A JOURNEY IN INTEGRATED DESIGN – THE RENEWAL OF KETCHUM ARTS AND SCIENCES BUILDING AT THE UNIVERSITY OF COLORADO, BOULDER

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ABSTRACT

The renewal of Ketchum Arts and Sciences Building began as a typical budget-constrained project to update this historic structure with modern windows, add insulation and a new heating, ventilation, and air conditioning system. Instead, the design team and client applied integrated design team techniques and decision criteria to produce an architectural and mechanical design that transforms the entire building into a modern system. In modernizing for energy efficiency, durability, and consistency to the architectural character, well-reasoned design choices were based on computational fluid dynamics, hygrothermal analysis, energy modeling and design team and contractor input.

The rigor with which the mechanical and architectural features were assessed in an integrated design team environment makes the renovation of Ketchum Arts and Sciences Building into a universal case study of how a historic structure is transformed into an energy efficient modern design. The final design is awaiting funding to be implemented.

Keywords: Historic, masonry, hygrothermal analysis, vapor, renovation, insulation, fenestration, displacement ventilation, energy efficiency

INTRODUCTION

The Ketchum Arts and Sciences Building, designed by Charles Klauder and built in 1938, is typical of the Tuscan Vernacular architecture that defines the University of Colorado at Boulder's main campus. A capital renewal program is planned to update the building to meet the objectives of the 21st century academic programs that are housed there. The existing thick masonry walls were not insulated and have low an effective R-value of approximately R-3. Steam radiators provided heat with ventilation and the cooling was provided by generous, graceful windows strategically placed to create natural stack ventilation. No mechanical cooling was included in the original design. The stairwells were designed as ventilation shafts which were controlled with manually operated clerestory windows at the third floor. This paper

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describes analysis methods used throughout the design with the codes and standards, analysis tools, and integrated design team decisions at each step of the renovation.

MAIN BODY

The four story building with a garden level is one of Charles Klauder's finest examples of Tuscan Vernacular architecture and is characteristic of the architectural style developed for the University campus. Character defining features of this style include stacked stone walls, red tile sloping roofs, large steel multi-paned windows and chimneys and other vertical tower elements. These character defining features needed to be retained even as the building will be brought up to 21st century standards. Although not a part of the University's Norlin Quadrangle Historic District, it is located immediately adjacent to it and continues the historic character of this district. Thus, the proposed capital renewal project is sympathetic to the historic character and materials of the building, while meeting the energy, comfort and durability goals for the project.

The Capital Renewal program is a pilot project for the State of Colorado with the aim to renovate building systems and add air conditioning to older buildings, thus renewing them for the next century. Capital renewal projects view the building as a whole that strives to improve the Facility Condition Index, provide lower utility and maintenance costs, and enhance the delivery of academic programs. This project is also seeking a LEED for New Construction Gold rating. Capital renewal differs from previous methodologies for upgrading other campus buildings which involved numerous small upgrades of each building system over a group of funding cycles. Programmatic space changes are not anticipated except those required to bring the building up to modern codes and accommodate the infrastructure improvements. The Capital renewal process allows for a holistic interpretation of the needs of the building, with the goal of maximizing the efficiencies by interrelating envelope upgrades with the mechanical system upgrades, overlaid with an individualistic approach to the existing conditions of the historic building. A construction manager general contractor (CMGC) was brought on board by the University so that the integrated process extended beyond the design team to incorporate constructability and true cost analysis. The overall process allowed for integrated solutions to optimize overall building performance as well as optimizing each component of that system.

One of the most important aspects of working with a historic building is to first step back and understand how the building was originally designed to function. From a systems perspective, the building had steam radiators with natural ventilation provided by operable windows. No mechanical ventilation was provided, instead, natural ventilation within the building was further encouraged by the design of the four story building which incorporated open stair towers as ventilation stacks to exhaust warm air through operable windows at the top of the stairs.

Modern fire code required that these stairways, which created the stack ventilation effect, be enclosed at each floor to limit the chimney effect during a fire event. Prior to the Capital Renewal Project, enclosure doors and gypsum board partitions were added at each floor. The earlier dismantling of the stack ventilation system, coupled with the deteriorated condition and difficulty of operating the windows, created a significant lack of fresh air and natural cooling throughout the building. The changes rendered over the years impacted the habitability of the structure, to the point that adding air conditioning and mechanical ventilation was required in order to continue use of the building. In order to minimize the size and maximize the efficiency of the inserted mechanical system, several systems were analyzed along with a variety of envelope upgrades, to develop the best system for this historic building. From a preservation perspective, the best approach would have been to reopen and encourage the natural stack ventilation, along with upgraded and rehabilitated envelope components and efficient control systems. Ultimately, this was ultimately not possible due to the stringent fire codes that do not allow more than two stories to communicate.

Window Selection

While the integrated design process had several different investigation tracks working simultaneously, the description of the design process begins with the windows. Window replacement can be a controversial issue for historic buildings due to the difficulty in replicating historic profiles, site lines and materials with modern off-the-shelf solutions. The original windows at Ketchum Arts and Sciences Building contribute to the historic character of the building, but have significant energy use impacts associated with non-thermally broken frames and single glazing. In addition, the windows were identified as having lead paint and requiring abatement.

The replacement of the windows with thermally broken aluminum frames and insulated glazing with low-e coatings reduces the heating and air conditioning loads of the building with the energy modeling results shown later in Table 1. Several companies have historically appropriate aluminum framed replacement windows and consulted with the design team, including Custom Windows, Graham Architectural Windows and Wausau Windows.

Due to the substantial amount of glazing on Ketchum, it is a critical preservation consideration that the replacement windows replicate the historic site lines and profiles of the original windows. The replacement windows specified have very low profile perimeters, true divided lites and retain the same operability as the existing windows in offices. Spaces that are not continually occupied, such as classrooms, stairwells and conference rooms, will not have operable windows, but from the exterior they will retain the venting profiles. Glazing was selected based both on insulating ability and external reflectivity of the glazing to ensure that the overall window assembly maintains the visual historic character. Envelope compromises for the historic character were minimal, but are evident in the decision not use highly reflective coatings on the glazing and to use true divided lights.

As with any historic building project, one must balance the needs of efficiency with the individual characteristics of the building. For instance, with Ketchum, the windows are a significant contributing factor to the historic character, but the interior has minimal historic trim or materials that substantially contribute to the overall character. There is minimal interior wood trim, and the texture of the plaster finish of the walls can be replicated utilizing a thin gypsum plaster veneer over the gypsum wallboard. Thus, the exterior walls themselves were an opportunity to upgrade the envelope without substantial detrimental effects to the historic character. The existing 1 foot, 2 inch thick masonry stone walls have a low effective R-value of approximately R-3. The exterior walls will be insulated and refinished with a plaster veneer over gypsum board, over the existing interior materials, to provide for a greater insulating value. New window sills were installed to cope with the deeper window profile and thicker exterior wall. This detail was extremely important as it is the location with the potential for a thermal bridge over the new interior insulation.

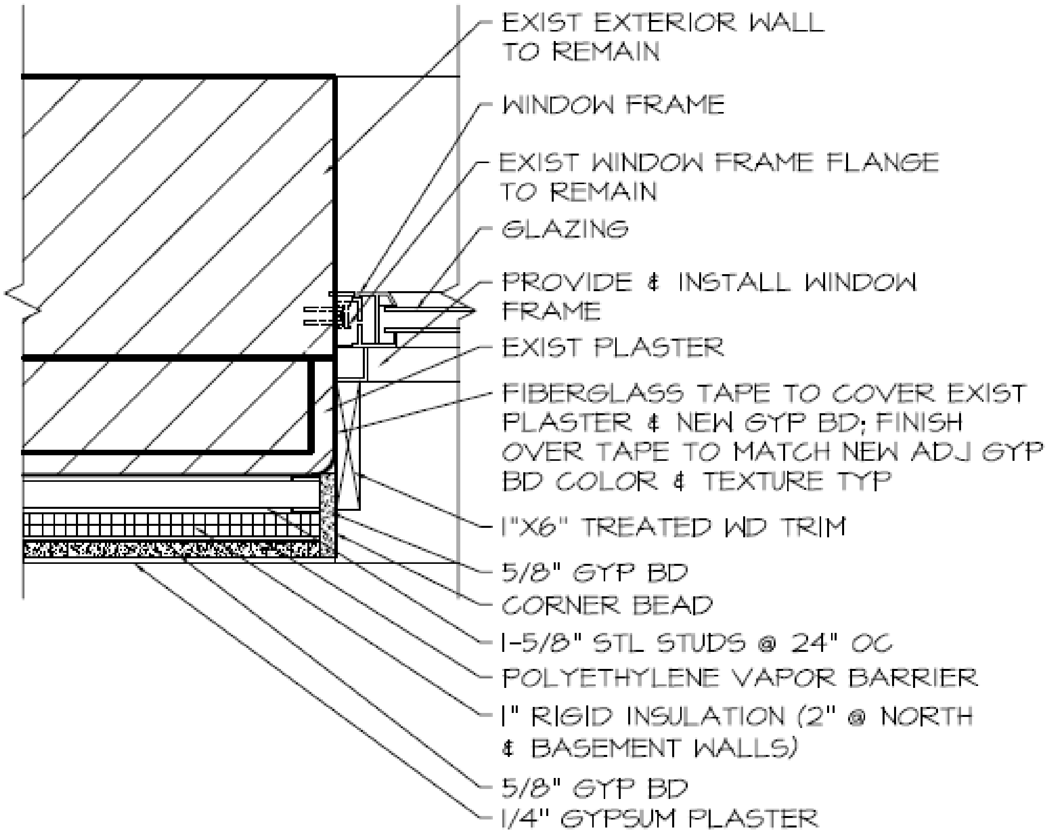


FIGURE 1: Window Jam Detail with Insulation Retrofit

Insulation and Hygrothermal Analysis

The original masonry wall construction contains no insulation and the team was concerned about potential condensation and freezing induced by adding insulation on the interior of the masonry walls.

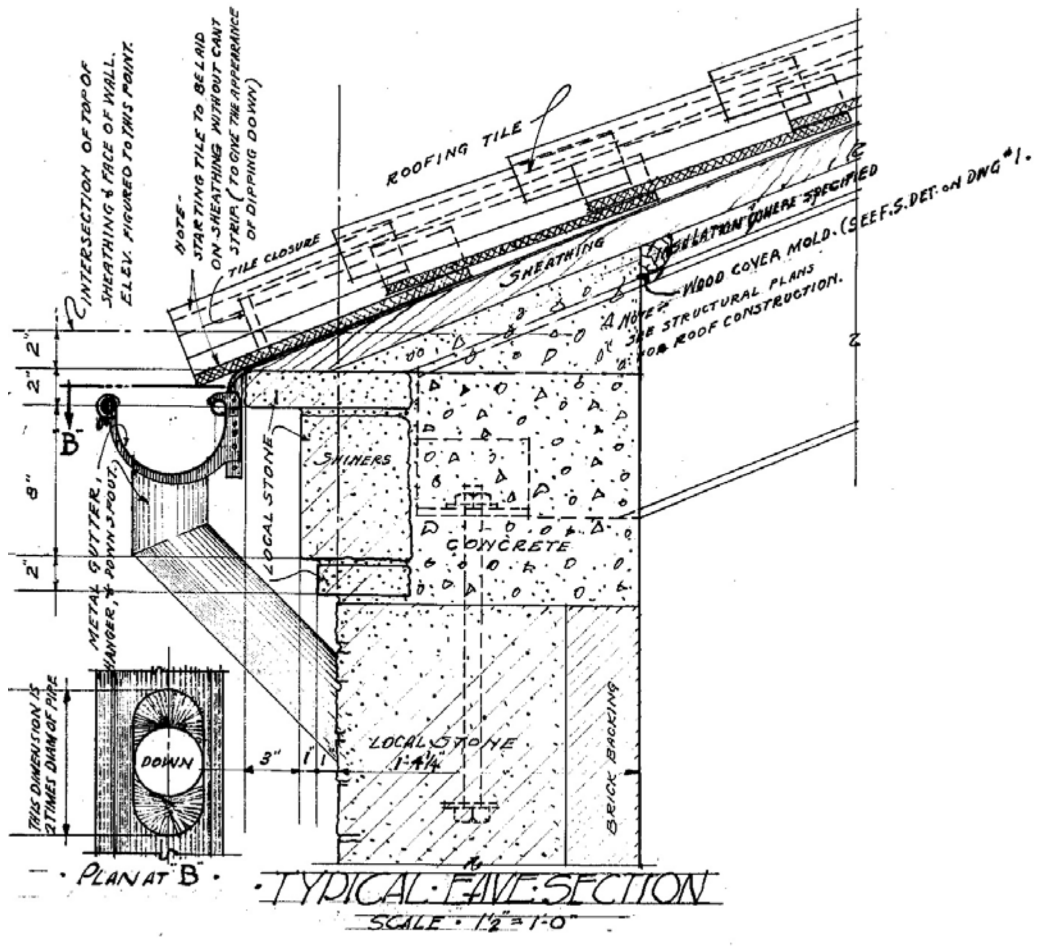


FIGURE 2: Original Drawing of Wall Section

Therefore, hygrothermal (moisture and heat) analysis described below was used to test wall performance of the entire assembly. This analysis lead to a design that includes multiple vapor barriers of paint, polyurethane vapor barrier, and foil faced and taped insulation.

The WUFI computer based analytical program for hygrothermal analysis (Fraunhofer Institute for Building Physics) was investigated as a possible tool. Because, the program did not have the historic material properties available, the consultant used a calculation method based on ASHRAE Fundamentals Simplified Hygrothermal Design Calculations and Analyses (ASHRAE 2009) to control specific design conditions of wall layers, and internal and external temperature and relative humidity. The analysis was performed for exterior design conditions of -3 F and relative humidity from 10% RH to 100% RH. The interior conditions were 70 F and relative humidity from 10% to 30% RH.

Diurnal weather data for Boulder shows that the average temperatures for December through March experience freezing (32 F) suggesting one freeze-thaw cycle per day. In extremely cold weather but sunny weather, a southern exposure may have more than one free-thaw cycle on as shadows pass over the wall.

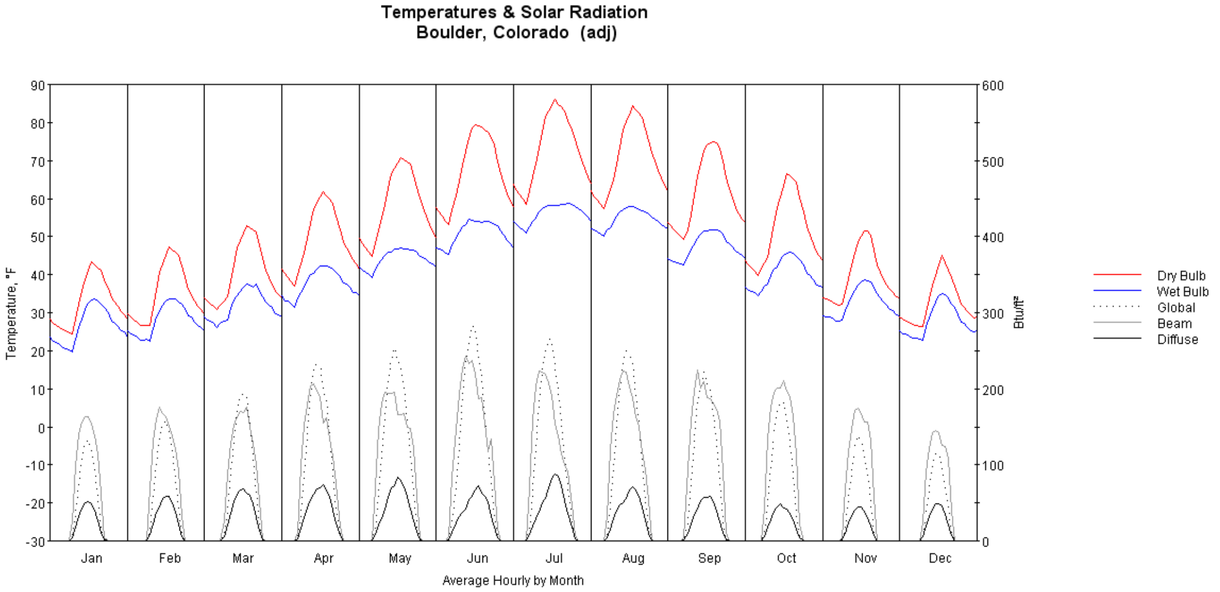


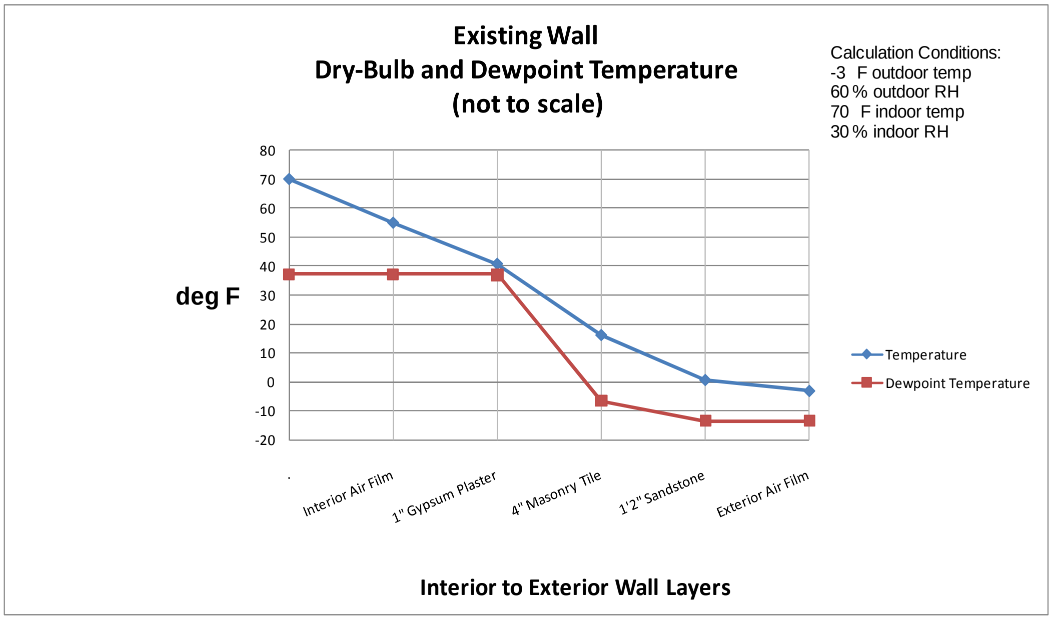
FIGURE 3: Monthly Average Diurnal Temperature Profile for Boulder, Colorado

Three different cases were analyzed to understand the impact insulation and vapor barriers on the design. First, the existing wall condition was modeled first to understand the current state of the masonry wall assembly, then insulation and vapor barriers were added. R-values of dry materials are used in this analysis.

The temperature profile in Figure 4 for the existing wall shows that it is warm enough that the temperature is above the dewpoint inside the wall and condensation does not occur beyond sacrificial mortar. Historically, mortar was expected to take the brunt of weathering and water on the exterior of the building, hence it is the sacrificial material of the assembly. It can easily be re-pointed with a matching mortar, and in solid masonry walls such as this, that was the original design intent. If the internal relative humidity were to rise to 40%, condensation would occur, but this is an unlikely winter condition for an academic building in Boulder.

interior -->exterior

Layer/Interface	Units		1	2	3	4	5	Total R-Value	Total U-Value
Layer		Interior Surface	Interior Air Film	Gypsum Plaster, 1.0 in	Clay tile, hollow, 1 cell deep, 4"	1'2" Sandstone (applied directly to masonry tile, Low Value - Berea)	Exterior Air Film	h·ft^2·°F/Btu	Btu/h·ft^2·°F
R-value	*h·ft^2·°F/Btu*		0.68	0.64	1.11	0.70	0.17	**3.30**	**0.303**
vapor permeance	*perm*		160.00	20.00	0.12	2.40	1000.00		
temperature at interface	*°F*	70	54.96	40.80	16.25	0.76	-3.00		
relative humidity at interface	*%*	30.0%	50.9%	86.2%	35.0%	50.2%	60.0%		
dewpoint temperature at interface	*°F*	37.184	37.148	37.004	-6.628	-13.468	-13.450		
Interface Condensation	*Yes/No*	No	No	No	No	No	No		



Calculation Conditions:
-3 F outdoor temp
60 % outdoor RH
70 F indoor temp
30 % indoor RH

FIGURE 4. Existing Masonry Wall Temperature and Condensation Profile

The next step investigated the proposed wall with taped 1” foil faced polyisocyanurate attached to hat channels. The manufacturer does not report the vapor permeance of the foil face as part of the product’s performance; it is estimated at a conservative value of 0.10 perm. The dry-bulb and dew point temperature profile for the proposed shows saturation conditions exist at the gypsum plaster because this surface is now on the cold side of the wall. The temperature at the existing gypsum plaster is cold enough to drop to dewpoint and allow frost or ice when it is -3 F outside. Variations in the external relative humidity did not change these results significantly and condensation does not occur when the internal relative humidity is 10% or less.

interior -->exterior

Layer/Interface	**Units**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total R-Value**
Layer		Interior Surface	Interior Air Film	Gyp Wall Board	Foil Face/Tape	1" Polyiso	Gypsum Plaster, 1.0 in	Clay tile, hollow, 1 cell deep, 4"	1'2" Sandstone (applied directly to masonry tile, Low Value - Berea)	Exterior Air Film	
R-value	*$h \cdot ft^{2} \cdot {}^{\circ}F/Btu$*		0.68	0.50	0.00	6.00	0.64	1.11	0.70	0.17	**9.80**
vapor permeance	*perm*		160.00	50.00	0.10	3.00	20.00	0.12	2.40	1000.00	
temperature at interface	*°F*	70	64.93	61.21	61.21	16.52	11.75	3.48	-1.73	-3.00	
relative humidity at interface	*%*	30.0%	35.7%	40.6%	21.6%	100.0%	100.0%	52.4%	56.5%	60.0%	
dewpoint temperature at interface	*°F*	37.18	37.16	37.10	22.83	16.52	11.75	-8.72	-12.30	-13.45	
Interface Condensation	*Yes/No*	No	No	No	No	Yes	Yes	No	No	No	

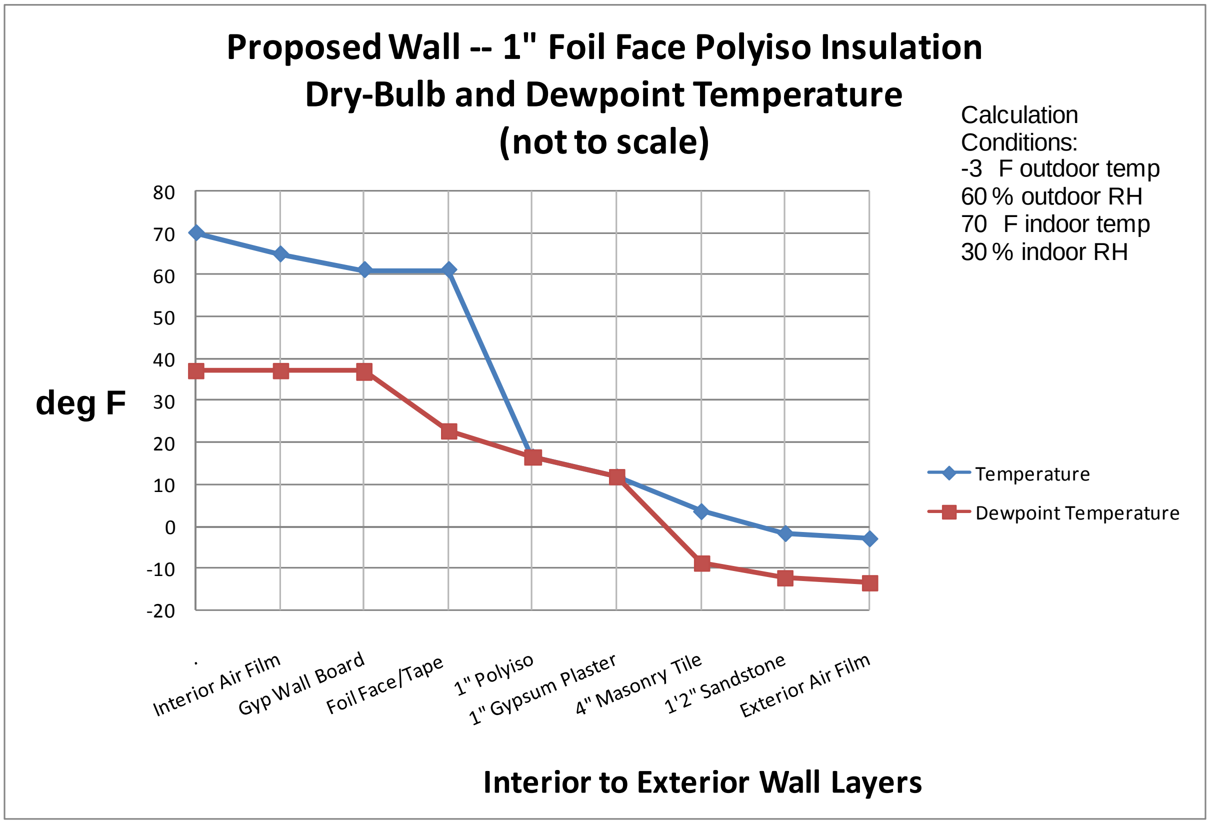


FIGURE 5. Temperature and Humidity Profile with Insulation Only Retrofit

Lastly, the wall permeance was reduced with a polyethylene vapor barrier placed on the warm side of the wall with a permeance of 0.03 perm. By reducing the vapor transmittance, the dewpoint never rises above the drybulb temperature and thus, there will be no condensation on the interior of the wall at these conditions. Notice that the insulation still causes a large temperature drop, but the vapor barrier provides a large dewpoint temperature drop as well because the relative humidity of the air is reduced. With the vapor barrier, condensation and potential freezing occur with internal relative humidity of 31% or higher and these conditions are not expected.

interior --->exterior

Layer/Interface	**Units**		**1**		**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total R-Value**
Layer		Interior Surface	Interior Air Film	Gyp Wall Board	Polyethylene Vapor Barrier	Foil Face/Tape	1" Polyiso	Gypsum Plaster, 1.0 in	Clay tile, hollow, 1 cell deep, 4"	1'2" Sandstone (applied directly to masonry tile, Low Value - Berea)	Exterior Air Film	
R-value	*h·ft^2·°F/Btu*		0.68	0.50	0.00	0.00	6.00	0.64	1.11	0.70	0.17	**9.80**
vapor permeance	*perm*		160.00	50.00	0.03	0.10	3.00	20.00	0.12	2.40	1000.00	
temperature at interface	*°F*	70	64.93	61.21	61.21	61.21	16.52	11.75	3.48	-1.73	-3.00	
relative humidity at interface	*%*	30.0%	35.7%	40.7%	17.6%	10.6%	59.9%	73.6%	47.2%	56.5%	60.0%	
dewpoint temperature at interface	*°F*	37.180	37.160	37.160	24.790	13.280	11.010	10.420	-10.100	-12.300	-13.450	
Interface Condensation	*Yes/No*	No	No	No	No	No	No	No	No	No	No	

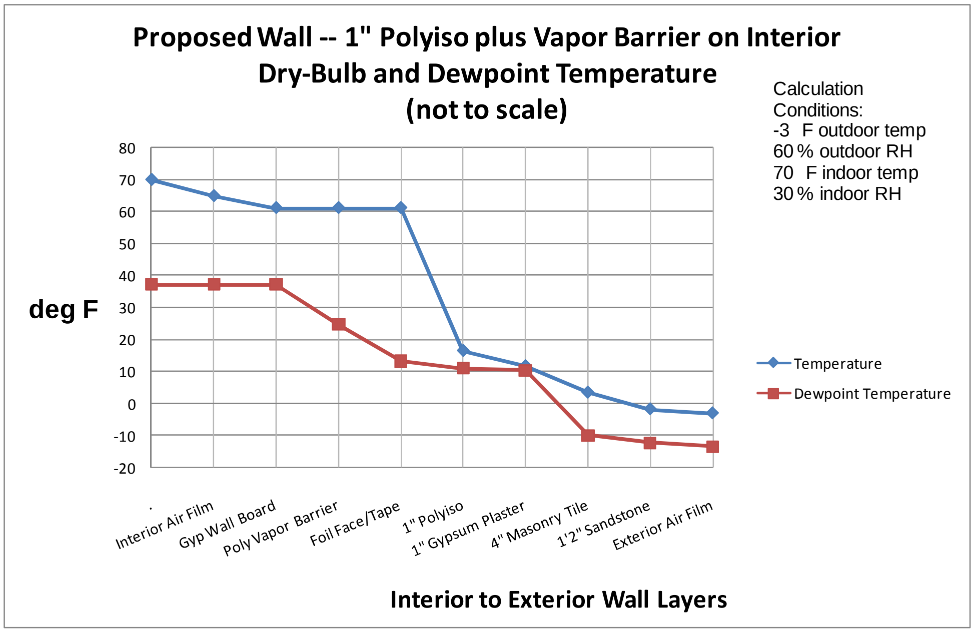


FIGURE 6: Wall Temperature and Humidity Profile with Insulation and Vapor Barrier Retrofit

The team decided to incorporate a robust design with multiple vapor barriers because the hygrothermal analysis demonstrates that the internal insulation with no vapor barrier (or a compromised vapor barrier) will cause condensation and potential freezing at the original gypsum plaster. Future building occupants will likely hang pictures or other activities that will compromise the vapor barrier and not be aware of the potential for water condensation damage to the building. Therefore, the design includes paint, the polyethylene vapor barrier, and the foil faced polyisocyanurate. The design also includes sealing wall penetrations such as electrical outlets to limit movement of air in and out of the wall cavity. The mechanical system selected has no equipment located at the perimeter of the building; therefore, there are no mechanical penetrations at the wall cavity.

An alternate of closed-cell spray insulating foam was investigated because it is an aggressive sealer with the properties of the vapor and air barrier and can be applied directly to the inner surface of the existing wall; however, it was not selected due to the labor required to mask the internal spaces for spray and the local construction practices in 2008 at the time of the investigation. This was a key example of the integration of contactor input into the final design decisions.

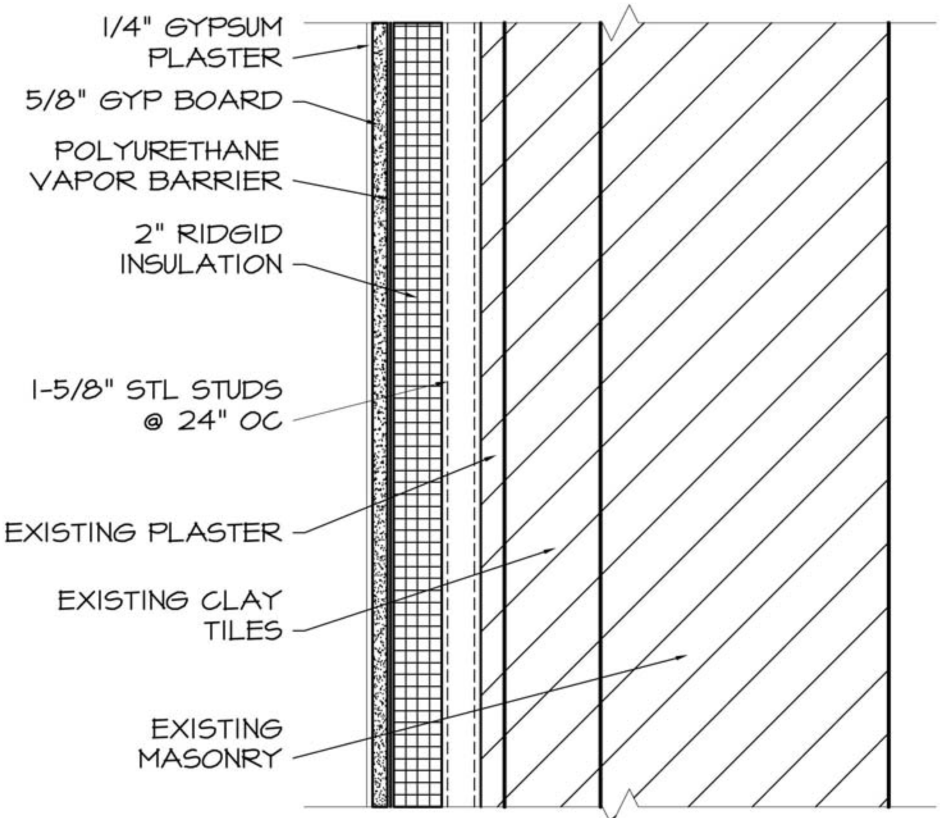


FIGURE 7: Wall Insulation Layers

Because of the choice to use board insulation, the final wall layer includes an air gap at the studs to accommodate electrical and technology wiring. With the board insulation, an air gap due to irregularity in the existing wall surface would be present if the configuration were changed so the insulation was placed next to the wall without stud or hat channels (as opposed to using insulating foam which has no air gap). The 1 5/8” air gap with studs adds to the insulation value of the wall making the total wall assembly approximately to R-11 (insulation values without air gap are used below in energy analysis to be conservative). The air gap of any size is not ideal because air will be in contact with the cold interior masonry surface with the potential for condensation. In order to address this, additional operation strategies to maintain the integrity of walls and reduce risk of condensation include recommendations for facility staff and building occupants to:

- maintain the vapor barrier and limit future exterior wall penetrations, such as hanging pictures on exterior walls;
- limit activities like cooking, humidification, or using aquariums, that create an interior relative humidity greater that 30% in winter;
- operate the building at a neutral or slightly (-4 Pa) negative pressure, ensuring that air will not leak outward in sufficient volumes cause damaging quantities of condensation on the back of cold insulated masonry (Straube and Schumacher 2007);
- re-point regularly to ensure excessive wetting of the exterior is avoided (Wilkinson et al. 2009).

Energy Saving Options

After adding the insulation with vapor barrier, the energy model was used to further optimize the amount of insulation recommended by floor and orientation and to pick the final glazing properties. By adding the insulation to the R-9.8 level, the heating balance point temperature (the temperature at which there is a call for heat) rises and the energy cost is reduced over $7,000 as compared to the original R-3.3 building as shown in Table 1. The next step was to evaluate the cost versus benefit of adding a second inch of polyisocyanurate for R-15.8 total at walls and the effects of an R-40 roof compared to an R-30 roof. The different options for wall insulation included the additional upgrade to R-15.8 for all walls, basement walls only, or north walls only. The additional insulation cost roughly $1.00/sf. Therefore, the design team selected R-15.8 for north walls only, R-9.8 for all others, plus upgrading the roof to R-40 roof to minimize the investment and maximize energy savings and comfort. Of several glazing options evaluated, the selected glazing is a combination of a shading coefficient of 0.42 on the South, 0.26 on the East and West and 0.31 on the North. All of the selected glazing products are available from the Cardinal Glass family.

TABLE 1: Energy Analysis Results for Envelope Options

SUMMARY	Energy Cost	Energy Savings	First Cost
	$/yr	$/yr	$
Existing Building R-3.3 Walls	$81,787		
Design Case R-9.8 Walls	$74,539		
EEM 1 Roof R-40	$73,899	$639	$8,101
EEM 2a 2" Polyiso R-15.8 Basement Only	$74,186	$353	$7,741
EEM 2b 2" Polyiso R-15.8 North Only	$73,920	$619	$11,745
EEM 2c 2" Polyiso R-15.8 All Walls	$72,866	$1,673	$40,355
EEM 3a Glazing SC: S-0.43, NEW-0.31	$74,321	$217	$0
EEM 3b Glazing SC: S-0.43, EW-0.29, N-0.31	$74,251	$287	$0
EEM 3c Glazing SC: S-0.73, EW-0.29, N-0.31	$73,798	$741	$0

Mechanical System Selection

In reality, much of the mechanical system investigation was completed prior to the details of walls and windows described above. Three HVAC system options were presented in the Schematic Design narrative. These options were:

1. Variable Air Volume (VAV) air handling units with conventional overhead distribution;
2. VAV air handling units with displacement ventilation distribution;
3. Dedicated outside air units with fan coil units and conventional overhead distribution.

Displacement ventilation has been used successfully in full-size classrooms for some time. For this project, computational fluid dynamics was used to demonstrate that a displacement ventilation system would operate with the desired stratification in the small offices on the garden level. In addition, site visits to local installations were beneficial for the facility staff to experience similar displacement ventilation systems in operation and the sensation of cool low velocity air entering low into the space, stratifying, and returned high to the air handling unit. The stratification is illustrated in Figure 8 with cool air entering low, being warmed by occupants, computers, and lights and rising to the ceiling.

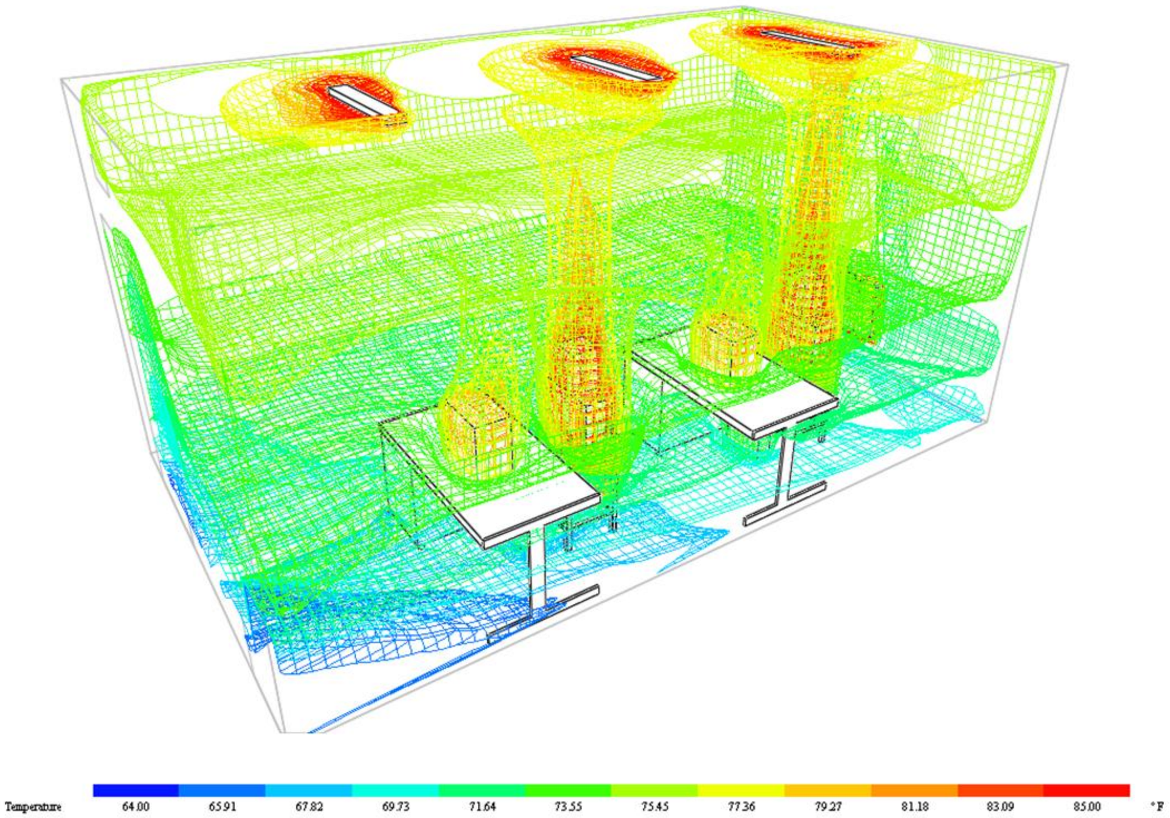


FIGURE 8: Stratification of Air in Small Offices with Computation Fluid Dynamics

The energy performance of the three systems were compared with the same energy parameters for all systems (envelope, lighting and receptacle power density, purchased chilled water and steam, etc.) except for those shown in Table 2. The amount of loads associated with the lighting, receptacle, and occupants was proportioned to the conditioned zone for Option 2 Displacement VAV based on the Simulation Guidebook because the energy modeling used the DOE2 simulation engine which does not account for stratification and instead assumes a fully mixed temperature in all spaces.

TABLE 2: Comparison of Mechanical System Options

System Type	**Overhead VAV**	**Displacement VAV**	**DOAS + 4-pipe Fan Coil**
Direct Evaporative Cooling	Yes	Yes	Yes
Supply air temp cooling	55 to 65 F	63 F	55 F
Supply air temp heating	95 F	63 F	95 F
Zone reheat coil	One per classroom	None	Fan coil
Max zone reheat delta T	40 F	NA	NA
Baseboards	No	Yes	No
Baseboard head/ delta T	NA	2 ft / 40 F	NA
Baseboard valve type	NA	Two way	NA
Max. airflow.	42,100 cfm	51,700 cfm	42,100
Min. airflow ratio	30%	30%	100%
Supply/return fan static pressure	3.5" TSP supply / 1.5" TSP return	3.5" TSP supply / 1.5" TSP return	Weighted average of: 3" TSP supply / 1.5" TSP return / 1" TSP fan coil
Fan motor control	VFD supply/return	VFD supply/return	Constant volume
Allocation of Load to Conditioned Zone[1]	People 100% Lights 100% Equipment 100%	People 67% Lights 50% Equipment 50%	People 100% Lights 100% Equipment 100%
1. Source CTG Energetics, Inc. Simulation Guidebook Vol. 1			

Energy performance was found to be very sensitive to the fan energy based on static pressure. The design team will minimize fan energy in the final design. The space heating and cooling energy shown in Figure 9 is higher for Option 1 and Option 2, because Option 3, the dedicated outside air system with fan coils, has no reheat with the fan coil system.

Because the difference in the energy performance of the three options is relatively small, it did not provide a clear cut direction for the system decision alone.

Table 3: Energy Results for Mechanical System Options

	Electricity	**Chilled Water**	**Natural Gas**	**Energy Usage Index**	**Energy Cost Index**	**Energy Costs**				
	kWh/yr	MMBtu/yr	MMBtu/yr	kBtu/sf/yr	$/sf	$/yr	% Diff	$ Electricity	$ Chilled Water	$ Steam
Overhead Variable Air Volume	362,280	420	794	41.1	$ 1.10	65,429		41,807	9,545	14,077
Displacement Variable Air Volume	358,830	439	761	40.7	$ 1.09	64,875	-1%	41,409	9,976	13,489
DOAS + 4 Pipe Fan Coils	410,550	311	654	39.7	$ 1.11	66,028	1%	47,377	7,067	11,583

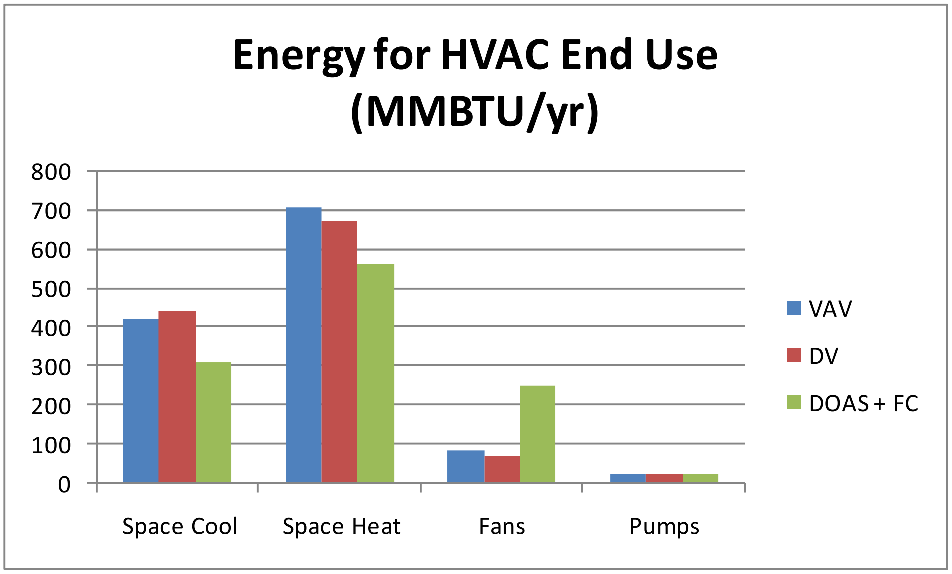


FIGURE 9: Energy Results for HVAC End Use Only

Ultimately, the contractor's estimate demonstrated that a retrofit with displacement ventilation was the lowest cost of the three options. After review with the design team and the University, Option 2 – VAV Air Handling Unit with Displacement Distribution was agreed upon as the basis of design. Advantages of the displacement system include:

- increased indoor air quality (IAQ) due to minimal disturbance of room contaminants;
- reduction of total building CFM, and therefore, smaller air handling units compared to a conventional overhead distribution system;
- decreased energy usage due to increased system discharge air temperature (64 degrees F compared to 55 degrees F required for conventional overhead distribution) allowing additional hours of free cooling;
- noise at diffuser termination has an NC<25.

In addition, space constraints in the building dictated that the possible mechanical room layout be as compact as possible. There was no existing mechanical room as the steam was supplied directly from the campus loop. The mechanical room layout and air handling unit configuration has been designed to lessen the impact on the third floor spaces. The air handling unit is stacked, with the return fan and economizer section located on top of the unit. This allowed utilization of clerestory space on the third floor. Extensive coordination with the design team and existing conditions has been performed to ensure that duct routing and diffuser placement fits within the building. Again, no duct work was originally designed into the building so all duct routing was new. The successful integration of the envelope work with the mechanical systems into this existing historic building could not have been done without the input of the entire design and construction management team.

CONCLUSIONS

The rigor with which the mechanical and architectural features were assessed in an integrated design team environment make the renovation of Ketchum Arts and Sciences Building into a universal case study of how a historic structure can be transformed into an energy efficient modern design. The design team conducted analysis of hygrothermal conditions, energy simulation, and computational fluid dynamics with an understanding of the tools' limitations to inform design decisions that enable Ketchum Hall to meet modern building performance standards that complement the historic structure. All parties including architect, engineers, building performance consultant, facility operations, and contractor contributed to the decision process to arrive at the final integrated design. Although not currently funded for construction, the project is ranked high on the State of Colorado's "wish list". It is the hope of the design team that this project will get implemented in the near future and a verification of the performance of the building can be done to compare with the modeled conditions. This information will be invaluable in proving to the University that a comprehensive approach to revitalizing their existing building stock is both cost effective and energy efficient.

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