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The Construction of Two Prototype Multi-Storey Air-Supported Buildings

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To treat a multi-storey building as a large, inflatable container forces the architect to consider design and construction criteria foreign to the building industry at large. While satisfactory progress has been made in the development of theoretical solutions for problems dealing with the structural and planning implications of a hyperbaric building environment, the time has come to consider practical issues.

This paper discusses the design, construction and operation of two prototype, multi-storey, air-supported buildings. The first building was completed in November, 1972 at the School of Building, University of New South Wales, Australia, and the second building was completed in April, 1973 at the School of Architecture and Environmental Design, California Polytechnic State University, San Luis Obispo, California, United States. In both cases the buildings were treated as student projects and aimed at the development of planning, organisational and constructional skills in the participating undergraduate student.

Introduction

While structural theories and experimental model analyses may establish theoretical feasibility, prototype buildings are required for a meaningful investigation of the practical implications and commercial viability of a new system of construction. Since the conception of the idea of treating a multi-storey building as a large pressurised cylindrical container in 1966, a considerable number of theoretical and empirical studies[3,5] have been undertaken by the principal author to analyse and provide acceptable solutions for the many unorthodox building conditions generated by fluid-supported systems of construction. A number of alternative solutions have been proposed for problems ranging from maintaining a hyperbaric building environment, general safety considerations, heat transfer through the thin plastic building envelope, the selection, installation and maintenance of mechanical plant to the design and operation of water and waste disposal services.[1,2] In each case the appropriate recommendations are based on a logical appraisal of the various factors found to interact in an artificially simulated situation. For example, to establish the requirements for emergency standby pressurisation equipment, predictions were made of the size of punctures likely to occur in the plastic enclosure during the life-span of the building, the approximate rates of air leakage, expected live loads due to occupancy as well as the mechanism and timing of a total collapse sequence.

These theoretical studies were finally extended to allow consideration of different types of fluid-supported structures closely related to the original proposal of a multi-storey air-supported container. In addition, time and cost estimates were prepared for the constructional stages of all of the principal fluid-supported building types. The following seven fluid-supported systems of construction have been considered in some depth by the authors to date.

Single-skin with cables

Building environment is pressurised and contained by an external flexible plastic membrane acting simultaneously as structure and enclosure. For purposes of wind bracing and reinforcement of the plastic skin, a cable network surrounds the membrane enclosure (Fig. 1a). The environmental pressure produces an upward supporting force on the underside of the roof plate from which the building floors are suspended by means of tension hangers or cables. An approximate increase of 1 lb per square inch (psig) ($6{\cdot}9\ \mathrm{kN/m^2}$) pressure above atmospheric pressure is required for each air-supported building floor. Accordingly, a ten-storey building would require an environmental air pressure of around 10 psig ($69\ \mathrm{kN/m^2}$). Access to the single-skin building is gained by means of an airlock entrance located at ground floor level.

Double-skin cellular

Structural support is provided by a continuous multi-cellular external membrane. Floors are suspended from a truss system at roof level which in turn is supported by the pressurised multi-cellular building enclosure (Fig. 1b). Once the cells have been inflated the pressurisation equipment will not be required again unless a leakage develops. Wind bracing may be provided by an external cable network or an internal bracing system. In this type of air- or water-supported building, the required cell pressure

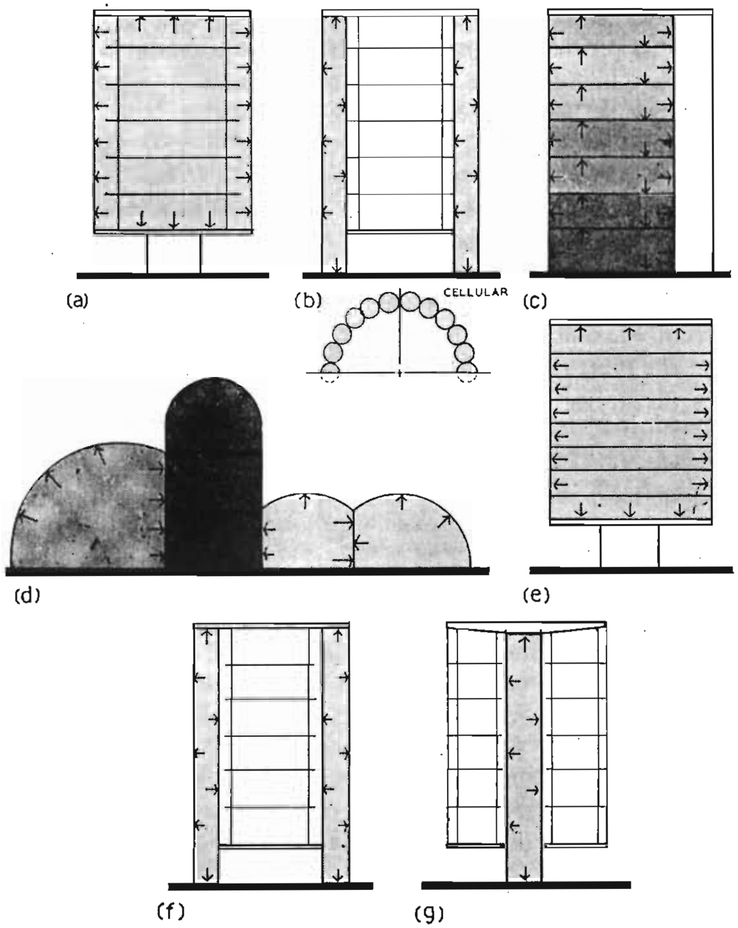

Fig. 1. *Principal fluid-supported building types; (a) single-skin with cables; (b) double-skin cellular; (c) single-skin multi-cellular; (d) multi-cellular multi-enclosure; (e) single-skin rigid membrane; (f) double rigid-flexible cylinders; (g) high pressure central core.*

is dependent on the ratio of floor area to the combined cross-sectional area of the cells. Since the cellular enclosure is pressurised independently of the building environment, higher pressures and, therefore, taller buildings are possible.

While the double-skin system provides superior thermal and sound insulation characteristics, its cellular structure and absence of environmental pressure offer a more readily acceptable margin of safety at the present time.

SINGLE-SKIN MULTI-CELLULAR
Building is divided into a number of separately pressurised compartments joined by airlock entrances (Fig. 1c). If the compartments are stacked vertically on a floor-to-floor basis, the required environmental pressure may be reduced incrementally from ground floor to roof level. While the airlock requirement for each floor may prove expensive, considerable savings will accrue in the construction of the floors themselves. For design purposes, the upward reaction due to pressure acting on the underside of each floor is required to be equal to the sum of the self-weight and superimposed live loads of each floor. Since the floors are literally floating on the supporting air pressure, they will experience maximum loads only when no live loads are acting. Accordingly, the structural stiffness of each floor may be further reduced by providing cable ties between floors in each compartment.

MULTI-CELLULAR MULTI-ENCLOSURE
Buildings consisting of a combination of separately pressurised compartments (multi-cellular) and individually defined but jointly pressurised spaces (multi-enclosure). Extremely versatile air-supported structures which may consist of multi-storey and single-storey sections, both requiring a hyperbaric building environment (Fig. 1d).

SINGLE-SKIN RIGID MEMBRANE
Building environment is pressurised and contained by a rigid metal or plastic membrane envelope acting as a short monocoque cylindrical shell under internal pressure, axial compression (*i.e.*, vertical building loads) and lateral wind loads (Fig. 1e). The required environmental pressure is calculated as a function of the membrane thickness rather than total building loads. In rigid membrane buildings floors may be suspended from trusses at roof level or preferably floors may be attached directly to the membrane envelope, thereby contributing to the overall stiffness and continuity of the air-supported structure.

DOUBLE RIGID-FLEXIBLE CYLINDERS
A building environment at normal atmospheric pressure is surrounded by two concentric cylinders adequately pressurised to support a suspended floor system at roof level (Fig. 1f). The internal rigid cylinder is required to resist horizontal air pressure in compression, while the external flexible membrane container is subjected to tension only. The pressurised annulus may be divided into separate cells or compartments for increased safety.

HIGH PRESSURE CENTRAL CORE
Building structure consists of one or more high pressure liquid columns acting as the supporting element of a hinged beam or truss system at roof level from which a number of annular floors are suspended (Fig. 1g). Columns in the height to diameter ratio range of 4:1 to 8:1 are normally pressurised to around 100 psig (690 kN/m^2). The internal pressure has the function of resisting local buckling in the rigid metal or flexible plastic column wall. Water rather than air is suggested as the pressure medium in view of its incompressibility.

The first prototype building

It is only natural that the single-skin air-supported structure (Fig. 1a) should have been selected to form the basis of the first full-size prototype building. Apart from offering the greatest structural efficiency, it also embodies the most severe architectural, environmental and constructional challenges to the building designer. During January, 1968, plans were first formulated for the construction of a full-size single-skin air-supported building to serve as an experimental structure for investigating the operational requirements of a building environment pressurised for structural support purposes. In the ensuing years every effort was made to generate interest and obtain financial sponsorship from the Australian plastics industry for the construction and testing of a small number of prototype fluid-supported buildings. Despite the obvious promotional and market development value of these early proposals, the plastics industry has been slow to respond. That the construction industry in general should resist the premature adoption of new techniques and materials is conducive to the protection of safety standards and must be considered a desirable restraining influence. At the same time this attitude will continue to force universities and other educational institutions to assume a sizable share of the responsibility for research into innovative systems of construction. It is, therefore, not surprising that the design and construction of what would appear to be the first multi-storey air-supported building should have been tackled by a group of undergraduate construction engineering students.

In April, 1972 the first decisive steps were taken to accomplish the design, construction and in-service operation of a three-storey fully air-supported prototype building as an undergraduate student project in the School of Building, University of New South Wales, Australia. At the outset of the project it was resolved that the building should be designed, documented and constructed by the students as a regular part of their classes in construction, architectural structures, building science, estimating and operational planning. Due to the spontaneous generosity of the New South Wales construction industry, the majority of materials were donated and delivered to the site before the commencement of the construction phase. A petty cash fund of some $300 (Australian) was established by the School of Building for miscellaneous material expenses and equipment hiring charges.

SITE SELECTION

The School of Building Research Laboratory is located in a converted bus maintenance building within walking distance of the campus. For a number of reasons it was decided that the proposed air-supported building should be constructed inside the research laboratory building. First, an existing movable 12-ton electric beam crane could be utilised as a convenient safety device and construction aid. In view of the participation of students and the experimental nature of the structure, much thought was given at the formulation stage of the project to the provision of a standby secondary structural support system. Second, the research area incorporates a well-equipped workshop under the control of a full-time laboratory technician. Tools and expert assistance would be available to the students throughout the construction stage. Third, the research building floor is subdivided into a number of 5-ft (1·5 m) deep maintenance trenches, one of which could conveniently serve as the airlock entrance to the building. A suitable space 25 ft by 25 ft (7·6 × 7·6 m^2) with a maximum usable height (to underside of beam crane) of 21 ft (6·4 m) and a 5-ft (1·5 m) deep, 4-ft (1·2 m) wide maintenance trench running centrally across the floor area was selected.

DESIGN

The dimensions of the building were primarily governed by the height restriction of the site and the strength of available membrane materials. The students insisted that

the building should incorporate at least two (2) fully air-supported floors suspended from roof level. To save on height, the floor-to-floor spacing was reduced to a minimum dimension of 7 ft (2·1 m) for the two suspended floors while the spacing between the ground and first floors was limited to 1 ft 6 in (0·45 m). It was argued that from a structural point of view the building would demonstrate the ability of the internal air pressure to support at least two floors of a multi-storey structure while leaving the ground floor with insufficient head room to function as a usable building space. This sacrifice was considered to be small in relation to the general structural concept of the building. To conserve further building height, the airlock entrance was sunk into the existing maintenance trench. As shown in Fig. 2, the overall height of the building from the bottom of the trench (airlock floor) to the top of the roof became 24 ft 0¼ in (7·321 m).

Since the stresses in the membrane enclosure of a single-skin air-supported building are directly related to the diameter, the horizontal dimensions of the proposed building were primarily governed by the strength characteristics of available plastic membrane materials. It was considered desirable for the membrane enclosure to be transparent thereby permitting a clear view into and out of the building. At the same time, it was necessary for the material to be relatively inexpensive, readily available and amenable to heat sealing jointing methods. A glass-clear 20 mil PVC film was finally selected partly because of its low cost and good transparency and partly due to the offer of a private company to fabricate the main building and airlock membranes free of charge. Tests conducted on the PVC material yielded the following results:

ultimate stress at approximately
400 % elongation = 36·5 lb/in (6·39 kN/m)
working stress at approximately
20 % elongation = 11·5 lb/in (2·01 kN/m)

Since these test results indicated that even under moderate tensile stress the membrane would experience substantial elongation, it was resolved to incorporate a number of horizontal cables in the exterior cable network. In this manner, the circumferential expansion of the envelope could be controlled at the environmental pressure required to maintain stability of the building structure.

The airlock was designed simply as a 4-ft (1·2 m) diameter cylinder featuring a built-in timber floor and a 7-ft (2·1 m) long vertical zip to serve as a convenient entrance and exit system.

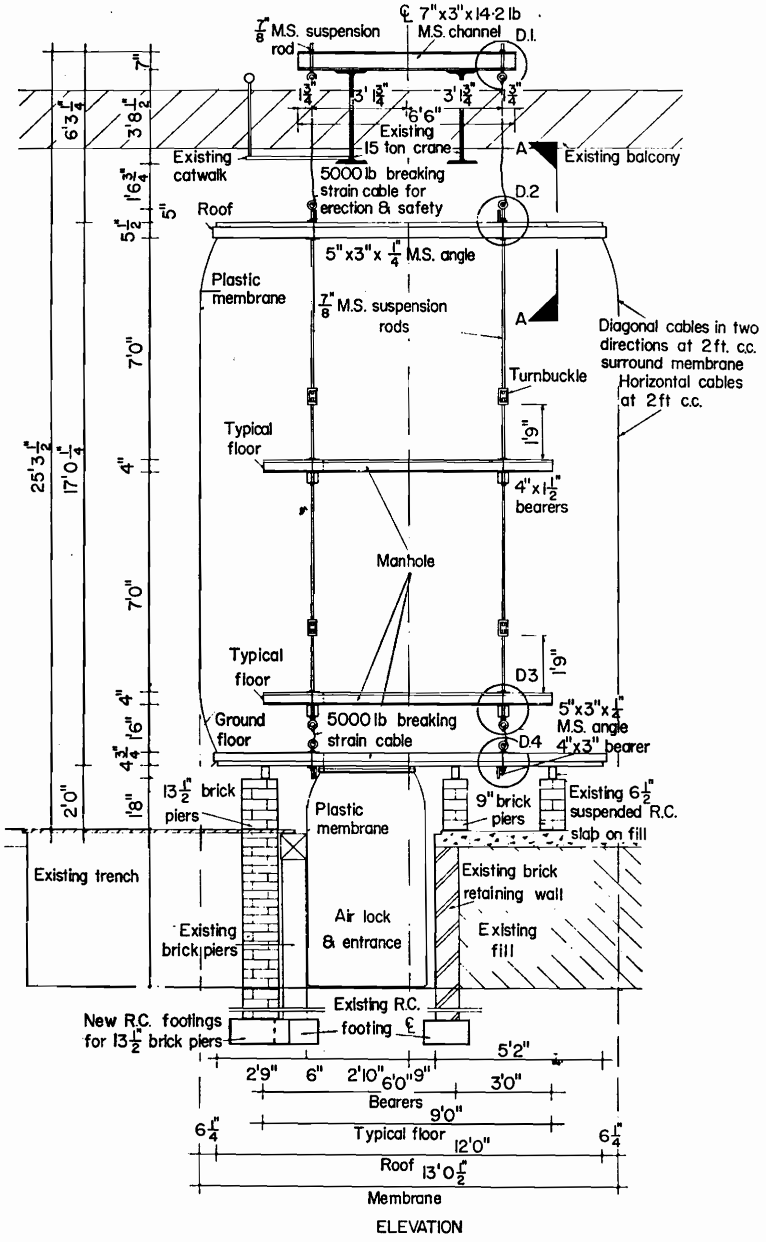

Fig. 2. Elevation of first prototype building.

Early, during the design stage of the project one of the students volunteered to investigate pressurisation requirements and implications on the design and construction of the building. Two alternative approaches for controlling the environment of the main building and the airlock were investigated. The two chambers could be pressurised separately or jointly. In view of the large difference in volume (25 to 1) between the main chamber 2,260 cu ft (64 m^3) and the airlock chamber 88 cu ft (2·5 m^3) and the simplicity of providing a connecting adjustable valve between the two chambers, it was resolved to pressurise the airlock by leaking air from the main building. Since the building would normally be operating at an environmental pressure greater than the minimum pressure required for structural purposes, it was felt that the sudden reduction in pressure experienced by the main chamber during the inflation of the airlock entrance would be negligible. A number of additional design factors related to the air-supported nature of the building structure were isolated:

(*a*) In view of the difficulty of eliminating all air leakages in the main building chamber, the pressurisation unit would need to operate at all times but at different rates. For example, during the inflation of the airlock the demand for air supply would be much greater than at other times. The following performance parameters were established for the selection of the pressurisation equipment:

(1) A pressure range of between 8 and 14 in water gauge (0·3 to 0·5 psig or 2·1–3·5 kN/m^2) would be required for the operation of the building. (The final design pressure, being dependent on the weight of the building, could not be calculated before the completion of most of the construction details pertaining to the floors, roof and suspension system.)

(2) The pressurisation equipment would be required to operate at variable speeds to allow for an air leakage rate of between 10 and 50 cu ft (0·28–1·42 m^3) per minute. (In the case of an electric D.C. motor, variations in speed could be achieved by means of a manually operated rheostat.)

(3) The pressurisation equipment would need to be capable of continuous operation over periods of at least 6 to 8 h. (It was assumed that in between

demonstrations and tests the building would be deflated and remain suspended by the safety cables attached to the overhead beam crane.)

Considerable difficulties were experienced later during the search for a suitable pressurisation unit. While it was generally agreed that a roots blower by virtue of its efficient operation over the required pressure range would provide the most economical solution, no such unit could be found in time in the Sydney metropolitan area. Eventually a discarded axial fan-blower (Spencer Turbine Co.) driven by a 3/4 horsepower (Black & Decker) continuous duty electric D.C. motor was discovered in the Aeronautical Engineering School and generously donated to our cause. Although limited to a maximum air volume capacity of around 20 cu ft per minute (0·56 m^3/min) at a static pressure of 10 in water gauge (WG) 2·5 kN/m^2, this unit performed well during the early operation of the building. It was finally relegated to a standby capacity after a larger axial fan unit had been obtained.

(*b*) The opening between the airlock entrance and the main building would need to be designed in a manner which would not allow the trap door to be opened before pressure equalisation between the two chambers had been completed. Existing design of pressure chamber doors would need to be studied and incorporated in the final construction details.

(*c*) Separate means of measuring the pressure in the main building chamber and the airlock would have to be provided.

(*d*) During the development of construction details, care would have to be taken to ensure the elimination of air leakage through the construction joints of the roof and ground floor and the point of attachment of the exterior building membrane.

(*e*) For safety reasons, a pressure release valve should be provided in the main chamber (possibly at roof level) to avoid rupture of the membrane due to over-pressurisation.

While the natural shape of a single-skin air-supported building is cylindrical, the apparent need for a circular roof and floor was viewed with some concern. The only readily available material suitable for the construction of the roof and floor was sawn (standard structural grade) timber and pressed coreboard. The requirement of circular floors would have resulted in considerable material wastage and fabrication problems. As a compromise solution, an octagonal shape was adopted on the assumption that this would have a minimal effect on the final cylindrical shape of the membrane enclosure.

CONSTRUCTION DETAILS

Having finalised the overall dimensions of the building, attention was focused on the construction stage and in particular the development of suitable construction details for the floors, roof, footings, main membrane and airlock attachments, suspension hangers and the pressure control system.

It became immediately apparent that the two suspended floors, roof and ground floor provided an excellent opportunity for prefabrication. Apart from savings in construction time, the adoption of a systematic fabrication method would broaden the proposed educational experience for the participating students. To prevent abrasion between the suspended floors and the exterior building membrane and at the same time simulate as closely as possible a real-life building situation, the size of the intermediate floors was reduced to 9 ft by 9 ft (2·7 × 2·7 m) leaving a clear space between the perimeter of each floor and the plastic membrane. (A similar air space has been proposed in commercial applications of single-skin multi-storey air-supported buildings for purposes of fire protection[1] and general protection of the building enclosure.) As shown in Fig. 3, each suspended floor consisted of seven 3-in by $1\frac{1}{2}$-in (76 × 38 mm) joists sandwiched between 13/16-in (20·6 mm) structural grade particle board and $\frac{1}{4}$-in (6·4 mm) low density composite board. The floors were to be supported by two sets of double bearers (4 in by $1\frac{1}{2}$ in or 102 × 38 mm) at 6-ft (1·8 m) spacing, while each set of bearers was planned to be suspended from roof level by two suspension rods at 6-ft (1·8 m) centres. The roof and ground floor presented an unusual structural problem. Apart from the action of much higher loads, it was necessary to consider two distinct loading situations. Under maximum internal pressure (the building was designed to sustain a maximum environmental pressure of 28 in WG (*i.e.*, 1 psig—6·9 kN/m^2)), the roof plate would be subjected to a uniformly distributed upward force of 144 lb per sq ft (psf) (6·9 kN/m^2) to be resisted by the four suspension cables at 6-ft (1·8 m) centres as well as the membrane (and cables)

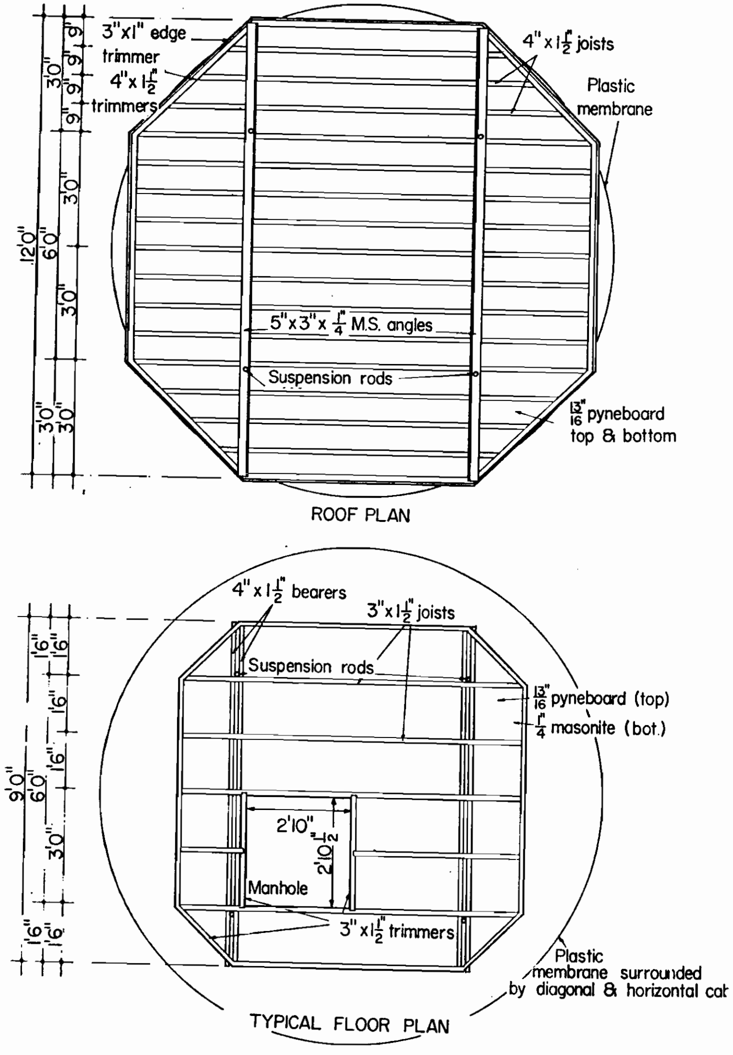

Fig. 3. *Typical structural floor plan (first prototype building).*

attached around the perimeter. During the construction stage and at other times when the building might be deflated, the roof would be required to support up to 10 persons while suspended from the overhead beam crane (Fig. 4). It was necessary to increase the size of the joists to 4 in by 1½ in (102 × 38 mm) and reduce the spacing to 9 in (229 mm) as well as provide 13/16-in (20·6 mm) structural grade particle board top and bottom. In addition, 5 in by 3 in by ¼ in (127 × 38 × 6·4 mm) mild steel angles were required to serve as bearers to resist the very large loads due to pressurisation. To minimise air leakage

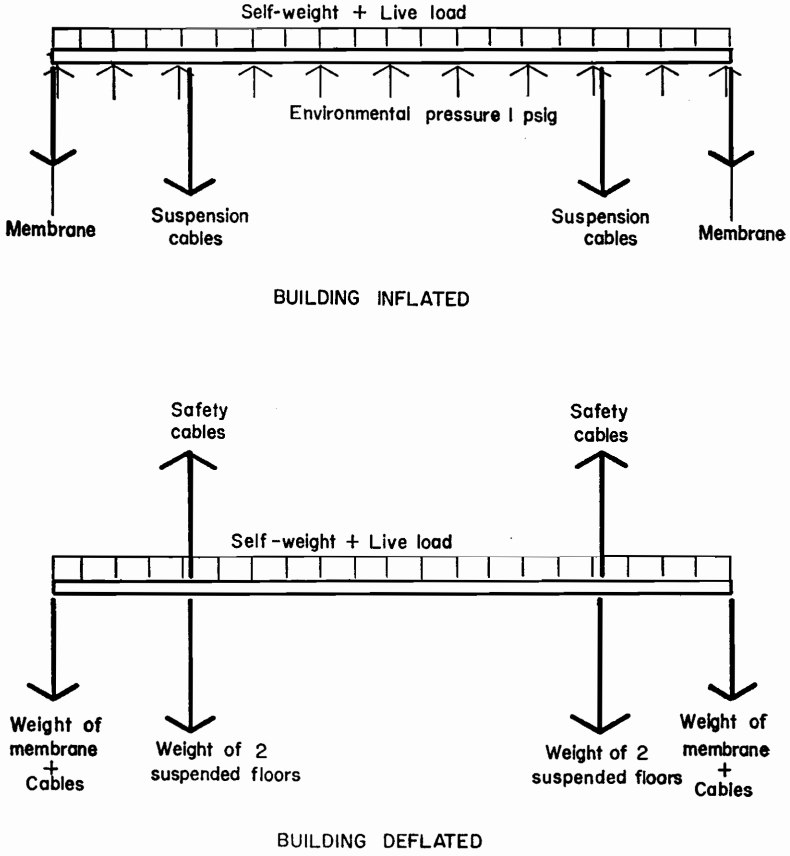

Fig. 4. *Loading conditions of the roof plate (first prototype building).*

through construction joints and nail holes, it was resolved to place a thin 10 (mil) polyethylene membrane between the joists and the upper and lower particle board sheets of the roof and ground floor respectively.

It was proposed that the two intermediate floors be suspended from roof level by cables fixed at each level to $\frac{7}{8}$-in (22 mm) diameter mild steel round rods bolted to roof and floor plates. Adjustments in floor levels could be made by the manual operation of turnbuckles located at a convenient height above each floor surface.

Considerable time was devoted to the development of a suitable construction detail for fixing the plastic membrane enclosure to the roof and ground floor perimeters. After evaluating a number of alternative proposals, it was decided to cut a 'V'-shaped groove into the perimeter fascia board as shown in Fig. 5; nail a $\frac{3}{16}$-in (4·8 mm) diameter fully insulated electric cord into the acute angle of the 'V' to provide a suitable seating for the membrane; drape the membrane over the floor (or roof) and tie a $\frac{5}{16}$-in (7·9 mm) diameter nylon cord around the perimeter to force the membrane into the 'V' groove. Next, the free end of the membrane would be returned over the nylon cord to form a loop and strapped into position by means of a continuous $\frac{1}{2}$-in (12·7 mm) steel packaging strip. Finally, it was proposed to fix a 3-in by 1-in (76 × 25·4 mm) trimmer over the membrane loop around the perimeter. The trimmer was to be screwed down at 9-in (229 mm) centres and since the nylon rope with the membrane looped around it was designed to protrude approximately $\frac{1}{8}$ in (3·2 mm) beyond the 'V'-shaped recess, it would be possible to apply considerable tension to the membrane loop. As an additional advantage, the trimmer could be retightened at regular intervals during the life span of the building.

It was proposed that the manhole entrance located in the ground floor between the airlock and the main building chamber be provided with a rebated timber trap door complete with rubber lining strips for sealing purposes. By virtue of the air pressure acting downward, it would, therefore, be almost impossible for the trap door to be opened from either side whenever the pressure in the main chamber exceeded the pressure in the airlock chamber. For purposes of equalising the pressure in these two chambers during entry and exit operations, a special valve was designed (Fig. 6) to be located in the trap door. The valve consisted of a 2-in (50·8 mm) diameter steel pipe capped at one end and provided with a number of 1-in (25·6 mm) diameter holes in a band

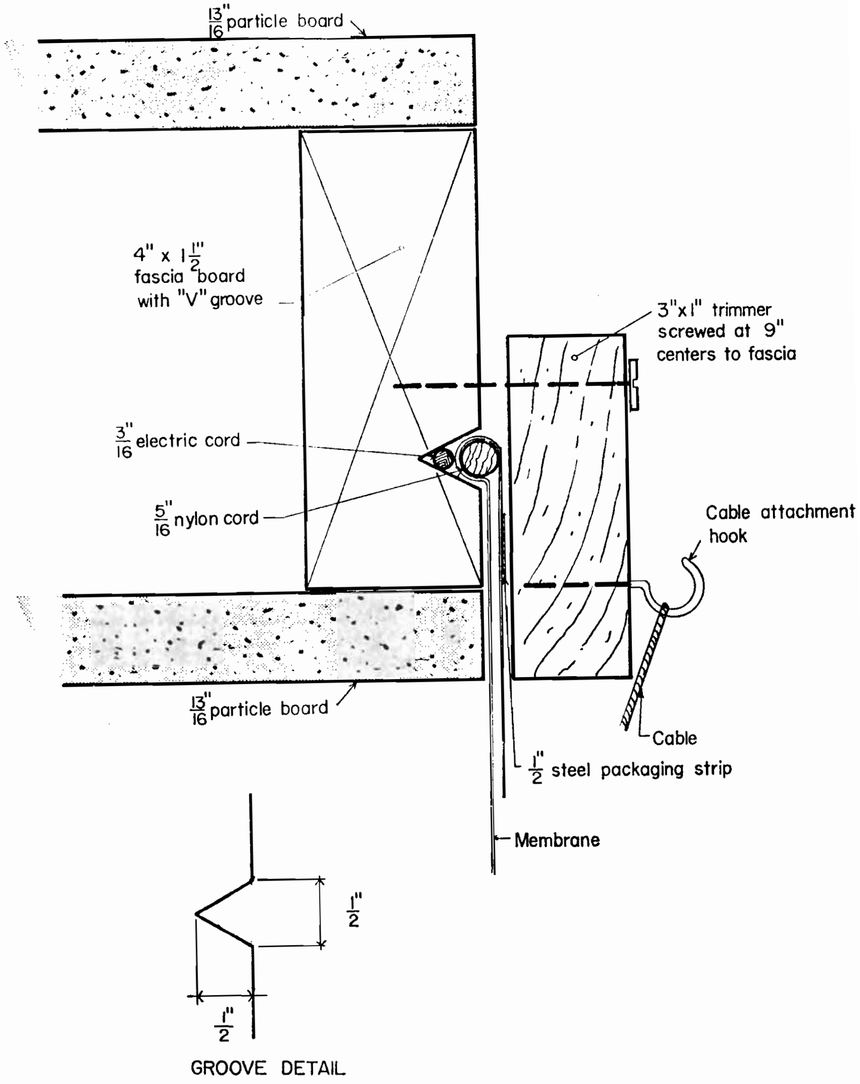

Fig. 5. *Membrane attachment detail (first prototype building).*

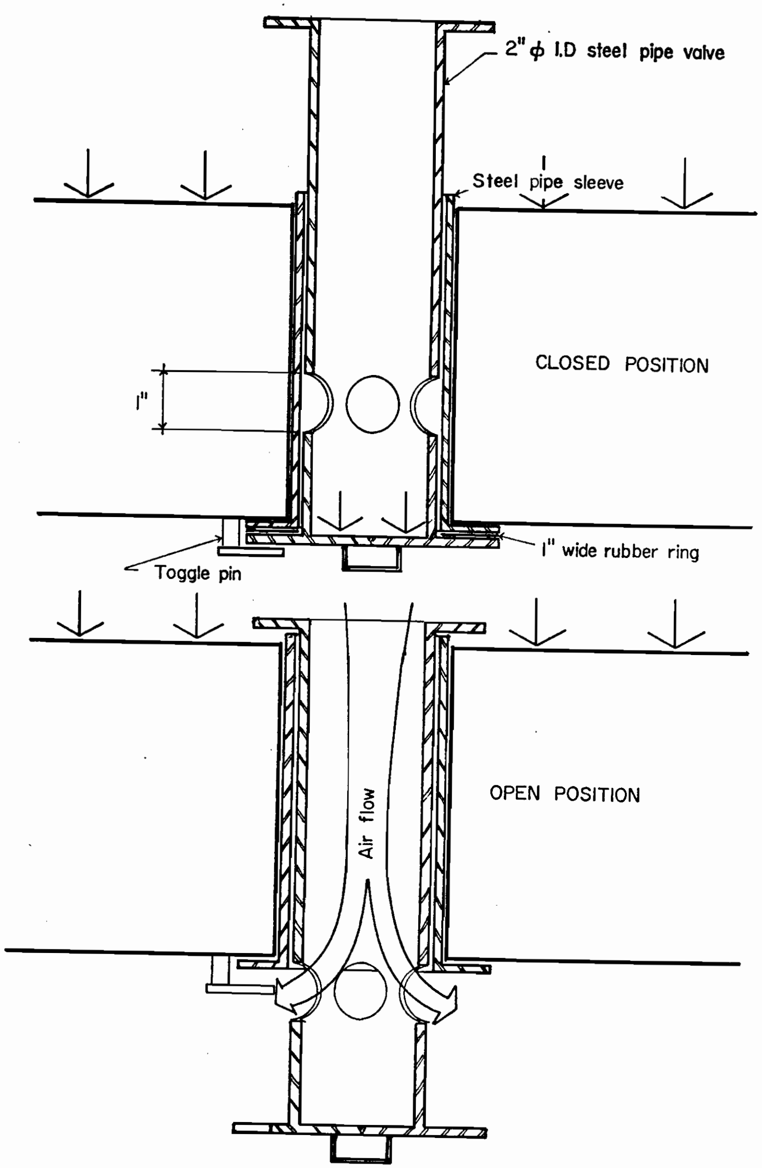

Fig. 6. *Airlock pressure equalisation valve detail (first prototype building).*

close to the sealed end. By moving the pipe a few inches up or down, the valve could be closed or opened as required. In case of excess pressure a weighted safety valve was allowed for at roof level, while two simple 'U'-tube manometers would suffice to monitor the pressures in the main building and airlock entrance.

CONSTRUCTION PLANNING

Considerable efforts were made to plan in advance the sequence of operations to be followed during the construction stage of the building. Detailed time and cost estimates were prepared by the students in their regular classes (Table 1). Allowances were made for the relative inexperience of the work force, although most of the students could count on six months or more of intermittent site experience. While time estimates of construction operations prepared by the students were often considered to be somewhat optimistic by more experienced staff advisers, it must be admitted in retrospect that most student estimates were very close to the mark. There is no doubt that the students benefited greatly from the detailed analysis of the construction project required for the development of accurate estimates and a meaningful precedence diagram.

As shown in Fig. 7, it was agreed that the construction phase should begin concurrently with the fabrication and assembly of the lifting gear and the construction of the substructure. This was to be followed by the prefabrication of the roof and floors ready for the commencement of the erection phase. Three alternative erection procedures were considered in detail.

(1) To simulate the erection sequence proposed for the construction of a typical ten-storey commercial building by the principal author in a previous publication.[1] This would have required the roof to be raised by internal pressure with a mobile crane functioning solely as a lateral stabiliser. With the roof in place, the external cable network could be fixed in position, the internal pressure raised and the floors hoisted up internally by using cables.

(2) To manually hoist up roof and floors from the overhead beam crane using chain blocks. With the membrane fixed in position around the perimeter of the roof before the commencement of the hoisting operation, it would only remain to fix the membrane to the ground floor after the completion of the hoisting operation.

(3) To hire a mobile crane and

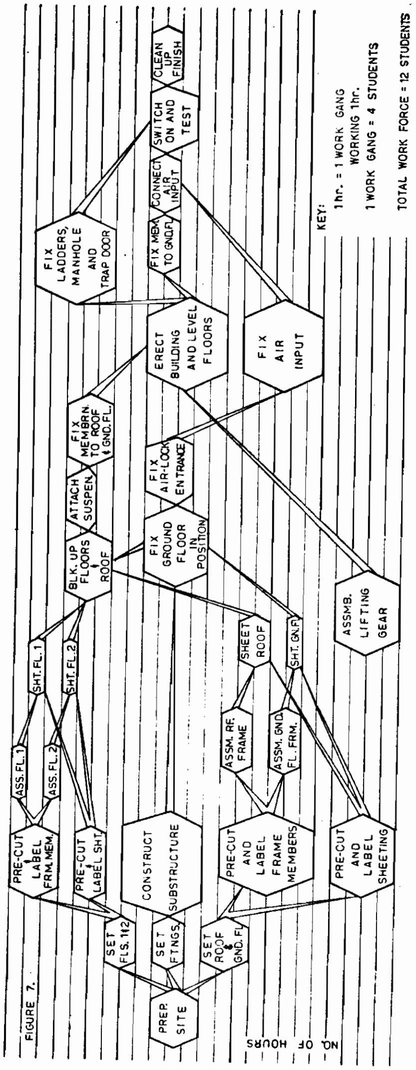

Fig. 7. *Precedence diagram describing construction sequence of first prototype building.*

hoist roof with intermediate floors attached into position in one lifting operation. Subsequently it would be necessary to use a movable scaffold platform to fix the membrane into position at roof level.

The final decision, made during a staff–student site conference one day before the erection operation was scheduled to take place, was to use alternative (3). Paramount importance was placed on safety considerations and lack of confidence in the ability of the membrane envelope to sustain (without cable reinforcement) the initial pressure required to lift the roof plate. In view of the structural rigidity required, the weight of the roof plate rose to approximately 1,420 lb (644 kg) compared with 560 lb (254 kg) for each of the suspended floors. Allowing for the weight of the membrane and suspension system, an initial pressure of around 4-in WG (1·0 kN/m^2) (producing a material stress of 10 lb per inch (1·8 kN/m^2)) would have been required to lift the roof under air pressure (alternative (1)). The adoption of alternative (3) was accompanied by one major disadvantage. A mobile scaffold supporting a working platform 18 ft (5·5 m) above ground floor level would be required for the attachment of the plastic membrane and the network to the suspended roof plate. In fact, later during the construction phase the erection of the scaffold tower was accomplished in less than two hours by four students.

THE CONSTRUCTION PHASE

Prior to the commencement of the construction phase the students were divided into work gangs and a foreman was elected. The seven construction days (Table (1)) which were estimated to be required for the completion of the project were spread over seven weeks with site work to proceed on every Tuesday morning. This allowed ample time for the solution of unforeseen problems and the rescheduling of activities, the delivery of additional materials and the collection of tools. It soon became apparent that the staggered arrangement of the construction days had a profound influence on the educational benefit enjoyed by the students. Between workdays all of the students were involved in at times heated discussions dealing with the organisational and practical aspects of the construction phase.

The various construction stages shown in Fig. 8 proceeded on schedule up to and including the attachment of the membrane. The particle and composite board surfaces of the roof and floors were first glued and then nailed to the joists. Finally the intermediate floors and roof were stacked on the

Table 1 *Preliminary cost estimate of first prototype building*

Activity		*Duration (Man-Hours)*	*Cost (Aus. $)*	
No.	*Description*		*Labour*	*Material*
		hours	$	$
A1	Assemble and fix steel footings	6	25.60	40.71
A2	Set out and pour concrete footings	8	20.96	18.60
A3	Build brick piers	4	11.08	6.46
A4	Construct ground floor	17	48.80	125.01
A5	Construct intermediate floors	20	56.00	127.92
A6	Construct roof	17	48.80	113.52
A7	Assemble and fix suspension system	16	62.40	228.02
A8	Attach membrane	8	22.40	283.00
A9	Inflate structure, hoist and fix into position	24	64.32	—
A10	Attach airlock membrane	2	5.60	55.68
	Total	122	365.96	998.92
		(*i.e.*, 7 days)	(*i.e.*, $1,364.88)	

Hypothetical labour costs based on:
Subcontractor = $5.00 per hour
Carpenter = $2.80 per hour
Labourer = $2.44 per hour
Bricklayer = $2.77 per hour
Total duration in days based on:
Effective working day = 3·5 hours
Effective work force = 5 students

ground floor with 2-ft (0·61 m) high blocks in between to enable the suspension attachments to be fitted. The entire hoisting operation was accomplished in 1½ hours using a hired 4-ton mobile crane. With the roof and intermediate floors safely suspended from the overhead beam crane the plastic enclosure was lifted up by ropes attached at four points near the upper edge of the membrane and tied with a $\frac{5}{16}$-in (7·9 mm) diameter nylon cord as planned. To enable the perfect

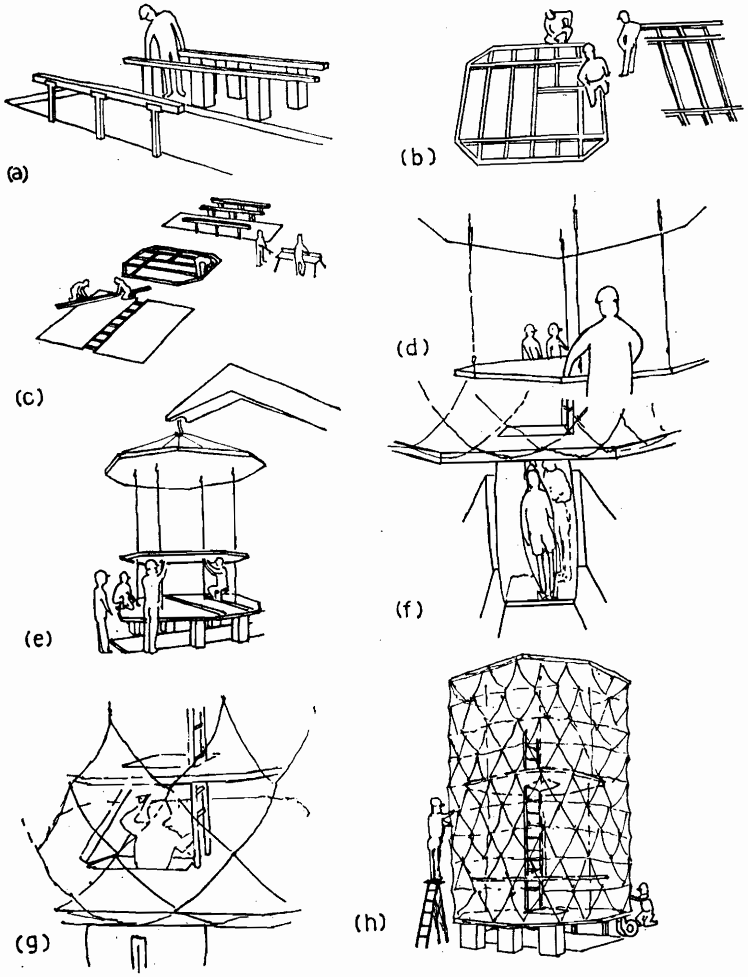

Fig. 8. Main construction stages (first prototype building).

positioning (levelling) of the membrane, a line had been drawn around the circumference at both ends indicating the positions of the lower edge of the roof and the upper edge of the ground floor respectively.

Unfortunately, no donation was obtained for the exterior cable network material. Every effort was made to purchase a plastic coated steel cable, which would prevent abrasion between itself and the membrane. It was absolutely necessary to use a metal cable with a much higher modulus of elasticity than the PVC membrane to achieve the required stress transfer from the membrane to the cable network. (As shown in Fig. 9, it is essential that the membrane bulges out between the cables thereby reducing the radius of curvature and stress in the membrane.) No cable material to this specification could be located in the Sydney area at a cost compatible with the budget available for the building project. There was no choice but to separately purchase steel cable and plastic tubing to be threaded on site. It required close to 20 manhours to cover the required 1,200 ft (370 m) of cable with the plastic tubing. Not only was this task very tedious and frustrating, but it was unforeseen and added 1½ workdays to the construction schedule.

Initial pressurisation of the main building chamber clearly demonstrated the need for horizontal cables in addition to the diagonal cable network. Without horizontal cables the PVC membrane expanded in diameter in direct proportion to increases in internal pressure until the ground floor started to lift off the footings. Horizontal cables were immediately added at 4-ft (1·2 m) centres between roof and ground floor, but to no avail. The spacing was too great, allowing the membrane to bulge out between the horizontal cable rings to such a degree that the ground floor again lifted off the footings. To add to the problem one of the horizontal cables broke during a trial pressurisation run. Fortunately, the fast reflexes of the fan operator and the sudden increase in volume of the main chamber saved the membrane from rupture. Following this near disaster the spacing of the horizontal cables was reduced to 2 ft (0·61 m) and the splices of the existing and new cables were carefully checked. Finally, on the ninth construction day, to the great delight of all concerned, the roof with the two suspended floors attached became air-supported for the first time (Fig. 9). As expected, the safety cables linking the roof to the overhead beam crane slackened as the roof rose by some 2 in (50·8 mm) under the upward force of the environmental pressure.

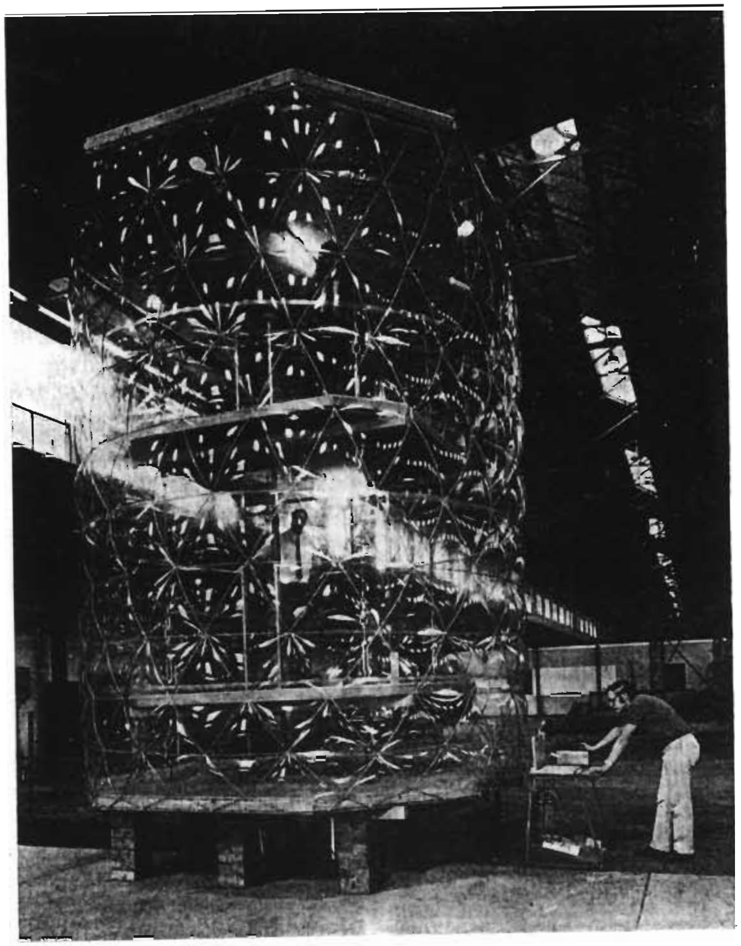

Fig. 9. The completed first prototype building.

(This upward movement had been allowed for in the adjustment of the suspension system between the lower intermediate floor and the ground floor.)

PERFORMANCE AND TESTS

During the following four weeks some 200 persons enjoyed the experience of walking on air. The following simple procedure was prescribed for entering or departing from the building:

> *TO ENTER—'Open the vertical zip of the airlock cylinder and step into the airlock; close the zip; open the pressure equalisation valve by rotating and pulling down; wait for pressure in airlock to equalise with pressure in main chamber (approx. 2 min); open trap door and ascend ladder into main chamber; close trap door and pull up equalisation valve.
>
> *TO DEPART—'Open the equalisation valve by rotating and pushing down; wait for the pressures in the airlock and main chamber to equalise; open the trap door and descend the ladder into the airlock; close the trap door and push up equalisation valve; open airlock zip and step out; close zip.'

It was noted that during the pressurisation of the airlock chamber the pressure in the main building fell quickly by 2 to 2½ in (0·5–0·6 kN/m^2) WG. During normal operation the building was maintained at a minimum environmental pressure of 12-in WG (3·06 kN/m^2) providing an upward force of approximately 6,400 lb (28 000 N) at roof level. Allowing for five occupants (180 lb (82 kg) each) and a loss in pressure of 3-in WG (0·7 kN/m^2) during entering, a safety margin of 2-in WG (0·5 kN/m^2) pressure or 1,000 lb (4,500 N) upward force remained to ensure the stability of the building at all times.

After the completion of the student project there remained the question whether or not it would have been possible to erect the building by first raising the roof plate under pressure and then hoisting up the suspended floors internally one by one, a most important consideration for the potential commercial application of the single-skin multi-storey air-supported building structure. Accordingly, early in 1973 another group of students under the guidance of three students from the former construction team undertook to test the feasibility of the proposed erection procedure. Masonry blocks were positioned in various locations on the ground floor to enable the first suspended floor to be lowered without damaging the attached turnbuckles. Similar masonry blocks were positioned on the first and

second suspended floors. All cable intersections of the exterior cable network were laced to ensure the correct positioning of the cables during deflation and subsequent inflation of the main building chamber. Four guy ropes were attached to the roof plate to enable the building to be held in a fairly vertical position during deflation and inflation. Next the main chamber was inflated and the safety cables to the overhead beam crane detached. The building was now ready for the deflation test to commence. The environmental pressure was reduced until the roof started to descend. As expected, considerable force was required to be exerted by the students handling the guy ropes to maintain the building in a reasonably vertical position. The roof plate and suspended floors were allowed to descend to about half height before the building was reinflated. During inflation the roof and attached floors were lifted by the air pressure to their final position without any adverse effect on the membrane enclosure. Throughout the test the building behaved in the predicted manner indicating the validity of the proposed erection procedure.

The second prototype building

The design and construction of the second prototype multi-storey air-supported building was undertaken by undergraduate students in the School of Architecture and Environmental Design at the California Polytechnic State University, San Luis Obispo, California, USA. The design concept developed by the students under the guidance of the authors involved a combination of separately and jointly pressurised spaces acting as a conglomerate of cells. This type of structure falls under the category of multi-cellular, multi-enclosure air-supported buildings. Multi-cellular indicates the existence of two or more sealed, and therefore separately pressurised, compartments while multi-enclosure refers to the ability of one continuous membrane to enclose any number of individually defined but jointly pressurised spaces.

DESIGN

The students saw the need for the development of air-supported building forms compatible with the allocation and function of spaces enclosed by the membrane envelope. While most existing commercially available single-storey air-supported buildings are either dome shaped or semi-cylindrical with quarter spherical or rectangular ends, these standard shapes are hardly conducive to the architectural planning of the internal building space. Particularly in the case of smaller buildings, such as homes, the provision of partitions and support services poses problems which have been largely ignored by the air-building industry. From the manufacturer's point of view, any deviation from the standard shape will involve time-consuming geometrical analyses as well as very intricate patterns and complicated jointing operations.

The final design adopted for construction (Fig. 10) consisted of a central two-storey cylindrical cell surrounded by four single-storey multi-enclosure domes. The dimensions of the multi-storey core were 10 ft (3·0 m) (diameter) by 16 ft (4·9 m) (height). Contrary to the first prototype building (Sydney), the air-supported floor was attached directly to the membrane enclosure at first floor level. In this manner floor loads were designed to be supported by the plastic membrane which in turn was supported by the environmental pressure acting on the underside of the dome-shaped roof cap. The four peripheral domes

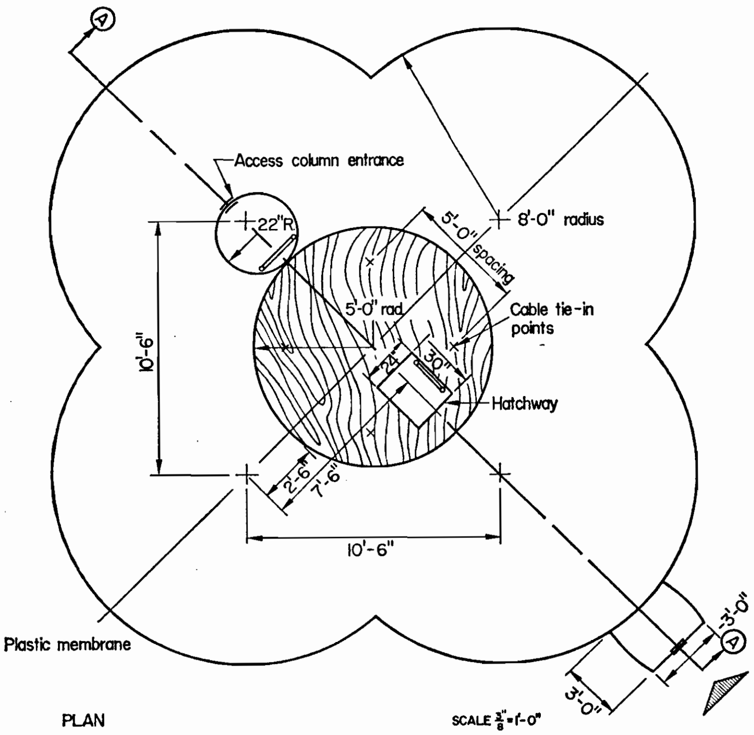

Fig. 10. *Design of the second prototype building.*

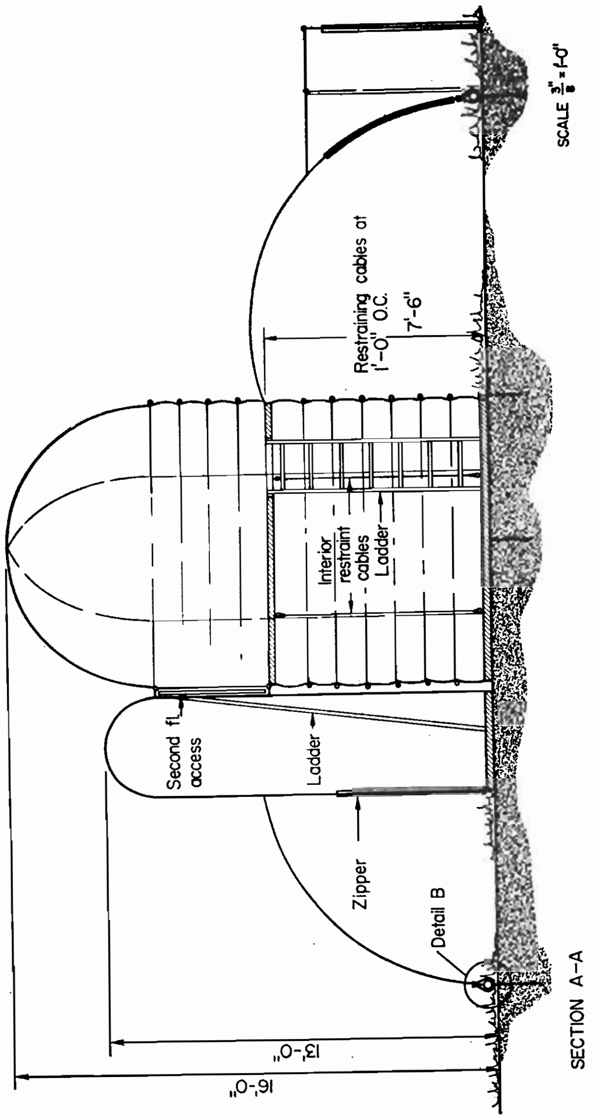

Fig. 10. *Design of the second prototype building (continued).*

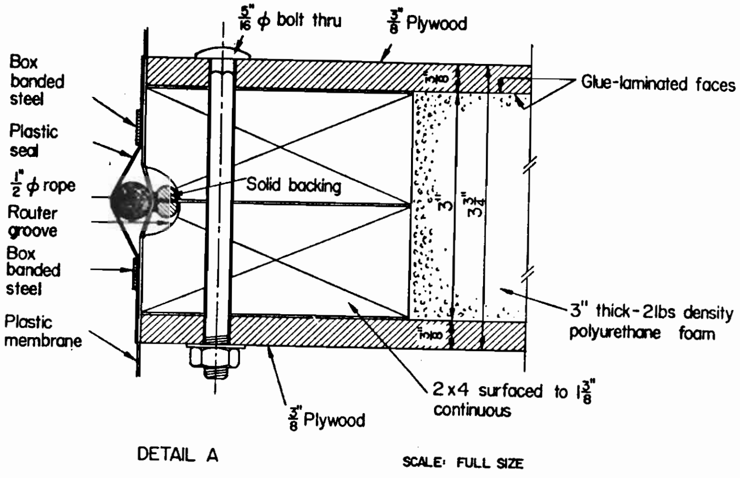

Fig. 10. *Design of the second prototype building (concluded).*

were 16 ft (4·9 m) in diameter, interconnected and pressurised indirectly through air-release valves located in the cylindrical wall of the core.

In view of the desirability of a transparent enclosure, glass-clear, ultra-violet stabilised (partially) PVC with a thickness of 20 mil was selected as the membrane material. A further important factor in this selection was the availability of an operational heat sealer most suitable for the jointing of polyvinyl chloride (PVC) films. While the construction of the building was funded by a $1,000 grant from the National Science Foundation, this sum was only adequate for the purchase of materials and did not include labour costs for the fabrication of the membrane enclosure. It was, therefore, resolved that the fabrication of the membrane using the existing heat sealer should form part of the construction process.

Estimates of the weight of the air-supported floor including occupants indicated that an environmental pressure of around 5-in WG (1·3 kN/m^2) would be required for the core chamber while 1-in WG (0·25 kN/m^2) would suffice for the surrounding domes. An exterior cable network consisting of concentric horizontal and radial vertical cables was, therefore, incorporated in the design of the two-storey cylinder. Much consideration was given to the alternative methods which could be adopted for providing a simple access system to the core chamber. The solution adopted for the first prototype building could not be applied in this case since the building was to be sited on a grassed area in which no excavation was permitted. It was finally decided to provide a 3-ft 8-in (11·2 m) diameter vertical airlock tube adjacent to the central chamber allowing access directly to the first floor level. However, the type of opening which could be employed between the airlock and the high pressure chamber remained a major source of concern for some time. Experience with the first prototype building suggested to the authors that some form of stiffening would be required around the penetrated area of the core membrane. At the same time due to the circumferential stresses in the membrane a vertical zip was likely to be unsatisfactory. The final solution consisted of a rectangular steel frame attached to the exterior cable network and taped to the perimeter of a 2-ft (0·61 m) square opening in the membrane. A 3-ft (0·91 m) square plastic flap attached at the top edge to the inside surface of the membrane served as a self-sealing door. The bottom edge of the flap was stiffened by means of a steel rod with a radius of curvature similar to that of the membrane enclosure. This simple device performed most efficiently during the operation of the building and suggested that the extra expense of providing more elaborate structurally self-supporting entrance systems of the type used in the first building may not be warranted in some instances.

Since the building was to be sited in the open, there was no opportunity for the provision of overhead safety ropes in case of sudden collapse. A self-supporting steel frame to be positioned inside the core chamber between the ground and first floors was proposed as an alternative solution. The frame was designed so that it could be used as a support platform during erection and yet permit the first floor to lift off and remain air-supported some 9 in (229 mm) above the frame during normal operation of the building. Threaded through the tubular columns of the frame were four cables acting as ties between the ground and first floors. These cables were designed to act as intermediate supports for the first floor plate whenever it was required to close the trap door and support the floor by air pressure acting on its underside. In other words, the first floor could be air-supported in two ways. First, with the trap door open the supporting force would be provided by the membrane enclosure due to the environmental pressure acting on the dome roof of the chamber (the normal form of operation). Second, with the trap door closed and the environmental pressure in the ground floor compartment greater than in the first floor compartment, the supporting force would be provided by the greater environmental pressure acting on the underside of the first floor plate.

CONSTRUCTION DETAILS

Several alternative methods of construction of the air-supported first floor plate were investigated, namely timber framing with plywood skins, timber framing with steel reinforcement and polyurethane foam core with plywood skins. While the latter offered by far the lightest structural solution, it was initially viewed with scepticism due to the absence of an accurate theoretical method of structural analysis. Accordingly, a 1-ft (0·30 m) wide and 8-ft (2·4 m) long test section was constructed for full scale load tests. The test section consisted of a 3-in (76 mm) thick polyurethane (2 lb density) foam core sandwiched between two $\frac{3}{8}$-in (9·5 mm) thick plywood sheets glued at the interfaces. Subsequent load tests demonstrated the inherent strength of this type of laminated construction. Shear failure of the foam core occurred at a maximum uniformly distributed load of 800 lb (12 kN/m) (*i.e.*, 100 lb per ft (1·45 kN/m)). Before the foam failed, a maximum deflection of 2 in (50·8 mm) was recorded at midspan. In view of this excellent test result the same construction was adopted for the building floor with the addition of blocking pieces at 2-ft (0·61 m) centres.

The membrane enclosure was designed to be prefabricated in eight sections, namely the central cylinder, the central dome cap, the airlock cylinder, the airlock dome cap and the four peripheral domes. While the patterns for the central chamber and airlock entrance were determined by the application of simple spherical geometry, the interface between the peripheral domes and the cylindrical core chamber required a much more complex geometrical analysis. One of the students with a sound background in mathematics volunteered to investigate this problem and finally developed a small computer program which provided a good estimate of the required shape. In view of the difficulties which would be encountered in heat sealing the resultant multi-curved seam, it was decided to tape the peripheral domes to the central cylinder. In the case of the dome sections, timber moulds were required to be built to serve as a firm base during the jointing operation.

As shown in detail (A) of Fig. 10, the construction detail of the attachment of the central cylinder membrane to the ground and first floors differed in no significant

respect from the detail adopted for the first prototype building (Fig. 5). However, while the latter was erected on brick pier and steel pipe footings, the second prototype building was designed to rest directly on a level surface. It was, therefore, proposed to anchor the central chamber by means of pipe stakes sliding through a series of eyebolts screwed into the curved edge of the ground floor. At the same time, it was decided to seam a 1-in diameter steel pipe into the hem of the four peripheral domes to be anchored to the ground with pegs.

CONSTRUCTION PHASE

The construction phase of the multi-cellular, multi-enclosure building began with the organisation of the students (20) into work gangs delegated with the responsibility of executing the separate phases of the project. As shown in Fig. 11, the construction of the building was planned over a period of 21 working days. The bar chart identifies the number of students involved (vertical axis) in each sequence and the time allotted to complete each operation. The structure was prefabricated in five general sections, namely the two floors of the central chamber, the peripheral domes, the central chamber, the airlock chamber and the entrance to the building. Again the search for a suitable inflation unit required more time than anticipated at the planning stage. Finally, two axial fan units were connected in series with a centrifugal fan to produce the required environmental pressure of 5-in WG (1·3 kN/m^2) for the two-storey central chamber.

The sequence of operations employed for the assembly of the prefabricated components is shown in Fig. 12. The location of the central cylinder and domes was set out with a white marking agent. After the ground floor had been set in place with the safety frame securely fastened, the first floor plate was lifted on to the frame and the interior cables attached. Next, the membrane cylinder was draped over both floors and fixed into position. This enabled the central chamber to be temporarily inflated so that the exterior network of plastic coated cables could be positioned. Finally, the membrane interface between the peripheral domes and the central cylinder was completed using a lacing technique in addition to the tape joint originally planned (Fig. 13). Full inflation of the structure required the operation of all three fan units at maximum power for six minutes. Subsequently, the environmental pressures of the central and peripheral chambers were monitored by two 'U'-tube manometers and controlled by regulating the speed of the

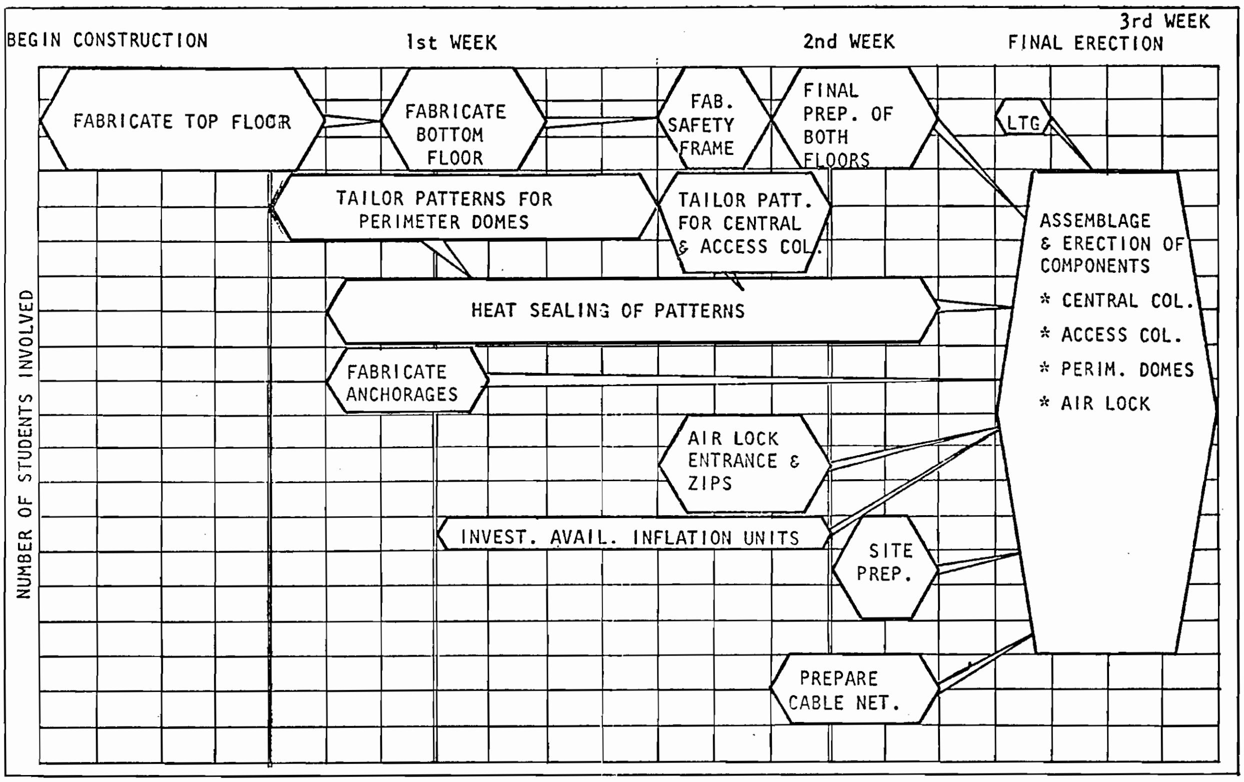

Fig. 11. *Bar chart describing construction sequence of second prototype building.*

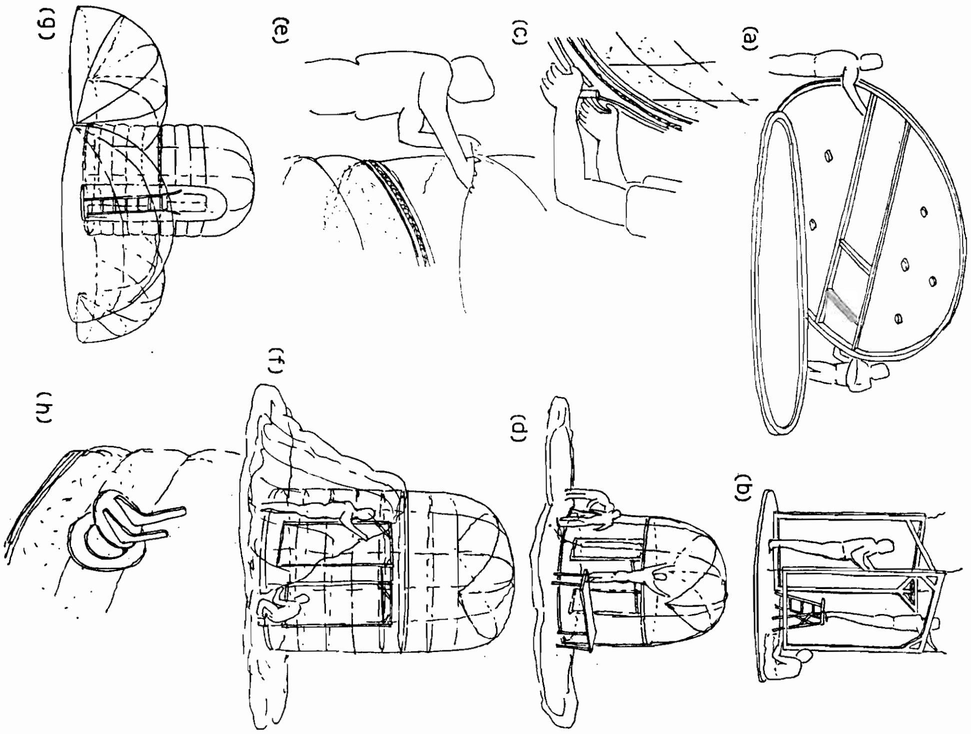

Fig. 12. *Main construction stages (second prototype building).*

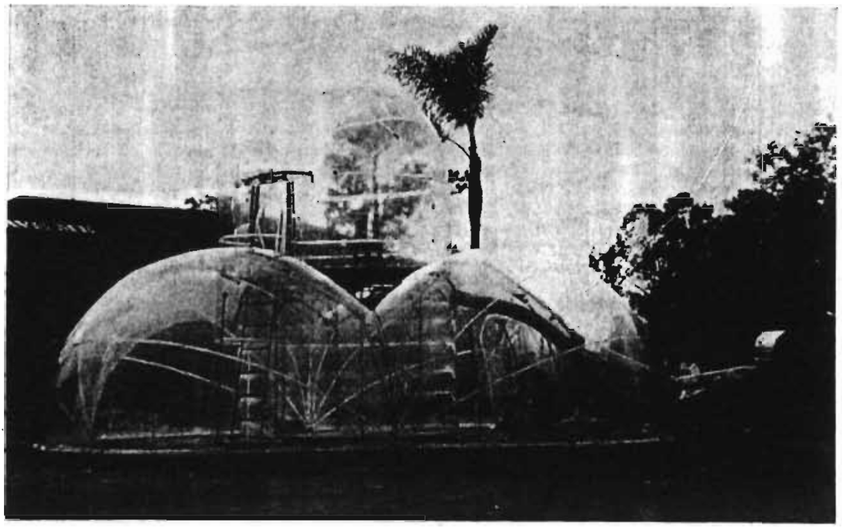

Fig. 13. *The completed second prototype building.*

centrifugal fan unit. After an initial running-in period, no difficulties were encountered in the regulation of the pressure in the peripheral chamber by adjustment of the air-release valves located in the membrane enclosure of the central high pressure chamber.

While 600 manhours were required for the construction of the building, the material cost totalled \$656.00 (US). It may be of interest to note that on the basis of a more suitable inflation unit such as a roots blower the daily operating costs of the building structure were calculated as \$1.20 for a total floor area of a little less than 750 sq ft (69 m^2).

OPERATION AND PERFORMANCE

The building remained open for public display over a period of ten days. During this time, at least 500 persons entered the peripheral chamber of the building while some 80 students and campus visitors were sufficiently interested to climb through the airlock cylinder on to the air-supported first floor level of the central chamber. The peripheral area of the building was connected to the outside by a short airlock tunnel fitted with a simple zip door at each end. Once inside the building, the following procedure was followed in entering or departing from the central two-storey chamber.

*TO ENTER—'Open the vertical zip of the airlock cylinder and step into the airlock; close the zip; ascend the ladder and slide the plastic flap sealing the entrance of the first floor compartment slightly to one side (pressure equalisation will proceed instantly); fold the flap back and climb on to the air-supported first floor; close the flap.'

*TO DEPART—'Slide the entrance flap slightly across the opening in the membrane enclosure (pressure equalisation will proceed instantly); fold the flap back and step on to the ladder in the airlock cylinder; close the flap and descend the ladder; open the zip and step out; close the zip.'

Observation of the environmental properties of the building continued under a variety of conditions of occupancy during the entire period of public display. Some fifty persons noted their reactions after experiencing the air-supported building environment. Their conclusions may be summarised as follows:

(*a*) The transparency and extremely low thermal resistivity of the PVC membrane resulted in high heat gains during daylight hours and correspondingly high heat losses during nights. For example, during the morning hours of 8:00 to 10:00 am while the external air temperature in the shade did not exceed 58°F (14°C), the building temperature rose to 75°F (24°C). By noon on the same day the indoor temperature had risen 22° F (12° C) above the outdoor temperature of 73°F (23°C). At night the indoor temperature quickly fell to the same level as the outdoor temperature.

(*b*) There was no noticeable effect of the hyperbaric environment (1 in WG (0·25 kN/m^2)) on entering the peripheral dome area. However, on entering the vertical airlock cylinder some persons experienced a slight pop within the middle ear. While no official complaints were recorded, it might be suggested that more care should have been taken in the design of the building to control the rate of compression and decompression in the airlock chamber. In view of the satisfactory performance of the airlock system in the first prototype building which required a much higher environmental pressure (10 in WG (2·5 kN/m^2)), it was assumed that the rate of pressurisation in the second prototype building could be virtually instantaneous.

(*c*) The acoustical environment of the building was clearly dictated by the curved form of the perimeter domes and central cylinder. In the inflated state, the impervious membrane acted as an acoustically hard (reflecting) surface. At the centre of each dome there was a distinct concentration of sound leading to echoes. Upon moving slightly out of the centre, the echo disappeared. Similar effects could be experienced in the central chamber, particularly at first floor level.

Structurally, the second prototype building performed extremely well in resisting wind gusts of up to 40 mph (64 km/h), which occurred on one occasion during the public display period.

From the architectural point of view, the building was designed to combine a number of separately defined spaces. Although the peripheral domes were structurally one space, they appeared to the internal viewer to possess individual qualities. At the same time, the central chamber became the focal point of the building with the first floor area offering the greatest degree of privacy.

In all, the results were most heartening and suggested that the multi-cellular multi-enclosure air-supported building type should warrant further experimental studies in the near future.

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