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Sproul Hall Cooling Load Reduction

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TTP 289 – Path to Zero Net Energy
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1. Executive Summary

Facilities management at UC Davis is looking into replacing Sproul Hall's aging HVAC system with a radiant system; however, an outside contractor determined through Trace 700 simulation that the number of radiant panels required to meet peak heating and cooling loads cannot be accommodated by the building's limited ceiling space.

The team was tasked with investigating actions which would reduce the building's peak cooling load to allow the limited number of radiant panels to adequately service the space. Initial investigation of the distribution of cooling load within the building showed that energy flow through the windows (by conductive heat flow or by radiative solar heat gain) accounts for the majority of the building's cooling loads. Consequently, the team focused on improvements to the building's windows: installing double pane windows, side fins, and overhangs. Double pane windows primarily targets window conduction loads while side fins and overhangs target window radiation loads.

The team used the Quick Energy Simulation Tool (eQuest) to model the building with the proposed radiant system in order to evaluate the magnitude of cooling load reduction as well as the associated reduction in required number of radiant panels provided by various window improvements. The majority of the building's spaces were identified to have peak cooling loads exceeding the radiant ceiling panel capacity and have been targeted for window improvements. The selection of measures to implement depended on the larger of the window-based loads: conduction or solar radiation. The measure which more effectively addresses the larger load is implemented first. Further measures were implemented until the total reduction in cooling load sufficiently reduced the number of required radiant panels to numbers achievable by ceiling space.

In order to achieve the required cooling load reductions to allow the proposed radiant system to meet Sproul Hall's peak demands, the following four measures have been recommended:

1. Install double pane windows, overhangs, and side fins for the 9th floor south offices
2. Install double pane windows for the 9th floor conference room
3. Install side fins for the 1st to 8th floor south offices
4. Install double pane windows for the 3rd to 8th floor northwest offices in the Seismic Addition

Table 1 shows the economic summary for each recommended measure. When bundled, the measures pay for themselves immediately.

Table 1: Measures Cost Summary

Measure	Electrical Energy Savings, kWh/yr	Peak Demand Reduction, kW	Gas Use Reduction, therms/yr	Energy Cost Reduction, $/yr	Radiant Panel Cost Reduction, $ (# panels)	Window Improvement Implementation Cost, $	Net Implementation Cost, $	Payback (yrs)
1	2,608	1.53	817	760	55,727 (133)	57,269	1,542	2.0
2	728	0.53	373	314	12,898 (31)	41,398	28,409	Beyond useful life
3	4,057	2.5	829	872	234,640 (560)	56,448	(178,192)	Immediately
4	637	0.64	156	155	10,056 (24)	65,472	55,416	Beyond useful life
Total	**8,030**	**5.2**	**2,175**	**2,101**	**313,412 (748)**	**220,588**	**(92,824)**	**Immediately**

2. Introduction

2.1 Planned Retrofits

Facilities Management (client) at UC Davis is considering replacing Sproul's aging heating, ventilation and air conditioning (HVAC) system consisting of fan-coils with a hydronic radiant system.[1] The proposed system is expected to be more energy efficient due to: (1) the use of water, with a higher heat-carrying capacity than air, to deliver heating and cooling energy, and (2) the use of radiation for heat transfer which is the primary mode influencing occupant thermal comfort.

The high heat carrying capacity of water, relative to air, reduces the distribution energy needed to move heating and cooling energy throughout the building. Further energy savings result from the delivery of heating and cooling service through radiative heat transfer from a body at higher temperature to a body at lower temperature instead of through modulating ambient temperature. This allows the system to heat at a lower water temperature and cool at a higher water temperature.

There are three main constraints with the proposed radiant system:

1) The potentially slower response time to changes in heating and cooling needs depending on the thermal mass of the medium (concrete slabs, metal plates, etc.) that supplies service to the space
2) The limited area available in each thermal zone to house the panels
3) The space dew point temperature (temperature below which condensation occurs) at peak loads which determines the radiant operating temperature in order to avoid condensation which potentially leads to mold growth and corrosion.

An outside consultant determined through a Trace 700 simulation that there is not enough ceiling space within each thermal zone to accommodate the number of radiant panels required to meet its peak cooling load. To verify this, the client and the Western Cooling Efficiency Center will carry out a pilot test in the summer of 2014.

The pilot test will evaluate the performance of twelve offices: six offices each on the 8th and 9th floor on the South side of the building. On each floor, the offices will be involved in the study as follows:

- 2 offices unchanged as baseline
- 2 offices in which fan coils are replaced with modern replacement fan coils
- 2 offices in which radiant ceiling panels will be installed

2.2 Scope of Work

The client has recruited a team from the Path to Zero Net Energy (ZNE) course to assist them in reducing the space heating and cooling load of Sproul Hall to allow the proposed radiant system to meet peak demands. Due to the operating limitation of the radiant system in cooling (operating temperature needs to be above the space dew point temperature to avoid condensation and consequent mold growth), lowering the cooling loads is of primary interest.

Based on discussion with the client, walkthrough of the Sproul Hall, and preliminary analysis of the building's loads, the ZNE team has targeted two aspects in an attempt to reduce the building's cooling demand:

1) Replacement of existing single pane windows with low-e, double pane windows
2) Installation of window overhangs and side fins to provide shading

A detailed modeling effort via the Quick Energy Simulation Tool (eQuest) was employed for analysis. The outputs of this study are as follows:

[1] refer to Section 3 for details on the building

1) Magnitude of cooling load reduction from window improvements
2) Reduction of required radiant panels to serve the reduced loads
3) Increase/decrease in implementation cost based on (1) and (2)
4) Achievable energy and cost savings of (1) and (2)

2.3 Prior Art

Radiant Cooling 2003 [1] presents the economics and some design considerations of radiant systems. It also discusses the public perception and the future of this type of HVAC system. Radiant systems are built on the principle of separating the sensible load from the latent load, with the former being handled by the radiant system and the latter by a dedicated ventilation unit. Since lower air flows are needed in this scheme, energy savings results. Some examples of succssful implementation in European buildings - the continent where this system is widely used - are presented.

Radiant Heating and Cooling chapter [2] of the 2007 ASHRAE Handbook: HVAC Applications presents the elementary principles behind radiant heating and cooling, with emphasis of the primary modes of heat transfer with this systems type (convection and radiation) and their effects on occupant thermal comfort. Governing radiative and conventive equations are presented. Appropriate settings for the application of radiant cooling and heating are presented and discussed.

Panel Heating and Cooling chapter [3] of the 2008 ASHRAE Handbook: Systems and Equipment presents the underlying principles of radiant heating and cooling and provides a procedure for the design of radiant heating and cooling systems. The methodologies to quantify thermal losses and panel performance are also presented. A multitude of design considerations including arrangement and humidity problems are discussed.

Radiant Heating and Cooling 2012 [4] discusses the various benefits of radiant systems in terms of thermal comfort and energy efficiency. Since the human wants to lose/gain body heat through radiation, radiant systems can provide a better perception of thermal comfort, which allows heating and cooling sources to provide heating at a lower temperature and cooling at a higher temperature and thus increasing their efficiencies.

Dundala 2003 [5] details the eQuest modeling methodology in evaluating the implementation of radiant heating systems in the historic S.T. Dana Building for LEED Energy Performance. Design considerations, inputs to the programs and associated results and conclusions are presented. The radiant system with dedicated outside air units was found to be superior in energy performance and service life compared conventional air systems.

Wiryadinata 2013 [6] outlines three general steps for achieving zero net energy in buildings: minimizing energy demands through building envelope measures, minimizing energy consumption through energy efficient measures at the system and occupant level, and installing renewable energy generation systems to offset the site's annual energy consumption. The paper highlights the economic benefit of implementing energy efficient measures that target the largest loads and in reducing on site demand before considering energy generation. The paper also describes various energy efficiency measures including double pane windows with low-e coatings, exterior shading, insulation for walls and roofs, and lighting occupancy controls.

3. Existing Building and Systems Description

3.1 Building Audit

At the end of March 2014, the ZNE team performed a walkthrough of Sproul Hall. Major findings of the visit are as described below.

Sproul Hall's heating and cooling needs are served by aging fan coil units, which are at the end of their useful life and plagued by condensation issues in the piping. To prevent further deterioration of the pipes, the system operates at a higher water supply temperature, thereby resulting in reduced cooling capacity and diminished occupant comfort.

A fan coil unit is housed in each office of Sproul Hall, and consists of a heating and cooling coil and a fan that is controlled via a manual thermostat on the unit. The coils receive heated or chilled water from the campus Central Plant through the building's 2-pipe distribution system. A photo of the unit is pictured in Figure 3.1-1.

Figure 3.1-1 Existing Fan Coil Unit

The building audit highlighted several problems with the current system. First, the covers of the thermostats were often stuck shut. As seen in Figure 1, building occupants created in-house solutions (such as paper clips) to access the thermostat. Also, the aging systems provide limited cooling capacity and the effects of the cool air are only felt if the occupant is very close to the vent.

Additionally, Sproul Hall utilizes single pane windows. Each office contains at least one single-pane window, as seen in Figure 3.1-2. Even though each window is equipped with blinds, the visit indicated that building residents do not operate them. The high number of single pane windows contributes to a high cooling load, whose demand cannot be met by the aging system. Ventilation is also a concern, since some windows within the building are inoperable (see Figure 3.1-3).

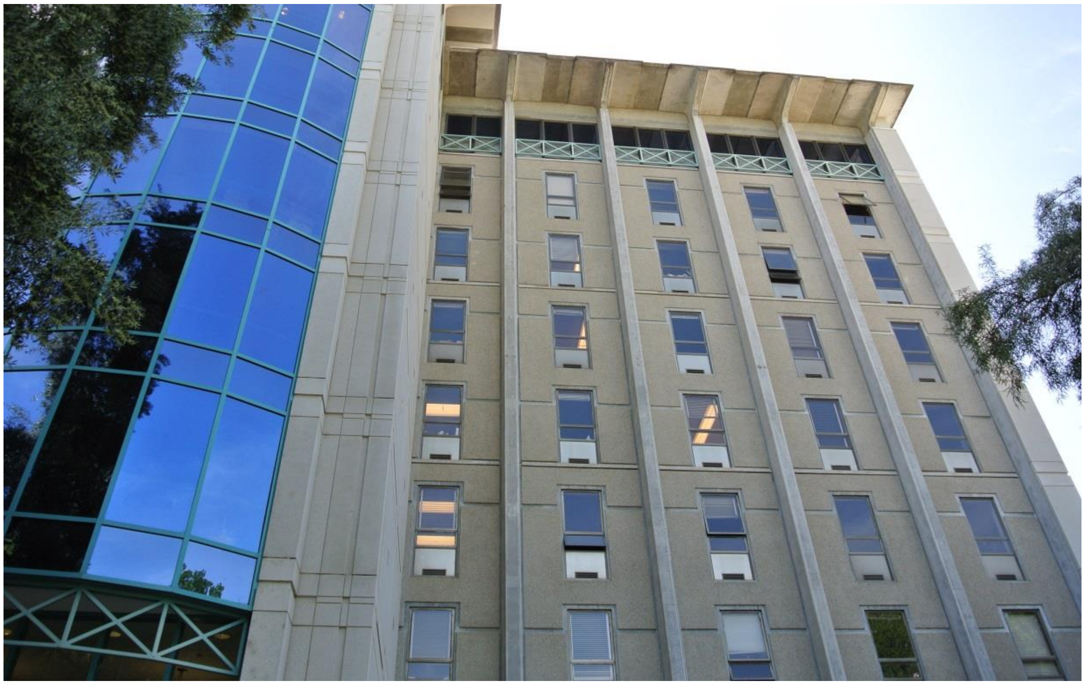

Figure 3.1-2 Single Pane Windows

Figure 3.1-3 Inoperable Windows

Finally, the design of the 9th floor differs from the other floors in that the roof overhang is utilized for the window shading. The large distance (relative to other floors) between the overhang and the window reduces the effectiveness of the roof overhang at blocking sunlight to the windows and reducing solar heat gain. Additionally, the 9th floor has more window area than any other floor, typically 3 to an office, as seen in Figure 5.

This will make it a challenge for radiant cooling to achieve its desired cooling capacity, which is of the greatest concern for its implementation.

Figure 3.1-4 Roof Overhang

Figure 3.1-5 9th Floor Windows

3.2 Detailed Site Description

Sproul Hall is a 50,850 sqft (approx.) building with 9 above-grade floors and 1 unconditioned basement located on the University of California, Davis (UC Davis) campus. It was constructed in 1963 and houses the Departments of Religious Studies, Comparative Literature, and Foreign Language. The building serves primarily as office space and operates from 7 am to 7 pm five days a week.

In the early 1990s, a seismic retrofit stipulating a structural add-on to the North side of the building was performed. The remainder of the building has remained virtually unchanged since its construction, which means Sproul Hall features the same single pane windows and un-insulated concrete walls from its initial construction. Figures 3.2-1 to 3.2-3 show the floor plans of the buildings, as extracted from the architectural drawings. Note that the original Sproul is a rectangular building. The protrusion on the north side is the seismic addition.

The basement is used as storage and houses the mechanical room. The latter houses chillers and boilers, which are no longer utilized due to steam and chilled water connected to the campus Central Plant. With the exceptions of the basement, stairs, restrooms and janitor's closet, all areas of the building are conditioned. Only the conditioned spaces contain windows. The following summarizes the major physical parameters of the building:

- 1^{st}-8^{th} floor
  - Floor-to-floor height = 10 ft
  - Floor-to-ceiling height= 8 ft
  - Original building windows = 2.8 ft x 4.9 ft (width x height)
  - Seismic building windows = 20.6 ft x 7.6 ft
- 9^{th} floor
  - Floor-to-floor height = 12 ft
  - Floor-to-ceiling height= 8 ft
  - Original building windows = 8.8 ft x 4 ft
  - Seismic building windows, North = 20.6 ft x 7.6 ft
  - Seismic building windows, East-West = 17.6 ft x 4 ft

The building's hydronic system consists of a 2-pipe circulation loop which supplies either chilled water (CHW) or hot water (HW) depending on the building load. No simultaneous heating or cooling is possible in this type of circulation loop. CHW at 44°F is supplied by the campus district loop from the Central Plant's chillers which have an efficiency of 0.8 kW/ton. The supply CHW is mixed with the return CHW to produce CHW at 54°F which is circulated by the 2-pipe system. Steam at 350°F is supplied by the Central Plant's boilers which have an efficiency of 80%. The supply steam is supplied to the building's steam-to-HW heat exchanger to produce HW at 180°F which is circulated by the 2-pipe system. All efficiency values were provided by the client. Based on the mechanical schedule, each fan coil has a minimum of 1/6-hp supply fan and is manually operated by a dial-type thermostat on each unit.

Please refer to section 5.2 for the building energy consumption and end-use distribution.

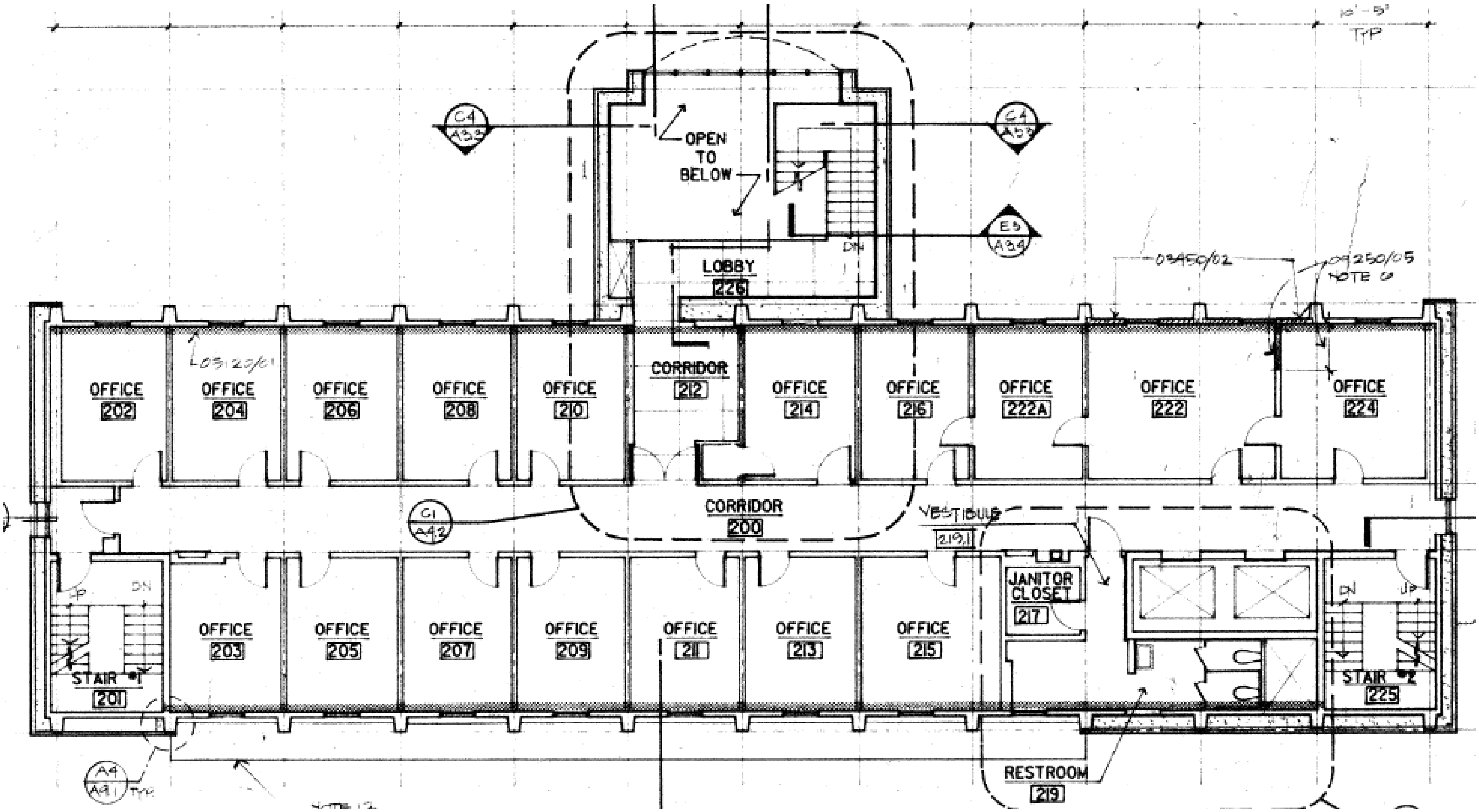

Figure 3.2-1 Ground Floor Plan

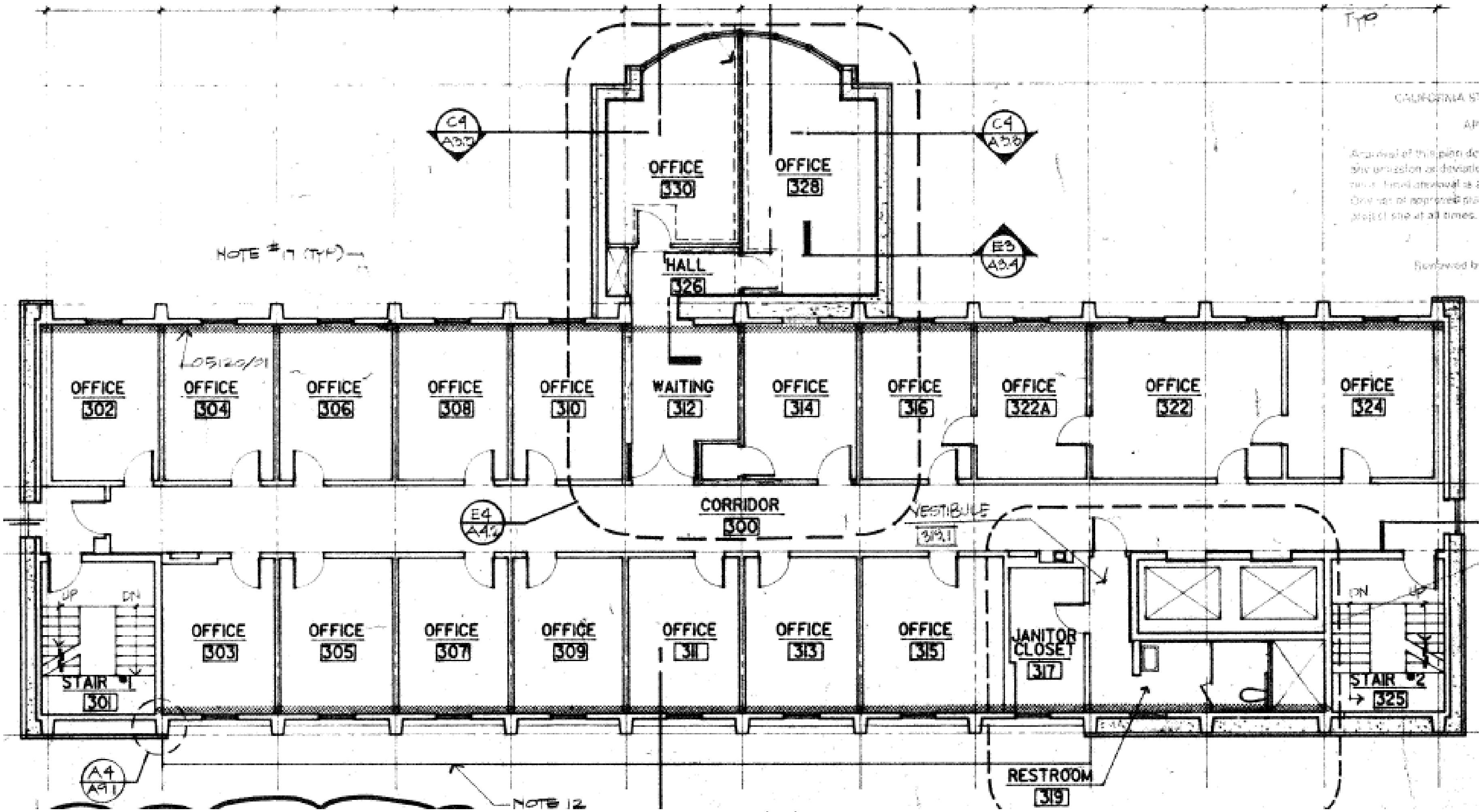

Figure 3.2-2 Mid (3rd-8th) Floor Plan

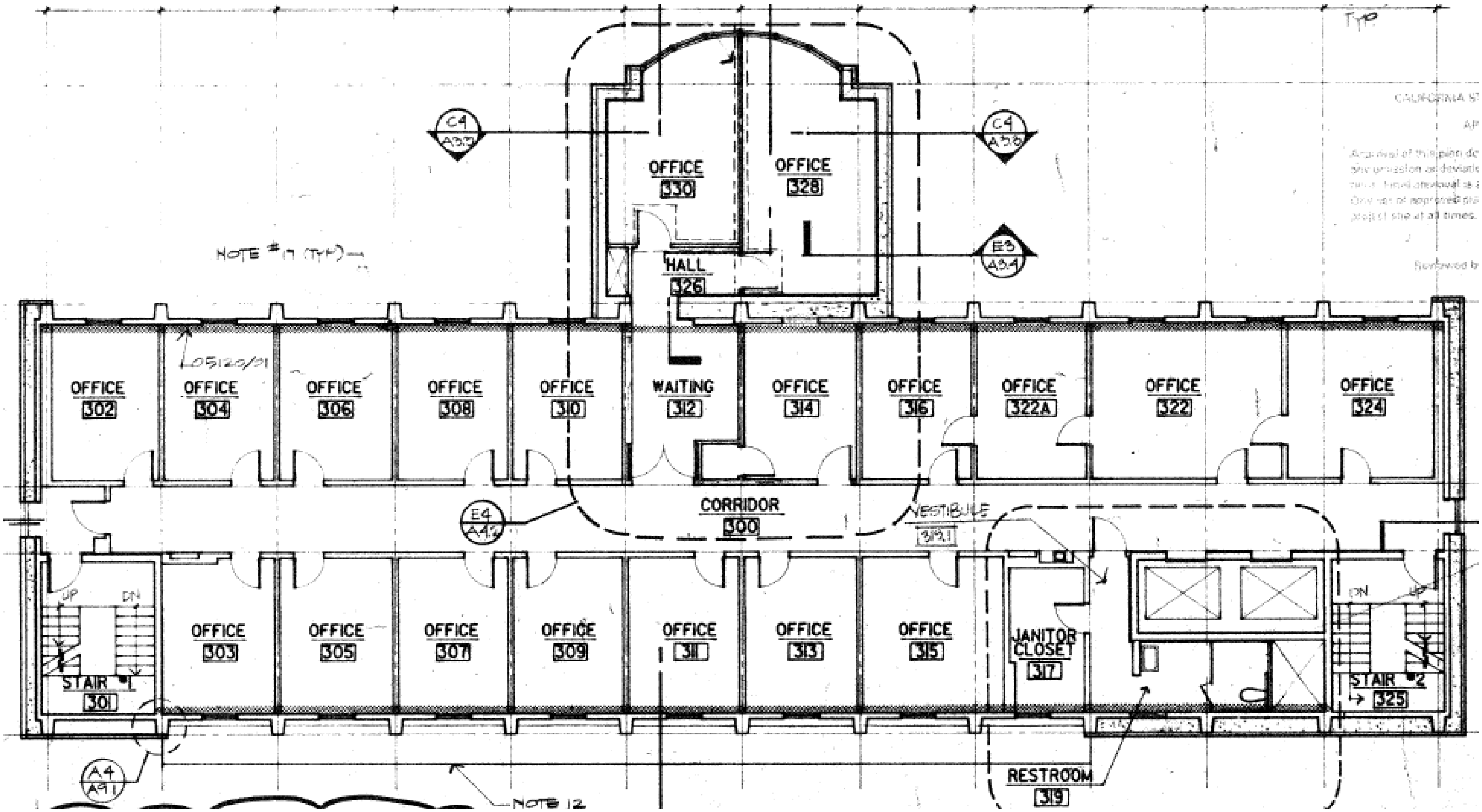

Figure 3.2-3 Top Floor Plan

4. Occupant Survey

After auditing the building for its physical features, the ZNE team surveyed the building occupants to understand their ambient comfort level so that the recommended measures would best serve their needs. The ultimate goal of installing a new HVAC system is to increase the comfort of the residents, while reducing the maintenance costs associated with the current system.

The survey contained questions to assess the various aspects of building performance, and how it affects its residents. The team asked about indoor air quality, thermal comfort, and how the resident uses features such as blinds, windows, and the current HVAC system to meet their needs. Highlights of the results can be seen in Appendix 8.1.

The results of the survey indicated that residents are displeased with the extreme temperature variation in the building. Many complained of it being too hot throughout the year. Respondents from the 8^{th} and 9^{th} floors were especially displeased with the high temperatures in their offices. During the winter, residents commented that the heater gets too hot and they do not have the ability to turn down the heating system.

Residents also value the ability to open their windows, and some noted that they wished their windows were easier to open. There was also an overwhelming positive response for new blinds. It appears that the reason why occupants do not currently operate the blinds is that they are broken, and too filthy to use.

Indoor air quality was also highlighted as an issue. Residents noted that regular cleaning does not take place in the building, so the buildup of dust and dirt is common in the office areas. This was noted repeatedly, and was reported to decrease workers’ ability to get their job done.

Overall, the results of the survey indicate that residents would benefit from an updated HVAC system, new windows and operable blinds. It is important that the new HVAC system is responsive to changes in outside temperature, as well as the needs of the building residents.

As stated on the scope of work, the ZNE team has focused on evaluating window improvements.

5. Methodology

5.1 Simulation Inputs and Baseline Model Calibration

eQuest simulation was utilized for analysis. This software package can be downloaded for free from www.doe2.com/equest/[7]. The existing building with the proposed radiant system was used as the baseline for measure analyses. However in order to calibrate the model to the existing building energy profiles, simulation was initially performed based on the building's existing HVAC. The model developed in this effort has been made available and should be consulted for specific details which are not presented in this report. This section describes the general methodology in the model construction.

First, the model Sproul Hall was built based on the existing building operation and systems. The following were defined:

1) Building footprint and individual thermal zones (conditioned and unconditioned)
2) Envelop specifications (walls, roof, doors, windows) based on supplied information. In general, concrete walls and roofs and single pane glazing have been specified. Exterior shading devices have been specified.
3) Occupied schedule: 7 am – 7 pm.
4) Energy end-uses
    a. Interior and exterior lighting
    b. Miscellaneous equipment to represent office loads (primarily)
    c. Domestic hot water heating
5) Air-side HVAC system:
    a. Fan coils
    b. Cooling/heating set points: 75F/70F (occupied), 82F/64F (unoccupied)
    c. Chiller
        i. Type: water-cooled, electric reciprocating (assumed)
        ii. Condenser type: open tower with variable speed fan
        iii. CHW supply temperature: 40F
    d. Boiler
        i. Type: steam, forced draft (assumed)
        ii. Supply temperature: 350F
6) Domestic water heater type: electricity.

Additional iterations were performed to calibrate the model to the building's actual energy consumption and demand. The following major parameters were adjusted:

- Lighting power density (W/sqft)
- Equipment power density (w/sqft)
- Envelop infiltration
- CHW and HW distribution losses
- Fan coil fan power

5.2 Building End-Use Distribution

Table 5.2-1 shows the comparison of the modeled and actual energy consumption and demand.

Table 5.2-1 Baseline Calibration, Fan Coil model			
Type	**Actual, FY2012-2013**	**Existing Baseline Model**	**% (Model vs. Actual)**
Annual Energy Consumption, kWh/yr	577,401	542,610	94%
Maximum Demand, kW	148	142	96%

The actual energy consumption and maximum demand represent electrical data metered at the building and does not include values for space cooling and space heating, which are supplied by the campus Central Plant. The California Energy End-use Survey (CEUS) space cooling and heating consumption for Small Office building category in the Sacramento climate zone (FCZ06 SMUD) was utilized as a rough guideline to estimate the existing baseline consumption for these two end-uses. Figure 5.2-1 shows the electrical end-use distribution of the modeled baseline.

The CEUS "Space Cooling" end-use is 18% of the building consumption and is an aggregate of the "Space Cooling", "Heat Rejection" and "Pumps" end-uses in the modeled distribution, which amount to approximately 15.5%. Since cooling is provided by the campus chillers which are more efficient relative to standard packaged DX units (typical for Small Offices), the modeled numbers are justified. The modeled "Ventilation" (10%) is smaller than the CEUS percentage (13%) as the majority of Sproul's fan coils are ductless units which do not incur distribution friction losses in typical applications.

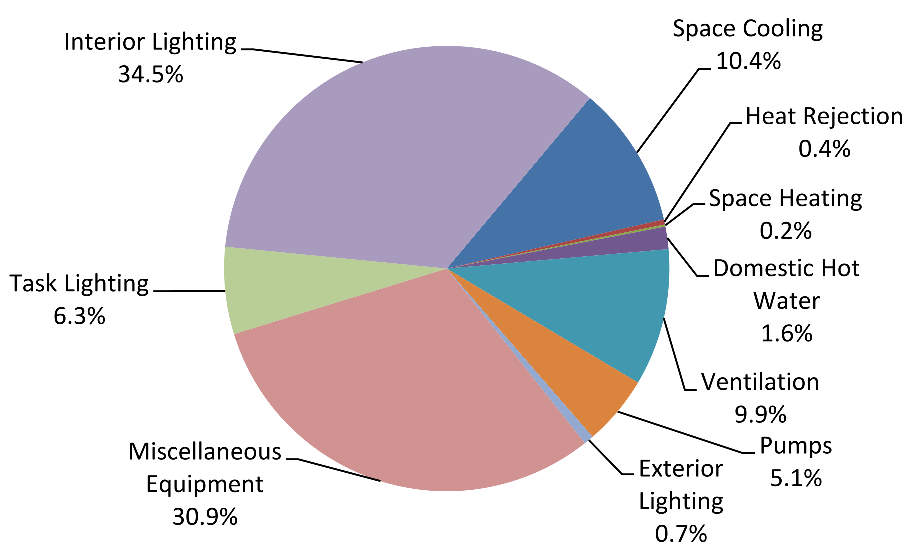

Figure 5.2-1 Baseline End-use Distribution, Fan Coil Model

The building's natural gas consumption is attributed entirely for space heating. Based on CEUS, a 50,850 sqft building (Sproul Hall) consumes approximately 11,500 therms/yr of gas. The modeled gas consumption is 14,686 therms/yr. Because of the campus district steam system which incurs distribution losses, the higher modeled gas consumption is justified.

5.3 Radiant Baseline Simulation

5.3.1 Radiant Baseline Energy Use

Since the client is moving forward with the installation of the radiant system (with modifications depending on the results of the summer pilot test), the baseline utilized for analysis purposes is the existing building with the proposed radiant system. The following major changes were made to the calibrated model:

- Set the fan coil fan power draw to 0.
- Increase CHW supply water temperature to 55F
- Decrease HW supply water temperature to 100F

Table 5.3-1 summarizes the major mechanical systems in the radiant model. Figure 5.3-1 shows the eQuest schematic of the water-side mechanical systems.

Table 5.3-1 Major Mechanical Systems, Radiant Model

Components	Type	Efficiency	Operating Temperatures
Circulation loop	2-pipe		45F cooling, 110 F heating (assumed)
Chillers	Hermetic Reciprocating, Water-cooled (assumed)	0.8 kW/ton	40F LWT
Steam boilers	Forced Draft, Steam (assumed)	80%	350F steam discharge
Steam-HW HX	Heat Exchanger	90%	180F hot water supply
Cooling tower (assumed)	Open Tower with Variable Speed Fan (assumed)	97% (fan motor)	78F design wetbulb, 7F approach
Domestic water heater	Electric Resistance	~100%	140F supply
Radiant panels	Ecophit V 1190x590		55F EWT, 10 ΔT cooling; 100F EWT, 10 ΔT heating (assumed)

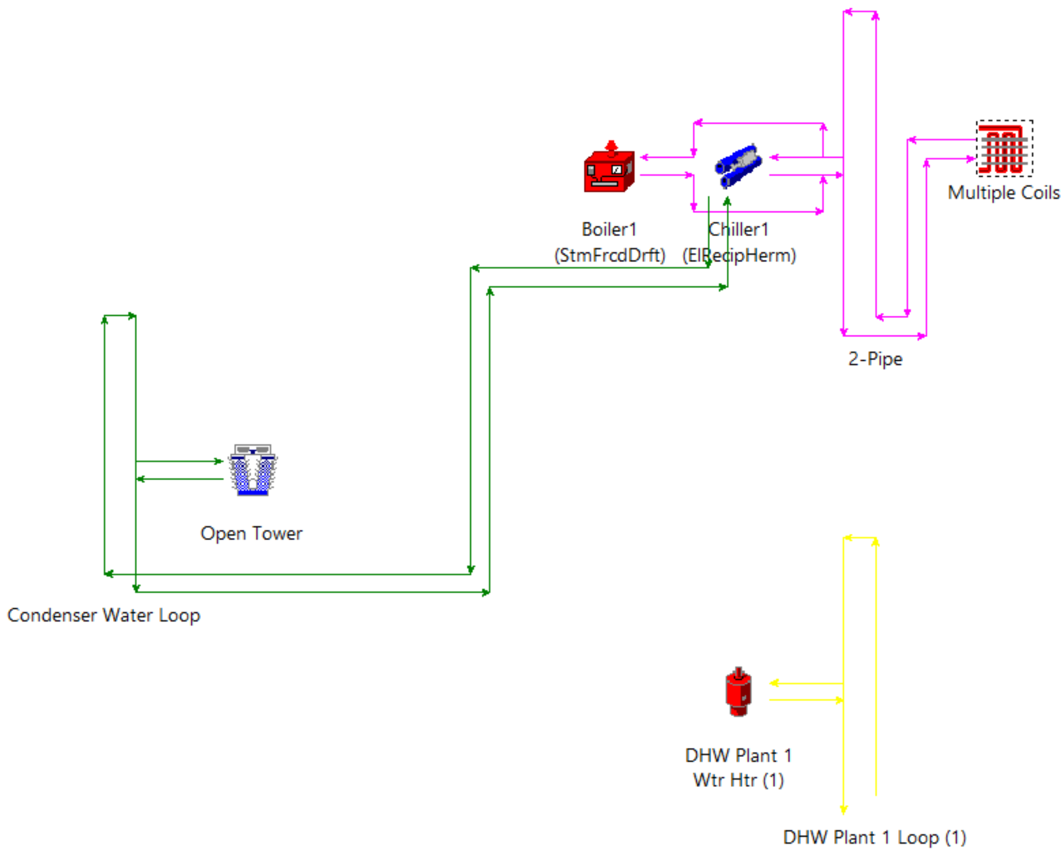

Figure 5.3-1 Water-side Schematic

Table 5.3-2 shows a comparison of the radiant baseline model energy consumption to the existing baseline model energy consumption. The results show energy and demand reduction from application of the radiant heating and cooling (approximately 11% electrical energy, 10% peak demand, 4% natural gas usage reductions). The largest reduction is attributed to the elimination of ventilation energy use. Additional savings result from the increase in cooling supply temperature and decrease in heating supply temperature.

Table 5.3-2 Comparison of Existing and Radiant Baselines

End-Use	Existing Baseline			Radiant Baseline		
	Electricity		Natural Gas	Electricity		Natural Gas
	Energy (kWh/yr)	Demand (peak kW)	(therms/yr)	Energy (kWh/yr)	Demand (peak kW)	(therms/yr)
Space Cooling	62,900	82.82		58,730	75.38	
Heat Rejection	2,210	3.60		2,200	4.44	
Space Heating	950	-	14,686	920	-	14,131
Domestic Hot Water	9,890	2.35		9,890	2.76	
Ventilation	60,450	17.20		-	-	
Pumps	30,860	16.09		29,600	15.66	
Exterior Lighting	4,370	-		4,370	-	
Miscellaneous Equipment	187,750	41.83		187,750	41.93	
Task Lighting	38,400	12.08		38,400	12.13	
Interior Lighting	209,940	52.58		209,940	52.72	
Total	**607,720**	**228.55**	**14,686**	**541,800**	**205.02**	**14,131**

Figure 5.3-2 shows the radiant baseline end-use distribution. Due to the elimination of ventilation energy use, all other categories share a large portion of the total energy use. However, the respective absolute energy use is smaller as shown in Table 5.3-2.

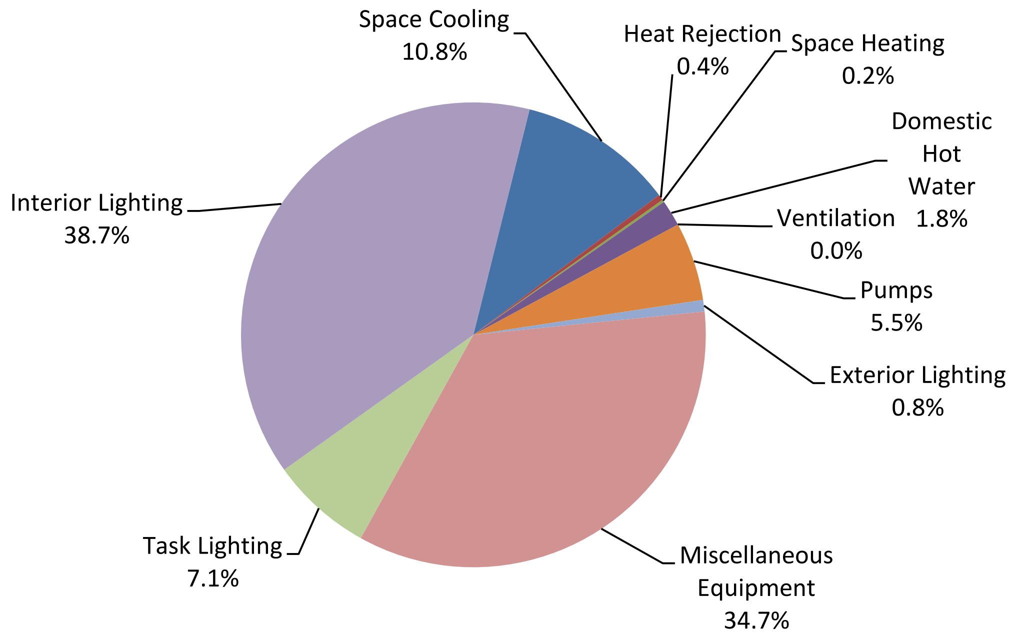

Figure 5.3-2 Baseline End-use Distribution, Radiant Model

5.3.2 Identification of Zones with High Cooling Loads

Four thermal zones within Sproul have been identified to have high cooling load intensity (kBtu/sqft ceiling space) relative to the room ceiling space and the radiant panel capacity. These thermal zones represent offices with identical load distribution and magnitude and are summarized in Table 5.3-3 below. The three digit zone labels represent the floor number (1st digit) and the room number (next 2 digits). Please refer to the floor plans in Section 3.2. Note:

1. Office 909 represents all conditioned south-side 9th floor rooms
2. Conference 926 is the only conference room in Sproul
3. Office 809 represents all conditioned south-side 1st-8th floor rooms
4. Office 830 represents all conditioned northwest-side 3rd-8th floor rooms within the seismic addition

Table 5.3-3 Zones with High Cooling Loads

		Design Load						
Building Side	**Room #**	**Date Time**	**Tdb (F)**	**Twb (F)**	**Tdp (F)**	**Load, Sensible + Latent (kBtu/hr)**	**Ceiling Space (sqft)**	**Load Intensity (Btu/hr-sqft)**
South	Office 909	11/17 14:00	102	71	54.5	9.101	161	56.5
North	Conference 926	7/21 19:00	98	70	54.5	21.647	426	50.8
South	Office 809	11/17 16:00	102	72	56.8	5.091	161	31.6
North	Office 830	7/21 19:00	98	70	54.5	7.74	213	36.3

Table 5.3-4 summarizes the performance of the radiant system for each zone at design conditions. Performance values were obtained from the Ecophit Design Tool for V1190x590 (1190 mm x 590 mm), which will be utilized in the summer pilot test. As shown for Office 809 zone, the required number of panels to meet the peak load is highly sensitive to the space design dew point temperature, which determines the panel operating temperature. Higher supply water temperature reduces the panel capacity. A temperature difference between supply and

return of 10F has been assumed in this analysis. Capacity increases with decreasing temperature difference but requires more panels to be connected in parallel. In all zones, the required number of panels exceeds the ceiling space.

Table 5.3-4 Radiant System Cooling Performance

Room #	Supply Temp (F)	Zone Design Temperature (F)	ΔT (F)	Capacity (Btu/hr-panel)	Maximum # Panels in Series	Peak Load Requirement (# Panels)	Ceiling Capacity (# panel)
Office 909	55	74	10	244.7	7	38	21
Conference 926	55	74	10	244.7	7	89	56
Office 809	57	74	10	209.1	9	25	21
Office 830	55	74	10	244.7	7	32	28

Figures 5.3-3 through 5.3-6 shows the distribution of loads for each heat sources for each zone type. In most instances window-based loads represent the large majority of the zone's cooling loads. Please refer to Section 6 for the load distributions in terms of absolute kBtu/hr values.

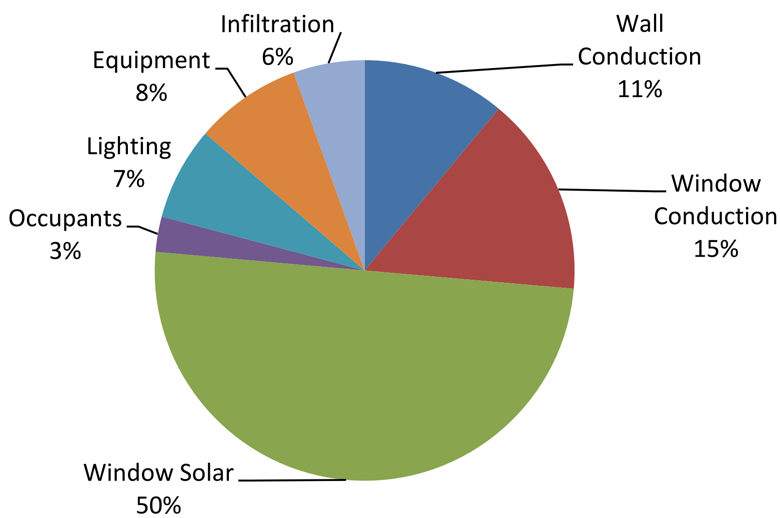

Figure 5.3-3 Office 909 Zone Type Design Load Distribution

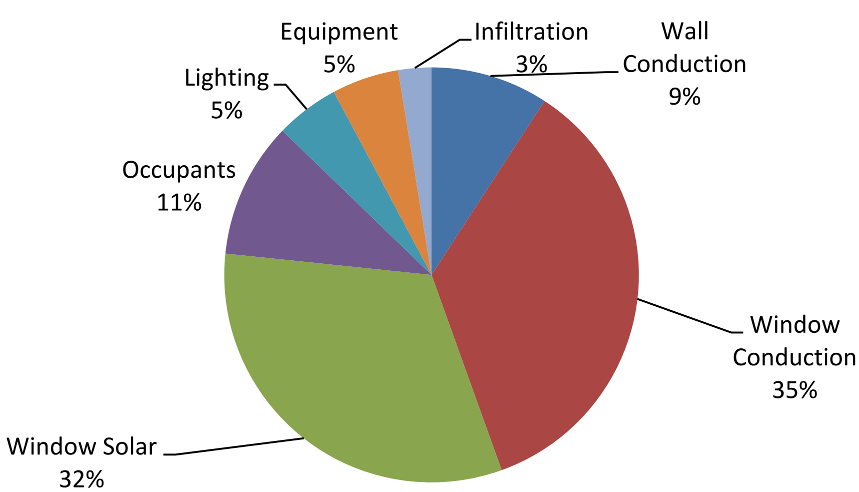

Figure 5.3-4 Conference 926 Zone Type Design Load Distribution

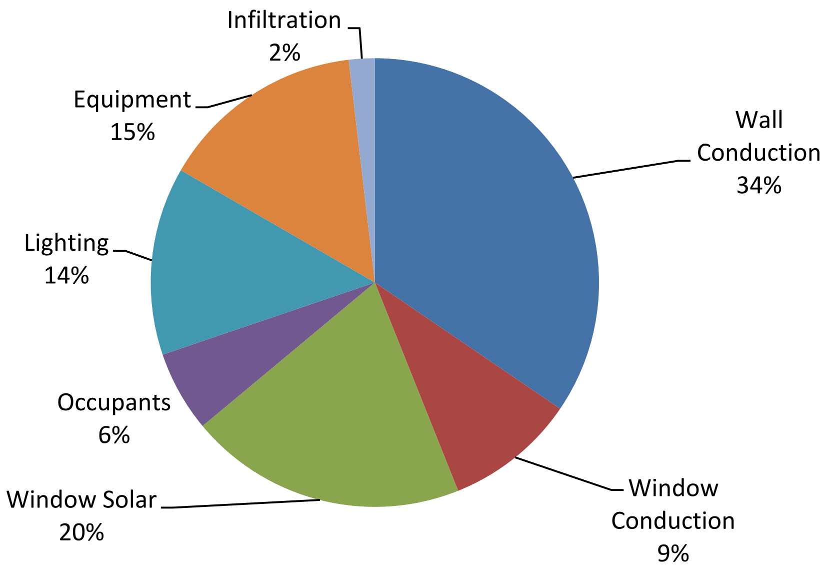

Figure 5.3-5 Office 809 Zone Type Design Load Distribution

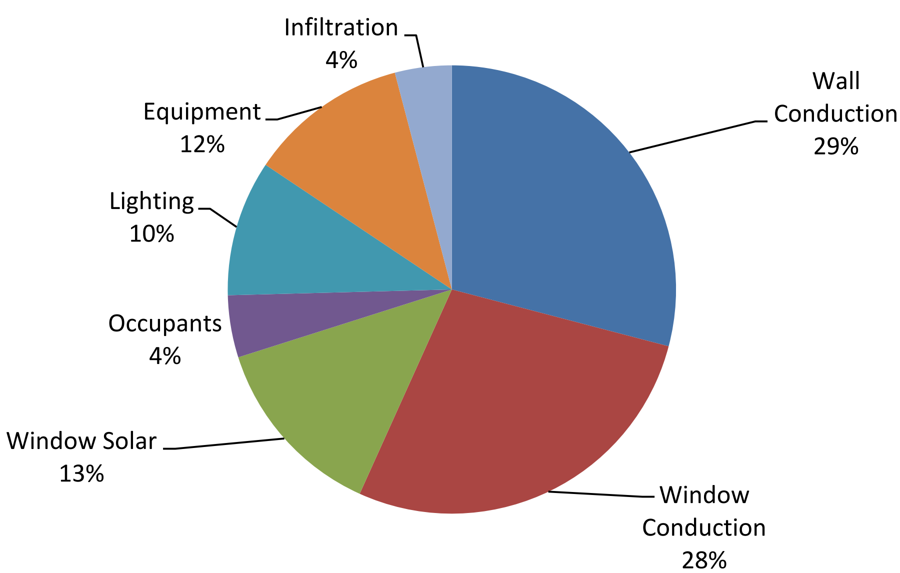

Figure 5.3-6 Office 830 Zone Type Design Load Distribution

5.4 Measure Background

As stated in the Scope of Work, this analysis addresses only window based corrective measures consisting of low-e double pane windows, overhangs and side fins for the main purpose of reducing the zone cooling loads. The following measures were analyzed in this report and detailed in Section 6:

1. Install double pane windows, overhangs, and side fins for the 9th floor south offices
2. Install double pane windows for the 9th floor conference room
3. Install side fins for the 1st to 8th floor south offices
4. Install double pane windows for the 3rd to 8th floor northwest offices in the Seismic Addition

Despite positive benefits in the form of passive lighting and solar heating in winder, windows are a major source of heat losses and gains during heating and cooling seasons, respectively. According to Arasteh 2006[8], approximately 24% and 32% of residential and commercial HVAC energy, respectively, is attributed to window-based loads.

There are three major types of energy flow that occur through windows:

(1) Heat flow in the form of conduction and convection
   a. A window's U-value indicates the rate of heat loss. The lower the U-factor, the greater the window's resistance to heat flow and the better its insulating properties.
   b. Additional panes markedly reduce the U-factor by creating still air spaces, which reduce heat flow and increase insulating value. These spaces can be filled with inert gases like Argon and Kyrpton for added insulation.

(2) Solar heat gains in the form of radiation
   a. The SHGC indicates the fraction of solar radiation admitted through a window. The lower the window's SHGC, the less solar heat it transmits.
   b. The 'e' in low-e coatings refers to emissivity. These coatings are spectrally selective: allowing for the transmittance of visible light while deflecting unwanted solar radiation.

(3) Airflow in the form of leakage

Overhangs and side fins are effective means of providing shading from direct incident solar radiation on the shaded surface based on the angle of the sun. These passive devices are typically designed to provide full shading in the summer and to allow full solar heating in the winter. However, in buildings with large cooling loads both in the summer and winter, winter-time solar heat gain unnecessarily adds to the zone's cooling loads.

5.4.1 Measure Decision Flowchart

The decision of which measure(s) to prioritize follows Figure 5.4-1. The first priority is given to the measure that best addresses the load type. The remaining measures are arranged in ascending implementation costs discussed in Section 5.4.2. After each measure, the zone cooling load is evaluated against the radiant system capacity to determine if sufficient reduction has been achieved. When the number of required panels to meet peak cooling loads can be accommodated in the ceiling space alone, load reduction is deemed sufficient. Subsequent measures are considered until this is the case.

Whenever sufficient load reduction is achieved, the decision to implement the next measure in the list depends on the net cost reduction, i.e. if the implementation cost of the measure is lower than the cost reduction from reduced number of radiant panels, then a positive cost reduction is achieved and the measure should be implemented in addition to the previous.

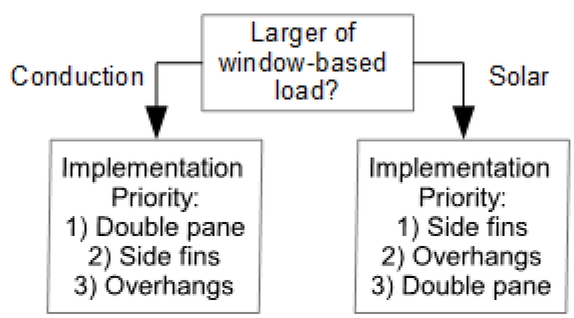

Figure 5.4-1 Priority Decision

5.4.2 Measure Implementation Cost

Table 5.4-1 summarizes the specifications and installed cost of equipment for the measures under consideration. Costs were obtained from the combination of:

- Vendor estimates: TWA Panel Systems for radiant panels material costs, Home Depot for window material costs, B&C Awnings for exterior shading devices installed costs
- 2014 BNi Facilities Manager's Costbook for window labor costs
- 2014 RS Means Mechanical Cost Data for radiant system installation.

Figures 5.4-2, 5.4-3 and 5.4-4 show images of the window, overhang and side fins, respectively. Even though the table presents a low-high range of installed costs, the high values were utilized in this report to be conservative.

NOTE: The ZNE team does not specifically recommend the products shown. They were presented for performance and cost analysis purposes. The client should consider multiple products to obtain the most cost competitive option.

Table 5.4-1 Implementation Cost Summary

Item	Description	Low Installed Cost	High Installed Cost
Double pane, low-e window	Jeld-Wen W-2500, operable with insect screen, U-factor = 0.3, SGHC = 0.27, includes removal of existing window	$88/sqft	$112/sqft
Overhang	B&C aluminum overhang, 3-ft depth, louvered	$51/sqft	$84/sqft
Side fin	B&C aluminum side fin, 3-ft depth, louvered	$16/sqft	$28/sqft
Radiant Panel	Ecophit V 1190x590, 7.56 sqft/panel	$419/panel	

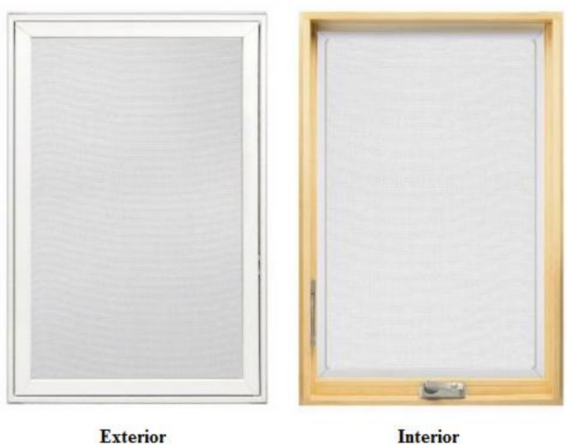

Figure 5.4-2 Jeld-Wen Window

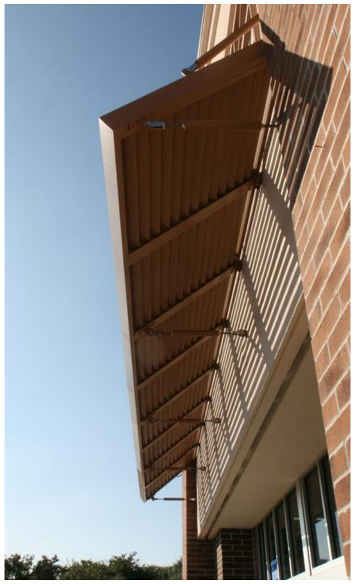

Figure 5.4-3 B&C Overhang

Figure 5.4-4 B&C Side Fins

5.5 Cost Analysis Equations

This section details various equations employed to perform cost analyses outside of the eQuest simulation. The annual electrical energy cost savings, ECS, is calculated as follows:

ECS = ES x ER

Where,

ES = annual energy savings, from eQuest, kWh/yr
ER = electricity rate, $0.072/kWh

The annual natural gas cost savings, GCS, is calculated as follows:

GCS = GS x GR

Where,

GS = annual energy savings, from eQuest, kWh/yr
GR = electricity rate, $0.7/therm

The simple payback, PB, for each measure is calculated as follows:

PB = (WIC – RCR)/(ECS+GCS)

Where,

WIC = implementation cost of window, side fins and/or overhangs, $
RCR = cost reduction due to reduction in required radiant panels, $

6. Results

Table 6 summarizes the results of measures analyzed in this report. Significantly long paybacks were calculated for measures considering only installation of double pane windows. However, when all the measures are bundled, the window-related measures recommended in this report pays for itself. To re-iterate, the main goal of the measures are to reduce the zone cooling loads via window improvements and not to necessarily recommend only cost-effective measures.

Table 6: Measures Cost Summary

Measure	Electrical Energy Savings, kWh/yr	Peak Demand Reduction, kW	Gas Use Reduction, therms/yr	Energy Cost Reduction, $/yr	Radiant Panel Cost Reduction, $ (# panels)	Window Improvement Implementation Cost, $	Net Implementation Cost, $	Payback (yrs)
1	2,608	1.53	817	760	55,727 (133)	57,269	1,542	2.0
2	728	0.53	373	314	12,898 (31)	41,398	28,409	Beyond useful life
3	4,057	2.5	829	872	234,640 (560)	56,448	(178,192)	Immediately
4	637	0.64	156	155	10,056 (24)	65,472	55,416	Beyond useful life
Total	**8,030**	**5.2**	**2,175**	**2,101**	**313,412 (748)**	**220,588**	**(92,824)**	**Immediately**

6.1 Measure 1: Install Double Pane Windows, Overhangs and Side Fins for the 9th Floor South Offices

Recommendation: Replace the 9th floor south-facing single-pane windows with low-e, double pane windows and install overhangs and side fins.

Electrical Energy Savings	=	2,608 kWh/yr
Peak Demand Reduction	=	1.53 kW
Natural Gas Savings	=	817 therms/yr
Energy Cost Reduction	=	$760/yr
Zone Cooling Load Reduction	=	29 kBtu/hr-sqft (51% of baseline)
Window Improvement Installation Cost (includes 25% Engr & Management Costs)	=	$57,269
Radiant Panel Cost Reduction (# panels)	=	$55,727 (133)
Net Implementation Cost	=	$1,542
Simple Payback	=	2 years

Figure 6.1-1 shows the exterior south view of the existing buildings. This measure deals with the 7 south-facing rooms marked in red. Figure 6.1-2 shows the proposed modification. Windows replacements are marked in green. Overhang & side fin additions are marked in white.

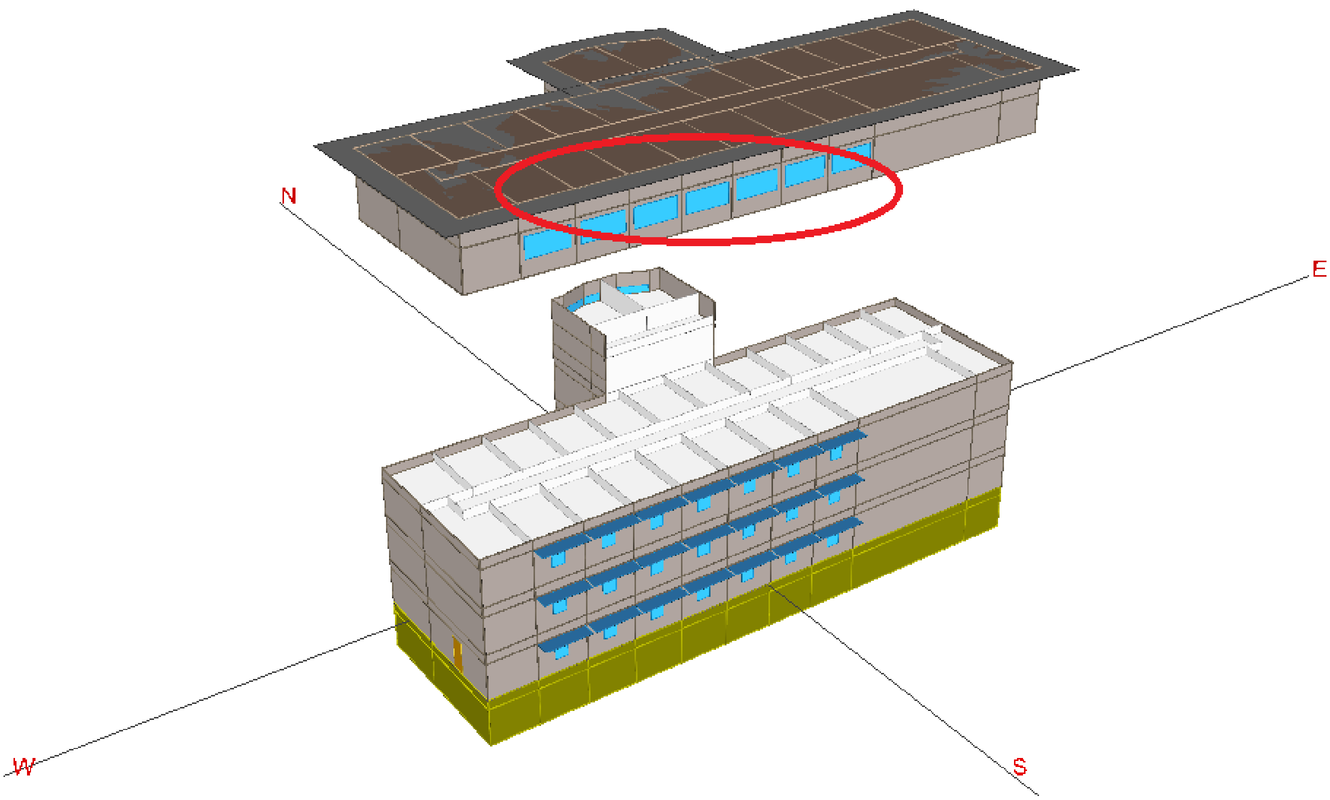

Figure 6.1-1 Baseline Façade

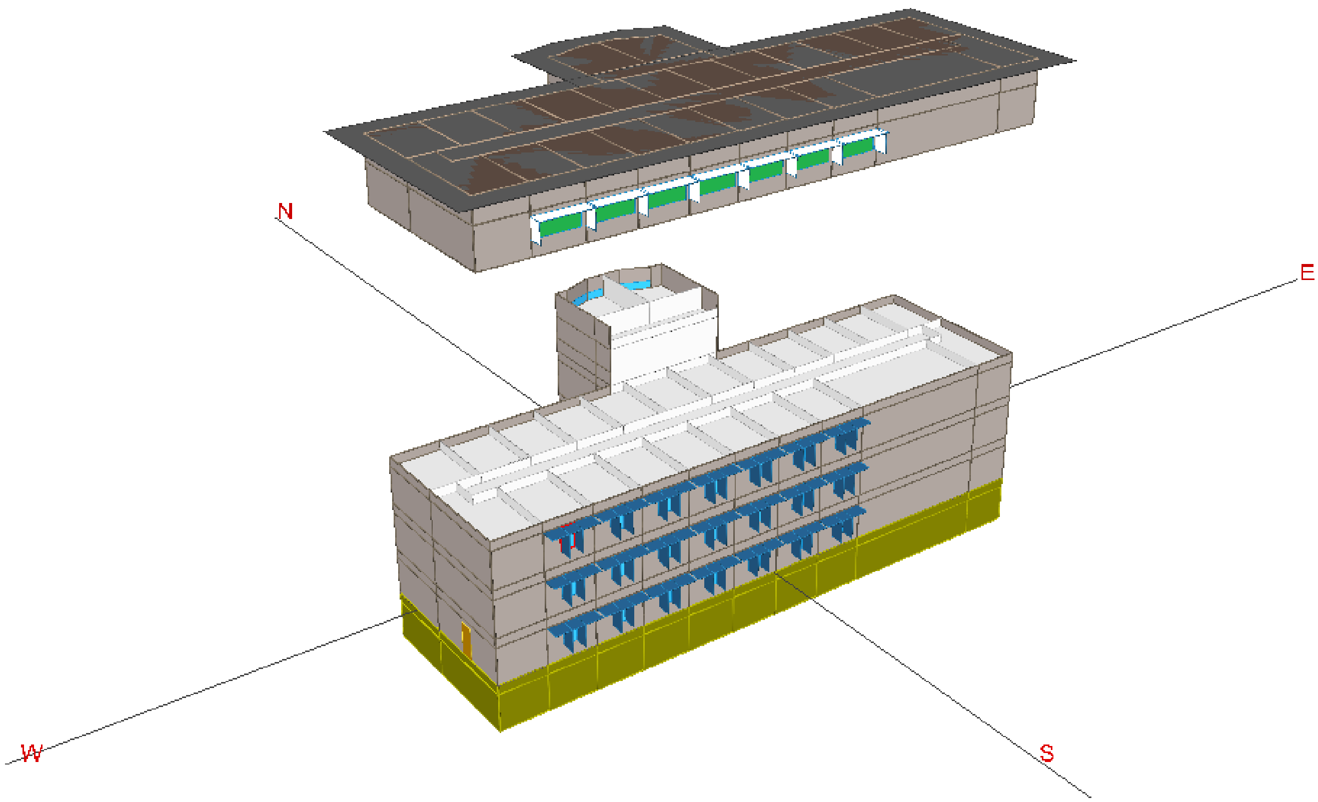

Figure 6.1-2 Proposed Measure

Implementation of this measure results in a 51% reduction in cooling loads to 27.95 Btu/hr-sqft or 4.5 kBtu/hr for one room. At 244.7 Btu/hr per panel capacity, the cooling load can be served by 19 panels per room, or a reduction of 19 panels per room from the baseline. Figure 6.1-3 shows the proposed distribution of cooling loads at design conditions for one room within the zone (Office 909), as compared to the baseline distribution. Note that discrepancies between the baseline and proposed non-window loads are due to the peak loads occurring at different days and/or time for the baseline (11/17, 14:00) and proposed (11/17, 15:00).

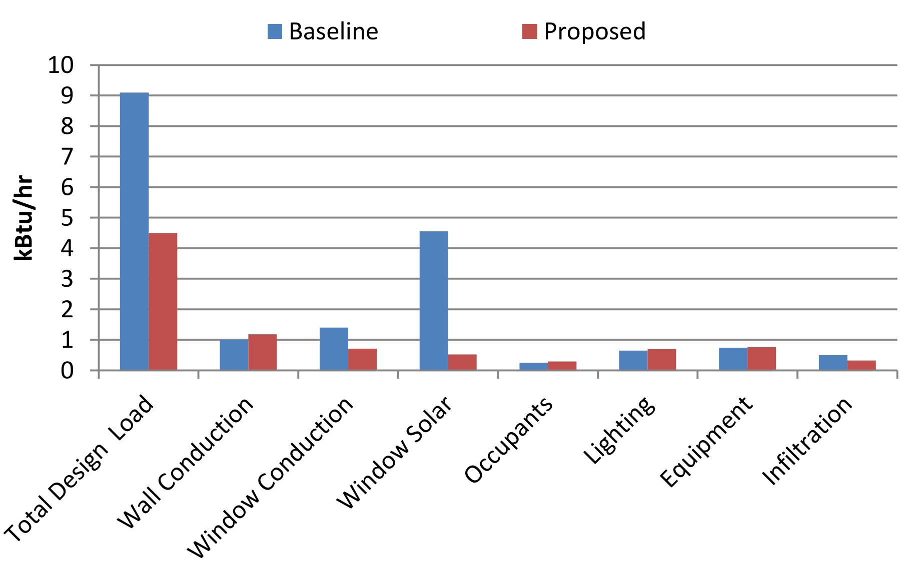

Figure 6.1-3 Office 909 Zone Type Design Load Distribution

Table 6.1-1 summarizes the implementation costs for this measure.

Table 6.1-1 Implementation Cost Summary				
Item	**Units**	**Area (sqft/unit)**	**Installed Cost ($/sqft)**	**Total Cost ($)**
South-facing windows	7	35.2	112	27,604
Aluminum overhang, 3-ft depth, louvered	7	26.4	84	15,523
Aluminum side fin, 3-ft depth, louvered	8	12	28	2,688
25% Engineering & Management				11,454
Subtotal				57,269

Implementation of this measure results in an estimated reduction of 133 panels for the entire south-facing rooms. At $419/panel, there is a potential cost reduction of $55,727. This results in a net implementation cost of $1,542 and a simple payback of 2 years.

6.2 Measure 2: Install Double Pane Windows for the 9th Floor Conference Room

Recommendation: Replace the 9th floor Conference Room's single-pane, blue-coated windows with low-e, double pane windows.

Electrical Energy Savings	=	728 kWh/yr
Peak Demand Reduction	=	0.53 kW
Natural Gas Savings	=	373 therms/yr
Energy Cost Reduction	=	$314/yr
Zone Cooling Load Reduction	=	17.8 kBtu/hr-sqft (35% of baseline)
Window Improvement Installation Cost (includes 25% Engr & Management Costs)	=	$41,398
Radiant Panel Cost Reduction (# panels)	=	$12,898 (31)
Net Implementation Cost	=	$28,409
Simple Payback	=	Beyond useful life

Figure 6.2-1 shows the exterior south view of the existing buildings. This measure deals with the building's only conference room which is also the most heavily windowed zone in the building (marked in red in Figure). Figure 6.2-2 shows the proposed modification. Windows replacements are marked in green.

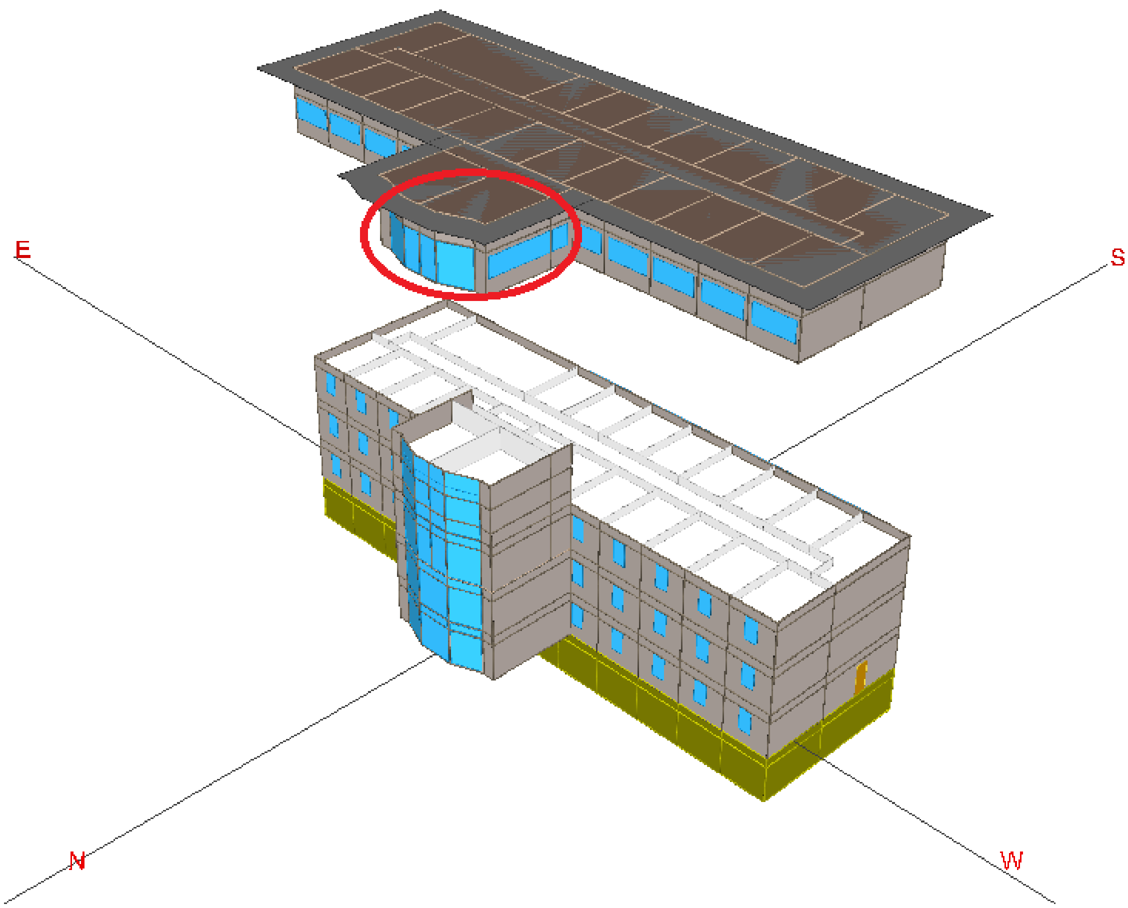

Figure 6.2-1 Baseline Façade

*Includes east-facing windows (not shown in Figure)

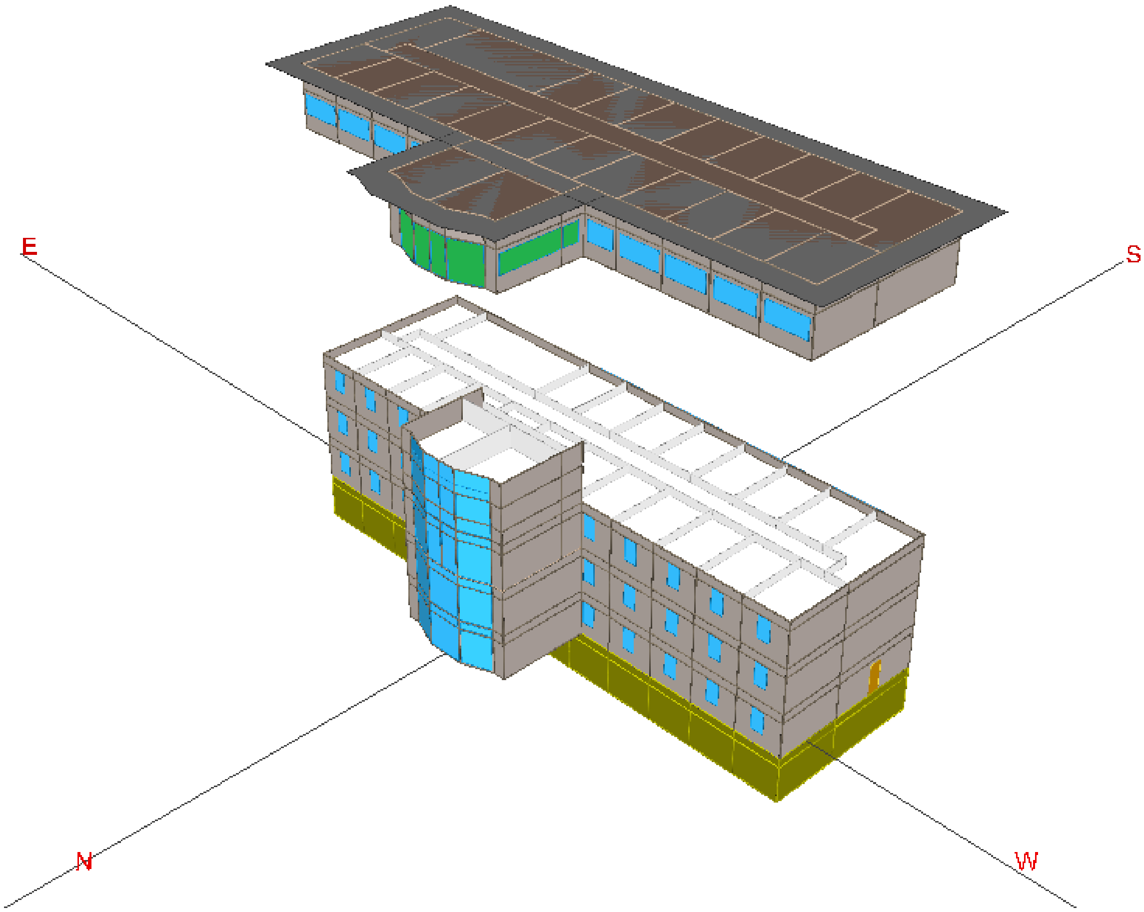

Figure 6.2-2 Proposed Measure

Implementation of this measure results in a 35% reduction in cooling loads to 33.23 Btu/hr-sqft or 14.154 kBtu/hr for the room. At 244.7 Btu/hr per panel capacity, the cooling load can be served by 58 panels per room, or a reduction of 31 panels from the baseline. Figure 6.2-3 shows the proposed distribution of cooling loads at design conditions for the conference room (Conference 927), as compared to the baseline distribution. Note that discrepancies between the baseline and proposed non-window loads are due to the peak loads occurring at different days and/or time for the baseline (7/21, 19:00) and proposed (7/21, 18:00).

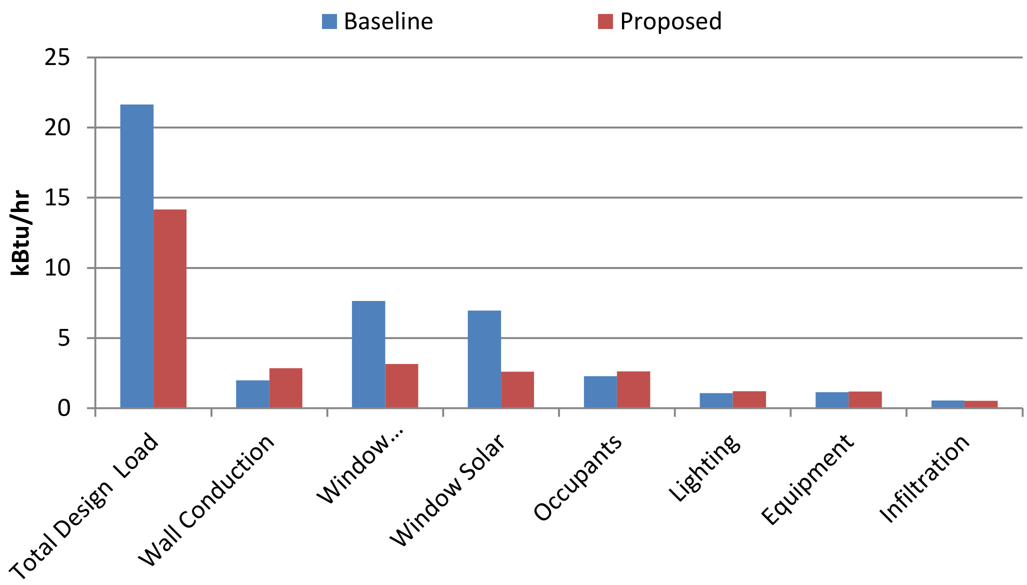

Figure 6.2-3 Conference 926 Zone Type Design Load Distribution

Table 6.2-1 summarizes the implementation costs for this measure.

Table 6.2-1 Implementation Cost Summary

Item	Units	Area (sqft/unit)	Installed Cost ($/sqft)	Total Cost ($)
North-facing windows	1	155.8	112	17,459
East West-facing windows	2	69.9	112	15,659
25% Engineering & Management				8,280
Subtotal				41,398

Implementation of this measure results in an estimated reduction of 31 radiant panels. At $419/panel, there is a potential cost reduction of $12,989. This results in a net implementation cost of $28,409 and a simple payback of over 90 years.

6.3 Measure 3: Install Side Fins for the 1st-8th South Offices

Recommendation: Install side fins for all of the south-facing 1st to 8th floor windows.

Electrical Energy Savings	=	4,057 kWh/yr
Peak Demand Reduction	=	2.5 kW
Natural Gas Savings	=	829 therms/yr
Energy Cost Reduction	=	$872/yr
Zone Cooling Load Reduction	=	10.4 kBtu/hr-sqft (32% of baseline)
Window Improvement Installation Cost (includes 25% Engr & Management Costs)	=	$56,448
Radiant Panel Cost Reduction (# panels)	=	$234,640 (560)
Net Implementation Cost	=	-$178,192
Simple Payback	=	Immediate

Figure 6.3-1 shows the exterior south view of the existing buildings. This measure deals with the 56 south-facing rooms (7 per floor) marked in red. Figure 6.3-2 shows the proposed modification. Overhang & side fin additions are marked in white.

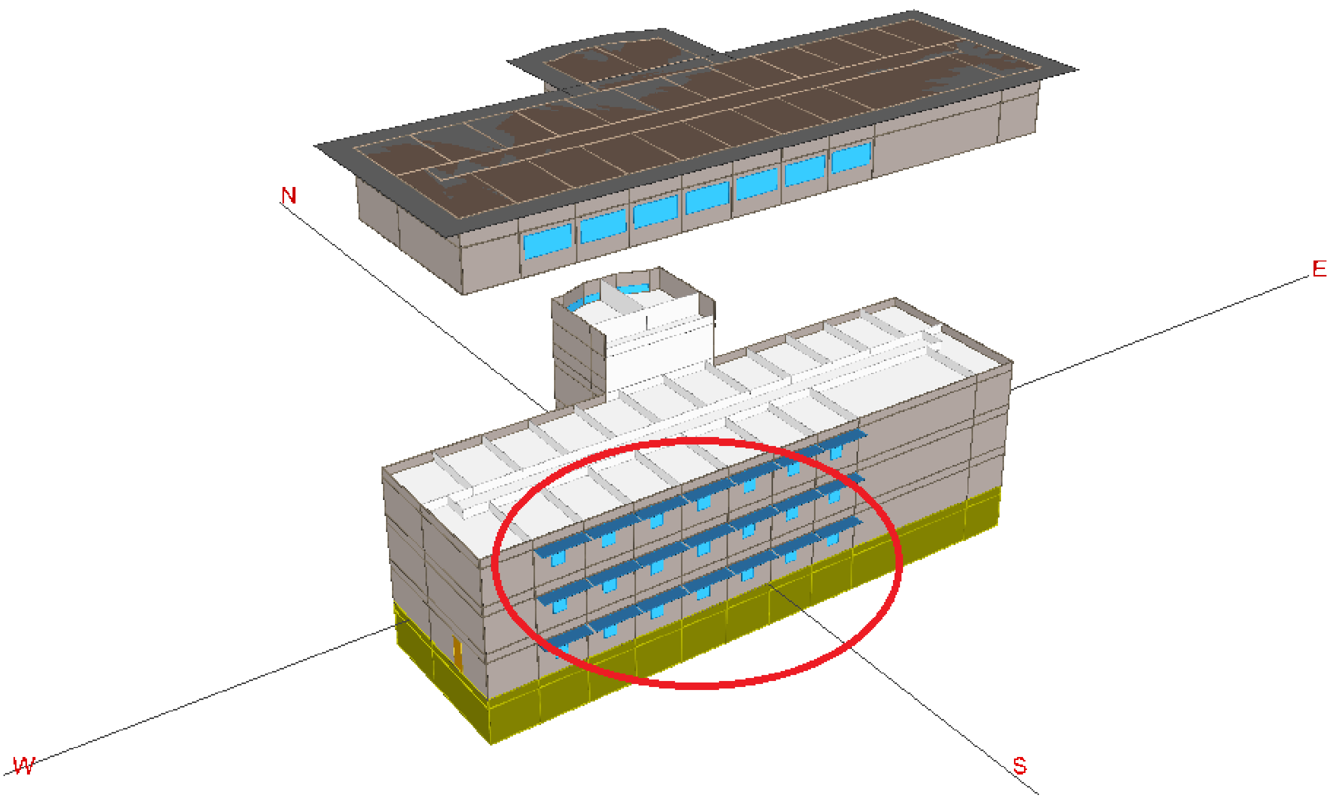

Figure 6.3-1 Baseline Façade

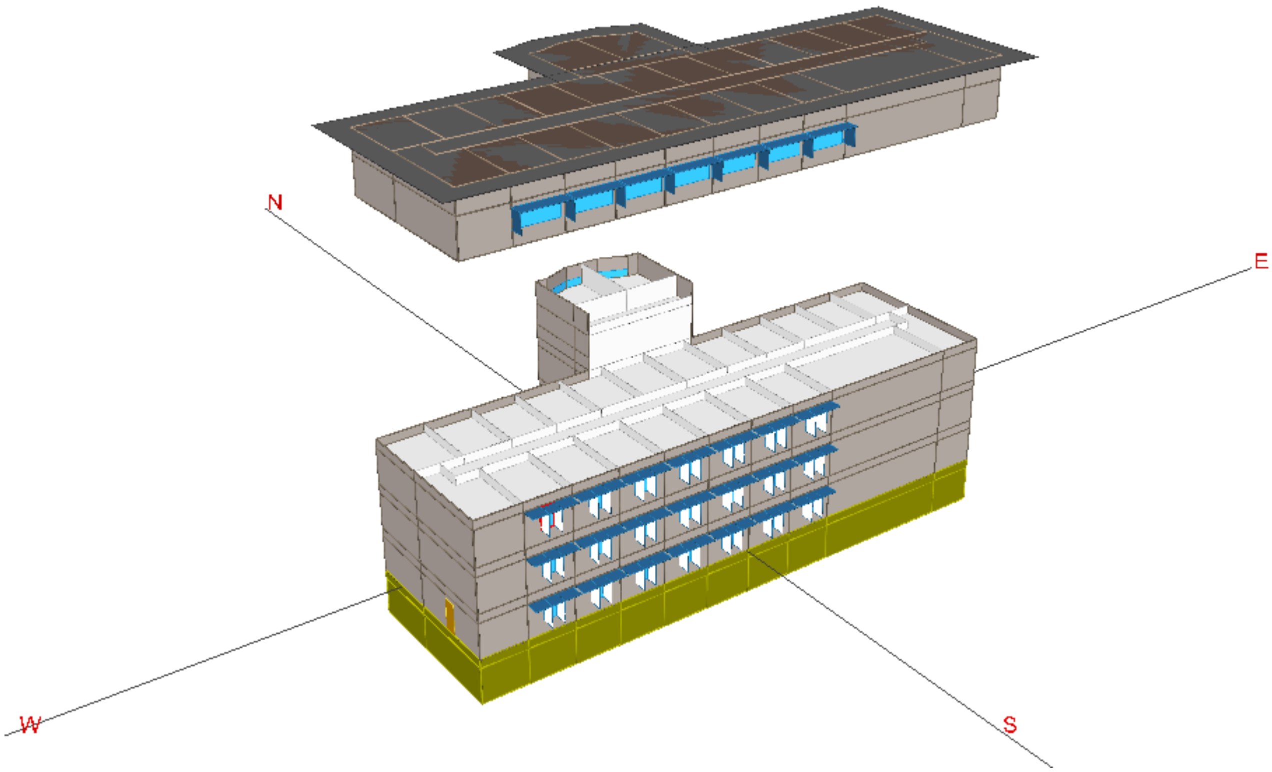

Figure 6.3-2 Proposed Measure

Implementation of this measure results in a 32% reduction in cooling loads to 21.6 Btu/hr-sqft or 3.48 kBtu/hr for one room. At 244.7 Btu/hr per panel capacity, the cooling load can be served by 15 panels per room, or a reduction of 10 panels per room from the baseline. Figure 6.3-3 shows the proposed distribution of cooling loads at design conditions for one room (Office 809), as compared to the baseline distribution. Note that discrepancies between the baseline and proposed non-window loads are due to the peak loads occurring at different days and/or time for the baseline (11/17, 16:00) and proposed (8/20, 18:00).

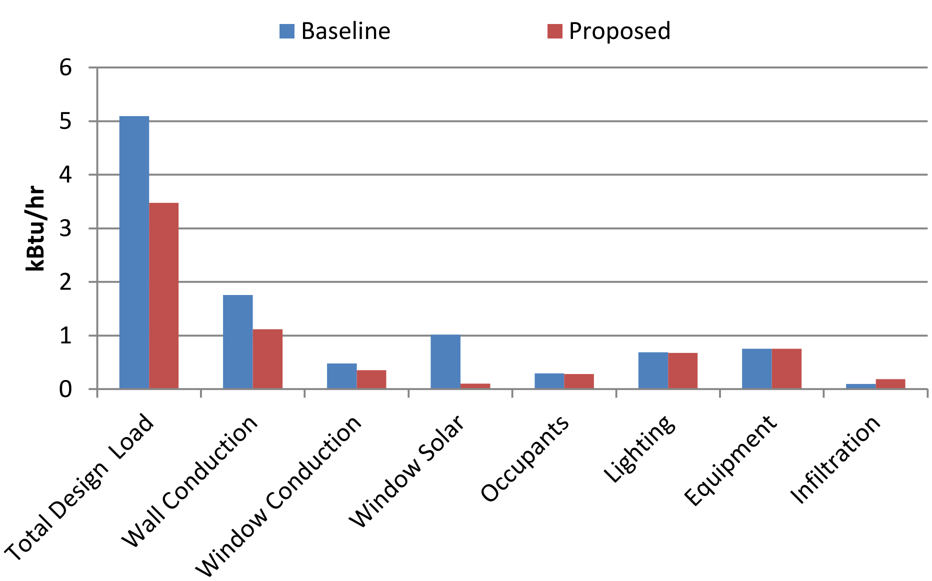

Figure 6.3-3 Office 809 Zone Type Design Load Distribution

Table 6.3-1 summarizes the implementation costs for this measure.

Table 6.3-1 Implementation Cost Summary				
Item	**Units**	**Area (sqft/unit)**	**Installed Cost ($/sqft)**	**Total Cost ($)**
Aluminum side fin, 3-ft depth, louvered	112	14.4	28	45,158
25% Engineering & Management				11,290
Subtotal				56,448

Implementation of this measure results in an estimated reduction of 560 panels for the entire south-facing rooms. At $419/panel, there is a potential cost reduction of $234,640. This results in a net implementation cost of -$178,192, which pays for the side fins immediately.

6.4 Measure 4: Install Double Pane Windows for the 3rd-8th Floor Northwest Offices in the Seismic Addition

Recommendation: Replace the single-pane windows of the 3rd-8th floor northwest offices in the seismic addition with low-e, double pane windows.

Electrical Energy Savings	=	637 kWh/yr
Peak Demand Reduction	=	0.64 kW
Natural Gas Savings	=	156 therms/yr
Energy Cost Reduction	=	$155/yr
Zone Cooling Load Reduction	=	4.8 kBtu/hr-sqft (13% of baseline)
Window Improvement Installation Cost (includes 25% Engr & Management Costs)	=	$65,472
Radiant Panel Cost Reduction (# panels)	=	$10,056 (24)
Net Implementation Cost	=	$55,416
Simple Payback	=	Beyond useful life

Figure 6.4-1 shows the exterior south view of the existing buildings. This measure deals with the 7 south-facing rooms marked in red. Figure 6.4-2 shows the proposed modification. Windows replacements are marked in green. Overhang & side fin additions are marked in white.

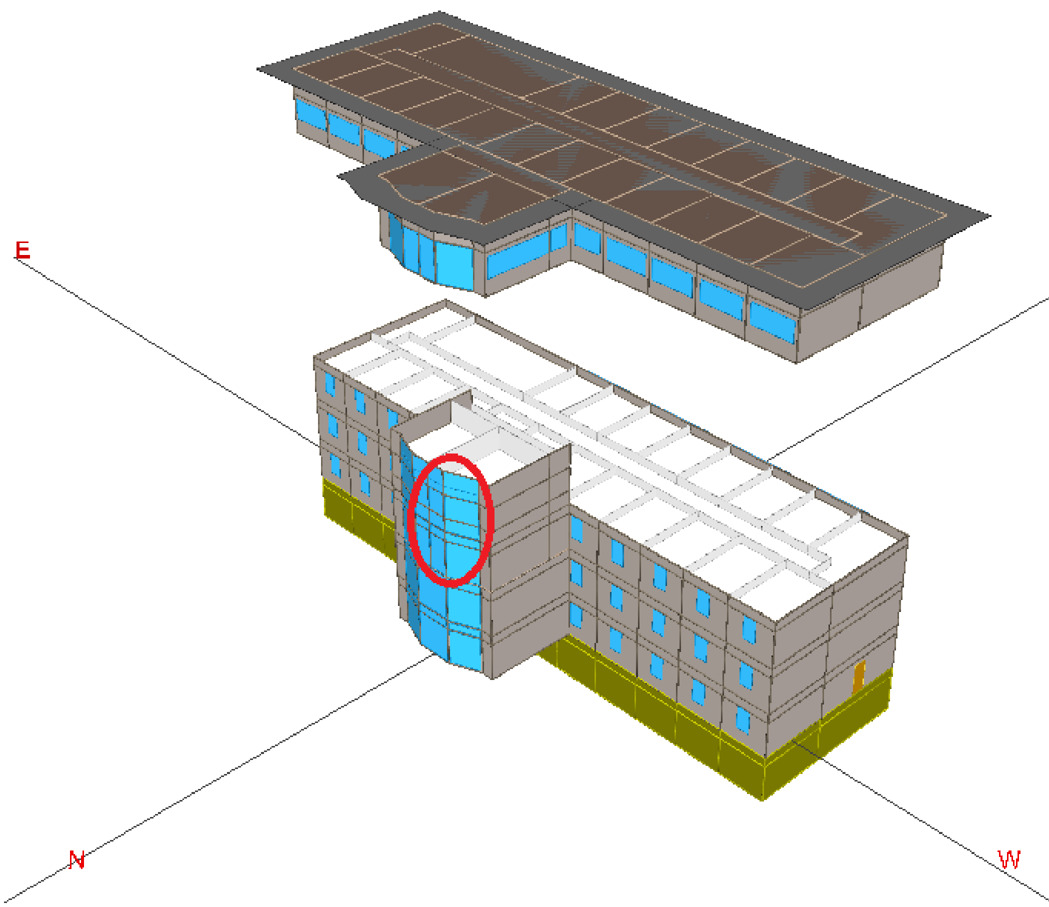

Figure 6.4-1 Baseline Façade

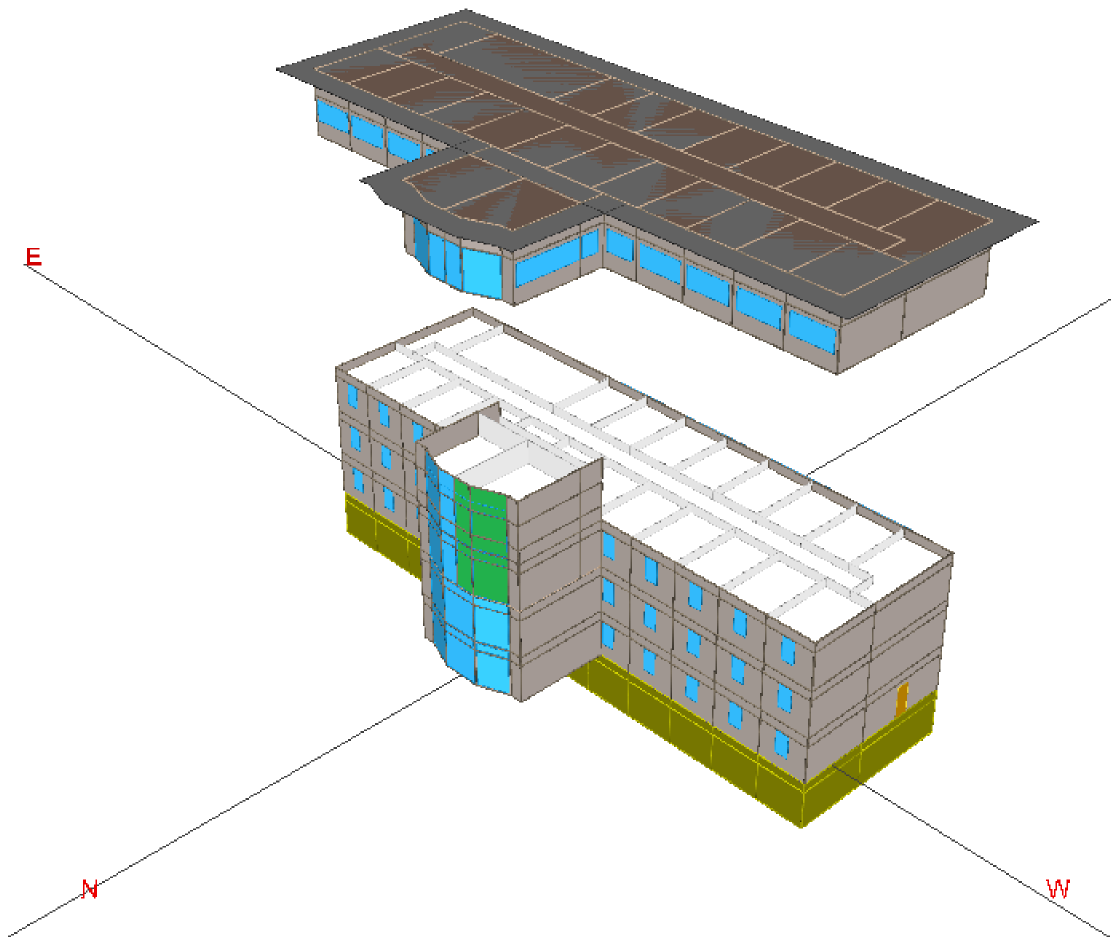

Figure 6.4-2 Proposed Measure

Implementation of this measure results in a 13% reduction in cooling loads to 31.25 Btu/hr-sqft or 6.56 kBtu/hr for one room. At 244.7 Btu/hr per panel capacity, the cooling load can be served by 28 panels per room, or a reduction of 4 panels per room from the baseline. Figure 6.4-3 shows the proposed distribution of cooling loads at design conditions for one room (Office 830), as compared to the baseline distribution. Note that discrepancies between the baseline and proposed non-window loads are due to the peak loads occurring at different days and/or time for the baseline (7/21, 19:00) and proposed (6/16, 18:00).

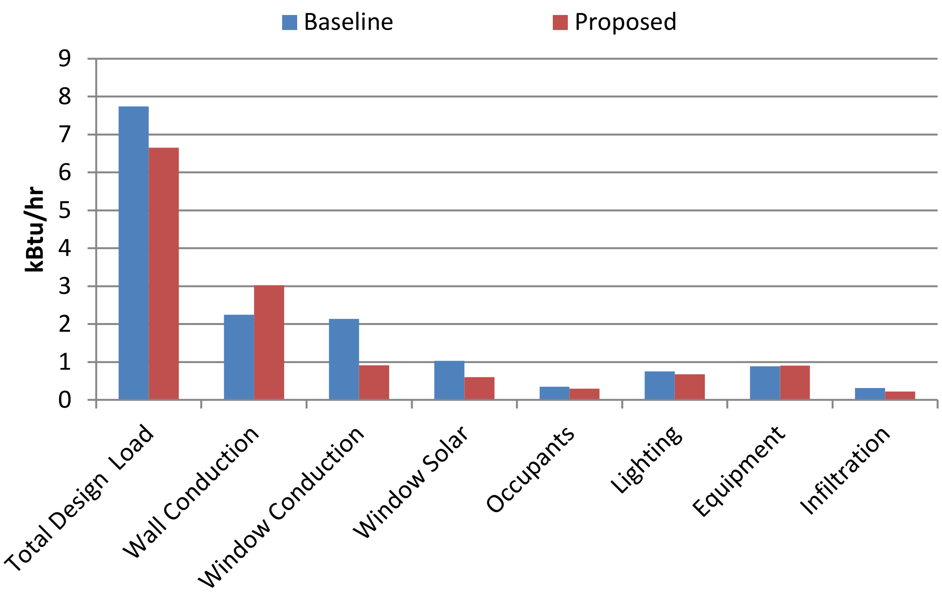

Figure 6.4-3 Office 830 Zone Type Design Load Distribution

Table 6.4-1 summarizes the implementation costs for this measure.

Table 6.4-1 Implementation Cost Summary				
Item	**Units**	**Area (sqft/unit)**	**Installed Cost ($/sqft)**	**Total Cost ($)**
North facing windows	6	77.9	112	52,378
25% Engineering & Management				13,094
Subtotal				65,472

Implementation of this measure results in an estimated reduction of 24 panels for the 3rd-8th floor northwest offices. At $419/panel, there is potential cost reduction of $10,056. This results in a net implementation cost of $55,416 and a simple payback of over 300 years.

7. Future Work

The team primarily addressed zones whose ceilings could not accommodate the number of radiant panels required to meet peak cooling loads. However other measures should be considered to further reduce the building's energy use and approach zero net energy. The following are some additional recommendations that the Team has identified:

1. Install double pane windows, overhangs and side fins in areas not addressed in this study
2. Implement building control functionality to automate operation of the operable windows during unoccupied period to enable night air cooling
3. Add insulation in zones with high loads attributed to wall and roof conduction losses

8. Appendix

8.1 Occupant Survey Results

Responses of the occupant survey are presented in following figures.

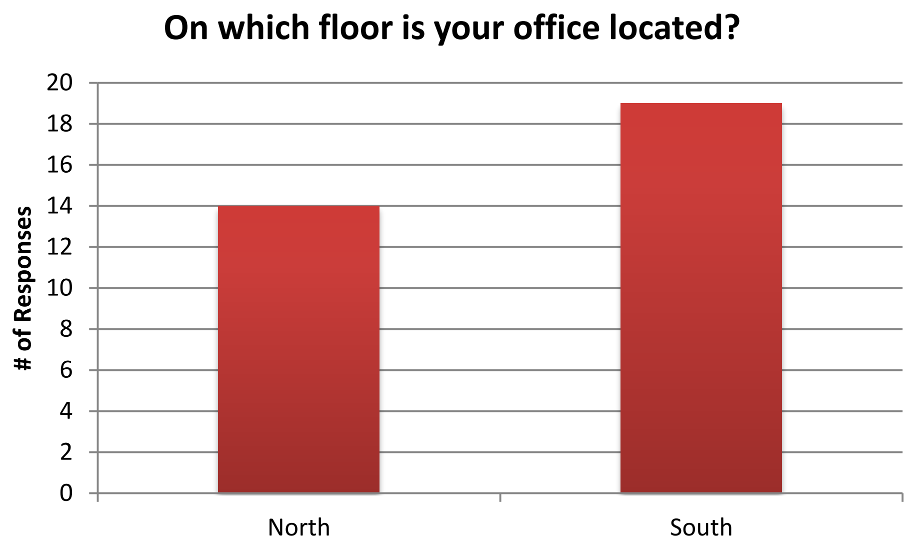

Figure 8.1-1 Responder Locations

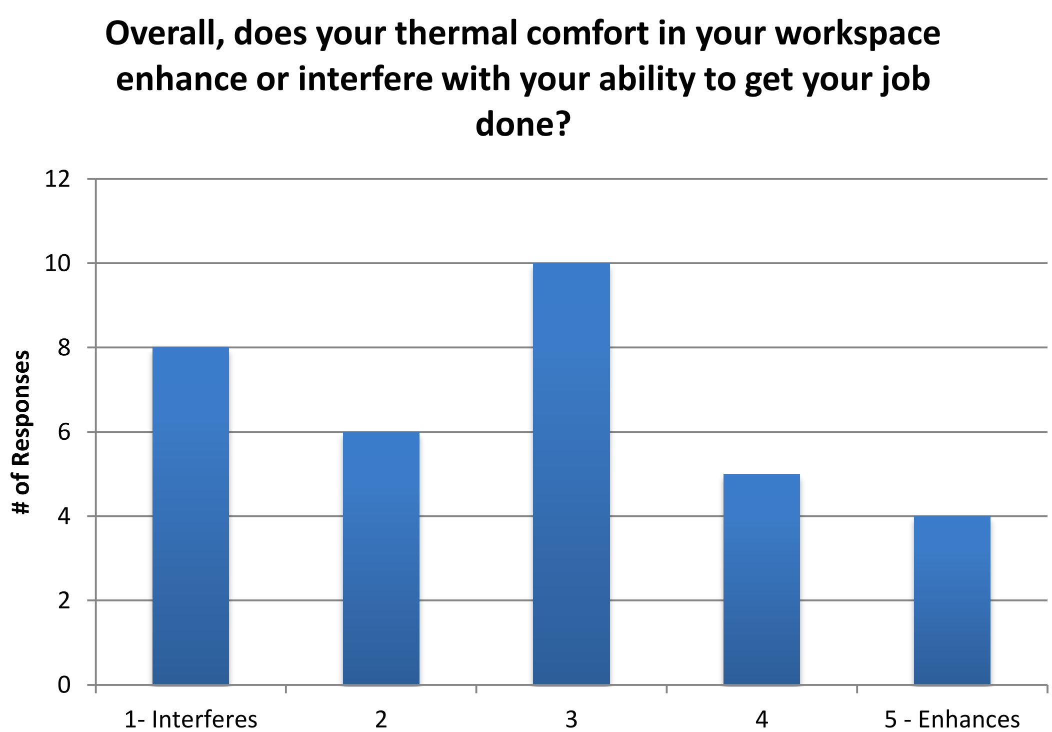

Figure 8.1-2 Thermal Comfort

Figure 8.1-3 Air Quality Satisfaction

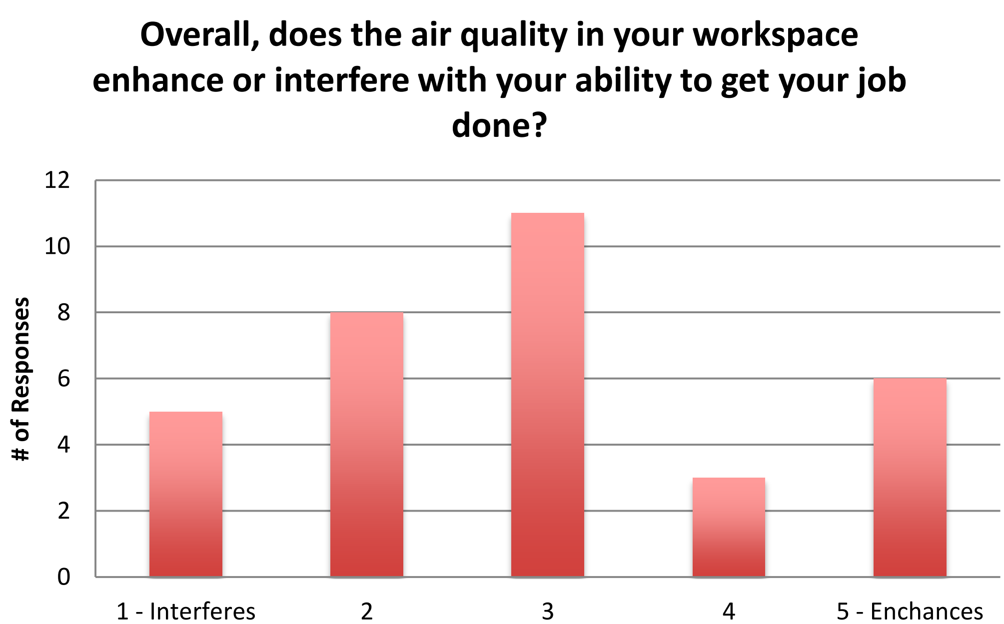

Figure 8.1-4 Air Quality Impact

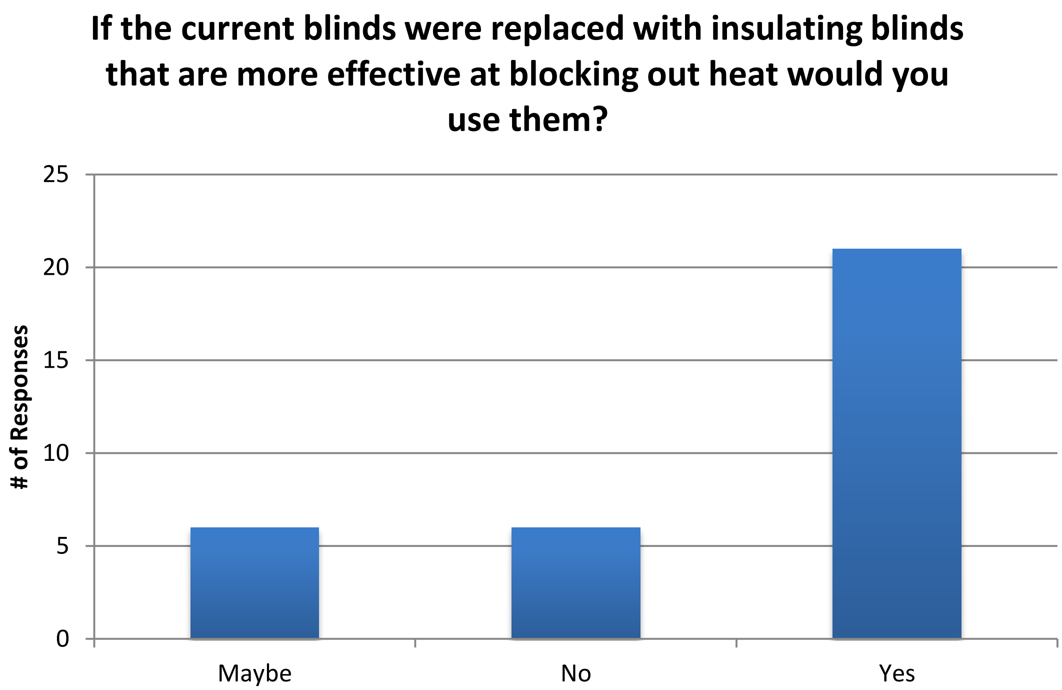

Figure 8.1-5 Interior Blinds

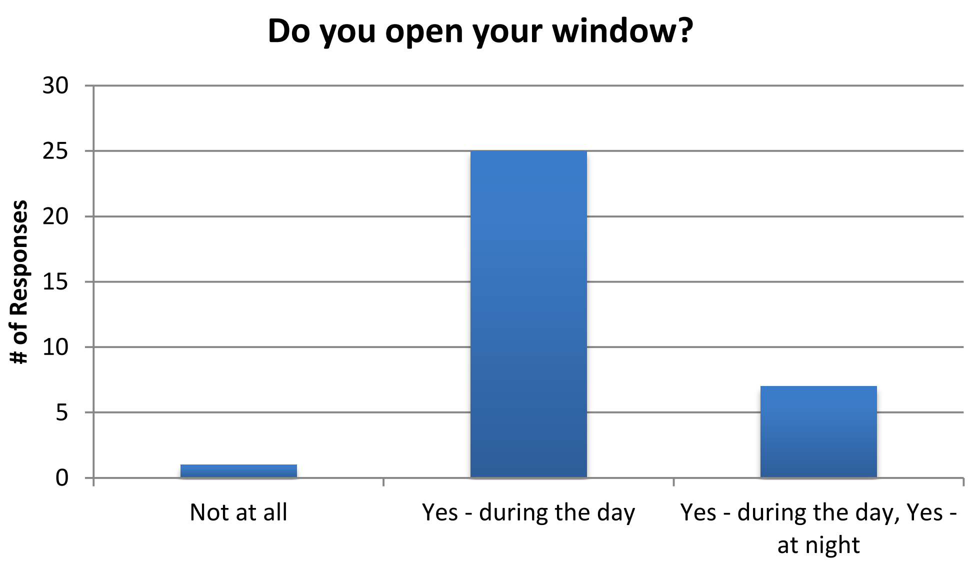

Figure 8.1-6 Passive Heating/Cooling via Operable Windows

8.2 References

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