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AIR STRUCTURES

THE ANALYSIS APPLICATION AND MANUFACTURE OF AIR STRUCTURES WITH REFERENCE TO CANADA

by

Stuart Critchley, B.Sc., A.C.G.I.

A Thesis
Submitted to the Faculty of Graduate Studies
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TITLE: THE ANALYSIS, APPLICATION AND MANUFACTURE OF AIR STRUCTURES

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SCOPE AND CONTENTS: The development and analysis of physical characteristics pertaining to the contruction, operation and maintenance of air structure systems is presented, with particular emphasis being given to Canadian applications. A design methodology appropriate to the design of air structures is introduced, and successfully utilised in the production of a structure installed in Nova Scotia in 1973. Further comparative examples are presented to illustrate the versatility of air supported structures with reference to future requirements.

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NOMENCLATURE

D = diameter of cylindrical section of an air structure.

Pi = inflation pressure of an air structure in inches w.g.

ℓ = overall length of an air structure.

w = overall width of an air structure.

h = overall height of an air structure.

R = radius of curvature of a membrane.

$N\phi$ = circumferential stress resultant of a membrane section, in lb./ft.

Nx = longitudinal stress resultant of a membrane section, in lb./ft.

q = stagnation pressure of a wind tunnel.

T = catenary cable tension in lb.

b = catenary cable span in ft.

P = effective pressure on an air structure section.

Cp = mean pressure over some area in terms of the stagnation pressure of the corresponding air flow.

Ce = wind exposure factor, describing the relative exposure of a particular site.

Cg = gust correction factor, describing the susceptibility of a particular structure to dynamic loads.

a = volume flow through an orifice in c.f.m.

Δp = a differ pressure across an orifice, in inches w.g.

$g\rho$ = density of air, lb./cu.ft.

Cv = coefficient of velocity of air flow through a particular orifice.

Ce = coefficient of contraction of air flow through a particular orifice.

Co = Co x Cv = 0.65 for air through an orifice of neglibible length.

inch w.g. = scale of pressure inches water gauge, (1 inch w.g. = 5.20 p.s.f.)

pr = local pressure tending to lift some surface in terms of the stagnation pressure of the corresponding air flow.

1 INTRODUCTION

The term air structure was first used by Lanchester [1] in a 1917 patent application. He described his invention as "a structure of large size in which a material of low permeability is employed in an erected state by air pressure."

A schematic illustration of the basic modern air structure system is presented in Figure 1. The commercial structures usually have a configuration produced by the combination of spherical and cylindrical elements, and can be produced in sizes ranging from smaller structures with dimensions of several feet, up to larger installations with maximum base dimensions of 200 feet in width and 500 feet in length. The membrane is stabilised against climatic loads by the pressurised air within the structure; this pressure is usually of the order 1-2 inches w.g. Make up air is constantly supplied to the system to replace any losses. These losses are mainly due to leakage around the base of the membrane, where it is anchored to the ground or foundation, and to diffusion of the air through the membrane. Anchorage is necessary to secure the membrane against both inflation and wind induced loads.

Air structures in use today can be categorised into two groups, namely:

i) single walled structures which utilize the volume within a single inflated membrane. These particular structures form the basis of this report, and as such are referred to as air supported structures or simply as air structures, and

ii) dual walled structures which utilize inflated tubes as structural members. Details of these inflated structures are reviewed in References 2-6.

The development and physical characteristics pertaining to the construction, operation and maintenance of air structure systems is presented. The analysis of a typical air structure is complex as a result of the significant effects on the inflated structure of the environmental parameters of wind and temperature which in turn affect the unpredictable behaviour of the membrane materials. Any structural design criteria must therefore satisfy three important considerations:

i) environmental conditions,

ii) strength and behaviour of the membrane fabric and other component materials, and

iii) interactive effects of the individual components which comprise the air structure system.

The successful implementation of this design methodology, developed by the author, is best illustrated in terms of the air structure installed in Nova Scotia in June 1973. The details of this design are presented; all constraints imposed as a result of the particular practical requirements are discussed in terms of three additional designs which permit further conceptual modifications to be introduced if and when necessary.

These applications have been specifically selected to emphasise the particular relevance of air structures to Canadian geographic and climatic conditions, the needs of industry and future development work.

2 THE DEVELOPMENT OF AIR STRUCTURES

The earliest recorded use of structural artefacts, which utilised membranes tensioned by air pressure can be traced back 2000 years, to the use of inflated animal skins as rafts on the Tigris and Euphrates [2]. Eighteen centuries later, balloon structures began to appear. These balloons were the forerunners of the present air structure, being constructed of fabric and equipped with a continuous air supply. The concept of using both the inflated membrane and the space it encloses is due to F.W. Lanchester [1], who in 1917 was granted a comprehensive patent. The patent describes "An Improved Construction of Tent for Field Hospitals, Depots and Like Purposes". In the application, Lanchester outlines numerous aspects of present day systems: suggested methods of anchorage, airlocks and inflation being of particular interest. Problems which various manufacturers had overlooked until the last decade in connection with anchorage loads around openings were predicted and solutions outlined [7]. A second example of this foresight is the recommendation for secondary inflation systems for use under heavy wind loads, which was adopted by one manufacturer following a structural failure in 1974 [8]. Other examples included in the text further illustrate Lanchester's foresight.

Lanchester made specific design proposals for a large dome to be built in London in 1938; the dome was not constructed due to the lack of satisfactory membrane materials. Wartime improvements in the textile industry produced materials for barrage balloons and other new inflated devices, such as parachutes and life rafts. Utilising these fabrics the first air supported buildings were produced, and used predominantly as artillery targets. Some structures, produced with stabilised tubes were used as tents by the allies in the North African campaigns.

Bird,[9] working at Cornell on problems of radar installations, proposed that the unreliable wooden structures being used to protect installations at that time be replaced by pressurised membranes. He predicted that these membranes would be more stable and would overcome problems of radar transmissibility through the wall. A series of experimental models proved the feasibility of the new structure, which Bird named the Radome. The first Radome was installed in Canada in 1952 [9].

Commercial interest in air structures was developed by Bird. After leaving Cornell his team founded Birdair to manufacture and to promote air structures. They firstly developed structures for use as warehouses, and in cooperation with Cooley, a fabric manufacturer, sold the first commercial air structure in 1957 [10]. A domestic swimming pool enclosure was then developed, but did not have the success which was predicted in 1957 [11]. This lack of success can largely be attributed to the use of transparent panels having a very short expected lifetime, which even today would make this venture, or its equivalent, unlikely to succeed.

During the following decade the principle users of air structures were exhibition architects, who enjoyed the freedom of form and relatively large free spans of the new buildings. The most famous example of these early structures is the Boston arts centre described in Reference 12. The architectural interest peaked in 1970 with the Osaka exhibition in Japan, which housed 14 air structures on its site. Photographs of the buildings and descriptions (in Japanese) may be found in Reference 13, and further details of the U.S. pavillion in 14, 15, and 16. This use in exhibitions increased the acceptability of the air structure, especially in Japan [17], for its use in industry and sport, and produced the necessary incentive for fabric manufacturers to improve and develop fabrics for this new market.

The first scientific and analytical interest was expressed by Otto [3], in 1962, who at that time pointed out the excessive competitive secrecy of the few air structure builders of that time. Otto suggested that it would probably damage the long term future of the industry. This reticence about technical information is still felt today. The lack of cooperation has caused failures of air structures which were produced by companies experienced in fabric utilisation but not in structural design. This is underlined by design loads used in some of these structures [18,19] which are orders of magnitude below the design loads in use today.

Otto has been the driving force in organising conferences [20,21,22] and attempting to coordinate world research through his laboratory in Germany. The main success of this effort has been in the areas of membrane analysis on a highly theoretical level, with little relevance to actual materials. Research into material properties and their improvement would be more useful to the industry at the present time.

Acceptance of air structures has been greatest in the U.S., western Europe and Japan. In total over 100 companies are now equipped to produce air structures. The Canadian market is being supplied mainly from the U.S. and Sweden.

3 AN OUTLINE OF THE CHARACTERISTICS OF AIR STRUCTURES

3.1 OPTIMUM AIR STRUCTURE SHAPES

Independent work by Otto [3], Brylka [23], Murata [24], and Minke [25] illustrates the infinite choice of possible shapes for inflated structures. In evaluating any system there are three specific areas of consideration. These areas can be discussed with reference to the more common basic shapes shown in Figure 2, which are produced by the combination of cylindrical and spherical sections:

i) End use of the enclosed volume will usually predetermine the requirements of a basic ground plan and the usable height (volume) of a structure. For example, the rectangular ground plan building shown in Figure 2(i) is produced from cylindrical sections and, finds use in both industrial and sporting applications. While tennis courts and industrial lots usually have this common ground plan, the tennis courts would require greater height than most industrial applications, or even other sporting applications such as swimming pool or ice rink enclosures. The spherically ended cylinder illustrated in Figure 2(ii) finds acceptance in the bulk storage of powder. Structures in this application generally have a relatively large height to width ratio, to suit the angle of repose of the material. This shape has also been used successfully to cover track and field areas, where excessive height is not necessary. The spherical structure, shown in Figure 2(iii), is most commonly used to form a protection for radar and communication equipment. Other shapes exist which combine these forms with either solid end walls or sections of existing buildings [27]. Absolute size limitations have not been approached for any structural shape; limiting spans of tens of miles have been shown to be feasible for dead load considerations only. However, as discussed later in the section on wind loading, the author is of the opinion that size will be limited by wind induced instabilities.

ii) <u>Membrane loads</u> are affected by both the aspect ratio (height/width) of a structure and the form of the structure. Otto [2] and Brylka [25] highlight the constant tension feature of soap bubble formed models, however, it should be noted that wind loads are the major structural consideration even in Canada, where wind speeds are not excessive as compared with say Japan. These non-uniform wind loads induce localised stresses even in spherical structures, hence the constant tension feature of a soap bubble which represents optimum conditions, cannot be obtained. It can be shown that the membrane loads are a function of both the pressure difference across and the curvature of the membrane structure. Figure 3 illustrates the form of the variation in maximum membrane loads as a function of aspect ratio, for a particular structural.width and wind speed [26]. Increasing the height of the structure produces higher local wind loads, and at the same time increases the curvature of the structure. The interaction of those two effects produces the minimum in membrane load shown in the Figure, at the optimum aspect ratio.

The basic shape of the structure affects the air flow and hence the wind loads on the structure. For example the more severe contours of the rectangular structure, Figure 2(i), are effective in reducing wind loading as compared to a spherically ended structure with similar dimensions.

The technique of reinforcing the membrane with cables, presented in Figure 2(iv) can be applied to all the previously described configurations. The purpose of cabling is to reduce the fabric loads by the introduction of load carrying cables. The cables are often in the form of a triangular or rectangular network and can be anchored at their intersections, or as illustrated in Figure 2(iv), as a series of parallel cables running along the structure. A second advantage of the cabled structure is its capability to stop the propagation of tears in a system, which is a usual mode of failure of the membrane system.

iii) Manufacturing considerations encompass material usage, ease of handling and assembly. In materials usage evaluation it must be noted that air structure fabrics are supplied in roll form, and that the most effective shape to produce is the cylinder. The cylinder has the added manufacturing advantage of straight seams, and like the sphere, has geometrically identical panels. The principle stress directions in a structural cylinder are made to coincide with the thread directions in a conventional woven fabric. At the present time the fabric cost comprises approximately 7% of the cost of total structure. Hence the lower labour content of cylinder panels, which require less cutting and marking than do spherical panels, overshadows any advantage associated with the reduction in scrap material. There are also difficulties involved in the assembly of spherical parts, caused by lack of fit between contiguous panels. This problem arises because the fabric panels will stretch in handling more easily on one edge where the thread direction is more oblique to that edge than on the adjoining edge of the next section. The extra care involved in match marking of these panels makes handling more time consuming and expensive.

Cabled structures are by nature of their complex panel shapes more difficult to cut and assemble; furthermore, fittings to locate the cables have to be attached to the membrane at regular intervals. These extra costs restrict the use of cabled structures to larger installations subject to heavy loadings. Raising the absolute size of the structures increases handling costs as the required sections become more difficult to maneouvre. These costs can contribute as much as 20% to the total cost of a larger air structure. For structures covering more than approximately 30,000 square feet, it is usually economical to use field jointed sections.

Consideration of the above factors enables the design of shape providing an optimal compromise, commensurate with both economics and application.

3.2 STRUCTURAL EFFICIENCY

The air structure system has only two major structural components:

i) The membrane, which when loaded in tension is inherently stable. Under load the membrane exhibits both large strains and deformations. Strains of up to 8% and deformations of up to 15% on radius of curvature are normally expected values [28]. These deformations in areas of high loading allow efficient carrying and distribution of localised loads, as the component of the membrane tension balancing the applied loads increases with the deformation. The stability of the system under dynamic loads is due to the damping provided by the second structural component, which in a conventional structure would be the compression member.

ii) The enclosed air. Unlike its conventional counterpart this compression member is inherently stable. In an unloaded condition the structure will take up the maximum volume -- minimum energy configuration, any loading will tend to force the structure away from this condition, and will decrease the volume; the accompanying increase in the internal pressure will tend to force the structure back to its original form.

This form of construction,unlike other buildings, should not be considered as a rigid structure, but rather as a dynamic system, which in terms of material usage is the most efficient building form available.

3.3 INFLATION REQUIREMENT

To replace leakage from the air structure, through 'crackage' around the base and doorways, and by diffusion a continuous air supply is required. In remote areas, this, air supply can be a severe limitation in the use of the air structure. The air flow requirement for the inflation of many structures which are occupied, is less than that required for ventilation or heating of the system. Since the primary purpose of the air supply is to pressurise the building and provide stability against climatic loads, additional air supplies are often provided for use under excessive loadings. Since hydro supplies often fail due to high wind conditions, it is advisable to have a standby power system available. These standby systems constitute a significant part of the cost of an installation and as such their cost has to be weighed against that of a probable systems failure in the event of a high wind and the damage to the structure and its contents. Reliability of the air supply systems is high, since they are based on the proven components of other air handling systems, the technology of which is well developed. The air structures operate in the same pressure range as these systems, between one half and two inches water gauge.

3.4 WEIGHT AND SIZE CONSIDERATIONS

The 24,000 ft.^{2} membrane described in this work had a total weight of 4800 lb., and a shipping volume of less than 200 ft.^{3}. These values illustrate the ease of transportation and handling of the completed structure which gives it a degree of portability not found in other structures of this size. The air structure can therefore be used to advantage in both seasonal and semi-permanent installations, where frequent handling of the membrane is necessary.

3.5 PRODUCTION

Production costs of air structures are predominantly factory costs related to the labour costs of handling the structure. These costs are considerably less than the costs of on-site building labour as emphasised by the trend towards factory produced building components used in modular design. The industry is not highly mechanised and requires about 20% skilled labour, the rest being unskilled; hence labour costs are kept to a minimum. In Canada, the building season is relatively short and can be economically extended if most of the work can be done indoors, to subsidise the extensive cost of winter site working.

3.6 THE DESIGN LIFETIME OF AIR STRUCTURES

At the present time, an expected design life for an air structure membrane is seven years. Five years ago, the usual figure quoted was three to five years. This limited lifetime is due to damage from both handling and environmental exposure of the membrane. This is an obvious disadvantage of the building and has led to the emphasis of the use of air structures on a temporary or semi-permanent basis. However, as is shown later, to replace the membrane after its useful lifetime is not expensive. Most forms of building require regular maintenance, and the membrane renewal can be viewed on this basis. As the fabric technology improves, the expected lifetime will doubtless increase.

3.7 ECONOMIC ASPECTS

The following figures are estimates based on the 20,000 square feet structure described in Chapter 7 and represent the customer costs. This structure was supplied with a foundation wall, two vehicular airlocks, two personnel airlocks, and heating and lighting systems.

Capital Costs	
Membrane Materials	$13,000.00
Factory Costs	4,000.00
Labour Costs	8,000.00
Foundation	14,000.00
Airlocks	23,000.00
Heating System	26,000.00
Standby Air Supply System and Control	1,000.00
Lighting	5,000.00
Installation	3,000.00
TOTAL STRUCTURE COST	$97,000.00

or $4.85 per sq.ft.

<u>Running Costs:</u> ($ per annum)

Inflation	$ 800.00
Heating	7,000.00
Lighting	900.00
Insurance	3,500.00
Membrane Replacement*	3,600.00
TOTAL COST PER ANNUM	$15,800.00

or .79¢ per annum per sq.ft.

In comparison a single story steel frame building with heating and lighting facilities would cost approximately $20 per sq.ft., a difference in initial outlay of over $300,000, which would more than adequately make up for the higher running costs of the air structure.

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* This figure is based on a linear amortisation over the expected 7 year membrane life.

4 COMPONENTS OF AIR STRUCTURES

4.1 MEMBRANE MATERIALS

The vast majority of air structures are fabricated using a coated fabric, in which a load carrying base cloth is protected from its environment by an impermeable coating. Three types of base cloth are in use at the present time. The first is nylon which until 1970, had by far the largest share of the market, but is presently losing this position to polyester. The polyester based fabrics are being used in all but the largest structures (structures whose smallest dimension is larger than 150 feet) [30]. In these larger structures, fibreglass is now the standard material [14].

Nylon and polyester cloths have many similarities, such as their high strengths in an unweathered state, and their extreme flexibility [31]. Coating of these two materials with other polymers presents little difficulty, good adhesion being easily obtainable with both materials. Nylon is the more elastic of the two, and is slightly less expensive than the polyester, whose main advantage over nylon is its higher resistance to aging and higher ultimate strength [33,34]. Nylon in some forms can be hydroscopic, an undesirable quality if the fabric has to be cut to shape thereby exposing the ends of base cloth filaments. Fibreglass is now being used in larger membrane structures of all types. The fibreglass cloth is less susceptible to degradation from exposure, and has a much higher modulus of elasticity and ultimate strength than the two materials previously mentioned. Problems which occur with the fibreglass cloth do not appear in nylon or polyester fabrics. Firstly, in its woven form the fibreglass exhibits cannibalisation - a term used to describe the damage caused by the abrasive interaction of the single filament yarns as the fabric moves under applied loads [34]. Secondly, the modulus of the fibreglass is almost constant. This factor, coupled with its high value, make the fabric inefficient in dealing with stress concentrations which occur at discontinuities in the structures such as doors and ductwork.

Before considering the details of the fabric properties, the fabric coatings which have considerable effect on these properties must be described. The coatings used require some of the properties of all building materials: these properties include high strength, ease of fabrication, toughness and abrasion resistance, stability under severe climatic influences, impermeability to gases and liquids, and flame resistance. Air structure materials need the added property of flexibility under a range of temperatures, often between -50 and +150°F., and must be able to adhere to the base fabric in use. Four polymers are in commercial use as coatings at the present time, polyvinylchloride, neoprene, hypalon, and teflon, (urethane is sometimes applied over p.v.c. coatings to provide additional abrasion and degradation resistance). p.v.c. is the most common coating and is also the least expensive. It has advantages over the other coatings mentioned in that it is thermoplastic and can be heat welded which can decrease fabrication costs substantially, as the welding is a semi-automatic process. The alternative coatings require two processes to make an airtight joint; sewing, sealing, and in some instances vulcanising is necessary. The cementing (sealing) is a manual process. p.v.c. is available in any colour required by the designer and can be translucent if necessary. It has high reflectivity of light which gives an advantage in an illuminated structure. The properties of p.v.c. are matched to requirements by the use of additives which can increase flexibility, flame resistance and abrasion resistance to acceptable levels. Susceptibility to ultra violet degradation is still the factor which limits the life of the fabric and the air structure. Details of the chemistry of these polymers and their aging processes can be found in Reference 35. In cases where design temperatures below -60°F. are expected, hypalon or neoprene must be used, either singly or in combination. (Hypalon being less susceptible to water absorption than is neoprene). These coatings do not deteriorate as rapidly as does p.v.c., having expected lifetimes of up to fifteen years, compared to seven years for the p.v.c. coatings.

The relative costs of p.v.c., neoprene and hypalon coatings are in the approximate ratio of 1:2:2.5.

Teflon, like hypalon and neoprene cannot be easily joined, but has excellent long term stability and abrasion resistance. Teflon can be made to adhere effectively to glass fibre with which it finds its application as a coating. Like the fibreglass, it is much more expensive than its counterparts, but in large structures in which membrane replacement or damage related costs could be excessive (in terms of manpower, lost revenue and damage to contents of a structure) the combination is finding increasing acceptance. An example of the use of this material is described for a roof installed on Pontiac Stadium in Reference 19. Table 1 summarises the relative properties of the coating and base materials.

In the case of nylon or polyester base fabrics, spun filament yarns are woven into cloth in a variety of commercial weaves. Two examples are the modified oxford and malimo used by the Seaman Corporation [37]. The modified oxford involves weaving pairs of threads in both warp and fill directions, in a manner used in simple basket weave with single threads. In the Seaman version of the malimo weave, the fill threads are simply overlaid on the warp threads and held in place by a third thread set applied by sewing in a quilting type process. As an extension of this method, Goodyear has produced a fabric with three principle thread directions [34].

The coating process involves passing the fabric through a series of rollers which spread and apply the coating to the fabric. Passing the fabric over these rollers has the effect of flattening the yarns into the ribbon like form which they exhibit in the final product. In some cases [37] the fabric may first be passed through a vat of the coating material to apply an initial thin coating which can improve the adhesion of the final product. A typical polyester fabric would have 8 oz. per square yard of base fabric coated with 20 oz. per square yard of coating. The fabric would be approximately 0.030 in. in thickness and would have the properties shown in Table 2, in which nylon and fibreglass fabrics are included for comparison. The final coating is usually applied with 60-75% of the coating material on the exposed side of the fabric, to improve its aging properties.

The structural behaviour of the fabric depends upon the following basic parameters:

i) Properties of the base fabric material,
ii) Geometric construction of the base fabric, and
iii) Properties of the coating material.

The above parameters are themselves variables dependent in turn upon:

i) Load configurations,
ii) Temperature,

iii) Environment, and

iv) Time.

Obviously, the analysis of coated fabrics is complex, as is their behaviour. Quantitative analysis of the fabrics have thus far been limited to the study of non-coated fabrics in a simple weave configuration. These analyses extend to the areas outlined below.

The basic prediction of the form of a uniaxial load extension curve has been attempted by Hearle, et.al. [38]. This approach to the problem is elementary, yet necessary for the future development of more detailed analyses which could at some later stage have a direct bearing on air structure fabrics. The uniaxial load extension curve can easily be obtained experimentally as outlined later.

In an analysis, the two thread direction fabrics are often assumed to be capable of supporting either unrestricted or zero shear forces. Topping has shown, again for an ideal fabric*, that shear modulus depends almost linearly on applied tensile loads, a conclusion justified experimentally in his paper, which also showed the coating to contribute to a marginal increase in modulus [39]. The effects of stress concentrations have been investigated, indicating a maximum stress concentration factor of three for a small slit in the fabric [39]. The case of small holes is of little importance in air structures because of infrequent occurrence; of more importance is the effect

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* An ideal fabric is one in which linearly elastic threads are assembled in a basket weave.

of wrinkling which commonly occurs due to manufacturing and material irregularities. Wrinkling has been studied briefly [40], with initial conclusions being drawn that the defects are not large stress raisers.

Experimental evaluation of structural fabrics is similarly not far advanced. Standard tests are basically uniaxial in nature, while the fabric behaviour is influenced very much by interaction of threads in biaxial loading. Since the fabrics in use have three principle thread directions at most, they must obviously be anisotropic materials. For example, the nylon and polyester materials are woven using a spun yarn, and therefore exhibit geometric nonlinearities, which are superimposed on those of the natural properties of the material to produce the complex form of uniaxial load extension curve presented in Figure 4. The forms of the curves vary for the different principle thread directions because of constructional methods, even if the thread count is equal in all principle directions. In spite of these properties, uniaxial test methods are universally used in commercial material testing and specification. The basic test involves the extension of a strip specimen to failure by methods similar to that described in ASTM methods [41].

In attempts to improve upon this test, and study biaxial behaviour, researchers have used inflated tubes [42], a bulging test [43], and cruxiform specimens [44]. Skelton

[44] produced sufficient results to show extreme sensitivity of Poisson's ratio to both absolute and relative stress values. Experimental problems prevented either tests to failure or the development of new standards. Qualitatively the biaxial loading is shown to increase stiffness, and would probably cause the ultimate tensile strength of the material to decrease by amounts depending upon the weave and the properties of the coating material.

The second standard test applied to structural fabrics measures tear strength, using the methods described in Reference 45 and outlined in Appendix I. These tear test values are particularly difficult to interpret; whilst they provide a means of comparison between competitive materials they have little practical value. The inadequacies of the test are twofold:

i) Tear rate dependence; in practice, a tear can propagate at a rate in excess of 600 ft./sec. which is orders of magnitude greater than that stipulated in the test procedures [46] or available on test machines. This high rate of tearing prevents the relative motion of the threads and hence their roping to inhibit the tear [47,48].

ii) Temperature; the temperature dependence is primarily due to a similar reduction in this mobility caused by the hardening of the coating materials at lower temperatures.

In many engineering materials, creep and fatigue are limiting factors on design loads. In structural fabrics protection against these phenomena has traditionally been in the form of a large safety factor to counteract the lack of experimental evidence. A recent preliminary study of these factors [49] was undertaken for fabrics in use in Japan. These studies, restricted again to uniaxial loading conditions indicate severe loss of strength with prolonged static and cyclic loading. A loss of 40% in the ultimate tensile strength resulted after loading the specimen for 25 hours at a load equal to 25% of the initial ultimate strength; a similar loss in strength occurred after 100 applications of a similar cyclic load. During these tests permanent extension of the fabric was encountered, together with an increase in material stiffness, see Figure 5. In the opinion of the present author the results presented underline the importance of both creep and fatigue behaviour of fabrics, however the possible effects of biaxial tension should have been considered in the interpretation of the results, as applied to air structure design. The interaction between thread sets resulting from biaxial loads could significantly effect both creep and fatigue properties. Creep strength could be increased as friction between individual fibres is increased by the normal loads from the separate thread sets. Fatigue strength could similarly be increased and the permanent extension and change in modulus reduced by the interaction of the thread directions which would tend to restore the original geometry.

Negligible data is available on aging, a characteristic which is extremely sensitive to the geographic location and the associated variables of temperature, solar radiation and pollution, both within and outside the structure. The published data reveals discrepancies as great as 40% [2,34].

Low temperature flexibility of membrane materials is another area of concern, standard tests being based on standards of the clothing industry. In such tests the fabric sample is cooled to the required temperature and bent, by hand, over a small mandril, and examined visually for cracks [50]. In these tests adhesion may be reduced between the coating and the base fabric, or cracks may be initiated within the coating; such defects may be susceptible to optical identification. In service, rapid bending will occur repeatedly due possibly to flutter under heavy wind loads during installation of the membrane. Furthermore in service the fabric may be subjected to a 100°F. temperature difference across its thickness, which would give rise to a gradient of 3000°F./in., which itself may raise stresses due to the composite nature of the material.

In the design of an air structure the designer is required to predict the response of the fabric in any stage of its aging process, to complex loading conditions and extreme temperature variations. This is a difficult objective since new material specifications, provided by manufacturers, are restricted to tensile and tear properties at 70^{o}F. It must be mentioned that experience has indicated that the materials in use perform adequately within the confines of conservative design. Future developments in experimental and analytical techniques could realise the full potential of these materials.

4.2 AIR SUPPLY EQUIPMENT

The basic requirements of the inflation system are twofold, to inflate the structure and to maintain the structure in that state.

Inflation of the structure requires a high volume flow rate at a relatively low pressure, sufficient only to maintain the weight of the fabric. The inflation period, usually less than forty minutes, must be minimised, as during this time the structure is at its most susceptible to wind damage. Once the membrane is tensioned and operating pressure is reached, the equipment must supply air at higher pressure, in sufficient volume to match the system losses and to stabilise the structure under load.

Principle losses are those due to leakage around the perimeter of the structure, and through airlocks and doors. Diffusion losses through the membrane are of increasing importance in larger air structures as the ratio of surface area to perimeter increases. Additional flow may be required for ventilation in high occupancy structures and in some industrial applications.

Calculation of these flows through 'crackage' and vents is based on the expression below [8]:

$$Q = 1096.5.Ao.Co\sqrt{\frac{\Delta P}{g\rho}}$$

where Q is the volume flow rate through the orifice in c.f.m.,

Ao is the area of the orifice in sq.ft.

Cc is the coefficient of contraction,

Cv is the coefficient of velocity,

Co = Cv.Cc = 0.65,

ΔP is the pressure differential in inches w.g.

$g\rho$ is the density of the air in lb./ft.^{3}

Flow through sealing devices, or such things as mechanical field joints have been measured in tests or estimated from practical experience; some typical values are shown in Table 3.

If temperature control is part of a system requirement, recirculation of air is usually required to provide adequate flow over the heat exchanger system, this necessitates an increase in air flow capacity of the actual system.

As is suggested in Canada's Building Code [54], two independent air systems are usually provided, each capable of supplying the full requirements of the system. This is necessary for safety and maintenance considerations.

Electrically driven centrifugal fans with backward inclined blades usually form the basis of the air supply systems. They are slightly more expensive than axial flow fans, but have the advantage of a quieter operation. Axial flow fans have a reversibility feature which necessitates their use in some military installations where powered deflation is a system requirement. A comprehensive survey of possible inflation systems was recently published by Tutt [55]. Characteristics of specific centrifugal fans can be found in Reference 56.

To control the system pressure supply various degrees of refinement are possible. The extremes are:

i) simple pressure control obtained by venting employing a partially open door. (this method was employed by Barracudaverken until April, 1974 [8])

ii) multiple pressure level control based on variations in wind speed and used for highly exposed systems such as the three quarter sphere Radome [3].

Use of wind energy to stabilise the inflated structure by 'venting' the structural membrane has been shown to be feasible [57] by modifying an earlier concept [1] in which structures totally supported by wind were considered.

A dual pressure level system having more general application, developed by the author, is illustrated in Figure 6. This system has been utilised in subsequent designs, and will be discussed in detail in Chapter 7.

The two pressure level system is used to reduce normal running costs in terms of heat loss, and to maintain a lower level of working load in the membrane. Auxiliary power for the system, while forming a substantial portion of the capital cost of the system is usually warranted, since most power failures occur in high wind situations which are dangerous to under-inflated air structures.

The inflation systems may be located inside or outside the structure depending upon the application. One fan being an integral unit with the heating system, the other, the standby unit, usually being an independent belted vent set.

4.3 FOUNDATION SYSTEMS

The purpose of the foundation system in an air structure installation is to transmit structural loads to the ground, and to seal the perimeter of the air structure against excessive air losses.

The principles of two of the most common systems used to anchor the membrane to the ground are shown in Figure 7. In Figure 7(i), the membrane is clamped continuously around the structure, while in Figure 7(ii), the membrane is held in place by a series of "catenary" arches. In the latter system the membrane loads are initially transferred to the cables assembled in pockets around the perimeter of the structure; the cables are then clamped to the foundation at regular intervals.

In comparing the two systems, it can be shown that the continuous system has the cost advantage while the arch system has structural advantages. The cost advantage of the continuous system is restricted to the factory level, where a simple straight edge of fabric is rolled and sealed around the rope. In the arch system, the cable pocket is attached to the structure in a premarked position and the structure completed before the cable can be threaded into position. In the arch system extra fabric is required to form the pockets and to form the sealing skirt. The skirt is not required on the continuously clamped foundation which is normally self-sealing.

The clamping system requires a continuous foundation usually fabricated from concrete or steel; this requirement can be disadvantageous for

i) a temporary installation,

ii) an unprepared site, or

iii) a structure in seasonal operation.

The structural advantage of the cable anchoring system stems from its flexibility, allowing movement of the structure without excessive point loading of the fabric.

Manufacturing imperfections in lengths do not produce large stress concentrations, (which are in evidence on continuously clamped structures). The cable system also permits the longitudinal stresses to be more effectively distributed than does the clamped system, since this latter system does not accommodate any strain along the membrane edge. This phenomenon is illustrated by observing the increase of strain in the membrane as a function of height above the ground in continuously clamped structures, such as the structure used by Seaway Terminals Limited in Hamilton Harbour.

The actual foundations employed in an air structure are dependent upon the use of the structure. Some examples of different foundations are shown in Figure 8. The screw or spreading anchors are used in temporary installations where a permanent foundation wall is not required. If correctly installed, in line with resultant membrane loads, large loads can be carried. For example a 12" diameter spreading anchor is rated at 4000 lbs. in an 8 ft. depth of clay soil. If soil conditions are such that deadweight systems of some kind are required, a concrete foundation is usually constructed. The concrete pier finds extensive usage in tennis court applications, as it can be simply capped, flush with the ground, when the structure is not in use. Additionally, the piers are inexpensive and permit rapid installation. Full concrete footings are used primarily in permanent installations. They provide a reasonably priced foundation and have the advantage of additional side height for the structure which provides protection for the structure from physical damage, and support for a drainage system.

Simple methods such as burying the membrane edges, [51] and the use of an integral waterbag system [11] work successfully in low load applications. These systems have many severe disadvantages which prevent their adoption in large structures; for example, the rapid aging of buried fabric and the inherent instability of the waterbag system must be considered. Any system which can support the vertical and horizontal loads and provides the necessary seal, warrants consideration in the air structure industry.

4.4 HEATING CONSIDERATIONS

Indirect fired space heaters using either fuel, oil or natural gas are the most usual heating units in air structure use. Standard industrial heating units are used having minor modifications which are often introduced to satisfy increased air pressure requirements. Detailed descriptions of these types of units are available [58].

An outdoor unit is shown in Figure 9; the units are often housed in existing buildings,within the structure or in specially built control centres for larger structures.

The size of unit required depends on the temperature rise and the heat losses from the system. Heat losses in air structures are considerably in excess of those of more conventional structures. The losses occur through the usual mechanisms of conduction and convection, and are increased in the case of the air structure by the direct loss of heated air in leakage from the structure. Using as an example the structure described in Chapter 7, the total heat loss of some 2,400,000 BTU per hour is made up of 1,600,000 BTU of heat loss through the membrane and the balance as a loss of heated air. The air structure can be compared to other buildings by using an effective heat loss coefficient which for this structure is 1.56 BTU/hr./sq.ft./°F. (This figure is based on a value of 1.08 for the 0.030 in. membrane which is proportionally modified to accommodate the increase in heat losses due to air flow.) This figure compares with 0.3 BTU/hr./sq.ft./°F. for a cavity wall type structure having an insulated roof; indicating the five to six-fold increase in heating requirements between the two systems [59].

Various attempts have been made to reduce these losses. The most successful method is that of attaching a second membrane within the air structure to provide an insulating air space, which can reduce the heat loss through the membrane to about 0.4 BTU/hr./sq.ft./°F. This method has only been applied to installations requiring high heat flows for long time periods [51]. As an extension to the double membrane concept, Laing [60] and Tulis [61] have developed multilayer membrane materials with properties which can be varied either mechanically, electrostatically or pneumatically. The reasons for lack of usage of these materials include their high costs; both initial and fabrication, (materials having a metal content cannot be H.F. welded). The overriding problem of these multilayer membrane systems is their weight, which could prevent their eventual use in terrestial applications due to a decrease in stability under wind loads.

While some researchers have attempted to change the membrane properties, others have endeavoured to make full use of the existing properties. At Moncton [62] solar radiation is being studied in the development of Goodyear's Greenhouse system [53]; at M.I.T. researchers have built a heat pump system which utilises an air structure as a heat trap.

Distribution of heat within the structure is controlled by air currents. These convection currents are affected by the forced air flows into the system, and by external wind effects. This latter effect is being studied extensively at the University of Western Ontario [63]. Industrial practice has shown that these currents produce a satisfactory heat distribution when using a single heat source in structures with up to 30,000 square feet of floor area.

The alternative to the usual heated air system is radiative heating which is used successfully in structures in which only a relatively small volume need be heated at any one time, such as the construction shelter mentioned in Chapter 8.

4.5 COOLING CONSIDERATIONS

There are three practical solutions to the problems of cooling an air structure system , depending on the degree of cooling required.

If the cooling is required only to prevent excessive heat build-up, then venting and having an increased air flow available to the system provides an economical solution. To produce more severe cooling, an air conditioning system may be incorporated into the air supply unit. This is not usually an economical solution unless the membrane is insulated as described in the previous section. Air conditioning systems are expensive and have an energy requirement of approximately three times that of a heating unit for the same system.

In some commercial installations notably in Germany and Japan [13], evaporative cooling is an economical solution to the problem. The properties of the membrane described in the previous section make the system quite effective. The system is usually used in industrial situations, where fire prevention codes require sprinkler systems; external systems can be added to these and used as a cooling system. The sprinkler system has the added advantages of cleaning the structure and slowing down heat induced aging of the membrane.

4.6 LIGHTING CONSIDERATIONS

Levels of illumination in common usage vary from the 20 foot candles found in corridors and stairways, through the 50 foot candles required for basic industrial assembly and inspection processes, up to as much as 500 foot candles used in highlighted floor displays [59]. In air structures the transmission and reflection properties of coated fabrics can often be utilised to provide efficient lighting.

For a usual white coated fabric the transmission of 30% of normally incident radiation is common, and allows natural light to be utilised under most conditions. This discussion applies only to p.v.c. and teflon coated materials, the other coating materials are opaque (see Section 4.1), and must rely on artificial illumination. Either a completely white, or light coloured membrane may be utilised, or in some cases, such as bulk storage areas, white sections may be included to aid the illumination of a darkly coloured structure. Using a full white membrane illumination of 50 foot candles is feasible with an over-cast sky. This lighting system has the advantage, when compared to that of utilising glass windows, of producing no bright spots or glare. This makes more effective illumination possible with lower average illumination parameters.

Two forms of artificial lighting are commonly applied to air structures. In Sweden, common practice is to suspend fluorescent lighting fixtures from the membrane.

This direct lighting system has three disadvantages. Firstly, the installation of the lighting equipment involves additional factory work on completed membrane sections and additional site work; both these factors contribute to increased costs and the decreased portability of the structure. The second problem is related to the bright spots and shadows associated with the light source and the motion of the structure under wind loads. The resulting movement of shadows considerably reduces the acceptability of the system. The final disadvantage is that of increased membrane weight which reduces the resonant frequency of the structure and can cause instability under high winds. To avoid these problems and to provide efficient lighting in an air structure it is therefore necessary to use indirect lighting, which, like diffused lighting has the advantage of even distribution. Usual air structure profiles form excellent reflective shapes for localised light sources. By locating floodlighting fixtures around the perimeter of the structure, and utilising the high reflectivity of the membrane of over 80% for small angles of incidence [64], optimum lighting conditions can be obtained. Mercury vapour lights provide an economical light source suitable for use in such installations [59]. The lighting fixtures used must be carefully located to prevent membrane damage under wind loads, and to ensure optimum light distribution.

4.6(b) ACOUSTICS OF AIR STRUCTURES

The properties of reflection and transmission of sound waves from a tensioned membrane provide the air structure with unusual characteristics. Sounds from within the structure are both transmitted through the membrane, and often reflected and focused by the membrane thereby enabling sounds to be transmitted across large distances. This can produce problems in industrial applications where noise from machinery has to be absorbed by independent systems. In most applications the phenomenon is little more than a nuisance to which users quickly become accustomed.

Membranes have been designed to absorb noise but are presently not in commercial use as a result of cost of production and the assembly of such membranes. In cabled and insulated structures, where the geometry is discontinuous, sound is dispersed and therefore presents no problem.

4.7 ACCESS REQUIREMENTS

In addition to the requirements of conventional buildings, the access points of air structures should prevent excessive air losses. An open personnel door of 7 ft. by 3 ft. could permit over 65,000 c.f.m. of air at 1-1/2 in. w.g. to escape. These air losses can be prevented by the use of either revolving doors or airlocks. Revolving doors are employed in high usage applications where the flow of personnel would require both airlock doors to be open simultaneously. However, in certain instances the airlock forms a connecting passage to a neighbouring building and as such causes little inconvenience to the user of the air structure.

The pressure difference across successive doors in the airlock produces a total force of 110 lb. per airlock per 1 in. w.g. pressure in the structure and as such an average force of 27 lb. is required to open each 7 ft. by 3 ft. door. The methods described later in discussion of fire exits can be applied to the airlock system. In Canada, air structures are normally required to comply with National Building Code standards on fire safety [65]. This code requires the use of outward opening of single doors for emergency exits. Various systems are in use to overcome the problems associated with the violent opening of such a door once it is released by the panic bar system as well as the excessive air loss which occurs once the door is fully opened. The most effective method involves the use of a counterbalancing weight which recloses the door after use. If the structure is operating at higher pressure necessitated by high winds (see Chapter 7) the door will not be completely closed but will close sufficiently to maintain the structure at a satisfactory pressure. This system has been successfully applied by the author in a number of installations. The main objection to the system, with reference to the incomplete closing of the doors at higher pressures, are usually raised by the patent holders of alternative systems [66]. These systems involve linkages which initially rotate the door about its vertical centre line, before opening the door completely. The increased complexity and hence reduced reliability of these doors limits their acceptance as fire doors. In airlock applications these doors are not all self closing, [51], and often have an equilibrium position of approximately 30° to the door frame; a feature which is highly undesirable for obvious reasons.

For vehicular traffic airlocks are constructed using overhead doors, usually incorporated into a commercial frame structure; the doors being interlocked to prevent their simultaneous opening. In high use applications, air curtains have been used with mixed success. Examples of their use are in the E.D. Smith plant in Winona, Ontario, and in the Consolidated Bathhurst installation in Quebec. The air curtain is normally used in series with a conventional door for use in case of failure of the air curtain system; the major disadvantages of its use being economic and physical. The installation costs of an air curtain are substantially more than those of an airlock. Large amounts of power are required; 40 HP being a typical value for a 12 foot by 12 foot door, which would correspond to the power necessary to inflate a 70,000 square foot air structure. Associated with the curtain are large air losses from within the structure, these losses restrict the use of this curtain particularly during high winds, i.e. higher inflation pressures. The high air speed within the curtain has produced a secondary problem in the Winnipeg installation; the 100 ft./second air flow causes a wind chill effect on the operators using the system.

A third system is in isolated use. Conventional rubber bumper doors are used with compensating springs which allow for the pressure differences. The reduced time of opening allows a larger structure to maintain acceptable inflation pressure. This system should be installed in series with a second door for use in the case of damage, or to permit usage of a higher inflation pressure.

In small or low occupancy structures, emergency exits often take the form of zippered or laced panels in the structure wall, which can be used in case of the collapse of the membrane.

Moving bulk goods in and out of the structures can be accomplished with relative ease. Loading chutes with simple flap valves are installed during the manufacture of the structure. These chutes enable loading to be done directly through the membrane. For bulk removal of material from the structure auger and conveyor systems can be used. Small air curtains or other seals are necessary modifications to conventional conveyor systems.

Any access to the system involves a hole in the membrane, usually at ground level; associated with these holes, are stresses which must be prevented from tearing the membrane and in the case of holes at ground level transmitted to the foundation. The area must also be air tight. The system used to satisfy these requirements is shown in Figure 10. The membrane loads are isolated from the access by use of a cabled arch, which may be continuous or may be attached to the foundation. The boot or transition piece connects the hardware of the door to the structure thereby providing an air tight seal. The boot must also accommodate motion in the structure. The extra fabric required to achieve this flexibility is damaging to the appearance of the structure as a whole, however a restricted transition piece can have disastrous consequences by increasing stress concentrations which could initiate tear in the fabric, see Appendix II and Figure 10. The use of excess material results in the problem of producing water and/or snow traps.

Two methods exist for assembly of the structure; in the first case the membrane is left intact and the transition piece attached to the outside (see Figure 10(ii)). In the alternative method the membrane is cut away in the factory and the boot attached to the inside face of the membrane. The first method enables the structure to be inflated into position for assembly onto the access fixtures, but can cause damage to the joint by a peeling action, an effect discussed in section 4.8.

4.8 JOINTING AND FABRICTION TECHNIQUES

The fabrication of air supported structures is still relatively unmechanised. In contrast to exceptions in the clothing industry where numerically controlled laser beams cut hundreds of thicknesses of fabric to produce men's suits, air structure sections are cut by hand held machines, from manually produced patterns laid out on a cutting table or shop floor, no more than 15 panels being cut simultaneously. The separate panels are then joined to produce sections of easily manageable size, which are in turn joined to form either the completed structure or large portions of the structure which will be assembled on the site.

The requirements of the joining technique are simple. The joint must be as strong as the base material, and it must be air tight. In addition, it must have closely controlled tolerances, as cumulative errors over thirty or forty panels could be disastrous, especially to a structure with a continuous foundation.

The most common joints in air structure materials are welded seams in p.v.c. coated fabrics. These are heat produced welds, dependent on the breakdown of electrical resistance of p.v.c. when subjected to high frequency alternating current. The two or more parts to be joined are located between a pair of electrodes, (usually pneumatically operated) which clamps the fabric while the current is passed through it and holds it in place until it cools to produce the weld. The production of a seam between two layers of 0.03 inch p.v.c. coated polyester would typically require:

Clamping pressure	15 psi
Energy input	400 watt.sec./sq.inch
Clamping time (under load)	4 seconds
Clamping time (cooling)	5 seconds

This process requires skilled operators because of the large variation in material properties within any batch. These variations can result in either weak seams or damage to the fabric from overheating. The strength of the seam produced in this manner is limited by the shear strength of the coated fabric and its adhesion to the base fabric, but is normally as strong as the base fabric under simple tensile loading, Figure 11(i), but is comparatively weak under a peeling type load, Figure 11(ii).

With other fabrics sewn seams are commonly produced by either stationary or moving machines [67]. After they are produced the seams must be sealed to make them air tight and to protect the thread from damage. This sealing is done either with a solvent type adhesive or by a tape applied over the seam [68]. In spite of the stress concentrations produced by the threads the strength of sewn seams can be as great as 80% of the strength of the base fabric, see Figure 11.

In some applications using neoprene fabrics cemented seams are used. These seams are produced by hand with the fabric clamped on shaped jigs to produce smoothly curved seams. Again seams with a strength equal to that of the base fabric can be produced by this method.

If the joint is to be subjected to any peeling loads then it must be sewn for all materials. Sewing can also be used to join dissimilar materials.

The field joints used on larger structures, for ease of assembly or other reasons, involve proprietry mechanical clamping devices, Figure 12. In many cases, especially in permanent installations, field welding equipment is finding increasing use.

5 STRUCTURAL DESIGN CRITERIA

5,1 WIND LOADS

Wind induced fabric loads are by far the largest loads exerted on the air structure system and can produce local pressures of as much as 40 lb./ft.^{2} in certain configurations. In comparison, the inflation pressure of 9 p.s.f. reduces to minor importance, and the 3 ounce per square foot fabric weight can be considered to have a negligible contribution. The larger component of the wind loads are as with most structures, the suction loads which often exceed the magnitude of the direct pressure loads by as much as 300%. Because of the air foil type profile of the structure,the lifting forces act over the majority of the surface area. To predict these loads for any given structure the results of wind tunnel tests are required; following some initial work by Beger [70], Dietz [28] and Nieman [71,72] have probably made the most significant contributions. Dietz produced non-dimensional design data for a range of parameters: more recently Nieman has described the pressure distributions which occur across a variety of structural shapes. Variables which affect the wind induced loads, in tests are:

i) the absolute size of the structure,

ii) the shape of the structure,
iii) wind speed and temperature,
iv) wind direction, and
v) inflation pressure.

The pressure distribution on a structure can be assumed independent of the size of the structures. Nieman showed this to be valid, using an indirect means, by varying the Reynolds number in a series of tests on the same model. It can therefore be inferred that the stresses induced in structures are directly proportional to their size (stresses being proportional to the product of the local pressure difference and the radii of curvature).

The shape of the structure effects the loads in three ways. Greater length to width ratios for structures of given form can produce a larger smooth contour to oblique winds and higher lifting pressure over this area. Similarily, a spherical or spherically ended structure produces higher pressures than does a cylindrically ended structure having more severe contours which facilitate the break up eddies. These effects are illustrated by Figure 13, which details Nieman's results for two structures of differing surface form. A difference of 20% in the peak pressure load is produced by the change in shape. For a fixed form of structure on a given ground plan there is an optimum height which will result in the membrane loads being minimised. This minimum is produced by a combination of the reducing radius of curvature and the increased exposure to wind loads. At low profiles the rapid decrease in radius of curvature is more effective in controlling the membrane stresses than is the increase in exposure which produces higher wind pressure loads.

It is well known that the wind has a stagnation pressure varying closely with the square of its velocity.

For normal wind speeds (0 - 100 m.p.h.) and air at S.T.P., this pressure q is approximated closely by

$$q = \frac{V^2}{2000} \qquad 5.1$$

where V is the wind speed in m.p.h. This pressure is affected by the density of the air which is in turn a function of the climatic conditions. Figure 14 presents a wind speed pressure chart, which can be used in conjunction with Figure 15 which provides the correction factors necessary for site altitude and temperature considerations.

All structures other than the sphere are sensitive to wind direction. This can be attributed to effective geometric changes and has been illustrated for inflated models tested at 30° intervals [71,72]. Hence, in testing, models should be rotated within a wind tunnel until the maximum load condition is observed.

Inflation pressure affects the load on the membrane both directly and indirectly. As a component of the pressure difference across the membrane it has a direct effect on the membrane stress levels. The effect of inflation pressure on the stiffness of the structure under wind load has an influence on the deformation of the structure, which in turn can modify the wind loads on the structure. Hence, specified inflation pressures and flexible models are effective variables for use in wind tunnel work. (Dietz' work has the limitation of having used rigid models). In consideration of these effects it is usual practice to use an inflation pressure held at the lowest value which ensures stability. The value of 0.55q* is shown to be satisfactory in the tests mentioned above for low profile structures [h/d < 1/2]. Table 4 summarises the requirements of other structural forms. At pressures below this value a depression is produced by the direct pressure on the windward side of the structure. This deformation may then traverse the structure resulting in shock loading on the membrane and anchor systems.

A severe limitation of all the published wind tunnel tests mentioned thus far, is that they were conducted in laminar tunnels, and as such can only describe steady state load conditions. In any design situation, the effects of turbulence should be considered. The literature indicates that much work is being done with a view to the modelling and simulation of wind boundary layer velocity profiles and the spectra of the individual components of the turbulence [73-84]. Advanced techniques use models of local

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* q - stagnation pressure in the wind tunnel

topography to develop the full load pattern for a particular situation. Boundary layer tunnels, such as Davenport's tunnel at the University of Western Ontario, are still few in number. Because of the low priority of air structures in relation to downtown development areas, air structure modelling is generally excluded from such tunnels; the one exception being the U.S. pavillion for Expo 70, Osaka.

The effects of turbulence are two-fold. While the turbulence plays a significant role in breaking up large eddy formation, i.e. vortex rolls and as such reduces loading, it also contributes to the dynamic loading of the structure. The passage of a severe area of turbulence can produce large "rollers" at separation points, say at the trailing edge of a building adjacent to the structure. The passage of this disturbance downstream, as a pocket of low pressure, can cause local distortion of the membrane as it is carried across the structure and may initiate a degree of instability. Recent work by Davenport has shown that the velocity of these disturbances is approximately one third of the mean wind speed [75]. The one structure tested in a boundary layer tunnel was the Osaka pavillion, which showed signs of instability at 120 m.p.h. in such a tunnel, after having proved to be completely stable at 200 m.p.h. in a conventional laminar wind tunnel [81] test. These values can be used qualitatively to show that smaller structures at similar inflation pressures would be stable under all but the most severe conditions, unless the fundamental frequency of the structure was reduced by either excessive weight in the membrane or by low inflation pressure. Additional weight can be introduced by the suspension of fixtures from the membrane, or by use of oversize cabling. The under inflation of a structure is quite common and does occur in installation or removal of the structure, at which time even under light winds the membranes can became unstable and suffer extensive damage from shock loading.

Steady state loads have been shown to be lower, by as much as 45% for conventional buildings in the boundary layer wind tunnel when compared to laminar wind tunnel tests, however, since no values are available for air structures whose behaviour is dynamic in nature under wind load, steady state values must be used for the present with some allowance being made for gusting effects.

Maximum design wind speeds for most locations in Canada are outlined in the National Building code [85], which is one of the most advanced in the world with respect to wind loading analysis. In the code a maximum design wind pressure P can be calculated for use with wind tunnel data for any particular structure. P is defined by the equation

$$P = q.Cg.Ce.Cp \qquad 5.2$$

where, q is a reference mean velocity pressure in lb./sq.in.

having a specified probability of occurrence. Values of q are tabulated in the code for use in all Canadian locations. Cg is a factor between 1 and 2.5 which describes the susceptibility of various types of structures to gusting effects. While air structures are not mentioned in the code obviously Cg for such structures is large, and a value of 2.0 would be appropriate, being between the extremes of concrete and shingled roofs. (Veltozi has suggested a factor of 1.69 to be applied to all forms of structure [84].) In other building codes outlined in Section 11.3, only Japanese and German codes mention air structures, but do not mention gust effects in suggested design methods. Similarly, U.S. and Swedish air structure manufacturer's standards neglect the subject.

Ce is an exposure factor which varies from 0.4 up to a maximum value of 1.0 for a structure totally exposed to the prevailing wind direction. Ce also allows for height of the structure above ground.

Cp is a pressure coefficient for the particular building in question and is evaluated from wind tunnel tests as a mean value of the pressure distribution, on some area of the structure.

5.2 SNOW LOADS

Excessive snow loads are a severe hazard to air structure installations. The damage is not caused by excessive loading of the membrane itself, but rather by the contact between goods or equipment housed within the structure and the membrane. Larger distortions occur when a section of the membrane inverts its curvature and becomes a snow and water trap [85].

The solutions to the problem involve the prevention of build up of snow. Taller structures are usually too steep to allow build up of snow to occur on the smooth membrane surface, but for larger and cabled structures this build up can occur. In remote areas it may be necessary to have additional heating capacity added to the structure as advocated by Bird for use in Radome installations, to prevent build up of snow by melting on contact with the structure. In less remote areas contract snow removal services can be utilised to prevent any build up, which could not be controlled by the normal heating capacity of the structure. The removal is a simple operation involving the use of a rope passed over the structure and moved sufficiently to dislodge any initial snow build up. The only structural failure due to snow on which the author has any information, was caused by drifting snow which blocked a structure's air inlet system; the necessary precautions can eliminate difficulties of this nature.

5.3 STRUCTURAL ANALYSIS

In any structural design problem the pre-requisites for a solution are:

i) Constituitive equations for the materials,

ii) Knowledge of the structural geometry, and

iii) Knowledge of the loading system.

It has been indicated earlier, in Section 4.1, that the behaviour of the usual membrane materials cannot be expressed analytically, either as a new material or after the material has been subjected to various environmental conditions. The structure's initial geometry is known; however the modifications induced by large strains and deformations during loading can only be estimated. In addition to these observations wind loads and their influence on the membrane form, and on the quasi-constant volume of compressible gas enclosed within the membrane, cannot be predicted completely. Clearly no exact analysis of the problem can be considered. As a first approximation to a solution the usual assumptions of membrane theory, i.e. only tensile stresses and no bending moments being transmitted by the material are employed. The assumptions of linearty and small strains can be justified for the basic analysis. The basic membrane approach is a widely applied basis for design [86-88].

Work in the early sixties describes a finite difference analysis to predict the non-linear displacements of axially symmetric surfaces of revolution under symmetric loads [89]. The principle of super-position was utilised as was a Mooney type constituitive equation [90]. Finite element techniques have since been used extensively as indicated by the following comments [91-92]. Oden used triangular elements to predict the geometric response of a heavy rubber sphere when inflated [93,94]. Jones has shown that curved quadrilateral elements are more suitable for this type of analysis [95]. Using such elements Leonard predicted the response of an infinite cylinder to a wind load distribution expressed as a simple sine function [96]. Li has developed an approach for arbitrary shells capable of handling a linearly elastic isotropic material [97]. Haug has used the direct stiffness method on fluid filled membrane structures and employed a coarse grid network with idealised materials [98,99,100].

Excessive computer time imposes a severe limitation on the general use of the finite element method, and as such has limited its application to the axisymmetric cases of either long cylinders or spheres; assumed distributions for the wind loads being expressed in analytical terms.

In cabled structures the finite element technique is more readily applied as the small cable strains remove one order of complexity [101,102]. However, large deformations and lack of accurate wind tunnel data have limited its success in design applications. The analysis for the U.S. pavillion at Osaka was based on this method [14]. The stresses when checked against those on the final structure were found to be within 25%, a satisfactory result [14]. This discrepancy could be due to the differences in both wind and material behaviour.

To analyse the problem completely we require:

i) material data and specifications, and

ii) the wind distribution over the whole structure for all compatible deformed shapes.

Computational costs escalate as a series of solutions is required for any particular structural analysis.

The designer is faced with the problem of producing a low cost, 'upper bound' solution from the data available. An acceptable solution can be found using membrane analysis for the following assumptions.

All deformations are neglected. While this is an unreasonable assumption for an exact solution it can be used in an upper bound solution. The justification for this depends on the nature of the structural deformation, which will increase local curvature in areas of high pressure differences, and will for example, in the case of a circumferential section of a cylinder, equalise the stresses along the hoop. Using the membrane theory assumptions of no bending moments and the negligible shear strength, the basic equilibrium equation for the element shown in Figure 16

gives $$R.\frac{\partial Nx}{\partial x} + \frac{\partial N\phi x}{d\phi} + RPx = 0,$$

$$R.\frac{\partial N\phi x}{\rho x} + \frac{\partial N\phi x}{\rho\phi} + R.Px = 0, \text{ and}$$

$$-\frac{N\phi}{R} + PR = 0, \qquad 5.2$$

where, R is the radius of curvature of the element,

Nϕ and Nx are membrane stress resultants,

Px, Pϕ, and PR are pressure forces acting in the x, circumferential and radial directions respectively.

can be reduced to

$$R.\frac{\partial Nx}{\partial x} + R.Px = 0,$$

$$\frac{\partial N\phi}{\partial\phi} + RP\phi = 0, \text{ and}$$

$$-\frac{N\phi}{R} + PR = 0. \qquad 5.3$$

For an element with two principle curvatures, under radial pressure only the corresponding equation is

$$-\frac{N\phi}{R\phi} - \frac{Nx}{Rx} + PR = 0 \qquad 5.4$$

It has been shown for air structure applications that this approach, when using an averaged pressure difference over the section in question, yields solutions within 10% of those given by a more thorough membrane analysis [87,103,104].

This method of analysis, modified slightly to suit a cabled structure, was used to analyse the design of a cabled structure erected in the Hamilton area; predicted slight deformation of the anchor system under wind loads justified this approach, see Chapter 8.

In a rigorous mathematical study it would be necessary to analyse the complete structure, but as is often the case manufacturing and production techniques accelerate design compromises. In most structures only one strength of material will be used. It becomes only necessary therefore to calculate the loads at the most highly stressed areas. Experience and observation indicate that the central section of a long structure for example is most highly stressed; wind tunnel tests confirm that the highest wind loads occur in these areas [72]. This could be inferred from the reduced membrane curvature, i.e. curvature in only one direction, in the cylindrical section, away from the influence of the end sections.

The development of yield criteria for use in fabric design should be considered once maximum stress levels have been established. The use of von Mises' criterion is suggested in the literature [3,28]. This has no theoretical or practical justification when applied to fabrics, which consist of two, or in some cases three, semi-independent thread systems. It would appear that the criterion should be subject to a maximum tension level in a malimo fabric, or some modified version for a conventional fabric where weave tensions interact. Selected criteria can only be established when satisfactory biaxial testing equipment and procedures are produced.

In addition to the establishment of yield criteria applicable to the material behaviour, special consideration should be given to the complexities introduced into the membrane as a result of seams and joints. In directions across the seams the strength of the seams must be considered, and in directions along the seams a reinforcing effect, dependent on seam width, is introduced, which increases the strength by between 3% and 6%.

6. CANADIAN APPLICATIONS

There are approximately one hundred air structure installations in Canada at the present time. The membranes for over 80% of these structures are imported in final form, mostly from Sweden. The balance of the membranes being fabricated in Canada using American materials.

Air structures are principally utilised in three of the areas of application discussed below,

i) Industrial,
ii) Recreational, and
iii) Constructional.

6.1 INDUSTRIAL APPLICATIONS

Industrial users account for approximately half of the air structure installations in Canada, and about three quarters of the covered area [105].

Together with the low costs of air structures, the large span and centre height make the structure ideal for warehouse use. Storage of bulk materials, such as fertilizers and wood pulp are current uses in Canada; for example fertilizer is housed in the 50,000 square foot structure shown in Figure 17, and Consolidated Bathurst store wood pulp in two structures in Portage Du Fort, Quebec, one of which is shown in Figure 18. In addition to the normal reasons for installing air structures for the two examples mentioned, i.e. protection of the fertilizer from water damage, and of the wood from freezing in winter, interesting additional points should be noted.

i) In the fertilizer applications the air structure replaced a conventional steel building which was chemically incompatible with the phosphate and suffered severe corrosion damage.

ii) In the wood pulp application pollution complaints against the company were reduced considerably as the structure eliminated drying and the resulting wind losses of wood chips.

The air structure can be designed to match the angle of repose of the material to provide an efficient volume for storage, approximately the natural form of the material. Loading can be accomplished by either using air-locks, or by using the conventional methods of the powder industries, in which the structure is filled using discharge hatches in the roof of the structure (which in the case of the air structure is automatically self-closing) and emptied by auger and conveyor mechanisms feeding either transporters or linked directly to process machinery.

The low cost of the air structure and short manufacturing time as compared to other structures, enable a company to rapidly respond to an increase in demand. The Volvo assembly and storage area described in Chapter 7 was occupied in June of 1973 - three months after an initial inquiry. The E.D. Smith Company of Winona, Ontario uses two air structures in their fruit processing plant. The low cost enables fluctuations in demand to be accommodated without large permanent investment in building hardware; if demand should fail, the structures have good resale value and can be quickly relocated.

For promotional and economical reasons, two air structure manufacturers utilise the large uninterrrupted floor space of air structures to produce their structures. The companies are Birdair of New York, and Barracudaverken of Sweden.

6.2 CONSTRUCTIONAL

Constructional shelters accounted for 15% of air structures built in North America in 1965, however, this would probably be an overestimate of current usage [106]. In Canada, the Ministry of Transport is the only current user of air structures for constructional purposes. Radar installations are assembled within a structure of the author's design, see Figure 19, allowing year round construction in the severest climate. One other Canadian structure is mentioned in the literature [107]; a two acre building site in Quebec, which was used throughout the winter of 1971 to 1972. Price described house construction in Europe which utilises air structures [3]; Jumph illustrates their use in transformer installations [108].

The large free space, low cost and a high degree of portability are sufficient justification for use of air supported structures. The ability to assemble an air structure over an existing building or remove the structure from a completed site is improved by use of field joints. Lifting equipment which is often needed can be housed within the structure and suspended from the membrane. This often requires an increased inflation pressure [3]. For occasional movement of large equipment a simple sleeve arrangement can be utilised [108].

Canada's severe climate and short construction season should warrant further investigation of this system.

6.3 RECREATIONAL

In Canada's long severe winter, the recreational use of air structures has recently increased rapidly. This increase, mostly in the covering of tennis courts, is well illustrated in Toronto where the six principle clubs are all using covered courts during the cold season, November to May of each year. This acceptance is attributable to the low cost and the advantages of free span, height, portability and lighting properties of the structure.

Hockey, unlike tennis, is well established in

Canada, and has sufficient financial support for conventional framed buildings, and to the author's knowledge, no air structure rinks have been installed in Canada. Rain has shown the feasibility of such structures for use in Canada [27]. Their use in Japan, where over fifty such facilities exist is further justification for their use in Canada [17].

Covered swimming facilities have been in use in the United States and Europe since the early sixties and smaller versions of those structures have had limited success in the milder parts of Canada where the swimming season has been extended into Spring and Fall. In these smaller units problems of anchorage design and stability often occur as the units are made to be competitive in price with small framed structures. In larger structures, reinforced fabrics and cost advantages allow the structure to compete favourably in the United States [109], but no installations have been made in Canada.

Track and field areas have been accepted by Humber College where the arena was modelled on the lines of the Harvard structure installed two years earlier in 1968. The structure is a basic cylindrical structure with spherical section ends, and was the forerunner of a number of more advanced projects in which both existing stadia and new complexes have been covered with either stationary or removable air structures [109]. Barlott proposed several air structure types for use in Montreal for the Olympic Games in 1976, for both stadia and residences, however, the projects have not come to fruition [110].

6.4 AGRICULTURAL

Use of transparent p.v.c. fabric for inflated greenhouses is being developed by Goodyear who have produced over twenty such structures [53]. In Canada, the short growing season could be substantially increased in the fruit and vegetable areas by employing structures for this purpose. Reports of threefold yield increases in tomatoe crops are reported in the United States using the system. Bleasdale pointed out design weaknesses which made the structures susceptible to wind damage in areas of high stress [7]. These effects are minimised by using a cabled design used in an experimental structure installed in Baltimore in 1972 [51]. The life expectancy of the structures, which is limited by the rapid degradation of the unsupported p.v.c by sunlight, has been increased to over two years by improvements in the p.v.c. chemistry. If the membranes are removed and stored through the severe winter months their life could be extended making the structure more economical in Canada's fruit and vegetable belt.

6.5 NOVEL APPLICATIONS

Novel air structures in Canada include the largest temporary air structure on the continent, and some of the smallest.

The large structure was a floating roof type fuel storage tank, 367 feet in diameter and 40 feet high. A new construction method (used by Horton Steel of St. Catharines, Ontario), involves the existence of the tank as an air structure for a few hours of its life. The sides and roof of the tank are assembled concurrently, the roof now being assembled on the ground within the walls; previously the roofs of such tanks were assembled in situ-a longer, more complex task. Once the roof is assembled, a series of small sealed inflated air tubes are used as a temporary seal around the perimeter of the roof, and a fan is used to "inflate" the roof into position, where its support system is installed while the tank functions as an air structure. The time saved is over two months and constructional costs are reduced by over $200,000. Metal air structures have been proposed several times since the 1930's but this is the first completed project [111,112]. In construction of large span shells air structures have been proposed as forms by several authors, either for concrete [113,114] or rigid plastics [115].

An equally functional example is the proposal by a Toronto company to incorporate air structured covers for settling tanks into its future sewage treatment plant designs; not to contain fumes but to reduce heat losses sufficiently to remove the need for heaters in the tanks during the winter months when ice formation can be a major problem.

The Firestone Company markets an inflatable dam, an example of this product is in use on the Beverly Swamp where water levels are controlled by varying the inflation of the weir.

Structures of interest and of possible use to Canadians in the future, include:

i) Military field hospitals, as used by the United States in Vietnam,

ii) Disaster area service buildings,

iii) Inflatable loading dock shelters for use in loading of rail cars and trucks, both in winter and in summer,

iv) Air bags developed recently in the U.S. for protection of both persons when travelling and goods in transit.

Future applications of air structures could be in the form of complete climate controlled communities, in either the Canadian Arctic, as studied by Couter [107], or on the moon as is being studied by N.A.S.A. N.A.S.A. have already used non-occupied air structures as satellites in which the weight and volume characteristics of air structures are most effectively utilised.

Projects of this nature require further improvements in the development of the membrane materials to combat increased pressure loads and demands pertaining to temperature variation and resistance to sunlight.

7 DETAIL DESIGN OF AN AIR STRUCTURE

7.1 SPECIFICATIONS AND REQUIREMENTS

The final purchaser of the air structure described in this chapter was Volvo Canada Ltd., Halifax, Nova Scotia. The structure was required in the spring of 1973, to extend the storage and assembly areas of the automobile plant. The basic specifications for the structure were outlined in April 1973 and are summarised below.

i) base dimensions of the structure of 120 ft. width and 170 ft. length,

ii) a centre height of 36 ft., together with a vertical clearance of 9 ft., measured 4 ft. inside the structure's base,

iii) a minimum inside temperature of 65°F.,

iv) minimum illumination of 50 ft. candles,

v) access for vehicles up to 20 ft. in length at two locations as indicated in Figure 20,

vi) four personnel doors, and

vii) minimal air flow for ventilation.

To initiate a design which satisfied these specifications, the following details had to be finalised with reference to the site location.

i) National Building Code design wind pressure for Halifax, $q = 8.4$ p.s.f. , [83].

ii) National Building Code, 2-1/2% January temperature for Halifax 4°F., [83].

iii) Site exposure factor, Ce = 1, for the totally exposed dockside area, [117].

iv) Soil condition -- compacted fill with a minimum bearing capacity of 4 tons per sq.ft.

v) Snow load, Halifax design snow load is 45 lb./sq.ft. In areas having similar load specifications the heat loss at 65° inside temperature has been proved to be adequate in preventing build up. The customer however was advised to secure a snow removal contract or to use available personnel to ensure that build up would not occur.

7.2 STRUCTURAL FORM

The rectangular site which was available for the structure suggested the use of the cylindrically ended form of structure, Figure 2(i). The accompanying advantages of optimum wind load characteristics, and materials usage are discussed in Section 3.1.

The aspect ratio for the structure was determined after consideration of the end use of the structure, which required passage of fork lifts around the perimeter of the structure. The use of an above ground wall as a foundation for the structure provides:

i) height close to the wall of the structure, and

ii) protection of the membrane from contact with the mechanical equipment using the area close to the wall.

The dimensions of the final structure are presented in Figure 20.

It has been shown that it is both unnecessary and uneconomical to use a cabled membrane in a structure of this size, i.e. 168 ft. x 118 ft.

7.3 MEMBRANE ANALYSIS

The maximum stresses occurring in a structure of this form are the circumferential stresses in the cylindrical portion of the structure denoted by the arrow AA in Figure 13(i). To calculate these stress levels it is necessary to estimate the maximum wind loads which occur on such a section and the corresponding inflation pressure. Wind tunnel data for this structure is not directly available, however results are available for a series of spherically ended structures which, as was shown previously, produce slightly higher wind load values than do the cylindrically ended structures. These values of wind load can therefore be interpreted as safe values for use in design. Figure 21 illustrates the variation of the wind load coefficient (as a function of the structural length to width ratio) on the most highly loaded cylindrical section of a series of rigid models tested in a laminar wind tunnel [28]. In these tests the wind load coefficient, Cp, is defined as the ratio of the mean lifting pressure on any section of the structure to the stagnation pressure in the wind tunnel.

For the structure in question,

$$\frac{h}{d} = \frac{36}{138}$$

$$= 0.26, \text{ and}$$

$$\frac{w}{\ell} = \frac{118}{168}$$

$$= 0.70$$

where h is the maximum height of the structure, d is the diameter of the cylindrical section, and w is the width of the structure and ℓ is the overall length.

The reported results were limited to structures with h/d values of 0.375, 0.500, and 0.750, it was therefore necessary to extrapolate values of the wind load coefficient, Cp, from these curves. A quadratic extrapolation was used which yields for $w/\ell = 0.70$.

$$C_p = 3.947\ (h/d)^2 - 3.853\ (h/d) + 1.8533 \qquad 7.1$$

substituting for h/d = 0.26 in Equation 7.1 enables a value to be determined for Cp, i.e. Cp = 1.12 in conjunction with data supplied by the National Building Code [83] to calculate an effective wind pressure, P, for the structural section. P is calculated from the expression:

$$P = Cp.Cg.Ce.q \qquad 7.2$$

where i) q is the maximum wind speed pressure, averaged over a period of one minute which can be expected to occur in any 10 year period; for this study a value of 8.4 lb./sq.ft. corresponding to a wind speed of 58 m.p.h. has been employed.

ii) Cg is the gust factor which describes the susceptibility of the structure to dynamic loads. A value of 2.0 has been adopted as was discussed in Chapter 5.1.

iii) Ce is a factor related to the exposure of the structure, and depends on both the location of the site and the maximum height of the structure under consideration. The site of this particular structure is a waterfront and is therefore completely exposed and the maximum value for Ce of 1.0 is warranted.

Hence the mean pressure on the most heavily loaded section of the structure can be obtained by substituting these values into Equation 7.2

$$p = 1.12 \times 2.0 \times 1.0 \times 8.4$$

$$p = 18.8 \text{ lb./sq.ft.}$$

As previously noted the optimum inflation pressure for use in a particular installation is the minimum pressure which will ensure stability under maximum wind loads. In a low profile structure such as this a value of 0.55 times the tunnel stagnation pressure has proved to be adequate in wind tunnel tests. To apply this factor in the evaluation of the required inflation pressure it is necessary to modify the design wind pressure by the gust and exposure factors as detailed below. Hence, the inflation pressure under maximum wind loads can be defined by

$$P_2 = 0.55\ (q.Cg.Ce) \qquad 7.3$$

where the terms in brackets represent the modified wind pressure.

Substitute the appropriate values and we have,

$$P_2 = 8.4 \times 2.0 \times 1.0 \times 0.55 \text{ lb./sq.ft.}$$

$$P_2 = 9.24 \text{ lb./sq.ft., or}$$
$$= 1.75 \text{ in. w.g.}$$

Having established the wind load and inflation pressure on a particular section it is possible to calculate the circumferential stress resultant, $N\phi$, of that section, in this case a maximum value is given by Equation 5.

$$N\phi_{max} = [P_2 + P] \, . \, R \qquad 7.4$$

where R is the radius of curvature of the cylindrical section of the structure having a value of 69 ft. for this particular study, and P_2 and P are defined by Equations 7.3 and 7.4 respectively, hence

$$N\phi_{max} = [9.24 + 18.8] \times 69 \text{ lb./ft.}$$
$$= \underline{1935 \text{ lb./ft.}}$$

To calculate a value for the longitudinal loads on the membrane an estimate for the mean wind pressure coefficient, Cp, over the end sections of the structure is required. The values given by Dietz cannot be justified in this case for three reasons:

i) The pressure distributions on the spherical ends of the models used have significantly higher values than the corresponding values for a cylindrically ended structure, see Figure 13.

ii) The application of this pressure distribution to the long cylinder analysis is valid only for those structures having an h/d ratio of 0.5, and

iii) Consideration is not given to the anchor system used, which can significantly affect the distribution of these stresses as discussed in Section 5.3.

An alternative method of evaluating a Cp value for the end section is to integrate and determine a mean value from the distribution curves presented in Figure 13, for the end section of a structure of similar configuration. The value of Cp calculated is equal to 0.38. This will be an overestimate of the value for the structure presently being analysed, as a result the lower profile of this latter structure [72]. This value applied to the free body diagram of Figure 22 provides an upper bound value for the longitudinal stress resultant Nx, given by resolution of forces along the structure.

$$Nx = [(P_2 + Cp.Ce.Cg.q)\ A + N\phi.w.\cos\theta]\ 1/\beta \qquad 7.5$$

where, N_x is the longitudinal stress resultant assumed to be equally distributed over the width of the structure,

$N\phi_{\ell}$ is the circumferential stress resultant of the cylindrical end section, given by:

$$N\phi_{\ell} = \Delta p.R,$$

A is the cross-sectional area of the structure and,

θ is the angle between the membrane edge and a vertical plane.

hence,

$$Nx = (9.24 + 6.38) \times 5695 + (9.24 + 6.4) \times 69 \times 118 \times 0.519$$

$$Nx = \underline{1091\ \text{lb./ft.}}$$

7.4. MEMBRANE MATERIALS

Following the arguments outlined in Section 4.1 a p.v.c. coated polyester fabric, of a malimo weave was chosen for use in the structure. Using the maximum load values of Section 7.3 an initial factor of safety of the membrane against uniaxial tensile failure of 3.6 is available with this material. Values in this area are in current usage, and are recommended in the few standards which exist, [49,116].

The specifications of this fabric are presented in Table 5, and test results for samples of the material are included in Appendix II.

Price and delivery of the fabric were also in its favour, as was the availability of suitable colour and paint. The structure is white with the Volvo trademark in 6 ft. high blue lettering in two places on the membrane. The expected life of the membrane (to 60% of original strength) is seven years, according to manufacturers of the material.

7.5 FOUNDATION ANALYSIS

a) Cable Loads

From the maximum membrane load calculations it is practical to deduce the maximum anchor loads. Figure 23 shows the catenary cable systems from which the cable load can be calculated, by equilibrium considerations in the plane of the membrane.

$$\text{i.e.} \quad T = \frac{1}{2.\ \sin\theta}\ [N\phi\ .\ b] \qquad 7.6$$

where:
T is the cable tension,
θ is the angle between the end of the cable and a vertical plane,
$N\phi$ is the circumferential stress resultant,
b is the distance between anchors.

In this case a tension of 4,750 lb. is calculated, hence, using the usual safety factor for a structural cable of 3.0, a 3/8 in. diameter galvanised aircraft cable is selected [122].

b) Foundation Wall

The final wall system is shown in Figure 24. The loads on the system are shown in Figure 24(i). The National Building Code [117] indicates that a factor of safety against overturning of 1.5 is required in retaining walls and similar structures.

Considering overturning loads about A in Figure 24 for a 1'0" section of the wall, the overturning moment, Mo, can be calculated as

$$Mo = 1600 \times 9/12 - 800 \times 3.79 - 1600 \times 0.5 \qquad 7.7$$

$$= 2632 \text{ lb.ft.}$$

This must be supplied by soil pressure, SP, in the surrounding earth, which for an assumed linear increase in pressure with depth gives

$$SP > \frac{Mo}{2} \qquad 7.8$$

i.e. $SP > 1300$ lb./sq.ft.

which is not excessive for the gravel fill at a 4'0" depth, [117].

Additional safety is provided by the friction and uplift forces in the soil, which are maximised by pouring into the trench in an excavated condition, or in areas where this is impractical the back fill must be recompacted on completion of pouring.

The reinforcement required was determined as described in Reference 59, with the additional provision of the regularly spaced stirrups which carry the membrane loads to the foundation. The main loads being carried by 8 number 6 reinforcing bars equally spaced within the cross-section of the wall. Vertical temperature reinforcement being provided by pairs of number 4 bars on 18 inch centres, see Figure 24.

Since the most important property required of the concrete in such a low load application is weight rather than strength a standard construction (2500 p.s.i.) concrete was specified.

7.6 AIR FLOW REQUIREMENTS

The air flow system must supply air to inflate, stabilise, ventilate and heat the structure, and control the pressure of the air within the structure. The inflation pressure selected for use are:

i) P_2, 0.75 inch w.g., is the normal operating pressure for the system, which is maintained at this level for wind speeds less than 30 m.p.h. Applying Equation 7.3, and Figures 14 and 15 indicates that the structure would be stable in winds of up to 52 m.p.h., when inflated at P_1.

ii) P_2, 1.75 inch w.g., is the operating pressure of the system, which is maintained at this level for wind speeds greater than 30 m.p.h.

A schematic of the air flow system which satisfies these requirements is presented in Figure 6. The unit provides inflation for the air structure to two operating pressures, P_1 and P_2, (in this case $P_1 = 0.75$ in.w.g. and $P_2 = 1.75$ in.w.g.). P_1 is the normal operating pressure and P_2 is the design pressure under high wind load conditions. The values of P_1 and P_2 are controlled by presetting the damping system D_1 and D_2. In this case D_2 is shown installed within the heating unit, with the primary inflation unit, fan I (in a non-heated structure fan I would be similar to fan 2). D_2 has two preset values controlled by a motor drive unit, while D_1 has one manually adjusted level. The normal operating pressure is provided by Fan I with the damping system in its normal position. Three over-ride systems, controlled by pressure switches, $PS_{1,2,3}$, are available for use in problem situations.

Situation I, high wind speeds

Under wind speeds greater than 30 m.p.h. PS_1 is closed, which in turn activates the damper D_1 moving it to its more open position. Closing PS_1 also activates Timers T_1 and T_2. T_1 holds the system in this configuration for 15 minutes, and thereby ensures the stability of the system, if after this time PS_1 is still closed P_2 will be maintained for a subsequent 15 minutes. T_2 after 15 seconds, switches PS_3 into a controlling position over-riding PS_1 whose function is described in situation 2 below.

It should be noted here that the system is safe under 30 m.p.h. wind loads at P_1. The purpose of the higher pressure setting is to pretension the structure before any higher wind speeds occur. The location of sensing devices should be made remote from the structure if possible, in order to be unaffected by it. If this is not practical then secondary switches around the structure or lower settings are advisable.

The reaction time in which the system changes from P_1 to P_2 is usually of the order 10 seconds, which is increased to 25 by the operation of T_2, this time should still be small enough to ensure the safety of the structure in the wind, which is unlikely to double in speed in this time.

Situation 2, failure of Fan I to maintain required pressure

Should the structure's pressure fall below the preset level of PS_2 in the case of normal operation or the level of PS_3 under wind load conditions, the switches activate Fan 2, which will supply additional inflation to the system. A warning system is initiated and a holding relay will maintain Fan 2 in operation until the system is manually reset.

Situation 3, power failure to the system

In the event of a power failure, relay R will close switch SS, and start the auxiliary generator, which will supply power to the system. Standard systems supplied with the unit switch back to main supply on its restoration, relays preventing the simultaneous supply from both mains and generator.

To finalise the details required to satisfy the air flow requirements it is first necessary to calculate the air losses occurring at inflation pressure P_1. These have the following components:

i) Perimeter leakage; previous experience has shown that a value of 6.0 c.f.m. is a reasonable estimate of the leakage through a one foot length of a catenary cable type anchor system, when a 2 ft. seal skirt is employed in conjunction with a concrete foundation at a 0.75 inch w.g. inflation pressure. In this installation there are 558 ft. of perimeter resulting in a total perimeter leakage of 3350 c.f.m.

ii) Leakage around airlocks; at P_1 an air loss of 14 c.f.m. is expected per foot of door edge [28], which occurs in the 152 ft. of such "crackage" in this application to produce a leakage of <u>2130 c.f.m.</u>

iii) Diffusion losses at P_1, account for .0045 c.f.m. per sq.ft. of membrane surface [34], which for the 25,300 sq.ft. membrane is a total loss of <u>110 c.f.m.</u>

The total loss due to leakage, at P_1, is therefore 5,590 c.f.m. In considering ventilation requirements of one complete air change per hour, in the structure with an enclosed volume of 470,000 cubic feet, additional flow of approximately 2200 c.f.m. is required, i.e. a total flow of 7,800.

The additional flow can be provided by the introduction of a circular vent into the membrane as in Figure 25. Using Equation 7.4 the required area of the vent can be calculated, [28],

$$Q = 1096.5\ CoAo\sqrt{\frac{\Delta P}{ge}} \qquad 7.9$$

where Q is the flow through the vent in c.f.m.,

A_o is the area of the vent in ft.^{2},

ΔP is the differential pressure in inches w.g.,

Cc is the coefficient of contraction,

Cv is the coefficient of velocity,

Co = Co.Cv = 0.65. [23], and

ge is the density of air in l6/cu.ft.

rearranging Equation 7.9.

$$Ao = \frac{Q}{1096.5.Co} \cdot \sqrt{\frac{ge}{\Delta P}} \qquad 7.10$$

$$Ao = \frac{2200}{1096.5.065} \quad \sqrt{\frac{.075}{.75}}$$

$Ao = .976$ ft.^{2}, which is equivalent to a 13.4 in. diameter circle.

Once the basic air flow, at P_1 has been established it is possible to calculate the increased flow at P_2. Equation 7.9 indicates that the leakage losses will increase in the ratio $\sqrt{P_2/P_1}$, or 1.53, hence the losses at P_2 will be 11,900 c.f.m. The losses through the seal skirt will be increased in a lesser ratio due to the increased sealing effect on the skirt, since no data is available on this behaviour the higher value is used. The standby air fan must be able to supply these requirements, and is selected accordingly, allowing 15% oversize to accommodate the approximate nature of the analysis. The pressure in the final system being determined by adjustment of the damper system D_2 in Figure 6. The fan unit selection was made using the characteristic chart shown in Figure 26. The unit used is a 13,500 c.f.m. belted vent set, and has a 27 inch diameter wheel which is driven by 7-1/2 H.P. induction motor, supplying air through a 4.2 sq.ft. outlet at 3200 ft./minute.

The main fan unit is an integral part of the heating system, discussed in the following section where its size is finalised with reference to the requirements of the heat exchange system in addition to the ventilation and air loss requirements established above.

7.7 HEATING REQUIREMENTS

The 2-1/2% January design temperature for Halifax, Nova Scotia is 4°F., hence the temperature rise required for a minimum temperature of 65° within the structure is 61°F. Heat losses occurring under these conditions are made up as follows:

i) Losses due to air flow, h_f, depend on the product of air flow, 12,000 c.f.m., mean specific heat of the air 1.12 BTU/°F./ft.^{3}, [59], and the temperature rise, i.e.

$$h_f = 12{,}000 \times 1.08 \times 61$$

$$h_f = 820{,}000 \text{ BTU/hr., and}$$

ii) Losses through the membrane, h_m, depend on the temperature difference, the area, and the effective conductivity, 0, of the membrane (usually defined for 15 m.p.h. winds), and estimated for this membrane as 1.08 BTU/hr./°F./ft.^{2}, i.e.

$$h_m = 61 \times 24{,}500 \times 1.08$$

$$h_m = 1{,}600{,}000 \text{ BTU/hr.}$$

These losses produce the total heating requirement, H, as

$$H = h_m + h_f$$

$$= 2{,}400{,}000 \text{ BTU/hr.}$$

The total heat requirement of 2,400,000, suggests the use of a 2.5 million BTU heater. Many standard, indirect fired, recirculating heaters are available. In the present application the over-riding consideration in the choice of the National Champion Unit was delivery time.

The standard unit is equipped with a 15 H.P. motor to provide the necessary flow of 21,000 c.f.m. over the heat exchanger at up to .75 inch w.g. back pressure. To accommodate higher back pressures, the fan system is modified by increasing the power supply to 20 H.P. and by changing the fan wheel geometry. The unit may be modified to use either natural gas or oil. In this case the natural gas was specified.

In this particular installation the purchaser of the air structure had an in-plant auxiliary power supply, which had sufficient capacity to support the full requirements of this air structure. The control system designed for use in this structure was described in Section 7.6 except that the auxiliary power switching was not required.

7.8 LIGHTING SYSTEM

The white membrane is sufficiently translucent to allow natural lighting to be used in the daytime. For nighttime use, 50 ft. candles of artifical lighting are supplied by 24 mercury arc units, manufactured by Westinghouse Canada Ltd. for use as floodlights. The lights are mounted in pairs on portable standards within the structure.

Basing a calculation on 80% reflectivity of the light from the membrane [37]

24 kw. at 52 lumens/watt provide
1.248,000 lumens.

of which 80% is reflected and distributed over the 118' x 168' structure,

$$\frac{1,248,000 \times 0.8}{118 \times 168} = 50.36 \text{ lumens/ft.}$$

$$\underline{\simeq 50 \text{ ft. candles}}$$

Final location and adjustment of the lights to ensure even distribution is determined on installation.

7.9 ACCESS

Airlock and emergency exit locations are shown in Figure 20. The airlocks, Figure 27, utilised metal buildings manufactured by a company near the site. An interlock system is incorporated to prevent simultaneous door opening. The airlocks are mounted on concrete decks integral with the main foundation.

The fire exit doors utilise standard kalamein fire doors, mounted in a welded steel frame. The doors are self-closing using a counter weight. The frame is attached rigidly to the foundation wall which removes the need for outside braces on the frame which are often necessary to support the door frame.

The transition pieces for both airlocks and exit doors are attached to the hardware by the detail shown in Figure 9(i), which provides a simple air tight joint, as the fabric tension pulls the roped edge taut against the strip. The cable arch is approximately in the form of a semi-elipse which effectively carries the full fabric tensions across the discontinuity in the fabric. The cable tension is 23,000 lb. for the larger span, a 3/4 in. galvanised aircraft cable is used to transmit the load to the foundation, which has an oversize anchor to carry the increased load.

The transition pieces are patterned to allow the motion of the structure under wind loads, as discussed in Section 4.7.

7.10 CONSTRUCTION AND INSTALLATION

The patterning of the structure is accomplished using proprietry techniques. The final structural shape involves large areas of single curvature involving flat panels with approximately straight seams. The main structural panels being cut and marked in 4 days (2 operators). Patterning and cutting of ductwork and transition sections involved a further three days, during which time assembly of the structure had started. The assembly absorbed 15 days, of full time effort by a "skilled" welder and helper, with longer manpower of up to 20 being required to manoevre larger sections as they were completed. The structure was assembled from 56" wide material using 1-1/2" wide welded seams. The catenary arches are fitted to each panel before assembly using a 3" wide welded seam. The transition pieces are similarly attached to the smallest practical section to reduce handling problems.

The cables are fitted on site, after the structure is spread out in its final position. Whilst it would be advantageous for factory content to cover this task, it cannot be done until all welding is completed because of the large induced currents caused by the welding process, and space requirements are such as to make the additional handling time uneconomical.

The 1-1/2" welds are tested in Section 11.1 and shown to be as strong in tension as the parent fabric.

Installation at the site was done by Halifax sub-contractors who installed the heating equipment, foundation airlocks, fans and controls before the membrane arrived on site. The emergency doors were made by a Hamilton company and shipped with the structure. On site final assembly was supervised by one member of the manufacturer's personnel.

The procedure involves:

i) Locating and spreading the membrane,

ii) Attaching the catenary cables to the membrane and the foundation.

iii) Lifting the membrane over the airlocks and fastening transition pieces and ductwork.

iv) Inflation, testing and inspection of the system, which is functioning satisfactorily.

8 COMPARITIVE DESIGNS

In this chapter four air structure designs are described in the areas in which they differ significantly from the structure in Chapter 7.

Figure 19 illustrates a section through a construction shelter used by the Canadian Ministry of Transport for the installation of radar equipment. The detail differences occur because the structure is temporary in nature, has an exposed site, and is spherical. The differences are:

i) Ground screw anchors or concrete friction piles are used as the foundation, depending on the location.

ii) A field jointing system is utilised to enable the structure to be removed from the completed installation.

iii) Localised heating within the structure is accomplished through the use of infra-red radiative heaters.

iv) The fans and the generating unit are located inside the structure.

and v) The fabric used has extra additives in its p.v.c. coating to provide extra flexibility at the extremely low design temperature of -40°F.

Alternative solutions for problems of extreme conditions are discussed by Weitz [127].

The small structure shown in Figure 28 was installed in Waterloo, Ontario early in 1974, as a domestic swimming pool enclosure. The small size of the structure allows the following design differences:

i) Continuous fastening of the membrane to the foundation can be used at a decreased cost over a catenary cable system because of the small loads involved, and the lack of manufacturing problems in holding design tolerances over the small length of the structure.

ii) The ratio h/d is greater than 1/2 which is unusual in a cylindrical structure but again because of the small size of the structure problems of stability do not arise.

iii) The entrance to the structure in this case is a simple fabric door on a polyethylene frame, suspended from the membrane. The low frequency of use limits the time the door is open and minimises any associated air loss.

iv) The size of the structure limits maximum stresses to about 200 lb. per foot and by using a fabric of initial strength 380 lb. per inch, a design life of about 15 years can be expected. Damage due to handling during installation and annual removal will probably be the limiting factor on the life of the structure.

The foundation design shown in Figure 29 was proposed for use in a pulp storage installation in Quebec. Standard doors and air ducting equipment could be mounted in the full height of the wall used. As in the warehouse structure this wall was required to protect the membrane from contact damage with a front end loader. A similar design was utilised by Dent [118] to accommodate a safety net system to prevent injury to occupants in the event of a catastrophic collapse of an air structure used in Blackpool Zoo in the U.K. The system's foundation allows maximum use to be made of the weight of the wall and the backfill on the footing, and requires minimal material usage on the foundation itself.

The structure shown in Figure 17 is not of the author's design. It was fabricated in 1974 by Baracudaverken, Djursholm, Sweden and installed in Hamilton, Ontario. The structure is 400 ft. long, 140 ft. wide and 42 ft. high at its centre. The structure is cabled by a parallel system of 7/8 inch diameter cables on 20 ft. centres. By introducing secondary curvature the membrane stresses are reduced in this case to about one third the level that would exist in a similar uncabled membrane. This is believed to be the first structure ~~ever~~ built with this particular configuration [119], a variation of one suggested by Otto, [3]. An analysis of the structure using a similar approach to that outlined previously and the same factor Cp of 1.05 produced the following figures, for a 60 m.p.h. wind load, (no gusting allowance), and the 2 in. w.g. used to inflate the structure:

Maximum fabric stress = 400 lb./ft.
Maximum cable load = 27,000 lb.

The initial purpose of the analysis had been to estimate the bending loads on the 1 inch diameter bolts used as shackle pins for the 1/8 inch cable. Applying elastic bending theory to the pin indicates that it would need a yield stress of some 380,000 lb./in.^{2} to prevent yielding under a 60 m.p.h. wind. Subsequent inspection of the structure after such a wind had occurred showed that several of the pins had in fact yielded. The pins were subsequently replaced by 1-1/2 inch diameter bolts.

This analysis allows two conclusions to be drawn:

i) that the analysis used produces reasonably accurate results, and

ii) the structure in question was designed without due consideration of wind load.

This structure illustrates the problem of stability mentioned earlier in this work. During installation the structure in question was inflated to 1/2 inch w.g. for a period of several days; at this pressure and under wind loads of approximately 25 m.p.h., an instability in the form of waves traversing the length of the structure at between 5 and 6 cycles per minute. This low stability at low inflation pressures gives some measure of the structure's stability when fully inflated. If the natural frequency of the membrane is assumed to depend on the root of the membrane tension, which is in turn related to the pressure difference across the membrane, i.e.

$$F = K_1\sqrt{N} = K_2\sqrt{(\bar{C}p.q + P_i)} \qquad 8.1$$

where F is the natural frequency of the membrane,

K_1 and K_2 are constants,

N is a measure of the mean membrane tension,

q is the stagnation pressure of the wind,

$\bar{C}p$ is the mean wind pressure coefficient for the complete structure, and

P_i is the inflation pressure.

This instability will be excited when the wind speed is in fixed ratio, K_3 to the frequency F, i.e. when

$$F = K_3V \qquad 8.2$$

where K_3 is the wind speed.

Substituting for V= 25 m.p.h.,and p_i= 0.5 in. w.g. in Equations 8.1 and 8.2 produces values of K_2 and K_3 which can be used with Equation 5.1 to predict that the structure will become unstable at wind speeds of approximately 50 m.p.h. Uncabled structures of similar size are stable under both sets of conditions mentioned above , the instability in this case being attributable to the increased weight and the decreased tension of the cabled structure, which must be compensated by higher inflation pressures. In the case of this particular structure a design pressure of 2.75 in. w.g. was specified [8].

9 CONCLUSIONS

This study has shown:

1. That air structures are feasible for low cost, large span temporary or semi-permanent applications.
2. That practical design methods exist, which provide acceptable solutions.
3. That certain limitations exist in these methods such as:
    a) Exact wind loads cannot be predicted unless improved testing methods are applied.
    b) Material properties cannot be predicted unless improved understanding and measurement techniques are developed, particularly in the areas of response to biaxial loads and aging.
    c) Exact analysis will have to incorporate 3a) and 3b) together with allowance for the effect of the enclosed air space.
4. That loss of stability could be the ultimate size limitation on single span air structures.
5. That potential areas of further development include:
    a) The analysis of the statistical nature of wind loading as applied to the decay in physical properties of the membrane materials.

b) Stability analysis of membranes, both local (wrinkling) and structural, as initially investigated by Yokoo et.al. [120].

c) Analysis of the effects of large transient temperature gradients on membrane materials.

d) Development of low cost insulating materials for air structures.

e) Improved wind tunnel studies perhaps with an extension of boundary layer testing applied to flexible photoelastic models developed from the rigid model, laminar flow tests of Donaldson [121].

If air structures are to be accepted in Canada then a code modelled on that in use in Japan, with the Canadian Structural Design manual's approach to wind loading, would be an ideal base to promote fair competition between the manufacturers of air structures, and would improve their reliability and increase the acceptance of air structures preventing failures such as that described in Section 11.2.

FIGURES

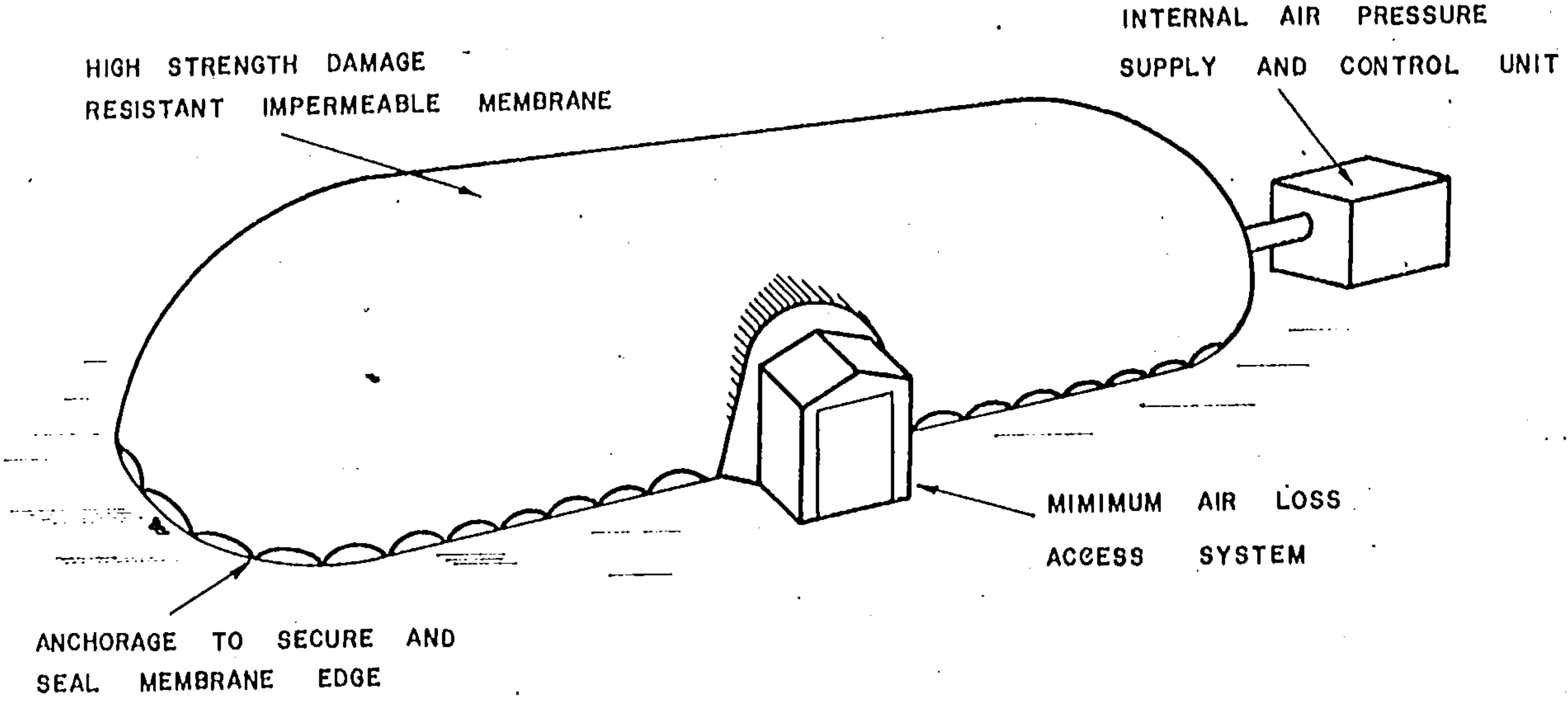
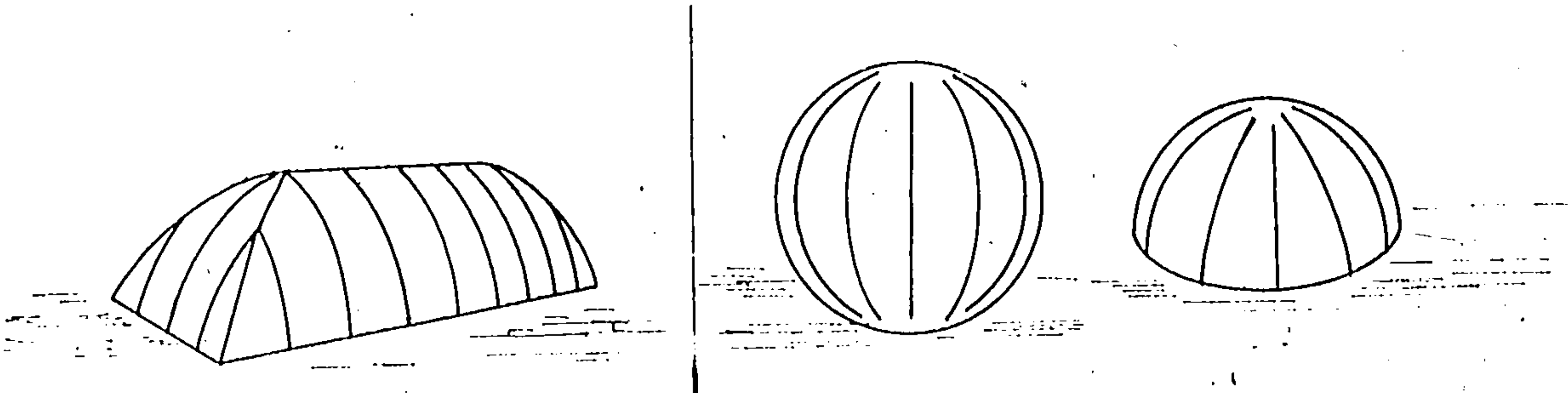
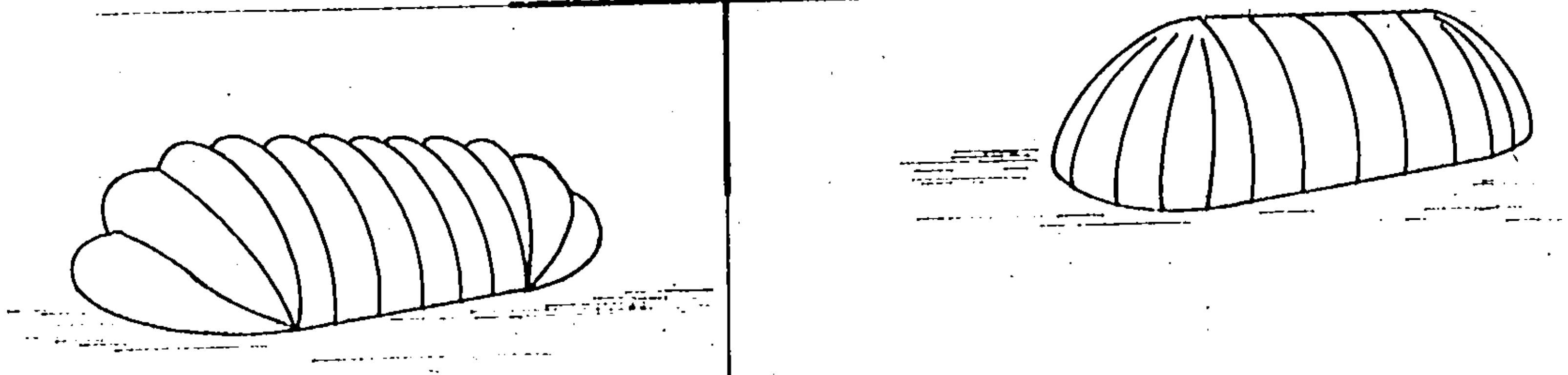


FIGURE I. MAIN COMPONENTS OF AN AIR STRUCTURE SYSTEM.



(i) COMBINATION OF CYLINDERS

(ii) SPHERICAL SECTIONS



(iv) CABLED STRUCTURES

(iii) COMBINATION CYLINDER AND SPHERE

FIGURE 2. COMMERCIAL AIR STRUCTURE SHAPES.

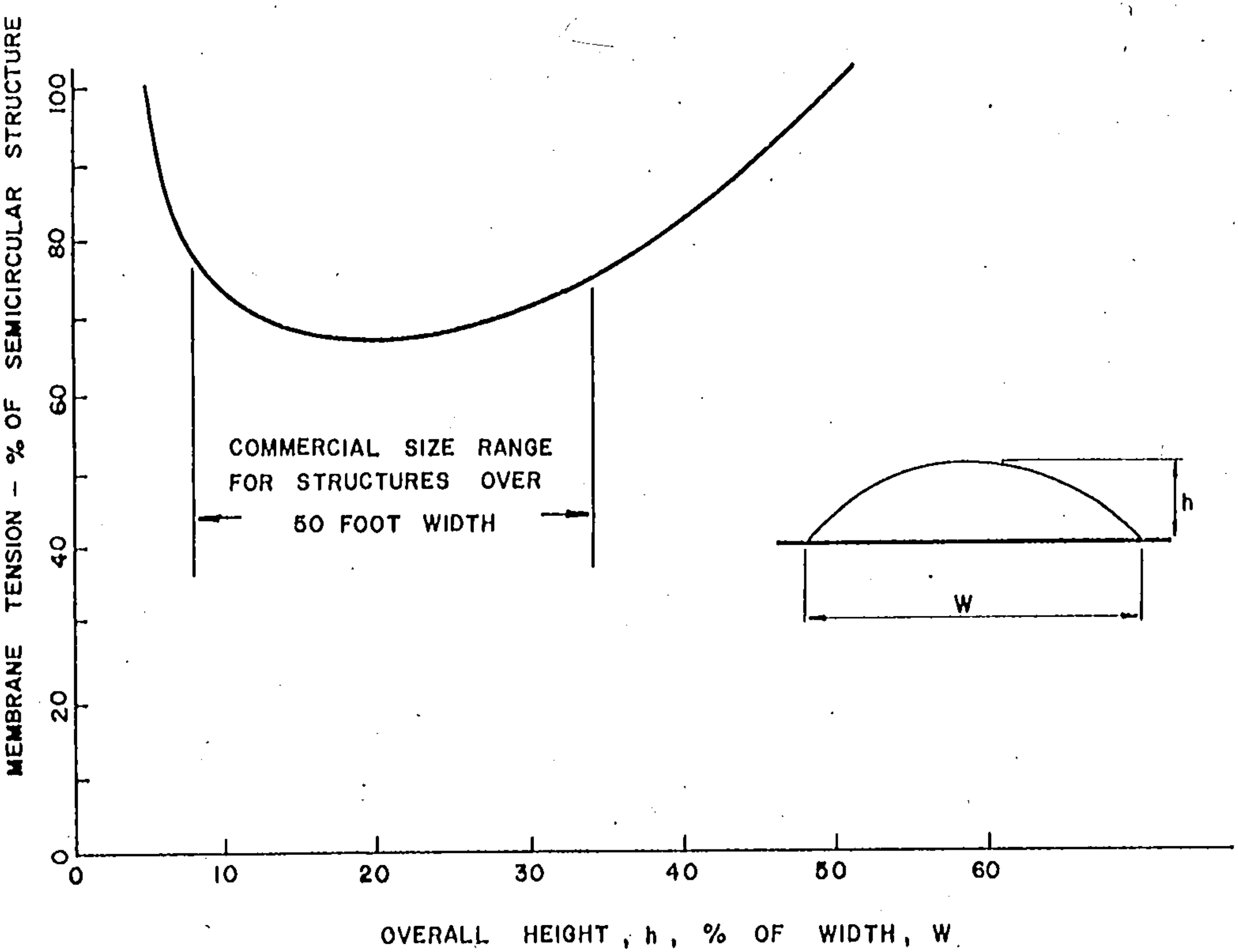


FIGURE 3. MEMBRANE UNIT TENSION AS A FUNCTION OF HEIGHT FOR FIXED WIDTH

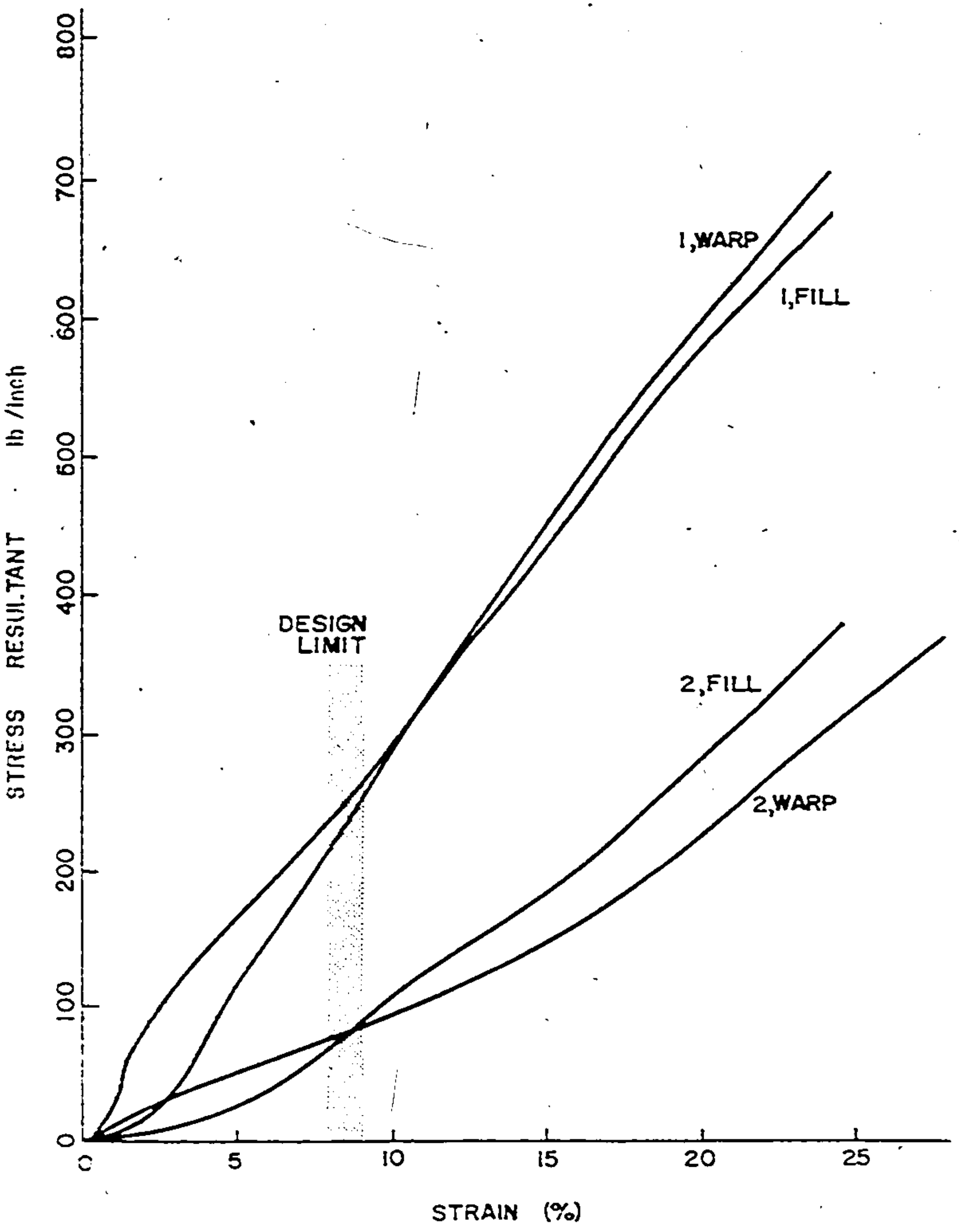


FIGURE 4(i) UNIAXIAL STRESS STRAIN CURVES FOR FABRICS 1 AND 2 DESCRIBED IN TABLE 2.

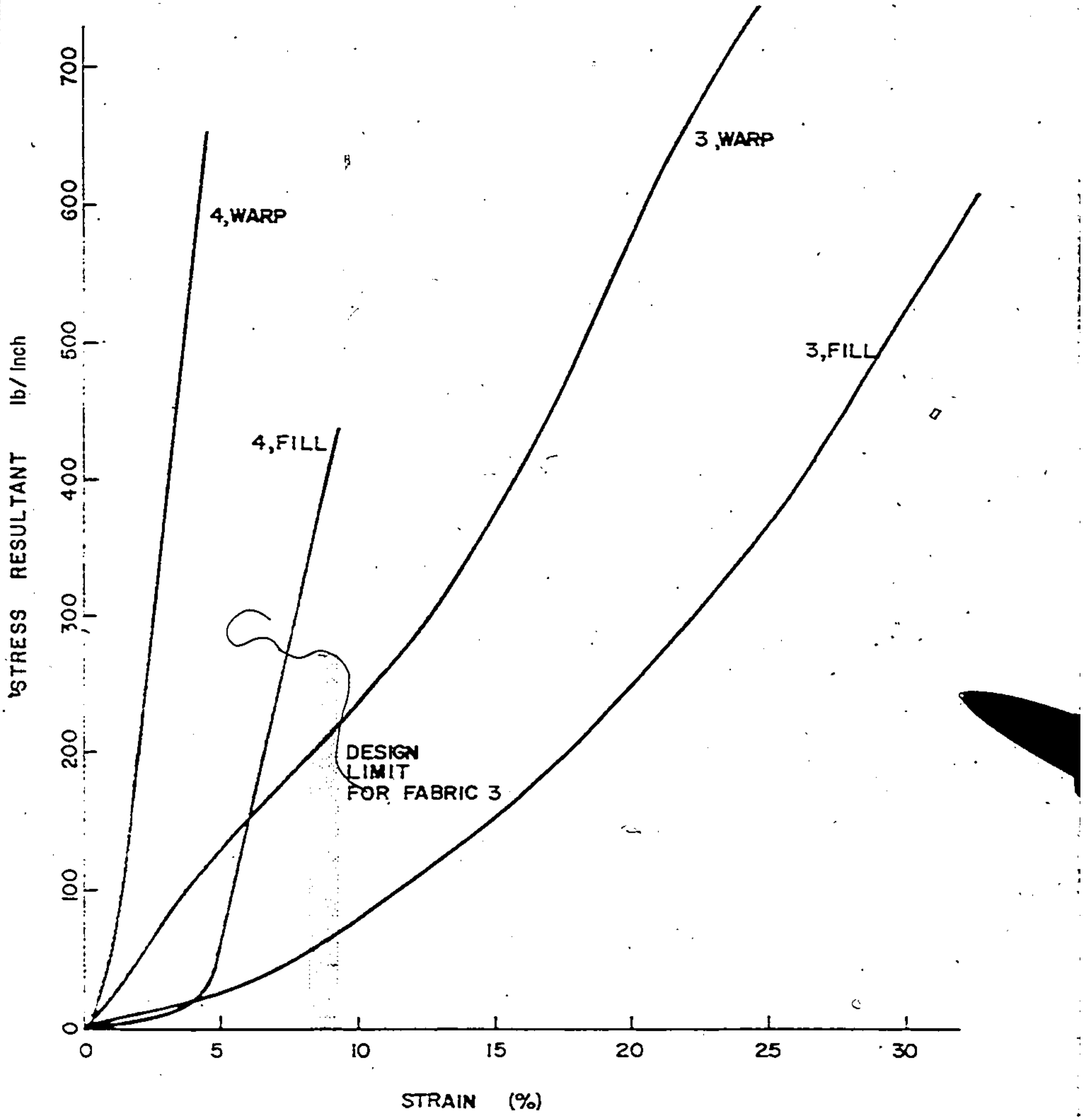
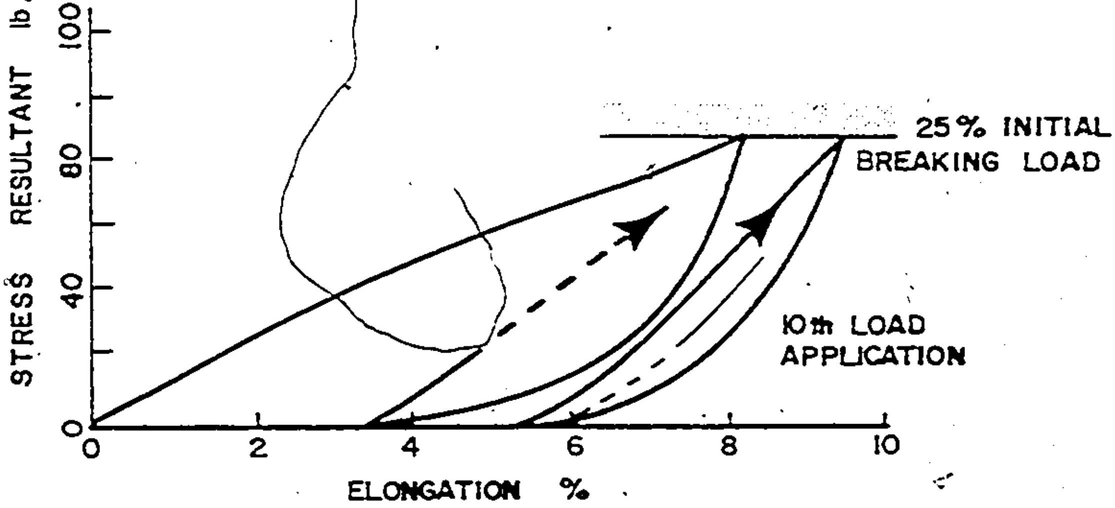
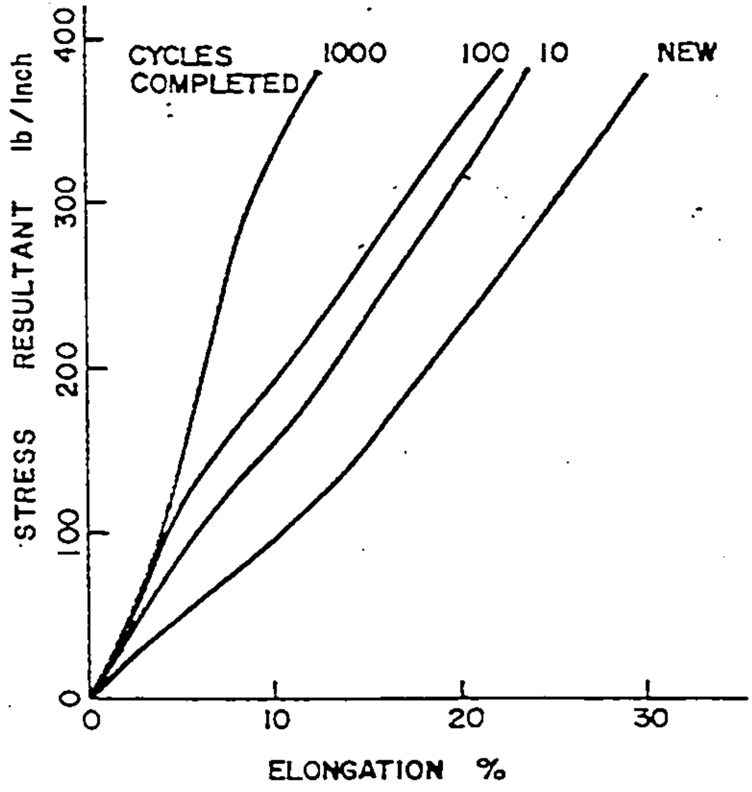


FIGURE 4(ii) UNIAXIAL STRESS STRAIN CURVES FOR FABRICS 3 AND 4 DESCRIBED IN TABLE 2.



CYCLIC LOAD VS EXTENSION



LOAD VS EXTENSION AFTER CYCLIC LOADING
(TO 25% INITIAL BREAKING LOAD)

FIGURE 5. EFFECTS OF CYCLIC LOADING ON WARP THREADS OF FABRIC 2 DESCRIBED IN TABLE 2.

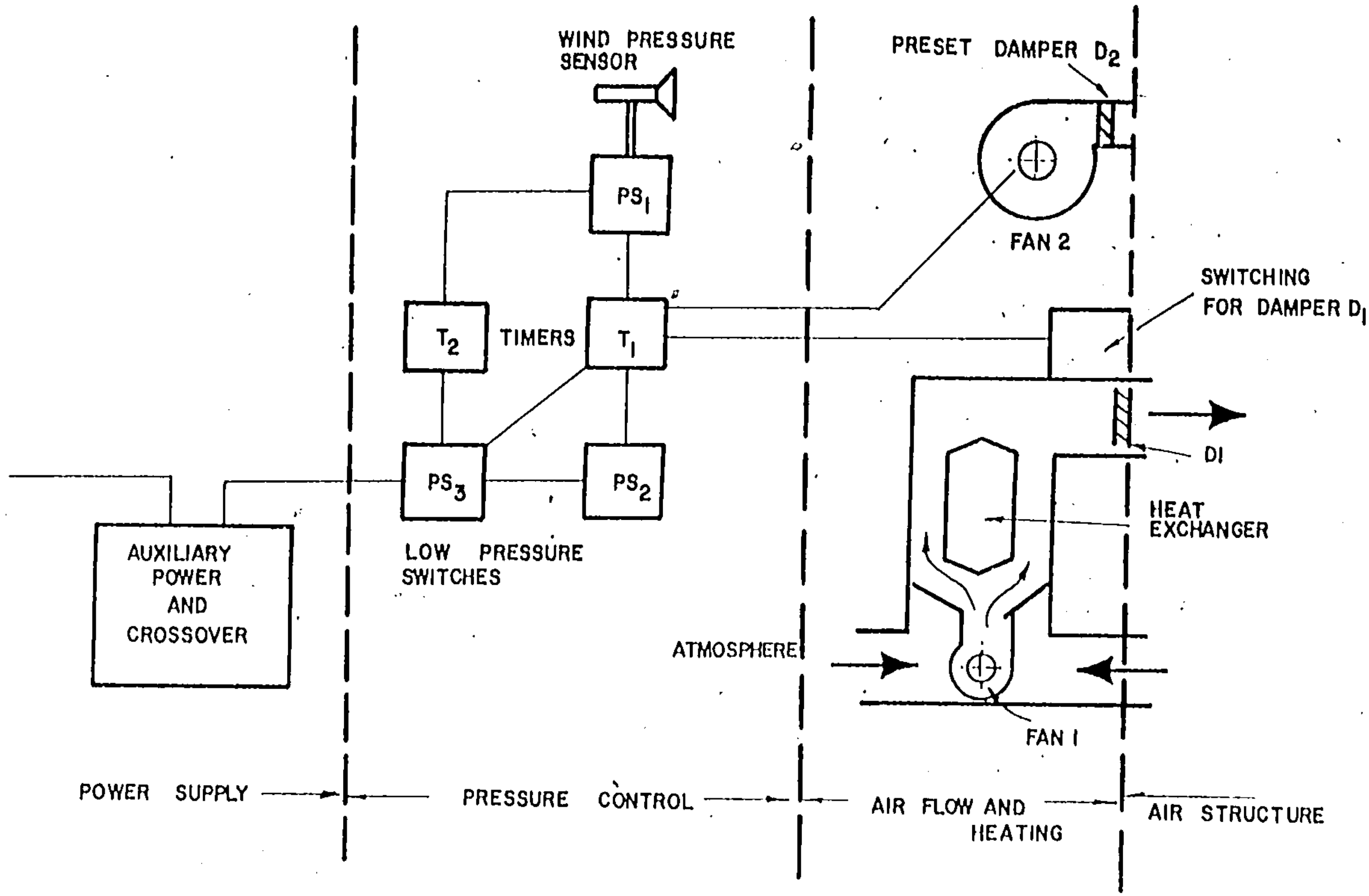


FIGURE 6 SCHEMATIC OF AN AIR STRUCTURE INFLATION SYSTEM.

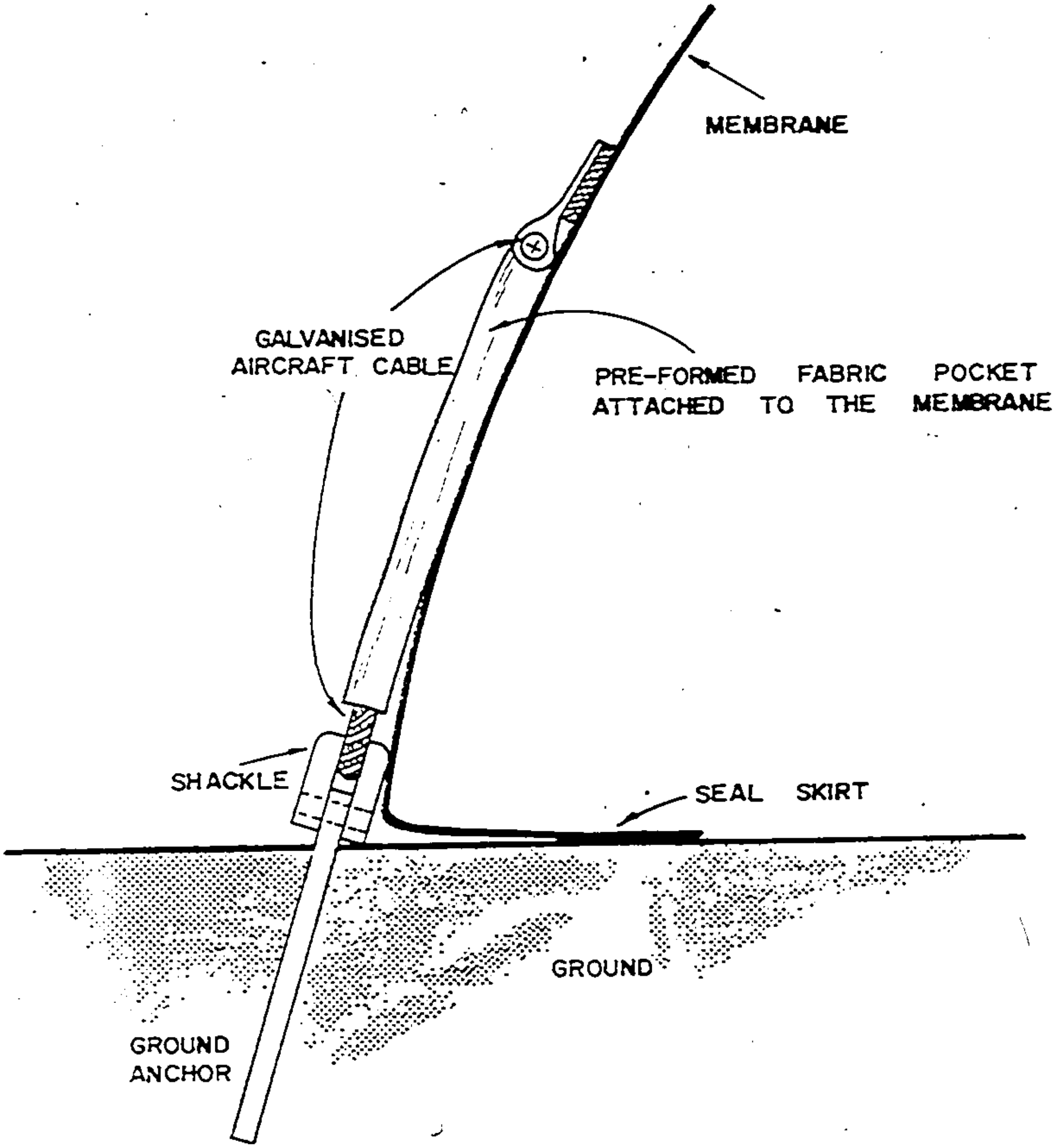


FIGURE 7(i) SECTION THROUGH CATENARY ANCHOR SYSTEM

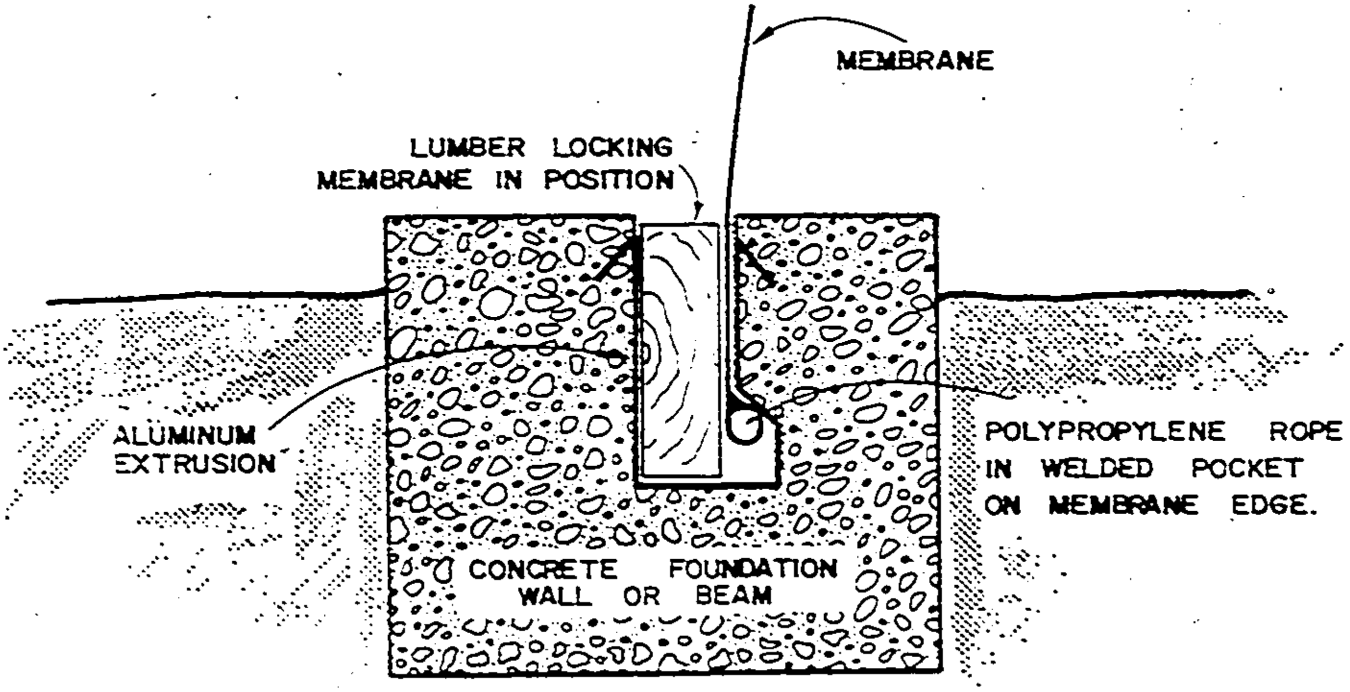
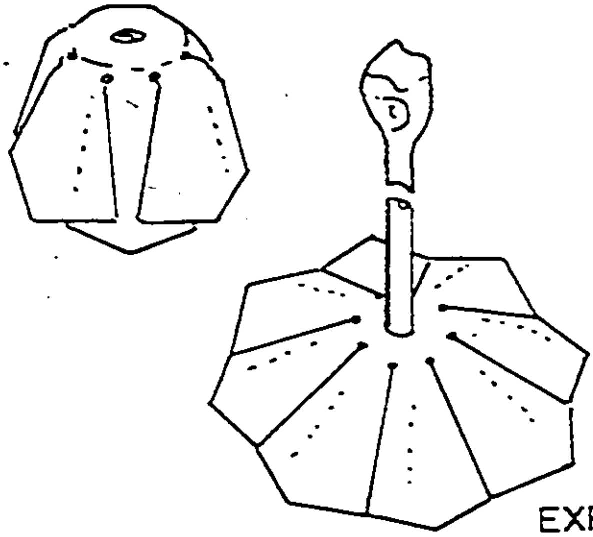
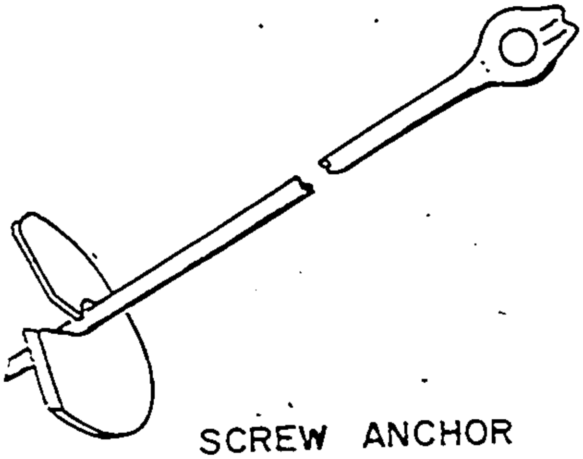


FIGURE 7(ii) SECTION THROUGH CONTINUOUS ANCHOR SYSTEM.

FIGURE 7(III). CATENARY CABLE SYSTEM.



EXPANDING ANCHOR



SCREW ANCHOR

FIGURE 8 GROUND ANCHOR SYSTEMS.

FIGURE 9. TYPICAL HEATING AND AIR SUPPLY UNITS.

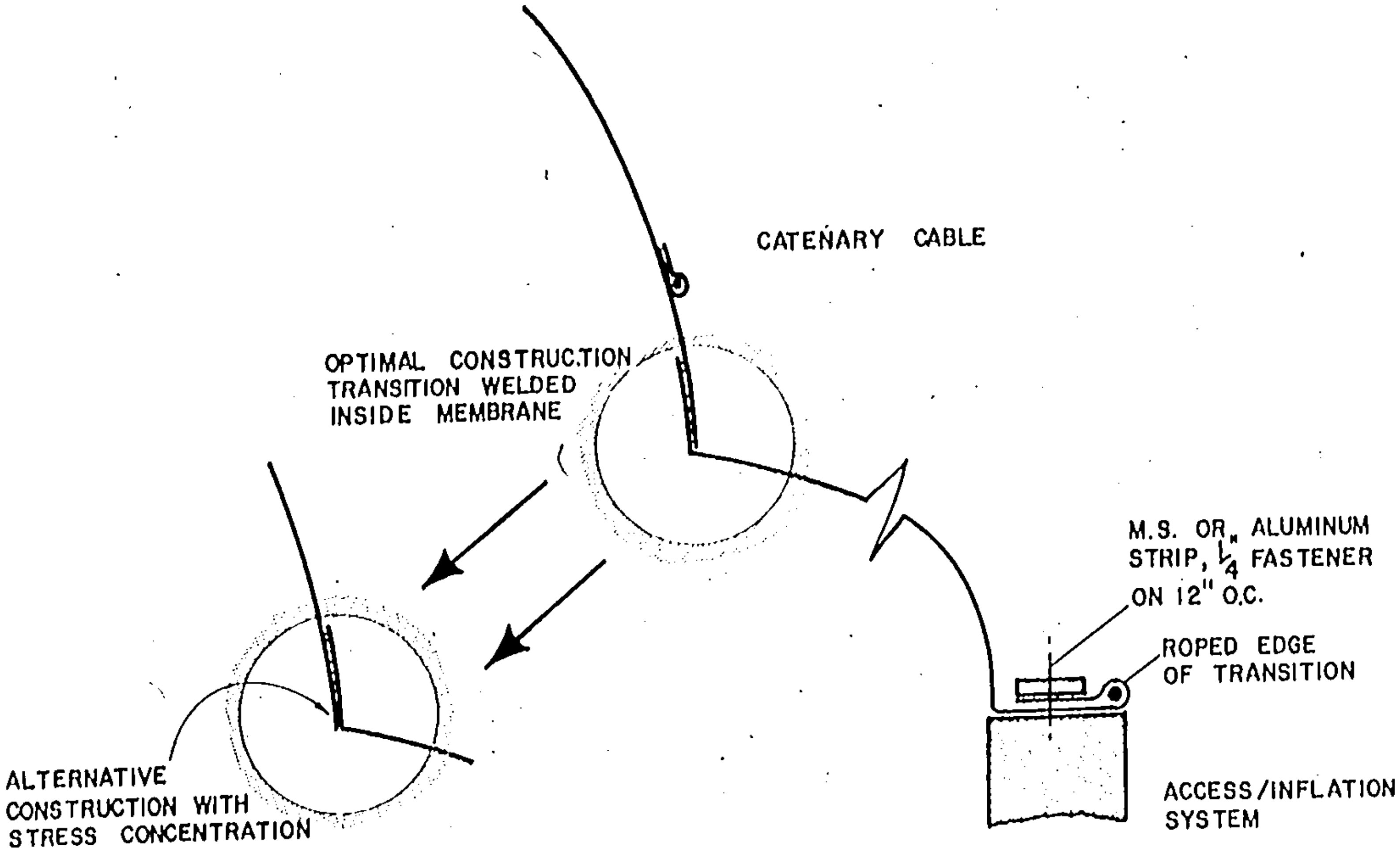


FIGURE 10 ATTACHMENT OF TRANSITION PIECES.

FIGURE 10 SHORT TRANSITION PIECE.

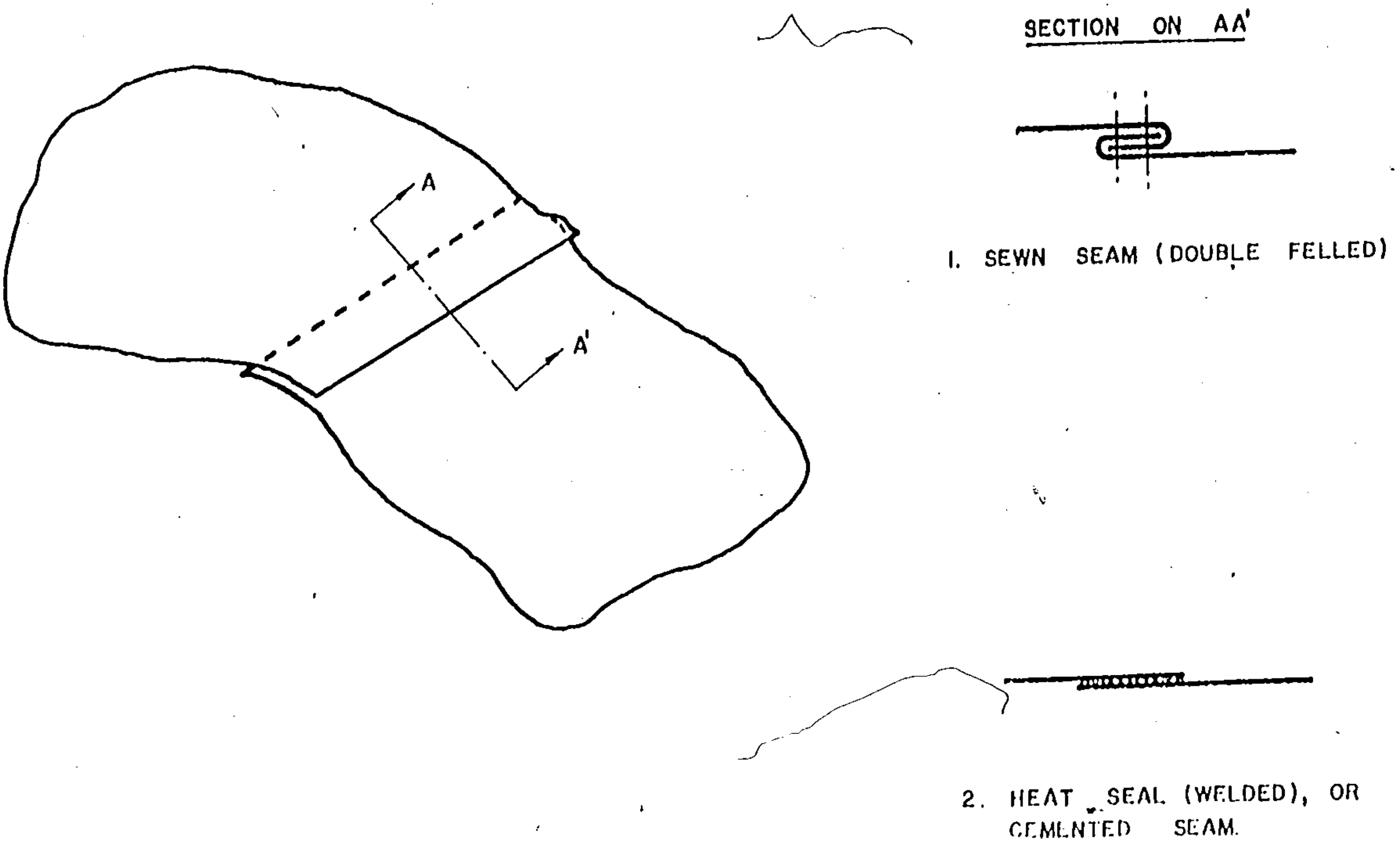
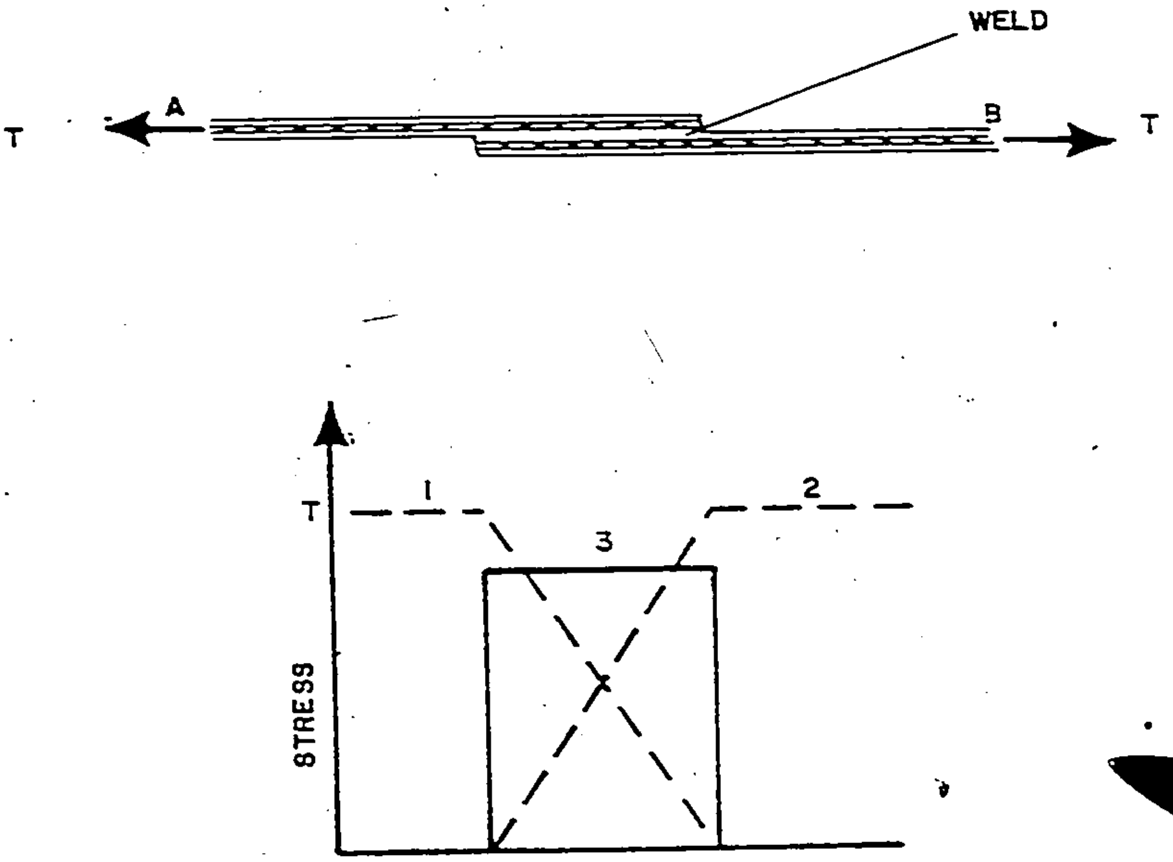
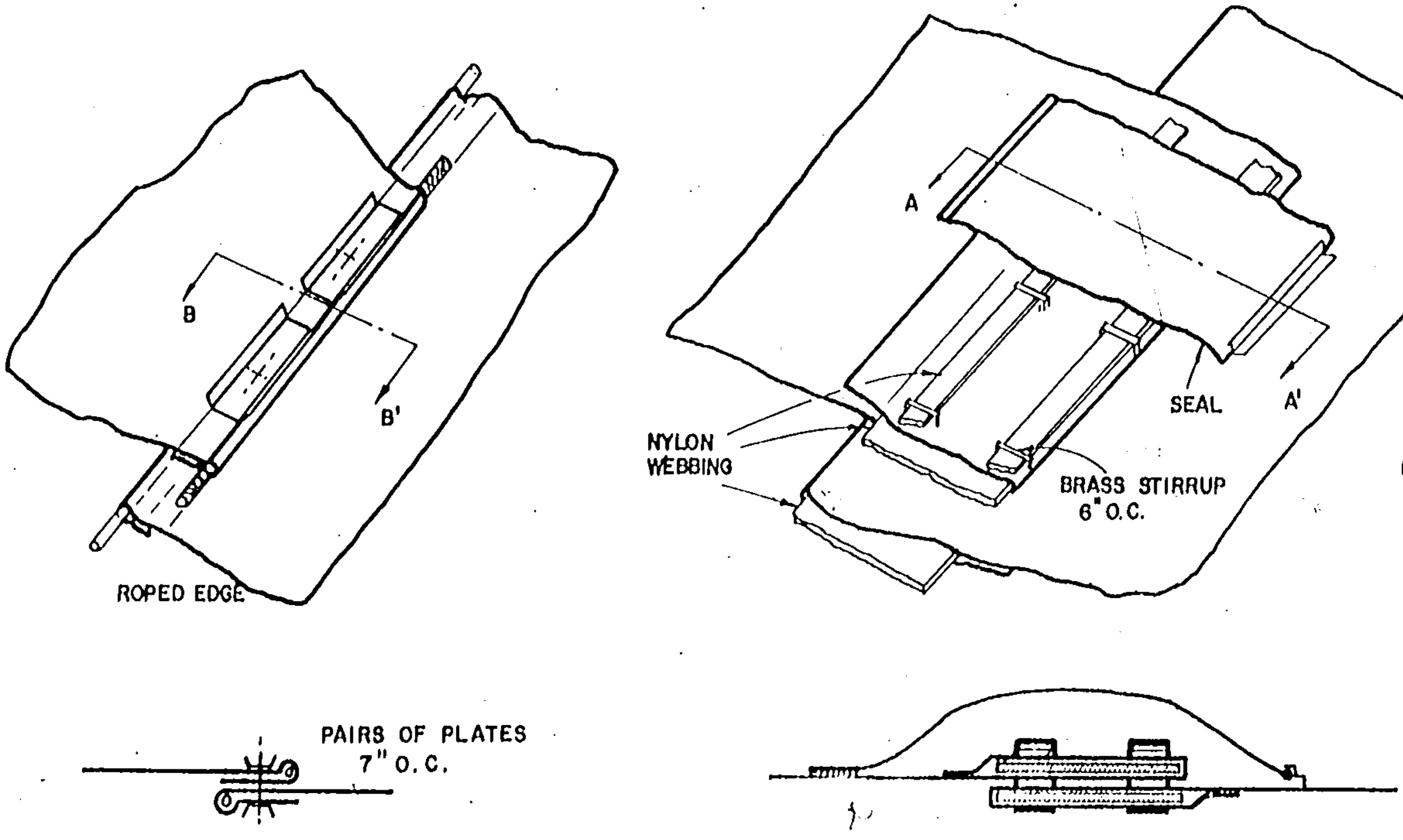


FIGURE II(i) STRUCTURAL FABRIC JOINTS



1,2 TENSION IN BASE CLOTH OF FABRICS A AND B.
3 SHEAR STRESS OF WELDED COATING.

FIGURE II(ii) STRESS DISTRIBUTION FOR WELDED SEAMS.



SECTION BB'

SECTION AA'

FIGURE 12 MECHANICAL JOINT SYSTEMS.

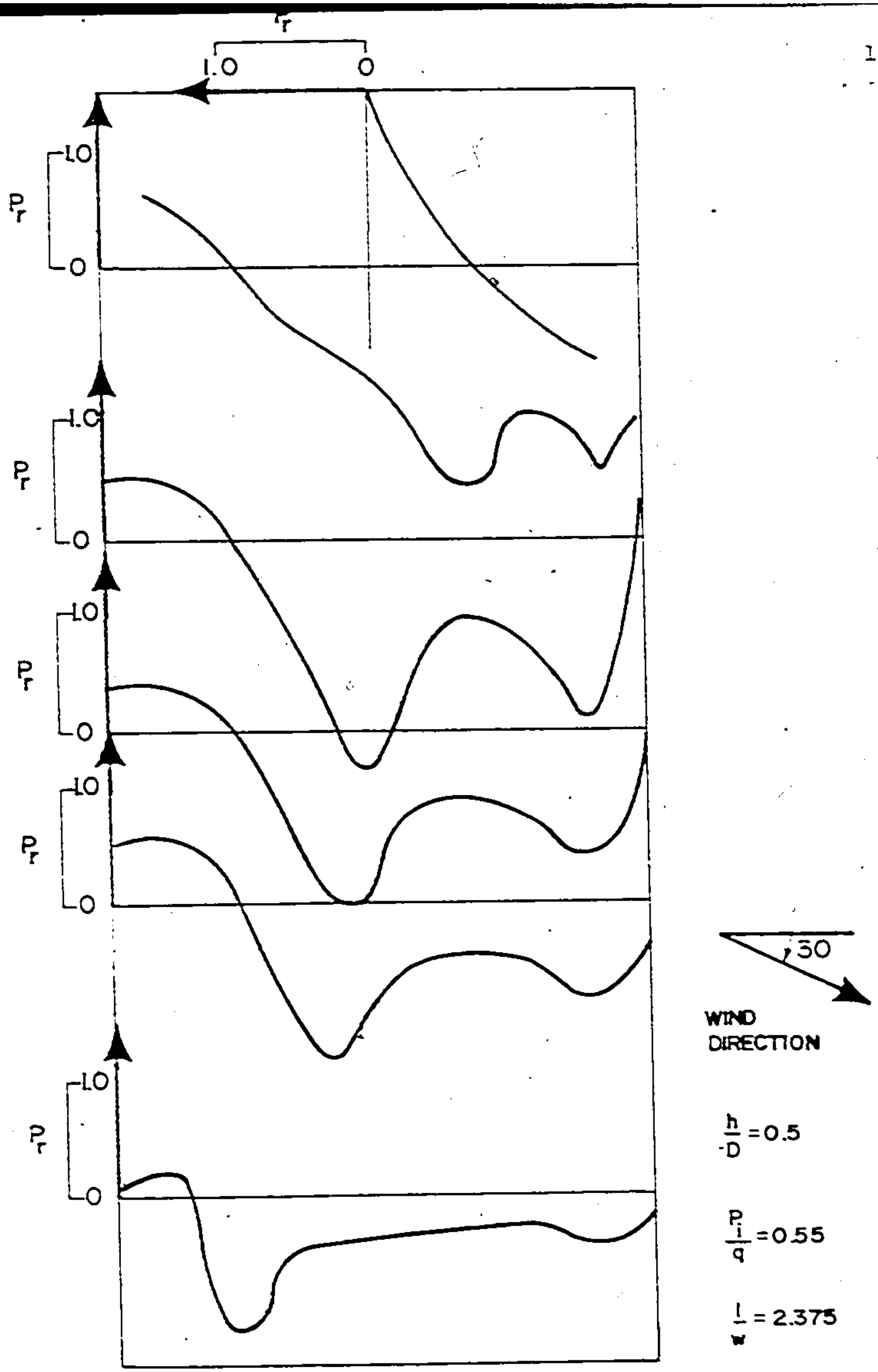


FIGURE 13(i) PRESSURE DISTRIBUTION OVER A RECTANGULAR PLAN AIR SUPPORTED STRUCTURE.

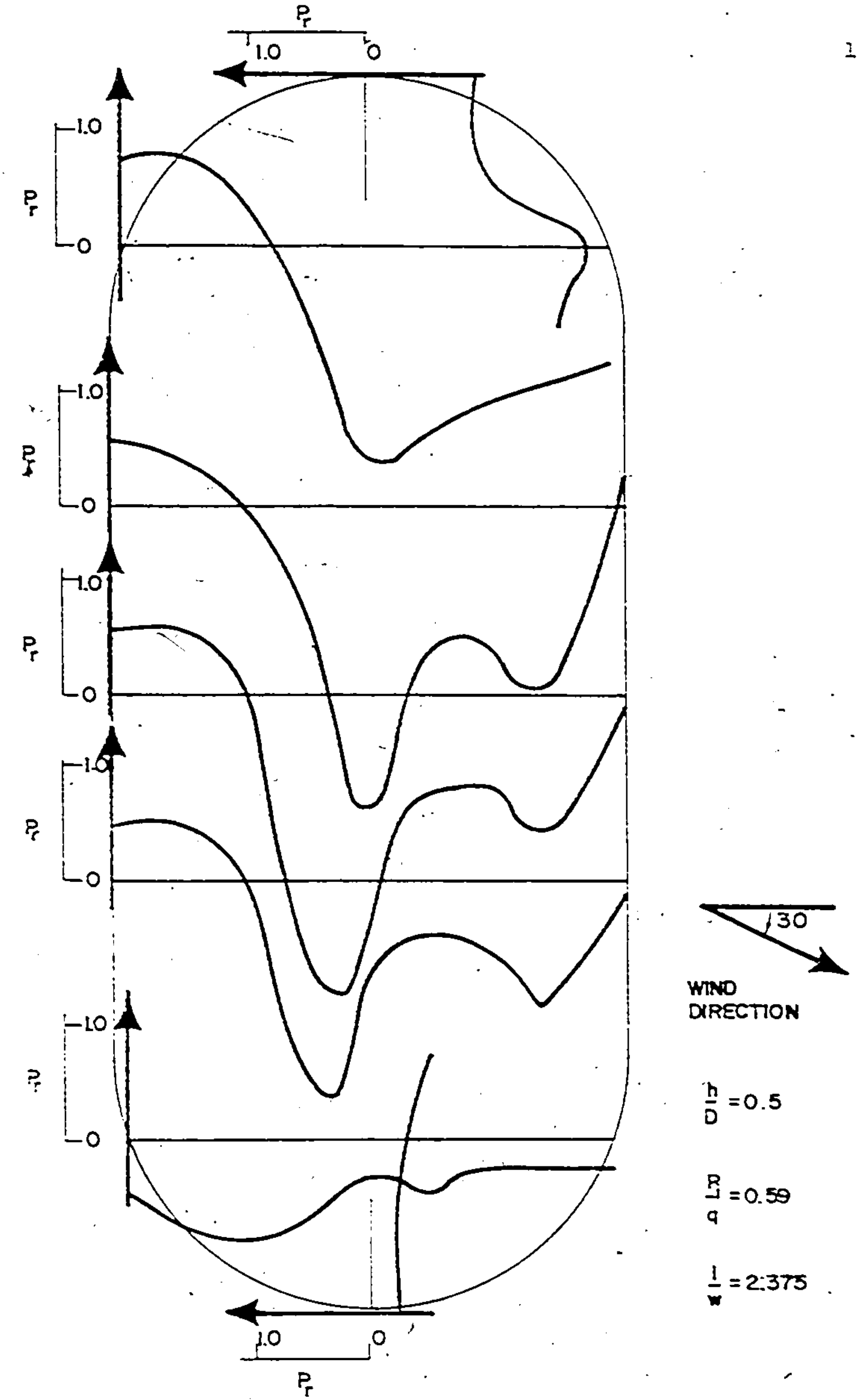


FIGURE 13(ii) PRESSURE DISTRIBUTION OVER A SPHERICALLY ENDED AIR SUPPORTED STRUCTURE.

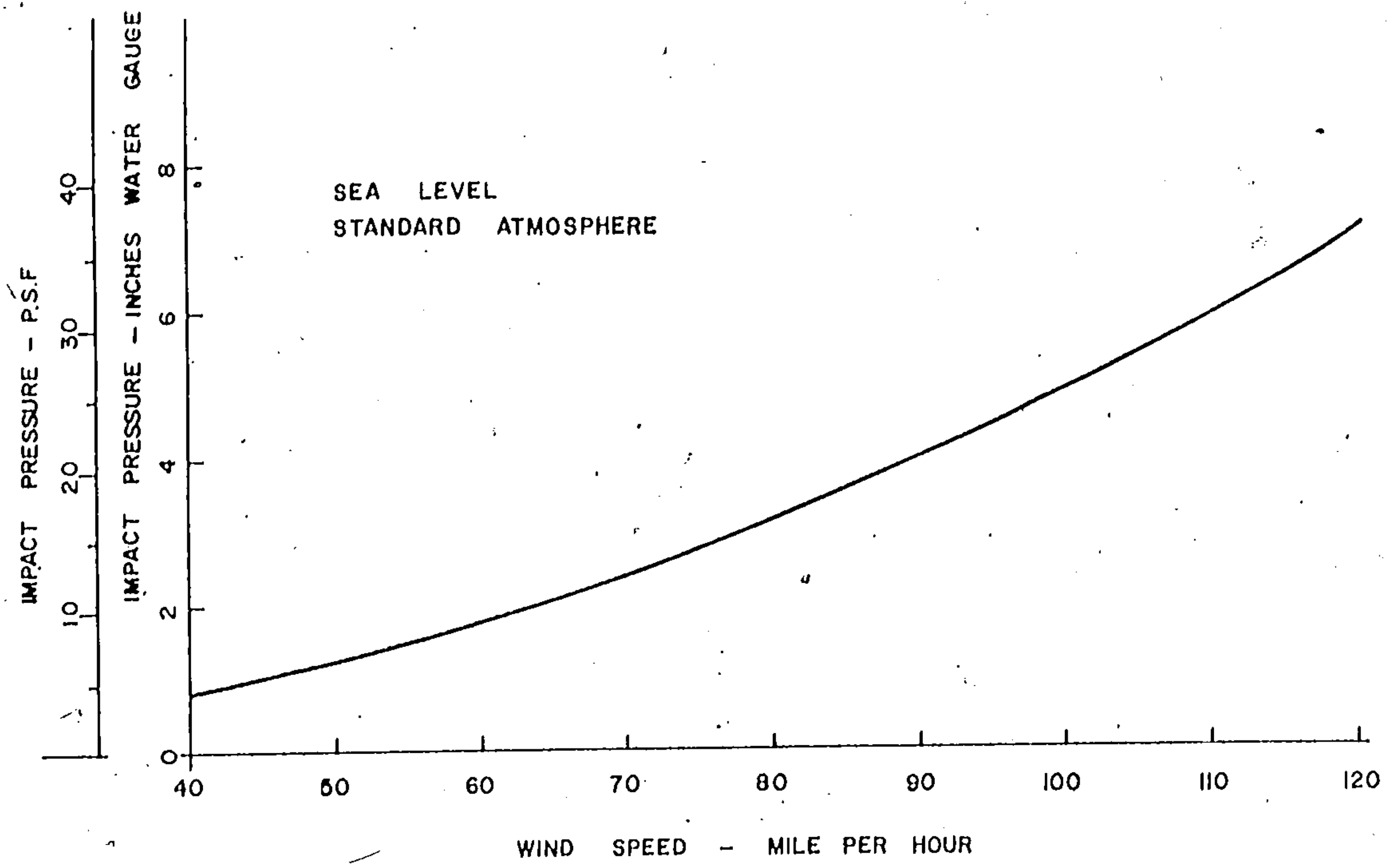


FIGURE 14. VARIATION OF IMPACT PRESSURE WITH AIR SPEED

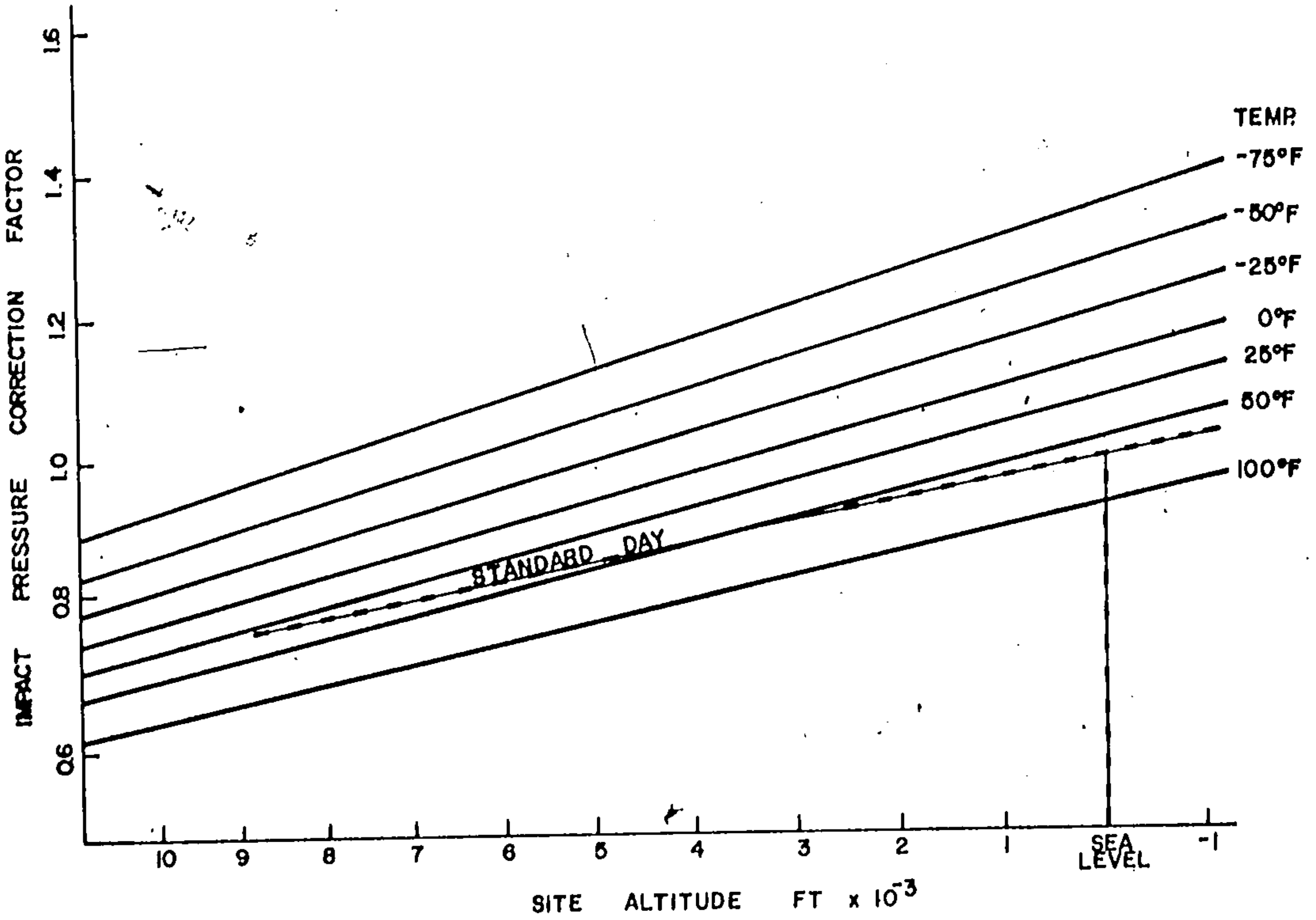


FIGURE 15. ENVIRONMENTAL CORRECTION FACTORS FOR WIND SPEED PRESSURE - CHART.

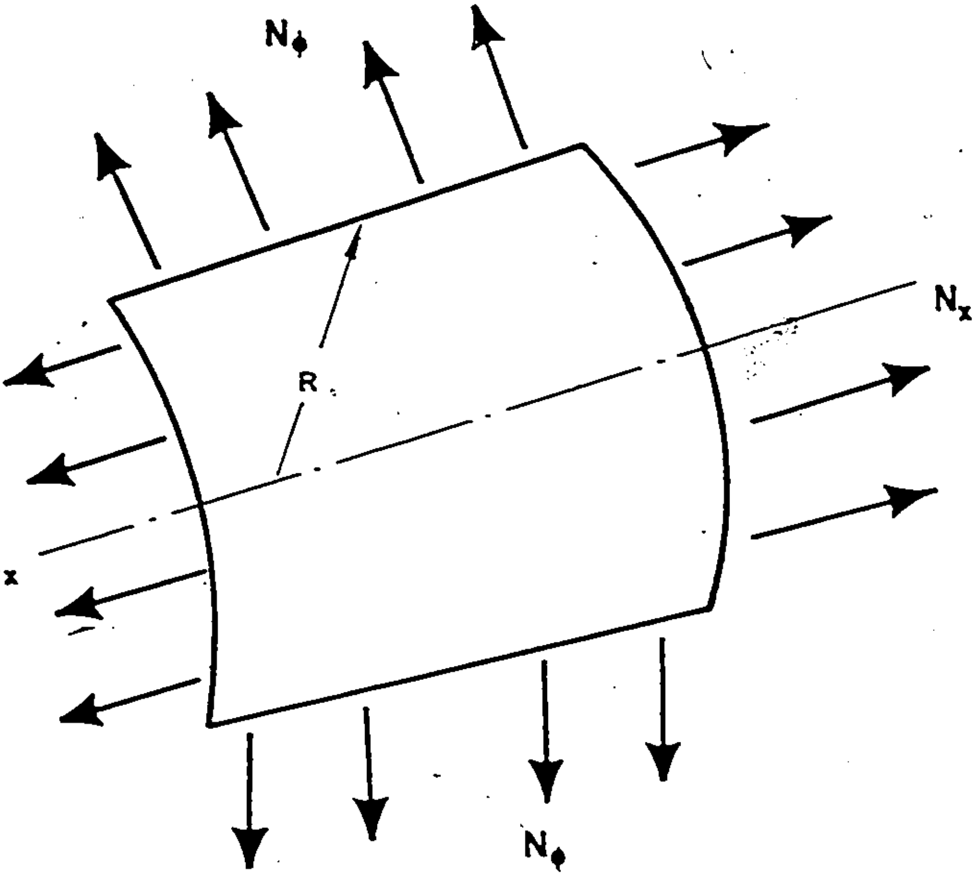


FIGURE 16 ELEMENTAL CYLINDRICAL SECTION WITH ONE PRINCIPAL CURVATURE.

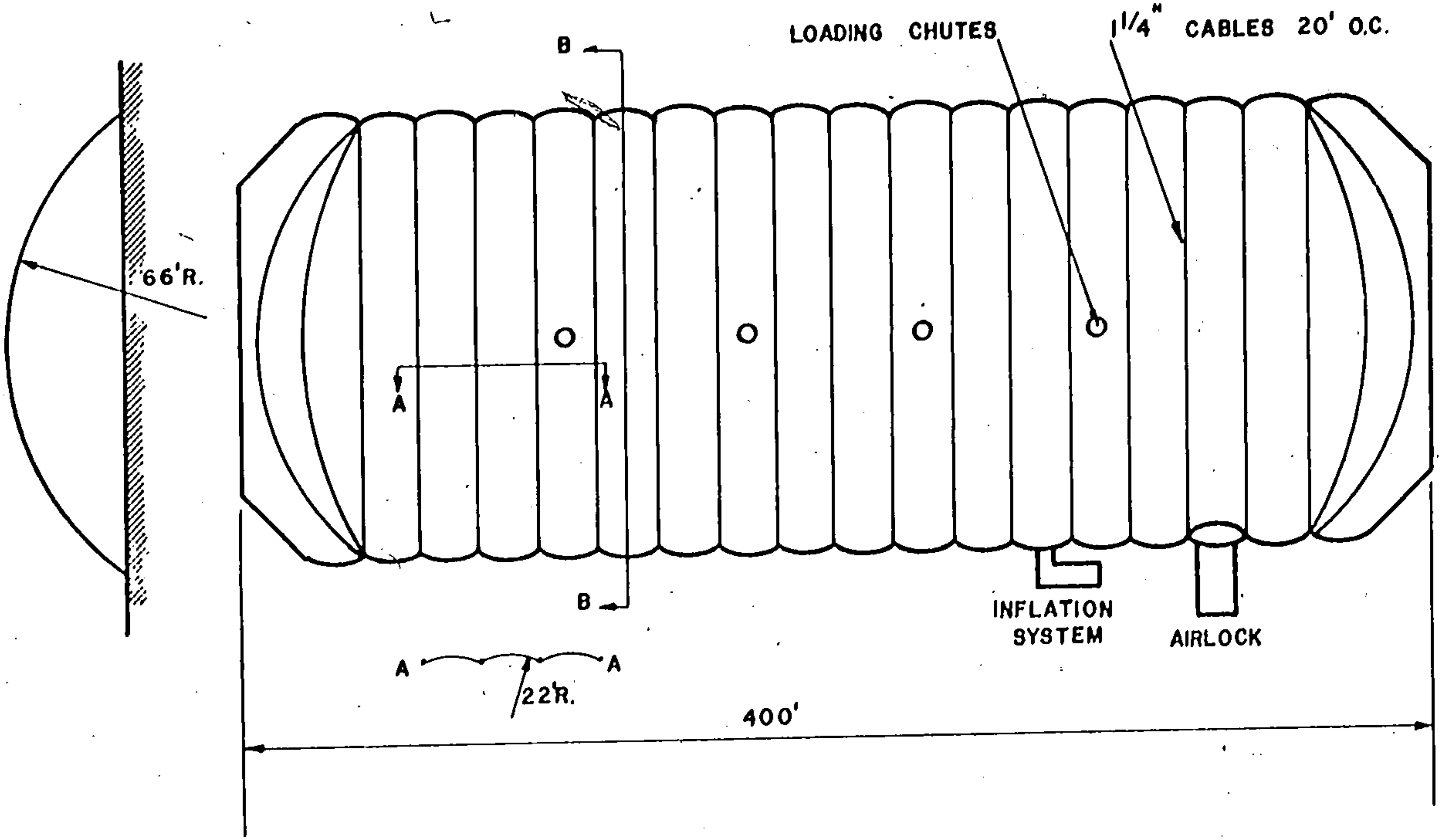


FIGURE 17 A CABLED AIR STRUCTURE IN HAMILTON

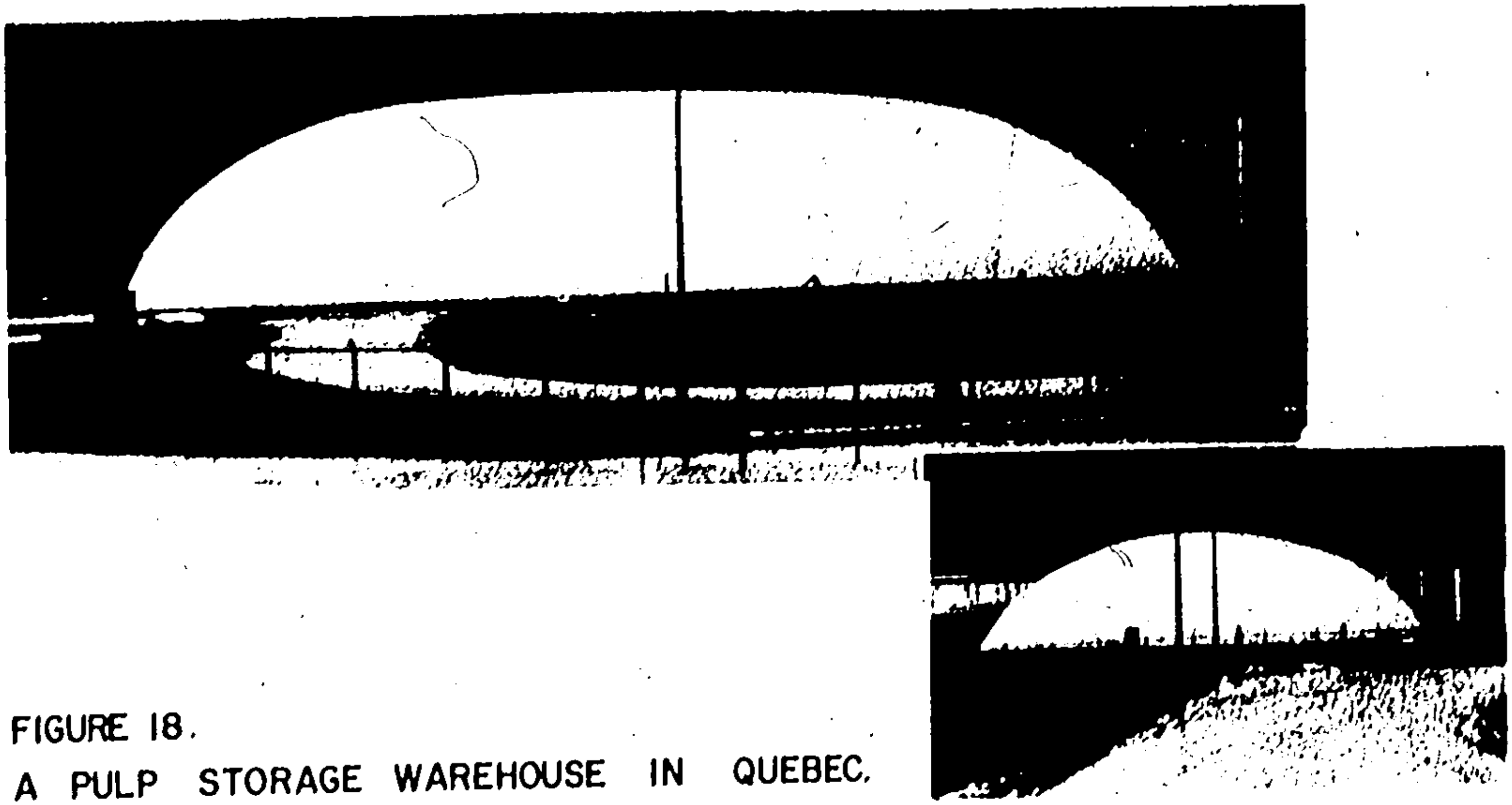


FIGURE 18.
A PULP STORAGE WAREHOUSE IN QUEBEC.

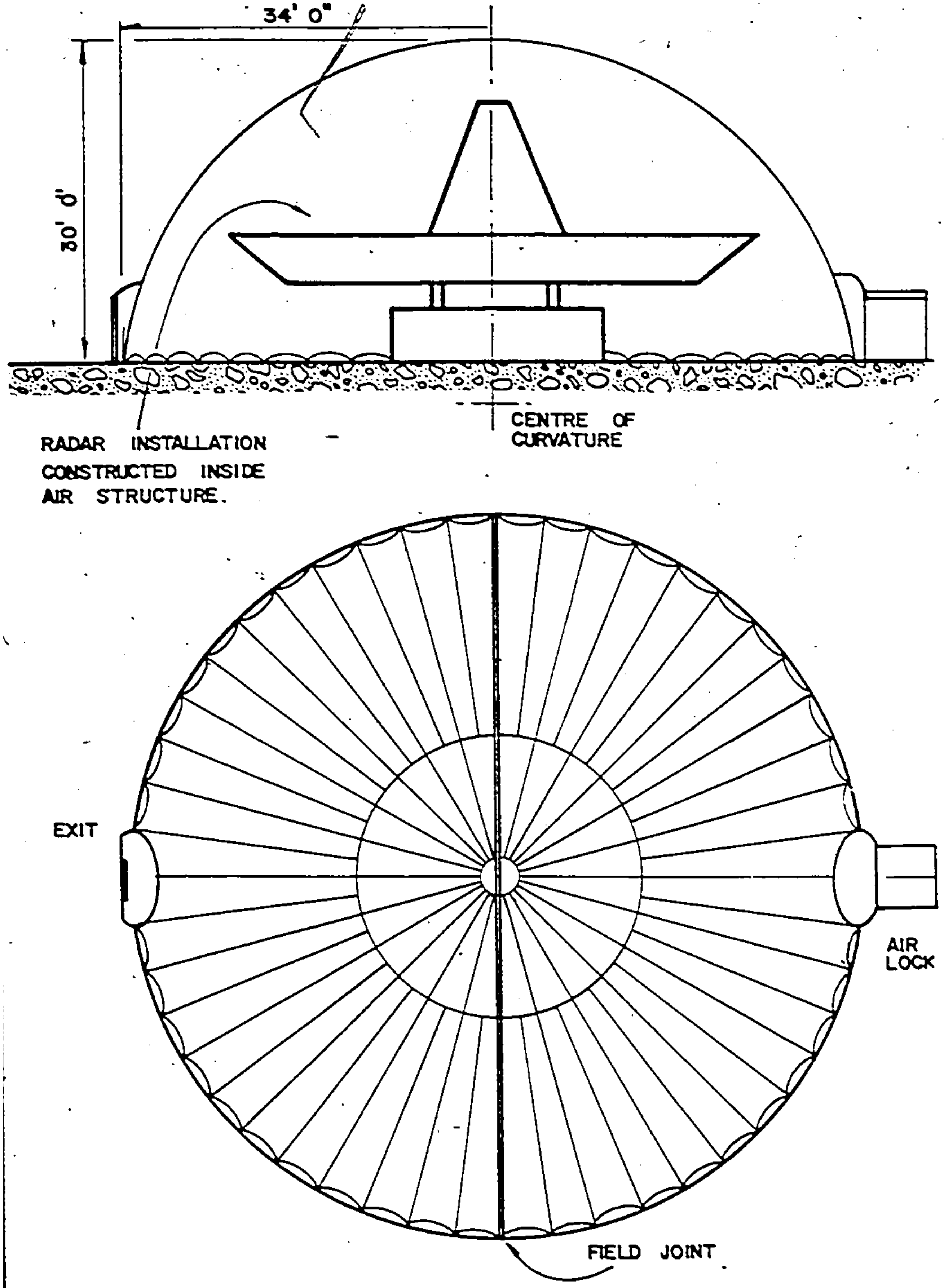


FIGURE 19. SPHERICAL SECTION, CONSTRUCTIONAL AIR STRUCTURE.

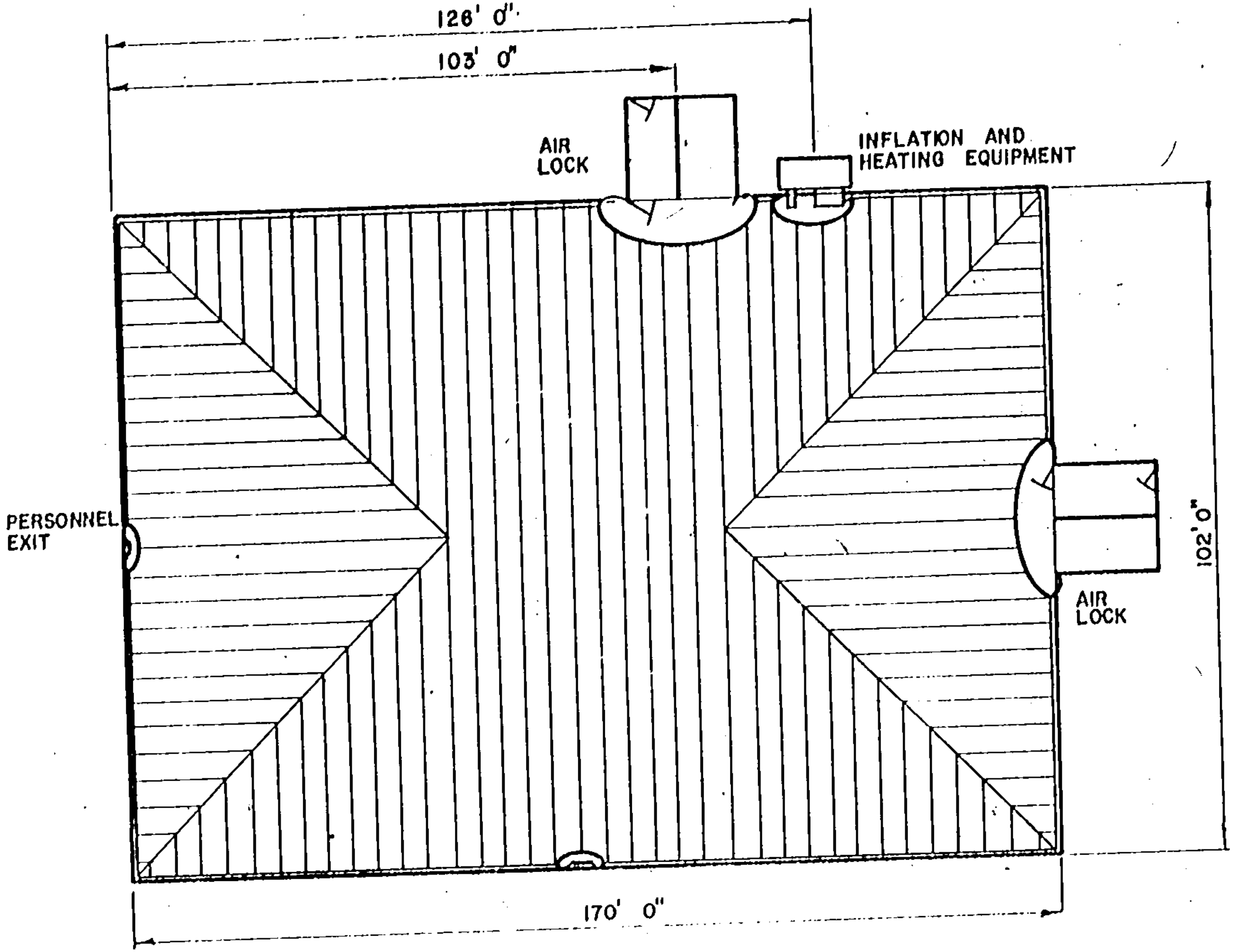


FIGURE 20(i) DIMENSIONS OF WAREHOUSE INSTALLATION.

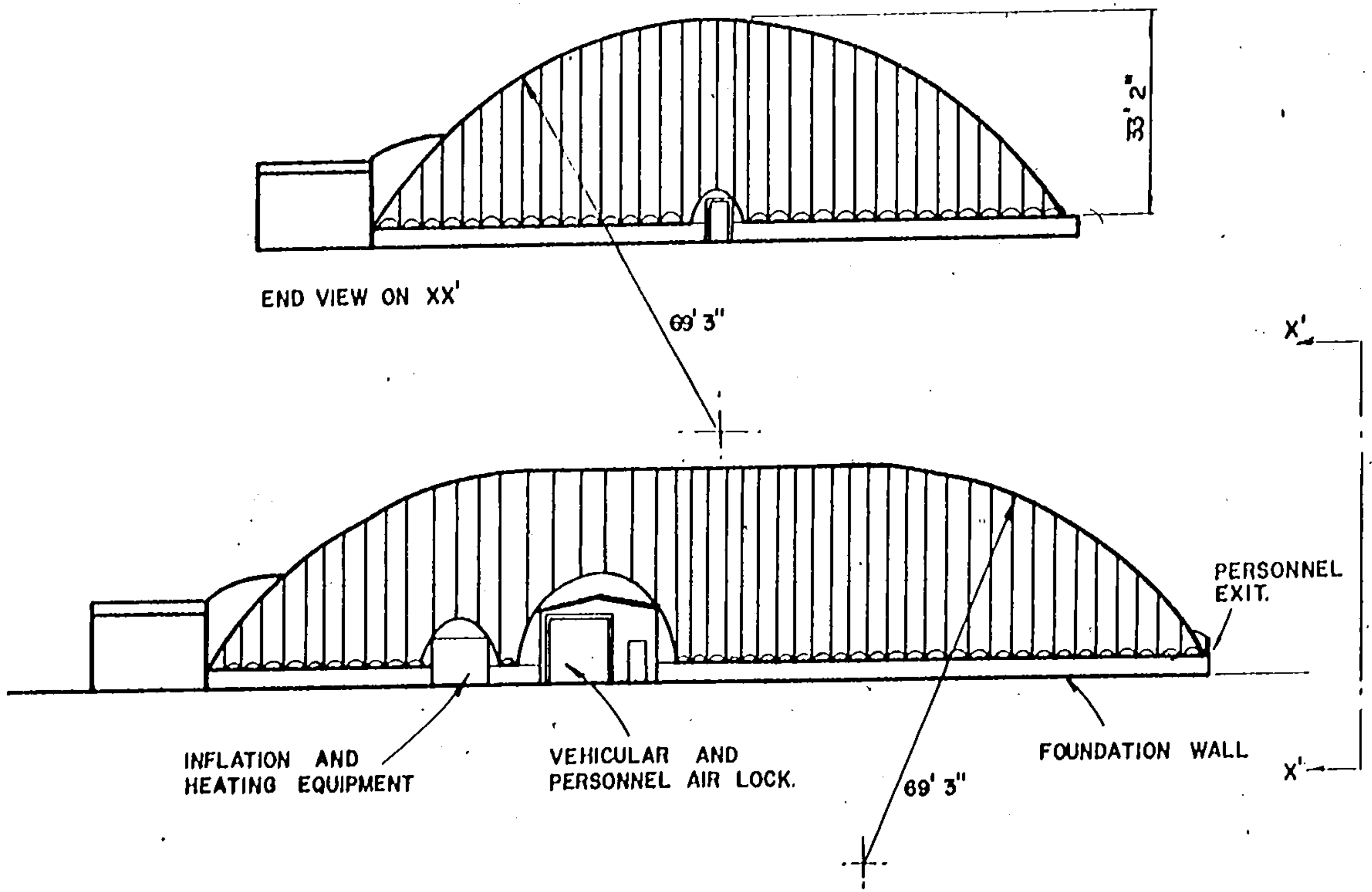


FIGURE 20 (ii) DIMENSIONS OF WAREHOUSE INSTALLATION.

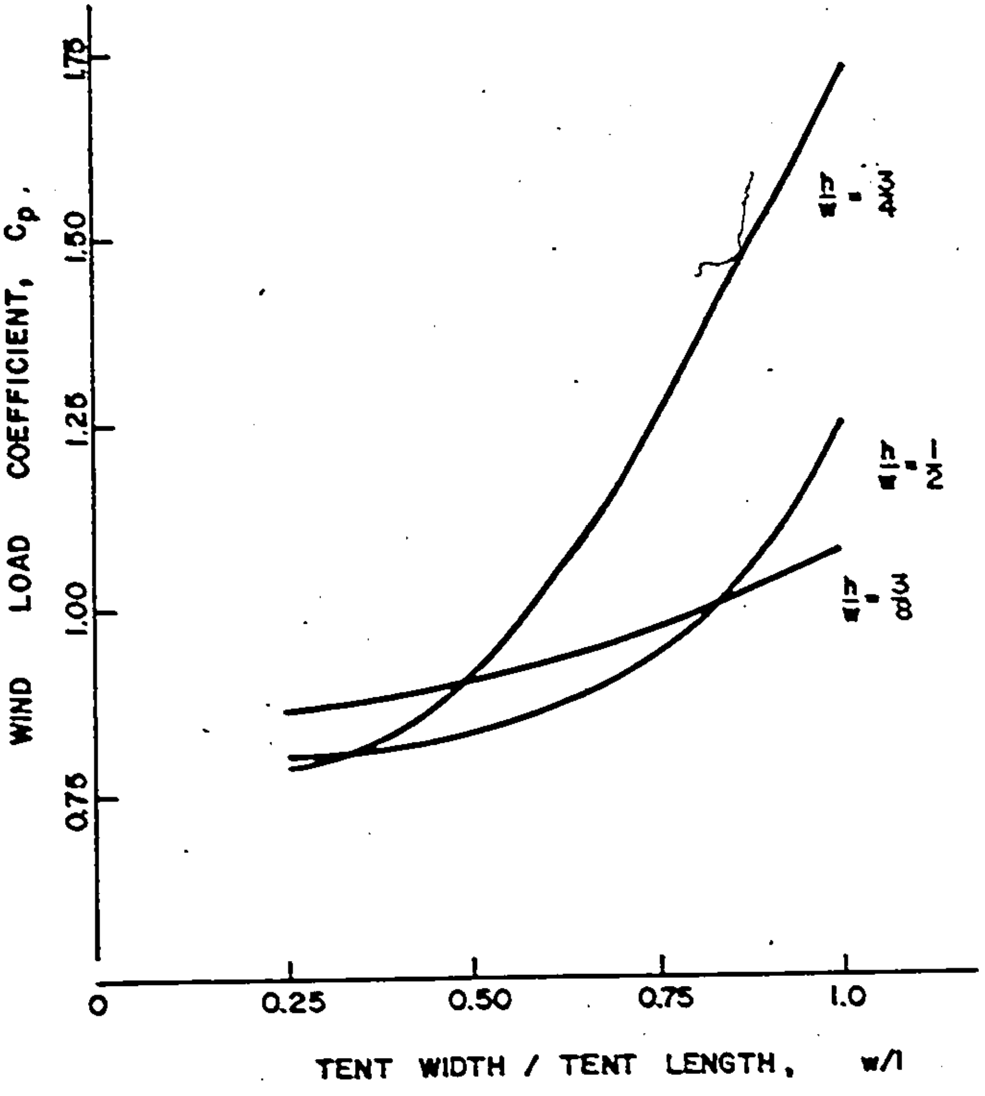
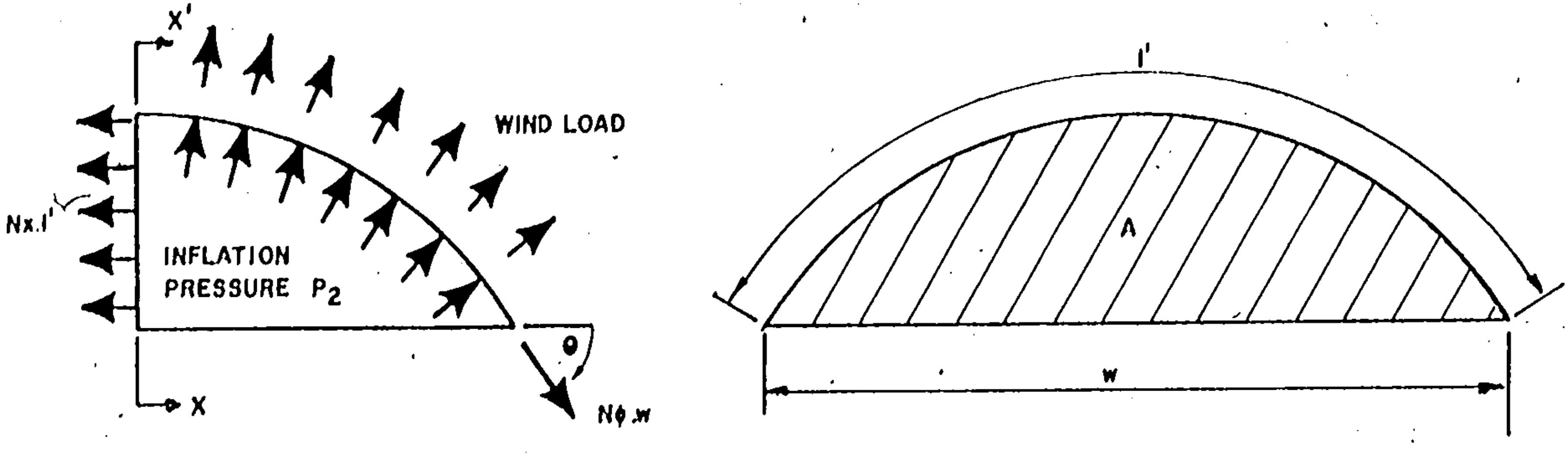


FIGURE 21 VARIATION IN WIND LOAD COEFFICIENT WITH STRUCTURAL DIMENSIONS FOR A SPHERICALLY ENDED CYLINDRICAL STRUCTURE.



SECTION ON XX'

FIGURE 22 FREE BODY DIAGRAM FOR DETERMINATION OF Nx.

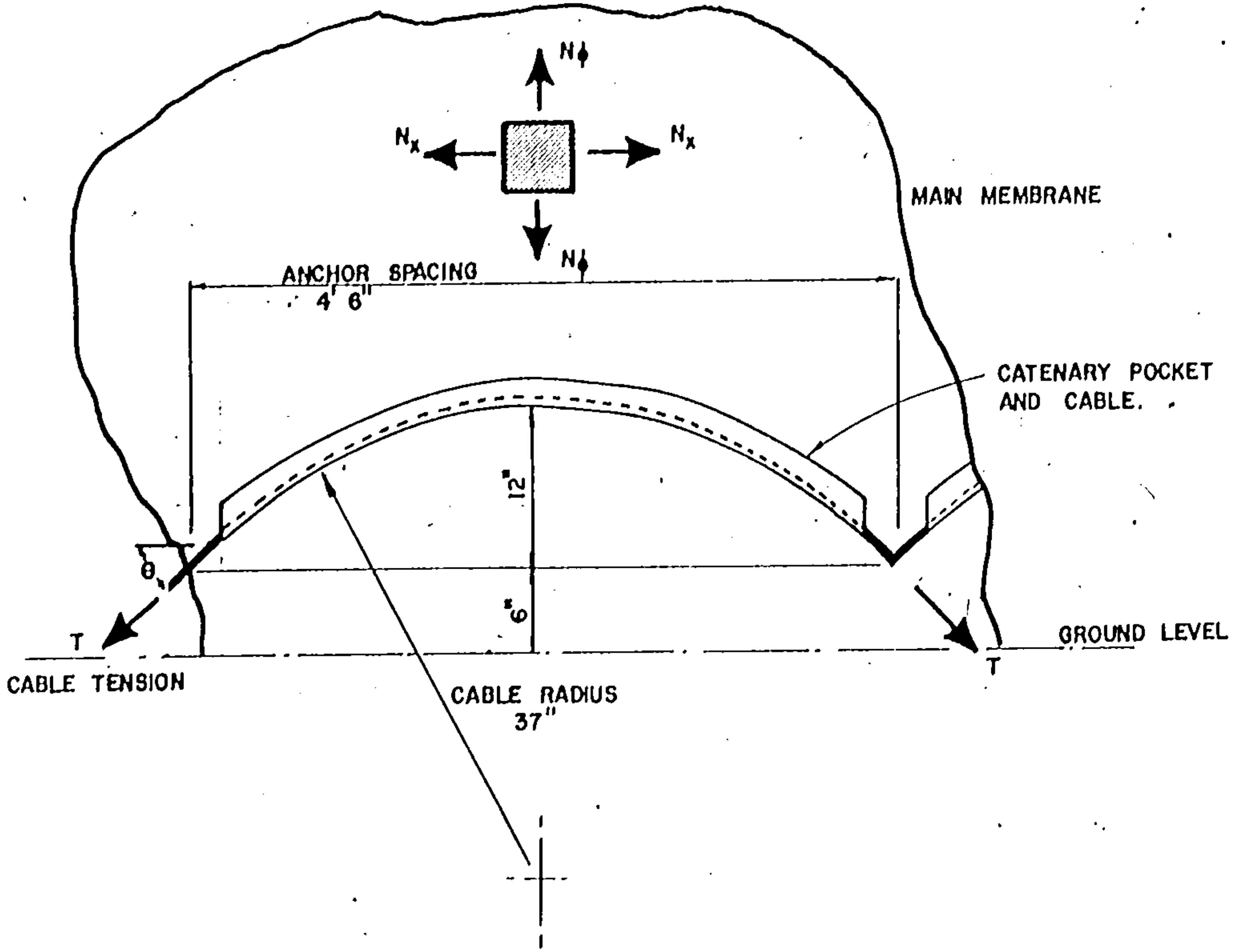


FIGURE 23. DIMENSIONS OF CATENARY CABLE SYSTEM (IN PLANE OF MEMBRANE).

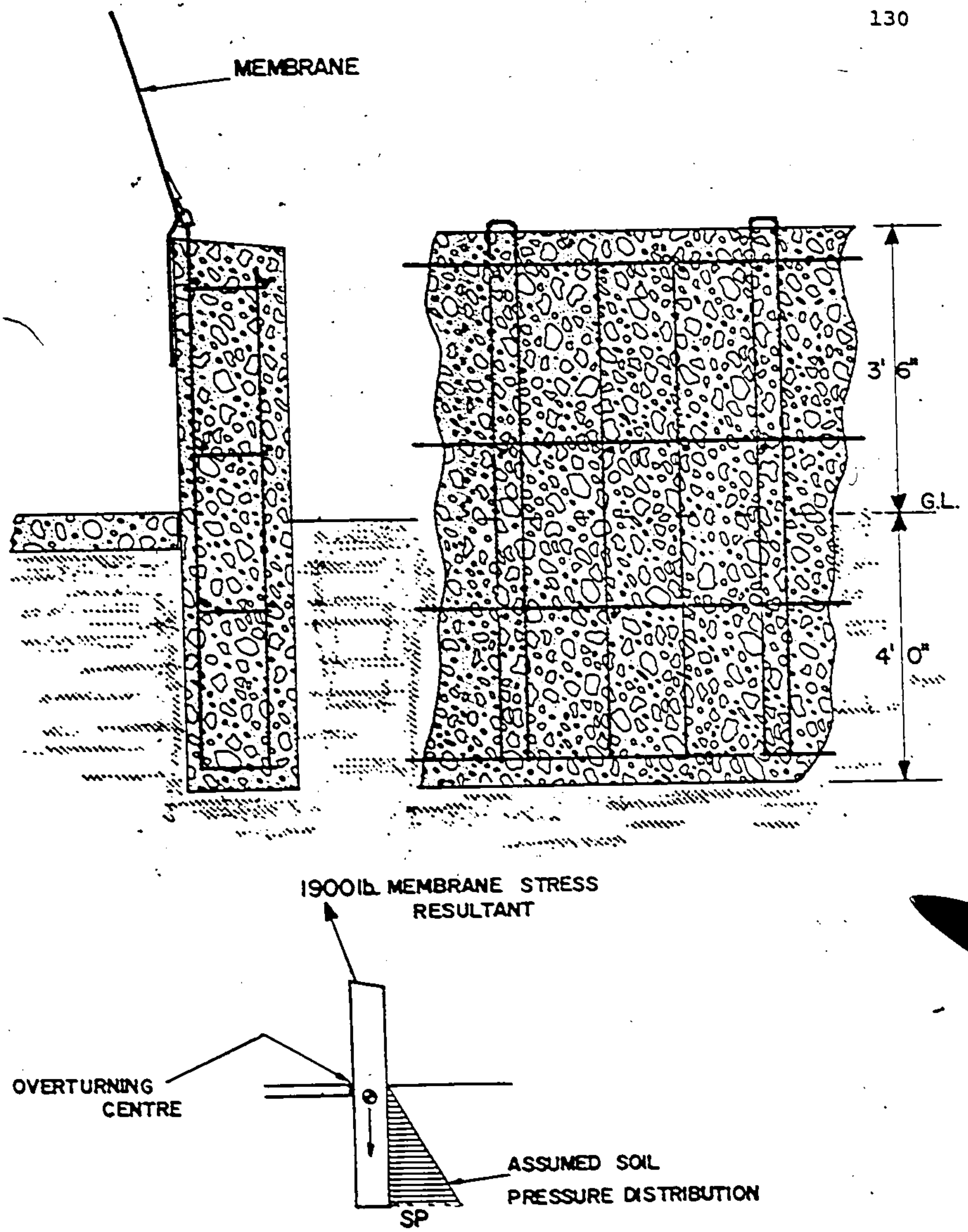


FIGURE 24 FOUNDATION BEAM DETAIL

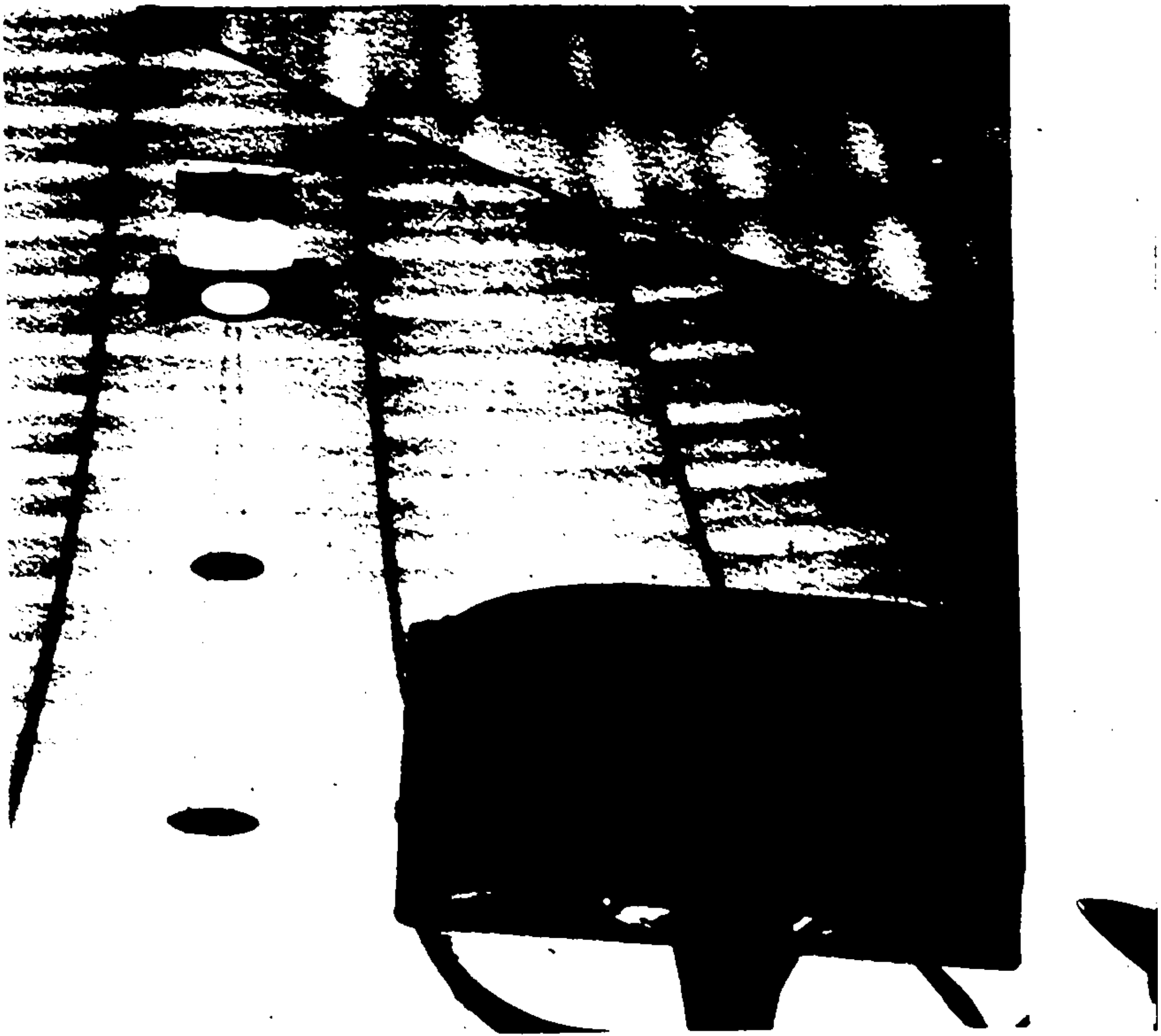
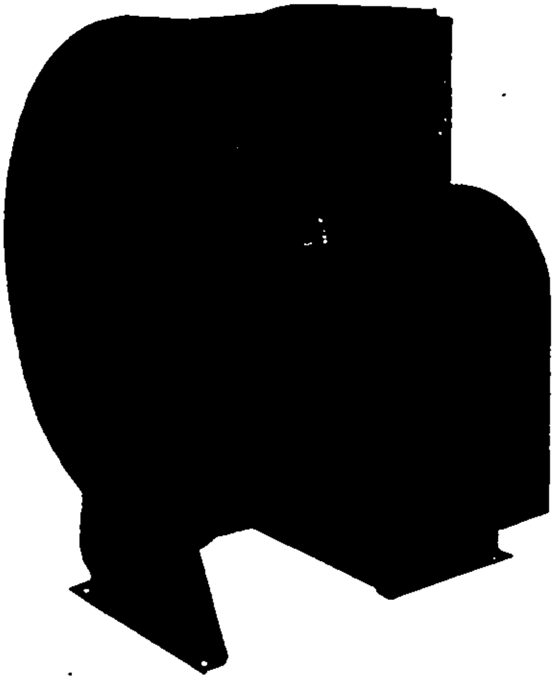


FIGURE 25. AIR STRUCTURE VENT AND LIGHTING.



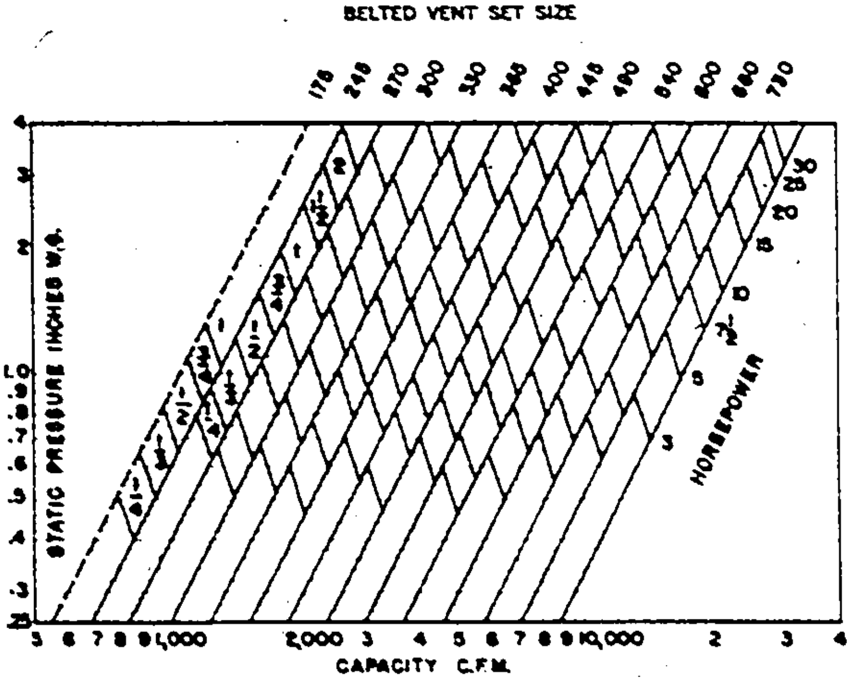


FIGURE 26. CENTRIFUGAL FAN CHARACTERISTICS.
(see reference 56)

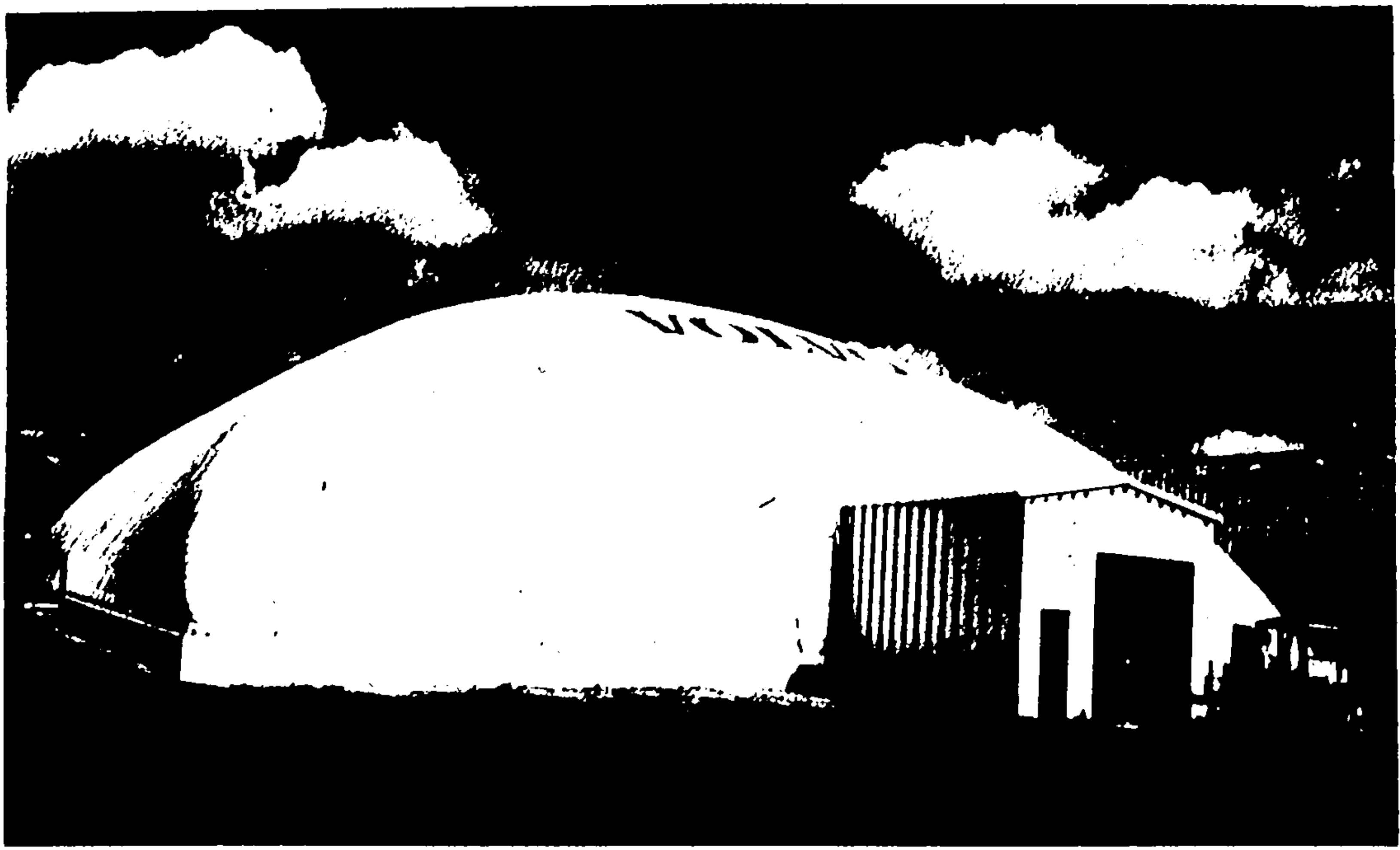


FIGURE 27. AUTOMOBILE PARTS ASSEMBLY AND STORAGE INSTALLATION.
HALIFAX, N.S.

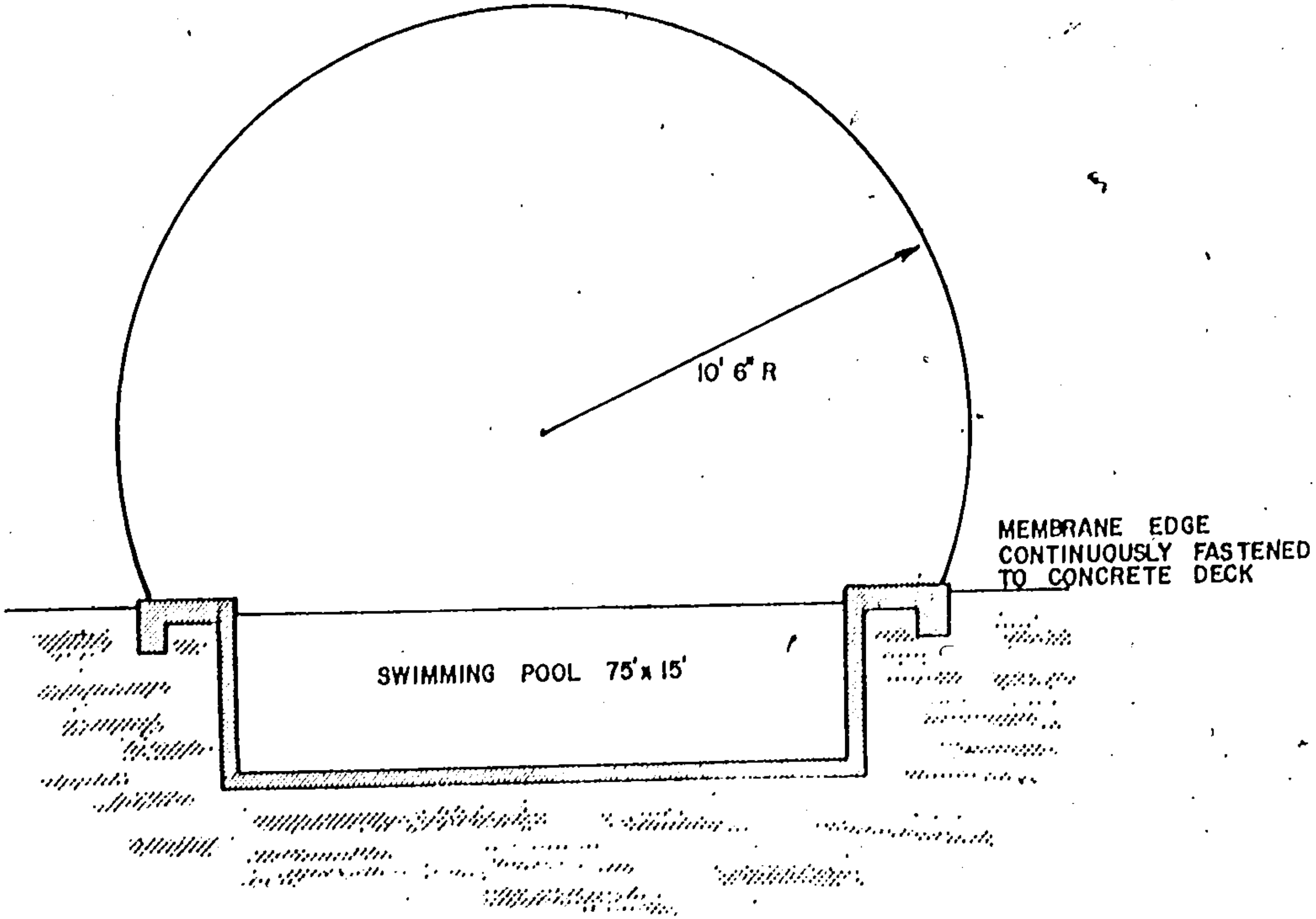


FIGURE 28. SECTION OF DOMESTIC SWIMMING POOL ENCLOSURE.

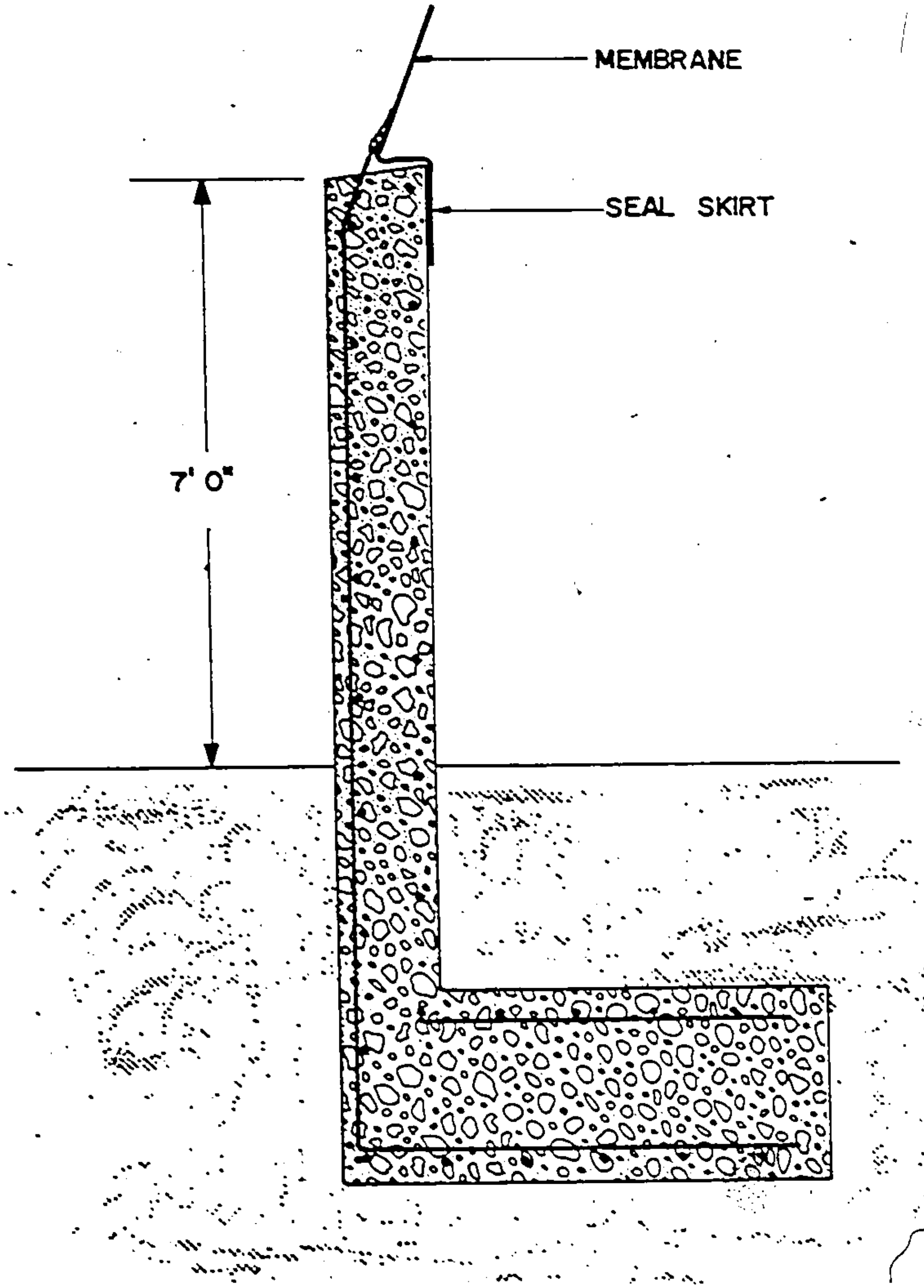
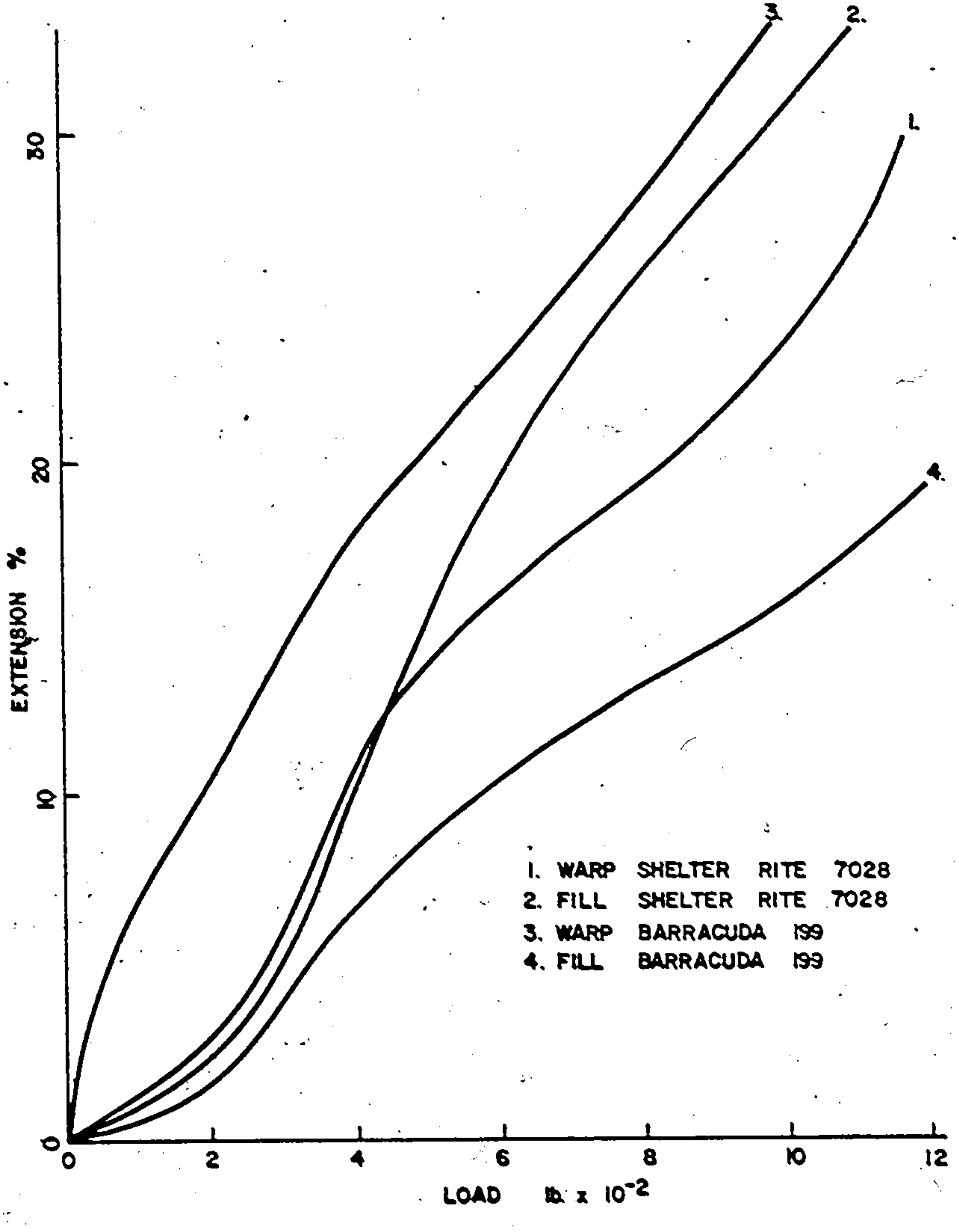


FIGURE 29. SECTION OF A FULL WALL FOUNDATION


3.
2.
1.
4.
30
20
10
0
EXTENSION %
0
2
4
6
8
10
12
LOAD lb. x 10^{-2}
1. WARP SHELTER RITE 7028
2. FILL SHELTER RITE 7028
3. WARP BARRACUDA 199
4. FILL BARRACUDA 199

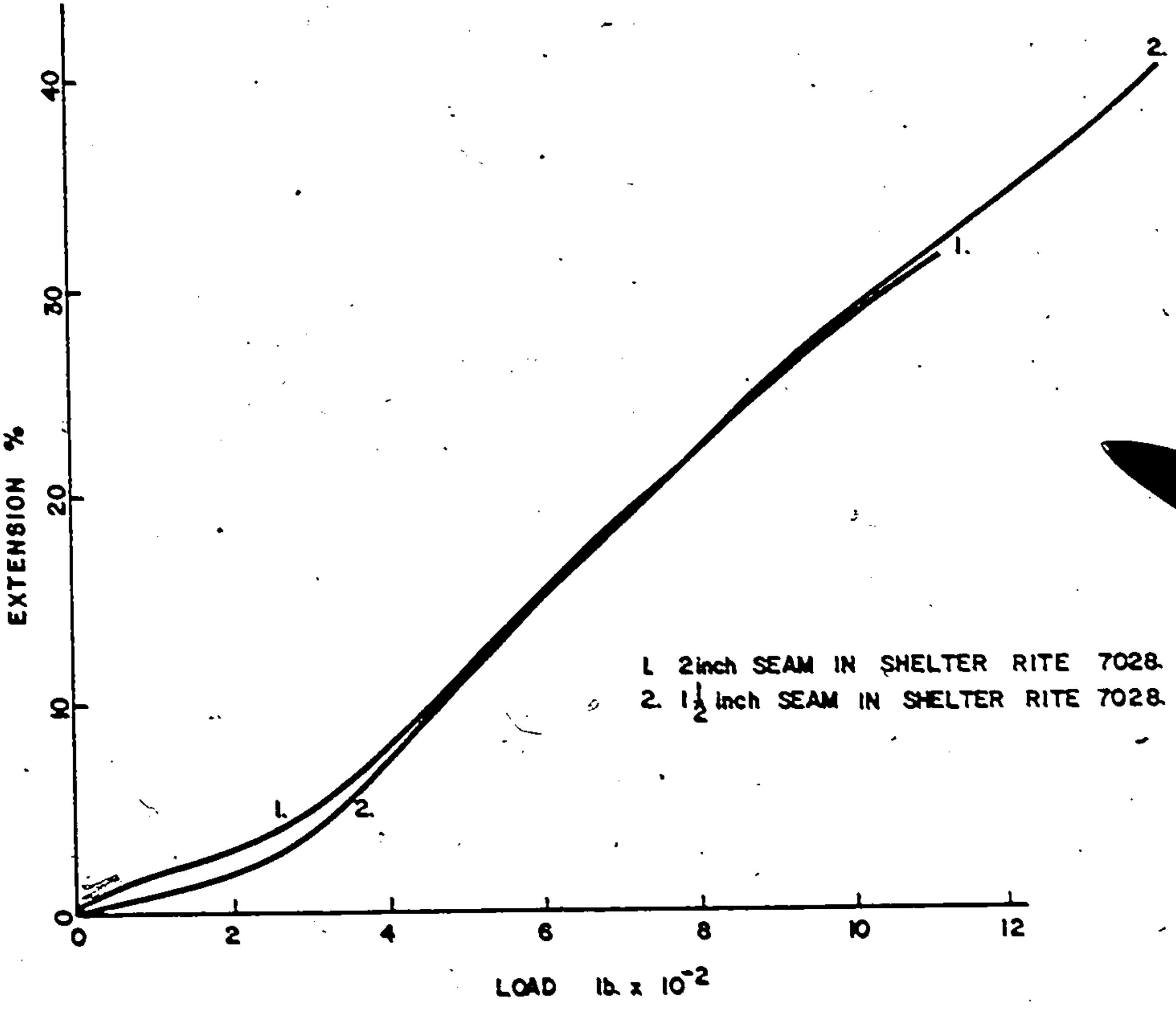


FIGURE 31. TENSILE TEST RESULTS ON WELDED SEAMS.

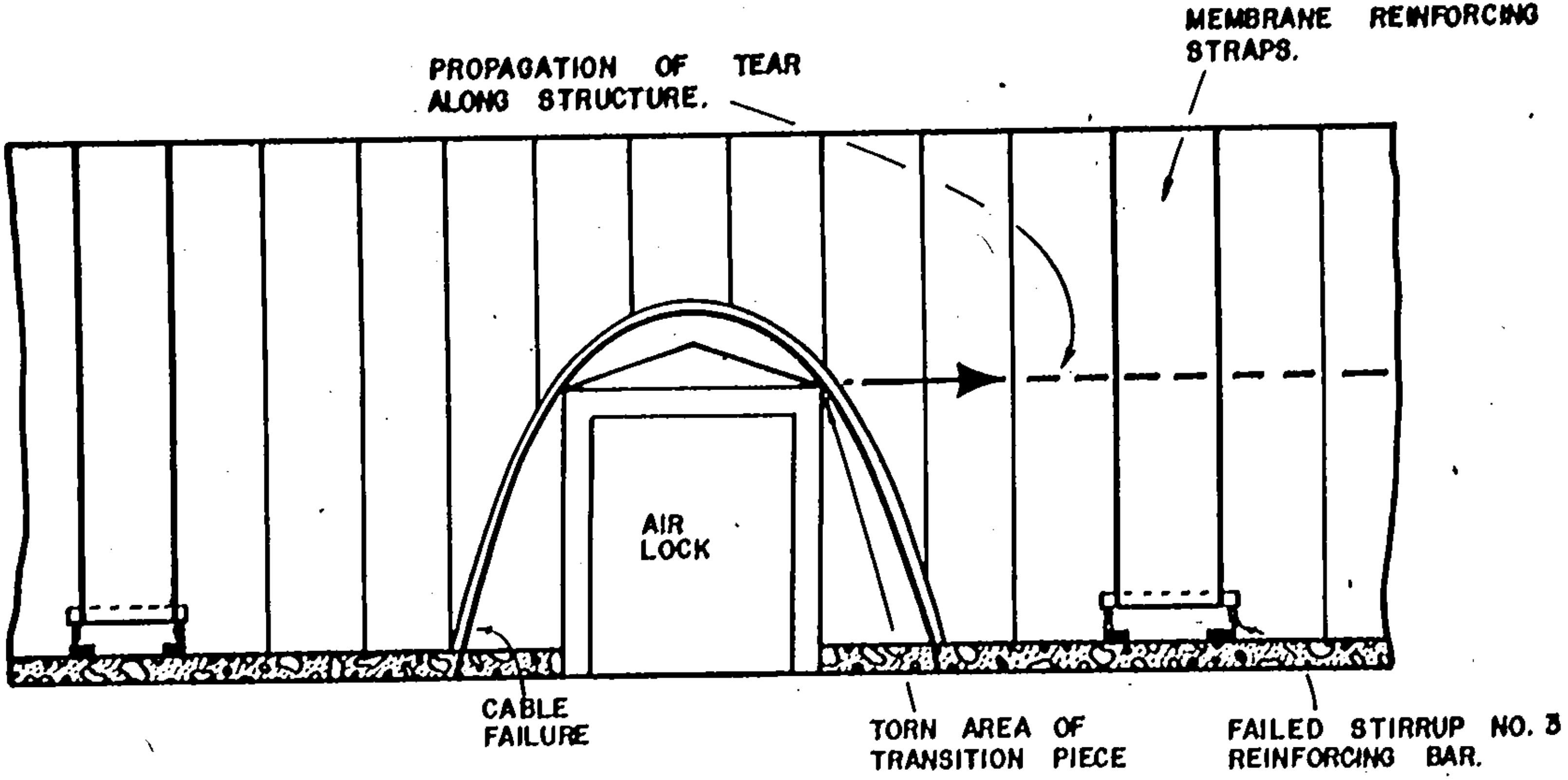


FIGURE 32. SCHEMATIC REPRESENTATION OF AN AIR STRUCTURE FAILURE
SIDE VIEW CENTRAL SECTION OF STRUCTURE

TABLES

1(i) COMPARATIVE SUMMARY OF BASE MATERIAL PROPERTIES

	NYLON	POLYESTER	GLASS
RESISTANCE TO SUNLIGHT	FAIR	GOOD	EXCELLENT
WATER	FAIR	GOOD	EXCELLENT
FLAME	FAIR	FAIR	EXCELLENT
LOW TEMPERATURE	GOOD	GOOD	GOOD
ABRASION	EXCELLENT	GOOD	LOW
SEAMS CAN BE SEWN	YES	YES	NO
CEMENTED	YES	YES	YES
WELDED	YES	YES	YES
TRANSLUCENCY	GOOD	GOOD	EXCELLENT
DIMENSIONAL STABILITY	FAIR	FAIR	EXCELLENT
STRENGTH	GOOD	GOOD	EXCELLENT
ADHESION TO POLYMERS	GOOD	GOOD	FAIR

1(ii) COMPARATIVE SUMMARY OF COATING MATERIAL PROPERTIES

	P.V.C.	HYPALON	NEOPRENE	TEFLON
TENSILE STRENGTH	GOOD	EXCELLENT	EXCELLENT	EXCELLENT
TEAR STRENGTH	FAIR	FAIR	EXCELLENT	GOOD
SEAMS CAN BE SEWN	YES	YES	YES	YES
CEMENTED	YES	YES	YES	YES
WELDED	YES	NO	NO	YES
RESISTANCE TO SUNLIGHT	FAIR	FAIR	FAIR	GOOD
CHEMICALS	GOOD	EXCELLENT	GOOD	EXCELLENT
FUNGUS	GOOD	GOOD	GOOD	GOOD
LOW TEMPERATURE	GOOD	POOR	FAIR	GOOD
ABRASION	FAIR	GOOD	GOOD	EXCELLENT
COLOUR RETENSION	GOOD	LOW	LOW	GOOD
TRANSLUCENCY	GOOD	LOW	LOW	GOOD
PERMEABILITY	LOW	LOW	LOW	LOW
COST	LOW	HIGH	MEDIUM	VERY HIGH

2. PROPERTIES OF SELECTED COATED FABRICS

FABRIC NO.	1	2	3	4
BASE MATERIAL	NYLON	NYLON	POLYESTER	FIBREGLASS
WEAVE	TWILL	PLAIN	PLAIN	PLAIN
YARNS/INCH WARP	42	45	22	19
FILL	42	36	23	27
COATING	HYPALON®	p.v.c.	HYPALON	p.v.c.
TENSILE STRENGTH (lb./in.) WARP	740	325	750	730
FILL	770	295	750	560
ELONGATION (%) WARP	28	25	30	4.7
FILL	27	19	30	8.9
MANUFACTURER	KURARAY	KURARAY	TORAY	FERRO

3. AIR LOSSES THROUGH STRUCTURAL COMPONENTS AT 1.75 in. INFLATION PRESSURE	
AIR LOCK DOOR PERIMETER	20 cfm/ft.
CATENARY ANCHOR WITH SEAL SKIRT ON UNPREPARED SITE	26 cfm/ft.
CATENARY ANCHOR WITH SEAL SKIRT ON CONCRETE FOUNDATION	9 cfm/ft.
CONTINUOUS CLAMPED FOUNDATION AS IN FIGURE 7	15 cfm/ft.
NUMBER 10 CROWN ZIPPER	16 cfm/ft.
0.035 inch P.V.C. (DIFFUSION)	0.07 cfm/ft.^{2}

4. REQUIRED INFLATION PRESSURE IN TERMS OF EFFECTIVE WIND PRESSURE, P

STRUCTURAL SHAPE	REQUIRED INFLATION PRESSURE
3/4 SPHERE	0.8 -1.0 P
1/2 SPHERE	0.65-0.7 P
CYLINDER WITH 1/4 SPHERE ENDS, (h/d)=0.5	0.6 -0.65P
CYLINDER COMBINATION, (h/d)=0.5	0.5 -0.55P

5. EXPERIMENTAL RESULTS (AND SPECIFICATIONS)

MATERIAL	THREAD DIRECTION	TENSILE STRENGTH		TEAR
		LOAD (lb)	EXTENSION (%)	STRENGTH (lb)
BARRACUDA TYPE 199 (NEW)	WARP	1140 (1073)	24 (19)	175 (200)
	FILL	1000 (934)	33 (30)	185 (200)
BARRACUDA TYPE 199 (AGED)	WARP	1130 (1073)	21.5 (19)	150 (200)
	FILL	1060 (934)	32 (30)	160 (200)
SHELTER-RITE TYPE 7028 (NEW)	WARP	1140 (1080)	26	>200 (275)
	FILL	1240 (1080)	36	>200 (275)
TYPE 7028 WITH 2 in. SEAM	FILL	1300	35	
TYPE 7028 WITH 1 in. SEAM	FILL	1440	40	

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11 APPENDICES

11.1 FABRIC TESTS

Objectives

To establish:

i) Uniaxial stress strain curves,

ii) Uniaxial strengths,

iii) Seam strengths for 1-1/2 in. welded seams, and

iv) Tear strengths for the three fabric samples described below.

Materials

i) Baracudaverken #195, a plain weave polyester fabric of 6 oz. per square yard coated with p.v.c. to a total weight of 25 oz. per square yard, in as new condition.

ii) As above, aged 18 months, under load in Hamilton.

iii) Shelter-Rite #7028, a modified malimo weave of 7.5 oz. per square yard polyester fabric, coated with p.v.c. to a total weight of 28 oz. per square yard.

Methods

i) The tensile tests of fabric and weld were carried out in accordance with ASTM method D1683 [91], tensile tests for fabrics. In this test an 8 in. x 2 in. rectangular specimen is gripped in flat jaws, with a gauge length of 3 in., and is extended to failure at 2 in./min.

ii) The tear tests followed ASTM method D2261 [45]. This test involves the propagation of a tear as the extension of a 3-1/2 in. slit cut lengthwise down the centre of an 8 in. x 3 in. specimen. The tongues produced are gripped in the jaws of the testing machine and the specimen extended.

An Instron recording testing machine was used in the tests, with a crosshead speed of 2 in. per minute.

The test differed from the ASTM standards in that since close agreement between results from pairs of samples was obtained the minimum number of tests suggested by the ASTM were not completed: further since full roll widths are usually used in structures samples were not limited to the central portion of the roll as suggested in ASTM. (No difference between these samples was noted.)

Results of the tests are presented in Figures 30 and 31, and summarised as Table 5.

Conclusions

i) All the measured uniaxial tensile strengths had values in excess of the manufacturer's specifications.

ii) The tear tests did not produce tearing similar to that occurring in a structural failure. In both types of fabric tested the threads tended to rope up and break away from the coating rather than failing rapidly in succession. Increasing the test speed to the maximum available did not influence the results. Tear propagation speeds of 600 ft./sec. are reported in recent literature on fabric failure [34].

iii) The malimo weave fabric had better low speed tear strength than did the conventional woven fabric of similar weight.

iv) The sample aged 18 months had not sufferred significant losses to its tensile strength, tear strength had reduced by approximately 10%. Because of the influence of the coating on the thread motion in the tear test, it is to be expected that the tear test will be more sensitive to aging than is the tensile test.

v) More scatter was noted in strain to failure than in stress values at failure. This can be attributed to differing initial geometry between samples.

vi) The welds were shown to be stronger than the base fabric, which failed away from the seam in all the tests. This increase in measured strengths over those noted in the tensile tests can be attributed to the increased strain in the coating which increases the ability of the sample to redistribute loads away from the shorter threads in the sample.

11.2 AIR STRUCTURE FAILURES

Of the four air structure failures mentioned below two were caused by membrane aging, one by defective membrane material and one by a design/maintenance error.

The Harvard University track and field house which was installed in 1968 failed in the spring of 1974. The structure was damaged beyond repair in high winds. Since the membrane was in its sixth year of use such aging of the p.v.c. coated nylon was to be expected. Damage to stored equipment could have been avoided by inspection of the structural material.

In Toronto a tennis court structure failed in the spring of 1973 in its third year of use. This structure was also p.v.c. coated nylon. Visual inspection of the membrane showed that the outer coating was cracked over large areas of the structure exposing the nylon to moisture which would accelerate its aging. This structure was occupied at the time of failure, under high (35 m.p.h.) winds. The occupants who were unhurt describe the failure as a rapid tear opening the structure across its centre, and causing a loud report[105]. It is probable that the tear started at localised damage caused in the annual reinstalling of the structure. The tear would propagate easily through the aged fabric. Such aging of coated nylon fabrics is not uncommon, and can be attributed to their greater extension under load causing higher stresses in the coating than would occur when the same coatings are applied to polyester. Visual inspection would have shown cracking and the risk of injury to occupants could have been avoided.

A material deficiency contributed to failure of a Ministry of Transport shelter only two weeks after initial installation. The shelter was installed in Northern Alberta and was unattended when failure occurred, under winds of over seventy miles per hour and temperature of less than -50°F. Structural damage to the structure and contents was extensive. It was postulated that snow had blocked the air intake to one of the structure's air supply systems which dropped the operating pressure of the structure, which under the extreme wind and low temperature was damaged by unstable motion of the fabric, which it was shown later had become brittle at the low temperature. Since the fabric had been specified as for its low temperature flexibility to -67°F., the suppliers of the structure and the fabric were held responsible and replaced the structure.

The failure due to design and maintenance problems occurred in a structure in Hamilton in January this year. The failure occurred in the early morning, security personnel on the site, a half mile from the structure reported a loud report being emitted by the structure. Wind speeds of 57 m.p.h. were recorded [8]. Inspection of the structure showed a horizontal tear in the membrane for about 90 ft., adjoining tears had propagated over the structure at two reinforcing bands. An airlock cable and a reinforcing bar anchor had also failed. See Figure 33.

An analysis of the membrane tension shows that mean design loads of 1400 lb./ft. hoop tension in the membrane would be acceptable. These loads would be reduced by 13.5% if equal stresses occur in the reinforcing straps as occur in the membrane, which is the same material. Applying these reduced loads to the catenary cable (Figure 32) for equilibrium gives from Equation 7.6

$$T = N\phi \; . \; b/2.\sin\theta$$

$$= 17{,}300 \text{ lb.}$$

A 5/16 diameter cable had been used which has a maximum breaking load 9,000 lbs., a safety factor of 3 is commonly applied to structural cables [122]. The following mode of failure is therefore suggested.

After the failure of the cable, at a previous repair, the fabric above the airlock would begin to move upwards, at the same time loads previously carried by the cable would be transferred to the areas of the membrane surrounding the airlock, mostly the restraining bands. The band anchor was unable to carry the increased load and broke at its corners. The fabric's upward motion would be restrained by the shorter section of the transition piece, and the highly localised shock load would initiate the horizontal tear in the membrane. The vertical tears probably occurring due to flapping of the loose membrane under the wind loads as it would be lifted against the restraining bands.

Contributory causes to the failure were therefore:

i) The small diameter of the cable, which would support the structure only if wind loads were not considered.

ii) The repair of the cable after a previous break, which only slightly damaged the membrane.

iii) The reinforcing band stirrups had right angle bends, (non-standard construction practice) which could initiate cracking of the bars.

iv) Lack of fullness in the transition piece, which would have allowed extra loads to be carried by the main membrane areas around the airlock.

v) The low temperature, which embrittles the fabric to a marked extent. It's probable that, the higher temperature at the time of the previous cable failure contributed to prevention of failure of the structure at that time.

vi) The structure was inflated to only 1/2 inch w.g. at this pressure applying the previous stability criteria the structure would only be stable up to 60 m.p.h., which could cause waves to be formed and travel over the membrane which could have initiated the failure.

Knowledgeable inspection of the structure on its installation would certainly have prevented its failure.

11.3 BUILDING CODES - A SURVEY

Canada

The Canadian Building Code mentions air structures briefly, suggesting:

i) that the secondary inflation system be sufficient to maintain the system under emergency conditions, and

ii) that conventional fire prevention separations between buildings be utilised.

(A brief description of Air Structures was given by Lutes [123] in the Canadian Building Digest.)

West Germany

In the German code [124] in addition to inflation systems requirements and location requirements, maximum structure sizes are included, together with standard inflation pressures up to 30 kp/m^2 being required for structures over 8m in height. Membrane stress calculations are based on simple thin cylinder analysis, with no allowance for end conditions, i.e.

$$N\phi = (P_i - P_a) R \qquad 11.1$$

$$Nx = (P_i - P_a) R/2 \qquad 11.2$$

where, P_i is the inflation pressure,

P_a is the effective wind load pressure, and

R is the radius of curvature of the membrane.

or on similar analysis for spherical structures, a single Cp value is specified for all conditions as -0.9, i.e.

$$P_a = -0.9q.$$

Safety and occupancy regulations are also included. Snow loading figures are also given but need not be considered if snow removal is provided.

Japan

Japan has the most comprehensive constructions standard consisting of 56 pages relevant to air structures and is mandatory in application, [125].

In addition to the usual building code requirements of access, fire safety, occupancy and maintenance, design specifications are given and are summarised below:

i) Maximum wind loads are specified for a range of structures, gust loading being based on conventional buildings at 1.5 x q and the Cp values varying with structural shape and being equivalent to those of Dietz [28]. Basic stress analysis similar to Equations 11.1 and 11.2 being applied.

ii) Materials which are acceptable for use must satisfy Japanese fabric standards as must any cables or ropes used in the construction. Safety factors of from 2.5 to 3.3 being required for the membrane and its joints, and 3.0 for cables and ropes.

iii) Internal pressure values similar to those discussed elsewhere in the report are specified, dependent on the height of the structure.

iv) Snow loads are detailed with provision being made for their application, or not, depending upon structural use.

v) Anchor and foundation requirements are made based on Dietz's results.

vi) Minimum specifications are made on the quality and type of inflation equipment, more than two fans being the requirement for any occupied structure for example.

vii) Maintenance and inspection are required on a regular basis, as are materials testing before issue of annual permits.

U.S.A.

In the U.S.A. the CPAI have a suggested standard, [116], with basic design stress tables, which ignore such variables as location or structural shape. Minimum standards are suggested for industrial adoption, cover anchor loads, and fabric loads and generalised patterning procedures. Minimum inflation pressure of 1.5 in. w.g. is suggested for all installations.

Basic regulations covering inflation systems, inspection (visual), exitways, flame resistance are covered in the seven page publication.

The U.S. is the only country whose fire safety codes discuss air structures specifically in detail. Independent tests on full scale structures have shown excellent behaviour in smoke removal and structural stability, in fire as early as 1967 [81,126], and CPAI [116] reports no fire damage in over 1700 structures over a three year period. California was the first state to accept air structures in 1973, it is expected that the other states will follow suit in the future.

U.K.

While Britain has an official standard it is more brief than that of the CPAI and requests that design specifications and methods be submitted with permit requests, in the areas outlined in the other codes, [127].

France

France has a code similar to but even more brief than that of the U.K.

Sweden

Sweden's code is similar but like the CPAI's standard it is the result of industrial co-operation and is not mandatory, [129].