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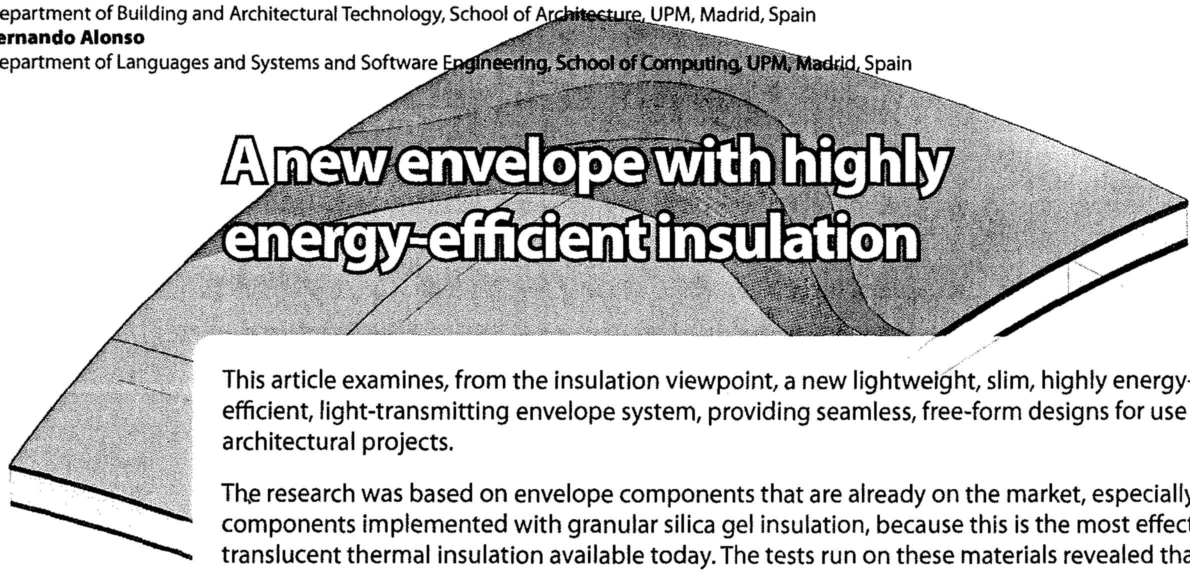


A new envelope with highly energy-efficient insulation

This article examines, from the insulation viewpoint, a new lightweight, slim, highly energy-efficient, light-transmitting envelope system, providing seamless, free-form designs for use in architectural projects.

The research was based on envelope components that are already on the market, especially components implemented with granular silica gel insulation, because this is the most effective translucent thermal insulation available today. The tests run on these materials revealed that there is no single component that has all the features required of the new envelope model. However, some do have properties that could be exploited to generate this envelope, namely the vacuum chamber of VIP panels, monolithic aerogel used as insulation in some prototypes and reinforced polyester barriers. By combining these three design components, the high-performance thermal insulation of the vacuum chamber, combined with monolithic silica gel insulation and the free-form design potential provided by materials like reinforced polyester and epoxy resins, we have been able to define and test a new, variable geometry, envelope insulation system with excellent energy-saving levels.

Above: High-specification 'skin' for new buildings may bring ground-breaking performance.

One of the major challenges for architects today is the insulation of buildings with a view to achieving energy-efficiency that provides not only economic and environmental savings but also improves user comfort and occupancy conditions.

Public administrations and professional associations the world over are trying to remedy the problem of energy-inefficient buildings, but these initiatives run out of steam when archaic, poorly evolved techniques that are ill-adapted to modern-day demands are used to build the envelope (skin) of our dwellings.[1,2]

Most of a building's energy transfers with the environment are through its skin, which is responsible for most of the energy losses. The new world energy regulations, called upon to regulate building energy efficiency, are more demanding than the former and obsolete regulations drawn up in an age when energy was very cheap. International examples are the Commission of the European Communities in the First Assessment of National Energy Efficiency Action Plans,[3] the United States Department of Energy (DOE)'s Commercial Building Initiative (CBI)[4] or the 'Evaluation Standard for Green Building' passed by the Chinese Ministry of Construction (MoC).[5]

These policies indirectly promote an increase in the thicknesses of outer walls because for centuries, thicker walls were the only way of properly insulating a building. Some architects like the Office for Metropolitan Architecture (OMA)[6] led by Rem Koolhaas or François Roche[7] among others have tried to directly or indirectly promote a policy whereby the façade does not compute as buildable area. This way they could make the outer skin thicker or generate multilayered skin components.

Other lines of research aim to minimise the building skin thickness by optimising its energy performance, also adding new architectural properties, such as the possibility of generating a structural skin or self-supporting façade or the option of providing tools to meet the architectural design requirements for modeling the façade according to environmental factors, such as solar capture, protection from environmental elements or for purely aesthetic purposes. These are alternatives that are now being studied and implemented by the Pritzker Architecture Prize winners Zaha Hadid,[8] Frank Gehry,[9] Rem Koolhaas,[10] Herzog & de Meuron,[11] Jean Nouvel,[12] Kazuyo Sejima and Ryue Nishizawa (SANAA)[13] and Oscar Niemeyer,[14] as well as other renowned architects like Future System, Toyo Ito, Ben van Berkel, West 8, Plot-Big, among many others, in their designs.

This research looks to those alternatives and to technology for new forms of generating energy-efficiency and new materials developed from materials in use today. To determine the feasibility of the new envelope system that we propose, we have compiled, examined and run laboratory tests on the information and material provided by commercial brands. We have compared this information with data supplied by other independent scientific tests run by Moner-Girona, Roig, and Molins[15-18] in the field of hybrid aerogels and organically modified silica aerogels as a means of material improvement and by independent laboratories like Zae Bayern in Germany[19] or the University of Denmark.[20]

Specifically, this article sets out a novel envelope system based on a study of the families of light-weight commercial panels manufactured using an envelope assembly of translucent, silica gel-based thermal insulation materials and determines its validity as a lightweight, slim, high energy efficient, light-transmitting (semitransparent) envelope component for use on the building market.

Theoretical study of the system

Today's architectural vanguard demands a building system such as is proposed in this research: a lightweight, variable geometry, seamless high energy performance system that also permits the passage of natural light and backlighting.

No system combining all these features exists as yet and similar systems are not absolutely free-form and translucent, are not seamless and/or have a very limited thermal response.

From the viewpoint of energy performance, we found that the insulation that best meets the needs of the new system that we propose is aerogels.[21,22] The four advantages of aerogels are:

a) **Transparency:** Monolithic aerogel light transparency can be as high as 87.6%.[23]

b) **Insulation:** It is an excellent insulator. The thermal performance of a 70mm nanogel-filled vacuum insulated panel (VIP) is better than a 270mm-thick hollow wall.[24]

c) **Lightness:** Aerogel is only three times heavier than air.[25]

d) **Versatility:** Monolithic aerogel can be shaped as required.

In the following we analyse translucent and transparent commercial panels, setting out their strengths and weaknesses and our findings as a result of this study.

Translucent systems

We have analysed systems composed of granular silica gel-filled polycarbonate, reinforced polyester and double-glazed VIPs.

a) **Nanogel-filled cellular polycarbonate panels** are the most widespread system on the market.

Strengths: It is a very lightweight material. It has a high light transmission index. It is a low-cost material for immediate use.

Weaknesses: Durability is low at only 10 years. These panels are very lightweight but very fragile to impact.

b) No more than two types of **reinforced polyester panels** are commercialised despite the potential of this material.

Strengths: Good mechanical properties. Good malleability. They could be shaped according to design needs but no existing system offers this option. Durability is also good.

Weaknesses: Existing systems have design faults, because they include internal aluminum carpentry or substructures, whereas there is, thanks to the characteristics of reinforced polyester, potential for manufacturing a self-supporting panel, as in the case of single-hull boats.

c) **Double-glazed VIPs** are still at the prototype stage.

Strengths: Thanks to the combination of vacuum and aerogel insulation, they provide the slimmest and best translucent insulation system in the building world (0.5W/m^{2}K). Additionally, the service life of the glazing and the aerogel is very similar.

Weaknesses: This component is fragile. The high cost of molding glass into complex geometries rules out its use as a free-form system. It is a system that depends on substructures and other components for use.

Findings: After a comparative analysis of over 147 commercial products and the detailed evaluation of the best eight (Figure 1), we can confirm that fibre-reinforced polyester resin panels have some unexploited design lines such as the design of insulation for variable geometry translucent skins, or structural improvement for use as a self-supporting component.

Figure 1 (right): Staggered beam interstitial structure.

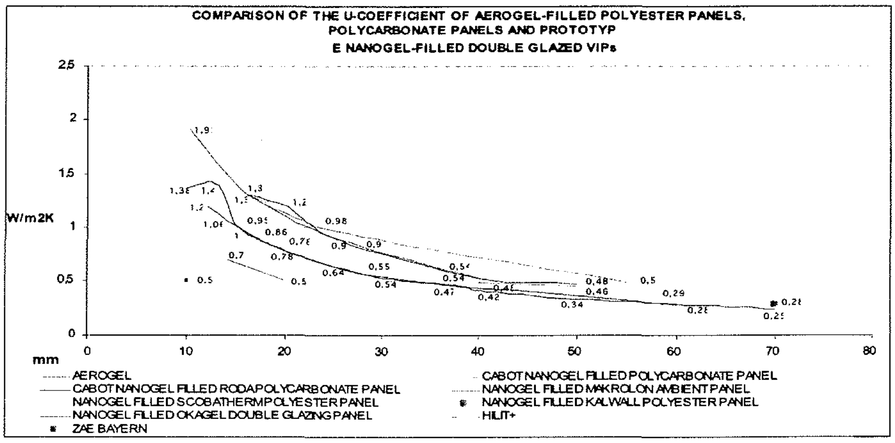


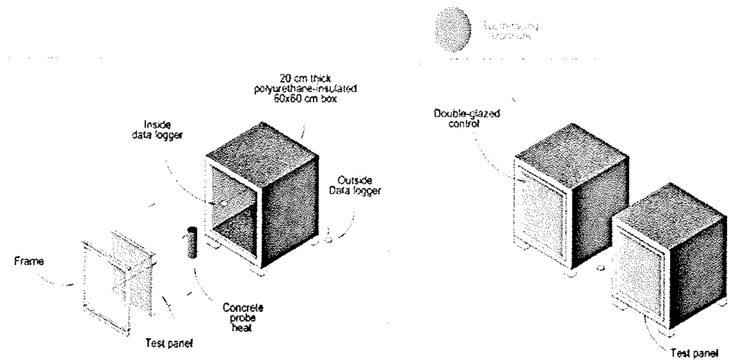
Figure 1 Comparison of commercial systems and prototypes

Looking at double-glazed VIPs, the data indicates that panels like these are the best commercial solution, as they offer the best thermal and acoustical insulation performance and optimal light transmission. At the acoustical and thermal level, the VIP is the best of the envelopes examined.

Transparent systems

All panels implemented with monolithic aerogel instead of nanogel are transparent. They have a high solar transmittance and low U-value. At present all these systems are non-commercial prototypes. Noteworthy are two aerogel-insulated double-glazed VIPs.

a) 4-13.5-4/21.5mm double-glazed vacuum panels filled with monolithic aerogel with a pressure of 1hPa in the aerogel chamber. The heat transfer coefficient has a U-value of 0.7W/m^{2}K for 14mm and 0.5W/m^{2}K for 20mm. This almost doubles the insulation performance of the best commercial translucent panel. Light



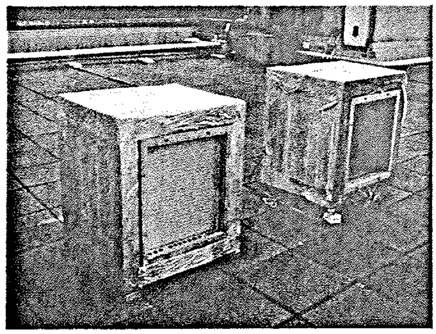


Figure 3 (above): Energy performance testing system.

transmission depends on the angle of incidence, but varies from 64.7% to 87.5%. The sound attenuation index is 33dB for a panel thickness of 23mm and noise reduction is expected to be improved to 37dB. There is a 10% to 20% energy saving compared with a dwelling that is glazed with gas-insulated triple glazing (argon and krypton).

b) 10mm double-glazed VIPs with aerogel spacers inside the core. The heat transfer coefficient for 10mm panels has a U-value of $0.5W/m^2K$. This is the best of all the panels studied so far, where light transmission is equal to glass.

Findings: From the analysis of the transparent panels, VIPs come the closest to what we are looking for in this research. The only arguments against VIPs are the high cost of molding glass into complex geometries, and that they use fragile double-glazing as a sandwich protection panel.

Experimental study

Following up the results of the theoretical study, we now compare these findings with the results of an empirical experiment and computer simulations of the real commercial panels, to which we had access.

Computer simulation

We used the Design Builder program to conduct a trial by computer simulation under the same environmental conditions as the empirical trials run on the other panels. Figure 2 describes the behaviour of a 25mm aerogel sheet. We find that the test space has a uniform inside temperature of between 18 and 37°C.

Empirical trials

The trials are designed to examine the energy performance of the material. These trials are based on the determination of thermal transmittance by the hot box method.[26] They were run on boxes with an inner dimentions of 60cm x 60cm x 60cm, insulated on five sides with 20cm of expanded polyurethane. One of the box faces was left open by way of a window. The study elements are placed in this opening using a specially insulated frame. The trial involves exposing two such boxes to a real outside environment to study their behaviour. The two boxes have two different windows. One is fitted with 6 + 8 + 6 double glazing with known properties as a contrast element and the other is fitted with the panel being studied. Data-loggers are placed inside each box for monitoring purposes. There is a thermal sensor on the outside to capture the temperature to which boxes are exposed. The boxes are set in a south-facing position as this is the sunniest exposure (Figure 3).

We ran 28 temperature-measuring trials using this system and compared the performance of different thicknesses of commercial panels with 6 + 8 + 6 double glazing. Four of these panels deserve a special mention:

a) **Trial-1:** 16mm nanogel-filled Cabot Lexan Thermoclear polycarbonate sheets.

Results: There is on average a 2.5°C improvement in thermal properties over the double glazing at night, and

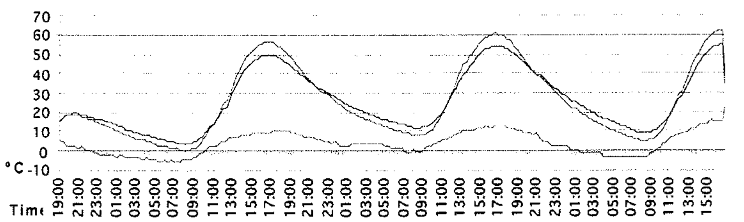


Figure 4 (right): Comparison of double glazing with 16mm nanogel-filled Cabot Lexan Thermoclear polycarbonate sheets.

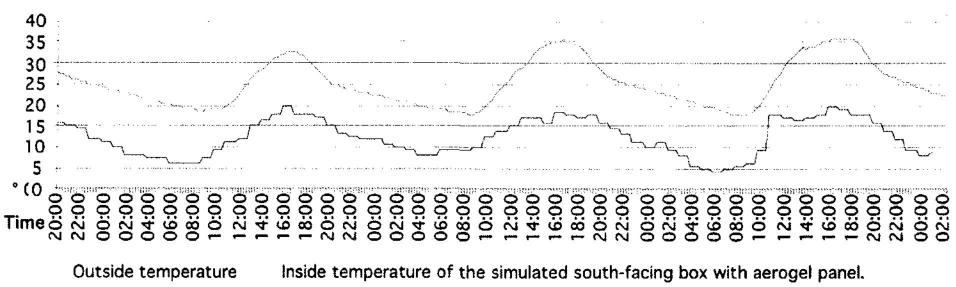


Figure 2 (below): Behaviour of a 25mm aerogel sheet.

it insulates almost 6°C more than double glazing when exposed to direct solar radiation (Figure 4).

b) **Trial-2:** 25mm nanogel-filled Cabot Lexan Thermoclear (triple-wall) polycarbonate sheets.

Results: There is on average a 2°C - 3°C improvement in

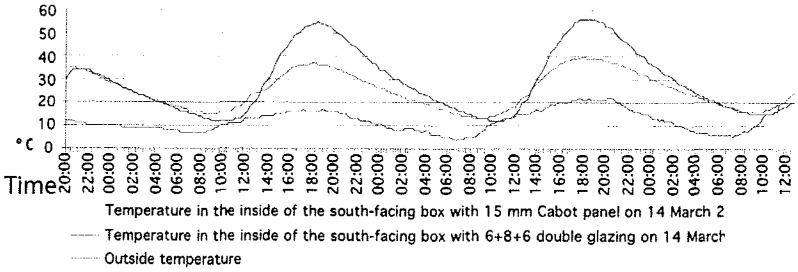


Figure 5 (left): Comaprison of double glazing with 25mm nanogel-filled Cabot Lexan Thermoclear polycarbonate sheets.

thermal properties over the double glazing at night, and it insulates 15 to 20°C more than double glazing when exposed to direct solar radiation (Figure 5).

c) **Trial-3:** Bayer Makrolon-Ambient S2S-25 sheet 25mm nanogel-filled twin-wall polycarbonate panel.

Results: Behaviour is very uniform. We get a 3°C improvement in thermal properties over the double glazing at night and it insulates 5°C more than double glazing when exposed to direct solar radiation (Figure 6).

d) **Trial-4:** 70 mm Okagel Okalux VIP Panel: Nanogel-filled vacuum insulation panel.

Results: Temperature is homogeneous ranging between 17°C and 32°C and there is an almost constant difference of from 3°C to 10°C compared to double glazing (Figure 7).

These four trials were evaluated and compared with the computer-simulated aerogel data (Figure 8) and data from the theoretical study. We found that, like the data output by the theoretical study, the real trials suggest that in terms of their behaviour, the materials are suitable for designing the new envelope system. The very flat loss curves in the plot describe a very low U-value. In terms of capture, there is a thermal difference of almost 30°C between the VIP panel and the worst of the tested panels. The difference between the VIP and the best-performing panel is almost 10°C in terms of loss and capture. We have confirmed the experimental datum that likens the behaviour of the VIP panel to that of the computer-simulated aerogel.

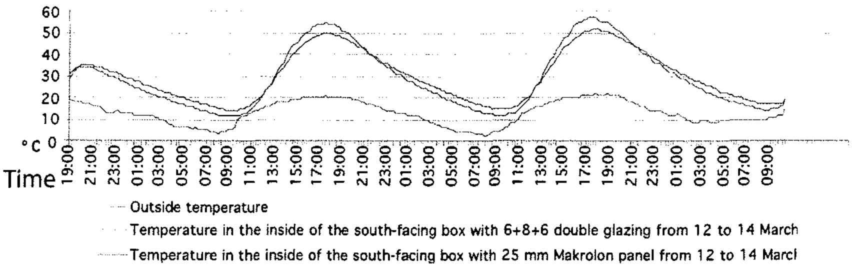


Figure 6 (below): Comparison of double glazing with 25mm Makrolon panel.

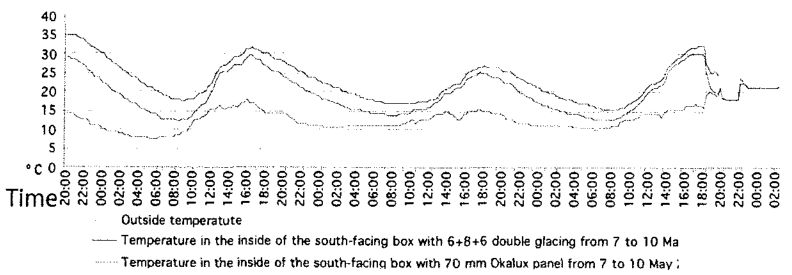


Figure 7 (left): Comparison of double glazing with 70mm Okalux panel.

From our computer-simulated experimental study, the data on organic aerogels supplied by the CSIC and the University of Barcelona and the data from studies at the University of Denmark on envelopes implemented with monolithic silica gels and the empirical trials conducted in this research, we arrive at the following conclusions.

1. The best-performing insulation system is the VIP system implemented with monolithic aerogel.
2. Thanks to its mechanical properties and because it can be used to fabricate variable geometry translucent skins, the natural cellulose fibre-reinforced epoxy resin matrix, whose performance is similar to E-type glass fibre, is the best envelope for the free-form, transparent, energy-efficient envelope system (F^2TE^3). These are key data that are useful for designing a new lightweight, slim, high energy efficient, light-transmitting envelope system, providing for seamless, free-form designs.

Proposal for a free-form, transparent, energy-efficient envelope system (F^2TE^3)

We propose a free-form design envelope system fabricated with cellulose fibres and polyester resin (or acrylic-based organic resin) and a vacuum core insulated with monolithic aerogel at a pressure of 100-50hPa. Being a self-supporting component, the system can perform structural functions and seams between panels are concealed by an outer coating applied in situ (Figure 9).

(a) An outer skin of natural cellulose fibre-reinforced epoxy resin matrix with similar performance to E-type glass fibre, coated with an outer layer of gelcoat to protect it from external agents. The panel's resistance, protection and variable geometry depends on this component.

(b) A thermal/acoustical insulation component composed of a monolithic silica gel-filled vacuum chamber.

Dimensions

We have to take into account the sol-gel process drying times required for the monolithic silica gel to generate

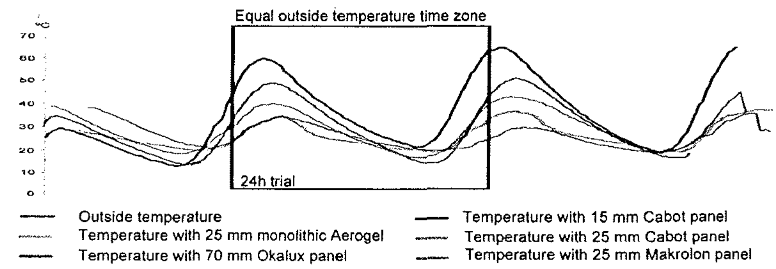


Figure 8 (below): Comparison of trials run on commercial panels at equal outside temperature.

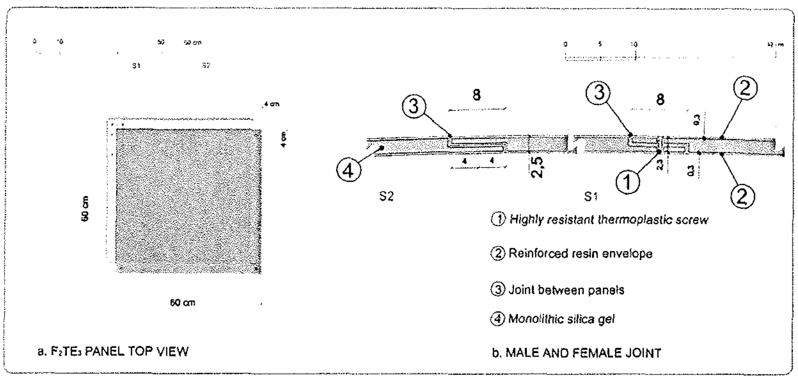


Figure 9 (above): F²TE³ Envelope Profile Design Materials.

a crystalline structure, the percentage of breakages due to size and above all the fact that existing autoclaves are able to generate monolithic gel pieces no larger than 55cm x 55cm. The panel sizes will be 60cm x 60cm (length/width) and panel thickness will depend on the use. We have studied a 25mm thick panel, composed of two sheets of 3mm-thick reinforced resin and a vacuum core filled with monolithic silica gel (Figure 10).

The density will range from 15kg/m² to 7kg/m² and the minimum admissible flexion radius will be approximately 4000mm.

- Light transmittance - D65. From 59% to 85% approx.
- UV absorption. 20% approx.
- Total energy. 61% approx.
- Horizontal and vertical U-value. 0,50W/m² K
- Thermal conductivity coefficient. 0,065mm/m°C (estimated).
- Possible heat- and humidity-induced dilation: 3mm/m approx.
- Maximum temperature. Should withstand temperatures from 120°C to 250°C
- Weighted sound reduction value. Estimated at 26-45dB.
- Impact resistance. Should be within the EN 356-P5A limit.
- Fire resistance. European (EN13501) resistance regulations compliant.

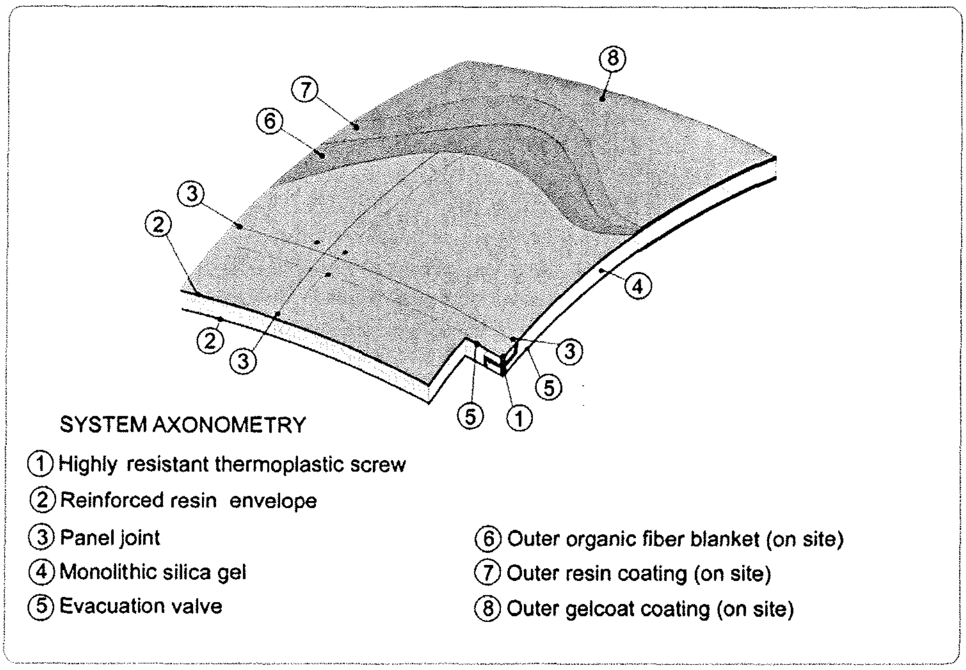


Figure 10 (above): F²TE³ system axonometry

Testing

A F²TE³ system with a thickness of 25mm has been computer simulated to examine its energy-saving behaviour compared with a computer-simulated aerogel envelope of the same thickness (Figure 11).

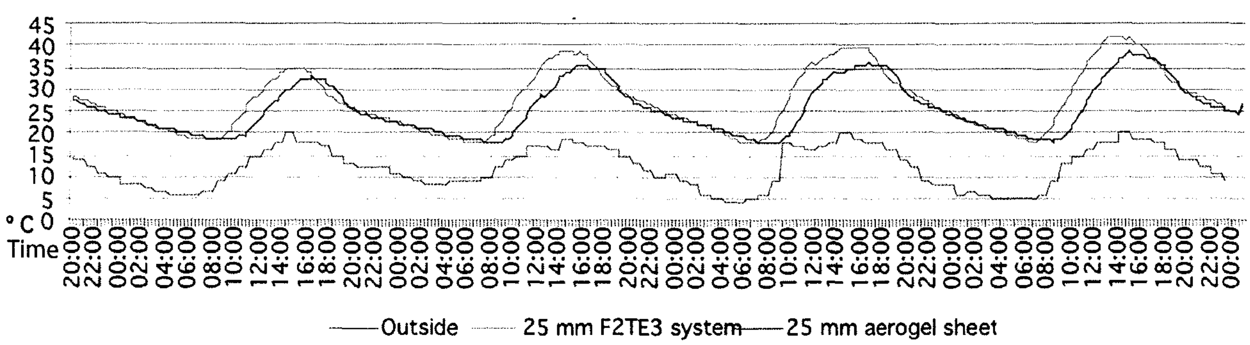
The F²TE³ system returns a result very close to what would be achieved with monolithic aerogel. F²TE³ performance almost equals aerogel in terms of heat loss, with a very similar flat curve (a difference of only 5°C), where the U-value is very small.

Conclusions

F²TE³ is a slim façade system that provides high energy efficiency with a seamless surface, providing for variable geometry and the option of building self-supporting structures into the same transparent system skin.

Computer-simulated trials have shown it to have almost identical energy efficiency properties to monolithic aerogel systems and VIP envelopes. This system revolutionises VIP systems, as it generates a transparent envelope but eliminates breakages due to fragility by substituting glass for a reinforced composite material.

Figure 11 (below): F²TE³ compared with 25mm monolithic aerogel.



Additionally, it offers the option of generating variable geometry designs.

The prototype F^2TE^3 system outperforms the systems existing on the market by combining some of the best properties of these systems and overcoming their weaknesses.

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