A SYSTEM OF SHELTER
FOR THE DEVELOPING NATIONS

by

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Dear Dean Belluschi:

In partial fulfillment of the requirements for the degree of Master of Architecture, I hereby submit this thesis entitled: A System of Shelter for the Developing Nations.

Respectfully,

Richard C. Newman
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There exists in the underdeveloped nations of the world an urgent need for hospitals, schools, and housing. To help meet this need, a portable air supported structure is proposed. This structure consists of two concentric domes supported by a system of air flow planned to provide optimum insulation and ventilation.
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Part I: PROGRAM

There are 2,915,500,000 people in the world. 1,341,900,000 of them are living in underdeveloped nations. Most of these people are without adequate facilities for health, education, and housing. In recent years, the more advanced countries have responded to this lack of facilities by offering economic assistance to the underdeveloped nations. In 1960, United States assistance approximated $2.0 billion dollars. United States private foreign investment totalled $0.7 billion. Other sources, principally the International Bank, The United Kingdom, and France, provided $1.3 billions, yielding a total 1960 capital inflow of $4.0 billions to the less developed areas. It is expected that this figure will greatly increase in the coming years. The Maxwell School of Syracuse University has estimated that $10.5 billion dollars will be needed every year to sustain an annual 2% increase in per capita Gross National Product in underdeveloped nations. A 2% increase is, however, very small. For the underdeveloped nations to close the gap between their living levels and those of the advanced countries, a much faster rate of growth is needed. This will require capital expenditures far greater than the $10.5 billions per year previously mentioned. 1

These large sums of money will be used to provide the improvements which the underdeveloped countries urgently need. Primary among these improvements will be hospitals, schools, housing, industries, etc. These are facilities which are required immediately; without them development cannot begin.

However, permanent structures of conventional construction (concrete, masonry, steel) require large investments in time and money. It will take many years of planning and fund raising before enough of these structures can be built to satisfy the pressing needs of the developing nations.

This thesis suggests, therefore, that a portable, inexpensive structure be employed to fill immediate needs in the period before permanent structures can be obtained. In the case of a hospital, for example, such a structure might be used for four or five years in a given locality. During this time planning, financing, and construction of the permanent hospital would take place. When the
permanent hospital was completed, the portable shelter would be taken down and transferred to another location and, possibly, another use.

What is needed to facilitate this approach to development is a suitable portable structure. It must have the following characteristics:

1. It must provide high quality space: properly lit, insulated and ventilated.

2. It must be flexible; it should be able to serve a variety of uses: hospitals, schools, mass housing, housing for construction workers, community centers, industries, etc.

3. It must be low in cost.

4. It must be easy to transport, erect, and take down. It must require minimum site work and afford maximum reuse of material.

This thesis is devoted to the design of such a structure. The above four points constitute its architectural program. The proposed solution to this program is discussed in Part II.
Part II: SOLUTION

A. Choice of an Air Structure as a Possible Solution.

Of the several types of structure available to the architect, one, better than any other, fulfills the requirements set forth in the Program. This is the air structure. Air structures can be portable, require a minimum amount of site work, and afford maximum reuse of materials. If properly designed, they can provide high quality space at low cost.

This thesis proposes a design utilizing air support principles as a possible solution to the problem of providing immediate shelter for underdeveloped nations. Before a detailed discussion of this design is undertaken, a general discussion of air supported structures is offered. This discussion is meant to acquaint the reader with the fundamental issues regarding air supported structures. Familiarity with these issues will better enable the reader to consider the specific design proposal offered in this paper.

B. General Discussion of Air Structures.

1. History

Air supported structures were first developed to house the large radar antennas being built by the United States as part of its early warning air defense system. Conventional structural methods had failed to provide the light weight, ease of erection, and air transportability required of this equipment which was to be installed in remote areas often accessible only by air. In addition, the heavier wall sections or framework required by conventional structures resulted in poor radio frequency transmission efficiency and excessive beam distortion.

"The development of an airtight, coated fabric structure, stiffened and stabilized solely by a small amount of air pressure was first suggested to the Air Force by the Cornell Aeronautical Laboratory in 1946. Preliminary wind tunnel tests and design studies and analysis was carried out during the next two years. The first full-scale prototype unit was erected in 1948."
Extensive materials development was carried out in conjunction with structural studies. Initially the choice of suitable materials was seriously limited. A few high strength yarns had been developed, but applications for structural fabrics were few and all the available materials had serious limitations. Flex characteristics, water absorption, adhesion of coating to the fabric, tear resistance -- all were major problems. Three materials were selected as being most suitable for use in air supported radomes: neoprene-coated Fiberglass; Fortisan Rayon, and nylon. Although each material was deficient in some respect, laboratory tests indicated that each material was capable of providing the required service life. Extensive field testing of these materials before undertaking production of the radomes was impossible; therefore, early experimental and production radomes were constructed of all three materials.

Since that time, continuous improvement of materials has taken place. A special dacron fabric with Hypalon coating was developed in 1956 for use on new air supported radomes. The material commonly used now in commercial installations is nylon fabric coated with vinyl or neoprene.

2. The Characteristics of Air Structures.

The major discovery in early experiments was that a slight difference of air pressure, as little as 0.65 psi over the surrounding atmospheric pressure, was sufficient to keep an air supported structure firm against a 200 mph wind. Much smaller inflation pressures, as little as .054 psi over the atmospheric pressure, were sufficient to withstand winds of 75-90 mph. Pressure differences like these are less than we experience daily due to changes in the weather.

Air structures are light weight, easy to handle, and easy to service and repair. They can be erected quickly and can cover large areas at lower cost than other structures. They are safe. The fabrics employed do not support combustion and there is no heavy structure overhead. In the case of power failure in pressurization equipment the skin settles very slowly. A properly designed structure may take from one to several hours to deflate completely.
3. The Types of Air Structures.
There are two basic types of structure based on the principle of air support.

a. Air Supported.

![Figure 1 - Air Supported Structure.](image)

This is the type used in the radomes discussed above. It is the purest form of air structure. It consists simply of a thin skin held up at all points by a minute force developed from a difference in air pressure between the inside of the building and the outside. It is the least expensive of the two basic types. Its cost, including pressurization equipment, is approximately $1.50 per square foot of covered area.

This system must be kept fairly airtight (not completely sealed, however; this would be undesirable for interior air would grow stale). Large permanent opening are not permissible.

A serious problem attached to this system is that of providing adequate thermal insulation. A single skin of white vinyl or neoprene nylon has a K factor of 1.2. A structure made of this has poor insulation. For example, in such a structure under a heavy sun load, the best that can be expected is that the inside air temperature will be $10^\circ$ higher than the outside.

b. Air Inflated.

![Figure 2 a. - Air Inflated Structure-Section](image)  ![Figure 2 b. - Section Through Ribs](image)

In this system, air under pressure acts as a sandwich material between sheets of fabric. Large openings are permissible because the
interior area of such a structure is not pressurized; only the walls and roof are inflated.

The insulating quality of this system is much better than that of the air supported system. The two skins give a combined K factor of .6, and the air space between further helps to reject solar heat.

Air inflated systems have been developed which operate on inflation pressures nearly the same as those required for air supported systems. To make this possible, the supporting ribs must be deep so that an adequate section modulus is obtained. About three times more material is needed for this system than for the air supported system, and more sealing is also required. As a result, the cost of air inflated systems is high -- $6.00 per square foot of covered area when constructed of the usual vinyl coated nylon. At this price, the economic advantage of air structures is lost, although the advantages of portability and prefabrication are retained.

4. Pressurization Equipment.

Inflation pressures for air supported structures are relatively low. They can be readily supplied with centrifugal blowers.

Pressure systems must be designed for higher capacities than normally required. This is to provide for fast inflation when the structure is being erected, as a partially erected structure is vulnerable. For example, a blower with a 3 horsepower motor will be operated at full 3 horsepower during inflation, then operated at one-half horsepower once the structure is up. Extra blower capacity provides normal support of the fabric plus wind and snow loading, it makes up normal air loss through leakage and door traffic, and can be used to control ventilation.

C. Proposed Design Solution.

1. Concept.

Figure 3 (next page) illustrates the design proposed in this thesis. An open fence is erected bounding a circle of D= 80'-0". Over this is placed an air supported
structure consisting of two domes, one within the other. The pressure within the inner dome is maintained at +.07 psi (0.07 psi greater than the atmospheric pressure), and the pressure between the two domes is maintained at +.054 psi. A flap of fabric is hung from the perimeter of the inner dome so that it is forced against the open fence by the pressure of +.07 psi in the building's interior, providing an air seal. A skirt of fabric is continued from the dome toward the ground and is terminated in a series of parabolic arches. Each of these arches has embedded in it a steel strand which collects the tensile stresses in the structure and transfers them to foundations in the ground.

Figure 3

Air is introduced into the interior of the building by four blowers, placed to achieve satisfactory air distribution. A series of air vents is placed around the perimeter of the inner dome, and another vent is placed in its center. One large vent is placed in the center of the outer dome. Air which is being delivered into the structure leaves by way of the perimeter vents of the inner dome, passes through the space between the two domes, and leaves through the vent in the center of the outer dome. In this way, heat collected between the two domes is constantly forced out. The vent in the center of the inner dome is used to allow
warm air which collects in that area to escape. The amount of air passing through the structure is determined by the number of air changes desired. All vents are carefully designed to allow this quantity of air to pass, and still maintain the necessary inflation pressures.

The material of which the structure is made is a plastic film or fabric coated with a micro-layer of aluminum (1/1,000,000" in thickness). This coating gives the fabric high reflectivity, greatly increasing the insulating quality of the structure.

The structure covers an area of 5000 square feet. This is enough to accommodate 500 people if used as an assembly space, and is felt to be a suitable size for most uses. However, should greater space be needed, the following provision is made: For ease of handling the dome is divided into four segments to be joined at the site. Greater area can be obtained by joining these segments into two semi-domes and adding barrel-vault sections between.

![Figure 4. - Plan View Showing Possible Expansion of Structure.](image)

Entry is gained by building a space inwards from the perimeter fence. This space becomes an airlock through which one passes into the structure. (For a detail of the entry, see the plan and section included at the end of this paper.)

The cost of this structure is estimated at $3.00 per square foot of covered area. This estimate is based upon experience gained by Bird Air Structures, Inc., and reflects the fact that the structure essentially consists of two single-skin structures, each of which would cost $1.50 per square foot of covered area. Thus the cost of shelter for an area of 5000 square feet will be approximately $15,000, not including the cost of foundations.
2. **Analysis and Design.**

Three sets of calculations are presented. The first is a structural analysis intended to determine the magnitude of forces developed in the air supported structure and the size of the foundations needed to resist these forces. The second is a structural analysis of the fence intended to determine the forces exerted upon it by internal pressure. The third is an analysis of the air-flow system intended to determine the size of vents.

a. **Structural Analysis of the Air Supported Structure.**

The structural analysis is performed in the following manner:

1. Skin stresses in the structure due to internal inflation pressures are determined.

2. Skin stresses due to wind loading are determined and are combined with stresses due to inflation pressure to determine maximum and minimum fabric stresses.

3. Maximum skin stresses are used to determine the size of the foundations.

Figure 5 introduces the notation to be used throughout this discussion.

---

**Figure 5: Shell of Revolution with Notations.**

- $N_\phi$, $N_\theta$: Unit normal forces.
- $P_z$, $P_x$, $P_y$: Surface load components.

The following sign convention is used: negative: compressive forces positive: tensile forces
1. Stresses Due to Inflation Pressure Only:

![Diagram of a dome with labeled pressures and dimensions]

Figure 6

Given: \( R_{\text{inner dome}} = 89' - 0'' \)
\( R_{\text{outer dome}} = 65' - 3'' \)

Inflation pressures: inner dome: \( / 0.07 \) psi
outer dome: \( / 0.054 \) psi

Pressure differentials: between A and B: \( / 0.07 - 0.054 = 0.016 \) psi
between B and C: \( 0.054 - 0 = 0.054 \)

Stresses in a sphere subjected to uniform loading over its surface may be determined by the following expression:

\[
N_\theta \phi = \frac{pr}{2}
\]  

(A)

Therefore:

(a). Inner dome.

\[
N_\theta \phi = \frac{pr}{2} = \frac{0.016 \times (89)(12)}{2} = 8.55\#/\text{in}.
\]

(b). Outer dome.

\[
N_\theta \phi = \frac{pr}{2} = \frac{0.054 \times (65.25)(12)}{2} = 21.2\#/\text{in}.
\]
(c). Tension in skirt due to inflation pressure.

First, the horizontal and vertical components of the above loadings must be determined.

1. Inner dome. Angle with the horizontal $= 27^\circ$.

\[
\begin{align*}
\sin 27^\circ &= 0.453 = \frac{V_1}{8.55} ; \quad V_1 = 3.88 \\
\cos 27^\circ &= 0.891 = \frac{H_1}{8.55} ; \quad H_1 = 7.6 
\end{align*}
\]

2. Outer dome. Angle with horizontal $= 36^\circ$.

\[
\begin{align*}
\sin 36^\circ &= 0.588 = \frac{V_2}{21.2} ; \quad V_2 = 12.5 \\
\cos 36^\circ &= 0.809 = \frac{H_2}{21.2} ; \quad H_2 = 17.15
\end{align*}
\]

Now combine to determine the components of loading in the skirt.

\[
\begin{align*}
V_1 + V_2 &= 3.88 + 12.5 = 16.38 \\
H_1 + H_2 &= 7.6 + 17.15 = 24.75
\end{align*}
\]

\[
\begin{align*}
\tan \alpha &= \frac{16.38}{24.75} = 0.662 ; \quad \alpha = 33^\circ - 30' 
\end{align*}
\]

This establishes the angle at which the skirt meets the ground.
Finally:

\[
\sin 33^\circ - 30' = 0.551 = \frac{16.38}{R} \quad \Rightarrow \quad R = 29.8\text{#/in.}, \text{ giving the total tension in the skirt due to inflation pressures.}
\]

(d). Reactions at each footing due to inflation pressures only.

1. Circumference of enclosed volume.

\[ C = \pi D = \pi (80') = 252' \]

2. Total tension around circumference due to inflation.

\[(29.8)(12)(252) = 90,000\# \]

3. Reactions at each footing.

The design calls for the air supported structure to be tied down at 20 points. Therefore:

\[ \frac{90,000}{20} = 4,500\# \]

This reaction has the following distribution:

```
3750
\[ \begin{array}{c}
4,500 \\
35^\circ - 30'
\end{array} \]
```

We perform the following check to verify the above result.

1. Determine the total vertical force exerted by the internal pressure on a horizontal projection of the dome. This horizontal projection has \( A = 5000 \text{ ft.}^2 \). Therefore:

for the inner dome: \( (.016)(144)(5000) = 11490\# \)

for the outer dome: \( (.054)(144)(5000) = 38,900\# \)
for the two domes combined: \(11,490 + 38,900 = 50,390\) #

2. Compare this result with the total vertical force determined in 1-d.

\[2480\#/\text{one footing} \times 20\text{ footings} = 49,600\#\]

The closeness of these two results indicates that our previous calculations are accurate.

2. Wind Loading:

The distribution of wind pressure over the surface of an air supported structure is best obtained through wind tunnel tests. At the time of this writing, no tests have been conducted on a structure like the one being discussed. However, approximations of the wind loading on the air structure can be obtained by analyzing the structure as a shell. This is the course that has been followed in this paper. A brief discussion of wind loading on shells, extracted from Pfluger, *Elementary Statics of Shells*, follows. For a detailed discussion, and for the derivation of the formulae used in this paper for calculations, the reader is referred to the following texts:


"The wind load on shells is composed of pressure on the wind side and suction on the leeward side. Only the load component acting perpendicularly to the middle surface \(p_z\) is of importance, since the components \(p_x\) and \(p_y\) are due to friction forces and are almost equal to zero. The distribution of wind pressure has been investigated by exact measurements only for cylindrical and spherical bodies. For example, in circular cylindrical bodies of rough surface, the average pressure distribution is as indicated in Figure 7a:

![Figure 7a](image)

![Figure 7b](image)
In order to calculate the wind pressure in any shell of revolution, we must rely on various assumptions. It is customary to use the following hypothesis, which has the merit of great simplicity:

\[ p_x = 0; \quad p_y = 0 \]

\[ p_z = p_w \sin \theta \cos \phi \]  

In this we denote by \( p_w \) the force per unit of the middle-surface at \( \phi = 0 \). Here \( \phi = 0 \) is defined as the angle at which the \( z \)-axis points in windward direction.

For the meridian and parallel sections, the expression in equation (B) indicates a sine-shaped distribution of the wind pressure. This distribution, however, should be regarded as a very rough approximation. For the sake of simplicity, we shall use equation (B) for cylindrical and spherical shells, since the introduction of more exact laws would unduly complicate our calculations. Figure 7b shows the distribution of pressure in a cylindrical container according to equation (B), as compared to the actually measured distribution shown in Figure 7a.

The remainder of the discussion quoted above is devoted to developing an expression for \( p_w \). This expression is found to be:

\[ p_w = 0.26q \]  

in which \( q \) = wind pressure

The following expressions are used to determine the internal forces, \( N_\theta \) and \( N_\phi \), in a spherical shell subjected to horizontal wind pressure:

\[
N_\theta = - p_w \frac{R}{3} \frac{\cos \phi \cos \theta}{\sin^3 \theta} \left[ 2 \cos \theta - 3 \cos \theta \phi \cos^3 \theta \right] 
\]

\[
N_\phi = p_w \frac{R}{3} \frac{\cos \phi}{\sin^3 \theta} \left[ 2 \cos \theta \phi - 3 \sin^2 \theta - 2 \cos^4 \phi \right] 
\]

The following procedure is employed to determine fabric stresses in the air supported structure when it is under wind loading:

1. Determine wind stresses at critical points of a shell having the same configuration as the air structure.

2. Add positive, that is, tensile, wind stresses to the tensile stresses caused by inflation pressure in the air supported structure. In this way, determine maximum tensile fabric stress.
3. Subtract negative, that is, compressive, wind stresses from the tensile stresses caused by inflation pressures. In this way, establish minimum tensile forces in the air supported structure. In no case may this tensile force be allowed to reach 0. The air structure depends upon constant tension throughout its skin for stability. If compressive wind stresses are found to exceed the tensile stresses produced by internal pressure, then the internal pressure must be increased.

In our calculations we take $p_w = 0.35q$, where $q = 20$ psf. $0.35q$ is felt to be a more conservative figure than the $0.27q$ mentioned previously. Therefore:

$$p_w = 0.35(20) = 7\text{psf}.$$ 

The following conditions are known (see Figure 8a):

(a). $R_{outer\ dome} = 65.25'$

(b). $\Theta_{maximum} = 36^\circ$; this is the angle at which the outer dome meets the horizontal.

(c). Tensile stress caused by inflation pressure in the air supported structure = $N_{\Theta,\phi} = 21.2\#$/in.

Wind stresses will be determined at the crown and at 20 points along the base. These 20 points are chosen to correspond with the location of tie-downs to footings. Since the dome is symmetrical in every direction and since a compressive force on the wind side has a corresponding tensile force on the leeward side, it will be necessary to calculate the loadings only upon $1/4$ of it.
1. Wind Stresses in the Outer Dome.

(a) $\phi = 0^\circ; \quad \theta = 360^\circ$

$$N_{\theta} = -7(\frac{65.25}{3}) \frac{(\cos 0^\circ)(\cos 360^\circ)}{\sin^3 360^\circ} \left[ 2 - 3 \cos 360^\circ - \cos^3 360^\circ \right]$$

$$N_{\theta} = -7(\frac{65.25}{3}) \frac{(1)(0.809)}{0.5883} \left[ 2 - 3(0.809) - (0.809)^3 \right]$$

$$N_{\theta} = -7(21.75) \frac{(1)(0.809)}{.203} (.103)$$

$$N_{\theta} = -62.5#/ft; \quad \frac{-62.5}{12} = -5.2#/in. = N_{\theta}$$

$$N_{\phi} = 7(\frac{65.25}{3}) \frac{(\cos 0^\circ)}{\sin^3 360^\circ} \left[ 2 \cos 360^\circ - 3 \sin^2 360^\circ - 2 \cos^4 360^\circ \right]$$

$$N_{\phi} = 7(\frac{65.25}{3}) \frac{(1)}{0.5883} \left[ 2(0.809) - 3(.588)^2 - 2(0.809)^4 \right]$$

$$N_{\phi} = 7(21.75) \frac{(1)}{.203} (-.282)$$

$$N_{\phi} = -212#/ft; \quad \frac{-212}{12} = -17.6#/in. = N_{\phi}$$

(b) $\phi = 18^\circ; \quad \theta = 360^\circ$

$$N_{\theta} = -59.6#/ft.$$ 

$$N_{\phi} = -201#/ft.$$ 

(c) $\phi = 360^\circ; \quad \theta = 360^\circ$

$$N_{\theta} = -50.4#/ft.$$ 

$$N_{\phi} = -170#/ft.$$ 

(d) $\phi = 54^\circ; \quad \theta = 360^\circ$

$$N_{\theta} = -36.6#/ft.$$ 

$$N_{\phi} = -124#/ft.$$
(e). $\phi = 72^\circ; \Theta = 36^\circ$

$N\Theta = -19.3\#/\text{ft.}$

$N\phi = -65.5\#/\text{ft.}$

(f). $\phi = 90^\circ; \Theta = 36^\circ$

$N\Theta = 0\#/\text{ft.}$

$N\phi = 0\#/\text{ft.}$

(g). loadings at crown; $\phi=0^\circ$; $\Theta=0^\circ$

$N\Theta = -7\left(\frac{65.25}{3}\right)\left(\frac{-\cos 0^\circ \cos 0^\circ}{\sin^3 0^\circ}\right) \left[2 - 3 \cos 0^\circ - \cos^3 0^\circ\right]$ \[
N\Theta = -7\left(21.75\right) \left(\frac{1}{0}\right) \left[2 - 3/1\right]
\]

$N\Theta = 0\#/\text{ft.}$

$N\phi = 7\left(\frac{65.25}{3}\right)\left(\frac{\cos 0^\circ}{\sin^3 0^\circ}\right) \left[2 \cos 0^\circ - 3 \sin^2 0^\circ - 2 \cos^4 0^\circ\right]$ \[
N\phi = 7\left(21.75\right) \left(\frac{1}{0}\right) (2 - 0 - 2)
\]

$N\phi = 0\#/\text{ft.}$

We see from the above that maximum wind loading occurs at $\phi = 0^\circ, \Theta = 36^\circ$; that is, at the base of the air supported roof at the point leading directly into the wind. Here:

$N\Theta = -62.5\#/\text{ft.} = -5.2\#/\text{in.}, \text{ and}$

$N\phi = -212\#/\text{ft.} = -17.6\#/\text{in.}$

Wind stresses diminish on either side of this point and reach 0 at $\phi = 90^\circ; \Theta = 36^\circ$; and at $\phi=0^\circ$ (crown). Figure 9 shows the distribution of wind stresses along the base of the structure and is representative of those along any parallel section of the dome.
The fabric of the structure cannot resist bending. All stresses in it must be tensile. The compressive stresses induced by wind will reduce the tension due to internal pressure, while tensile wind stresses will increase it. Since strain is proportional to stress, the fabric on the wind side will contract in proportion to the compressive stress acting on it and the fabric on the leeward side will stretch in proportion to the stresses acting on it. The compressive and tensile stresses are assumed to be equal in magnitude. Therefore, strains on the wind side will be equal to strains on the leeward side. As a result, the volume of air enclosed between the inner and outer domes will not change. Its pressure will remain constant. Therefore, the inner dome will remain under constant pressure and receives no stress due to wind. The outer dome takes total wind loading.

We have determined wind stresses in the outer dome and may now proceed to determine maximum and minimum fabric stresses.

On the leeward side, wind stresses are tensile and must be added to the stress due to inflation pressure. Thus:

\[ N_\theta = 21.2 + 5.2 = 26.4 \text{#/in.} \]

\[ N_\phi = 21.2 - 17.6 = 38.8 \text{#/in.} \]


On the wind side, wind stresses are compressive and must be subtracted from the tensile stress caused by internal pressure. Thus:

\[ N_\theta = 21.2 - 5.2 = 16.0 \text{#/in.} \]

\[ N_\phi = 21.2 - 17.6 = 3.6 \text{#/in.} \]

Tension is maintained under design wind conditions and the structure therefore is safe.

3. Design of Footings.

Since the wind may come from any direction, it is necessary that the footings be designed to take the maximum value for \( N_\theta \) determined above. That is, 26.4#/in.

Thus, we have: 26.4 - 21.2 = 5.2#/in.

\[ 5.2 \times 12 = 62.5 \text{#/ft.} \]

\[ (62.5)(252) = 15,700 \text{#} \]

\[ \frac{15,700}{20} = 790 \text{#}; \text{ the increased reaction any single footing must furnish.} \]

Therefore, the total reaction at any single footing is:

\[ R = 4500 + 790 = 5290 \text{#}. \]

\[ H = 3750 + 656 = 4406 \text{#} \]

\[ 33 \text{o}-30' \]

\[ V = 2480 + 436 = 2916 \text{#} \]
Actually the new loading does not enter the tie-down skirt at the same angle at which the skirt meets the ground. Previous calculations for footing reactions took this into account, and in these calculations the tie-down is truly the resultant of the forces in the two domes. In this case, however, deflection makes it difficult to establish the angle at which the outer dome will transfer forces into the tie-down skirt. It is felt, however, that assuming the outer dome to enter the tie-down skirt at the same angle at which the skirt meets the ground introduces an error of only a small order of magnitude, and is satisfactory for these calculations.

Two solutions for footings are offered:

a. Isolated footings.
Figure 10 illustrates a footing which consists of a bored shaft with its bottom belled out and filled with concrete. This footing resists the tension loading from the structure by utilizing the weight of the earth. For it to be displaced, it must displace the entire cone of earth above it (shaded in Figure 10).

The exact size of this cone depends upon the angle of repose of the particular soil involved. For an example, we will assume the dimensions shown in Figure 10. We will assume the weight of the soil to be 100#/CF.

Therefore:

\[ V = \frac{1}{3} \pi (4.5)^2 (5.5) = 116 \text{ CF} \]

\[ (116) (100) = 11,600\# \]

This weight will produce a reaction adequate to resist the loading of 5290# from the structure and to provide a good factor of safety. To resist lateral displacement of individual footings in certain soils, it may be desirable to introduce horizontal members connecting the footings together.

This solution requires the use of an earth-borer which might be truck mounted and motor-driven.

b. Grade Beam.

For situations in which no earth borer is available, a concrete grade beam, requiring only hand labor, may be used.

It must be designed to resist in compression the horizontal forces exerted upon it and to resist by its dead weight the vertical forces exerted upon it.
Thus, we have:

(1). For compression: \( \pi D = 2 \pi R = 2 \pi (54) = 339'. \)

Loading may be assumed to be uniform and is found to be:

\[
\frac{(4406)(20)}{339} = 262\text{#/ft.} = p
\]

Therefore: \( C = pR = 262 (54) = 14200\#
\)

Using \( f_c = 400\#/\text{sq.in.} \); assuming weak concrete,

\[
\frac{14200}{400} = 35.2\text{ sq.in.}, \text{ required.}
\]

(2). For vertical load: \( (2916)(20) = 58,320\#, \text{ total vertical load.} \)

Assuming the weight of concrete to be \( 150\#/\text{CF} \),

\[
\frac{58,320}{150} = 390 \text{ CF of concrete.}
\]

The cross-section area of a beam to provide this mass is:

\[
A = \frac{390}{339} = 1.15 \text{ ft.}^2
\]

\[
A = 1.15 (144) = 166 \text{ in.}^2
\]

This figure yields a section 12.9" square.

It is seen that the uplifting force requires a section much greater than that required to resist horizontal forces, and is the determining section in this design.

To provide an adequate factor of safety, a beam 1' - 3" square is suggested. Its total weight over the 339' circumference is: \((1.25)^2 (339) (150) = 79,000\#, \text{ to resist the imposed load of 58,320#.}\)
b. **Analysis of the Fence.**

The fence which is used to restrain the air seal of the structure is considered as a tension ring. This fence must not be connected to the air structure above it. Enough space must be left between the top of the fence and the air structure to allow the air structure to deform without meeting the fence.

The specific design of the fence is variable; it may differ depending upon where the structure is used. All that is required of it is that it be strong enough to resist the loading placed on it by the interior pressure of 0.07 psi. The following calculations indicate the loadings upon the fence and the size of members which might be used.

We will assume, for sake of example, a chain-link fence 8' - 0" high with vertical supports every 10' - 0" O.C.

1. **Vertical supports.**

![Figure 12a](image)

![Figure 12b](image)

From Figure 12a, \((10)(8) = 80 \text{ sq.ft.}\)

\[(80)(144)(.07) = 805\#\] load uniformly distributed on each vertical member.

\[
\frac{(805)(8)}{8} = 805 \text{ ft.-lbs.} = M \text{ on each member.}
\]
Possible solutions:

(a). steel: 
\[(805) (12) = 20,000 \text{ (I/C)}\]
\[.480 = \text{I/C} \]
\[\text{pipe: 2.375" O.D.} \]
\[2.067" \text{ I.D.} \]

(b). aluminum: 
\[(805) (12) = 22,000 \text{ (I/C)}\]
\[.440 = \text{I/C} \]
\[\text{pipe: 2" O.D.} \]
\[1.624" \text{ I.D.} \]

2. Horizontal Members.

![Figure 13](image)

(a). Projected area of \( \frac{1}{2} \) the fence:

\[(80) (8) = 640 \text{ sq. ft.} \]
\[(640) (144) = 92,000 \text{ sq. in.} \]

(b). Loading from internal pressure:

\[(92,000) (0.07) = 6450\# \]

(c). Tensile stress in horizontal fence members:
(d). Possible solutions:

1. steel: allowable $T=20,000$#/ sq. in.
   
   $\frac{1612.5}{20,000} = .085$ sq. in.

   pipe: .540" O.D.
   
   .364" I.D.

2. aluminum: allowable $T=22,000$#/ sq. in.
   
   $\frac{1612.5}{22,000} = .0735$ sq. in.

   round tubing: .625" O.D.
   
   .527" I.D.

c. **Air Movement Analysis.**

This is the procedure followed in this discussion:

1. Calculate the volume of the zone of occupancy of the building.

2. Determine desired air change.

3. Determine the pressure differentials existing between different parts of the structure.

4. Determine the distribution of vents required for proper ventilation.
5. Determine the total area $A$ of vents, using the following expression for the flow of air through a nozzle:

$$Q = Y M C A \sqrt{\frac{2 g \Delta p}{\rho}}$$

in which

- $Q =$ air flow in CF/second.
- $A =$ cross section area of throat of nozzle in SF.
- $g =$ gravity acceleration
- $\Delta p =$ pressure differentials (absolute) in psf.
- $\rho =$ density of air in #/CF.

and $Y M$ and $C$ are nozzle correction factors.

6. Based upon the distribution of vents determined in 4., determine the size of each vent in the system.


In our problem:

![Figure 15](image-url)
1. Volume of Zone of Occupancy (shaded in diagram):

\[ A_{\text{enclosure}} = \pi (40^2) = 5000 \text{ ft.}^2 \]
\[ V_{\text{zone of occupancy}} = 9(\pi) (40^2) = 9(5000) \]
\[ V = 45,000 \text{ ft.}^3 \]

2. Air Change:
   (a). minimum allowable: 6 air changes/ hour
   (b). optimum: 10/ hour

Design for optimum condition, though this will increase blower capacity and cost.

\[ 10 \times 45,000 \text{ ft.}^3 = 450,000 \text{ ft.}^3 / \text{hour} = 7500 \text{ ft.}^3 / \text{minute} \]

3. Pressure Differentials:
   (a). Between zones A and B.
   \[ .07 - .054 = .016 \text{ psi} \]
   (b). Between zones B and C.
   \[ .054 - 0 = .054 \text{ psi} \]

4. Required Placement of Vents:
   (a). Inner Dome: 1 center vent
       20 perimeter vents, equally spaced.
       For proper venting of roof: \( \sum \) 20 perimeter vents = 3 X center vent
   (b). Outer Dome: 1 center vent

5. Area of Vents:
\[ Q = Y M C A \sqrt{\frac{2 g \Delta p}{\rho}} \]
where: \( Q \) = flow in CF/second
\( A \) = cross section area of throat in ft.\(^2\)
\( \rho \) = density of air in \#/ft.\(^3\)
\( \Delta p \) = pressure differential in psf
\( g \) = gravity acceleration: 32.2 ft./sec.\(^2\)

and \( Y, M \) and \( C \) are nozzle correction factors.
\( Y = .98 \)
\( M = 1 \)
\( C = .965 \)
Therefore, in our problem:

\[ Q = \frac{7500}{60} = 125 \text{ ft.}^3/\text{second}. \]

\[ \rho = 0.075 \text{#/ft.}^3 \quad \text{(density of dry air at sea level at 700 F.)} \]

\[ g = 32.2 \text{ ft./sec}^2 \]

\[ \Delta p \text{ between } A \text{ and } B = 0.016 \text{ psi X } 144 = 2.3 \text{ psf}. \]

\[ \Delta p \text{ between } B \text{ and } C = 0.054 \times 144 = 7.75 \text{ psf}. \]

(a). Inner Dome.

\[ 125 = (0.98) (1) (0.965) A \sqrt{2 (32.2) (2.3)} \]

\[ 125 = 0.98 (0.965) A \sqrt{1980} \]

\[ 125 = 0.98 (0.965) A (44.45) \]

\[ 125 = 0.42 A \]

\[ \frac{125}{42} = A; \quad A = 2.98 \text{ ft}^2; \quad \text{total area of inner vents.} \]

\[ 2.98 \times 144 = 428 \text{ in.}^2 \]

Now, let \( X = \text{total area of perimeter vents}; \)

Then \[ \frac{X}{20} = \text{area of 1 perimeter vent}. \]

And \( X/3 = \text{area of center vent (from § 4)} \)

\[ X/3 = 428 \text{ in.}^2 \]

\[ 4X/3 = 428 \]

\[ X/3 = 107 \]

\[ X = 321 \text{ in.}^2 \]

\[ X/3 = 107 \text{ in.}^2 = \text{area of center vent, inner dome}. \]

\[ \text{and} \quad \frac{X}{20} = \frac{321}{20} = 16.05 \text{ in.}^2 = \text{area of one perimeter vent}. \]

\[ . \text{ Center vent, inner dome:} \quad \frac{\pi D^2}{4} = 107; \quad \pi D^2 = 428 \]

\[ D^2 = 136; \]

\[ D = 11.8" \]

\[ \text{Perimeter vents, inner dome:} \quad \frac{\pi D^2}{4} = 16.05 \text{ in.}^2 \]

\[ \pi D^2 = 64.20 \]

\[ D^2 = 20.4 \]

\[ D = 4.5" \]
(b). Outer dome - single vent.

125 = (.98) (l) (.965) (A) $\sqrt{\frac{2(32.2)}{.075}}$ = 7.75

125 = " " $\sqrt{6650}$

125 = (.98) (l) (.965) (A) (81.4)

125 = 77A

$\frac{125}{77} = A ; \ A = 1.625 \text{ ft.}^2$

$1.625 \times 144 = 234 \text{ in.}^2$

$\pi D^2/4 = 234$;

$\pi D^2 = 936$

$D^2 = 298$

$D = 17.25''$

An ISA nozzle will be used in all cases. Figure 16 below shows its proportions.

Figure 16

At the time of this writing, no final decision has been made as to the best material for the structure. This decision can only be made after testing and pricing the different possibilities. A discussion of four possibilities follows:

a. A nylon and neoprene or vinyl fabric coated on one side with a micro-layer (1/1,000,000") of aluminum. This aluminum coating can be expected to reflect up to 94% of the light and heat striking it.

Usual procedure, as followed by BirdAir Structures of Buffalo, N.Y., has been to use a nylon fabric impregnated with neoprene for air structures. This material at a thickness of .020", has an allowable tensile stress of 100#/ in. and an ultimate of 300#/ in. These values make this material adequate to resist the stresses occurring in our structure.

In this solution, it will be necessary to protect the aluminized surface from direct contact with water. Since it is so thin, it would be quickly deteriorated by the action of water upon it. To solve this problem, the aluminized surface of the outer skin could be protected be a layer of clear hypalon over it.

The usual white neoprene or vinyl coated nylon fabric has a life expectancy of 6-7 years. The addition of the aluminum coating and a layer of hypalon can be expected to increase this figure. The amount of this increase, however, must be determined by testing.

b. A nylon and neoprene fabric with a ply of .00025" aluminized Mylar included between the inner and outer skins of the roof. In this system the aluminized coating would be protected from the weather by the outer skin of the roof. This combination of materials would have the same life as the nylon and neoprene fabric, about 6-7 years.

c. Aluminized Mylar in combination with Dacron threads for the structural skin. Mylar has a tensile strength of 25,000 psi; thus a thin layer, .02",
will produce the strength necessary for loading and a substantial factor of safety in the proposed design. However, since Mylar is a film, and not a woven fabric, it has poor tear resistance; once a tear is started, it is easily continued. Therefore, the use of Mylar alone is not suggested. By laminating the Mylar to a Dacron mesh, necessary tear resistance could be obtained. The aluminized surface would have to be protected from the action of water as in the other solutions. This would be accomplished by making the coated side of the outer dome the side away from the weather. Weatherable grade Mylar would be used — this has a maximum life span of 7 years.

d. "Tedlar" PVF Film used as a coating over any of the above possibilities, or, aluminized and in combination with a Dacron mesh, as the structural skin. "Tedlar" is essentially an outdoor film with excellent weatherability. It has been used and tested as a tough, lasting surface for prefabricated metal surfaces. Its properties are:
1. outstanding weatherability
2. High flex life over a broad temperature range.
3. High tensile strength — 15000 psi @ 68°F.
4. Outstanding resistance to thermal degradation.
5. High dielectric strength, heat sealability.
6. Excellent dimensional stability.

"Tedlar" PVF Film has been just recently developed by the DuPont Chemical Co. DuPont has not yet made any definitive estimate of its life span. Indications are that it is at least three times more weather resistant than the best conventional liquid finishes. In a weatherometer test, plywood covered with "Tedlar" did not deteriorate after 3000 hours exposure, while plywood covered with conventional paint failed after 506 hours. 6

4. **Blower Size.**

The air movement analysis indicated that optimum air change requires
7500 ft.\(^3\)/ minute. Four blowers, spaced equally around the structure, are recommended. Thus, each blower must supply 1875 ft.\(^3\)/ minute against the internal pressure of 0.07 psi. A blower which may be used for this job is the S150EP, manufactured by the American Blower Division of the American Radiator and Standard Sanitary Corporation. This blower has a 3/4 HP motor and will supply 1920 ft.\(^3\)/ minute at an outlet velocity of 1500 ft./ minute. It has a retail cost of $226.50. The addition of weather hoods, screen inlets, and shutter valves will somewhat increase this cost, making the total cost of the blower system approximately $1100.

5. Fabrication.

The structure will be fabricated of identical gores electronically sealed together. The fabric will be cut from rolls 52" wide. The gores, dimensioned to facilitate maximum use of material, are 15.2" wide at their tops, and 37.1" wide at their bottoms (see Figure 17).

![Figure 17](image)

For the arrangement of gores in the structure, see the drawings of the top and bottom domes included at the end of this paper.

6. Weight and Sectionalized Construction.

The structural skin weighs approximately 2.5 oz./ ft.\(^2\). The weight of the entire dome is approximately 4150#. The dome is divided into four equal segments, each weighing about 1040#, a convenient weight for shipping and handling. These segments are packaged separately and joined at the site. The joint is accomplished
through the use of overlapping layers of fabric with metal fasteners glued within. A detail of this joint is included at the end of this paper.

7. **Lighting.**

Natural lighting can be accomplished in several ways. If a transparent material, such as Mylar, is used, the density of the aluminum coating can be controlled to regulate the amount of light passing through it. Certain gores will be left uncoated. When this is done, these clear gores of the inner and outer dome will be placed in a staggered arrangement, rejecting direct sunlight, but trapping light between the two roof layers. Thus, indirect light will be provided for the interior of the building.

If a translucent material, such as white nylon w/neoprene is used, certain of these panels will be left without the aluminum coating and placed in a staggered arrangement as described above. In this solution, it is unlikely that very much light will pass through the aluminized fabric, and the number of uncoated gores may have to be increased. This will to some extent decrease the insulating value of the system.

In any solution, the final distribution of coated and uncoated gores, and the density of coating, will be determined by the quantity of light and degree of insulation required.

It is felt that the arrangement of coated and uncoated gores herein proposed will not only provide a satisfactory solution as far as quantity of light is concerned but, by breaking down the surface of the dome into a regulated pattern, will enhance the quality of interior space.

At night, light will be beamed from the top of interior partitions up to the roof and from there reflected downwards to provide general lighting. This system, coordinated with a pattern coated and uncoated gores, will make the structure particularly handsome from the exterior at night. At this time, a pattern similar to that produced in the interior under daylight will be produced on the exterior.

8. **Plan Arrangements.**

Plan arrangements will vary widely. Four possible arrangements are shown
among the drawings at the end of this paper.

Interior partitions may be of any material. Individual rooms may be roofed, or left open, as desired. The floor may be of any material; stabilized earth, however, is a good solution. Bathrooms and other spaces in which ventilation is particularly important should be placed at the perimeter of the building near the perimeter vents of the inner dome. Since there is a forced, one-way air flow in the structure, fumes from these spaces will be forced through the perimeter vents and exhausted through the central vent of the outer dome.

9. **Heating.**

Two methods of heating the building are suggested.

a. The blowers may be used to introduce heated air into the building.

b. Radiant lamps may be placed on the floor and beamed toward the roof. Thus, radiant heat will be reflected in a general distribution back to the floor.
Part III: CRITIQUE

Let us review the Program set forth in Part I and consider if this design satisfies it.

1. The structure must provide high quality space, properly lit, insulated, and ventilated.

The system of air flow and the use of aluminized fabric will produce a space well insulated from solar heat. The blower and vent system has been carefully designed to provide optimum ventilation. The placement of uncoated gores in a staggered arrangement will admit indirect light, while excluding direct sunlight.

In addition, the proposed structure will have satisfactory acoustics. The inner dome, because it is relatively flat, will not focus sound within the space as it would if it had greater curvature.

A problem which has not been adequately considered is that of sound isolation within the building. Designs for interior partitions to control sound must be developed.

A possible problem will be the noise of rain on the structure. To what extent the air space between the two domes will deaden this noise is not known.

Still another problem concerns the entry. The entry suggested in the design is low in cost, but is not suitable for handling large, constant traffic, because then too much air will be lost through the doors. In this situation, revolving doors will be necessary. These will increase the cost of the structure.

2. The structure must be flexible; it should be able to serve a variety of uses.

The structure provides covered, well-insulated and ventilated open space of large dimensions. Such space is suitable for hospitals, schools, assembly spaces, industries, mass housing, and many other uses.
The circular form of the structure, however, does introduce some planning limitations. It is not felt that, for the uses intended, this is a serious problem. The shape of the building is a result of the structural principles involved, and any limitations which this shape imposes must be weighed against the advantages which the system offers.

3. It must be low in cost.

Estimates indicate that the cost of the structure will be approximately $3/SF of covered area, or $15,000. This is considered to be a very satisfactory figure.

4. It must be easy to transport, erect, and take down. It must require minimum site work and afford maximum reuse of materials.

Before erection, the proposed structure consists essentially of four packages of fabric, each weighing 1040#, and four blowers, each in a box 34" on a side. Any of these can be easily transported; can, in fact, be flown and parachuted into location when necessary.

All that is required at the site is that the foundations be placed, the fence erected, the four segments of the dome joined, and the dome attached to the foundations. Once this has been done, the whole building, covering 5000 ft.², can be erected in less than 30 minutes.

The four segments of the dome can be rapidly joined using the method previously described. The fence can be erected reasonably quickly if it is constructed of prefabricated components (metal pipe sections, chain-link, wood, etc.). The foundations will require more time, for digging, pouring, and setting. This is the slowest part of the construction procedure and should be made the subject of further study.

When the structure is to be moved, all material, with the exception of the concrete in the foundations, can be reused.
This thesis has developed in detail a prototype structure providing well insulated and ventilated, inexpensive, portable space. It has not developed in the same detail the uses for the space; it has only suggested them.

To solve the problems which specific uses will introduce, further research will be necessary. This research should include:

1. The development of low cost facilities for plumbing, heating, lighting; power generating, etc. Some work has been done in this field by U.S. industry -- the General Electric Co., for example, has developed several interesting proposals for low cost village electrification.7

2. The development of low cost equipment for hospitals, facilities for schools, machinery for industries, etc.

3. The development of light weight materials to combat noise -- both interior and exterior. As mentioned before, sound isolation between different areas within the structure is a problem. This problem can only be solved through materials research. Likewise the problem of impact noise on the roof. Foams, grafted to the structural fabric, or even acting as the structure itself, are a possible solution, and should be studied.

4. The development of structural fabrics with a longer life span. "Tedlar" PVF Film may be one such material.
NOTES


3. This discussion is derived from a conversation between the author and Mr. A.C. Smith of BirdAir Structures, Inc., Buffalo, N.Y.

4. From Pfluger, Elementary Statics of Shells.

5. Aluminized Mylar has been developed by the National Research Corporation for use as insulation in space vehicles. For information about it, see the brochure, "NRC-2 Insulation," printed by the National Research Corporation, 70 Memorial Drive, Cambridge 42, Mass.

6. For more information on both "Tedlar" and Mylar films, write to E.I. DuPont de Nemours & Co., Inc., Film Department, Wilmington 98, Delaware.

7. (same as 1.).
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A SYSTEM OF SHELTER FOR DEVELOPING NATIONS
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I. PHOTOGRAPHS OF MODEL
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S. PLAN 1/16' = 1'-0"
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INNER DOME PLAN, SHOWING LOCATION OF VENTS AND ARRANGE-
MENT OF CLEAR AND GHITED
DOES. 

1/4" = 1'-0"
A SYSTEM OF SHELTER FOR DEVELOPING NATIONS
MASTER IN ARCHITECTURE THESIS
M.I.T. RICHARD C. NEWMAN 1962
B. OUTER DOME PLAN 1/4"=1'-0"