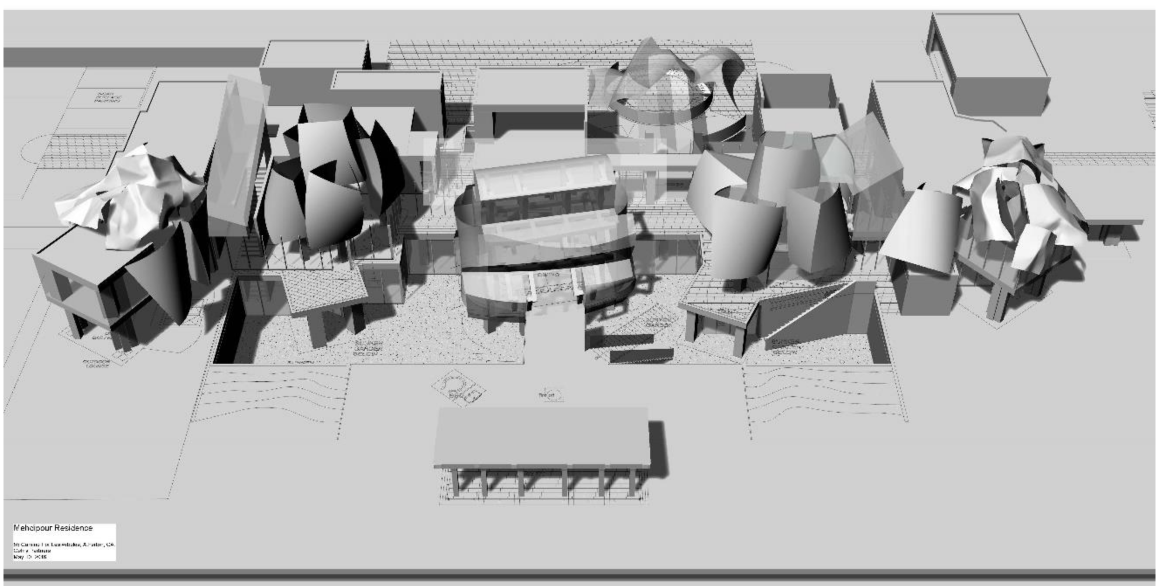
Atherton Residence
Solar Chimney Study

55 Camino Por Los Arboles

Atherton, CA 94027



Prepared for Gehry Partners, LLP

By Adroit Energy

July 19, 2016

Katy Hamilton

Contents:

Local Climate Analysis

Atherton, San Mateo Country is in California Climate Zone 3

California Climate Zone 3

Reference City:	Oakland San Francisco
Latitude:	37.75 N
Longitude:	122.2 W
Elevation:	10 ft

Design Day Data

	Oakland (F)	RH	San Francisco (F)	RH
Winter 99%	34		35	
Winter 97.5%	35		38	
Summer 1%	85	MCWB 64	82	MCWB 64
Summer 2.5%	80	MCWB 64	77	MCWB 63

Degree Days

	OAK	SFO	Half Moon Bay	Redwood City
HDD	2909	3042	3770	2563
CDD	128	108	11	486

HDD = Heating Degree Days (base 65F)
CDD = Cooling Degree Days (base 80F)

Climatic Design Priorities

Winter: Insulate
Reduce Infiltration
Passive Solar

Summer: Shade
Allow natural ventilation

Title 24 Requirements

Package	C	D
Ceiling Insulation	R38	R30
Wood Frame Walls	R25	R13
Glazing U-Value	0.42	0.67
Maximum Total Area	14%	20%

Basic Climate Conditions

	OAK	SFO
Summer Temperature Range (F)	29	23
Record High Temperature	113 (1960)	106 (1961)
Record Low Temperature	14 (1930)	20 (1932)

Climate

The climate of Zone 3 varies greatly with elevation and the amount of coastal influence. Areas with more coastal influence experience moderate temperatures year round with precipitation in the winter and fog likely from June through mid-August.

Inland from the beaches and sea cliffs, local geography may reduce the fog cover, lessen the winds, and boost summer heat.

Winters are moderately cold with most of the annual rain falling between October and March. Winter sunshine nevertheless is plentiful. Summers are warm and dry, but the nights are cool. Rain is rare during the summer months.

A need for heating is the dominant design concern, but the climate is mild enough that energy consumption is relatively low.

*courtesy of Pacific Gas and Electric

Atherton is in California Climate Zone 3 for state permitting and energy efficiency requirements. Climate Zone 3 ranges from Atherton at the southern end, and is primarily a coastal zone that follows north and south around San Francisco Bay north to southern Solano County. Its' reference city is Oakland, which has some different characteristics from Atherton, which is west and south of Oakland on the opposite side of San Francisco Bay. Atherton is located at the far south end of the Climate Zone, just north of Climate Zone 4, which encompasses Palo Alto and San Jose. Many of the characteristics of Atherton's climate data and history, may be more in conjunction with climate Zone 4, where San Jose is the reference city.

Climate Zone 3

California Climate Zone 4

Reference City:	San Jose
Latitude:	37.35 N
Longitude:	121.9 W
Elevation:	70 ft

Basic Climate Conditions

	(F)
Summer Temperature Range	23
Record High Temperature (2000)	109
Record Low Temperature (1990)	19

Design Day Data

Winter	99%	34		
	97.5%	36		
Summer				
	1%:	85	MCWB	66
	2.5%:	81	MCWB	65

Climatic Design Priorities

Winter: Insulate
Reduce Infiltration
Passive Solar

Summer: Shade
Allow natural ventilation
Distribute Thermal Mass
Use Evaporative Cooling

Title 24 Requirements

Package	C	D
Ceiling Insulation	R38	R30
Wood Frame Walls	R25	R13
Glazing U-Value	0.38	0.67
Maximum Total Area	14%	20%

Climate

The Central Coastal Range is inland of the coast but has some ocean influence which keeps temperatures from hitting more extreme highs and lows. This zone covers many microclimates from northern to southern parts of the state. The reference city is in the northern-most part of the zone.

	San Jose	Gilroy	Sunnyvale	Paso Robles
HDD	2335	2278	2643	2934
CDD	574	913	220	956

HDD = Heating Degree Days (base 65F)
CDD = Cooling Degree Days

Seasons are sharply defined. Summers are hot and dry with a large daily temperature swing. Summers are hot enough that cooling is necessary. Winters are cool but not severe. Heating is necessary on many days in the winter.

Days are typically clear with the coastal range blocking much of the fog and high winds.

*courtesy of Pacific Gas and Electric

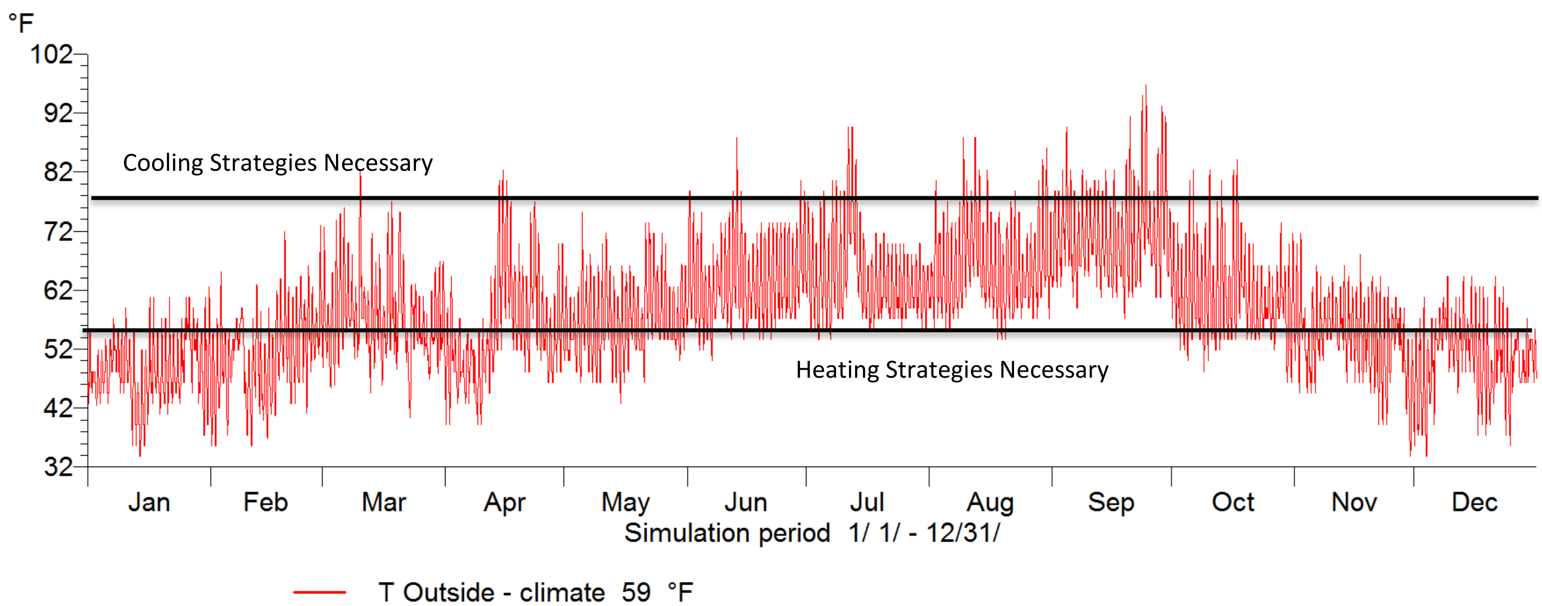
Design Degree Days

	Climate Zone 3 Oakland	Climate Zone 4 San Jose	Extrapolation for Atherton between Oakland & San Jose
Heating Degree Days	2909	2335	2622
Cooling Degree Days	128	574	351

The primary design load for the project will be for heating. With few cooling days without extreme temperatures, natural ventilation will be able to address a significant portion of the cooling requirements.

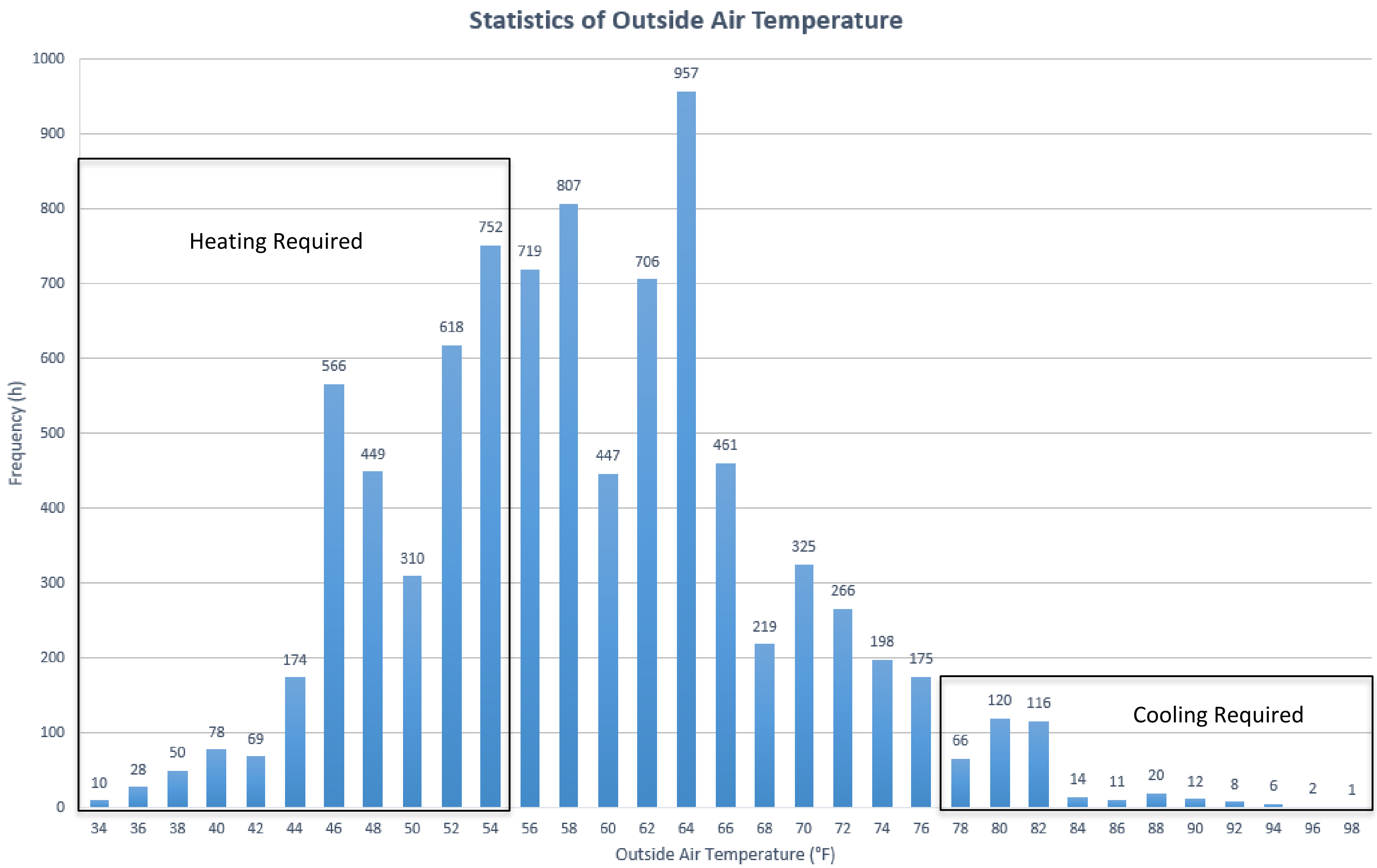
Outside Air Temperature

Mountain View CA, Moffett Airport



Frequency of Outside Air Temperature

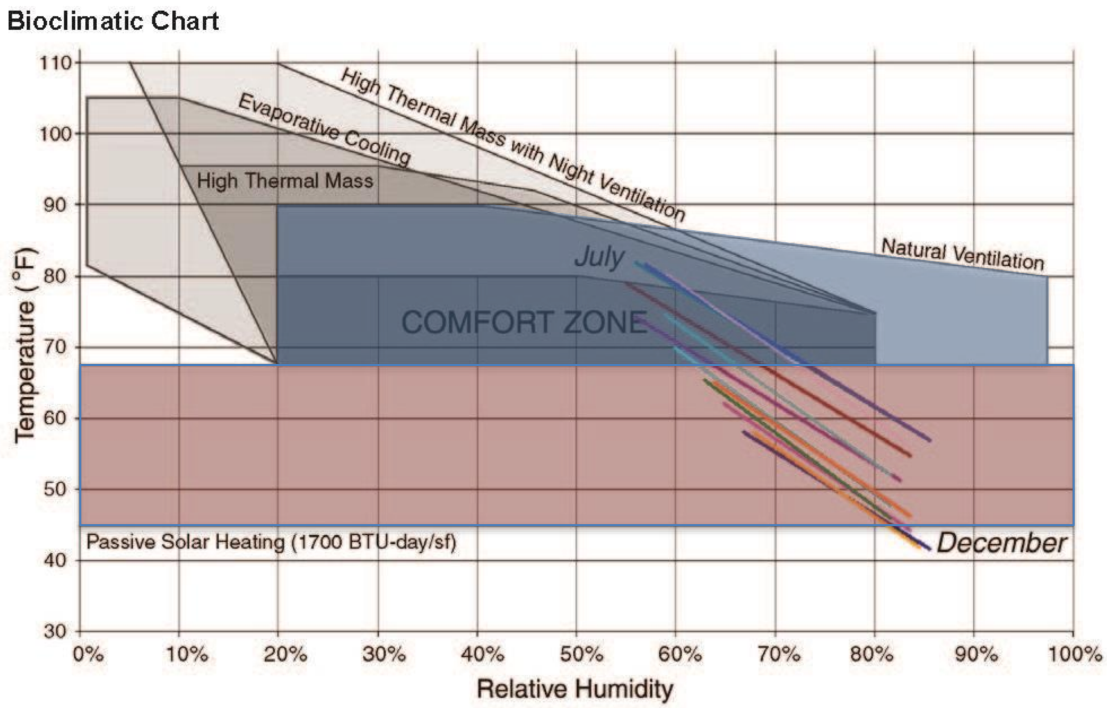
Mountain View CA, Moffett Airport



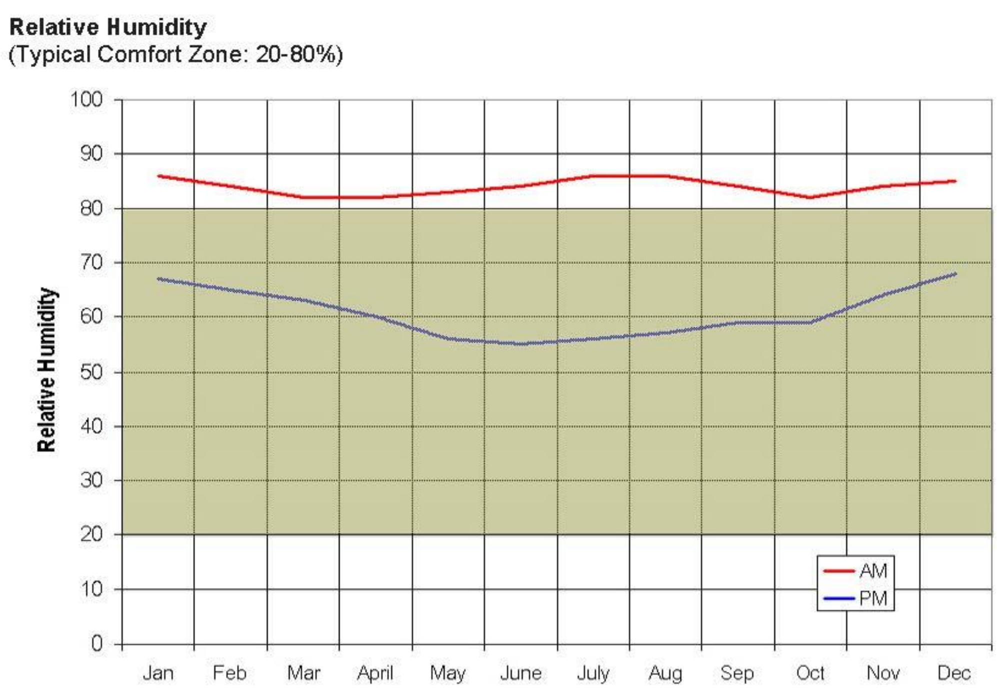
Frequency is in Bin Hours

Heating Required:	36%
Cooling Required:	4%
No Heating or Cooling:	60%

Relative Humidity Data for Climate Zone 4



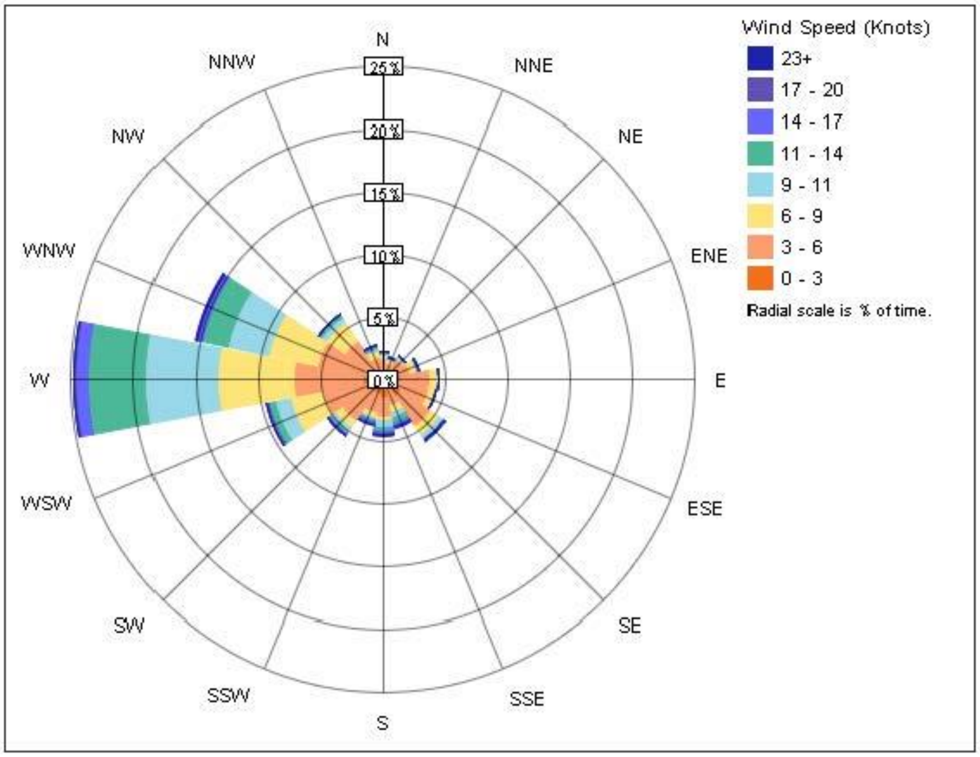
This chart illustrates by month (color lines) applicable energy efficient strategies including natural ventilation (shaded blue) and passive solar heating (shaded red).



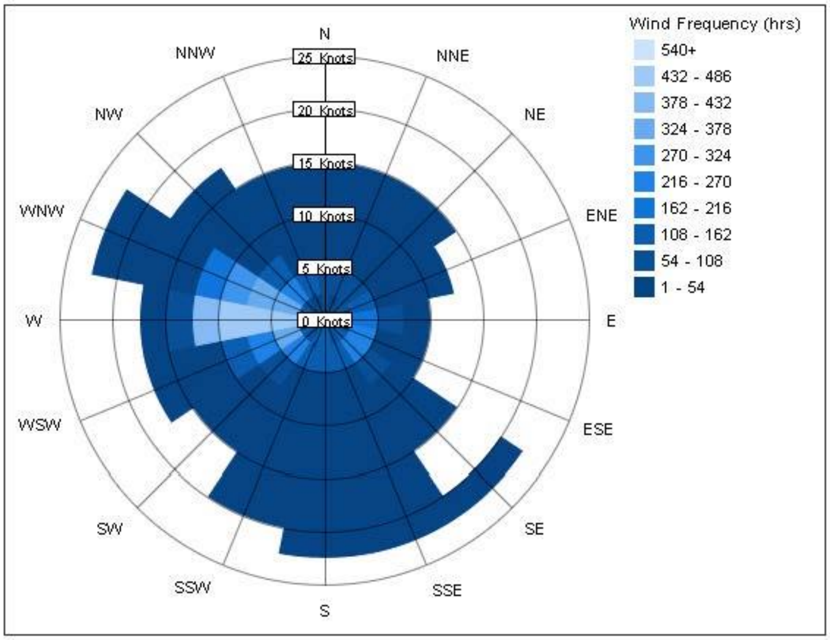
Wind Data

Annual Wind Rose (Speed Distribution)

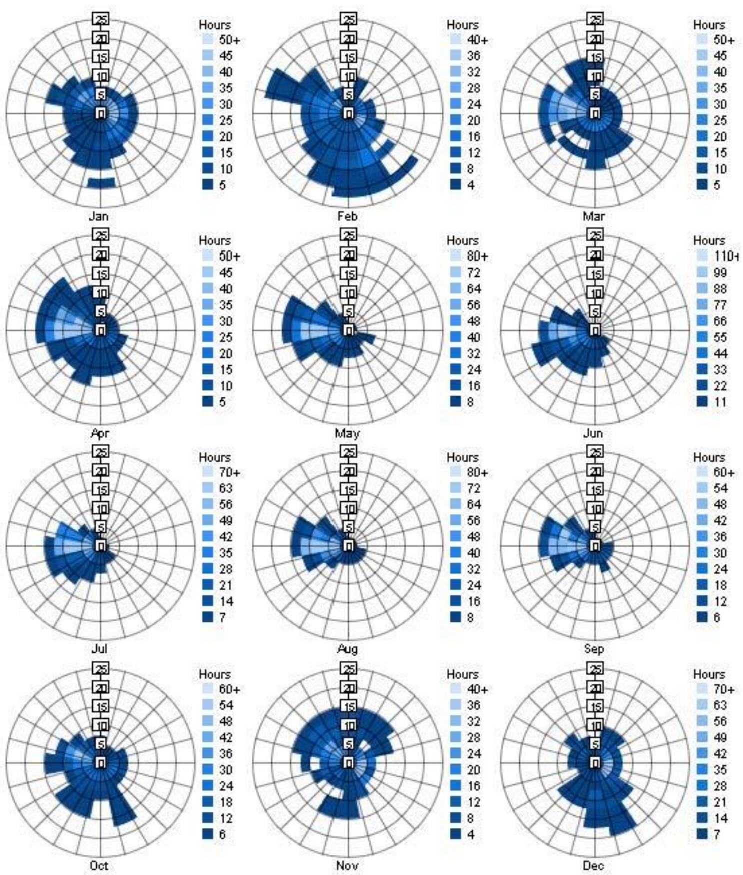
Atherton CA Weather Station #4736



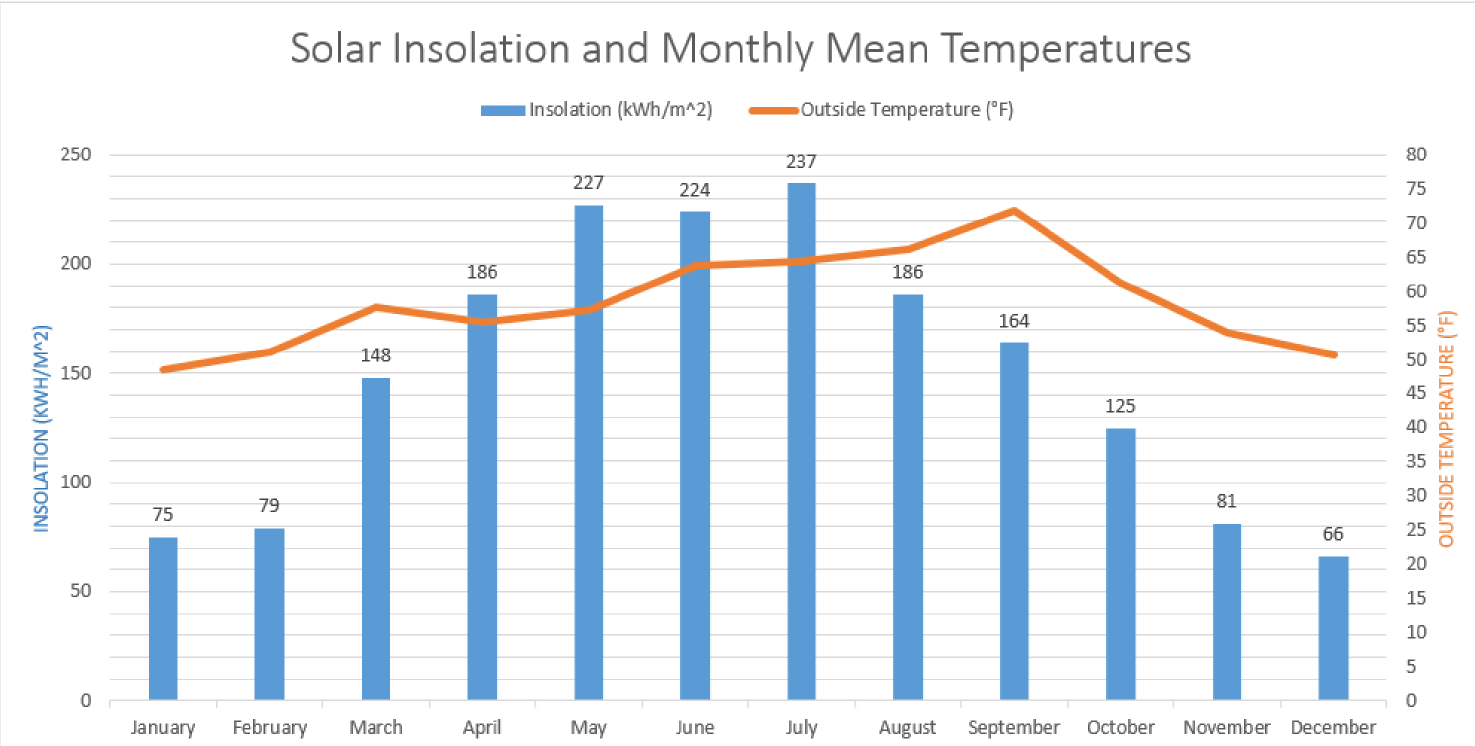
Annual Wind Frequency



Monthly Wind Frequency



Solar Access



Horizontal Insolation: 1,796 kWh/m^2
Yearly Mean Outside Temperature: 59 °F

Climate Analysis Conclusions

- Both California Climate Zones 3 and 4, recommend utilizing natural ventilation as a design strategy during summer months for energy efficiency.
- There is a greater demand for heating than cooling at the site.
- A properly design natural ventilation strategy can satisfy the majority of the cooling demand.
- There are only a very few hours mechanical cooling may be required for 100% thermal comfort.
- Passive solar heating is viable for a significant amount of the year.
- Relative humidity is well within the comfort zone during PM hours.
- Prevailing winds for the area are from the west.
- There is a large degree of direct solar gain, 1,796 kWh/m^2 throughout the year. From April through August, direct solar control through glazing will be necessary.

Narrative Description

This report analyzes three spaces within the project for their natural ventilation functioning as "solar chimneys". The three spaces are the Living Room, Dining Room, and Great Room.

A solar chimney, also known as a "thermal chimney" is vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building. This can be accomplished by direct solar gain through glazing surfaces or on the mass of the volume in combination with open windows or vents that facilitate the natural flow of air through the space. Solar chimneys can be used to decrease the energy used by mechanical systems, (HVAC). Both California Climate Zones 3 and 4, recommend utilizing natural ventilation as a design strategy during summer months for energy efficiency.

Wind driven ventilation, such as cross ventilation, relies on wind behavior which creates positive and negative pressure on the exterior surfaces of the building. Buoyancy driven ventilation is based on air density which arises from temperature differentials within the volume. Lower apertures allow cool air to enter low in the room, while the upper volume heats up the air and it exhausts out the top of the space. The area of openings and height of the space determine the velocity of air moving through the volume. Buoyancy Driven ventilation increases with temperature difference and height.

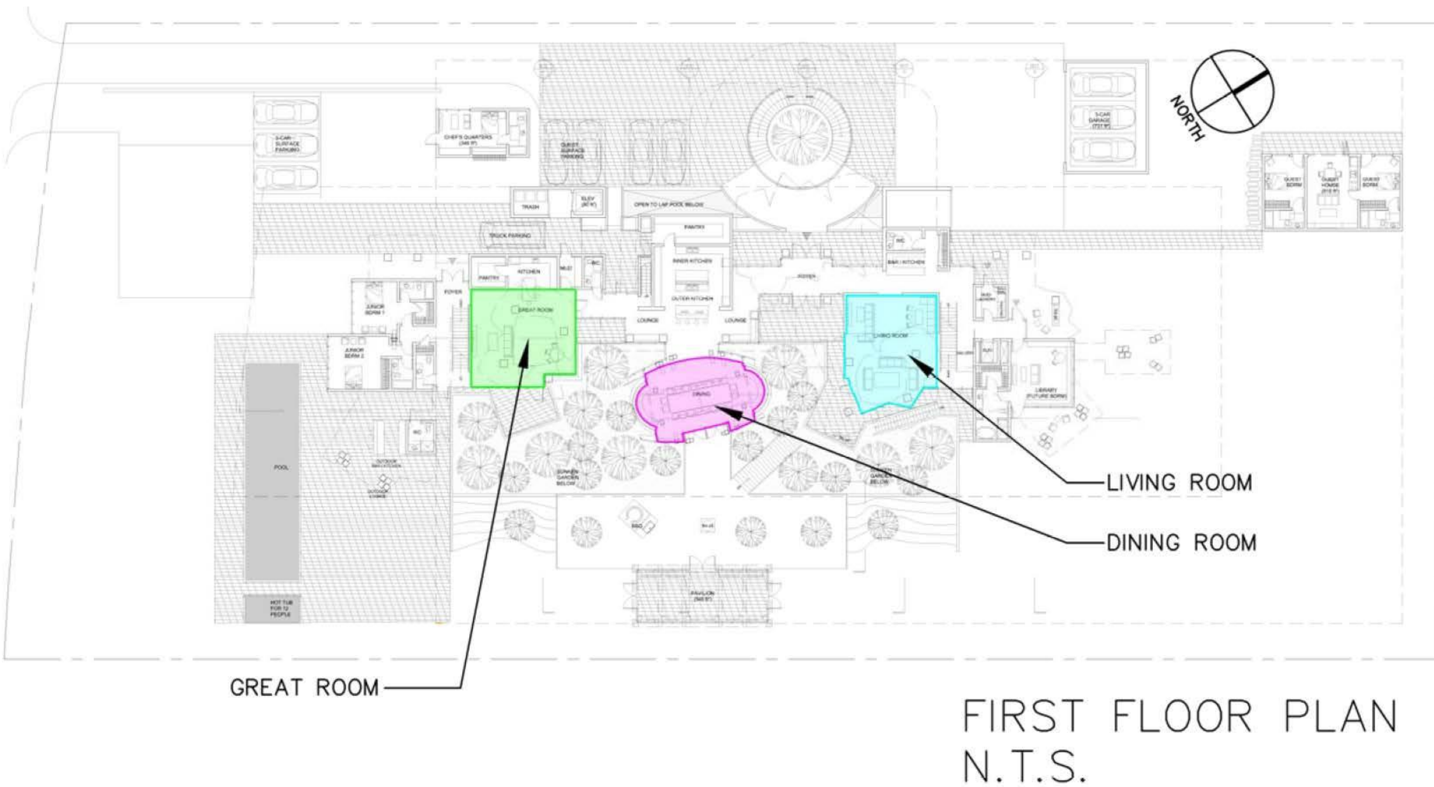
An advantage of buoyancy driven ventilation over wind driven, is it does not relay on wind. Hot, still summer days can still utilize natural ventilation. This study examines buoyancy driven ventilation in detail, with the knowledge that the prevailing winds will create an assist with the proper orientation.

For each of the three volumes we looked at the following characteristics:

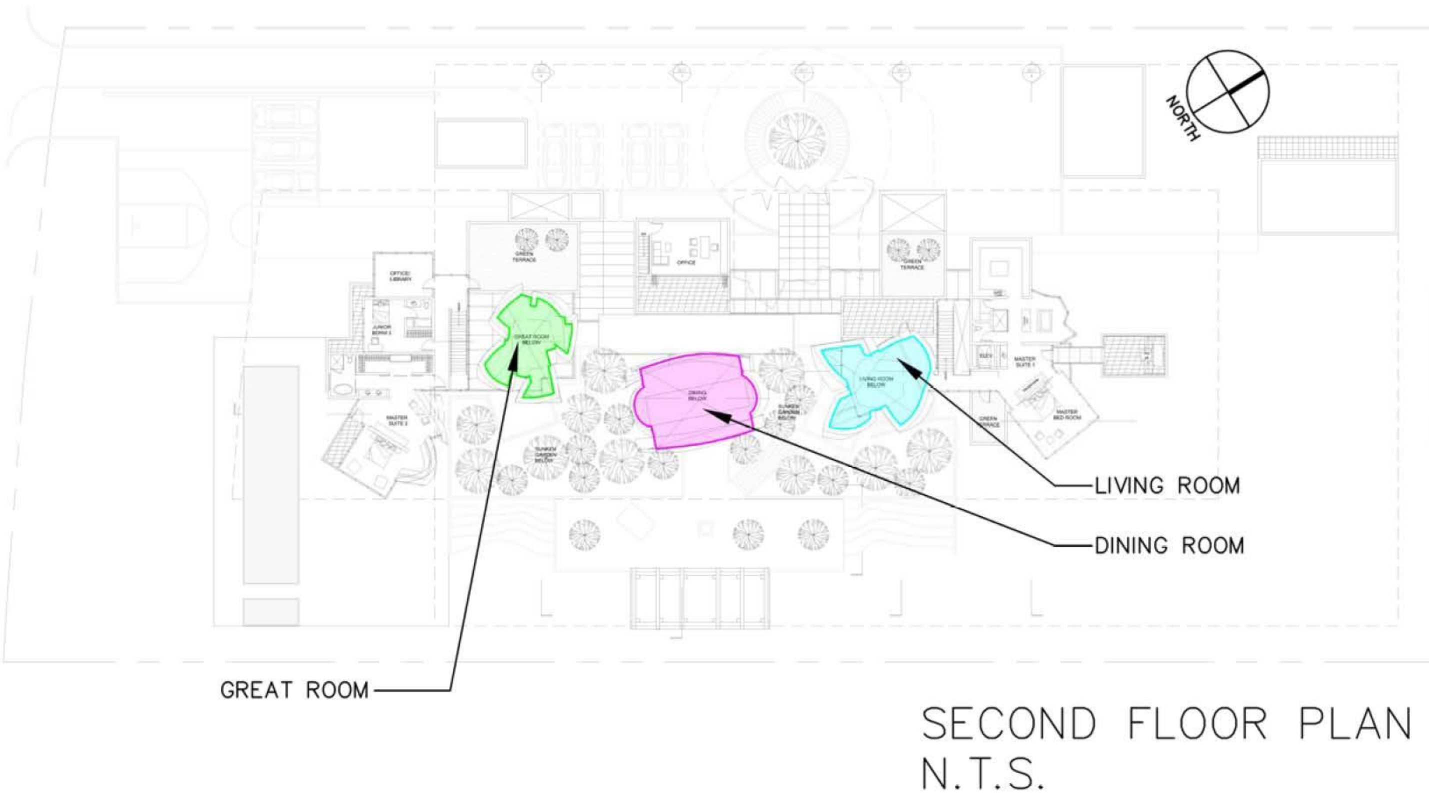
- Height of the ventilation shaft
- Air inlet opening and position
- Air outlet opening and position

For Buoyancy driven ventilation, the free open area at the top outlet opening will determine the size the free open area of the bottom air inlet opening. The greatest flow per unit area of openings is obtained when inlet and outlet areas are equal.

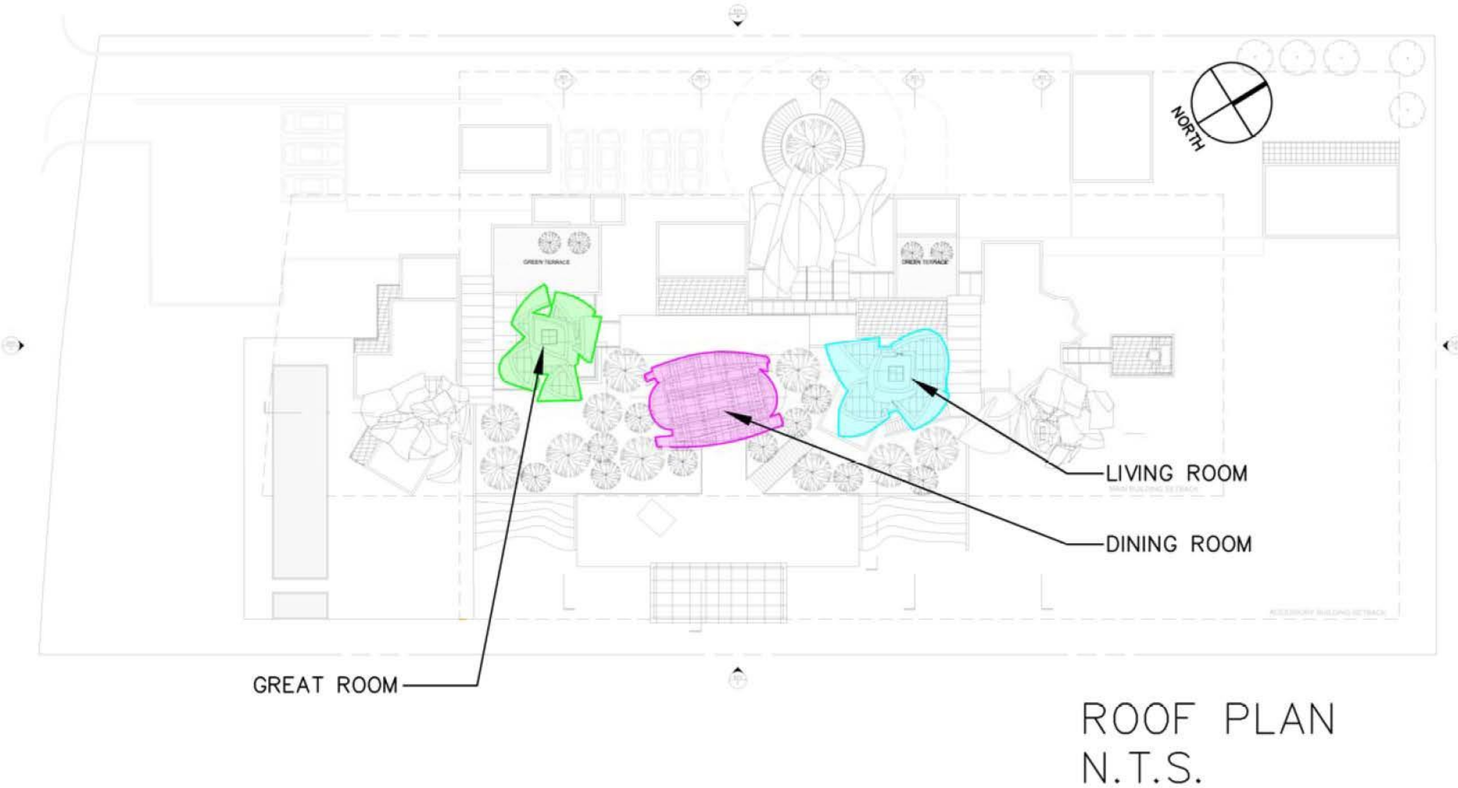
First Floor Plan



Second Floor Plan



Roof Plan



NORTH
GREEN TERRACE
GREEN TERRACE
LIVING ROOM
DINING ROOM
GREAT ROOM
ROOF PLAN
N.T.S.

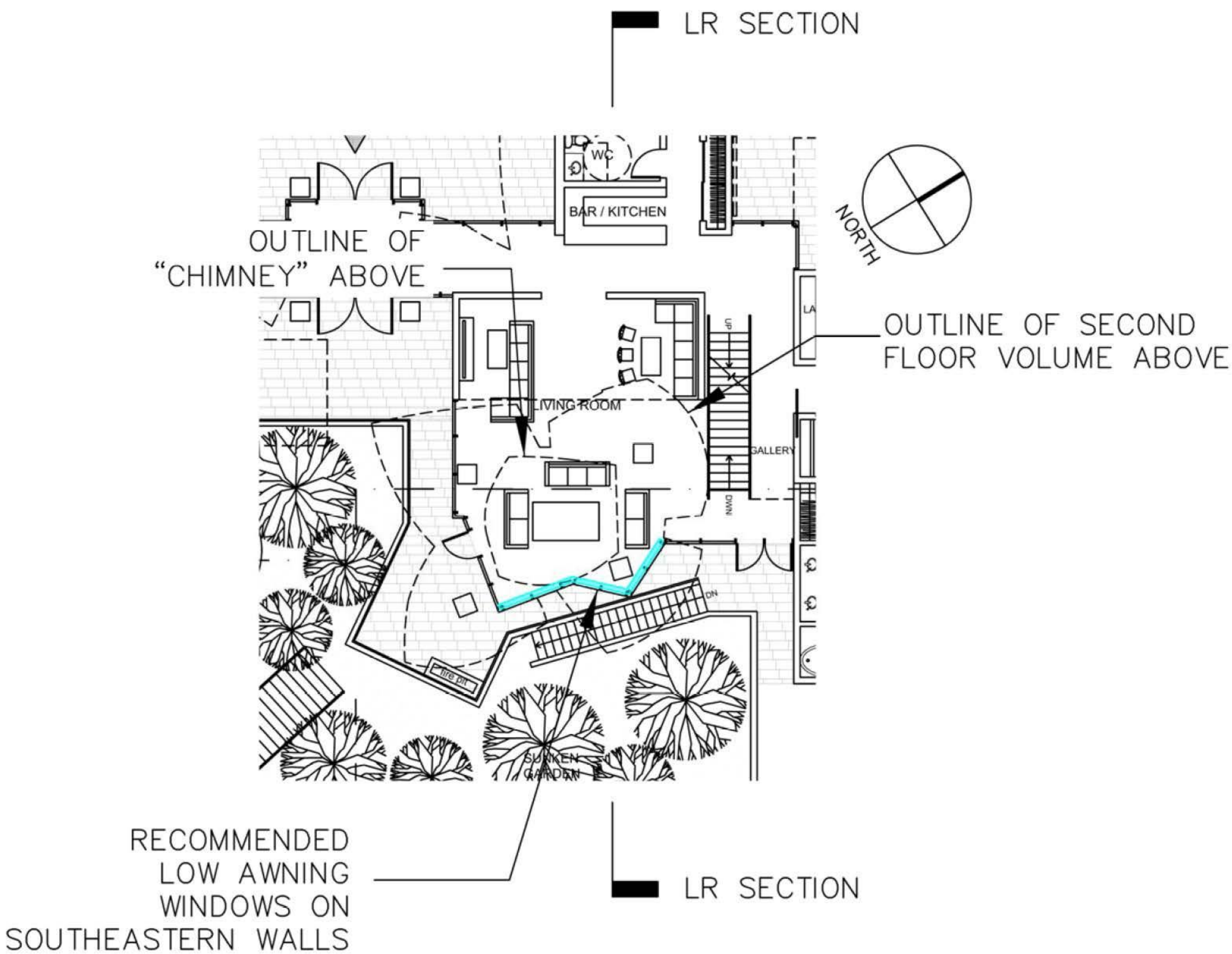
Tree Shading

The existing trees on the site to remain are located on the southwest and northwest of the project. These will not affect the solar gain on the Dining Room and Living Room solar chimneys. The 40’ tree to the southwest of the Great Room, will affect solar gain through the late afternoon hours in the winter months, but is not close enough to affect the summer time solar heat gain from the southeast and south.

FIRST FLOOR PLAN OVERLAY SHOWING
EXISTING TREES TO REMAIN

Living Room

The living room, located on the north end of the building, is a two story volume with a "solar chimney" above. The effective height of the solar chimney is from the first floor to the top of the volume. The first floor glass on the south eastern side is well shaded from the second floor wall structures. The skylight at the top of the solar chimney volume faces Northwest. The curved walls surrounding the second floor volume and chimney will be a standard size light tan brick. This will create a thermal mass surrounding the volume. Additionally, the solar gain on the south and east will assist in generating upward air flow.



Living Room Dimensions

Dimensions:

First floor area: 730 ft^2

Volume: 13,258 ft^3

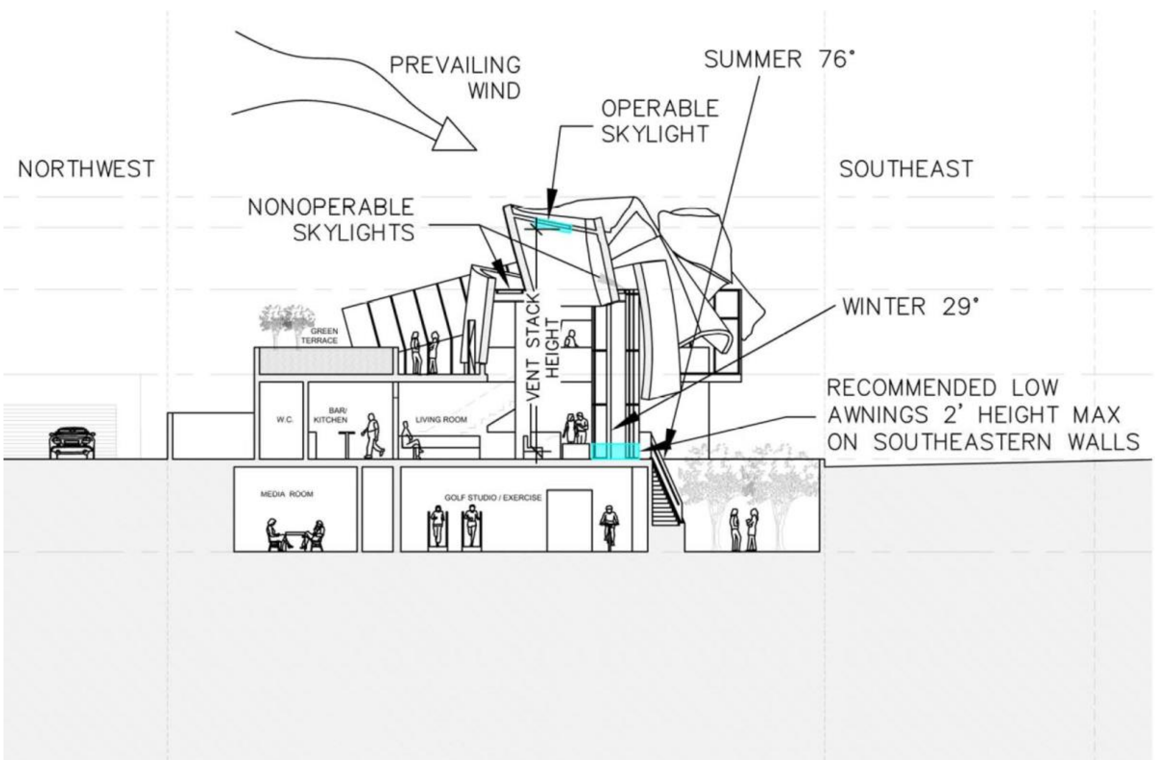
Solid Wall Surface Area: 3,522 ft^2, assume 50% surface area has direct solar gain = 1,761 ft^2

Roof Glazing/Skylight Surface Area: 350 ft^2

Preliminary Estimated Heating/Cooling Load: 9,000 - 12,000 BTU/hr (3/4 - 1 ton)

Design Features:

The non-operable skylights/roof glazing areas at the top of the second floor volume are planned to have automated shades when there is direct solar gain, primarily in summer months.



LR SECTION
N.T.S.

Living Room Calculations

To determine the airflow rate for the volume the sensible heat equation calculates the cfm required to cool the space based on the temperature delta.

Sensible Heat Equation: $Qs = 1.08\ Q\Delta t$

Where:

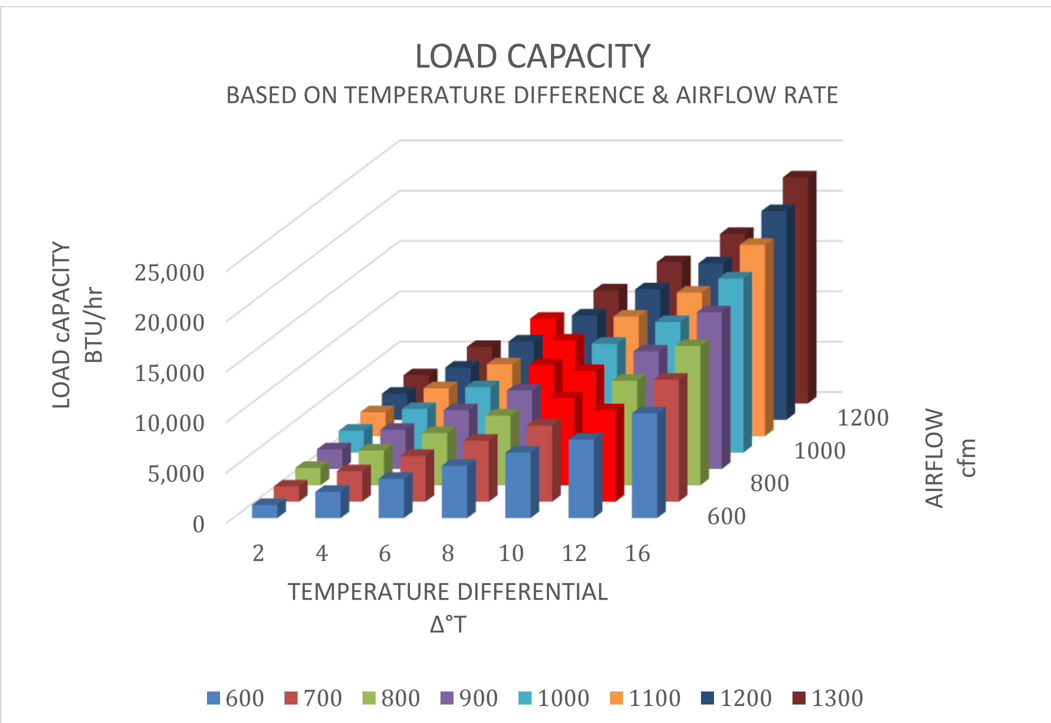
Qs = Sensible heat gain (cooling load), BTU/hr

Q = Airflow rate, cfm

Δt = temperature difference between indoors and outdoors, °F

Estimated cooling load for the space is 9,000 BTU/hr.

cfm	Temperature Difference between Indoors and Outdoors °F						
	2	4	6	8	10	12	16
600	1,296	2,592	3,888	5,184	6,480	7,776	10,368
700	1,512	3,024	4,536	6,048	7,560	9,072	12,096
800	1,728	3,456	5,184	6,912	8,640	10,368	13,824
900	1,944	3,888	5,832	7,776	9,720	11,664	15,552
1000	2,160	4,320	6,480	8,640	10,800	12,960	17,280
1100	2,376	4,752	7,128	9,504	11,880	14,256	19,008
1200	2,592	5,184	7,776	10,368	12,960	15,552	20,736
1300	2,808	5,616	8,424	11,232	14,040	16,848	22,464
	BTU/hr						



At a 10 °F ΔT, to meet the estimated cooling load, the air velocity of the space must be 800-900 cfm.

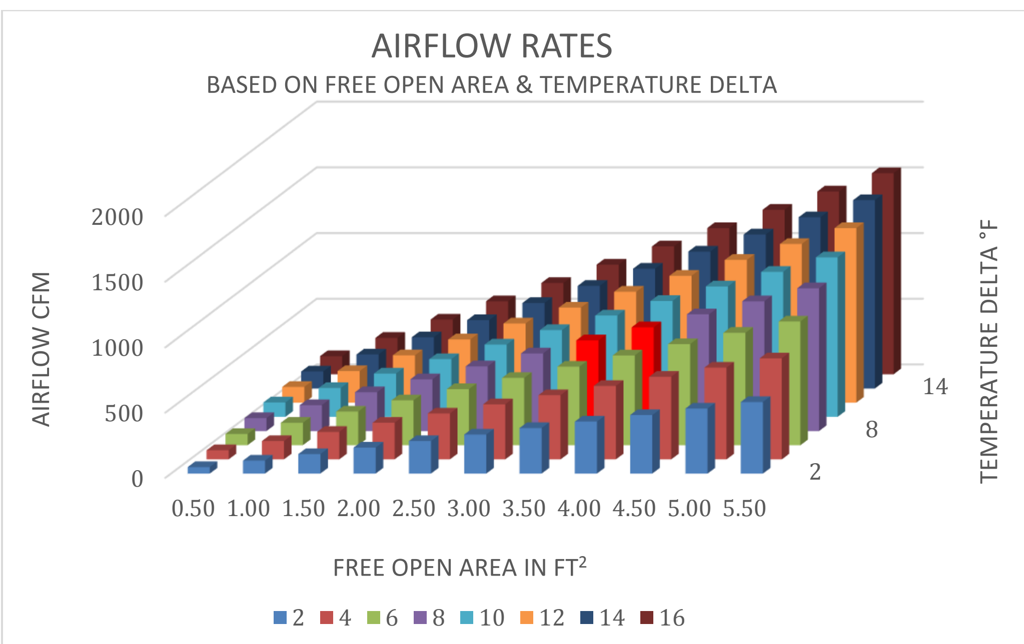
To determine the free open area required to generate the airflow rate of 800-900 cfm at 10 °F ΔT:

Buoyancy Driven Airflow: $Qs = 60CdA\sqrt{2gH((Ti - To)/Ti)}$

Where:

- *Qs* = Airflow rate, cfm
- *Cd* = discharge coefficient for opening, 0.065
- *A* = free open area, ft^2
- *g* = gravity, 32.2 ft/s^2
- *H* = Height of Vent Shaft from center of lower opening to bottom of top opening
- *Ti* = Temperature, indoor, °F
- *To* = Temperature, outdoor, °F

ΔT	Free Open Area ft^2										
	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50
2	50	100	150	199	249	299	349	399	449	499	549
4	70	141	211	282	352	422	493	563	634	704	774
6	86	172	258	344	430	516	602	688	775	861	947
8	99	198	298	397	496	595	694	793	893	992	1091
10	111	221	332	443	553	664	775	885	996	1107	1218
12	121	242	363	484	605	726	847	968	1089	1210	1331
14	130	261	391	522	652	783	913	1044	1174	1305	1435
16	139	278	418	557	696	835	975	1114	1253	1392	1532
	cfm										

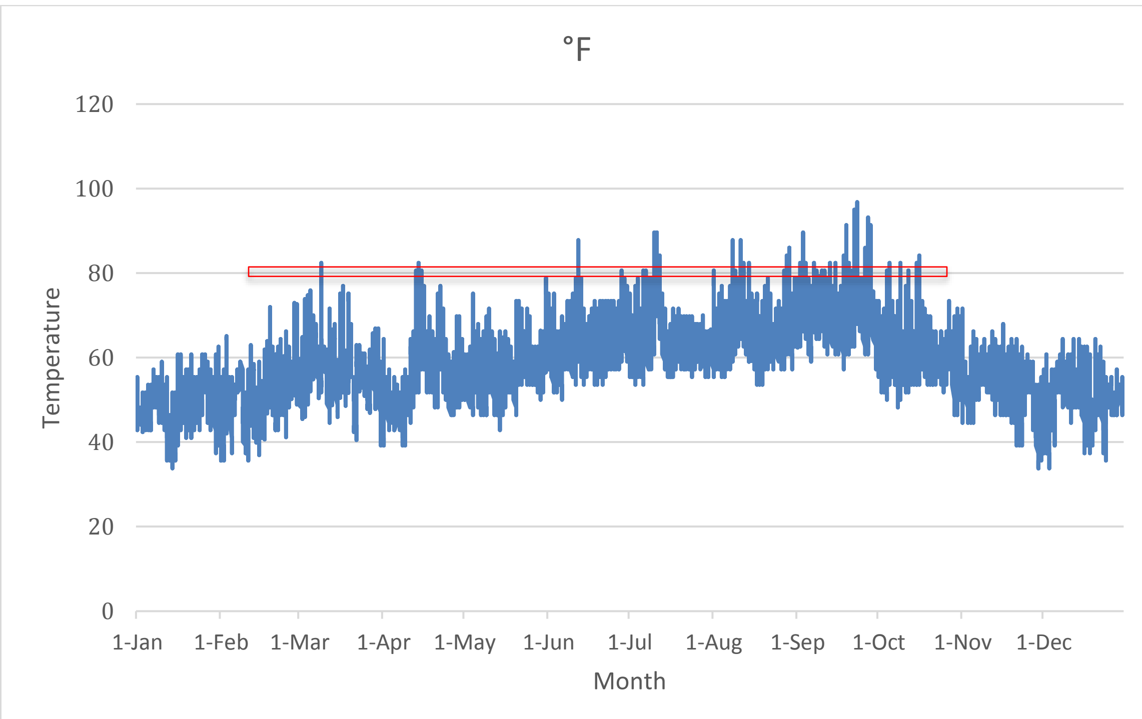


A free open area of between 3.5 ft^2 and 4.0 ft^2 is required for 885 cfm at 10 °F ΔT.

To determine the height required to generate the airflow rate of 800-900 cfm at 10 °F ΔT:

	Free Open Area ft²										
	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50
Current Height	111	221	332	443	553	664	775	885	996	1107	1218
Minus 4 ft	102	204	306	409	511	613	715	817	919	1022	1124
Δ cfm	9	17	26	34	43	51	60	68	77	85	94
	cfm										

The current height represents an 8.3% improvement in the effectiveness over a scheme that is 4 feet lower.



8.3% equates to 30 hours of mechanical cooling that would be required if the tower were 4 feet lower.

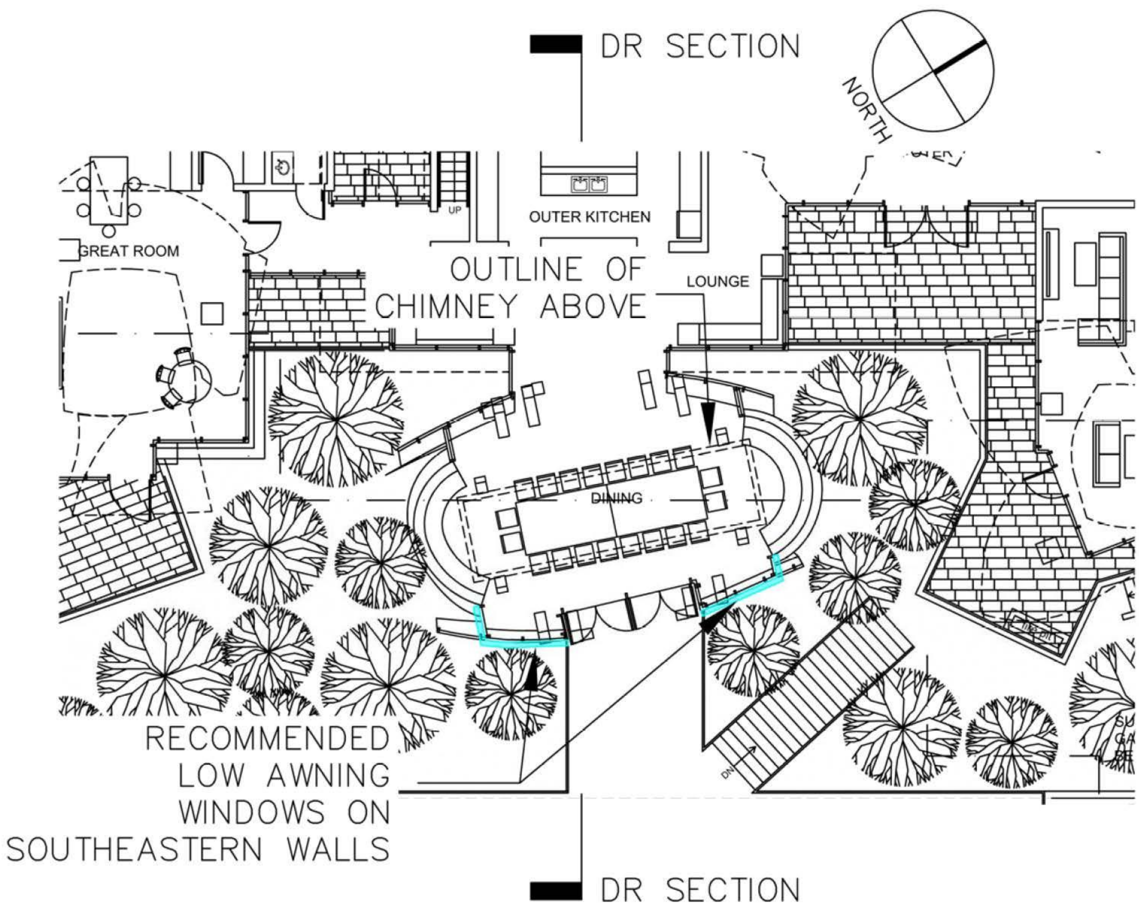
The above graph is an approximate visual range of the additional mechanical cooling hours gained.

Conclusions

- The northwest facing skylight in the solar chimney will primarily rely on buoyancy driven ventilation during April through September, the months when there is a call for cooling.
- The mass of brick around the volume will help create temperature stratification within the chimney; this assists buoyancy driven ventilation by creating a greater temperature differential between the interior and exterior.
- A 10 °F ΔT between interior and exterior will require an airflow rate of 800 – 900 cfm. With the effect of the solar gain on the mass of the solid walls, a 10 °F ΔT is a reasonable expectation of a temperature differential between the interior and the exterior.
- The free open area is required to be between 3.6 ft^2 and 4.0 ft^2.
- This will give a rate of 3.6-4.0 air changes per hour for the entire volume.

Dining Room

The Dining Room, located in the center of the project, is a three story volume and is the "solar chimney". The walls on the northwest and southeast sides are glass and the walls on the north and west sides are solid. The cathedral ceiling is approximately 30 feet in height. Directly below and to the southeast is a lower level garden area.



DINING ROOM PLAN
N.T.S.

Dining Room Dimensions

Dimensions:

First floor area: 597 ft^2

Height of Vent Stack: 28 ft (centerline of low windows to bottom opening of skylight)

Volume: 14,717 ft^3

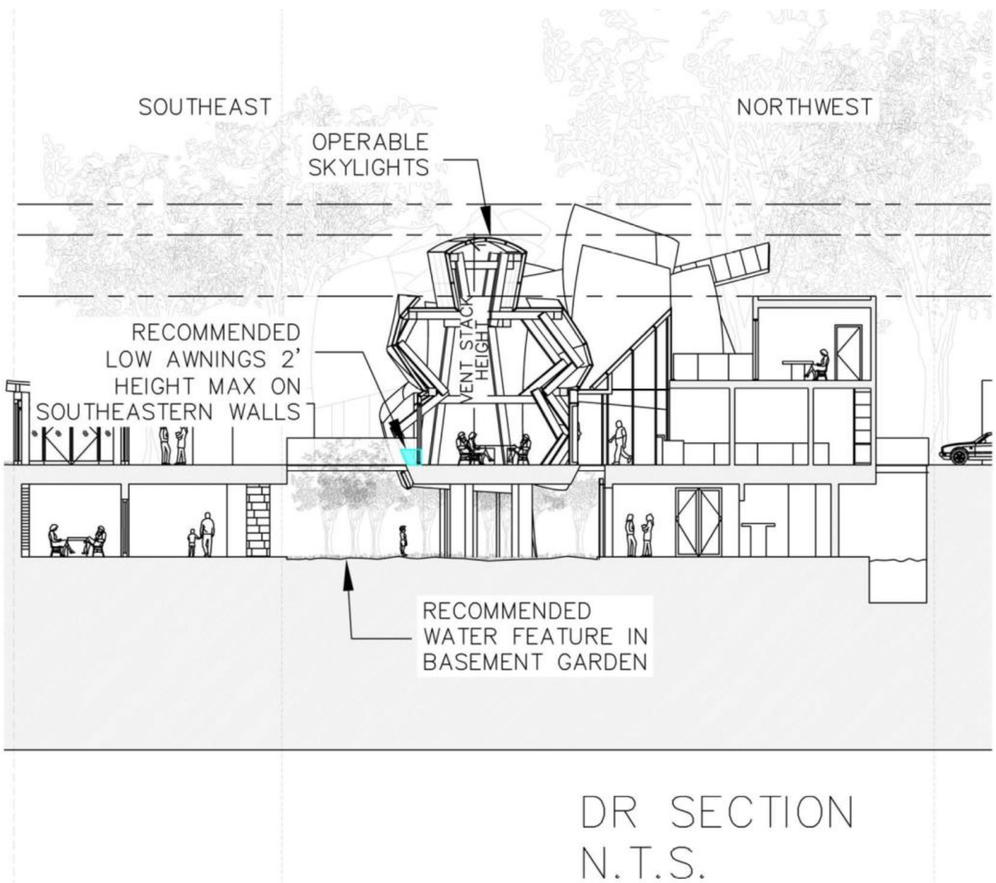
Solid Wall Surface Area:

Roof Glazing/Skylight Surface Area:

Preliminary Estimated Heating/Cooling Load: 12,000 – 18,000 BTU/hr (1- 1/2 ton)

Design Features:

All glazing is planned to have automated shades to control direct solar gain in the space.



Dining Room Calculations

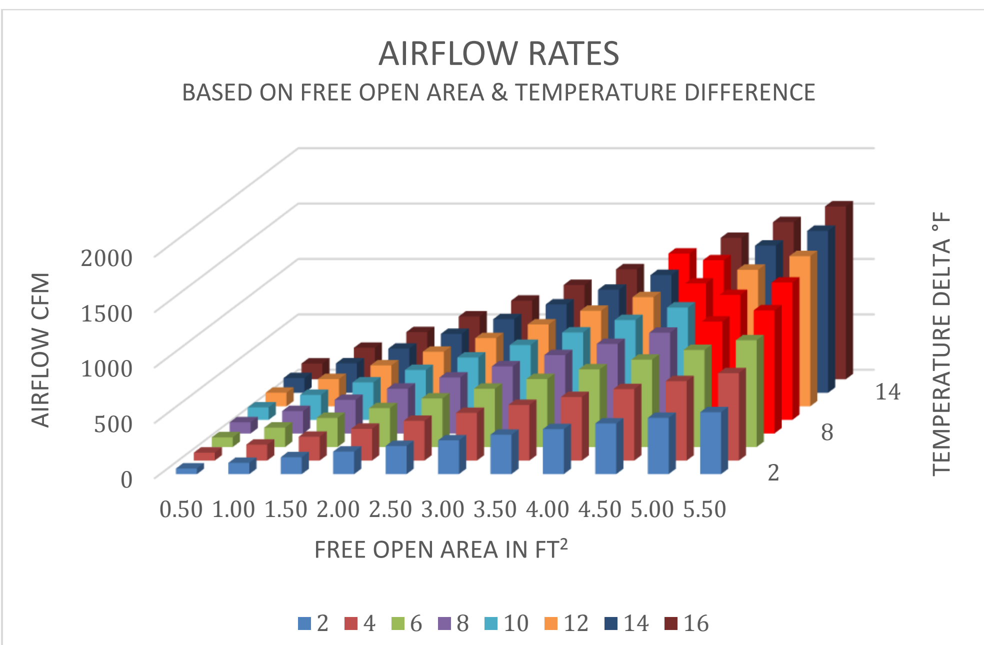
Buoyancy Driven Airflow: $Qs = 60CdA\sqrt{2gH((Ti - To)}/Ti)$

Where:

- Qs = Airflow rate, cfm
- Cd = discharge coefficient for opening, 0.065
- A = free open area, ft^2
- g = gravity, 32.2 ft/s^2
- H = Height of Vent Shaft from center of lower opening to bottom of top opening
- Ti = Temperature, indoor, °F
- To = Temperature, outdoor, °F

At 28 ft height for the vent shaft, the airflow generated is as follows:

ΔT	Free Open Area ft^2										
	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50
2	51	102	152	203	254	305	356	406	457	508	559
4	72	143	215	287	358	430	502	574	645	717	789
6	88	175	263	351	438	526	613	701	789	876	964
8	101	202	303	404	505	606	707	808	909	1010	1111
10	113	225	338	451	564	676	789	902	1014	1127	1240
12	123	246	370	493	616	739	863	986	1109	1232	1356
14	133	266	399	532	664	797	930	1063	1196	1329	1462
16	142	284	425	567	709	851	993	1134	1276	1418	1560
	cfm										



Sensible Heat Equation: $Qs = 1.08\ Q\Delta t$

Where:

Qs = Sensible heat gain (cooling load), BTU/hr

Q = Airflow rate, cfm

Δt = temperature difference between indoors and outdoors, °F

Estimated cooling load for the space is 12,000 BTU/hr.

cfm	Temperature Difference between Indoors and Outdoors °F						
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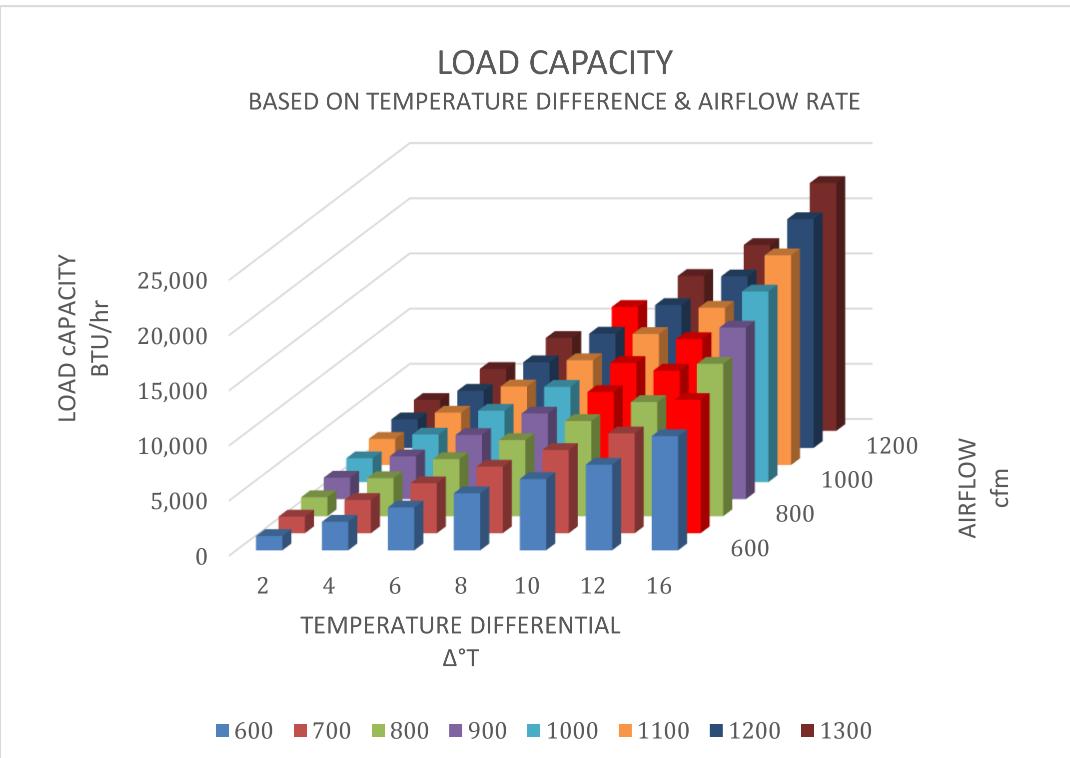
800	1,728	3,456	5,184	6,912	8,640	10,368	13,824
900	1,944	3,888	5,832	7,776	9,720	11,664	15,552
1000	2,160	4,320	6,480	8,640	10,800	12,960	17,280
1100	2,376	4,752	7,128	9,504	11,880	14,256	19,008
1200	2,592	5,184	7,776	10,368	12,960	15,552	20,736
1300	2,808	5,616	8,424	11,232	14,040	16,848	22,464
	BTU/hr						

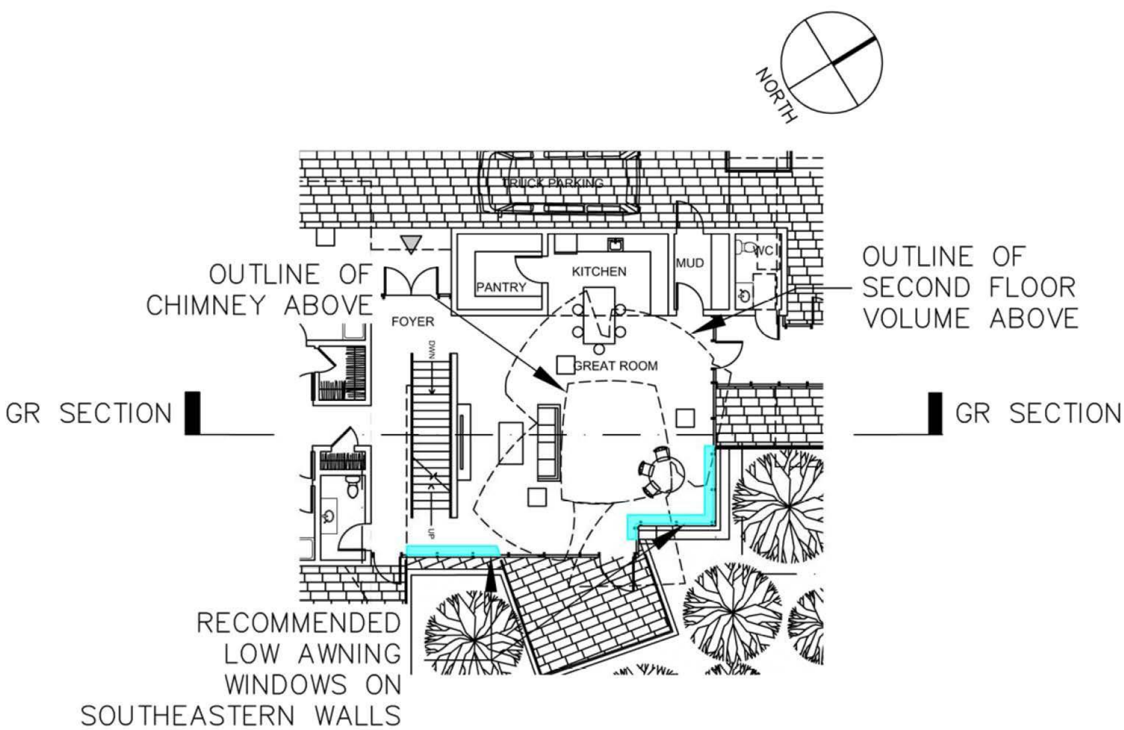


Dining Room Conclusions

- The operable skylights at the top of the solar chimney will be most effective opening to the West and Northwest.
- The greater the temperature difference between the interior and the exterior will allow for greater cooling capacity with the solar chimney. By allowing controlled direct gain into the upper glass volume will help create warmer temperatures for stratification.
- A 10 °F ΔT between interior and exterior will require an airflow rate of 1,100 – 1,200 cfm.
- The free open area is required to be between 4.8 ft^2 and 5.4 ft^2.
- This will give a rate of 4.4 – 5.0 air changes per hour for the entire volume.
- The addition of a water feature in the lower level below the Dining Room, can act as an evaporative cooler and chill down the exterior air temperature allowing cooler air to flow into the low awning windows.

Great Room

The great room is very similar in volume and construction as the living room. It located on the southern end of the building with a two story volume and a "solar chimney" above. The first floor glass is not as well shaded from the second floor wall structures as the Living Room first floor glass. The northeast and southeast glazing either side of the exterior patio, are close to the lower level garden. The skylight at the top of the solar chimney faces southwest.



GREAT ROOM PLAN
N.T.S.

Great Room Dimensions

Dimensions:

First floor area: 741 ft^2

Height of Vent Stack: 28 ft (centerline of low windows to bottom opening of skylight)

Volume: 13,601 ft^3

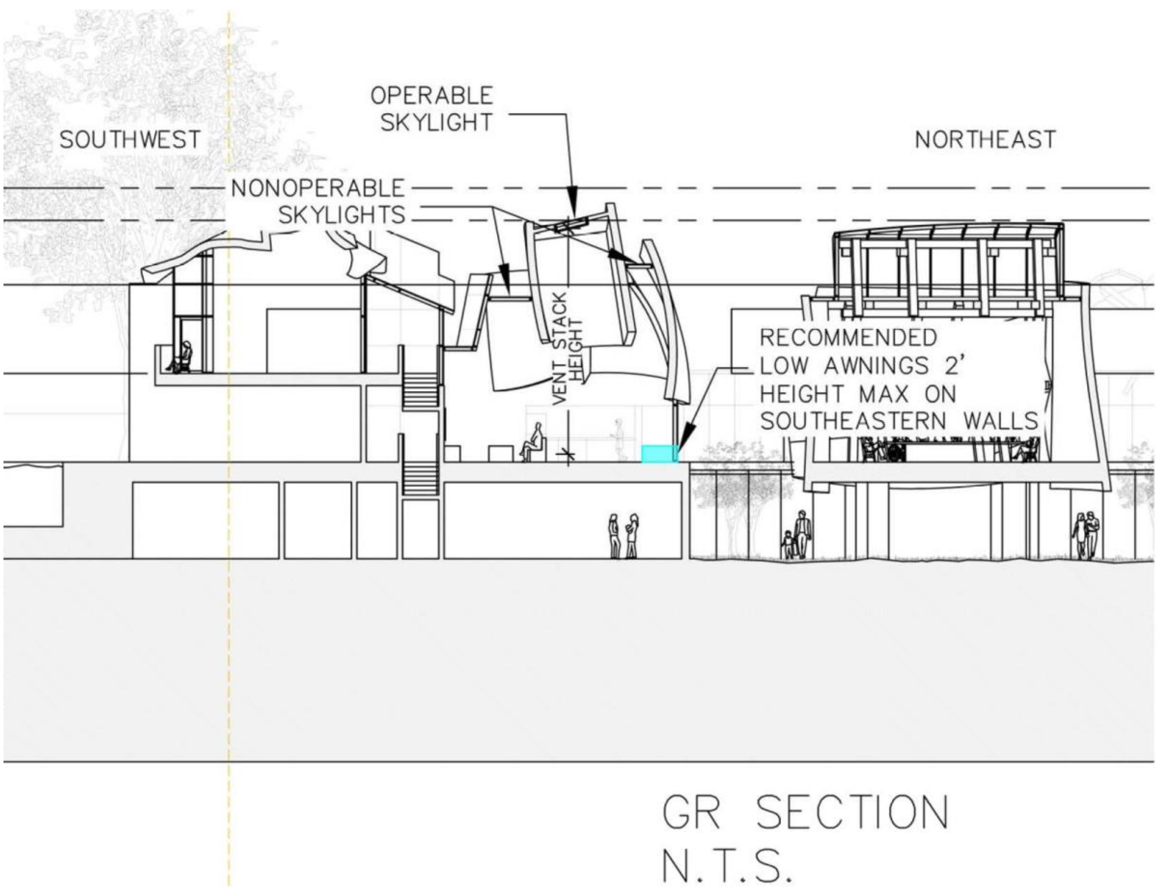
Solid Wall Surface Area: 2,870 ft^2, assume 50% surface area has direct solar gain = 1,435 ft^2

Roof Glazing/Skylight Surface Area: 450 ft^2

Preliminary Estimated Heating/Cooling Load: 9,000 - 12,000 BTU/hr (3/4 - 1 ton)

Design Features:

The non-operable skylights/roof glazing areas at the top of the second floor volume are planned to have automated shades when there is direct solar gain, primarily in summer months.



GR SECTION
N.T.S.

Great Room Calculations

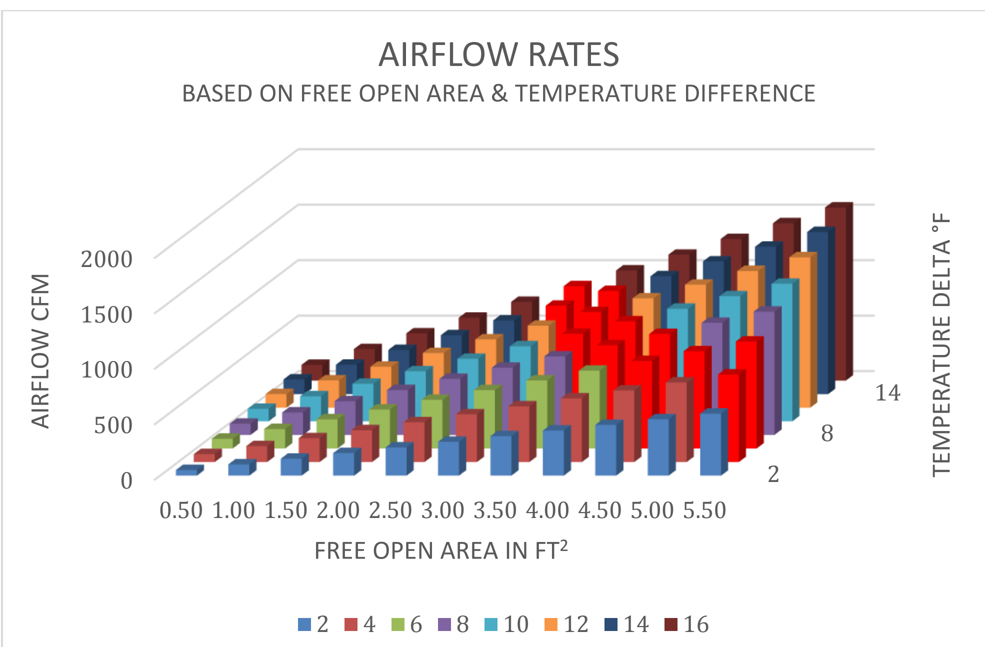
Buoyancy Driven Airflow: $Qs = 60CdA\sqrt{2gH((Ti - To)/Ti)}$

Where:

- Qs = Airflow rate, cfm
- Cd = discharge coefficient for opening, 0.065
- A = free open area, ft^2
- g = gravity, 32.2 ft/s^2
- H = Height of Vent Shaft from center of lower opening to bottom of top opening
- Ti = Temperature, indoor, °F
- To = Temperature, outdoor, °F

At 28 ft height for the vent shaft, the airflow generated is as follows:

ΔT	Free Open Area ft^2										
	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50
2	51	102	152	203	254	305	356	406	457	508	559
4	72	143	215	287	358	430	502	574	645	717	789
6	88	175	263	351	438	526	613	701	789	876	964
8	101	202	303	404	505	606	707	808	909	1010	1111
10	113	225	338	451	564	676	789	902	1014	1127	1240
12	123	246	370	493	616	739	863	986	1109	1232	1356
14	133	266	399	532	664	797	930	1063	1196	1329	1462
16	142	284	425	567	709	851	993	1134	1276	1418	1560
	cfm										



Sensible Heat Equation: $Qs = 1.08\ Q\Delta t$

Where:

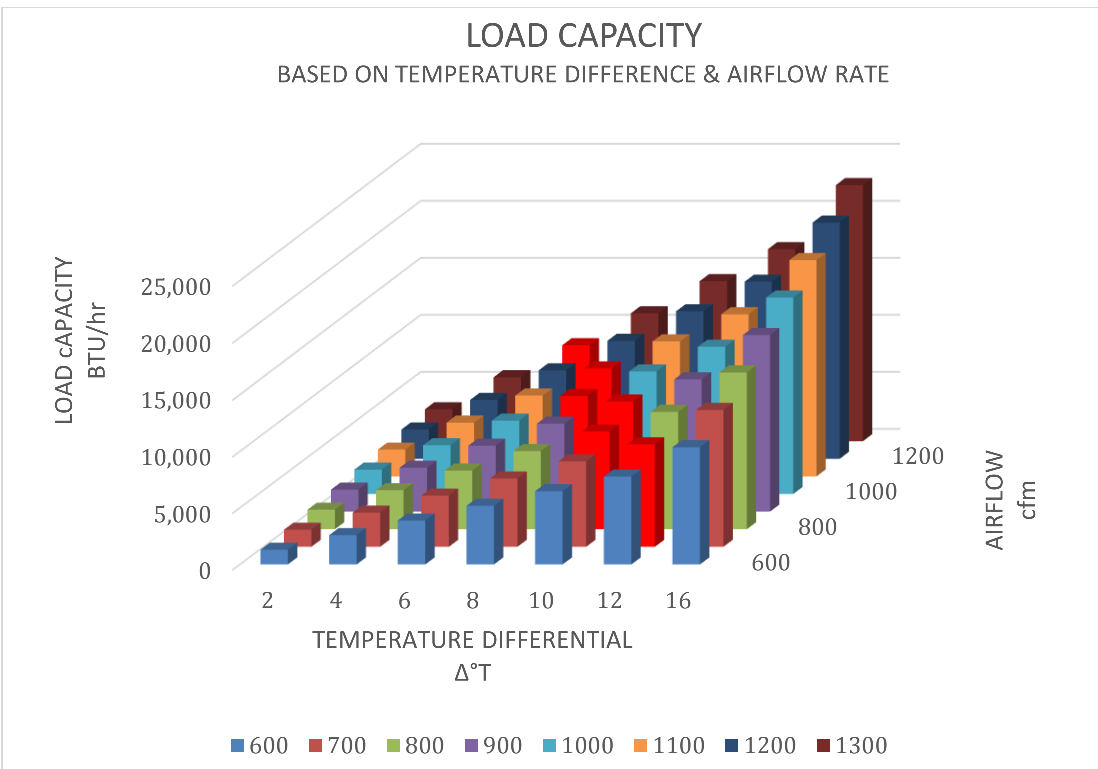
Qs = Sensible heat gain (cooling load), BTU/hr

Q = Airflow rate, cfm

Δt = temperature difference between indoors and outdoors, °F

Estimated cooling load for the space is 9,000 BTU/hr.

cfm	Temperature Difference between Indoors and Outdoors °F						
	2	4	6	8	10	12	16
600	1,296	2,592	3,888	5,184	6,480	7,776	10,368
700	1,512	3,024	4,536	6,048	7,560	9,072	12,096
800	1,728	3,456	5,184	6,912	8,640	10,368	13,824
900	1,944	3,888	5,832	7,776	9,720	11,664	15,552
1000	2,160	4,320	6,480	8,640	10,800	12,960	17,280
1100	2,376	4,752	7,128	9,504	11,880	14,256	19,008
1200	2,592	5,184	7,776	10,368	12,960	15,552	20,736
1300	2,808	5,616	8,424	11,232	14,040	16,848	22,464
	BTU/hr						



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Great Room Conclusions

- Automated shades on the first floor glass will help control unwanted direct solar gain.
- A 10 °F ΔT between interior and exterior will require an airflow rate of 800 – 900 cfm.
- The free open area is required to be between 3.5 ft^2 and 4.0 ft^2.
- This will give a rate of 3.5 – 4.0 air changes per hour for the entire volume.
- Similar to the Dining Room, the addition of a water feature in the lower level below, can act as an evaporative cooler and chill down the exterior air temperature allowing cooler air to flow into the low awning windows. The greater the temperature differential, the more effective the natural ventilation will be.

Solar Chimney Development Recommendations

The calculations for each solar chimney yielded the following data:

	Estimated Cooling Load BTU/hr	Airflow Rate Required cfm	Free Open Area Required ft^2
Living Room	9,000	800 - 900	3.6 -4.0
Dining Room	12,000	1,100 – 1,200	4.8 – 5.4
Great Room	9,000	800 - 900	3.5 -4.0

- The higher the vent shaft, the greater the capacity for cooling, so keep the lower openings as close to the floor as possible and adjacent to the lower level garden openings. Lower outdoor temperatures are anticipated in the low level garden, which will assist in cooler temperatures entering the lower openings in the solar chimneys.
- Automated shades on glazed surfaces will be key to controlling the solar gain. An alternate to automated shade could be dynamic electrochromic glass that changes light visibility based on direct solar gain. (i.e. sageglass.com)
- A weather station will be required for monitoring insolation (solar gain) and outdoor air temperature.
- The following is a recommended sequence of functioning for a full mechanical cooling design:
    - 1ST stage cooling to be natural ventilation
    - 2nd stage cooling to be automated shade control
    - 3rd stage cooling to be radiant floor cooling
    - 4th stage cooling to be fan coil air conditioning and dehumidification if 100% thermal comfort is required at all times.
- Radiant floor cooling can be further defined into active and passive modes if utilizing ground source heat pumps. In passive mode the ground hydronic loop would bypass the compressor and flow water through the radiant floor cooling at or near the actual ground temperature (~65 °F). Active mode would utilize the heat pump compressor to chill the water to a lower temperature.
- The solar chimneys can also be utilized for nighttime cooling strategies and for ventilation flushing sequences.

Next Steps

- A building energy model to determine the exact heating and cooling loads for each zone can be used to confirm the free open areas required for the solar chimneys.
- A CFD analysis (computational fluid dynamic) with weather data should be done to confirm the calculations in this study.
- A computer modeled daylighting study will determine amount of solar gain through the glazing and effects on the building load.