic film that shows virtually same structural behavior in every direction, while many of the woven fabrics are considered as anisotropic materials. ETFE foils that are manufactured in roll of sheets cut out to form pillows with special methods. IPS can be assembled between two to five layers. Multilayered foil joined together at the edges and inflated to form a sealed pillow. Held within a support frame, these panels can be used as glazing. The internal pressure pre stresses the foil and enables it to resist the loads as wind and snow.

In various sources it can be seen that the synonym of the term pillow can be replaced by cushion, which is not wrong. But in present study, the system will be called as pillow systems, instead of inflated cushion systems.

3.2. Evolution Of The Pillow System

Inflatable pillow system applications have been effectively impressed by various constructional improvements. Although ETFE has been known for more than 50 years, it has not been fully exploited by the construction sector. Developments in structural systems like tension structures and pneumatic structures have affected pillow systems. Researches on architectural membranes have resulted as better materials, and systems, which are essential for pillow system. Those innovations motivated air supported and inflatable structure applications mostly in 70s. Furthermore, in the 1960's and 70's plastics and other synthetic materials did gain a certain importance in building, but they soon left their place as a result of their inappropriate application or technical deficiencies.

In other words, the evolution of the recent system depends on developments of many fields related with engineering and material sciences as briefly explained in the domain of the study.

One of the early examples of the foil pillows as transparent cladding was on the giant space frame at Expo’70 in Osaka, Japan. The structure designed by the architect Kenzo Tange and engineer Prof. Kawaguchi. These pillows were made from polyester foil, which has excellent tension properties but low tear strength and grades in sunlight. Since then, fluoropolymer foils have been developed with better properties.

Dr. Herbert Fritz who is a retired polymerchemist of Hoechst AG. introduces himself as the inventor of the ETFE in 1976. He explains that the basic idea for producing the film was to use it as a solar collector and later on as a long lasting membrane material for buildings. (www.eden-project.co.uk)

In 1977, engineer David Geiger began investigating pillow systems as solar control systems. He had studied the use of three layer membranes as solar collectors. The upper and middle membranes are both split: the south facing half of the upper membrane is transmissive, the north facing half reflective and the south facing half of the middle membrane reflective, north-facing half transmissive. During the summer the solar cell is closed and the air layer between membranes is inflated so that the middle membrane rests against the upper membrane, making a continuous reflective surface that reduces heat load. During the winter the cell is open; the middle membrane rests against the lower membrane, and solar energy absorbed by the cell can be radiated or conducted to the space below.

In addition to those developments, pillow systems have been used for optimizing internal climate control. For the Florida Junior collage at Jacksonville, similar solar cells were proposed to dehumidify interior air. Air warmed by the cells is passed through silica gel, where it losses enough moisture that, when mixed with air intake the desired moisture level is obtained. The silica gel is dried by additional hot air from the solar cells, which is pumped through the gel and evacuated outside. According to Robbin T. (1996) such opportunities to use membrane cells as heating and cooling machines have been neither fully tested nor implemented.

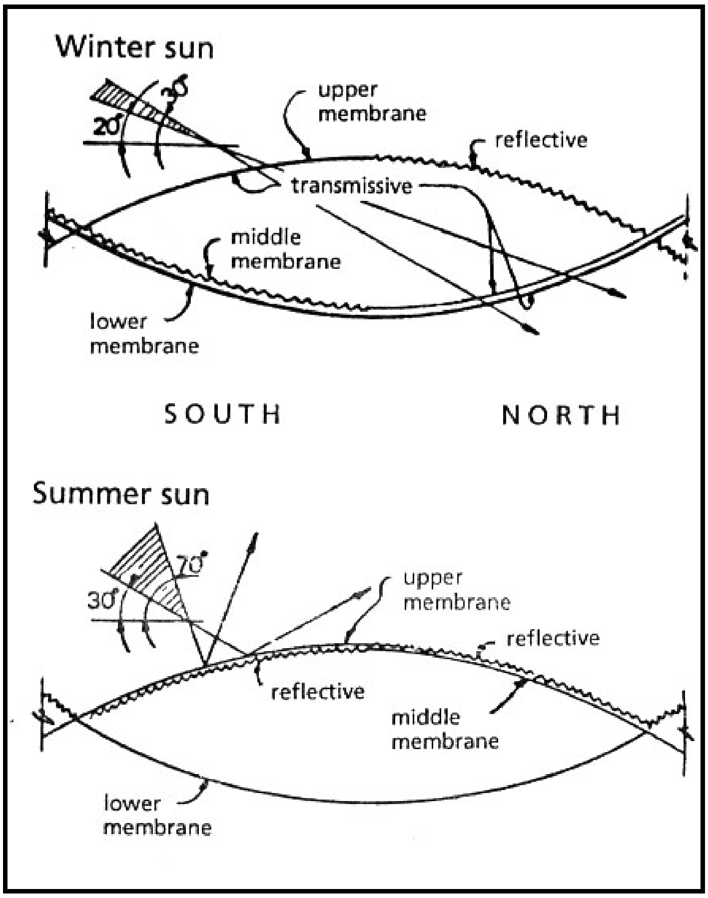


Fig. 3.4. David Geiger’s Air Pillows As Solar Cells
Source: Robbin T., 1996

In 1981, in a collaborative project, Buro Happold, Arne Fullerton and Frei Otto developed a design using inflated cushions of a fluoro-polymer foil such as a cladding to a 14 ha air supported structure top enclose a township at 58 ^{o} N in Alberta, Canada. Since that time foil pillow systems have been used successfully on projects worldwide.

Architect Volker Giencke’s greenhouse structure in the botanical garden of Graz University (1982-93) is also a forerunner of this line of development. It comprises an aluminium structure, the arches of which follow the lines of thrust, and it is covered with multilayer acrylic sheets curved in two planes. Transparent acrylic panels with double curvature used as glazing in order to improve thermal insulation. Hollow structural sections are used as heating radiators. All four glasshouses share the same technology and control systems. The parabolic structure is built in aluminium supported with steel cables. Double curved acrylic sheets achieve a 98 percent light transmission, the highest so far achieved internationally (A.Review, 1996/10)

Fig. 3.5. Graz Greenhouse by Volker Giencke
Source: Architectural Review, 1996/10

In 1983, Foiltec Company designed a zoo in Arnheim, Holland, which was created as the only self-sustaining man made ecology. This early IPS project was a cable suspended structure. Arnheim Zoo, which is also known as the Burger Zoo, is one of the longest lasting ecological systems to function trouble-free. Foils are chosen to create the ideal roofing and cladding system for simulated environments, allowing a large section of the UV (ultraviolet) spectrum to be transmitted.

Fig. 3.6.Arnheim Zoo Roof
Source: www.foiltec.com

Since it has been presented as a zoo and botanical garden glazing system at the beginning of 80's, IPS has proven its performance in many cases with various needs. Framing and clamping systems, has developed for bespoke systems, which has accelerated its commercial applicability as glazing or a total building envelope. It has been subsequently used in various buildings predominantly in the UK and Germany.

3.3. Components and The Structure Of IPS

IPS structure consists of pneumatic pillows re-strained commonly in aluminium extrusions and supported by a lightweight structure. The pillows are manufactured from between two and five layers of a modified co-polymer called ethylene-tetra-fluoro-ethylene (ETFE). The pillows are inflated with low-pressure air between 200-1000 Pa (200-1000 N/m^2) to provide insulation and resist wind and snow loads. Therefore it's possible to investigate system in three sections, according to its components;

- Glazing, which is maintained by pillows,
- Frame structure and supporting elements,
- Other subsidiary equipments needed for inflation.

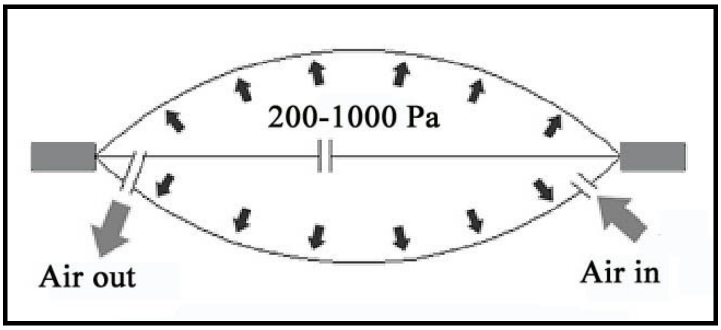


Fig. 3.7.Triple Layer Foil Construction Scheme

This cladding system comprises a number of foils of a UV stable fluoro-polymer ETFE welded into pillows. The pillows are restrained around their perimeter by aluminium extrusions, which are in turn fastened to a supporting primary structure. A pillow comprises at least two foils, however more foils can be added into the system to enhance the claddings' insulation properties.

The pillows can be fabricated in any size or shape with limiting factor being the wind and snow loads that the cladding has to resist. Pillows can be manufactured in large sizes and can span a much greater distance than conventional cladding technologies. This provides designers with the opportunity to integrate the design of the cladding with the primary structure, and develop aesthetics of simplicity and elegance.

According to Vector Company, (2002) the properties exploited from materials nature like toughness, high resistance to tearing, and ability to work harden over a 300-400 % elongation range means that system can naturally deal with very large deflections in the support structure. This has allowed the development of bespoke lightweight structures such as uni-axial cable nets and large-scale geodesics.

As the pillows are pneumatically pressurized the forces generated in the pillows by inflation and external loads such as wind and snow, have to be carried by the primary structure. The loads determine the size (the span) of the pillows and the amount of rise of the glazing. These in-plane loads are generally in equilibrium with only the normal component having to be engineered for. The perimeter structure however needs to be sized to accommodate these loads.

Fig. 3.8.Sky-workers in Eden Project
Source: Davey P, 2000, Equilibrium

This system can also accept virtually all building movements, and thus one can design structures, which have much greater deflections than other cladding technologies permit. Pillows confront some of the planeloads and wind load. Thus, their effects to the structural system are reduced which affects not only to the cladding or roof structure but also whole structure including the foundations.

As other cladding and glazing solutions in the market design and engineering of the pillow system is a very specialist area in terms of the materials' quality and performance. In order to have the most benefit of the system, and to ensure that the structural grid and cladding interface is optimised, designers and engineers should get an early consultation in the development of design phase.

3.3.1. Glazing (Pillows)

The performance of the IPS depends on the pillow form and the material used as glazing in the system. As determined before, ETFE is a thermoplastic copolymer derived from the polymerization of the Ethylene and Tetrafluoroethylene (Teflon®) monomers (www.crestcoating.com). This membrane material used for buildings is not a woven fabric but a foil; a polymer film sheet, usually formed into inflated pillows. Although investigated and used for several decades, foils have become truly useful for the first time with the introduction of an ETFE foil, a partly crystalline plastic.

Plastic sheeting, as used in architecture today, allows creation of the building skin that are unique in their permeability to light and UV radiation. ETFE has proved most effective in this context. Its extremely low weight (350 g/m2 for a thickness of 200 um), its high permeability to light, its great chemical resistance to acids and alkalis, its relatively long life (more than 20 years without significant change in its mechanical and optical properties) and its almost complete recyclability make fluoropolymer sheeting most valuable and economical building material. (Karsten, 2002)

To ensure that a thin membrane transmits the various directional loads to which it is subject solely in the form of tensile stresses and without folding, a prestressing process is necessary.

This can be achieved in two basic forms:

- Pneumatically Prestressed Structures,
- Mechanically Prestressed Structures.

Although there are several applications of EFTE foils, the present research is intended in pneumatically supported multilayer membrane systems made of ETFE foils. Pillow as glazing inherits the properties of ETFE material. Common material properties are given in Appendix A. ETFE sheet are tested by various institutions and special test laboratories. Results of similar properties may show differences in limits.

Because of the high strain characteristics of ETFE foil it is possible to install a flat unstressed membrane into a planar boundary frame and develop the rise of the pillow to approximately 10 percent of its span solely through elastic strain of the material under inflation. But that may not be appropriate for situation when a higher pillow rise is required to reduce stresses under load, or when the boundary frame is curved or warped (www.tensys.com).

In double or triple layered applications, pillow systems may affect the result of values. Although light transmittance values will remain same in similar applications thermal transmittance may change up to 20 percent due to frame design affected by ETFE sheets. Horizontal sheets are much more capable to insulate heat as shown in the figure below.

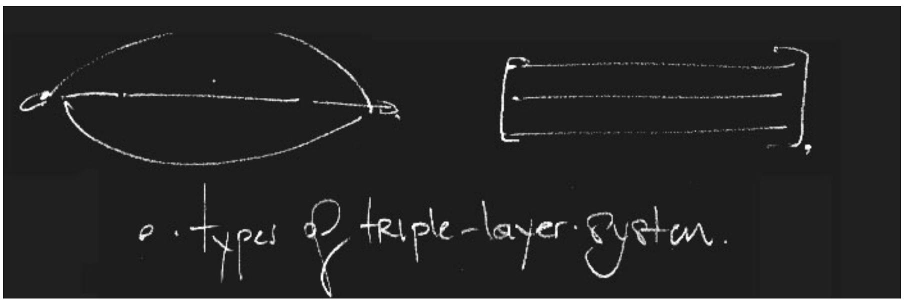


Fig.3.9. Pillow Form Differences Affect Thermal Performance

According to Skyspan, (2002) there are several different types which can be mentioned as transparent, opaque and printed. Naturally ETFE sheets produced clear. White and blue foils are produced in limited amounts. Other colored foils may obtained upon request. Common uses of triple layered pillow are, white clear white, white white white, white clear clear. Other alternatives are available related with the needs of design. Printed foils are used commonly for triple layered pillows with variable shading option. Prints can be applied as color or silver patterns.

An important point about the forming of the pillow structure is the load analysis and wind pressure tests. Under load analysis the variation of pressure within the pillow must be considered, especially for load cases with a combination of wind pressures and suctions. It can be specified either constant pressure, constant volume or constant mass of air within a closed cell during its 3D finite element analysis (www.tensys.com).

ETFE has an optimal welding property, but because of the excellent tear strength mechanical connection possibilities like sewing, clamping, nailing, riveting are compatible for stabile roof constructions. In membrane constructions welding capability of the fabric is a very important issue in terms of economy. When welding is not possible, membranes have to be joined by sewn seams or expensive metal joints. For instance another fluoropolymer film PTFE (generally known with its trade name Teflon) is used as coating on the top of architectural fabrics. But, its high melting point, which is 327^{o}C, makes welding process almost impossible for most of the applications. According to Nowofol Co. thicker materials suffer problems with the thinning of the foil near the joint. For this reason producers prefer to limit the thickness to less than 200 microns.

Inflation of Each pillow in Eden Project, which is 75m^2 at maximum, takes between 15 minutes to 3 hours to install. (www.arup.com) In the case of Festo HQ, Transition of the pillows takes 6 minutes to be fully completed. Inflation time of the pillows depends on the power of the inflation units and size of the pillows used.

Fig. 3.12. Elongation Tests of ETFE
Source: www.vector-foiltec.com

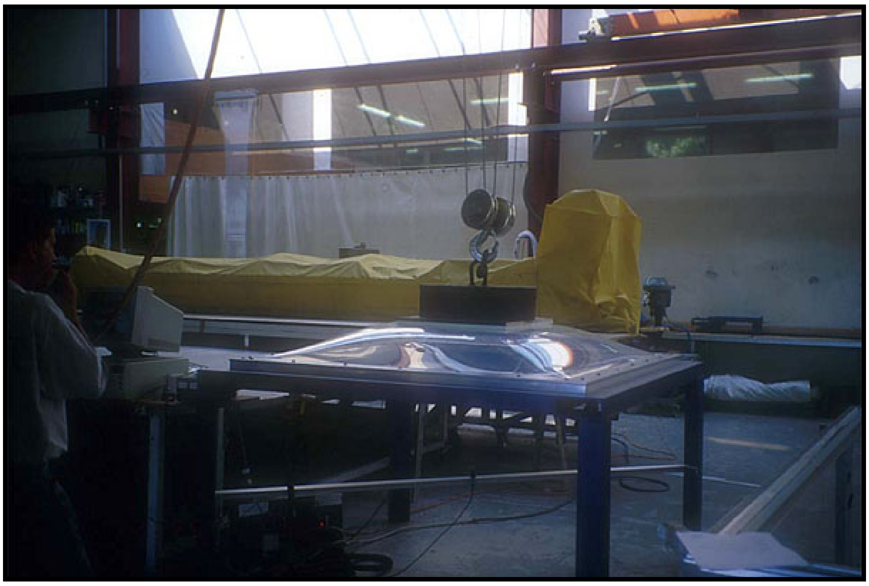


Fig. 3.13. Pressure Tests of ETFE
Source: www.vector-foiltec.com

3.3.2. Supporting Elements of IPS

Pillow structures consist of at least two membrane layers, with the intermediate space inflated to a slight excess pressure (usually about 200 to 1000 pascals) to provide stability. That obtains the structure to be very lightweight that shapes the structure underneath. Pillow systems with made of ETFE sheets are different than those of pneumatic structure, which have been used commonly in 70's. Typically system works similar to other conventional frame and clamping systems. The type of clamping mechanism varies but most commonly consist of special aluminium boundary profiles, which are supported by steel or timber substructures or cable nets. Like the most lightweight systems, the forces in the pneumatic system need to be resisted by a support structure. The resulting loads are a function of the shape of the foil and applied loads. However adjacent foils tend to balance out the loads generated by the shape of the foil itself, with the supporting structure needing to be designed to resist any applied loads such as wind. Thus, the underneath structure and perimeter structure has to resist the forces occurred by pillows and the lateral wind loads. This may cause the need for an extra support by cable in the center of the pillow construction. So that, in terms of a failure in the structure and unexpected increase in applied load for a short time, that may be useful for the structure and the pillows. According to Watts, (2001) a very light net integrated to design, often incorporated on the inner surfaace of the material to withstand very high snow loads. As shown in figure of the Westminster Chelsea Hospital Roof Detail, cables may be used under pillow structure connected to the clamps. Diameter of the steel cables may vary according to the need of the design.

Pillows, among the structure can be virtually manufactured in any size and the shape. Structure is not a dominant factor for the shape of construction. However the limiting factors of the pillow size is the wind and the snow. As the pillows are very lightweight structure should only need the be support its of weight. But like other lightweight systems, the structure is prone to deflection. The flexible nature of the system causes to absorb some of the structural movements by the pillows. In those cases, pillows work as movement joints that allow the entire structure move in limits without any collapse in the structure. According to the design this may be exploited by underneath structure. However applied loads such as snow, needs a special care in design of supporting structure. Although it can be carried by pillows, under excessive loads top layer may invert allowing all the layers act under in tension.

In view of the limited load-bearing strength of the membrane, the maximum span of a pneumatic element is about 4.5 m in the case of elongated forms and roughly 7.5 m for circular or square elements. Larger spans require additional support in the form of beams, trusses and cables or cable nets. The membrane material is not a woven fabric, which was previously used in inflatable structures. Therefore mechanical properties of the membrane need to be supported periodically according to the opportunities of design. ETFE foil is used commonly for its transparent nature as a cladding above cable structures. In case of Hampshire tennis court a uni-axial cable net supports 6000m^2 of white ETFE pillows. It has constitutes a huge glazing in order to take skylight in the form of cladding.

Fig. 3.14. Hellabrun Zoo - Lion Zoo
Source: www.pfeifer.de

In the case of lion house in Hellabrum Zoo, Munich, for instance the pneumatic elements are spanned between a prestressed cable net. The flexible nature of the pillows increase architectural applicability for non-planar applications. The usage of the pillow structure is like a high performance membrane cladding rather than a glazing. Another striking example is the Eden Project in England, where the domes, with spans of 130m at its maximum, consist of ETFE pneumatic elements of different sizes partly supported by a cable network. The Masaola Rainforest house in Zurich zoo has an arched roof with pneumatic elements up to 106m in length (probably the longest in the world) and spanning a distance of roughly 4m. Besides Masaola Rainforest House, at Kings hospital atrium 26m clear span is obtained with 3.6m wide pillows. In Magdeburg Leisure pool IPS used in 30m clear span without extra support. A good example of the use of ETFE membranes in the construction of the swimming pools can be found in the new arched roof over the modernized Moby Dick Bath in Rülzheim (Karsten , 2002).

Rather than the structural choice, system can be used in collaboration with any structural material that may hold the structure up. Clamps and frames that surround the ETFE pillow are generally made of aluminium and steel. Therefore frames may be connected to the load bearing elements of the structure.

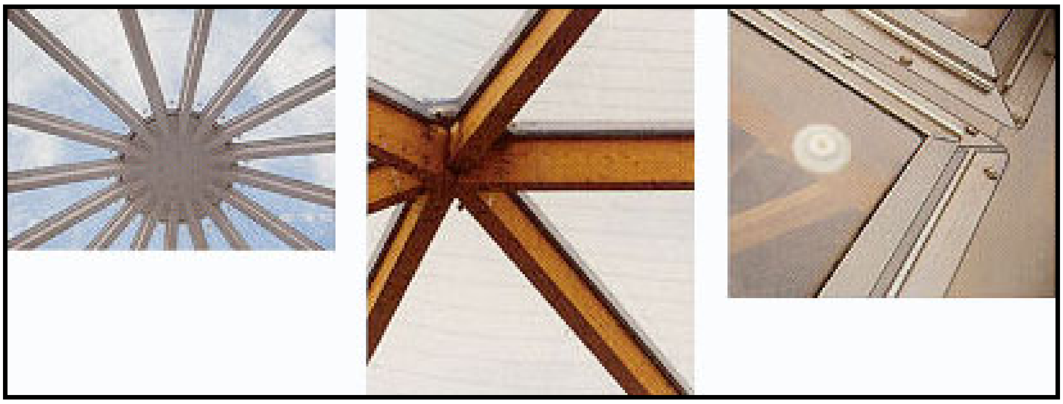


Fig. 3.15. Various Supporting Element Choices For IPS
Source: Texlon, 2003

Modular system of the IPS, reduces the initial installation cost, saves time in the construction site. In order to get excellent form-free application opportunities of IPS, envelope could be conceived in various frame sizes, which will affect production time and cost. ETFE Pillows can be tailored in any size and shape with limiting factor being the wind and snow loads that the cladding has to resist. It is also suitable for lightweight canopies and cantilevered applications.

According to Buitink-Technology, the profiles used are made of corrosion proof aluminium alloy. The sealing profiles that are UV and waterproof and weather proof retain their elasticity. In order to prevent corrosion designer should be aware of aluminium frames are capable of corrosion when connected to steel. To ensure corrosion proof nature, substructure should be stainless steel or properly galvanized steel.

3.3.3. Other Components of IPS

An inflation system is required to maintain the pillows at a constant pressure of between 200-1000N/m^2. This may achieved using centrifugal fans with backward curved aerofoil blades. These centrifugal fans with humidity controls and filters prevent moisture and dirt from entering to the pillows. The characteristics of such fans ensure a reasonably constant pressure over a range of air flow rates. This helps to ensure a fairly constant air pressure even when the flow rate increases to compensate for unplanned leaks. More complex centrifugal fans can also be linked to sensors that would allow the inflation system to vary the internal pressure of the pillows to handle with applied loads. According to Tanno, (1997) who was a Façade engineer of Buro Happold, air inflation is provided by means of low power electrical fans connected to the pillows via a network of flexible pipes. Fans are simple units consisting of a running fan and a stand-by fan. One of the motors is rated 220 Watts and is permanently on standby whilst the other, rated at 100 Watts, is switched on and off by a pressure switch connected to a reference pillow. The main blower is thus only operating for approximately 50 percent of the time with power usage being in the order of 50 Watts. Fans are normally equipped with a gauge and electronic switch that monitors air pressure in the pillows and allows the fan to run automatically to top up pressure in the foils if it is not at the desired level. According to Skyspan, (2002) generally an area under 250m2 only one fan is required. Two fans are normally used per 1000m^2 of foils system.

Other system requirements are air pipes and their connection accessories. The amount of pressure in pillows depends on the climate and the frame size. The pressure size may change by the click of a switch or it may be used in accordance with sensors. These sensor, as a part of building automation systems, can arrange the previously determined climatic conditions inside. By adapting sensors in to the system a partial intelligence will be obtained. That may also save environmental responsiveness to the building. PV solar batteries save the energy needed for the fans.

Polat, (2003) who is a representative of the Switzerland based firm; Texlon, explains that each inflation unit contains two compressors with auto-change – over to provide complete security. Robinson-Gayle et.al discusses that these electric fans has a consumption of almost 50 Watts for 1000m^2.

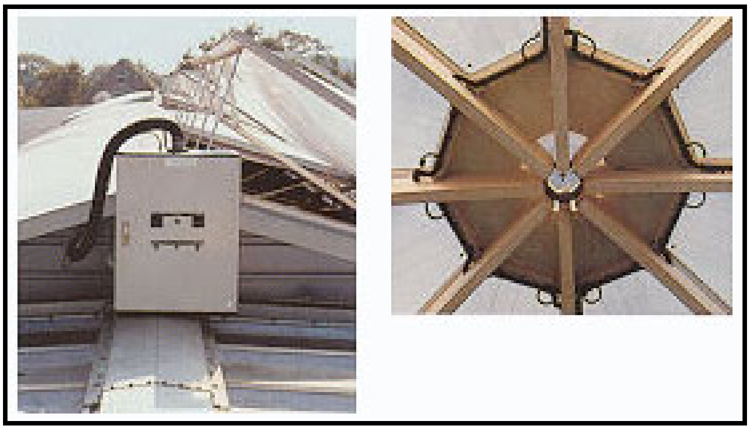


Fig. 3.16. Inflation Equipments Mounted On Roof Structure
Source: Texlon, 2003

According to Gill C. of Buro Happold for one of the early examples; Westminster Chelsea Hospital Roof, each fan has a power requirement of around 100 Watts. In case of Eden Project fans are running half of the day and they have an electricity consumption of 100W in 1000m^2. As in Eden Project Solar collectors; photovoltaics could be added to the system in order to save electricity from solar radiation.

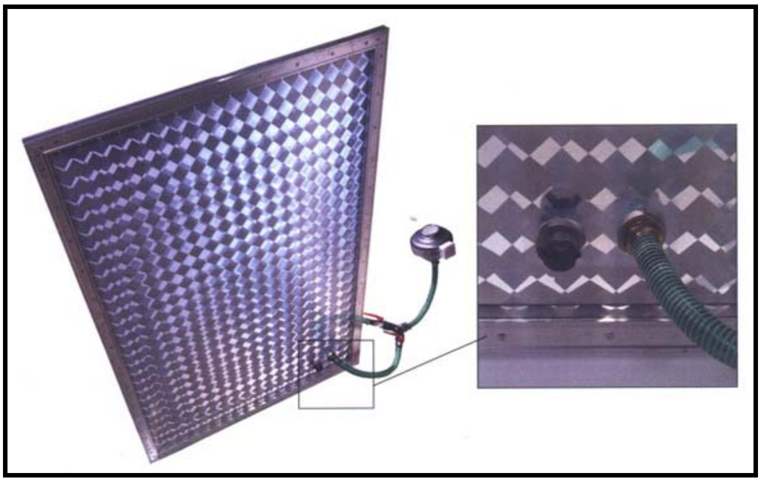


Fig. 3.17. Checkerboard Patterned Pillow And Inflating Equipments
Source: Buitink-Technology, 2002

In an event of an explosion of a pillow, system goes on working properly. This may obtain by using one-way pneumatic valves. These new generation valves called as intelligent valves. These valves will be able keep the air inside the pillow by their structure. That will save time to the user for the repair before the pillows are over affected by climatic conditions.

In variable shading system, which can be used only in three layer applications, needs same equipments but in a different working concept. Pneumatic systems are much more complex than standard triple layered pillow systems. Both chambers of the pillow designed to have different pressure amounts if needed. Therefore perforated sheet in the middle of the standard three layered pillows are no longer exist. According to the situation, mid layer can have tensile stress when the pressure in the chambers is not equal. There is an extra air pipe for the other chamber that directly goes in to it.

Fig. 3.18. Moducel LKS Air Handling Units provided by Eaton-Williams Co.
Source: www.eaton-williams.com

Fig. 3.19. Centrifugal Fans of Eden Project
Source: www.edenproject.com

3.4. Classification of Inflatable Pillow System Types

In order to explain the system that is introduced above, classifications are made; according to the number of membrane layers of the system uses, according to the primary supporting structure and according to the form and the function in the following chapters.

3.4.1. Classification According To The Number of Membrane Layers

The IPS forms from two to five layers. Although it is possible to make a construction with 4 and 5 layers, because of the feasibility of the designs, it is not recommended and implicated until present study carried out.

The common applications are categorized as follows:

- Single layer applications
- Double layer applications
- Triple layer applications
- Triple layer applications with variable shading technology

Membranes in single-layer construction are drawn taut to their edges, where they are fixed and mechanically tensioned. In view of the lower load-bearing strength of ETFE sheeting in comparison with woven fabric, the use of the former is limited to relatively small structures. Larger areas can be covered with ETFE membranes if additional intermediate supports are provided. The membrane roof at the Walchensee Power Station in Kochel is the largest ETFE structure of this kind of existence. (Barthel, 2002)

The German Federal Environment Foundation, in Osnabrück completed in 2002, is also covered with a single layer ETFE membrane. According to Barthel, the lightweight nature and high light transmittance of the foil exploited by the designer in order to obtain an outdoor ambiance in the ventilated atrium. Ventilation maintained by movable sunblinds. (Barthel, 2002)

Fig. 3.20. Walchensee Power Station
Source: www.covertex.de

Double layer applications rarely used in comparison with the triple layer applications. Double layer use preferred where the high light gain is important rather than the thermal insulation. Therefore it is mostly suitable for zoos, commercial greenhouses and sport centers in warm climate. Heat transmission coefficient is almost equal to glass double glazing. U–values of the multilayered membrane application are explained in thermal transmission criteria of IPS section.

Double and triple layered applications can be used easily inside narrow frame systems. Increase in pillow layers results a change in framing system. The framing mechanism completely changes and clamping details naturally follow them. Height of the frame increases, which is basically means that standard extrusion die is no more used for these applications. Manufacture of new profiles results as an extra cost for its usage. Addition to that as height of the profiles increases structural shading increases, which destroys the unique appearance of the system.

Pneumatic wall and roof elements are often executed with a tautly stretched third (middle) layer. As a rule, this has no load bearing function, but it divides the volume of air within the pillow into two linked chambers, thereby improving the thermal insulation. Bearing in mind the slenderness of the pillow along the lines where the lines are joined together, conventional three layer structures of this kind achieve U-values of about 2.0 W/m^2K.

Barthel, (2002) discusses the thermal properties of the both double and triple layered pillow applications can be upgraded by changing the type of the frame, and the position of the pillows. If the upper and lower layers are fixed to the primary structure independently or each other, the U-value can be improved by up to about 20 percent.

3.4.2. Classification According To The Primary Supporting Structure

Classification of the primary supporting structure can be evaluated in several ways; according to the types of the structure and according to the material types of the supporting structure. Structural choice is generally affected by the function and the environmental condition of the building in order to exploit the systems properties at maximum. Flexible and lightweight nature of the pillows encourages designers to conceive bigger and higher structures with IPS made ETFE foil.

In contemporary examples, IPS substructures are commonly designed as:

- Cable net structures (Prestressed and uni-axial)
- Skeleton structures (non-planar and planar grid frame)
- Geodesic domes
- Vault structures (Barrel-vault and rampant barrel–vault)

Cable net structures are another variation of light-weight tension structure. The process of form finding is due to the same physical laws as textile membrane structures, such as counter curved and pre-stressed. They may be considered as woven textile with the same strength in warp and weft directions, just the distances between the ‘threads’ or the tension cables are bigger. Cable nets are often used in combination with textile membranes, when the forces become heavy for the membrane alone to carry. Cable net structures can also be constructed as stand-alone units. The gaps between the crossings of parallel cables can be covered with conventional materials like glass, timber, polycarbonate or metal plates as well as ETFE pillows as in case of Hellebrunn Zoo and Hampshire Tennis And Health Club. Cable net structures are often preferred for animal cages without infill between cables.

Skeleton structure is a structural system that consists of columns and beams. These structural elements constructed conventionally with various material types such as laminated wood, reinforced concrete or steel. As in case of the National Space Science Center that is conceived by Grimshaw, skeleton system is basically used for IPS application.

Geodesic dome that is developed by Buckminster Fuller is a spherical covering system. This consists of tetrahedron and octahedrons. Dome creates double curvature appearance while infill panels may be planar and non planar as in the pillow structures. Eden project is a successful example of complex geodesic domes which is 60m high at its maximum.

Vault structure consists of concave elements that commonly constructed traditionally with stone and brick. The whole structure obtained by translating an arc in order to maintain concave form. Among many types of vault structures; most common types are rampant and straight-barrel. Vault structures are preferred commonly for skylight and atrium roofs for IPS application. The long span and less structural shading is the outcome of this type of structural system.

3.4.3. Classification According To The Type of Usage

An initial classification could be made according to the usage of Inflatable Pillow System made of ETFE Foils:

- Roofing (vertical)
- Cladding (horizontal)
- As Total Envelope (both vertical and horizontal)

3.4.3.1. Inflated Pillow Roofing System

Inflated Pillow Roofing System (IPRS) defines the usage, where it is commonly used against gravitational, vertical loads. These include rain and snow loads as well as partly human loads when it is essential. The IPRS could be used tilted according to the horizon line. In that case it can act as a part of the façade, which makes the more stable and durable for hail attack. It is also more efficient than solely vertical use. However, environmental noise due to raindrops could be reduced in a limited value. Tilted roof solution is also beneficial for architectural details, so that drainage problems could be solved easily.

Fig. 3.27. Darwin Museum Roof Close Up
Source: www.hok.com

There are three kind of roofing systems with IPS in the market these are listed as below:

- Transparent roofings (with clear and dotted foils)
- Translucent roofings (with colored foils)
- Roofings with flexible shadowing, (with variable shading)

The white pigmentation is standardized to a total-light transmittance of 50-55%, but also different colour concentrations are possible. The transmitted light becomes nearly completely scattered, which leads to an absolutely even and non-reflective lighting (indoor tennis centres). Additional the white pigment is absorbing the total UV-light, so that under white pigmented ETFE also UV-sensitive goods could be stored for long times. *(*www.nowofol.de)

Metal vaporizing (e.g. Aluminium) on ETFE surface allows an exact regulated light transmission by keeping the visible transparency. If vaporizing intensity becomes increased, a total sunlight reflection (like a mirror) could be achieved, which is used mainly in solar technology, or for decorative effects. (www.nowofol.de)

According to Haack and Höpfner Architects middle layer of the Allgut petrol station roof is printed with 16 mm diameter silver dots in order to reduce heat and light gain.

Fig. 3.28. Allgut Petrol Station Close Up
Source: Haack and Höpfner Architects, 2003

Fig. 3.29. Close Up From The Atrium Of Chelsea and Westminster Hospital
Source: Robinson-Gayle et.al, 2001

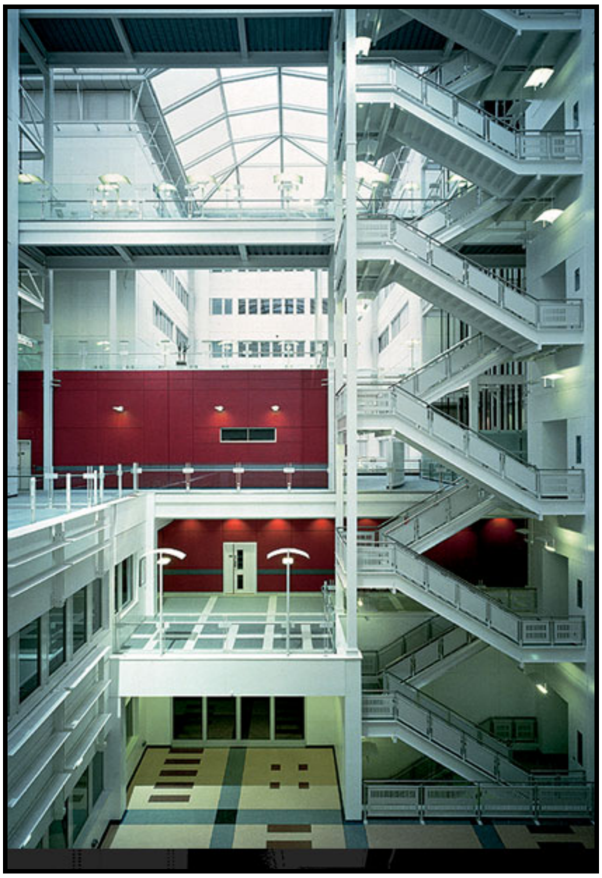


Fig. 3.30. Westminster Chelsea Hospital Atrium Roof
Source: www.foiltec.de

Printing is another option for ETFE foils. ETFE can become printed either total or partly with all RAL-colours. Printing is used either for decorating or for shadowing against sunlight. (www.nowofol.de) In only Triple layered applications, upper two layers of the pillow structure can be also manufactured with a specific printing design that an unlimited variability of light transmission that can be regulated from daylight to complete darkening. (www.nowofol.de) As in the case of Festo HQ checkerboard pattern is used to get a light transmission between 15% and 65 percent. Besides that a leaf pattern is used for the DSD pavilion in Expo 2000 for the change of visual effect inside and outside the structure.

In 1992, Buro Happold used a rigid frame and foil system for the Westminster Chelsea Hospital atrium roof, with an overall nave and crossing transepts and with short spans of approximately 20 meters. Continuous air pressure was supplied to the air cushions through the aluminium frames. The largest cushion, 3 by 4 meters, was inflated to a depth of 600 millimeters at a low pressure of 400 pascals (about 5 pound per square foot). (Robbin, 1996)

3.4.3.2. Inflated Pillow Cladding System

Inflated Pillow Cladding System (IPCS) defines the usage where it is conceived for total façade enclosure, or a part of the façade. While the façade act as a filter between indoor and outdoor, also whole protects the building against lateral loads such as wind loads more efficient than any of the façade claddings. Its outstanding structural performance reduces the total wind pressure on the building.

Although recent information on the statically wind behaviour of the IPCS is not enough, calculations are made due to traditional load analysis methods. The advantages of the IPCS against wind loads will be discussed in the further chapters.

Cladding with inflated ETFE foil contains a very low risk against hail attack according to its positioning. On the contrary, if the pillow subjected to direct attack by human, it would be demolished. But IPCS system is much more durable than traditional pneumatic structures. Unexpected collapse of the total enclosure is not possible because of its modular structural system.

Addition to that it is possible to exploit the light and visual transmission properties of the pillow. As in the case of Munich Allianz stadium opaque foils may be applied to the design to ensure better privacy and security. They may be either printed or colored for commercial uses. However, designer should be aware of vandalism and safety issues, which may result in design as a limited use of pillows where it can be reached easily by human and animal attack.

The places where the safety issues are excluded, like greenhouses, botanical gardens usage of pillow system as a façade element can be reliable. Environmental risks like animal attack or flying sticks due to hard climatic conditions should be considered. Vertical usage of the pillows in façade construction, may need cable support due to direct wind load. Structural analysis should be undertaken before construction. On the contrary supporting structure may be minimized due to wind dampening nature of the pillows.

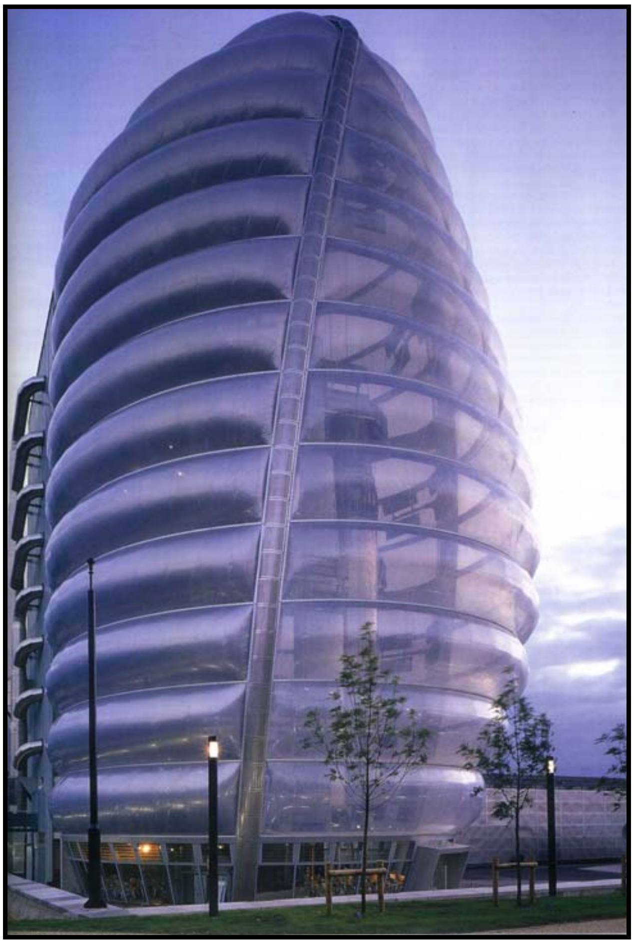


Fig. 3.31. NSSC Façade Cladding
Source: a+u 385, 2002

3.4.3.3. Inflated Pillow System As Total Envelope

Inflated Pillow System as a total envelope of the building could be determined as total peripheral multilayer skin made of ETFE foils. This peripheral form involves system properties both negative and positive discussed above. This kind of usage saves a formal freedom to the designer. Because of the nature of the cladding material, it could be designed in curved forms; as well as double curvature applications could be possible.

Fig. 3.34. Ozone Laboratory
Source: www.lab42.architecture.uni-siegen.de

The President of Birdair Inc., L. James Newman Jr., is also enthusiastic about ETFE foils. He points to their low cost, their translucency, and their color, which makes interesting architectural applications possible. (Robbin, 1996)

All foil cushions are thermal insulators, especially when formed into double cushions with three layers of foil. The seams, heat-welded to make them airtight, are clamped into frames made of aluminium extrusions. (Robbin, 1996)

Buro Happold Consulting Engineers has developed two types of frame supports: a rigid frame like a replacement window, and a cable-strengthened flexible frame that allows the cushions to move under wind load and thermal expansion-in effect, a faceted tension membrane. In areas where snow loads are heavy, thin stainless steel wires can support the foil panels, which are limited in width to 3.6 meters but can be more than 15 meters in length. ETFE foils lose strength at 60 degrees centigrade (140 degrees Fahrenheit), hence would probably not be useful in extremely hot climates. (Robbin, 1996)

Hampshire Tennis and Health Club is a flexible covering 6.000 square meters in size for ten indoor tennis courts with panels 3 by 18 meters. The cable net is hung from the poles and anchored into the ground. The clamping extrusions have been designed for the full range of movement anticipated. (Robbin, 1996)

Fig. 3. 35.Hampshire Tennis and Health Club
Source: www.

3.5. Environmental Control Criteria of IPS

Usage of foils is increasing in architecture. ETFE sheet are holds and important amount of consumption among other sheet materials in market. Along with the need for sunlight and increase in environmental consciousness, application of skylights and atriums as a design element has been increased. Architecture has changed its way in order to conserve energy. IPS provides economy on climatization and lighting, which are very important management expenses in building lifetime costs. These are the reasons of preference IPS as a building component.

Environmental possibilities of every material used on a building is an important issue, have to be known by designers. Architect and engineer Moritz determines the principle criteria for the use of membranes in terms of the constructional physics as: thermal, climatic, acoustical protection they provide and optical properties (Moritz, 2002). These responsibilities are to make the building sheltered against environmental effects of the nature and manmade environment. Building skin controls the effects of the environment; building skin forms the first line of defense. Basic performance criteria expectations of the building skin can be classified as follows:

- Control the effects of light
- Control the effects of solar heat
- Control the noise level

- Obtain security
- Control the effects wind
- Control the humidity level

Preference of IPS as a glass substitute depends on the advantage of structure against other glazing systems. IPS can be used for facades as traditional glass applications. IPS can also be used for roofs and skylight systems where glass is not preferred especially for long spanning structures. Any material thought to be used instead of glass should response the properties of glass and other glazing systems made of glass. Transparency is a very important issue in architecture and it is not obtained by most of the building materials. Among this little amount of materials, commonly thin materials obtain limited light transmittance. On the other hand thin materials are not capable to resist thermal transmittance. When possible, membranes are preferred for most of the applications where the light transmission is needed.

IPS made of ETFE foils promotes architecture an alternative glazing system. ETFE obtains the most of the properties of the system. But the pneumatic structure saves system an outstanding insulating value which other membranes are not capable. Besides the advantages and disadvantages that will be discussed in the next section, IPS has a long life expectancy and already has proved its durability with worldwide applications.

3.5.1. Light Transmittance And Vision Control

Light transmission is an important factor for IPS that is used as building skin. ETFE foils each have a %95 light transmissions for 200μm foil. Thinner foils transmit the light in higher amounts like % 97. Therefore IPS is a good choice for atriums and skylights to get the light especially in deep holes of the building. According to the B&O Hightex translucency of the ETFE membranes is about 95% with in the range of 400 - 600 nm, with a scattered light at proportion of 12% and direct light at a proportion of 88%.

Besides the high light transmission rate the most important property of IPS is hidden in the light spectrum. Therefore, light spectrum is important in terms of IPS light control. Comparing with other materials, ETFE sheets main property is, especially the high level of UV transmittance in the spectrum, which is between 150nm and 750nm. Transmission of UV-A, UV-B is possible through the ETFE sheets. UV-A has a light transmittance of 100 percent whilst UV-B has 50 percent. UV-C is not transmitted through the film. It is not even reaches to the earth's surface. Harmful UV-C is absorbed by atmosphere in stratospheric ozone. UV light is vital for animal life and plant growth. Plants need UV light for photosynthesis. But on the other side UV light has a negative effect on bacteria growth. Therefore it is highly beneficial in order to protect from bacterial diseases. These are the reason that IPS is preferred for greenhouses and zoos, and also atriums where high light is needed in wide spectrum. Besides the benefits for plants, UV-A is also beneficial for humans and animals. UV-A obtains suntan and other biological processes for human skin.

The Growth of a plant depends on the existing spectrum of solar radiation. The reasons are on the one hand the photosynthesis and on the other hand the antiseptic effect regarding to the growth of damaging bacteriums. As shown in the figure 3.38, the German word *"Wirkungsgrad"* means the degree of effectiveness regarding to an antiseptic effect. This effect is a function of the transmittance of the radiation. The degree of the effectiveness depends on the wavelength. The gradient of the function is not linear. The best effect is located at a wavelength between approx. 150 and 350 nm. The chart shows the connection between Transmittance (wave length) of the building cover (foil, glass) and the prevention (% of effect) of bacterium-growth. (Moritz, 2003)

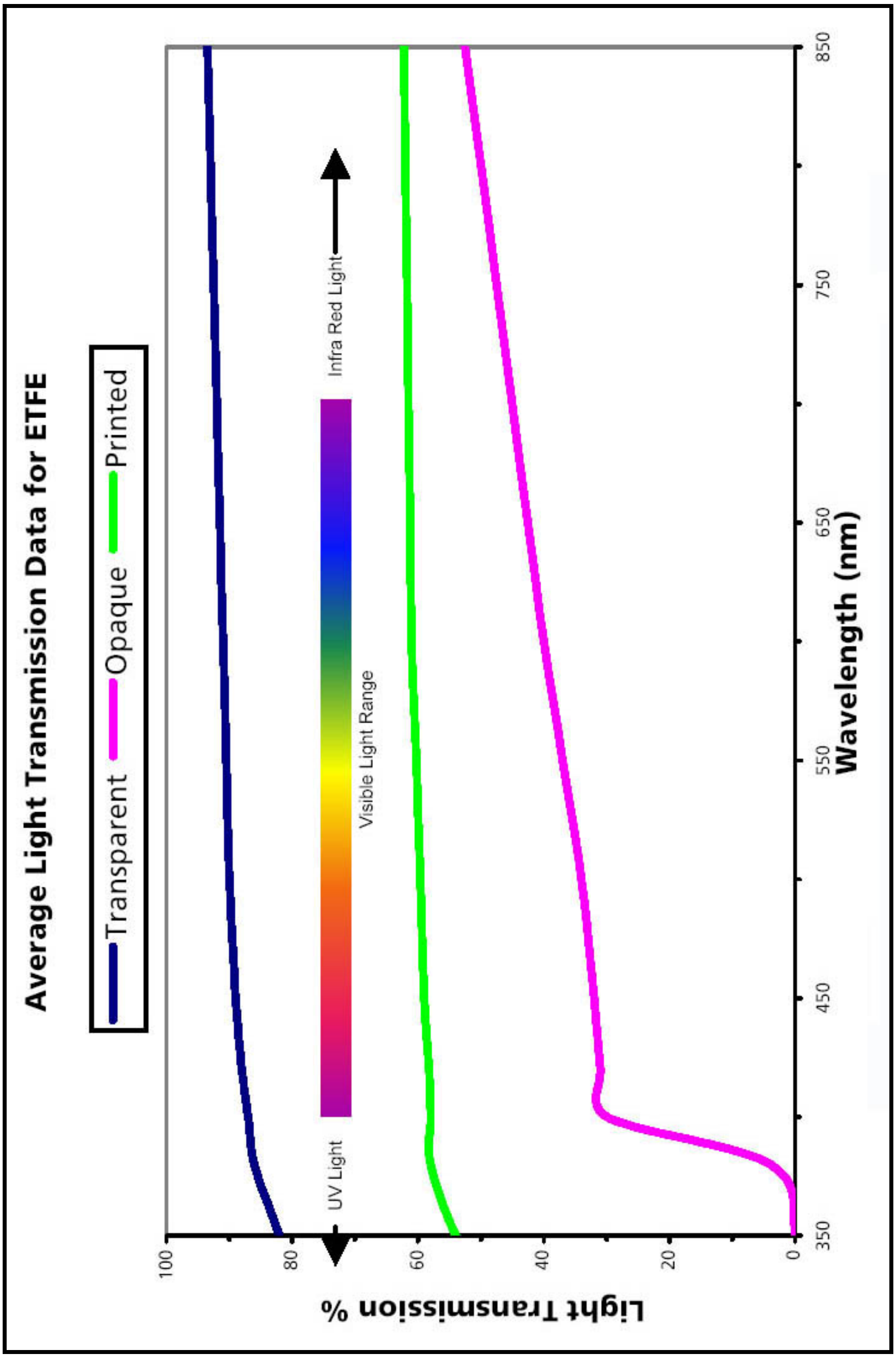
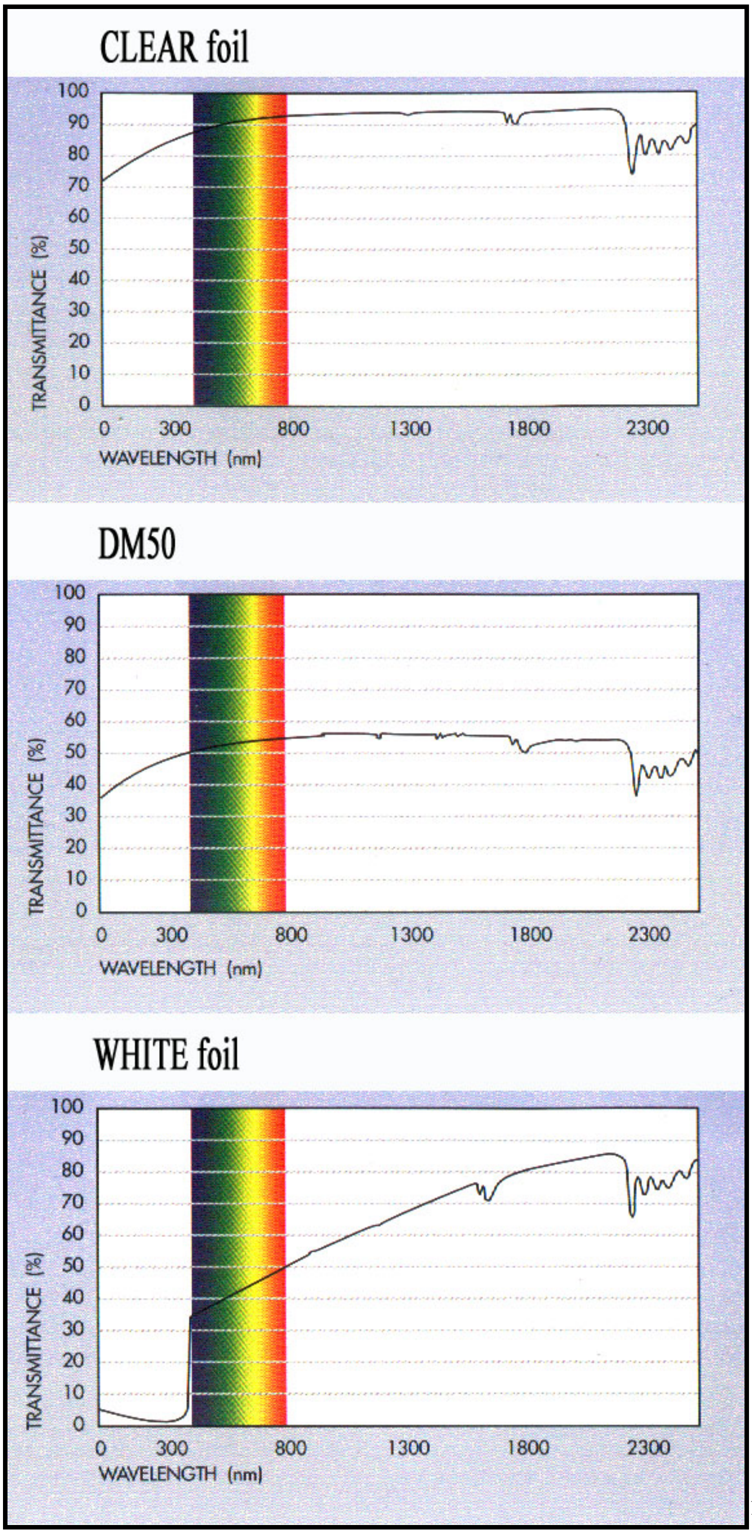


Fig. 3.36. Average Light Transmission Data of ETFE
Source: Skyspan Data Sheet, 2000



[1]

Fig. 3. 37. Light Transmittance Performance of Foil Types
Source: www.vector-foiltec.com

[1] DM50 is the trade name of printed pillow system named Texlon produced by Vector-Foiltec Co.

For a triple layer pillow structure (upper layer 200μm, middle layer 100μm, inner layer 200μm), the degree of light transmission for vertical incidence is $\tau = 0.7$. This value gives the translucency important for life of humans, animals and plants.

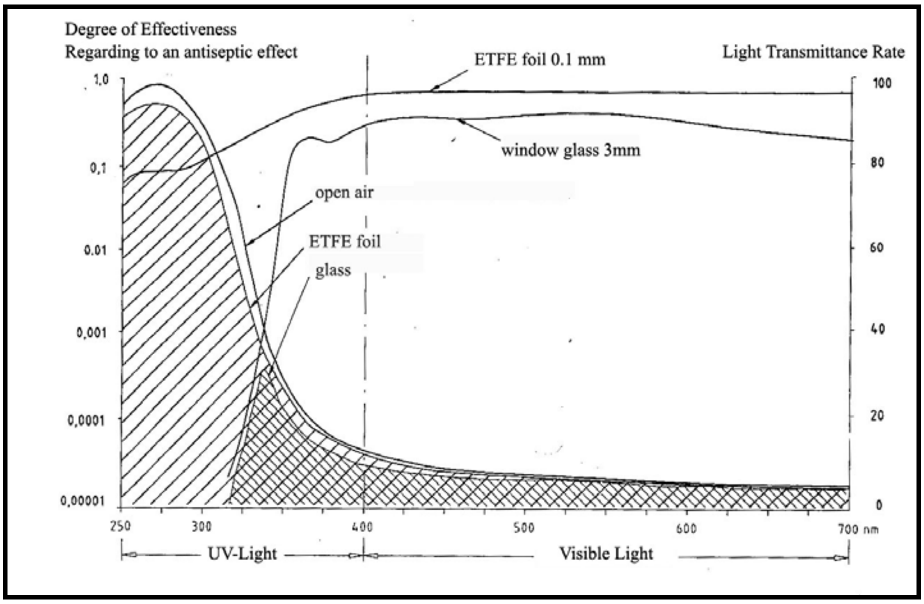


Fig. 3.38. Connection Between Transmittance (Wave Length) Of The Building Cover (Foil, Glass) And The Prevention (% Of Effect) Of Bacterium-Growth
Source: Dr. Stefan Lehnert, Intelligent Architecture, Nov/Dec. 2000

Along with the thermal transmission ETFE is an ideal material for transmissive control criteria. Inflatable pillows made of ETFE have a self-cleaning advantage. In addition to that absorption rate of the foil is very low. Surface of pillows never gets dirt, which may reduce these transmissive values of IPS.

Although it is said that %95 light transmittance is obtained with ETFE foils, the real amount of light passing is lower in IPS. In double or triple layer applications these amounts decreases to %78 –87. UV light values decreases in conjunction with visible light transparency. Using white sheeting, the UV spectrum can be eliminated almost entirely. White sheets has a total light transmittance approx. 50-55%. Skyspan, (2002) discusses that the system with opaque foils is ideal for southern hemisphere or areas where UV light is unwanted. Opaque foils have a visible light transmittance of 40 percent.

ETFE foils can be completely or partly printed with RAL colors. Printed foils can be used in order to reduce light transmittance and excessive brightness of sun. Standard productions of the ETFE foils are transparent and translucent white foil. White layer can be used as a middle layer where that is used in Waterworks Pavilion at Earth Center or as three layer where that is used in Hampshire Tennis and Health Club to reduce the eyecatching sunlight. According to Skyspan, (2002) printed films are generally consist of transparent film printed with reflective silver dots 15mm diameter at 45mm centers. Printed systems average light transmission is 60 percent. However average light transmission through silver areas only 30 percent.

Fig. 3.39. Waterworks Pavilion at Earth Center, Doncaster
Source: Detail, 2000/6

Transparent and translucent foils can be illuminated by lighting accessories. Therefore interesting qualities of ETFE foil lie in the relationship between their reflections, absorption and transmission of sunlight, especially in the visible light between 390nm and 770 nm. Foils reflect the color that is chosen. Allianz Arena is the only example of this kind of application, which will be constructed for New Munich Stadium designed by Herzog de Meuron.

Foils can also be dotted by color. Silver coated paints can increase reflectance rate of the pillow in order to limit heat gain. These printed pillows could be used in terms of intelligence. Negative and positive printed sheets are used in outer and middle layers. Inner layer does not have to be printed. It can be either transparent either completely printed. This system needs one more pneumatic valve to change the pressure level inside the pillow. This is used in triple layer system. Middle layer, which is commonly stress free in standard triple layer applications, does not have any pressure balancing holes in variable shading system. So that two separated cavity can be pressurized not equally. When needed middle layer moves up and blocks the light passing through the outer layer. In these kinds of applications light transmittance rate depends on the shape of print. This technology called as Variable Shading Method. System obtains an intelligent opportunity for design when much light is unwanted. Light comfort can be arranged automatically by a sensor or manually by a click of a switch.

Furthermore, ETFE has a very low reflectance level. This saves an advantage of glare free design. Although ETFE foils are very transparent, when inflated as a double and triple layer pillow, visual perception is decreased naturally in parallel with the direction of the look. The rates given are valid only for the center point of the pillow where the sheets are almost parallel to each other.

In addition to these, from the lightweight nature of the EFTE foils, structure of the IPS is narrow. Thus supporting structures when conceived of extruded aluminium does impede the view at minimum. Welding opportunity of ETFE sheets promotes long spanning without extra support that contributes visual mass unity of the building skin.

Another point to ensure best light transmittance value is providing dried air for pillows, not to increase humidity inside. If not, humidity will block the visual perception; moisture stick on the sheets will make the pillows translucent.

The foil can be produced with a translucent body tint. The density, colour and number of layers can be varied. Generally it is recommended that, the use of a white body tint to ensure internal daylight colour rendering. The translucency of the envelope can be further varied through the construction of multi-layered cushions, with different combinations of white, clear, and coloured foil. In addition there is matt surfaced foil, which can further enhance the designers choices.

Foiltec has developed dynamic capabilities within IPS that can intelligently adapt and transform their transparency, aesthetics, and thermal properties as the sun moves across the sky, responding to specific program and climatic requirements.

Open Position

Closed Position

Fig. 3.40. Variable Shading Technology with Complex Pneumatic Systems
Source: www.foiltec-vector.com

Variable shading technology has turned indoor spaces into environments that can control or dramatize the effects of the sun. In the Festo Headquarters and the Solarlux Showroom both in Germany the architects used variable shading system. To achieve this dynamic shading, various positive and negative print patterns can be developed and printed on the outer two layers of a three-layer system. The simple change of position of the second or middle layer, either to the top or bottom of the system, can transform the system's transparency.

The Festo Headquarters used a bold checker-board pattern to achieve a variable transparency between 5% and 65% and in the Solarlux Showroom the designer developed a pattern with alternating stripes - where the stripes themselves are 50% transparent allowing the system to adjust from 45% - 85% transparent. The range of transparency of the system is project specific and is determined by the designer's intentions and building performance.

3.5.2. Thermal Transmission Control and Variable Shading Technology

Light transmittance and solar heat transmittance are not directly proportional. Light transmission rate of a material does not mean the rate of solar heat transmission in the same time. This depends on the wavelengths of light in the spectrum. The ratio between light transmittance coefficient and solar heat transmittance (thermal heat transmittance) coefficient is a good criterion for evaluation. As the ratio increases, the success of the solar control of the glazing increases (Türkseven, 1996). Insulating glasses (solar control glasses) are discussed in Chapter 2.

The sunlight that hits to the surface of glazing material shows three types of behaviour. Some of the solar energy passes through glazing material while some of the solar energy is reflected back. Some part of the sunlight absorbed by glazing material changes into heat, which is in long wavelength in the spectrum.

Solar heat transmittance of a given material is measured with U-value. In order to understand heat transfer rates of a building component, U-value is preferred. U-value is the measurement of heat transfer through a given material. In other words, it can be described as the transmission of heat through material, which compose building envelope, outer shell. Although in German measurement system (DIN), k-value is similar to the coefficient of heat transmittance, there can be little differences in rates. Except these different calculations U-value is capable to measure more specific results for summer and winter conditions. Therefore thermal transmittance coefficient is an important aspect has to be considered in design, in order to choose appropriate building material with a high insulation property. So that, glazing materials should ensure insulating values of a wall and try to reduce heat losses through glazing.

$$\text{U-value} = W / (m^2 \times K) = \text{energy (kcal)} / m^2 \times C^{o}$$

Table 3.4. U-value Formula And Explanation

Inflatable pillows made of ETFE sheets are used in increasing numbers for transparent and translucent building skins. They are preferred with their high insulating values. As explained, pillows are manufactured in multilayer forms. As layers are increased in number U-values of the building skin increases. Thus, IPS does not need any extra coating for insulation rise. Table 3.2 below shows the coefficients of heat transmission of ETFE sheets.

Addition to that Tanno (1997), explains that a standard three layer pillow has a U- value of around 1.95 W / (m^2×K), which is considerably better than triple glazing when used horizontally. Tanno discusses that pillows thermal performance can be further enhanced by the addition of further layers, which can be treated with Low-E coatings. By addition of the Low E coatings U- value can be reduced below 0.6 W / (m^2×K).

Number of ETFE Layer	**U-value***	**k-value***	**g-value*[2]**
Single Layer	5,1	x	between 0,05-0,85
Double Layer	3,5	2,94	
Triple Layer	2,0	1,96	
Four Layer	1,5	1,47	
Five Layer	x	1,18	

*Data given are approximate rates.

Table 3.5. Coefficient of Heat Transmission of ETFE Sheets
Source: B&O Hightex and www.buitink-technology.com

The solar energy passed through the pillow strikes to the objects inside, transforms to long wave energy that causes heat. The object subjected to sunlight can be ground as well as human. Thus, inside heat blocked by building skin increases by time. This is also called as green house effect originated by building skins. The reason for that is the UV and visible light that enters to the building transforms to the longwave energy (heat), which was captured inside the building.

The common usage of IPS with double and triple layer systems have 3,5 and 2,0 W / (m^2×K) heat transmission coefficients which are very high in transparent glazing

[2]g-value: Solar Gain Factor

market. Designers should be informed by the thermal effect of the surrounding frame. Frame construction has an important effect on U-value that should not be undervalued. All frame structures that have direct contact with the outside environment should have thermal breaks inside the frame structure.

System’s multi layered construction can be exploited to create climatic envelopes that sense their environments and change their insulation and solar transitivity as required. By printing overlapping gestalt graphics on multiple layers and integrating the cushions with sophisticated pneumatics, the different graphics can be moved together and apart from each other.

This enables to vary both the amount of solar gain penetrating the building and the visual appearance of the envelope. Not only can this phenomenon be exploited to control the amount of solar transmission through the envelope but it can also be used to vary the number of air chambers within a cushion, thereby changing its U value. These unique properties enable designers to create buildings that are energy efficient, cost effective and visually responsive to changing climatic conditions.

For instance, Hanover DSD’s variable skin building enclosing an exhibition of re-cycling modulates the atria’s internal climate by reacting to the sun and changing its transmission. The facade is water-cooled and the building generates an internal cyclone as part of the visitor attraction.

Variable shading technology saves extra internal comfort depends on the user demands. This additional technology of the ETFE pillows ensures solar penetration and solar shading options. So that, user may change inside lighting conditions whenever wanted. This method allows user a chance to exploit indoor as an public street or an impressive indoor ambiance with the limited light gain.

Fig. 3.41. Variable Shading Technology Used At Patterned Roof of Festo AG
Source: www.foiltec.de

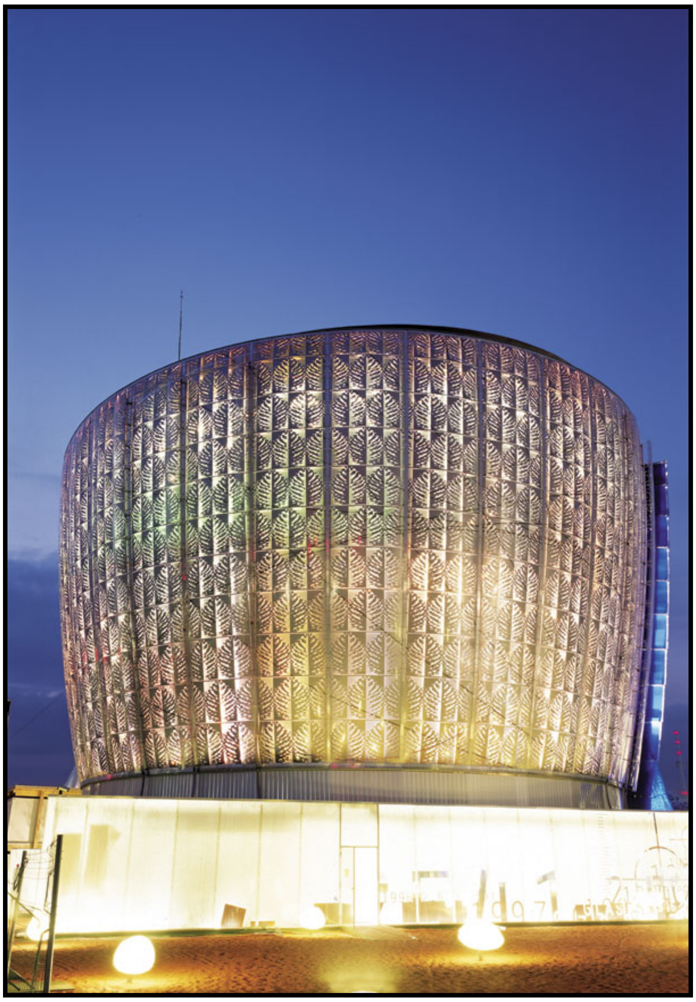


Fig. 3.42. Duales System Deuschland, Hannover Expo 2000
Source: www.d

Through the use of complex system of pneumatics the gestalt graphics are moved apart to allow natural light to penetrated the internal environment. (Vector, 2002). Whilst the perception of the pillows changes, the light and thermal transmittance values are change in accordance with the movement of the middle layer. Both chambers of the pillow differ from each other. As shown in the Figure 3.25, the picture on the right demonstrates when the mid layer is virtually stick to the top layer. Therefore graphics or pattern is no more visible.

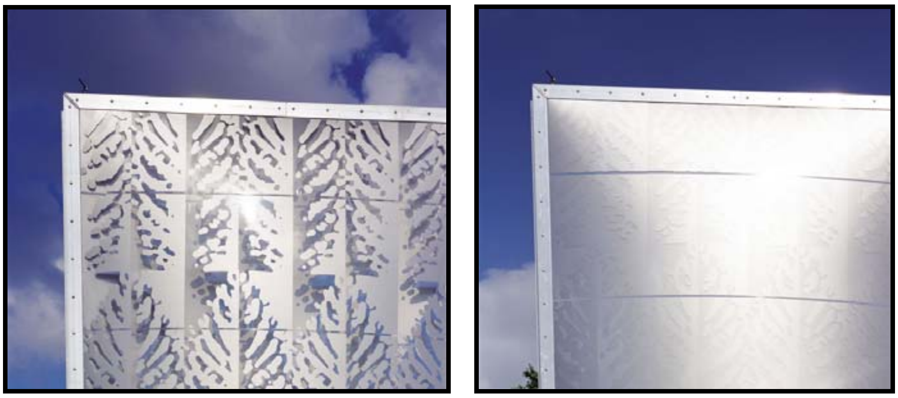


Fig. 3.43. Solar Penetration
Source: www.foiltec.de

At a flick of a switch or receipt of an environmental signal the gestalt graphics overlap to provide solar shading and internal comfort. According to the German manufacturer Vector Company (2002), the variable skin takes about 60s to change and provides an ever-changing spectacle to office workers and visitors in Festo. This system also used in several buildings. In cases of DSD Pavilion in Hanover Expo and Solarlux showroom in Germany are the successful applications of the solar shading and solar penetration.

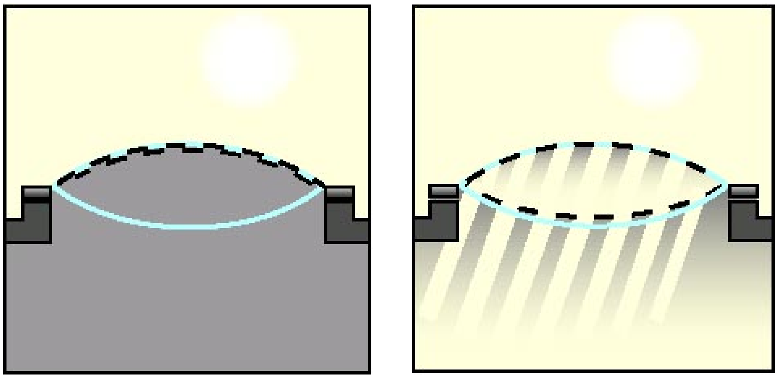


Fig. 3.44. Variable Shading
Source: www.foiltec.de

3.5.3. Acoustical Control

Sound and noise control is another environmental criteria of a building skin. This criterion gains importance in critical places like, airports and places affected traffic generated noise. As known, there are two types of sound transmittance in the environment. One of them is transmitted by air. That is why that type of noise called as air noise. The other sound transmission type is structure borne noise. Structure born noise is transmitted by building components such as walls and slabs. That is mostly generated by hitting those components of the building. Construction materials have various sound transmittance values and behaviours. Surface qualities and density have also effect acoustical control. Besides that, internal design quality of a space is important in terms of a correct acoustic.

Most of the membrane systems have very low sound insulation and absorption as most of the thin construction materials. ETFE foil has a sound reduction index of 10dB, which is considerably low. Robinson-Gayle et. al. (2001) determines it as virtually non-existent when it comes to sound control. According to Robinson-Gayle they transmit practically all sound with a R_w (dB) of 8. Sound of rainfall and strong wind can be heard inside. Designers should be aware of the sound performance of the pillows in order to take precautions.

Commonly ETFE pillows have a mass of less than 1kg/m^2 (three-layer), which is light in comparison to other membranes. Therefore IPS is not capable to reduce the externally generated sound level. But this saves another opportunity to the designer. As the cladding does take the external sound in, it also transmits the internal generated noise back to the outdoor. ETFE is an acoustically soft material. As in other transparent other transparent glazing, IPS made of ETFE does not reflect the noise back. This means lower reverberant times and a more comfortable indoor environment.

IPS made of ETFE is an ideal system for places covered with spherical domes and other structures that have focusing effect of hard acoustic cladding. Otherwise that acoustically hard material can disturb the internal comfort by making the speech unintelligible. Although ETFE sheets sound reduction index is very low that may be an opportunity for designers. When used appropriately, that may be useful for atriums, circulation halls of shopping centres and similar places that people idle and spend time due to the increased comfort level. That option may reduce expenses for sound dampers against internal sound level and/or reverberation times.

The taut skin of the outer surface can create significant noise under these conditions. Noise levels of up to 85 dB can be sustained under heavy rain. For a light drizzle or rain, a reduction of approximately 30dB may be achieved (Skyspan, 2002).

IPS can be fitted over noise sensitive areas such as libraries and offices by fitting rain suppressers designed to reduce rain and hail generated noise. Additionally spaces that tend to be quiet also require acoustic insulation to prevent noise that ingress into the space. As in case of Orange Company office building, circular pillow system adapted to the roof structure as light wells, which are also designed to reduce internal noise level by letting the noise out through the circular wells. On the other hand decorative sound dampers are used as rain suppressors.

Fig. 3.45. Orange Company Light And Sound Wells And Rain Sound Suppressors
Source.www.foiltec.de

According to Morris (2000), who is the manager of Vector Foiltec Company describes the acoustical improvements on IPS structures. The company is recently working on jelly sound dampers for a better sound reduction index.

Lacon House in figure 3.28 and Adastral House's lightweight roofs absorb internally generated noise reflected from the glass and stone cladding thus improving room acoustics. (Vector, 2002) In the atrium footfall and speech is not reflected around so the internal space can be very quiet, but on the other hand rain is easily audible.

Fig. 3.46. Lacon House Atrium
Source: www.vector-foiltec.com

3.5.4. Safety and Security Control

Building skin is the envelope that provides safety and a security line for structures. Building skin separates indoor and outdoor environments protect against wind, rain, snow, heat and cold shortly all environmental possibilities. Besides, building skin should protect the building against fire, robbery and unauthorized entrances. Therefore robustness is important in terms of safety. Building skin should have appropriate strength in order to keep safe users. Building skin should also be airtight and watertight. Building skin can be formed in a monolithic way or it can also be a system assembled with more than one material. In both case, material properties are gaining much importance for security reasons in building regulations and local legislations.

Among other fluoropolymer EFTE foil has a very high tensile strength, elongation (machine and transversal) and tear resistance. These high mechanical properties make the foil an ideal construction material. ETFE foil is an almost isotropic film, which shows the same elongation quality in both directions.

ETFE foil has a high elongation property. According to Foiltec Co. Elongation at break is 150-200% that is tested with ASTM D 1708. ASTM D-882 tests are resulted between 45-650%. Buitink-Technology Co. realizes similar elongation rupture tests at 23 ^{o}C and 160 ^{o}C resulted between 150-200% maximum elongation. According to the test results "Instrom at 100mm/min" elongation at break is 300-400% (Vector-Foiltec).

Inspections on ETFE foil made by Koch Membrane Co. shows that tensile strength of the sheet are almost similar in both directions. According to Koch, tensile strength in machine direction is between 51 and 58 N/mm^2 while in transverse direction is between 53-54 N/mm^2.

Tear strength of the foil is another important property can be exploited in pillow structures. Building skin is not only affected by climatic conditions but also affected by living creatures including human. Skyspan (2002) categorizes the damage into three types; Human, Environmental and Animal. Therefore robustness is also an expectation from IPS. Nature of the foil used in IPS is a soft material, and can be damaged by vandalism. Human damage can be avoided by limiting the amount of access possible to the area. Direct projectile attacks and strikes with pointed materials and sharp objects may destruct the area subjected. Allianz Arena Football Stadium will be the largest structure in Germany with an estimated ETFE membrane area of 65.000m^2 (Moritz, 2002). Flying sticks and similar objects are the reasons of environmental damage whose probability is relatively quite low. Any sharp objects need to hit almost exactly normal to the surface of the foil to cause rupture. Animal damage is a common form of damage. Birds cannot perch ETFE. This type of the damage can be eliminated by stringing fishing line along the length of the perimeter clamp mechanism, which limits the animal access possibilities (Skyspan, 2002).

In case of a small damage in the pillows can be eliminated with self-adhesive ETFE stickers. But large holes that need intensive welding can be re-assembled in production halls. According to the test results of DIN 53515 at 23^{o}C, tear strength of the foil is 180 N/mm, which means small holes will not propagate (Foiltec, 2002). On the contrary, common test method for membranes DIN 53 363 gives tear strength between 400-500 N/mm (Skyspan, 2002).

Whenever IPS has its annual maintenance, pillows can hold workers walking on them. IPS has a load bearing capacity that is $75kg/m^2$. In the case of Eden project in Cornwall, 11-12 m diameter pillows are 2m heights in the center.

ETFE Property		**Unit**	**Test Method**	**Typical Values**
Tensile Strength				
	longitudinal	N/mm^2	DIN EN ISO	>40
	transversal	N/mm^2	527-1	>40
Elongation at Break				
	longitudinal	%	DIN EN ISO	>300
	transversal	%	527-1	>300
Tensile at 10% Elongation				
	longitudinal	N/mm^2	DIN EN ISO	>20
	transversal	N/mm^2	527-1	>20
Modulus in Tension				
	longitudinal	N/mm^2	DIN 53457	1000
	transversal	N/mm^2	DIN 53457 0,5%sekante	1000
Tear Strength				
	longitudinal	N/mm	DIN EN ISO	>300
	transversal	N/mm	on trapezium	>300
Shrinkage				
	longitudinal	%	150 ^oC/10min.	0-5
	transversal	%	150 ^oC/10min.	0-5

Table 3.6. Mechanical Properties Of Nowoflon ET – 6235 Product
Source: Nowoflon ET Fluoropolymer Film Technical Sheet

Due to lightweight nature of the sheet, underlying structure is getting narrower in comparison. Therefore in case of a fire, with a high melting point of ETFE foil (270 ±10 ^oC), IPS will save users life under the structure. ETFE is flame retardant and classified as B1 according to DIN 4102 without additives, which means very hard to burn. According to NF P 92-505 ETFE foil is classified M2. ETFE fluoropolymer film of Nowofol Co. is awarded with *"Allgemeines bauaufsichliches Prüfzeugnis"* as a flame retardant material from Otto-Graf Institute of Stuttgart University. Koch Membrane Company determines the foil as self-extinguishing up to incombustible. The presence of fluorine makes the membrane self-extinguishing.

ETFE Property	Test Method	Typical Value
Flame Retardance	UL 94	V-0
	DIN 4120	B1*

* Measured on 200µm film

Table 3.7. Flame Retardance Properties Of Nowoflon ET – 6235 Product
Source: Nowoflon ET Fluoropolymer Film Technical Sheet

Maximum permanent service temperature of the Nowoflon ET and Hostaflon ET are +150 ^{o}C. Foils are in service for a short time (6-8 hours) at 230 ^{o}C. In Addition to that, in case of a fire event, the flame demolishes the thin foil and IPS lets the heat and plume away, which contains dangerous gases. System saves time to the people to run away before the whole structure collapse. Total collapse of the structure is eventually delayed due to the heat decreased inside the structure. This self-venting nature of the system prevents flashpoint, where the air temperature inside causes spontaneous combustion any flammable materials (Skyspan, 2002). Whenever the space designed as a high ceiling or as the flame cannot reach to the pillow structure, optional sensors may detect the fire and open the ventilation windows for emergency. Therefore it is suitable to design IPS including ventilation holes. Those holes may be used for exhaust of smoke and fresh air ventilation.

ETFE Property	Test Method	Typical Value
Melting Range	DSC 16 ^{o}K/min	275 ^{o}C ±10

Table 3.8. Melting Range Of ETFE Foil
Source: www.buitink-technology.com

Under fire conditions any hot gases impinging on the cushion/s at a temperature above approx. 200°C will soften the foil. As the foil is under strain from inflation, the foil will fail and shrink back from the plume effectively venting the fire to atmosphere. ETFE sheets produce toxic fumes under fire. According to Skyspan Co. by products are Carbon Monoxide (CO) and Hydrogen Fluoride (HF). However, as the ETFE foils have a very low mass-volume ratio, these toxic fumes are usually in substantial.

In case of a collapse in the pillow structure lightweight and narrow structure cause less damage, which may be a life saving option for dwellers. The plastic range cannot be exploited in construction, but it results in a benign behaviour in the material in terms of safety. In other words, failure does not occur suddenly, but only after significant increase in loading. (Moritz, 2002) As mentioned before, EFTE foil has a melting temperature of 270 ^{o}C (Nowofol, 2002). But foil does not produce hot drops (non burning drip), which is very important for building safety regulations.

Although IPS has a lightweight and soft nature among other glazing types, it can resist strong winds. The stiffness of the foils is maintained by the internal air pressure of the foil and the shape of the pillows. The pillow s may be stiffer by increasing the internal air pressure. If required, an air pressure sensor may be fitted which automatically increases the air pressure inside the foils to control the excessive deformations in the system. Nansei Yacht Club in Japan has a typhoon resistant glazing that is able to withstand 200mph winds. According to Foiltec Company IPS can resist a wind suction load of 220kg/m^2 (45lb/ft^2) and a snow load of 300kg/m^2 (65lb/ft^2). In some cases extra stainless steel or nickel wire netting can be useful to reinforce the system. Therefore, designer should be aware of annual wind measurements in the design process. Wind tunnel tests are important in this manner. Besides IPS is hail resistant. According to the Foiltec pillow structures are resistant to hail attack proved by SIA 280.

In case of an earthquake or a structural movement pillows can absorb some the deformation, buckling nature of the pillows saves people under the structure from falling parts of any broken glazing.

Finally the ETFE foil is highly electrically insulating, so that the material is frequently used for industrial applications (Buitink-Technology). Thus, it is commonly preferred for insulating wires, cables with the materials high electrical characteristics (www.ersinger.com).

3.5.5. Humidity Control

The reason of the condensation on the surface of the glazing depends on the temperature differences of glazing surfaces and the moisture level. Constant flow of air or a wind commonly prevents the existence of humidity that may happen on the surface of the glazing. IPS has an advantageous position with its air filled nature. The temperature of the air in the chambers of the pillow may minimize the huge temperature differences. Flow of air does not let the moisture stack on the foils.

Addition to that, condensation that may exist on the surface of the foil can be avoided by arranging the humidity. As the internal air temperature of the foil is usually similar to the internal air temperature of the enclosed space, condensation does not occur on the surface of the foil. As a precaution dehumidified dried air is inflated through air pipes. Besides this HVAC calculations should be made for the fold air exchange per hour for a single pillow unit.

Where a permanently high level of humidity exits as in swimming baths, condensation within the pillows can be avoided by ensuring a constant flow of air through them. Special channels should also be incorporated into the construction to drain of the any condensation that forms on the internal face.

3.6. Usage Of IPS As Glazing System

According to the worldwide manufacturers of the foil, it has been used for several industrial applications of fluoropolymer**.** Architectural fabrics, automotive materials, cabling materials, food processing, pharmaceutical and biotechnological manufacturing, and semiconductor manufacturing are the areas of study for manufacturers.

There is a very wide range of architectural applications for the pneumatically supported pillow system, including basically the following:

- Institutions, hospitals, education centres
- leisure and sport centres swimming-pools, tennis and football stadiums
- tropical environments greenhouses, zoos
- shopping malls, office buildings, atriums
- skylights and canopies

Although in various sources the usage of the system described as a cladding type, pillow structure is used as a glazing system as previously explained in section 3.4.3 of the present study.

Fig. 3.47. Mobydick Bath in Rülzheim
Source: www.membranstatik.com

3.6.1. Advantages Of IPS

Using partially of fully as a building envelope, IPS made of ETFE foil will bring several advantages and opportunities to the designers. These advantages can be explained by means of their structural and aesthetical contributions and their effects on cost.

IPS is basically a pneumatically supported membrane system. Therefore it can be considered among other lightweight systems. Lightweight nature of the membranes, coupled with the lightness of air as supporting system, makes the pillow structures very important glazing systems for the contemporary architecture. Furthermore flexibility of the membranes saves optimum applicability in terms of double-curvatured design. Both flexibility and lightness obtains a deduction in the total weight of the structure, from roof to the foundations. Relatively low weight of the structure results as a less material in order to support the system and resist vertical and lateral loads. This also means narrower structural members. System is also ideal for retractable structures.

Addition to this flexibility and lightness ensure a safer structure. Structural movements like earthquake can be easily absorbed or diminished by structural members. Similarly wind and snow loads are treated to lateral and vertical loads dampen loads. Because of the reduction in load that is transmitted to the main structure, IPS maintains narrow and less load-bearing materials for buildings. Furthermore because of the flexibility of the pillows, there will be less or no need for the movement joints. In case of a structural collapse lightweight envelope causes less harm or damage, which is very important for human life. Another advantage of the ETFE pillows occurred by their high fire security performance. Pillow structure saves human life by postponing the structural collapse in case of a fire inside the structure. ETFE foil does not allow hot droplets which is expected for most building regulations. ETFE foil has a wide service temperature, which makes it ideal for warm climate applications.

Pillows that are made of ETFE membrane can be used in large sizes. Up to 25m pillows can be manufactured. The increase in area covered with pillow causes less connection and less detail. It also ensures less structural shadow inside the structure. Less connection details enables better insulation in terms of weather and water penetration. Gaskets are not needed in clamping systems. That also prevents heat flux between inside and outside.

Addition to that less details, increases the applicability of the system by non-experienced workers. Therefore experienced worker need and labor time can be reduced. All these structural advantages of the systems enable a cost efficiency, which is very important.

Other structural advantages of the system related with the ETFE membrane, can be explained as its long-life and self-cleaning property of the pillows. Pillows have an expected life of up to 60 years. Due to its non-stick property, pillows don’t need frequent cleaning. Rain cleans dust and other dirt away. Regular cleaning is offered between 5-10 years, due to environmental conditions. In case of damage, although little holes do not propagate, pillows can be repaired by tape or could be easily taken out of the clamps to reinstall a new pillow. Thus, maintenance of the system is relatively easy, and cost beneficial in comparison with other glazing systems. High elongation property of the ETFE prevents people from the effects of the bomb blast.

The material is recyclable. ETFE can be melted and produced again with adding virgin products with a very few energy. Therefore it can be reused when needed. It is not a petrol-based product whilst not harmful to the environment. The low embodied energy of the pillows saves and environmental cost for the human life.

The pillow structure made of ETFE foil has also advantages in terms of environmental control criteria, as they are comprehensively explained in Chapter 3.5. Pillow structure has a very high light transmittance. The advantage of the light transmittance obtains an extreme deduction in electricity expenses. It is also permeable both UV and visible light. Pillows are advantageous for gaining high UV light in terms of photosynthesis. So that crop or harvest production increases. ETFE foil can also be printed with color and graphics that reduces light and heat gain. Thermal properties of the pillow systems are absolutely better than the single glazing. Due to application and the design of the pillows thermal transmittance coefficient can be decreased. That saves a deduction in heating and cooling expenses. Because of the nature of the membrane, it is acoustically soft, does not reflect the internally generated noise to the back inside. Therefore it is not needed to use expensive sound suppressors.

Most of the structural properties of the IPS and the ETFE foil cause cost conservation in overall structure, in its life cycle. Besides that advantageous of the system, IPS pillow saves elegant view with its unique transparency.

3.6.2. Disadvantages Of IPS

Acoustically soft nature of the foil transmits the externally generated noise. The low thickness of the material results as a low acoustical reduction index. Traffic noise and rain noise can be felt inside the building heavily. Therefore it could be needed sound dampers or a second tough skin to be applied. Unintelligent use of pillows may result as a cost consumption for additional sound suppressors.

The pillows are vulnerable by strikes on purpose. The direct attacks with a sharp edge objects will damage the foil. Environmental affects sometimes may destruct the pillows. Sharp sticks and tree branches may also puncture foil. Although the stickers made of the same material, can be a way of solution, serious damages and scratches have need to replaced by a new pillow.

Although the ETFE foil has a high melting property, membrane could be loosening at 60^{o}C and softening at 200^{o}C. Therefore it not recommended for very hot climates.

Another obstacle for the use of pillows is the feasibility. In order to get better thermal properties (U-values) 4 and 5 layer applications may be used. But this results a change in frames and the structural system. Profiles and the substructure obtain structural shadow. Thus, use of 4 and 5 layer pillow structure affects total cost. In other words, the more layers you take the more expensive it is. Addition to that the evaluation of the system depends on the progress in the clamping and framing system. Profiles may cause unwanted thermal bridges. To avoid heat loss through profiles plastic based clamping stripes should be used in any case.

Although the energy can be saved by solar batteries, if electricity goes off the system will need an extra supplier or mobile electricity generators. Therefore systems should have a stock generator whether it can be needed or not. That is one of the common disadvantages of the pneumatic systems.

Besides that whether the building in use or not, pillows need continuous inflation, and so that system goes on consuming electricity which is almost 50 Watts per hour.

3.8. Production And Manufacture of Inflatable Pillow Systems

There are number of ETFE foil producer in world. These companies produce fluoropolymer for a wide range of industrial applications, from architectural fabrics to semiconductor and pharmaceutical and biotechnological manufacturing. Although the architectural membrane foil that produced is almost the same, their trade names differ among companies.

ETFE sheeting is manufactured in three main stages – polymerization, granulation, and extrusion - before it is tailored into its final form. According to Robinson-Gayle et. al. (2001) ETFE is manufactured from fluorspar, hydrogen sulfate and trichloromethane (CaF_2, H_2SO_4 and $CHCl_3$). The fluorspar or fluorite is the largest natural store of fluorine; it is found all over the world and is often mined in conjunction with limestone. These raw materials are used to make chlorodifluoromethane, a class II substance under the Montreal treaty on ozone depleting substances that does not contribute to global warming. This undergoes pyrolysis at 700^{o}C to give CF_2=CF_2 which can be polymerized using US patent no. 4016345. The by-products of this process are $CaSO_4$, HCl and HF. The calcium sulfate and hydrogen fluoride are used to make more fluorspar and the other waste products are incinerated. The polymerization process uses water and a dispersing agent this process is carried out at approximately 125^{o}C.

Robinson-Gayle et.al. explains that ETFE is sold in granules by manufacturers, it is heated to its softening temperature of 170^{o}C in the hopper of an extruder. The extrudate is then blow moulded into large sheets 50-250μm thick. Sheets can be produced in thicknesses up to 250um and with a maximum width of 1.55m. The sheets are heat welded together to form the multilayer pillow. The inflated pillows are suspended in aluminium or steel frames. The finished pillows ready for installation on site require a tenth of the energy to transport when compared with similar construction in glass due to its much lower density.

The raw material is admitted under the Montreal Treaty and is not a petrochemical derivative. The production process is an enclosed water based process and does not involve the use of any solvents. In addition to that the process used to manufacture the pillows does not require any additives to the co- polymer system and other products are not mixed. According to Robinson-Gayle, (2001) pillows can be directly removed from it frame and washed. It can be recycled by heating it to its softening temperature after cleaning process. The softening temperature is low so that it is not a very costly operation. The material is therefore recyclable and many components are produced from recycled material by adding virgin ETFE into the process.

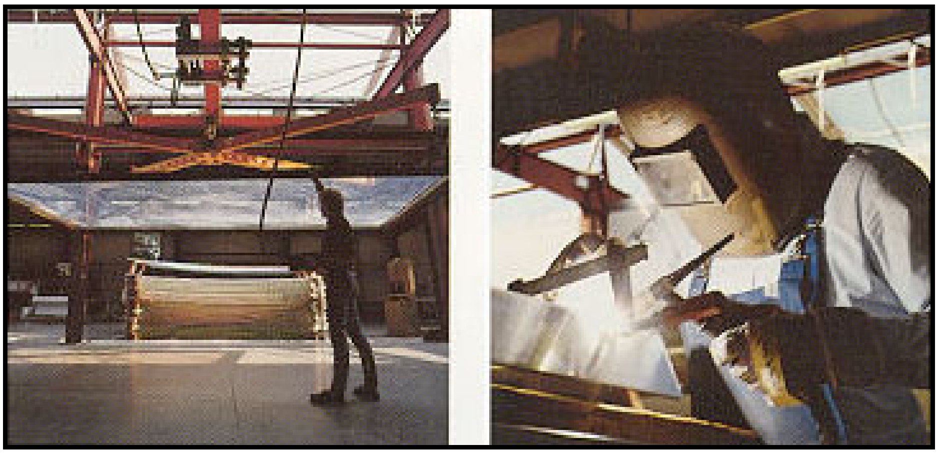


Fig. 3.48. Assembling Pillows And Frames
Source: www.texlon.ch

The pillows are laser cut on a computer controlled vacuum plotter in the world. Therefore problems, which can be occurred due to shrinkage, can be minimized. However the pillow, which is not provided by computer calculations may be inflated by pressure. But for the right inflation size, foil has to be cut with calculations. In other words; any rectangular shaped frame glazed by irregular shapes of foil. Tensys manufacturing firm explains that with appropriate software programs it is possible to develop wrinkle-free surfaces, even when inflated with in highly non-planar boundary frames. (www.tensys.com)

Fig. 3.49. Computer Aided Manufacturing
Source: www.nowofol.de

Pillows can either be completely prefabricated in the factory or can be clamped into their supporting framework on site. For instance; ETFE cladding of the Eden biomes. The lightweight structure weighs less than the air it contains. Due to techniques used in construction site it is possible to make a scaffold free erection. Vector explains that workers peaked at erecting $1000m^2$ a day during the height of the erection period, which saved time for other applications in the construction site. On the contrary Temiz, (2003) explains that comparing to IPS, element façade system which is the most prefabricated system among glazing systems, allows a maximum erection almost $200m^2$.

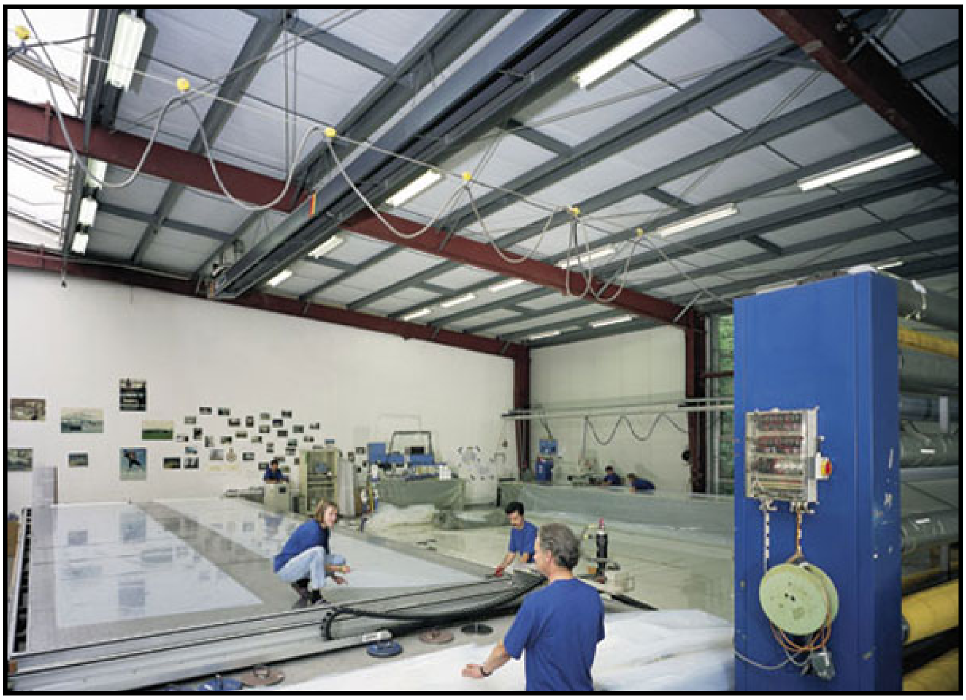


Fig. 3.50. Production Hall of Tensys Company
Source: www.foiltec.de

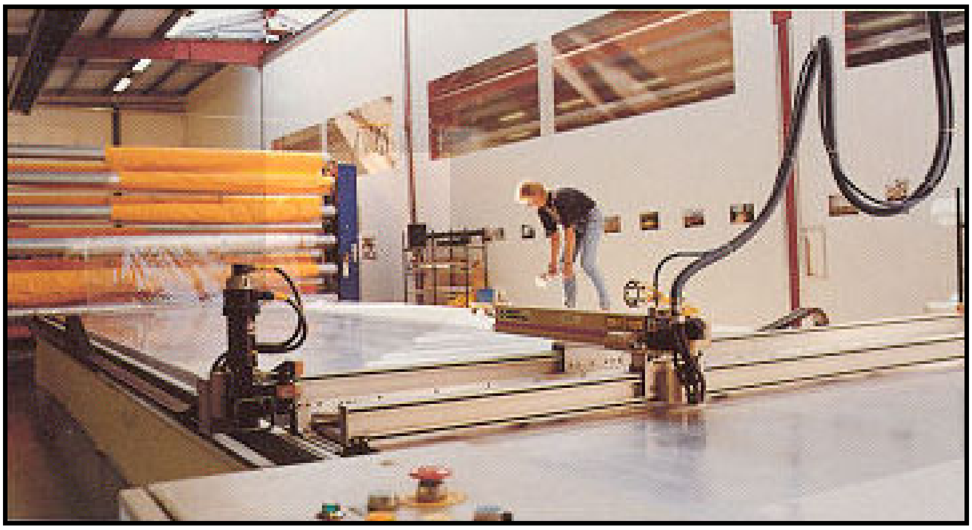


Fig.3.51.Production Hall of Texlon Company
Source: www.texlon.ch

Fig. 3.52. Application Of IPS As A Skylight
Source: www.buitink-technology .com

Fig. 3.53. Application Of IPS And Bird Protection String Around The Frame
Source: www.buitink-technology .com

Chapter 4

APPLICATIONS OF THE INFLATABLE PILLOW SYSTEM

This chapter gives brief information about applications, which were built after 1990s'. Applications are selected around Europe. They are mostly constructed in United Kingdom and Germany.

Previously determined contemporary applications are as below:

- Eden Project
- Hellabrunn Zoo (Lion House)
- Westminster Chelsea Hospital
- Festo AG
- National Science and Space Center
- Allianz Arena Munich Stadium

4.1. THE EDEN PROJECT (1995 - 2001), Cornwall, UK

Fig 4.1. The Bird-Eye Of Eden Project
Source: www.edenproject.com

Client	*Eden Project Ltd.*
Architects	*Nicholas Grimshaw & Partners:*
Structural Engineer	*Anthony Hunt Associates*
Steelwork Contractor	*Mero UK (biomes); Snashalls (visitor centre); Pring & St Hil (biome link)*
Design and Build contractors	*McAlpine Joint Venture*
Services Engineer	*Arup*
Cladding Consultant	*Arup*
M+E Subcontractor	*Colston*
Subcontractors & Suppliers	*ventilation air duct systems; roof and glazing to visitor centre and biome link Allan Roofing & Glazing Systems; glass louvres on biomes Levolux A T, M & V, Germany; fixed glazing on biomes Mero/Foiltec (UK Offices)*
Contract Value	*£ 75 million size 23,000m^2*

DESIGN

The Eden project, housed in a former china quarry in Cornwall, is a giant botanical garden. Project was the brainchild of architect Tim Smit, who is now the chief executive of Eden. The project idea has adapted the principles of the Agenda 21, which were established at the United Nations Conference for Environment and Development in Rio in 1992. As explained in various sources; project conceived to "promote the understanding and responsible management of the vital relationship between plants; people and resources, leading towards a sustainable future for all."

The idea of this project was simple: to create a world-class tourist destination that would tell the story of humankind's relationship with plants. Visually it had to provide a spectacular theatre high enough to house the towering trees of the rainforests, wide enough for the sun-baked escarpments of the Mediterranean. This construction’s phase 1 is completed in May 2000 and it opened in March 2001. The Eden Project is the world's largest self-supported transparent envelope, with individual panels up to 860 square feet in area. 232 panels are intelligently controlled and operable for ventilation (www.burohappold.com).

Project architects, Nicholas Grimshaw & Partners based their design around the geodesic dome, brainchild of the visionary architect Richard Buckminster Fuller, who is dreamed roofing over entire cities to create new and exciting living spaces. The geodesic principle, which involves joining together flat surfaces to form a curved shape was the space frame specialist Mero (UK)’s idea. A geodesic line is the shortest distance between two points on a curved surface and provides the platform for true freeform architecture. To further strengthen the hexagons, separate diagonals connect the node points of the layers together. According to Barker, structure of the Eden Project is the first of its kind on this scale in the world, is called the "hex-tri-hex" (Barker, 2001).

Barker (2001) explains that, the indoor structures were to be giant conservatories called "biomes," which would be built on the side of the south-facing slopes of the clay pit, providing a natural presentation arena for the plants. The structure comprises three biomes, areas designed to represent three distinct climates found around the world. Each biome comprises four domes, strengthened by steel arches where they intersect. The shape provides maximum size and strength, using minimum steel and hugging the contours of the clay pit's varying contours (Barker, 2001).

The domes of the Eden Project are the largest geodesic domes built yet, reaching 60m in height in places and spanning enough land to house 29 football pitches. They are made of lightweight galvanised steel tubing of varying sizes, created and cut by a computer Stretching over 26,000m^2, the project comprises of eight geodesic domes forming two biomes for trees and plants (www.arup.com). There is also an outdoor biome, a visitor centre, an outdoor amphitheatre and an access road. The visitor center is the entrance to the complex. Inspired by the laws of nature, the structures are made up of connecting hexagons, pentagons and triangles, forming a sphere.

The project includes two indoor environments, one for humid tropics and the other to house a warm temperate climate, along with the extensive outdoor garden for cool temperate plants. The Humid Tropics Biome is a multi-domed greenhouse that recreates the natural environment of a tropical rainforest. This larger biome covers 15,590 square meters or 1.55 hectares and is 55 meters high, 100 meters wide and 200 meters long (Barker, 2001). Warm Temperate Biome is 6,540 square meters or 0.65 hectares in area, 35 meters high, 65 meters wide, and 135 meters long (Barker, 2001). Roofless Biome is an open area with varied plant life from the temperate Cornwall area.

These biomes are accessed via a visitor centre and link structure. “The Link”, a grass-roofed building that blends into the surrounding landscape, giving the impression that the biomes rise out of the ground. It is basically two structures in one, providing a corridor linking the biomes as well as an exhibition, refreshment, and toilet facilities area. The Link is sunk into the landscape, with the dining areas fronted by a sweeping glazed wall shaded by louver screens (Barker, 2001). Link is a low-tech building, which was conceived as a complete contrast with the space-age biomes.

This building is even designed so that it can change over time. The ETFE pillows are built to detach easily from the steel frame, so they can be replaced should a more efficient material come along.

Fig. 4.2. Fan coils inflation equipments and ventilation blinds
Source: www.eden-project.co.uk

According to Arup, who did the environmental engineering, Eden project places its focus upon the environment and sustainable energy. Photovoltaic and solar power are used to pump air into the ETFE cells and solar panels provide water to the visitor centre (www.arup.com).

The heating of the biomes is assisted by the insulating quality of the ETFE panels. It is also facilitated by sustainable climate control mechanisms, whereby the heat of the sun is stored in the thermal mass of rock upon which the domes are constructed. This regulates the daily temperature and can radiate heat during the night (www.arup.com). Heating is provided from large fan heaters, which are supplied with hot water by an underground heating main. The direction, strength, humidity, and temperature of the airflow is controlled by computer software. It controls the openings at the top and bottom of the domes. Hot air is dispersed via the top and replacement cooler air is drawn in at the bottom (www.architectureweek.com).

FOIL PILLOWS

Williams (2002) explained that the sizes of the structural members at Eden would have been prohibitively large to support a traditional glazing solution and transparent plastics would have degraded and could not have supported the geometries involved.

The Eden Project designers formed ETFE material into extremely sturdy pillows, each made from three sheets of ETFE foil welded together along the sides, one on top of the other, with layers of air pumped in between them. In this greenhouse project NOWOFLON®ET-film is used to cover completely with pneumatic pillows (www.nowofol.de). Thus, biomes covered with 2 m deep inflated pillows with diameters of between 10 and 11 m made up of three to four layers of ETFE. Each pillow is attached to a web of interlocking steel tubes. Each dome actually has two web layers, one with hexagonal and pentagonal panels and one with triangular panels. The hexagonal and polygonal pillows of ETFE consist of three or four layers into which air is pumped by a solar-powered heating system. Once inflated the pillows provide more insulation than glass could. The total Eden structure uses 625 hexagons, 16 pentagons and 190 triangles. The air layers provide increased insulation without decreasing the amount of sunlight that shines through. The most important thing about these ETFE pillows is that they are adjustable: On a colder day, they can be pumped up with more air to provide better insulation; on a hotter day, they can be partially deflated to allow more cooling (Harris, 2001).

Fig.4.3. Interior View Of The Eden Project
Source: www.edenproject.com

Fig.4.4. Foil Pillows Of Eden Project
Source: www.edenproject.com

STRUCTURE

After conceiving a couple of alternatives of Victorian style structures applicated before as in Waterloo Station, Eden's designers decided not to use traditional materials and structures in this greenhouse project. Geodesic dome structure is the best solution to meet the contours of the site without so much afford and change in the topography. Mero (UK), Nicholas Grimshaw and Partners, and structural engineer Anthony Hunt Associates worked together to develop these series of intersecting domes. They realized that conventional cladding material; glass was too heavy, inflexible, and dangerous for this application (Barker, 2001). The hexagonal primary structure, designed by Grimshaw and Hunt, consists of a tubular steel space frame connected by means of standard node elements. Other than the nodes, there is an inner net based on a triangular and hexagonal grid. The structure is, therefore, resolved in smaller units, which reduces the weight and thus facilitates transportation along the narrow lanes of Cornwall (Detail, 9/2000).

The inspiration for the junction was again found in the natural world: Whalley refers to the way in which dragonflies' wings - lightweight skin composed of a hexagonal cell structure - are connected to the body. The decision to adopt a more freeform structure made it possible to keep a pace of the changing state of the pit: if the sides of the quarry moved, the domes could simply be reduced or increased in size. Whalley says; “The hexagon appears again and again in nature. Think of flies' eyes or honeycomb. It is the most efficient shape, in that it minimises the tube lengths in comparison with the surface area” (Allen, 2001).

As in case of Eden Project, designing these sort of domes, which should follow the contours of the site, is a geometrically hard exercise. Eden's designers describe the domes as giant bubbles that can be set down just about anywhere. One advantage of this geodesic dome shape is that it adapts easily to most ground surfaces. In geodesic domes, the loads are not transmitted to the ground as point loads via columns, but in a linear form along the entire perimeter of the structure, thereby eliminating the need for costly deep foundations. Only a minor remodelling of the site was necessary, since the dome structure can dip into the uneven topography at almost any point (Detail, 9/2000).

Fig.4.5.Ventilation Louvers Of Eden Project
Source: www.edenproject.com

Fig.4.6. Foil Pillows Of Eden Project
Source: www.edenproject.com

The steel frame of the geodesic dome is incredibly strong relative to its weight. This weight (667 tons) is dispersed evenly throughout the entire structure so that the dome only needs support around its base, leaving lots of room for the plants inside. The edges of the dome rest on a sturdy foundation necklace, an underground concrete wall around the perimeter of the structure. (Harris, 2001).

The structure was further refined by introducing an inner layer, which meant that member sizes could be reduced from as much as 500mm in diameter to less than 200mm. At the point where two spheres of different sizes meet, the hexagons change shape to allow members to join the steel arch trusses, which form the primary structure linking the domes (Allen, 2001).

The structural frame of the biomes is a three-dimensional space frame in circular hollow sections. The frame comprises an icosahedral geodesic outer layer with an inner layer of hexagons/pentagons and triangles. The centre points of the outer layer define the hexagons/pentagons of the inner layer, which form triangles under the outer frame nodes. Separation of the two layers is by circular hollow sections connecting the nodes of the hexagons/pentagons (Allen, 2001).

The frame spans from front to back on to anchored reinforced concrete strip foundations. Structural stability for each of the biomes is afforded by the shell action of the combined intersecting domes, anchored to the foundations by pinned connections. Around the perimeter of the spheres the inner structural members are brought out to meet the outer members, forming pinned connections to the foundations. The roof structure is designed to accommodate the forces and movement due to temperature effects by 'breathing' alone. Because of the nature of the pillow system there were no need for the movement joints within the roof structure (Allen, 2001).

The biomes were erected with a combination of cranes (static and mobile) and scaffolding. The scaffolding made the Guinness Book of Records. At 58.5 meters, it was the highest freestanding structure in the world. The scaffolding also broke the record for the largest volume in one structure, at 195,600 cubic meters. The ETFE pillows made and fitted by the German company Foiltec, were installed by construction workers using mountain-climbing techniques (Barker, 2001).

Fig.4.7. Construction Phase Of Eden Project (1)
Source: www.edenproject.com

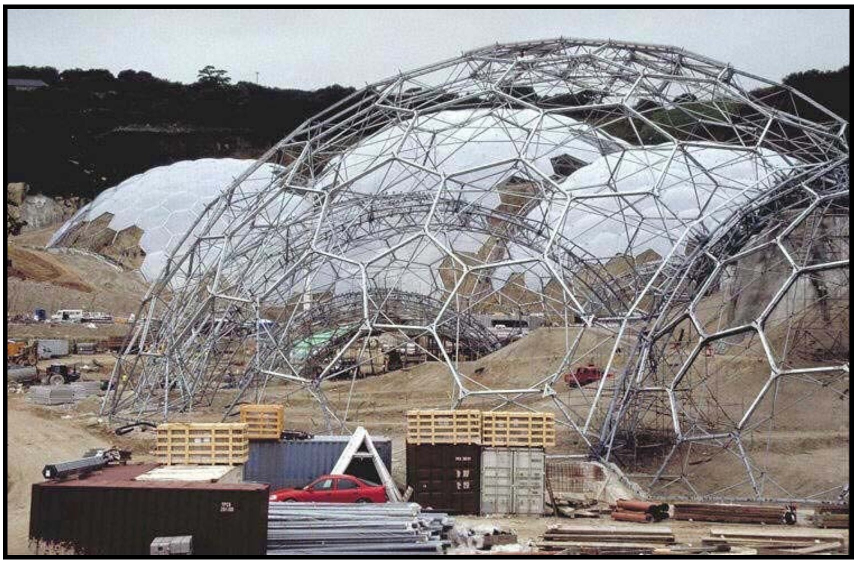


Fig.4.8. Construction Phase Of Eden Project (2)
Source: www.edenproject.com

4.2. HELLABRUNN ZOO (JUNGLE HOUSE), Munich, Germany

Fig. 4.9. The External View Of Hellabrunn Zoo
www.pfeifer.de

Client *MunchenerTierpark Hellabrunn AG*

Architects

General **:***Buro Herbert Kochta Architekt BDA, project architect E.Lehner*

Landscape architect : *Büro Teutsch + Partner*

Cable net structure : *Büro IPL-Ingenleurplanung Leichtbau*

Structural engineering

Cable net and membrane: *Büro IPL-lngenieurplanung Leichtbau (design); KOCH HighTex GmbH (general contractor); Schlaich, Bergermann + Partner (in cooperation with the contractor)*

Reinforced concrete structure and substructure: *lngenieurburo Dieter Herrschmann*

Specialist consultants

HVAC **:** *lngenieurburo Bergbauer*

Thermal/moisture insulation **:** *Prof. Schaupp, GrUnwald*

Term planning, site supervision **:** *lngenieurbUro Zinner & Sohn*

Installations **:** lngenieurbüro Bergbauer

Electrics planning **:** *lngenieurbüro IBE RoIf Günther*

Contractors

General contractor & roof **:** *KOIT HighJex GmbH*

Facade **:** *Glasbau Seele*

DESIGN

The Hellabrunn Zoo, which is situated in Munich Zoo at the foot of the Harlaching hill in a landscape protection zone, is completed in 1995. As a novel zoo concept, visitors separated from animals only by glass panes. So that, animals can move around freely in natural setting. A little stream with waterfall, walk-on 'hills' and sumptuous tropical and subtropical vegetation create the impression of a visit to the jungle.

This building has an octagonal plan, which is symmetrical about one axis and defined by curved edge cables. The covered plan area of this building is 1140 m^2. Two visitors entrances are situated on the northwest side and animal boxes for large carnivores are arranged along the facades, some of them having access through the facade into open-air enclosures. On the longitudinal side facing the entrances lies an artificial planted hill. There are number of bird boxes and other ancillary rooms are located together with the delivery entrance under this hill. In the middle part, on both sides of the mast foundations, there is a plant area without underlying ground slab.

STRUCTURE

For the natural growth of the plants and their protection from parasites and diseases maximum levels of UV-light are necessary. In addition to that, the minimum temperature may not drop below 12 ^{0}C. These considerations require investigating of wide-span structures and transparent cladding systems in design stage of this building. At the end, the solution of a cable-net roof emerged with a cladding of pneumatic foil pillows.

In the Jungle House, two 17-m high masts carry the pre-stressed net structure, which are made from high-grade steel cables with a mesh width of 2 x 2 m. This two cable-braced tubular steel masts; a straight compression tube is stabilised through a three-chord tie bracing of round steel bars with star shaped spreaders. These spreaders made from short compression struts and arranged along the mast length. While at the masthead, the ridge and eye cables are connected, which at the same time laterally support the mast tip; at the base, the masts are pin-supported on the reinforced concrete substructure. The edge masts consist of simple tubular steel columns. Briefly, the structure is composed of double radial cables (ϕ 18 mm) and single hoop cables (ϕ16 mm); at the top it is supported by four ridge cables (ϕ32 mm), held at the edge by edge cables (ϕ 36 mm) and anchored at its eight corner points by masts, guy cables (ϕ36 mm) and injection anchors.

This structural system and foil pillows are resistant to external loads such as snow and wind loads. Snow loads are carried by the internal pressure into the lower foil of the pneumatic pillows and into the radial cables of the net, which introduces its load mainly into the ridge cables connecting the masts. The statutory snow loads to DIN 1055 were fully allowed for in the structural calculations. Wind loads are carried by ring and radial cables into edge cables and substructure. The net cables are joined through movable high-grade steel cable clamps, onto which the edge clamping arrangement of the pillows are fastened. The pillows have been developed into cutting patterns along edge and surface seams and are connected via a boltrope edge and by special aluminium-edge profiles to the cross clamps of the cable net and to the edge cable clamps. The cable clamps of radial and ring cables are connected with a central bolt and are free to rotate, so that the mesh angles can adjust freely to adapt to the three-dimensionally curved cable-net surface.

The net edges are 3.5 m above the ground; there the net cables are equipped with a swaged closed cable fitting which is pin-joined through a flexible one-bolt connection with two forked connecting elements, which in turn are fastened to a two-piece, circular edge cable clamp. At the net corners the edge cables are connected via fork fittings directly to the head plates of the edge masts. The four ridge cables running from one masthead to the other are joined at the junctions with the radial net cables through a welded cable clamp. The net cables are connected to its lower plate stiffener by a swaged fork fitting and a flexible one-bolt connection. Under the ridge cable and suspended from it run a cable tray and the supply pipes for the pneumatic pillows. The ridge is closed on top through a grating, serving as a service walkway, and by a double-layer of ETFE-foil above it connected with the membrane pillows along their edge. This unorthodox solution allows walking on the ridge and at the same time provides a transparent and thermally insulated ridge covering. The ridge cables are continued on the other side of the mast down to edge guys, forming eye shaped openings, which are closed with mechanically operated ventilation louvers.

Fig. 4.10. Hellabrun Zoo Interior (1)
Source: Schock, 1997

Fig. 4.11. Hellabrun Zoo Interior (2)
Source: Schock, 1997

CONSTRUCTION

For the installation of the roof structure scaffolding was erected in the interior. After positioning of the masts, the cable net was assembled on the scaffolding from single cables connected at the nodes by cable clamps and raised gradually. However, the edge areas inaccessible from the scaffold had to be worked from the net. The net was pre-stressed from ridge and edge cables to 8 anchor points. The prefabricated pillows were fixed first along one side of the High-Tex cushion profile, rolled out sideways, tensioned and finally fixed on the other cushion side. The entire construction period totalled 3 years.

FOIL PILLOWS

The pneumatic foil cushion system is most suitable system for this building. An alternative cladding system exploring overlapping small polycarbonate panels had to be excluded because of its large air permeability and the resulting unsatisfactory thermal insulation.

The foil pillows are composed of two fluoropolymer foils (t = 0.2 mm). This roof allows photosynthesis to take place and temperature to be controlled. The translucency of the roof structure is important for plant growth totals approx. 90%. Besides that, the translucency of the foil itself in the UV ranges amounts to 96%. The 64 wedge-shaped pillows (max. b = 2.5 m, max. I = 18 m) are filled individually with dried and purified outside air via separate, flexible and closable cushion feeds through a pressure pipe running along under the ridge, which helps to prevent condensation and to preserve the translucency of the pillows.

The inflation pressure varies according to the external loading, wind and snow, and is controlled by a computer system, which can compensate minor damage of the membrane through a pressure increase. The pressure normally amounts to 250 pa and can be increased to 350 pa if required. For the inflation of the pillows altogether 4 fan units are provided, with one main and one reserve blower. The latter serve to ensure the safe working of the system even in case of breakdown of a main blower, and also serve to increase the air volume in case of damage to the membrane. The air supply is controlled centrally using an anemometer located at one of the masts.

The wind and rain-proof connection of the foil cladding with the heated steel and glass facade must be able to tolerate large deformations of the roof, e.g. under snow load. The connection is made through curved tube pillows, which are fastened to the upper edge of the facade, held in position with cables and pressed against the roof pillows by their inflation pressure. In addition to the air supply controlling the pressure, relief valves are installed, which open at a sudden pressure increase under load and thus allow a fast pressure adjustment. A further internal sealing tube, running parallel to the edge belly cables provides an almost perfect air seal and at the same time prevents the escape of small tropical birds.

The aluminium edge sections, which hold the transparent foil pillows at the edge, proceed from the ridge radically down to the lower net edge. These High-Tex-aluminium extrusions, which are consisting of three principal aluminium extrusions and an extruded cover strip section, are bolted directly onto the radial cables. The ring cables are connected with a spacer piece to the radial cables underneath and are located under the foil pillows, so that these can deform unhindered under load. The 'belly cables' common in earlier cushion structures were not used here. They are, however, used along the edge, to hold the sealing tube in place.

VENTILATION

On two sides of the masts ventilation ducts proceed to the air intake funnels located at the mastheads. In the winter months, these air intake funnels serve as forced ventilation and the air speed had to be kept much lower than in similar ventilation systems. Through the funnel shape the air cross section is expanded which decreases the air speed. According to the HVAC calculations a 10.5 - fold air exchange per hour is sufficient for the single cell cushion roof, so that even given extreme outside temperatures the inside temperature does not move outside the required tolerance band. On the other hand, during the summer months, the building is ventilated by natural stack effect through two large net openings. They consist of lens-shaped areas cut into the membrane and closed by acrylic glass louvres individually supported by stainless steel brackets sealed to each other. They can be moved continuously and have their aperture angles regulated electronically. The system can be opened so that the entire net eye area is available as a ventilation opening.

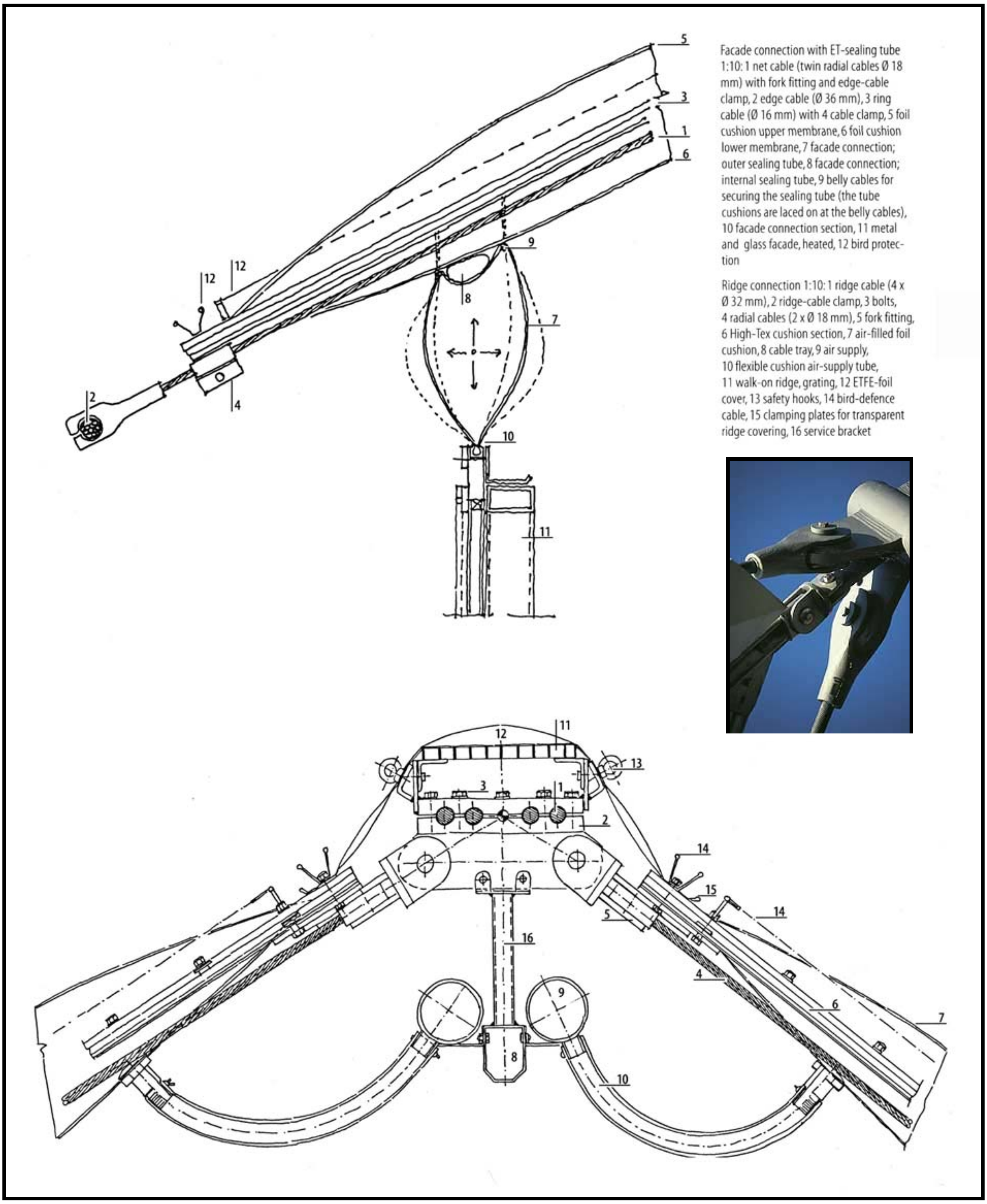


Fig. 4.12. Detail Of Cable Net Structure
Source: Schock, 1997

4.3. WESTMINSTER AND CHELSEA HOSPITAL ROOF, London, UK

Fig.4. 13. Westminster & Chelsea Hospital
Source: www.foiltec.com

Client	*Northwest Thames Regional Healty Authority*
Architect	*Sheppeard Robson Limited*
Structural Engineer	*Buro Happold*
Atrium Roof contractor	*Sheetfabs, Nottingham*
Texlon Foil supplier	*Vector Foil Ltd, London*

DESIGN

Glass is the usual choice for the transparent material of an atrium roof. However, it is heavy, especially if double-glazing is needed to reduce heat losses, and a substantial structure is needed to give a glazed roof sufficient strength and stiffness. At the heart of the new Westminster & Chelsea Hospital is a vast barrel-vaulted atrium, 116 metres long and 85 metres wide, with four transepts. In view of the large area to be covered it seemed likely that recent developments in the field of lightweight structures might present some alternatives to the traditional glazing solutions (Interaction).

It is interesting to note that the principles and logic behind this roofing system are virtually identical to Paxton's glazed ridge-and valley system which he developed for the Crystal Palace roof (except for the pneumatic element). But it is in the nature of any innovation, then, as now, that it is not possible to predict at the beginning of a project what the most suitable design will turn out to be. On this project, considerable time and effort for design development was needed in the early stages to achieve an original solution, which would finally bring substantial benefits compared with conventional roofing systems. The risk in such an investment in resources is inversely proportional to the level of confidence in the skills of the design team (Interaction).

Fig. 4. 14. Internal View Of Westminster & Chelsea Hospital (1)
Source: www.foiltec.com

Chelsea and Westminster Hospital, is the largest hospital in England that is serviced in July 1992. A key feature of the design is the arrangement of the main buildings around a large central atrium. The atrium unifies and organizes the entire complex with light and warmth, and is the largest naturally ventilated atrium in the world (www.burohappold.com). This atrium not only creates a flexible internal space at the heart of the building, but also greatly reduces the area of the wall cladding exposed to weather. For this space to be successful, the roof had to be capable of allowing a high percentage of natural light passes through into the rooms adjoining the atrium as well as down to the ground floor. This building utilizes segments of transparent, translucent, and operable foil panels to create a natural and cost-effective lighting and ventilation scheme (www.vector-foiltec.com).

STRUCTURE

Buro Happold used a rigid frame and foil system for the RHWL's Westminster Chelsea Hospital atrium roof, with an overall nave and crossing transepts and with short spans of approximately 20 meters (Robbin, 1996).

The atrium space is 116 m long with an aisle 18 m wide running the full length with four cross transepts increasing the width to 58 m in each case. Consequently, the roof could be arranged to span the 18 m distance across transept and aisle with additional structure required only at the junction of aisle and transept. As Cook (1994) said, the structure is designed to act as a series of three pin arches spanning across the void, springing from a perimeter gutter beam. This beam resolves thrusts by spanning horizontally between internal or external corners of the roof where the reaction is carried in vertical bracing. The gutter is held above the general building level by means of steel struts, allowing ventilation louvers to be installed within the perimeter frame. Aisle arches meet transept arches along diagonal valley lines. Local horizontal thrusts at these corners are resolved by horizontal cross struts, which connect across to diagonally opposite corners in the perimeter gutter beam.

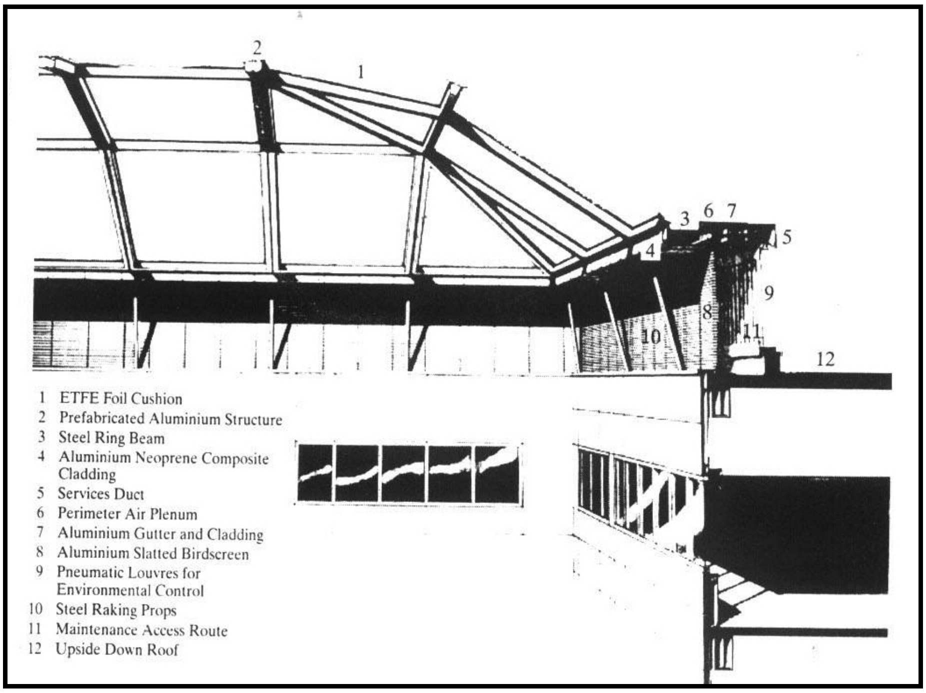


Fig.4. 15. Section Drawing Showing Components Of Atrium Roof
Source: www.foiltec.com

The roof form adopted to provide structural support for the foil pillows is a series of barrel vaults along the aisle and transepts with each barrel being terminated in a curved end section. Taking due allowance of the size to which the foil panels can be produced, the support structure was provided on a grid approximately 4 m X 3 m. (Cook, et al., 1994).

The arches themselves were developed to provide integral fixing flanges for the pillows and a simple erection technique with a minimum of complex connections on site. Half arches were made up as frames, each of which could carry two foil panels. Members along the side of a frame are half of a box arch member, which is bolted to the other half member of an adjacent frame once on site. Each frame is itself stable once the opposing frame is installed to complete the arch. Prefabrication of units such as this reduced the problems of tolerance for the fit up of the pillow panels and reduced the number of site connections required (Cook, et al., 1994).

The frames were designed initially on the basis of using glass reinforced poly-ester resin (GRP). This would have provided a smooth self-coloured surface and would avoid the need for exposed nuts and bolts if local site lay-up were permitted at joints. GRP does not corrode and degradation could have been avoided by addition of sufficient LV inhibitors and additional weathering resistance to the external gutter surfaces between panels. The flexibility of GRP in comparison with steel or aluminium was not significant as the cladding system is tolerant of movement. CRP allowed a reasonably complex arch section to be developed incorporating flanges for fixing the foil pillows and the air supply lines for the pillow (Cook, et al., 1994).

The very low weight offers enormous potential to achieve both lightness and economy in the supporting structure. Both glass-reinforced plastic and aluminium alloy were considered as materials for making the arched supporting frames, and both have very much better strength-to-weight and stiffness-to-weight ratios than steel. Although the aluminium alternative was finally chosen for its low maintenance needs and superior durability, it also has a particular manufacturing advantage. Aluminium alloys can be formed into extremely complex cross-sections by extrusion through a die. This production technique enabled the many different functions of both the supporting frame for the foil pillows and the structural ribs of the barrel vault to be achieved using just two different extruded sections. The requirements were that the frame and ribs should: (Interaction).

- have a high section stiffness (second moment of area);
- support the stainless-steel wire grid;
- allow watertight fixing of the pillow foils into their frame;
- house the air-supply duct needed to inflate the foil pillows;
- incorporate an external gutter for rainwater;
- provide drainage channels for condensation forming in the box section;
- provide small drainage channels to catch condensation forming on the underside of the pillows;
- provide brackets for bolting together the various components and achieving waterproof joints;
- incorporate hooking points for internal cleaning gantries. (Interaction)

By extruding only one half of a box arch, the problem of extruding closed boxes was avoided. Sections of extrusion were cut and welded off site to form the “figure-of-eight" frames. Site assembly required connection to be made only around the perimeter of each unit. Site welding was not required. The flexibility of aluminium compared with steel was not significant in the context of a roof clad in foil. The lightness of the frames was a considerable advantage on site, reducing required crane work (Cook, et al., 1994).

The new roofing system thus developed was not produced by taking an existing system and improving individual parts. There was a fundamental rethink as to how to achieve the required performance of an atrium roof. The result is a remarkably tight integration of structure and services: no one part can be changed without affecting some or all of the others - a singular solution for a unique set of circumstances (Interaction).

CONSTRUCTION

The roof installation proceeded according to programme and was unusually rapid for a structure of this size. This speed allowed for an early start on installation of internal cladding. The roof is performing up to expectations and transmits a very high level of natural light into the atrium, which functions as a primary communication space via bridges at every level, as well as a vital central forum at ground level. Whilst the technology of using foils as roofing materials is relatively new, the problems are all soluble by the application of engineering principles. This form of roof cladding offers clear advantages over more conventional systems and seems destined to become increasingly important for future construction needs (Cook, et al., 1994).

For easy construction it would also be necessary for the pillows to be pre-assembled as self-contained units, which could be carried into position and fixed from the outside. The pillows that were developed in this way are about 4 metres x 3 metres in area and 250 mm thick at their centre. These pillows were inflated to a depth of 600 millimeters at a low pressure of 400 pascals (about 5 pound per square foot) (Robbin, 1996). They have a thermal performance and transparency similar to triple glazing but at about one fiftieth of the weight (Interaction).

FOIL PILLOWS

This fact alone made the use of a fabric membrane roof cladding unattractive and pointed to a glass or foil solution. Glazing of the roof would have added to the building weight, would have required a heavy roof support structure and would have been expensive. The use of a lightweight clear foil roof cladding system was selected as the best option (Cook, et al., 1994).

The key to good thermal insulation in glazing is the air gap between the glass sheets. Transparent foils of plastic can also be used to contain the air and are very much lighter but alone, such a combination of materials has no useful structural properties. These ideas were judged to be worth developing for this large atrium roof, especially in view of the high insulation that might be achieved (Interaction).

ETFE foil, a material that a few years ago tended to be thought of as a cheaper, lighter, shorter-life glass substitute made Chealse and Westminster Hospital respectable (“Products” Architects’ Journal, 2002). Although clearly not as versatile as more conventional fabric based materials, ETFE is highly appropriate where a support matrix can be provided. Indeed these pillows also provide a thermal performance rather better then double-glazing for approximately a quarter of the weight (Pugh and Cook, 1995).

Fig. 4.16. Internal View Of Westminster & Chelsea Hospital (2)
Source: www.foiltec.com

To increase the thermal insulation it was decided to use three foils and it proved viable to create flat pillows of different shapes by clamping the foils at their edges and keeping them inflated by air maintained at slightly (0.5 per cent) above atmospheric pressure (Interaction). This foil layer needed to be only 30 microns thick for being unstressed. Whilst the outer layer is 200 microns thick, the inner layer, which is not stressed by external loads, is only 150 microns thick (Cook, et al., 1994).

As a security against plastic elongation, a series of light steel cables is suspended beneath the bottom film layer. Under wind suction, the outer layer is more highly stressed and its thickness was chosen to ensure that adequate safety against plastic elongation was maintained. Under snow load, the outer layer will tend to invert once the load exceeds the inflation pressure of 500 N/m^2 (Cook, et al., 1994). However, due to the presence of plant enclosures on the roof around the perimeter of the atrium roof, drifting snow could produce much greater snow loads locally. As an increase in internal pressure would require an increase in film thickness (which would be expensive), the use of a safety net of cables was preferred and this net was suspended beneath each panel (Cook, et al., 1994).

INFLATION SYSTEM

The foil panels were delivered to site set in their extruded aluminium clamping frames. Each panel could be hand carried on site and installed by a series of bolts around the perimeter. The air supply for inflation was provided by means of individual pipes leading off a supply pipe running inside each arch. An inflation system is required to maintain the pillows at a constant pressure of between 400 and 500 N/m^2. This is achieved using centrifugal fans with backward curved aerofoil blades. The characteristics of such fans ensure a reasonably constant internal pressure over a range of airflow rates. This helps to ensure a fairly constant air pressure even when the flow rate increases to compensate for unplanned leaks (Cook, et al., 1994).

In the event of damage or removal of a single pillow, the air loss is constricted by the supply pipe, which is only 20 mm diameter. The fans are capable of providing the additional flow required to maintain a virtually constant inflation pressure in all remaining pillows. Air is supplied by 8 inflation units around the roof. Each unit supplies air to approximately 40 pillows and has one running fan and one stand-by. Each fan has a power requirement of around 100 Watts (Cook, et al., 1994).

4.4. FESTO TECHNOLOGY CENTRE (Festo HQ), Stuttgart, Germany

Fig.4. 17. External View Of Festo Technology Centre
Source: www.pfeifer.de

Architect *Architekturburo Jaschek*

Glass facade manufacturer *Okalux*

DESIGN

A new technology centre has been constructed at the headquarters of Festo, a multi-national manufacturer of pneumatic equipment, in Esslingen, Germany. The Festo Company is the world market's technology leader for pneumatic control systems and power tools. The designer of their new headquarters, Architect Jaschek, collaborated with their client to create a building that spole of Festo's technology-driven and ecologically sensitive design approach. This challenge stepped beyond the typical commercial approach to create additional space, and successfully represents Festo's progressive strive to be the technology and ecological leader in their market **(**www.burohappold.com).

The architect designed six finger-like buildings that are connected by a central spine, which serves as the entry area for each of the fingers. Out of the five interstitial spaces between the finger masses, three have been covered with a state-of-the-art Foiltec System, converting them into dynamic multi-function atrium spaces. Foils

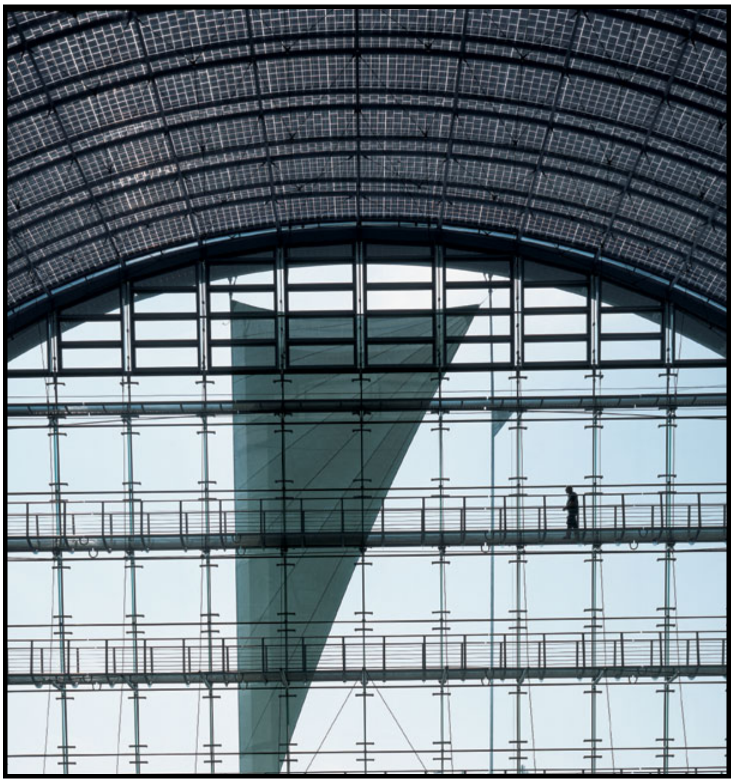


Fig. 4.18. Festo HQ Roof Close Up (1)
Source: www.vsp.com

Fig. 4.19. Festo HQ Roof Close Up (2)
Source: www.vsp.com

span the barrel-vault structure over varying distances between 45 feet and 70 feet. The architect envisioned the roof to be light and transparent, and at the same time, climatically responsive. Foiltec designed an integrated shading system intended to keep solar gains in critical climate conditions to a minimum, enabling the atria to be temperature-controlled without mechanical cooling systems. This pneumatically operated roof provides variable shading, responding both to climatic conditions and to the occupants' needs.

Fig.4. 20. Internal View Of Festo Technology Centre
Source: www.pfeifer.de

STRUCTURE

Festo Headquarter has three V-shaped atria roofed with pneumatic pillow structures and enclosed on their south sides by glass facades held in place by delicate wire-rope cable structures. The atria act as meeting places for the company's employees, and serve as buffer zones to provide passive solar energy gains (www.arplus.com).

The structural system, consisting of steel hollow sections and interior cables, takes most of the suction loads from the roof and the integrated glass end-wall facade **(**www.burohappold.com). The glass facades were manufactured by Okalux in

Marktheidenfeld, Germany. They comprise a series of glass panels, 2.4m x 2m in size, each of which is fastened with four clamps to a cable net structure. This in turn is rigidly connected with compression and tension rods to a secondary, curved cable net, which takes up lateral wind loads. Inward flexing due to wind-generated stresses is taken up by horizontal wire ropes; outward flexing due to wind-generated suction is transmitted to the building's ground-floor slab or conducted to points beneath the roof girders by vertical wire ropes (www.arplus.com).

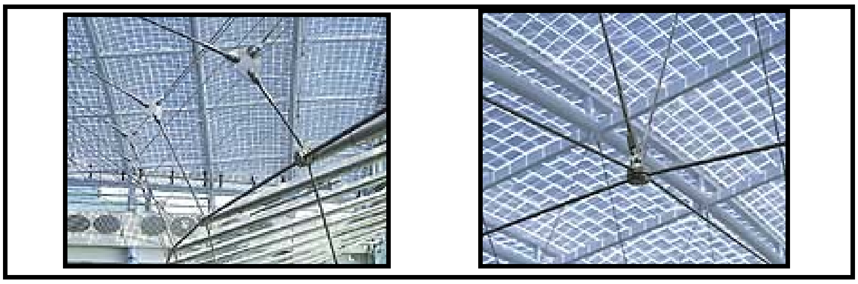


Fig.4. 21. Details Of Roof Structure
Source: www.pfeifer.de

FOIL PILLOWS

In the Festo Headquarters the architect used “variable shading system” in Germany. The variable skin takes about 60 second to change and provides an ever-changing spectacle to office workers and visitors in Festo (Vector). This technology has turned indoor spaces into environments that can control or dramatize the effects of the sun. This variable skin building modulates the atria’s internal climate by reacting to the sun and changing its transmission to maintain internal climate. These 1200sqm roofs use this chessboard gestalt pattern to modulate and change the amount of solar gain and light penetrating the atria. To achieve this dynamic shading, a bold checkerboard pattern used to achieve a variable transparency between 5% and 65% (www.foiltec.com). The upper foil of the three-layer system has a positive and the middle one has negative pattern. By changing the position of the middle layer to either the top or the bottom of the system, the transparency and the insulating value of the roof can be adjusted (www.burohappold.com). The range of transparency of the system is project specific and is determined by the designer's intentions and building performance.

4.5. NATIONAL SPACE SCIENCE CENTRE (Rocket Tower), Leicester, UK

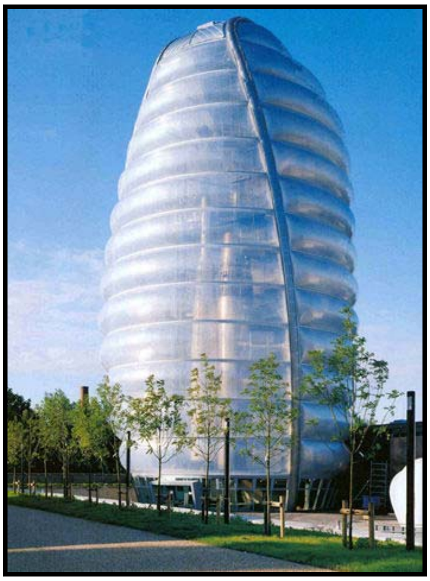


Fig.4. 22. External View Of NSSC (1)
Source: www.skyspan.com

Architect *Nicolas Grimshaw & Partners, UK*

Consultants

Structural and services engineers	*Ove Arup & Partners*
Construction team	*Sir Robert McAlpine Ltd*
Steelwork contractors	*SH Structures Ltd*
Project managers	*GardinerTheobald Management Services*
Landscape consultants	*Land Use Consultants*
Cladding consultants	*Montressor Partnership*
Fire engineering consultants	*Locke Carey Associates*
Exhibition designer	*Haley Sharpe*

DESIGN

The National Space Science Centre, a landmark Millennium Project for the East Midlands, is a catalyst for the promotion of public interest in space science. This building, which its height is 41 m and its size 7,200 m^2, combines an exhibition venue of international standing and a new centre of excellence for education and research affiliated to the University of Leicester. The building has been designed to reflect its proximity to the historic Abbey Pumping Station. Located on a former 'brownfield' site on the north bank of the River Soar, it occupies the majority of the riverside frontage in the shell of a disused storm-water tank. Its development as an amenity represents a significant environmental improvement, both for the immediate neighbourhood and for the city as a whole. The tower is designed both as a showcase for high-profile exhibits and as a tangible example of the use of innovative technologies, giving particular emphasis to the nature and efficient use of the materials employed (www.grimshaw-architects.com).

Fig.4. 23. External View Of NSSC (2)
Source: a+u 385, 2002

Nicholas Grimshaw & Partners was awarded this project following an architectural competition in 1996. This building’s construction is started in September 1996 and completed in June 2001 for the £17.5m contract value. The practice's original winning design envisaged that the centre would take up the whole volume of the tank and utilise the retaining walls as part of the building envelope. The brief was subsequently re-evaluated, following a Site and Structural Investigation. The final design comprises two principal elements: a main exhibition space, created as a square-plan structure within the disused tank, and an annexed rocket tower (www.grimshaw-architects.com).

STRUCTURE

It is a large double height space built on a lightweight 14m-grid steel frame. As such, it can accommodate a flexible arrangement of exhibition display systems as well as the full integration of structure and service zones, although most plant is situated off-site reinstating the functional relationship of the former pumping station as the remote energy hub to the disused sewage tank (www.grimshaw-architects.com).

The main building is set back from the edge of the tank on all sides, but is visually related to the entrance boulevard by the spiralling geometry of its landscaped roof plane. This spiral culminates in the geodesic dome of the planetarium, which perforates the hollow ribbed concrete roof slab and thus acts as a foil to the soaring vertical form of the Rocket Tower. The circulation routes in, around the planetarium, and onto the mezzanine walkways are arranged around the spiral theme, directing the public into the Rocket Tower. They then scale the sides of two 35 metre high rockets via mast climbing lifts accessed off the mezzanine floor of the main building (www.grimshaw-architects.com).

The spatial volume of the tower has been defined by the dimensions of its intended exhibits, with its highest point dictated by that of the largest rocket installed. The roof falls to its lowest point where it covers the concrete stair access to the wide floor plates. Acting as viewing platforms, from which the smaller exhibits are suspended, these allow close-up inspection of the satellites, rockets and space hardware (www.grimshaw-architects.com).

The volumetric requirements of the tower are expressed in its structural skeleton - curving CHSs braced by a vertical concrete stair cove. The form is sculptural, but informed primarily by function: derived from careful consideration of the manufacturing requirements of both the steel and the envelope it supports (/www.grimshaw-architects.com/).

The primary curving structure is composed of a series of simple arcs of varying radii attached end-to-end and rotated one to the other. As an arc can be defined by three points in space, the overall primary structure and volume of the tower can be defined by no more than seven points in space - only two more than that required for the definition of a simple rectangular box. The principal benefit of such a considered design is that it can be precisely translated to the workshop floor, in terms of simplicity of both explanation and assembly. Simply curved CHS arcs could be welded directly together and tested in their correct configuration prior to being transported to site (www.grimshaw-architects.com).

FOIL PILLOWS

As the visitor approaches the centre, the varying opacity of the building's skin is revealed. An outer layer of perforated metal has a two fold effect: it homogenises the building's external appearance, masking windows, louvres and other penetrations in the wall behind; it also forms a foil that can be back or front lit to change the building's external aspect from all visitor approaches. It is anticipated that, should funds become available, a large-scale public artwork based on light effects could be incorporated into this scheme. By addressing ideas of relative perception, integral to an understanding of science and space research, this work would re-establish the architectural intention of the double facade, as an extension of the exhibition theme (www.grimshaw-architects.com).

Fig.4. 24. The Internal View Of NSSC
Source: a+u 385, 2002

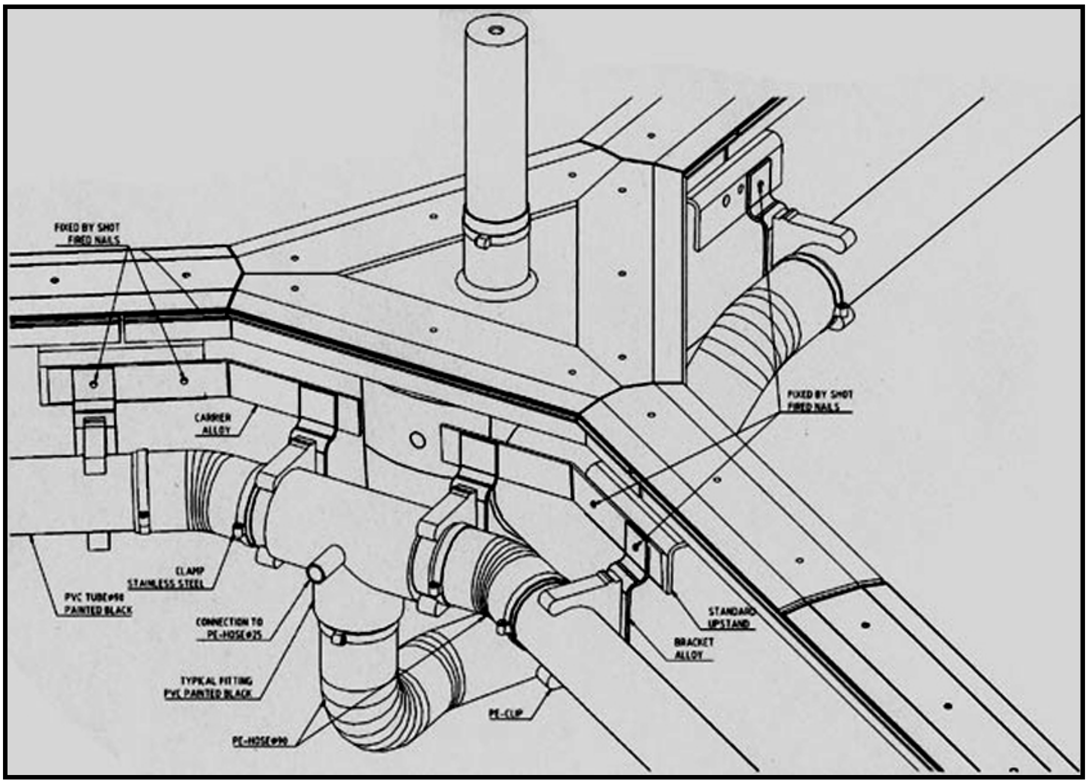


Fig. 4.25.Eden Project Node Connection and Inflation Equipment Detail
Source: Intelligente Architectur, 2000

Fig. 4.26.Eden Project Node Connection Detail Close Up
Source: Detail, 2002 / 12

Forming part of the NSSC, this 42 metre high exhibition tower adopts the aesthetic of space travel. Stretched between a lightweight steel structures, the façade consists of three-layer ETFE- membrane pillows 3m. high and up to 20 m. in length. The polythene material is resistant to UV radiation and has a self-cleaning surface. With a gridded coating it was possible to achieve varying degrees of transparency. Although the material has an expected life of 60 years, the fixings are designed to facilitate the replacement both of individual pillows and of the existing rockets with new ones. The three- dimensional curved form of the tower and the lightweight façade material allowed the legible steel structure to be reduced to a minimum (Detail, 12,200).

While the natural formation of steel structure provides a positive supporting skeletal framework, the resulting interstitial spaces are complex non-geometric, non-rational 3-Dimensional forms, ideally suited for the form-making skills and techniques derived from sail making and employed within the patterning and manufacturing techniques associated with ETFE. Each interstitial space could be computer modelled and panels of material cut, patterned and welded to their required 3-Dimensional forms (www.grimshaw-architects.com).

Briefly, the resulting envelope is achieved with great efficiency - enclosing a complex 3-Dimensional space with minimal secondary support mechanisms and troublesome joints and junctions. The steel and ETFE solution greatly increases the efficiency (while reducing the cost) of the overall tower form. While the tower can be clearly defined by its reference to its space, skin and structure, its concern with the natural properties of its materials gives it an organic shape that at once derives from the rockets it houses yet manages to avoid direct stylistic reference to space age themes (www.grimshaw-architects.com).

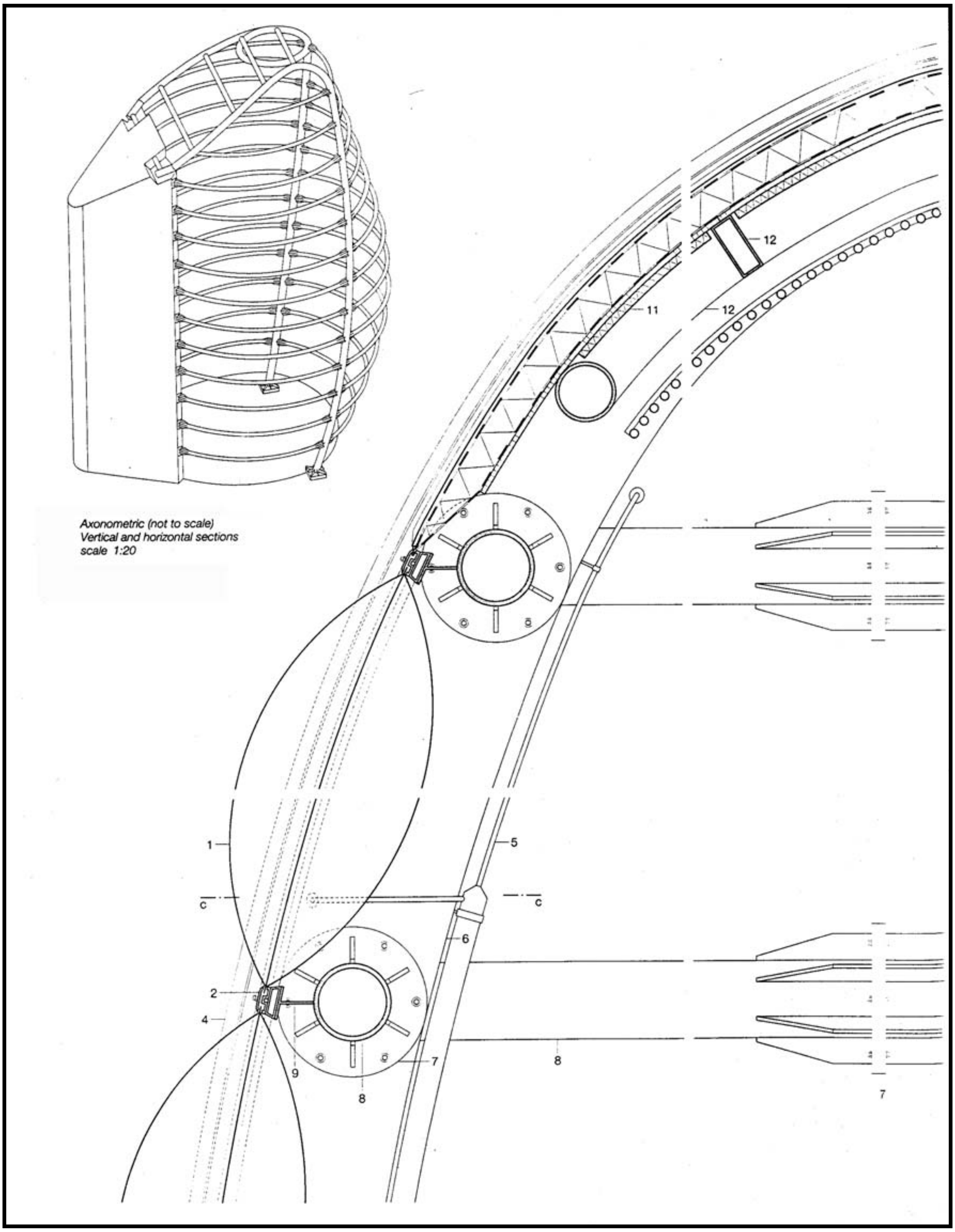


Fig. 4.27. NSSC Detail And Axonometric View Of The Structure
Source: Detail, 2002 / 12

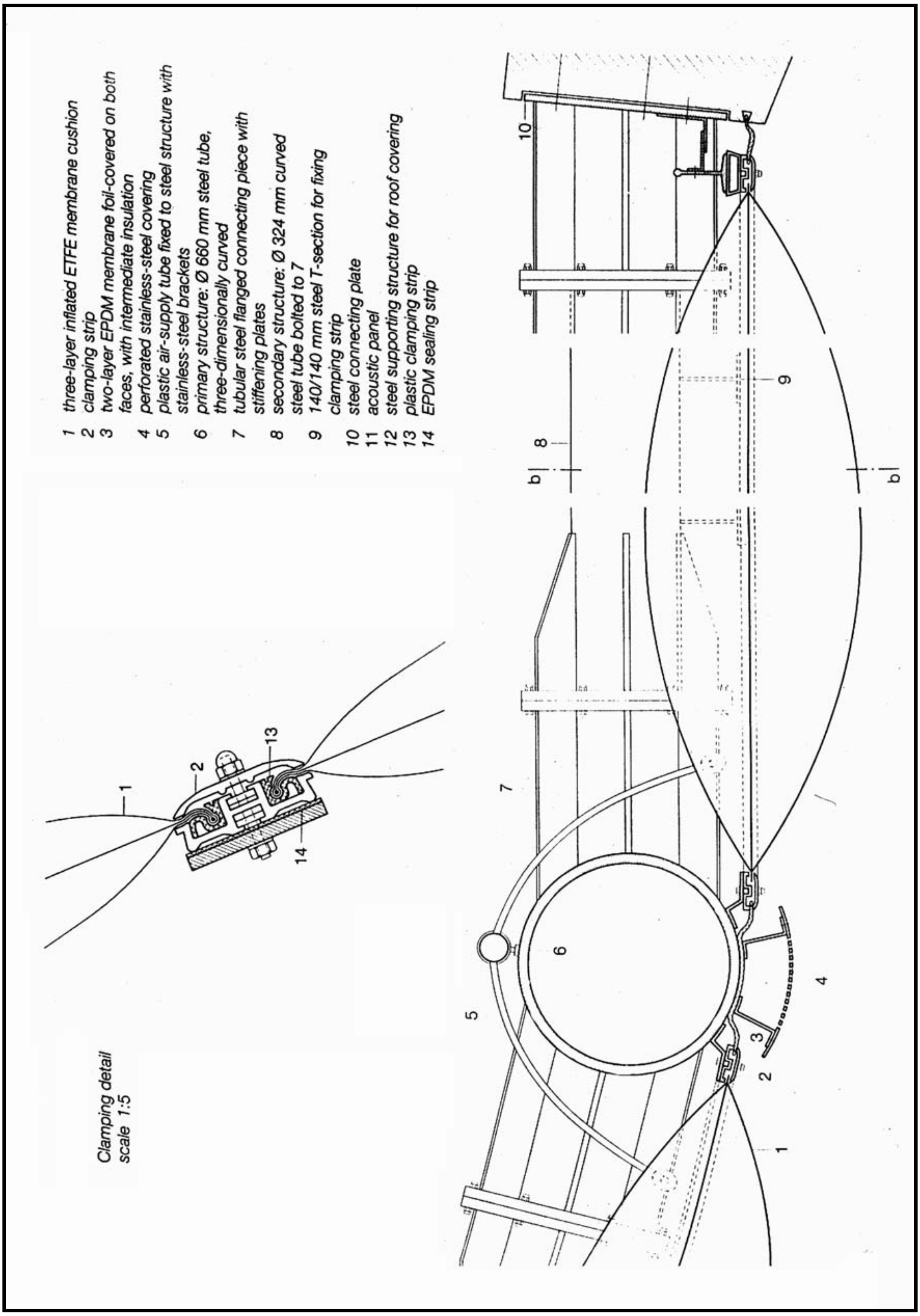


Fig. 4. 28. NSSC Clamping Detail And The Section Of The Structure
Source: Detail, 2002 / 12

4.6. MUNICH STADIUM, Fröttmaning in Munich

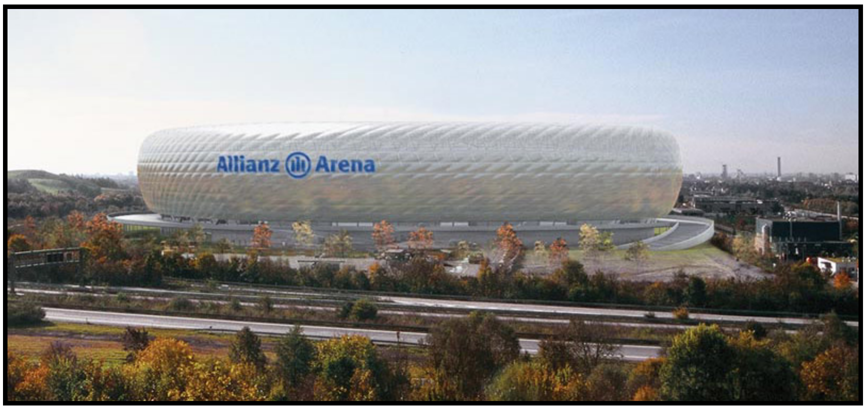


Fig.4. 29. External View Of Munich Stadium
Source: www.worldstadiums.com

Architects *Jacques Herzog and Pierre de Meuron*

Client *FC Bayern Munich*

Dimensions

Stadium dimensions:	*258 m x 227 m x 50 m*
Stadium circumference:	*840 m*
Area occupied by stadium:	*37,600 m²*
Total site area:	*171,000 m²*
Esplanade dimensions:	*600 m x 133 m*

DESIGN

The stadium, which was made jointly by Alpine Bau Deutschland GmbH and Swiss architects Jacques Herzog and Pierre de Meuron, is going to be constructed in the north of Munich. The construction of building is started in Autumn 2002. The Basel-based architects won the design contest with their concept for a modern and innovative football stadium, the like of which has never been seen before. The local media have already nicknamed the structure the life belt ("Schwimmreifen") or rubber boat ("Schlauchboot") because of its unusual appearance. There is a gastronomy and leisure areas, halls of fame, 3 playgroups, club shops, office and conference facilities, spacious media facilities, food services, 2 fan restaurants: the TSV 1860 restaurant in the North stand and the Bayern restaurant in the South stand, each seating approx. 1,500, 1 family restaurant, 1 terrace restaurant, 1 press cafeteria, 1 cafe-bar inside the building.

In another view, the new Munich stadium, the cost of which was put at 280 million euros (176.3 million pounds), will replace the ageing multi-purpose Olympic stadium that was built for the 1972 Summer Games and was the stage for West Germany's final triumph over the Netherlands in the 1974 World Cup. The arena, which will seat 66,000 and will be completed in April 2005, will also become the home of Munich's two first division clubs, Bayern and TSV 1860.

This project represents an innovative interpretation of the football stadium of the future. A cascade of colour can be projected onto the smooth lozenge-shaped exterior, which takes the form of a curved translucent shell, infusing the structure with an almost magical poetry. The three-pier seating arrangement guarantees every single one of the 66,000 spectators a close up view of the action, combining raw emotional interaction with all the comforts of a modern stadium.

Fig.4.30. The Image Of The Munich Stadium (Allianz Arena)
Source: www.worldstadiums.com

FOIL PILLOWS

This new football stadium that is Munich's landmark, has long stood as a symbol of the city around the world. Solutions are now being developed to meet constructional and safety requirements, especially in respect of the outer skin. In the open areas of the stadium, the inflated “pillows” provide protection against wind and rain for the 60,000 spectators. The thermal separation between the general areas and the heated spaces- for VIPs, offices, etc.- is in the form of storey- height double-glazing (Fuchs, 2002).

Openable pillow elements are planned for ventilation and smoke extract. More than 1,000 rhomboid inflated pillows, with an edge length of approximately 8m, are required for the outer skin. These will be filled with conditioned (dried) air and can adapt automatically to changing loads from wind and other sources by means of a pressure regulation facility. Over the roof and to some areas of the façade, the membrane is transparent, but the main areas are translucent white. With a thickness of 0.2 mm, the transparent membrane would have a light transmittance of about 95 per cent. Beneath the roof construction, a partially retractable sun shading system is planned with reflecting and also sound-absorbing qualities (Fuchs, 2002).

This building is a further example of the scope for illumination and lighting effects that can be achieved with plastic. The facade is fashioned from light. It will be illuminated according to which team is playing: a white and blue or red and white pattern will play over the exterior as if it was an enormous LED screen, celebrating the home side. The light can be made to pulse or simply glow. The entire stadium can appear white, red or blue. Small blue squares of light race like shooting stars over the milky shell. The stadium breathes, pulsates in blue, red or white light. Large white and blue lights circle the stadium, which appears ready for take-off at that moment. There are a number of lighting scenarios possible, which can be activated to reflect the ambient mood in the Arena. The beacon summons the approaching fans with their club's colours, increases the excitement and anticipation. Goals and other major incidents during the game can be celebrated in light on the facade. And even the areas away from the immediate vicinity of the pitch are not excluded from the pulsating atmosphere. At the end of any football day, the light follows the fans home, maintaining the atmosphere generated by the on-field incidents.

Important questions were raised in respect of the behaviour of the membrane if exposed to fire or vandalism. The material is fireproof and subject to damage only in the area of direct projectile attack. Excluding vandalism, the anticipated maintenance should be very small in comparison with conventional forms of construction. With an estimated membrane area of 65,000 m2, the stadium will be the largest structure in Germany covered with ETFE (Fuchs, 2002).

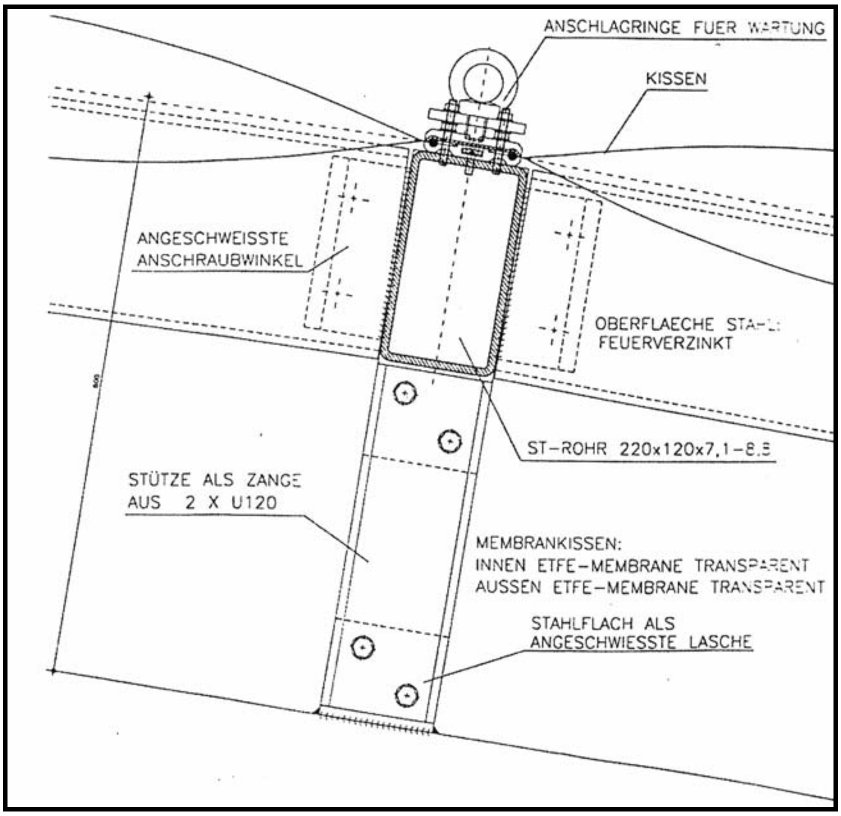


Fig. 4.31.Munich Allianz Arena Stadium IPS Detail
Source: Detail, 2002/12

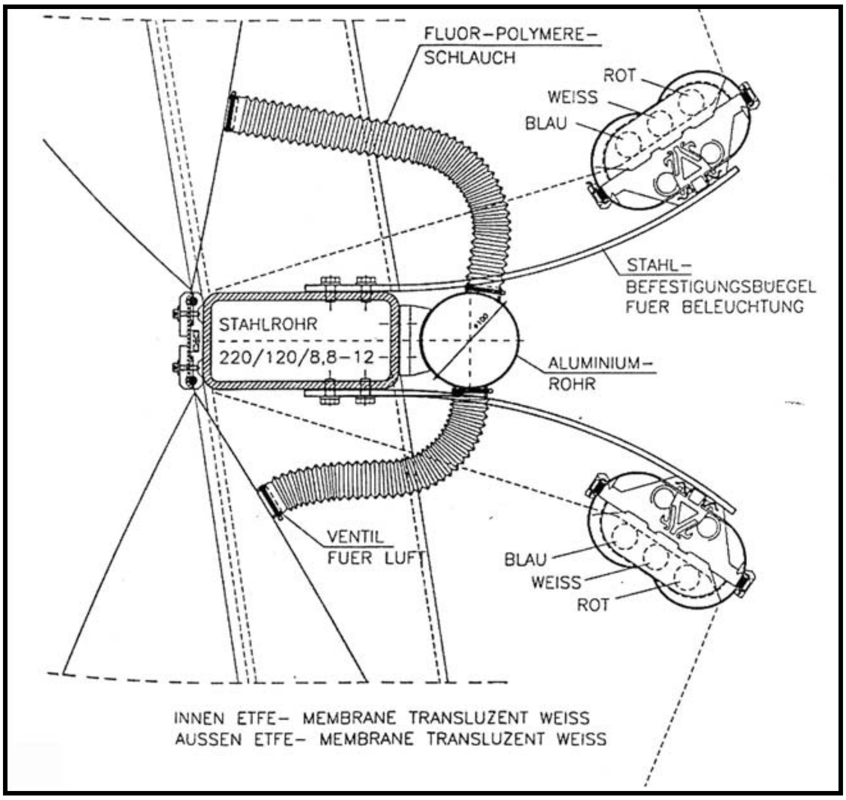


Fig. 4.32.Munich Allianz Arena Stadium Inflation and Lighting Detail
Source: Detail, 2002/12

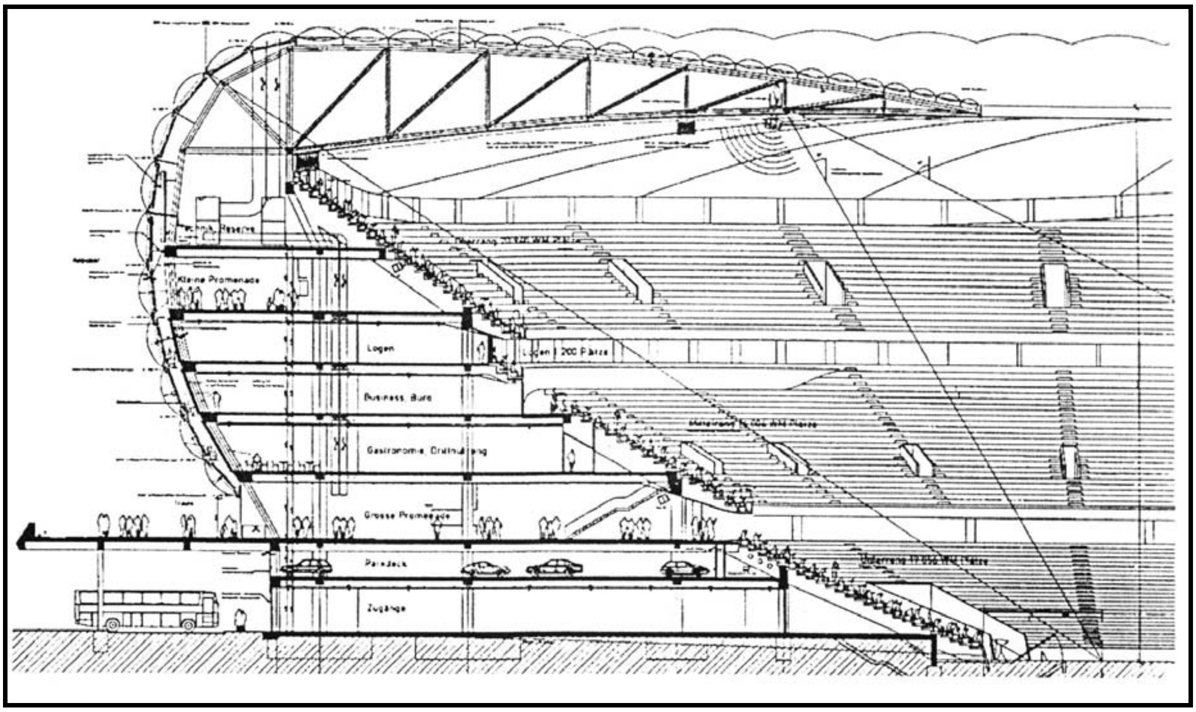


Fig. 4.33. Munich Allianz Arena Stadium Section
Source: Detail, 2002/12

Fig. 4.34 Munich Allianz Arena Project Rendering Red Lighted
Source: www.worldstadiums.com

Chapter 5

COMPARISON OF ENVIRONMENTAL CONTROL CRITERIA AND COST ANALYSIS OF IPS

5.1. Comparison of Environmental Control Criteria of IPS and Conventional Glass Glazing Systems

Environmentally sensitive, climate controlled buildings promoted the use of transparent building materials. Glass has been commonly used in glazing applications for atrium and overhead glazing. However, there are many situations where glass is not a practical option because of the geometry of the building (Robinson-Gayle, 2001). Alternatives of glass have been used for glazing with their limited capabilities. Polycarbonates and other plastic based materials are still in use for glazing purposes.

Although thermoplastic ETFE membrane can be solely used as an architectural membrane, usage of ETFE as a glazing material is feasible with multilayered applications. Pillow form saves optimum properties expected from a glazing element. In order to make a comparison between conventional glass glazing systems (CGGS) and IPS, their environmental control properties should be discussed.

In the present study, Conventional Glass Glazing Systems are determined as glass glazings, which have one or more than one pane of glass known as insulating glasses. CGGS also consist of modified glass panes with coating and gases.

5.1.1. Comparison of Light Transmittance and Visual Perception

Thickness is an important issue for light transmission through glazing materials. ETFE foil has been commercially produced as sheets, between 50-200 μm thickness. There are three types of foil; clear, opaque and printed. All types of foils have different light properties. In multilayer applications light transmittance values may change due to usage of the foil. According to Buitink Technology Co. light transmittance of the clear ETFE foils are as below:

Foil Trade Name		Wavelength	Light Transmittance
Hostaflon			
	Visual light	380-780	94-97
	UV light	320-380	83-88
Nowoflon			
	Visual light	380-780	96
	UV light	320-380	>95

Table.5.1. Light Transmittance in Specific Wavelengths
Source: Butink-Technology, 2002

Glass has been produced in various thicknesses. Production range of glazing glass is produced commonly between 2 and 19mm in dimension limited with the ovens. There have been also produced colored glasses between 3 and 10mm. (www.yildizcam.com.tr) Insulating glasses are usually assembled with 3 and 6mm glasses. According to Akyürek, Pekışık (2003), single pane of standard 6mm of glass has approx. 88 percent light transmittance of visible light between 380-780nm. whilst the standard double glass glazing has maximum 78 percent. Robinson-Gayle (2001) explains that ETFE foil has a light transmission of between 94-97 percent whilst ordinary 6-mm glazing transmits 89 percent.

Figure 2.5. also shows the light transmittance rates of double glasses produced by Şişecam patent in Turkey.

As one can figure out, double and triple layered ETFE has lower light transmittance values when compared with single layer. However, double and triple layered ETFE pillow applications are still higher than double glass glazing.

Furthermore natural daylighting takes into account not only the total percentage of light transmitted but also the range of frequencies transmitted which is important for color rendering. When compared as whole spectral transmittance, ETFE foil is capable to transmit the UV light, which is very limited for ordinary glass. This property of the ETFE foil is important for greenhouse and zoo applications. UV lights have vital importance for plant life in order to make photosynthesis as well as animal life. Figure 5.1 shows transmission rates of both materials in the spectrum. According to Dr. Fritz,

(2001) although glass transmits an amount of the UV in the solar spectrum, there is a remarkable difference in the growing results and the quality, which can be seen in the taste of tomatoes. (www.eden-project.co.uk)

Excessive glare and heat transmittance is a feature of any transparent building material. As Robinson-Gayle (2001) explains that measures should be taken to eliminate glare (too much light) and solar radiation inside for both transparent material. In addition to that Barker (2001) explains that ETFE is not degraded by sunlight.

Addition to that white foil blocks UV light like glass glazing systems. One layer can be appropriate for eliminating short wavelength. White foil also ensures low-glare with its 40-60 percent light transmittance. On the other hand Moritz (2002) explains that THV coated ETFE is permeable to diffuse light (low-glare) in the daylight spectrum. THV coated ETFE has a light transmittance of 90 percent. Standard glazing glass may cause excessive light that penetrates inside. Glass offers visual clarity, but has many drawbacks. Clear glass does not diffuse the light and in greenhouse applications hot spots are the result. Therefore they should be colored or coated with reflective coatings. These additional changes in glass in creases cost while decreasing thermal and optical transmittance values. According to Yaşasan Glass Company ,(2003) light transmittance rates changes between 78-36 in commercially available double glazing units.

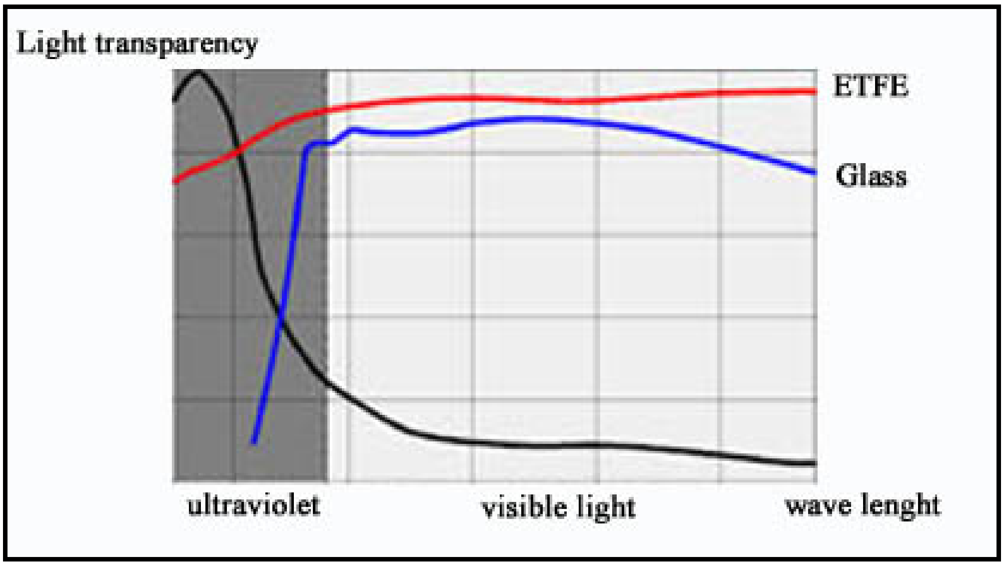


Fig.5.1. ETFE and Glass Spectral Chart
Source: www.foiltec.com

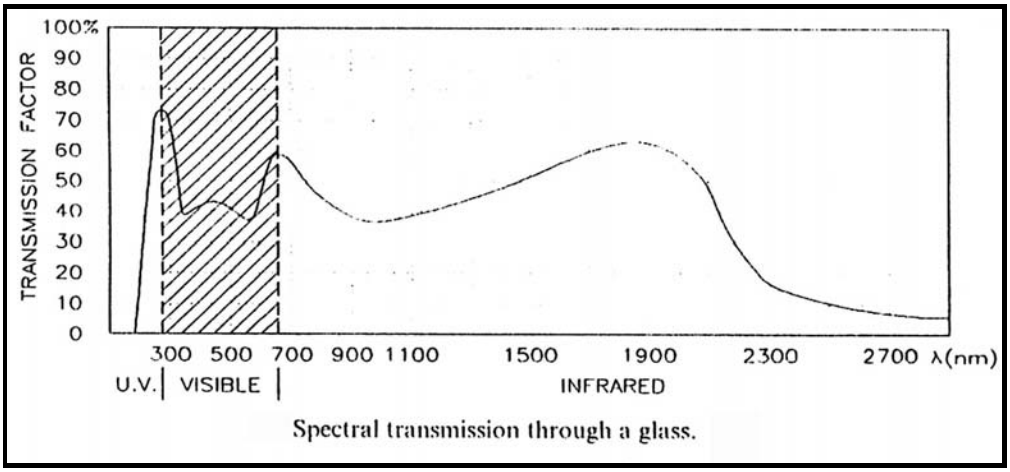


Fig.5.2. Spectral Transmission Through Glass
Source: Serra. R. 1998

Another factor is picture transmission, which can also be named as visual transmission. Although a very high amount of light is transmitted the picture rendering is not equal to that of glass. Double curvature form of the pillows may distort the lettering whilst it is possible to see the clouds below an atrium roof.

In addition, although the base material is very transparent ETFE foil can be treated in a number of different ways, similar to glass, to manipulate its transparency and radiation transmission characteristics. The foil can be over printed with a variety of surfaces to affect transmission, or printed with graphic patterns to reduce solar gain whilst retaining transparency, or can incorporate a white body tint to render the foil translucent. The degree of translucency then can be manipulated by adding additional layers of foil into the system.

In conclusion, IPS has a better light transparency than conventional glass glazing systems. However pillow system can interrupt the vision due to curved nature. Visual transparency is also an ongoing debate for those working with glass. Glass and ETFE foil can glare and lose its transparency in high amounts of sunlight due to its high reflectance value. Architects and engineers should consider reflectance property of standard clear glass that is approx. 8 percent of the visual light. According to Yaşasan, (2003) this value increases with additional glass panes and coatings between 14 – 9 percent in commercially availability. Reflective coatings have better reflectance values.

5.1.2. Comparison of Thermal Transmittance

According to Barker, (2001) multilayered ETFE has better insulation properties than glass. Figure 3.4 explains the coefficients of heat transmittance of pillows in terms of its multilayer usage. U-value of the double layer is 3.5 W/(m2*K) whilst Pilkington and Isıcam double layer glass has an u- value 3.2). On the other hand triple layered pillow systems' u- value is appox. 2.0 W/(m^2*K) which is better than low-E coated double glazing units.

Low-e glazing units or tinted glass may adversely affect indoor plants, which change the spectral quality of the light entering a building. There are also concerns that the incomplete spectrum of light entering a building through low-e glazing may have an adverse effect on human health, particularly elderly and the infirm who are forced to spent a lot of time indoors.

5.1.3. Comparison of Acoustical Performances

The internal environment is considerable more comfortable with lower reverberant times that if the cladding had been constructed from an acoustically hard material such as glass. On the other hand ETFE foils are virtually non-existent against noise. They have sound reduction index R_w between 8-10 dB. In comparison, glass has a sound reduction between 29-41 dB. ETFE pillows may affect the internal comfort in positive and negative ways due to usage and design. Therefore designer should be aware of the acoustical performance of the both material.

Although the ETFE pillows sound reduction index is lower than the glass glazing, usage of double-glazing does not mean that double glazing contributes to the acoustical comfort. Addition to that, single glass glazing has better sound reduction index than of the same width double glazing. The Figure shown below explains the acoustical performances of single layer glazing.

Glazing Type	Sound Reduction Index (dB)
12mm single glass	~31
10mm single glass	~30
6mm single glass	~27
6 mm laminated glass	~29
0.2mm ETFE foil	~10

Table.5.2. Sound Reduction Index Of Single Layer Glazing Materials

According to Onat and Sönmez, (2002) there are generally two ways of improving glass glazing acoustical performance;

- Changing the width of the external glazing,
- Changing the width of the air space (cavity)

Changing the width of the external glazing up to 10mm increases the acoustical performance, and maintains an index of 40dB. The increase in width and usage of double glass glazing units (standard and laminated unit) has commonly limited effects on acoustical improvement. On the other hand, second method; change in cavity affects the transmittance of noise. It is explained that 20 cm cavity between panes of 6mm glass increases sound reduction index to 41 dB. Furthermore increasing the width of a pane according to the adjacent pane approx. 33% reduces the transmittance of the sound a little bit more. (Onat and Sönmez, 2002)

Addition to that SP6 gases filled in the cavity improves the acoustical performance of the double glazing. As explained the usage of the argon and krypton gases which improves the thermal insulation, does not affect the sound transmittance.

IPS can even be fitted over very noise sensitive areas such as libraries and offices by fitting rain suppressers designed to reduce rain generated noise below that is experienced by conventional transparent cladding. Conclusively, glass can be thought as a secondary skin that may improve the use of pillows in terms of acoustics.

Glazing Type	**Thickness and Cavity**	**Sound Reduction Index (dB)**
	3 mm	29
	4 mm	30
	5 mm	30
	6 mm	31
	8 mm	34
	10 mm	33
	12 mm	34
	15 mm	36
Standard Glass	19 mm	37
	(3+0,38+3)	32
	(3+0,76+3)	32
	(4+0,38+4)	33
	(4+0,76+4)	34
	(5+0,38+5)	34
	(5+0,76+5)	36
Laminated Glass	(8+0,76+8)	36
	4 + 12 + 4	31
	5 + 6 + 5	32
	6 + 12 + 6	33
	4 + 12 + 8	34
	4 + 12 + 6	35
	6 + 12 + 8	35
	4 + 12 +10	35
	6 + 12 +10	37
	8 + 12 + 10	37
Insulation Glass	10 + 12 +10	39
Glass Block	190 x 190 x 80	40

Table.5.3. Effect Of Glass Glazing Types To The Sound Insulation
Source: www.yildizcam.com.tr

5.1.4. Comparison of Safety And Security Performances

In order to make a building light in means of weight, rather than designing structural elements from concrete or steel, which makes the total construction relatively heavy-weight, one may think of the lightness of cladding. Lightness can be obtained by reducing the facade weight as called dead in calculations. Lightweight envelope design becomes a very crucial issue in this situation. Further more, number of materials has much importance for façade designers as well as their individual weight becomes the focal point.

According to Tanno (1997), ETFE foil is flexible material, which can take extremely high short term loading. This makes it ideal material for use where there is a risk of explosion. It is able to absorb shock loading without risk of fracture, breakage or structural overload / collapse. On the other hand glass represents a brittle nature, which is a major concern in a bomb blast or similar shock load situation. Glass works as a plate in bending. This structural action is the same irrespective of the type of glass being used. In a double glazed unit there is some load sharing between the outer and inner panes with the outer one taking the most of the load.

IPS has been also preferred for its exceptional security properties. As in case of London Treasury, IPS chosen for its longevity and exceptional resistance to terrorist threat. ETFE pillows can be manufactured in large sizes and can span a much greater distance than conventional cladding technologies. Traditional rigid-edge roofing or cladding has its weak points at the edges. This new system’s high flexibility enables one to engineer much larger vents and movable structures than conventional technologies allow. Movement inherits in any building causes boundary edges to fail over time. In essence, the structure moves, and glass panels expand and contract within the frame and this differential movement is experienced as a frictional force at the interface between the two. (Williams, 2002) In pillow system this movement is taken up within the ETFE material itself. Morris (2002) states that no differential movement is taken up in the frame.

It has been used several times for windows in rooms subjected to ethanol vapour and condensation, where pressure surges also occur (as a result of the process taking place in the room). Regular glass windows could not absorb these pressure surges, which forced the room out of alignment. The problem was solved with ETFE foil windows (in combination with a special antistatic, gastight stretch ceiling). (www.buitink-technology.com)

The advantages of ETFE compared to glass are significant reduction of weight, optimizing the robustness during transportation, achieving a certain flexibility of the modules and increasing of module productivity by transmitting the total sunlight spectrum (from UV to IR) to the solar cells. (www.nowofol.de) The lightweight nature of the pillow saves time in erecting and scaffolding in the construction site. As in the case of Eden project the structure weighs less than the air it contains. Therefore the erection was awarded by Guinness Records. The three layer pillow weighs only 1kg/m^2 without framing and clamping which is not comparable with glass glazing systems. The double glazing systems weighs approx.15-30 kg/m^2. Therefore conventional glass glazing systems require a strong frame. A sophisticated base & cap (aluminum and rubber gasket) glazing system is needed or leaks, especially on overhead glazing, will surely occur. Often numerous panes of glass are required in a roof slope, resulting in horizontal mullion bars that dam water and can easily lead to leaks. Insulated glass should not overhang the eave, requiring a horizontal mullion bar at this location.

Fig.5.3. Workers Installing The Chelsea and Westminster Hospital Roof
With a Part Of Frame Glazed with ETFE
Source: AD 65, 1995

IPS is a flexible system. When the clamping is neatly installed, the pressure of the clamp creates a watertight seal. One of the great advantages of IPS is that gaskets are not required to achieve a watertight seal. The more parts of a glazing system, the more likelihood for leakage. Gaskets in glazing system caps will often shrink, creating a gap for water to enter. ETFE pillows can be installed directly in contact with frame, eliminating gaskets or glazing tape.

When the performance of a building's total exterior envelope is calculated (including heating, lighting and mechanical equipment costs) membrane-glazing systems can be better than glass. This energy efficiency, coupled with its durability and flexibility of pillows can be exploited in several applications. Pillows in comparison to glass glazing applications are also having an advantage of easiness in installation. Lower labor is needed. In terms constructional safety, risk reduced by working with flexible and lightweight materials. According to Barker, (2001) ETFE pillows in Eden Project can support 400 times its own weight. Three layered IPS weights approximately 1kg/m2. Therefore it is expected from one m^2 pillow to support $400kg/m^2$. On the other hand Skyspan (2002) explains that system should be designed with an awareness of wind and snow loads.

Glass Glazing Type	Glass Width (mm)	Glass Weight (Kg/m^2)
Clear Float Glass	2	5.50
	3	7.18
	4	9.63
	5	12.15
	6	14.70
	8	19.70
	10	24.60
	12	30.25
	15	36.00
	19	45.00
"ISICAM®" Double Glazing	3+3	15.50
	4+4	20.00
	5+5	25.00
	6+6	29.00

Table 5.4. Weigh Of The Glass Glazing Systems According To Their Width
Source: www.yasasan.com

5.2. Cost Analysis of IPS

The reason for using a transparent material is to get high light transmittance through the material into the building. Thus, transparent glazing also saves a visual link between inside and outside. Besides free form opportunity of membranes are used for their translucent property. Traditional glazing material: *"glass"* has been used for centuries without any alternative in the market. Improvements in polymer technology: new plastics and their properties exploited in building construction. Ethylene Tetra-Fluoro-Ethylene is a copolymer that is adapted to the construction in sheets. Therefore, this new plastic foil found an appropriate place in architecture as a part of the building skin, mostly as glazing. Usage of IPS made of ETFE membrane ensures cost benefits in most cases. According to Vector-Foiltec Company membrane roofs offer a cost effective and technically superior alternative to conventional structures.

Usage of pillow systems is explained in previous chapters. The results of the IPS usage are important in terms of building economy. Due to the nature of the system, costing of ETFE foil systems and all other membrane materials must be looked at as an entire cladding solution rather than as a direct replacement for any particular material. As in other glazing systems the material used in the system are important in the total cost of the system. Therefore, systems' cost can be explained through the dominant material, ETFE membrane. Much of the systems properties are in close relation with the membrane itself.

Cost efficiency of the system has to be discussed in three ways:

- the cost of Inflatable Pillow System itself,
- the cost occurred by the construction technique of the building skin,
- and its effect to the lifetime cost of the building. (Maintenance Cost)

Although the costs per square meter are given examples of the IPS above, that may be problematic to determine the real cost of the building. Due to several advantages of the system, total costs of a building can be reduced. Williams, (2002) explains that IPS structure costs 30 to 50 percent than traditional steel and glazing systems. Addition to that, Tanno (1997), explains that pillow system with ETFE foil can be installed roughly half the price of a conventional high performance glass envelope.

According to Williams (2002), British Museum's roof cost in the region of ₤2000 per m^2 whereas it could have done with IPS for around ₤600 per m^2 that is including the design fees. He adds that preferring IPS in specific applications structure becomes light in all senses of the word and therefore material can be used to their optimum effect.

According to the sales manager Aresi of Cannobio Co. (2002) that is a membrane fabrication firm in Italy, a double layer system on a space frame dome has an average cost of 300 Euro/m^2 with the clamping and essential accessories and erection.

Architect John Höpfner of Haack + Höpfner Architectural Firm (2002) expresses the cost efficiency of the IPS used in Allgut Petrol Station:

> *"We want to use of natural daylight at maximum. All this, at no extra cost to standard station. The very cost efficient pneumatic cushion as roof allowed this at low cost and high quality. This we did expect and achieve to the satisfaction of client, customer and -surprisingly - many collegues."*

Fig.5.4. Allgut Petrol Station Canopy
Source: Haack + Höpfner Architectural Firm website

Architect Moritz (2002) who is a professor at Technical University of Munich determines the costs for a one layer system amounts approximately 200 €/m^2 (in Germany) and for a triple layer-system approximately 350 €/m^2 (for a cushion system including the air support, clamps, connections above the supporting structure). He also adds that the variable shading system is more expensive due to sophisticated pneumatics.

In addition to that, expensive costs for transportation reduced by the light and thin nature of the pre-assembled frames in factory. The risks like cracking of a glass pane in transportation are not available. Therefore payments for insurance will be cut down during construction. Due to lightweight frames, labor prices like handling and erection will be much more lower than any other traditional system. In some cases scaffolding is not needed, which will affect the cost of construction.

One of the major opportunities that system ensures is the high light transmittance. Glazing does not block the light that enters through the structure. Very high amount of the light reaches to the depths of the building. So that, there will be a deduction in lighting expenses. With the awareness of the system advantage from the design phase, IPS saves extra expenses for electrical appliances. Less electrical appliances need low-maintenance and change in time. According to Akyürek and Pekışık (2003), glass used in botanical gardens and greenhouses is commonly 3 mm and 4 mm float glass. They added that one percent (%1) increase in light transmittance results as a one percent (%1) increase in production or crop.

Hampshire Tennis And Health Club has a white foil which gives the high levels glare free light for the players. Double layer pillows that are consisting of white and clear foils save to the club over £20.000 per annum in the lighting costs while giving spectacular appearance form outside.

In the case of Westminster and Chelsea Hospital that was covered by IPS, each running fan has an electricity consumption of 100W for approx. 500 m^2 (Cook, 1994). According to Cook, (1994) at Westminster and Chelsea Hospital, London, such a system was developed and incorporated into a sub-frame of purpose made aluminium arches to provide an extremely cost effective solution to the problem of enclosing a deep central atrium. According to Polat, (2003) from Texlon Firm in Switzerland, Westminster Chelsea Hospital Atrium, which is the world's largest naturally ventilated atrium, saves £10.000.000 in heating and ventilation.

Fig.5.5. Hampshire Tennis And Health Club
Source: www

In addition Williams explains that in Eden project there is an electricity consumption of 100 Watts for 1000m^2 where the fans are running half of the day. As in case of Eden Project, solar powered buildings with photovoltaic panels may easily solve electricity expenses. Tanno (1997) explains that the energy consumption used by the inflation units is minimal because the blower units only need to maintain pressure, they do not nee to create air flow. As explained in chapter 3, two electric motors share the working hours by switching. In this way, consume 50 Watts of energy per day. Furthermore Robinson-Gayle et. al.(2001) agrees that electric fan uses a small amount of energy approximately 50 Watts for 1000m^2 which equals to half of the consumption of a light bulb.

Another major deduction is possible with IPS structures. As known, energy is a major expense for buildings in their lifetime. Heating and cooling systems are responsible for the energy consumption. Heat insulating factor of IPS (lower U-value) helps uncontrolled heat flow through building skin. This property of IPS works also in summer season as heat shield. IPS doesn't let excessive heat flow through the glazing. Therefore system reduces cooling expenses of the building. As known, cooling is an expensive issue than heating the building. IPS reduces cooling and heating system equipments in number. Eventually, high costs of those systems can be eliminated from the design phase. Decreased equipments in number occupy less space in the building. There can be saving for the spaces not constructed or for the narrow structure due to fewer loads.

Low-maintenance is an additional option of the system. An annual maintenance from the outside of the glazing is enough in most cases. According to Foiltec there is one known customer having cleaning for the lower layer once in a five-year period. Inflated ETFE sheets are extremely resistant to dirt. Material has ability to self-cleanse. They do not absorb any chemical and dirt. IPS does not need monthly cleaning. Therefore mud, pest, dust are washed away with wind and rain, further reduces the lifetime costs to very low levels. However Skyspan recommend s a periodic cleaning depending on the location. According to Watts (2001), the internal face of the pillow within the building can became slightly dirty due to small amounts of static electricity that can be presented in the material. According to Tanno (1997), internal foil is usually cleaned on a 5-10 year cycle depending on the dirt in the internal atmosphere. Therefore expensive internal access equipment is not required for cleaning, which may be solved by low-tech, cheap methods like rope access as accost effective solution. Tanno, discusses the extruded materials smoothness and its' anti-adhesive property, and advices an external cleaning frequency of more than 4 years. In comparison with glass glazing systems, the self cleaning property of IPS saves maintenance cost and initial investment costs for cleaning expensive equipments.

Addition to those cost deductions described above, ETFE sheets are highly durable. Most producers and manufacturers are expecting a life span more than 20 years. Furthermore Skyspan, which is the manufacturer of Eden Project, is giving 60 years of life expectancy for the total building skin. Therefore IPS does not need to be renovated in short terms.

Lightweight nature of the ETFE pillows also maintains a cost advantage for architects and designers. IPS underlying structure does not need to be very heavy. Thus, a decrease in supporting structure and narrow elements of the structure are an additional deduction in expenses of the building. Whenever it's used partly or a total enclosure, due to less loading to the structure, the foundations can be decreased in size. The soil under the lightweight structure does not necessitate any special treatment. Furthermore the entire system can be realized by a scaffold free construction technique as previously did in Eden Project. Therefore application of the system does not need high lifts in many cases that should be owned or rented by the contactor. According to Williams (2002), IPS obtains a reduction in size and quantity of material used for the roof support structure. He adds that commonly about 10 times the amount of the steel is used in columns and beams than is needed for support purposes, primarily just to provide stiffness. If one considers the roof weight approx. 3kg/m2, than it has been better understood that the requirement for self-support effectively becomes the only criterion for the structural members.

As in case of Eden Project, in Cornwall, If glass had been used for the entire structure it would have needed three times as much steel to support it. Thus designers chose to use IPS made of ETFE. (Cornish Guardian, 2000)

Lightweight nature of IPS is also a cost beneficial situation for movable structures or ventilation holes in the structure. Thus, any ventilation or movable part does not need high-powered hydraulic systems that may increase cost.

In case of a movement of the soil or a limited earthquake, IPS absorbs some of the movement between frames. Soft pillows can shrink and then can return to their original situation without any deformation in the glazing. There is no need to replace the glazing for those limited situations. In addition to that IPS brings a solution to the expensive movable joint need. Williams explains that IPS is soft-tech system with its real soft nature rather than a high-tech glazing system. This saves maintenance cost of building skin in lifetime.

Although wind control property of IPS is discussed in previous chapters, IPS structure is a cost effective solution for glazing. In case of strong wind and wind suction, pillows absorb some of the effect of wind as they adapted themselves in earthquake. In this way, they only transmit a limited part of the wind load to the structure. Structure becomes narrow, and thus results as a cost benefit. Although it's hard to calculate the positive effect of the pillows in to the structure measurements, it is commonly used as a factor and will be learned in progress by trial-error.

Tearing resistance against propagation is another positive opportunity that saves deduction in lifetime expenses. In case of an attack or a small damage to the pillow can be repaired by ETFE foil adhesive tapes. The whole glazing does not need to be replaced by a new pillow.

Besides that, one of the very important properties obtained by the ETFE foil is the welding capability of the membranes. That saves a great labor for clamping and fixing the pillows in to the frames.

Fig.5.6. Adastral Houses High-Tech Atrium lets the noise out, Warner Bros.
Source: www

As pillow glazing is very light, single layer with a mass of 350 g/m2, it is acoustically soft and doesn't reflect internally generated noise back to the occupants. This natural feature of cladding means that cost intensive counter measures such as the integration of acoustic absorbers into the internal walls are usually completely unnecessary.

Hanover Social Housing that is a social housing project organizes budget accommodation around a shared communal garden roofed in an IPS variable skin. According to Vector Group the savings in the internal cladding to the residential blocks more than paid for the roof and internal landscaping, making the scheme a highly cost effective in terms of maintenance.

Fig.5.7. Hanover Social Housing
Source: www

In the case of Arnheim Zoo built in 1981, IPS maintains self-sustaining man made ecology. No other chemical fertilizers and insecticides are needed to sustain the environmental criteria. As described by Vector Group, zoo has been tuned over the last ten years to operate completely naturally that means virtually no-maintenance.

Fig.5.8. Arnheim Zoo Internal Views
Source: www

According to ETFE producer Nowofol Company (2003) transparent film prices are given due to film thickness. It is determined that additional costs like slitting hold 5% of the cost. There can be proportional costs for amount of edge trimming in correlation to standard width 1550mm.

Prices f. Quantity	**f. Thickness 100 µm**	**25µm**	**30µm**	**50µm**	**100µm**	**150µm**	**200µm**	**250µm**
< 10kg	< 60 m^2	3,15	3,80	5,85	11,75	17,60	23,45	29,30
/10kg	/60 m^2	2,90	3,50	5,45	10,85	16,30	21,70	27,15
/50kg	/300 m^2	2,80	3,35	5,15	10,35	15,50	20,70	25,80
/100kg	/600 m^2	2,70	3,20	5,00	10,00	14,95	19,95	24,95
/250kg	/1500 m^2	2,60	3,10	4,75	9,55	14,30	19,10	23,85

*All prices are Euro/m^2

Table 5.5. Price List of Nowoflon ET-foil 6235
Source: Nowoflon Technical Data Sheet, 2003

On the contrary white foil with various thickness between 100-250µm, which has a light transmittance approx. 50-55%, is only 1,00 Euro/ m^2. In addition primer coating to one side like bonding with EVA (Ethylene Vinyl Acetate) in thickness 150µm / 775mm width costs 7,50 Euro/ m^2.

ETFE is completely recyclable material. Furthermore many other components of IPS can be produced from recycled material (Vector-Foiltec, 2002). ETFE foil can be easily recycled by heating it to the melting temperature, which is approx. 270^{o}C. But, virgin ETFE needs to be added at the point of manufacture. Foils may also be disposed of in a landfill situation – apart from a very small amount of Hydrogen Fluoride gas (HF) released over time, material is essentially inert.

Energy efficient is an important issue for the IPS. Energy efficiency of the system can be argued due to its embodied energy and energy conservation. According to Vector Group, the embodied energy of the system is very low. However energy conservation is very high with its high insulation and solar gain. On the other hand according to Erengezgin, (2002) aluminium itself is a material that its embodied energy is very high than most of other conventional construction material in the sector.

However, aluminium profiles has a negative effect on the subject, it has been preferred almost in every cladding and glazing application.

Bespoke production systems are generally considered as expensive applications in construction sector. Extrusion technology, wide clamping system choice and recycling ensures a deduction in production. Besides the high initial costs of the bespoke system, the entire building becomes cost effective with IPS in lifetime.

The lightweight foil often results in cost savings for the underlying structure, and spans and shapes can be accomplished that would not be possible with glass. (www.buitink-technology.com) IPS self cleanses under the action of rain. Thus results as a decrease in lifetime costs of the building. Most of the curtain wall applications need special care and extra systems for regular cleaning. ETFE foil has a very low surface tension. Dirt and mud will be swept away in the first rain falls down.

According to Foiltec Company, pillow form saves a highly energy efficient cladding due both to its environmental performance and its low embodied energy, which is less than 1% of conventional technologies. Although designers consider the resource consumption, which is used as energy in buildings in their lifetime, embodied energy is another point that they should be aware of. Embodied energy of the materials can be determined that the amount of energy use to produce material and includes the energy associated with mining, mineral purification and processing. (Robinson-Gayle et. al., 2001)

Embodied Energy	**ETFE Foil**	**6-mm Float Glass**
EE (GJ/ t)	26.5	20
EE per m^2 (MJ/M^2)	27.0	300

Table 5.6 Embodied Energy For ETFE Foil And Glass
Source: (Robinson–Gayle et. al. ,2001)

As shown in table 5.6 although embodied energy difference per tonne is not in huge amounts between ETFE and glass, embodied energy of glass in m^2 is approximately 10 times more than ETFE foil.

The much greater pillow sizes minimize structural shading. This is also related with the production limits of ETFE foil. ETFE Foil has a width of 1.55m, which can be easily weld one by another. ETFE film can be joined by thermal impulse welding at 30 ^{o}C. That application extends the limits while glass and other substitutes have to be connected with extrusions, clamps and bolts.

Chapter 6

CONCLUSION

This study, which focuses on an alternative glazing system in construction technology, has aimed to discuss applicability and feasibility of the inflatable pillow system as a substitute for conventional glass glazing system that has been used in architecture by an objective point of view. Exploring the varying sources of reference, the study aimed to compare both systems of glazing by investigating their performance.

Most of the constructional materials and systems, even glass glazing has been transformed by the increasing energy consciousness of the consumers at the end of the 20^{th} century. Glass has been used for centuries, which became an industrial material with so many varieties in the building sector. It has been used without alternative because of its transparent nature. Transparency and high light transmission rates of the advanced glass glazing improved its architectural applicability in contemporary buildings. In the line with the increasing technology and demand, glass and plastic based materials such as polycarbonate panels, fibreglass and PVC foil, have improved.

The Inflatable Pillow System (IPS), which is materialized by ETFE that is a thermoplastic fluoropolymer, is used as alternative to glass glazing system in recent architectural applications because of it’s economical life-span, safety and security criteria and low maintenance cost. The ETFE, which is produced as a folio in different thickness by the way of extrusion, use both as a one layer isotropic architectural membrane and also use as multi layered. The effectiveness of IPS depends on the number of layer, the thickness of folio and the usage of membrane material. ETFE foil, which it has low embodied energy during production, is sustainable and therefore ecologic material.

It is also possible to say that, IPS is so suitable and effective for spaces that they don’t shelter people continuously in it such as greenhouses, botanical gardens and zoos. Besides that, when it is considered that the provided easiness on maintenance, reduced operating and maintenance costs; applying this system for school, hospital, sport halls, shopping and entertainment centres will be so useful. This system also use for atriums and roof lights.

IPS consist of an assembly of the two or more ETFE foil layers welded together and put as an infill inside a special manufactured frame, which are supported with lightweight structural elements. Pillows are air supported by the help of pneumatic fan units. Pillow system is compared with the conventional glass glazing systems according to the their technical properties, manufacture and application processes, and environmental control criteria which are optical thermal, acoustic performances and security properties. In the line with the information got; the results are summarized as below:

- Comparing with the conventional glass glazing systems, IPS provides a more flexible design opportunity. While easy welding nature of foil saves bigger amounts of glazing surface, the flexible nature of the system provides nonplanar applications possible without the need of a second process. In other words, the usage of pillow system made of ETFE foil saves architectural freedom comparing to the conventional systems in terms of building envelope. In addition to that lightweight nature and less detail solutions obtain a easy installation and easy maintenance construction method.

- In contrast with the glass panes ETFE foil is very lightweight. One layer weighs 350 gr./m^2, while ordinary 3mm glass pane weighs approx. 7 kg/m^2. Therefore IPS transmits fewer loads to the main structure where it is used. Pillow system reduces structural loads and movements and also does not have thermal tensions on its surface as glass glazing systems. In addition, flexible and lightweight nature of the IPS system reduces the risk factor that will be formed during transportation, application and also reduces the risks of accident during earthquake and similar hazards. On the contrary usage of glass has some obstacles in particular applications.

- Mechanical properties of the IPS give opportunity to glaze wider surface area when compared with glass glazing systems. Although the width of foil (1.50m) is smaller than the commercially available glass width, the welding property makes the membrane extended up to 7.5m for particular applications. Therefore supporting elements; muntins and mullions are excluded from the design, which reduce detail problems and structural shading in terms of aesthetics and efficiency. However, as a result of fewer loads bearing capacity of the membrane, pillow forms made of ETFE are not capable for the cladding purposes without support. Advanced foil material of the future that has high load bearing capacity, will possibly cover wider areas with pillow system.

- In contrast with the pneumatic systems, inflatable pillow system needs support for the pillows. But this minimized support is not as much as in glass systems. Air supported pillows' shape provides a structural opportunity against lateral forces such as wind and earthquake. Pillows absorbe some of the pressure of the wind and therefore transmits less forces to the main structure of the building, which also reduces extra structural elements and need for a heavy foundation in the construction. Flexibility of the membrane itself also absorbs the movements and reduces the need for the movement joints.

- IPS provides better light transmission compared to glass glazing system. By means of the ETFE folio, which is usually produced transparent, can be produced opaque or patterned, in question light transmission can be controlled. This material can pass highly rate of the UV rays, which are between 280-400 nm. in spectrum according to glass. ETFE is an ideal material especially for green houses, atriums and roof lights. Besides that, by the way of " variable Shading Method" that can only be realized on three layered applications, there can be designs that are environmentally sensitive to indoor and outdoor conditions. Thus, the light and heat gain of building can be tuned manually or automatically with the help of sensors.

- IPS provides better thermal performance compared to glass glazing system. The heat transmission value of two and/or three layered applications is similar with glass. This system is water and air proof and it has minimum joints and this provides heat conservation for building. The value of heat conservation can be decreased by adding the layers to the system and preferring selective coating materials. In addition to that, in terms of environmental control criteria the IPS give most ideal results in temperate climates.

- IPS shows worse acoustical performance compared to the glass glazing system although it is up to design. Because of the acoustically soft nature of the material, sound can penetrate to the both sides of the building envelope without any obstacle. In contrast with the glass panes system saves lower reverberation times that increases the internal comfort. This may be an opportunity for designers that should be exploited in the early design phase in terms of aesthetics and economy. While acoustic property can be seen as a disadvantage in particular buildings such as office buildings, it can be an advantage for the buildings such as botanical gardens.

- ETFE folio prevents flames to spread, delays the structure of the building to collapse and proves high fire safety compared to the glass glazing system. The folio doesn't drip molds during fire, but it may have a problem of getting loose at 60^{o} C. Because the material doesn't have a fragile structure like glass, in spaces where there is a risk of implosion the strong pressure of implosion is reduced.

- IPS whether there is life inside or not the air pressure must always be constant, which requires the air pumps working continuously, has a negative influence on the building economics compared to the glass glazing system. Because of this case the electricity expenses can be solved with the use of photovoltaics. In opposite condition, the folios may inflate like sails or may deflate. This uncontrolled situation may cause the material to be worn out in shorter time.

- IPS has a high investment cost at he beginning but reduces the upkeep and undertaking expenses in building's economical life compared to the glass glazing system. Because the material has easy application and the expenses for transport and insurance is less, the performance of investment and design expenses when compared to glass systems the material offers a great cost advantage.

As a result, ETFE folio end Inflatable Pillow Systems, the latest results of the researches of the mobile process of construction and material sectors has brought up a new dimension for conventional glass glazing systems. This system is an ideal glazing system with its high level of environmental control criteria, technical performance, usage period and the low expenses but it hasn't taken the place of glass systems yet. Beside the advantages offered to the building, the system has some disadvantages, may be ideal for limited applications.

Briefly, the use of transparent, lightweight and elastic material and glazing systems made up of this material as building envelope or as a part in the building reduces the distance between the terms of "glazing" and "membrane coating", or maybe in future the boundary between these systems may be removed. So, in short time it's not expected that these systems will occupy the place of conventional glazing systems, it's projected that Inflatable Pillow Systems will be understood by designers and the applications which are related to will increase.

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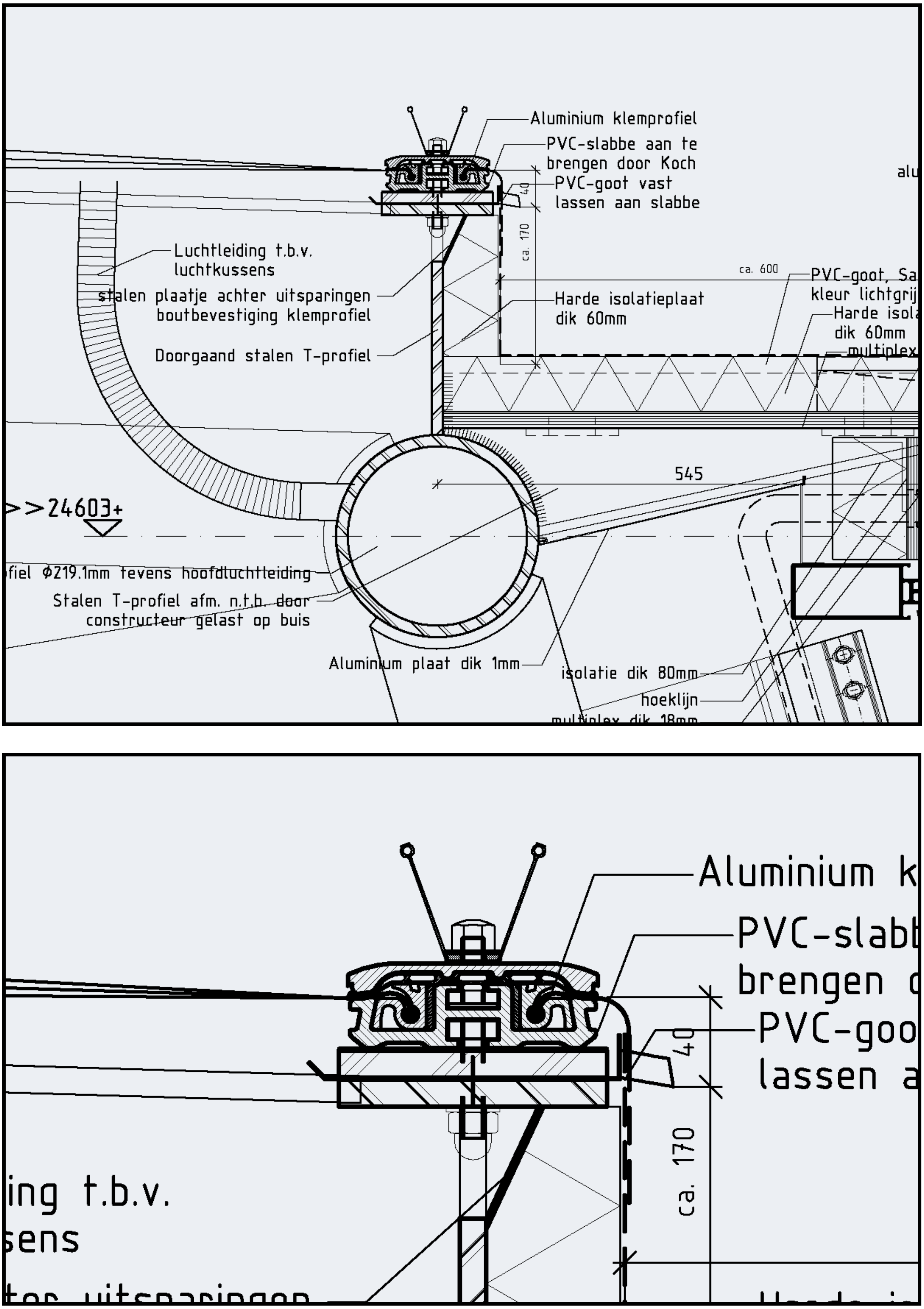

Fig. 3.10. Details of Arena Center, Halle, Amsterdam (Arch: Benthem Crouwel)
Source: www.bouwenmetstaal.nl/hallen

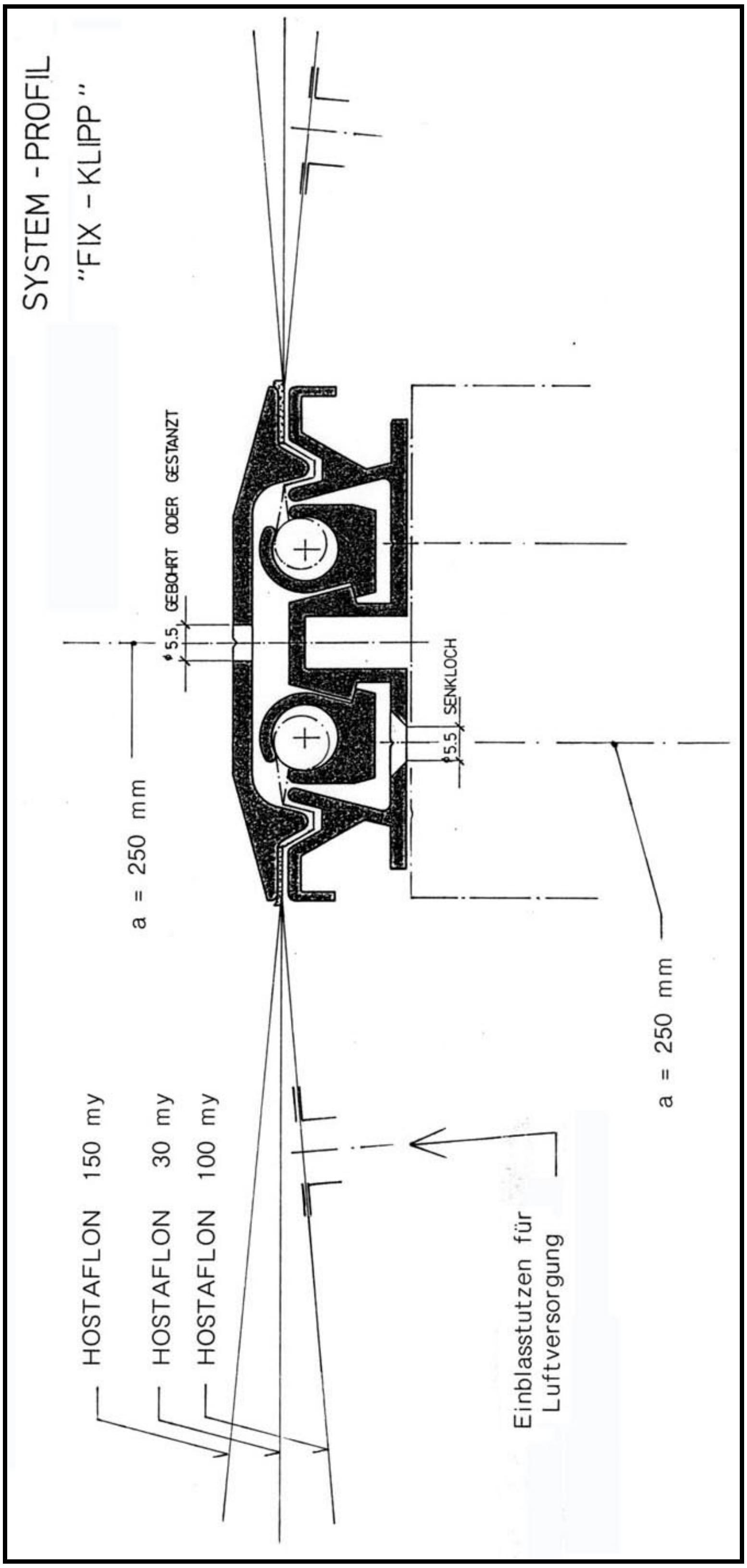

Fig. 3.11. System Detail Of Pillow System
Source: www.texlon.ch

Fig.3.21. Workers Installing Etfe Foil Panels In The Dome Ceiling
Source: www.apexphoto.com

Fig.3.22. Each ETFE pillow is secured in the steel framework
Source: www.apexphoto.com

Fig. 3.23.Bocholt Leisure Pool
Source: www.foiltec.com

Fig. 3.24.Avifauna Butterfly House
Source: www.vsp.com

Fig. 3.25.Installation and Clamping Of Pillow System
Source: www.buitink-technology.com

Fig. 3.26.Skyspan HQ
Source:www.skyspan.com

Fig. 3.32. Earth Center External View
Source: Detail, 2000 / 6

Fig. 3.33. Earth Center External View IPS Close Up
Source: Detail, 2000 / 6

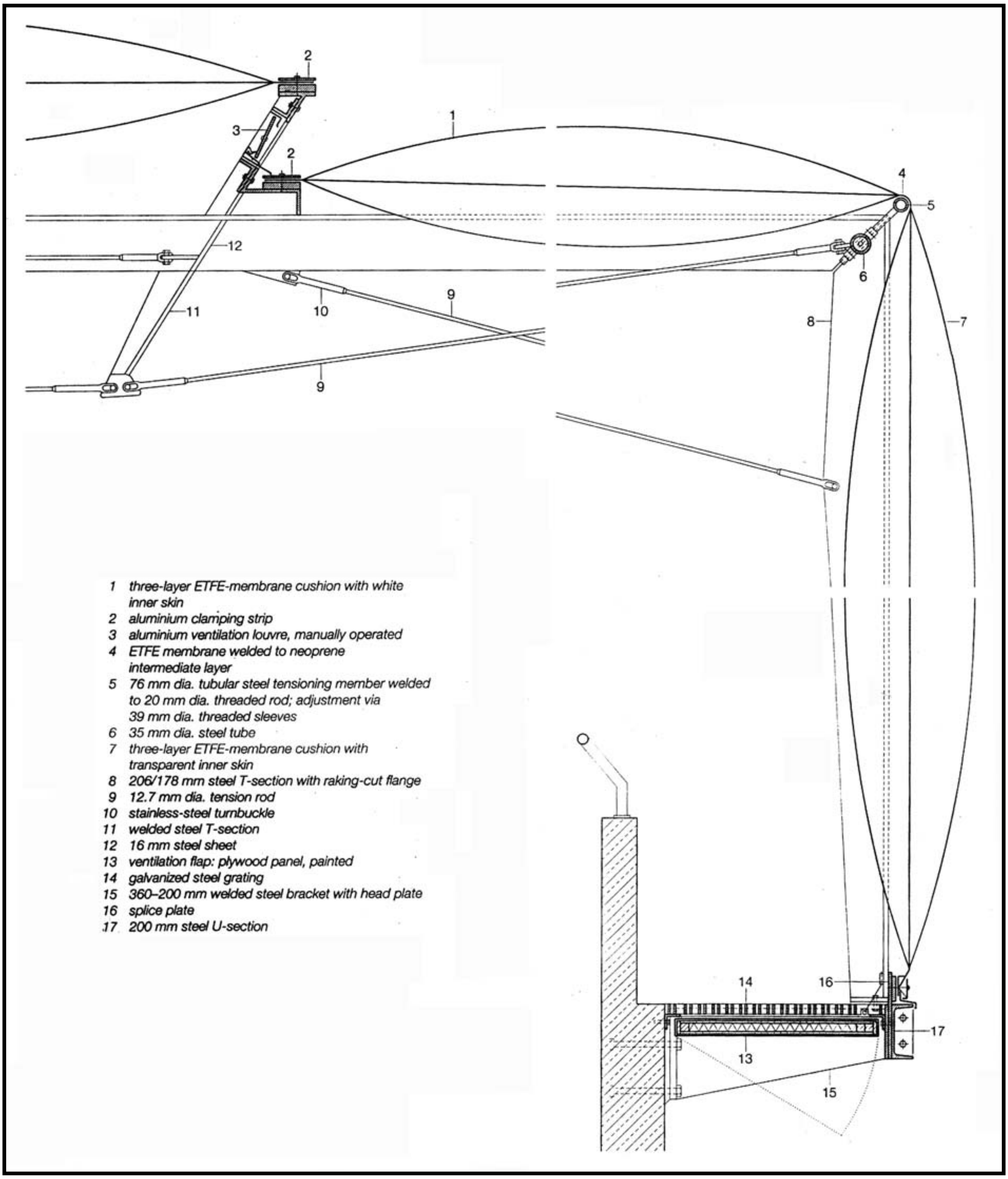

Fig. 3.34. Earth Center IPS Detail of the Roof and Facade
Source: Detail, 2000 / 6

NAME OF THE PROJECT	STRUCTURE	SPAN SIZE	PILLOW SHAPE & SIZE	INT. PRESSURE
EDEN PROJECT	Geodesic dome		Hex-tri-hex, 10-11m	
MASAOLA RAINFOREST HOUSE	Arched steel truss	106m - 4m trans.	Non-planar Rectangular, 3 / 23m, 4.2 / 23m	
WEST. CHELSEA HOSPITAL	Barrel-vault steel	18-20m	Rectangular, 3 / 4m	400-500 pa
MUNICH ALLIANZ ARENA	Grid steel frame		Rhomboid shaped 8m edge length	
HEMPSHIRE TENNIS HEALTH CLUP	Uni-axial cable net	36	Non-planar rec., 3 / 18m	
GERRY WEBER TENNIS STADIUM	Grid steel frame		Rectangular	200 pa
WATER PAVILLION AT EARTH CENTER	Steel frame		Rectangular	
NATIONAL SPACE & SCIENCE CENTER	Grid steel frame	14 m	Non-planar rectangular, 3 /20m	
HELLABRUNN ZOO	Prestressed cable net		Non planar, max. 2.5 / 18m	250-350 pa
BRAUN AG OFFICE ROOF SKYLIGHTS	Steel frame		Rectangular, 5 / 12m	
FESTO AG	Barrel-vault steel	13.5-21.0m	Non-planar	

Table 3.1. Pillow Properties of The Particular Applications

Project Name	Place	Country	Date	Number of Foil	Foil Width	Foil Transparency
Eden Project	Cornwall, London	**UK**	1995-2000	**3**		
Hellabrunn Zoo (Lion House)	Hellabrunn,Munich	**Germany**	1995	**2**	200/200μm	
Masaola Rainforest House	Masaola, Zurich	Switzerland	2003	3	R200/100/180, F200/100/150μm	
Pavillion at Earth Center (Waterworks)	Doncaster	UK	2002	3		white inner foil
Duales System Deutschland DSD	Expo2000	Germany	2000	3 VST*		
Westminster Chelsea Hospital	Westminster	**UK**	1992	**3**	200/30/150μm	
Festo AG	Esslingen, Stuttgart	**Germany**		**3 VST***		
National Science and Space Center	Leicester	**UK**	2001	**3**		
Allianz Arena Munich Stadium	Fröttmaning N. of Munich	**Germany**	2005	**3**	200/200/200 (?)μm	WRB illuminated
Hempshire Tennis and Health Club	Southampton	UK	1992	3		white foil
Gerry Weber Tennis Stadium	Halle, Westfallen, North Rhine	UK		2	200/200μm	
Mobydick Pool, Rulzheim	Rulzheim	Germany	2000?	3	200/80/200μm	
Prienavera Pool	SE Bavaria, Chiemsee Prien	Germany	2000?	3	200/100/200μm	

* VST, Variable Shading Technology.

Table 3.2. Foil Properties Of The Particular IPS Applications

Project Name	Country	Primary Structure of IPS	Pri.Str. Material
Eden Project	UK	Geodesic Dome w/ Tension Rods	Aluminium
Hellabrunn Zoo (Lion House)	Germany	Cable Mast Structure	steel
Masaola Rainforest House	Switzerland	Arched Beam	steel
Pavillion at Earth Center (Waterworks)	UK	Frame System w/ Tension Rods	steel
Duales System Deutschland DSD			steel
Westminster Chelsea Hospital Roof	UK	Extruded Aluminium	Aluminium + steel
Festo AG	Germany	Steel Arch Beam w/ Tension Rods	steel
National Science and Space Center	UK	Steel Frame w/ Tension Rods	steel
Allianz Arena Munich Stadium	Germany	Steel Frame	steel
Hempshire Tennis and Health Club	UK	Cable Mast Structure	steel
Gerry Weber Tennis Stadium*	UK	Steel Girder, Tension Rods	steel
Mobydick Pool, Rulzheim	Germany	Arched Beam	wood
Prienavera Pool	Germany	Arched Beam	wood

* Retractable Structure

Table 3.3. Primary Structure Types and Materials of Particular IPS Applications

Project Name	Place	Country	Date
Eden Project	Cornwall, London	UK	1995-2000
Hellabrunn Zoo (Lion House)	Hellabrunn,Munich	Germany	1995
Masaola Rainforest House	Masaola, Zurich	Switzerland	2003
Pavillion at Earth Center (Waterworks)	Doncaster	UK	2002
Duales System Deutschland DSD	Expo2000		2000
Westminster Chelsea Hospital	Westminster	UK	1992
Festo AG	Esslingen, Stuttgart	Germany	
National Science and Space Center	Leicester	UK	2001
Allianz Arena Munich Stadium	Fröttmaning N. of Munich	Germany	2005
Hempshire Tennis and Health Club	Southampton	UK	1992
Gerry Weber Tennis Stadium	Halle, Westfallen, North Rhine	UK	
Mobydick Pool, Rulzheim	Rulzheim	Germany	2000
Prienavera Pool	Souteast Bavaria, Chiemsee Prien	Germany	2000

Table 4.1. Particular IPS Applications Constructed After 1990s

Appendix A

General film properties of the ETFE foil are classified as below:

- Thermoplastic and a fluoropolymer
- Isotropic sheeting or a film
- Material is not a petrochemical derivative
- Water based / not solvent
- Density of ETFE Foil is 1.7 - 1.75 g/ cm^3
- Melting point of 275° C, although the foil softens below this temperature (200^{o}C)
- Resistant to temperature extremes - short time up to 230°C
- ETFE Foil is with in the low flammability category B1 when tested to DIN 4102
- The presence of Fluorine makes the material self-extinguishing.
- ETFE Foil is considered to be Class 0 under UK regulations.
- ETFE Foil has an oxygen index (LOI) 35% when tested to ASTM D 2863/77.
- ETFE Foil is classified M2 (i.e. no burning drips) according to NF P 92-505.
- Highly durable (life span >20 years); it is virtually unaffected by aging
- The material is recyclable
- Wide service temperature (from -200°C to +150°C)
- It does not degrade under Ultra Violet light or atmospheric pollution.
- Extremely resistant to dirt and self cleaning property, due to low surface tension
- Resistance to tear and penetration
- Resistant to hailstone impact
- Excellent resistance against UV and weathering
- Does not harden, yellow or deteriorate over time
- Does not degrade under UV light or atmospheric pollution
- Excellent weather stability
- Optimal resistance to chemicals
- Material is highly elastic
- Lightweight, 200µm single layer weighs 350g/m^2
- Sound reduction index of less than 10 dB.
- Acoustically soft (triple layer weighs approx. 1 kg/m^2)
- Good insulation value, depending on the number of layers

- The foil provides excellent electrical insulation, making it suitable for many industrial uses.
- High degree of light transparency. The foil is transparent (92 - 96%)
- The foil is permeable to UV light (UV- A %100, UV-B %50)
- High light transmittance from UV- to IR-range
- To regulate light permeability, the foil can be supplied printed or white
- High tensile strength at break
- High elongation range (% 300-400)
- High tensile strength (40-50 N/mm^2)
- High tear strength (400-500 N/mm)
- Very smooth surface due to extrusion
- Can be printed with graphic patterns
- Outstanding separating quality
- Excellent weldability
- High variety of mechanical film connection possibilities like sewing, nailing, clamping etc.
- Tailor made optimizing of film properties

General Properties of IPS are as shown below:

- Lightweight
- Flexible
- Good environmental and climatic control properties
- Cost effective
- Energy efficient, minimizing building energy consumption
- Ecologically friendly technology
- Extremely long lasting, it can be used as the permanent building envelope.
- Very low level of embodied energy
- Virtually total (architectural) freedom in terms of shape
- Low maintenance buildings
- Can be manufactured in large sizes
- Can span much greater distance than conventional cladding technology
- High resistance to environmental attacks
- High resistance to bomb blast

- High resistance to strong winds
- High resistance to sand storm
- Self venting under fire condition
- Maximizing internal comfort
- Solar shading can be achieved
- High light transmission in multilayer
- Can be translucent or printed to limit light and heat gain
- The density, color and number of layers can be varied
- Outstanding insulation properties (low U-value)
- Reduces heat loses due to air infiltration
- React to the sun and change their transmission and insulation throughout the day
- Reduces need for a heavier load-bearing structure
- Reduces need for a heavier foundation
- Reduces need for movement joints
- Considerably less initial investment cost than the cost of conventional roof structures
- Reduces the life cycle cost (maintenance) to very low levels
- Reduces risk in construction
- Reduces insurance cost for transportation during construction
- Prevent flashover or catastrophic structural collapse of the primary structure
- Does not reflect internally generated noise back to the occupants.
- Can penetrate the rain sound
- Reduces the need for sound suppressors for specific application
- Increase harvest and quality in greenhouses.
- Minimizes structural shading
- Enables suntan, prevents skin diseases

Appendix B

UV Radiation

Energy that is emitted in the form of electromagnetic waves with a wavelength of **1-380nm**, which is composed of UV-A, UV-B, and UV-C light; UV-A light being the longest wavelength and having the smallest energy and UV-C light being the shortest wavelength and having the highest energy. All UV-C light and most UV-B light is filtered out of the atmosphere via the ozone layer. However, UV-A light travels to the surface of the earth.

Source: [Environmental Pollution; v88n2; 219; 1995.] [Photochemistry and Photobiology; v51n6; 757; 1990.]

UV-A

Ultraviolet light that has wavelengths of **320nm to 400nm**. The wavelengths of this light are shorter than visible light and are not absorbed in the stratosphere by ozone.
[Deep Sea Research Part I: Oceanographic Research Papers, v. 48, p. 741-759]

Source: Atmospheric Chemistry Glossary

UV-B

An ultraviolet wavelength of light between **280nm and 320nm** whose intensity is increasing at the earth's surface (probably causing increases in skin cancer), This UV increase is because of decreases in stratospheric ozone.
[Research and Development Magazine; v39; 18LS; 1997.] [Chemical and Engineering News; v71; 12-13; 1993.]

UV-C

Light that spans the spectrum with wavelengths of **10nm to 290nm**. These wavelengths of ultraviolet light are extremely dangerous to human and animal tissue and is totally absorbed in the stratosphere by ozone and molecular oxygen.

Source: [Environmental and Experimental Botany, v. 45, p. 1-9]

UV Radiation Definitions
Source: www.webref.com

Pilkington (Australia) Ltd.

Insulated Glazing Performance Data

Product Name	Nominal Thickness	Visible		Solar		UV	U-Value	Shading	Max Size *	Weight
		Trans.	Refl.	Trans.	Refl.	Trans.		Co.		m^2
Optifloat™										
Optifloat™ Clear	3+12Air+3	80	14	74	14	55	3.1	0.91	2440x1220	15
	4+12Air+4	78	14	71	14	52	3.1	0.89	2440x1400	20
	5+12Air+5	78	14	68	12	47	3.2	0.87	2540x1840	25
	6+12Air+6	76	14	64	12	44	3.2	0.84	3000x2000	30
	8+12Air+6	74	14	62	11	42	3.2	0.82	3000x2000	35
	10+12Air+6	73	13	59	11	39	3.1	0.78	3000x2000	40
	12+12Air+6	72	12	56	10	36	3.1	0.75	3000x2000	45
Optifloat™ Grey	4+12Air+4	49	7	49	8	28	3.2	0.67	2440x1400	20
	5+12Air+5	42	7	43	7	24	3.3	0.61	2540x1840	25
	6+12Air+6	38	6	38	7	20	3.3	0.56	3000x2000	30
	10+12Air+6	23	6	22	6	15	3.3	0.39	3000x2000	40
	12+12Air+6	16	5	17	5	12	3.3	0.34	3000x2000	45
Optifloat™ Green	4+12Air+4	73	13	49	9	31	3.2	0.66	2440x1400	20
	5+12Air+5	71	13	44	8	28	3.3	0.62	2540x1840	25
	6+12Air+6	68	12	39	8	23	3.3	0.58	3000x2000	30
	10+12Air+6	60	10	29	6	11	3.3	0.47	3000x2000	40
Optifloat™ Bronze	4+12Air+4	55	9	50	9	25	3.2	0.67	2440x1400	20
	5+12Air+5	49	8	44	7	18	3.3	0.63	2540x1840	25
	6+12Air+6	45	7	39	7	15	3.3	0.58	3000x2000	30
	10+12Air+6	29	6	24	6	6	3.3	0.42	3000x2000	40
ComforTone®										
ComforTone® Grey	4+12Air+4	49	7	49	8	28	3.2	0.67	2440x1400	20
	5+12Air+5	42	7	43	7	24	3.3	0.61	2540x1840	25
ComforTone® Green	4+12Air+4	73	13	49	9	31	3.2	0.66	2440x1400	20
	5+12Air+5	71	13	44	8	28	3.3	0.62	2540x1840	25
ComforTone® Bronze	4+12Air+4	55	9	50	9	25	3.2	0.67	2440x1400	20
	5+12Air+5	49	8	44	7	18	3.3	0.63	2540x1840	25
ComfortPlus™										
ComfortPlus™	6.38+12Air+6	54	13	36	9	<1	2.1	0.52	3000x2000	30.4
Laminated										
Clear	6.38+12Air+6	74	13	61	11	<1	3.2	0.81	3000x2000	30.4
Grey	6.38+12Air+6	37	6	41	7	<1	3.2	0.6	3000x2000	30.4
Bronze	6.38+12Air+6	45	7	42	7	<1	3.2	0.61	3000x2000	30.4
Blue-Green	6.38+12Air+6	60	10	51	9	<1	3.2	0.71	3000x2000	30.4
Coolblue	6.38+12Air+6	60	10	55	9	<1	3.2	0.75	3000x2000	30.4
Translucent	6.38+12Air+6	57	9	47	8	<1	3.2	0.66	3000x2000	30.4
Evergreen®	6.38+12Air+6	57	10	23	5	<1	3.3	0.41	3000x2000	30.4
High Performance Tones										
Evergreen®	4+12Air+4	64	12	36	8	13	3.3	0.53	2440x1400	20
	5+12Air+5	65	12	35	7	15	3.3	0.53	2540x1840	25
	6+12Air+6	57	11	26	6	11	3.3	0.44	3000x2000	30
Supergrey™	4+12Air+4	15	4	12	4	3	3.4	0.5	2440x1400	20
	6+12Air+6	7	4	6	4	1	3.4	0.23	2540x1840	30
Arctic Blue™	4+12Air+4	57	9	38	7	26	3.3	0.55	2440x1400	20
	6+12Air+6	49	9	28	6	19	3.3	0.46	2540x1840	30

Pilkington (Australia) Ltd.

Insulated Glazing Performance Data

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans.	U-Value	Shading Co.	Max Size *	Weight m²
Suncool® High Performance Reflective										
TS21 on Clear	6+12Air+6	19	19	12	20	9	2.9	0.25	3000x2000	30
TS30 on Clear	6+12Air+6	27	16	18	15	14	3.1	0.33	3000x2000	30
SS22 on Clear	6+12Air+6	20	20	12	19	9	2.9	0.26	3000x2000	30
SS08 on Clear	6+12Air+6	7	38	5	33	4	2.7	0.15	3000x2000	30
TS21 on Green	6+12Air+6	17	15	8	12	3	2.9	0.22	3000x2000	30
TS30 on Green	6+12Air+6	26	13	11	10	5	3.1	0.27	3000x2000	30
SS22 on Green	6+12Air+6	17	16	8	12	4	3	0.22	3000x2000	30
TS21 on Grey	6+12Air+6	9	8	7	10	3	2.9	0.22	3000x2000	30
TS30 on Grey	6+12Air+6	13	8	11	9	4	3.1	0.27	3000x2000	30
SS22 on Grey	6+12Air+6	10	9	8	10	3	3	0.23	3000x2000	30
Suncool® High Performance - Laminated										
SS22 on Clear	6.38+12Air+6	20	26	15	27	<1	3.2	0.28	3000x2000	30.4
TS30 on Clear	6.38+12Air+6	31	18	21	19	<1	3.3	0.36	3000x2000	30.4
TS21 on Clear	6.38+12Air+6	22	24	14	27	<1	3.2	0.27	3000x2000	30.4
SL20 Grey	6.38+12Air+6	10	10	10	13	<1	3.3	0.25	3000x2000	30.4
SL20 Bronze	6.38+12Air+6	12	13	10	14	<1	3.3	0.25	3000x2000	30.4
SL20 Green	6.38+12Air+6	15	20	12	19	<1	3.3	0.27	3000x2000	30.4
SL20 Coolblue	6.38+12Air+6	15	20	13	21	<1	3.3	0.27	3000x2000	30.4
SL20 Silver	6.38+12Air+6	18	26	14	24	<1	3.3	0.28	3000x2000	30.4
Eclipse™ Reflective Glass										
Eclipse Grey (#2)	6+12Air+6	17	14	21	11	3	3.3	0.38	3000x2000	30
Eclipse Bronze (#2)	6+12Air+6	21	19	24	14	3	3.2	0.41	3000x2000	30
Eclipse Blue-Green (#2)	6+12Air+6	30	33	23	17	4	3.2	0.39	3000x2000	30
Eclipse Gold (#2)	6+12Air+6	29	43	26	32	2	3.2	0.4	3000x2000	30
Eclipse Clear (#2)	6+12Air+6	36	42	38	27	8	3.2	0.55	3000x2000	30
Eclipse Evergreen (#2)	6+12Air+6	28	25	15	12	2	3.3	0.31	3000x2000	30
Eclipse Arctic Blue (#2)	6+12Air+6	23	20	16	12	4	3.3	0.33	3000x2000	30
SolarE™ Laminates (New S4 Range)										
S4 Neutral	8.38+12Air+6	53	12	35	11	<1	2.1	0.51	3000x2000	35.4
S4 Standard	8.38+12Air+6	49	11	24	7	<1	2.2	0.38	3000x2000	35.4
S4 Grey	8.38+12Air+6	32	7	24	7	<1	2.2	0.38	3000x2000	35.4
S4 Green	8.38+12Air+6	44	10	18	6	<1	2.2	0.31	3000x2000	35.4
S4 Blue	8.38+12Air+6	38	10	19	6	<1	2.2	0.32	3000x2000	35.4
SolarE™ Laminates										
E4 Clear	8.76+12Air+6	61	12	41	9	<1	2.1	0.58	3000x2000	35.8
E4 Clear	8.76+12Air+6	61	12	40	9	<1	2.1	0.56	3000x2000	40.8
E6 Clear	12.76+12Air+6	60	12	38	8	<1	2.1	0.54	3000x2000	45.8
E4 Standard	8.76+12Air+6	62	14	33	8	<1	2.1	0.48	3000x2000	35.8
E6 Standard	12.76+12Air+6	60	12	28	6	<1	2.1	0.43	3000x2000	45.8
E4 Grey	8.76+12Air+6	43	8	34	8	<1	2.1	0.5	3000x2000	35.8
E6 Grey	12.76+12Air+6	33	6	27	6	<1	2.1	0.41	3000x2000	45.8
E4 Standard I3	8.76+12Air+6	31	6	21	5	<1	2.1	0.35	3000x2000	35.8
E4 Standard I4	8.76+12Air+6	54	11	35	7	<1	2.1	0.49	3000x2000	35.8
E4 Green	8.76+12Air+6	58	12	27	7	<1	2.1	0.42	3000x2000	35.8
E6 Green	12.76+12Air+6	50	10	19	5	<1	2.1	0.32	3000x2000	45.8
E6 Green I3	12.76+12Air+6	25	5	11	4	<1	2.2	0.24	3000x2000	45.8

Pilkington (Australia) Ltd.

Insulated Glazing Performance Data

* Units are limited to a maximum of 150kg this may effect the maximum size which can be manufactured.
Notes - Pilkington clear float has been used as the backing glass
Typical measured values of Pilkington production are provided
All performance data is calculated using LBL window 4.1 software, Ashrae standard summer conditions have
The Ultraviolet spectrum is from 300nm to 380nm

PILKINGTON

SMART GLASS SOLUTIONS

Pilkington (Australia) Ltd.

Single Glazing Performance Data

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
Optifloat™										
Optifloat™ Clear	3	89	8	86	8	71	5.9	1	4600x2860	7.5
	4	88	8	84	8	67	5.9	0.98	4600x2860	10
	5	88	8	82	7	65	5.9	0.97	4600x3120	12.5
	6	87	8	80	7	62	5.9	0.95	5100x3120	15
	8	85	8	77	7	57	5.8	0.93	5100x3120	20
	10	83	7	73	7	54	5.8	0.89	5100x3120	25
	12	82	7	70	7	48	5.8	0.87	5100x3120	30
	15	80	7	65	7	44	5.8	0.82	4600x3210	37.5
	19	78	7	60	6	40	5.8	0.78	4600x3210	47.5
Optifloat™ Grey	4	55	5	57	5	34	6.3	0.77	4600x2860	10
	5	48	5	52	5	30	6.3	0.73	4600x3120	12.5
	6	43	5	47	5	25	6.3	0.69	4600x3120	15
	10	26	5	27	5	12	6.3	0.52	4600x3120	25
	12	18	5	21	5	9	6.3	0.47	4600x3120	30
Optifloat™ Green	4	82	8	58	6	37	6.2	0.77	4600x3120	10
	5	80	8	53	6	34	6.2	0.73	4600x3120	12.5
	6	78	7	49	6	29	6.3	0.7	4600x3120	15
	10	69	6	36	5	14	6.3	0.6	4600x3120	25
Optifloat™ Bronze	4	62	6	59	6	30	6.2	0.78	4600x2860	10
	5	56	5	54	5	23	6.3	0.75	4600x3120	12.5
	6	51	5	49	5	19	6.3	0.7	4600x3120	15
	10	33	5	30	5	7	6.3	0.55	4600x3120	25

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
ComforTone®										
ComforTone® Grey	4	55	5	57	5	34	6.3	0.77	4600x2860	10
	5	48	5	52	5	30	6.3	0.73	4600x3120	12.5
ComforTone® Green	4	82	8	58	6	37	6.2	0.77	4600x3120	10
	5	80	8	53	6	34	6.2	0.73	4600x3120	12.5
ComforTone® Bronze	4	62	6	59	6	30	6.2	0.78	4600x2860	10
	5	56	5	54	5	23	6.3	0.75	4600x3120	12.5

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
ComfortPlus™										
ComfortPlus™	6.38	62	10	44	8	<1	3.9	0.61	3300x2440	15.4

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
Laminated										
Clear	6.38	89	7	77	7	<1	5.9	0.92	3660x2440	15.4
	6.76	88	7	75	7	<1	6	0.9	3660x2440	15.8
	7.52	88	7	74	6	<1	6	0.89	3660x2440	16.6
Grey	6.38	44	5	47	5	<1	6.1	0.67	3660x2440	15.4
Bronze	6.38	52	6	54	5	<1	6.1	0.72	3660x2440	15.4
Blue-Green	6.38	73	6	68	6	<1	6	0.84	3660x2440	15.4
Coolblue	6.38	76	6	73	5	<1	6	0.88	3660x2440	15.4
Translucent	6.38	65	6	58	6	<1	6	0.76	3660x2440	15.4
Evergreen®	6.38	66	6	29	5	<1	6.2	0.55	3660x2440	15.4

Pilkington (Australia) Ltd.

Single Glazing Performance Data

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
High Performance Tones										
Evergreen®	4	73	8	43	6	16	6.3	0.66	4600x3120	10
	5	73	8	43	6	19	6.3	0.66	4600x3120	12.5
	6	65	8	33	6	13	6.3	0.58	4600x3120	15
SuperGrey™	4	17	4	14	4	4	6.5	0.44	5100x3300	10
	6	8	4	8	4	1	6.5	0.39	5100x3300	15
Arctic Blue™	4	64	6	45	5	31	6.3	0.69	5080x3150	10
	6	56	6	35	5	23	6.3	0.6	5080x3150	15

Suncool® High Performance Reflective										
TS21 on Clear	6	21	19	15	20	12	5.3	0.36	3660x2140	15
TS30 on Clear	6	30	15	22	15	15	5.6	0.44	3660x2140	15
SS22 on Clear	6	22	20	15	19	12	5.4	0.36	3660x2140	15
SS08 on Clear	6	8	38	6	33	6	5	0.23	3660x2140	15
TS21 on Green	6	18	17	10	12	4	5.3	0.34	3660x2140	15
TS30 on Green	6	27	12	14	10	6	5.6	0.39	3660x2140	15
SS22 on Green	6	19	16	10	12	5	5.8	0.34	3660x2140	15
TS21 on Grey	6	10	8	9	10	3	5.3	0.34	3660x2140	15
TS30 on Grey	6	16	8	14	9	5	5.6	0.4	3660x2140	15
SS22 on Grey	6	11	9	10	10	4	5.4	0.34	3660x2140	15

Suncool® High Performance - Laminated										
SS22 on Clear	6.38	23	26	18	27	<1	6.15	0.40	3660x2140	15.4
TS30 on Clear	6.38	35	17	26	19	<1	6.15	0.48	3660x2140	15.4
TS21 on Clear	6.38	25	23	17	27	<1	6.15	0.39	3660x2140	15.4
SL20 Grey	6.38	11	10	12	13	<1	6.5	0.38	3660x2140	15.4
SL20 Bronze	6.38	13	13	12	14	<1	6.5	0.38	3660x2140	15.4
SL20 Green	6.38	17	20	15	19	<1	6.4	0.38	3660x2140	15.4
SL20 Coolblue	6.38	13	20	16	21	<1	6.4	0.38	3660x2140	15.4
SL20 Silver	6.38	20	26	17	24	<1	6.4	0.38	3660x2140	15.4

Eclipse™ Reflective Glass										
Eclipse Grey (#2)	6	19	14	27	10	4	6.2	0.52	3302x2438	15
Eclipse Bronze (#2)	6	23	19	31	13	4	6.2	0.54	3302x2438	15
Eclipse Blue-Green (#2)	6	33	32	28	16	6	6.2	0.51	3302x2438	15
Eclipse Gold (#2)	6	31	42	33	31	2	6.1	0.5	3302x2438	15
Eclipse Clear (#2)	6	39	40	49	25	11	6.2	0.65	3302x2438	15
Eclipse Evergreen (#2)	6	30	24	18	11	3	6.4	0.44	3302x2438	15
Eclipse Arctic Blue (#2)	6	25	19	20	11	5	6.4	0.46	3302x2438	15

Low E Glass										
Pilkington Energy Advantage™	4	82	11	68	11	56	3.6	0.83	5100x3210	10
	6	82	10	65	10	49	3.6	0.81	5100x3210	15

Pilkington (Australia) Ltd.

Single Glazing Performance Data

Product Name	Nominal Thickness	Visible Trans.	Visible Refl.	Solar Trans.	Solar Refl.	UV Trans	U-Value	Shading Co.	Max Size	Weight m^2
SolarE™ Laminates (New S4 Range)										
S4 Neutral	8.38	61	9	44	10	<1	3.9	0.6	3300x2440	20.4
S4 Standard	8.38	56	9	30	7	<1	4	0.48	3300x2440	20.4
S4 Grey	8.38	37	6	30	7	<1	4	0.48	3300x2440	20.4
S4 Green	8.38	50	8	22	6	<1	4.1	0.41	3300x2440	20.4
S4 Blue	8.38	44	8	23	6	<1	4.1	0.42	3300x2440	20.4

SolarE™ Laminates										
E4 Clear	8.76	69	8	51	7	<1	3.8	0.69	3660x2440	20.8
E4 Clear	10.76	69	8	49	7	<1	3.8	0.66	3660x2440	25.8
E6 Clear	12.76	68	14	47	13	<1	3.7	0.62	3660x2440	30.8
E4 Standard	8.76	71	10	40	7	<1	4.1	0.58	3660x2440	20.8
E6 Standard	12.76	68	8	34	5	<1	3.9	0.52	3660x2440	30.8
E4 Grey	8.76	48	6	42	6	<1	3.9	0.59	3660x2440	20.8
E6 Grey	12.76	37	5	33	5	<1	3.9	0.51	3660x2440	30.8
E4 Standard I3	8.76	36	5	26	5	<1	4.0	0.45	3660x2440	20.8
E4 Standard I4	8.76	62	8	41	6	<1	3.9	0.59	3660x2440	20.8
E4 Green	8.76	66	8	34	6	<1	4.1	0.52	3660x2440	20.8
E6 Green	12.76	57	7	23	5	<1	3.9	0.41	3660x2440	30.8
E6 Green I3	12.76	28	5	14	4	<1	4.0	0.33	3660x2440	30.8

Typical measured values of Pilkington production are provided
All performance data is
calculated using LBW
The Ultraviolet spectrum is from 300nm to 380nm

PILKINGTON

SMART GLASS SOLUTIONS

Appendix D

Gewebematerial (ohne Gittergewebe)	Material-typ	Flächen-gewicht [g/m²] nach DIN 55 352	Mindestwerte der Zugfestig-keit Gewebe [N/5 cm] Kette/Schuss nach DIN 53 354	Bruch-dehnung Gewebe [%] Kette/Schuss nach DIN 53 354	Weiterreiß-festigkeit Gewebe [N] Kette/Schuss nach DIN 53 363	Knickbe-ständigkeit	UV-Be-ständigkeit	erreichbare Feuerbeständig-keit nach DIN 4102	Transluzenz [%]	Lebens-erwartung (a)	Standardfarben	häufige Anwendungen
Baumwollgewebe		350 520	1700/1000 2500/2000	35/18 38/20	60 80	sehr gut	ausreichend	B2	unterschiedlich	< 5	große Farbauswahl auf Anfrage	temporäre Konstruktionen, mobile Konstruktionen, wandelbare Konstruktionen, permanente Konstruktionen, geringer Spannweite
PTFE-Gewebe		300 520 710	2390/2210 3290/3370 4470/4510	11/10 11/10 18/9	ca. 500/500	sehr gut	sehr gut	A2	bis ca. 37	> 25	Standard weiß, weitere Farben auf Anfrage	wandelbare Konstruktionen, insbesondere Schirmkonstruktionen
ETFE-Gewebe, THV- beschichtet		250	1200/1200			sehr gut	sehr gut	B1	bis ca. 90	> 25	Standard weiß und natur weitere Farben auf Anfrage	Innenanwendungen, belastungsbedingt auch Außenanwendungen
Polyestergewebe, PVC-beschichtet	Typ I Typ II Typ III Typ IV Typ V	800 900 1050 1300 1450	3000/3000 4400/3950 5750/5100 7450/6400 9800/8300	15/20 15/20 15/25 15/30 20/30	350/310 bis 1800/1600 580/520 800/950 1400/1100 1800/1600	sehr gut	gut	B1	bis ca. 4,0	> 20	Standard weiß, große Farbauswahl auf Anfrage	temporäre Konstruktionen mobile Konstruktionen wandelbare Konstruktionen permanente Konstruktionen Standardsysteme
Glasfasergewebe, PTFE-beschichtet		800 1150 1550	3500/3500 5800/5800 7500/6500	7/10 bis 2/17	300/300 bis 500/500	ausreichend	sehr gut	A2	bis ca. 13	> 25	Standard weiß, begrenzte Farbauswahl auf Anfrage	permanente Konstruktionen Standardsysteme, nicht wandelbar
Glasfasergewebe, Silikonbeschichtet		800 1270	3500/3000 6600/6000	7/10 bis 2/17	300 570	ausreichend	sehr gut	A2	bis ca. 25	> 20	Standard weiß, begrenzte Farbauswahl auf Anfrage	permanente Konstruktionen nicht wandelbar
Aramidfasergewebe, PVC-beschichtet		900 2020	7000/9000 24500/24500	5/6	700 4450	gut	ausreichend	B1	prinzipiell keine	> 20	Standard weiß, große Farbauswahl auf Anfrage	permanente Konstruktionen großer Spannweite, nicht transluzent, nicht wandelbar
Aramidfasergewebe, PTFE-beschichtet			projektbezogen, begrenzt einstellbar			gut	ausreichend	A2	prinzipiell keine	> 25	Standard weiß, begrenzte Farbauswahl auf Anfrage	permanente Konstruktionen große Spannweite, nicht transluzent, nicht wandelbar
Folienmaterial	**Material-typ**	**Flächen-gewicht [g/m²] nach DIN 55 352**	**Zugfestig-keit Folie [N/mm²] nach DIN 53 455**	**Reiß-dehnung Folie [%] nach DIN 53 455**	**Weiterreiß-widerstand Folie [N/mm] nach DIN 53 363**	**Knick-beständig-keit**	**UV-Be-ständigkeit**	**erreichbare Brandschutz-klasse nach DIN 4102**		**Lebens-erwartung (a)**	**Standard-farben**	**häufige Anwendungen**
ETFE-Folien	50 µm 80 µm 100 µm 150 µm 200 µm	87,5 140 175 262,5 350	64/56 58/54 58/57 58/57 52/52	450/500 500/600 550/600 600/650 600/600	450/450 450/450 420/440 450/430 430/430	ausreichend	sehr gut	B1	bis ca. 95	> 25	Standard transparent weiß oder blau, weitere Farben oder Bedruckung auf Anfrage	Zoologische Anlagen Gewächshäuser Schwimmbäder Fassaden und Atrien
THV-Folie	500 µm	980	22/21	540/560	255/250	gut	gut	B1	bis ca. 95	> 20	Standard transparent weitere Farben auf Anfrage	Innenanwendungen Außenanwendungen geringer Spannweiten
PVC-Folien						gut	ausreichend	B1	bis ca. 95	< 5	diverse Standardfarben	Innenanwendungen

Membrane Materials Property Chart
Source: Moritz, 2000/6

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