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Movable Membrane Roofs for the Arenas in Nîmes and Zaragoza

Couvertures amovibles en toile pour les arènes de Nîmes et de Saragosse

Wandelbare Membrandächer für die Arenen in Nîmes und Saragossa

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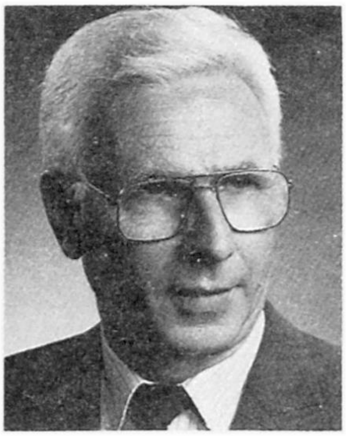

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SUMMARY
A general survey of the different movable roof concepts is given. Two recent movable roofs, the membrane cushion roofs in Nîmes and the partly fixed retractable membrane roofs in Zaragoza are described.

RÉSUMÉ
Dans un premier temps sont évoqués d'une facon générale, les différents types de couvertures amovibles. Ensuite sont décrites deux toitures amovibles récentes: la "lentille pneumatique" de Nîmes et la couverture toilée semi-rétractable de Saragosse.

ZUSAMMENFASSUNG
Zuerst wird ein allgemeiner Überblick über die verschiedenen Konzepte wandelbarer Dächer gegeben. Dann werden zwei neuere wandelbare Dächer beschrieben, das Membrankissendach in Nîmes und das teils feste, teils bewegliche Membranoach in Saragossa.

1. GENERAL SURVEY

There are several occasions, where we might want to have the choice for changing from an open air location to a covered, roofed one and vice versa: movable roofs are the solution! Generally, there are 3 different concepts for using such a roof influencing consequently their structural layout:

- A temporary roof is needed from time to time to protect against too strong sunshine or more often, especially in our continental climate, to protect against rain. Thus only a roof, which can be moved in or off within a short period of a few minutes, will provide an adequate shelter.

  Outdoor theatres, sports facilities like tennis courts, restaurants or other recreation and leisure areas may, although generally more comfortable in open air use, look for such a bad weather protection, which only guarantees uninterrupted performances and full use. - Roofs for this type of use are normally not designed to withstand heavy winterstorms or snow loads.

- The second group of roof serves the same purpose in summer, but in addition covers and protects the theatre or sports area also during winter. The necessity to carry snow loads roughly at least triplicates the maximum loads which result in a much stronger, stiffer and hence less foldable membrane and in much thicker cables to suspend the roof with of course rapidly decreasing ductility. So the roof adds not only weight and looses flexibility, but also adds costs. An alternative would be to provide a snow melting system by blowing warm air underneath the membrane, but it seems to be quite risky to rely totally on such equipment, especially, when it will be needed and used only very rarely but should be maintained and checked regularly. Therefore it is adviseable, when using a melting system, to nevertheless stick to a much reduced but nevertheless adequate level of safety in case of a mechanical system-shortfall.

- The third type of roof is installed only for the winter season and will be taken off in spring for the open air summer season. Although this roof is only 'moved' twice a year, it should be mentioned here, since nearly all roofs of this type are membrane structures and since this type is the most popular of all movable roofs.

Different requirements need different design approaches. For the first roof type the most simple design shows membrane strips, hooked to parallel ropes, stressed between two rigid supports. The membrane strips, i.e. their front or end piece, are pulled forward and backward manually by thin diameter endless slings, moving on rollers at those same supports. Similar systems, the vela, had been in use already in the old Roman theatres for shading the arena and they can be seen today in garden restaurants or small theatres, doing the same job only with more modern materials like a PVC-coated polyester membrane, steel ropes and nylon slings. By welding the membrane strips together the roof today normally is continuous, protecting a larger area also against rain.

While the membrane moves along the parallel ropes, it is folded - or unfolded - in one direction, the distance of the hooks determining the fold depth. The folded membrane can be parked/stored on either end. A variation to the parallel is the trapezoidal rope arrangement; here the folded membrane - folded in both directions - can only be parked at the narrower end, widening, while it is pulled along the spreading ropes.

In both cases the membrane is moved along parallel or semi-parallel straight ropes and hence the membrane also remains plain. Therefore it is obvious that this type of roof is rather flexible under wind loads and therefore its application is limited to smaller roofs of a few hundred squaremeters only.

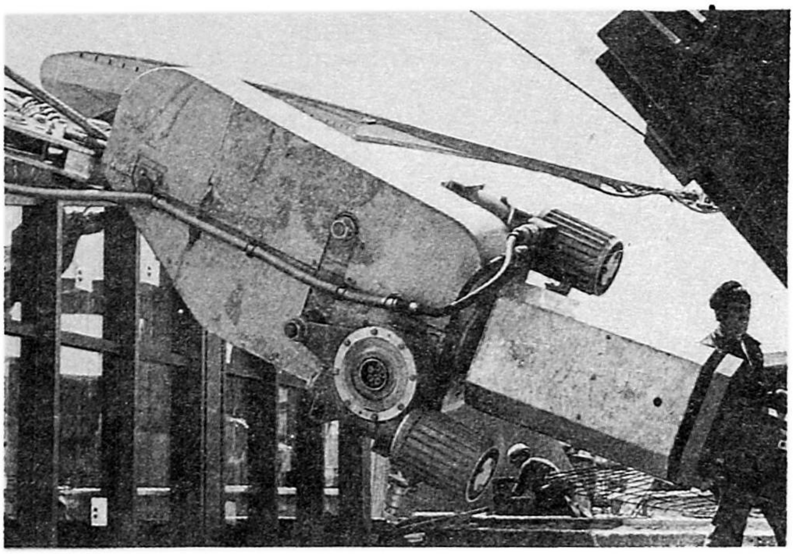


Fig. 1
Swimming Arena Düsseldorf
Membrane roof in closed stretched position.

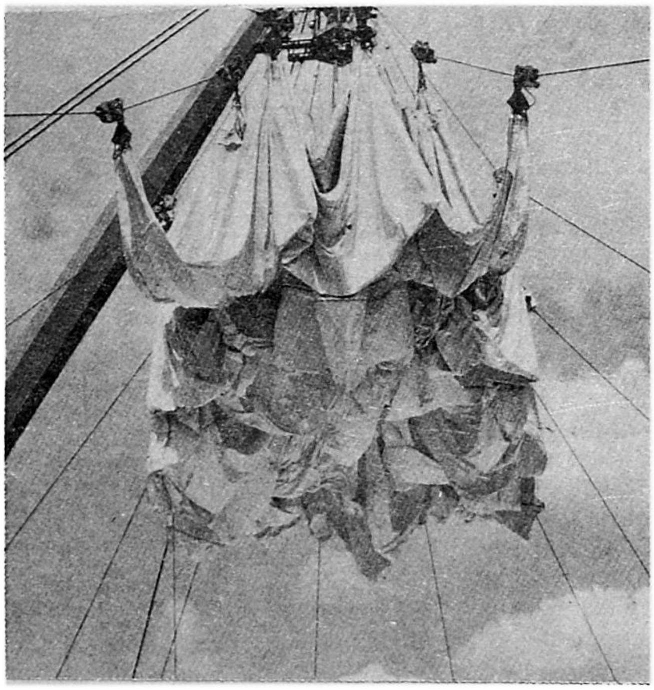


Fig. 2
Swimming Arena Düsseldorf
Membrane roof in open-air position; the tractors have pulled up the membrane edges along the main cables.

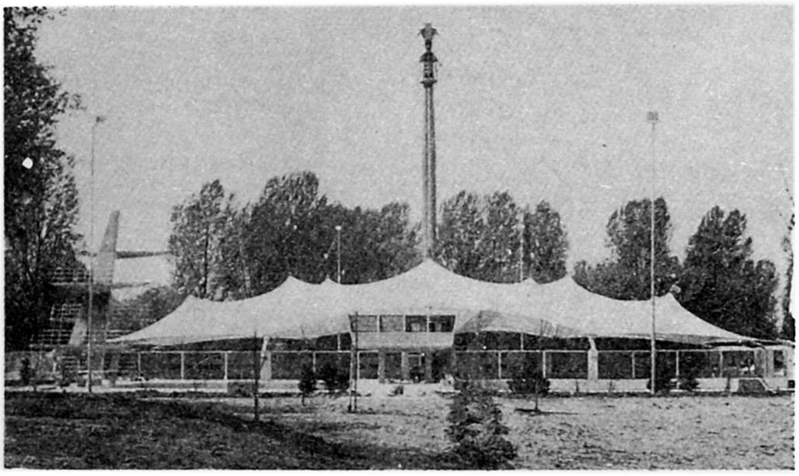


Fig. 3
Swimming Arena Düsseldorf
Tractor in base position, docked to the anchorage.

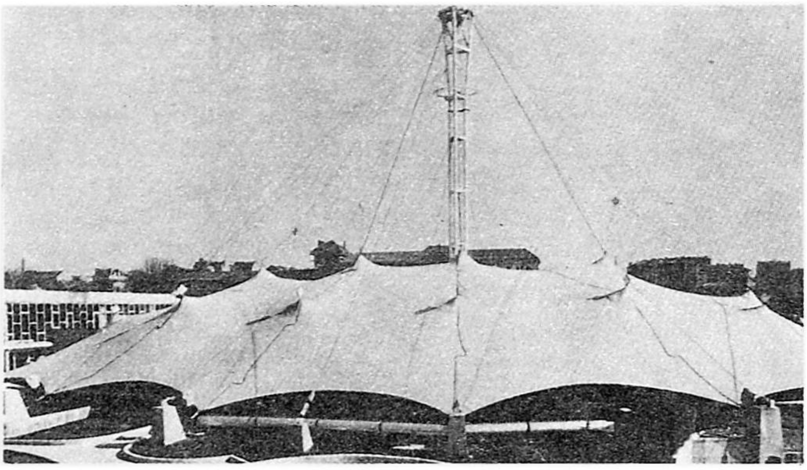


Fig. 4
Swimming Arena
Boulevard Carnot, Paris.
Membrane roof covers an area of 2 200 m^2.

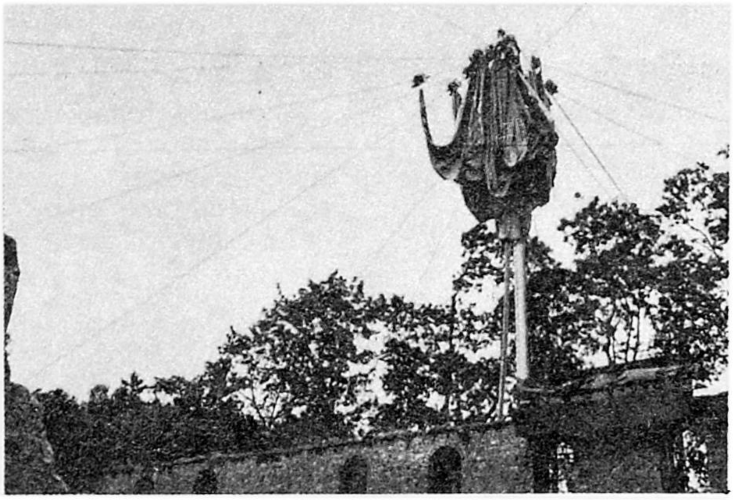
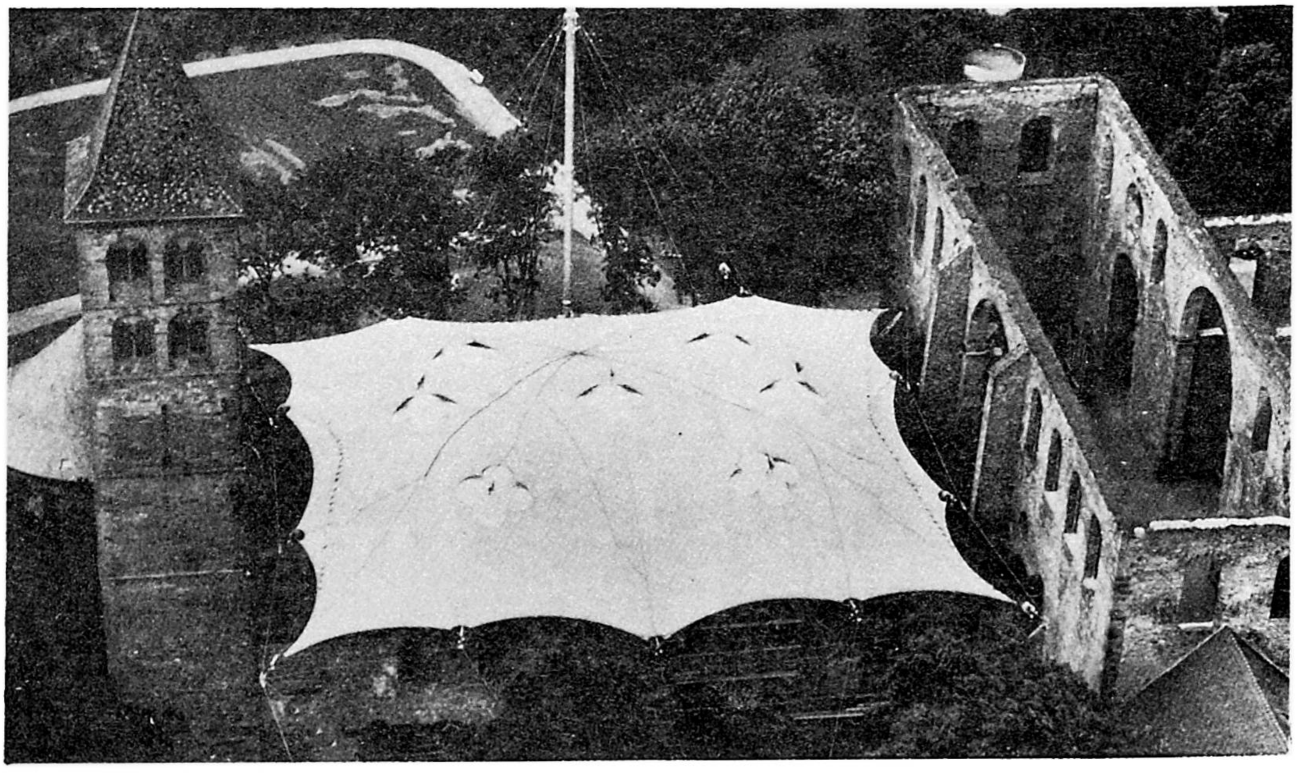


Fig. 5 + Fig. 6
Theatre Bad Hersfeld
Membrane roof of 1 450 m^2, in squeezed top position and in closed stretched, nearly rectangular shape.



For larger areas and larger loads the membrane should have a double curvature in order to prestress it and to get more stiffness and stability. Most structures, built so far, show a synclastically curved membrane dome, which is suspended from a number of main cables at numerous support points distributed uniformly over the membrane area and put under prestress against these cables, while rigidly held along its circumference (see Figs. 1 - 6). Of course, the main cables must all lead to and be anchored in one central top point, from where they can spread out to form a circular, elliptical or any other roof shape in plan. Only so the membrane can from its stretched shape move and fold together to one central bulb.

Two schemes have been applied so far for moving the membrane:

- The main cables are fixed to their anchors and don't move. The membrane support points are movable - sliding - along the main cables. The outer membrane edge is attached to a tractor, which travels along the main cable and thus pulls or pushes the membrane for closing or opening the roof. These tractors (see Fig. 3), mostly electrically driven, must be strong enough not only to move the membrane, but also to prestress it to a sufficiently high level, since most of these roofs belong to type 2., i.e. they are designed for snow loads. Several roofs of this system have been built in France and Germany in the seventies mainly to cover swimming arenas, as Figs. 1 - 6 demonstrate.

- For extremely large roofs the membrane can't be moved any longer by tractors, due to the excessive forces. Here every membrane support point must be directly suspended by a cable from the central top point and this cable itself pulls the membrane up when the roof is to be opened. The best example for this type and most spectacular, because largest movable membrane roof at all, covers the Olympic Stadium in Montreal. 21 main cables prestress the membrane and in winter, when it is permanently closed, carry the heavy snow loads to the tower tops. During the lifting operation the main cable forces are much smaller, therefore they roll over large diameter wheels in the tower top and are extended by smaller cables which actually lift the roof by pulling the main cables and which are small enough in diameter to be reeled on winch drums situated at tower base. While the roof moves up, 17 points along the outer edge are guided by winch cables from their lower anchorages, which lateron are needed to pull the membrane down again and anchor it along its periphery. [1].

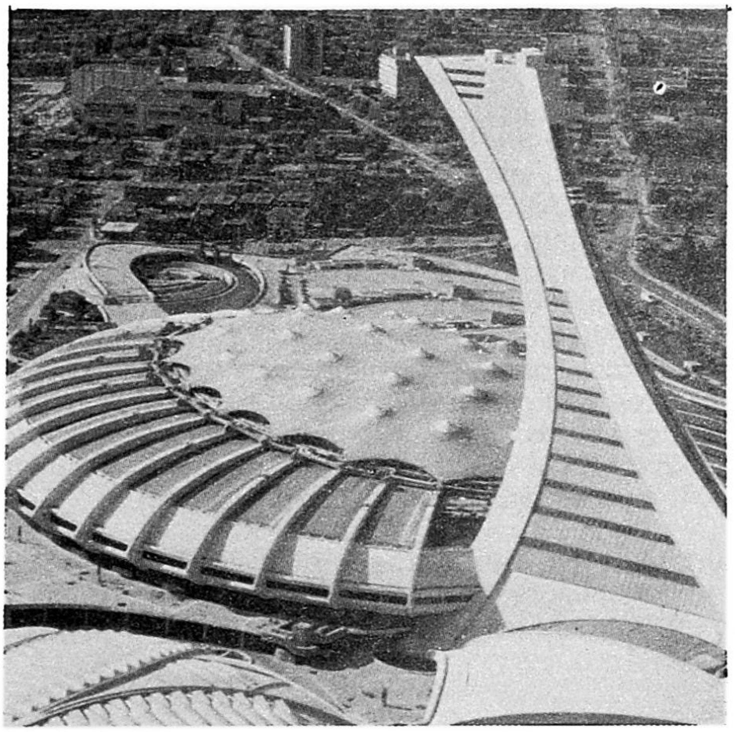


Fig. 7
Olympic Stadium Montreal
Membrane roof area: 20 000 m^2;
suspended from a 170 m high
tower.

Nearly all structures of the third group, erected only for the winter season, are air-inflated membrane domes, most of them covering tennis-courts or other sports facilities. They are simple and quick to be erected and dismantled and very economical because they don't need more than the membrane itself, a simple anchorage and the blowers. Since a failure of such a dome would not cause severe damage, because it only would come down slowly to the ground due to a release of pressure, the dome design normally does not include snow loads; it relies on a melting system by warming up the blown-in air.

2. ROOF FOR THE ARENA IN NIMES

A more elegant and attractive version of these 'winter roofs' has been designed and built recently for the old Roman Arena in Nimes in France. The City wanted to use the central area of the arena, not only open air in summer, but also during winter for operas, rock concerts, different sports events or exhibitions, which required an elliptical roof of nearly 60 x 90 metres free span, covering upto 8,000 visitors.

Of course, the new roof should be extremely light in order not to overload the old structure, and all modifications to the old stone work should be kept to a minimum.

The structure consists of an air-inflated membrane cushion, which is edged by a steel ring. The flexible hollow box-type steel ring is supported by 30 columns, each of them about 10 metres high. Cable bracings at the vertices of the ellipse stabilize the roof structure.

The maximum height of the upper membrane is 8.5 metres, which keeps the roof within the upper level of the outer old stone wall. The rise of the lower membrane of the cushion had to be limited by architectural and functional considerations to 4.2 metres. The resulting nearly doubled level of forces, acting on this slightly curved membrane, necessitated its reinforcement by a cable net.

The upper and the lower membrane are edged by 30 garland cables each. These garland cables transfer the membrane forces at 30 points into the steel ring.

An inclined transparent facade of 480 lamella-type elements of polycarbonate plates with light aluminum webs closes the "winter-hall" along its parameter.

All structural details have been designed with due consideration of the annual erection/dismantling procedure. The steel ring, a welded hollow box beam with outer dimensions of 300 x 500 mm only, made of 25 mm plates, is polygonal and loaded at its 30 kink points by the membrane, but also totally stiffened and stabilized by the membrane cushion. The 30 elements of the ring are coupled by 2 large diameter pins at each joint only. The ring is situated eccentrically to and inside of the columns and its brackets are again fixed to the columns by large pins, which form a hinge to avoid bending in the columns, but which also facilitates the assembly and disassembly of this detail. The membrane cushion or their garland cables respectively, as well as the lower cable net, are also coupled onto these ring nodes. This concentration of connections in single points allows an easier organisation of the workers and also the equipment during the erection process. The tubular columns of 300 mm diameter are mere compression members with their hinges at top and bottom ends. They allow a stress-free deformation of the entire structure under temperature variation.

The membrane cushion consists of 4 different membranes: the upper and the lower one, each of about 4,000 squaremetres, the sealing membrane connecting those two and finally the garland membrane, which spans from the parameter of the cushion to the steel ring, covering the A-shaped openings inbetween.

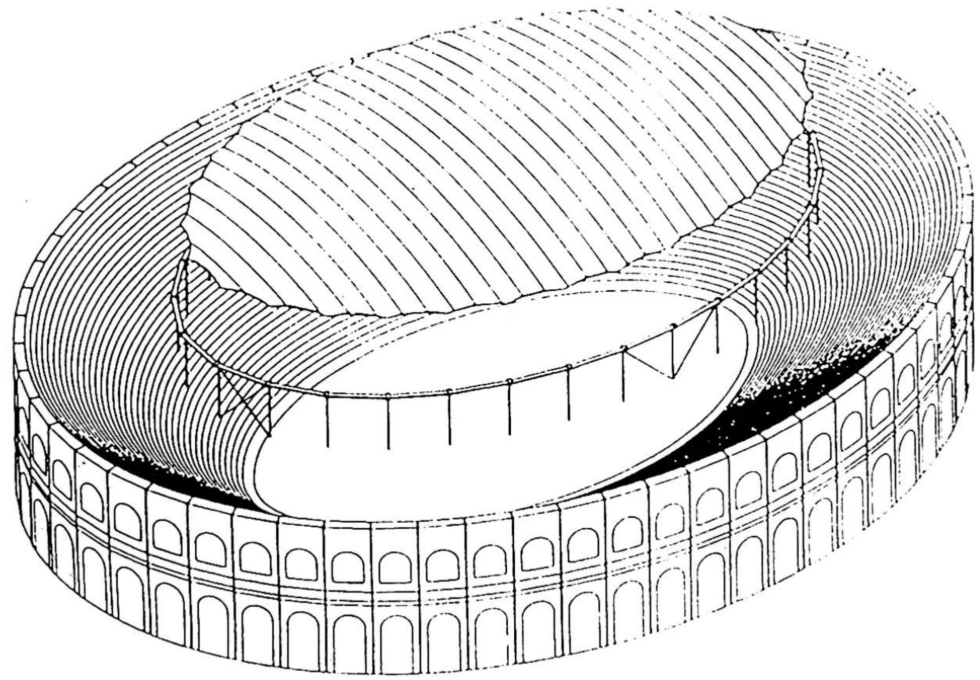


Fig. 8 Arena in Nimes
The main components of the roof structure: The air-inflated cushion with its garland-shaped edge, the steel-ring and the 30 columns with the four bracings at the vertices of the structure.

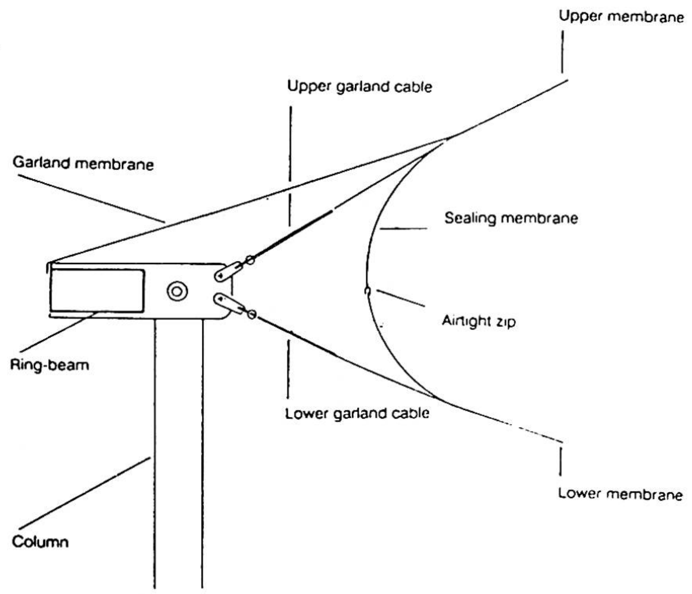


Fig. 9 Arena Nimes
Vertical section at the perimeter of the cushion.

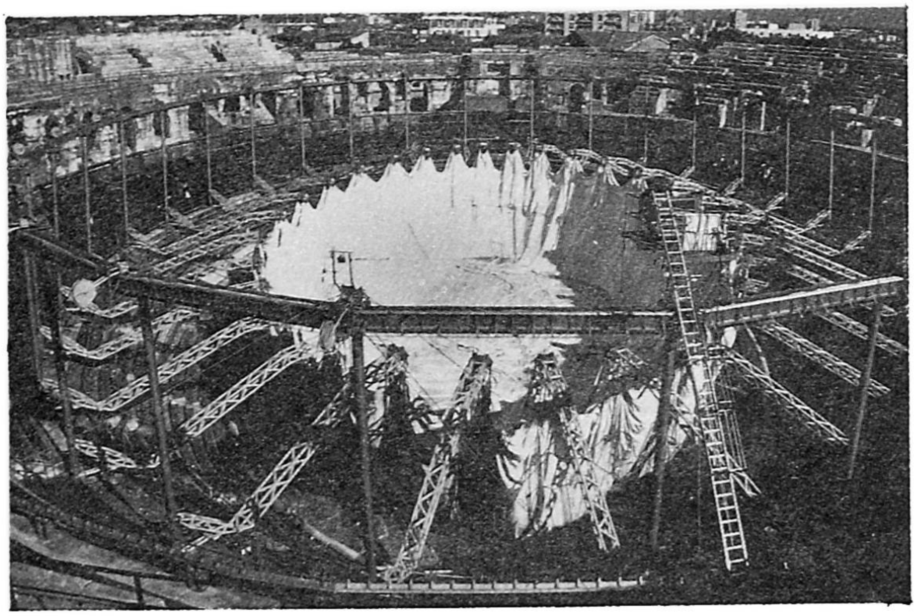


Fig. 10
Arena Nimes
Membrane cushion during lifting by the help of 30 outriggers.

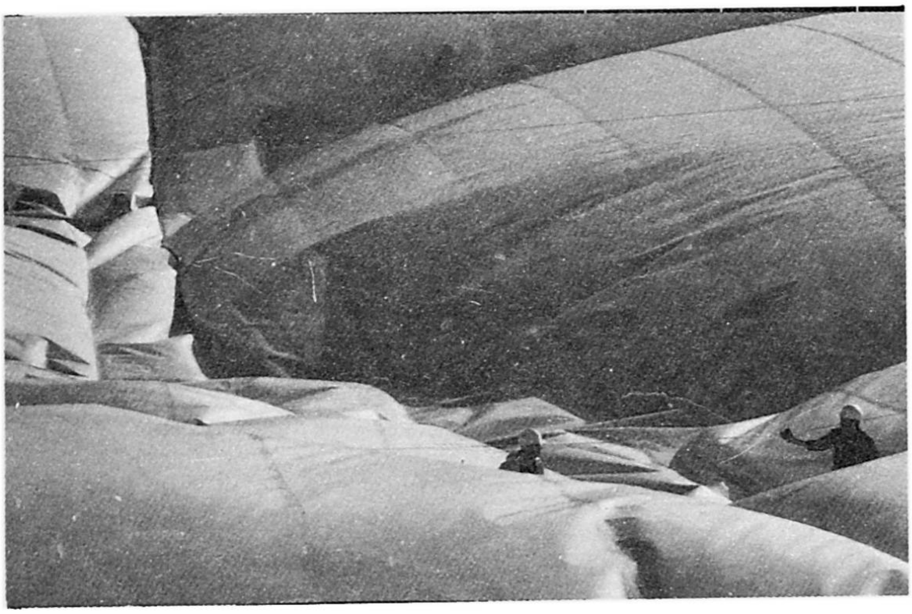


Fig. 11
Arena Nimes
Membrane cushion during inflation lasting only 20 minutes.

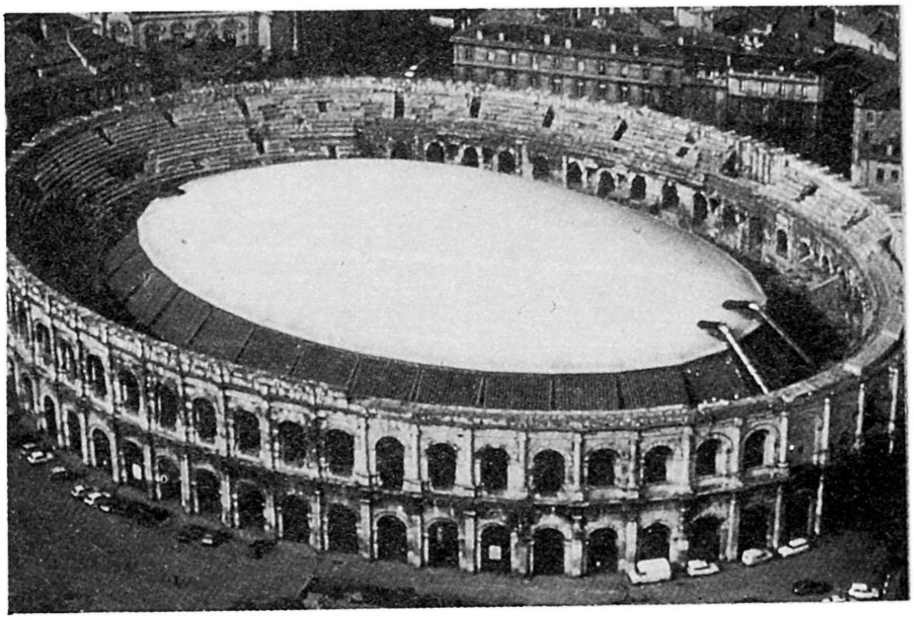


Fig. 12
Arena Nimes
Inflated membrane cushion

All membranes are PVC-coated polyester fabrics. This type of material has been chosen because of its good ability to be folded and stored each year, and because of its high load bearing capacity. Of course, the ultimate strength for the 4 types of membranes vary and go up to a tensile strength of 150/130 kN/m for the warp/weft direction under short-term loading and 23° C. The single 2.5 metre wide strips of each large membrane have been joined by a 80 mm high frequency weld and in addition 4 backstitch sewings. The lower membrane requested a reduced strength only, since it's lying on the cable net and therefore spans an area of 7 x 7 m locally only. The sealing membrane connecting the upper and the lower membrane and thereby completing the air-inflated cushion, can be opened along its equator. This allows separate handling and storage of the 2 large membranes. The 2 parts of the ceiling membrane can be joined by a loop-fastener which is responsible for the transfer of forces and by a zip which ensures proper air-tightness of the cushion. The translucent garland membrane is the only membrane which is not air-supported.

The air pressure within the cushion is provided by 4 blower units which are placed on a platform, 10 metres beside the roof structure. 2 large ducts connect the cushion and the blowers, 2 of which run by electricity, the others are Diesel-powered. Only one of the 4 blowers is sufficient to run the system, the others act as emergency units. The air pressure within the cushion is controlled by a central unit. The nominal internal pressure is 0.4 kN/m^2. If the outside temperature goes below 10° C, defined as the limit for the possibility of snow fall, the pressure will be raised upto 0.55 kN/m^2 automatically. Further manual pressure regulation is possible in case of excessive even higher snow loads.

The annual erection/dismantling which normally is done within a period of 3 weeks, can be split up into the following main steps:

- installation of each second of the 30 columns with the hydraulic lifting units on top already installed;
- lifting of the entire steel ring which had been preassembled on ground. Together with the lifting units on top the columns now act as cranes;
- installation of the remaining 15 columns;
- Placement of the 30 outriggers which are necessary for the lifting of the membrane cushion;
- in the arena: assembly of the cable net, unfolding of the lower and the upper membrane;
- installation of the garland cables;
- the cushion which still lies partially folded in the central area, is attached now to the outriggers;
- lifting up of the entire roof and inflation of the cushion;
- dismantling of the outriggers;
- installation of the facade;
- installation of the heating and the all-electric and scenic equipment.

Out of all these activities the lifting of the complete steel ring, as well as the lifting of the entire roof, are the two most important steps:

The lifting of the ring is done with 0.6 inch strands which are connecting the ring and the hydraulic units at the top of the columns. The hydraulic units are pulling up the ring in small intervals. They all have the same stroke and are all connected to the same pressure pipe system. This guarantees perfect symmetry during the ring lifting.

The lifting of the entire cushion, including the cable net, is the second important and critical phase, because it includes a period where the entire cushion is lifted and floating in the air without being stabilized by its internal pressure. The 4,000 squaremetre membrane acts a large sail if it would be attacked in this situation by heavy wind loads. The lifting procedure therefore is depending from a good weather situation. On the other hand, this lifting, including the attachment of the cushion to the ring and the inflation of the cushion itself, is done within a period of only 5 hours, which is short enough to be safely covered by a weather forecast.

For lifting the membrane cushion, the 30 outriggers, hinged to the column bases, are pulled upwards by the same lifting units at the columns tops by 0.6 inch strands again. While lifting the outriggers turn upwards and thereby take the cushion off the ground into the air. In their final position the top of the outrigger meets the ring node. The cushion then has to be fixed only to the ring. Here again the hydraulic lifting system guarantees a synchronous lifting. This is of utmost importance, because at this time the ring beam is not yet stabilized by the cushion, but already loaded by the erection forces. The lifting itself needs about 2 hours only, with additional 2 hours to attach the cushion to the ring. The inflation of the cushion is done within less than 1 hour.

Since all structural details have been carefully designed for this annual "moving" process and because a special simple, but nevertheless effective equipment had been designed especially for this roof structure in Nimes, a fast and therefore economical and safe erection could be achieved as the experience of the last 3 years proves.

3. ROOF FOR THE ARENA IN ZARAGOZA

The existing old arena had been erected at the end of the 18th century in the centre of Zaragoza itself. Until now the arena had been used only for bull-fights during a few days of the year. Then the owner of the arena, the City of Zaragoza, decided to convert the arena into a multi-functional hall for concerts, music festivals and all other type of sports events. This meant for the new roof:

- since the roof is to rest on the old three-storey structure, it should be as light as possible in order not to overload the old masonry.
- only a roof covering and protecting the whole arena, can guarantee the performance of a concert or other musical event.
- for bull-fights, which also will take place in future in this arena, the interior part should be kept open and only the area of the grandstands could be covered by a roof.

The new roof is circular in plan with an outer diameter of 82.7 metres. The outer ring with a width of 23.35 metres, covering the spectators' area, is a permanent membrane structure, supported by a primary cable system. The inner circular part of 36 metres diameter can be covered by a retractable membrane. This layout fullfils all the above mentioned requirements.

The primary structure for the outer permanent roof consists of an outer steel box compression ring, 800 x 500 mm, filled with concrete, 64 lower radial cables, attached to a lower inner ring cable, 32 upper radial cables, attached to an upper ring cable, and 16 tubular steel columns, securing the distance between the upper and lower ring cable. The membrane itself is placed inbetween the lower radial cables, is anchored to the lower inner ring cable and stressed and fixed to the outer steel ring directly. The cable/steel structure is stable in itself without the membrane and is prestressed to such a level that under maximum downward forces - 0.5 kN/m^2 snow load plus wind pressure - which mainly load the lower cables, the upper cable system doesn't get slack.

The retractable inner membrane roof also needs a primary structure, which is shaped similarly to the outer cable system: 16 upper and 16 lower radial cables, all starting from the inner ring cables, where attached to the 6 m long steel columns, lead to one common central fixed node. Its counterpart, the movable node, is placed below and forms the peak of the "Chinese head"-shaped inner membrane roof. The two node parts are connected by an electrically driven screw jack.

The membrane is suspended from the lower radial cables by sliding carriages at a distance of about 2 metres, so they can move along these cables from the inner "open" position to the stretched "closed" position towards the lower ring cable. When arriving there, the front carriage is guided into its exact final position, where it is locked by a pneumatically moved pin. After the membrane has been docked at all 16 outer anchorage points, the central movable node is lifted by the screw jack by about 70 cm and thus the whole inner membrane roof gets its final prestress. All individual steps of the moving anchoring and stressing procedure are monitored and controlled by one central board and can also be influenced/corrected from here when operated manually. Normally the roof opens or closes simply by pushing a button, that means completely automatically.

The distance between the inner ring cable of the permanent roof and the garland cables of the retractable membrane roof, is closed by a wide translucent rain gutter, made of plexi glass. This gutter is dewatered at 4 points by pumps towards the outer main drainage system.

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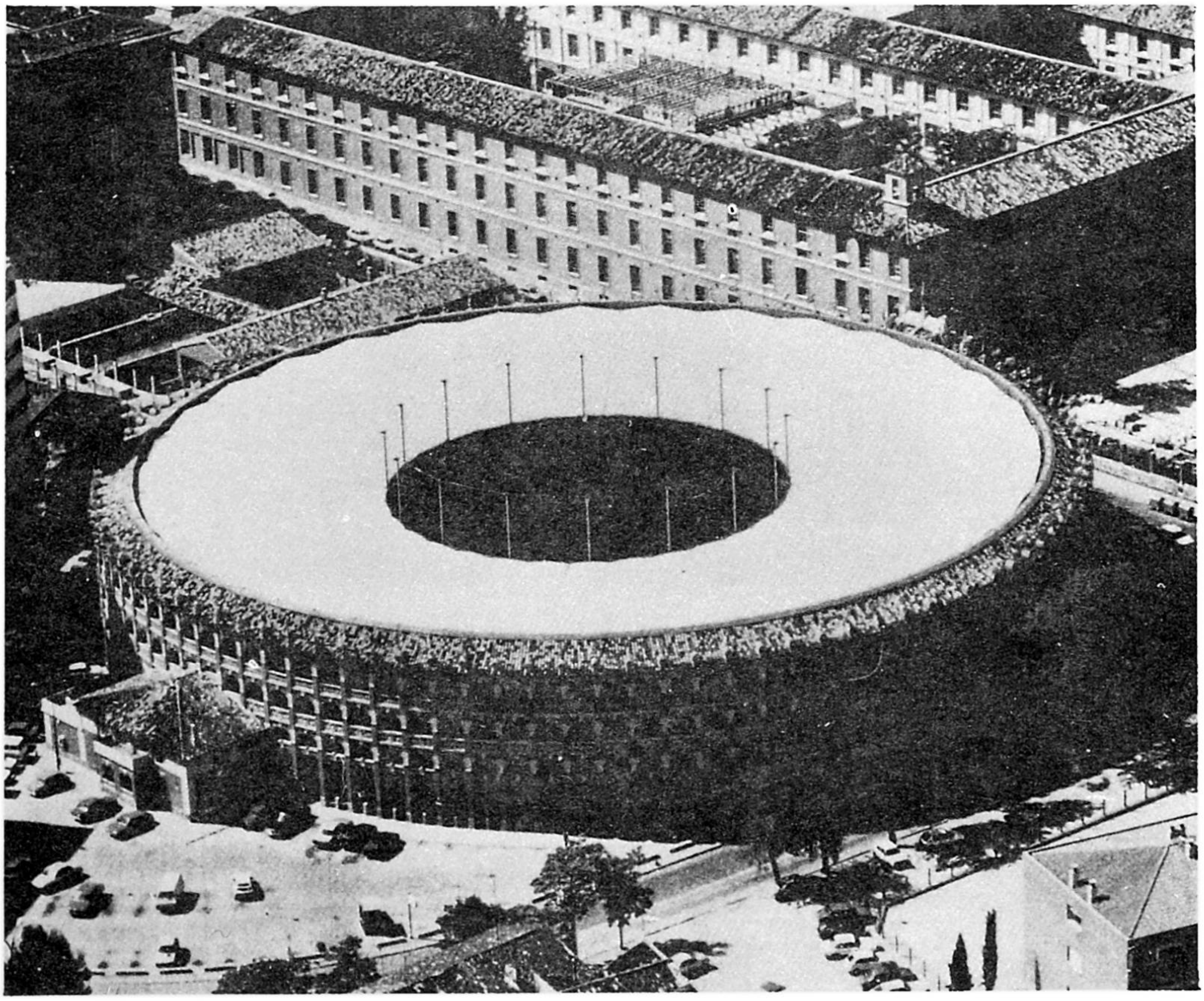

Fig. 13 Arena Zaragoza
Top view of the old arena with the permanent membrane roof.

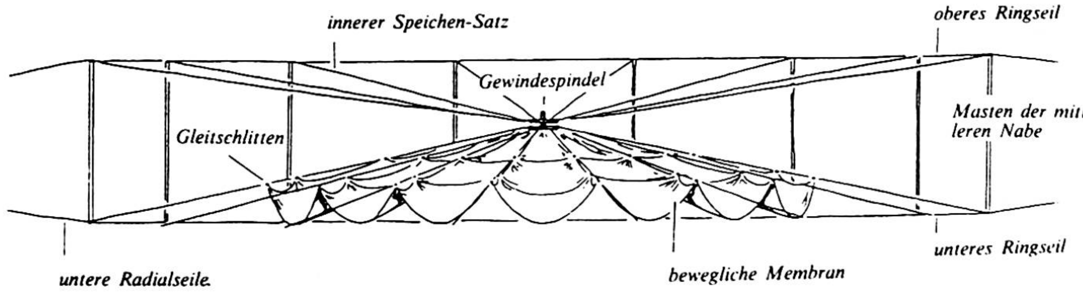

Fig. 14 Arena Zaragoza
Concept of the retractable inner membrane roof.

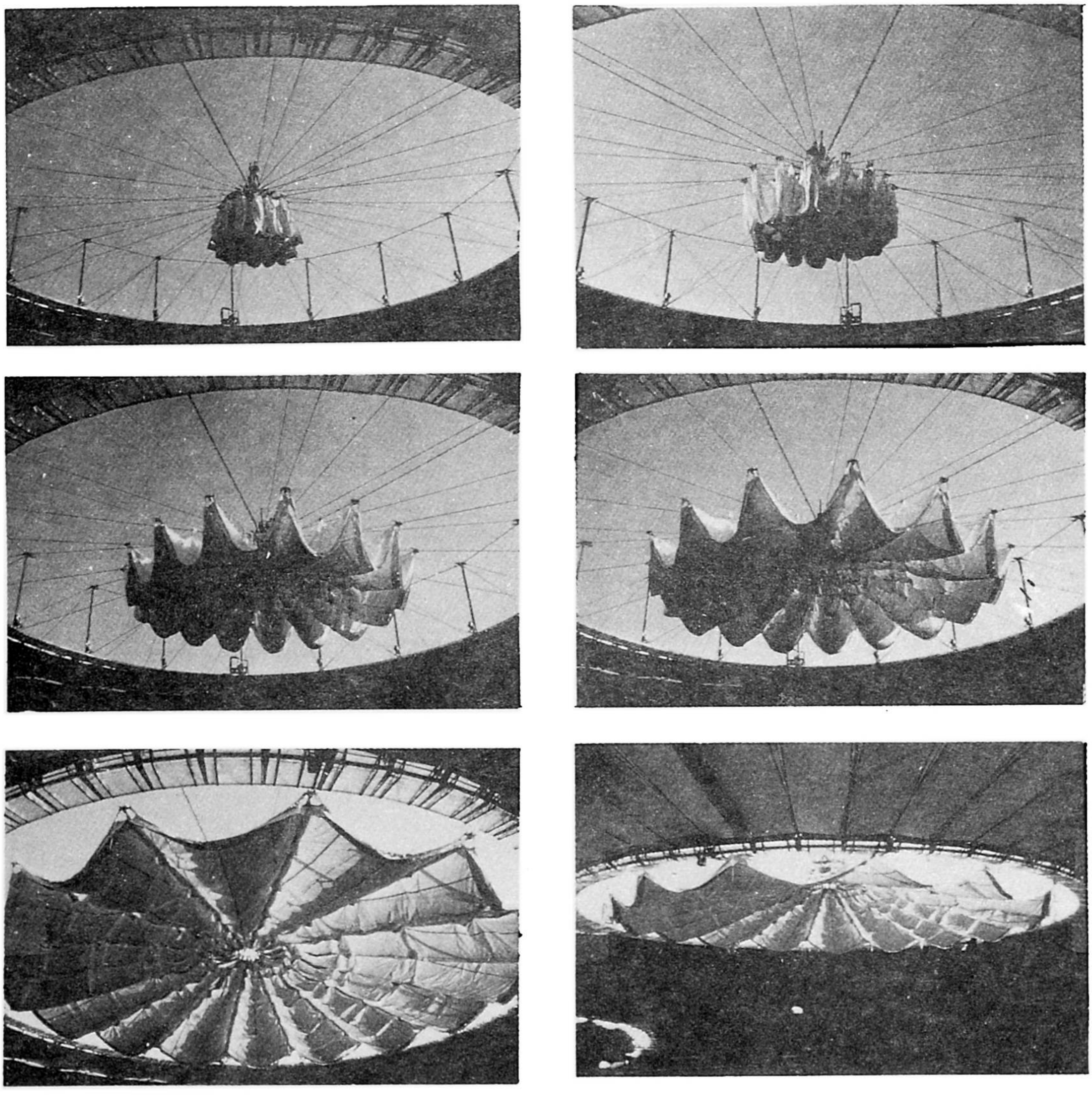

Fig. 15 Arena Zaragoza
Opening/closing procedure of the 1 000 m² inner membrane roof.