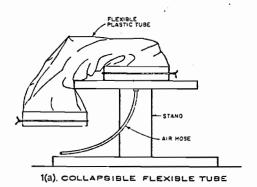
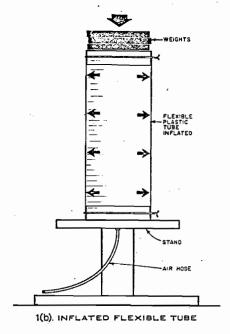
# Pneumatic Construction Applied to Multistory Buildings

Extension of the principles of pneumatic construction to include multistory buildings is discussed by Peter R. Smith, Senior Lecturer in Architectural Science at The University of Sydney (Australia) and Jens G. Pohl, Lecturer, School of Architecture and Building, University of New South Wales

he possible utilization of sealed membranes supported by a small internal air pressure1 has now become a practical solution for a number of architectural problems. We are familiar with the application of pneumatic enclosures to sports arenas, hermetically-sealed food stores, and warehouses, as well as temporary convention and exhibition stadiums. In all of these cases, lightness of weight, mobility, and the possibility accommodating large spans (sometimes in excess of 200 ft) have led to the adoption of air-supported structures. Even though these airhalls form a unique class of construction, and unquestionably provide an economically enclosed space suitable for specific functions, they are nevertheless of relatively small importance in a building industry preoccupied largely with multistory construction.

The potentialities of a newly developed structural system may be gaged, in part at least, by its versatility in being able to satisfy expected future trends on a broad basis. Accordingly, pneumatic con-

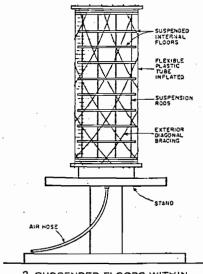




struction will develop into a more significant structural system, if its principles may be extended to include multistory buildings. Recent research conducted at the Department of Architectural Science, University of Sydney (Australia), dealing with specific aspects of pneumatic construction has culminated in the development of pressurized multistory membrane buildings2.3. The underlying principles of the proposed system are illustrated (1,2). Let us consider a flexible plastic tube sealed at both ends (1a). Although this tube has no load-bearing capacity in the deflated state, it becomes a stable compression member when subjected to a proportionate internal air pressure (1b). A membrane column depends upon internal pressure for its shape, resistance to bending, local buckling, and torsion. For short columns, this resistance will be a function of the magnitude of the internal pressure as well as membrane thickness, section modulus, and elasticity.

It is thus possible to utilize the load-bearing capacity of this type of column, whether the load is applied externally to the free end or suspended internally in the form of floors (2). Furthermore, taking into account that the normal floor load considered in the design of high-rise buildings is in the vicinity of 140 psf, it is logical to expect that for every 1 psi (i.e., 144 psf) internal pressure above external atmospheric pressure we will be able to support one floor of a multistory structure.

While the structural morphology of this pneumatic system is straight-



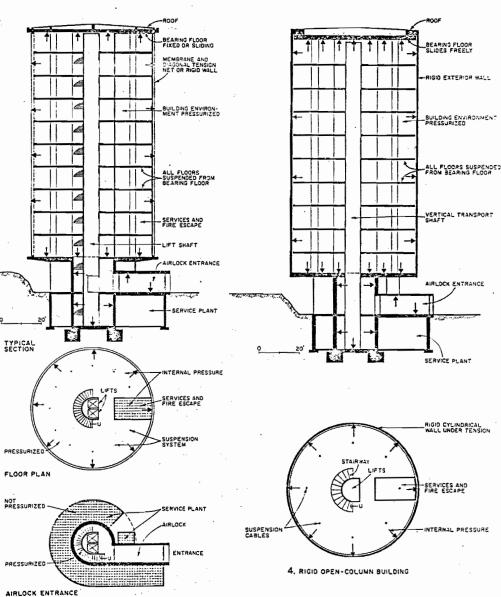
2. SUSPENDED FLOORS WITHII INFLATED PLASTIC TUBE

forward and may indeed appeal to the progressive architect and engineer due to its simplicity, its practical application will nevertheless require the solution of a number of complex, technical problems:

- (a) Physiological effects of the compressed air environment.
- (b) Performance of suitable membrane materials.
- (c) The nature of the relationship of internal pressure to loadbearing capacity (i.e., pressure-utilization efficiency).
- (d) Safety, in respect to maintenance of design pressure and fire hazard.
- (e) The mechanical problems associated with entry and exit from a pressurized environment.

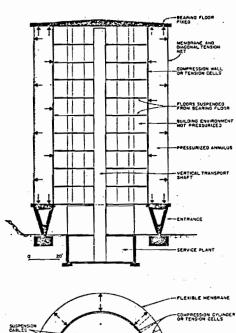
The physiological aspects of ambient, hyperbaric conditions and the performance of membrane materials TYPICAL have been dealt with extensively,2.3.4 so that a brief summary of the conclusions reached will suffice here. According to medical research reports, it seems likely that there will be no long-range physiological effects after subjection to pressures below two atmospheres absolute, regardless of duration or rate of decompression. For this reason a tentative pressure range of 1 to 2 atmospheres absolute (i.e., 0 to 14 psi internal pressure, above external atmospheric pressure) has been adopted for the design of multistory, pneumatic buildings.

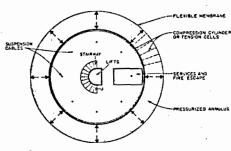
The most distinguishing characteristic of membrane buildings is undoubtedly that structure and enclo-



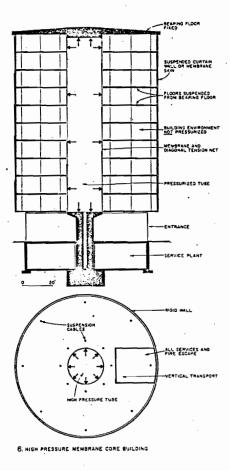
3. PNEUMATIC CRITERIA FOR 10 STORY OFFICE BUILDING

Following a discussion of basic structural variations, the authors report on severa spects of fire protection, offer a discussion of erection techniques, and analyze the problems of pressurization and air-conditioning equipment.





5. CELLULAR MEMBRANE-NETWORK BUILD



sure are synonymous. In this regard it is likely that we have found a means of utilizing plastics as an efficient structural material. As the result of a recent investigation regarding suitable, commercially available membrane materials, it was concluded that nylon scrim-based laminates capable of developing a yield strength of 1000 lb per in., or more, are most suitable for this application. However, indications are that for most projects it will be desirable to use an external tension net as a means of reinforcing the membrane. Under these conditions the required membrane strength will be simply a function of the mesh-size. A tension net in direct contact with the building membrane may be more efficient in stablizing the building laterally.

Experiments conducted in our laboratories have indicated that the structural pressure-utilization membrane buildings (i.e., the ability of a membrane column to support an axial load in proportion to its internal pressure) diminishes rapidly for slender columns and high pressures. In this respect we have been able to develop relatively simple formulas for the design of multistory, pressurized, membrane buildings with slenderness ratios (i.e.,  $\frac{1}{r}$ ) of less than 30. From a general point of view, if the tentative physiological pressure limit of 2 atmospheres absolute and a height to diameter ratio of 2 to 1 are not exceeded, then the pressure-utilization will be above 80 percent.

The safety of a membrane building will depend on the satisfactory performance of two structural elements - the internal air-pressure and the membrance envelope. In this respect the satisfactory performance of the membrane material is critical in regard to tensile strength, tear resistance, weatherability, and fire resistance. Furthermore, to offset any decrease in pressure as a direct result of leakage or localized membrane rupture, the duplication of critical mechanical equipment will be justified.

## Basic Structural Variations

A typical design of a 10-story office building based on pneumatic criteria is shown (3). Access to this building is gained by means of an airlock tunnel at ground floor level. It has been assumed that the rate of pressurization will be slightly less than the time required for an adult person to walk at a comfortable pace the distance between airlock-doors. Having entered the ground floor lobby, the normal choice of vertical transport is provided (i.e., lifts or staircase). Each floor level is planned to incorporate a service space comprising sanitary requirements, ducts, and fire-escape staircase. At the perimeter of these floors, movable screens are fitted and these serve the dual function of allowing acoustical and visual privacy as well as providing an effective fire barrier if necessary. At ground and basement level, substantial plant areas are required for air-conditioning and pressurization equipment. These areas are not pressurized. An interesting variation of these principles is illustrated (4), where mainly for convenience of erection the top bearing floor is not rigidly fixed to the membrane envelope. Accordingly a rigid, self-supporting membrane has been chosen so that the building envelope can be erected to full height before the building is pressurized. From a technical point of view we are concerned here with an open, pressurized column supporting a load on a piston,

which is in itself supported by internal pressure.

Objection to a pressurized building environment does not necessarily rule out pneumatic construction systems. Two systems that do not require pressurization of the building environment are illustrated (5.6). In the cellular membrane-network building (5), a pressurized annulus (which may be of a cellular nature) provides structural support for 10 suspended floors. In fact this is basically a double-skin system carrying with it the advantage of thermal and acoustical insulation. The extra expense of cellular systems may be warranted when design considerations, such as minimum heat transfer. indestructibility. predominate.

Normally, in this type of building the cross-sectional area of the annulus would be equal to the floor area, so that our assumptions regarding pressure-utilization would still apply. However, this is not the case when a high-pressure column is situated at the center of the building and annular floors are suspended from a cantilever beam system (6). Here we may expect a pressure-utilization of as low as 40 percent. Thus, a column of cross-sectional area A sq ft (slenderness ratio less than 60), pressurized to 100 psi, may be capable of supporting 10 floors of 4A c sq ft area each. While benefits that are fundamental to the fully pressurized, flexible, membrane-network buildings (3) are sacrificed in the high-pressure system, the Letter may nevertheless provide a convenient compromise solution to the conservative investor and building authority.

# Aspects of Fire-Protection

Within the context of presently accepted standards of fire-resistance, multistory membrane buildings will present problems that may well seem insurmountable at first sight. However, since existing regulations c. n-

not be amended to fully realize the potential structural applications of plastics, it may be necessary to reevaluate fundamental concepts on the basis of relating fire-hazard to the complete structure. In the case at hand, it is clear that economic risk must be sacrificed in relation to the danger to human life. The problem of fire-protection for multistory, pressurized, membrane buildings will thus be tackled in respect to:

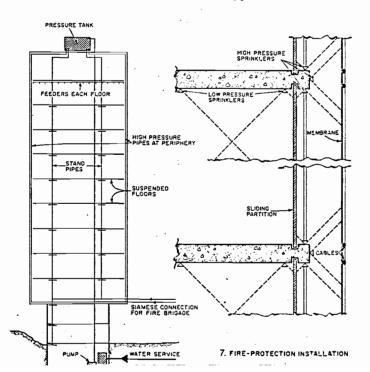
- (a) Minimization of fire-load<sup>5</sup> in relation to structure, cladding, and contents. It seems likely that the effective fire-load of a building could be reduced by providing separate fire-rated storage units for areas containing a high density of combustibles. In isolating combustible content we are able to reduce the fire-protection of the noncombustible structure and concentrate treatment in smaller areas more effectively.
- (b) The installation of effective fire-services in the form of detectors, shielding systems, and deluge sprinklers that will allow sufficient time for mass evacuation before structural

failure can take place. It may be desirable to plan evacuation in two stages: first, to a fire-rated shelter at basement level within the building confines; second from this shelter to the exterior.

Consideration must be given to shielding of the membrane envelope from radiation, and heat insulation of the suspension cable system. In the first case, the authors have proposed the installation of automatically controlled, reflective, sliding screens positioned at the perimeter of each floor (7). In the case of a fire at any point, 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 sprinkler nozzles will spray water against the membrane and the reverse side of the screens.

# **Erection Techniques**

Pneumatic structures of the type described will require new procedures for erection, new sequences of assembly, and different allocations of manpower. The suspension scheme depends upon a framework of Vierendeel-type trusses or a beam sys-



Since continuous maintenance of internal pressure is essential for structural sta. y, the topic of safety leads to several vital considerations.

tem at the top, with main supporting fixtures at the perimeter. From these, whole floors or units are suspended by means of high-tensile steel cables. First floor to basement level will be a normal compression structure with circular, prestressed-concrete walls enclosing all pressurized areas. Suspended floor slabs will be prestressed and poured sandwich fashion similar to normal lift-slab construction routine. In most cases trades will be able to commence work inside the building at an early stage in construction (i.e., as soon as membrane and cable-network are in position). A more detailed master program based on main erection operations is outlined (8) for the four building types previously described. Time schedules have been expressed as a percentage of total time to obviate the need for specific time allotment at this early development stage.

There is some justification in the thesis that the shortage of skilled craftsmen and experienced labor in the Western World will, in the face of greater demands, increase the cost of those buildings that are planned and constructed by conventional methods, requiring a large amount of skilled labor. The problem is particularly acute in urban areas where multistory buildings are required in increasing numbers. In this context the pneumatic-suspension system will realign the work of skilled labor for greater efficiency. The construction program, by virtue of a higher content of prefabricated components and the ability to mechanize on-site erection operations, will lower erection time with subsequent savings in labor costs and investment losses. A variety of advanced technologies applicable to buildings can be utilized. In addition to the industrial techniques that are readily applied to the construction of membrane, cable-network, and the high percentage of nonload bearing elements, one can employ the latest techniques for lifting heavy loads that have already

been developed in other construction fields. It is thus apparent that the erection of pneumatic buildings requires little development work, by being able to draw upon existing methods of engineering construction.

# Pressurization and Air-Conditioned Equipment

The concept of a sealed, pressurized building at once eliminates the infiltration of dust, unwanted hot or cold air, and even rainwater leakage into the building, but introduces a stringent requirement for conditioning and changing the air and maintaining its pressure.

The range of pressures 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, that 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 aftercooling would be necessary in summer. The winter requirement would depend upon the rates of air exchange between the building and the outside air. Since the building is sealed against air exchange with the atmosphere, fresh air will need to be supplied to the occupants; and since the membrane is envisaged as a thin and partly transparent envelope, considerable transfer of heat by conduction and radiation can be expected. Therefore, an air-conditioning system will be required which provides enough makeup air to supply oxygen to the occupants, and which controls the temperature and humidity within a comfortable range. The make-up air will replace air lost through accidental leakages and through the entrance air-lock. It is intended that the total make-up air should be considerably greater than these losses, so that an additional self-balancing air escape will be provided to control the internal pressure and allow any excess air to escape. This will also take care of changes in air pressure due to diurnal temperature changes. Accidental leakage up to the amount of air which would escape through this valve will therefore cause no harm to the building.

The total heat gain in sunlight conditions is likely to be much higher than for a conventional building because:

- (a) There is no optimum orientation for a circular building.
- (b) There is no provision for sunshading in the basic pneumatic building as described.
- (c) The transmission of heat by radiation and conduction through a thin membrane will approach that of the glass in a conventional building, and will occur over the whole of the vertical surface.

The maximum solar heat falling on a cylindrical surface occurs when the sun's altitude is in the range 30-40 degrees. (The intensity of radiation normal to the sun's rays falls off as the altitude decreases. This fallingoff is much more rapid at altitudes below about 30 degrees. The sun strikes a maximum projected area of the cylindrical surface when the altitude is zero.) This maximum corresponds to about 4 P.M. on a summer afternoon in Sydney, at which time the air temperature may be also close to its maximum. It also occurs even in midwinter, so that on a sunny winter day considerable cooling may be required.

Let us assume a building 60 ft in diameter and 120 ft high, with a design temperature difference of 20 degrees between inside and outside, and a thermal transmittance (U-factor) of 1.10 for the membrane. This will be compared with a conventional square building of similar area, having windows occupying 25 percent of the external wall area, and using typical values for U-factors of the walls and roofs. Ap-

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2	FABRICATION OF MEMBRANE AND SUSPENSION FITTINGS												
3	INSTALLATION OF PRESSURIZATION SYSTEM.												13
4	POUR FLOOR SLABS AND BEARING FLOOR IN LAYERS AT FIRST FLOOR LEVEL.												11 12 14
4 <sub>A</sub>	POUR FLOOR SLABS AND BEARING FLOOR IN LAYERS AT GROUND LEVEL.												
5	PREPARE ALL FLOORS FOR FITTING MEMBRANE AND CABLE NETWORK.							,					10 18 <u>A</u>
5 <sub>A</sub>	ERECTION OF RIGID EXTERIOR WALL AND CABLE FITTINGS.												8 9
6	MEMBRANE THREADED OVER FLOORS AND FIXED IN PLACE.												
7	LIFT BEARING FLOOR TO FULL HEIGHT WITH CRANE AND SMALL INTERNAL PRESSURE, ROOF FIXED AND FLASHED.												ART L
8	CABLE NETWORK FIXED IN PRELIMINARY POSITION.												PLOW-CHART
9	PREPARE FLOORS FOR HOISTING, PRESSURIZE TO FINAL DESIGN PRESSURE.												
10	FLOORS LIFTED IN POSITION ON SUSPENSION CABLES.												5 1 .
10 <sub>A</sub>	ERECTION OF INNER WALL TO FULL HEIGHT AND CORE TO BE DE-PRESSURIZED.					000000							4 3 3
11	CONSTRUCTION OF STAIRCASES, SERVICE DUCTS, PERIMETER PARTITIONS.												
II <sub>A</sub>	FIX CURTAIN WALL OR MEMBRANE.												1 2
12	ADJUST CABLES TO FINAL POSITION.												<b>A A</b>
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HIGH PRESSURE MEMBRANE-CORE BUILDING

CELLULAR MEMBRANE NET-WORK BUILDING RIGID OPEN-COLUMN BUILDING

8. SCHEMATIC ERECTION SEQUENCE AND FLOW-CHART FOR FOUR VARIATIONS OF PNEUMATIC BUILDINGS

Apart from the direct saving that tend to favor the membrane building, the authors conclude that there will undoubtedly be considerable indirect savings in respect to labor and erection time.

proximate figures for external heat gain are tabulated below:

Heat gain (Btu/hr) due to	Membrane Building	Conventional Building
Wall		
conductivity	500,000	237,000
Wall direct		
radiation	1,060,000	324,000
Wall diffuse		
radiation	340,000	110,000
Roof conductivity	22,000	22,000
	1,922,000	693,000

Thus, the heat gain of this membrane building at the worst time is about three times that of a conventional building. The radiant heat gain through the membrane can be substantially reduced by coating all but the "vision strips" with an opaque, reflecting surface such as a metallic coating or a highly reflective white paint. Using a reflectivity to solar radiation of 0.80 over three-quarters of the surface reduces the total external heat load of the membrane building to about twice that of a comparable conventional building.

In the example taken above, an air-supply at the rate of six air changes per hour (at atmospheric pressure, i.e., three changes per hour at two atmospheres) would permit a heat exchange of 700,000 Btu/hr with a temperature difference of 20 degrees between inlet and outlet. For the peak cooling condition, it would be necessary either to increase the air supply to about 12 changes per hour at 1 atmosphere, or to use secondary cooling such as chilled-water fan-coil units within the building. If additional air-handling is used, it should be carried out in a high-pressure circuit with the acceptable minimum of make-up air, since the energy required to compress the make-up air to building pressure could otherwise add greatly to the energy needed for cooling the building.

Although the thermal performance of the pneumatic membrane building in its simple form is substantially inferior to that of a conventional building, the situation could be greatly improved by the addition of

reflective coatings to the spandrels, and even of partially-reflective coatings to the window strips; by adding flexible insulation material to the opaque sections of the membrane; and by the addition of sunshading devices externally. Horizontal sunshading louvers could be hung from the top bearing floor on the external side of the membrane and attached at intermediate points to the existing cable-network. In this case, that portion of the heat load which is produced by solar radiation impinging directly on the building enclosure could be reduced at will as a function of the vertical spacing and horizontal projection of the louvers. The desirability of doing any or all of these must be evaluated by considering also the essentially simple, demountable nature of the building. The effect any such addition would have on the speed and ease of erection of the envelope needs to be viewed against the cost of operation over the expected life of the structure.

From the considerations of heat load, air supply, and access, it becomes clear that the pneumatic building has particular merit where the number of occupants is small and the anticipated life is not great. In the case of a building housing mainly equipment or materials, the delay of ingress and egress through the airlock, the problems of fire escape, the need for fresh-air supply and the need for transparent areas in the membrane are all reduced.

# **General Safety Considerations**

Since continuous maintenance of the internal pressure is essential to the structural stability of a multistory pneumatic building, the topic of safety is heavily dependent upon:

- (a) The satisfactory performance of the pressurization equipment in being capable of sustaining an increased air-input under emergency conditions.
- (b) The ability of the building membrane to resist tearing after punctures have occurred.

Because of the requirement of reliability, the design of the mechanical equipment will present problems not usually encountered in building construction. The provision of standby plant, and probably alternative energy sources, will be necessary. It may be pointed out that single-engined aircraft and helicopters are accepted as a reasonable risk, being solely dependent on a single power unit. A better analogy for the pneumatic building would be the multipleengined airliner, which is capable of operating with part of its power system out of action.

Let us now consider the performance of the building membrane. One type of plastic material, at present available to satisfy the performance requirements, such as tensile strength, weatherability, etc., is a nylon scrim base laminate coated with a PVC or PVF film externally and polyurethane internally. The nylon scrim has the ability to localize rupture by developing a fairly high tear-strength. Should the building membrane be punctured by accident or as an indirect result of civil disturbances (e.g. bullets and larger projectiles), and this perforation remains localized due to the tearresistance of the material, then the continuing stability of the building structure will be purely a question of pressurized air-input. The design of the mechanical equipment can therefore be dealt with statistically; i.e., what is the probability of failure in relation to the effective size of a puncture that may occur in the lifetime of a building?

i.e., lower material cost and

insurance

must balance

lower equipment cost

risk

In fact, the designer is taking a calculated risk (i.e., insurance risk) that the conditions which would cause the building to collapse will not occur during its lifetime. It may be noted that the proposed theory of "differential load factors" is based on

<b>ExilC</b> infe Confection	tingresses or degrees in conventional beliefs conventional beliefs	
Foundations	40%	Lighter overall weight.
Floors (incl. beams)	—10%	Smaller spans are possible with supension system.
Columns		Suspension cables only above first floor.
External Walls	60%	Plastic membrane and cable-network only.
Air-Conditioning	+100%	More elaborate plant required.
Fire Services	+30%	Greater protection needed for membrane.
Internal Finishes	20%	No wall finishes required.

identical premises.6 A similar sort of risk is taken in any structural design. The natural desire to have the greatest economy compatible with a sufficiently improbable risk is reflected in the gradual reduction of factors of safety in structural codes. In the present case, the risk is one of total collapse in the event of an appreciable, sudden loss of pressure, and therefore the probability of this happening must be made extremely remote by adequate design safeguards.

On the other hand, the pressurized membrane-cable-network building, by virtue of its flexibility, is much more resistant to damage by earthquake or by the blast from an explosion than a conventional building constructed of more brittle materials. This property could be exploited in regions subject to seismic disturbances.

## The Mechanical Building

The economical aspects of pneumatic buildings are strongly influenced by

a set of variables not so far considered in multistory, architectural construction.

- (a) Full realization of material strength due to the conversion of axial load forces into tensile stresses. In this regard pneumatic structures will invite the use of high-strength materials, leading to the application of more accurate and critical design theories.
- (b) 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.
- (c) In those cases where the building environment is required to be pressurized, we are able to consider structure and enclosure as one entity. Moreover, the enclosure will be continuous, thus eliminating problems associated with joint sealants, drainage, expansion, and moving parts.

The type of pressurized building envisaged here has obviously not yet been developed to the stage of practical construction, although a design has been prepared for an experimental three-storied prototype. Therefore, any attempt to estimate costs will be largely intuitive, based on the assumption that some previous experience had in fact been gained in erecting a building of this type. The principal differences are listed (see table).

Apart from the direct savings which tend to favor the membrane building, there will undoubtedly be considerable indirect savings in respect to labor and erection time. The desirability of predetermining lifespan on the basis of a dynamic, replacement policy will become a necessity for this type of multistory building. We may in fact treat pneumatic structures as mechanical buildings, designed for specific requirements and governed by critical performance standards on par with aeronautical engineering concepts.

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- la Plastic membrane tube sealed at both ends 1b Same tube in the pressurized condition acting as a stable compression membe
- With the addition of suspended floors, a multistory building evolves
- Typical multistory pressurized, membrane-cable-network building.
- Rigid open-column building Cellular membrane-network building
- 6. High pressure membrane core building Fire-protective installations
- 8. Master program of main erection operations