Structural Opportunities of ETFE (ethylene tetra fluoro ethylene)

by

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ABSTRACT

An exploration of ETFE (ethylene tetra fluoro ethylene) foil cushions was performed in its use for building cladding. ETFE foil cushions consist of alternating layers of ETFE film and air cavities. An inflation system pressurizes the foil cushions prestressing the film layers to carry applied load. The ETFE cushion system is an extremely lightweight plastic offering considerable advantages over traditional cladding materials. ETFE foil cushions are self-cleaning, highly transparent to light, resistant to weathering and can be manufactured in almost any shape and size. Incorporating ETFE into a building's cladding results in a more efficient and low maintenance structure. ETFE foil cushions are successfully being implemented in cladding for botanical gardens, zoo buildings, and swimming pools. ETFE is currently finding its place as an effective alternative to glass in more traditional buildings as roofing for courtyards, atria, and shopping malls.

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CHAPTER 1. INTRODUCTION

Plastics in construction and especially in building cladding offer a lightweight, high strength, low cost alternative to glass and other cladding systems. Plastics are not just for use in temporary exhibitions anymore. New plastics have been developed and are resistant to ultraviolet rays and experience no discoloration. The variety of plastics is growing: their life spans and quality increasing. ETFE (ethylene tetra fluoro ethylene) is a plastic that is inspiring a change in the way buildings are designed.

ETFE is a relatively new material successfully being implemented for use in cladding. ETFE has 95% light transmission of all frequencies but does not offer the clear visibility of glass. The first projects utilizing this extremely lightweight, almost completely transparent material were botanical gardens, zoo buildings, swimming pools and exhibitions. ETFE is finding its place in more traditional buildings as roofing for courtyards, atria, shopping malls, and stores. The attraction to ETFE is the considerable savings on material required to support the cladding. This savings translates into a more efficient building structure and a low maintenance cladding system. An ETFE cladding system offers a flexible alternative to traditional glass cladding which is sensitive to slight movements of the building's primary structure. ETFE, whether used as a single-layer membrane stretched between framework or as pneumatically prestressed cushions, has the ability to adapt to deformations of a structure.

ETFE is not just an attractive alternative to glass. The plastic material is inspiring new designs and concepts of how cladding can influence and cooperate with a building's primary structural design. When utilized for appropriate applications, ETFE can be an exceptional choice for cladding. Contemporary buildings and cladding designs are extending the limits of appropriate applications of ETFE.

1.1 ETFE Discovery

ETFE (ethylene tetra fluoro ethylene) is a relatively new material in the building industry gaining popularity in cladding use for modern structures. However, ETFE is not a new development in the plastics industry; it is commonly used for tank construction, wire insulation, and packaging of food and pharmaceuticals. First developed by Dr. Plunkett in 1938 at Dupont, it is one of the seven fluoropolymers generated from the invention of PTFE (poly tetra fluoro ethylene) or the plastic more commonly known as Teflon®. Each of the fluoropolymer PTFE relatives have unique material properties, ETFE is has the distinctive capability of being extruded. ETFE is a thermo-plastic and can be heated and extruded through a die producing a thin film.[18] Fluoropolymers are a class of plastics that contain both carbon and fluorine. ETFE is a copolymer of ethylene and tetra fluoro ethylene and is known as a "tough polymer." The ETFE film manufactured by Dupont is Tefzel®. Many other plastics manufacturers produce ETFE under different names such as 3M's Dyneon® and Nowofol's NOWOFLON®.

1.2 Manufacturing Process

Unlike many synthetic plastics, ETFE is not a derivative of a petrochemical. ETFE starts as a combination of fluorspar (CaF_2), hydrogen sulfate (HSO_4), and trichloromethane ($CHCl_3$) called chlorodifluoromethane (CHF_2CL). Chlorodifluoromethane is a raw material classified as a class II substance under the Montreal Treaty on ozone depleting substances; it does not contribute to global warming. No Class I materials or ozone depleting substances are used in the manufacturing process of ETFE.[23] The chlorodifluoromethane is then manufactured into tetra fluoro ethylene (TFE) in the process described below. The by-products formed are calcium sulfate ($CaSO_4$), hydrogen fluoride (HF) and hydrochloric acid (HCl). The calcium sulfate and hydrogen fluoride are reused to produce more fluorspar which can be used again as an input into the manufacturing process.

The process takes place at 125 degrees Celsius.[22] The TFE is then polymerized with ethylene to produce ETFE (25% ethylene and 75% TFE).[17] Polymerization is a chemical reaction that constructs a long molecular chain using small basic molecules each with a double bond. The entire ETFE manufacturing process is water based and does not include use of any solvents or additives. The result of the process is an ETFE powder. The next step is granulization: heating up the powder to 265-285 degrees and forming ETFE granules. ETFE producers sell the material in granules which can be formed into many different products including a sheet, rod, and film. The ETFE product used in the building industry for cladding is ETFE film, also referred to as ETFE foil. The dehumidified granules are placed in an extruder then melted by the friction created by metal screw as well as external heating: the process occurs at 250 degrees Celsius. The ETFE is dehumidified again under a vacuum and filtered through a sieve. Lastly, the material is pushed out through a nozzle. The ETFE film is extruded through a die at a thickness of 30-200 microns. The typical width of extruded sheet of ETFE foil is 1.2-1.55 m.[17] ETFE film can be manufactured in three product types: transparent film, translucent film, and film printed with a graphical design. Additionally, colored foil can be produced by adding pigments to the material during the manufacturing process. The fabrication of ETFE is still quite specialized, most of the manufacturers are found in Germany. ETFE manufacturers often provide the entire cladding system and oversee the film production, pillow fabrication, and erection of the pillows onto the support structure.

CHAPTER 2. ETFE PRODUCTS FOR USE IN BUILDINGS

The ETFE product that is predominant in the construction industry for membrane use is ETFE film. ETFE film can be utilized as a single layer stretched between two supports or in many air-trapping layers to create a foil cushion, also called a pillow. For both uses, the ETFE material requires a pretensioning process so the film transfers imposed loads through tension only without folding.[16] The single layer ETFE film membranes rely on mechanical prestressing to transfer loads to the primary structure. The multi-layer ETFE cushions use air to prestress the film layers and carry applied loads. This paper will concentrate on the latter use of ETFE in a pillow or cushion capability. A brief description of the use of singly layer ETFE film is given below, and an example of its use in a roofing system is included below in section 2.1.

2.1 Mechanical Prestressing

The single layer ETFE film panels are similar in usage to their cushion counterparts. The ETFE panels are supported by a primary structure. The size of each membrane panel is limited by load capacity of the ETFE material: a factor of thickness and area. The single membrane is stretched to the frame edges and fastened. The maximum size of mechanically inflated cushions is approximately 1.5 meters long. The single layer ETFE membrane takes advantage of doubly counter curved surfaces increasing its load capacity by using two way action of the material. The mechanically prestressed panels are much smaller than their pneumatically controlled counterparts because the ETFE supports the load with only its material strength. Single layer, mechanically prestressed ETFE is used for small roofing projects.

2.2 Pneumatically Prestressed

ETFE cushions are of the most interest for use in structural engineering applications. ETFE foil cushions are an ideal cladding solution for covered tennis courts, hospitals, swimming pools, overhead sky lighting and atria. The pillows exhibit ideal material properties appropriate for building envelopes: low weight, good thermal properties, high solar radiation, ultraviolet resistant, light transparency, and geometric flexibility.

2.2.1 ETFE Foil Cushions

Pneumatic pre-stressing has made great strides in the PVC-coated polyester fabric field. The technology has extended to the field of transparent cladding. Now pneumatic prestressing plays an important role in ETFE cushion roof systems enabling long distances to be spanned. ETFE pillows are created by connecting two or more layers of ETFE film shapes together around their perimeter. The cushion consists of layers of ETFE foil and air. The pressurized air stabilizes the pillow and prestresses the system to take load. This pressure is usually between 200 and 1000 Pa. The cushions puff up a distance of approximately 0.10-0.15 of the span width.[17] The film used for fabricating an ETFE inflatable is between 100 and 200 microns thick.[22] A typical ETFE cushion has between 2 and 5 layers of film and a corresponding number of air pockets. Each ETFE foil cushions weighs approximately 2 – 3.5 kg per square meter. The actual pillow weighs less than 2% of equivalent glass cladding, while the entire pillow system including aluminum connection and steel frame support weighs between 10% and 50% of conventional glass-façade structure.

There are many manufacturers of ETFE foil cushion systems, most of the companies are in Germany. Vector Special Projects, Vector Foiltec, and Skyspan each have developed their own cushion cladding system. The first application of an ETFE cushion system was in the Netherlands for a building at the Burgers Zoo in Arnheim in 1982. Since then, Vector Foiltec has manufactured ETFE cladding systems for three more buildings at the zoo. ETFE foil cushions have experienced the most popularity for cladding use in UK and Germany.[22]

2.2.2 Size

The size of the inflatable cushions depends on load capacity of the material, the area of the load applied, and the spacing of the supporting frame structure supporting. The cushions can be produced in any imaginable size and shape, respecting snow and wind loading capacity. The load imposed on the cushions is a function of pillow span and rise of the cushion. Vector Special Projects' company design guideline limits a rectangular ETFE foil cushion size to 3.5 m by any length. Triangular cushions take advantage of two way action in loading and can exceed those dimensions specified for rectangular inflatables.[23] Karsten Moritz is a partner in the engineering company Engineering + Design and Professor Rainer Barthel is head of the department of structural planning of the University of Technology in Munich and partner of Barthel and Maus, an engineering consulting company in Munich. Moritz and Barthel recommend a maximum span of 4.5m for one-way pillows and 7.5 m for round or square pillows (two-way cushions).[16] Greater pillow widths can be achieved by adding reinforcement to the film layers of the cushion such as a cable grid net or additional layers of ETFE film.

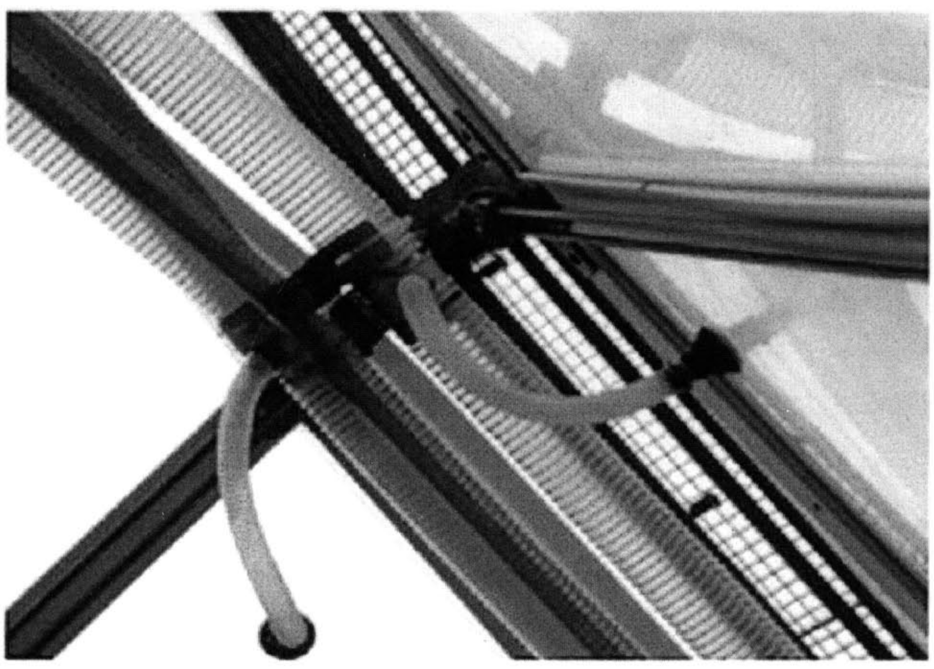

Figure 1: ETFE membrane with air supply hose [24]

2.2.3 Inflation System

An inflation system continuously controls the air pressure in the ETFE foil cushions. The air supply does not continuously passing air through the system but instead maintains the pressure in the cushions. The inflation system consists of a fan that filters the air, pumps it into the pillows, finally, regulates the humidity of the air inside the cushions. Typically one or more inflation units are required to maintain the pressure of the cushions over a 1000 m^2 area. Air dryers are used in conjunction with the blowers to minimize humidity in the cushions which can result in condensation on the inside of the pillows. Condensation is a concern at cushion connections; channels can be built into the aluminum extrusions to filter out this water. Condensation can also pose a problem when the temperature inside the building is significantly different that the temperature outside. The air pressure inside the cushions is typically 200-750 Pa and can be increased to support higher loads. The inflation system can be connected to sensors that actively control the fan to adapt to different loading situations. During snowstorms or high wind, sensors can automatically increase the pressure inside the cushions to support the additional load. Perhaps this wireless resource could be expanded to control different sections of the cladding separately for truly adaptive support. The air pressure within cushions resists applied loads, but under excessive applied loads deflection of the top foil layer allows the remaining film layers to take the additional load in tension.

Altering the amount of air between the layers of ETFE also modifies their insulating properties. A higher air pressure increases the volume of air inside the pillows and thus, increases the insulation of the building. This property can be manipulated to meet changing weather conditions. More air is pumped into the foil cushions to provide more insulation to the building on cold days while on hotter days the cushions are deflated to allow heat to escape.

2.2.4 Framing

The ETFE foil pillows are normally installed with aluminum clips and supported by a steel, timber, or cable grid net. Extruded aluminum framing is fastened to the primary structure and clamps the pillows in place. The joint between the pillows and the aluminum framing includes beading (EPDM gaskets) for waterproofing the connection. The aluminum framing is attached to the primary structure by plates and bolts. Special care must be taken with placement of the bolts hole so that screws do not pierce the pillows.

2.2.5 Construction

As a new material, there is currently limited knowledge about the assembly and erection of ETFE cladding. It is recommended that manufacturers either assemble the pillow systems themselves or oversee the process if others will be in charge of the erection. The ETFE foil cushions can be either prefabricated or assembled on site. For construction undertaken by Vector Special Projects, the ETFE cladding system is assembled on site with use of local materials when available. The aluminum is manufactured in the United Kingdom and usually brought to a factory local to the project site where the aluminum components including the extruded perimeter connection are produced. The ETFE cushions are made in Germany and then transported via car or shipping container to the site. Finally, the cladding system is then fabricated by hand using electric tools.

ETFE sheeting is manufactured at widths ranging from 1.2 – 1.55 m wide. Structures making use of the capabilities of ETFE will probably require a larger span of film and connection of the sheets as necessary. A beading is required to weld ETFE film sheeting edges to each other. The beading is an aluminum bar, a polyvinyl chloride (PVC) cord, or an ethylene propylene diene monomer (EPDM) cord. The beading is place between overlap of the two ETFE film edges and welded together thermally. The result is a translucent 10 mm thick seam between the film pieces, but almost imperceptible due to the large expanse of the ETFE panels.

Special tools are required to connect the cushions to aluminum frame, especially when a beading is used at the pillow joints. The aluminum edging parts are screwed together to fix the ETFE cushion and beading in a positive joint.[17] It is important to arrange the bolts so that they will not damage the ETFE film of the cushions. Lastly, special care must be paid to the curvature of the roof to maintain continuous water runoff. Ponding water can cause significant problems because the film layer continues to deform and collect more water. Design should account for the volume of water that could collect in ultimate deformations of the pillows.

CHAPTER 3. ETFE MATERIAL PROPERTIES

All fluoropolymers have, high and low temperature capabilities, great durability, low friction, very high electrical and chemical resistance and good thermal properties. Strong bonds within the fluoropolymer prevent degradation of the material under extended exposure to weather conditions and ultraviolet radiation. Therefore, application of a coating is not necessary to preserve the material toughness of ETFE. ETFE is very stable material and fire-resistant.[17] If on fire, ETFE exhibits self extinguishing properties. ETFE is unique because of its mechanical toughness. It is much stiffer and stronger than PTFE but has a lower working temperature. ETFE does not deteriorate, discolor, or harden as it ages. A typical ETFE film has a weight of approximately 175 g/m^2 for a film thickness of 100 microns.

Table 1: Material Properties for ETFE film, by thickness [14]

Thickness	[μm]	**50**	**80**	**100**	**150**	**200**
Weight per unit area†	[g/m^2]	87.5	140	175	262.5	350
Minimum Tensile Strength*	[N/5cm]	64/56	58/54	58/57	58/57	52/52
Fracture Strain*	[%]	450/500	500/600	550/600	600/650	600/600
Tear Resistance‡	[N]	450/450	450/450	430/440	450/430	430/430

†according to DIN 55 352, (DIN = German Institute for Standardization)
*warp/weft, according to DIN 53 354 or DIN EN ISO 527
‡warp/weft, according to DIN 53 363

3.1 Light Transmission

ETFE has 94-97% light transparency and 83-88% ultraviolet light transparency. All the light frequencies are transmitted through the film evenly throughout the visible light spectrum so colors viewed through ETFE are not disrupted. This high light transmission performance makes ETFE very popular for use in greenhouses and botanical gardens. However, due to the curved proportions of the cushions the light is refracted when passing through the film, forming a slightly distorted visual image. If almost complete transparency is not desired, the film can be manipulated with different surface textures or tints. The film can be printed with a graphical design or texture to influence light transparency. The effect can be multiplied by increasing the layers of ETFE.

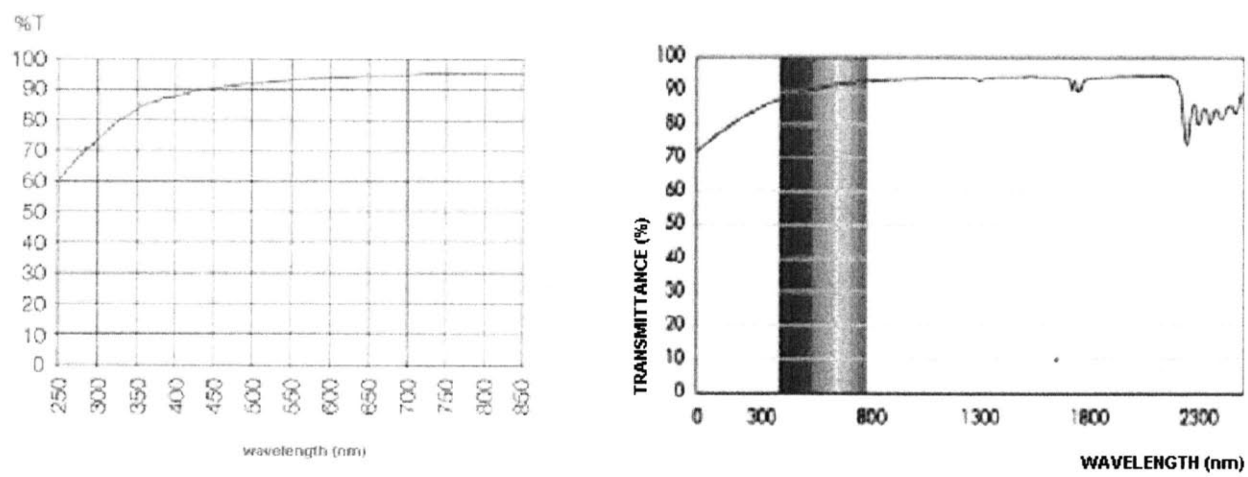

Figure 2: a)Light transmission of NOWOFLON® [17]; b)And of Texlon® system [25]

An innovative solution to reducing solar gain is using actively controlled ETFE pillows that contain differentially pressurized air chambers. Intermediate layers of the cushion are printed with opaque graphics and will alternately cover and uncover each other creating an adaptive shading roof. The Duales System pavilion at the Hanover Expo in 2000 featured an ETFE roof and wall system. The layers of the foil pillow were printed with a positive and negative leaf pattern. Altering the air pressure inside the cushions changed the transparency of the building's face from opaque to translucent.

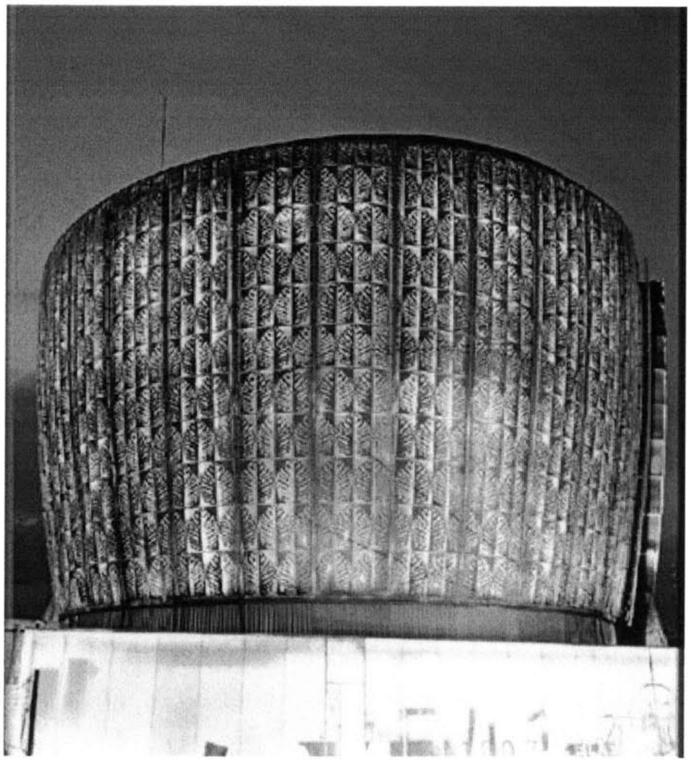

Figure 3: Duales System pavilion at Expo 200 in Hanover, Germany [9]

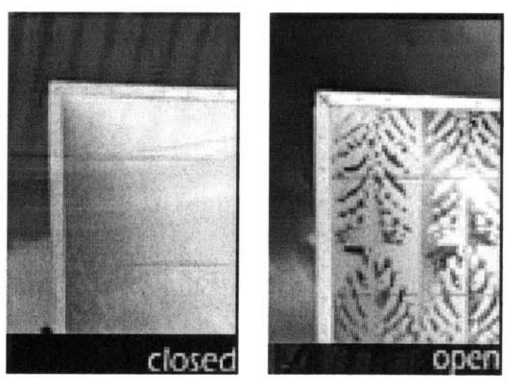

Figure 4: Duales System at Expo 2000 Pavilion, Hanover, Germany [9]

3.2 Strength Properties

ETFE film is an extremely flexible plastic membrane that can support high short term loading. ETFE foil experiences large deflections under extreme loading conditions. The tear propagation strength of ETFE film is 180 N/mm. The breaking strength of ETFE is 50 N/mm^2. However, the fracture strength of ETFE is less valuable than the yield strength. ETFE cushions are not designed for failure in the plastic rang because of the large deformations of up to 800% at fracture strength. The yield point for ETFE film is 21 N/mm^2 or 23 N/mm^2.[17] The yield strength is a function of temperature, loading rate, load history, and stress state. ETFE is very ductile material and demonstrates good failure behavior: the large deformations before breaking point visually indicate yielding and future failure.

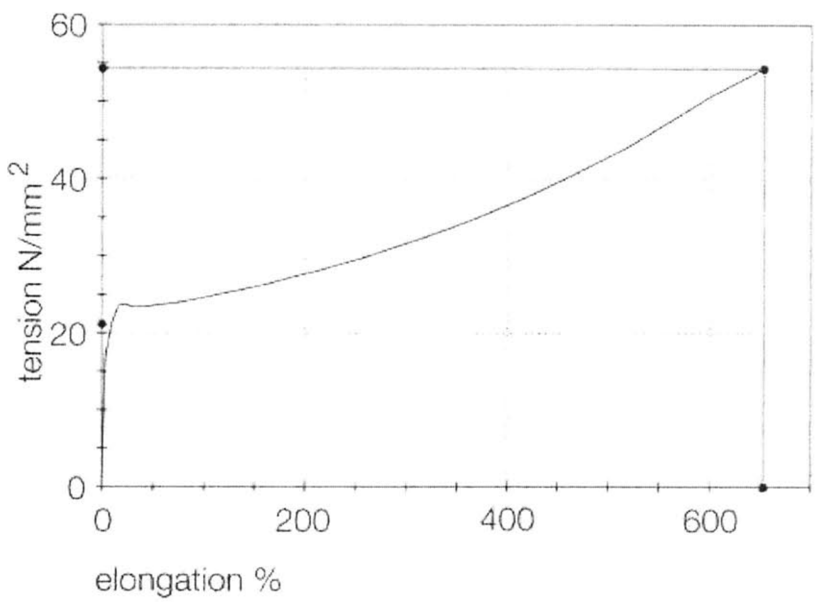

Figure 5: Stress-strain distribution for NOWOFLON® [17]

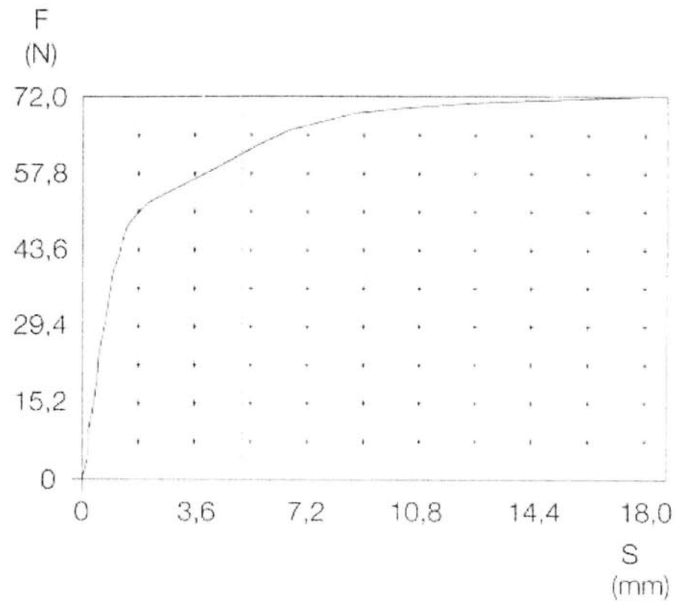

Figure 6: Force-deformation graph for NOWOFLON® [17]

3.3 Insulation

ETFE foil pillows exhibit better insulating properties than triple-glazed glass. The cushions are highly insulating because they trap air in between the layers of film. The insulation provided by an ETFE cushion system can be multiplied by adding more layers of ETFE film. A standard three layer cushion has a U value of 1.96 w/m² ° K.[23] The cushion's U-value measures the insulation efficiency of the cladding. A lower U-value indicates a better insulation ability of a material or system. The middle layer of a typical ETFE film cushion is solely for insulating purposes. The additional film layer creates two divided air cavities which vastly improves the thermal capacity of the ETFE pillow. If the layers are welded to the aluminum connection to the steel frame separately , the outer layer is fixed to the primary structure and the inner layer is fixed to primary structure, then the U value can be further increased about 20%.[16] Coatings developed especially for fluoropolymers can be utilized to manipulate insulating properties of ETFE cushions. For example, a low E coating can be applied onto the film to increase insulating capacity.

CHAPTER 4. ADVANTAGES AND DISADVANTAGES

4.1 Advantages

The current use of ETFE in building cladding in the construction industry is to replace traditional glass glazing. An effective glass alternative provides a building with all of the benefits of glass without any of its shortcomings. The following is a list of ETFE's advantages over glass:

- high UV transparency
- high insulation
- lightweight
- great life expectancy
- self cleaning
- offers more green design opportunities
- great shape/size variety
- longer spans.

ETFE cushions have greater insulating properties than double glazing: the insulation capability of a three-layer ETFE foil pillow is equivalent to triple glazed glass cladding.

Table 2: U-values of ETFE cushion and glazing options [25] [23]

ETFE Cushion, No of foils	U Value
2	2.94 $Wm^{-2}K$
3	1.96 $Wm^{-2}K$
4	1.47 $Wm^{-2}K$
5	1.18 $Wm^{-2}K$

Glass	U Value
Single Glazing	6.3 $Wm^{-2}K$
Double Glazing	3.2 $Wm^{-2}K$
Triple Glazing	1.9 $Wm^{-2}K$

ETFE is more transparent to visible and ultraviolet light than glass. A standard three-layer ETFE foil cushion transmits 94-97% visible light and 6mm single glazing transmits 89% visible light. Significant attributes of the ETFE foil cushion are geometric flexibility and light weight. The cushions can be manufacture in any size or shape. ETFE film has an extremely low dead weight of 350 g/m^2 at a thickness of 200 microns.[17] It is very chemically resistant to acids and alkali, and it is almost completely recyclable. Lastly, a significant advantage to using ETFE cushions for building cladding is its flexibility. The building envelope does not need to be isolated from possible deflections of the primary structure. Structures using ETFE membrane technology can exploit this property to design large span, flexible buildings. In short, utilization of an ETFE cladding system is an economic and sustainable choice for appropriate installations.

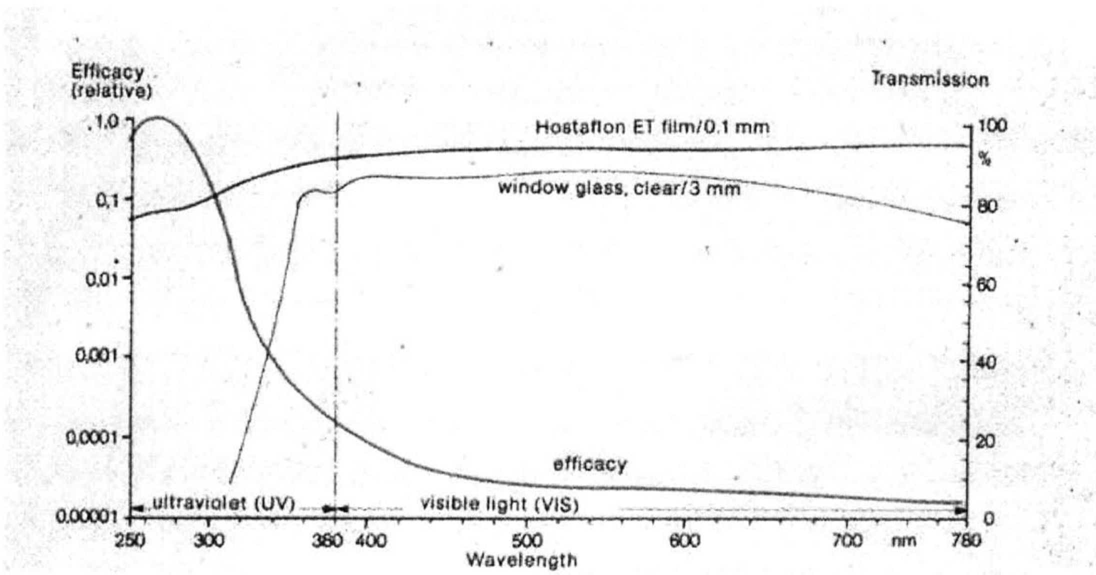

Figure 7: Light Transmission Comparison of Hostaflon® and 3 mm glazing [13]

4.2 Disadvantages

There are some drawbacks to the utilization of ETFE for cladding in building applications. The most apparent physical characteristic of ETFE cushions is that the film does not offer clear vision and thus, is not appropriate for transparent applications.

The ETFE cushion system has high acoustic transparency: the pillows transmit almost all sound from the outside and creates additional noise from impact on the roof surface such as raindrops. A measure of acoustic insulation is the R_w-value or the coefficient of fading. The R_w-value measures a material's capacity of acoustic insulation. A three-layer ETFE foil pillow has an R_w-value of 8 dB. Comparatively, the R_w-value of glass double glazing is 42db. This system characteristic can be mitigated by including acoustic insulation. In general, the lack of acoustic insulation provided by the pillows is a drawback of the material. However, it could be deemed as a desirable system attribute in special situations. Finally, a potential danger to the ETFE cushion system is damage of the pillows from sharp puncture. Sharp points such as a bird's beak can penetrate the cushions. However, even if the surface is torn, ETFE is resistant to tear propagation. The hole can be mended on site or that particular pillow can be replaced. The advantages and disadvantages of ETFE are further illustrated in the case studies presented in chapter 6.

CHAPTER 5. MAINTENANCE AND SUSTAINABILITY

5.1 Maintenance

The cushions are easily replaced or mended and do not require access from inside of the structure. Maintenance can be performed from the outside of the structure by mending a pillow onsite or removing it from the frame and replacing it. ETFE is resistant to weathering due to environmental causes such as ultraviolet light and pollution. Therefore, when exposed to the elements it experiences no chemical or physical degradation and maintains its strength.

ETFE film's self-cleaning attribute is one of its most attractive when considering maintenance costs of cleaning a large greenhouse. ETFE is a modified version of Teflon® and is anti-adhesive as a result. The plastic has extremely high surface tension and occasional rainfall is adequate to cleanse the pillow. Furthermore, this non-stick property prevents formation of algae or dirt collection on the pillow surface. The inside face of the pillows does not benefit from occasional rain so the internal surface of the pillows do need to be cleaned every 5 – 10 years. ETFE film pillows are in danger of tearing as a result of direct penetration, however the film has considerable tear propagation resistance. A puncture will penetrate the layer of ETFE foil but will not continue to its perimeter. If the cladding system ever catches fire, the ETFE cushions exhibit self-extinguishing properties. The film will shrink away from the flame and allow it to vent out of the structure. The inflation units are a primary part of an ETFE cladding system. Keeping a constant air pressure level inside the ETFE foil cushions is necessary to support the applied loads of the structure. The inflation system consists of a primary blower and a backup. The maintenance of these units is essential to the operation of the cushions. The most important part of maintenance is not the foil itself but the connections between the cushions. Controlling the stress concentrations at the joints will maintain a long lifespan of the structure.

5.2 Sustainability

Affiliates of Brunel University in Middlesex and Buro Happold Consulting Engineers in London conducted a study of the environmental effects of ETFE manufacture and use for building cladding. The study compares ETFE foil cushions to 6 mm glass and concluded the following about the sustainability of ETFE for building use.

> "ETFE foils can improve the environmental performance of a building from two points of view: there is the opportunity to reduce the overall environmental burden incurred by the construction process itself; and there is also the opportunity to reduce the burden of the building during its lifetime. This is all dependent, however, on the ability of Architects and Engineers to take advantage of both the flexibility and limitations of ETFE foil cushions."[22]

The actual pillow weighs less than 2% of equivalent glass cladding, while the entire pillow system including aluminum connection and steel frame support weighs between 10% and 50% of conventional glass-façade structure.

Table 3: Comparison of ETFE and glass properties [22]

		ETFE Foil	Glass
Ultimate tensile strength	[N/mm^2]	40-46	50-100 (toughened) 10-20 (annealed)
T_g, glass transition temp.	[C°]		600
T_m, melting temp.	[C°]	150	1200
Hardness	[N/mm^2]	31-33	5500
Yield stress	[N/mm^2]	30-35*	
Fracture mechanism		Plastic deformation	Brittle fracture
* yield stress is temperature dependent			

The utilization of ETFE foil pillows decreases the amount of material required to support structural cladding, in this case, steel and aluminum. Compared to glass, the pillows have very good insulating property; and therefore, help reduce energy consumption used for temperature control. Solar gain can be altered by putting low E coatings on the ETFE film or using a patterned film. The positive/negative leaf printed ETFE foil illustrated in Figure 4: Duales System at Expo 2000 Pavilion, Hanover, Germany [9] is an example of variable lighting controlled by the air pressure level inside the foil cushions. The estimated life expectancy of the pillows is more than 50-100 years.

At the end of life, the ETFE film can be recycled in the original manufacturing process. The recycling of ETFE cushions is aided by the absence of additives in the manufacturing process, requiring only the ETFE material and heat. A torn, old, or misshapen cushion is simply removed from the structure, cleaned, heated to melting temperature along with virgin ETFE granules, and extruded again to create more ETFE film.[22] Vector Special Projects manufactures all of its cushions from recycled material and use more than their own waste by using other manufacturer's waste products.

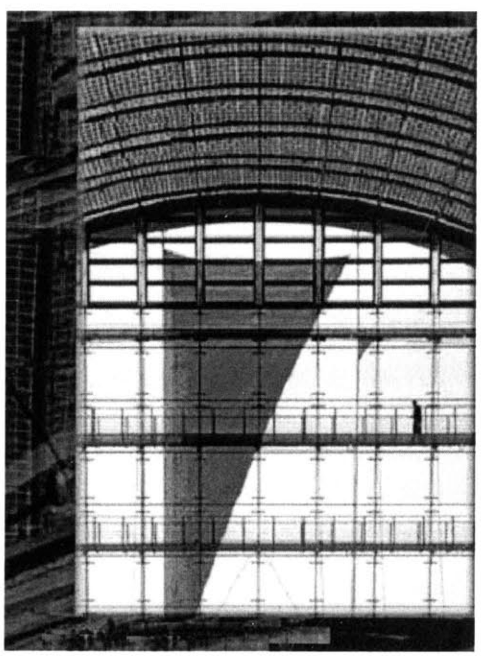

Figure 8: Festo Technology Centre closed and open in Esslingen Stuttgart, Germany [9]

The amount of material required to clad a building with ETFE pillows is extremely low. A typical foil roof (according to Vector Special Projects figures) weighs 450 grams per square meter. A glass roof without accounting for the substantially larger support system required to support it weighs upwards of 50,000 grams per square meter. An ETFE cushion roof system weighs 25 – 100 times less than any transparent roof alternatives and uses 50 – 200 times less embodied energy per square meter.

Table 4: Embodied energy for ETFE foil and 6 mm float glass [22]

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

ETFE has the same non-stick property of its relative material, PTFE or Teflon. This attribute make the material self cleaning. The internal face of the pillows does require occasional cleaning but the building owner will significantly reduce levels of water and detergent consumption due to this material characteristic. High light transmission of ETFE could reduce the need for artificial light in inside a building. The ETFE cushions have excellent insulating properties: a building with highly insulating cladding is easier to heat and cool. Inflation units continuously control the air pressure in the ETFE foil cushions and require continuous energy to power the air supply. However, the energy consumption of the inflation system is not as large as expected. The inflation unit used by Vector Special Projects is composed of two backward air foil blowers powered by electric motors: one 100 Watt electric motor is actively controlled by sensors on a reference foil cushion paired with a 220 Watt backup electric motor. The main inflation unit only operates for about half the time, using approximately 50 Watts or half the cost of a light bulb.[23] Ultimately, ETFE film is more than providing a more sustainable alternative to glass. The new material has inspired innovation in building energy usage. An architect from FTL Happold, Nicholas Goldsmith, created a tent pavilion using ETFE film. Goldsmith encapsulated photovoltaic cells in the ETFE film membrane of his solar pavilion exhibited at the National Design Museum in New York in 1998.

CHAPTER 6. CASE STUDIES

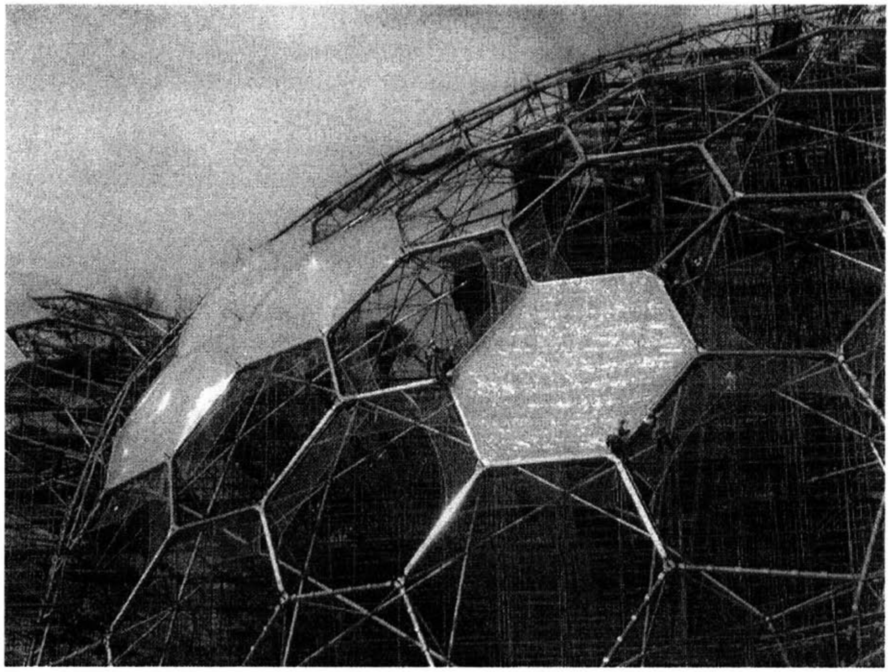

Figure 9: Eden Project biome under construction [21]

6.1 Eden Project

The Eden Project consists of two biome structures located on the north side of a 15 hectare wide old clay pit in Cornwall, United Kingdom. The concept for the massive structure was conceived by Tim Smit, an ex-music industry executive.[21] The architects for the project are Nicholas Grimshaw & Partners. The Eden Project engineer is Anthony Hunt Associates. These two companies previously collaborated on the Waterloo Eurostar Terminal in 1993 in London. The china clay quarry is an ideal locale for a greenhouse: it experiences heavy rainfall, consistent sunlight, and mild temperatures. The clay pit with high cliffs and white tips is the remains of Cornwall's china clay industry and this project finds a new use for an otherwise abandoned site. The Eden Project aims to recreate the world's biodiversity in an elaborate geodesic dome structure. Each environment of the world is represented and celebrated by the ambitious project partially funded by British Millennium Fund and the European Union.

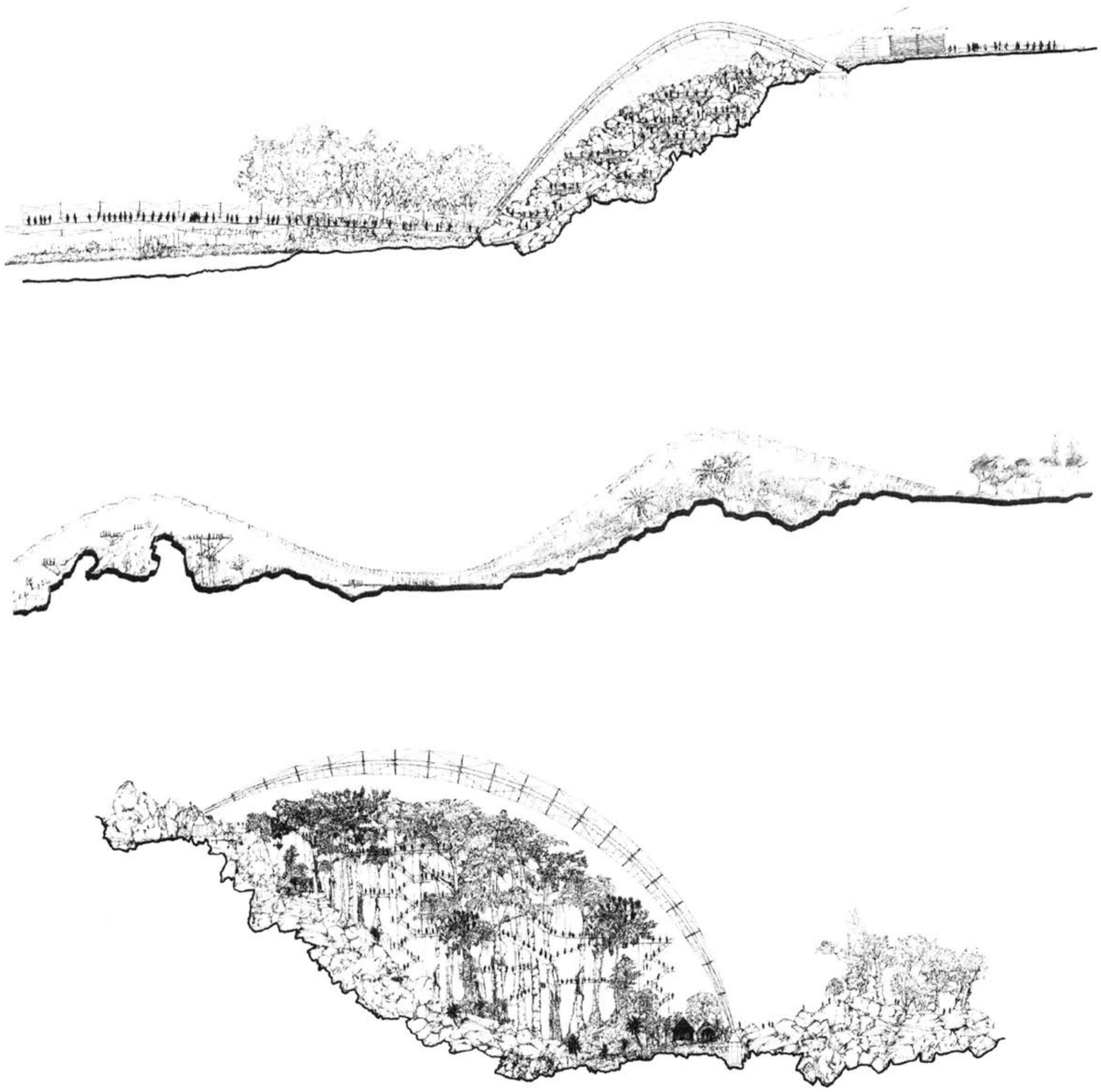

Figure 10: Initial design of Eden Project [11]

6.1.1 Initial Design

The initial design for the structure was similar to the design team's previous railway station, only four times wider of a span. It simply consisted of trussed steel arches connected by pin joints to the top of the quarry rock walls, nestling the garden into the vacant pit. ETFE was included in the initial design of the Eden Project as the cladding material of choice. A lightweight structure was necessary due to the limited load bearing capacity of the clay pit soil. The cushions were to be 10m by 3m, supported by aluminum frames which in turn are supported to the steel truss frame 60 m at its highest point.[11] An electronic building management system controlling air flow through the pneumatic ETFE pillows was also in the first scheme of the greenhouse. The rock walls were intended to be utilized for their natural thermal capability of absorbing heat during the day and releasing it during the night. The Eden Project was envisioned as not only a place to display foliage but also a place of learning and conservation.

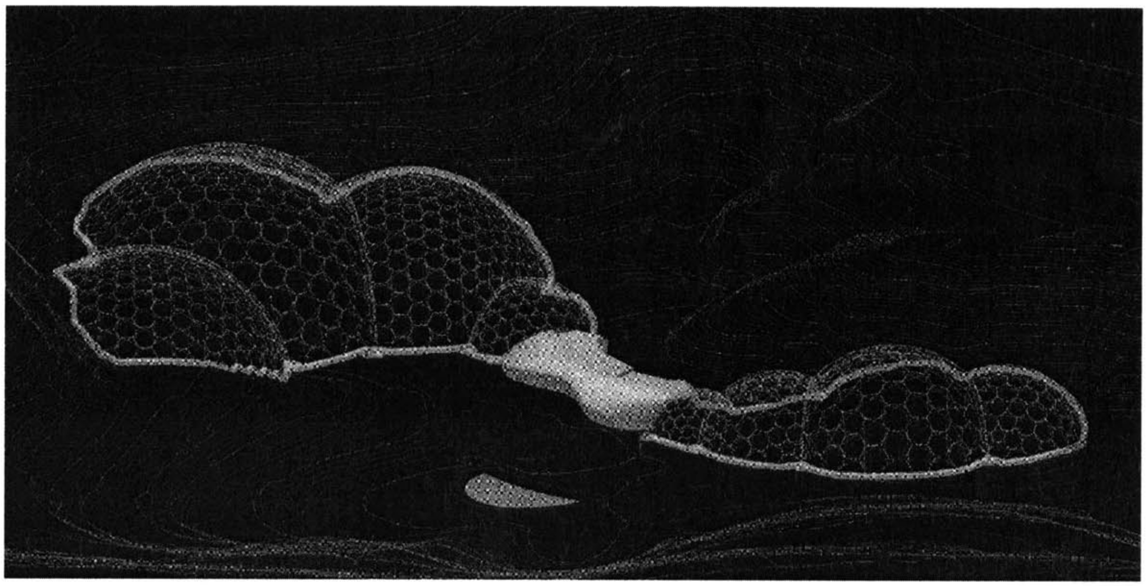

Figure 11: Rendered drawing of Eden Project site [13]

6.1.2 Final Design

The Eden Project consists of two greenhouse dome biospheres or "biomes." The two structures are each composed of connected geodesic spheres. The smaller biome houses the Mediterranean warm temperate environment. The larger biome, home to the tropical rain forest environment, is 240 m long, 110 m wide, and 55 m high. Both biomes cover a column-free area of 23,000 m2. [7] The original aim of the structure was to recreate these climates in the United Kingdom but in a natural way: giving the vegetation the appropriate height and area. Basically this means they need a very expansive structure. The tropical trees grow up to 40 m high requiring the dome to be taller than that.[28] Another significant goal of the greenhouse was to achieve the best light transmission to the garden and thermal capacity of the pillows by maximizing the size of the hexagons and minimizing the amount of steel support structure.

The design for the greenhouse was not changed to its actual shape until quite late in the process. The final design of conjoined domes was inspired by an earlier castoff for a single dome structure and addressed the issue of the quarry's changing geometry (it was still be quarried during design phase of the project). An additional benefit of the intersecting spheres instead of the trussed arches is ease of construction. The geodesic shells are constructed from repeated members of specific lengths. The domes are not traditional geodesic forms based on triangular geometry. The Eden project uses pentagonal and hexagonal shapes to maximize sunlight to the greenhouse, reduce time required for construction, and decrease the amount of necessary structural framing members. The pentagonal and hexagonal geometry varies for each biome in size and frequency, the pattern is scaled for each of the domes.

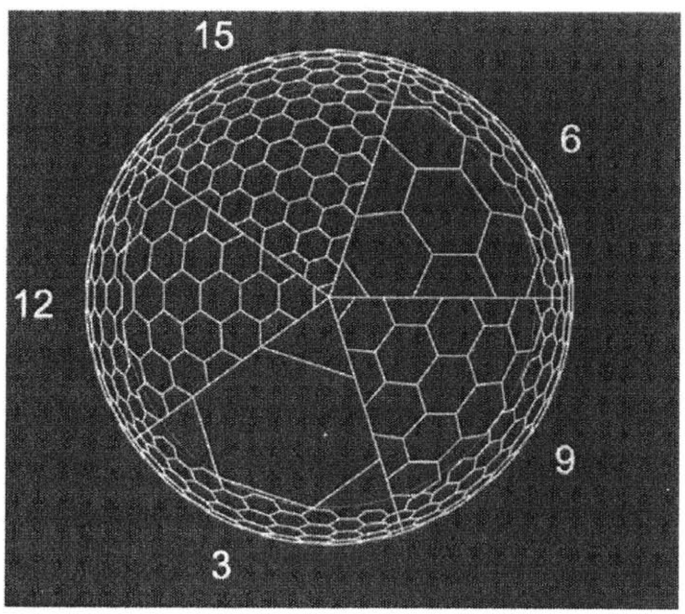

Figure 12: Geometric analysis of pillow frequency of biomes [21]

Table 5: Cushion size and frequency for both biomes [13]

Bubble ref:	Radius (m)	Frequency side length approx. (m)	Hexagon depth (m)	Structural Cusshions	Number of (or part)	Hexagons (or part)	Pentagons	Triangular opening vents)	Principle tube diameters Top Boom	Bottom Boom	
Human Tropics Biome											
A	49.972	15	4.391	1.6	129	103	1	25	193.7	88.9/114.3	76.1
B	62.465	15	5.488	2	163	137	1	25	193.7	114.3	88.9
C	49.972	15	5.4391	1.6	155	128	2	25	193.7	114.3	76.1
D	24.986	9	3.634	1.3	58	42	1	15	193.7	114.3	76.1
Total											
Warm Tropics Biome											
E	18.74	9	2.725	1	67	40	2	25	193.7	60.3/76.1	60.3
F	28.109	9	4.088	1.5	88	60	3	25	193.7	76.1/88.9	60.3
G	37.479	9	5.451	2	96	68	3	25	193.7	88.9/114.3	60.3
H	28.109	9	4.088	1.5	75	47	3	25	193.7	60.3	
Total					326	215	11	100			
				All Biomes	831	625	16	190			

The geodesic domes are constructed of two layers steel tubular members connected by spherical nodes. The outer layer is composed of hexagonal shapes and the inner layer follows a pentagonal pattern. The two layers of the biome are connected to each other by secondary steel members. The double layer increases the bending resistance of the structure and proved cost effective because both layers minimized their member cross sections and use simply fabricated members. The two layer scheme provides stabilization for the structure. The domes do not resolve their vertical due to their intersections with each other and the irregular site geometry. Additionally, the biomes do not resolve their respective horizontal thrusts because the spheres are different sizes. There are steel stiffening arches: three chord triangular steel trusses at the biome intersections to carry the vertical and horizontal thrusts back to the dome supports. The unresolved geometry is most apparent at the dome intersections where the shapes seem to be cut haphazardly. The biomes were constructed on site using a temporary framework and then erected after assembly.

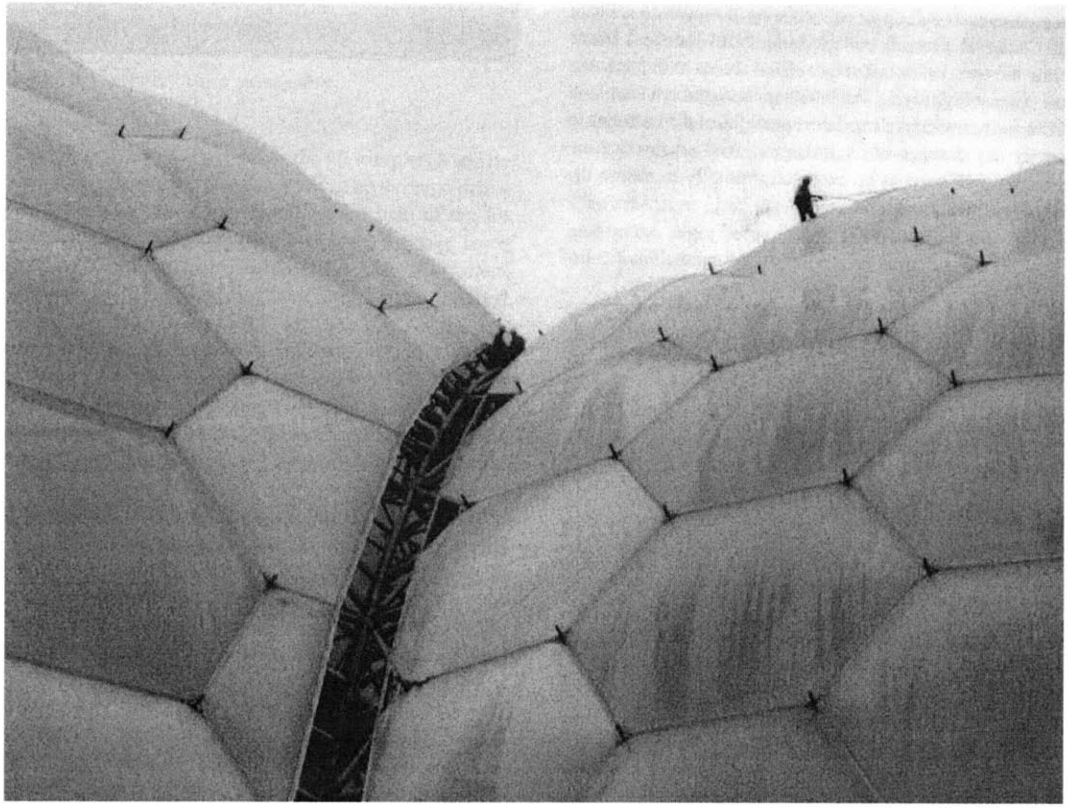

Figure 13: Steel truss at sphere intersection [21]

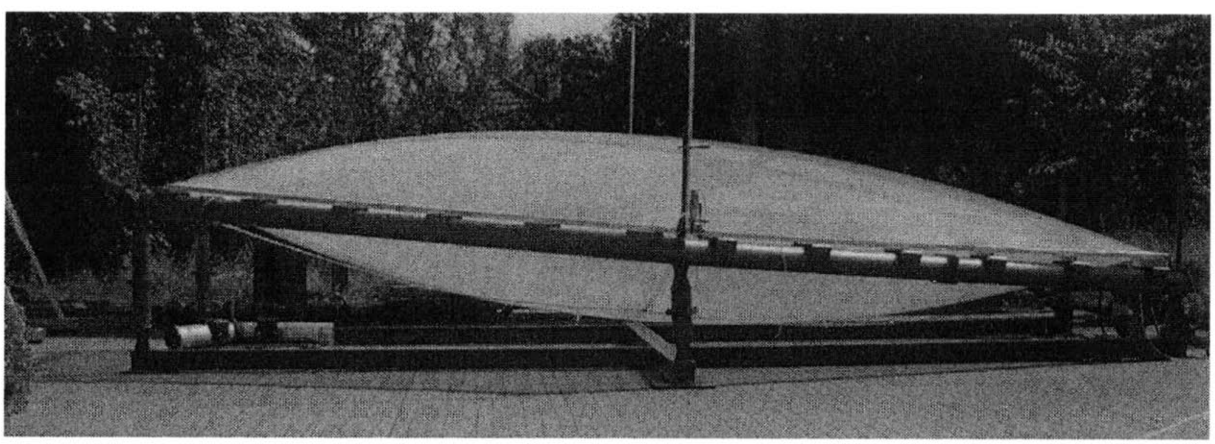

Figure 14: Eden Project hexagonal test pillow [21]

6.1.3 Cladding

When considering the cladding of the Eden Project, the design team desired a "responsive structural system that could adapt to changing loading conditions."[28] ETFE was the material of choice from the start of the design process. For horticulture, it performs much better than glass in terms of energy and growth. The architects and engineers exploited its capabilities to create a large lightweight adaptable structure. Mero GmbH and Foiltec GmbH were the contractors for the steel frame and cladding system. The double layer shell uses steel tubular frames consisting of members smaller than 200mm for the wide-spanning structure. There are two layers of ETFE, but not a cushion layer on each grid of the biome, as one might expect. The outer dome has a double layer of hexagonal ETFE cushions and the pentagonal shell has none.

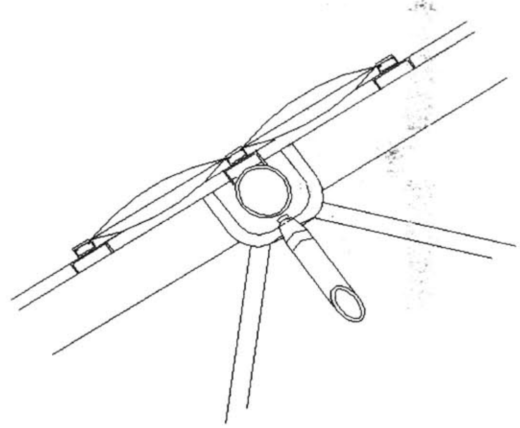

Figure 15: a) Spherical node connections[21]; b) membrane connection detail [17]

The ETFE cladding system for the Eden Project was the result of many tests performed on the material. Particular attention was paid to dynamic biaxial loading, weld strength, and capacity of connections to aluminum frame. Welding of the ETFE film is extremely important because ETFE is extruded in sheets of 1.2 – 1.55 m. Weld strength plays a substantial role in creating an 11m wide hexagon. Additionally, wind tests were conducted on a model size of the project. The tests concluded that the pillow was not strong enough: the hexagon required reinforcing. The first solution to the problem was to reinforce the ETFE cushion with a cable net: an expensive solution that could possibly puncture the film through friction. The final solution was to double up the outer membrane of the pillow: the two layers share the applied environmental load.

Alan Jones, chairman of Anthony Hunt Associates and project engineer for the Eden Project explains the motivation for using ETFE.

> "We could have used flat sheets of glass, but that would have been very inefficient, because it would have meant a lot more dead weight and there would have been much more steel needed in the roof to support it, And of course, the biggest double glazed glass panel you can easily purchase is 4 m x 2 m."[21]

Jones also highlights geometric and size flexibility, ease of maintenance and repair, ultra-violet light transmission, and lifespan as attractive attributes of ETFE for use in the greenhouse project. ETFE provided a lightweight alternative that could easily adapt to the biome geometry without complicating construction scheduling or creating difficulties in erection. The pillows provide better insulation and are more weather resistant than the traditional material choice for greenhouses: glass. The cushions for the Eden Project consisted of three layers of ETFE foil only 0.2mm thick and 2 m deep and they span over 11m. The hexagonal panels have 5.5 m sides, are 11 m wide and have a surface area of 75 m^2. The cushions are welded around their perimeter forming the ETFE pillow.

The multiple layers of film do not affect transparency from the inside and in fact, increase insulation of the domes. ETFE was the perfect material to achieve the design team's objective of maximizing light to the greenhouse by minimizing primary support structure. The three film layers create two air cavities; each layer's air pressure is maintained by hoses connected to an air supply system. There is a small aperture through the middle ETFE layer to equalize the pressure between the two air voids. With respect to insulation, the calculated U-value of the Eden Project cushions is 2.7 W/m^2K.[27]

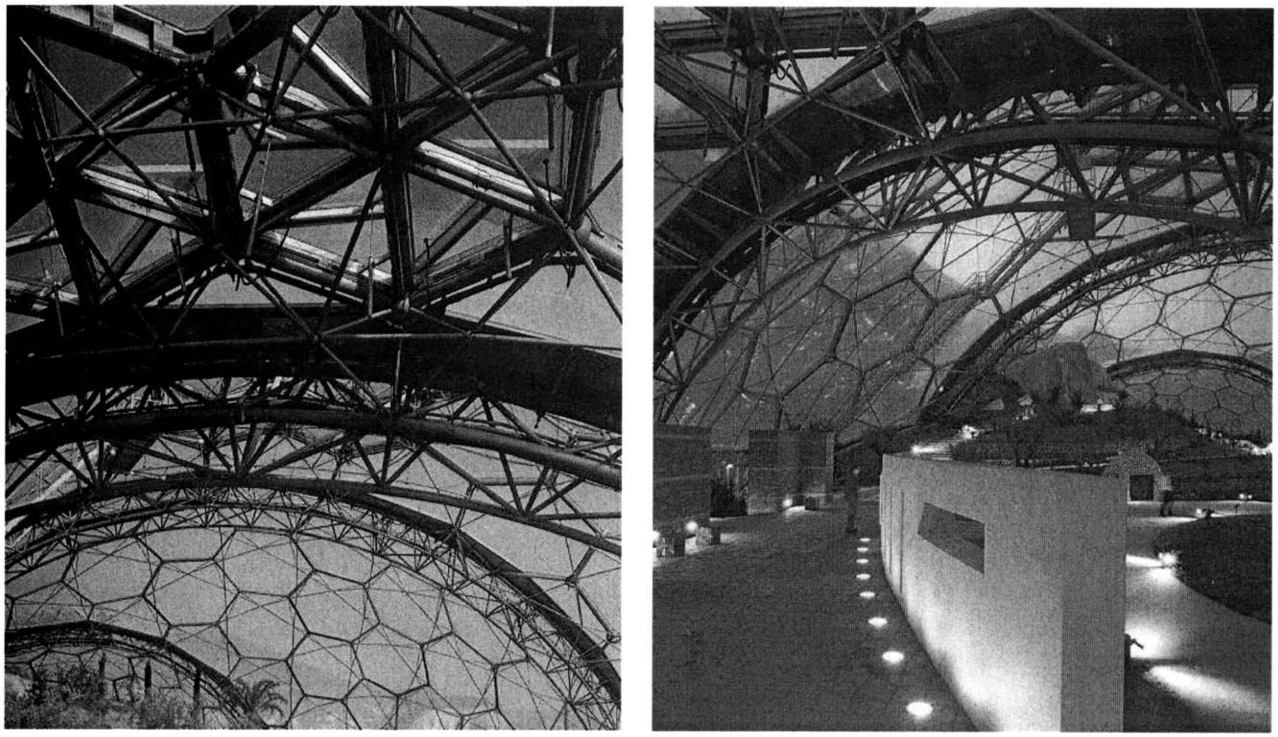

Figure 16: Inside of Eden Project domes [6]

The Eden Project takes advantage of one of ETFE's primary drawbacks: acoustic transparency. The pillows can actually magnify sound from the outside such as rain drops. This effect actually enhances the sensory experience when visiting the gardens and therefore, no acoustic insulation was installed in the biomes. The acoustic transparency of ETFE for the Eden Project was not considered a drawback at all, but an advantage. The Eden Project consists of enormous pillows that have the potential of deflating and collecting water. The material will undergo large strain deformations and can collect large quantity of water, up to 80 tons of water. The steel geodesic dome was designed to carry the possible load of ponding water.

ETFE was the optimal choice for cladding the enormous gardens of the Eden Project. The ETFE entails substantially less primary support structure: minimizing material, transportation, and monetary and environmental costs. Finally, the ETFE cladding uses less than 1% by volume of the double glazed glass required to cover the Eden Project.

6.2 Other ETFE projects

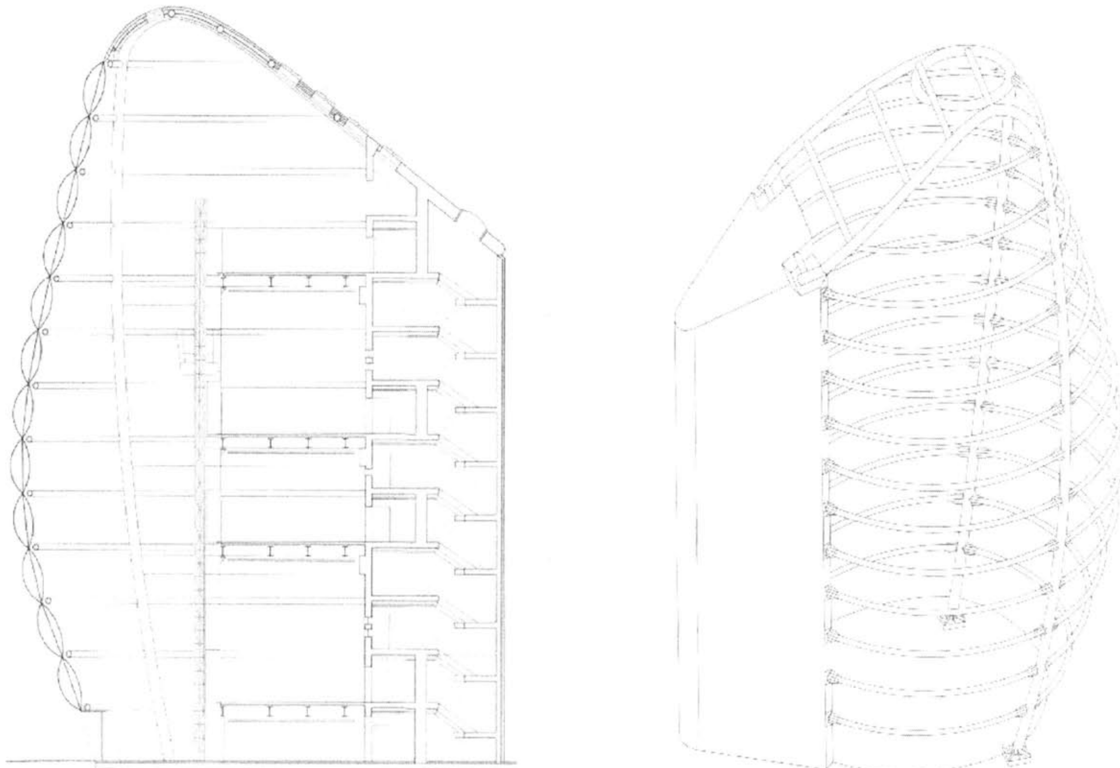

Figure 17: Schematic elevation of Rocket Tower [19]

6.2.1 National Space Center, Leicester, UK

The National Space Center in Leicester, United Kingdom features a curved 42-meter high exhibition Rocket Tower. The Rocket Tower was designed by architects Nicholas Grimshaw & Partners and engineering was provided by Ove Arup & Partners. The structure is clad with three-layer ETFE cushions that wrap around its curved volume, creating continuous bands of pillows around the building. The ETFE membrane layer covers more than 2,000 m^2, the largest pillows measuring more than 3 m high and 20 m long. The cushions of the tower have a gridded coating and are printed with a silver dot matrix graphic, both act to reduce the solar gain through the thin membrane. The ETFE foil pillows are supported on circular steel tube members. The connections of the pillows are designed to facilitate easy replacement of the cushions providing space to accommodate the installation of future exhibits. The inflation system is a network of vertical channels that are fed from blowers in the back of the structure.

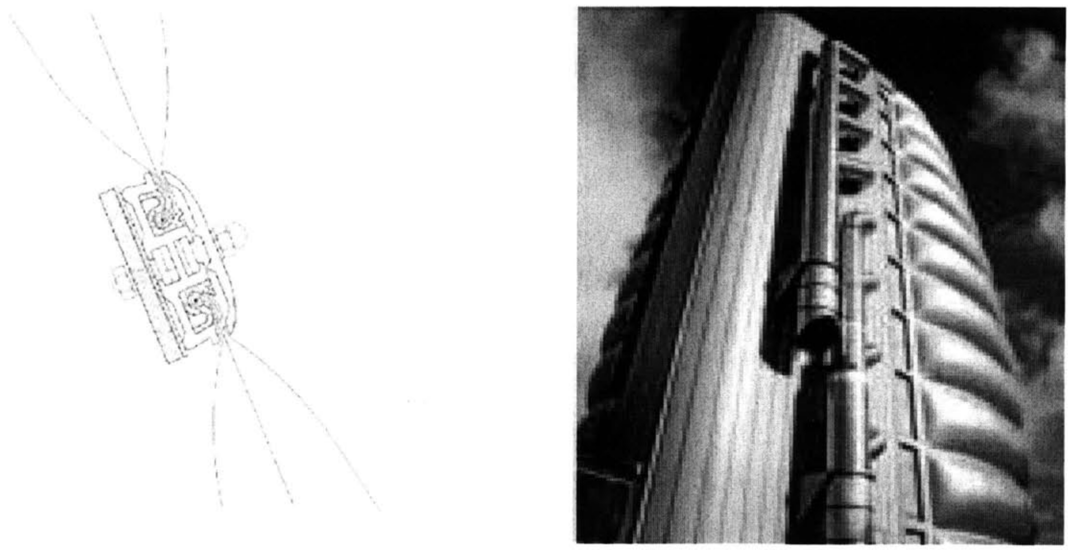

Figure 18: a) ETFE cushion connection detail[19]; b) View of Rocket Tower [25]

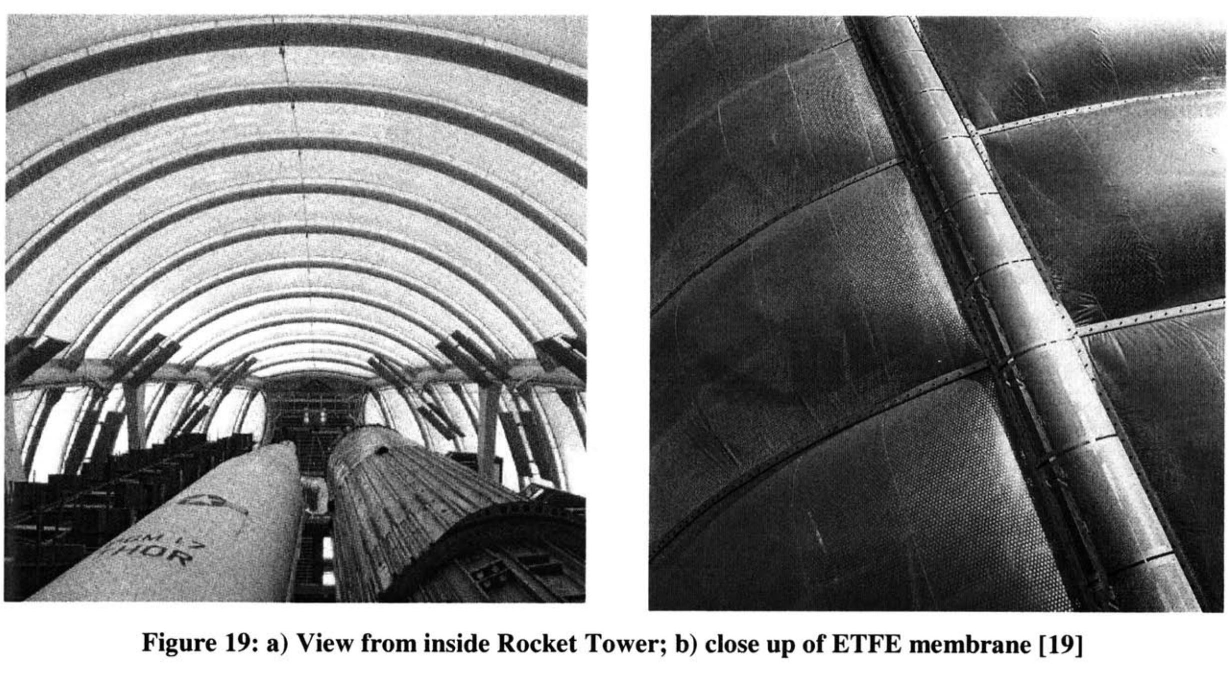

Figure 19: a) View from inside Rocket Tower; b) close up of ETFE membrane [19]

6.2.2 Vista Alegre Arena, Madrid, Spain

The Vista Alegre arena in Madrid Spain hosts a variety of sports, theatre, and music events. The arena holds 14,000 spectators and is probably most famous for its bullfights. The renovation of the previously open-air bullfighting arena was part of an urban renewal project in the Vista Alegre district. The roof was designed by civil engineering firm Schlaich Bergermann and Partner. The centerpiece of the $2.8 million project is the large pneumatic cushion roof. The roof is a double layered ETFE/PVC polyester retractable cushion that moves up and down. The roof open in two minutes and provides the arena with natural ventilation and sunlight. The outer layer is PVC polyester which is translucent, durable and has a lifespan of over 20 years. The inner layer is ETFE and due to its transparency, cannot be seen from the seats below. The circular roof has a 50 m diameter and an area of 5,000 m^2.

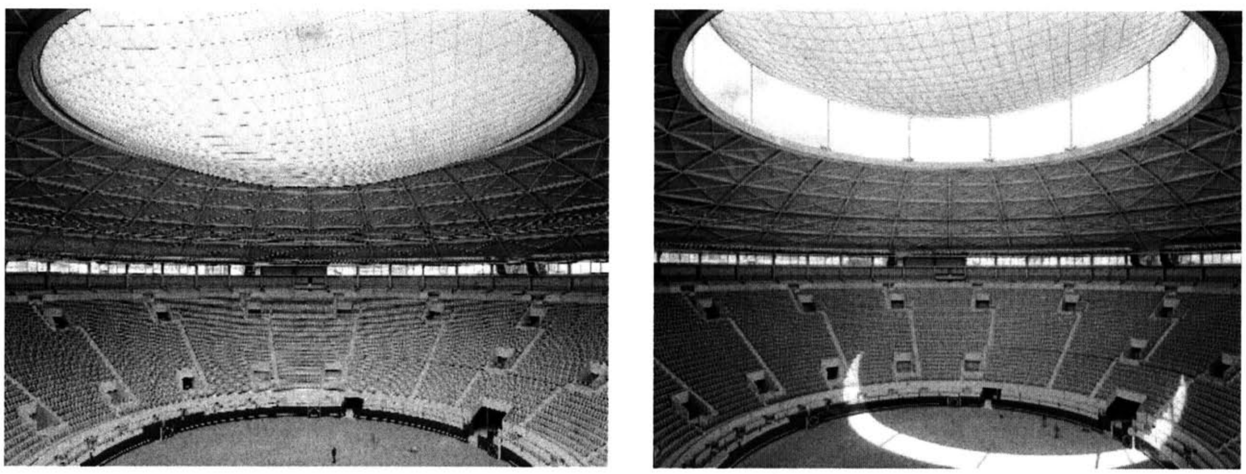

Figure 20: Vista Alegre roof in the closed and open position [24]

6.2.3 Allianz Arena, Munich, Germany

The new football stadium in Munich, Germany is shared by two football clubs: FC Bayern and TSV 1860. Construction began in fall of 2002, the stadium is a curved shell designed by Swiss architects Herzog & de Meuron. The roof is a double layered ETFE membrane pairing white translucent and transparent foil layers. The stadium will highlight the ETFE façade by projecting colors on it during the night. The façade of the shell is composed of printed foil cushions that will be illuminated with different team colors at night.

Figure 21: Computer rendered model of Allianz Arena [1]

There are 2,816 cushions that span up to 2 m by 4.25 m and are composed of foil layers of 0.22 mm thickness. The ETFE film pillows cover an approximately area of 65,000 m^2. The ETFE roof cushions are designed for snowfall up to 1.6m. The cushions are all unique rhomboid shapes, the same cushion shape only occurs twice in the structure. This variety of shapes and sizes would be difficult to achieve with traditional glazing but is easily accomplished with ETFE cushions. The roof and some parts of the arena's façade are transparent and the remaining portion of the cladding is composed of translucent white ETFE film. The Allianz Arena cladding system also features opening panels to provide the stadium with natural ventilation.

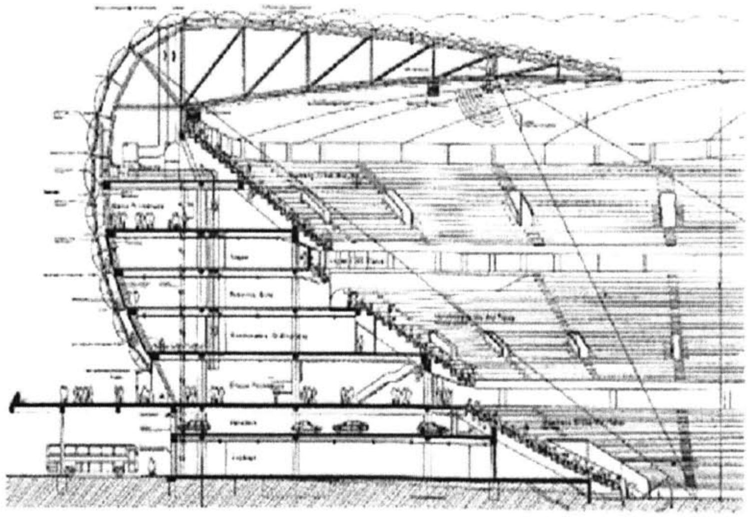

Figure 22: Cross-section of stadium [20]

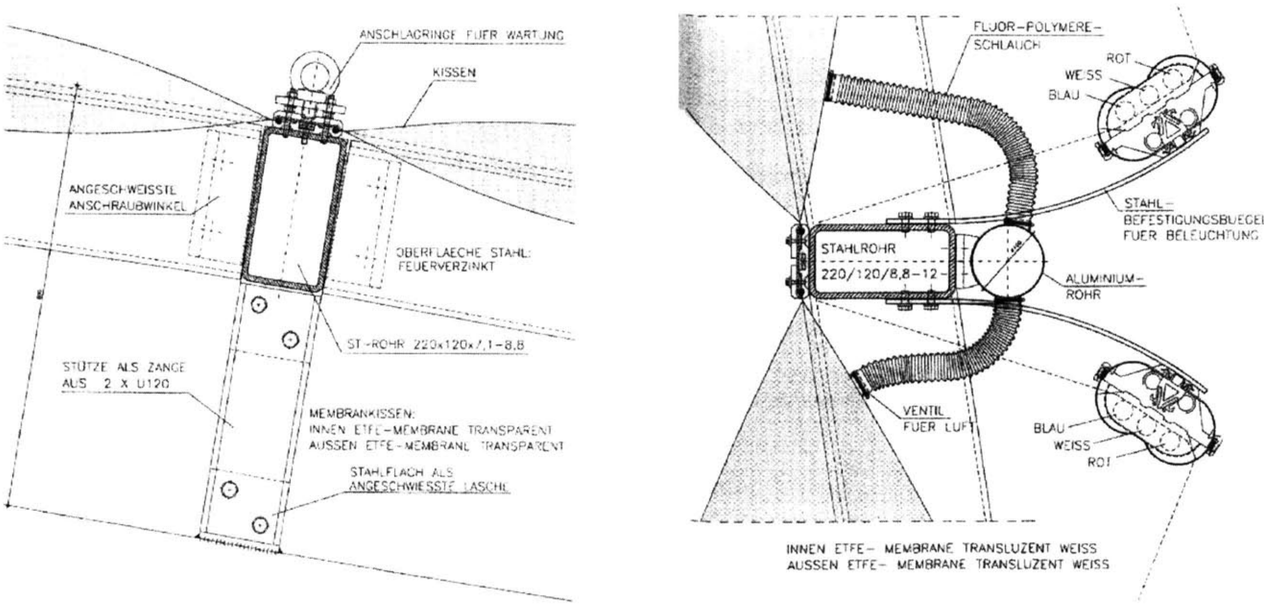

Figure 23: Connection details for ETFE cushions of Allianz Arena [20]

6.2.4 Information Centre in Kochel Am See, Bavaria, Germany

The Information Centre in Kochel Am See is located in Bavaria, Germany and accommodates 100,000 yearly visitors to the neighboring 1924 power station. The center was designed by German architects Hauschild and Boesel and the ETFE roofing was constructed by Covertex GmbH in 2001. The roof is a single-layer, mechanically prestressed ETFE membrane sheeting 200 μm thick. The roof covers an area of 390 m^2 and has a total weight of 180 kg. The roof can support a distributed snow load of 165 kg/m^2. The primary structure of the information center consists of prefabricated laminated timber arches that span up to 27 m. The ETFE layer is stretched between aluminum tubes which are laid over the timber arches. The ETFE sheeting is pretensioned by stainless steel clamping strips.

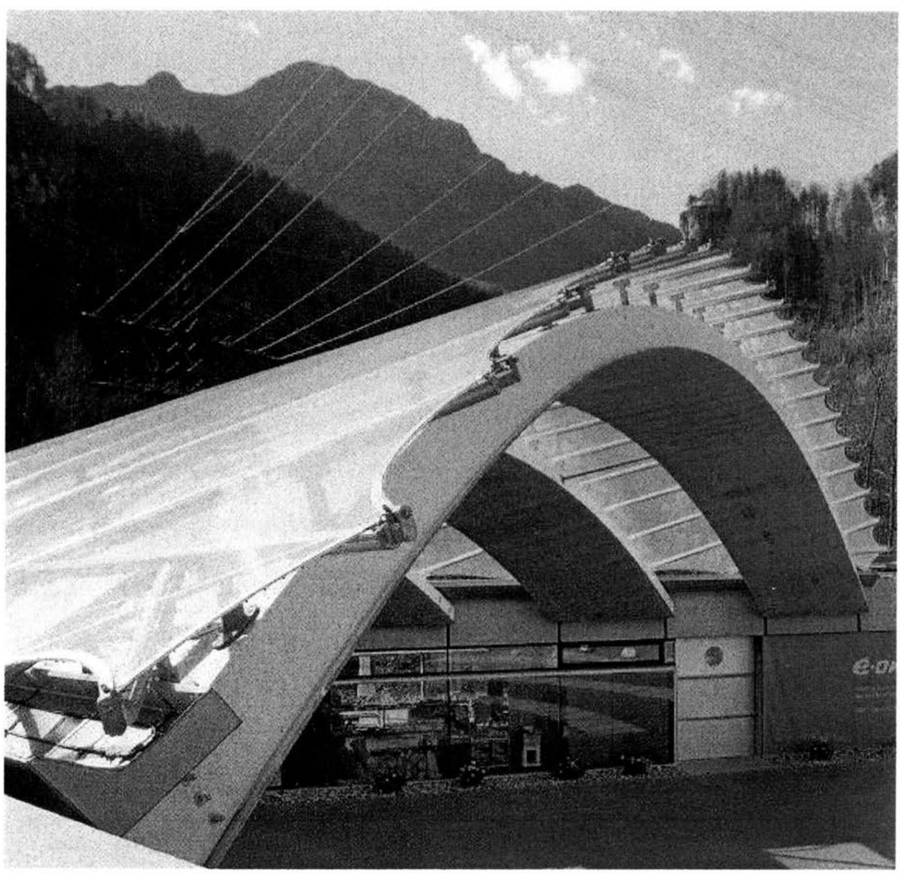

Figure 24: Information Center in Kochel Am See [12]

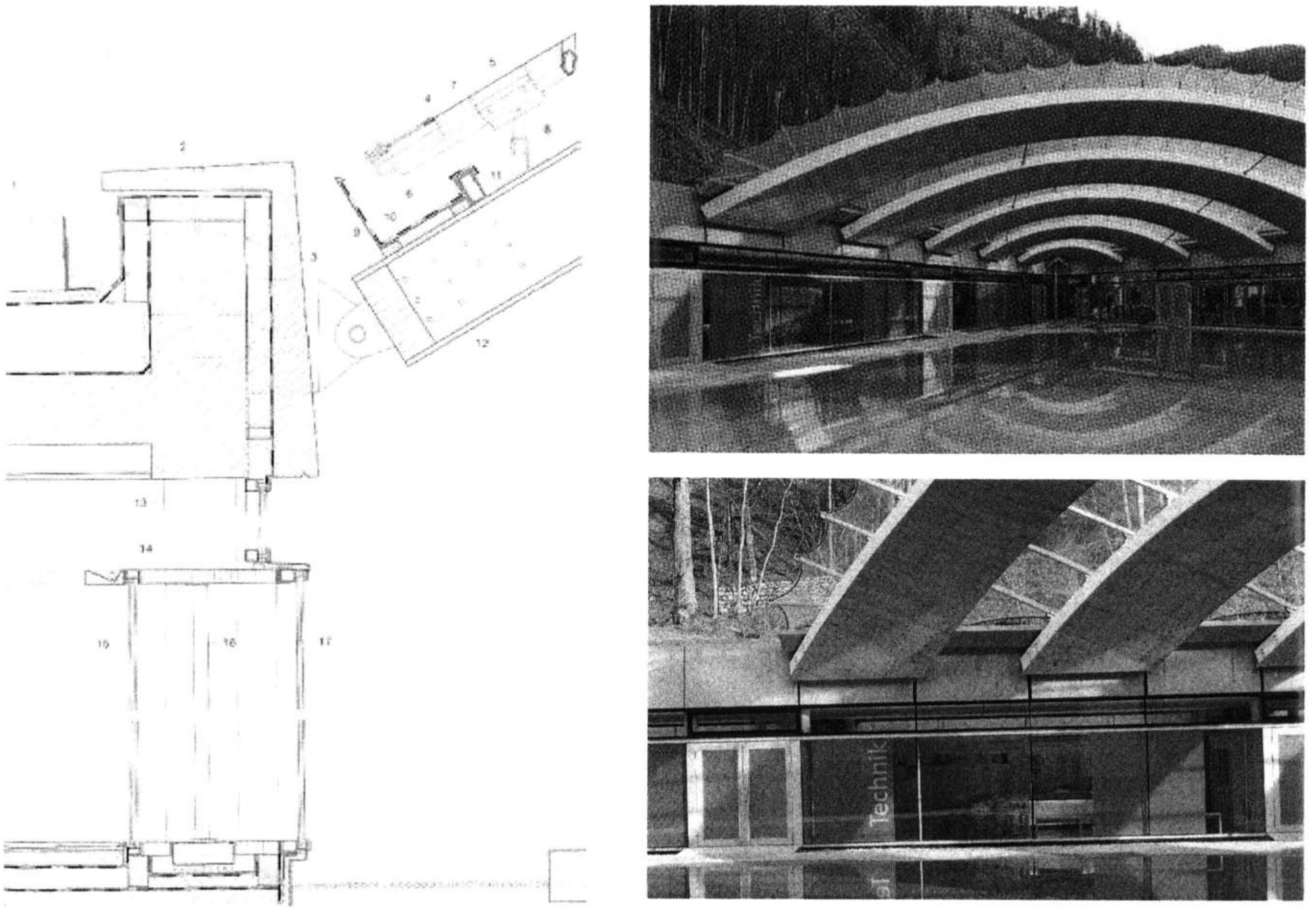

Figure 25: a) Connection details single ETFE membrane; b) View of roof from inside [12]

CHAPTER 7. DESIGN EXAMPLE FOR BBC NORTH GARDEN

The Boston Botanical Center project is the design of a greenhouse for the new property reclaimed by the Central Artery and Tunnel Project in Boston completed as a class project in the Masters of Engineering program at MIT. The CA/T project placed the I-93 corridor, built in 1959 that snaked through the center of Boston underground. The construction began in 1991, reached 94% completion in 2004 and will ultimately come to a close in 2005. The space left above ground is the new Rose Kennedy Greenway. It has been proposed that the greenway would be an ideal home for the botanical garden, sponsored by the Massachusetts Horticultural Society. The greenhouse will include a variety of garden spaces, including tropical rainforest, desert environment, and biodiversity learning garden. Additional building spaces are an office for garden staff Massachusetts Horticultural, an auditorium, and a café. The construction of this botanical garden on the Rose Kennedy Greenway will be a new cultural attraction and visual icon promoting environmental sustainability. ETFE was the material of choice for the cladding of the North Garden. ETFE has good thermal properties, high solar radiation, light transparency, self-cleaning surface making it an optimal material for use in a greenhouse structure.

7.1 Cushion System

Therefore, the use of ETFE for the roof system in the north garden will significantly reduce the overall dead load of the roof and the greenhouse. The roof system consists of the ETFE pillows, a steel tube frame support, an air inflation system with hoses connecting each cushion, and steel clips to connect the pillows to the frame. The ETFE cushions for the North Garden will be three layers of 0.4 mm thick ETFE film that create two air cavities. This is a typical cross-section of an ETFE pillow. The cushions will all be rectangular, ranging in size from 5 feet by 5 feet to 5 feet by 12 feet. There are 32 moveable ETFE shutters located on the central spine of the ellipsoid space frame. The moving ETFE cushions are supported by steel trusses connected to the steel tube frame. These select ETFE cushions will rotate around the frame axis and permit both light and air to enter the garden. The rotation of the shutters is automatically controlled by wireless sensors monitoring humidity, temperature, and air pressure outside the garden. When the weather conditions are optimal, the ETFE panels will be opened.

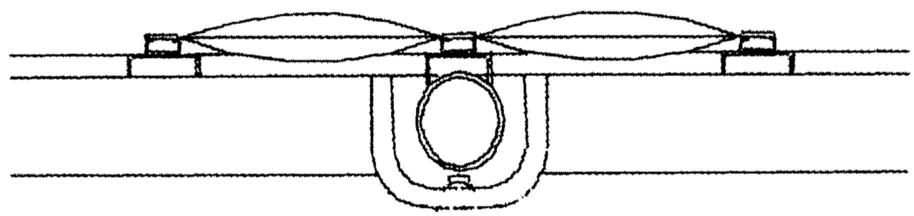

Figure 26: Connection detail for North Garden of BBC project

7.2 Frame Design

The North Garden and South Garden are essentially separate structures sitting on a common platform. The shape of the two greenhouses was created by centering an ellipse on the chosen site of the Rose Kennedy Greenway and extruding it into an ellipsoid. The two spaces were created by removing the area of Hanover Street, which cuts at a 21 degree angle to the centerline of the form from the ellipsoid. The North Garden uses an ETFE cladding system on its steel space frame structure. The steel space frame has numerous advantages in conjunction with the utilization of an ETFE cushion envelope. The most significant of these advantages is the reduction of material use and light weight. In a space frame structures such as Buckminster Fuller's geodesic domes, the members carry force largely in the axial direction, efficiently using their cross-sectional area. An important element of a greenhouse is continuity so one of our design requirements was a column-free space. Space frames and ETFE cladding are an ideal solution for a large volume of space unobstructed by support columns. Lastly, the space frame is an important design feature of the North Garden to differentiate the two greenhouse spaces and really make them unique.

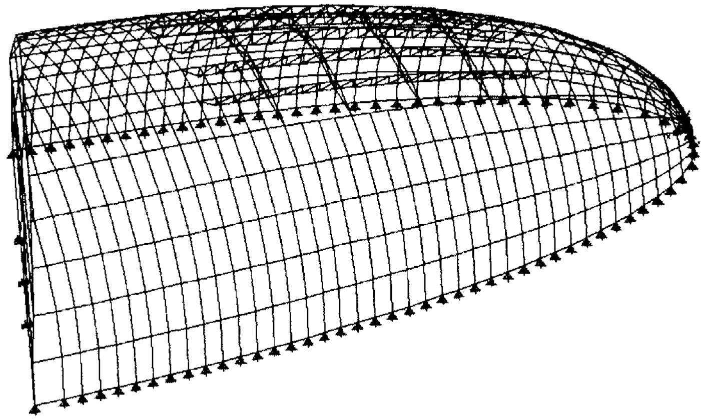

Figure 27: SAP2000 model of North Garden frame

7.2.1 Connections

Constructability issues in the ellipsoid space frame will be addressed by standard sized hollow steel tube members and identical spherical connection nodes. These measures should minimize construction time and difficulty. The joint node is a steel ball with four holes in the directions of connected members. In the North Garden space frame, the members come together at right angles. Therefore, the spherical nodes have holes at 0, 90, 180, and 270 degrees. The steel tube members are prefabricated to have a solid end which is embedded with a bolt hole. The ends bolt into the ball joint: each node of the space frame is a pin connection.

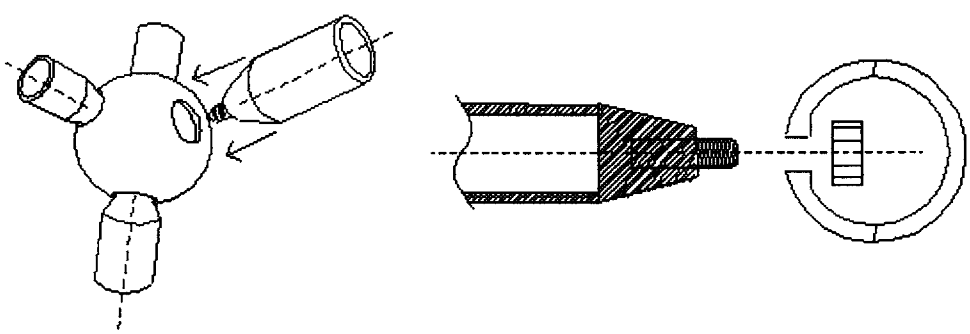

Figure 28: Connection detail for North Garden frame [26]

7.2.2 Moving Panels

A complexity in the North Garden space frame structure is the moveable shutter system that provides the North Garden with direct sunlight and natural ventilation on good weather days. The light weight of the ETFE pillows is ideal for large span opening vents in the cladding system. The shutters are ETFE panels that will rotate around their frame axis, permitting natural lighting and ventilation. The panels will be connected to environmental sensors monitoring temperature, humidity and air pressure. The opening and closing of the shutters will be controlled by the sensors: opening during optimal weather conditions. A truss system was added to address this discontinuity in the space frame at these opening points to support the changing load of the ETFE panels in their different positions. The truss consists of steel wide flange sections and the selection of small cross section members will not distract the continuity of the North Garden shape.

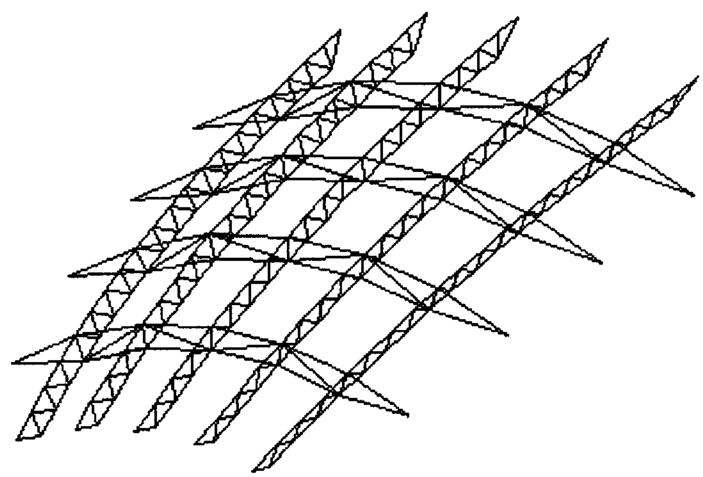

Figure 29: Computer model of truss members at moveable ETFE panels (SAP2000)

7.2.3 Loadings Applied

The design of the space frame was performed by relying on computer analysis because of the shape and moveable shutter complexities. The vertical and horizontal forces of the ellipsoid are not resolved because the structure is approximately half the ellipsoid cut at an angle. These loads are supported by the steel bracing on the south face of the garden and the concrete pedestal on which the frame sits. The loads applied on the roof were distributed along the length of the members. Snow and wind loads were of primary concern during the design of the North Garden frame because the building is located in New England and subject to harsh winter weather. The applied loads were use in the analysis of the North Garden space frame were a basic wind load of 21 psf and snow load of 30 psf all per the Massachusetts Building Code.

7.2.4 Air System

The inflation system for the Boston Botanical Center's North Garden will consist of air blowers that maintain air pressure in the ETFE foil cushions. The North Garden requires 8 inflation units, each blower will have a backup blower in case of malfunction. Due to the large area of the pillows, condensation is a special consideration. Air dryers will be installed in the inflation units to prevent the collection of moisture inside the pillows. During the winter, the inflation system will maintain the pillows at a higher pressure to support the additional load due to snowfall. The air blowers will be connected to wireless sensors that monitor humidity, air pressure, and temperature levels. The data collected will actively control the inflation system to adapt to different loading situations. The information will also be used to automatically open the rotating ETFE panels when weather conditions are optimal.

7.3 North Garden Assessment

The North Garden of the Boston Botanical Garden project is an ideal structure for utilization of an ETFE cladding system. The purpose of the structure is to grow vegetation and accommodate visitors. An ETFE building envelope will maximize light transmission while providing the city with a unique cultural attraction. Additionally, maintenance costs are minimized by the cushion's self-cleaning properties saving water and money. The insulating properties of the cushions are unsurpassable when coupled with its low dead weight and the fact that it does not need a separate support structure.

The ETFE foil cushions work well with the ellipsoid space frame which dictates the size of the foil pillows. The steel tube space frame creates open rectangular spaces ranging in size from 5 ft by 5 ft to 5 ft by 12 feet. The film cushions that fit into the spaces are well below the max span for one-way and two-way action pillows. Perhaps this is the problem with the North Garden design: it is not maximizing the ability of ETFE. The design of the space frame was completed and then the foil cushions specified for the frame design. The two-way cushions can span approximately 25 x 25 feet and the one way cushions 11.5 ft by almost any length. An improved design of the greenhouse structure would optimize the size of the panels by considering the maximum span of ETFE and considering its effect on the primary structure members. ETFE has the ability to surpass its role as a glass and instead be an opportunity for a collaborative design between structure and cladding.

CHAPTER 8. CONCLUSION

8.1 Applications

ETFE cladding is the perfect material for greenhouses because of low dead weight, excellent ultra violet light transmission, and thermal properties. The main design concern for botanical gardens is a large, column-free volume and excessive sunlight. Therefore, ETFE is an optimal building skin solution for efficient greenhouse structures that are easy to maintain. The material has been similarly successful in zoological buildings, temporary exhibitions, theaters, and stadiums. The applicability of a lightweight, sustainable, easy to maintain, interesting ETFE roof or façade is not limited to large structures. ETFE is suitable for courtyards, atria, and skylights in more traditional office, residential, and institutional buildings. Incorporating ETFE into traditional structure cladding has the potential to decrease environmental costs of construction by minimizing support structure and costs of operation by reducing cleaning and insulation expenses.

8.2 Considerations for Design

The ETFE foil cushion system is dependent on a primary structure to take vertical and lateral forces. The ETFE membrane transmits loads to the primary structure through the prestressed film layers and an aluminum extrusion that connects the cushions to the primary structure. Design of an ETFE cushion system should take advantage of the absence of a secondary support structure for the cladding. The ETFE envelope should cooperate and inspire the design of the primary building structure. The wind load capacity of ETFE pillows is approximately 200 kg/m^2 and snow load capacity is about 300 kg/m^2. Sizing of the pillows is controlled by these two values. Karsten Moritz of Engineering and Design states the importance of collaboration between architects, engineers, and industry for the construction of a successful ETFE building envelope.

> "Constructions using sheeting, like all membrane construction, are characterized by the interplay of design and load bearing structure, and between form, material and load. Hence

architects, structural engineers and manufacturers should work together very intensively even at the design stage. "[16]

The majority of ETFE suppliers come out of Germany and that country has taken the lead in establishing design code for the material. Texlon®, the ETFE cushion system developed by Vector Foiltec is the first ETFE cladding to gain "general construction approval" from Germany building regulations. The system includes ETFE foil cushions maintained by an air supply system at 200Pa and included cable net reinforcement. TOYOFLON®, the ETFE film produced by a Japanese company, Toray Advanced Film Co., Ltd. and NOWOFLON®, the film produced by Dyneon®, a 3M company have both been approved as a fire resistant material for use in building construction.[16]

8.3 Future of ETFE

Currently, there are very few design guidelines for the use of ETFE in cladding for structures, especially outside of the Europe. A system of standard testing, strength criteria, and codes are necessary including separate specifications for mechanically prestressed and pneumatically prestressed film sheeting. There should be a focus on connections as they are an essential part of the design of an ETFE cladding system. A design guideline regarding recommended connections between the foil pillows and the frame and secondly, the welded connection between the film pieces is indispensable. Greater use in popular structures like the Eden Project should motivate the industry to establish design guidelines. The future of ETFE is very bright, it has been successfully in use for over twenty years and is benefiting greatly from the popularity of several high profile projects. ETFE offers all of the advantages of glass except clear visibility and offer distinct advantages in terms of support structure, sensitivity to building deformations, geometric flexibility and constructability. The increasing utilization of ETFE cladding systems will lead to industry standards and eventually design guidelines that will concrete ETFE's future in the construction industry.

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CHAPTER 9. APPENDICES

Appendix A: Material properties for Texlon ETFE foil [9]

Structural Properties		
Test Standard	**Test Description**	**Resultant**
ASTM D-882	tensile strength at break	34,000 / 7,000psi
ASTM D-882	elongation at break	45/650%
PA 201 / SSTD 12-99	Small Missile Impact Test	Pass
PA 203 / SSTD 12-99	Cyclic Load Test	Pass at 60 psf

Weather Resistance		
Test Standard	**Test Description**	**Resultant**
Xenotest 150/Hanau	Weathering resistance	no change
ASTM D-570	water absorption - 24 hours	0.01%
ASTM D-495	air resistance	122 seconds

Transparency		
Test Standard	**Test Description**	**Resultant**
ASTM D-1003	transparency	95%

Flammability		
Test Standard	**Test Description**	**Resultant**
UL 94	Flammability Rating	V-0
NFPA 101	Surface Burning Characteristics	Class A
ASTM D-1929	Flash-Ignition Temperature	878°F
ASTM D-635-98	Rate of burning	HB - no visible combustion.

Appendix B: Texlon roofs: environmental considerations [23]

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Texlon Roofs: Environmental Considerations

Introduction

Texlon Roofs are constructed from a modified copolymer Ethylene Tetra Flouro Ethylene. The ETFE Foil is extruded into thin films and supported in an aluminium perimeter extrusion which is supported on the building frame. The films are given a structural a stability by being inflated to approx. 220 Pa.

The environmental evaluation of the technology needs to consider the production processes for the constituent materials, the features and changes that occur to those materials during the life of the building, and finally the possibility to recover the raw materials after the demolition of the building.

Consideration also needs to be given to the environmental performance of the material as a component of the building, and what effect that component has on the energy usage and comfort levels enjoyed by the building occupants.

It is also critical in any environmental analysis to consider the quantities of materials being used and the embodied energy costs for a given environmental performance.

System Components

1 ETFE Foil

ETFE Foil also known as Hostaflon ET Foil is a modified copolymer of alternatively linked Tetraflouroethylene and Ethylene Monomer units. The raw material is a class II substance admitted under the Montreal Treaty called Chlorodifluoromethane (CHF_2CL). The raw material is not a petrochemical derivative.

Class I materials which are regarded as harmful to the ozone layers of the environment are not used during the manufacturing process.

The raw material is first transformed into the monomer TFE which is then transformed by polymerisation into the polymer ETFE. The production process is a water based process, is completely enclosed, and does not involve the use of any solvents. On manufacture the basic material is then extruded into thin films of between 30 and 200 microns thick depending on the application. The extrusion process is a relatively low energy user involving heating the material to approx. 250 °C prior to extrusion

The Foil is manufactured in rolls of material 1550mm. The foils are then welded into sheets to suit the application. This process is quick and again a low energy user.

The material does not degrade under UV light, sunlight, weather or atmospheric pollutants, and has a very long life. We currently do not know how long this is but do know that no chemical or physical changes are observed after exposure to tropical sunlight for over 30 years. We therefore estimate the design life to be in excess of 50-100 years.

The material is recyclable and indeed we construct all our valves and cushions feeds from recycled material. Currently we use more than our own waste for these activities. We therefore import and recycle waste generated by others.

2 Aluminium

The cushions are restrained in a light weight aluminium frame.

Aluminium requires a high level of energy for its production. On the other hand it offers a very long life as surface oxidisation of the material forms a protective layer which prevents further corrosion. The material is readily recoverable and recyclable after usage.

3 EPDM

The cushions incorporate a small amount of EPDM into their construction in the form of perimeter seals. We are currently researching the environmental aspects of EPDM but to date have been advised that the production process is benign.

The System

The ETFE Cushion roofs offers a highly energy efficient cladding technology for two major reasons:

Firstly the quantity of material used to clad a building is very low. A foil roof has a weight of approx. 450g/m^2. This compares with a polycarbonnate roof of approx. 12,000g/ m^2. or a glass roof at approx. 50,000 g/ m^2. These figures do not take account of further weight savings in the primary structure which can be achieved using foil.

In other works the foil roof is between 25 and 100 times lighter than other transparent roofing technologies. Once the embodied energy used in material production is taken into consideration one can see that Foil roofs use between 50 and 200 times **less** embodied energy per square meter than the alternatives.

Erection and transportation

The building components are assembled on site from their constituent parts. The aluminium is extruded in the UK and fabricated into the system components at a factory near to the building site where possible. The cushions are fabricated in Germany and transported to site, depending on quantity, by car or container. As the quantity of material is small and the material can be close packed transportation costs are minimised. Again in comparison to a glass or polycarbonnate roof transportation is probably about a tenth or less as the material can be rolled. Erection is by hand using electric tools, and large areas are erected in a short space of time .

Performance

Insulation transmission and translucency

Foil roofs offer the designer the opportunity of developing an extremely energy efficient building envelope which technically outperforms other alternatives. The cushions in themselves are highly insulative by the nature of the fact that they trap air . In addition the foils can be treated with a variety of treatments to make them more efficient as insulators, more or less translucent or to manipulate their solar radiation transmission characteristics. For example low E coatings can be applied to the film or a whitener can be embodied in the material, alternatively a dot matrix of silvered PTFE dots can be applied to limit solar gains. In other words the roof technology can be tailored to suit the particular environmental objectives required by the building envelope for any individual building.

Infiltration

In addition to the above Foil Roofs are extremely energy efficient in that being a pressurised system no heat losses though infiltration occur. This is a huge area of energy wastage which is frequently ignored. Furthermore when comparing foil performance with other technologies one must always examine what effect infiltration over a period of time particularly as gaskets weathering polycarbonnates and glazed roofs loose their plastisizers, harden and allow air leakage to increase over time.

Acoustical considerations

Foil roofs are acoustically fairly transparent. This means that they act as absorbers when viewed in terms of room acoustics. Environmentally this means that considerable savings can be made in acoustic treatments made to walls which are required when using a glass or polycarbonnate roof.

Cleaning and Maintenance

ETFE Roofs being constructed from material which is very similar to Teflon do not require any external cleaning as they self cleanse under the influence of rain. This means that external gantries are not required. Equally as internal cleaning cycles are long internal gantries are usually omitted from Foil Roofs. Access being gained from Cherry pickers or via abseiling.

Appendix C: General description of the Texlon roofing system [23]

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General description of The TEXLON Roofing System

ETFE Foil Roofs consist of pneumatic cushions comprising of between 2 and 5 layers of a modified copolymer Ethylene Tetra Flour Ethylene. The ETFE Foil is extruded into thin films and supported in an aluminium perimeter extrusion which is supported on the building frame. The Cushions are inflated by a small inflation unit to approx. 220 Pa, which gives the foil a structural stability and gives the roof high insulation properties.

Life

ETFE Foil is unaffected by UV light, atmospheric pollution and other forms of environmental weathering. The material has been extensively tested both in the laboratory and out in the field and no degradation or loss of strength is observed. The material does not become brittle or discolour over time. It is anticipated that the material has a life in excess of 40 years.

Transparency

ETFE Foil is very transparent across the visible light region (389 – 780nm) having a light transparency of approx. 94-97% of total light. Transmission across the ultraviolet range (320 – 380nm) is also very good (83-88%). It is also important to note that the Film has high absorption in the infra red range, a property that can be exploited to reduce buildings energy consumption.

Solar Control

Whilst the base material is very transparent, ETFE Foil can be treated in a number of different ways 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 can then be manipulated by adding additional layers of foil into the system.

Colour Rendering

Due to the good transmission characteristics colour rendering under an ETFE Foil roof is extremely good, being as daylight across the visible light range.

Insulation

A standard three layer cushion has an U value of 1.96 $w/m^2 \, ^\circ K$. This is better than triple glazing when used horizontally (glazing manufactures figures are for vertical glazing which considerable enhances the figures). The cushions insulated qualities can be further enhanced by the addition of further layers of foil.

Inflation Units

The cushions are inflated by inflation units. The energy consumption used by the inflation units is minimal because the blower units only need to maintain pressure, they do not need to create air flow. A Roof is generally powered by one or several inflation units with each inflation unit maintaining pressure to approx. $1000m^2$ of roof . An inflation unit comprises two backward air foil blowers powered by electric motors. One of the motors is rated at 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 cushion. The main blower is thus only operating for approx. 50% of the time with the power usage being in the order of 50 Watts i.e. half the cost of a light bulb.

Air Dryers

The inflation units can easily be fitted with dehumidifiers to dry air being feed to the cushions. We would recommend that this be considered for high humidity environments such as swimming pools.

Power Failure

In the event that an area experiences a power failure, the ETFE Foil roof will maintain pressure for several hours due to the non return valves built into the inflation system. Should the power failure extend for a longer time span, then no harm will come of the roof. Should high winds also be experienced then the slack cushions can flog and make a loud cracking sound. For this reason we recommend that if prolonged power failure is experienced than a small generator is utilised to power the inflation units until power is returned to the grid.

Safety / Explosion Risk

ETFE Foil is a flexible material which can take extremely high short term loading. This makes it an ideal material for use where there is a risk of explosion. Equally if there is a risk of vandalism ETFE Foil cushions do not break and fall out of their frames risking life below.

Replacement

Should an ETFE Foil cushion become damaged the panel can be easily replaced from outside with no internal access being required. Small repairs are easily effected to the Foil in situ.

Fire

ETFE Foil has low flammability and is self extinguishing. The cushions self vent in the event of fire as the hot plume causes the foil to shrink back from the source of the fire allowing the fire to vent to atmosphere. The quantity of material in the roof is insignificant in fire terms and one does not experience molten drips of Foil from the roof.

Acoustics

A foil roof is acoustically relatively transparent. This means that the foil acts as an acoustic absorber for room acoustics, enhancing the internal perceived environment.

Cleaning

Unlike fabric structures ETFE Foil is an extruded material. This means that the surface is extremely smooth. This smoothness couples with ETFE Foils anti adhesive properties means that the surface does not attract dirt, and any dirt, such as bird droppings is washed off whenever it rains. ETFE Foil roofs never need to be cleaned externally. Internally foil roofs are usually cleaned on a 5-10 year cycle depending on the dirt in the internal atmosphere. This usually means that expensive internal access equipment is not required as the long cleaning cycles make rope access a cost effective solution.

Weight

ETFE Foil cushions are extremely light weight weighing only 2 - 3.5 kg/m².

Cushion Size

Cushions can be manufactured to any size and shape the only limit being the wind and snow loading. This in turn is effected by the cushions orientation i.e. is it horizontal or vertical.

As a general design guide for rectangular cushions the cushions will span 3.5m in one direction and as long as one requires in the other i.e. cushions 3.5m x 30m are possible.

For triangular cushions where the foil is two way spanning the size can be increased.

Should the designer require larger cushion sizes than described above larger cushions can be manufactured by incorporating reinforcement into the internal and external foils of the cushion.

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Forces exerted by the TEXLON System

Camber approx. f $\geq$ 0,1 x L

Roof pitch	Wind suction Ws= -0,6 kN/m2 (- 0,60 x 0,80 x 1,25)		Wind pressure Wd = 1,00 x cp kN/m2 (cp x 0,80 x 1,25)		Typical snow load S = 0,75 kN/m2 Includes reduction for roof pitch >30		
Alpha	Hu = Ho	Vu = Vo	Hu = Ho	Vu = Vo	Hu	Ho	Vu = Vo
0°	-0,88 x L	-0,30 x L	/	/	0,938 x L	0,938 x L	0,375 x L
10°	-0,88 x L	-0,30 x L	/	/	0,860 x L	0,988 x L	0,364 x L
15°	-0,88 x L	-0,30 x L	/	/	0,812 x L	1,000 x L	0,350 x L
20°	-0,88 x L	-0,30 x L	/	/	0,761 x L	1,003 x L	0,331 x L
25°	-0,88 x L	-0,30 x L	0,35 x L	0,16 x L	0,706 x L	0,993 x L	0,308 x L
30°	-0,88 x L	-0,30 x L	0,46 x L	0,21 x L	0,650 x L	0,975 x L	0,281 x L
35°	-0,88 x L	-0,30 x L	0,57 x L	0,26 x L	0,515 x L	0,822 x L	0,219 x L
40°	-0,88 x L	-0,30 x L	0,68 x L	0,31 x L	0,400 x L	0,677 x L	0,165 x L
45°	-0,88 x L	-0,30 x L	0,79 x L	0,36 x L	0,295 x L	0,527 x L	0,116 x L

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The Key Properties Of EFTE Sheeting	Value	Test Method
Melting Range	275° C ± 10	DSC 16 K/min
Elongation at break	150 % - 200 %	Test pieces acc. To ASTM D 1708
Fatigue strength	N/mm² - no break	DIN 53 452
Deformation under load	4,0 % - 6,0 %	ASTM D 621 P=15 N/Mmm², t=100h
Heat deflection With Vicat Needle VST/B/50 in the air	134°C	DIN 53 460
Ball pressure hardness	31 N/mm² - 33 N/mm²	DIN 53 456
Cold fracture – longitudinal Cold strength – transverse	Minus 180°C Minus 160°C	DIN 53 372
Tear strength – propagating	180 N/mm	DIN 53 515, 23°C
Moisture pick up	None	DIN 53 471
Weathering resistance	No change	Xenotest 150/Hanau
Light transmission	95%	Ulbricht globe/system light bulb
Foil weight 100 μ	175 g/m²	
Flammability rating	B1 (flame retardant none burning drip)	DIN 4102
System properties and specifications K – v – r values – 2-layer roof K – v – r values – 3-layer roof K – v – r values – 4-layer roof K – v – r values – 5-layer roof	2,94 W/m²K 1,96 W/m²K 1,47 W/m²K 1,18 W/m²K	
G value (coefficient of transparency)	Between 0,05 and 0,85	