Multi-Story Pneumatic Buildings Revisited

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Abstract

This paper describes the concept of pneumatic structures applied to multi-story buildings. In such buildings an internal environmental air pressure acting on the underside of the roof supports floors that are suspended from roof level. A continuous plastic membrane surrounded by an external cable-network for reinforcement purposes contains the pressurized building environment in a similar fashion to the container of a pressure vessel. The paper explores safety considerations, fire protection measures, special requirements relating to water and sanitary services in a hyperbaric environment, airlock entrance and emergency egress provisions, construction and erection considerations, cost projections, and the structural design process. The paper concludes with a brief discussion of alternative structural air-supported configurations and fluid-inflated systems in which the building environment is not pressurized.

Introduction

As suggested by the title the purpose of this paper is to revisit a novel structural concept for multi-story buildings that the author researched as a doctoral thesis in architectural science some 40 years ago (Pohl 1970)[1]. At the time it occurred to the author that it should be possible to replace the vertical load-bearing structural components of a multi-story building with a pneumatic system or, succinctly stated, to treat the building as a pressure vessel. For example, if we assume a 9-story building with a circular floor plan and increase the air pressure within the building above the ambient external atmospheric pressure, then there will be an upward force exerted by the internal air on the underside of the roof. This upward force could be utilized to support the floors of the building if they are suspended from the roof (Figures 1 and 2).

Several skeptical questions immediately arise. How much pressure would be required? Surely a great deal, because the floors of multi-story building are normally constructed of concrete and/or steel and are therefore quite heavy. However, further analysis provides a surprising answer. Building loads are measured in pounds per square foot (LB/SF) units while air pressure is measured in pounds per square inch (LB/SI) units. Since there are *144 square inches (SI)* in one square foot (SF) and the floors of a multi-story office building are normally designed for a combined live and dead load of around *140 LB/SF*, it should be possible to support one floor for every *1 LB/SI* of air pressure above atmospheric pressure. Yes, but what about the impact of the hyperbaric environment on the occupants of the building? Experience with deep sea divers and medical research of the bends syndrome has shown that persons are able to change from atmospheric pressure to higher pressures up to twice atmospheric pressure instantaneously without the danger of nitrogen bubble formation in the blood stream. Divers that descend to depths beyond *33 feet (FT)* are required to surface gradually to avoid decompression sickness. Therefore, if we tentatively limit the air pressure in the building environment to less than two

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[1] Post Graduate (Ph.D.) Program, Department of Architectural Science, University of Sydney, Sydney, Australia.

atmospheres, say 90% of standard atmospheric pressure[2] or *13 pounds per square inch above ambient atmospheric pressure (psig)*, then we should be able to support at least 12 floors plus the roof. In other words, if a 2:1 pressure gradient is not exceeded then persons should be able to instantly enter and exit the air-supported building without experiencing any adverse physiological effects (Pohl 2013, 50).
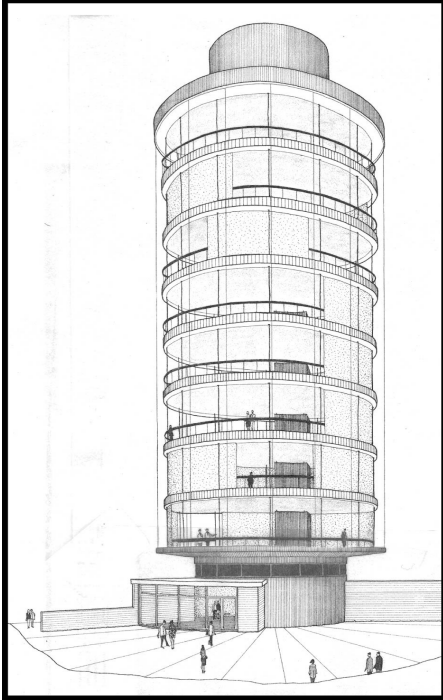

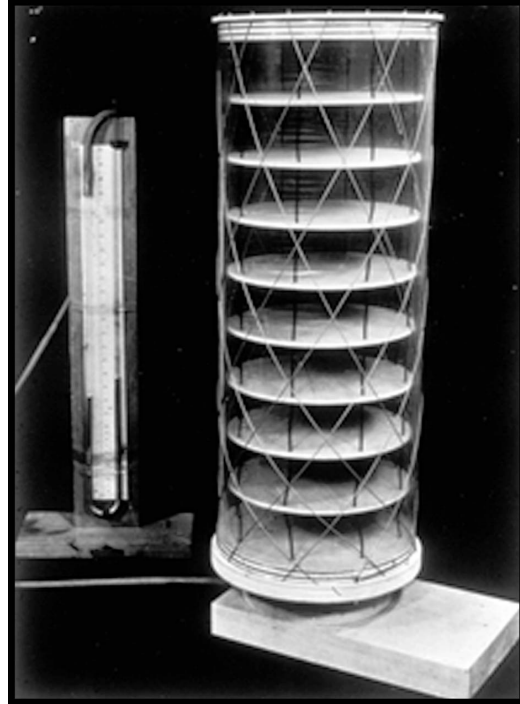Figure 1: Conceptual drawing of a multi-story air-supported building

Figure 2: Scale model of a 9-story air-supported building structure

How can it be ensured that air will not leak out of the building? The external walls of a normal building regardless of whether multi-story or single-story are by no means airtight. Yes, even though there will be some air exchange between the inside and outside of an air-supported building as part of the normal ventilation requirements, this does not obviate the need for an air tight building enclosure. However, it is a unique feature of a multi-story air-supported building that the enclosing envelope is also the principal structural element of the building. Its function is to contain the air pressure that supports the roof from which the floors are suspended. Since the envelope is entirely in tension and derives its stability directly from the air pressure that it contains, it is governed by a set of design criteria that are quite different from orthodox building facades. Most of these design criteria can be satisfied by plastic membrane materials that are easily reinforced, joined and modified with plasticizers, fillers and pigments. However, the plastic membrane is unlikely to have sufficient tensile strength and will therefore need to be reinforced by an external cable-network, which will also brace the building against wind forces.

What about safety? Since the structural integrity of a multi-story air-supported building is entirely dependent on maintaining adequate air pressure inside the building, is it in fact feasible to design such a building so that it is sufficiently safe for human occupancy? Primary among

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[2] Standard atmospheric pressure is *14.7 pounds per square inch (psi)* which reduces by about 1% for every *330 feet* above sea level. Air pressures above atmospheric pressure are usually denoted with the units '*psig*'.

these safety considerations are the tear resistance of the envelope, protecting the envelope from radiation in the case of a fire within the building, prolonging the deflation period if the envelope is punctured in multiple places, and mass evacuation of the building occupants in case of a catastrophic event. As will be shown in subsequent sections of this paper all of these safety concerns, as dangerous as they may appear, are amenable to solution approaches.

There are many other aspects of multi-story air-supported buildings such as desirable material properties of the membrane enclosure (Pohl 2013, 51), cable-network functions (Pohl 2013, 61), pressure-utilization efficiency (Pohl 2013, 53), structural design process (Pohl 2013, 89), air-lock entrance and egress facilities (Pohl 2013, 59), thermal insulation (Pohl 2013, 57), water supply and sanitary services (Pohl 2013, 59), air-conditioning system (Pohl 2013, 58), erection and construction considerations (Pohl 2013, 66), and comparative cost comparison (Pohl 2013, 73), all of which warrant further detailed discussion[3]. This paper can provide only a summary review of the principal aspects.

Fire Protection Strategies

In the context of presently accepted standards of fire-resistance multi-story air-supported buildings will present problems that may well seem unsolvable at first sight. It will be necessary to re-evaluate fundamental concepts on the basis of relating fire-hazard to the complete structure. Starting with the well established assumption that economic risk should be relegated to secondary importance in relation to the danger to human life, the following guiding principles are proposed:

> *Principle 1:* Minimization of the building's fire-load in relationship to structure, enclosure, and contents. It seems plausible that the effective fire-load of a building can be reduced by providing separate fire-rated storage units for areas containing a high density of combustibles. In isolating combustible content in high density units it should be possible to reduce the potential fire-hazard of the non-combustible structure and concentrate treatment to smaller areas more effectively.

> *Principle 2:* The installation of effective fire services in the form of detectors, radiation shielding systems, and deluge sprinklers to allow sufficient time for mass evacuation before catastrophic structural failure takes place. It will be desirable to plan evacuation in two stages: first, to a fire-rated shelter at basement level within the building confines; and, second, from this shelter to the exterior.

Measures must be applied to shield the membrane envelope from radiation and thermally insulate the suspension cable system. In the first case, it is proposed to provide automatically controlled reflective, sliding screens around the perimeter of each floor (Figure 3). In the case of a fire occurring at any point within the building, these screens will slide between the fire and the membrane acting as shields against radiation, heat transfer, and flame penetration. At the same time, deluge type sprinklers will spray water against the membrane and the external side of the screens (Figure 4). The screens themselves will need to be designed to the requirements of applicable building code fire-rating standards for structural members. It is suggested that with these measures in combination with mass evacuation provisions it should be possible to achieve an acceptable degree of fire-protection for a multi-story air-supported building.

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[3] A comprehensive and more detailed analysis of the design and constructability of multi-story air-supported buildings is provided in Pohl J. (2013); 'Multi-Story Air-Supported and Fluid-Inflated Building Structures'; CreateSpace, 7290 Investment Drive, Suite B, North Charleston, South Carolina (SC 29418).
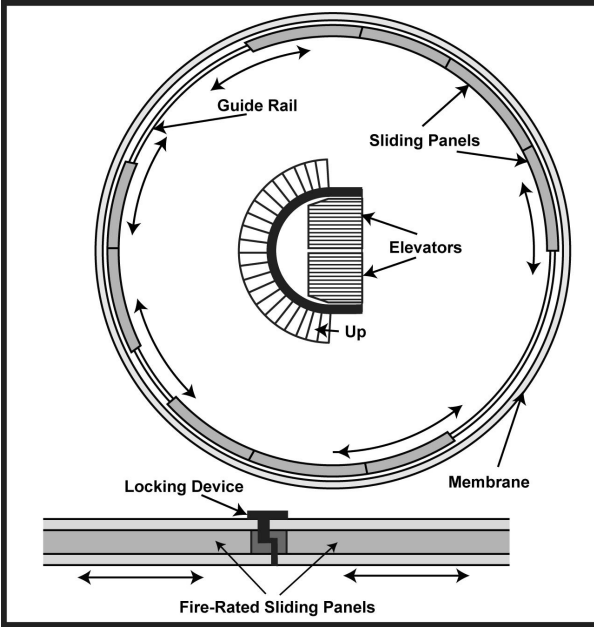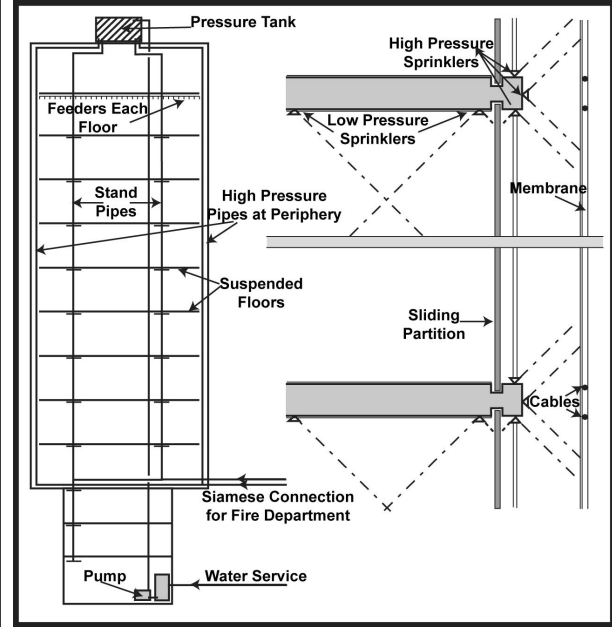
Figure 3: Fire-rated perimeter screens

Figure 4: Fire protection installation

Safety Factors

The structural integrity of a multi-story air-supported building is heavily dependent upon the reliability of the pressurization equipment to maintain an adequate internal air pressure even if the building enclosure has been punctured. With such a critical role assigned to the mechanical equipment (i.e., ventilation and air-conditioning) standby plant and an alternative source of electricity in case of a power failure will be necessary. In addition, strict maintenance and inspection programs similar to those applied to commercial aviation will need to be applied by local building authorities.

Special consideration will need to be given to the performance of the membrane enclosure. The type of currently available plastic material that will satisfy the performance requirements related to tensile strength and weatherability is a scrim base laminate coated with films such as polyvinyl chloride (PVC) or polyvinyl fluoride (PVF) externally and polyurethane internally. The scrim layer has the ability to localize rupture by developing a high tear resistance. If the building membrane is punctured by accident or as an indirect result of civil disturbance or as the direct outcome of an act of terrorism (e.g., bullets and larger projectiles) and this perforation remains localized due to the tear-resistance of the membrane material, then the continuing stability of the building will be largely a question of pressurized air input. The design of the mechanical equipment can therefore be dealt with statistically, namely: What is the probability of failure in relationship to the effective size of a puncture that may occur during the lifespan of the building?

While such a calculated risk has become acceptable in commercial aviation it is unlikely to be acceptable in the near future in buildings, which are occupied for much longer periods. Total collapse of a multi-story air-supported building is no more acceptable than the total collapse of any orthodox building structure. The integrity of the pneumatic structure must be maintained for a sufficient period of time following a disastrous event to allow the building to be evacuated. This will require the provision of an emergency pressurized shelter immediately below the

building, to avoid the inevitable time delays associated with the airlock entrance to the building on the ground floor.

In addition, the fire-rated perimeter sliding panels that are proposed for shielding the membrane from the heat radiation of an internal fire may be assigned a secondary structural function under emergency conditions. If, for whatever reasons, the internal building pressure falls below a specified level these shields would be automatically activated to slide into predetermined positions around the perimeter of each floor. Considering that the occupancy live load assumed during the design of the building is likely to be much greater than the actual live load at any time during the lifespan of the building and that the perimeter panels are optimally located to support the floor above, the proposed additional structural function assigned to these panels can be easily accommodated.

The proposed safety provision for a multi-story air-supported building subjected to a loss of internal pressure due to equipment failure or catastrophic air leakage can be summarized in stages, as follows:

> *Stage 1:* As the internal air pressure falls below a *first alert* level the normal air-outlet is automatically shut off and standby pressurization equipment is automatically activated.

> *Stage 2:* If the internal air pressure continues to fall below a *second alert* level the perimeter panels are automatically activated to slide into predetermined positions on each floor. In addition an alarm is automatically activated to initiate evacuation of the building occupants to the pressurized emergency shelter in the basement of the building.

> *Stage 3:* Should the internal air pressure remain below the *second alert* level evacuation from the emergency shelter to the external environment will be initiated concurrently through several airlocks located around the perimeter of the shelter.

It should be noted that a multi-story, air-supported cable-network building is ideally suited for resisting earthquake loads. First, it is a very flexible building with few rigid structural joints. The building is essentially a cylindrical container with the internal air-pressure providing stability. Second, the external cable-network is optimally located at the furthest distance from the neutral axis at the center of the building. Therefore, the building acting as a column has the largest possible moment of inertia. Third, the external cables wrapped around the pressurized membrane container serve as an excellent bracing mechanism. They are oriented in three directions, at an angle of *63º 26'* on either side of the vertical and horizontally and at an angle of *90º* to the vertical (Pohl 2013, 61). The bracing provided by the cable-network in combination with the membrane provide a degree of ductile stability that is not achievable with orthodox steel or reinforced concrete structural frames.

Building Services

Apart from fire protection, there are several other non-structural characteristics that distinguish a multi-story air-supported building from its conventional counterparts. For a start, not only does the ambient internal air pressure need to be maintained, but it also needs to be controlled within fairly strict limits. Certainly the concept of a sealed, pressurized environment introduces a stringent requirement for conditioning the air and, above all, maintaining the internal pressure. The pressure range indicated, 0-14 psig, is well below the usual range of reciprocating compressors but above that of centrifugal blowers. The most appropriate method of achieving pressures toward the upper end of this range would probably be with a rotary vane compressor, which could conveniently be directly coupled to a high-speed motor or to a turbine. The output

of the compressor would be at an elevated temperature so that additional cooling would be necessary in summer. The winter requirement would depend upon the rates of air exchange and heat exchange between the building and the outside air.

The effect of a hyperbaric building environment on the design and installation of sanitary fittings does not appear to have received much attention in the past. The pressure inside single-level air-buildings is obviously too small to have any effect on sanitary installations, and in the case of high pressure caissons the maximum allowable exposure times are severely limited by the applicable codes for physiological reasons. Therefore, the problems posed in this area by multi-story air-supported buildings are without precedent and may require new waste removal systems and equipment. In its overview purpose it is not the intention of this paper to deal with the design of sanitary plumbing suitable for a hyperbaric environment, but merely to set out the special conditions encountered in these buildings and suggest tentative methods of catering for these in the light of presently available sanitary systems.

Sanitary fixtures are appliances (e.g., basins, water closets, showers, and so on) installed in a building for the purpose of receiving and passing graywater[4] and blackwater[5]. They are presently designed to prevent gases that may arise from decomposed organic matter from infiltrating into the building. The fixtures are connected ultimately to a public drainage system, while the passage of gases into the building is prevented by means of a water seal, normally incorporated directly in the fixture.

First, let us consider the question of water supply for a multi-story air-supported building with an internal design pressure of up to *14 psig*. A considerable amount of boosting will be required to overcome this environmental pressure for the purpose of feeding mains water into storage tanks at the roof or basement level. If the pressure in the mains is *50 psig* then an increase of 30% in pump capacity will be required in comparison with an orthodox building. The accompanying increase in cost is likely to be quite small, if not negligible.

Unfortunately, the problem of waste disposal will present greater complications. Under present conditions no local government authority is likely to tolerate the discharge of excremental matter into a public sewerage system at *14 psig* pressure. To overcome this restriction one of the following two procedures could be adopted with a minimum of alteration to accepted plumbing practices. Unpressurized service areas could be provided within the multi-story air-supported building. While this would require individual airlocks at each floor level, existing fixtures and reticulation may be used without modification. A simpler method would be to provide airlock mechanisms within waste pipes. In this case the function of the water seal is preserved and the waste will reach the sewer after passing through one or more stages of decompression. This method can be further improved by combining a number of similar waste pipes at a central decompression unit. It seems highly probable that these waste pipes would require artificial ventilation at 14 psig pressure, in conjunction with the central air-conditioning system.

To summarize, a hyperbaric building environment of less than one atmosphere of additional pressure should have little impact on water supply, apart from the necessity of providing pumps of approximately one third greater capacity than in an orthodox building. The rate at which the water must be boosted is likely to exceed the limit of draw permitted by the local water utility.

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[4] Graywater is defined as water from showers, bathtubs, kitchen and bathroom sinks, hot tub and drinking fountain drains, and washing machines.

[5] Blackwater is defined as water containing human excreta, such as wastewater from toilets.

Although water utilities are willing to accept a considerable drop in mains pressure for emergency purposes, near negative pressures can of course not be tolerated. Therefore, even purely from the point of view of fire services the multi-story air-supported building will require considerable tank storage. Low level storage is likely to be preferable, with the actual volume being determined by agreement with the fire department and water utility. Since there is a need for storage at low level it will be worthwhile to make it adequate and minimize that at high level in the building, thereby reducing the weight to be carried by the internal pressure of the building.

Construction Considerations

The first floor to basement levels will be normal compression construction with circular, prestressed, post-tensioned concrete perimeter walls enclosing all pressurized areas. The entrance to the building at ground level will require an airlock, which should be as unobtrusive as possible so that persons entering the building will be largely unaware that they are entering a pressurized environment. In addition to the main building entrance provision will need to be made for at least two emergence airlock facilities that will expedite the mass exit of the building occupants from the basement evacuation shelter to the outside, in case of a fire or other structural emergency.

The erection procedure, assembly sequence, and allocation of manpower for the air-supported portion of the building will differ markedly from current construction practices for steel and reinforced concrete building frames. The suspended floor system depends upon a framework of trusses or a beam system at roof level, with main supporting fixtures around the external perimeter (but inside the membrane enclosure) and a smaller number around the inner perimeter of the underside of the air-supported roof. From these the floors are suspended by means of high-tensile steel rods. The rods are not continuous but in approximate story-height sections that are connected vertically by means of turnbuckles. The secondary role of the turnbuckles is to provide a convenient mechanism for adjusting the story-height and for leveling each individual floor horizontally.

Experience with the construction of a two-story prototype air-supported building (Pohl 2013, 105) suggests that the joints for the suspension rods should be about one foot below the underside of each floor. Longer rods would make it difficult to thread the rods through the prepositioned gusset plates located on the upper and lower surface of each floor during the erection of the building. A *100 FT* diameter building would likely require in the order of 16 suspension rods equidistantly spaced around the outside perimeter of each floor and probably no more than four around the inner perimeter[6].

Since a crane will be required for several major construction tasks, such as hoisting of the roof and floors, the configuration of the crane assembly warrants further consideration. It is suggested that the crane assembly consist of four towers positioned at equal spacing around the perimeter of the building on rails. As shown in Figure 5, the crane towers are connected by trusses across the top of the building and are able to swivel in unison 90° around the central vertical axis of the building. In this way the crane assembly provides a framework with four lifting points above the roof and at the required distance from the center of the building. This allows the roof to be lifted to its final height by attachment of the four crane cables to the outside perimeter in 3, 6, 9, and

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[6] This assumes that the floor is annular in shape with a central hole of about 20 FT diameter to allow for a winding staircase around an elevator shaft.
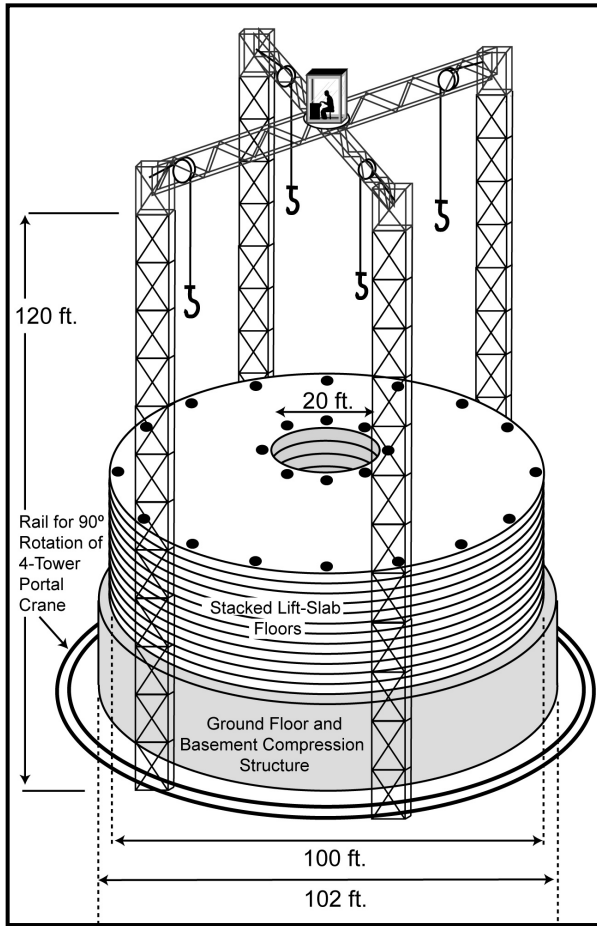
12 o'clock positions (Figure 6)[7].

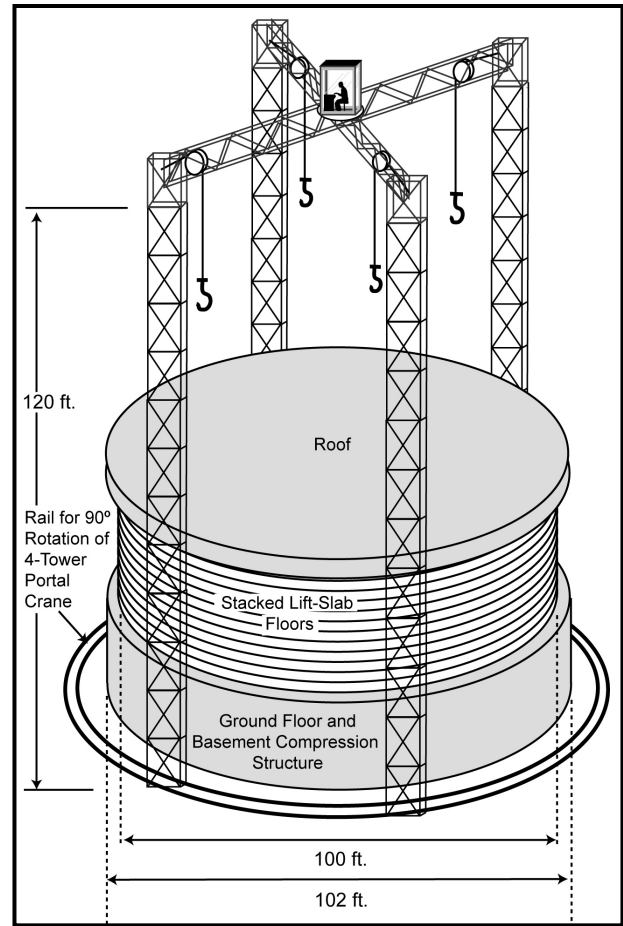Figure 5: Portal crane assembly for the erection sequence

Figure 6: Erection stage prior to hoisting of roof and floors

The draping of the relatively fragile plastic building envelope around the roof and floor plates, while these are stacked in lift-slab fashion on top of the ground floor compression structure, is perhaps the most exacting task during the construction sequence (Figure 6). There are several complicating factors that raise technical questions:

1. Even though the membrane material per unit area is very light, since it has to be in one piece the complete membrane tube for a realistic building will weigh several tons (e.g., almost *10 tons* for a 12-story building with *100 FT* diameter floors). How can this relatively heavy and fragile building component be handled and moved into position on the construction site?

2. The membrane cannot be easily attached to one or more cranes because the stress level at the point of attachment could exceed the strength of material. For example, if the full weight of the membrane is lifted concurrently at four equidistant points then the load at each pick-up point could exceed *5,000 LB*. How should the membrane be configured (i.e., folded) while it is moved on site? How

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[7] The roof will need to be structurally designed for a four-point pick-up in support of the erection procedure.

can the membrane be lifted by crane(s) so that it does not tear? What kind of lifting equipment will be required to maneuver the membrane into position over the stacked floors and roof?

3. The membrane is a fairly tight fit around the roof and the first floor (i.e., the top level of the ground floor compression structure). It will be extremely difficult, if not impossible, to drape the membrane over the roof if it is in the shape of a cylinder that is just slightly larger in diameter (i.e., 1 or 2 inches) than the diameter of the roof. Even if physically possible it is likely that the membrane would be damaged, or at least severely tarnished, during such an intricate operation. Would it be possible to manufacture the membrane as a single flat sheet, which is provided with a vertical joint that can be connected to form a cylinder after the membrane has been draped around the roof and first floor?

4. As an alternatively course of action consideration could be given to moving the membrane into position around the stacked floors before the roof is constructed. Could the membrane be adequately protected so that it would not be damaged or tarnished during the construction of the roof?

It would appear most convenient to move the membrane on-site horizontally rolled-up in the shape of an annulus. This will allow slings to be wrapped around the annulus at four equidistantly spaced positions, to serve as crane pick-up points. At least two mobile cranes would be used for the on-site movement of the annulus.

While the roof is being lifted the air pressure inside the membrane envelope will need to be just sufficiently raised to stiffen the membrane as a cylinder. An internal air pressure of no more than a *¼ psig* will be sufficient to produce a taut building envelope without creating unnecessary material stress in the membrane. The function of the internal air pressure during this stage of the construction process is to maintain the cylindrical form of the building envelope for the attachment of the external cable-network, and to allow construction personnel to enter the building through the ground floor compression structure and prepare the floors for hoisting.

Once the roof has been lifted into its final position by the external portal crane it will block the hoisting of the floors. For this reason four equidistantly spaced open vertical pipes will need to be embedded in the roof near its outer perimeter. The diameter of these four pipes must be large enough to allow the four crane cables to pass freely through the roof as the floors are being hoisted one-by-one. Before the lifting of each floor the internal air pressure in the building must be increased proportionally to allow for the weight of the floor that is next in sequence to be hoisted. After all of the floors have been lifted into their final positions the crane cables can be withdrawn to allow the pipes to be capped at both ends, so that the building is airtight.

The attachment of the external cable-network should proceed in the following order. First, the diagonal cables should be placed into position in both directions at the optimum angle. This is followed by the attachment of the horizontal cables, which can be tied to the intersections of diagonal cables at reasonable intervals to hold them in place. Only after the cable-network has been fully installed should the internal air pressure be raised incrementally to first support the roof and then the suspended floors as they are sequentially hoisted into position. Thereafter the internal air pressure in the building can be adjusted to its final design level.

Comparative Cost Projections

Any attempt to predict with accuracy the cost of construction of what would be the first full-size

multi-story air-supported building is fraught with danger. The construction or manufacture of any first-of-its-kind artifact must be viewed as being experimental and will often involve costly errors in judgment that are relatively easily corrected in later editions of the same artifact. From a general point of view there are several intrinsic characteristics of multi-story air-supported buildings that should lead to significant cost savings and at the same time there are also potential construction difficulties and lifetime safety requirements that are unique to pneumatic structures.

On the positive side, full realization of material strength due to the conversion of axial loads into tensile stresses will invite the use of high-strength materials, leading to the application of more accurate and critical structural design methodologies. At the same time with the efficient use of materials in tension, minimum-weight design criteria become relevant as a means of optimizing the strength-weight ratio of the structure. Since the membrane enclosure is continuous, problems associated with joint sealants, drainage, expansion, and moving parts are eliminated. However, the membrane enclosure also introduces a new set of problems related to material lifespan (e.g., ultraviolet light degradation), thermal insulation and fire protection.

On the negative side, the on-site erection process is greatly complicated by the requirement to wrap the membrane enclosure around the roof and floors in one or a small number of very large pieces. To achieve this feat without damaging the relatively fragile plastic membrane will require very special care and timing coordination. Second, the requirement of a fairly elaborate portal crane assembly for lifting the roof and floors (Figure 6) before the air inside the building can be pressurized and function as the principal structural support element will be an erection cost factor. Third, a fairly elaborate electronic monitoring and control system will be required to ensure the structural integrity of the building in case of puncture of the membrane enclosure or fire. The safety of the building occupants is dependent on the proper functioning of these controls to an extent that is common practice in air transportation, but has hitherto not been associated with buildings.

The principal construction cost differences between a 12-story building of orthodox construction (i.e., reinforced concrete or steel frame) and an air-supported building of the same dimensions can be projected for the superstructure, external enclosure, and heating, ventilation and air-conditioning (HVAC) components, as follows:

Superstructure: Up to a 70% reduction in cost can be expected since the air-supported building does not require columns and only minimal internal bracing around the central core. The floor suspension system is required to resist only tensile forces and bracing is provided by the external cable-network, which is in an optimum location to perform this structural function[8]. Again, the external cables are subjected only to tensile forces allowing the full tensile strength of the cable material to be exploited.

External Enclosure: While the continuous membrane of the building enclosure poses some erection problems, its material and fabrication costs will be a fraction of the equivalent costs of a metal and glass curtain wall or a precast concrete façade with windows. Even taking into account that the plastic membrane may have to be replaced periodically during the lifespan of the building a 70% reduction in cost should be achievable[9].

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[8] The cable-network is located furthest away from the neutral axis of the building, giving it the largest moment of inertia that is achievable within the footprint of the building.

[9] It should be possible to replace the membrane enclosure from the interior while the building remains under internal air pressure.

HVAC: The requirement of air pressurization and standby equipment suggests a substantial (40%) additional cost for the air-supported building. This is perhaps a conservative estimate because much of the cost of an air-conditioning system is associated with the heating, cooling, and distribution (i.e., ductwork) facilities that do not have to be duplicated in the standby equipment. Only the pressurization facilities and fans need to be duplicated in the standby plant.

More minor cost differences are expected to apply to the following components:

Foundations: The air-supported building is much lighter than a multi-story building of orthodox construction in respect to the self-weight of the structure and external walls (i.e., dead loads). Therefore, at least a 10% reduction in the cost of footings should be achievable.

Floors Below Grade: A 10% increase in cost is projected due to the requirement of a basement capable of serving as an emergency mass evacuation space. This space needs to be pressurized and requires at least two exits with airlock facilities.

Floors Above Grade: A 20% increase in costs is projected to allow for prestressed post-tensioned floors and the special fittings that will be required to attach the floors to the suspension system.

Roofing: The roof will need to support the full load of 11 suspended floors. It is expected to be designed as a series of steel trusses radiating from the center. However, the trusses will not be subjected to cantilever action since the underside of the roof rests on a cushion of air distributed evenly over its entire surface. Therefore, a 20% increase in cost should be considered a conservative projection.

Wall Finishes: A projected 20% reduction in cost accounts for the fact that no external wall finishes are required.

Plumbing: A 20% increase in cost is projected to allow for the boosting of mains water and the provision of centralized or distributed decompression units for waste disposal. Admittedly, this estimate may be on the optimistic side considering the potential problems associated with waste disposal in a hyperbaric environment.

Electrical: A 10% increase in cost is projected to allow for the additional control systems that are required for the operation and monitoring of the airlocks and the internal air pressure within the building, as well as the movement of the sliding fire-rated panels around the perimeter of each floor.

These cost projections are based on the construction of a first-of-its-kind prototype building and do not make allowance for any cost reductions that are likely to accrue as experience is progressively gained with the construction of multiple instances of this building type.

Design Formulas and Pressure-Utilization Efficiency

The principal structural design formula for multi-story air-supported buildings that relates the geometry and vertical loads of the building to the required internal air pressure is discussed in Pohl (2013, 38-41, 92-95). The formula is based on the experimental research and theoretical analysis performed by the author in the late 1960s (Pohl 1970, 132-134, Appendices 8B and 9B) as part of his doctoral dissertation. In Pohl (2013, 92-95) it is shown that for air-supported buildings with a height to diameter ratio of less than 5:1 (i.e., slenderness ratio of less than 30) several of the terms in the base formula have a negligible impact on the final result and can

therefore be deleted. The simplified design formula for an air-supported building with an external cable-network reduces to:

$$P = (k\, W\, r^2) / (R^2 \cos\theta) [(\cos\theta / (k\, A_{CA})) + (e / Z_{CA})] \; \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where: P = internal air pressure (psig)
k = number of vertical (diagonal) cables
W = total axial vertical load (LB)
r = radius of a single vertical (diagonal) cable (IN)
R = radius of building (IN)
θ = angle to vertical of vertical (diagonal) cables (degrees)
A_{CA} = total cross-sectional area of all vertical (diagonal) cables (SI)
e = axial vertical load eccentricity (IN)
Z_{CA} = modulus of section of vertical (diagonal) cables (IN^3)

Closer inspection of equation (1) indicates that the internal pressure is dependent on the total vertical building load (*W LB*), the number (*k*) and cross-sectional area (*A_{CA} SI*) of the vertical cables inclined at an optimum angle to the vertical of 63°26', the building radius (*R IN*), and the loading eccentricity (*e IN*). The eccentricity can be taken as either a function of the building radius or, perhaps more appropriately, as a multiple of the slenderness ratio (e.g., double the slenderness ratio)[10].

Structural Design Process

The structural design of a typical multi-story air-supported building begins with architectural design decisions relating to the diameter of the building, the number of suspended floors, the story height between floors, and the occupancy classification. The footprint of the building is expected to be circular since the natural shape of the envelope acting as a container of the internal air pressure is cylindrical. To ensure a uniform distribution of pressure throughout the internal building environment the diameter of the floors is recommended to be *2 FT* smaller than the diameter of the building. This provides a *1 FT* clear space between the edge of each floor and the building enclosure. However, the diameter of the roof and the ground floor that will respectively serve as top and bottom fixing points for the cylindrical building envelope will be equal to the building diameter.

Next, the membrane enclosure material will need to be selected. To accommodate daylighting, view, and thermal insulation considerations it will consist of multiple, transparent, translucent, externally reflective, and opaque sections that are heat-sealed together. Even the strongest plastic membrane materials available today (2013) will not have sufficient tensile strength to resist the outward force exerted by the internal air pressure. For example, in the case of a *102 FT* diameter building footprint and internal air pressure of *10 psig* the circumferential tensile stress generated in the membrane enclosure will be *12,240 LB/IN*. If we assume a membrane thickness of ⅛ IN (i.e., 0.125 IN) then the tensile stress in the membrane will be *97,920 psi*. This is certainly far beyond any transparent plastic membrane material. Therefore, an external steel cable-network consisting of both diagonal vertical (at an optimum angle of *63º 26'* to the vertical in both directions (Pohl 2013, 61)) and horizontal cables will be required to strengthen the plastic building enclosure. Since the modulus of elasticity of steel is much greater than that of suitable

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[10] Slenderness Ratio (SR) = $2H/(R^2/2)^{0.5}$ where H (IN) and R (IN) are the building height and radius, respectively (Pohl 2013, 40).

plastic materials, the membrane will bulge out between cables and in this way transfer most of the air pressure load onto the steel cables.[11]

The building occupancy and floor construction determines the live and dead loads that are required to be supported by each floor. For an office building with public access applicable building codes may prescribe a live load as high as *100 LB/SF*, while the self weight (i.e., dead load) of a reinforced concrete floor is likely to be around *50 LB/SF*. Based on the author's experience the spacing of the external cables will be about *4 FT* for the vertical diagonal cables and *2 FT* for the horizontal cables. Finally, the maximum wind speed that the building must be capable of resisting will depend on its location.

Structural Design Results for a Typical 10-Story Office Building

The structural design results for a typical multi-story air-supported building with a cable-network surrounding the plastic building envelope and serving as the principal structural component is shown below. The building has both a height and diameter of *100 FT*, giving it a height to diameter ratio of *1*. As explained previously, to facilitate the erection of the building envelope during construction the diameter of the nine suspended floors is *98 FT* to provide a *1 FT* wide gap between the perimeter of each floor and the building envelope. The eccentricity of the vertical load is assumed to be twice the slenderness ratio (*SR*) or *12 IN* from the central axis of the building. Since the building is intended for an office occupancy normal building loads applicable to public buildings have been assumed (i.e., *100 LB/SF* live load and *50 LB/SF* dead load). Finally, horizontal wind loads are based on a maximum wind speed of *110 mph*, which would likely apply to a coastal location.

(1) Assumed Design Data:

modulus of elasticity of membrane material =	2,000,000 psi
modulus of elasticity of steel cable material =	29,000,000 psi
design strength of membrane material =	15,000 psi
design strength of steel cable material =	60,000 psi
building form constant for wind drag forces =	0.60
optimum angle (to vertical) for diagonal cables =	63° 26'
approximate spacing of diagonal cables =	4 FT
approximate spacing of horizontal cables =	2 FT

(2) Entered Design Data:

building diameter =	100 FT
floor diameter =	98 FT
number of air-supported floors =	10 (including roof)
building height =	100 FT (with ground floor)
membrane thickness =	0.125 IN
live load =	100 LB
dead load =	50 LB
wind speed =	110 mph

---

[11] The moduli of elasticity of steel and plastic are approximately 29,000,000 psi and 2,000,000 psi, respectively. Since the stress in the membrane is directly proportional to its radius of curvature, it follows that the more the membrane bulges out between cables the smaller its radius of curvature and the smaller its tensile stress. For typical cable spacing and a *102 FT* diameter building the stress in the membrane is expected to be reduced from *97,920 psi* to below *10,000 psi*.

(3) Derived Design Data:

$$
\begin{aligned}
\text{total building load} &= 11{,}361{,}089 \text{ LB} \\
\text{building slenderness ratio (SR)} &= 5.7 \\
\text{assumed vertical loading eccentricity} &= 11.4 \text{ IN (twice SR)} \\
\text{building height to radius ratio} &= 2.0
\end{aligned}
$$

(4) Calculated Cross-Sectional Membrane Properties:

$$
\begin{aligned}
\text{cross-sectional membrane area} &= 471.2 \text{ IN}^2 \\
\text{membrane thickness around perimeter} &= 0.125 \text{ IN} \\
\text{section modulus of membrane} &= 141{,}372 \text{ IN}^3 \\
\text{moment of inertia of membrane} &= 84{,}822{,}936 \text{ IN}^4
\end{aligned}
$$

(5) Calculated Internal Air Pressure Based on Membrane (only):

internal design air pressure (no wind and membrane only) =   10.47 psig (efficiency = 0.96)

(6) Calculated Preliminary Diagonal Cable Size and Spacing:

$$
\begin{aligned}
\text{tension in diagonal cables due to air pressure} &= 101{,}904 \text{ LB} \\
\text{number of diagonal cables} &= 79 \\
\text{spacing of diagonal cables} &= 3 \text{ FT } 11.72 \text{ IN} \\
\text{diameter of diagonal cables} &= 1.47 \text{ IN}
\end{aligned}
$$

(7) Calculated Preliminary Cross-Sectional Cable Properties:

$$
\begin{aligned}
\text{cross-sectional cable area} &= 134.2 \text{ IN}^2 \\
\text{equivalent cable thickness around perimeter} &= 0.080 \text{ IN} \\
\text{section modulus of cables} &= 89{,}989 \text{ IN}^3 \\
\text{moment of inertia of cables} &= 53{,}993{,}392 \text{ IN}^4
\end{aligned}
$$

(8) Calculated Internal Air-Pressure Based on Diagonal Cables:

internal design air pressure (cables) =   10.45 psig (efficiency = 0.96)

(9) Calculated Wind Force Results Based on Cable-Network:

$$
\begin{aligned}
\text{additional air pressure to resist wind force} &= 0.32 \text{ psig} \\
\text{deflection due to wind force} &= 0.03 \text{ IN} \\
\text{tension in diagonal cables due to wind force} &= 4{,}595 \text{ LB}
\end{aligned}
$$

(10) Calculated Final Diagonal Cable Size at Original Spacing:

$$
\begin{aligned}
\text{tension in diagonal cables due to air pressure} &= 106{,}252 \text{ LB} \\
\text{number of diagonal cables} &= 79 \\
\text{spacing of diagonal cables} &= 3 \text{ FT } 11.72 \text{ IN} \\
\text{diameter of diagonal cables} &= 1.50 \text{ IN}
\end{aligned}
$$

(11) Calculated Final Cross-Sectional Cable Properties:

$$
\begin{aligned}
\text{final cross-sectional cable area} &= 139.9 \text{ IN}^2 \\
\text{equivalent cable thickness around perimeter} &= 0.083 \text{ IN} \\
\text{final section modulus of cables} &= 93{,}828 \text{ IN}^3 \\
\text{final moment of inertia of cables} &= 56{,}296{,}960 \text{ IN}^4
\end{aligned}
$$

(12) Final Internal Air-Pressure Based on Diagonal Cables:

final internal design air pressure (cables) =   10.45 psig (efficiency = 0.96)

(13) Final Wind Force Results Based on Cable-Network:

final air pressure to resist wind force	=	0.32 psig
final deflection due to wind force	=	0.02 IN
tension in diagonal cables due to wind force	=	4,595 LB

(14) Final Combined Vertical plus Wind Loads Pressure:

final combined air pressure (wind plus vertical load)	=	10.77 psig (efficiency = 0.93)

(15) Calculated Final Revised Cable Size at Original Spacing:

tension in diagonal cables due to air pressure	=	110,847 LB
number of diagonal cables	=	79
spacing of diagonal cables	=	3 FT 11.72 IN
diameter of diagonal cables	=	1.53 IN

(16) Calculated Horizontal Cable Size and Spacing:

tension in horizontal cables due to pressure	=	158,256 LB
number of horizontal cables	=	49
spacing of horizontal cables	=	2 FT 0.49 IN
diameter of horizontal cables	=	1.83 IN

(17) Calculated Building Envelope and Cable-Network Weights:

total weight of building envelope and cable-network	=	267,495 LB (7% of dead load)
weight of plastic membrane	=	22,907 LB
weight of 79 diagonal steel cables	=	106,426 LB
weight of 49 horizontal steel cables	=	138,162 LB

(18) Calculated Length of Each Cable and Total Length:

length of each diagonal cable	=	224 FT
total length of diagonal cables	=	17,662 FT
length of each horizontal cable	=	314 FT
total length of horizontal cables	=	15,394 FT

As shown in steps (5) to (8) it is necessary to perform preliminary calculations to determine the approximate internal air pressure so that the approximate vertical (inclined) cable size can be established. This cable size is then adjusted to take into account the weight of the cable-network and the increased internal pressure due to wind forces.

Conclusions

Objection to a hyperbaric building environment does not necessarily rule out pneumatic construction systems. For example, the pneumatic structural component could be confined to a ring of air-inflated cells around the perimeter of the building. Such an annulus of pressurized columns would be capable of supporting a roof from which a number of floors are suspended. This is essentially a double skin system carrying with it the advantage of superior thermal insulation and the disadvantage of reduced structural efficiency.

In more general terms the following seven types of multi-story air-supported and fluid-inflated building types can be identified (Figure 7), namely: single-skin with cable-network; double-skin cellular; single-skin compartmentalized; multi-cellular multi-enclosure; single-skin rigid membrane; double-skin rigid-flexible membrane; and, high pressure central core.

Single-Skin with Cable-Network: This is structurally the most efficient fluid-supported building type and the primary focus of this paper. In principle it may be described as consisting of a pressurized building environment that is contained by an external flexible plastic membrane acting concurrently as structure and enclosure. For purposes of wind bracing and reinforcement of the plastic skin, a cable-network surrounds the membrane enclosure (Figure 7(a)). 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 internal air pressure of approximately *1 psig* above the ambient atmospheric pressure is required for each air-supported building floor. Accordingly, a 10-story building will require an internal, environmental air pressure of around *10 psig*. Access to the single-skin cable-network building is gained by means of an airlock entrance normally located at ground floor level.
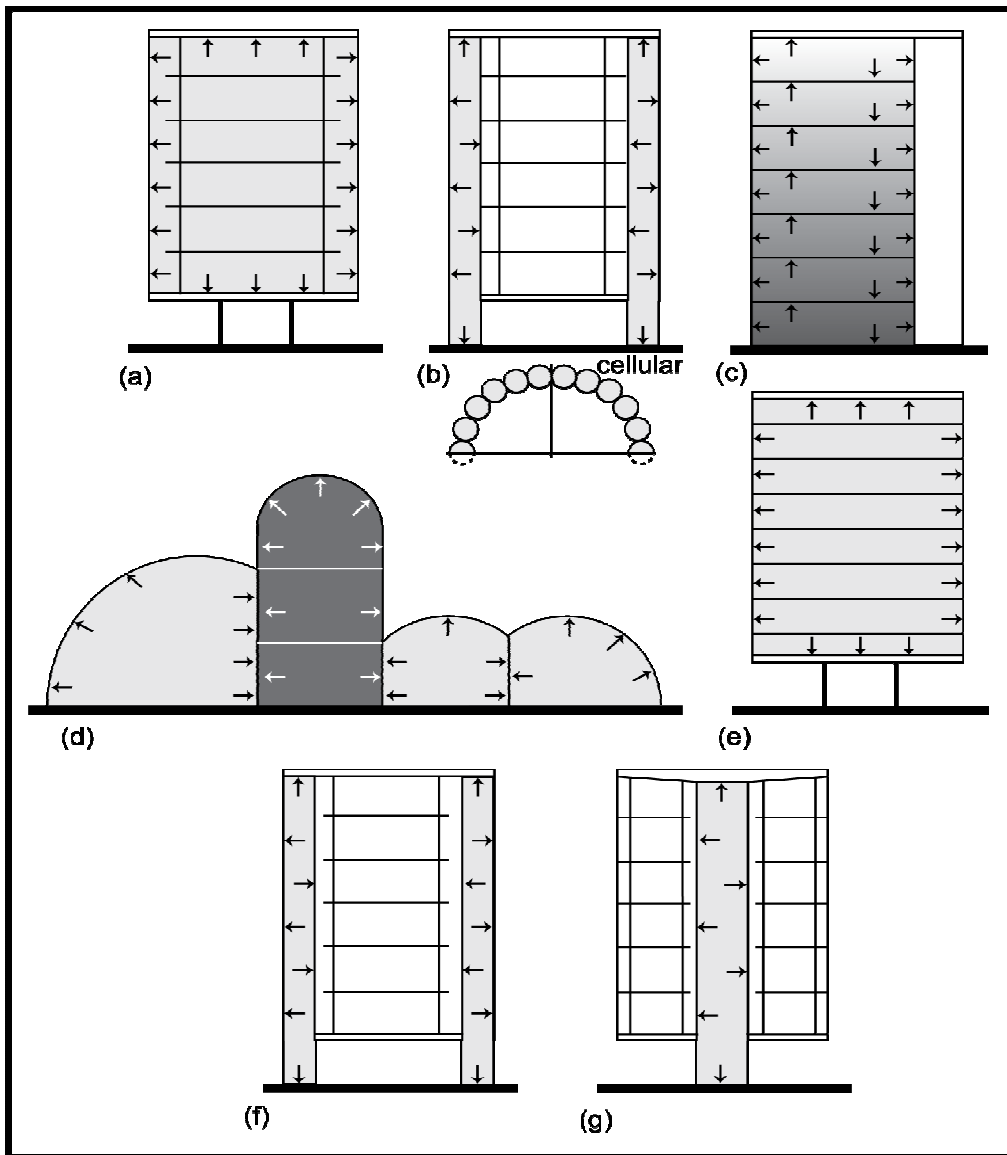
Figure 7: Multi-story air-supported and fluid-inflated structural configurations

Double-Skin Cellular: In this configuration structural support is provided by a continuous multi-

cellular annulus around the perimeter of the building. Floors are suspended from a truss system at roof level that in turn is supported by the pressurized multi-cellular building enclosure (Figure 7(b)). Once the cells have been inflated the pressurization equipment will not be required again unless a leakage develops[12]. Wind bracing may be provided by an external cable-network or an internal bracing system. In this type of fluid-inflated building structure the required cell pressure is dependent on the ratio of the floor area to the combined cross-sectional area of the cells. Since the cellular annulus is pressurized independently of the building environment, higher pressures and therefore taller buildings are possible. As mentioned previously, while sacrificing structural efficiency the cellular configuration provides the designer with opportunities for achieving superior thermal control and a higher factor of safety that might be more acceptable for terrestrial buildings.

The three alternative design configurations of the double-skin cellular building type shown in Figure 8 vary only in respect to the size and location of the structural cells (i.e., the pressurized columns) and the placement of the service core in the layout of each floor. As discussed previously the cross-sectional area of each structural cell is dependent on the number of cells, the total vertical building load (i.e., live load and dead load), the internal pressure, and the tensile strength characteristics of the cell wall material. The smaller the combined cross-sectional area of the cells in proportion to the area of one floor, the higher the internal cell pressure will need to be. This suggests that in most cases a rigid cell wall material such as metal or a filament-wound composite is likely to be preferred. In this case the structural design of each cell will be governed by thin-walled monocoque cylinder design principles (Pohl 2013, 157).
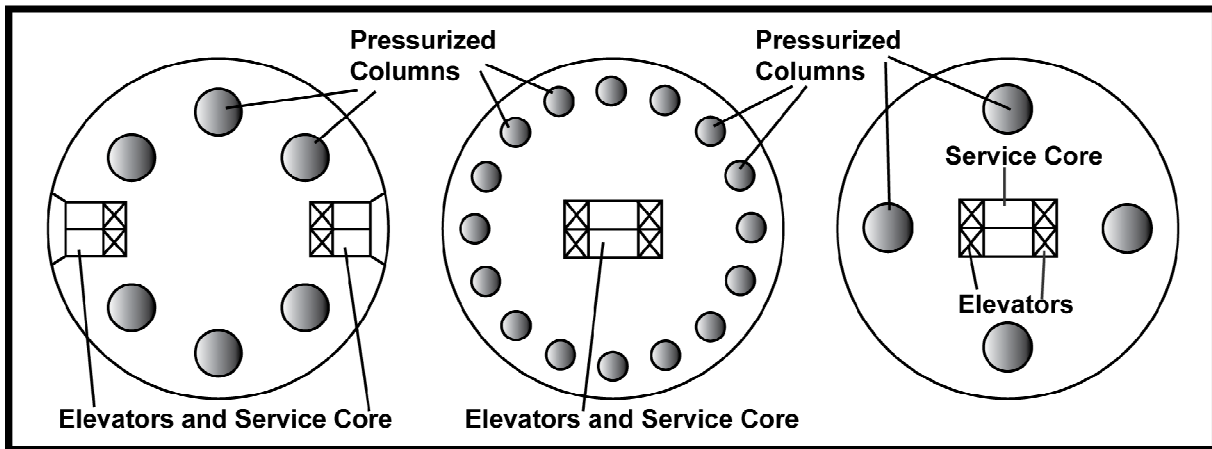

Figure 8: Typical floor layouts of the double-skin cellular fluid-inflated building type

Single-Skin Compartmentalized: In this air-supported building type separately pressurized, compartmentalized floors are stacked vertically on top of each other (Figure 7(c)). This requires airlocks to be integrated into each floor plan since the internal pressure of each floor compartment will increase proportionally for the lower floors. While this building type is still classified as an air-supported (as opposed to fluid-inflated) building, the underlying structural concept differs markedly from the standard multi-story air-supported single-skin building with

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[12] The term fluid-inflated is used in preference to air-inflated because a pressurized medium other than air may be preferred. For example, Pohl (2013, 133-136) describes a prototype building with a central column that is pressurized with water. The column serves not only as the principal structural component but also as a heat store for solar energy collected at roof level.

either a flexible (Figure 7(a)) or rigid (Figure 7(e)) enclosure. Since 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. Although the airlock requirement for each floor may prove expensive, cost 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. This leads to some interesting structural possibilities. First, the normal load-balancing principles commonly used in the design of post-tensioned prestressed concrete floor slabs may be applied to counteract the self-weight of the slab during construction. After construction the internal pressure of the compartment immediately below the slab will support the floor uniformly over its entire underside like an air-mattress. This means that both the dead and live loads are supported by the air pressure without the bending forces that a horizontal member would normally be subjected to coming into consideration. Instead, since the internal air pressure of the compartment has to be sufficient to support maximum live loads the floor plate will be subject to reverse loading and tend to dish upward like the top plate of a pressure vessel. These dishing forces can be counteracted by vertical ties between the top and bottom slabs within each floor compartment.

Multi-Cellular Multi-Enclosure: As shown in Figure 7(d), this air-supported building type consists of a combination of separately pressurized compartments (i.e., multi-cellular) and individually defined but jointly pressurized spaces (i.e., multi-enclosure). It is described in some detail in Pohl (2013, 116-124) as a prototype air-supported building that was constructed as an architecture graduate student project at Cal Poly, San Luis Obispo, California. Individual design configurations may include combinations of multi-story and single-story air-supported sections, both requiring a hyperbaric building environment.

Single-Skin Rigid Membrane: The building environment is pressurized and contained by a rigid metal or filament-wound composite membrane envelope acting as a short monocoque cylindrical shell under internal pressure, axial compression (i.e., vertical building loads) and lateral wind loads (Figure 7(e)). The required pressure of the internal building environment is dependent not only on the building loads but also on the thickness of the membrane enclosure. In single-skin rigid membrane buildings floors may be suspended from trusses at roof level or attached directly to the membrane envelope, thereby contributing to the overall stiffness and continuity of the air-supported structure.

Double Rigid-Flexible Cylinders: The internal building environment, which is at normal atmospheric pressure, is surrounded by two concentric cylinders adequately pressurized to support a suspended floor system at roof level (Figure 7(f)). 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 pressurized annulus may be divided into separate cells or compartments for increased safety.

High Pressure Central Core: In this fluid-inflated building type a high pressure liquid column acts as the supporting element of a hinged beam or truss system at roof level from which a number of annular floors are suspended (Figure 7(g)). Depending on the proportional relationship between the total cross-sectional column area and the typical floor area, columns in the height to diameter ratio range of *4:1* to *8:1* would need to be pressurized to around *100 psig*. The internal pressure has the function of resisting local buckling in the rigid metal or filament-wound composite column wall.

References

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