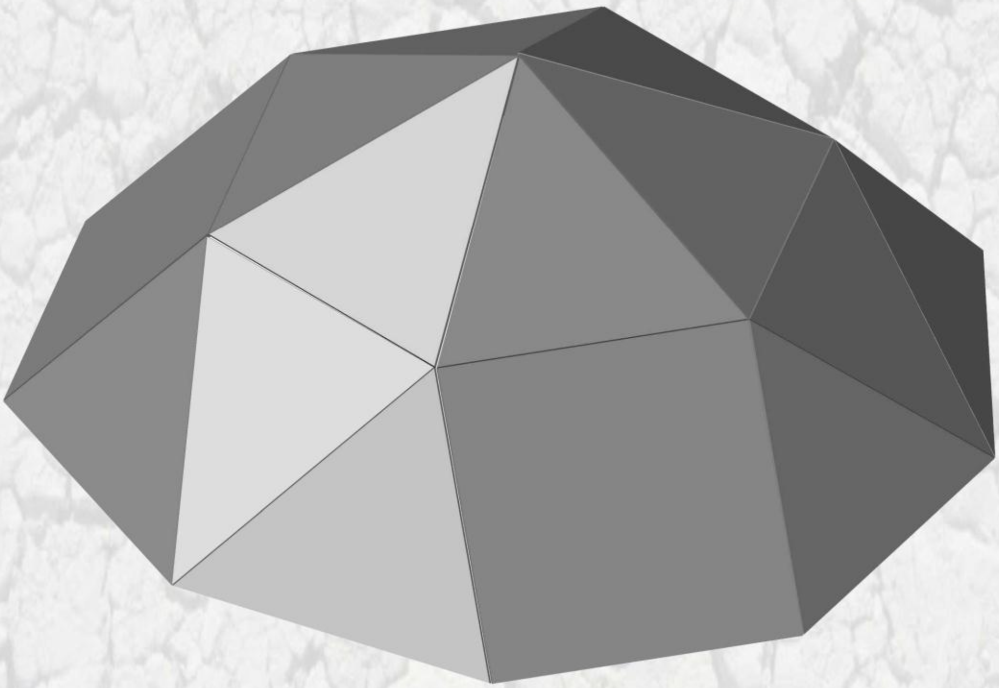
The Analysis and Construction of a Nearodesic Tri-Dome



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Written for
The Alberta Regional Burning Man Community

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Executive Summary

This report analyzes the loading resistance and the construction methods of a temporary event structure, the Tri-Dome, intended for use at Burning Man, an annual event held in the Nevada Desert.

This report was created based on the knowledge gained from the completion of the Civil Engineering Technology Program at SAIT Polytechnic, by utilizing the experience of industry professionals, and first-hand knowledge of experienced members of the Alberta Regional Burning Man community.

The Tri-Dome in this report is constructed from 1.5" Enerfoil polyisocyanurate rigid insulation panels held together with 6" bi-directional filament tape. The materials for constructing the Tri-Dome are readily available, and the dome itself is easy to assemble.

The Tri-Dome's strength is tested and is found capable to resist the most critical loads (wind loads of up to 90mph) encountered at Burning Man.

The construction methods and testing conducted in this report advances the construction methods used by the Alberta Regional Burning Man community.

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List of Illustrations

Introduction

This report analyzes the loading resistance and the construction of a Tri-Dome constructed from rigid insulation panels.

Purpose

This report is written for the Alberta Regional Burning Man community to advance the construction methods in use for creating temporary structures, as a graduation requirement for the Civil Engineering Technology program at SAIT Polytechnic (www.SAIT.ca).

This report can also be used as a reference for individuals with a basic construction or engineering background seeking to construct or improve upon the design or material selection of the Tri-Dome.

Background

For one week every August in Nevada's Black Rock Desert, a temporary city of over 50,000 people is assembled on a dry, seasonal lakebed for an event called Burning Man. "Burning Man is an annual experiment in temporary community dedicated to radical self-expression and radical self-reliance" [1]. These principles encourage participants of the event to release their creativity in the form of artwork, engineering, music, and celebration.

Burning Man is held hours from any town, and therefore anything an individual needs to survive must be brought in with them and later trucked out, leaving no trace. The event takes place in the harshest of climates, so shelters must be designed to withstand hot days, cold nights, and high winds.

When this report was written shelter designs used at Burning Man were a mix of some well thought out structures, tents, RVs and home-built design experiments. Several designs featured low waste building practices and strong geodesic structural geometry, as shown in Figures 1 and 2 below.

Figure 1: Shelters Found at Burning Man
Source: [2]

Figure 2: Planned Structures Found at Burning Man
Source: [3]

The Tri-Dome in this report is designed as a temporary structure suitable to provide shelter at Burning Man held in the Black Rock Desert in Nevada. The dome is constructed from rigid foam insulation panels joined together with an adhesive tape calculated and tested to resist wind loads encountered at Burning Man. The insulation panels selected in this report provide excellent thermal resistance making them well suited for the desert. Recommendations on the assembly of the Tri-Dome are made based on the challenges experienced during the dome's first erection.

Scope

The following items are included within the scope of this report, as they were deemed most critical to the safety and performance of the Tri-Dome at Burning Man:

- Determination of end user requirements at Burning Man
- Calculation of wind loads on the Tri-Dome
- Comparison and selection of materials for:
    - Flexural strength
    - Compressive strength
    - Suitability for application
    - Cost
- Construction and testing of a scale model Tri-Dome
- Construction of a full-size Tri-Dome
- Determination of tie down requirements
- Summary of costs
- Recommendations

This report excludes the following:

- Testing tie down requirements
- Testing UV ray resistance
- Testing solar absorption
- Testing all material properties
- Testing the insulation value of the constructed model
- Testing the model in a wind tunnel
- Testing durability in exposure
- Testing internal temperature performance
- Analyzing geotechnical requirements for dome anchors
- Determining anchorage design
- Determining fire ratings
- Determining if the Tri-Dome design and material selection complies with national and international building codes

Methods

Industry Contacts

Members of the team visited SPAR-Marathon Roofing and had a meeting with the store manager Rick Jaithoo to discuss design considerations required, and the benefits verses limitations of selecting polyisocyanurate IKOTherm panels for the design.

Architect and Building Science Instructor Paul Ledaire met with the team to offer advice on material selection and general considerations for temperature control in a desert environment.

Chris Petrell from the Burning Man Organization’s Department of Public Works provided data from the weather station and prevailing wind direction detail for the site location.

Robin Wylie, an experienced Burning Man participant and local Hexayurt builder, provided material selection recommendations based on his personal experience at Burning Man.

Mike Hermann, an experienced member of both the Alberta Regional Burning Man community and Protospace, provided space to build the full-size Tri-Dome and assisted with its assembly.

Steve Paul, Educational Technologist for the School of Construction at SAIT Polytechnic, volunteered his time and guidance for the testing of materials.

Roofmart Customer Service Representative, Ray Jeffrey, provided a discount on the purchase of the panels required for the full-size assembly.

Applied Learning

Testing the yield load of materials considered for the Tri-Dome assembly followed laboratory procedures set out within the Strength of Materials course.

Structural Design provided the basis for calculating and assessing the wind loads encountered in the Nevada desert.

The knowledge gained in Building Science provided the basis for selecting panels that would create a structure with temperatures within the human comfort zone.

Skills gained within Construction Methods, Civil Drafting, and Estimating were also utilized for this report.

Advanced Learning

The calculations of specified wind loads on a sphere were made using the "User's Guide-NBC 2005 Structural Commentaries (Part 4 of Division B)" under the guidance of Jacqueline Vera P.Eng.

The principles developed for materials testing and theoretical load testing of structures were combined and adapted to provide the basis for developing the testing procedures used in this report.

Further communication skills were acquired from a proposal to SAIT Polytechnic's Innovative Student Project Fund (ISPF) review panel to obtain the required funding to build and test a full-size Tri-Dome.

Preview

This report outlines three types of zero waste dome designs and the reasons for selecting the Tri-Dome design. The wind loads in the Black Rock Desert during Burning Man acting on the dome are calculated. The resulting forces from the wind calculations were used to test the insulation panels and tape. A material comparison and testing of critical attributes of the insulation panels and tape was conducted. A 1:4 scale model of the Tri-Dome and a full-size roof panel was constructed and tested. Assembly procedures for the construction of a full-size Tri-Dome are provided, and recommendations are made to mitigate problems that were experienced in its assembly.

Dome Selection

Performance Criteria

To select a design that was suitable for the conditions found at Burning Man, experienced members of the Alberta Regional Burning Man community were consulted and the following criteria was developed.

The dome must possess sufficient strength and high insulation properties. The dome must also be easy to assemble and transport, and be onsite repairable. Of lesser importance, the dome should be affordable, aesthetically pleasing and create zero-waste in its construction.

Geodesic Dome

A shape that is geodesic is one that uses straight lines and flat surfaces to create a shape that is sphere-like in appearance and performance. Because of the flat surfaces and straight lines, the strength of the sphere shape can be realized with materials that are readily available.

A geodesic dome, invented by Buckminster Fuller in the late 1940s, is an enclosed half-spherical structure made from carefully arranged triangles of varying sizes [4]. These triangles work together to create a very strong structure [4] that evenly distributes and transfer loads to the ground surface. An example of a Geodesic Dome is shown in Figure 3.

According to an online article on Geodesic Domes, "The dome is a structure with the highest ratio of enclosed area to external surface area, and in which all structural members are equal contributors to the whole" [4].

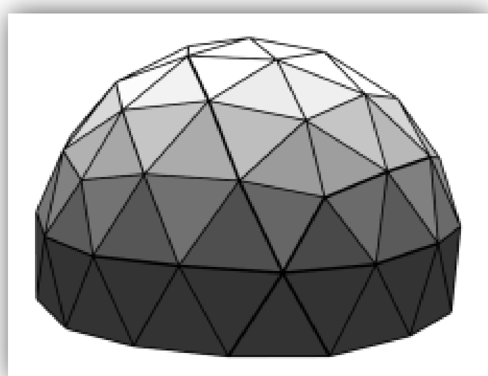


Figure 3: Example of a Geodesic Dome
Source: [5]

Hexayurt

The Hexayurt is a modern-day, easy to build, structure based on the same mathematical principles found in the geodesic dome combined with the visual appearance of a yurt, a circular shaped structure with a conical roof as shown below in Figure 4.

Figure 4: A Hexayurt found at Burning Man
Source: Adapted from: [6]

What makes the Hexayurt different is that its geometry has been modified so that its entire structure is created from standard 4'x8' panels. "The Hexayurts are made from only one kind of triangle: an 8'x8' isosceles triangle, rather than the strangely-shaped triangles which are standard for Fuller-style geodesic domes" [7]. These triangles are created by cutting and taping a 4'x8' panel into its new shape, thus becoming a zero waste structure.

Zero Waste Nearodesic Dome

There are two distinct Zero Waste Nearodesic Dome designs created by Edmund Harriss [8]: the Tri-Dome and the Quad-Dome. Both designs combine the zero waste properties of a Hexayurt with the half-spherical shape of a geodesic dome.

When constructed using identical construction methods and materials, the Tri-Dome and Quad-Dome compare equally with most of the performance criteria previously identified.

To assist in selecting between the two designs, both structures were constructed using 1x2in pieces of paper scotch taped together. This provided a good indication of how easy each design would be to construct, and allowed a comparison between the two structures based on the overall strength of the structure.

Quad-Dome

Although visually the more appealing of the two structures, it was easy to determine by pushing a finger on the top of the scaled model that the Quad-Dome showed weakness in the design of its roof that would easily fail under certain loading conditions. Specifications for the Quad-Dome can be seen in Figure 5 below.

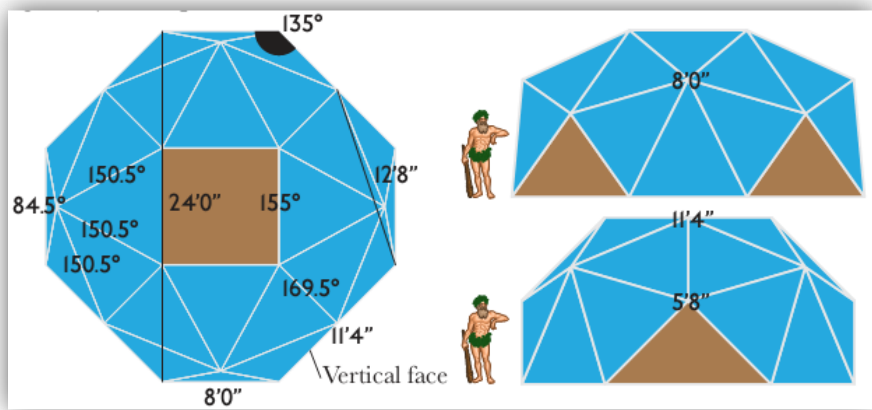


Figure 5: Quad-Dome Specification
Source: Adapted from: [8]

The shallow angles on the Quad-Dome created a weak point that would be incapable of withstanding the wind conditions found in the Black Rock Desert.

Tri-Dome

The Tri-Dome, shown below in Figure 6, showed much greater strength under the same loading condition and was therefore chosen as the stronger of the two Nearodesic dome designs.

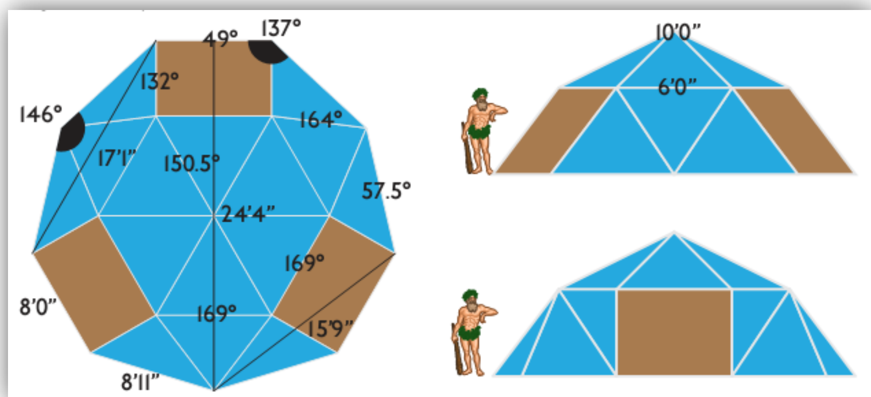


Figure 6: Tri-Dome Specification
Source: Adapted from: [8]

Loads

"Structural loads can be divided into three categories: permanent loads (such as dead load and earth pressure), variable loads (such as use and occupancy, snow and wind loads), and rare loads or situations (such as earthquake or fire)" [9: A-4].

The materials used for the Tri-Dome are insulation panels and tape. As the weight per panel is negligible, the permanent dead loads can be omitted. However the weather conditions at Burning Man must be considered in the loads calculation. Because Burning Man is held in a desert during mid-summer, snow can be ignored as a variable load. Rain precipitation at this time is negligible [10].

Wind load is the most significant load for the Tri-Dome design when used at Burning Man; therefore only wind loads are discussed and calculated in this report.

> The specified external pressure or suction due to wind on part or all of a surface of a building shall be calculated using the formula
>
> $P = I_w q C_e C_g C_p$
>
> where
>
> p = specified external pressure acting statically and in a direction normal to the surface, either as a pressure directed towards the surface or as a suction directed away from the surface,
> Iw = importance factor for wind load, as provided in Table 4.1.7.1.,
> q = reference velocity pressure, as provided in Sentence (4),
> Ce = exposure factor, as provided in Sentence (5),
> Cg = gust effect factor, as provided in Sentence (6), and
> Cp = external pressure coefficient, averaged over the area of the surface [11:4-16]

The National Building Code of Canada 2005 provides a formula for calculating wind pressure. As the Tri-Dome is a round structure the wind pressure (Figure 7) it experiences is not the same as the normal building structures. "For rounded structures (in contrast to sharp-edged structures), the cross-wind pressures vary with the wind velocity and depend strongly on the Reynolds Number" [9:I-38].

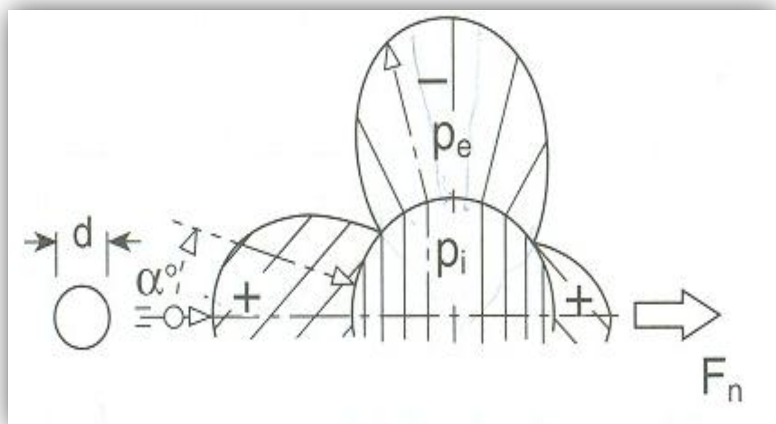


Figure 7: Wind Pressure on Round Structures
Source: Adapted from: [9: I-38]

Wind Load Calculation

The principal forces acting on the Tri-Dome at Burning Man are wind forces. It was determined that the loading conditions of the Tri-Dome would be similar to that of a half-sphere.

To calculate the wind pressure on the Tri-Dome all the factors in the wind pressure formula must be specified for round structures.

$P = I_w q C_e C_g C_p$ [11:4-16]

- Wind load factor = 1.4,the wind load factor should be 1.4 when the dead loads are neglected [11]
- Importance factor of wind load Iw=0.8, for normal importance [11]
- Exposure factor Ce= 0.9 [11]
- Gust effect factor Cg= 2.0 [11:4-17]
- External pressure coefficient Cp is shown in Table 1 below

Table 1: External Pressure Coefficient Cp

$\alpha =$	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
C_p	+1.0	+0.9	+0.5	-0.1	-0.7	-1.1	-1.2	-1.0	-0.6	-0.2	+0.1	+0.3	+0.4

Source: [9:I-38]

Calculate Reference Velocity Pressure: q

The reference velocity pressure is defined as

> the reference velocity pressure, q, shall be the appropriate value determined in conformance with Subsection 1.1.3., based on a probability of being exceeded in any one year of 1 in 50 [11:4-17].

Since the reference velocity pressure, q, in Nevada, where Burning Man is located, is not available in the table provided by the National Building Code of Canada it must be calculated based on the basic wind speed, V_b, for Nevada. According to the website "Wind Speed by Zip" [12], the basic wind speed for Nevada is 90mph.

> The wind speeds and corresponding velocity pressures used in the Code are regionally representative or reference values. The reference wind speeds are nominally one-hour averages of wind speeds representative of the 10m height in flat open terrain corresponding to Exposure A or open terrain in the terminology of the User's Guide - NBC 2005, Structural Commentaries (Part 4 of Division B) [13:c-8].
>
> True one-hour averaged wind speed records from over 100 stations for periods from 10 to 22 years formed the basis for most of the wind pressures provided in the Table. The wind velocity pressures, q, were calculated in Pascals using the following equation:
>
> $$q = \frac{1}{2}\boldsymbol{\rho}V^2$$
>
> where $\boldsymbol{\rho}$ is an average air density for the windy months of the year and v is wind speed in metres per second. While air density depends on both air temperature and atmospheric pressure, the density of dry air at O°C and standard atmospheric pressure of 1.2929kg/m3 was used as an average value for the wind pressure calculations [13:c-8].

The reference (design) wind speed V is calculated based on the basic wind speed with the formula in *Structural Analysis of Geodesic Domes* written by Marek Kubik. [14, Appendix C]

$$V = V_z = V_z V_b k_1 k_2 k_3 k_4 = 30 \text{ m/s [14]}$$

The value of reference wind speed V, wind velocity pressure q in any one year of 1 in 50 (1/50) can be calculated in the formula above [14] also the q value is available in Table C-1 [13:c-9]. The value of wind velocity pressure is 0.54kPa

$$q\ (1/50) = \frac{1}{2}\boldsymbol{\rho}_{@20°C}V^2 = 0.54\text{kPa [13:c-9]}$$

All the detailed calculations above are shown in Appendix A: Calculations.

Calculate Wind Pressures P to Different Angles

The wind pressures P on the Tri-Dome panels at various angles, $\alpha°$, are shown below in Table 2.

$P = I_w q C_e C_g C_p$ [11]

Table 2: Wind Pressures at Different Angles

$\alpha =$	0°	15°	30°	45°	60°	75°	90°
P(KPa)	1.09	0.98	0.54	-0.11	-0.76	-1.20	-1.31
P(psf)	22.74	20.46	11.37	-2.27	-15.92	-25.01	-27.28
$\alpha =$	105°	120°	135°	150°	165°	180°	
P(KPa)	-1.09	-0.65	-0.22	0.11	0.33	0.44	
P(psf)	-22.74	-13.64	-4.55	2.27	6.82	9.09	

Source: Primary, see Appendix A: Calculations

Pressure Gradient

The methods outlined in the NBC Commentary were adapted to the geometry of the Tri-Dome. The radial pressure changes from 0° to 180° were applied to the cross section of the Tri-Dome (Figure 8). Because the Tri-Dome is not completely spherical, the radial pressure changes, shown in Figure 8, were applied to the surface of the Tri-Dome. Figure 9 illustrates how the pressures (RED) transition to suction (BLUE).

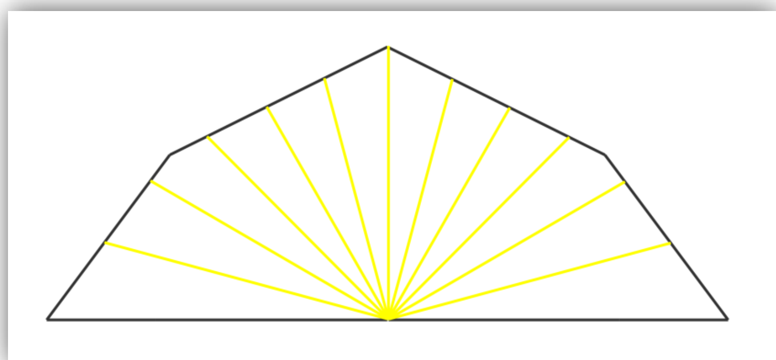


Figure 8: Radial Pressure Changes 0° to 180°
Source: Primary

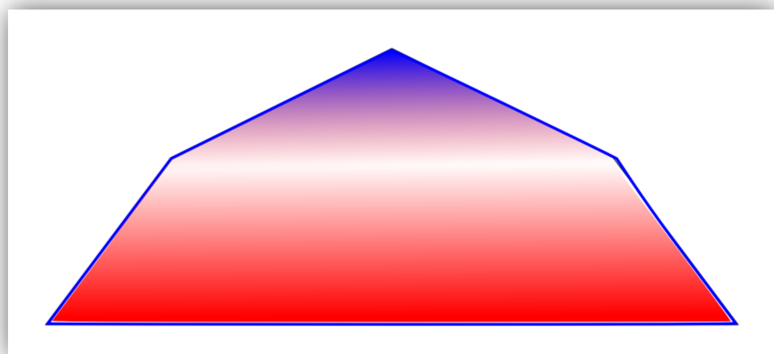


Figure 9: Gradient of Pressure (RED) to Suction (BLUE)
Source: Primary

Resultant Forces on Panels

AutoCAD was used to accurately map the location of the radial transitions. The resultant forces acting on each element are specified in Appendix A.

The radial transitions were applied to the individual elements of the Tri-Dome as shown in Figure 10. Figure 10 illustrates the radial transitions on the roof elements, the rectangular elements and 3 triangle assemblies found on the base of the Tri-Dome. The resultant forces acting on each area were calculated by taking the Area found in AutoCAD and multiplying by the average pressure.

$$F = \frac{P_1 + P_2}{2} \times Area$$

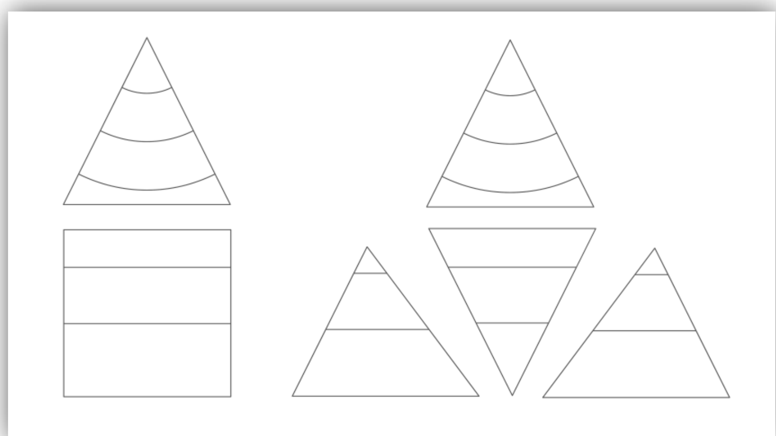


Figure 10: Radial Transitions on Tri-Dome Elements
Source: Primary

Resultant Forces on Tape

The tensile forces acting on a tape joint were calculated for the most critical joint on the Tri-Dome. The rectangular element on the windward side of the dome collects half of the forces of the adjacent triangular elements and applies them to the 8′ tape joint between the rectangular element and the triangular roof element. In addition to these forces the adjacent triangular element on the roof section applies uplift forces to the tape. The details of the following calculation can be found in Appendix A. A diagram of the forces and calculation is provided in Figure 11. The resultant tensile force acting on the tape joint was calculated to be $26\frac{lb}{in}$. The specified bi-directional filament tape has a tensile resistance of $220\frac{lb}{in}$ which provides a factor of safety of 8.46.

$$F = \frac{F_{lateral}}{cos\,\theta} \; or \; F = \frac{F_{uplift}}{sin\,\theta}$$

$$F_{per\ inch} = \frac{F}{Distance}$$

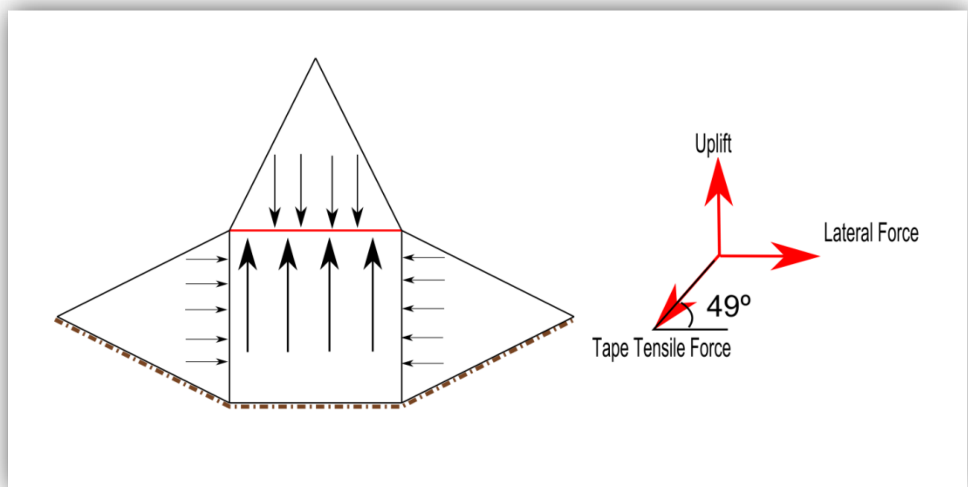


Figure 11: Tensile Force Acting on a Tape Joint
Source: Primary

Material Selection

To be selected as a panel material for the Tri-Dome the material had to meet criteria that were determined to be the most critical for the end user application. Materials that were unavailable in 4′x8′ sheets were not considered because the Tri-Dome design requires 4′x8′ sheets.

Because of strict rules on waste at Burning Man, Type I and II polystyrene EPS (Expanded Polystyrene) panels were also not considered due to their tendency to shed polystyrene balls when damaged. The criteria chosen are as follows:

- Availability
- Strength
- Expense
- Weather resistance
- Preparation time

Criteria

Availability

Due to the total dimensions of the panels required for the dome, approximately 4’x8’x3’ stacked on top of each other, it was important that the panel material be available locally to avoid large shipping or transportation costs. Should any damage occur it is necessary that panels be regularly stocked and available to the end-user for purchase in low-volumes. There is not a wide selection of 4’x8’ rigid insulation panels available in the Calgary area. The panels selected for comparison and that are available in Calgary are as follows in Table 3.

Table 3: Insulation Panel Availability

Material	Available At
Owens-Corning C-200 Foamular	Home Depot
IKO Enerfoil	Roofmart
IKO IKOTherm	Marathon Roofing

Source: Primary

A suitable tape in the required dimensions was found to be difficult to obtain locally. Online suppliers were found to stock a variety of tapes with an acceptable shipping time.

Strength

Flexural strength is a critical component for this comparison. Given the span of the panels, 8ft, it was later correctly confirmed by testing that the insulation would fail by flexure. Factors that affect the flexural strength of the insulation panels are brittleness of the insulation, tensile resistance of the facer (if applicable), and deflections.

In a typical construction application, supporting elastic roof coverings, structural components are required to not deflect more than their length divided by 180 [15:1-146] ($\frac{8'}{180} = 0.5"$ maximum per panel). Because the Tri-Desic dome is a temporary shelter with a limited usable life span and no brittle finishes like drywall it is not necessary for the insulation panel to meet requirements for deflections typically specified.

The compressive strength and bearing capacity of the insulation panels was determined to be negligible in this application. The rigid insulation panels were tested according to ASTM D1621 by the manufacturers and meet the values that were calculated (Appendix B).

The Tri-Dome design uses tape to secure all joints. The tape must have sufficient tensile strength to resist the forces acting upon the dome joints. The tensile resistance of each tape is tested by the manufacturer and provided as a force the tape can resist per inch of tape perpendicular to the acting force (lb/in).

Expense

After consultations with the end-user, it was determined that an acceptable cost per use for the Tri-Dome is $100. The length of tape consumed per use as waste (joints that are cut on takedown) is calculated to be approximately two 60yrd rolls of tape. With an expected service life of 10 uses, the amortized panel cost must be less than or equal to $100 minus the cost of tape.

Weather Resistance

All materials used in the Tri-Dome are expected to be exposed to UV rays, rain, wind, and dust. The foam insulation should at no point be exposed to UV rays as polystyrene and polyisocyanurate will degrade quickly [16]. The tape used for joints exposed to UV rays are expected to be replaced with each use. Because the tape's exposure is limited to the length of Burning Man (7 days), significant degradation due to UV rays is not expected and is not being considered [16]. All materials should be resistant to water, and be expected to resist abrasion due to wind [16].

Preparation Time

The time required to prepare the materials prior to assembly is a factor that was used to compare the materials. Preparation of a panel includes protection of edges ensuring UV and weather resistance, and if needed adding paint or foil facer.

Panel Comparison

The following panel materials meet the availability requirements and are compared in this report.

IKOTherm

The IKOTherm panel (Figure 12) is manufactured by IKO and is distributed nationally as flat roof insulation suitable for modified bitumen, built-up or single-ply roof systems [17]. It features a closed cell polyisocyanurate core with a fiberglass reinforced paper facer [17]. It is available in the Calgary area at Marathon Roofing.

Figure 12: IKOtherm Insulation Panel
Source: [17]

Foamular

Foamular (Figure 13) is an extruded polystyrene insulation board with no facer manufactured by Owens-Corning [18]. It is available in a wide range of thicknesses at Home Depot stores nationwide.

Figure 13: Owens-Corning Foamular Insulation Panel
Source: [19]

Enerfoil

Enerfoil (Figure 14) is manufactured by IKO and distributed nationally as building envelope insulation solution [20]. It has aluminum foil facers surrounding a polyisocyanurate core [20]. It is available in the Calgary area at Roofmart.

Figure 14: Enerfoil Insulation Panel
Source: [20]

Panel Cost Comparison

A comparison of the cost of panels is shown in Table 4 below. Further cost detail can be found in Appendix E.

Table 4: Panel Cost Comparison

Panel Material (Thickness)	Cost per panel	Cost per use (21 panels @ 10 uses)
IKOTherm 1.5"	$20.40	$42.84
Foamular 1.5"	$45.14	$94.79
Enerfoil 1.5"	$33.14	$69.59

Source: Primary

Panel Preparation Comparison

Both the IKOTherm and Foamular products would require significant preparation time to make the panels suitable for exterior exposure.

In addition to be being water absorbent, the IKOTherm's glass fiber reinforced facers provides an unsuitable surface for tape to adhere to. The Foamular material has no facer at all and will require paint or a facer to resist UV. To solve these problems the faces would need to be painted or a suitable foil facer would need to be adhered. To paint one side of the 21 panels in the Tri-Dome would require an area of 672 ft^2 (4'x8'x21) or approximately 25' by 25'. The time required to apply the required coats of paint or adhere foil facers to the panels was deemed to be excessive, nor was a suitable work area readily available. Therefore, both the Foamular and IKOTherm products were removed as potential materials for the Tri-Dome.

Panel Strength Comparison

Detailed material properties of the IKOTherm, Foamular, and Enerfoil panels are available in Appendix B. The results of critical factors in material testing done by the manufacturers are available in Table 5. All three products have similar compressive strengths [17],[20],[21],[22],[23]. The flexural strength of the

Foamular product was tested at less than half the strength of the IKOTherm and Enerfoil panels [17],[20],[21],[22],[23].

Table 5: Panel Strength Comparison

	Flexural Strength (kPa)	Compressive Strength
Foamular	300 [21]	140 (20)[21]
IKOTherm	607/479 [22]	140 (20)[17]
Enerfoil	618/805 [23]	124 (18)[20]

Source:

Enerfoil Selected

The Enerfoil polyisocyanurate panel was selected for use and further testing as a material for the Tri-Dome. Enerfoil panels are available nationwide at a reasonable cost and have similar or greater strength than the other panels that were compared. Because Enerfoil panels have a foil facer they are weather resistant and require the least amount of preparation time.

Tape Selection

The adhesive tape used in the Tri-Dome must be suitable to resist the stresses acting on the tape. The types of stresses that can act on tape follows in Figure 15. It is the combination of these resistive properties that ultimately provide the strength of the tape [24].

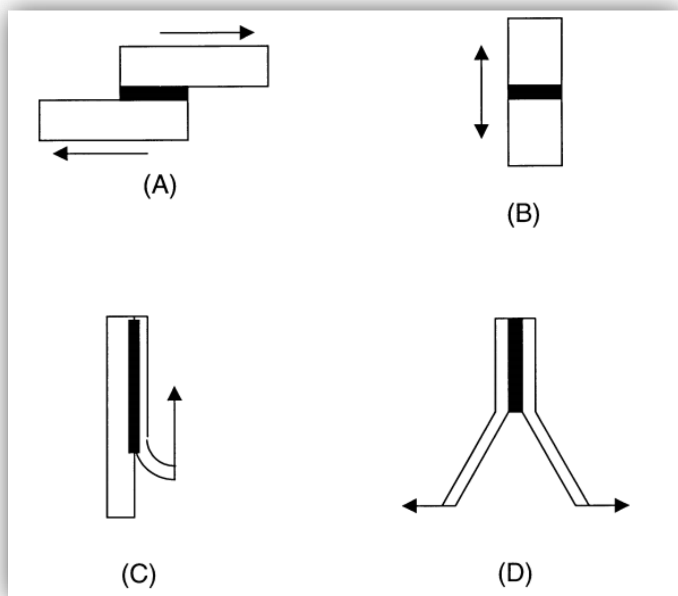


Figure 15: Typical Stresses that Separate Tape Joints. (A) Shear, (B) Tension, (C) Peel, and (D) Tear.
Source: Adapted from: [24]

Shear

When the face of a panel is loaded the forces transfer across the panel to the edges. Shear forces develop between the tape and panel which is resisted by the tape's adhesive as shown in Figure 16. Factors that affect the shear resistance of the joint are the adhesive's bond with the panel's facer material and hold strength. The adhesive bond and hold strength are tested as a single property by the tape manufacturer and given as an adhesion value in ounces per inch of contact area to stainless steel. It was determined that the aluminum facer used in the Enerfoil panel would produce similar results to that of stainless steel and this value was not adjusted when used in calculations.

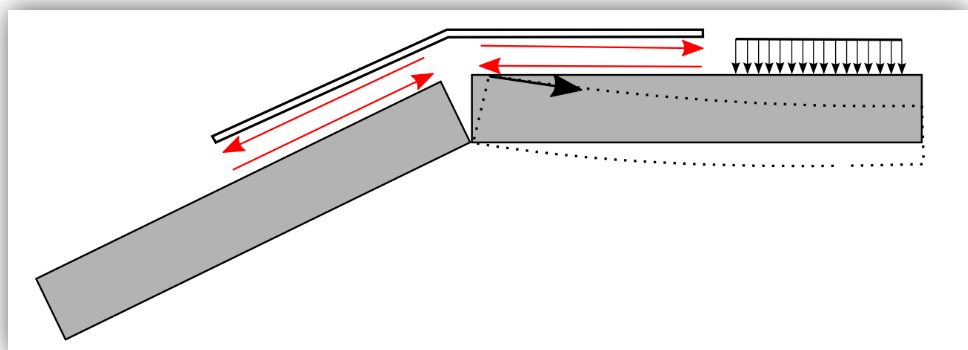


Figure 16: Shear Forces on Taped Joints
Source: Primary

Tension

Tension forces build up in the tape as the tape transfers forces to the adjacent panel as shown in Figure 17. This tension force (pulling) is resisted by the tape and given by the manufacturer as pounds per inch of tape. The elasticity of the tape is also tested by the manufacturer and is given as a percentage (%) of length elongation before the tape will fail.

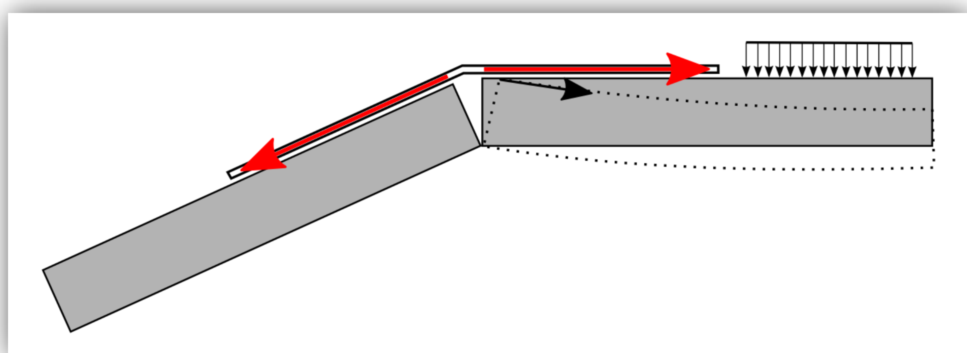


Figure 17: Tension Forces on Taped Joints
Source: Primary

Peel

Because the Tri-Dome panel edges are designed with limited to no bearing surface the tape must have sufficient peel resistance to resist the forces acting upon it (Figure 18). This property is only provided by the manufacturer for tape with a paper backing as the adhesion of the tape to that backing, not to a benchmark material (stainless steel). It was determined that this property was not critical to the construction of the Tri-Dome because peel failure did not occur during the testing of materials.

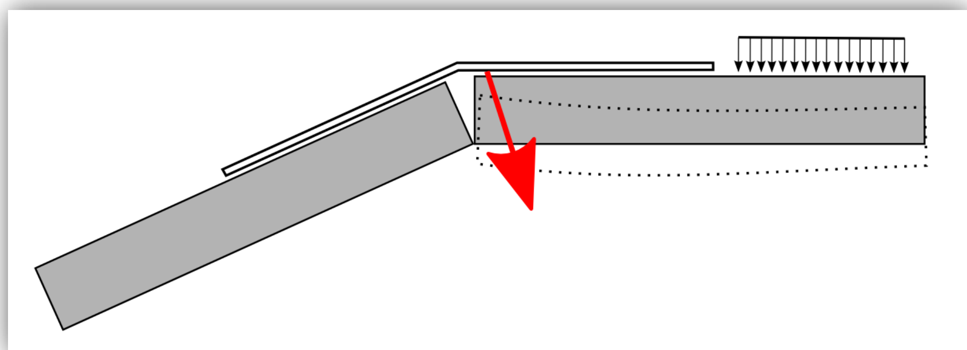


Figure 18: Peel Forces on Taped Joints
Source: Primary

Tear

If a tensile failure or a cut were to occur on a taped joint a tear would form. A tear concentrates the uniform tensile forces acting along its length to the tip of the tear as a point load as shown in Figure 19 [24]. This tear would expand until sufficient tensile resistance was met. If a tensile failure were to occur on the Tri-Dome the tensile forces acting on the tape would increase proportionally to the size of the tear. Because the resulting force would be greater than the initial force that caused the failure, a rapid tear of the entire joint would occur. It was determined that because a tear failure would only follow a tensile failure or cut, that tear resistance is not a critical factor for tape selection.

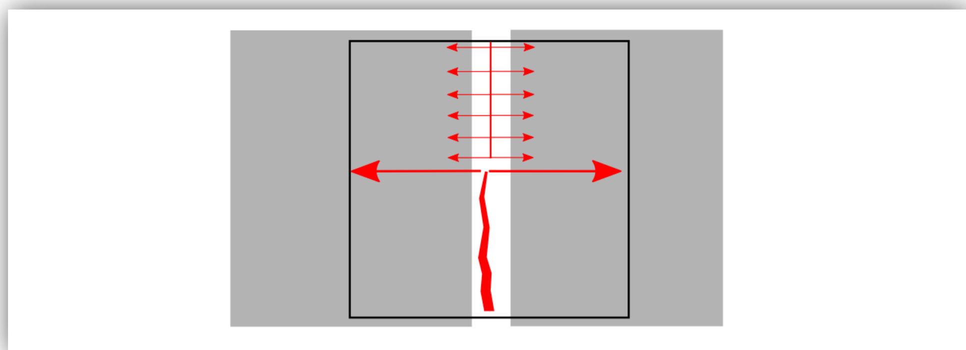


Figure 19: Tear on a Taped Joint
Source: Primary

Adhesion

The adhesion performance of a tape is affected by several factors governed by the adhesive type used. Performance can vary depending on the chemical composition used by the manufacturer. The two types of adhesive used in the considered tapes are rubber based, and acrylic based solvent.

Rubber adhesives require no time to cure and provide some moisture resistance [25]. Rubber adhesives are also sensitive to temperature [25]. As the adhesive heats up it becomes gummy and loses resistance to shear and peel. An example of a rubber based adhesive tape is Duct Tape [25].

Acrylic based solvent adhesives require a cure time specified by the manufacturer usually in the 6-12 hour range [25]. Acrylic solvents perform well at high temperatures and are moisture resistant [25]. Extended exposure to moisture will not result in failure [25]. Examples of acrylic adhesive tapes are foil tapes, and Tuck Tape [25].

Foil Tape

Foil tapes are typically used for sealing ductwork and general HVAC (Heating, Ventilation, and Air Conditioning) applications where high temperature resistance is required. Manufactured from aluminum, they are highly weather and UV ray resistant. In Calgary foil tapes are readily available only in 2.25" widths which limits their use in the Tri-Dome. The foil tape used for testing and construction of the Tri-Dome was similar to the tape shown in Figure 20. It was selected to protect the cut edges of the polyisocyanurate panels from weather and UV. The foil tape is also used to repair the foil facer of damaged panels.

Figure 20: Foil Tape 2.25" Width
Source: Adapted from: [26]

Bi-Directional Filament Tape

The tape used for testing and construction of the Tri-Dome was JVCC 762-BD [27] and is shown in Figure 21. This bi-directional filament tape is a fiberglass reinforced polypropylene tape [27]. The fiberglass reinforcement provides tear resistance and tensile strength of 220lb/in in both longitudinal and transverse axis [27]. Even though the JVCC 762-BD uses a rubber based adhesive [27] which is susceptible to high temperatures and UV, this tape has been successfully used at Burning Man for many years [28]. Because this tape has proven performance at Burning Man and its material properties exceed the specification [Appendix B] it was selected to be used for all structural connections.

Figure 21: Bi-Directional Filament Tape Used For the Tri-Dome
Source: [29]

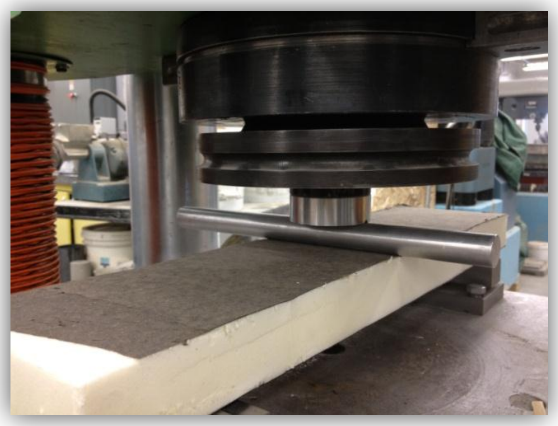
Material Testing

The main structural panels were tested in the Concrete Lab (DE129) at the SAIT main campus on February 10, 2012. To prove the strength of Enerfoil Panels; centre point loading tests were performed. According to the test results and corresponding calculations the stress and flexural modulus of the Enerfoil panels were determined.

Flexural Test

The Enerfoil panel was selected for the construction of the Tri-Dome. A centre point load test was performed using the Universal Testing Machine assisted by Steve J. Paul, Educational Technologist in School of Construction at SAIT Polytechnic. This machine was used to measure the yielding load, bending stress, and bending of flexural modulus of testing materials. The IKOTherm panels were also tested to compare the yielding load and flexure.

Four identical centre point load tests were carried out using the Universal Testing Machine with all samples having the same dimensions. Tests included IKOTherm whole panel test, Enerfoil whole panel test, Enerfoil panel cut in half and the two parts taped together with 150mm (6in) Bi-Directional Filament Tape, and Enerfoil panel cut in half with the two parts taped together with 48mm wide foil tape. Figures 22-29 below show all four tests and the module of failure.



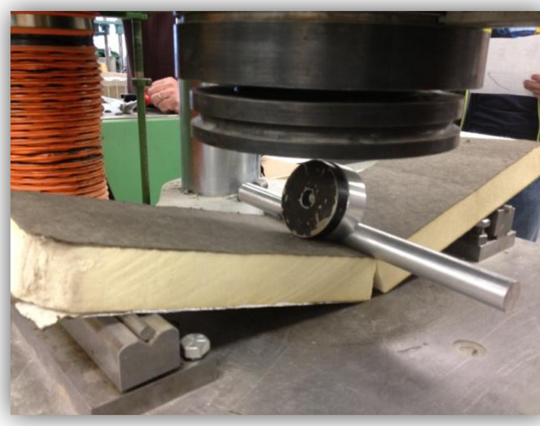


Figure 22: Testing on IKOTherm Panel
Figure 23: Model of Failure of IKOTherm Panel
Source: Primary

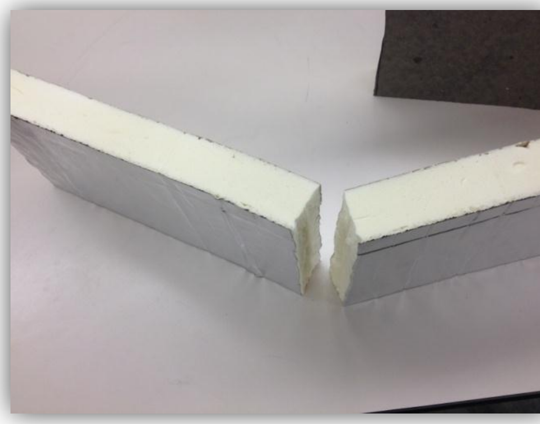


Figure 24: Testing on Enerfoil Panel
Figure 25: Model of Failure of Enerfoil Panel
Source: Primary

Figure 26: Testing on Enerfoil Panel with Bi-Directional Tape
Figure 27: Large Deflections are Observed
Source: Primary

Figure 28: Testing on Enerfoil Panel with Foil Tape
Figure 29: Model of Failure of Enerfoil Panel with Foil Tape
Source: Primary

After each loading test, the graph of the yield force load (kN) and the position was printed and are shown in Appendix C. Lab data from the four tests are shown in Table 6 below, except for the test on the Enerfoil panel with the Bi-Directional tape as the deflections on the test were so large that the module of failure was not reached.

Table 6: Flexural Test Data

Type of Panel	Yield Force (N)	Length (mm)	Width (mm)	Thickness (mm)	Deflection at Yield Point (mm)
IKOTherm	973.6	460	150	40	16.75
Enerfoil	1080.6	460	150	38	55.30
Enerfoil with foil tape	766.4	460	150	38	19.80

Source: Primary

For the test of the Enerfoil panel cut in half with the two parts taped together with 150mm (6in) Bi-Directional Filament Tape, a maximum point load of 1035.7N with a deflection of 55mm was measured before the test stopped.

Calculation of Bending Stress and Bending of Flexural Modulus

With knowledge gained from the Strength of Materials class the bending stress and flexural modulus was calculated (see Appendix A) from the lab data (Appendix C) [30].

Bending Stress $\sigma_s = \frac{3pl}{2wt^2}$

Bending of Flexural Modulus $E_s = \frac{pl^3}{4wt^3y}$

p—Yield Force
l—Length
w—Width
t—Thickness
y—Deflection at Yield Point [30]

Table 7 below shows the results of the Bending Stress σ_s and Bending of Flexural Modulus in each flexural test. (The Enerfoil panel with Bi-Directional Filament Tape on centre test is not shown.)

Table 7: Bending Stress and Flexural Modulus

Type of Panel	Bending Stress (MPa)	Bending of Flexural Modulus (MPa)
IKOTherm	2.80	147.34
Enerfoil	3.44	57.77
Enerfoil with foil tape	2.44	114.44

Source: Primary, see Appendix A: Calculations

For the test of Enerfoil panel cut in half and the two parts taped together with 150mm (6 in) Bi-Directional Filament Tape, the maximum load before the test stopped the Bending Stress was 3.30MPa and bending of flexural modulus was 55.67MPa.

Material Test Results

Based on the observations made during the test as well as the data collected and their corresponding calculations, the following conclusions can be made about the properties of the test materials under various conditions:

- IKOTherm Panel
  - Brittle failure
  - Minor deflections until failure
- Enerfoil Panel
  - Brittle failure
  - Major deflections
  - Greater flexural strength than IKOTherm
- Enerfoil Panel cut in half with 6" Bi-Directional Filament Tape taped on centre
  - No failure
  - The test stopped before the panel failed, because the test sample touched to the bottom of the machine
  - Huge deflections
  - The bi-directional filament tape withstood greater tensile stress
- Enerfoil Panel cut in half with 17/8" Foil Tape taped on centre
  - Brittle failure
  - Less deflection than Enerfoil panel only
  - The bottom joint failed under sheared tape

Panel Flexural Resistance

To ensure the Enerfoil panels are sufficient to resist wind loads acting on them the flexural resistance of the section must be calculated (detailed calculations are in Appendix A) and compared to the flexural load acting on the panel. Figure 30 illustrates the material testing setup. The shear force (Vr) (Figure 31) and bending moment (Mr) was calculated using the following equations. The bending moment of the section tested was calculated to be 0.1227kNm.

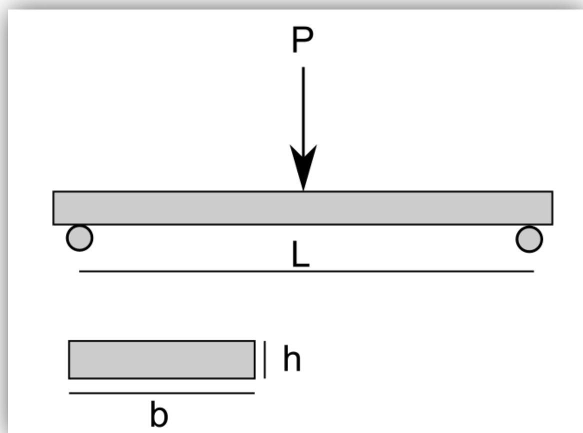


Figure 30: Panel Material Testing Diagram
Source: Primary

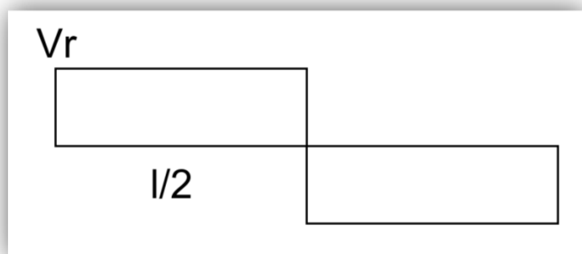


Figure 31: Shear Force Diagram
Source: Primary

$$Vr = \frac{P}{2}$$

$$Mr = Vr \times \frac{l_{sample}}{2} = 0.1227kNm$$

Maximum Pressure Forces Acting Between 0° and 15°

The critical section where the panel must span 8′ while subject to 1.09kPa (Appendix A) of pressure was analyzed. Based on the moment of resistance, calculated above, the following equation was then used to calculate the uniform distributed load a section with an 8′ length is capable of resisting. Figure 32 illustrates the area under consideration. Using the following equation the factored distributed load able to be resisted was calculated to be $0.16509\frac{kN}{m}$.

$$Mr = \frac{wl2}{8} \qquad w_r = \frac{8 \times Mr}{l_{bottom}^2} = 0.16509\frac{kN}{m}$$

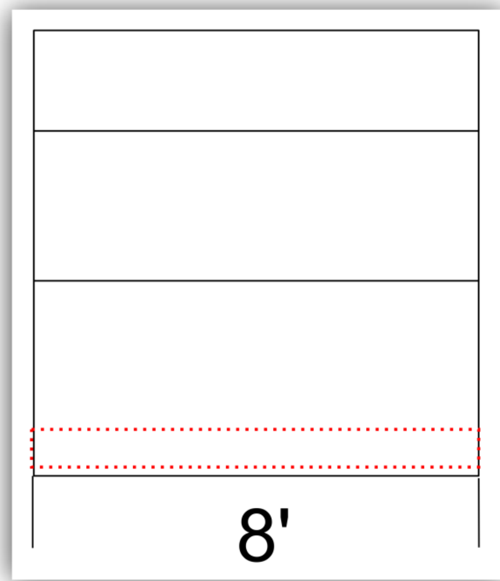


Figure 32: Rectangle Element Material Resistance
Source: Primary

The calculations below convert the pressure acting on the panel into a uniform distributed load equal in width to the section under consideration. A factored distributed load was calculated to be $0.1635\frac{kN}{m}$ yielding a factor of safety of 1.01.

$$w_f = Pressure \times b$$

$$w_f = 1.09kPa \times 0.15m = 0.1635\frac{kN}{m}$$

$$F.S. = \frac{0.16509}{0.1635} = 1.01$$

Maximum Suction Forces Acting Between 75° and 90°

Using the same methods the flexural resistance and acting forces can be calculated. Figure 33 illustrates the area under consideration. This area is subject to the largest loads on the Tri-Dome.

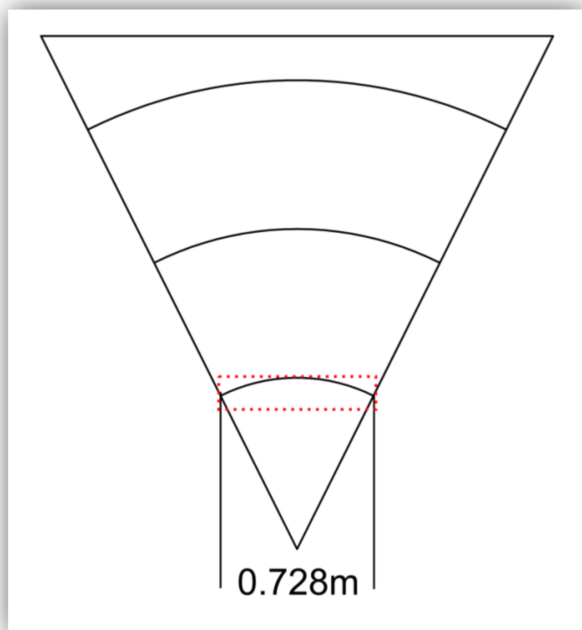


Figure 33: Triangle Roof Element Resistance
Source: Primary

The following equations were used to calculate a factor of safety of 11.2 for this area. The length was measured in AutoCAD and the details of the calculations may be found in Appendix A.

$$w_f = Pressure \times b = 0.1965\frac{kN}{m}$$

$$w_r = \frac{8 \times Mr}{l_{bottom}^2} = 1.85kPa$$

$$F.S. = \frac{1.85}{0.16509} = 11.2$$

Scale Model Testing

A 1:4 scale model was constructed by using the same materials (Enerfoil panel and Bi-Directional Filament Tape) as the full-size model. To prove the strength is sufficient enough to safely use at Burning Man; four types of tests were done in the lab.

Load Test

A load test was performed to determine the strength of the scale model. In order to prove the strength of the Tri-Dome, a distributed load test on the roof of a 1:4 scale model was performed.

To ensure the load was evenly distributed one sandbag was placed on each of the six panels on the roof. The weight of each sandbag was 25kg (55lb). Since the roof of the Tri-Dome was not flat sandbags on opposing sides of the roof were held together using duct tape (Figure 34). This allowed the sandbags to rest securely on the roof.

Figure 34: Deflection Measurement on Load Testing on Scale Model
Source: Primary

The deflection of the Tri-Dome was measured against time as an indicator of the model's ability to resist changes in shape due to application of a 150kg (330lb) distributed load. Deflections were measured from the tip of the roof to a fixed point before loading. An initial distance of 74.0cm (29.1in) was recorded. After five minutes of loading a distance of 75.5cm (29.7in) was recorded. The deflection distance was recorded at five minute intervals for twenty minutes. The 150kg (330lb) load was removed from the roof and the Tri-Dome was allowed to rest unloaded for twenty minutes. A final deflection distance of 0.8cm (0.3in) was recorded. Load test data is shown below in Table 8.

Table 8: Load Test Data

Elapsed Time	Distance (cm)	Deflection (cm)	Load Status
0	74.0	0	No load
5 minutes	75.5	1.5	Load
10 minutes	75.5	1.5	Load
15 minutes	75.5	1.5	Load
20 minutes	75.6	1.6	Load
40 minutes	74.8	0.8	No load

Source: Primary

Impact Test

An impact test is different from the distributed load test in that it focuses on point loads. To simulate an impact with measurable results a pendulum was used. The pendulum used was a rope supporting a sandbag from a beam directly above the Tri-Dome. The sandbag at rest was at a point where it touched one rectangular panel of the Tri-Dome. The distance between the top rope supporting and the ground was 1.55m (5.1ft). The height between the top rope supporting and the bottom of the sandbag was measured for each test (Figure 35).

Figure 35: Distance Measuring for the Impact Test on the Scale Model
Source: Primary

The sandbag (25kg/55lb) was at rest 0.2m (7.8in) from the ground and then was lifted (as a pendulum) to a point 0.9144m (3.0ft) from the ground and released to swing into the square panel. After calculations (Appendix A) the resulting force on the square panel was determined to be 459.5595N (103.31lbf). A cracking sound was heard when the sandbag hit the panel, but no visible damage was found on the surface of the panel. The impact test was repeated three more times with similar impact forces (Table 9). The square panel did not break until the fourth impact test was performed with an impact force of 304.7655N (68.51lbf) (Figure 36, Table 9).

Figure 36: The Broken Square Panel on Impact Test
Source: Primary

Table 9: Impact Test Data

Test	Distance between top support and ground (m)	Distance between top support and bottom of sandbag (m)	Height of sandbag (m)	Angle between the vertical and rope in Radians (degrees)	Impact Force (N)	Condition
1	1.55	1.35	0.9144	1.081(61.94°)	459.5595	Good
2	1.55	1.34	0.9900	1.140(65.32°)	533.1447	Good
3	1.55	1.35	0.9800	1.135(65.03°)	526.5049	Good
4	1.55	1.50	0.6096	0.893(51.17°)	304.7655	Broken

Source: Primary

Repair Test

The same pendulum test was performed after the rectangular panel had failed. The repair test was used to determine the durability of the sample after repair. For a Tri-Dome to be used in Burning Man it must be proven that it can be repaired to resist significant forces and wear.

After four impact loads in the Impact Test the tested square panel was broken (Figure 37) and was re-taped (Figure 38) using bi-directional filament tape. The re-taped square panel was subjected to three additional impact loads for the Repair Test. The test results show that the re-taped square panel was comparable in strength to the original panel and no significant damage was observed after the three impact loads of the Repair Test (Table 10).

Figure 37: The Broken Panel
Figure 38: The Re-taped Panel
Source: Primary

Table 10: Repair Test Data

Test	Distance between top support and ground (m)	Distance between top support and bottom of sandbag (m)	Height of sandbag (m)	Angle between the vertical and rope in Radians (degrees)	Impact Force (N)	Condition
1	1.55	1.39	0.6096	0.828(47.44°)	266.9468	Good
2	1.55	1.39	0.7620	0.968(55.46°)	356.3773	Good
3	1.55	1.35	0.9144	1.096(62.80°)	476.9829	Good

Source: Primary

The conclusion of the repair test is that the re-taped rectangular panel was as strong as the original panel.

Panel Missing Test

After the bottom square panel of the 1:4 scale model was re-taped, the repaired Tri-dome could still resist the strong impact loads (e.g. 476.98N/107.23lbf) with no visible damage. Considering the extreme weather conditions at Burning Man the Panel Missing Test was carried out.

The Proctor Standard Hammer (24.5N weight [31:86]) was manually used to apply significant force on the re-taped bottom square panel until failure. The subsequent deflections absorbed by the dome and the panel could easily be seen. As the force applied on the panel gradually increased the re-taped square panel finally broke off from the Tri-Dome after eleven impacts over twenty-nine seconds (Figure 39).

Figure 39: The Missing Panel from the Tri-Dome
Source: Primary

With the bottom square panel missing, the sandbags were again settled on the top of the Tri-Dome to perform the Missing Penal Test. The sandbags were fixed in the same method as in the Load Test with duct tape. The initial distance between the tip of the roof to the top of the fixed point was 74.5cm (29.33in).This distance increased to 76.2cm/30in (1.7cm/0.67in deflection) after four sandbags—100kg (220lb) was loaded on the roof. When the fifth sandbag was loaded (total load: 125kg (275lb)) the Tri-Dome collapsed catastrophically (Figure 40).

Figure 40: Missing Panel Test
Source: Primary

The Tri-Dome failed because the bottom of the dome was not secured which allowed the corners of the failed panel to deflect outward. This deflection impaired the geometry and the structure collapsed. The major failure that caused the collapse was the failure of the foil paper on the panel rather than the panel itself. The pictures below (Figure 41-43) show the failures of the dome.



Figure 41, Figure 42, and Figure 43: The Failure of the Panel
Source: Primary

Model Test Results

To prove the Tri-Dome design was strong enough to be used under the extreme weather conditions at Burning Man, four types of strength tests were carried out on the 1:4 scale model. The test results of Load Test, Impact Test, Repair Test, and Panel Missing Test are shown below.

- Load Test: Under the 150kg (330lb) distributed load on the top the maximum deflection was 1.6cm (0.63in). After removing the load the final deflection was 0.8cm. No damage or failure was induced on the 1:4 scale model by this test.
- Impact Test: Under the 533.15N (200lb) maximum impact load on the bottom square panel the 1:4 scale model was in good condition with no significant cracks on the testing panel. The bottom square panel was broken under 304.77N (68.52lb) impact load after several tests. Mode of failures was due to the foil facer not the tape.
- Repair Test: Under the 476.98N (107.23lb) maximum impact load on the bottom re-taped square panel the 1:4 scale model remained in good condition with no significant damage on the testing panel.
- Panel Missing Test: Under the 100kg (220lb) distributed load on the top the deflection was 1.7cm. Under the 125kg (275lb) distributed load on the top the 1:4 scale model collapsed.

Model Test Observations

During the scale model testing, the following observations and recommendations were made:

- The geometry of the structure allowed for relatively even force distribution.
- All joints on the roof should be taped both inside and out as it was later revealed that the roof panel which had the most deflection had not been properly taped on the inner side.
- The structure can hold its shape with the roof taped only on the inside without any loads acting on the structure. However, this is not recommended as the load resistance is drastically reduced.
- Taping the outside bottom edges of the dome to a tarp could assist in maintaining the structures' geometry by preventing the panel edges from deflecting outward.
- The structure was stronger after repairs were made. According to the material test, it was determined that the bi-directional filament tape adds strength to the panel.
- The failure of a whole panel may not lead the entire structure to collapse, which will allow time to make repairs.

Full-Size Panel Testing

The top triangle panel for the roof of the Tri-Dome was constructed in full-size. The 4’x8’ Enerfoil Panel was cut in half and tape together by Bi-Directional Filament Tape. (Figure 44)

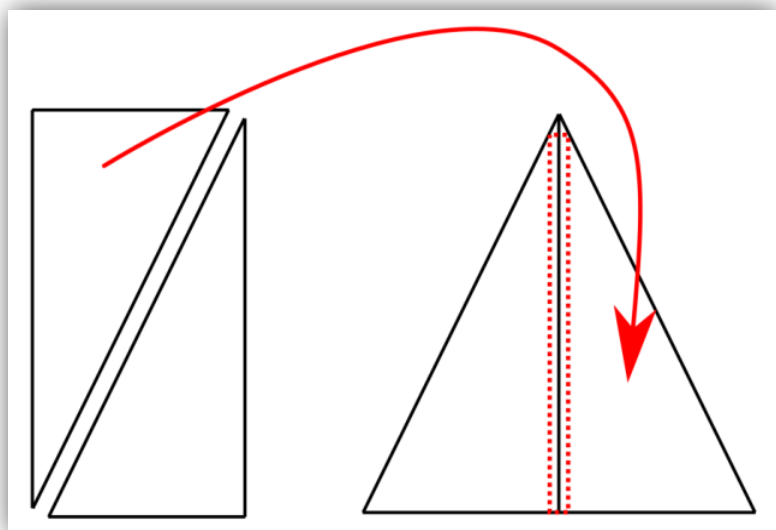


Figure 44: Top Triangle Panel Construction
Source: Primary

The full-size panel was settled on a level surface and the initial distance from the panel to the floor was recorded as 28.5 in (72.4cm). Then a 130kg load was evenly distributed on the top of the panel (Figure 45). The distance from the panel to the floor was recorded again as 26.5 in (67.3cm) (Figure 46). There was 2in (5.1cm) deflection. No damage or cracks were observed on the panel.

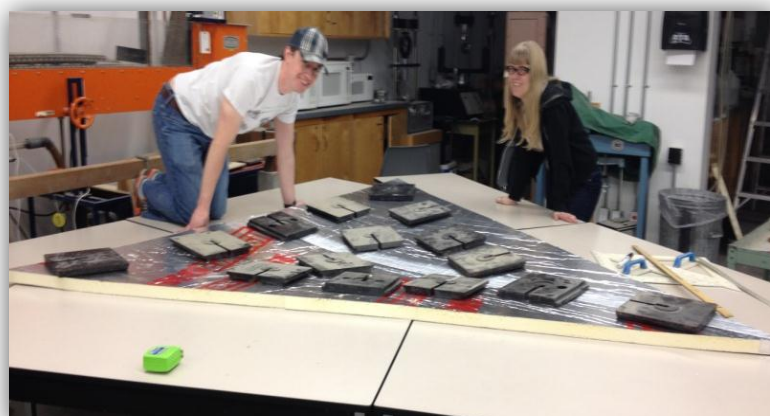


Figure 45: Distributed Load on the top of Full-Size Panel
Source: Primary

Figure 46: Distance from the Panel to the Floor
Source: Primary

Another 20kg (150kg loads total) was added. The distance from the panel to the floor was recorded as 26in (66cm). The deflection changed to 2.5in (6.4cm). After 5min of testing the distance from the panel to the floor was still 26in (66cm). There was no change for deflection. The 150kg load was removed from the top and the distance from the full-size panel to the floor was back to 28in (71.1cm). All the data is shown in Table 11 below.

Table 11: Full-Size Panel Test Data

Test	Load on top (Kg)	Distance between panel to the floor (in)	Deflection (in)
1	0	28.5	0
2	130	26.5	2.0
3	150	26.0	2.5
4	150 (5min after 3rd test)	26.0	2.5
5	0	28.0	0.5

Source: Primary

The full-size top triangle panel test proved that the full-size panel of the Tri-Dome is flexural and strong enough to resist the load condition at Burning Man.

Full-Size Construction

Construction of the full-size Tri-Dome in this report was made possible because of funding provided by the SAIT Polytechnic Innovative Student Project Fund (ISPF).

Panel Preparation

On-site setup time can be significantly reduced by pre-fabricating the elements of the Tri-Dome. The Tri-Dome is made from two elements, triangles (Figure 47 and 48), and rectangles (Figure 52 and 53).

Triangular Element

To fabricate the triangular elements IKO Enerfoil panels were cut in half to form right-angle triangles. The edges were taped with 2.25" foil tape to provide protection to the polyisocyanurate from moisture and UV rays (Figure 49). The right-angle triangle pieces were taped together as shown in Figure 50. The panels are taped a second time to form a hinge joint to facilitate transport (Figure 51).

Note: When preparing the triangular elements it is important to alternate the cutting angles in order to maintain the same outward face on the Tri-Dome.

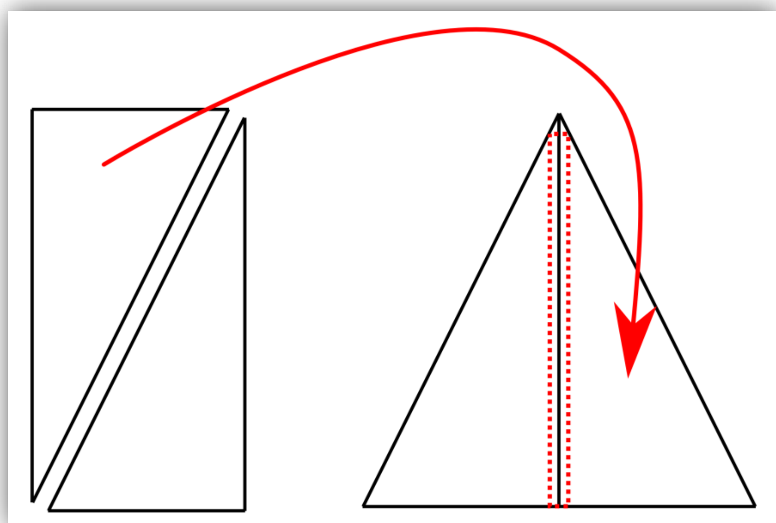


Figure 47: Cut and Tape a Triangular Element
Source: Primary

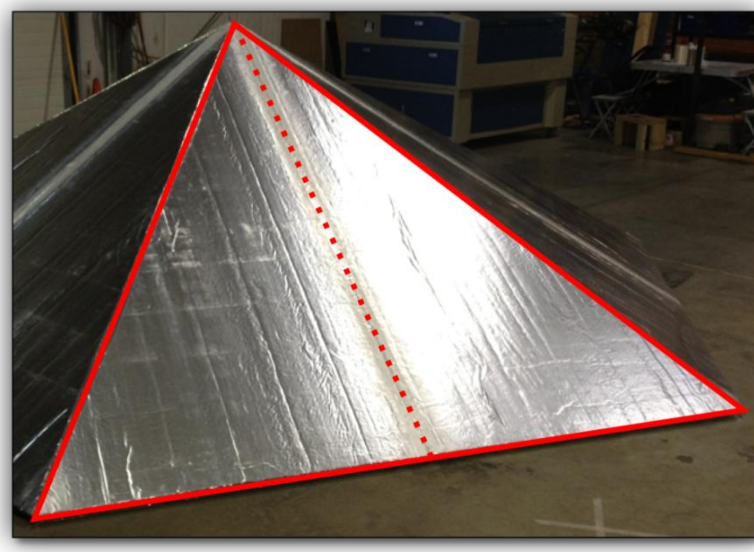


Figure 48: Triangular Element of the Tri-Dome
Source: Primary

Figure 49: Foil Tape Protected Polyisocyanurate from UV rays and Weather
Source: Primary

Figure 50: Tape Joint on a Triangular Element
Source: Primary

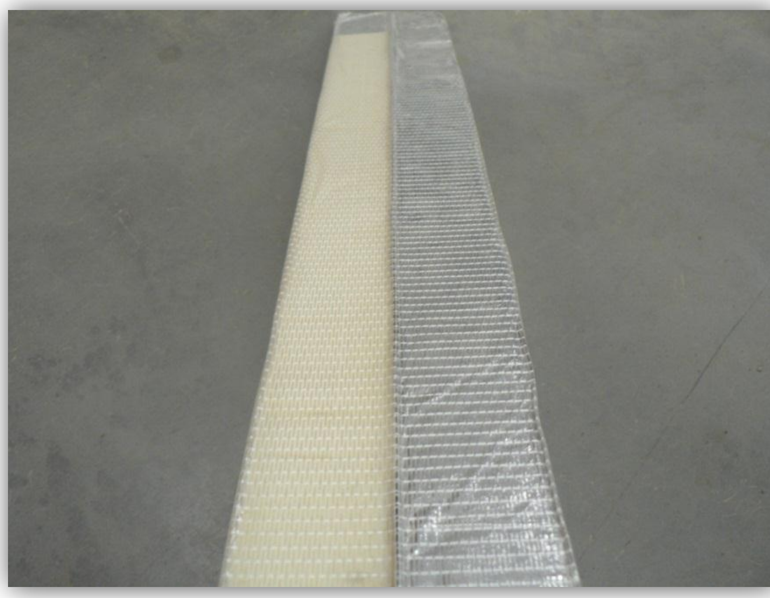


Figure 51: Hinge Joint on a Triangular Element
Source: Primary

Rectangular Element

Fabrication of the rectangular elements required the same edge protection procedure as the triangular elements mentioned earlier only on intact 4'x8' panels of IKO Enerfoil. The full panels were then joined on their long edge as shown in Figures 52 and 53 in the same hinge joint as the triangular elements.

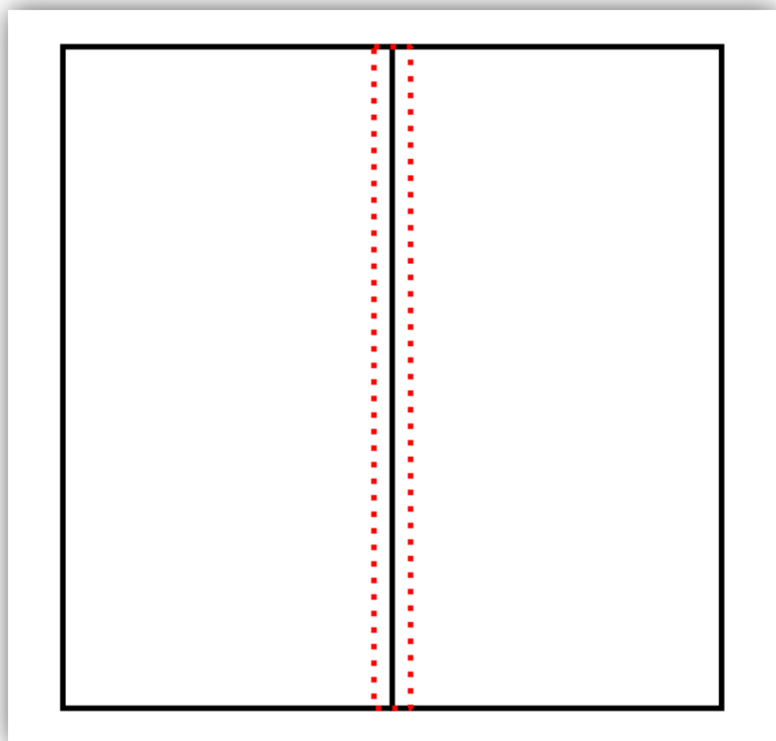


Figure 52: Tape a Rectangular Element
Source: Primary

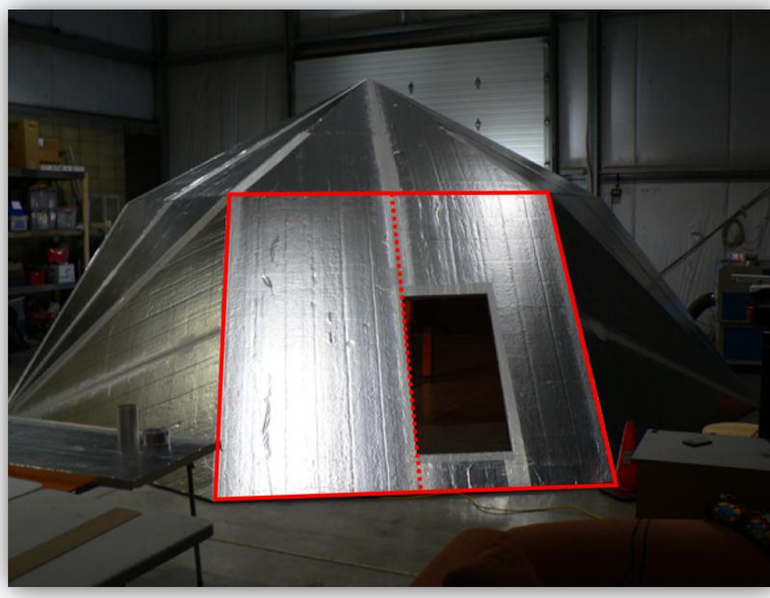


Figure 53: Rectangular Element (with door).
Source: Primary

Setup Procedure

The six triangular elements that make up the roof assembly were laid out, outer face down, and taped together. The assembly was flipped so that the outer face was up (Figure 54). The roof assembly was then raised and the final inner tape joint was taped from the inside (Figure 55).

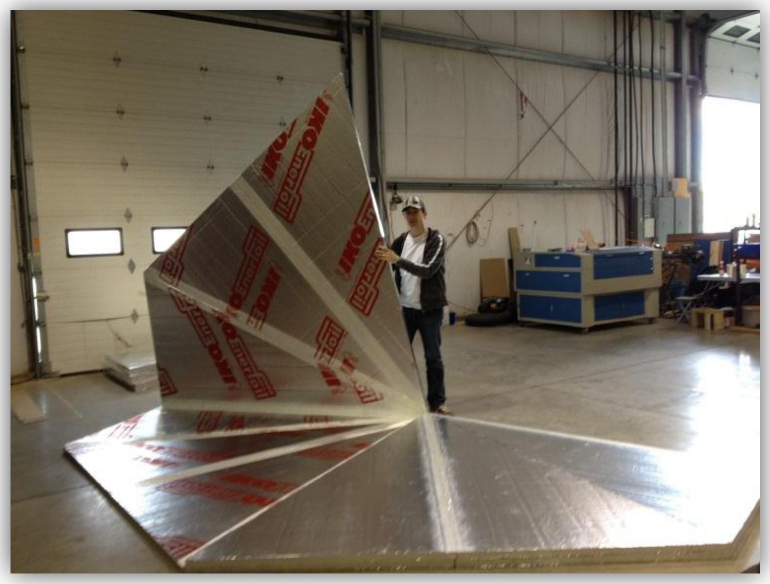


Figure 54: Flipping the Roof Assembly
Source: Primary

Figure 55: Fully Assembled Roof
Source: Primary

The bottom section of the Tri-Dome was separated into three sections for assembly. Each section was made up of one rectangular, and three triangular elements (Figure 56). Only inside joints are taped prior to full assembly. Each section is capable of standing freely while the other two are being assembled.

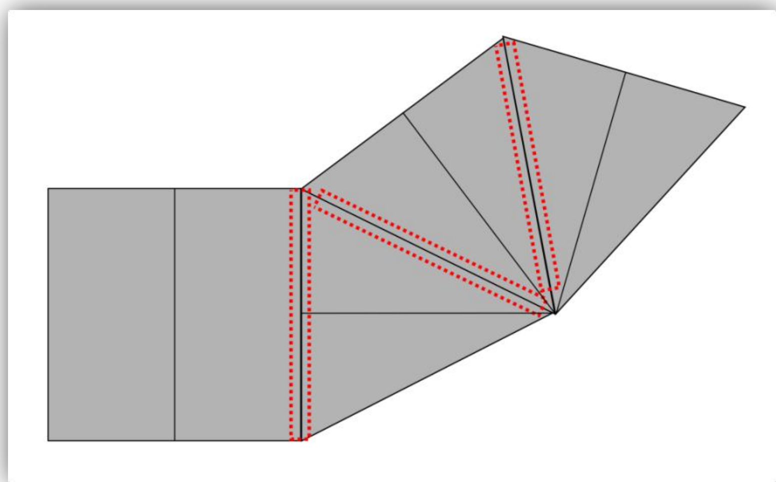


Figure 56: Assembly of One of Three Bottom Sections
Source: Primary

When all three bottom sections were assembled, they were joined together (Figures 57 and 58). Because of the unique geometry of the Tri-Dome when all bottom sections are taped together the base will aid in the final configuration, requiring very few adjustments.

Figure 57: Assembly of the Bottom Section
Source: Primary

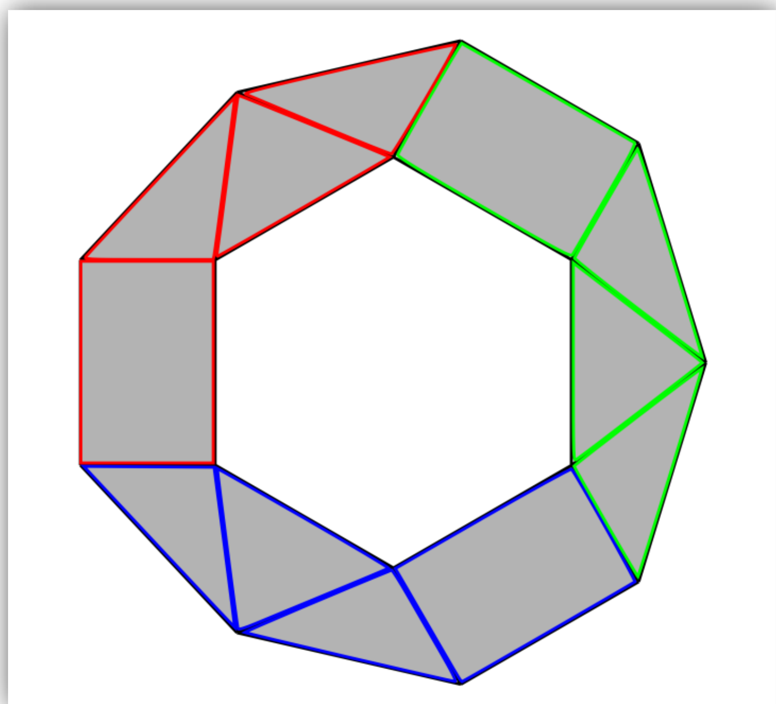


Figure 58: Top View of Assembled Base.
Source: Primary

After adjustments to ensure the base sat according to specification, a door was cut for access (Figure 59). The roof was lifted over the base and into position. Once in position the 6 joints that attach the roof to the base were taped inside and out.

Figure 59: Assembled Tri-Dome
Source: Primary

Recommendations for Assembly

Based on experience gained in the construction of the Tri-Dome the following recommendations are made for assembly.

- The Tri-Dome requires a large staging area when assembling individual elements. It is recommended that a space at least twice the base area of the Tri-Dome be available.
- The procedure outlined for assembly in this report requires an ingress method to lift the roof into position. It is recommended that a door be cut into a rectangular element before the base is assembled.
- The alignment of the base sections can be difficult if the angles in the Tri-Dome specification are not correctly observed. It is recommended that the position and top height of the rectangular elements be accurately laid out prior to assembling the base (Figure 60).
- The panels and elements made from the panels used in the Tri-Dome are very light and will catch in the wind. It is recommended that all elements be assembled completely before starting the assembly of the roof and base.
- The roof is lifted overhead onto the base and may be difficult to control in the wind. It is recommended that a lanyard be taped to the roof to assist in a controlled lift.

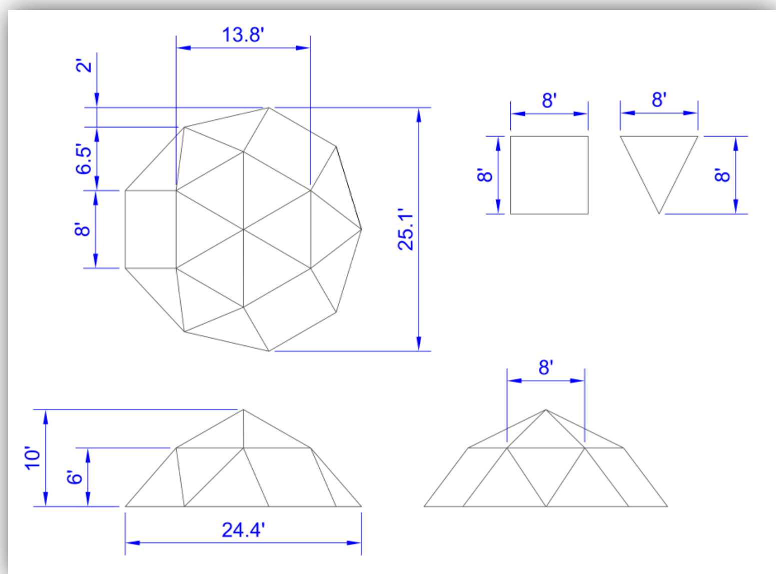


Figure 60: Distance to Tri-Dome Corners
Source: Primary

Recommendations for Disassembly

Based on experience gained in the disassembly of the Tri-Dome the following recommendations are made.

- Care should be taken to ensure that the foil tape used to protect the polyisocyanurate is not damaged when cutting tape joints.
- Alternating between cutting outside and inside joints in an accordion fashion can facilitate later assembly. If using this method, ensure that the tape gap in the outer joints is filled with paper or masking tape to reduce the chance of the tape adhering to itself.

Tie Downs

The resultant lateral force acting on the dome was calculated by the following equation given by the *User's Guide-NBC 2005 Structural Commentaries* [9] and may be found in Appendix A.

$$F = C_f \times q \times C_g \times C_e \times \frac{\pi d^2}{4}$$
$$F = 1993\ lb$$

This calculated lateral force in conjunction with the total uplift force is used to calculate the required resistive strength required for a tie down. Each tie down is designed to resist the full uplift and lateral forces resulting in a comfortable factor of safety should any one tie down be damaged, vandalized, or otherwise compromised as shown in Figure 61.

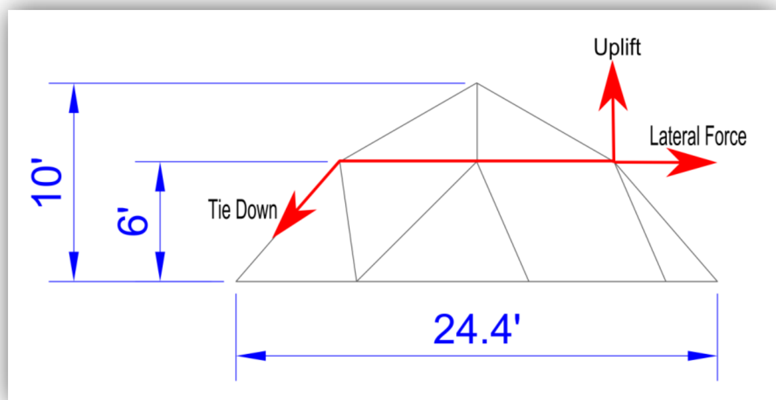


Figure 61: Uplift, Lateral, and Tie Down Forces
Source: Primary

The specified resistive force required for each tie down was calculated, shown in Figure 62, using the greater of the following equations and found to be 3080lbs (Appendix A). A value for Theta of 48.5° was found to be optimum. This angle is the same as the angle the rectangular element allowing anchors to be placed directly adjacent to the Tri-Dome, which will reduce the chance of accidental damage and alleviate tripping hazards.

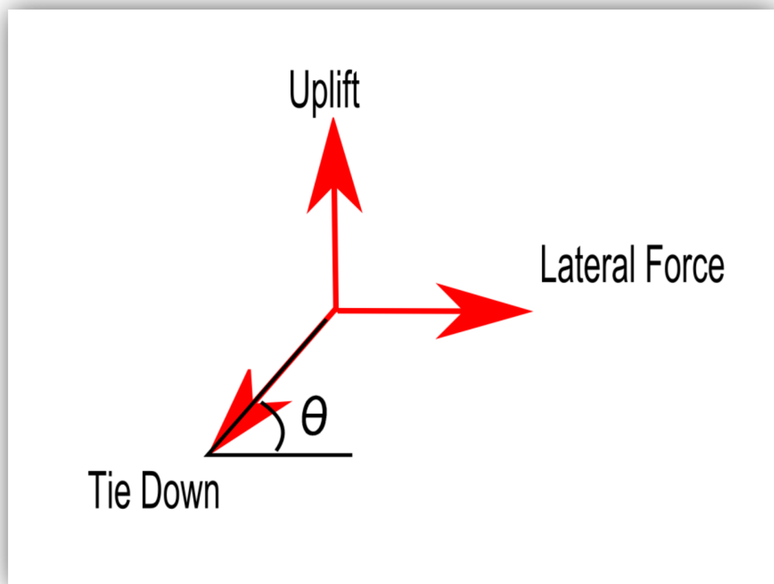


Figure 62: Tie Down Force Diagram
Source: Primary

$F = \frac{F_{lateral}}{\sin\theta}$ or $F = \frac{F_{uplift}}{\cos\theta}$

Eye loops must be used to create connection points in the rope ring for the tie downs to connect to. A suitable knot for this purpose is the Alpine Butterfly knot [32] (Figure 63). It is important to note that knotting rope significantly reduces its tensile strength. The Alpine Butterfly retains 61% to 72% of its strength under tensile load [32]. Because of this reduction the specified tensile force must be increased. The following equation was used to determine a tensile resistance of 5050lb required for rope when using the minimum tested resistance of the Alpine Butterfly knot.

$$F_{rope} = \frac{F_{tie\ down}}{0.61}$$

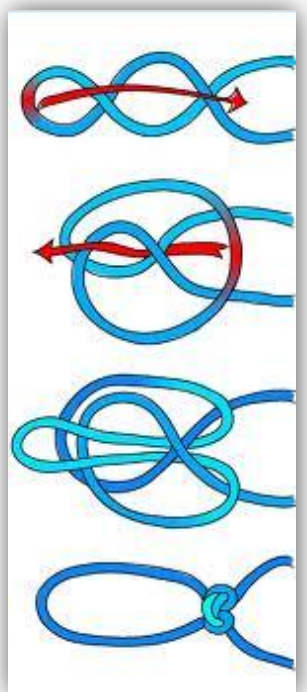


Figure 63: Alpine Butterfly Knot
Source: [33]

The rope ring, marked in red on Figure 64, transfers the loads acting on the Tri-Dome to the tie downs. Because the dome is transferring loads to the rope the area of contact between the rope and the insulation panel is under compressive stress on the leeward side of the Tri-Dome. No matter how the Tri-Dome is rotated three 8' lengths of rope in the ring will be transferring loads from the Tri-Dome. The following formula was used based on a rope diameter of ¾" to calculate a compressive stress of 14.26PSI acting on the insulation. The Enerfoil panels have a compressive strength of 18PSI (Appendix B) resulting in a factor of safety of 1.26.

$$\sigma = \frac{Force}{diameter \times Length}$$

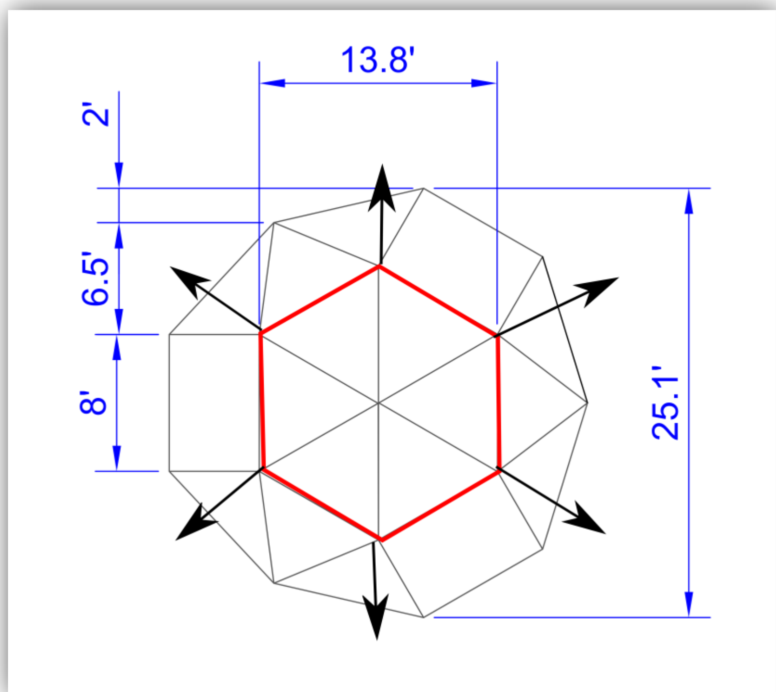


Figure 64: Tie Down Ring
Source: Primary

In the event of a failure of a single tie down it is important that the adjacent tie downs be able to resist the loads acting on them. The following diagram (Figure 65) shows a failed tie down on the windward side and the forces acting on the adjacent tie downs. Should the windward tie down fail the force on the adjacent tie downs was calculated and are sufficient to resist the forces acting on them.

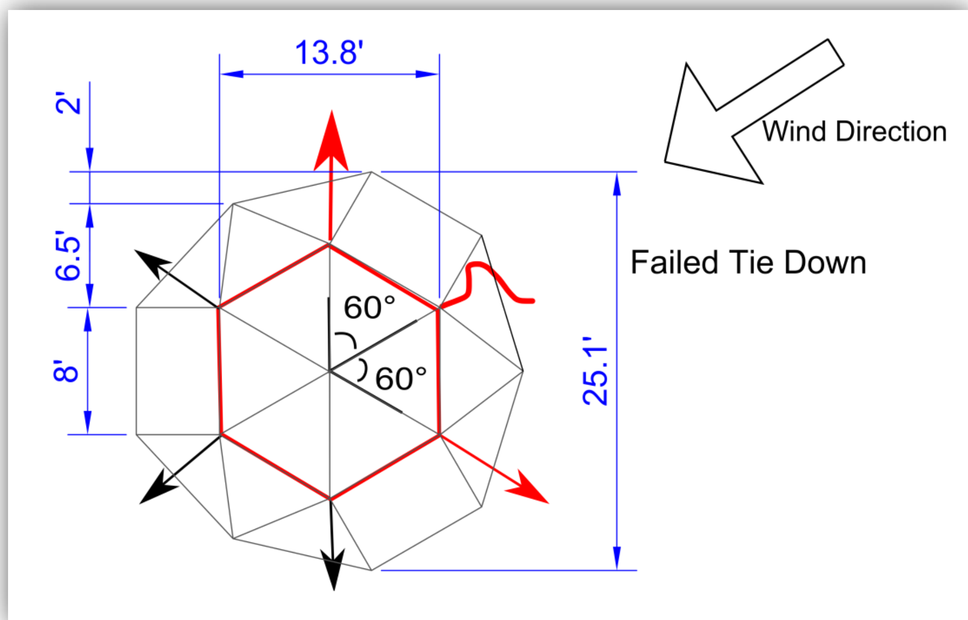


Figure 65: Failed Tie Down
Source: Primary

Additional tie downs at the 10' level are recommended to improve overall stability of the Tri-Dome. A plan of the recommended tie down locations and a detail of the ring joint are shown in Figure 66. Tie downs anchor points are located away from entrances that may be constructed in the rectangular elements and are sufficiently close to the Tri-Dome to avoid trip damage. A detail of an anchor able to resist the specified load is not provided by this report because of the wide range of soil conditions that may be encountered. All anchor designs should be tested before implementation.

Each tie down is required to be able to resist at least 3080lbs in tension. While many materials may be used for this application this report recommends the use of 2" wide DOT certified ratchet straps with a working load limit of at least 3080lbs. For the ring material shown in the following detail it is recommended that 3/4" double braid polyester rope with a tensile resistance of at least 5050lbs (Appendix A) be used. Double braid polyester rope is high strength and low stretch [34] making it well suited to this application.

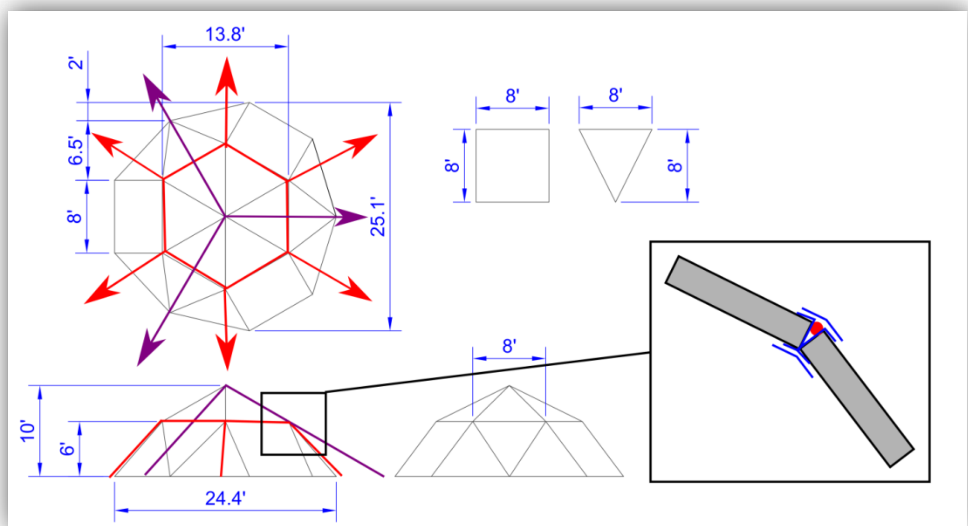


Figure 66: Tie Down Plan, Section, and Elevation Views.
Source: Primary

It is important to note that the tie down plan recommendations made within this report have not been tested and therefore should be tested prior to implementation.

Conclusion

The Tri-Dome design was selected because it has strong geometry, and has a large useable space.

The principle forces acting on the Tri-Dome are wind loads. The wind load pressure gradient was calculated based on a perfect sphere as outlined in the *User's Guide – NBC 2005 Structural Commentaries (Part 4 of Division B)*[9]. The resultant forces acting on the gradient and the forces acting on the most critical tape joint was calculated. The tape at this joint has a factor of safety of 8.46.

IKO Enerfoil (1.5") polyisocyanurate insulation panels were selected for use in the Tri-Dome. The Enerfoil panels were selected because they have the least preparation time, an acceptable cost, are available nationwide, have a weather resistant foil facer, and equal flexural and compressive strength compared to the Foamular and IKOTherm panels.

Bi-filament tape was selected for use because it has a high strength and is a proven tape for use at Burning Man. Foil tape was recommended for protecting the edges of the polyisocyanurate panels from UV light, and weather conditions.

Samples of Enerfoil panels were tested in the Universal Testing Machine for flexural strength. This test was repeated with a bi-filament taped joint. This data was used with the calculated wind pressures to determine a factor of safety of 1.01 given a worst case scenario.

A scale model of the Tri-Dome was constructed and was tested with a distributed load. The model was also subjected to an impact test until failure. The failure was repaired, retested, and resisted further impact testing until the model was manually failed. The Tri-Dome model was retested with the failed panel missing under distributed load. The damaged model resisted 100kg of 150kg previously tested before failure concluding that the Tri-Dome can survive the loss of a critical element long enough to make repairs. A full-size Enerfoil triangular element was load tested. The element was subjected to 150kg of distributed load and suffered no permanent deflections.

A full-size Tri-Dome was constructed. Recommendations on assembly and disassembly were made. Calculations for suitable tie downs and a tie down plan were made. Tie downs with a working tensile resistance of 3080lb attached to a rope ring with a tensile resistance of at least 5050lb are required. Two-inch DOT certified ratchet straps for the tie downs and ¾" double braid polyester rope with Alpine Butterfly knots are suitable for the use in the tie down plan found in Appendix D.

The construction methods and testing conducted in this report advances the construction methods used by the Alberta Regional Burning Man community by providing detailed analysis of material testing, wind calculations, and a plan to safely tie down a Tri-Dome. This report can also be referred to when constructing a Tri-Dome or improving on the Tri-Dome design and material selection.

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Appendix A: Calculations

Wind Load Calculation

Reference (design) Wind Speed V

Basic Wind Speed V_b

"Basic wind speed is based on peak gust speed averaged over a short time interval of about 3 seconds and corresponds to 10m height above the mean ground level in an open terrain (Category 2)[14]". According to [12], basic wind speed for Nevada is:

V_b= 90mph = 144.84Km/hr = 40.23 m/s
$V_b \approx$ 40 m/s

Reference Wind Speed V

$V_z = V_b k_1\ k_2\ k_3\ k_4$ [14: Appendix C],[36]
V_z = design wind speed at any height z in m/s,
k_1 = probability factor (risk coefficient) (see 5.3.1),
k_2 = terrain roughness and height factor (see 5.3.2),
k_3 = topography factor (see 5.3.3)
k_4 = importance factor for the cyclonic region (see 5.3.4)

NOTE: The wind speed may be taken as constant up to a height of 10 m. However, pressures for buildings less than 10m high may be reduced by 20% for stability and design of the framing. [14][36].

k_1 = 0.75, from Table 12 below. When basic wind speed is 39m/s, k_1 value for temporary sheds is 0.76. When basic wind speed is 44m/s, k_1 is 0.73. Therefore, when basic wind speed is 40m/s, k_1 value is 0.75.

Table 12: Risk Coefficients for Different Classes of Structures in Different Wind Speed Zones

Class of Structure	Mean Probable design life of structure in years	k_1 factor for Basic Wind Speed (m/s) of					
		33	39	44	47	50	55
All general buildings and structures	50	1.0	1.0	1.0	1.0	1.0	1.0
Temporary sheds, structures such as those used during construction operations (for example, formwork and false work), structures during construction stages, and boundary walls	5	0.82	0.76	0.73	0.71	0.70	0.67
Buildings and structures presenting a low degree of hazard to life and property in the event of failure, such as isolated towers in wooded areas, farm buildings other than residential buildings, etc.	25	0.94	0.92	0.91	0.90	0.90	0.89
Important buildings and structures such as hospitals, communication buildings, towers and power plant structures	100	1.05	1.06	1.07	1.07	1.08	1.08

Source: [36:23]

K_2 = 1.0, from Table 13 below. The height of Tri-Dome used at Burning Man is less than 10m, and assuming it belongs to Terrain Category 2, "Category 2 – Open terrain with well-scattered obstructions having height generally between 1.5 and 10 m [36:25].

Table 13: K_2 Factors to Obtain Design Wind Speed Variation with Height in Different Terrains

Height (z) (m)	Terrain and height multiplier (k_2)			
	Terrain Category 1	Terrain Category 2	Terrain Category 3	Terrain Category 4
10	1.05	1.00	0.91	0.80
15	1.09	1.05	0.97	0.80
20	1.12	1.07	1.01	0.80
30	1.15	1.12	1.06	0.97
50	1.20	1.17	1.12	1.10
100	1.26	1.24	1.20	1.20
150	1.30	1.28	1.24	1.24
200	1.32	1.30	1.27	1.27
250	1.34	1.32	1.29	1.28
300	1.35	1.34	1.31	1.30
350	1.37	1.36	1.32	1.31
400	1.38	1.37	1.34	1.32
450	1.39	1.38	1.35	1.33
500	1.40	1.39	1.36	1.34
NOTE: For intermediate values of height z and terrain category, use linear interpolation.				

Source: [36: 24]

k_3 = 1.0, assuming at Burning Man Community, there are no hills, cliffs or escarpments that channel the wind are nearby. [36:30-5.3.3]

k_4 = 1.0, the Tri-Dome used at Burning Man is a temperate structure, non-industrial nor structure of post–cyclone importance. [36:30 5.3.4]

So, the value of reference wind speed V is

$$V = V_z = V_b k_1 k_2\ k_3\ k_4$$
$$= 40\text{ m/s} \times 0.75 \times 1.0 \times 1.0 \times 1.0$$
$$= 30\text{ m/s}$$

Reference Velocity Pressure q

$q = \frac{1}{2}\boldsymbol{\rho}V^2$ [13:c-8]

$\boldsymbol{\rho}$ is dry air density, where at 0°C $\boldsymbol{\rho}$ is 1.2929kg/m^3 [13:c-8]. Since the Burning Man Community is in Nevada's Black Rock Desert, the dry air density $\boldsymbol{\rho}$ is used as 20°C. $\boldsymbol{\rho}_{@20°C}$= 1.204kg/m^3 [35].

So the value of reference velocity pressure q is

$$q = \frac{1}{2}\rho V2$$
$$= \frac{1}{2} \times 1.204\text{kg/m3x } (30\text{ m/s})\ 2$$
$$= 0.54\text{ KPa}$$

Wind Pressure P

Since the Tri-Dome is in round shape, the wind pressure (Figure 67) on it is different with the normal buildings.

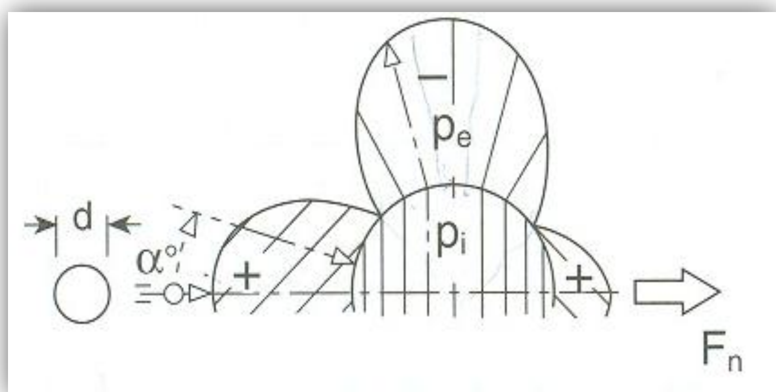

Figure 67: Wind Pressure on Round Structures
Source: [9:I-38]

The formula for wind pressure at different angles on the rounded structure is

$P = I_w\, q\, C_e\, C_g\, C_p$ [11:4-16]
q = 0.54 KPa, is calculated above.
C_e= 0.9, exposure factor [11:4-17], where

$$C_e = \left(\frac{h}{10}\right)^{0.2} = \left(\frac{3.0\ m}{10}\right)^{0.2} = 0.786 < 0.9$$

C_g= 2.0, gust factor [11:4-17]
C_p, external pressure coefficient, from Table 14, is different at different angles.

Table 14: External Pressure Coefficient Cp

$\alpha =$	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
C_p	+1.0	+0.9	+0.5	-0.1	-0.7	-1.1	-1.2	-1.0	-0.6	-0.2	+0.1	+0.3	+0.4

Source: [9: I-38]

Iw =0.8, from Table 15 below, for low importance category, since the Tri-Dome is a temporary structure.

Table 15: Importance Factor for Wind Load, I_w

Importance Category	Importance Factor, I_s	
	ULS	SLS
Low	0.8	0.9
Normal	1	0.9
High	1.15	0.9
Post-disaster	1.25	0.9

Source: [11:4-17]

So the wind pressures at different angles are

$$\begin{aligned} P_{@\ \alpha = 0°c} &= 1.4 \times Iw\ q\ Ce\ Cg\ Cp \\ &= 1.4 \times 0.8 \times 0.54\ KPa \times 0.9 \times 2.0 \times 1.0 \\ &= 1.09\ KPa \\ &= 22.74\ psf \end{aligned}$$

$$\begin{aligned} P_{@\ \alpha = 15°c} &= 1.4 \times Iw\ q\ Ce\ Cg\ Cp \\ &= 1.4 \times 0.8 \times 0.54\ KPa \times 0.9 \times 2.0 \times 0.9 \\ &= 0.98\ KPa \\ &= 20.46\ psf \end{aligned}$$

$$\begin{aligned} P_{@\ \alpha = 30°c} &= 1.4 \times Iw\ q\ Ce\ Cg\ Cp \\ &= 1.4 \times 0.8 \times 0.54\ KPa \times 0.9 \times 2.0 \times 0.5 \\ &= 0.57\ KPa \\ &= 11.37\ psf \end{aligned}$$

$P_{@\ \alpha = 45°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-0.1)
= -0.11 KPa
= -2.27 psf

$P_{@\ \alpha = 60°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-0.7)
= -0.76 KPa
= -15.92 psf

$P_{@\ \alpha = 75°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-1.1)
= -1.20 KPa
= -25.01 psf

$P_{@\ \alpha = 90°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-1.2)
= -1.31 KPa
= -27.28 psf

$P_{@\ \alpha = 105°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-1.0)
= -1.09 KPa
= -22.74 psf

$P_{@\ \alpha = 120°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-0.6)
= -0.65 KPa
= -13.64 psf

$P_{@\ \alpha = 135°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x (-0.2)
= -0.22 KPa
= -4.55 psf

$P_{@\ \alpha = 150°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x 0.1
= 0.11 KPa
= 2.27 psf

$P_{@\ \alpha = 165°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x 0.3
= 0.33 KPa
= 6.82 psf

P$_{@\ \alpha\,=\,180°c}$ = 1.4 x Iw q Ce Cg Cp
= 1.4 x 0.8 x 0.54 KPa x 0.9 x 2.0 x 0.4
= 0.44 KPa
= 9.09 psf

Net Lateral Force Calculation

$F = C_f \times q \times C_g \times C_e \times \frac{\pi d^2}{4}$ [9:I-38]
Where,
Cf = 0.2, $[9\!:\mathrm{I}-38]$
q = 0.54 calculated above
Cg = 2.0[11]
Ce = 0.9[11]
d = 7.62m

$$F = 0.2 \times 0.54 \times 2.0 \times 0.9 \times \frac{\pi(7.62m)^2}{4} = 8.865\ kN = 1993\ lb$$

Individual Tri-Dome Elements Calculation

The areas in Figure 68 and 69 were found using AutoCAD and multiplied by the average pressure acting on the area in Excel using the following formula.

$$Force\ Total = Area \times \frac{(P_1 + P_2)}{2}$$

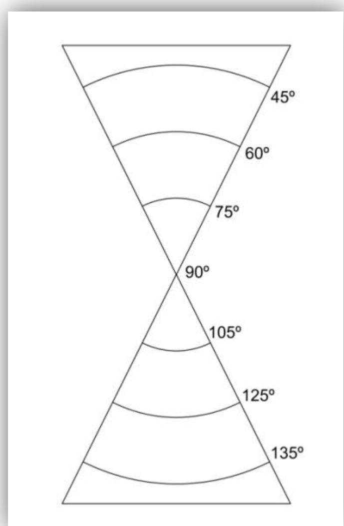

Figure 68: Radial Pressure Changes on Tri-Dome Roof Elements
Source: Primary

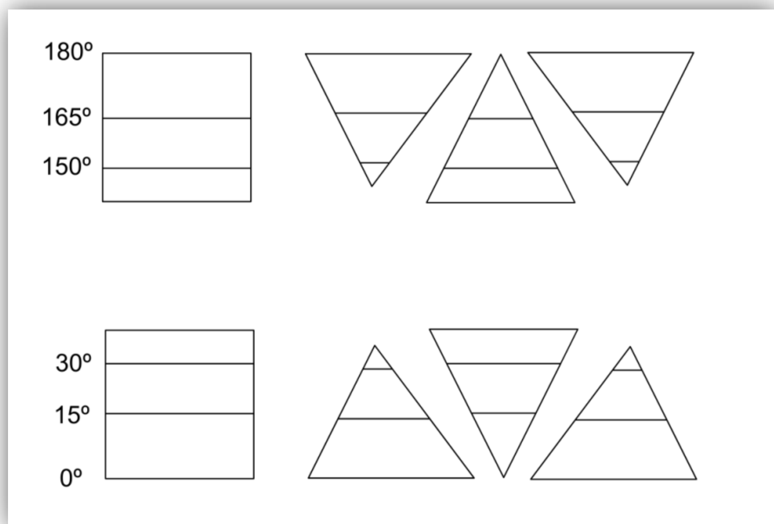

Figure 69: Pressure Changes on Tri-Dome Base Elements
Source: Primary

Example of 90° to 75° on a roof element of the windward side:

$$\text{Force}_{90°\text{-}75°} = \text{Area}_{90°\text{-}75°} \times \frac{(P90° + P75°)}{2}$$

$$-0.367kN = 0.307m^2 \times \frac{(-1.31kPa + \ -1.09kPa)}{2}$$

Table 16: Roof Element on Windward Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
90°-75°	0.307	-0.367	-82.534
75°-60°	0.766	-0.667	-149.881
60°-45°	1.229	-0.535	-120.323
45°-30°	0.671	-0.037	-8.208

Source: Primary

Table 17: Roof Element on Leeward Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
90°-105°	0.307	-0.384	-86.286
105°-120°	0.766	-0.750	-168.616
120°-135°	1.229	-0.535	-120.323
135°-150°	0.671	0.146	32.832

Source: Primary

Table 18: Rectangular Element on Pressure Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
30°-45°	1.340	0.292	65.587
15°-30°	2.002	1.526	342.965
0°-15°	2.604	2.693	605.402

Source: Primary

Table 19: Rectangular Element on Suction Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
135°-150°	1.340	-0.073	-16.397
150°-165°	2.002	0.436	97.990
165°-180°	2.604	0.992	223.043

Source: Primary

Table 20: Base Inverted Triangular Element on Pressure Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
30°-45°	1.218	-0.066	-14.901
15°-30°	1.194	0.260	58.453
0°-15°	0.561	0.214	48.054

Source: Primary

Table 21: Base Inverted Triangular Element on Suction Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
135°-150°	1.218	0.265	59.603
150°-165°	1.194	0.910	204.585
165°-180°	0.561	0.580	130.431

Source: Primary

Table 22: Base Triangular Element on Pressure Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
30°-45°	0.094	0.020	4.601
15°-30°	0.816	0.621	139.713
0°-15°	2.063	2.134	479.730

Source: Primary

Table 23: Base Triangular Element on Suction Side

	Area (m2)	Force Total (kN)	Total Force (lbs)
135°-150°	0.094	-0.005	-1.150
150°-165°	0.816	0.178	39.918
165°-180°	2.063	0.786	176.742

Source: Primary

Tape Stress per Inch

$$Load\ on\ Tape = \frac{\sum Rectangle + \sum Base\ Triangle}{(8' \times 12)}$$

$$18.24\ \frac{lb}{in} = \frac{(65.587lb + 342.965lb + 605.402lb) + (4.601lb + 139.713lb + 479.730lb)}{8' \times 12}$$

Total Uplift Force

X = Σ windward uplift
Y = Σ leeward uplift
$F_{uplift} = 3(\mathrm{X}) + 3(\mathrm{Y})$
$F_{uplift} = 3(408.06\ \mathrm{lb}) + 3(360.95\ \mathrm{lb}) = 2307\ lb$

Tie Down Tensile Resistance

Tie down forces are shown in Figure 70.

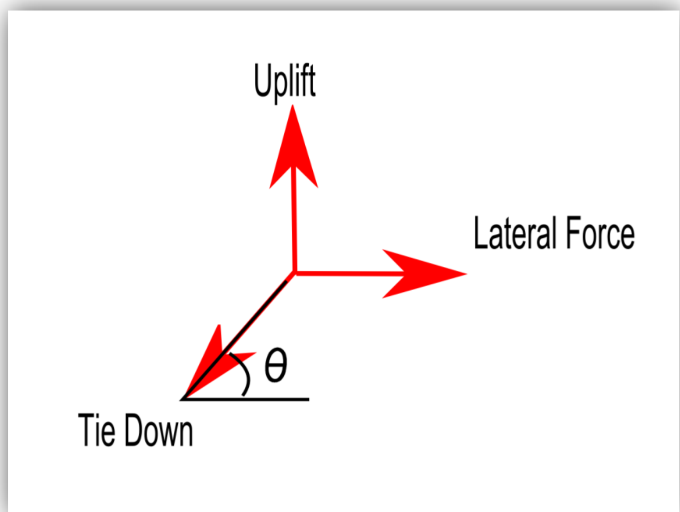

Figure 70: Tie Down Force Diagram
Source: Primary

$$F = \frac{F_{lateral}}{\cos\theta}\ or\ F = \frac{F_{uplift}}{\sin\theta}$$

$$F = \frac{2307\ lb}{cos48.5°} = 3080\ lb$$

$$F = \frac{1993\ lb}{sin48.5°} = 3007\ lb$$

$3080\ lb > 3007\ lb \therefore use\ 3080\ lb$

Rope Tensile Resistance

$$F_{rope} = \frac{F_{tie\ down}}{Knot\ Reduction}$$

$$F_{rope} = \frac{3080\ lb}{0.61} = 5050\ lb$$

Rope Compressive Stress

$$\sigma = \frac{Force}{diameter \times Length}$$

$$\sigma = \frac{3080\ lb}{0.75\ in \times (3 \times 8' \times 12)} = 14.26\ PSI$$

Failed Tie Down

$$\Sigma \mathrm{F}_x = -F_{acting} + 2(F_{adj\ Tie\ Down} \times cos60°)$$

$$F_{adj\ Tie\ Down} = \frac{3080lb}{2 \times cos60°} = 3080\ lb$$

Forces on Tape

$$F = \frac{F_{lateral}}{\cos\theta}\ or\ F = \frac{F_{uplift}}{\sin\theta}$$

$$F = \frac{1638\ lb}{cos49°} = 2497\ lb$$

$$F = \frac{408\ lb}{sin49°} = 541\ lb$$

$$F_{per\ inch} = \frac{Load}{Distance}$$

$$F_{per\ inch} = \frac{2497\ lb}{(8' \times 12)} = 26\frac{lb}{in}$$

Panel Flexural Resistance at 8’

$$Vr = \frac{P}{2}$$

$$Vr = \frac{1035.7N}{2} = 517.85N = 0.51785kN$$

$$Mr = Vr \times \frac{l_{sample}}{2}$$

$$Mr = 0.51785kN \times \frac{0.474m}{2} = 0.1227kNm$$

$$Mr = \frac{wl_{bottom}^2}{8}$$
$$w_r = \frac{8 \times 0.1227kNm}{(2.4384m)^2} = 0.16509\frac{kN}{m}$$

Maximum Pressure Forces Between 0° and 15°

$$w_f = Pressure \times width$$

$$w_f = 1.09kPa \times 0.15m = 0.1635\frac{kN}{m}$$
$$F.S. = \frac{0.16509}{0.1635} = 1.01$$

Maximum Suction Forces Between 75° and 90°

$$l_{suction} = 0.728m$$

$$w_f = 1.31kPa \times 0.15m = 0.1965\frac{kN}{m}$$

$$w_r = \frac{8 \times 0.1227kNm}{(0.728m)^2} = 1.85kPa$$

$$F.S. = \frac{1.85}{0.16509} = 11.2$$

Material Properties Calculation

Bending Stress σ_s

Calculations to support information found in Table 6 & 7 follows:

Bending Stress $\sigma_s = \frac{\mathbf{3pl}}{\mathbf{2wt^2}}$ [30]

p—Yield Force, different values for different materials.
l—Length
w—Width, w = 150mm
t—Thickness

EKOTherm Panel

$$\sigma_s = \frac{3pl}{2wt^2} = \frac{3 \text{ x } 973.6N \text{ x } 460mm}{2 \text{ x } 150mm \text{ x } (40mm)^2} = 2.80 \text{ MPa}$$

Enerfoil Panel

$$\sigma_s = \frac{3pl}{2wt^2} = \frac{3 \text{ x } 1080.6N \text{ x } 460mm}{2 \text{ x } 150mm \text{ x } (38mm)^2} = 3.44 \text{ MPa}$$

Enerfoil panel cut in half and the two parts taped together with 150mm Bi-Directional Filament Tape

$$\sigma_s = \frac{3pl}{2wt^2} = \frac{3 \text{ x } 1035.7N \text{ x } 460mm}{2 \text{ x } 150mm \text{ x } (38mm)^2} = 3.30 \text{ MPa}$$

Enerfoil panel cut in half and the two parts taped together with 48mm Duct Tape

$$\sigma_s = \frac{3pl}{2wt^2} = \frac{3 \text{ x } 766.4N \text{ x } 460mm}{2 \text{ x } 150mm \text{ x } (38mm)^2} = 2.44 \text{ MPa}$$

Bending of Flexural Modulus E_s

Bending of Flexural Modulus Es= $\frac{\boldsymbol{pl^3}}{\boldsymbol{4wt^3y}}$ [the same as the green one in Materials Testing]

y—Deflection at Yield Point [30]

EKOTherm Panel

$$E_s = \frac{\boldsymbol{pl^3}}{\boldsymbol{4wt^3y}} = \frac{973.6N \text{ x } (460mm)^3}{4 \text{ x } 150mm \text{ x } (40mm)^3 \text{ x}16.75mm} = 147.34 \text{ MPa}$$

Enerfoil Panel

$$E_s = \frac{\boldsymbol{pl^3}}{\boldsymbol{4wt^3y}} = \frac{1080.6N \text{ x } (460mm)^3}{4 \text{ x } 150mm \text{ x } (38mm)^3 \text{ x } 55.30mm} = 57.77 \text{ MPa}$$

Enerfoil panel cut in half and the two parts taped together with 150mm Bi-Directional Filament Tape

$$E_s = \frac{\boldsymbol{pl^3}}{\boldsymbol{4wt^3y}} = \frac{1035.7N \text{ x } (460mm)^3}{4 \text{ x } 150mm \text{ x } (38mm)^3 \text{ x } 55.00mm} = 55.67 \text{ MPa}$$

Enerfoil panel cut in half and the two parts taped together with 48mm Duct Tape

$$E_s = \frac{\boldsymbol{pl^3}}{\boldsymbol{4wt^3y}} = \frac{766.4N \text{ x } (460mm)^3}{4 \text{ x } 150mm \text{ x } (38mm)^3 \text{ x } 19.80mm} = 114.44 \text{ MPa}$$

Scale Model Impact Load Calculation

As shown in Figure 71 below: F = mgtanφ; tanφ = $\cos^{-1}(\frac{H-h}{d})$

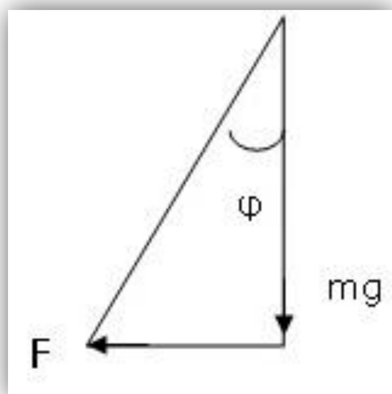

Figure 71: Force Diagram
Source: Primary

F—Impact force on the testing panel, N
m—Mass of the sandbag, 25kg
φ—Angle between the vertical to the rope, radians
H—Distance between top supporting and ground, 1.55 m
h—Height of sandbag, m, from Tables 9 & 10
d—Distance between top supporting and bottom of sandbag, m, from Table 9 & 10

Calculations to support the impact force F on the panel at different tests found in Table 9 and 10 follows:

Impact Test

Test 1: h=0.9144m, d=1.35m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.9144}{1.35})$ = 1.081

F = mgtanφ =25kg x 9.81 m/s^2 x 1.081= 459.5595N

Test 2: h=0.9900m, d=1.34m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.9900}{1.34})$ = 1.140

F = mgtanφ =25kg x 9.81 m/s^2 x 1.140= 533.1447N

Test 3: h=0.9800m, d=1.35m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.9800}{1.35})$ = 1.135

F = mgtanφ =25kg x 9.81 m/s^2 x 1.140= 526.5049N

Test 4: h=0.6096m, d=1.50m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.6096}{1.50})$ = 0.893

F = mgtanφ =25kg x 9.81 m/s^2 x 1.140= 304.7655N

Repair Test

Test 1: h=0.6096m, d=1.39m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.6096}{1.39})$ = 0.828

F = mgtanφ =25kg x 9.81 m/s^2 x 0.828= 266.9468N

Test 2: h=0.7620m, d=1.39m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.7620}{1.39})$ = 0.968

F = mgtanφ =25kg x 9.81 m/s^2 x 0.968= 356.3773N

Test 3: h=0.9144m, d=1.35m

tanφ = $\cos^{-1}(\frac{H-h}{d})$ = $\cos^{-1}(\frac{1.55-0.9144}{1.35})$ = 1.096

F = mgtanφ =25kg x 9.81 m/s^2 x 1.096= 476.9829N

Appendix B: Material Specifications

Foil Tape

3M

Aluminum Foil Tape

431 • 439L (Linered)

Technical Data

Product Description

3M™ Aluminum Foil Tape 431 and 439L is a 2-mil nominal dead soft aluminum foil with transparent acrylic adhesive for many permanent sealing, holding, splicing or masking applications requiring the protection offered by a foil backing.

IMPORTANT: 3M™ Aluminum Foil Tape 431 and 439L are not intended for medical usage. Neither 3M nor the Food and Drug Administration have evaluated or reviewed this tape for medical application. User assumes all risk and liability whatsover in connection with usage of product in a medical application.

Product Construction

Backing	Adhesive	Color	Liner (3M tape 439L)	Standard Roll Length
Aluminum foil	Acrylic	Shiny silver	Tan kraft paper with silicone release	60 yds. (55 m)

Typical Physical Properties

Note: The following technical information and data should be considered representative or typical only and should not be used for specification purposes.

			ASTM Test Method
Adhesion to Steel:		41 oz./in. width (45 N/100 mm)	D-3330
Tensile Strength at Break:	3M tape 431	19 lbs./in. width (338 N/100 mm)	D-3759
	3M tape 439L	18 lbs./in. width (315 N/100 mm)	D-3759
Elongation at Break:	3M tape 431	5%	D-3759
	3M tape 439L	3%	
Backing Thickness:		1.9 mils (0.05 mm)	D-3652
Total Tape Thickness:		3.1 mils (0.08 mm)	D-3652
Liner Thickness:	3M tape 439L	5.6 mils (0.14 mm)	D-3652
Water Vapor Transmission Rate:		0.1 gms H_2O/100 sq. in./24 hrs. (1.55 g/m^2/24 hrs.)	D-3833
Temperature Use Range:		-65° to 300°F (-54° to 149°C)	
Weight:		0.0096 lbs./yd./in. width (.0049 kg/m/24 mm)	

Features

- Flame resistant. Meets U.L. 723, Class "L" low flammability rating (File R 7311).
- Meets requirements of F.A.R. 25.853(a).
- Foil backing provides an excellent reflective surface for both heat and light.
- Good aging performance both indoors and outdoors.
- Low moisture vapor transmission rate offers excellent sealing and patching performance.
- Best results attained when applied to clean dry surface above 32°F (0°C).

3M™ Aluminum Foil Tape

431 • 439L (Linered)

Application Ideas	• Seal and patch tears in truck trailers, as well as other outdoor equipment. • Reflect heat away from sensitive areas. • Thermal heat conduction. • General purpose holding, patching, sealing applications – indoors or out. • Splicing of thin gauge foils. • Good maskant in electroplating of aluminum because it will not contaminate the bath. • Decorative.
Storage	Store under normal conditions of 60° to 80°F (16° to 27°C) and 40 to 60% R.H. in the original carton.
Shelf Life	To obtain best performance, use this product within 24 months from date of manufacture.
Product Use	All statements, technical information and recommendations contained in this document are based upon tests or experience that 3M believes are reliable. However, many factors beyond 3M's control can affect the use and performance of a 3M product in a particular application, including the conditions under which the product is used and the time and environmental conditions in which the product is expected to perform. Since these factors are uniquely within the user's knowledge and control, it is essential that the user evaluate the 3M product to determine whether it is fit for a particular purpose and suitable for the user's method of application.
Warranty and Limited Remedy	Unless stated otherwise in 3M's product literature, packaging inserts or product packaging for individual products, 3M warrants that each 3M product meets the applicable specifications at the time 3M ships the product. Individual products may have additional or different warranties as stated on product literature, package inserts or product packages. 3M MAKES NO OTHER WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OR ANY IMPLIED WARRANTY ARISING OUT OF A COURSE OF DEALING, CUSTOM OR USAGE OF TRADE. User is responsible for determining whether the 3M product is fit for a particular purpose and suitable for user's application. If the 3M product is defective within the warranty period, your exclusive remedy and 3M's and seller's sole obligation will be, at 3M's option, to replace the product or refund the purchase price.
Limitation of Liability	Except where prohibited by law, 3M and seller will not be liable for any loss or damage arising from the 3M product, whether direct, indirect, special, incidental or consequential, regardless of the legal theory asserted, including warranty, contract, negligence or strict liability.

ISO 9001:2000

This Industrial Adhesives and Tapes Division product was manufactured under a 3M quality system registered to ISO 9001:2000 standards.

3M

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Industrial Adhesives and Tapes Division

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Bi-Directional Filament Tape

Scotch®
Bi-Directional Filament Tape
8959

Technical Data — **March, 2003**

Product Description

Scotch® Filament Tape 8959 is a bi-directional specialty packaging tape reinforced with continuous glass yarns in both the longitudinal and transverse direction along with a biaxially oriented polypropylene backing. The polypropylene backing provides good abrasion, moisture and scuff resistance. The adhesive is specifically formulated to provide good adhesion to a wide variety of surfaces including metallic, plastic, and fiberboard.

Construction

Backing	Adhesive	Reinforcement	Backing Color
3M™ Scotchpro™ film	Pressure sensitive synthetic rubber resin	Bi-directional glass yarn	Clear

Typical Physical Properties

Note: The following technical information and data should be considered representative or typical only, and should not be used for specification purposes.

		ASTM Test Method
Adhesion to Steel:	100 oz./in. width (109 N/100 mm width)	D-3330
Tensile Strength:	150 lbs./in. width (2600 N/100 mm width)	D-3759
Elongation at Break:	6%	D-3759
Total Thickness:	5.7 mil (0.14 mm)	D-3652

Features

- High cross-direction tensile strength.
- Allows printing and illustrations to be seen through the tape.
- Excellent shear and initial adhesion.
- Excellent aging.
- Protection of filaments and adhesive to provide longer package life.
- Performs better than paper backings when exposed to outdoor and humid environments.
- Resists center seams slitting in both machine and cross direction, increasing the performance of the tape.
- Excellent holding power under wide range of application conditions with minimum amount of tape.
- Hold with minimum rubdown, doesn't require water to activate.
- Boxes remain closed for long periods of time.

Scotch® Bi-Directional Filament Tape
8959

Available Sizes	Standard Widths:	.75 in. (19 mm), .98 in. (25 mm), 2.0 in. (50 mm), 3.0 in. (75 mm)
	Core Size (ID):	3 in. (76.2 mm)
	Lengths:	60 yds. (50 m)

Application Techniques

An extensive line of application equipment is available including portable hand-held dispensers and stationary definite-length dispensers. Application of Scotch® Filament Tape 8959 is most easily accomplished at room temperature. At colder tempertures, approaching 32°F (0°C), the adhesive becomes firm. Once applied, Scotch® Tape 8959 performs well throughout the normal temperature ranges typically encountered by packaged products in shipping and storage environments.

Storage Conditions

Store behind present stock. Store in a clean, dry place. Temperature of 40-80°F (4-26°C) and 40-50% relative humidity are recommended. Rotate your stock.

Precautionary Information

Refer to Product Label and Material Safety Data Sheet for health and safety information before using this product. For additional health and safety information, call 1-800-364-3577 or (651) 737-6501.

For Additional Information

To request additional product information or to arrange for sales assistance, call toll free 1-800-362-3550 or visit www.3M.com/packaging. Address correspondence to: 3M Industrial Adhesives and Tapes Division, Building 21-1W-10, 900 Bush Avenue, St. Paul, MN 55106. Our fax number is 651-733-9175. In Canada, phone: 1-800-364-3577. In Puerto Rico, phone: 1-787-750-3000. In Mexico, phone: 52-70-04-00.

Important Notice

Limitation of Remedies and Liability

ISO 9002

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3M Center, Building 21-1W-10, 900 Bush Avenue
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10% post-consumer

Printed in U.S.A.
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Enerfoil Panel

IKO Enerfoil

Typical Physical Properties

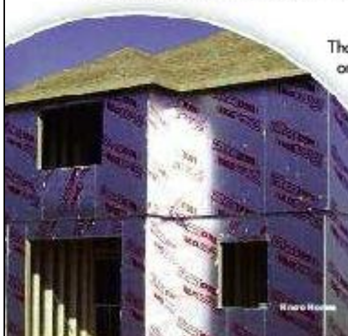
Characteristic	Units	Typical Value	Specification	Test Method	Standard Limits
Length Tolerance	in. (mm)	± 0.16 (± 4)	CAN/ULC-S704	ASTM C303	+ 0.25 (+ 6) - 0.16 (- 4)
Width Tolerance	in. (mm)	± 0.08 (± 2)	CAN/ULC-S704	ASTM C303	+ 0.16 (+ 4) - 0.08 (- 2)
Dimensional Stability (MD/XD) At 70°C, 97% R.H.	%	< 2	CAN/ULC-S704	ASTM D2126	MAX: ± 2
Water Vapor Permeance	ng/Pa•s•m²	< 15	CAN/ULC-S704	ASTM E96	=/< 15
Water Absorption	% by Vol.	< 1.0	CAN/ULC-S704	ASTM D2842	MAX: 3.5
Compressive Strength	kPa (psi)	124 (18)	CAN/ULC-S704	ASTM D1621	MIN: 110 (16)
Thermal Resistance Value* Thickness: 0.5 in. (12 mm) 0.75 in. (18 mm) 1.0 in. (25 mm) 1.5 in. (38 mm) 2.0 in. (50 mm) 3.0 in. (75 mm)	Btu•hr•ft²•°F (RSI)	3.1 (0.54) 4.5 (0.81) 6.2 (1.08) 9.3 (1.62) 12.4 (2.16) 18.6 (3.24)	CAN/ULC-S704	ASTM C518*	-
Service Temperature	°F (°C)	-40 to 212 (-40 to 100)	-	-	-
Flame Spread Index Smoke Density Index	-	< 55 < 100	-	ASTM E84	-

*Stated thermal resistance values are based upon conditioning requirements and test methodology found in ULC S-704 and ASTM C518 for foil-faced polyisocyanurate insulation. As a conservative estimate for long-term thermal resistance design value, R6 (RSI 1.05) per inch thickness is typically used. Since R-value claims among various polyisocyanurate brands may vary, it is best to consult independently verified test data such as that found in Canadian Construction Materials Centre (CCMC) Evaluation reports. Please see IKO's CCMC Evaluation Report #13188-L (as well as CCMC Report #'s 12422-R and 13104-L) for more information.

Storage

- It is recommended that **Enerfoil** be stored indoors.
- If left outside, ensure that it is covered with a moisture-resistant material.
- Keep on a level surface, elevated at least 4" (102 mm) above ground.

Note: **Enerfoil** should not be used below grade where it is subject to water infiltration.



Thank you for considering IKO Premium Insulation products. For additional information on IKO's full line of superior Building Envelope, Roofing and Waterproofing products please call: **1-888-766-2468** or visit our web site at:

www.iko.com

Note: The information in this literature is subject to change without notice. All values shown are approximate. IKO assumes no responsibility for errors that may appear in this literature.

IKO Setting the Standard

IKO TECHNICAL DATA SHEET

STOCK NO. 41803XX ***March, 2009***

IKO ENERFOIL SHEATHING

IKO Enerfoil is a rigid, polyisocyanurate foam insulation with high thermal properties. It is constructed from closed cell polyisocyanurate foam core bonded on each side to aluminum foil facers during the manufacturing process. IKO Enerfoil is designed to be non-structural sheathing in cavity wall, stud wall or cathedral ceiling construction. IKO Enerfoil Sheathing is dimensionally stable and can be sized with ease. It is also lightweight and easy to handle. It has a high thermal R-value that provides outstanding insulation protection, which helps to reduce costs. IKO Enerfoil Sheathing is available in a board size of 1220 mm x 2440 mm (4' x 8') or 1220 mm x 2740 mm (4' x 9') and in a wide range of thicknesses from 12 mm to 76 mm (1/2"-3"). IKO Enerfoil Sheathing is produced according to the requirements of CAN/ULC S-704 for Type 1, Class 1 materials, and ASTM C1289 Type I, Class 1. It is also listed with CCMC under report number 13188-L. IKO's roofing products are produced and designed with consideration for environmental responsibility and sustainability, incorporating quality recycled components whenever possible, manufactured in facilities that comply with the most stringent government environmental regulations, and can therefore be a part of any "green" construction project.

CHARACTERISTIC		UNITS	NOMINAL VALUE	SPECIFICATION	TEST METHOD	STANDARD LIMITS
LENGTH TOLERANCE:		mm (in)	±4 (±0.16)	CAN/ULC-S704	ASTM C303	+ 6 (+ 0.25) -4 (-0.16)
WIDTH TOLERANCE:		mm (in)	±2 (±0.08)	CAN/ULC-S704	ASTM C303	+ 4 (+ 0.16) -2 (-0.08)
DIMENSIONAL STABILITY : (AT 70°C, 97% R.H.)	MD: XD:	%	PASS	CAN/ULC-S704	ASTM D2126	MAX: ± 2
WATER VAPOUR PERMEANCE:		ng/Pa•s•m²	PASS	CAN/ULC-S704	ASTM E96	≤ 15
WATER ABSORPTION:		% by Vol.	PASS	CAN/ULC-S704	ASTM D2842	MAX: 3.5
COMPRESSIVE STRENGTH :		kPa (psi)	PASS	CAN/ULC-S704	ASTM D1621	MIN: 110 (16)
THERMAL RESISTANCE VALUE THICKNESS:	12mm (0.5 in.) 18mm (0.75 in.) 25mm (1.0 in.) 38mm (1.5 in.) 50mm (2.0 in.) 75mm (3.0 in.)	RSI (Btu•hr•ft²•°F)	0.54 (3.1) 0.81 (4.5) 1.08 (6.2) 1.62 (9.3) 2.16 (12.4) 3.24 (18.6)	CAN/ULC-S704	ASTM C518	-
FLEXURAL STRENGTH :	MD: XD:	kPa	618 / 805	CAN/ULC-S704	ASTM C203	≥ 275
TENSILE STRENGTH:		kPa	69	CAN/ULC-S704	ASTM D1623	≥ 24
SERVICE TEMPERATURE:		°C (°F)	-40 to 100 (-40 to 212)	-	-	-
FLAME SPREAD INDEX: SMOKE DENSITY INDEX:		-	≤ 55 ≤ 125	-	ASTM E84	-

Stated thermal resistance values are based upon conditioning requirements and test methodology found in ULC S-704 and ASTM C518 for foil-faced polyisocyanurate insulation. As a conservative estimate for long-term thermal resistance design value, R6 (RSI 1.05) per inch thickness is typically used. Since R-value claims among various polyisocyanurate brands may vary, it is best to consult independently verified test data such as that found in Canadian Construction Materials Centre (CCMC) Evaluation reports. Please see IKO's CCMC Evaluation Report # 13188-L (as well as CCMC Report #'s 12422-R and 13104-L) for more information.

The information on this Technical Data sheet is based upon data considered to be true and accurate, based on laboratory tests and production measurements, and is offered solely for the user's consideration, investigation and verification. Nothing contained herein is representative of a warranty or guarantee for which the manufacturer can be held legally responsible. The manufacturer does not assume any responsibility for any misrepresentation or assumptions the reader may formulate.

IKOTherm Panel

TECHNICAL DATA SHEET

STOCK NO. 4180XXX | **April, 2010**

IKOTHERM

IKOTherm polyisocyanurate foam insulation is a rigid, polyisocyanurate foam insulation with high thermal properties. It is constructed from closed cell polyisocyanurate foam core bonded on each side to fiber-reinforced facers during the manufacturing process. IKOTherm polyisocyanurate foam insulation is designed to be part of modified bitumen, built-up, or single-ply roof system. IKOTherm polyisocyanurate foam insulation is dimensionally stable and can be sized with ease. It is also lightweight and easy to handle. It has a high thermal r-value that provides outstanding insulation protection, which helps to reduce heating and cooling costs. IKOTherm polyisocyanurate foam insulation is available in board sizes of 1220 mm x 2440 mm (4' x 8'), or 1220 mm x 1220 mm (4' x 4'), and in a wide range of thicknesses. IKOTherm polyisocyanurate foam insulation is produced according to the requirements of CAN/ULC S-704 for Type 2, Class 3 materials, and ASTM C1289 Type II, Class 1, Grade 2. This product is listed under CCMC listing #13037-L and is FM and UL approved. IKO's roofing products are produced and designed with consideration for environmental responsibility and sustainability, incorporating quality recycled components whenever possible, manufactured in facilities that comply with the most stringent government environmental regulations, and can therefore be a part of any "green" construction project.

CHARACTERISTIC	UNITS	TYPICAL VALUE	SPECIFICATION	TEST METHOD	STANDARD LIMITS
LENGTH TOLERANCE:	mm (in)	±4 (± 0.16)	CAN/ULC-S704	ASTM C303	+ 6 (+ 0.25) -4 (-0.16)
WIDTH TOLERANCE:	mm (in)	±2 (± 0.08)	CAN/ULC-S704	ASTM C303	+ 4 (+ 0.16) -2 (-0.08)
DIMENSIONAL STABILITY(MD/XD) AT -29°C: AT 80°C: AT 70°C, 97% R.H.:	 % % %	 -0.02/-0.03 -0.02/-0.17 0.30/0.80	CAN/ULC-S704	ASTM D2126	 max: ±2 max: ±2 max: ±2
WATER VAPOUR PERMEANCE:	ng/Pa•s•m²	PASS	CAN/ULC-S704	ASTM E96	>60
WATER ABSORPTION:	% by Vol.	PASS	CAN/ULC-S704	ASTM D2842	max: 3.5
COMPRESSIVE STRENGTH[1]:	kPa (psi)	PASS	CAN/ULC-S704	ASTM D1621	min: 140 (20)
FLEXURAL STRENGTH (MD/XD):	kPa (psi)	607/479 (88.5/69.8)	CAN/ULC-S704	ASTM C203	min: 275 (39.3)
LONG TERM THERMAL RESISTANCE (LTTR): THICKNESS: 25 mm (1 in) 50 mm (2 in) 75 mm (3 in) 100 mm (4 in)	m^2•K/W (LTTR)	 1.05 (6.0) 2.10 (12.1) 3.21 (18.5) 4.33 (25.0)	CAN/ULC-S704	CAN/ULC-S770	-

1 Tested on cured sample, using chord modulus at 10% deformation.
Note: LTTR values shown are for "metric" thicknesses, and will vary slightly from 1", 2", 3" and 4" values.
172 kpa (25 psi) product available by special request, which would conform to ASTM C1289 Grade 3 requirements.

The information on this Technical Data sheet is based upon data considered to be true and accurate, based on laboratory tests and production measurements, and is offered solely for the user's consideration, investigation and verification. Nothing contained herein is representative of a warranty or guarantee for which the manufacturer can be held legally responsible. The manufacturer does not assume any responsibility for any misrepresentation or assumptions the reader may formulate.

IKOTHERM POLYISOCYANURATE

IKOTherm is a rigid, polyisocyanurate foam insulation with high thermal properties. It is constructed from a closed cell polyisocyanurate foam core that is bonded on each side to fiber-reinforced facers during the manufacturing process. IKOTherm is designed to be part of a modified bitumen, built-up or single-ply roof system.

IKOTherm insulation is dimensionally stable and can be sized with ease. It is also lightweight and easy to handle. Its high R-value thermal resistance provides outstanding insulation protection, which helps to reduce energy costs.

IKOTherm is available in standard 1220 mm x 2440 mm (4' x 8') or 1220 mm x 1220 mm (4' x 4') sizes. IKOTherm Tapered is available in 1220 mmx 1220 mm (4' x 4') size. The top surface of IKOTherm Tapered is manufactured with a slope of 1/16", 1/8", 3/16", 1/4" or 1/2" per foot to provide for positive roof drainage.

FEATURES AND BENEFITS

- Cost-effective.
- Compatible with all types of roofing systems.
- Dimensionally stable.
- Excellent compressive strength.
- Excellent thermal R-value.
- Excellent performance in fire tests.
- High-temperature resistance for hot mopping applications.
- Approved for direct installation on the roof deck without a thermal barrier (CAN/ULC S126M compliance).
- Meets U.S. (ASTM C1289) and Canadian (CAN/ULC S704) product standards.
- ISO 9001-2000 Registered Facilities.

BUR & MODIFIED BITUMEN SYSTEMS

IKOTherm is applied by fastening each panel to the roof deck with Factory Mutual approved fasteners (appropriate to the deck type) and plates. IKOTherm panels of up to a maximum 1220 mm x 1220 mm (4' x 4') may be adhered to a suitably prepared concrete roof deck and vapor barrier with a full mopping of hot Type II or Type III asphalt or approved cold adhesive. The edges of the board must butt up against each other and the joints of adjacent panels must be staggered. IKO, NRCA and the CRCA recommend the installation of an overlayment board prior to the application of built-up roofing, such as 12.5 mm (1/2") IKO Fiberboard or 3 mm (1/8") IKO Protectoboard. For best roof system performance, an overlayment board should be installed under the roof membrane. The roof covering can then be installed according to the membrane manufacturer's specifications.

BALLASTED SINGLE-PLY SYSTEMS

IKOTherm panels are loosely laid on the roof deck. The edges of the board must butt up against each other and the joints of adjacent panels must be staggered. The roof covering can then be installed according to the membrane manufacturer's specifications.

FULLY ADHERED SINGLE-PLY SYSTEM

IKOTherm panels are securely fastened to the roof deck with Factory Mutual approved fasteners (appropriate to the deck type) and plates. IKOTherm panels of up to 1220 mm x 1220 mm (4' x 4') may also be adhered to a suitably prepared concrete roof deck and vapor barrier with a full mopping of hot Type II or Type III asphalt. The edges of the board must butt up against each other and the joints of adjacent panels must be staggered. The roof covering can then be installed according to the membrane manufacturer's specifications.

TEST RESULTS

Property	Test Method	Typical Value
Thermal Performance	CAN/ULC S770	See Thermal charts
Compressive Strength	ASTM D1621	140 kPa (20 psi)*
Under Deck Flame Spread	CAN/ULC S126	PASS
Dimensional Stability	ASTM D2126	all conditions MD and XD: <2.0%
Water Vapor Permeance	ASTM E96	57 ng/(Pa·s·m²) (1 perm)
Water Absorption	ASTM D2842	1% by volume
Service Temperature	CAN/ULC S704	-73°C to 121°C (-100°F to 250°F)

*172 kPa (25 psi) product available by special request. All above IKOTherm test results were produced according to CAN/ULC S704, and ASTM C1289. Note: IKOTherm not to be used on exposed or inverted roofs.

THERMAL VALUES

Thickness*		RSI Units** LTTR	R-Value** LTTR
mm	Inches		
25	1.0	1.04	6.0
38	1.5	1.54	9.0
45	1.8	1.89	10.9
50	2.0	2.10	12.1
63	2.5	2.65	15.3
68	2.7	2.88	16.4
75	3.0	3.21	18.5
83	3.3	3.54	20.4
89	3.5	3.77	21.7
100	4.0	4.33	25.0

* Additional thicknesses available upon request. **Typical Values: The long term thermal resistance (LTTR) values of IKOTherm Roof Insulation were determined in accordance with CAN/ULC S704 using CAN/ULC S770. These values can be used as design R-Values that more closely represent the anticipated thermal performance over the life of isocyanurate foam insulation products. Note: The IKOTherm product is produced to "inch" thicknesses, so the R-value numbers should be regarded as more accurate than the RSI values, which have been calculated from the rounded mm equivalents.

Member of:

Thank you for considering IKO Premium Roofing products. For additional information on IKO's full line of superior Commercial/Industrial Roofing and Waterproofing products please call: **1-888-766-2468**, or visit our web site at: **www.iko.com**

Foamular Panel

07 21 13.13.OCC

FOAMULAR® C-200 Extruded Polystyrene Rigid Insulation
FOAMULAR® CodeBord® Extruded Polystyrene Rigid Insulation

Product Data Sheet

Components

Polystyrene insulation is manufactured from polystyrene resin and extruded into rigid boards.

Recycled materials incorporated into polystyrene board fabrication are obtained from one source:

- "Post-industrial" (or "pre-consumer") source: materials recycled from industry-wide manufacturing waste that can be recycled to fabricate polystyrene boards.

TECHNICAL DATA

Applicable Codes and Standards

Applicable National Building Code of Canada or provincial building Code

Canadian Standards (Underwriters Laboratories of Canada (ULC))

- CAN/ULC-S701, Standard for Thermal Insulation, Polystyrene, Boards and Pipe Covering
- CAN/ULC-S102.2, Standard Method of Test for Surface Burning Characteristics of Flooring, Floor Covering and Miscellaneous Materials and Assemblies

Canadian General Standards Board (CGSB)

- CGSB 71-GP-24M, Adhesive, Flexible, for Bonding Cellular Polystyrene Insulation

American Standards:

- ASTM C177, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
- ASTM C203, Standard Test Method for Breaking Load and Flexural Properties of Block-Type Thermal Insulation
- ASTM C518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
- ASTM D696, Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between -30°C and 30°C With a Vitreous Silica Dilatometer
- ASTM D1621, Standard Test Method for Compressive Properties of Rigid Cellular Plastics
- ASTM D2126, Standard Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging
- ASTM D2842, Standard Test Method for Water Absorption of Rigid Cellular Plastics
- ASTM E96, Test Methods for Water Vapor Transmission of Materials

Health Canada/Workplace Hazardous Materials Information System (WHMIS).

Visit www.owenscorning.ca for a current copy of the Material Safety Data Sheet (MSDS) for *"CELFORT® extruded polystyrene insulation".*

Canadian Construction Materials Centre (CCMC) Product Evaluation

FOAMULAR® C-200 and FOAMULAR® CodeBord® extruded polystyrene rigid insulation comply to CAN/ULC S701, Type 3 and have a CCMC listing.

Codes & Standards Compliance:

- Meets Montreal Protocol 2010, CFC, HCFC Free
- Zero Ozone Depletion Potential
- 70% Less Global Warming Potential

Product Evaluation Listing Number
CCMC 13431-L

TABLE 1 Physical Properties

Properties	Test Method	FOAMULAR® C-200 & FOAMULAR® CODEBORD® (CAN/ULC- S701, Type 3)
THERMAL RESISTANCE [1] R value per inch (ft² hr °F/BTU) RSI value per 25 mm (m² °C/W)	C518 or C177	5.0 0.87
COMPRESSIVE STRENGTH, min [2] (psi) (kPa)	D1621	20 140
WATER ABSORPTION (maximum % by volume)	D2842	0.40
WATER VAPOUR PERMEANCE, max. (Perm) (ng/Pa.s.m²)	E96	0.80 45
WATER CAPILLARITY	–	None
WATER AFFINITY	–	Hydrophobic
FLEXURAL STRENGTH, typical (psi) (kPa)	C203	44 300
LINEAR COEFFICIENT OF THERMAL EXPANSION (in/in/°F) (m/m/K)	Modified D696	2.7×10^{-5} 4.9×10^{-5}
DIMENSIONAL STABILITY, max. (% linear change)	D2126	1.5
MAXIMUM SERVICE TEMPERATURE (°F) (°C)	–	165 74

[1] Thermal resistance per inch of thickness (25 mm)

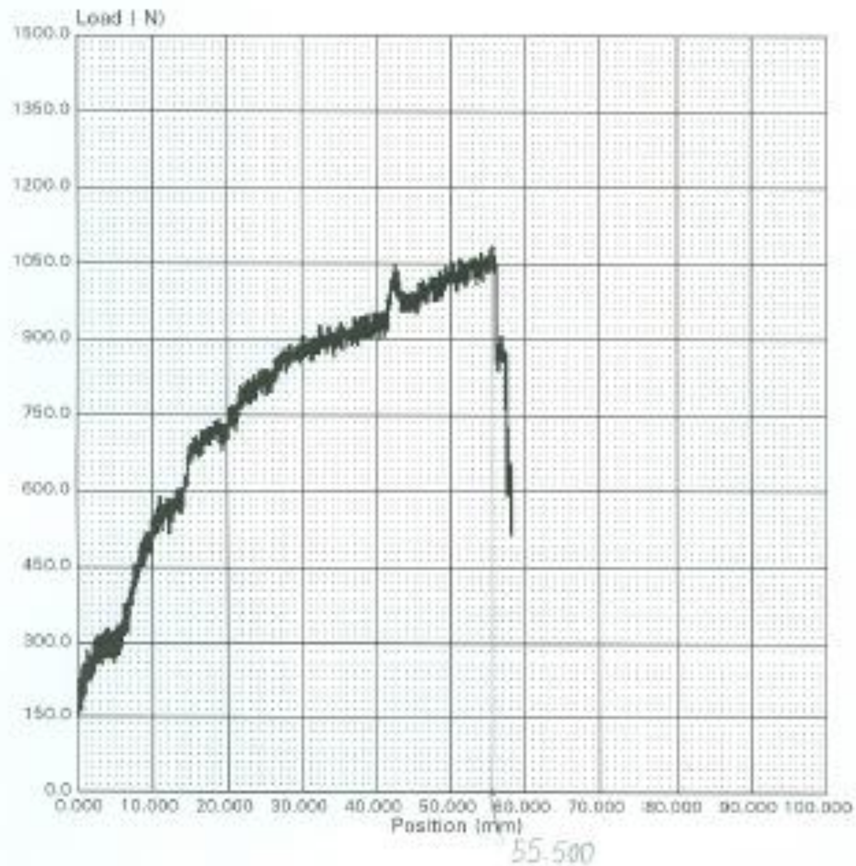
[2] at 10% deformation or yield

Appendix C: Flexural Test Data

Enerfoil Panel

RESULTS

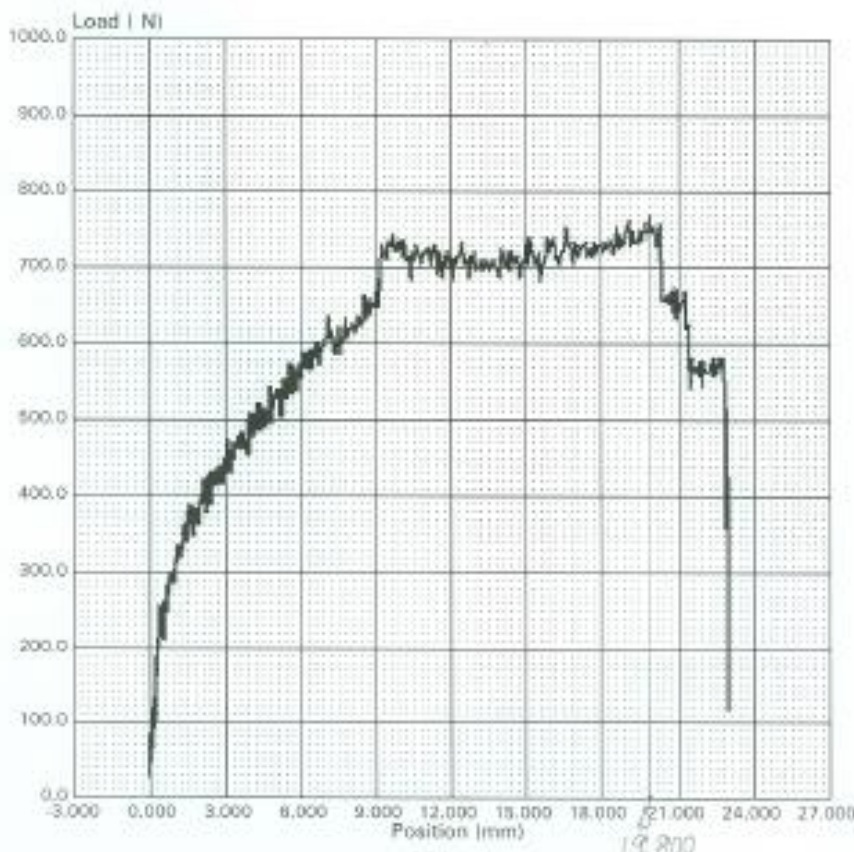
Date:	02-10-12
Time:	14:24:40
Data Buffer(% full):	26.8
Specimen ID#:	30
Specimen Type:	BEAM-Center Point Loading
Length (mm):	467.995
Gage Length (mm):	467.995
Area (sqmm):	376.8
Peak (N):	1080.6



Enerfoil Panel with Foil Tape

RESULTS

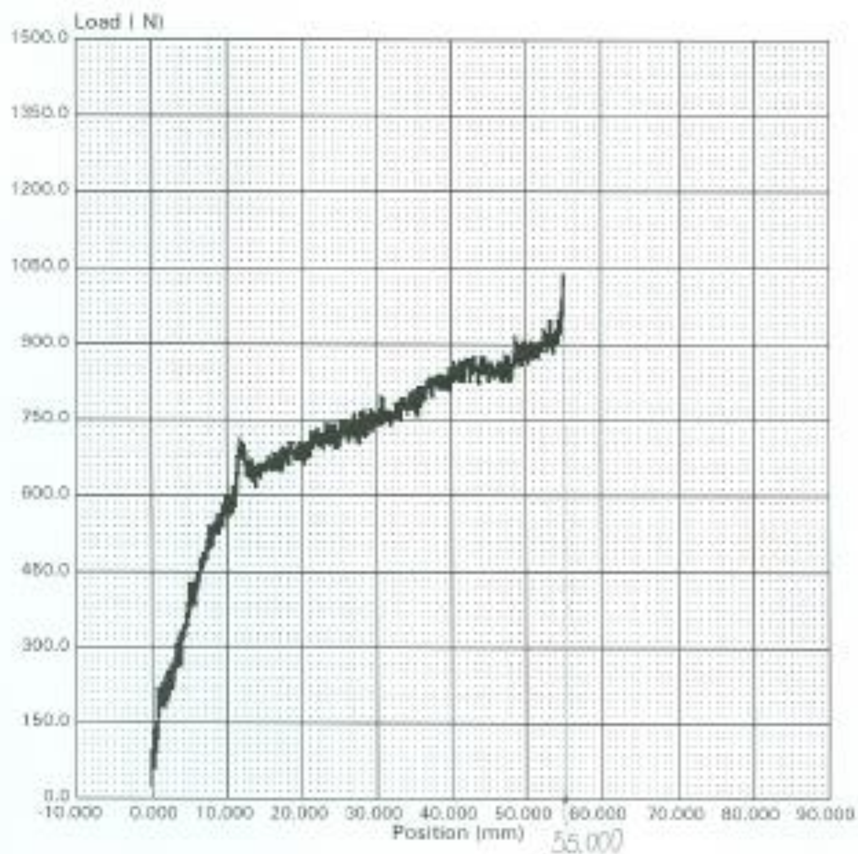
Date:	02-10-12
Time:	14:58:46
Data Buffer(% full):	5.9
Specimen ID#:	30
Specimen Type:	BEAM-Center Point Loading
Length (mm):	467.995
Gage Length (mm):	467.995
Area (sqmm):	376.8
Peak (N):	766.4



Enerfoil Panel with Bi-directional Filament Tape

RESULTS

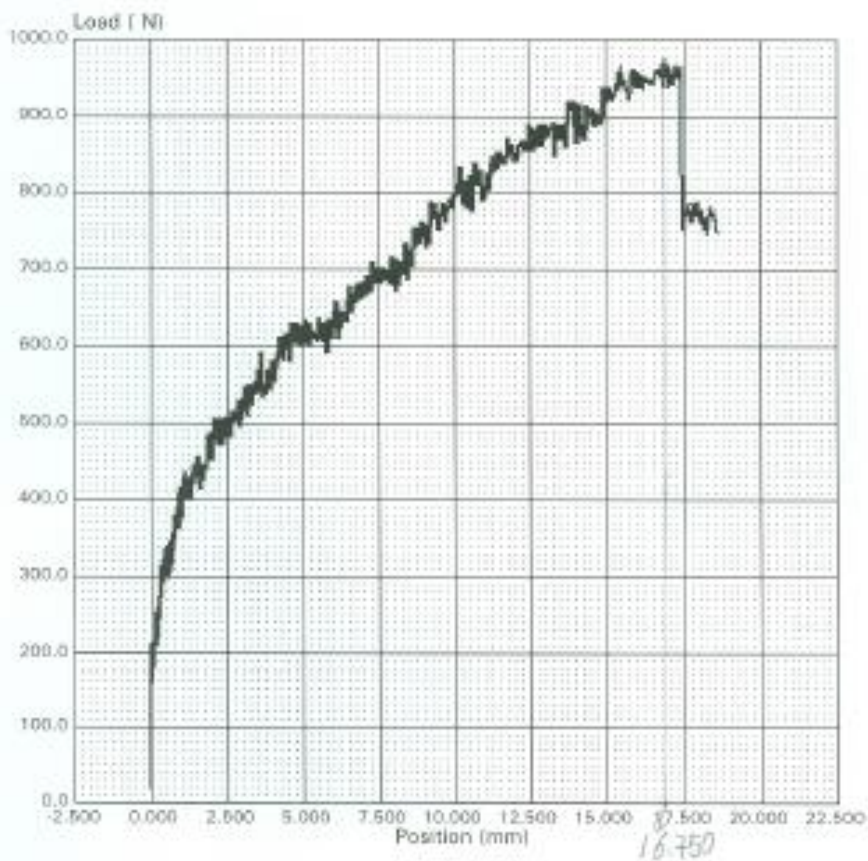
Date:	02-10-12
Time:	14:45:05
Data Buffer(% full):	12.3
Specimen ID#:	30
Specimen Type:	BEAM-Center Point Loading
Length (mm):	467.995
Gage Length (mm):	467.995
Area (sqmm):	376.8
Peak (N):	1035.7



IKOTherm Panel

RESULTS

Date:	02-10-12
Time:	14:08:17
Data Buffer(% full):	6.9
Specimen ID#:	30
Specimen Type:	BEAM-Center Point Loading
Length (mm):	467.995
Gage Length (mm):	467.995
Area (sqmm):	376.8
Peak (N):	973.6



Appendix D: Tri-Dome Specifications

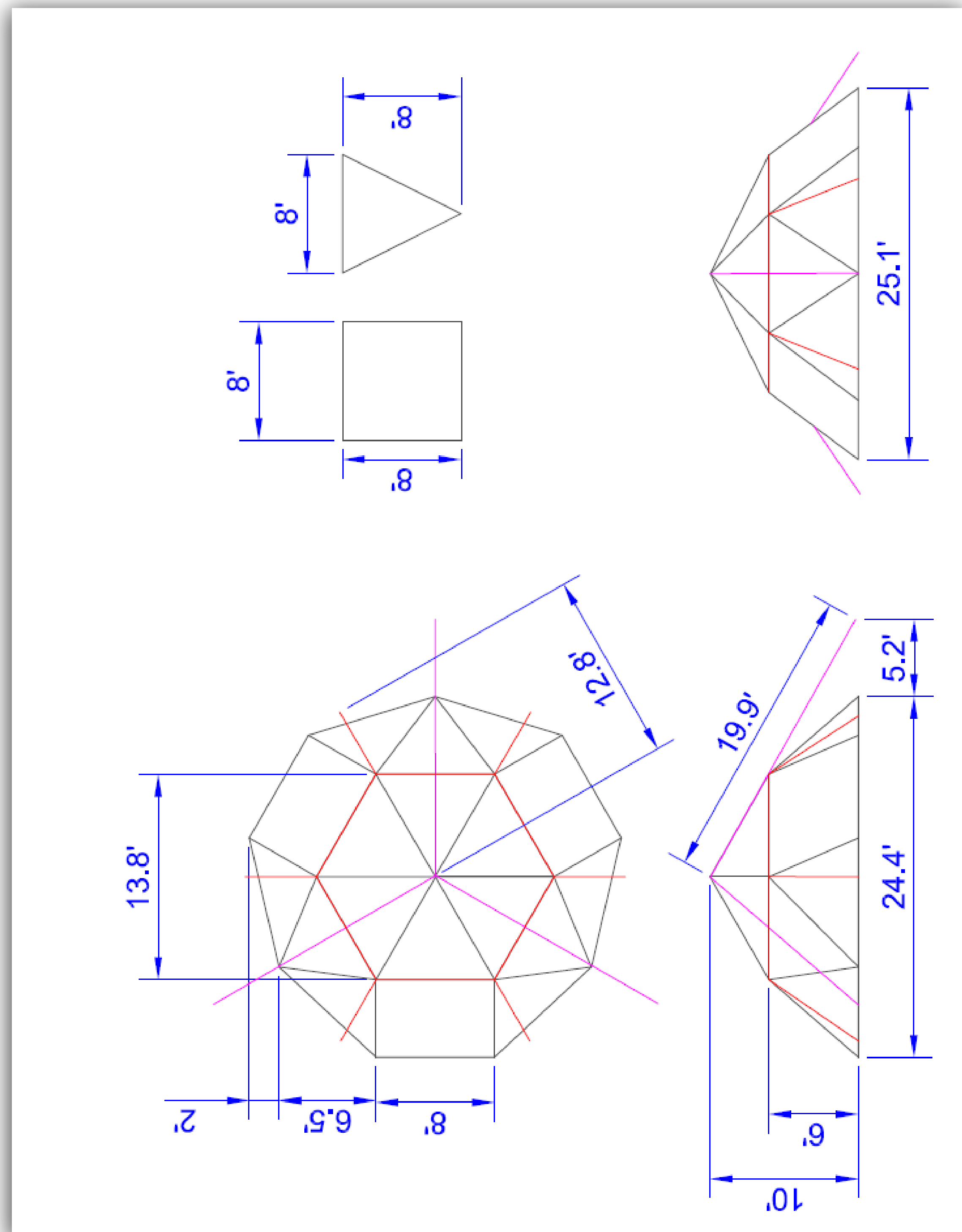


Figure 72: Tri-Dome Specifications
Source: Primary

Appendix E: Summary of Costs: Full-Size Tri-Dome

Table 24: Cost Summary

	Quantity	Price	Subtotal	Broker/GST	Total
JVCC 762-BD Bi-Directional Filament Strapping Tape 6 in. x 60 yds	5	34.12	170.60	43.61	214.21
Enerfoil 4ft x8ft x1.5in	21	33.14	695.94	34.80	730.74
Foil Tape 2.25 in x 50 yds	6	11.99	71.94	3.60	75.54
					1020.48

Source: Primary