Inside Beijing's Big Box of Blue Bubbles

A multidisciplinary design team employed an innovative digital process to produce a surprising, highly integrated envelope-and-structure combination.

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It might seem like an obvious choice of design parti: A facility built to host the swimming and diving events for the 2008 Summer Olympics in Beijing should be all about water. But realizing such a concept in bricks and mortar is far from straightforward, and more challenging still if the designers intend to create more than a container, but hope to capture the “spirit” of water. “We wanted the building to dematerialize, to change moods, to react to changes in the environment around it,” says Min Wang, a design principal with China Construction Design International (CCDI), a state-run design institute that worked on the project.

But despite the difficulty of realizing such an abstract goal, the National Swimming Center’s international and multidisciplinary design team, composed of the Australian architecture firm PTW, engineers from the Sydney office of Arup, and a group from CCDI, managed to pull it off. They created a building that not only embodies some of the elusive characteristics of water, but one that tightly integrates skin, structure, and the performance requirements of an Olympic-level sports venue [for more on the project, see page 100].

Continuing Education

Use the follow ing learning objectives to focus your study w hile reading this month’s Continuing Education article.

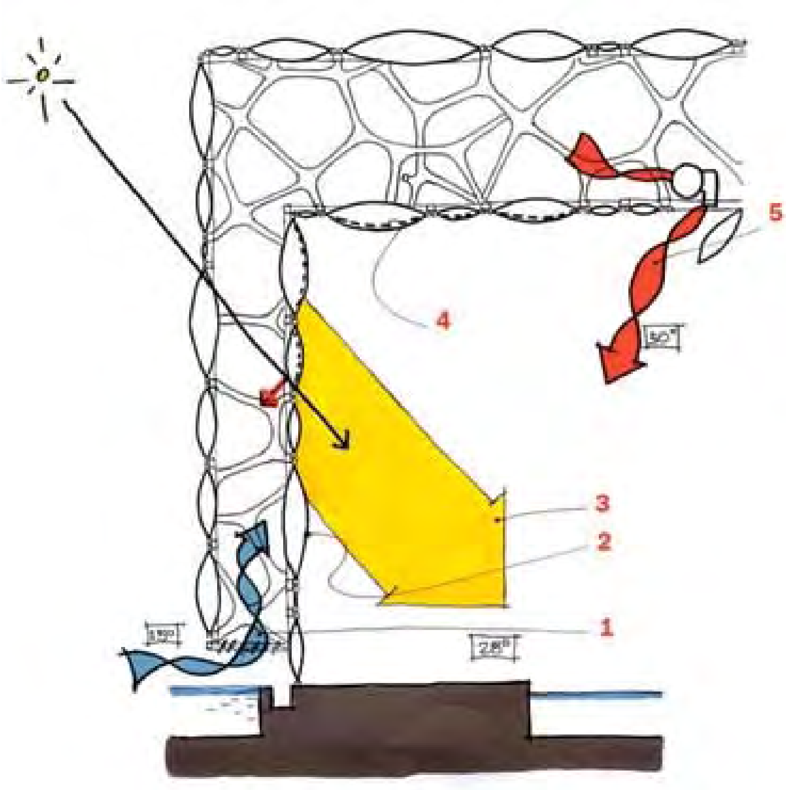
Learning Objectives - After reading this article, you w ill be able to:

1. Describe the Water Cube?s building envelope and its performance benefits.
2. Describe the Water Cube?s structure.
3. Discuss the process of digital form finding employed to produce the Water Cube?s design.

Naturally, the designers didn’t use bricks and mortar for the $100 million, boxlike structure known as the Water Cube. The consortium, which was awarded the project through a competition in mid-2003, chose steel and a space-age plastic, ethylene tetrafluoroethylene (ETFE). The material, a cousin of Teflon, which the team used to create translucent pillows for the building’s cladding, is strong and resistant to degradation from ultraviolet light and air pollution. By electing to envelop the building in it, the design team could treat the Swimming Center as an insulated greenhouse, capturing the energy from the sun for heating and lighting. ETFE was more appropriate for such a use than glass, the design team reasoned, because of better acoustic and insulating properties, and it is lightweight, which eliminated the need for a secondary structure to support the skin.

Photo: © Iwan Baan

In order to create a building structure and ETFE enclosure with the desired references to liquid, the team members explored the geometry of soap bubbles, studying the work of Irish physicists Denis Weaire and Robert Phelan. In 1993, the pair proposed a solution to the so-called Kelvin problem (named after late 19th-century British mathematician William Thomson Kelvin) that asks how to divide space into an equal number of cells with the least surface area between them. Weaire and Phelan's "foam" is made up of a combination of polyhedra with either 14 or 12 faces. Despite its regularity, the honeycomblike structure was well suited to the team's goals because "when viewed at an arbitrary angle, it appears totally random and organic," says Tristram Carfrae, leader of the group of engineers from Arup.



VENTED CAVITY:
TYPICAL OPERATION

1. Fresh external air circulates within cavity.

2. ETFE pillows perform like a greenhouse enclosure.

3. Controlled daylight and radiant heat illuminate and passively heat pool.

4. Operable ETFE switches on or off to shade interior.

5. Fan-assisted, preheated fresh air is returned to pool.

With the exception of the elimination of operable shading, the Water Cube's cavity wall was realized almost unchanged from the competition entry scheme.

Drawing courtesy ARUP

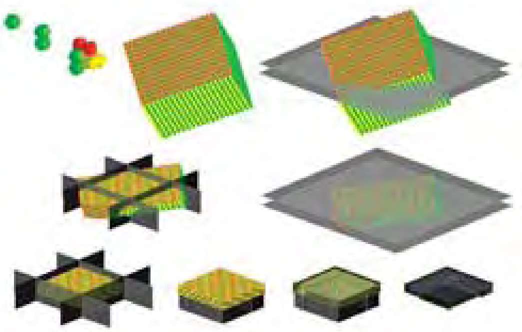
Although Weaire and Phelan's foam forms the basis of the structure, there is only one spot in the building where their "pure" geometry is clearly recognizable—the second-floor Bubble Bar. Here, a collection of ETFE-clad polyhedra encloses a room where visitors can sip champagne.

Elsewhere in the building, the underlying geometry is hard to discern because of the team's form-finding process. In order to develop a building structure from the theoretical foam structure, the designers from CCDI wrote a script that would allow them to assemble an infinite array of the Weaire-Phelan units, rotate it in three dimensions, and then slice the packed cells to create a box 584 feet square in plan and 102 feet tall. They then removed three interior volumes for halls devoted to swimming and diving competitions, the pool for water polo, and the leisure center. From the foam left behind after this virtual cutting and deconstruction process, they created a space frame by replacing the edges of the polyhedra with steel tubes that meet at spherical nodes. They decided to encapsulate the space frame in 4,000 bubblelike, air-filled ETFE pillows to create a vented cavity 12 feet wide within the walls and one that is 25 feet deep within the roof, protecting the steel structure from the corrosive humidity of the pool environment.

During the day, diffuse sunlight provides much of the lighting for the Water Cube's interior spaces, such as the competition pool (right). At night, the building becomes a glowing blue box (below) with the help of LEDs.

Photo © Iwan Baan (top); PTW (below)

The result is a seemingly irregular, but in actuality a rigorous and buildable structure-and-building-envelope combination appropriate for earthquake-prone Beijing. The on-site welded space frame, with column-free spans of up to 396 feet, is highly efficient, nonlinear, nondirectional, and remarkably stable. The ETFE cladding, which weighs just 1 percent of an equivalent glass panel, contributes to the building's seismic performance, since it helps reduce the gravity and lateral loads that the structure would be subject to during a temblor, explains Carfrae.



As the basis of the building structure, the design team studied the work of physicists Denis Weaire and Robert Phelan. The pair proposed a honeycomblike structure made up of polyhedra with either 14 or 12 faces (left) as the solution to the so-called Kelvin problem. The designer team assembled an infinite array of these cells, rotated them in three dimensions, and then sliced them to create a box 584 feet square in plan and 102 feet tall (right). The second-floor Bubble Bar (bottom) is the only place in the Water Cube where Weaire and Phelan's "pure" geometry is still visible.

Photo courtesy PTW (bottom); PTW/China State Construction Engineering (top left); illustration: ARUP (top right)

The ETFE cavity wall and roof also provide thermal efficiency. The double skin is designed to capture solar energy to heat the swimming pools and the building and light the interior spaces. The building collects 20 percent of the solar energy that lands on it, equivalent to covering the 340,000-square-foot roof with photovoltaics, according to Arup. The firm estimates that the Water Cube saves 30 percent of the energy typically devoted to lighting and half of the energy that would be required to heat a well-detailed and well-insulated metal-clad box.

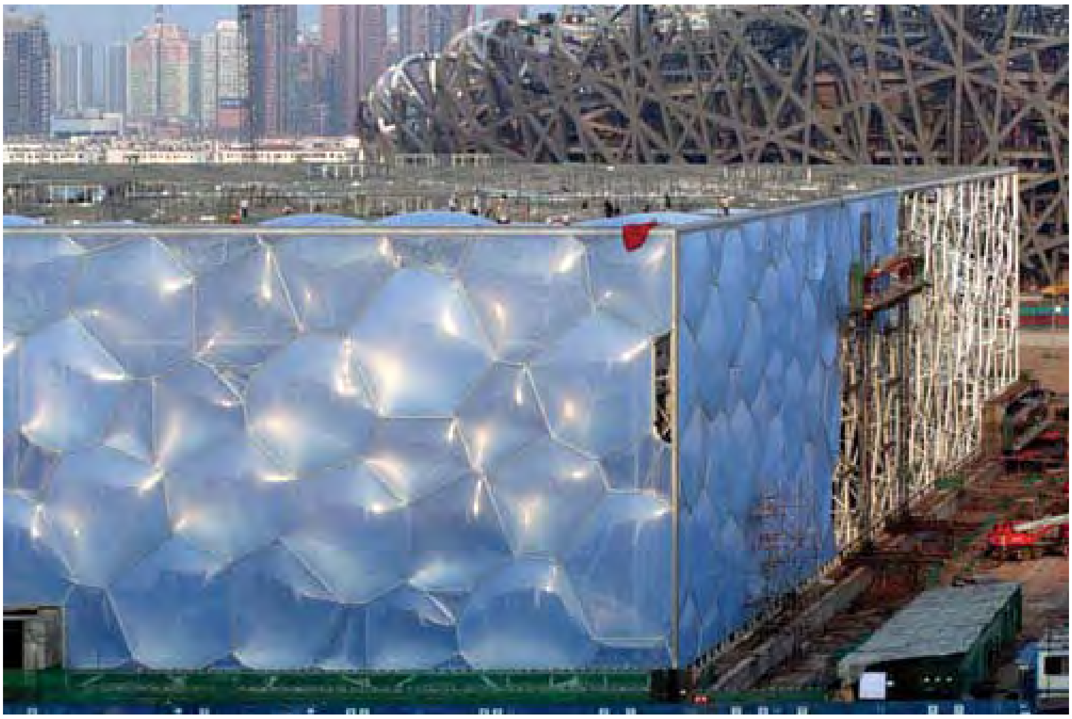
The Water Cube relies on the thermal mass provided by the pool water and surrounding concrete to retain heat during the day and release it at night. The double skin allows the venting of excess heat in the summer but permits its containment during the winter, when solar gain is most beneficial. The concept was realized almost unchanged from the design team's original competition entry scheme.

One of the few features of the envelope implemented differently in the built Water Cube is the solar control strategy. The team originally imagined the inner ETFE cladding as an operable and variable surface, providing the facility's managers with the ability to turn shading on or off, depending on the desire to admit sunlight and control glare within the Water

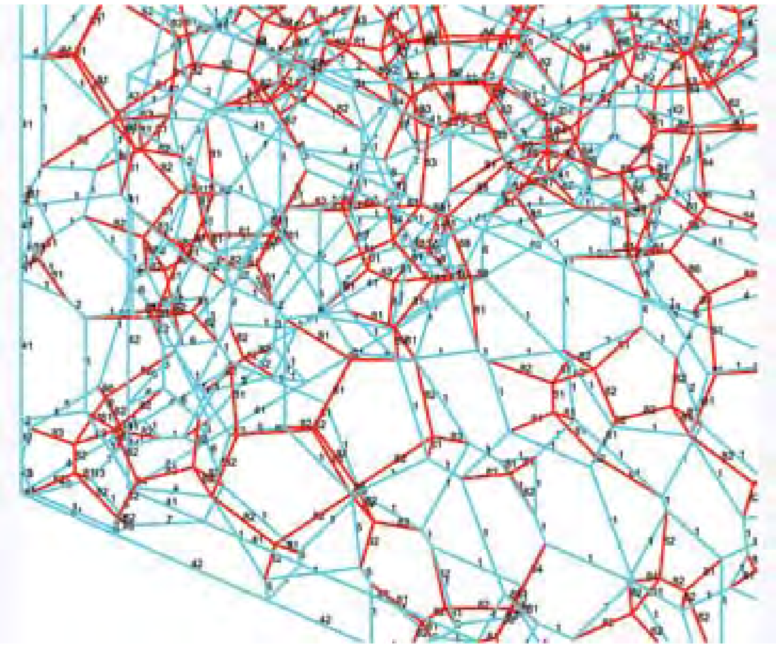
Cube's various spaces. But in the end, the designers opted for a fixed aluminized frit pattern that blocks between 10 to 95 percent of visible light. The frit is most dense on areas of building skin that enclose areas where direct sun is least desirable and glare would be most distracting. For example, the roof over the competition pool admits only 5 percent of visible daylight due to strict broadcast-industry lighting-control requirements.

The building's on-site welded space frame consists of 22,000 steel tubes connected at spherical nodes (top). Workers encapsulated the Water Cube's structural frame in 4,000 ETFE pillows, installing up to 30,000 square feet of the material each day (below).

Photo courtesy Vector Foiltec



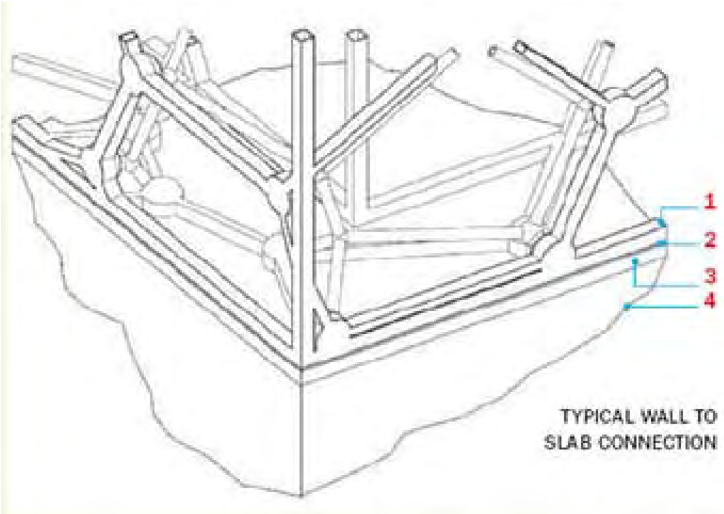
Though much of the building's heating needs are satisfied through passive means, some spaces within the Water Cube do require mechanical cooling, setting up a challenge for designers. In the competition pool area, "it was tricky to keep the swimmers warm and wet and the spectators cool and dry," says Carfrae. In order to cope with the differing requirements of the building's various types of occupants, the engineers relied on the displacement ventilation principle, supplying cool air through an underseat supply system, conditioning only the zones occupied by spectators.



Software that Arup developed helped designers optimize and size these components (above) and generate a 3D model as well as traditional 2D construction documents (below).

1. Base of space frame
2. Steel plate
3.Steel angle
4.Concrete slab

Drawings courtesy Arup



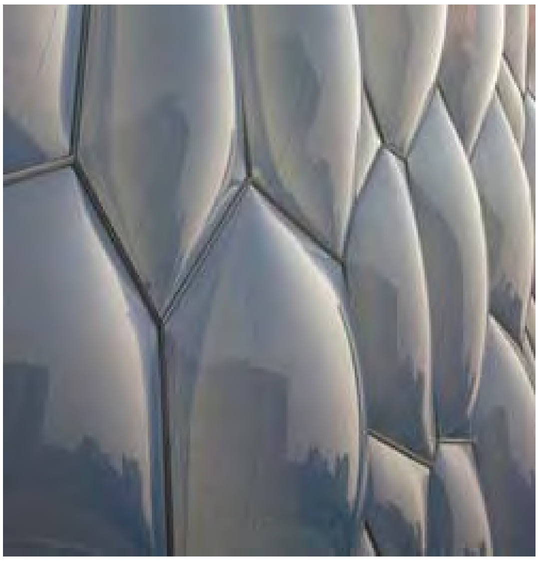
Digitally driven

The Water Cube's structure is the outcome of applying sophisticated analysis and optimization software that Arup's engineers created in-house specifically for this project. The program helped the designers examine the space frame under various loading scenarios to determine the size, shape, weight, and other properties for each of the 22,000 steel tubes. These characteristics were automatically recorded in a database and a 3D model, which in turn were used to produce the construction documents.

Team members say that the process of digital form finding, analysis, and documentation employed to produce the Water Cube was cutting edge for a building designed largely in late 2003 and completed earlier this year. "There is a lot of talk about autogenerated architecture, but this was one of the first projects where such a process was realized," says Chris Bosse, a former project architect at PTW and now head of the Laboratory of Visionary Architecture (LAVA), in Sydney.

Because of the high degree of automation that the parametric process afforded, the team could generate a complete set of new construction documents in less than a week following a major change in the Water Cube's configuration, according to Carfrae. But speed was not the only advantage. The process also ensured accuracy. Prior to construction, the team issued the 3D model, traditional 2D drawings, and the database to the contractor. They did not worry about potential conflicts between the various media (or resulting construction errors) since "it was all the same information conveyed in different ways," he says.

Fabrication of the ETFE pillows depended heavily on the digital information. The digital files controlled operation of the foil-cutting equipment, the same way CAD files run a plotter. This step in the fabrication process was not completely automated, however. The data did require some manipulation, especially to address areas of the building skin where the bubble shapes are interrupted, such as those around corners and openings. "There was still a large human factor involved," says Edward Peck, director of design and development for Vector Foiltec. The international company, headquartered in Germany, partnered with a Chinese curtain-wall manufacturer to engineer, fabricate, and install the ETFE cushions.

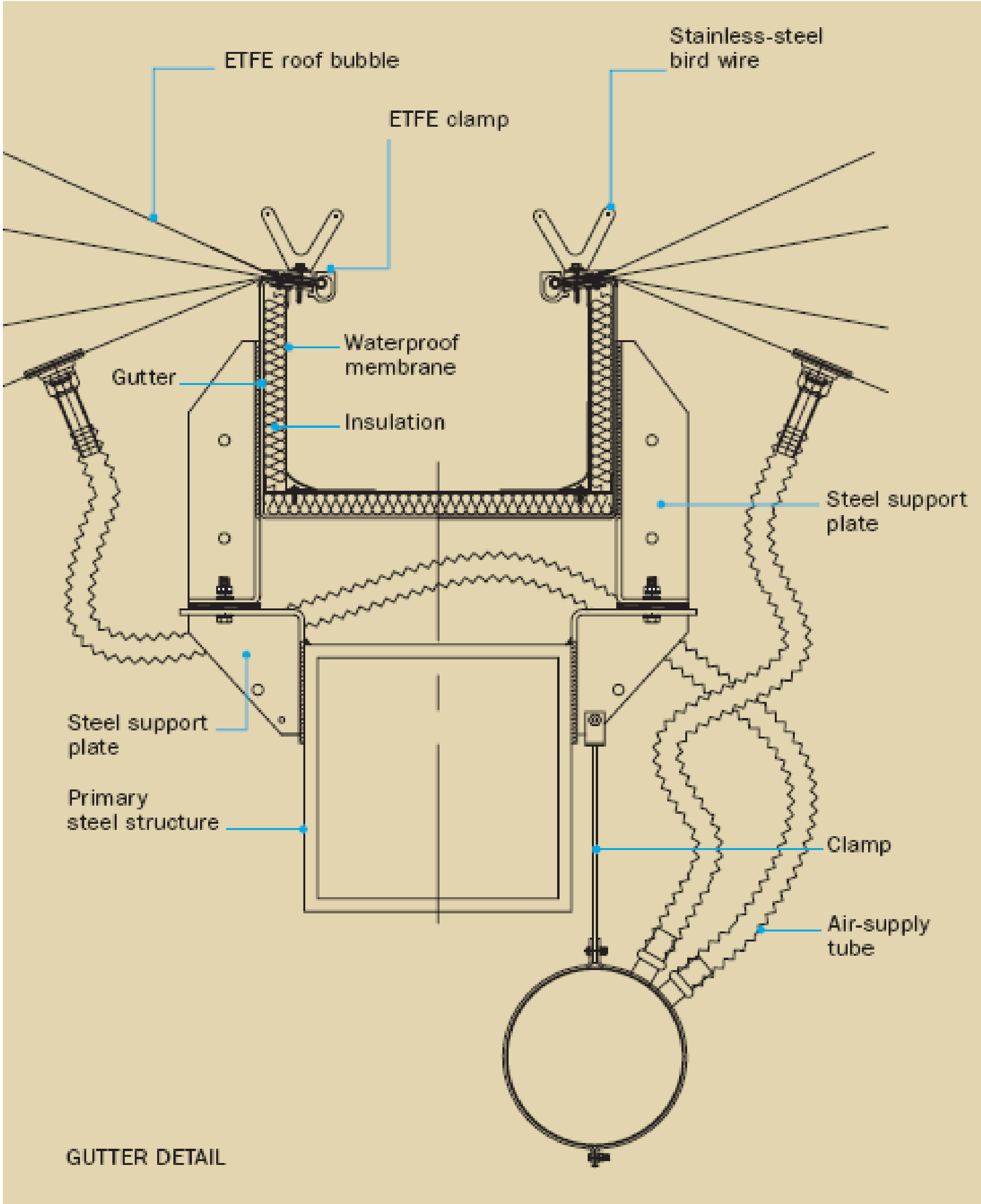


Vector Foiltec assembled the pillow layers from 5-foot-wide sheets of ETFE. Because the designers specified that the resulting seams, visible under certain conditions, should align from pillow to pillow, none of the patterns for the 4,000 bubbles are exactly the same.

Photo © Michael Goodman

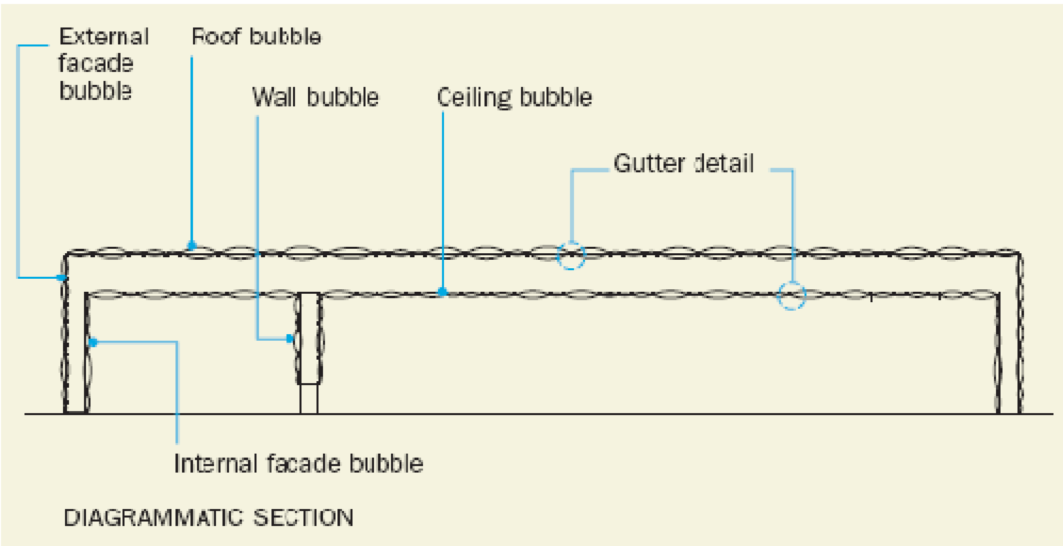
Most of the cladding cushions are composed of three layers of of 0.008-inch-thick ETFE foil. But those located in areas of high wind loads, particularly corners, have two or three more. These extra layers provide "load sharing"—they help the building skin withstand the additional pressure and suction exerted on those spots, since making the foils thicker was not an option, says Stefan Lehnert, Vector Foiltec managing partner. At thicknesses greater than 0.01 inches, the material becomes too brittle, he explains.

To create the rounded pillow surfaces, Vector Foiltec cut 5-foot-wide sheets of ETFE into shapes that resemble sections of a banana peel. The company then assembled the pieces into larger sheets, some as wide as 30 feet, via heat welding. The pattern for each of the 4,000 cushions is unique, even though there are only 15 pillow types in the walls and seven in the roof. Since none of the pillows have exactly the same orientation, and since the design team required that the heat-weld seams run continuously from one pillow to another, from the roofline to the ground, the result is that no two cushions are alike, explains Lehnert.



Details for attaching the ETFE pillows to the Water Cube's structural frame vary depending on their location.

Drawings courtesy Vector Filtec



After assembling the foils, workers transported the cushions to the site and attached the ETFE layers into aluminum extrusions that secure the pillows to the space frame. They then inflated the pillows with 18 radial ventilators permanently installed in the building. Because the pillows will gradually lose air, the building management system constantly monitors the pillows and signals the ventilators to supply filtered and dehumidified air when the pressure falls below a desired level.

Dirt typically washes off ETFE when it rains. But because of Beijing's construction dust and other particulates, the cube requires some manual cleaning.

Photo © Michael Goodman

Collecting and conserving

Appropriately, some of the building's most innovative features are its systems for handling water. Unlike most swimming pools, which send filter backwash water to the municipal wastewater systems, the Water Cube collects such gray water for treatment and returns it to the pool. The system substitutes rainwater collected from the roof for the small amount of gray water lost in the treatment process. The strategy lessens the burden of the building on Beijing's wastewater infrastructure and makes it less dependent on the city's already constrained fresh-water supply. "The idea was to make it as self-sufficient as possible," says Carfrae.

To visitors, the gray-water-recycling and rainwater-harvesting systems will be invisible. For them, the bubbles (and the Olympic competitors) will steal the show, especially at night, when the Water Cube becomes a glowing blue box with the help of LEDs integrated into the pillow frames. During the day, it is sometimes soft and playful, or cold and hard-edged, depending on the weather and the angle of the sun. This ability of the building to transform is perfectly in keeping with the design team's goals: "Water has no fixed image," says Wang. "It can be still, it can reflect the sky, or it can have big waves."

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