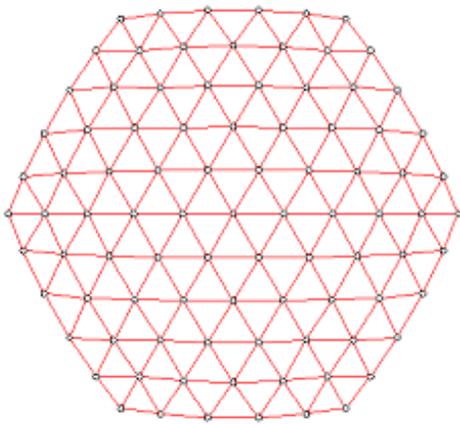


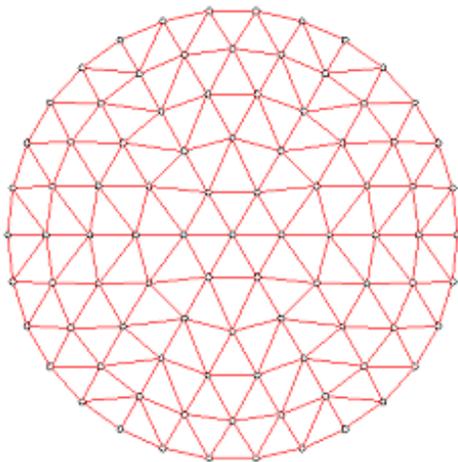
Aluminum Dome Design

Geometry Constraints

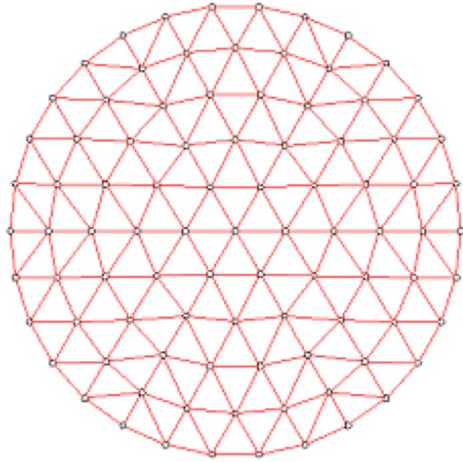
There are several geometry constraints in the design of an aluminum dome roof. The first constraint is the physical geometry. It would be ideal for a dome roof to have all of the beams the same length and all of the panels the same size. This would make design, manufacturing and construction simple. However, by making all the beams the same length, the dome would not have any curvature. It would be a flat surface and would not have much (if any) structural strength. The best dome geometry would be a geometry that maximizes structural strength and minimizes the number of different beam lengths and panel sizes. A design such as this one exists:



However, this design has an obvious problem. The base ring is not concentric unless the dome is a full hemisphere. Another geometry with all rings in the dome concentric is possible:



This geometry is used quite frequently in aluminum dome roofs. The concentric geometry has an obvious advantage. However, this design is not as efficient structurally as the first design. Another geometry used quite frequently in aluminum dome roofs is a combination of the two above geometries. In this design, there is a transition from the first geometry to a concentric base ring throughout the dome or within a few rings in the dome.



The geometry transition in the above example is subtle and barely noticeable in the plan view. This design is stiffer than the first design and it has a smaller variation in the beam lengths.

The final geometry of a dome may be further modified due to other geometry constraints. These constraints may dictate the final geometry. The most common are:

1. Aluminum coil width. A panel's shortest altitude must be less than the coil width.
2. Beam interference at the hubs. There must be adequate room between adjacent beams connecting at the hubs.
3. Load and structural constraints.

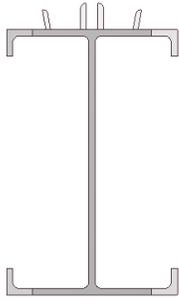
The engineering problem of the final geometry of an aluminum geodesic dome is common with many other engineering problems as it is comprised of the various design constraints.

Dome Components

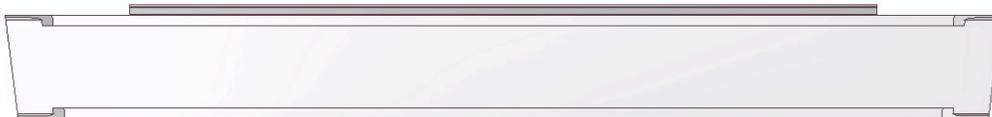
An aluminum geodesic dome is a relatively simple product with only 3 major fabricated components and several minor components. Major components are the components that comprise the majority of the dome material and fabrication cost. The minor components are components that are needed to complete the dome but usually the combined cost of these components is not more than 20% of the total dome cost. The 3 major components on a dome are the beams, connection hubs, and panels. The common minor components are the batten bars, supports, hub covers, flashing, vents, manways, skylights, etc.

Beams or Struts

The dome beams are extruded 6061-T6 or 6005A-T6 aluminum alloy. 6061-T6 and 6005A-T6 have the same minimum strength properties. 6005A-T6 is a relatively new alloy that has some advantages over 6061-T6. The main advantages are a better finish, less sensitive timeframe to quench after extruding, and its ability to be air quenched instead of water quenched for most extrusion sizes. Finally, it costs a little less, mainly due to the easier quenching process for the extruder. The protrusion on the top of the beam must be milled or cut back to allow the beam to bolt to the connection hub.



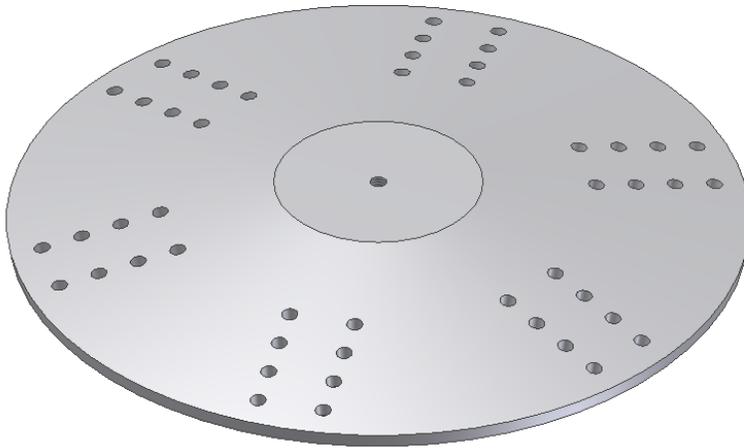
This aluminum dome beam extrusion is typical. Note the protrusions on the top. The protrusions are the attachments for the dome panels and batten bar. The batten bar holds the dome panels in place and is attached by a $\frac{1}{4}$ " tri-lobe screw in the slot at the center of the beam. The flange stiffeners at the end of each flange are typical for a thin-wall beam extrusion. The flange stiffeners increase the allowable compression and bending in a thin-wall shape by about 20-25%. They also increase the weak-axis moment of inertia, section modulus and radius of gyration without increasing the width of the beam. They are not needed on thicker shapes.



The above sketches show a 3d rendering of a fabricated dome beam.

Hubs

The hubs are the connections where the beams are joined. The hub is a circular dish with a center hole punched for placing on the forming die to coin the angle needed from the dish. The center hole is tapped on the top hub for attaching the hub cover. There are four possible common aluminum materials that can be used for the hubs: 6061-T6 extruded flat bar, 6063-T6 extruded flat bar, 6061-T6 hot rolled plate and 5052-H34 hot rolled plate.



Structural Analysis

An aluminum dome roof is a 3-dimensional space frame. The reactions in a small space frame can be solved with simple statics. However, an aluminum dome roof is usually not a small space frame. The solution of the reactions could easily be a system of linear equations with several thousand equations and several thousand unknowns. Therefore, the use of a finite element model is a necessity.

The FEA Model

FEA is an approximate solution method for a beam element very similar to numeric integration.

The FEA model is constructed from the calculated geometry of the dome. The protrusions at the top for the batten bar attachment are not used in calculating the centerline of the beam. The pier connection is also modeled using a series of beam elements. The dome is usually cantilevered toward the inside of the tank from the tank shell. The pier induces significant bending moments into the dome. Therefore, a design consideration is to keep the pier as short as possible. All connections between all beam elements are modeled as 100% moment resisting in both axis. The connection between the dome and the tank is modeled as a pinned connection with a frictionless slide in the radial direction. Boundary elements are placed at tangent and vertical locations from this point to model the frictionless slide, to get reactions in the tangent direction, and to get reactions in the vertical direction.

1. The dead load of the frame is calculated as a linear distributed load on the beam. This load is calculated from the cross sectional area of the beam + the cross sectional area of the batten bar + the cross sectional area of the protrusions on top of the beam. An additional point load is placed at each node location that is equal to the mass of the hub plates + the mass of the hub cover.
2. All other loads, dead load of the panels, wind, snow and seismic are calculated from the tributary areas of the panel supported by the adjacent beams. See Figure 9.

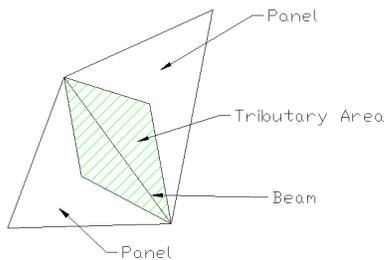


Figure 9
Tributary Area of Beam with 2 adjacent Panels.

Dome Stress Analysis

The method used for determining allowable stress is Part I-A Specification for Aluminum Structures Allowable Stress Design, The Aluminum Design Manual.

Allowable Stress Design with aluminum is in many ways similar to Allowable Stress Design with steel. The 6061-T6/6005A-T6 alloys used in this dome design have a minimum yield stress of 35 ksi. A36 steel is only 1 ksi higher. A common grade of aircraft aluminum alloy 2024-T4 has a minimum yield of 59 ksi. Some more exotic grades of aluminum have even higher minimum yield stress. Aluminum is a strong material. The alloys used in this dome are not the 5-10 ksi yield beer can alloys most people are familiar with. These alloys are high strength structural alloys. There are two primary differences between aluminum and steel that leads to several additional factors to check in aluminum design:

1. Aluminum can be easily extruded. Metal can be placed at exact locations in a structural member. Thin wall sections are easily made. Stiffeners can be easily added to a structural member. All of the structural members in this dome are extruded. These members cannot be rolled and they would be impossible to economically manufacture in steel.
2. The modulus of elasticity of aluminum is only 10100 ksi. Aluminum is about 3 times more flexible than steel.

As a result of the two above facts, there are several more rules in aluminum design when compared to steel design. Most of these rules deal with issues of local buckling of thin wall shapes, edge stiffening, other element stiffening, allowable compression and buckling. Most of these rules are given in Part VII Table 2-21 in the Aluminum Design Manual. Note: This table does not include all of the rules for Allowable Stress Design. The complete set of rules is in Part I-A.

Other Stress Considerations

A dome can be a non-linear structure! The linear stress analysis discussed in Sections 3 and 4 of this document may be invalid if the dome is non-linear. AWWA D103-97 addresses this issue in equation 39:

$$w = \frac{2,258 \times 10^6 (I_x A)^{1/2}}{(SF) R^2 L}$$

Where

- w = Allowable Load (pressure in PSF)
- I_x = Strong Axis Moment of Inertia of strut of the smallest strut in the dome
- A = Cross Sectional Area of Strut of the smallest strut in the dome.
- R = Spherical radius of dome in inches
- L = Average member length
- SF = Safety factor (1.65)

This formula was first published in ASCE *Journal of the Structural Division* in 1965 by Douglas Wright, in a paper entitled “Membrane Forces and Buckling in Reticulated Shells.” This concept was further expanded by Kenneth Buchert in “Split Rigidity Theory.” There are some important limitations in this theory. The equation assumes all dome members to be the same length. It is impossible to construct a dome with all of the members the same length. Therefore, an average length is used. The formula does not consider minute manufacturing defects or field installation defects in the geometry—the dome is assumed to be a perfect sphere at the hubs. The formula assumes all the struts have the same cross sectional area and moment of inertia. AWWA also applies this formula to all domes. In reality this formula is not applicable to all domes. Some domes are linear frames, some are non-linear frames, and others are somewhere in between. This is in many ways similar to columns. There are short columns, slender columns and intermediate columns. Another way of describing this concept is domes can behave as linear frames, non-linear shells, or something in between a frame and a shell.

Another acceptable method of calculating the critical buckling load is a non-linear finite element analysis.

This design limitation is more important than the allowable stress per the Aluminum Association, since almost all known failures of aluminum domes have been caused by non-linear buckling.

Design Automation

While it is possible to hand calculate all of the components needed to fabricate a dome, it is not very practical to do so due to the time required and the fact that the frame analysis finite element

solution must be solved by a computer due to the size of the matrices involved. At AluminumDomes.com, we have developed a proprietary software solution for this problem. Our software is a modern object-oriented model. This object-oriented model includes the basic geometry, fabrication components and the frame analysis solution. The model is also very flexible and will be extended to other aluminum structures in the future.