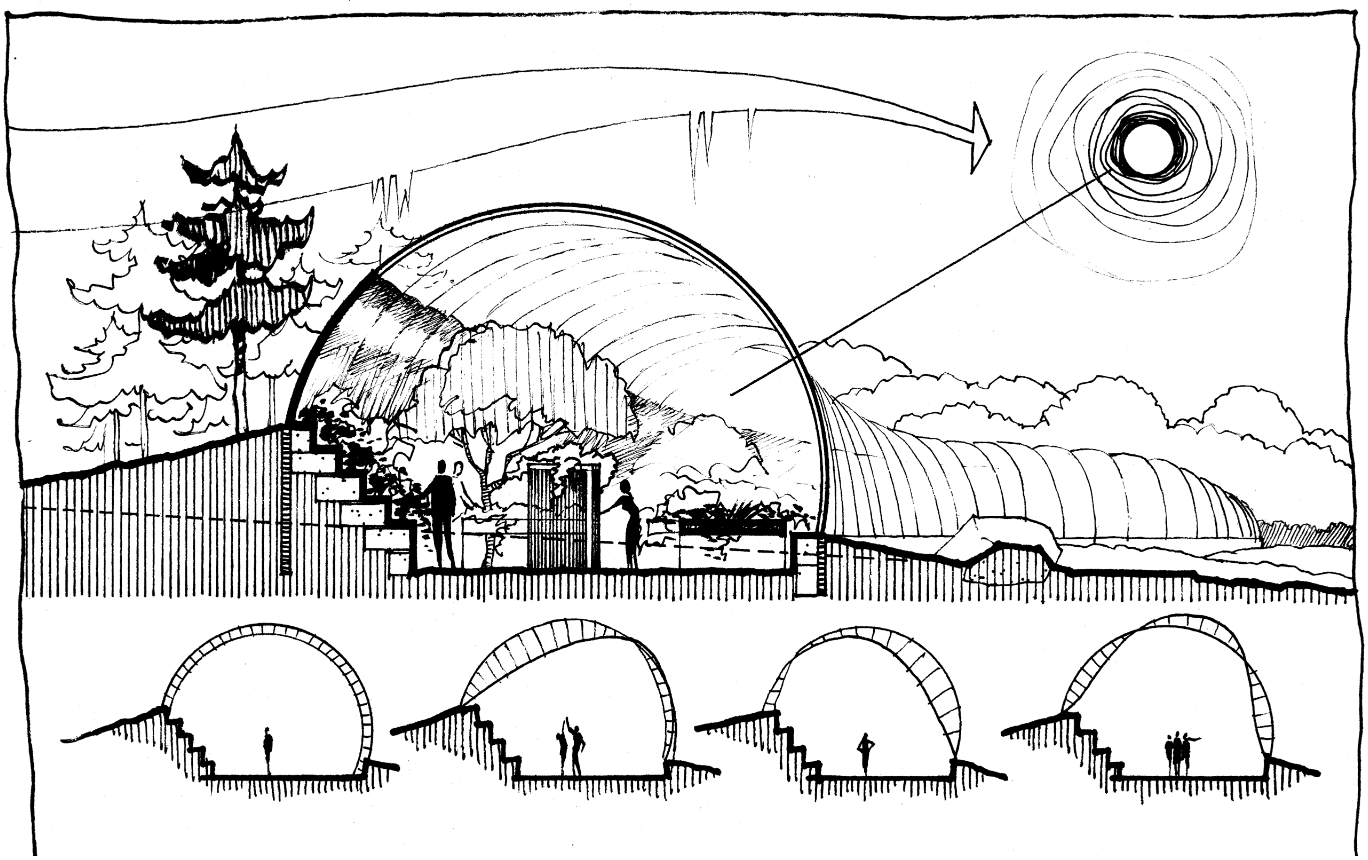

Modeling and Design of Future Bioshelters

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There are myriad design possibilities for the next generation of bioshelters. Questions that need to be answered concern such difficult design tradeoffs as light vs. warmth and such elegant design synergies as aquaculture units doubling as heat storage. Building shape, glazing, thickness of insulation, insulated area, and internal components influence the interior solar climate. Creating computer models to test such design variables is considerably more economical than putting up separate buildings to do so. The computer model, called SUNAI1, explores domes with different types and numbers of solar membranes, with different aspects (height-to-diameter ratio) and with various interior configurations of soil, plants, and water.

Description of the Program

DOME1 dynamically simulates solar dome temperatures based on hourly weather data measured at Boston's Logan Airport. The weather data consists of wind speed, temperature, total incidence of solar radiation, and a computed breakdown into direct and diffuse sunlight components. In comparison to Logan, New Alchemy on Cape Cod experiences lower wind speeds, slightly higher temperatures, and more sunlight.

The shape of the dome is approximated by 50 facets. Light penetration of each facet is based on the solar incidence angle with respect to the facet and a transmission function based on the glazing materials (five glazing configurations are tested). Structural framing reduces the effective glazing area. Light penetrating the dome and hitting the opposite glazing is partially transmitted and partially reflected back into the dome.

The absorption of entering light is divided three ways according to the solar elevation. The three absorptive surfaces are

1. Translucent aquaculture silos.
2. Soil.
3. Plant surfaces in thermal equilibrium with the air.

The heat storage elements are: air (includes plant mass), the water of the aquaculture units, and soil subdivided into three layers (0–3, 3–12, and 12–36 in. in depth).

Heat flow driven by temperature differences occurs between

1. The adjacent layers of soil.
2. The topsoil layer and interior air.
3. Water and interior air.
4. Interior air and exterior air.

Interior–to–exterior heat exchange includes a combined conduction/convection/radiation coefficient for the dome glazing and a comparable term for the structural members. Air infiltration comprises additional heat loss and depends on air humidity and wind speed.

Easily varied input parameters include the following:

1. Dome radius and height.
2. Shading from structural framing.
3. Thermal conductivity of' structural framing.
4. Glazing configuration (number of layers and types of glazing, including Southwall Corporation's HEAT MIRROR.
5. Reference air infiltration rate and wind speed dependence.
6. Average dome humidity.
7. Plant cover as a fraction of total ground area.
8. Ground corrugation factor (corrects air/soil heat transfer area for raised growing beds).
9. Soil thermal conductivity and heat storage capacity.
10. Number of' standard–size solar ponds (5 ft diameter and 5 ft high water–filled silos).
11. Overheating temperature above which heat is vented to the outside.
12. Time interval of the simulation.

The computer, directed by DOME i, takes TMY weather data, combines it with the hypothetical building's characteristics, and predicts the resulting light and temperature levels within. The computer makes its predictions by moving through imaginary time in small increments (or steps), calculating temperatures within the building at each step. This is the process of computer simulation. For all simulation runs that follow, the interval was six minutes. For each time interval the program computes rates of heat flow according to present temperature differences and insulation rate (sunlight intensity) as thus rates of' temperature change. These rates determine temperatures at the next time point and ultimately the temperature fluctuations through time.

The simulated temperatures may be slightly underestimated because

1. Air film thermal resistances on the inside and outside of the dome skin may be considerably higher than the standard ASHRAE (American Society of Heating, Refrigration, and Air Conditioning Engineers) coefficients used. The dome's shape may foster low turbulence air flow along its inner and outer surfaces, creating a thick insulating air film.
2. Reflection of' light into the dome off the ground surrounding the dome is not considered.
3. Heat production from compost is not considered.

On the other hand, the simulated temperatures may be slightly overestimated because

1. Ground perimeter heat loss is not considered.
2. Reflection of' light off interior surfaces and back out the dome is not considered.

Results

The results of the DOME1 simulation are summarized in Tables 1, 2, and 3. The program's weather data covers the period from January 15 to February 14, and encompasses the harshest combination of cold weather, cloudiness, and low sun angles. In all runs the dome diameter is set at 80 ft. The model assumes the dome contains no active fan-driven heat storage components, but does include 36 solar ponds (5ft diameter and 5ft high water-filled silos).

Although the computer calculates new light intensities every hour, and new heat flow rates and temperatures every six minutes, the information from a month long simulation can be summarized by the following five numbers.

1. Light intensity inside the dome striking the plant beds, averaged over the month (BTU /ft-2 /day). Compare these figures to 550 BTU/ ft-2 / day for average light levels striking the ground outside.

2. Average midpoint temperature of dome air: the *midpoint* between daily minimum and maximum temperatures, averaged for the month. This is near, and probably slightly higher than, the average temperature. The outside average midpoint temperature was 28.8 F for the simulation month.

3. Average daily temperature swing of dome air: the *difference* between daily minimum and maximum temperatures, averaged for the month. The average daily temperature swing for outside air was 12.4 F for the simulation.

4. & 5. Monthly temperature extremes for dome air. the coldest and hottest temperatures found inside the dome over the entire simulation month. The outside air temperature extremes were 6' and 55' F. The inside overheating temperature, at which venting occurs, is 80 F for all the following simulations.

All five variables affect plant productivity within the dome. Higher light levels enhance plant growth. All crop varieties have an optimum average temperature and an optimum day/night temperature swing (cool night temperatures reduce plant respiration, encouraging more efficient growth). Extremely low and high temperatures can permanently damage crops. Temperatures that persist below freezing can destroy even cool-weather crops, and temperatures above 80-85 F often cause bolting and bitter flavor.

Table 1. CONDITIONS IN HYPOTHETICAL DOME BIOSHELTERS-JAN. 15 TO FEB. 14.

Glazings	Aspect (a)	Interior Light Level (b)	Temperatures *(F)*		
			Avg. Midpoint	Avg. Daily Swings	Monthly Extremes
Three (heat mirror)	1/4	277	55.3	13.9	42.4-74.3
	3/8	323	55.0	15.1	39.7-74.8
	1/2	378	53.0	16.4	36.3-73.6
Three (reg. film)	1/4	345	53.6	16.5	37.8-74.7
	3/8	394	51.7	17,5	34.8-73.6
	1/2	453	49.6	18.5	31.7-72.3
Two reg. layers	1/4	358	48.4	16.4	32.3-69.5
	3/8	408	46.7	17.4	29.7-68.5

1/2	469	46.1	18.2	27.1–67.8

(a) Height/diameter; diameter is always 80 ft.
(b) Light has the units BTU / sqft / day on the plant beds,

Table 1 compares solar domes with different numbers and kinds of glazings, and with different height–to–diameter ratios (aspects). The glazings considered are the following:

1. Three layers of solar covers. The interior and exterior glazings are made of low–iron glass. Between them lies Suntek's Heat Mirror, a film that transmits some sunlight but reflects back into the dome most of the infrared radiation that Would otherwise represent a heat loss. Heat Mirror must be placed in a dessicated space between layers of vapor–impervious material (e.g., glass).

Maximum Light Transmission: 60%
Heat Loss Coefficient: 0.23 BTU sqft/ hr/degree F

2. Three layers of standard solar covers. Low–iron glass or a plastic equivalent make up the inner and outer skins. Between them lies a highly transparent solar film (e.g., one mil Teflon FEP film).
Maximum Light Transmission: 74%
Heat Loss Coefficient: 0.40 BTU/ft–2/hr/F

3. Two layers of standard solar covers, consisting of low–iron glass or a plastic equivalent.
Maximum Light Transmission: 78%
Heat Loss Coefficient: 0.60 BTU ft –2 /hr/ degree F

These glazing alternatives represent a very important trade–off between light transmission and insulating value.
The height–to–diameter ratios, or aspects, considered are:

1. A shallow 1/4 dome with a maximum height of 20 ft and a diameter of 80 ft.
2. A moderate 3/8 dome with a height of 30 ft.
3. A full hemisphere (1/2)) dome with a height of 40 ft.

Table 2. INTERIOR LIGHT LEVELS AND MINIMUM TEMPERATURES FOR VARIOUS DOME GLAZINGS AND ASPECTS, INDEXED TO THE HEAT MIRROR SANDWICH AND TO THE SHALLOW 1/4 DOME. BASED ON DATA FROM TABLE 1.

Light Index (Ratio):
Glazing Comparison
3 w/H.M. = 1.0
3 w/Film = 1.20 to 1.25
2 Layers = 1.24 to 1.29

Minimum Temperature Index (Degrees Fahrenheit)
Glazing Comparison
3 w/H.M. = 0.0
3 w/Film = – 4.6 to – 4 9
2 Layers = –9.2 to –10.1

Aspect Comparison
1/4 = 1.0
3/8 = 1.14 to 11.17
1/2 = 1.31 to 1.36

Aspect Comparlson

1/4 = 0.0
3/8 = –2.6 to –3.0
1/2 = –5.2 to –6.1

Table 1 shows that during even the harshest month, the triple–glazed domes create all acceptable greenhouse environment. The table also reveals three very important trends:

1. The higher the aspect of the dome, the more light strikes the plant beds.
2. The higher the aspect of the dome, the wider the temperature swings and the lower the minimum monthly temperatures.
3. The heat mirror glazing sandwich creates the warmest temperatures but the lowest light levels, while the two layers of glazing create the highest light levels and the coolest temperatures.

The 3/8 aspect heat mirror dome and the 1/4 aspect regular triple glazed dome represent the best compromise between light and warmth. Temperatures are a bit lower than the Cape Cod Ark, while light levels are slightly higher.

Table 3. AIR AND WATER TEMPERATURE DATA FOR VARIOUS DESIGN CONFIGURATIONS AND MODEL COEFFICIENTS JAN. 15 TO FEB. 14.(a)

	Temperatures (degrees F)					
	Inside Air			Solar Ponds		
	Midpoint Avg.	Avg. Daily Swing	Monthly Extremes	Midpoint Avg.	Avg, Daily Swing	Monthly Extremes
STANDARD RUN						
3 w/H.M.	55.0	15.1	39.7–74.8	55.8	3.1	45.4–65.0
3 w/Film	51.7	175	34.8–73.6	52.7	3.6	42.2–62.9
2 Layers	46.7	17.4	29.7–68–5	47.8	3.6	38.2–58.0
ALUMINUM STRUCTURE AS THERMAL BRIDGE						
3 w/H.M.	50.6	14.8	35.0–69.6	51.5	3.0	41.4–63.3
3 w/Film	48.8	172	31.9–70.0	49.9	3.5	39.7–61.7
2 Layers	44.9	17.1	27.9–66.7	46.1	3.5	36.9–57.1
LOWER AIR INFILTRATION RATE						
3 w/H.M.	57.5	15.5	43.1–78.9	57.7	3.2	48.7–67.8
3 w/Film	53.3	18.0	36.9–78.1	53.8	3.7	44.0–65.2
2 Layers	47.7	17.8	31 1–72.2	48.4	3.7	39.1–59.8
NO SOLAR PONDS						
3 w/H.M.	54.5	24.6	31.9–80.0	54.8	4.5	41.9–67.1
3 w/Film	51.6	27.8	27.3–80.0	51.8	5.0	391–65.0
2 Layers	47.4	27,6	23.4–80.0	47.3	4.8	35.0–60.5

NO PLANT COVER						
3 w/H.M.	53.9	11.3	40.1–70.4	55.9	2.7	45.9–644
3 w/Film	50.3	13.1	34.9–69.4	52.7	3.2	42.6–62.5
2 Layers	45.3	132	29.9–648	47.8	3.1	38.6–57.7
FLAT GROUND, NO RAISED BEDS						
3 w/H.M.	55.3	16.9	38.8–76.8	55.7	3.3	45.2–65.1
3 w/Film	52.0	19.5	338–757	52.6	3.7	42.0–62.6
2 Layers	47.0	19.2	289–705	47.7	3.7	381–58.2
WET, HEAVY SOIL						
3 w/H.M.	55.4	14.3	40.3–74.8	56.3	3.1	45.6–66.8
3 w/Film	51.8	16.7	352–728	52.8	3.6	42.3–64.3
2 Layers	467	166	30 1–676	47.9	3.6	38.3–59.5
DRY, LIGHT SOIL						
3 w/H.M.	55.0	15.9	39.1–75.5	55.5	3.2	45.3–64.5
3 w/Film	51 7	185	342–744	524	3.7	421–62.5
2 Layers	46.7	18.3	29.2–69.5	47.6	3.7	38.1–58.1
LOWER RELATIVE HUMIDITY (50%)						
3 w/H.M.	56.3	15.2	40.0–76.7	57.1	3.2	46.3–67.4
3 w/Film	52.4	17.7	35.3–74.6	53.3	3.7	42.7–645
2 Layers	472	17.5	30.1–69.5	48.1	3.6	38.5–58.8

(a) height is always 30 ft, diameter 80 ft. Aspect is therefore 3/8

Table 3 evaluates the thermal impact of various design options (design testing), and examines changes in assumed model coefficients (sensitivity testing). In all cases a 3/8 aspect 80 ft diameter dome is tested with the three glazing configurations listed above. All the results are compared to the "standard run," which matches the results listed in Table 1. Table 3 lists solar pond water temperatures as well as interior air temperatures.

In the standard run, the model assumes the aluminum framing for the geodesic structure has a thermal R-value of one (plus air film resistance). This insulating value could be provided by 1/4 in. foam covering the inner or outer surface of the aluminum framing, or by a 1 in. wood spacer between inner and outer aluminum ribs.

The first design test in Table 3 looks at what happens if the aluminum structure is continuous from interior to exterior, creating a thermal "bridge" or "short circuit" for escaping heat. The change lowers minimum temperatures in all cases. It most drastically affects the best-insulated dome glazed with heat mirror (causing a 4.7 degree F drop in minimum temperature) and least affects the worst-insulated double glazed dome (causing only a 1.8F drop). Insulating the structural members is more critical in the well-insulated design because heat loss from uninsulated members is great relative to the small total heat loss.

The second design test, reducing the air infiltration rate, demonstrates the inverse of the same principle. Lowering the air infiltration rate makes a significant improvement in the well-insulated heat mirror dome (a 3.4 degree F gain) and a lesser improvement in the double glazed dome (a 1.4 degree F gain).

The third design test removes the aquaculture component from the building. With the removal of this major thermal mass, all the domes exhibit 10 degree F wider average daily temperature swings, and 6-8 degree F lower monthly minimum temperatures. This computer run demonstrates the critical role solar ponds play in storing heat.

The drop in minimum temperature is greatest in the heat mirror dome. Successive degradations in dome insulation or heat storage cause lessening decrements in temperature. In the extreme cases of no insulation or no storage, nighttime dome temperatures could drop no lower than ambient temperatures. Hence we find that the more poorly insulated dome configurations have less to lose by reductions in heat storage.

The inverse of the heat storage principle is demonstrated in the next case. Here the plant cover is removed (in the standard run, plants cover 70 percent of the available surface area). This allows sunlight to strike the soil directly, rather than striking plant leaves that in turn heat the air. Thus removing the plant cover increases the effectiveness of soil heat storage. As the heat-retention principle suggests, this leads to a 0.4 degrees F improvement in minimum temperatures for the heat mirror dome, but only a 0.2 degrees F increase for the double glazed dome. In absolute terms, plant cover is not a critical factor in either case.

In the standard run, soil surface exchange area is enhanced by taking into account the sides of walk-way trenches between raised plant beds (a 1.4 times greater surface area than flat was assumed). As shown in Table 3, a flat growing surface yields slightly wider temperature swings and slightly lower minimum temperatures. The drop is small, but perhaps significant (0.9 degrees F for heat mirror, 0.8 degrees F for double glazing).

The last three runs change assumed coefficients in the model, and provide what is known as a sensitivity test. The first two of these runs examine the assumed properties of the dome's soil. In the first run, a wetter and heavier soil than that in the standard run is assumed. In the second run, a drier and lighter (e.g., higher humus content) soil is assumed. The wetter and heavier the soil, the better it holds and conducts heat. The extremes between wet and dry soil properties account for only a 0.9 degrees to 1.2 degrees F change in minimum temperatures of the simulation runs. The model is therefore not very sensitive to the unknown properties of the particular soil in the dome.

The last run alters the assumed average relative humidity of the air. At typical indoor temperatures, small changes in relative humidity represent large changes in air heat content because of the heat content of the water vapor. Losing humid interior air means a much greater heat loss than losing dry air of the same temperature. The standard run assumes a relative humidity Of 70% whereas the last run assumes 50 percent. A 0.4 degrees to 1. 1 degree F increase in minimum temperature results. The average relative humidity is a large unknown in the model; in the Cape Cod Ark relative humidity cycles as low as 30 percent during the day and as high as 100 percent at night. The relative humidity has more impact during the day, when temperatures are elevated, since warmer air holds more water vapor at a given relative humidity. In future models it may be worthwhile to model the humidity cycles directly, although the present model does not seem unduly sensitive to different assumed humidities.

In summary then, four conclusions can be drawn:

1. An acceptable winter greenhouse environment is created by a triple glazed dome (with or without the special heat mirror film) containing solar ponds and situated in coastal New England.
2. The shallower the dome the darker and warmer the interior becomes
3. Better insulation, more heat storage, and more heat-storage exchange surface all reduce temperature swings and raise temperatures.
4. Insulation and heat-storage improvements have a greater temperature effect on already well insulated domes.

The next step in modeling solar domes is to examine them with opaque, insulated walls having reflective inner surfaces. Examining light entry through separate facets of clear domes can suggest the best glazing/insulation boundary for domes partially clad with opaque insulation. The facets transmitting the least amount of light should be insulated first.

Figure 1 shows the average daily incoming light transmitted through 300 facets of a double-glazed hemispherical dome. Figure 2 depicts light entering each facet, minus light that enters from the opposite side, shoots through the dome, and exits out that facet. Negative numbers occur along the steep northern facets in Figure 2, indicating that more sunlight leaves through these facets than enters. To maximize winter light levels on the growing beds, it is actually desirable to cover these facets with reflective foil to bounce outgoing light back into the building.

When using Figures 1 and 2, two caveats about the assumptions behind the model are in order:

1. No ground reflection is included in the model. This assumption underestimates light entry for steeper southerly surfaces.
2. Diffuse radiation is assumed evenly distributed across the sky. In fact, diffuse radiation clusters around the sun's position (see sky distribution patterns of diffuse radiation diagrammed on p. 82 of Duffie and Beckman's *Solar Engineering of Thermal Processes.* The assumption tends to underestimate light entry on steeper south sides, overestimate it on the north.

Future versions of the computer model will examine north wall insulation, movable night insulation, and other shapes (such as Quonset and A-frame). With the climates of all these design options quantified by the computer model, we can then predict the crop productivity and capital cost of each design option. We will then know which design gives the maximum yield of organically grown off-season vegetables per dollar invested.

Figure 1. Incoming light gain transmitted through 300 facets of a double–glazed dome. Logan Airport, Boston, Massachusetts for a statistically typical January 15 to February 14 period.

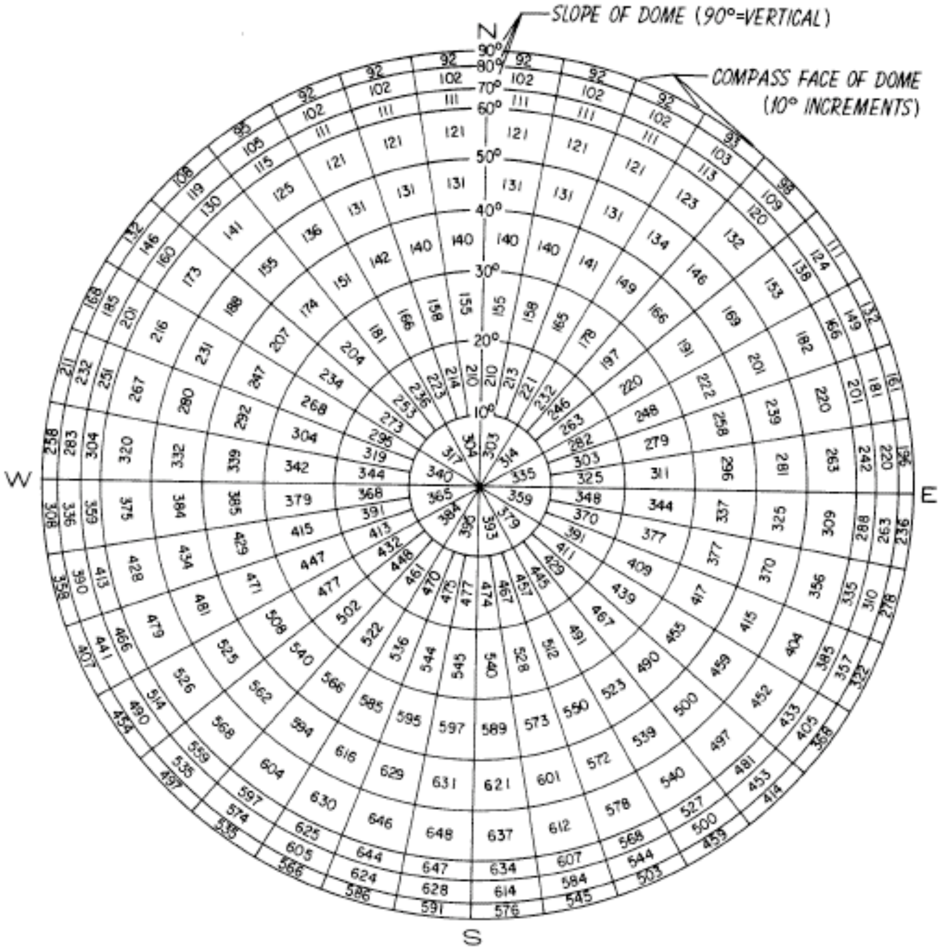

Figure 2. Net light gain (entering minus exiting light) through 300 facets of a double glazed dome. Logan Airport, Boston, Massachusetts for a statistically typical January 15 to February 14 period.