STAINLESS STEEL MEMBRANE ROOF

A DESIGNERS' HANDBOOK SERIES

Nº 9034

Produced by
AMERICAN IRON
AND STEEL INSTITUTE

Distributed by
NICKEL
INSTITUTE

knowledge for a brighter future

STAINLESS STEEL MEMBRANE ROOF

A DESIGNERS' HANDBOOK SERIES
Nº 9034

Originally, this handbook was published in 1980 by the Committee of Stainless Steel Producers, American Iron and Steel Institute.

The Nickel Institute republished the handbook in 2020. Despite the age of this publication the information herein is considered to be generally valid.

Nickel Institute

communications@nickelinstitute.org
www.nickelinstitute.org

STAINLESS STEEL MEMBRANE ROOF

The material presented in this booklet has been prepared for the general information of the reader. It should not be used without first securing competent advice with respect to its suitability for any given application. While the material is believed to be technically correct, neither the American Iron and Steel Institute, the Committee of Stainless Steel Producers nor the companies represented on the Committee warrant its suitability for any general or particular use.

Contents

Stainless Steel Membrane Roof

Long Span—Low Cost—Fast Erection

Introduction

What are the characteristics of an ideal long-span roof?

Most architects would agree that several features are necessary for an optimum design. For example, a *clear span without internal columns* is a prerequisite, especially for sports arenas, airport terminals and hangars, and exhibition halls. In many parts of the country attendance figures at professional sporting events have improved as a result of having a totally enclosed stadium with controlled environment.

The *capability to cover large areas* ties in closely with the totally enclosed sports arena concept. To hold 60,000 or more spectators, stadiums would require a roof structure spanning several hundred feet. For large spans of conventional design, the structural depth of the roof support system, as well as the resulting cost, increases dramatically with increasing area. An optimum roof design *minimizes structural depth.*

Cost, which includes material cost, labor and construction, the cost of borrowing money, and the cost of roof *maintenance* is always a factor.

A roof has to be *aesthetically pleasing*, especially for large structures. Because of its imposing size, a large, clear-span roof becomes a highly visible landmark, so it must be acceptable to the surrounding community.

Structural integrity is a major factor assuming greater importance today because of increased liability and the recent rash of failures in large-span roof structures.

And, far from least, maintenance is a continuing concern in that most roofs need periodic repair and occasional replacement.

Interestingly, over 2000 years ago Roman architects attempted to construct an optimum wide-span roof. They were fairly successful, with the first tension structure using rope and canvas to cover the Colosseum. This concept was followed by the stone arches and domes of the Roman, Gothic and Renaissance periods, which were primarily compression structures.

With the development of steel and reinforced concrete, large clear-span areas were covered with truss and space frame supported roofs, which unfortunately have the disadvantage of requiring considerable structural depth.

About 60 years ago, someone realized that an extremely efficient way to cover large column-free areas was to support the roof structure by air pressure, such as the fabric balloon structure over enclosed tennis courts. While this is an efficient way to cover a large area, fabrics have limited life, are susceptible to damage and unsuitable where efficient climate control is desired.

In 1980, long-span roofs enter a new era with all-stainless steel membranes as a new type of permanent roof structure, which embraces all the ideals of the optimum roof concept. This booklet discusses the concept and describes the design, fabrication and construction of the first stainless steel tension membrane roof.

Figure 1

Figure 1—The first installation of the all-welded, air-supported stainless steel membrane roof at Dalhousie University, Halifax, Nova Scotia. The low-profile roof structure is 300 feet long by 240 feet wide, and only 1/16 inch thick! The membrane roof covers the university's sports complex.

The First Air-Supported Stainless Steel Membrane Roof

The gleaming dome of the new $11-million sports center at Dalhousie University, Halifax, Nova Scotia, Canada, is the world's first stainless steel air-supported membrane roof (Figure 1). Constructed of Type 304 stainless steel sheet 1/16 inch thick, the low-profile roof structure is 300 feet long by 240 feet wide in the shape of a super ellipse. The 1¼ acre roof is supported by 0.05 pounds per square inch (psi) air pressure, which is roughly the difference between the first and tenth floor of a high-rise building. If air pressure should drop, the roof will deflate into a concave shape, but still securely anchored at its perimeter and still capable of supporting its full design load.

At its center, the roof dome is 35 feet above the floor; walls are 25 feet high. The unique design obviates upright support columns as well as the customary network of structural steel normally required to span such a large area (Figure 2). In fact, the total depth of the roof structure is the thickness of the membrane—1/16 inch!

Thermal and acoustical insulation, as well as lights and sound system, are suspended from studs welded directly to the membrane.

The dome roof covers a three-level sports complex consisting of field house and running track, class and locker rooms, squash, handball and raquetball courts, and a 50-meter olympic-size swimming pool.

The creation of this all-around athletic facility presented a real challenge to the university. Zoning regulations restrict the height of buildings in the area to 35 feet, and they restrict the extent to which the site can be covered. Consequently, the three levels were accommodated below ground, Figure 3.

Accordingly, the site was excavated to a depth of 45 feet—in solid rock. If the roof had been of a more conventional structure, an additional 10-20 feet of excavation would have been required, adding substantially to construction costs.

The Membrane Concept

A membrane structure is essentially a thin skin designed to carry a load, as for example a child's balloon or an inflated cushion. Inflated, the cushion can support a modest

Figure 2—Inside view of the sports complex showing the large, clear-span area of the field house. The dome roof is 35 feet above the floor; walls are 25 feet high. Insulation, lights, and sound system equipment are suspended from studs welded directly to the roof membrane.

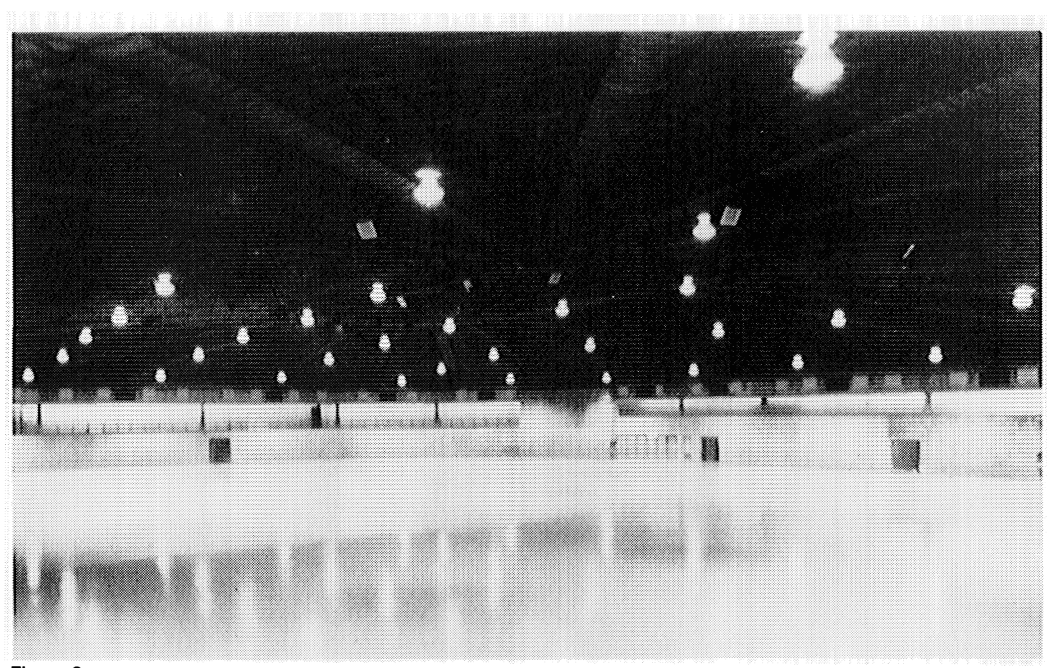


Figure 2

Figure 3

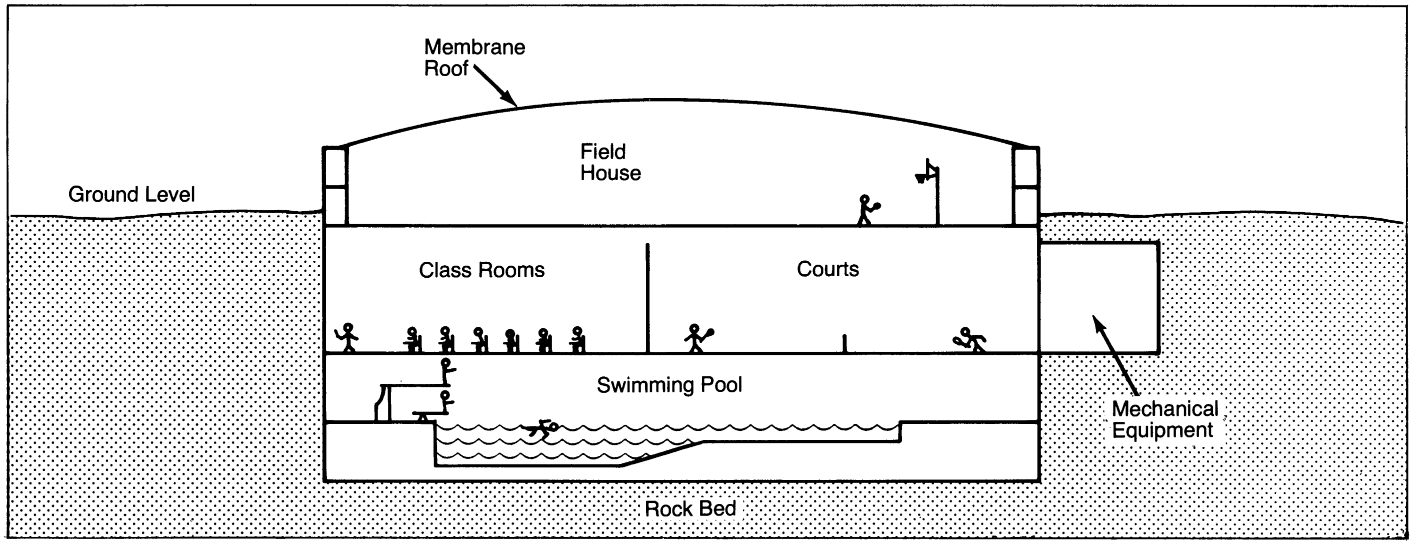


Figure 3—Cross-sectional drawing of the Dalhousie sports complex showing the three activity levels. At ground level is the field house, which is the only pressurized area supporting the membrane roof. On the next level down are locker rooms, class rooms, and squash and raquetball courts. On the lowest level is the 50-meter swimming pool.

Figure 4—The membrane roof can be seen as a small segment of a large theoretical sphere, and it consists of two basic structural elements; (1) the steel membrane and (2) the peripheral compression ring. These two units form an integral unit in which horizontal forces are in balance, and vertical forces, are transferred to the ground by supporting walls.

load because the air inside puts the skin in tension. Substitute steel and the cushion can support substantially greater loads.

By taking a small round segment of the cushion or balloon and surrounding it with a compression ring that counterbalances the skin tension—as visualized by the drawing in Figure 4—a practical monolithic structure is created. Using this monolithic structure in a roof design, the two elements—the steel membrane and the peripheral compression ring as illustrated in Figure 4—form an integral unit in which the horizontal forces are in balance and vertical forces are transferred to the ground by walls supporting the ring. Structurally, the stainless steel membrane roof is analagous to air-supported fabric roofs (Figure 5) and steel cable-suspended roofs (Figure 6), both of which are in common use today.

Theory Studied

During the late 1960's, The International Nickel Company (INCO) conducted a program to study the feasibility of metallic membrane systems. The study concluded that the essential properties a metal must have to serve efficiently in a permanent tension membrane structure are:

1. High strength to permit the use of thin material.

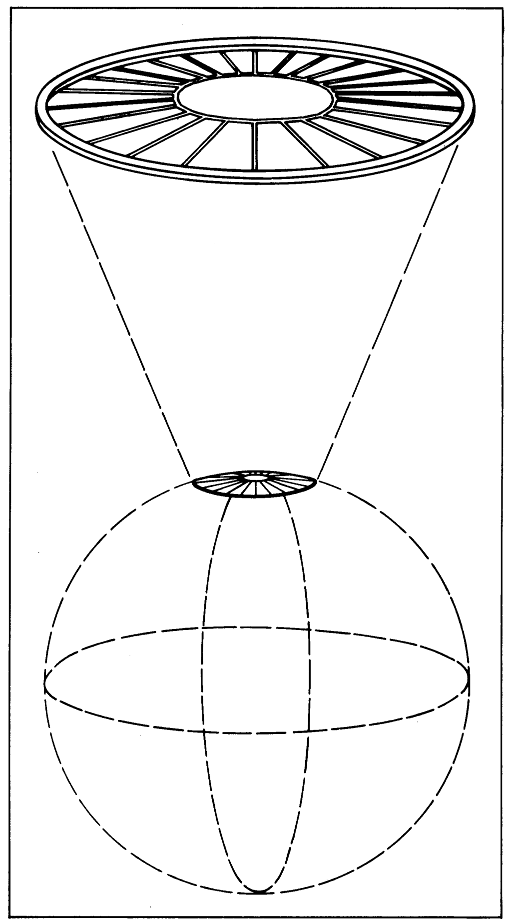


Figure 4

Figures 5 and 6—Structurally, the stainless steel membrane roof is analagous to air-supported fabric roofs and steel cable suspended roofs, both of which are in common use today. Each of the two structures are essentially in tension, and each requires a compression ring to balance the horizontal forces.

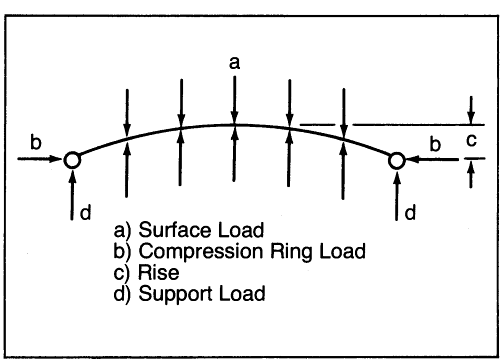


Figure 5

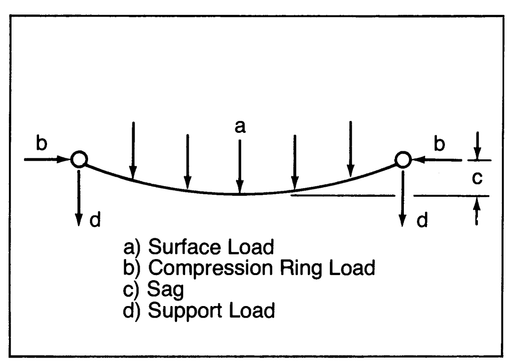


Figure 6

Figure 7

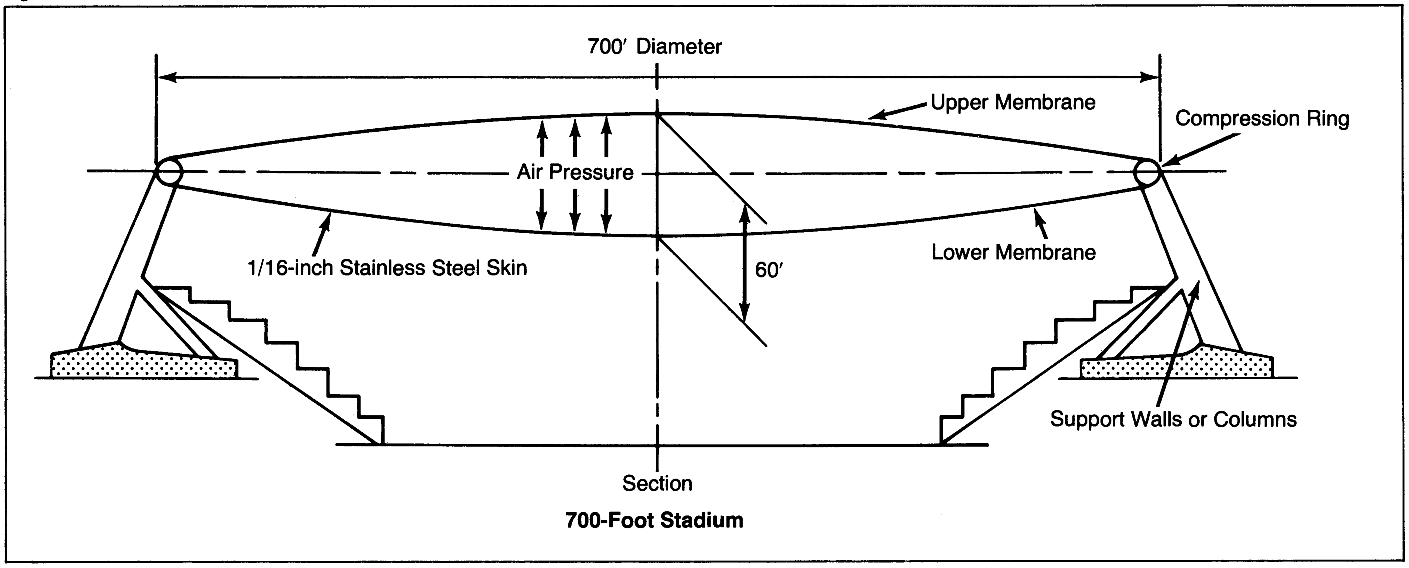


Figure 7—In the late 1960's a design study was conducted on a double-membrane structure covering a 700-foot diameter arena. The upper and lower membranes were stretched inside a compression ring and made airtight to confine air pressure —thus generating only tensile stresses similar to an inflated cushion.

Figure 8—This is a model of a membrane structure, constructed in the early 1960's to demonstrate the theory. The skin is 0.001-inch thick stainless steel. The model was used to provide an understanding of behavior under various loads (using sand) and loading conditions (point loads such as illustrated).

2.Good corrosion resistance to provide long-term durability.
3.Good toughness to resist puncturing and tearing.
4.Excellent weldability for ease of fabrication.

A chromium-nickel stainless steel was chosen as the optimum structural material because it meets all the above criteria.

Following conceptual studies, INCO initiated a design project to demonstrate the practicability of a stainless steel membrane structure. The example selected for this project was an air-inflated double-membrane roof (Figure 7) to provide a clear-span coverage of a 700-foot diameter area.

The roof design comprised an upper and lower membrane, stretched inside a circumferential compression ring. The two membranes would confine pressurized air and thus, only tension stresses would be generated. The structure became, in effect, a stainless steel air-inflated cushion.

In addition, INCO built and tested a 16-foot scale model using 0.001-inch thick stainless steel foil to verify theoretical considerations and to provide an understanding of behavior under various loads and loading conditions (Figure 8). It showed stability under all conditions. The results of the design project and model were reported by Siev and Kuentz in 1971.

In these early studies, stainless steel sheet demonstrated itself to be an ideal material for a tension membrane roof, but there were two problems to overcome before it could be practically applied to a building structure. First if the roof membrane were constructed flat, it could not assume the significant double curvature of a spherical, dome shape, because the stainless steel is not intrinsically "stretchy" enough. If it could remain flat, no problem. However, without sufficient curvature, the forces required to support the roof would be just too great for both the membrane and compression ring.

On the other hand, permanently building the membrane with the required double curvature, by cutting the sheet into pie-shaped segments and assembling the segments over a dome-shaped form, solves one problem but leads to other difficulties. Constructing a dome-shape form is difficult and impractical. Also, once the membrane was supported by air, it could not be allowed to deflate or the membrane would lose tension and fail through buckling.

Therefore, the key to a successful stainless steel membrane roof structure is the technique of making an initially flat steel membrane assume a significant spherical shape without creating unduly large stresses, at the same time assuring that tension would be maintained. Even if there is a loss of air pressure and the roof deflates from a convex to a concave shape, tension must be maintained. This feature was proven by a recent deflating of the roof at Dalhousie. The roof went from convex to concave and back to convex without any difficulty.

Figure 8

Figure 9

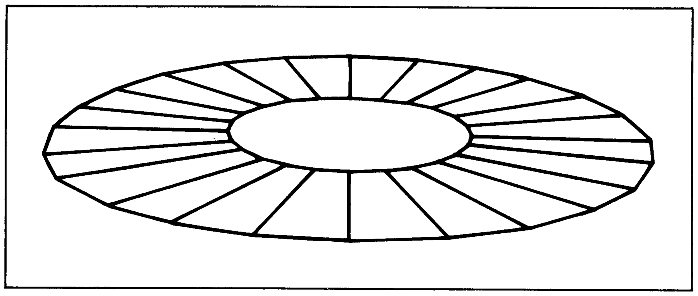
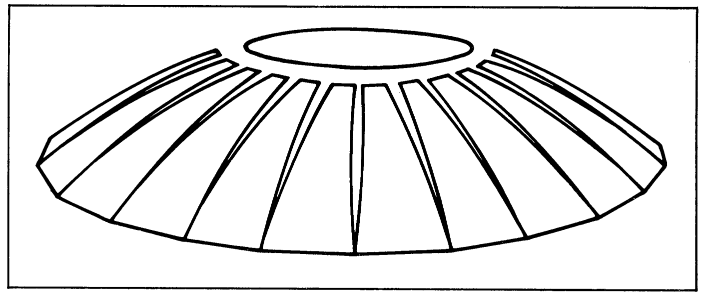


Figure 10



Figures 9 and 10—These figures help to illustrate the problem of how a metal membrane must be made to assume a double curvature. Cut into pie-shaped segments and placed on a flat surface, all pieces fit closely together, but on a spherical plane, there are spaces between segments because the spherical surface has greater area than the flat circle.

Double Curvature Solved

A Toronto consulting engineer, D.A. Sinoski, also was working on the membrane roof concept, during the late 1960's. Both the Sinoski and INCO designs had independently arrived at similar conclusions. They both came up with a membrane structure that would consist of a number of trapezoidal segments, a regular polygon for the center segment, and a peripheral compression ring. However, Mr. Sinoski solved the difficult problem of achieving double curvature in the stainless steel membrane.

Basically, the stainless steel membrane achieves the stretch necessary to assume a spherical shape by mechanical means.

To see how a metal membrane can be made to assume a significant double curvature from a flat sheet, consider a flat circular sheet of stainless steel cut up into pie-shaped segments (Figure 9). Now imagine these pieces applied to a hypothetical spherical (dome-shaped) surface with the base diameter the same as the diameter of the original sheet of steel (Figure 10).

There are spaces between the segments because the spherical surface has a greater area than the flat circle. If there are a sufficient number of segments, they need only go into very slight double curvature to be part of a spherical surface. In reality, the spaces are not large at all. For a 500-foot diameter roof with a 16.5-foot rise, dimension *a* in Figure 11 is 8.5 inches and dimension *b* is 2.25 inches.

By enlarging the spaces and bridging them with preformed spring sheet stainless steel, it is possible to make a membrane that will lie flat on the ground for construction and then stretch out to a spherical curvature when it is pushed up by air pressure or when it hangs in suspension.

When the preformed contraction joint is put into tension, it flattens out. If the tension is relieved, it springs back to its original shape. Because of the inherent stretchiness that the contraction joints impart to the membrane, the membrane can go from flat to spherical and back, and yet remain in tension at all times (Figure 12).

By prestretching the radial contraction joints in graduation from the rim inward, the increased opening required to achieve spherical curvature can be obtained. The circumferential joints around the center segment are all extended the same amount.

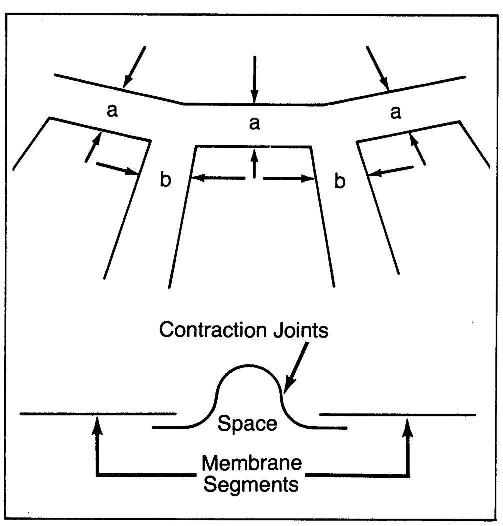


Figure 11

Figure 11—For a 500-foot diameter roof, with a 16.5-foot rise, the spaces between segments (as illustrated in Figure 10) are really quite small. Dimension a is 8.5 inches, while dimension b is 2.25 inches. By bridging the spaces with a spring contraction joint, the membrane can assume both a flat as well as a spherical shape. Tension is maintained by the contraction joints between segments.

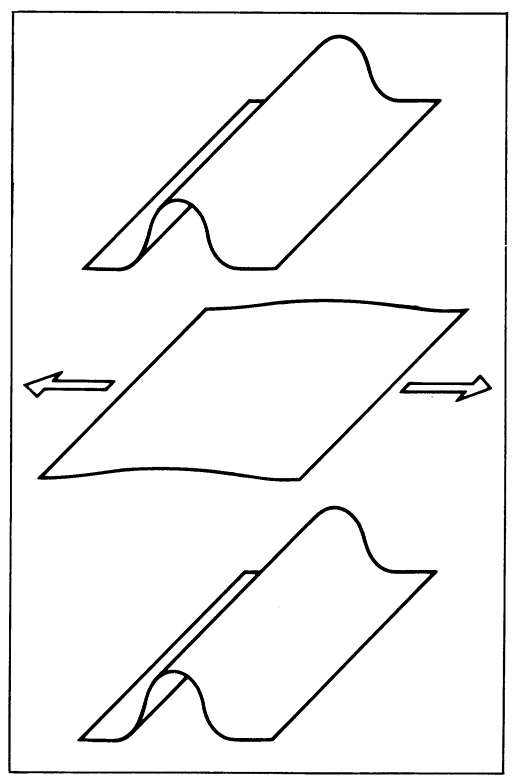


Figure 12

Figure 12—When the preformed contraction joint is put into tension, it flattens out. If the tension is relieved, it springs back to its original shape. Because of the inherent stretchiness that the contraction joints impart to the membrane, the membrane can go from flat to spherical and back, and yet remain in tension at all times.

Figure 13

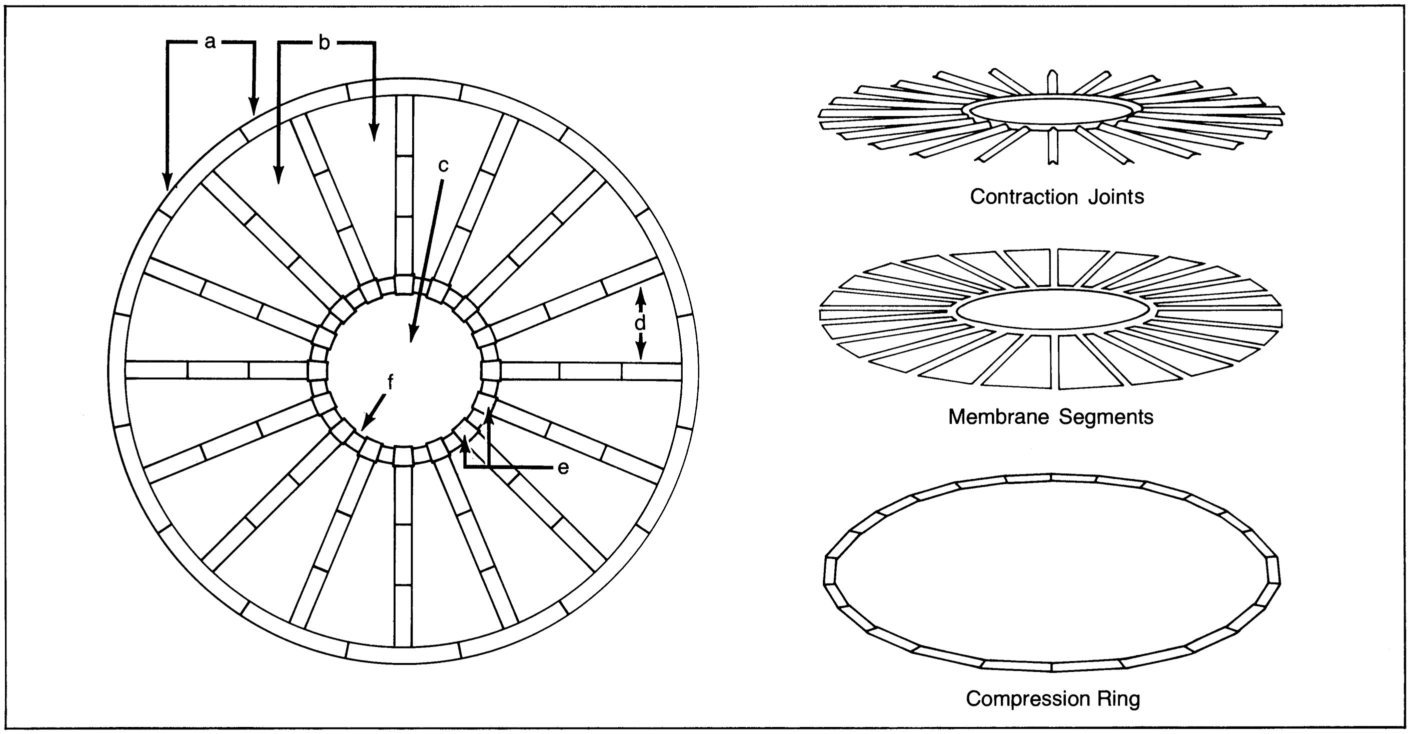


Figure 13—This shows arrangement of the compression ring (a), the pie-shaped membrane segments (b), center segments (c), radial contraction joints (d), closure joints (e), and circumferential contraction joints (f) of the air-supported stainless steel membrane concept. All major components are shop fabricated; minimum field assembly is required to join components.

Figure 14—This illustrates how 48-inch wide stainless steel sheet is cut into trapezoidal segments and joined to form a large pie-shaped segment for a membrane roof. For the Dalhousie roof, Type 304, 1/16 inch thick, was used. If the roof is round, all pie-shaped segments can be identical.

The contraction joints are the basis of the Sinoski design, for which patents are held in the United States, Canada, and several other countries. Sinoski refers to his design as a Meniscus steel membrane roof structure because of its basic shape. The essential elements of the Meniscus roof, as shown in Figure 13, consist of the membrane segments, the contraction joints, and the compression ring.

The Dalhousie Design

For the Dalhousie Sports Complex, the membrane segments are 1/16-inch thick Type 304 stainless steel with a yield strength of 37,000 psi. The steel was delivered to the fabricator in 48-inch wide coils. The coils were unrolled and cut into trapezoidal segments, which were welded together to form 24 pie-shaped segments and a center segment, as suggested by the drawing in Figure 14.

To suit the sports complex plan shape, the roof is a super ellipse. Consequently, the membrane segments are of several different shapes. If the roof were perfectly circular, then all segments would have been identical.

The contraction joints are also 1/16-inch thick Type 304, but temper rolled to a ¾-hard condition which resulted in a minimum yield strength of 135,000 psi, thus providing the necessary spring characteristics.

The compression ring was made from cast-in-place reinforced concrete, to which are attached ⅜-inch thick Type 304L anchor plates. During construction, the perimeter of the membrane was welded to this plate, thus connecting it securely to the compression ring. A second covering plate was bolted to the top thus completing the closure. The compression ring itself is actually an inverted U-shape structure, which forms the walls and roof of the running track (Figure 15).

The structural engineering of the Dalhousie Complex roof structure was handled by Carruthers & Wallace Limited, Rexdale, Ontario. The engineers conducted an incremental finite element analysis to determine stresses throughout the membrane and compression ring, they analyzed wind and snow-load conditions,

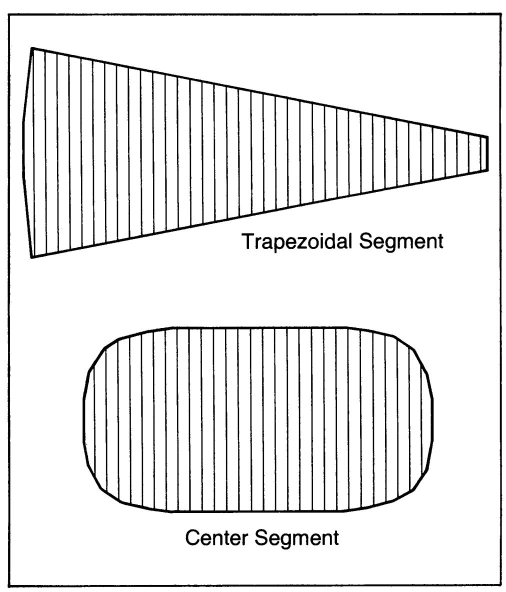


Figure 14

Figure 15

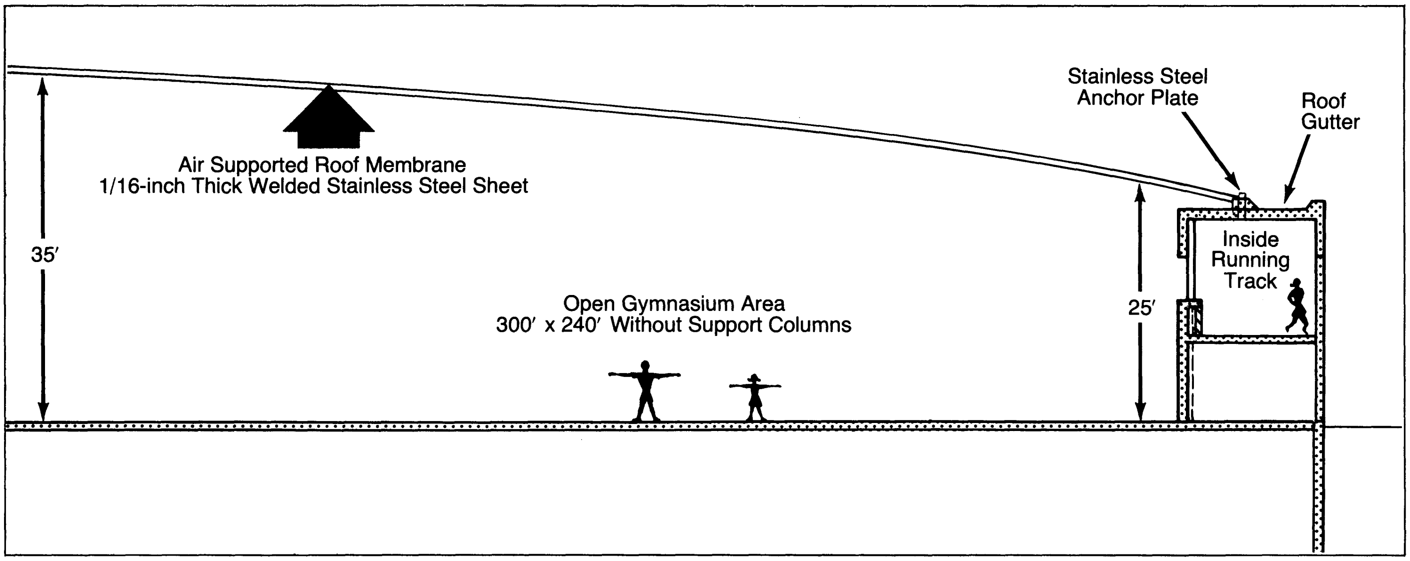


Figure 15—The compression ring is actually a cast-in-place concrete structure, which forms the walls and roof of the running track. Attached to a curb on top are ⅜-inch thick Type 304L stainless steel plates to which are attached membrane segments and contraction joints. The segments are welded to the plate, and another plate is bolted to the top.

and they conducted wind tunnel tests on a model constructed of thin plastic sheet.

In considering the snow-load conditions, an analysis of Halifax meterological statistical data suggested that the maximum snow load would be 27 pounds per square foot. In the inflated condition, air pressure could be increased in the building to support the load; however, it was feared that the increased pressure could possibly make the conventional emergency exit doors difficult to operate properly. Therefore, it was decided that provision should be made to melt snow before it accumulates. This is easily accomplished by directing air, heated to 140F, to flow between the roof membrane and the insulation suspended beneath it. Since warm, dry air was going to be slowly circulated in this manner to prevent condensation on the membrane, this seemed to be a more practical solution to snow accumulation. Should the roof deflate—that is subside to a concave position—connections are provided at the center to allow water to drain. Therefore, the design stress on the inflated roof is 2,000 psi; deflated, the stress under design snow load is 27,000 psi.

Dynamic tests were conducted at the University of Western Ontario, which has a boundary layer wind tunnel. A scale model of the sports complex was constructed, with an inflated roof of plastic film, complete with models duplicating surrounding buildings and landscape (Figure 16). The reason for this test was to insure the roof did not exhibit any instability or undesirable response to wind. Therefore, measurements were made of movement in the membrane, not stress.

The results showed that winds would cause some limited distortion of the membrane roof, but no resonance. The test suggested that during strong winds, slight movement of the roof would be discernable to people inside through slight movement of the lights.

Figure 16—Dynamic tests were conducted in a boundary layer wind tunnel on a plastic film model of the membrane roof. The model, complete with building and terrain features, showed that the magnitude of roof movements due to wind conditions would not be objectionable.

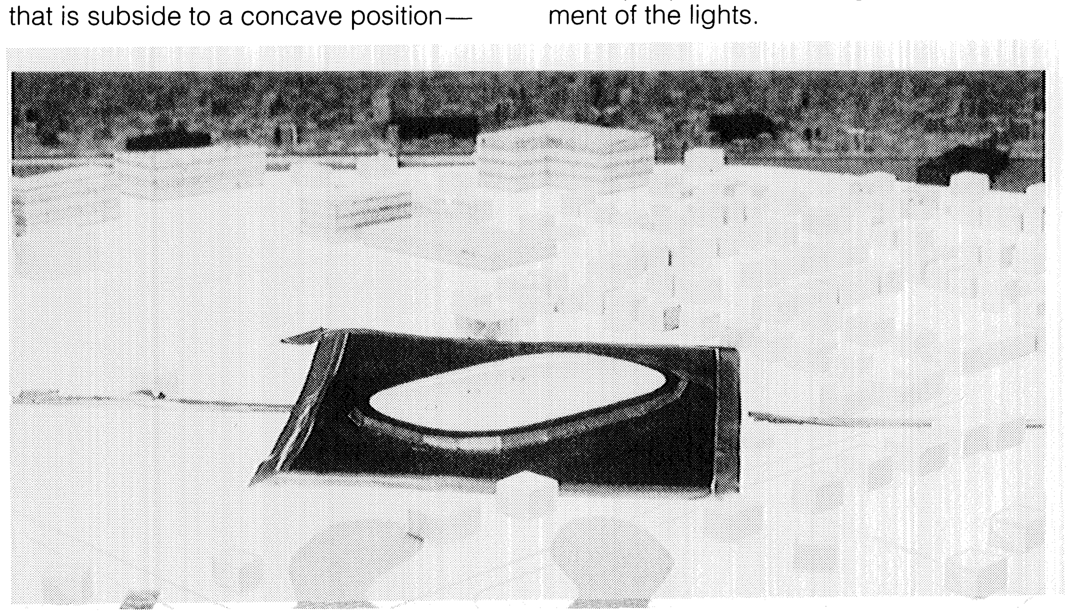


Figure 16

Figure 17—Trapezodial sheets of stainless steel were welded together to form pie-shaped membrane segments. Two sheets were first tack welded and then clamped in a long welding fixture where a lap seam weld was completed by automatic GMAW. The welds were then cleaned of weld-heat discoloration and then vacuum tested for air tightness.

Figure 17

Shop Fabrication

Blenkhorn and Sawle Limited, St. Catharines, Ontario, handled shop fabrication and field erection of the membrane roof, for which the company developed several innovative fabrication techniques.

The coiled, 48-inch wide stainless steel sheet was unrolled, flattened, and cut to trapezoidal shapes ranging in length from 3½ feet to 45 feet, which was necessary to make up the pie-shaped segments, as illustrated previously in Figure 14.

First, the longest two sheets were overlapped ½ inch and "tack" welded on 2-foot centers using a spot welding technique.

This section was then moved to a special welding fixture where it was clamped and a continuous seam weld made automatically (Figure 17). The weld was cleaned to remove heat tint discoloration and then inspected by vacuum to insure weld soundness. This procedure was followed for each successively smaller segment until the entire pie shape segment was complete.

As the sheets accumulated in the forming of each membrane segment, they were coiled onto an 8-foot diameter roll (Figure 18), consisting of several plywood discs mounted on an axle. The diameter was selected to prevent permanent coil set in the stainless steel, and each roll accommodated two to five membrane segments. Now, instead of having an impossibly large and unmanageable sheet of stainless steel to ship, each roll was a single manageable unit that fits any standard size trailer truck.

Contraction Joints

There are two basic contraction joint requirements: radial and circumferential. The radial joints fit between pie-shaped segments; circumferential joints are used between the center segment and the pie-shaped segments where they meet toward the center. All contraction joints—except those located at the perimeter—were formed into a similar shape (not unlike the Greek letter omega).

The material, as discussed earlier, was 1/16 inch Type 304 temper rolled to ¾ hardness, which resulted in a minimum yield strength of 135,000 psi. This was necessary to provide the necessary spring characteristics.

Figure 18—As sheets were joined to form membrane segments, they were coiled onto eight-foot diameter rolls consisting of several plywood discs mounted on an axle. The large diameter was selected to prevent permanent coil set in the stainless steel. These coils were easily transported by truck to the construction site.

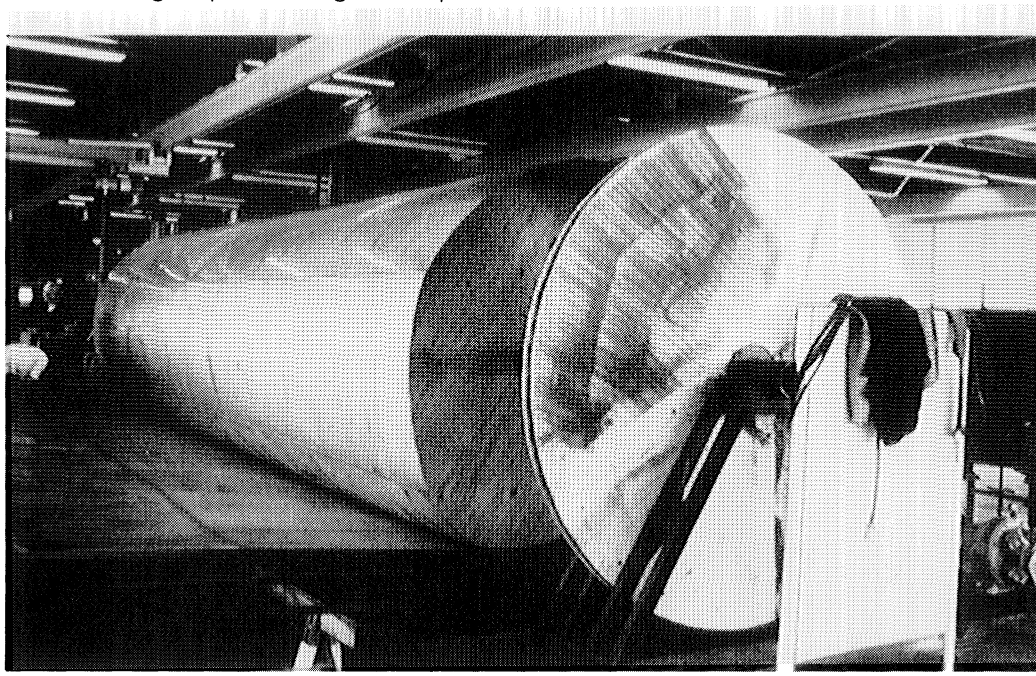


Figure 18

Figure 19—Sequence for forming flat stainless steel sheets into a U-shaped contraction joint. Because of springback in ¾-hard stainless steel, considerable overbending on the brake press was required. All joint sections, except those attached to the compression ring, were made identical. Those attached to the ring were in a graduated shape from flat to U.

Forming of the contraction joints was accomplished on a press brake equipped with a bull-nose open die, consisting of a four-inch diameter, Schedule 120 pipe for the top die and and open V of hardened steel for the bottom die. Lubricant was provided to minimize die marks.

The forming sequence is shown in Figure 19. Because of the springback characteristic of ¾-hard stainless steel, considerable over-bending was required. All joint segments were made identical except those attached to the anchor plate on the compression ring. These were made in a "graduated" shape, U-shaped at one end and flat at the other.

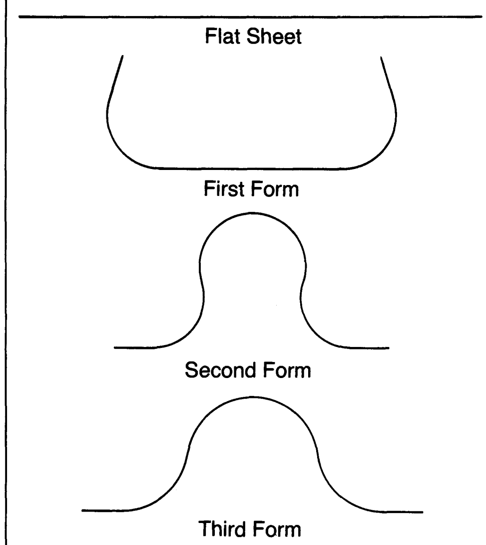
The next step in the fabrication of the contraction joints was to accurately pre-extend each one by the amount necessary to allow it to stretch into an almost flat condition as the roof assumed spherical curvature during inflation. Naturally, the joints nearest the apex would assume the greatest stretch (see Figure 10), so these were pre-extended the least. Conversely, those nearest the compression ring would stretch the least during inflation, so they were pre-extended the most. Those contraction joints attached to the compression ring itself were made differently, as explained in the previous paragraph.

Calculations of the measurements between membrane segments were made by computer, and pre-extention of the contraction joints was accomplished by hydraulic means. As each contraction joint was extended in the hydraulic unit, temporary jigs were installed to maintain the correct pre-extension until field installation was complete.

To accomplish pre-extension, Z-shaped bars were spot welded along each side of each contraction joint, as shown in Figure 20. The hydraulic extender gripped the Z bars, and expander jigs were attached after the correct distance was achieved (Figure 21). Extension tolerances were held to ± 1/32 inch. After the roof was inflated, the expander jigs were removed; the Z bars remained.

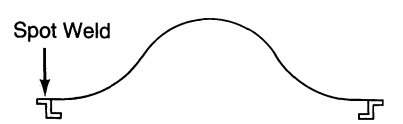
Finally, three 12-foot joint sections were manually welded together in the shop, creating a shipping length of 36 feet. This reduced field welding by two-thirds. The sections were then crated (Figure 22) for shipment by truck to the site.

Figure 19



Forming Sequence for Contraction Joints

Figures 20 and 21—To accomplish pre-extension of the contraction joints, Z-shaped bars were welded along the longitudinal edges. The hydraulic expander gripped the Z-bars, and expander jigs were attached after the joint was pulled to the correct width. Pre-extension tolerances were ± 1/32 inch. When the roof was inflated, the jigs were removed.



Z-Bar Attached to Contraction Joints

Figure 20a

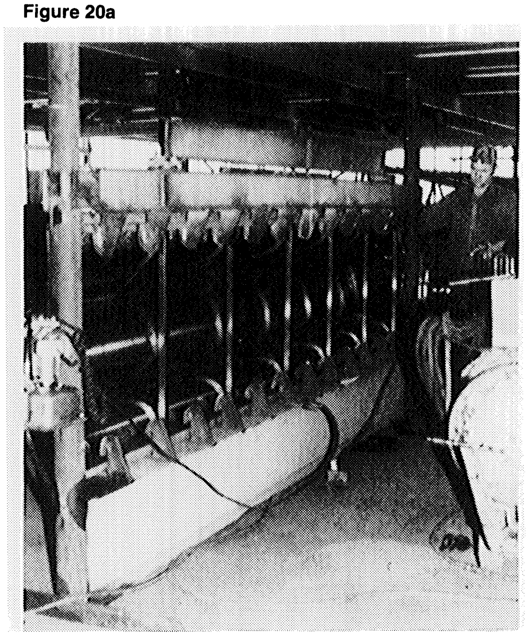


Figure 20b

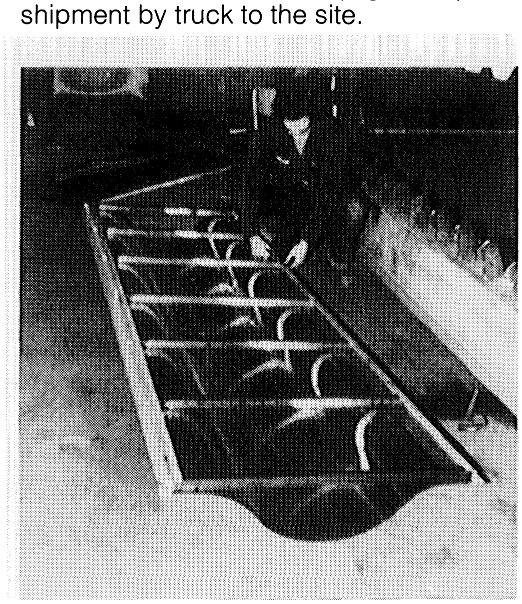


Figure 21

Figure 22

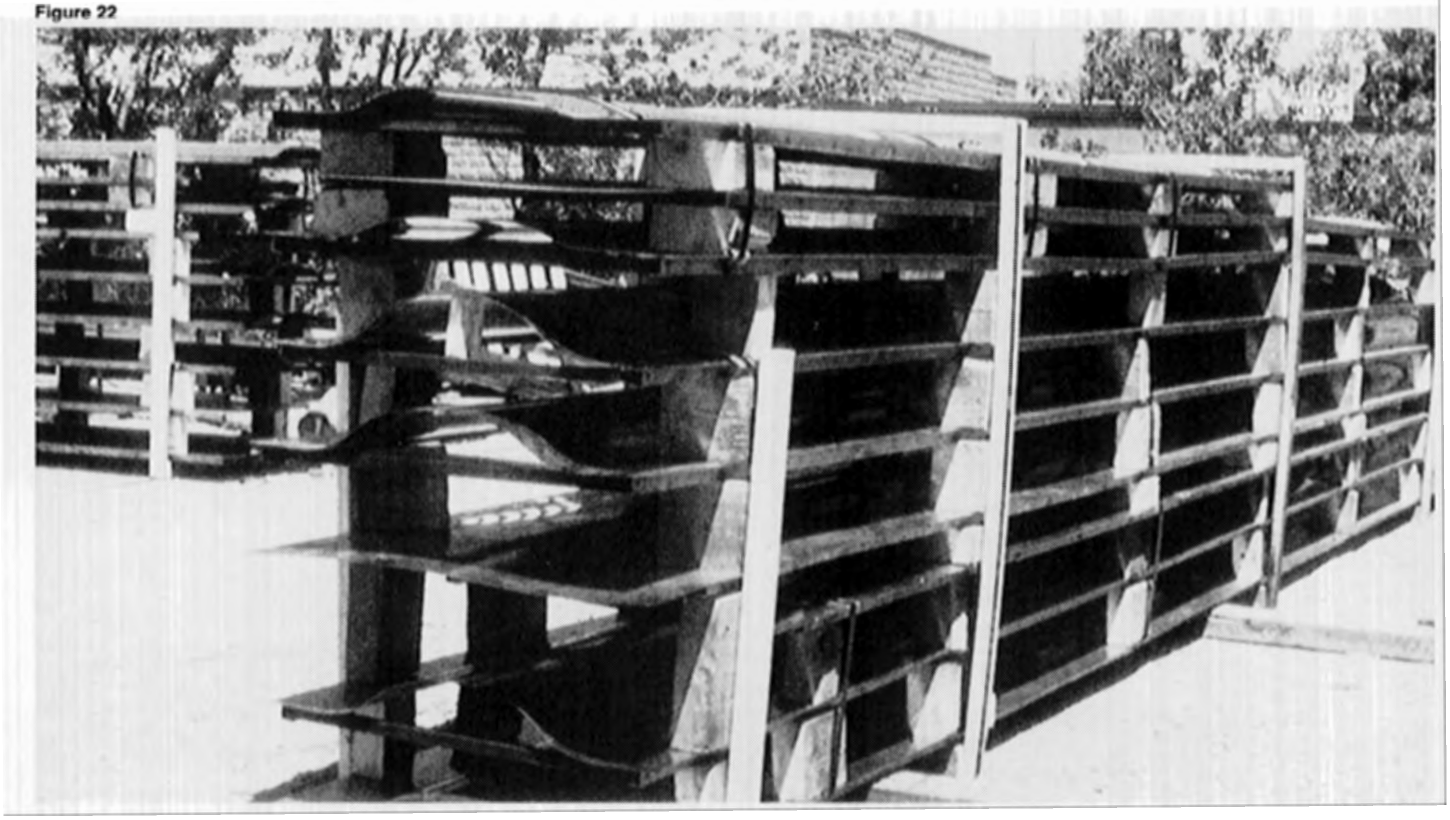


Figure 22—Three 12-foot long contraction joint sections were welded together by manual GMAW, forming 36-foot sections which were crated for shipment to the job site. Welding three sections together in the shop reduced field welding of the joints by two-thirds. The sections have different bend profiles because they were pre-extended to specific widths.

Field Erection

The first stage in the field assembly was the casting of the concrete compression ring, which caps the perimeter wall structure. It is, in fact, the roof of the running track that follows the complete building perimeter. A curb (Figure 23) forming part of the compression ring was left for completion at a later date to allow for accurate positioning of the stainless steel anchor plates.

The anchor plates have, in addition to anchor studs, leveling legs (bolts), which allowed for accurate height adjustment. Each plate was welded to the next, forming a continuous stainless steel strip to which were attached the membrane and contraction joints. When the concrete work was completed, the plate and stud combination became an integral part of the compression ring.

While the compression ring was being constructed, a temporary plywood deck was installed at anchor plate level. This was the platform on which the membrane roof was assembled and, later, from which

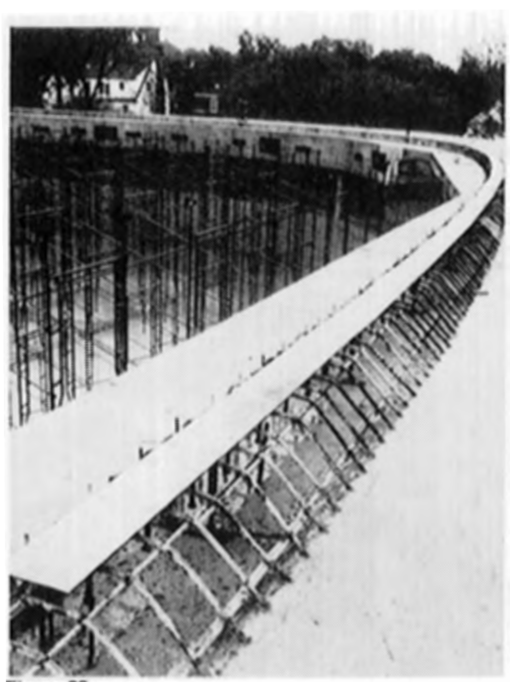


Figure 23

Figure 23—A concrete curb on top of the compression ring is where stainless steel anchor plates are attached. These plates have, in addition to anchor studs, leveling legs, which permitted accurate height adjustment. When the concrete was placed in the curb section, the plates and studs became an integral part of the compression ring.

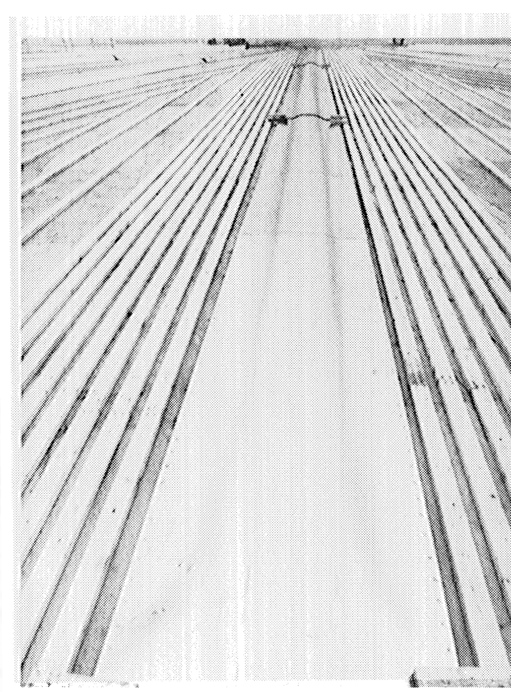


Figure 24

Figure 24—Contraction joints for the entire roof were laid out in position on a wooden, scaffold-supported deck. Wood filler strips on the deck permitted accurate positioning of contraction joints and membrane segments, which overlapped. Joints were assembled completely by manual GMAW before membrane segments were installed.

Figure 25

Figure 25—Coiled membrane segments were unrolled and positioned between contraction joint sections —much in the same manner as unrolling a paper towel. A cable winch was anchored at the center, and the pull was applied to a spreader bar, which in turn was attached to the segment. This distributed the force evenly.

the ceiling system (lights, sound, insulation) was installed. Reusable concrete formwork was used on the deck, and this, in turn, was supported by standard steel scaffolding. This deck was required only because the decision was made to build the roof at roof level rather than at ground level. If the latter method had been chosen, scaffolding might not have been required. (See page 18 for discussion of this alternate method.) However, the compression ring would have had to be of a different design to allow its being constructed and raised with the roof membrane.

The contraction joints were then installed and welded together, forming a single continuous component running from the anchor plate to the contraction joint sections around the center segment. All joints, radial as well as circumferential were positioned (Figure 24). Wood filler strips on the scaffolding deck allow for accurate positioning of the membrane segments in relation to the contraction joints, to which are attached Z bars and expander jigs.

The coiled membrane segments were then lifted in a sling and placed on supports, which were set up on the compression ring. A segment was then uncoiled —much in the same way one pulls a paper towel from a roll—and pulled onto the deck (Figure 25). The section was positioned so it overlapped the contraction joints on both sides, and then was spot welded. At this point, the overlap tolerance was rather liberal— ± 2 inches.

Then the seams were automatically lap welded, using a technique very similar to that used to join the segments in the shop. To protect the welding operation, a moveable shelter was placed over the joint being welded (Figure 26). This was necessary to prevent wind from disturbing the shielding gas, thus assuring a proper weld. Weld discoloration was then removed, and the entire seam checked by vacuum.

Finally the perimeter anchorage was completed by welding the membrane to the lower anchor plate and installing the upper anchor plate (Figure 27). All that was required at that point to turn the one-and-a-quarter acres of welded stainless steel sheet into a dome roof was to switch on the ventilating fans.

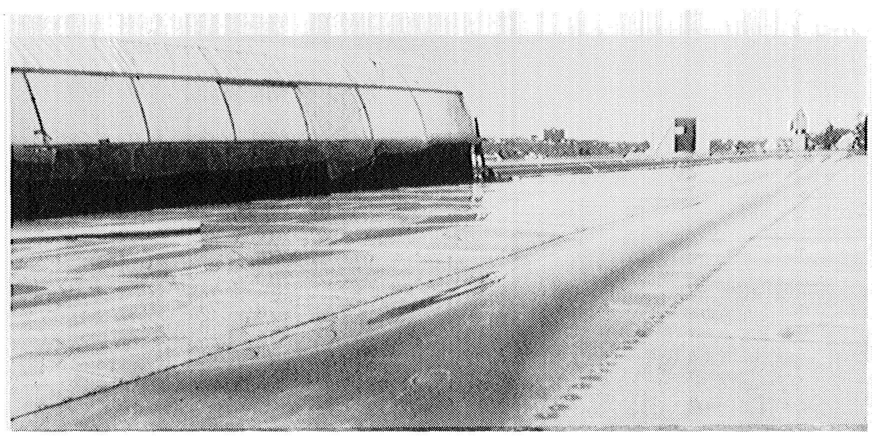


Figure 26a

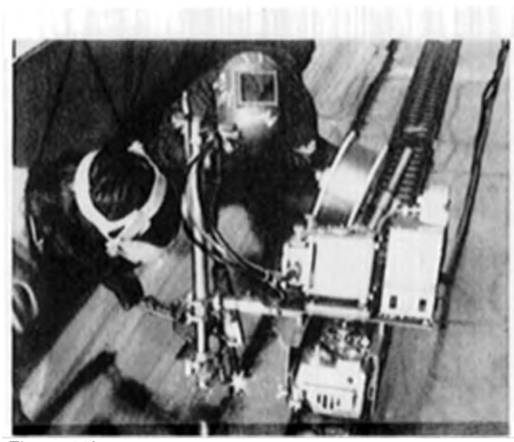


Figure 26b

Figure 26—After segments were properly positioned, GMAW tack welds were made. Following this, the seam lap weld was completed by automatic GMAW. To protect the welding operation from wind and weather, a moveable plastic tent was positioned over the weld area, and the flaps weighted with sand bags. Welds were cleaned and vacuum inspected.

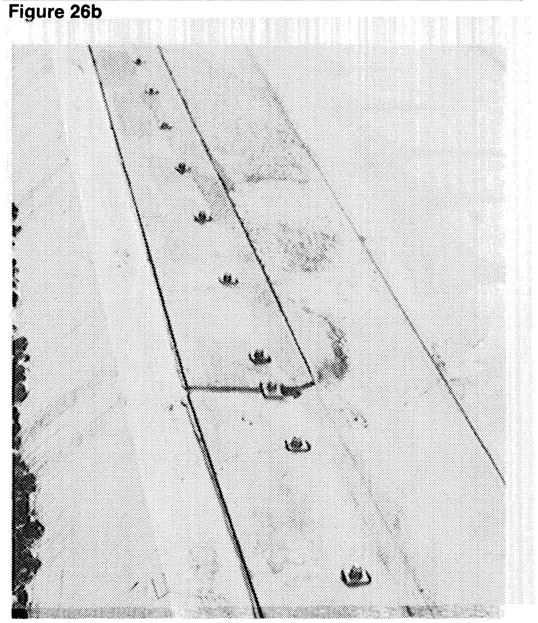


Figure 27

Figure 27—After the segments were welded to the anchor plate, another plate was bolted to the top. Plates and any part of the concrete curb or compression ring that might contact the membrane either inflated or deflated were given a rounded "bull nose" shape. Plastic sealant was inserted between membrane and top plate to prevent accumulation of dirt.

Figure 28

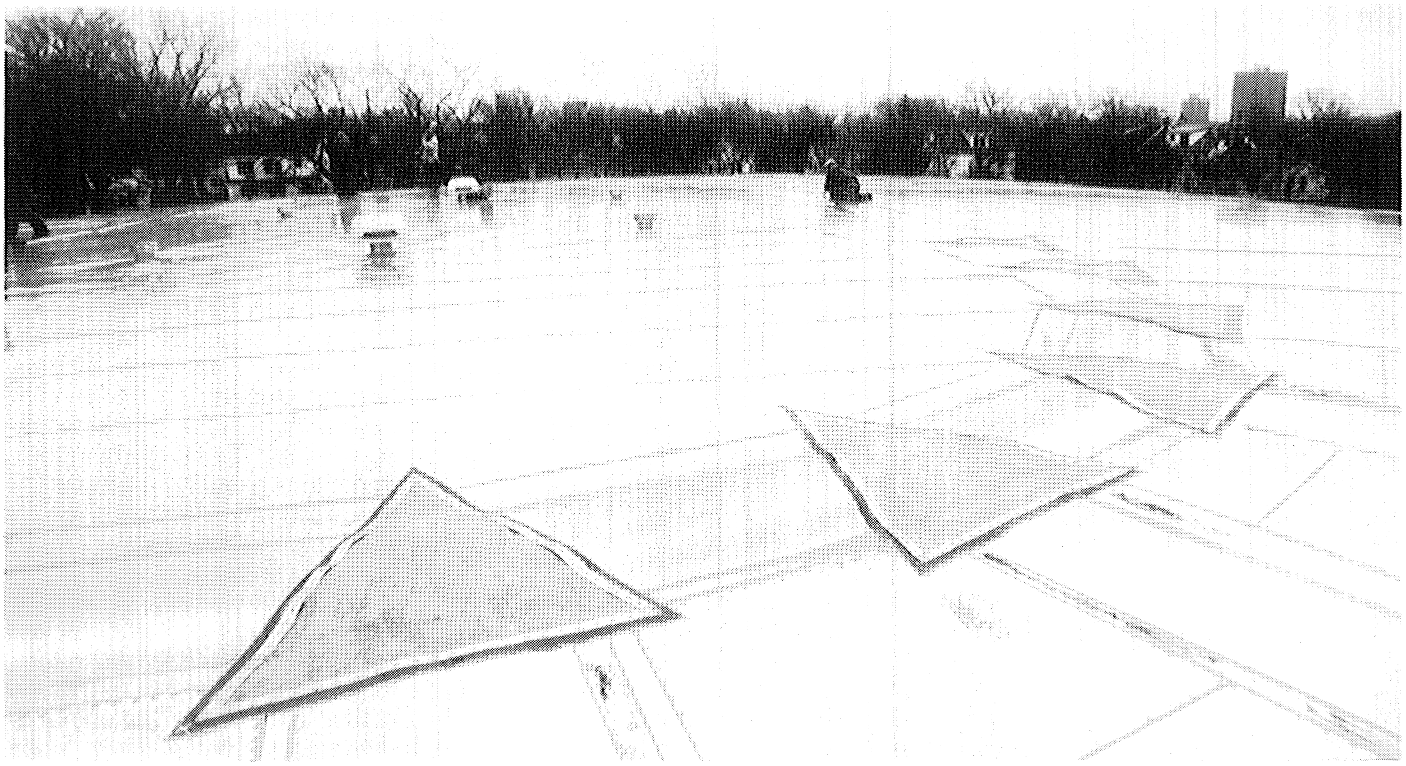


Figure 28—One part of the membrane roof not completely welded is the junction between radial and circumferential contraction joints. At these points, expansion and contraction is bi-directional, so an airtight seal was provided with a polyurethane sheet bonded to a stainless steel frame, which allowed necessary flexibility.

The Compression Ring

A circular compression ring resists the inward pull of the membrane in pure compression. Horizontal bending moment is introduced, in addition to compression, when the shape is elliptical. Discernable horizontal deflections are to be expected in such compression rings when the membrane is heavily loaded, such as by snow when deflated. Although the fitting of the compression ring to the running track at Dalhousie resulted in a ring of greater horizontal flexural stiffness than necessary, provision was made in the exterior supporting walls and the inner columns to accommodate this movement.

Fabrication Details

The tack or spot welds made during shop fabrication of the membrane sections and used to joint the membrane to contraction joints at the site, were actually one-side plug welds made with a slightly modified, crutch mounted GMAW torch. The torch nozzle was straightened, and to complete the plug welds, the operator merely carried the torch down the joint making welds at specified intervals.

Seam welds, both in the shop and at the site, were made with an automatic GMAW torch and feeder mounted on a Koike crawler. Shop travel speed was 60-65 inches per minute (250 amperes at 24-26 volts), while travel speed in the field was slowed slightly to 50 inches per minute (185 amperes at 22-23 volts). Filler metal was 0.035 inch diameter Type 308 high-silicon weld wire, which is the normal material for welding Type 304 stainless steel. All manual welding was GMAW at 100 amperes, 21-23 volts.

Shielding gas for the entire project was A-1025, a mixture of helium, oxygen, carbon dioxide, and argon. Gas flow was 35 cubic feet per hour. The gas combination was selected because it provides excellent puddle control, deep penetration, and high deposition rates. The welding was done using direct current produced by a constant voltage power source, with the electrode positive.

Welders and weld procedures were properly qualified with appropriate Canadian agencies, which included stress testing of specimen welds. Test results showed that welds on annealed sheets exceeded 83,000 psi tensile strength, and welds between annealed and hardened sheets exceeded 112,000 psi tensile.

Also, the fabricator exercised care in assuring that all joints, prior to welding, were properly cleaned and free of grease, oil or any other foreign matter that could upset weld chemistry.

There is one place on the roof where welding was not possible; that is the junction between the radial and circumferential contraction joints. At this point, movement of the joint during inflation was in two directions. This area, therefore, was sealed with a polyurethane sheet bonded to a stainless steel frame, which allowed bi-directional movement (Figure 28).

Mechanical Requirements

The 0.05 psi air pressure required to maintain the dome shape of the roof is provided by a fairly standard system of ventilating fans and ducts. One fan with a 75 horsepower motor capable of delivering air at 35,000 cubic feet per minute, but operating only at approximately 60 percent of capacity, is required to maintain pressure. However, three fans were installed—two as backup units—along with an emergency diesel engine power source. Air delivered to the building can be heated to 140F (if needed for snow melting) by steam from the university's central power plant.

In the event that all systems fail for an extended period, the roof merely deflates to a suspended (concave) position without damage. This situation would not present any hazard to occupants.

Only the field house is pressurized, the other two lower floors are not. Connecting doors are of a revolving type to minimize pressure loss. Emergency exit doors are provided, which are not normally opened. A fire sprinkler system was installed around the perimeter of the field house.

Stainless steel bolts, stud welded to the stainless steel membrane, support lights, sound system, and insulation. A standard insulation grid is suspended 12 inches below the membrane (Figure 29). The radius of the dome is shallow enough for the long grid members to bend, following the same curvature as the dome itself. The grid retains insulation, which performs thermal as well as accoustical functions. A constant dry air stream is passed through the space between the insulation and membrane to minimize condensation.

A Nelson stored-arc stud welder was used to fasten studs to the membrane. By limiting the input energy with this equipment, no heat tint appeared on the upper surface, nor was there any indication on the surface to suggest the presence of studs. Two types of studs were used; 3/16-inch diameter studs with flattened and pierced ends hold the ceiling components, while 1/4-inch diameter threaded studs were used to support utilities.

Mechanical engineering design and supervision were provided by Chebucto Engineering Ltd., Halifax, Nova Scotia.

Benefits

Durability—The all-welded stainless steel membrane offers a permanence and durability not hitherto available in air-supported roofing systems. Stainless steel's longevity has been well established on roofs, such as the 50-year old Chrysler Building in New York City. No deterioration has been detected on this building.

Structural Efficiency—The less material required to build a structure, the more efficient the structural principle. Only 1/16 inch stainless steel weighing approximately 2.62 pounds per square foot is required for the membrane.

Safe—The stainless steel membrane roof shows no loss of structural integrity in the highly unlikely event that disaster strikes by knocking out all electricity and standby systems. The roof simply reverts to a suspended-type roof that will continue to support its full design load indefinitely.

The transition from convex to concave profile would occur in a smooth, gradual

Figure 29—A standard insulation grid is suspended 12 inches below the membrane. The radius of the dome is shallow enough for the long grid members to bend, following the same curvature as the dome itself. The insulation performs both thermal and accoustical functions. Dry air between membrane and insulation prevents condensation.

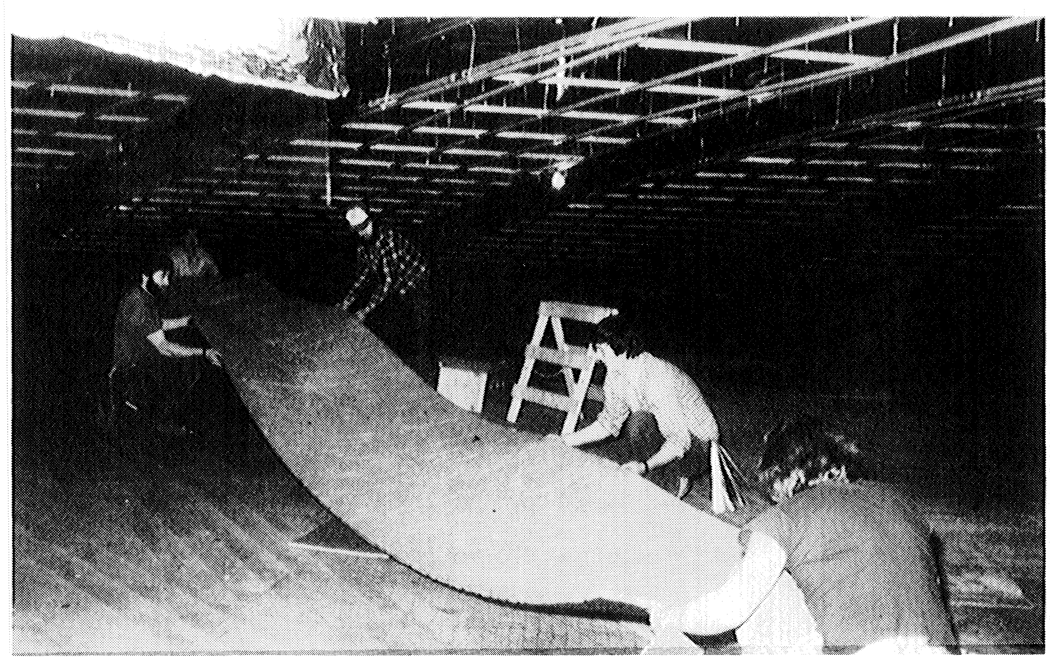


Figure 29

Figure 30

Figure 30—Safety is one of the important features of the air-supported stainless steel membrane roof. Since the roof is always in tension, it can at no time go into compression and buckle —there would not be a progressive collapse from local failure of a member. The roof is also quite safe for people to walk on.

process cushioned by air. With restoration of air pressure, the roof membrane would reinflate to its original dome profile. Since it is always in tension, it can at no time go into compression and buckle—there would not be a progressive collapse from local failure of a member.

Stainless steel membrane roofs are inherently safer in this regard than any other wide-span type of structure that could be built. This is because there are no discrete elements to a membrane. Local failure of the membrane to carry load would only cause redistribution of stresses. It could not cause progressive collapse.

Another reason that a ductile membrane is so safe is that it will stretch if overloaded. Type 304 stainless steel work hardens when it stretches and becomes stronger. The radius of curvature of a membrane also decreases if the membrane stretches, thus increasing the resistance of the membrane to the imposed load.

In addition to these safety factors, the stainless steel membrane has better fire resistance than conventional roof structures. Because the membrane is a tension member, it cannot fail by buckling when it gets hot. Steels are nonflammable and stainless steel has sufficient tensile strength at temperatures up to 1200F to support itself without exceeding yield. It is also safe for people to walk on the roof as shown in Figure 30.

Labor Efficient—For buildings this size and larger, the cost of the stainless steel membrane roof is substantially lower than that of any kind of conventional long-span roof structure. Efficient labor utilization is the reason.

The main items involved in the fabrication of the roof membrane are shearing, forming and welding. All of this work, except for about 30 percent of the welding, is performed in the shop. Even the on-site welding is automatic, conducted in near shop-like conditions.

Low Capital Cost—The high degree of structural and labor efficiency previously described are the main contributors to cost savings. In addition, no special abuttments are required, and the extreme light weight of the membrane reduces foundation costs. Also, no separate water proofing membranes, such as tar and gravel, are required.

Speed of fabrication and erection at the site are capital cost considerations in that the membrane roof will probably take less time and allow earlier building occupancy. Also, it is possible to construct the roof on the ground adjacent to the building and then be lifted into place. (See page 18 for further discussion of alternate construction methods.) This will permit the simultaneous construction of walls and roof.

The curves in Figure 31 give at a glance a generalized picture of the cost of various types of roof structure. The curves compare relative average costs, which, of course, fluctuate according to location, labor rates, inflation, and field conditions. Also, the curves represent the roof structure *and* decking and roofing.

Minimum Maintenance Costs—Other favorable comparisons can be made with respect to ongoing maintenance requirements. Rigid roofs require leak-prone expansion joints. Builtup roofs are subject to mechanical damage, bubbling, cracking, and other leak-causing problems. They all require periodic repair and many will require complete replacement.

In contrast, the all-welded stainless steel membrane is leak-proof and maintenance-free. Thermal expansion and contraction result in only slight changes in the radius of curvature. No joints or builtup roofing are required, and stainless steel's durability is a well-proven fact.

Energy Efficient—The energy requirement to keep the roof inflated is very minimal. Only 0.05 psi air pressure is required, which is easily provided by a normal ventilation system.

Materials requiring a large energy input in their production, such as tar and felt, large tonnages of structural steel or synthetic fabrics are replaced by a single sheet of stainless steel, which uses recycled scrap as its basic ingredient.

Also, its minimal enclosed volume, due to the low rise of the dome, reduces the heating and cooling load on the building. Thermal and accoustical insulation is hung directly from the roof membrane. The designer, however, has to consider the need to pressurize the building, which requires special attention to doors and windows.

Additional Features

One might reason that one of the features of an ideal roof is translucency to take advantage of natural daylight. A plexiglass dome or a central translucent fabric can be mounted in a stainless steel roof but only at some sacrifice of permanence, durability and thermal insulation. No translucent materials have durability comparable to stainless steel.

Figure 31—
(a) Column and joist
(b) Space frame
(c) Suspended cable (bicycle wheel)
(d) Structural dome
(e) Concrete dome
(f) Air-supported fabric
(g) Double membrane, stainless steel
(h) Single membrane, stainless steel

Note:

The average cost figures on which these curves were based include roof structure, decking, and roofing materials.

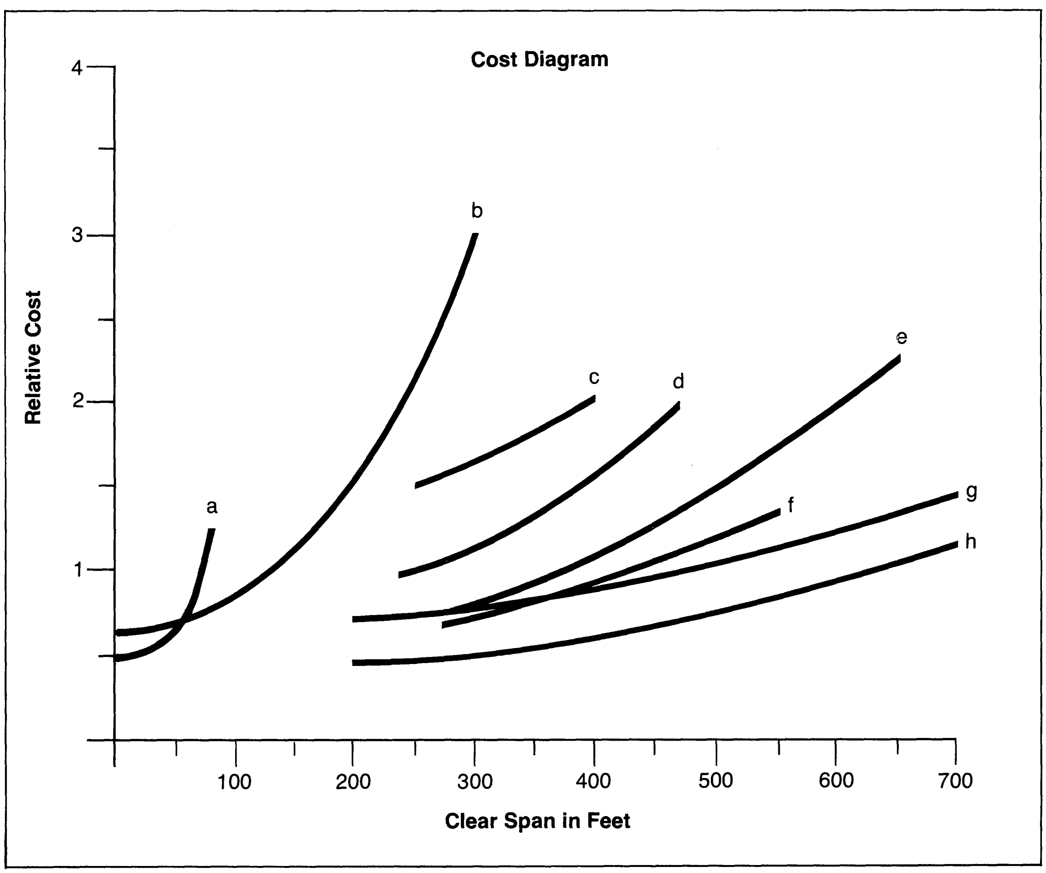


Figure 31

Alternate Construction Methods and Applications

An interesting application for the stainless steel membrane concept is floating covers for liquid storage tanks. For this application the design is essentially the same as the air-supported roof, consisting of a membrane and compression ring. For a floating cover, however, the membrane remains flat with buoyancy provided by the compression ring, which is a series of pipe pontoons.

The advantages of the stainless steel floating covers are corrosion resistance, good buoyancy, fire resistance, and they can be constructed inside existing tanks.

In addition, the membrane roof can be used for water reservoirs, gas holders, sewage plant digesters or clarifiers, warehouses, airport passenger terminals, airport hangars, cold-storage buildings, stadiums and sports arenas. If it is not practical to pressurize the building, a pressurized double membrane system can be used, following the early INCO concept, as illustrated in Figure 7, page 6.

Figures 32 and 33—Alternate methods for constructing and erecting roof.

Alternate Erection Methods

The Dalhousie installation described on previous pages required a scaffolding to be erected to the level of the compression ring, on which were assembled the membrane roof segments. There are other methods, however, which can eliminate the need for a scaffolding and attendant costs. Small membrane roofs or covers, such as for tanks, can be constructed adjacent to the job and then lifted into position with one or two cranes, Figure 32. For large roofs, such as for a sports arena, the membrane can be constructed at ground level and then jacked to final elevation. The supports for the compression ring can be

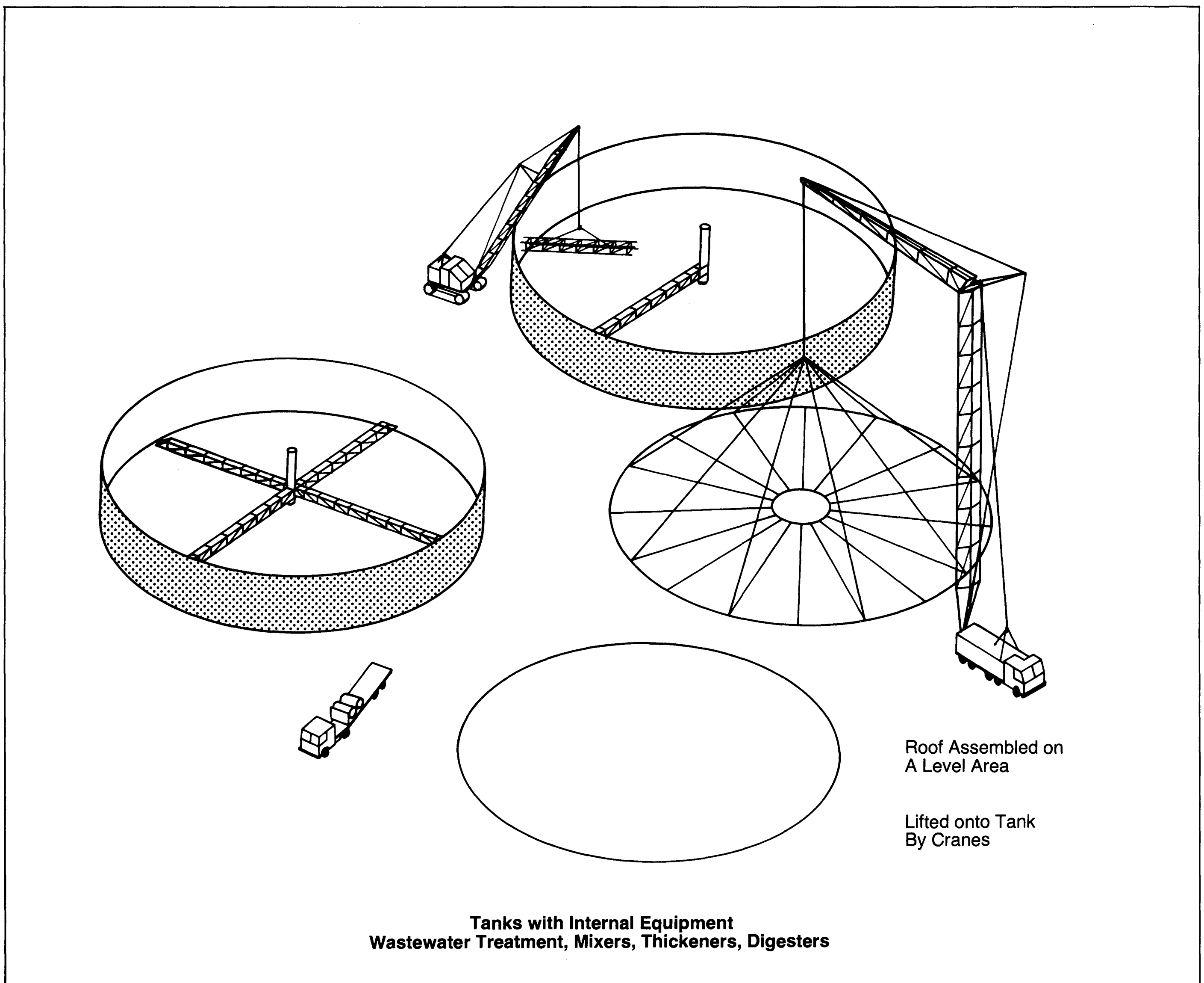


Figure 32

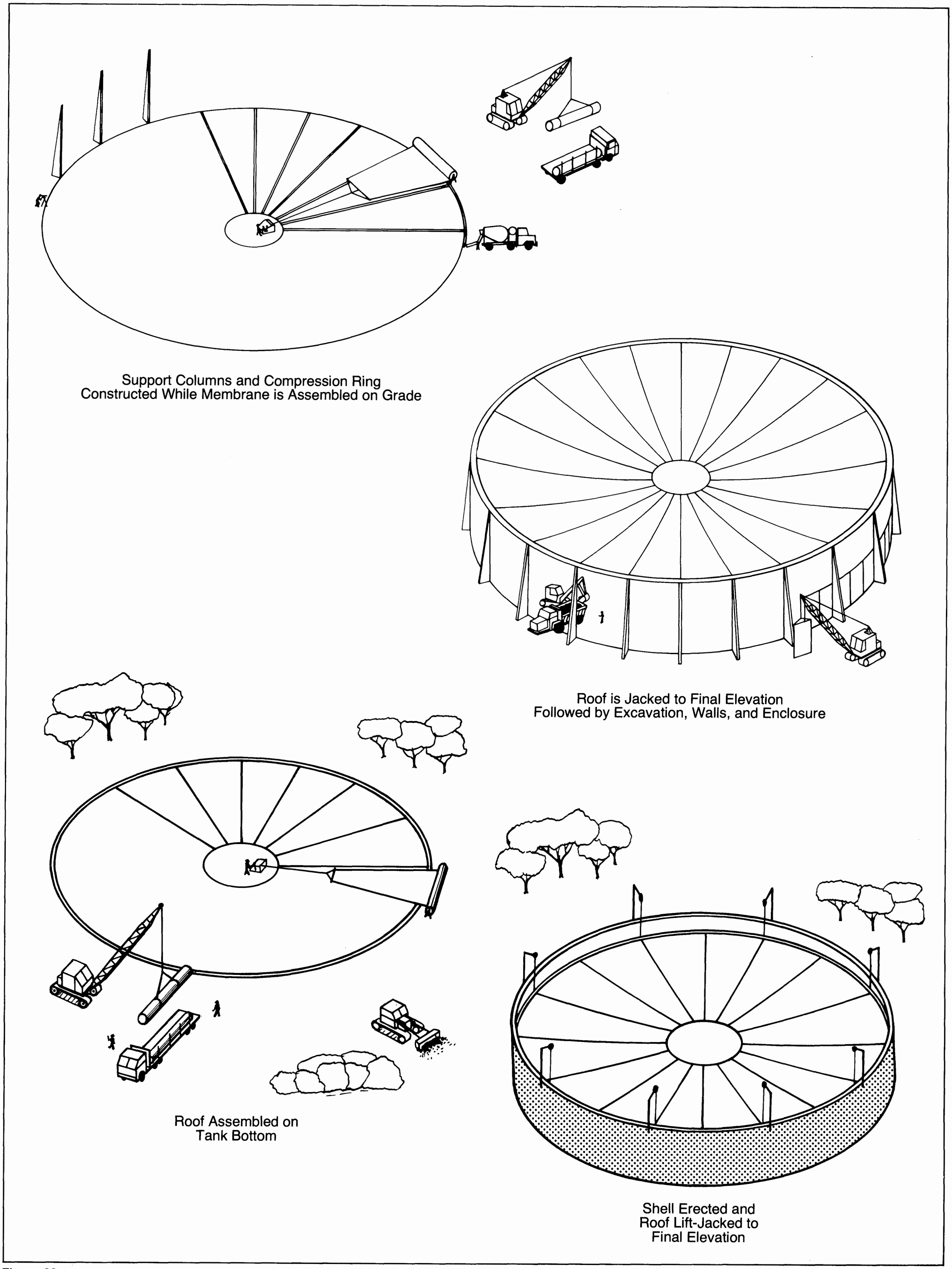

Support Columns and Compression Ring
Constructed While Membrane is Assembled on Grade
Roof is Jacked to Final Elevation
Followed by Excavation, Walls, and Enclosure
Roof Assembled on
Tank Bottom
Shell Erected and
Roof Lift-Jacked to
Final Elevation

Figure 33

slip-formed in concrete (Figure 33) as the roof is being fabricated.

For example, a proposal was made for a 700-foot diameter air-supported membrane roof for a stadium in Canada, the details of which are shown in Figures 34 and 35. The proposal presents two alternate schemes. Scheme I suggests that only the perimeter service towers and roof be constructed first, followed by construction of seating and field facilities, which could be constructed under the roof (Figure 34). In Scheme II, the entire perimeter construction, including seating, would be built prior to lifting the compression ring and membrane. This would require that the diameter of the roof be reduced to about 500 feet, which allows the roof to clear the seating. Support would be provided by cantilever beams extending from the towers, inwards over the seating (Figure 35).

Scheme I appears to offer the most advantages: least cost, greatest flexibility to the architect, protected environment for most of the construction, and short lead time.

Figure 34—Scheme I for erecting 700-foot diameter roof over a stadium in Canada. In this method, perimeter service towers and roof are constructed first. Roof is jacked into position and weighted with ballast. Balance of construction can then be completed under protection.

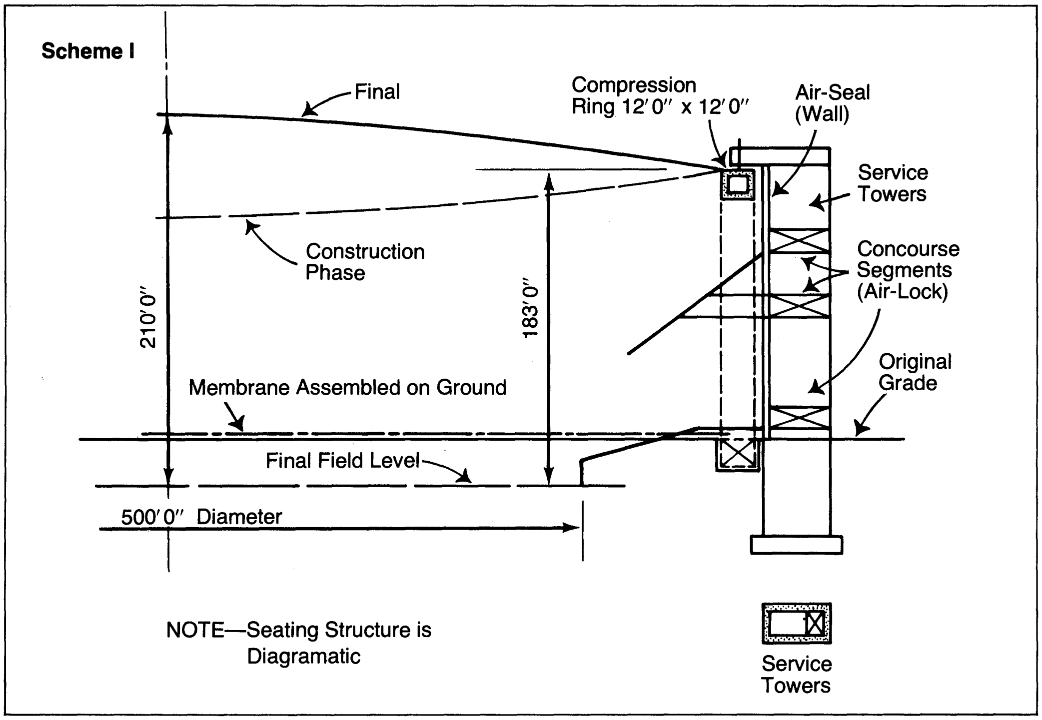


Figure 34

Figure 35—Scheme II for Canadian stadium in which the entire perimeter construction, including seating, would be built prior to lifting the roof membrane and compression ring. Support would be provided by cantilever beams extending from towers, inwards, over the seating.

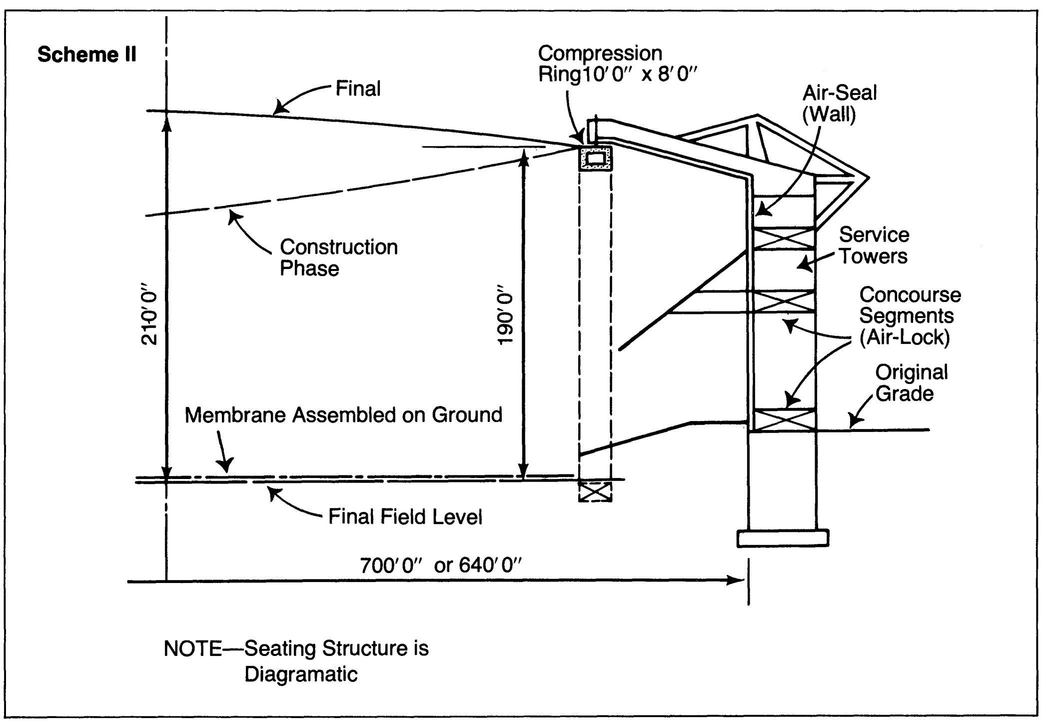
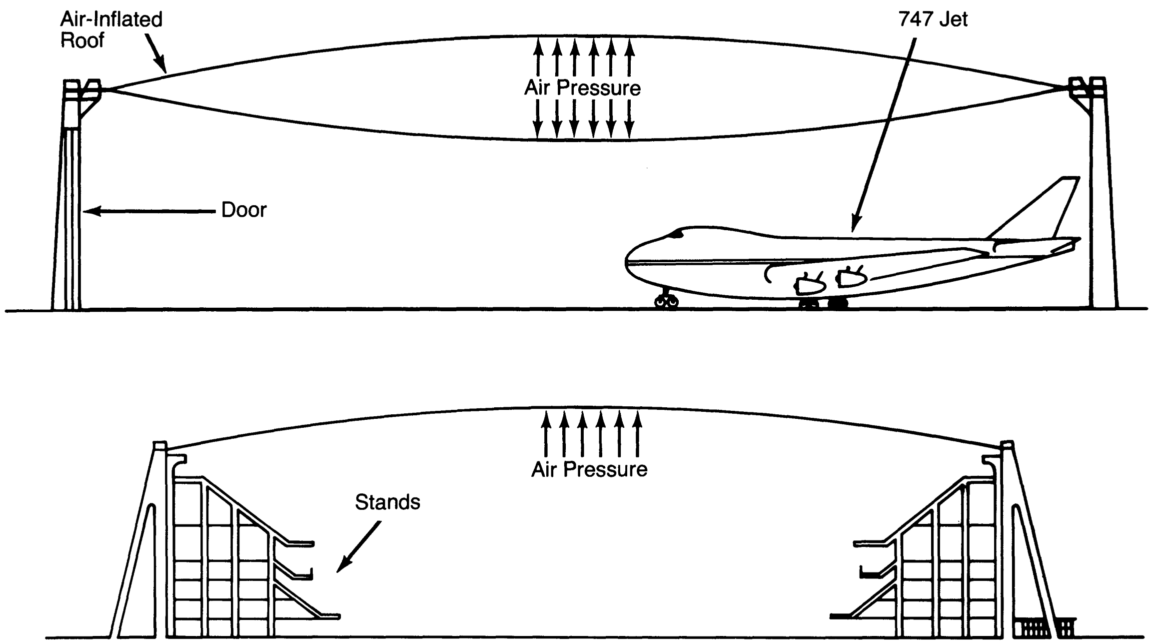


Figure 35

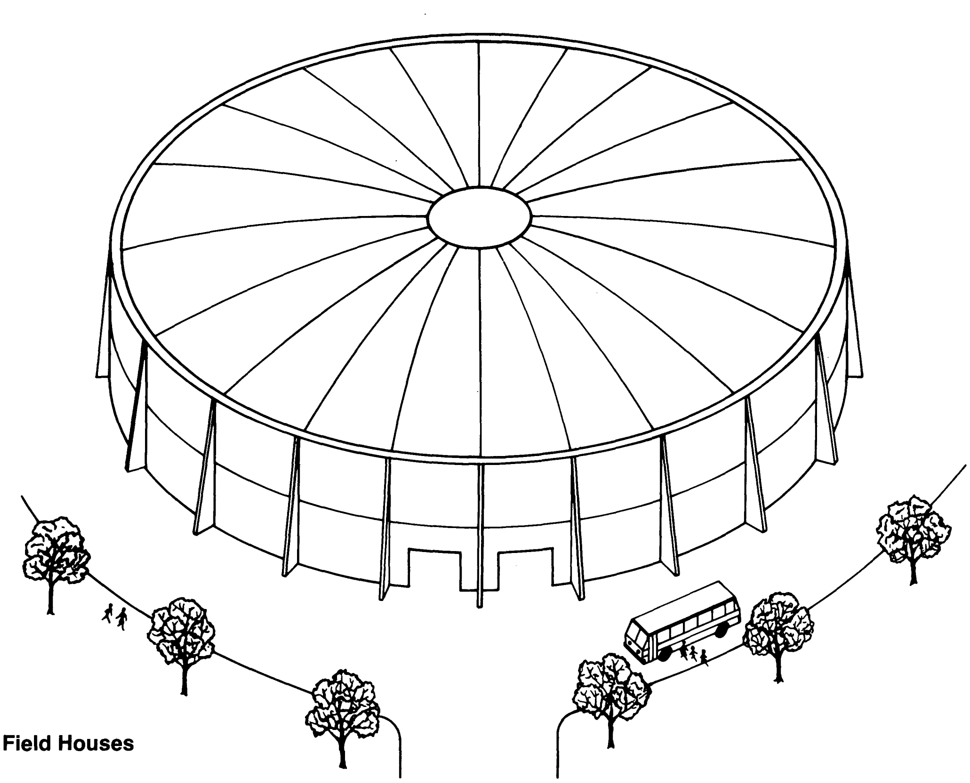
Summary

The stainless steel air-supported membrane roof offers an optimum design with a combination of advantages not available with other roof systems. These advantages are:

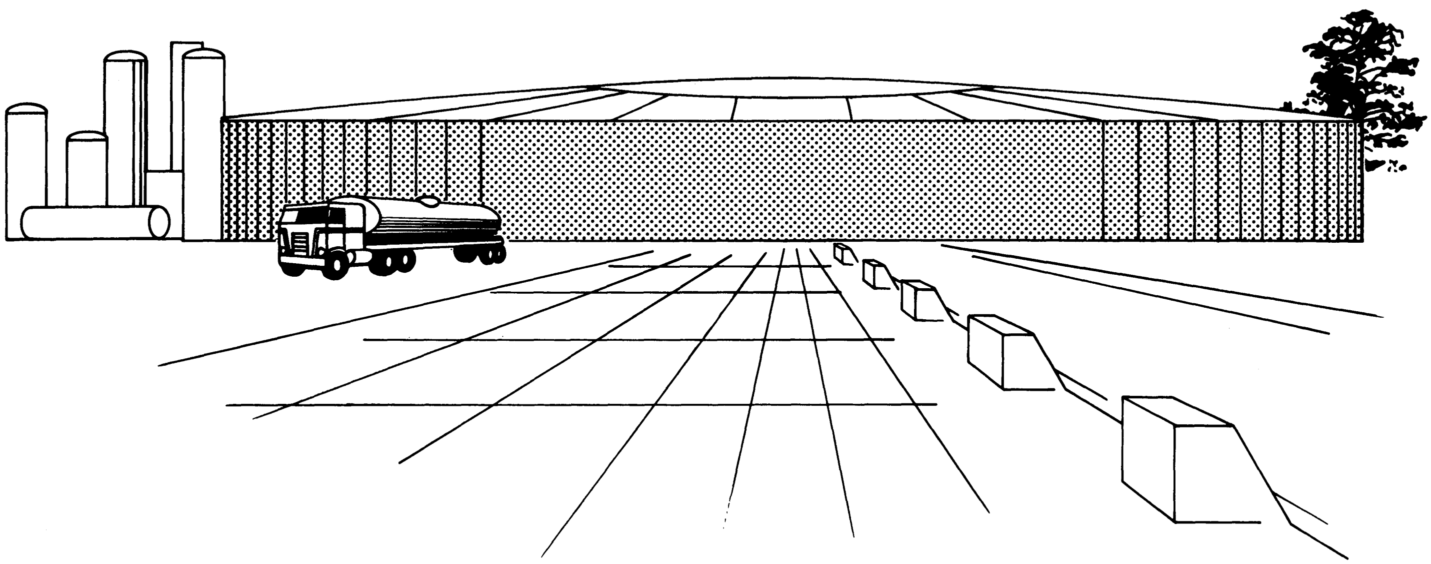
- Clear span
- Large area coverage
- Maintenance-free
- Low cost
- Fast erection
- Ground level construction
- Adaptable to existing structures
- Safe
- Efficient
- Aesthetically pleasing
- Low profile
- Leak-proof
- Adaptable to many different shapes



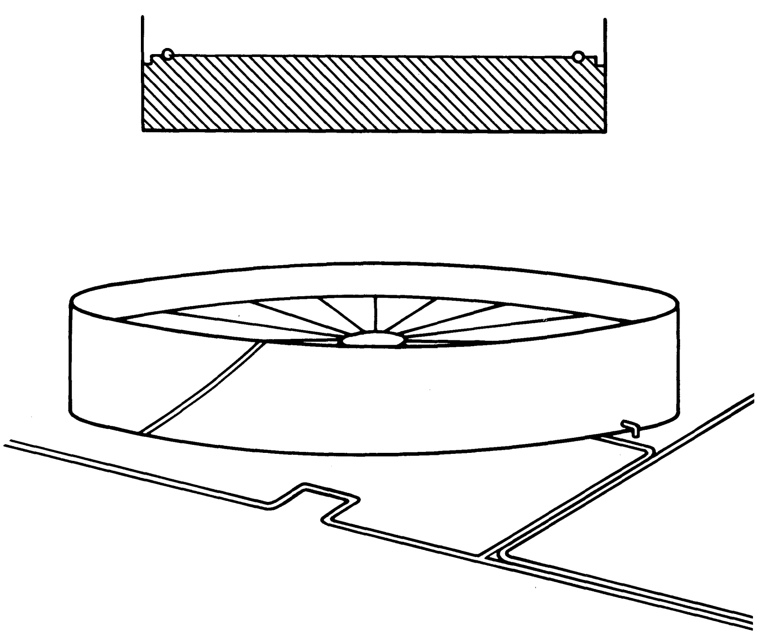
Alternate Methods for Pressurized Membrane Roof



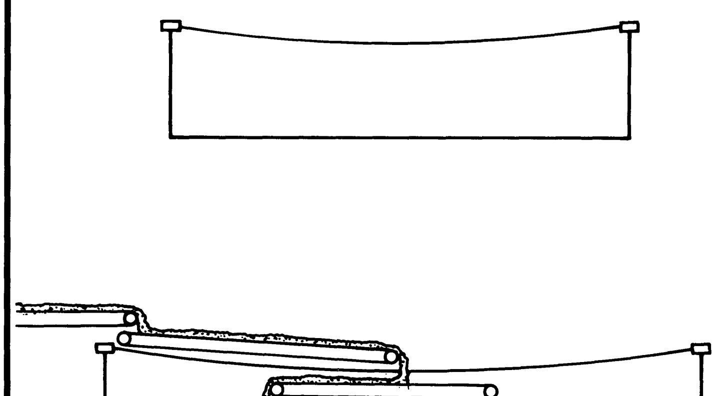
Stadiums, Arenas, Field Houses



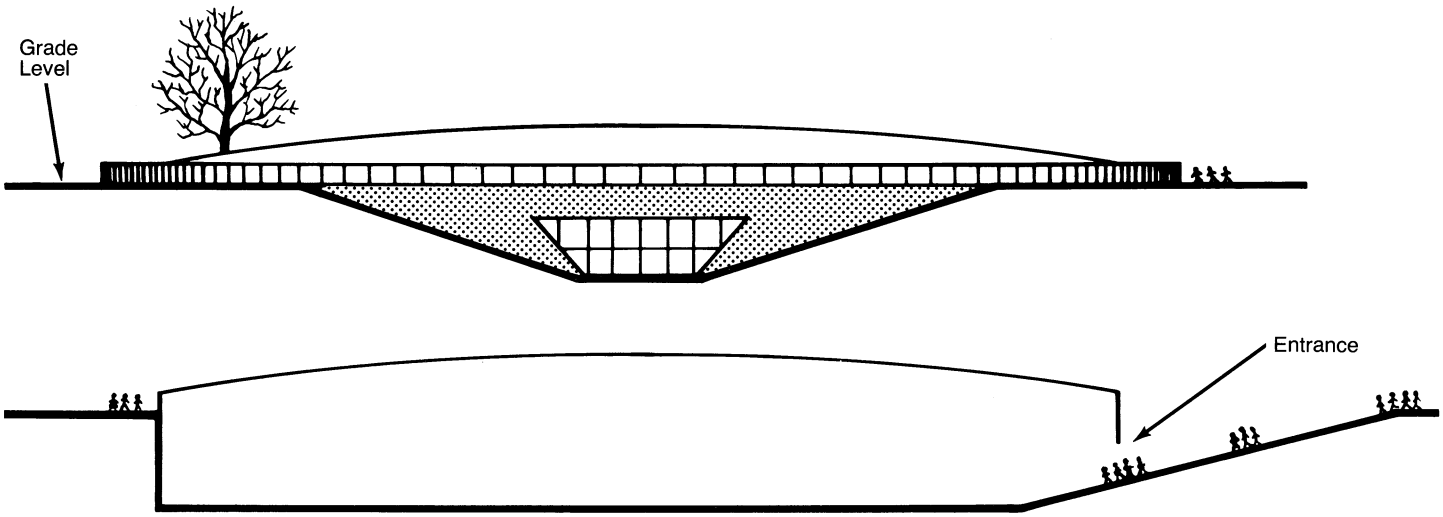
Large Vertical Storage Tanks
For Oil, Water, Chemicals



Storage Tanks with Floating Membrane Cover

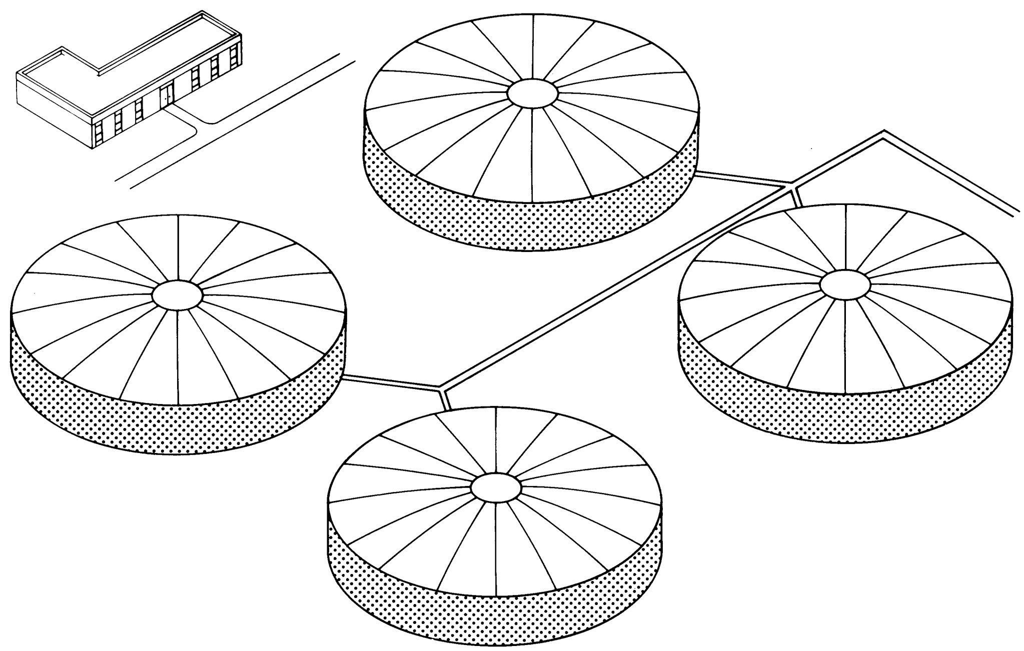


Storage Buildings with Suspended Membrane Roof

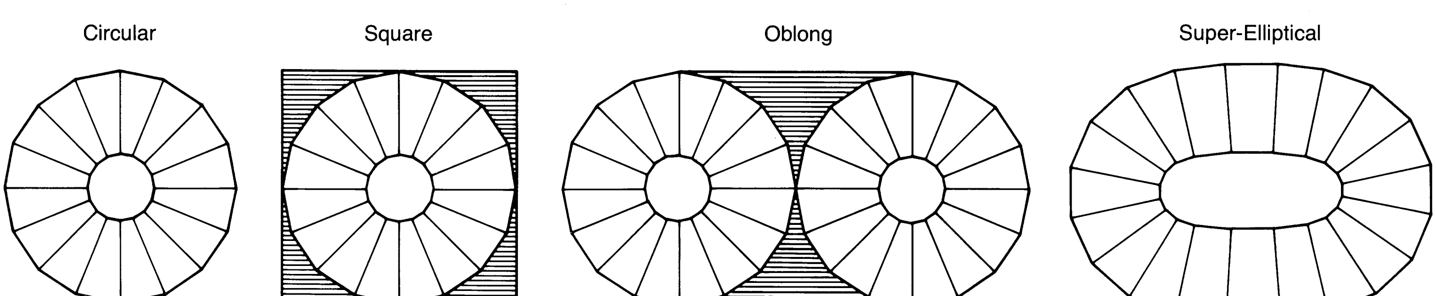


Below Grade Building

The building is below grade. The meniscus stainless steel roof is featured architecturally. A moat or fence is used to keep people off the roof.



Sewage Plant Digesters



Various Roof Configurations