The Eberly Campus Community Center
Uniontown, PA

Moisture and Utilization Problems in an Existing Building:

Small Steps Toward a Greater Energy Gain

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Eberly Campus Community Center

Penn State Fayette Campus
Uniontown, PA

Project Team:
Owner: The Pennsylvania State University
Architect/MEP: Burt Hill
Structural: Barber & Hoffman, Inc.
GC: Walter Mucci Construction Co., Inc.

General Information:
Building size: 52,000 sq. ft.
Overall project cost: $10.6 Million
Use: Multi-purpose facility
Stories: 1 floor, with 2nd floor mechanical rooms.

Architecture:
Contains an arena, fitness facilities, a food court, office/ conference space, a theater/auditorium, and a gymnasium/ banquet hall.
Modern steel and glass exterior combining with red brick to recall existing campus architecture.
Repeating curves throught building, further emphasized by the central front fountain.

Structural:
2-way slab-on grade, varying 4″ to 6″ concrete, brick spread footings under load bearing walls
8″ CMU wall system, with W-shape and pipe columns to help carry the load
W-beams and joist system supporting metal deck roof

Mechanical:
Localized air handling units serving the large spaces
Fan coil units and slot diffusers in the office spaces
Radiant panels in locker rooms and training rooms
Separate unit ventilator, exhaust system, and make-up air unit for the food service area
Air-cooled condenser, exterior chiller, and natural-gas fired boiler to serve the loads.

Electrical:
New 500 kVA Transformer with emergency generator
480/277V, 3 ph. 4 w. 1200A Main Distribution Panel
TVSS module protection on panels
Typical lighting includes linear flourescent troffers and metal halide highbays depending upon use
Grounded to building main water line

Special Systems:
Telecom: Theater, fitness area, and dining area sound systems
Food Service: Walk-in refrigerator, hot and cold food displays, coffee bar

Construction:
Design-bid-build delivery method
Lump sum general contract
Bid date: March 27, 2003
Building dedicated: August 19, 2004

PENNSTATE

~ Heather Stapel ~
Mechanical Building Systems Option
http://www.arche/thesis/eportfolio/2007/portfolios/HMS179

Executive Summary

Energy efficiency, green design, LEED ratings – these words are commonly used in the building industry. New projects are increasingly designed to be environmentally conscious, and the definition of an energy conscious building is reaching new heights of expectation and complexity. While new building designs are staying abreast of the energy savings demands, some older and existing buildings are suffering. Many of these buildings have been designed with a lower first cost economic goal while annual energy costs have been given less priority. As energy rates continue to increase, there will be an increasing market for an energy performance overhaul of less efficient existing buildings. This report contains a detailed analysis of an existing building with several problems, and proposes a solution that will help to alleviate those issues.

Several studies have been performed to assist in this analysis. To evaluate the existing moisture problems, an on site study of the existing wall conditions has been performed and has been supplemented by research with the LBNL WUFI 4 program. The selected dehumidification system has been modeled in EES equation solver program to show the system performance characteristics. After the selection and design of the dehumidification system, the building energy performance was modeled using the Trane Trace 700 energy modeling software. Finally, over 70 parametric runs with different controls options were completed to find the most optimal combination of equipment and different schedules. A life cycle cost analysis determined the payback period of the selected system, and compared it to the costs of the current configuration.

To supplement the mechanical systems analysis, a variety of other building systems had to be checked for coordination with the moisture problems and redesign. Therefore, calculations have been performed to confirm that the structural and electrical systems can support the additional loads required by the renovation. A construction analysis of the costs involved with the renovation, as well as an analysis of the direct and indirect costs of the moisture problems has been performed to assist with the mechanical life cycle cost analysis. Finally, an acoustical study of the auditorium space was performed to determine the acoustical response of the space to various space relative humidity levels.

The culmination of these studies has resulted in a recommendation for replacing the current modular air handling units with a modular version of series active desiccant wheels produced by the same manufacturer. Control of these units will be supplemented by carbon dioxide sensors and humidity sensors to regulate air handler operation through demand control ventilation. In addition, the air handlers will be upgraded from a dry bulb based economizer cycle to an enthalpy based economizer cycle. Building equipment schedules have been finalized to a load following operation during peak hours and a 100% purge cycle overnight. These changes have resulted in a 30% total energy use reduction and a 30% reduction in total emissions produced. This building is an excellent example of energy inefficiency in existing buildings. Often simple procedures can cause large energy savings at minimal cost. Undoubtedly the building industry will be asked to perform more of these analyses in the future.

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Author's Acknowledgements

This project has been a year long effort which has drawn out all of my knowledge and expertise acquired over the past few years. While I am very proud of my efforts, this report would not have been possible without the support of dedicated industry professionals, my professors, my classmates, and my family and friends. I would like to thank them all for their patience, their advice, and their guidance throughout this challenge. I am forever in their debt.

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1. Project Overview

The Eberly Campus Community Center is a 52,000 square foot multipurpose facility located on Penn State's Fayette Campus in Uniontown, PA (Fig. 1.1). Completed in August of 2004, it has been in operation for roughly three years now. As originally designed, the community center is a harmonious collection of several large spaces with highly variable occupancies. The main spaces of the building include a cafeteria and kitchen, a theater, a sports arena, a banquet hall, and fitness facility spaces. The building also houses offices for the campus sports directors and other building administrators. An image of the building layout has been provided in Fig. 1.2.

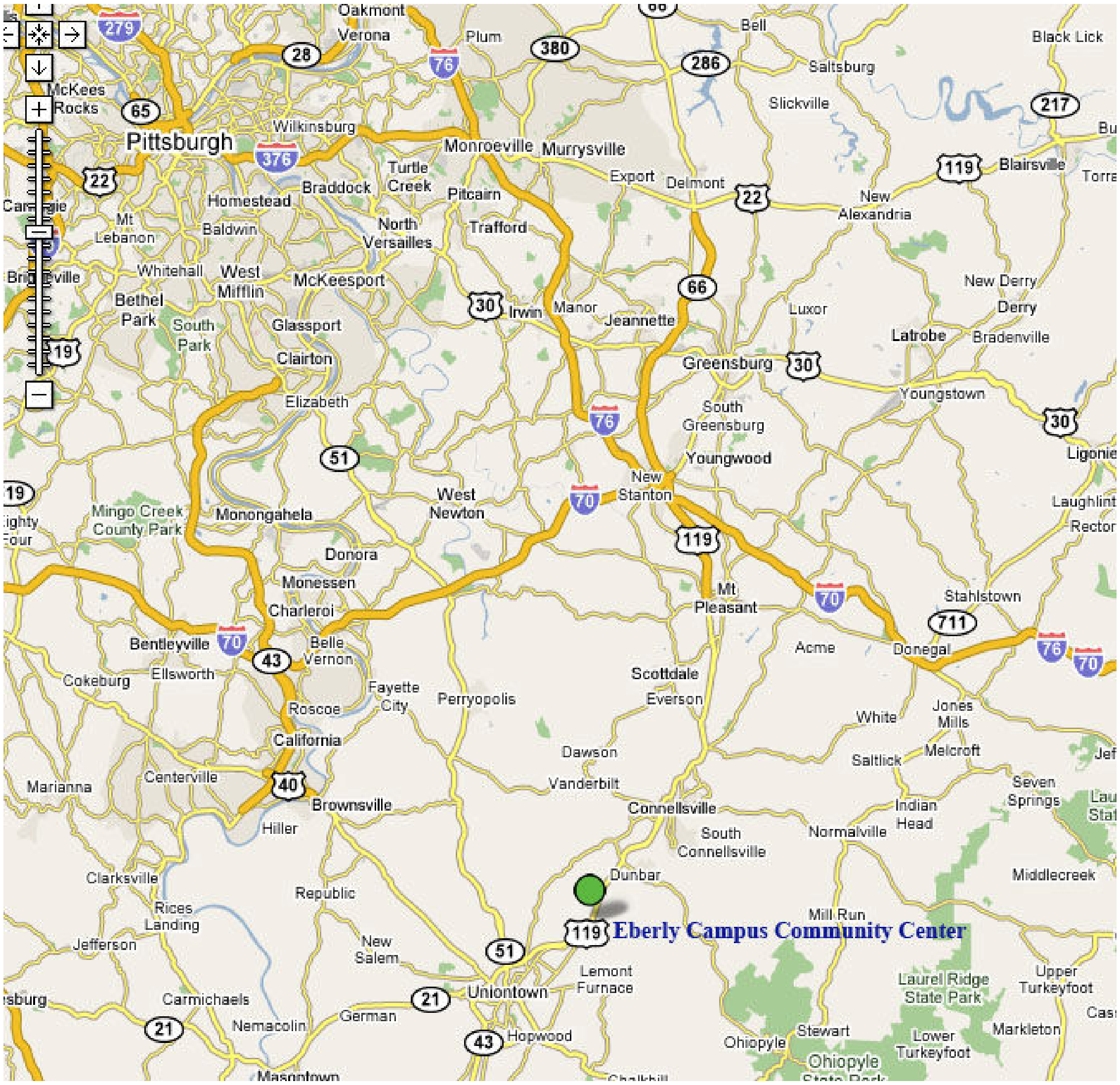


Figure 1.1: Location of the Eberly Campus Community Center

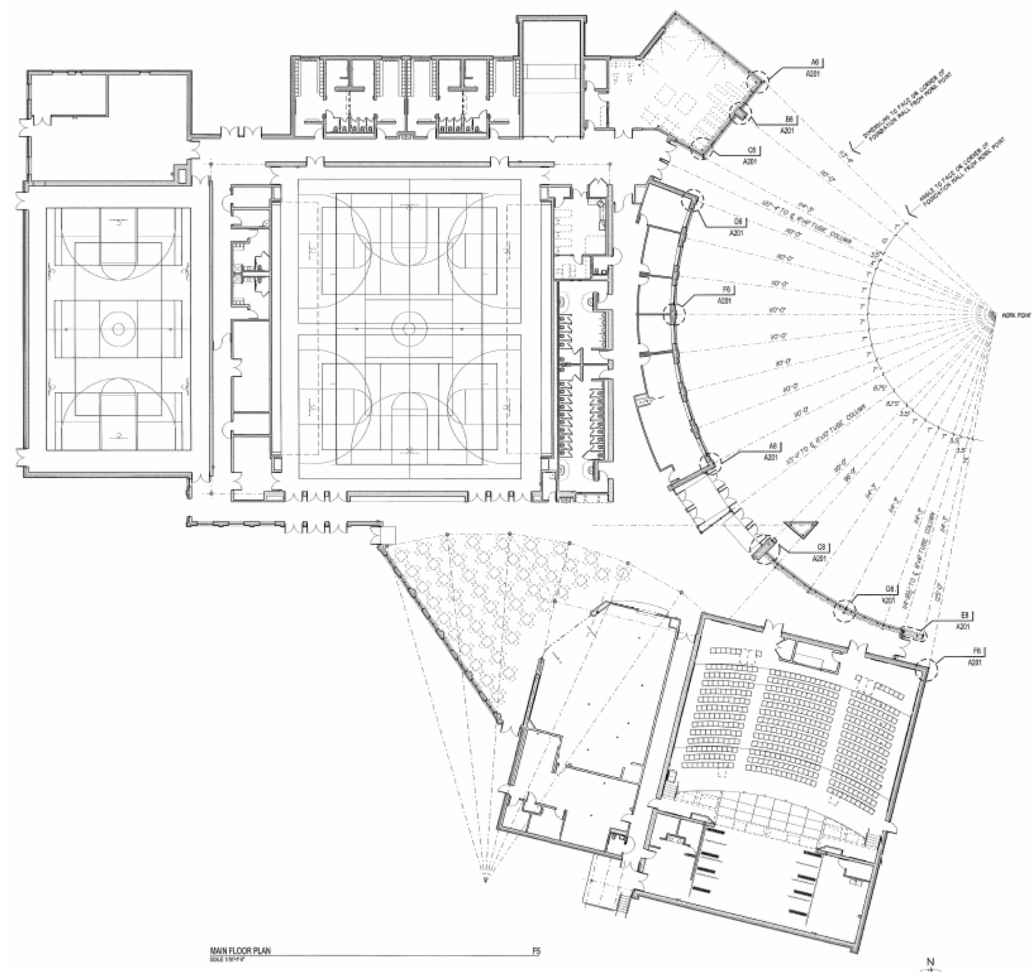


Figure 1.2: Eberly Campus Community Center Base Floor Plan

The Center was commissioned by Penn State Fayette after a grant from Robert E. Eberly, one of the main donors of the Penn State Fayette Campus. Because the funding was only sufficient to cover about 2/3 of the building cost, the building was designed primarily to be economical. Finalized construction costs amounted to $10.8 Million. Therefore, while the building will work adequately for its needs, it is not operating at its optimum potential from a building systems perspective. The building systems inside the center include extensive telecommunication and lighting systems within the auditorium, specialized process cooking and dishwashing equipment within the kitchen, and the building mechanical, electrical, structural, and control systems.

While all of the above building systems contribute to the operating energy requirements of the building, the building mechanical system in particular is operating at sub-optimal conditions. As designed, the mechanical system consists of eight single zone air handling units, two multi-zone air handling units, fan coil units for individual offices, radiant heating with transfer air ducts in the unoccupied zones, a 225 ton air cooled helical rotary chiller, and two natural gas fired cast iron boilers producing 2498 MBH each.

Single zone variable volume air handling units are arguably the best equipment choice for conditioning large spaces with variable occupancies. They provide direct control from the load to the source without the danger of overheating and overcooling other connected zones. The air handling units used in this project have been designed to serve zones with occupancies varying from zero occupants all day to a peak occupancy load of 1200 occupants lasting several hours. Dry bulb controlled outdoor air economizers have been implemented to gain energy savings from OA on cooler days. To achieve additional energy savings without the need for complex control scheduling, the systems are controlled by carbon dioxide sensors located within the space, providing demand controlled ventilation. While this system seems energy conscious, there are several other steps may be implemented to create additional energy savings. These steps will be explored in depth throughout this report.

Working in tandem with the mechanical system, the electrical system provides 1200 VA of power for the entire facility, an emergency generator, the stage lighting and sound systems, and a large volume of fluorescent proffer lighting interspersed with metal halide highbay fixtures in the gymnasium spaces. The largest energy density for the electrical system is located in the kitchen and dishwashing facilities. As these facilities are necessary process loads and are in daily use, electrical energy savings through reduction of these loads are implausible and have been neglected. Likewise, Penn State has already begun replacing all fluorescent troffer lights with more efficient type fluorescent bulbs, so a lighting fixtures redesign will only provide diminishing returns for the cost involved.

Supporting the mechanical and electrical system, the structural system is a composite masonry and steel design. Two-way floor slabs combined with spread footers and the occasional pile complete the foundation system. Composite metal decking supported by W-shape steel beams bearing on CMU walls creates the support system for the mechanical rooms. The design of the mechanical room structural systems was determined through a D + L loading with a 150 PSF live load. The structural system of the mechanical rooms is very important in a mechanical systems renovation, and the above information is necessary for determining the feasibility of the mechanical renovation.

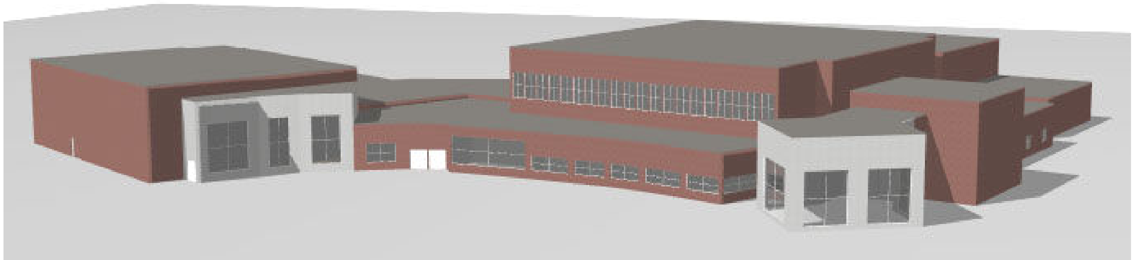


Figure 1.3: Design Builder Energy Model Rendering Shadows are shown during midmorning in April

2. Building History

2.1 Previous and Continuous Problems

As mentioned above, the Eberly Campus Community Center has been operating for about three years now at less than optimal conditions. Most buildings acquire an operating history of small glitches and problems through the time of their use. The mechanical system in this project is no exception to this rule. However, the most significant operating problem encountered within this building is associated with the building envelope system. The problem was noticed in the final stages of building construction, and has been affecting the building performance and energy use during its entire three year operating history.

It was during the final stages of construction that the building moisture problem was first noticed. The hardwood gym floor had been finished and sealed per the specifications, and the contractor continued constructing the finishes inside the building while the sealant dried. However, as construction continued, the hardwood floor was never observed to dry. This was the first indication that the building had a moisture control problem. The hardwood floor had to be refinished, with attention to the relative humidity of the space while the new finish dried. As the building became operational, more moisture problems have been observed. The theater space – a relatively unused space with no windows and demand controlled ventilation – has received the most damage due to the moisture problems. Images of the moisture damage at the site are available in Figure 2.1. Warped wooden paneling on the walls, bubbling of wood veneers over soffits, and shrinkage of the stage curtain by 6” in one year are physically observable effects of the moisture problem. At the peak of the humidity problem, the curtain would feel wet to the touch. Such supersaturated air conditions are far above normal and should be changed immediately.

The natural consequences of operating a heated space at 80 – 95% RH with no light and little air circulation began to appear about a year and a half ago. Mold growth was observed along the seat cushions of the front row of seats. The seating had to be removed and replaced, but this also served as a warning flag for the extreme conditions. In an attempt to deliver a solution, the building owner has had three consultations with Logical Automation, the controls provider, and countless other discussions with the professionals related to the project. The only effective solution at this point has been the cycling of the air handling unit cooling coils at 100%, 24 hours per day.

2.2 Temporary Solutions

Unfortunately, though this scheduling solution is effective and has a cheap first cost, this solution is far from ideal and should be considered only as a temporary fix. Constantly running the air conditioning units increases the building energy use dramatically. Though the chiller would be operating at a better efficiency with its constant and stable load, the energy consumed when compared to the original design energy use negates any benefit that may be gained from a more efficient chiller. Other side effects to this solution were observed in the operating history of the gymnasium.

Figure 2.1: Moisture Damage in the Auditorium. Left: Warped wooden paneling. Top Right: 6” shrinkage of the building curtain. Bottom Right: Underside of the wood panel pulling back from the wall.

The constant load on the cooling coils, in combination with an unfortunate choice in the placement of the zone thermostats, caused condensation to collect and freeze on the exterior the supply ductwork above the main gymnasium. This condition was partially caused by the fact that the thermostats were placed along a doorway that directly communicated with exterior doors. The gym and the exterior were separated only by the width of an 8’ hallway. During the summer, students using the gym would open both the interior gym doors as well as the adjacent exterior doors to let in the fresh air. The thermostats would detect the incoming 80 °F air, and immediately begin cycling more cool air through the system. However, the increase in the cool air supply rate should not have been enough to cause such a dramatic decrease in temperature. The humidity ratio within the space should not have been high enough to cause condensation on the outside of an air duct supplying 55 °F air. Because all of the building cooling coils were running at peak output, the supply air temperature dropped far enough not only to cause condensation on the exterior of the ductwork, but to actually freeze the condensation to the steel.

In addition to the existing moisture problems, the building is also severely underutilized. While this problem is impossible to solve through engineering efforts, it must be taken into account when performing a system redesign. The spaces are only used at about 20 – 30% capacity. Other spaces – particularly the theater - lie dormant for days or even weeks at a time. This underutilization causes the equipment to operate at less than peak conditions. Also, if the spaces are not seeing the predicted loads, the thermostats will not call for cooling, which will exasperate the mold problem. Spaces that have no carbon dioxide or thermal loads will not receive the benefit of either running cooling coils or outside air. The resulting humid stagnant air is an excellent culture dish for bacteria, mold, and other airborne pathogens.

Controlling the building moisture permeation and its utilization by the occupants are beyond an engineering scope. To remove such a widespread humidity problem would require reconstruction of the entire building envelope. Envelope reconstruction for this particular facility would be very difficult, as the wall system consists of a fully grouted brick exterior and a load bearing CMU interior, and the floor system consists of cast-in-place concrete slabs. Increasing the utilization of the building would be a business enterprise best undertaken by the university. Therefore, it is impossible to solve the building’s current problems at the source. However, control of the interior spaces is manageable through careful application of mechanical systems and controls. The following pages contain a thorough study of mechanical redesign possibilities as well as recommendations based upon the results of those studies.

3. Existing Conditions: Site Visit

3.1: Initial Hypotheses

In preparation for the required studies, multiple trips were taken to survey the existing site conditions. The building's history with mold and moisture had led to several hypotheses about the origin of the problems, and these hypotheses needed to be investigated. The initial hypothesis stated that the building envelope assembly was incorrectly constructed. Not only were there no vapor barriers specified in any of the plans or specifications, but there may have been an error in the construction process of the building itself. The construction crew may have installed the vapor barrier in the wrong location within the wall or have forgotten the building insulation. As the insulation in this particular building assembly was specified as extruded polystyrene rigid insulation – this particular insulation is a vapor retardant in itself – the inclusion or exclusion of the insulation could have a significant impact upon the building's thermal and moisture performance. Therefore, the site visit required testing to ascertain whether or not the building insulation, at least, was present.

A second hypothesis stated that the weep holes in the face brick had been forgotten or clogged with mortar in the construction process. The weep hole is a very necessary part of a brick cavity wall, as it allows the moisture entering through the porous face brick to drain out of the bottom of the wall assembly. When the weep holes are unavailable as a drainage path, the water will migrate into the building interior as opposed to the exterior. Vapor pressures tend to equilibrate, and the building interior generally will be less humid than the exterior during the rainy season. Therefore, if the weep holes had been neglected in some way, they would incur significant moisture permeation.

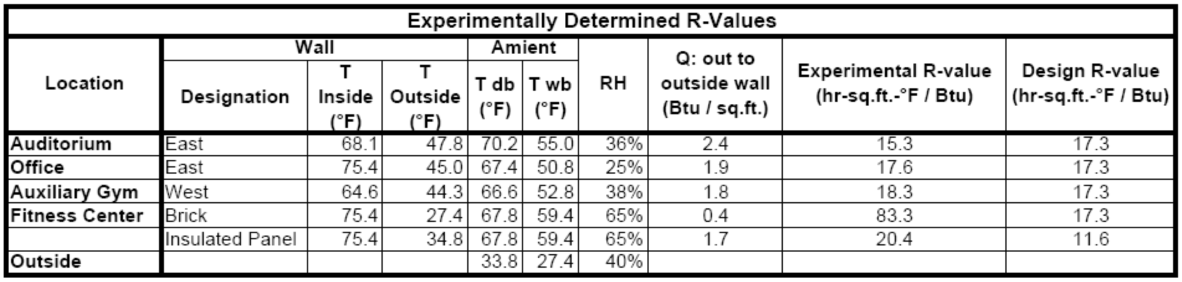
Another possible source of the building moisture problem that required on-site verification was the application or lack thereof of joint sealant between the base of the cavity walls and the top of the slab. The joint of any two building surfaces is the weakest point of the building envelope in terms of moisture penetration. The proper joint sealant and backer rod assembly at this crucial juncture so close to the ground is necessary for maintaining the integrity of the space.

Finally, the last hypothesis estimated that the floor system had been constructed or designed incorrectly, so that moisture was making its way up through the concrete slabs on grade. This hypothesis was reasonable, as the first observable indication of the moisture problem was through the ruin of a floor assembly in the center of the building. The location of the gymnasium rendered the space more vulnerable to moisture permeation through an incorrectly constructed floor, as the water had the longest drainage path to the outside from the center of the building, and therefore had more chance of collecting and migrating to the surface.

3.2: Investigation Methods

The first hypothesis was the most complex to investigate. Determining the existence of insulation within a wall assembly without disassembling the wall itself is problematic. To avoid messy and undesirable physical observation techniques, a more indirect approach was devised. A laser surface temperature sensor was employed to determine the conditions of the interior and exterior air, as well as the temperature on the interior and exterior surfaces at points along the wall. Readings were taken at intervals along the entire perimeter of the wall exterior and interior surfaces. The resulting temperatures were used to calculate an approximate R-value of the entire building wall assembly, and then compared to the calculated R-value of the designed assembly. There were some problems in attaining credible exterior wall surface temperature readings because brick has a large absorbance factor for solar energy as well as a relatively high thermal mass. Therefore, south sections of wall were giving temperature readings of 80 F on a 27 F day, and north sections of the wall were giving temperature readings of 27 F on the same day. Temperature readings such as these – readings obviously affected by the exterior radiant conditions and not showing pure conduction and convection characteristics – were removed from the study. However, enough data remained from to compile a list of the R-values of the major perimeter spaces within the building that had brick cavity walls. A table incorporating the calculations and their results is included below, Table 3.2.1. The brick walls all experimentally produced R-values confirming that their construction met the architect's specifications. While this discounted the hypothesis of a lack of building insulation, there was no experimental way to determine the location or existence of the possible vapor barrier, so further investigation must be pursued to completely discount this hypothesis.

Table 3.1: Experimentally Determined R-Values



Experimentally Determined R-Values

Location	Wall			Amient		RH	Q: out to outside wall (Btu / sq.ft.)	Experimental R-value (hr-sq.ft.-°F / Btu)	Design R-value (hr-sq.ft.-°F / Btu)
	Designation	T Inside (°F)	T Outside (°F)	T db (°F)	T wb (°F)				
Auditorium	East	68.1	47.8	70.2	55.0	36%	2.4	15.3	17.3
Office	East	75.4	45.0	67.4	50.8	25%	1.9	17.6	17.3
Auxiliary Gym	West	64.6	44.3	66.6	52.8	38%	1.8	18.3	17.3
Fitness Center	Brick	75.4	27.4	67.8	59.4	65%	0.4	83.3	17.3
	Insulated Panel	75.4	34.8	67.8	59.4	65%	1.7	20.4	11.6
Outside				33.8	27.4	40%			

The second and third hypotheses were easily determined by visual inspection. After a short examination of the exterior wall, it was obvious that the weep holes installed were from the correct manufacturer, and that they were installed at the correct spacing of 24" on center, a few inches above the ground along the bottom header of the brick wall. See Figure 3.2.1 for a visual confirmation. The examination of the wall surfaces mentioned above also determined that correctly applied joint sealant was present in the areas where the brick wall was bearing upon concrete slab. Therefore, the second and third hypotheses, though common causes of moisture problems in many buildings, were not the culprit in the current case.

Figure 3.1: Existing Wall Conditions Top Images: Weep Hole in the Correct Location. Lower Images: Concrete Slab to Brick Wall Connections

The final hypothesis, an incorrectly constructed floor, proved indeterminate from an on-site investigation. Unfortunately, though this hypothesis has been a prime suspect in this moisture investigation, the only way to determine the actual built floor assembly was to start digging holes or drilling cores in the slab on grade. As the building owners could not allow a deconstructive analysis of their building for the purposes of a simple research investigation, this hypothesis remained unexamined during the site visit.

4. Building Envelope Analysis

4.1: Introduction to the WUFI Building Envelope Modeling Program

As mentioned in section three, the hypotheses involving the construction of the exterior walls have been unable to be validated by the on-site investigation. As recourse to actual physical investigation, the IBP / ORNL WUFI 4 Program has been introduced to the project. The WUFI program is a specialized hygrothermal analysis program that can compute the moisture and water loads at all points within a building assembly for the entire course of several years. Its outputs include total moisture accumulations in all of the assembly components, analysis of mold growth conditions on all interior wall surfaces, relative humidity of the components in a real time video output, and other useful applications. Therefore, the wall system and floor system in question have been modeled extensively, with many different parametric runs, involving different possible assembly errors to see if any one combination would produce a remarkably high moisture load.

4.2: Wall Systems Analysis

Several variations of the walls include a base model of the wall as it was designed, a model of the wall with a vapor barrier in the correct place, a version with the vapor barrier in the wrong place, and then copies of these models with additional acoustical insulation on the interior surfaces, and all of the above models facing different cardinal directions. In addition, the floor system was modeled with the vapor barrier in the designed position, without a vapor barrier, and the vapor barrier in an incorrect position. The full results of the WUFI analysis are included in Appendix A. For a full view of the brick cavity wall system in question, see Figure 4.1 below.

It was found that North and East facing walls tended to retain about 20% more moisture than South facing walls, while West facing walls retain on average about 5% less than the base South facing wall. This is understandable, given that the maximum wind driven rain load lies to the West. The amount of water hitting the surfaces is much higher in West facing walls; therefore, the water has more mass with which to facilitate its exit. The Eastern and Northern walls receive less wind driven rain load, and will absorb the moisture as it slowly makes its way down the wall surface. This moisture has to be released through evaporation as opposed to mass transport through the weep holes, causing a higher overall moisture load in the Eastern and Northern facing surfaces. For a diagram of the solar and wind driven rain loads, please see Figure 4.1.

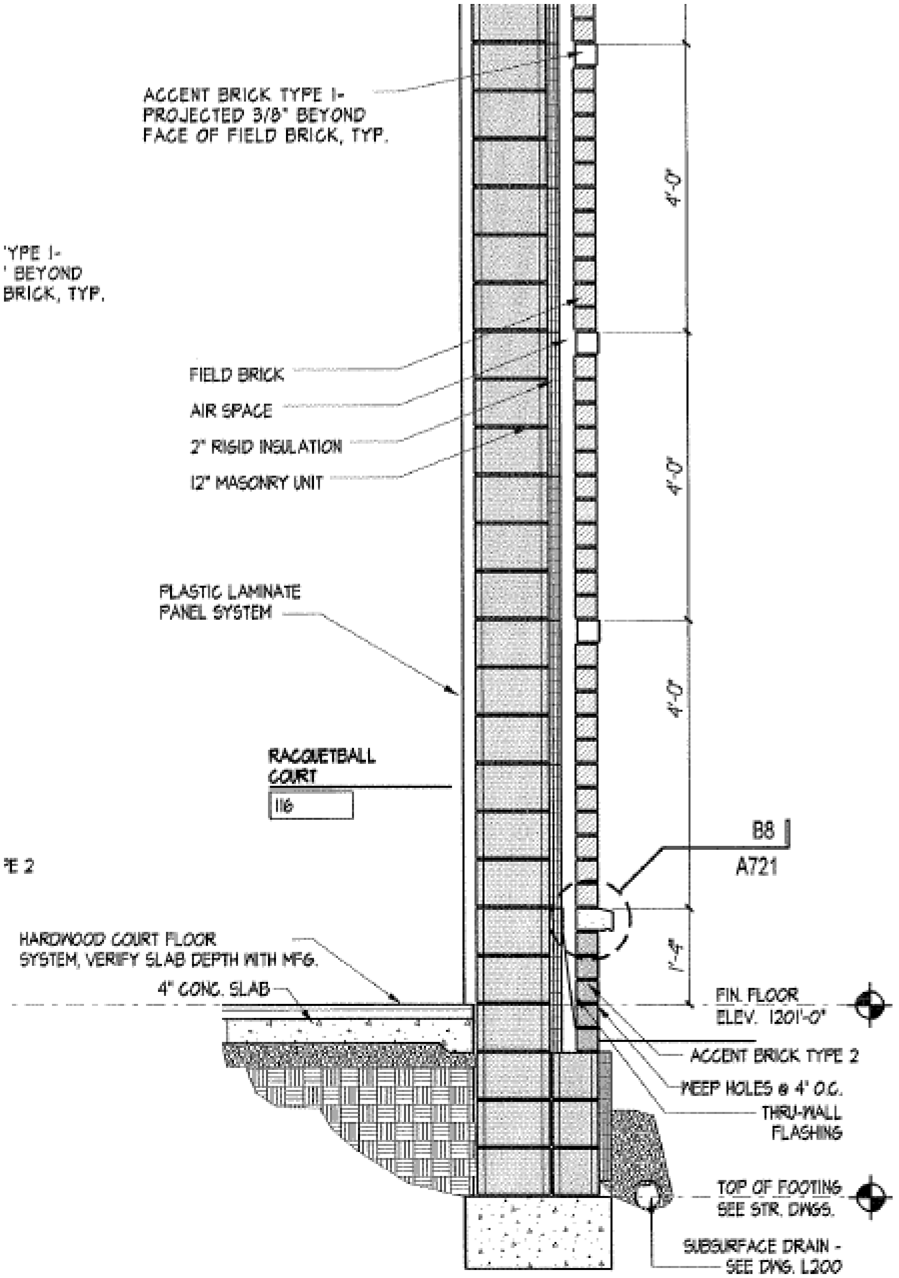
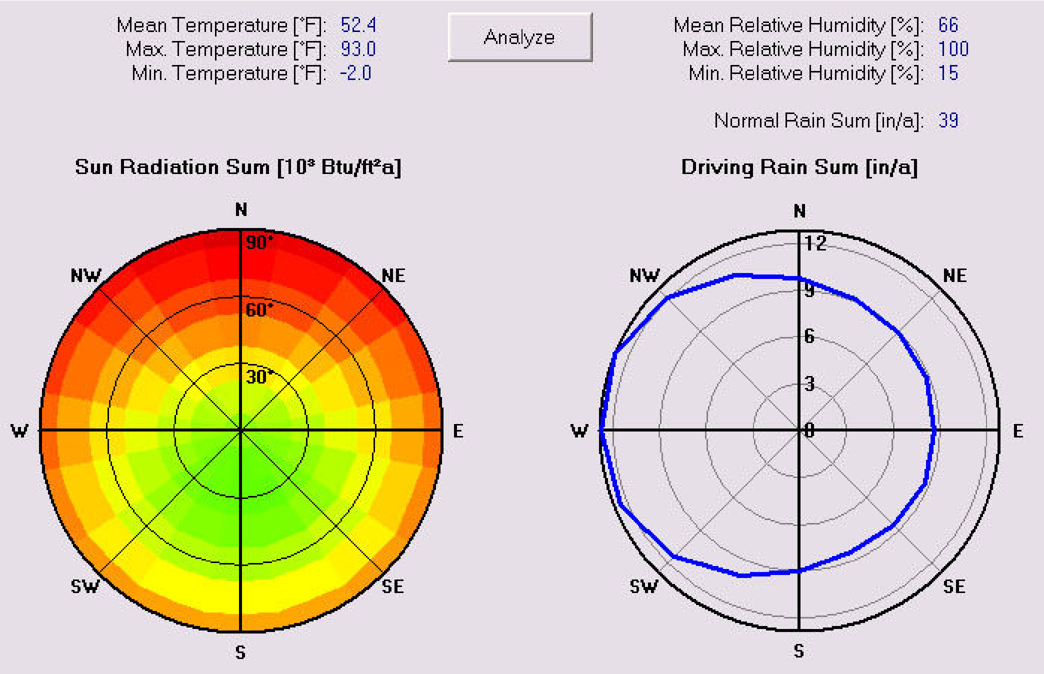


Figure 4.1: Typical Brick Cavity Wall System

In addition to variable moisture loads caused by direction, the assemblies themselves caused great differences in the moisture load of the wall. Those assemblies with acoustical wall insulation placed on the interior surface reached hygrothermal mold growth conditions between the acoustical wall insulation and the CMU wall. These assemblies would also see about 80 – 90% relative humidity in the space between the acoustical insulation and the wall (see Figure 4.2). This could partially explain the presence of mold growth in the auditorium. Additionally, hygrothermal conditions were reached on the interior of the acoustical wall insulation surface when a vapor barrier had been installed in the correct position.



Mean Temperature [°F]: 52.4
Max. Temperature [°F]: 93.0
Min. Temperature [°F]: -2.0

Mean Relative Humidity [%]: 66
Max. Relative Humidity [%]: 100
Min. Relative Humidity [%]: 15

Normal Rain Sum [in/a]: 39

Figure 4.2: Solar and Wind Driven Rain Loads

4.3: Floor Systems Analysis

Finally, the floor surfaces were modeled using the correct components, but as a roof with the correct surface facing the interior. As these results will not be entirely consistent with the performance of an actual floor system, they must be taken with some skepticism. However, they provide an excellent basis of comparison for the relative performance of different floor systems. It was found that hygrothermal conditions were reached on the interior surfaces on models of the floor system as it was designed, and the floor system without a vapor barrier. However, there was a noticeable decrease both in the total assembly moisture retention and a lack of interior hygrothermal conditions in the assembly that placed the vapor barrier on the outside of the insulation layer underneath the concrete slab (Figure 4.3). However, the water content in the interior layer (the concrete slab) was reduced in the base "as designed" model.

After a thorough review of the results of the WUFI 4 modeling, it was determined that the currently designed wall systems provide the best performance for the given building. However, if vapor barriers had been installed per current industry practice, or if they had been installed in the wrong position as well, this could be the potential cause of the building moisture problem. The floor systems, according to WUFI and its hygrothermal analysis, are the most probable culprit for the current moisture problem. In addition, the interior relative humidity levels at the surface of the floor varied between 50 – 60%, as opposed to a steady projected 50% RH for the interior of the wall systems. Therefore, it seems that the floor system is projected as having the greatest moisture permeation. However, the model is inconclusive, and further studies with experimental assembly performance or a simple physical examination should be performed to accurately determine the source of the current moisture problems within the building.

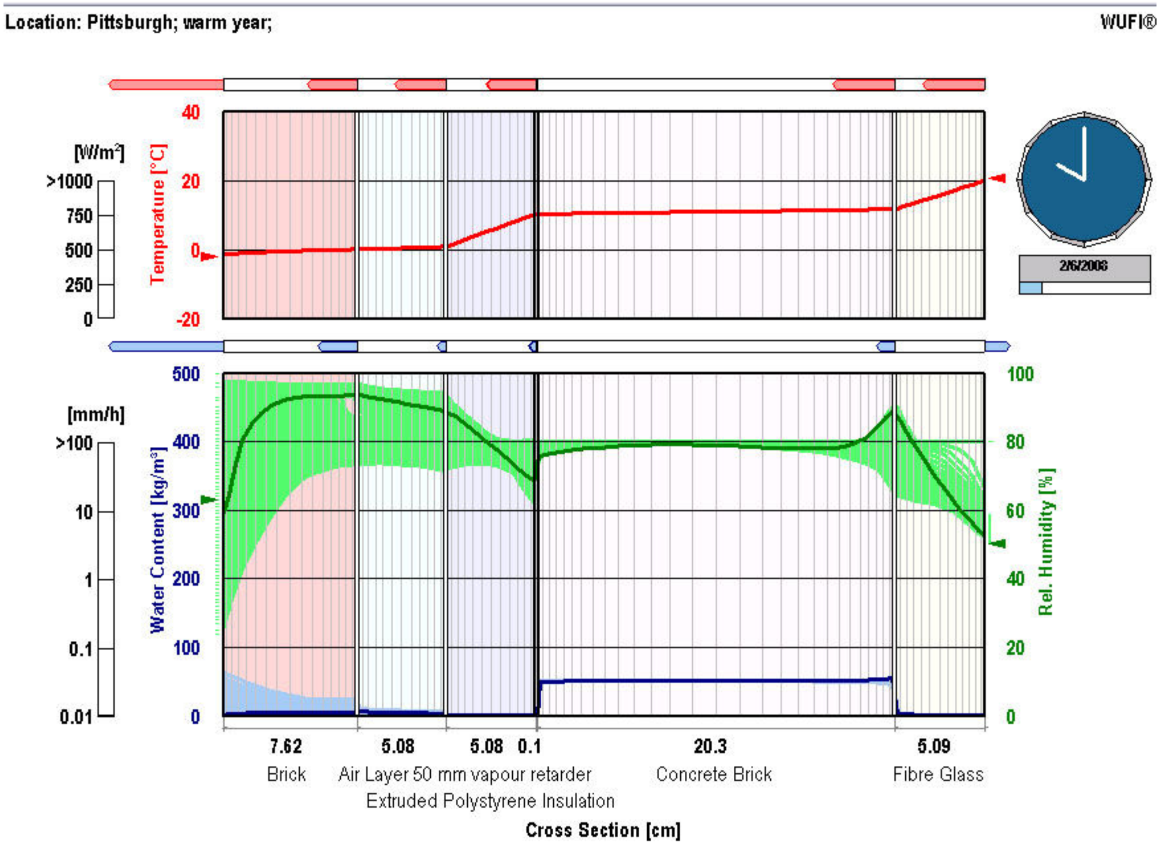


Figure 4.2: Relative Humidity Loads in Cross Section Note: This assembly includes interior acoustical wall insulation and a vapor barrier located in the correct position.

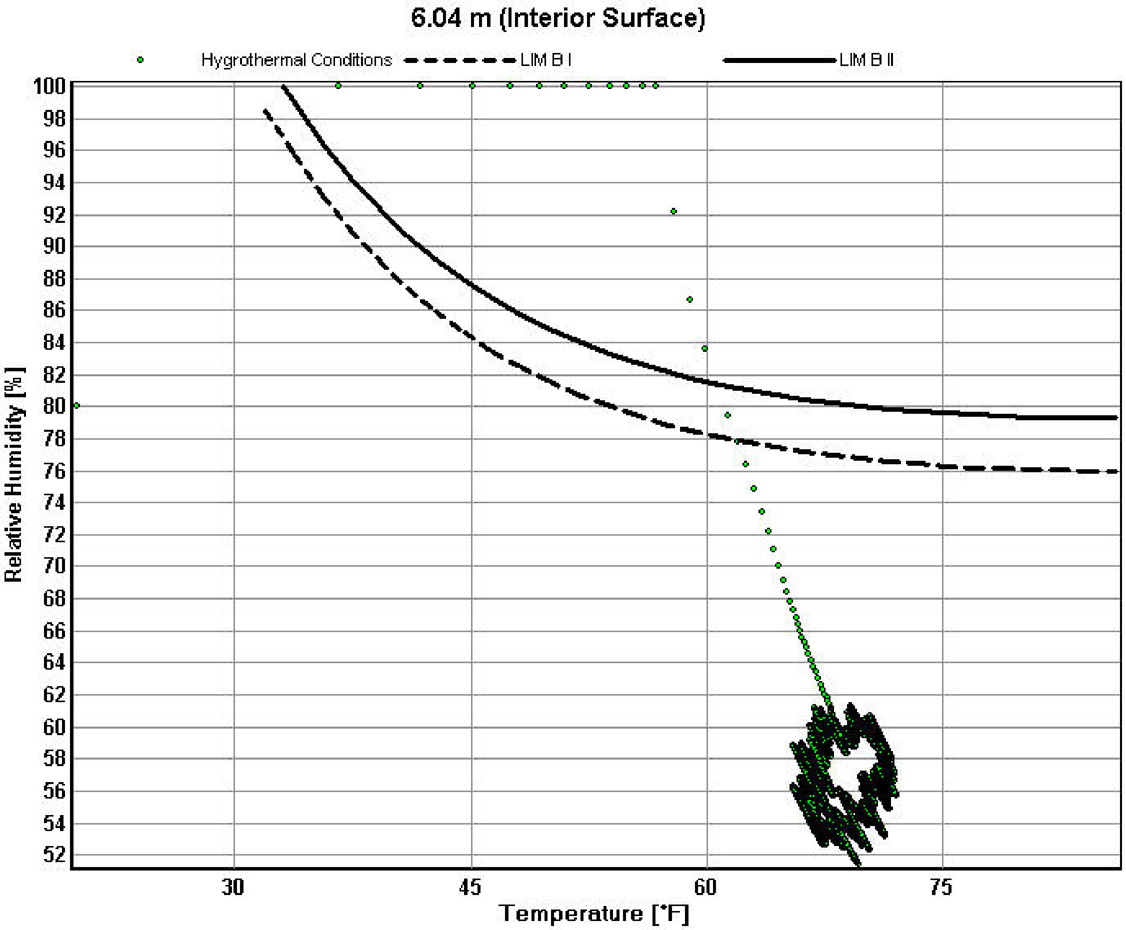


Figure 4.3: Hygrothermal Conditions on the Interior of the Floor Slab Note: Due to potential modeling inconsistencies, the floor simulations should be used on a comparative basis only. Mold growth conditions are denoted by green dots above the parabolic lines.

5. Mold Remediation Considerations

The history of the project described in section two mentioned that the facility has had documented problems with mold growth. This particular problem was described casually by the building personal, and the only mentioned remediation efforts consisted of removing the offending auditorium seats and replacing them with a matching set. The visible mold was removed, and the problem seemed to be solved. Unfortunately, the WUFI model described in the previous section predicts the accumulation of mold underneath the acoustical wall panels that are present over a large percentage of the space wall surfaces. Mold remediation should include a thorough examination into the surfaces of the building components, particularly in those spaces underneath the carpeting, wall coverings, and other possible places for mold growth.

After the mold infested components are removed from the space, all of the space surfaces may be cleaned with a biocide to remove the remaining spores. This is not recommended by the EPA except in extreme cases where individuals highly allergic to mold will be present. The best recommended practice is the drying out of the moist materials and preventing further high moisture levels. However, since this building is a public building service a wide range of individuals and it has existing moisture problems that have not been completely solved, a biocide wash down is highly recommended. After the mold remediation measures are complete, it is recommended to vacuum all surfaces with a HEPA filter bagged vacuum cleaner to thoroughly remove all possible traces of mold spores.

While these remediation measures would have been encouraged at the time of the contaminant removal, they must be considered before any action is taken to fix the current moisture problems within the space. Before commencing with a proposed solution, an OSHA certified technician should be hired to inspect the building areas to insure that no mold infestations currently exist. Proper remediation measures should be taken on the basis of the inspection. With these efforts, any new solutions put into practice will commence operations with a completely clean building.

The possibility of mold growth should be taken into consideration with the moisture removal proposed solutions. Figure 5.1 was taken from the Burnett and Straube book, Building Science for Building Enclosures. As shown in the figure, mold growth is caused by the relative humidity of the space, the time that the space is exposed to moisture, the temperature of the space, and the quality and type of surfaces that are within the space. Unfortunately, only two of the four variables are able to be modified significantly. Both the space temperature and the space finishes are arbitrarily decided by the owner, and both will have to remain unchanged through any proposed renovation efforts. However, the time and amount of the humidity load both have direct bearing upon the appearance of mold growth.

Both of these factors should be considered in any moisture removal system design, especially when considering the controls of the system. A high moisture load may not be left in the building while the building is unoccupied for an extended period of time. The humidity levels within the space must be consistently within the acceptable window to discourage mold growth, or another mold problem may easily occur. Therefore, the selected moisture removal system must be designed to work independently of the building occupant loads and effectively remove enough moisture at all times to prevent the growth of mold in the space.

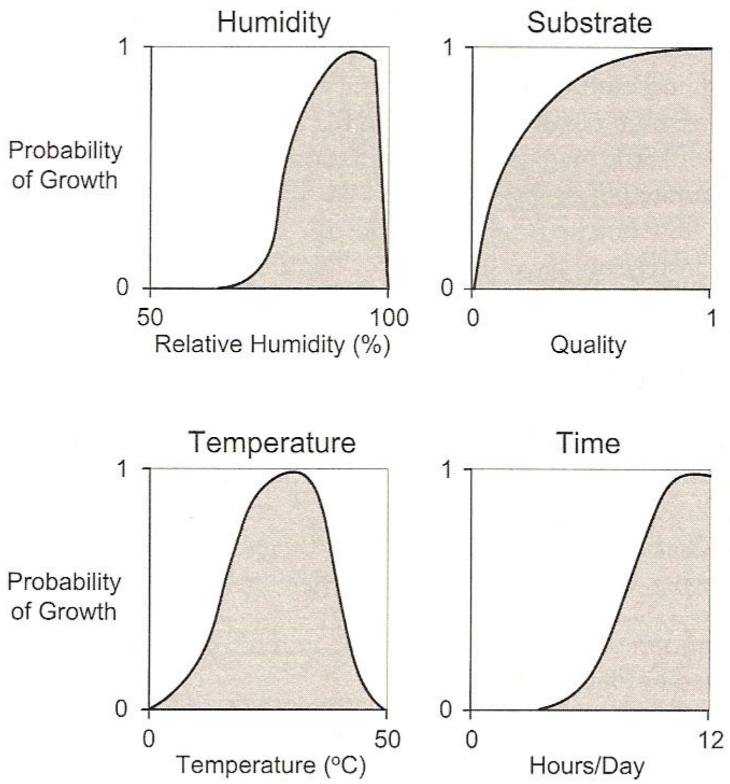


Figure 5.1: Factors Affecting Mold Growth

6. Moisture Removal and Dehumidification Systems

When considering the removal of moisture in a building, the number of available methods is limited. If the source of the moisture is not a specific leak, and the building simply has high latent loads to counteract, there are really only two basic types of systems that will provide the required performance: condensing the water out of the air by dropping the temperature through cooling coil operation, and physically removing the water from the air stream with the use of desiccants wheels and liquid desiccants. Cooling coils require much more energy to operate than desiccant wheels while providing an equivalent amount of water removal. Because the coil must cool the air down below the air dew point to remove the water, to remove equivalent amounts of water, the amount of cooling energy required increases dramatically. In addition, the cooler air stream is now unsuitable to be applied to the space and must be reheated, using more energy.

Desiccant wheels are more energy efficient than cooling coils because they are only acting as transport to remove the water from the interior air stream. The only associated energy costs are the required electricity to turn the wheel, and the energy cost of regeneration air. As regeneration air streams can often be heated through waste heat from other building process loads, desiccant dehumidification systems are good candidates for manufacturing facilities with specific humidity control requirements, or large operation buildings with onsite power generators. The requirement for exhaust heat energy to regenerate the desiccant wheel as it removes the water from the supply air limits the range of applications where desiccant wheels can be economically feasible. Liquid desiccants are so financially prohibitive that they have been removed from consideration in this study.

A survey of the three available humidity control options provides two possible candidates, one of which seems to have an integral flaw for a small educational application. Cooling coil dehumidification seems to be the best option, as desiccant wheel dehumidification is requires expensive equipment and a readily available exhaust heat stream to provide energy efficient operation. The cooling coil solution is the temporary solution that is in place in the building today. It seems to be an adequate solution, as the interior relative humidity during my site visit was maintained at several percentage points below the exterior relative humidity of 40%. However, it is wasting an incredible amount of energy to be running the cooling coils 100% of the time simply to lower the space humidity levels. While desiccant wheels may require regeneration heat, there may be a configuration that may save some of the wasted energy currently being poured into the cooling coils. Therefore, the application of some form of desiccant dehumidification has been researched to prove the economic feasibility of this form of dehumidification.

7. Series Desiccant Dehumidification

A relatively new dehumidification method available on the market is series desiccant dehumidification. The concept behind this unit is not to use the desiccant wheel to remove water from the supply air stream, but to use the desiccant wheel to enhance the performance of the cooling coil dehumidification performance. See Figure 7.1 for a schematic layout of a typical series desiccant dehumidification unit layout. The outside air and the return air mix to create an air stream at a relatively low humidity ratio. That low humidity air stream passes through the regeneration side of the desiccant wheel, increasing its humidity ratio and regenerating the desiccant wheel in the process. The humidified air then passes through the cooling coil, condensing a larger latent load while using nearly the same amount of energy to reach the same supply air conditions as a normal cooling coil unit. After leaving the cooling coil, the air passes through the removal side of the desiccant wheel, lowering the humidity ratio of the cool air far below saturated conditions. Therefore, the process allows the cooling coil to remove a considerably larger amount of moisture while providing supply air at a relative humidity that is below 100%.

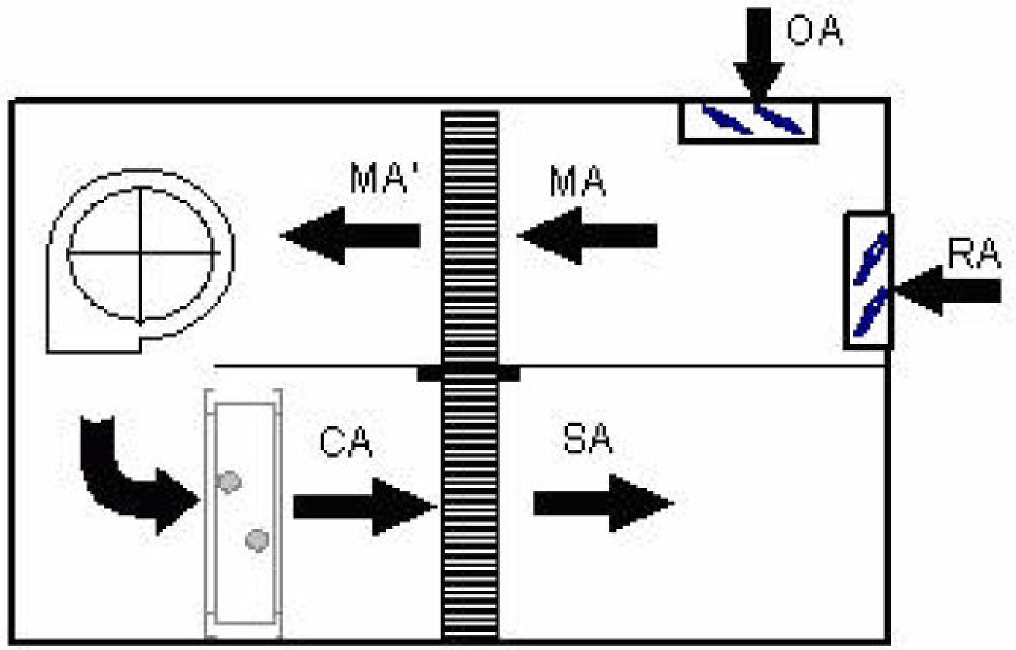


Figure 7.1: Basic Series Desiccant Wheel Layout This image was taken from the manufacturer's Technical Information Bulletin

The unit here is shown with only the base cooling coil and desiccant wheel arrangement, but there are units available with a preheat coil as well. The preheat coil would be used to increase the performance of the desiccant wheel, as the warmer air temperatures will make desiccant performance more efficient. As the temperature only needs to be raised to about 80 to 100 °F for optimum desiccant performance, the preheat coil does not need an exceptionally high quality heat source to get the desired performance. Often, installations can use a heat exchanger in the chiller to use some waste heat from the condenser water loop and get enough heat for the desired performance criteria.

This desiccant system can work with such low temperatures due to a special formulation of the applied desiccant. Additionally, the desiccant used is activated alumina, a Type III desiccant whose performance is shown graphically in Figure 7.2. As

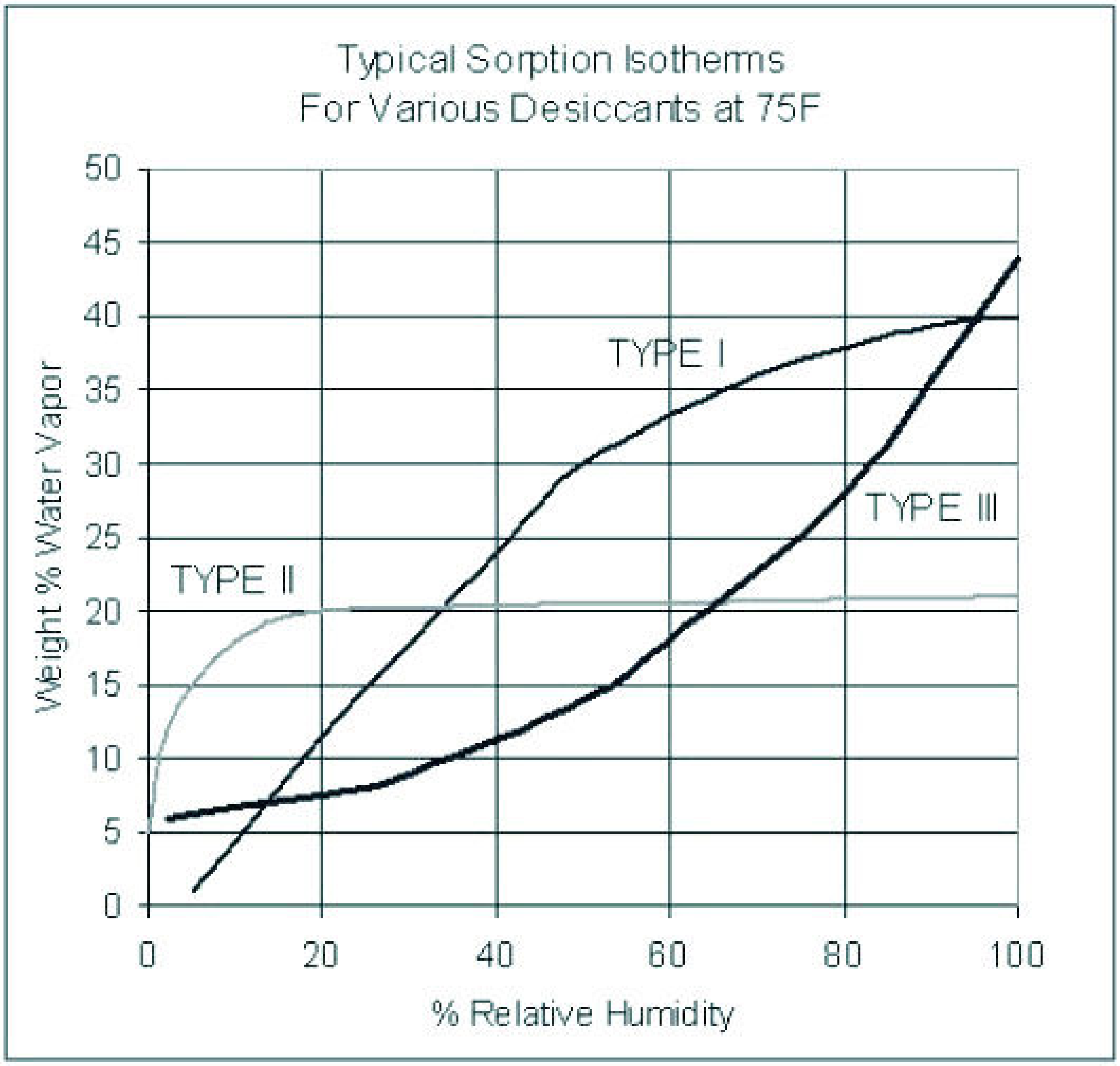


Figure 7.2: Performance Properties of the Selected Desiccant This information was taken from the manufacturer's Technical Information Bulletin

Looking at the Type III Isotherm, it becomes obvious how the series desiccant system can function with little to no regeneration heat. As opposed to typical desiccant wheel installations, that use a Type II Desiccant, the Type III desiccants rate of water absorption increases exponentially as a function of the air relative humidity. This means that on the cooling coil side of the cycle, where the relative humidity of the air leaving the coil approaches 100%, the desiccant wheel will absorb up to 40 – 50 % of its own weight in water. Once the cycle reaches the intake air side, the water is quickly rejected, as the desiccant hits the lower relative humidity air and can only hold about 15 – 20% of its own weight in water. Obviously, this cycle would not be as effective as an installation in buildings with an existing high relative humidity load, as the desiccant will not be as efficient in performance. However, after enough time of operation, the humidity levels within the space should be reduced and even out to provide efficient operation of the equipment.

One benefit due to the use of this system is the flexibility of its control. As the series desiccant system is independent of high heat exhaust side regeneration air, the system can be run at any time without any outdoor air intake. If the space relative humidity levels are rising without any call for ventilation – such as in the case of an unused space – the unit can cycle on and remove some of the humidity without using the extra energy normally required for conditioning intake outdoor air.

As a final incentive for building owners, the system is currently being manufactured as a part of a modularized air handling unit system. It's ease of installation, ability to be constructed in relatively tight spaces, and adaptability to the requirements of the given building are qualities that are usually only found in custom-built air handling units. While the cost of this system practically doubles the cost of the base modularized air handling unit, the efficiencies of operation and other benefits could render this a valuable piece of equipment in many different applications.

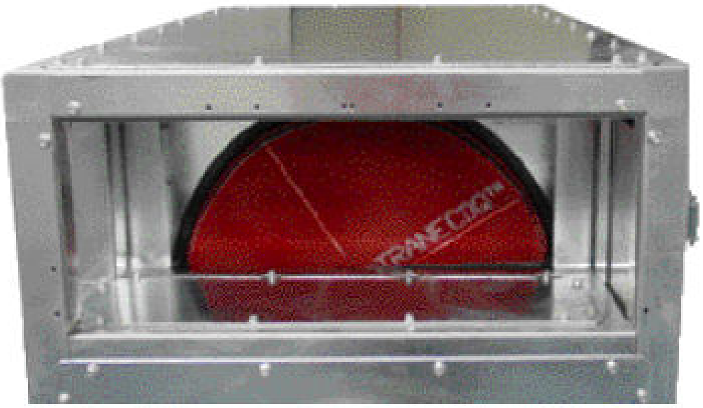


Figure 7.3: Image of the Desiccant Wheel Module Image was taken from the manufacturer's Technical Information Bulletin

8. Applicability of Series Desiccants

8.1: Application to the Project in General

Upon consideration of the benefits of this system, the application of series desiccant dehumidification to this project seems to solve many of its problems. The desiccant wheel will improve the energy efficiency of the cooling coils currently being used. With the series system, there is no need for the extensive piping and hookups that would be required for an active regenerative desiccant wheel system, and no need for the addition of a heat exhaust regeneration system. The system can easily be cycled during unoccupied times without excess energy use, which will work excellently with the current underutilization problems that persist in the operational cycle of this building. Meanwhile, the desiccant system can remove a greater quantity of water vapor during its time of use, therefore requiring less system operation time than the current air handling units to remove the same amount of moisture.

Moreover, the desiccant wheel is made to interact with the modularized air handling system of a certain manufacturer. The air handling units currently being used in the project happen to be the necessary modularized units made by that particular manufacturer, and will interface easily with the addition of a desiccant wheel. The renovation can be made more sustainable as some of the modules may be available for re-use, saving cost and material. Also, because the units are sized to match existing modularized systems, there should be minimal space constraints for the application of one of these systems, and the new systems should easily fit into the existing mechanical rooms.

Of course, the application of these wheels to the current project will have negative aspects as well. The modification of the equipment will cost hundreds of thousands of dollars. Changing the mechanical equipment will mean changing the structural loads on the existing floor system, which may require modification. The desiccant wheel addition would cause an increase in required fan energy due to the pressure drop over the desiccant wheel, and the controls and operating motor for the desiccant wheel module will cause additional drain on the electrical power system. These aspects must be evaluated along with the energy performance and other benefits of this system to enable the building owner to make an informed decision. However, from an initial analysis standpoint, this system seems to easily solve some of the worst problems existing within this facility.

8.2: Specific Application to Building Spaces

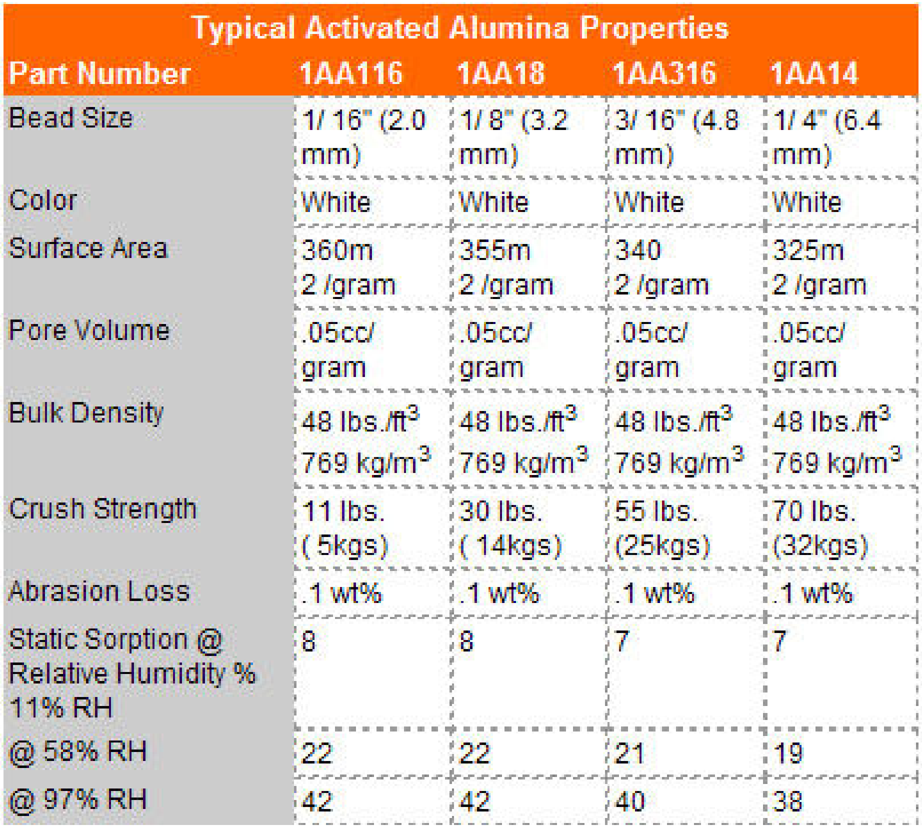
With this in mind, only certain air handlers were chosen to receive the desiccant wheel upgrade. The selected air handlers were chosen due to the spaces they served. The chosen spaces were: the auditorium, the auxiliary gym, the main arena, and the fitness center. The auditorium has no windows, and has been proven to have both mold and moisture problems. It is also the most underutilized space within the building, sometimes seeing weeks pass between times of use. Therefore, the auditorium has become the top priority space in this renovation. The main arena was selected because it also has a history of moisture problems, with the condensation freezing on the air ducts, and the arena floor needing to be refinished before the opening of the building. Selecting the auxiliary gymnasium was a matter of smaller priority, as it has had no recorded problems. However, it is also an infrequently used space, with no windows and only concrete block walls. It was deemed important to have a reliable means of moisture control within this space if only to reduce the amount of energy being used to currently dehumidify this large space. Finally, the fitness center was selected because it was the only space to have a 65% relative humidity during the site investigation. As the investigation took place during the middle of February, the space should have had a much lower humidity load. The space was under use at the time and therefore should have had the air handlers running to remove the carbon dioxide load in the space. The space humidity loads could undoubtedly become higher during the spring and summer months, when the outdoor humidity is at its peak.

While only four spaces were chosen to receive the upgrade, those spaces account for eight out of the ten building air handling units. The two air handling units that were not selected serve the offices and the dining space, and the racquetball courts. These spaces are high occupancy and used frequently, with no identified moisture problems, and are very open to light and air. The racquetball courts are surrounded by soundproof glass which will let in natural light from the nearby exterior entranceway. In addition, the dining and office spaces are mostly enclosed by a curtain wall system that is less susceptible to moisture infiltration. Moisture problems caused by a curtain wall system can be classified as leaks. There will be actual water entering the building. The CMU block walls are much more deceptive in their moisture permeation, because they absorb the water and evaporate it to the interior or the exterior depending upon the relative vapor pressures of the water on either side. Therefore, the final two air handling units have been excluded from the analysis in the interest of saving initial cost, while gaining energy savings and the ability to efficiently operate at periods of no use for the underutilized spaces.

While the EES model includes an analysis of the desiccant dehumidification system with preheat coils, the preheat coils have been modeled after the existing heating coils. It is a common practice to scavenge regeneration heat for the preheat coils for these systems from the condenser water loop. However, this method of heat recovery is unavailable and even undesirable in the current project. The building chiller is a packed air cooled unit. It would be difficult, if not impossible, to remodel the chiller to include a heat exchanger on its condenser water line. Also, the construction time and costs would be increased by the necessity of more piping and pumping equipment. Leaving the heating coil in the air handling unit will allow the same unit to handle summer and wintertime loads, and the heating coil will act only as a preheat backup when the desiccant unit can not handle the entire humidity load. In regards to the effects of the new system on the chiller: the desiccant units can slightly increase the cooling load needed in the coil. However, the use of the desiccant wheels should reduce the overall daily use required from the cooling coils, and therefore, any additional cooling requirements from the use of the desiccant wheels will be compensated for by the reduction in the system time of operation.

9. System Modeling: Product Performance

As this product is relatively new to the market, there are no catalogs or product information sheets available. This product, released in 2005, has only a few scattered information bulletins available right now. The sales engineers will not provide any performance information, will not let project engineers size their own units, and will only offer to size the units for your project. Therefore, to be able to produce a working energy model, a credible facsimile of the performance of the product and its various components has been necessary. To produce this estimate, a model of the system has been produced in the EES Equation Solver program. Inputs and product performance were introduced through the manufacturer's technical bulletins about the system, and the EES program's psychrometric functions helped to contribute to make a working model. The referenced technical bulletins are included in Appendix B, and the EES Programs and other working spreadsheets are included in Appendix C. Information found about activated alumina desiccants is included below in Table 9.1. Other required information includes the desiccant isotherm chart found in Figure 7.2, and the chart of the desiccant wheel pressure drops, included in Figure 9.1. Several safety factors were incorporated into the program, so that any performance estimates will be extremely conservative, as much of the modeling parameters were based upon technical reports and assumptions, as opposed to concrete experimental data.



Typical Activated Alumina Properties

Part Number	1AA116	1AA18	1AA316	1AA14
Bead Size	1/ 16" (2.0 mm)	1/ 8" (3.2 mm)	3/ 16" (4.8 mm)	1/ 4" (6.4 mm)
Color	White	White	White	White
Surface Area	360m 2 /gram	355m 2 /gram	340 2 /gram	325m 2 /gram
Pore Volume	.05cc/ gram	.05cc/ gram	.05cc/ gram	.05cc/ gram
Bulk Density	48 lbs./ft^3 769 kg/m^3	48 lbs./ft^3 769 kg/m^3	48 lbs./ft^3 769 kg/m^3	48 lbs./ft^3 769 kg/m^3
Crush Strength	11 lbs. (5kgs)	30 lbs. (14kgs)	55 lbs. (25kgs)	70 lbs. (32kgs)
Abrasion Loss	.1 wt%	.1 wt%	.1 wt%	.1 wt%
Static Sorption @ Relative Humidity % 11% RH	8	8	7	7
@ 58% RH	22	22	21	19
@ 97% RH	42	42	40	38

Table 9.1: Typical Activated Alumina Properties

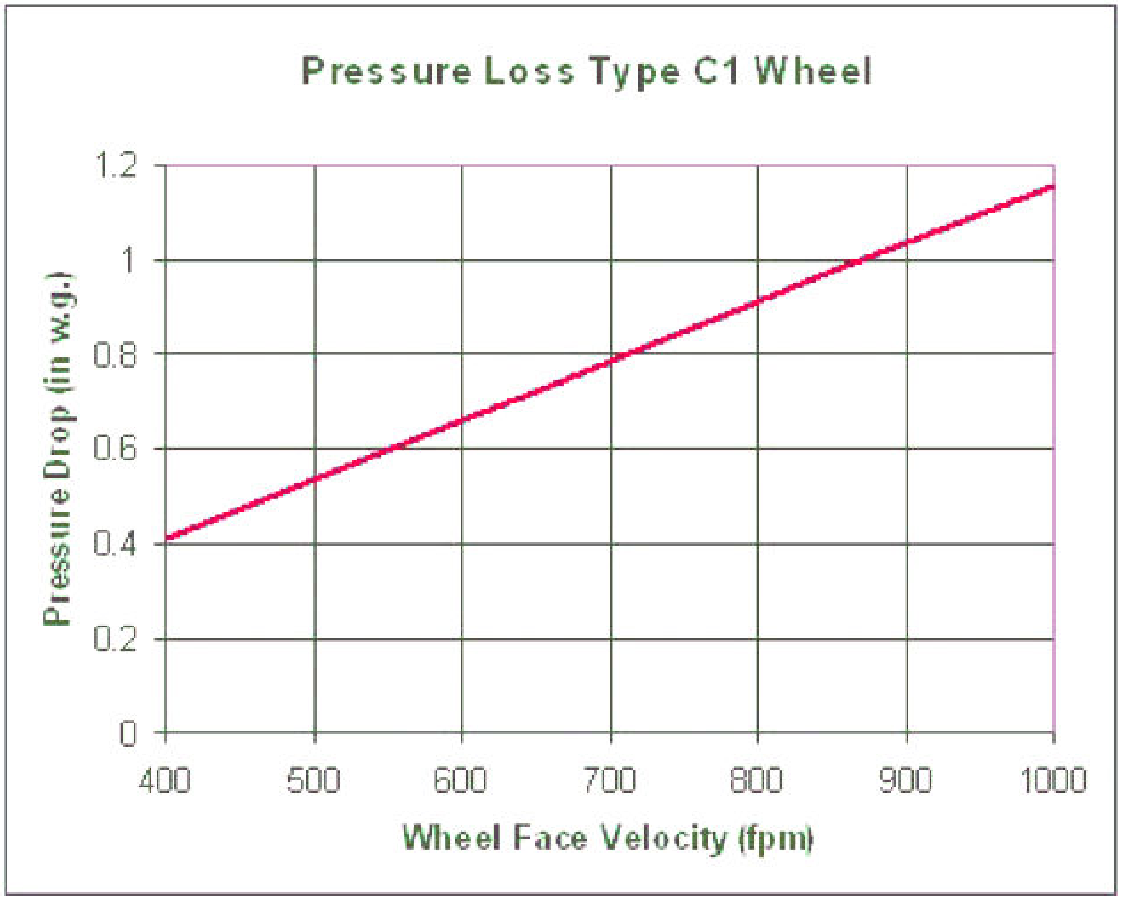


Figure 9.1: Desiccant Wheel Pressure Drop This image was included in the manufacturer's Technical Information Bulletin

The model was developed so that the user can input all of the operational components of the selected modularized system, and the program will output air state points before and after all of the components, the sensible, latent, and total energy use of the cooling coil, the grains of water removed per hour by the system, and the efficiency of the desiccant wheel. Some of the project inputs must be gained from the accompanying spreadsheet, as the application of the desiccant wheel will increase the fan BHP and the system pressure drop.

A variety of different configurations were modeled using six different models. These models included modeling the base air handler with its original preheat, the air handler performance using cooling coils only, and the air handler performance only recirculating air to remove the latent load. The second set of models included modeling the desiccant wheel system with the preheat coil, with cooling coils only, and running with only recirculated air as well. The results from these programs have been collated into one table, which is represented by table 9.3 below.

The inputs used in the modeling of these systems were limited to modeling of four different air handler types. Four spaces within the building had been selected as humidity control priority zones, as mentioned in the previous section. These four spaces were analyzed in the desiccant wheel performance model in preparation for modeling the total building energy savings.

Other model inputs included outdoor air conditions at the worst dehumidification design day, the worst cooling design day, and a selection of other dry bulb and wet bulb pairs to model the system performance during mixed heating and cooling seasons. The design humidity and cooling conditions are included in table 9.2 below.

Design Conditions From ASHRAE Fundamentals 2005 at Pittsburgh International Airport, in °F					
Cooling design conditions	**Percent**	**DB**	**MCWB**	**-**	**Occurs in:**
	0.4	89.8	72.5	-	July
Dehumidification design	**Percent**	**DP**	**HR gr/lbm**	**MCDB**	**Occurs in:**
	0.4	72.3	125.4	79.7	July

Table 9.2: Cooling and Dehumidification Design Conditions

The model outputs, included in table 9.3, prove that the desiccant system without preheat uses about 7% more energy than the original air handling units, while it removes about 30% more moisture than the original air handlers. It is interesting to note that the desiccant wheel using preheat as a regeneration source removes about 75% more moisture than the original air handler. If the moisture problem persists in the future, the system heating coil can be run as a preheat option at selected times to give a boost to the desiccant wheel performance during peak humidity loads. This option, of course, uses a great deal more natural gas energy, and so must be used sparingly, and only as needed.

These numbers do prove the system’s benefits, but the lack of energy savings in comparison with the relatively small dehumidification boost seem to be mediocre and almost not worth the expense of the system installation. At this point it is good to note again that the modeled performance is very conservative. Manufacturer reports and images of the outputs of the manufacturer sizing program indicate that the system operates at an equal or even greater efficiency of moisture removal for even less energy than the original system. The relative gains of using this system to combat the space humidity load seem to be worth the relatively small energy gain. The performance and energy use outputs from this model have been used further as inputs for the building energy model.

EES Program Results - Dehumidification Design Day Conditions							
Original AHU Performance	**Gr / Hour Removed**	**# AHU's**	**Total Gr/Hr Removed**	**CC Latent Heat (Btuh)**	**CC Sensible Heat (Btuh)**	**CC Total Heat (Btuh)**	**Sensible Heat Ratio**
Aux. Gym	1,831	1	1,831	126,329	137,454	263,783	0.52
Arena	1,859	4	7,436	160,340	174,807	335,147	0.52
Fitness	1,724	1	1,724	69,386	79,508	148,894	0.53
Theater	1,849	2	3,698	116,911	123,921	240,832	0.51
Original Desiccant Performance							
Aux. Gym	3,239	1	3,239	215,641	137,454	353,095	0.39
Arena	3,553	4	14,212	299,543	174,807	474,350	0.37
Fitness	2,738	1	2,738	105,435	79,508	184,943	0.43
Theater	3,360	2	6,720	206,212	123,921	330,133	0.38
AHU without Preheat							
Aux. Gym	1,833	1	1,833	126,440	137,312	263,752	0.52
Arena	1,861	4	7,444	160,484	174,622	335,106	0.52
Fitness	1,726	1	1,726	69,444	79,434	148,878	0.53
Theater	1,850	2	3,700	117,016	123,785	240,801	0.51
Desiccant without Preheat							
Aux. Gym	2,406	1	2,406	145,628	137,312	282,940	0.49
Arena	2,570	4	10,280	190,808	174,622	365,430	0.48
Fitness	2,121	1	2,121	76,945	79,434	156,379	0.51
Theater	2,470	2	4,940	136,163	123,785	259,948	0.48
AHU, no Preheat, Recirculation Only							
Aux. Gym	1,568	1	1,568	108,175	123,925	232,100	0.53
Arena	1,560	4	6,240	134,579	155,761	290,340	0.54
Fitness	1,539	1	1,539	61,950	73,825	135,775	0.54
Theater	1,590	2	3,180	100,546	111,739	212,285	0.53
Desiccant, no Preheat, Recirculation Only							
Aux. Gym	2,074	1	2,074	125,028	123,925	248,953	0.50
Arena	2,176	4	8,704	160,826	155,761	316,587	0.49
Fitness	1,901	1	1,901	68,765	73,825	142,590	0.52
Theater	2,137	2	4,274	117,400	111,739	229,139	0.49

Table 9.3: EES Model Output

10. Progressive Analysis of Energy Savings: Energy Model

Two different building energy models for this project have been developed with both the Energy Plus front end program, Design Builder, and with the Trane Trace program. The Energy Plus program had been undertaken as a learning experience and as a basis of comparison for the results of the Trane Trace program. There are relative merits to both programs. However, the Trane Trace program was selected as the final modeling tool both to retain consistency with the findings of previous background reports, and because of its easily read, detailed breakdowns of the annual building energy use.

10.1: Base Building Models

The initial building energy analysis included a simple model of the building in its original designed state, with the current building occupant underutilization input into the building schedules. This analysis was entitled the base case, and has served as a benchmark for comparison for the other parametric runs that were performed. Unfortunately, the base case building model is an inaccurate rendering of the current building energy use, as the building is currently using its air handlers – and more specifically, its cooling coils – at 100% load, 100% of the time. Therefore, the most important parametric run of the building model is the run entitled “Cooling Coils 100% On,” as this run models accurately the annual building energy performance in its current state.

Tables 10.1 and 10.2 show the results of the base case and cooling coils 100% on runs, respectively. Only a quick glance it required to see the impact of this temporary moisture remediation measure upon the annual building energy use. From a mathematical comparison standpoint, the current equipment schedules are using about 60% more energy annually than the base case of the original building design. Obviously, new solutions for the building moisture problem need to be determined to help deflate the current energy consumption.

Base Case				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,032,727.60	1,052,184.30	1,026,228.80	1,035,213.00
Gas Consumption (Therms)	3,829.10	3,789.10	3,491.20	3,789.60
Total Energy Consumption (kBtu / yr)	109,782.10	111,732.40	109,234.70	109,995.10

Table 10.1: Base Case Annual Building Energy Use

Current Conditions - Coils 100% On				
Alternative	Base Loads	Full Arena Load	Full Theater Load	Full Theater and Arena Load
Electric Consumption (kWh)	1,611,815.80	1,707,772.30	1,611,232.10	1,603,971.30
Gas Consumption (Therms)	9,653.70	10,015.10	9,686.80	9,813.50
Total Energy Consumption (kBtu / yr)	175,212.10	185,418.50	175,187.10	174,577.00

Table 10.2: Cooling Coils 100% On Annual Building energy Use

10.2: The Effects of Equipment Changes

After this initial analysis, the base cases have been established that form the groundwork for all of the following energy studies. The next study was based upon the inclusion of the series desiccant system into the cooling coils 100% on, or the current case. The study results are posted below in Table 10.3.

Desiccant Wheels - Coils 100% On				
Alternative	Base Loads	Full Arena Load	Full Theater Load	Full Theater and Arena Load
Electric Consumption (kWh)	1,645,949.50	1,742,176.40	1,654,321.00	1,639,353.40
Gas Consumption (Therms)	9,622.50	10,230.00	9,655.00	9,785.20
Total Energy Consumption (kBtu / yr)	178,674.50	189,167.70	178,644.40	178,170.40
Total kBtu/yr Saved	-3,462.40	-3,749.20	-3,457.30	-3,593.40
Percent Decrease from Current Case	-1.98	-2.02	-1.97	-2.06

Table 10.3: Inclusion of the Desiccant Wheels

As predicted by the EES model, the inclusion of the desiccant wheels caused a slight increase in the total annual energy consumption in comparison to the current case with the cooling coils always running. In an effort to increase the system energy savings from negative numbers to positive, the next step was to upgrade the existing dry bulb based economizer system to an enthalpy based economizer system. The application of the enthalpy based economizer will cause energy savings when used in conjunction with most systems. However, the enthalpy based economizer serves a dual purpose with this system. Not only will the new enthalpy based controls save energy, but they will also prevent undesirable humid outdoor air intake whenever possible. Thus the enthalpy based economizer will save energy through direct application and through the prevention of additional humidity load intake. This study has been compiled in Table 10.4.

Desiccant Wheels, Enthalpy based Economizer - Coils 100%On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,529,858.50	1,611,802.50	1,533,323.10	1,527,469.00
Gas Consumption (Therms)	9,029.10	9,324.60	9,018.20	9,142.90
Total Energy Consumption (kBtu / yr)	166,162.20	174,864.30	166,505.50	166,037.30
Total kBtu/yr Saved	9,049.90	10,554.20	8,681.60	8,539.70
Percent Decrease from Current Case	5.17	5.69	4.96	4.89
Percent Decrease From Desiccant Wheel	7.00	7.56	6.80	6.81

Table 10.4: Inclusion of an Enthalpy Based Economizer

While a 5% reduction in total energy use is in general known as a good thing, this alone will not make the purchase of half a million dollars worth of equipment economically feasible. A second look at the energy model inputs for the desiccant wheel showed that the input effectiveness was far below the normal desiccant wheel effectiveness. Comparing this information with the desiccant wheel analysis outputs from the EES program, it was determined that the effectiveness of the wheel was determined from the 0.4% Design Dehumidification Load day. As this day only occurs for 0.4% of the year, the other available effectiveness numbers were examined. The average effectiveness of the desiccant wheel from the other temperature cases increased to between 20 and 40%, depending upon the particular unit in question. As most of the other parametric resulted in a much greater and uniform desiccant wheel effectiveness across the rest of the design temperatures, the next run of the energy model involved modeling the desiccant system at its average day effectiveness. This was actually a more accurate assumption in the modeling of the building performance, as the conditions within the building would be operating at less than peak design conditions for all but a few hours in every year. This new assumption was duly modeled, and the results were placed in Table 10.5.

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - Coils 100%On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,511,134.80	1,587,244.30	1,510,555.40	1,503,354.40
Gas Consumption (Therms)	8,968.50	9,202.40	8,999.90	9,131.70
Total Energy Consumption (kBtu / yr)	164,181.10	172,220.90	164,154.80	163,556.10
Total kBtu/yr Saved	11,031.00	13,197.60	11,032.30	11,020.90
Percent Decrease from Current Case	6.30	7.12	6.30	6.31
Percent Decrease From Desiccant Wheels	8.11	8.96	8.11	8.20
Percent Decrease From Enthalpy Economizer Alone	1.19	1.51	1.41	1.49

Table 10.5: Increased Desiccant Efficiency

Unfortunately, or perhaps fortunately, the increase in desiccant wheel efficiency caused no remarkable decrease in energy utilization. While the modification of this assumption provided sadly small results, it is comforting to know that the building annual energy use is not overly sensitive to the desiccant wheel efficiency.

10.3: The Effects of Scheduling Changes

All of the above models have made small incremental decreases in the annual energy use of the building. While these component refinements and additions are all impressive and necessary, none of the above models have been modified to account for the increase in the dehumidification efficiency of the system. With the modeled dehumidification system removing 30% more of the latent load in the system on the 0.4% worst dehumidification day, the need for the system to be running should decrease by at least 30%. Therefore different scheduling options have been tried to account for the improved efficiency of the moisture removal system. The originally proposed scheduling option called for the air handlers to follow only the building loads during the day, and then run at 100% load overnight to remove the accumulation of 14 hours of humidity. The weekend schedule followed the same pattern for Saturday operation, while Sunday operation was reduced to 50% for the entire day, as the occupant load becomes zero for that day, and the only humidity load to counteract is the load caused by the building permeation. The air handlers should be sufficient to counteract the building humidity load while following the occupant load during daylight hours, as the dehumidification process has become about 30% more efficient, and the building is extremely underused – meaning that the majority of the space loads should be coming from building permeation as opposed to the occupants. The results of the initial schedule change are in Table 10.6.

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - 100% On at Night, 50% On - Sundays				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,154,734.80	1,147,650.90	1,190,394.60	1,154,755.50
Gas Consumption (Therms)	5,412.60	5,577.90	5,262.40	5,448.60
Total Energy Consumption (kBtu / yr)	123,942.60	123,391.10	127,436.00	123,982.60
kBtu / yr Saved	21,242.00	25,437.90	19,924.00	21,342.00
Percent Decrease from Current Case	38.90	50.27	37.47	40.81

Table 10.6: Nightly Purge Scheduling

Again, an average 40% energy reduction is an excellent goal for any building renovation. However, the success of this scheduling change raises questions about the results of further inquiry into schedule manipulation. To this end, a second possible schedule has been devised that takes into consideration the increase in the dehumidification efficiency due to the desiccant wheels as well as a smoother load profile. The proposed schedule again follows the occupancy loads during the day, but with a 60% increase to accurately remove the humidity load as it occurs. The night purge has been reduced to 50%, and the Sunday loads have been left at 50% all day. The results of this scheduling trial are included in Table 10.7.

Better Efficiency Desiccant Wheels, Enthalpy based Economizer - 60% On at Night, Follow Loads with Around 30% Increase				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,308,571.40	1,301,008.30	1,359,849.30	1,308,446.90
Gas Consumption (Therms)	7,384.30	7,548.90	7,400.70	7,419.30
Total Energy Consumption (kBtu / yr)	141,771.00	141,169.80	147,039.10	141,795.10
Percent Decrease from Current Case	21.47	31.34	19.14	23.12

Table 10.7: Higher Percentage Load Following Schedule

Comparing the results presented in Table 10.7 with the results presented in Table 10.6 proved that there are diminishing returns to smoothing the equipment based utilization loads. The initial nightly purge schedule has several benefits, including the off-setting of peak equipment loads to off peak demand times, have a greater utilization of the enthalpy based economizer with the cooler night air, and a lesser demand for outdoor air, as a directly load following schedule during building occupancy will call for only the minimum required outdoor air.

After reviewing the results presented above, as well as the results from countless other parametric studies included in Appendix D, the Nightly Purge scheduling option with an enthalpy based economizer and better efficiency desiccant wheels. A final alteration to the model was necessary, as the original desiccant wheel model did not include the power requirements for the wheel motor. While the power requirements are extremely small – 1/80 HP, 0.3 FLA for each motor – this additional energy use should be modeled to show the impact upon the system as well as to get a more accurate snapshot of the building energy use. The results of this final parametric run are included below in Table 10.8.

Better Efficiency Desiccant Wheels, Enthalpy based Economizer - 100% On at Night, 50% On - Sundays - Add Power for DW Motor				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,154,831.40	1,190,490.90	1,154,851.80	1,147,746.80
Gas Consumption (Therms)	5,412.60	5,262.40	5,448.60	5,577.90
Total Energy Consumption (kBtu / yr)	123,952.50	123,992.40	127,445.90	123,401.00
Percent Decrease from Current Case	38.92	45.49	41.29	41.47
Additional Energy from Tb. 10.6 (kBtu / yr)	9.90	601.30	9.90	581.6

Table 10.8: Nightly Purge Schedule with DW Motor Power

This final display proves that the desiccant wheel motor horsepower is insignificant in comparison with the other annual loads on the building. The significant jump in the annual power caused by the arena load can be easily explained, as this is the highest occupancy space, and it contains four out of the eight remodeled air handling units. Through the careful repetition and study of various parametric studies, the best configuration of equipment and scheduling has been determined. These selections can now be applied to the building, and other studies, such as life cycle cost and initial construction cost may commence.

10.4: Final Equipment, Scheduling, and Control Selections

As stated above, the final equipment selection consists of the modularized series desiccant wheel with an enthalpy based economizer cycle. The finalized schedule has been selected as the nightly purge schedule. While the system and the schedule have both been chosen, their control elements remain to be specified. Currently, the large variable occupancy spaces are controlled by carbon dioxide sensors installed within the space. These sensors provide demand controlled ventilation, which is an excellent method for controlling these types of spaces to provide adequate performance without wasting energy. While this control option is excellent for limiting the ventilation based energy use in these spaces, this will not help to control the cycling of the dehumidification system. The final recommendation for the new equipment control options is to combine the demand controlled ventilation and its associated carbon dioxide sensors with humidity sensors. In effect, the system will supply demand controlled ventilation and demand controlled dehumidification. The humidity sensors will be set to a certain humidity ratio. When that ratio is exceeded, a relay will communicate with the system to turn it on if it is not already on, or to increase its flow rate if it is on. The carbon dioxide sensors will of course have the primary control of the system. If the set maximum carbon dioxide levels are exceeded, the system will automatically cycle to ventilation mode whether or not the space humidity requirements are being met. As soon as the carbon dioxide levels drop down to acceptable levels again, the outside air dampers will be closed, and the system will revert to control by the humidity sensor. The humidity sensor will have the power to cycle the air handling units on in a pure recirculation capacity. This system will allow the dehumidification system to perform its function with a minimum amount energy wasted on conditioning outdoor air, and grant it a flexibility of self control that is not tied to any occupancy or temperature constraints. The selected control sensor should be able to tie into the existing building controls system as well.

Through the above mentioned equipment, scheduling, and controls selections, a remarkably more energy efficient building can emerge from behind the building at its current state.

11. Renovation and the Physical Constraints

After the selection of the system and its attendant schedules and controls, layout and placement of the systems had been determined. As the selected systems are modularized with specific dimensions and performance characteristics for each component in a certain box, the layout of the new air handling units became a jigsaw puzzle with certain requirements to the layout. Clusters of the required modules were input into AutoCAD and arranged to fit the required schematic layout. The requirements for the new air handler layout had to work with the following parameters: the desiccant wheel must be aligned through the upper and lower deck as a single module; the cooling coil must be downstream from the regenerative half of the desiccant wheel; the fan must be upstream from the cooling coil to prevent heat gains to the supply air; any installed heating coils should be placed before the regenerative side of the desiccant wheel; and finally, the water absorption side of the desiccant wheel should be the final piece of equipment on the supply air side of the system. These requirements basically dictated the arrangement of the air handler modules, so that there were no variations from this base design template.

After the layout of the air handler modules is accomplished, they must be evaluated by their ability to fit into the space. Fortunately, as the new air handler layout requires stacking the modules into upper and lower decks, the footprint of the air handlers remained the same or even decreased somewhat. The planned supply air CFM will not change, as the thermal and occupancy loads will remain as designed. Therefore, the existing ductwork and piping systems can remain as installed, with only the hookups undergoing demolition and rebuilding during the renovation. The air handlers can remain upon their existing concrete pads, and there are no calculated coordination problems with the slight enlargement of the air handlers in the vertical dimension.

The only foreseeable physical constraint occurs in the location of the main arena air handling units. As the mechanical rooms for this space have exceedingly limited floor space, the existing air handlers have been installed in a three tier module configuration that is hard to duplicate, dimension wise, with the series desiccant system. The mixing box has been located hear a side wall, making the possibility of a standard duct connection that fits within the modular system of the manufacturer nearly impossible. To complete this connection, either a non-modular mixing box with a side air intake must be fabricated, or an impossibly distorted outdoor air plenum will have to be constructed. The final solution for this problem would need to be detailed with the local manufacturer sales representative. All layouts of the four different system types are included in Appendix E. A typical section for a main arena mechanical room is included below in Figure 11.1.

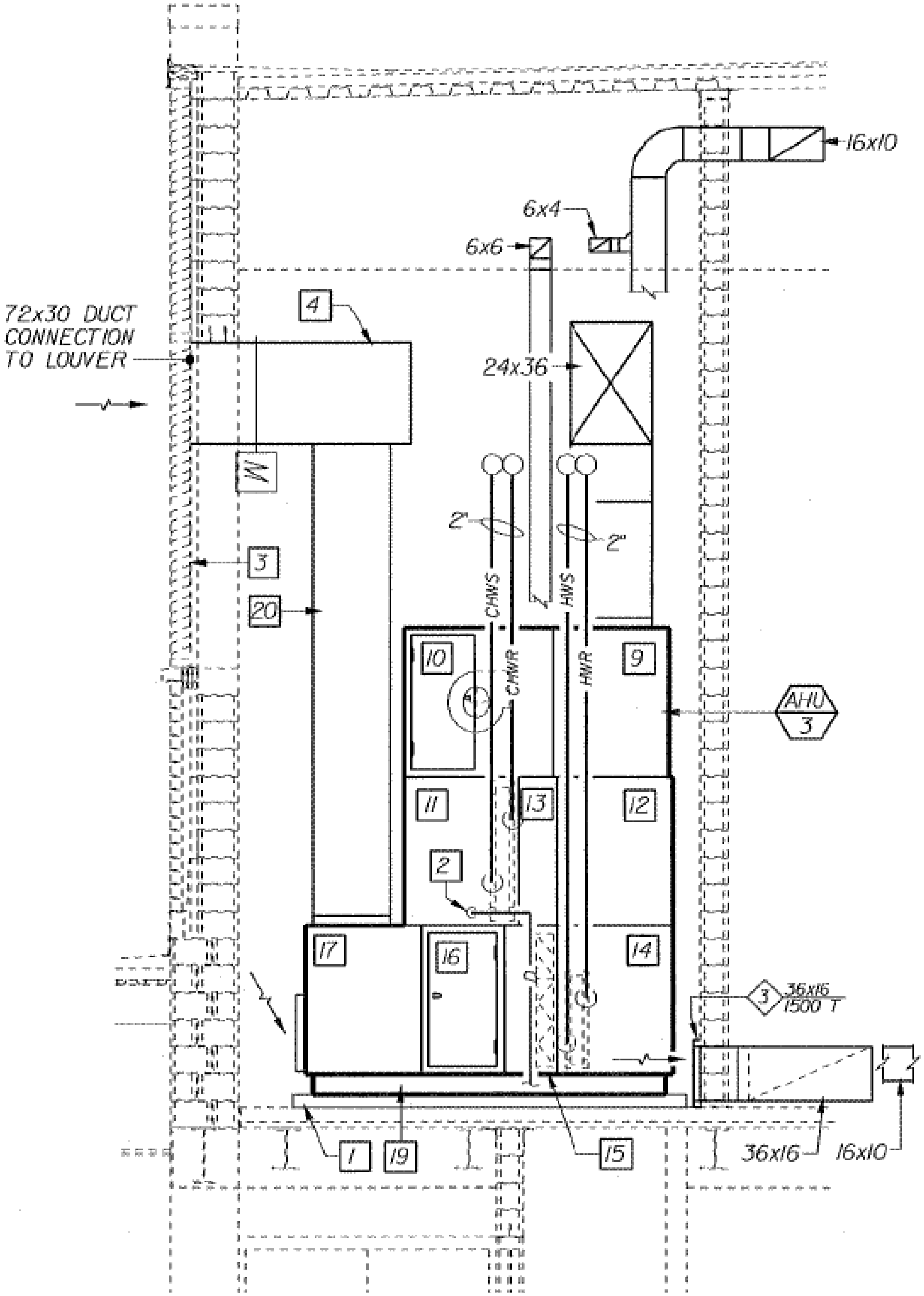


Figure 11.1: Typical Air Handler Layout for the Main Arena

12. Renovation and the Electrical System

Any renovation of a single building system has the potential to affect all of the other building systems. While this proposed renovation only adds about 0.5 BHP to the fan power use of each system, and 1/80 HP to the electrical system due to the desiccant wheel motors, the electrical systems must still be checked. The additional fan power for each system has been included in the original EES model background calculations in Appendix C. After the additional loads for each air handler had been determined, they were added to the air handler connected load on its corresponding panel board. Then the load for each panel board was re-summed and that load was compared to the specified breaker size for that panel board.

The panel boards were discovered to have been oversized, and therefore they could accommodate the extra load with no problem. As the mechanical panel board containing most of the air handlers was directly tied back to one of the main panel boards that contained the rest of the air handlers, only two of the building panel boards were affected by this change before the power supply path went back to the main distribution panel. A copy of the panel board sizing and calculations have been included in Appendix F.

After it was determined that the panel boards could handle the additional load, the individual circuits and the feeders to the panel boards were checked for the capacity to handle the loads. Using the NEC wire sizing table for the specified wires, the feeders and branch circuits were found to be sufficient for the new connected loads.

While studying the electrical drawings for the panel board and feeder sizing, it became apparent that the grounding system could have a potential ground loop. The power quality provided through the electrical system is very important to functioning of all of the powered systems within the building. Ground loops will disrupt this power quality and cause steady damage to the connected equipment. Therefore any problems with the building grounding system should be investigated immediately.

It was discovered that the building grounding system was designed with two jumper cables leading from the main bus to two points of ground contact: a traditional tripod pin grounding connection, and a grounding connection to the building supply water line (see Figure 12.1). While grounding connections to the water supply main are allowed as long as the water supply line has sufficient ground contact and is made out of metal, more than one ground connection are usually discouraged. More than one ground connection can cause dangerous ground fault loops, drain building power, and create over voltages and harmonics along the power supply lines within the buildings. Therefore, the 2005 version of the National Electric Code has been consulted to check if the designed system is code compliant.

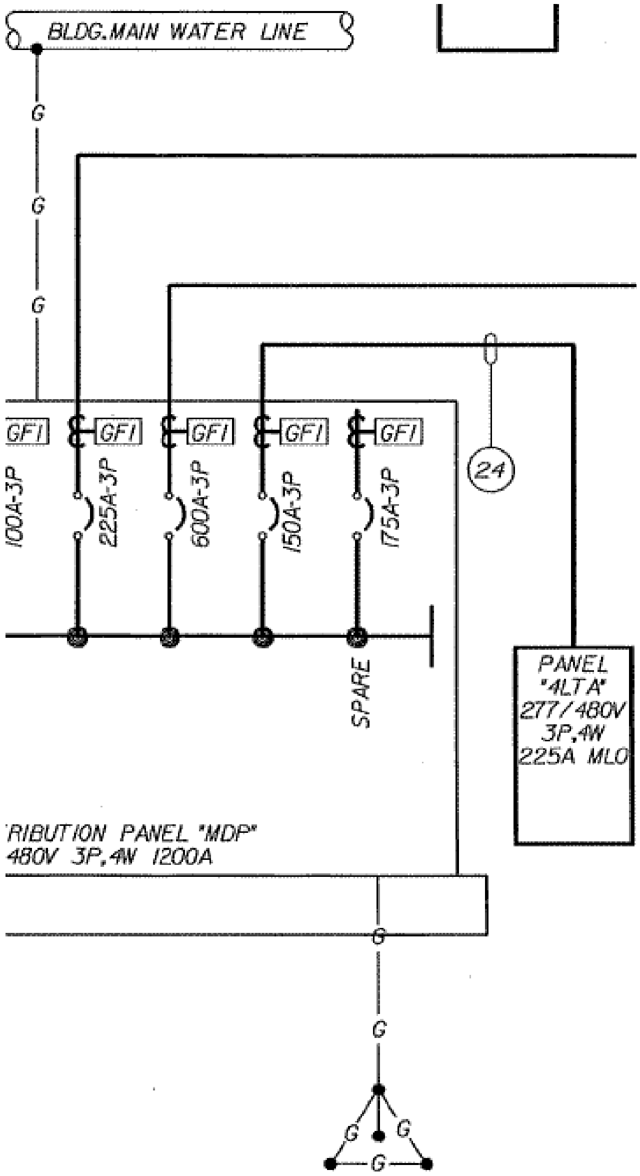


Figure 12.1: Ground Point Connections

A thorough study of the National Electric Code section on grounding revealed that a supplemental ground source must be provided when using the building supply water main as the main point of grounding connection. Referenced sections included Section 150.104: Bonding of Piping Systems and Exposed Structural Steel, Section 250.52: Grounding Electrodes, and Section 250.53: Grounding System Electrode Installation. The above calculations and checks proved that the system is adequately designed for optimum ground performance, and has enough capacity to serve the proposed mechanical system renovations.

13. Renovation and the Structural System

The mechanical redesign unfortunately increased the bearing loads across the equipment pads by about 20 pounds per square foot. The system was designed following the Allowable Stress Design method. While this method does not incorporate safety factors as the Load Resistance Factor Design method does, the building mechanical spaces were designed to a load of D + L, with 150 PSF allowance for the live load. Therefore, it is a given that the structural system will be able to handle the addition of a 20 PSF distributed load over an area already designed to hold heavy equipment. However, the structural system may not be able to support the new weight requirements and continue to uphold its required live load of 150 PSF. Therefore, detailed calculations have been completed to determine the bearing capability of the mechanical room floor systems.

Calculation of the estimated mechanical loads have been included in Appendix G. Cut sheets of the floor system from the specified manufacturer have been included and compared to the calculated equipment loads. It was found that the selected floor deck system can support the additional mechanical loads as well as the required mechanical room live loads with some capacity to spare. In addition to the floor slabs, the floor beams were also studied for the possibility of failure with the application of the mechanical loads.

An LRFD analysis of the floor beams that would be directly impacted by the application of the mechanical renovation also revealed that most of the beams could support the weight requirements. The floor beams directly under the equipment in the main arena mechanical rooms exceeded lateral-torsional buckling limits. It is proposed to reinforce the flange stability at the time of renovation with stiffener plates at several points along the beam in question to guard against eventual failure due to this limit state.

A further check of the girder supporting the beam loads across a clear span below the fitness center mechanical room found that the selected girder will also be subjected to lateral-torsional buckling. However, a stiffener plate placed at the midpoint of the beam will create adequate support conditions.

As a final structural check, the masonry bearing walls were checked for the support capacity to carry the beam loads. Figure 13.1 from the 2001 Masonry Designers' Guide was used to determine compliance. Using this figure, as well as the known bearing loads from the beams, it was determined that the masonry walls could support the loads in question.

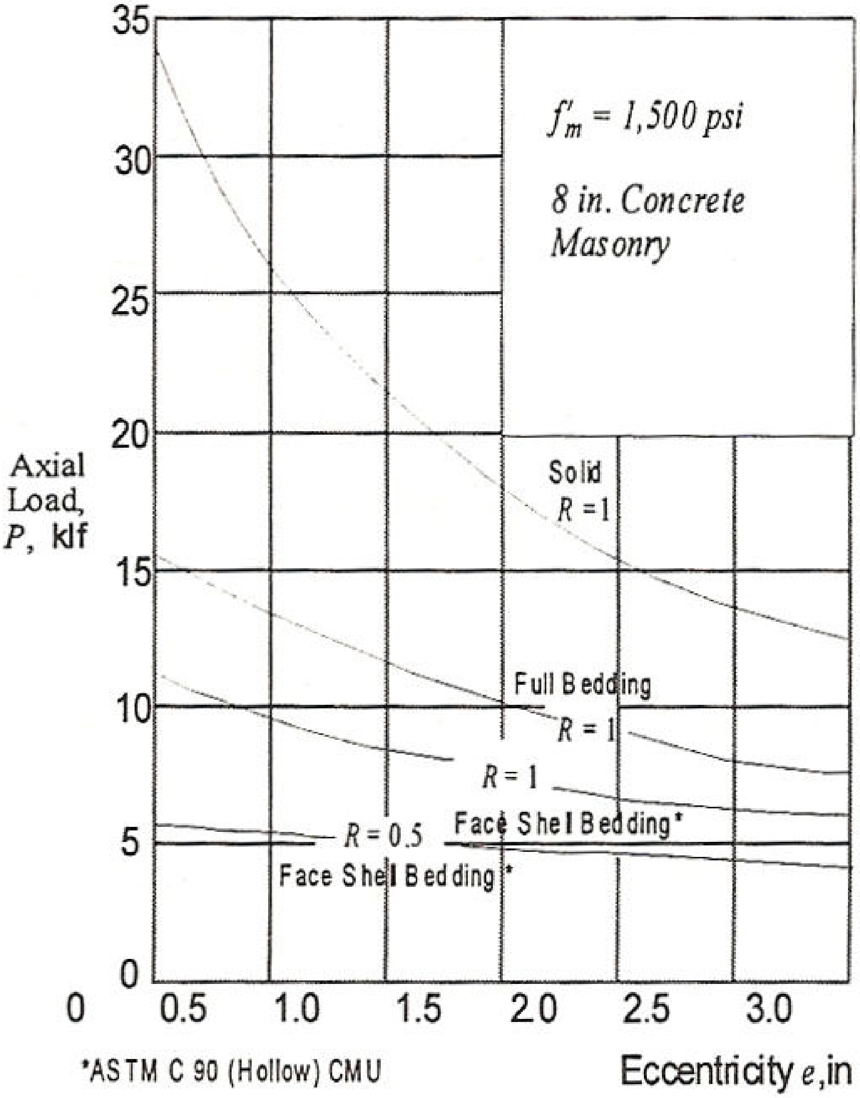


Figure 13.1: Masonry Design Loads

14. Renovation and the Auditorium Acoustics

Just as the renovation of the building mechanical system can affect all of the other building systems, the mechanical renovation can also indirectly affect the performance of the interior building materials. Moisture permeated building materials will perform differently at different frequencies as opposed to a building material with its normal degree of water impingement. Even the relative humidity of the space air will cause a change in acoustical performance characteristics within the space. In view of these concerns applied to the high moisture loads within the auditorium space, an acoustical analysis has been performed for the auditorium space at several different relative humidity levels.

The analysis incorporated performance characteristics of air at various humidity levels, as well as experimental data provided from a study by Ozdeniz and Yilmazer (see Works Cited) on the acoustical performance of perlite plates at various humidity and moisture conditions. A sample of the collected data is provided below in Figure 14.1.

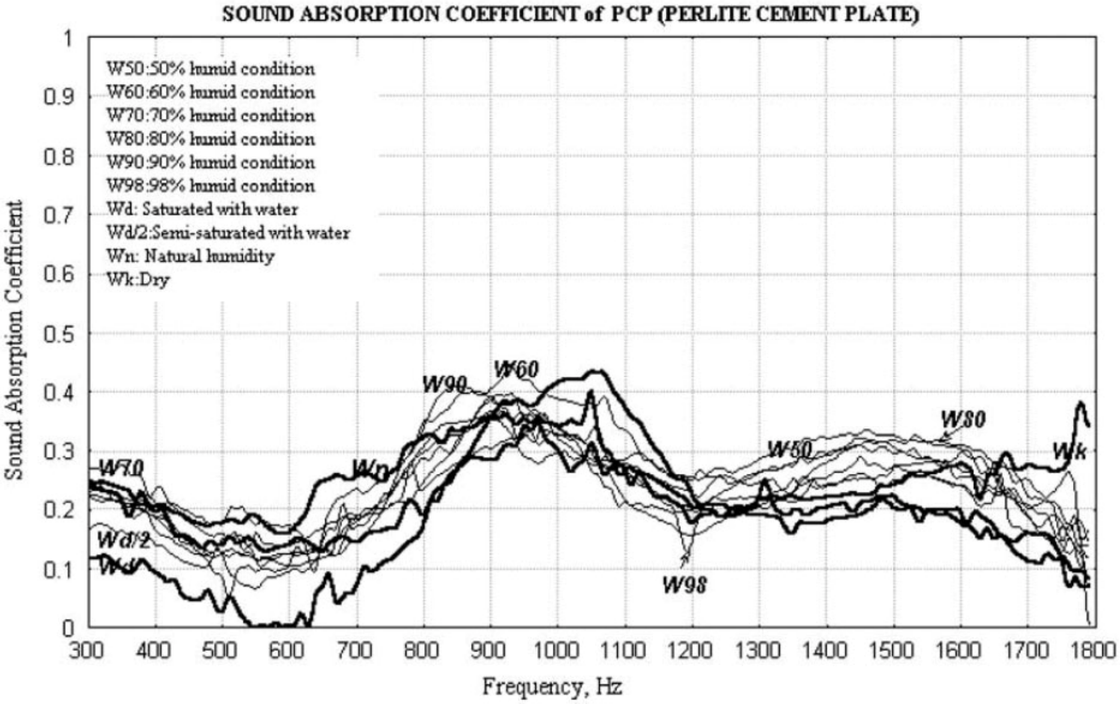


Figure 14.1: Acoustical Performance at Various Relative Humidity Points

While perlite plates are not used in this auditorium space, the absorption coefficients of this material closely parallel the absorption coefficients of the space gypsum board bulkhead and acoustical wall panels. Therefore, the absorption coefficients of this material at various relative humidity levels have been used for these two surface types within the acoustical calculations. This information was input into a model for the reverberation times of the space. The model output included the effects of different occupancy loads and relative humidity levels upon the space reverberation time. For a section view of the auditorium, see Figure 14.1.

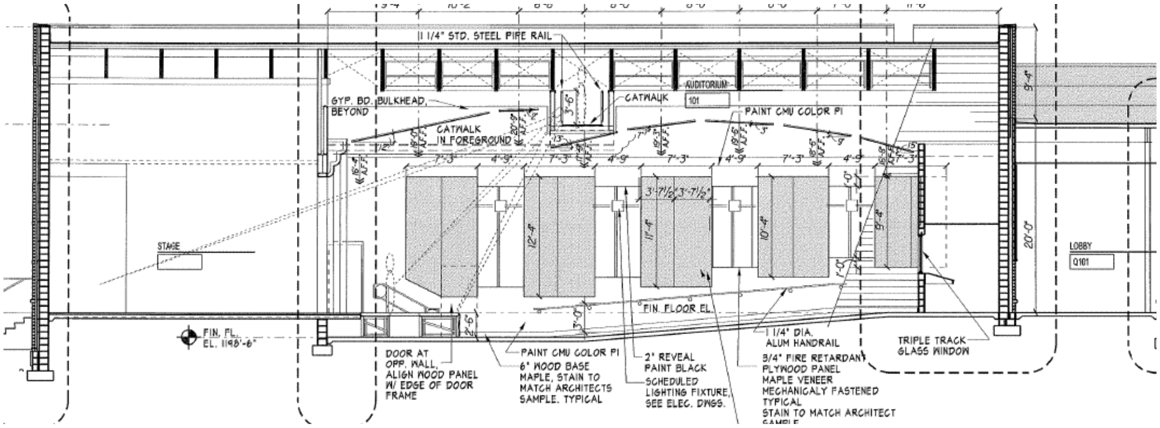


Figure 14.2: Longitudinal Section of the Auditorium

According to the reverberation time calculations, the space is currently performing at a slightly lower reverberation time than is recommended for a multipurpose auditorium of this type. However, this auditorium was intended to be used primarily for the school drama club's presentation of plays, and not intended primarily as a musical use space. Therefore, a shorter reverberation time would be preferred for this type of application.

The relative humidity ratios had a different effect upon the reverberation time depending upon the frequency of the sound being produced. The low frequencies tended to decrease in reverberation time as the relative humidity increased. The same effect was observed in the middle range frequencies. The upper frequencies would achieve higher reverberation times at higher and lower relative humidity levels, while the reverberation time would decrease in the middle to high relative humidity range. These fluctuations in the reverberation times of the higher frequencies were extremely sensitive to the fluctuations in the space air relative humidity. As the space air is the largest material quantity within the space, it is unsurprising that the humidity level within the air would have a large effect upon the space reverberation times. Additionally, the air is the medium within which the sound is moving. While the relative humidity of the air increases, there are more molecules of water within the air to disrupt the path of the sound and therefore decrease the reverberation time of that particular sound.

There are quite a few drawbacks to the reverberation time's dependence upon the relative humidity of the space. Not only will the decreased reverberation times contribute to a thinning of the quality of the sound, but any musicians within the space will be grossly affected by the changing reverberation times of the wall system. From the musician's perspective, changing reverberation time levels will affect the style and amount of intensity that need to be put into the music. The decreasing lower frequency reverberation times and increasing higher frequency reverberation levels will create a very unbalanced sound for a group of musicians. Lower toned instruments will want a higher reverberation time to give a richer quality to their notes and make the notes seem to linger within the space. The lower instruments produce low energy, low frequency sounds that tend to easily die out and travel slower than the notes of the rest of the musicians in the group. Higher pitched instruments will desire a lower reverberation time. As the pitches and sound qualities of higher pitched instruments tend to produce a more strident, cutting tone, the higher frequency reverberation times should be shorter, as less time is needed to gain the attention of the audience. Also, the brighter pitches of the higher frequency instruments are generally complimented by a shorter reverberation time and do not require any extra reverberation time to help them reach the ears of their listeners.

A performance space that will shorten the reverberation times of the lower notes and increase the reverberation time of the higher notes will produce a very uneven sound quality for the musicians, and as the reverberation time will change as the space relative humidity increases, there is a good chance that the acoustical characteristics of the space will be changing during a performance setting with a high latent load from the audience. As this will steadily decrease the quality of sound from the musical group, the audience may not remember their experience favorably, and in the end, the community usage of the venue may decrease to some degree.

Figure 14.3: Media Image of the Auditorium Space

The reverberation time is also directly dependent upon the space occupant load. Audience members act as a large blanket of absorbent material. The reverberation time will decrease dramatically with the application of the audience to the space. This is another condition for which any musicians or actors must learn to compensate during their rehearsals, or they may sound off balance and incomplete when they try to play or project their voice within a space that has unfamiliar and changing reverberation times.

In conclusion, while the relative humidity does affect the space reverberation time, the space reverberation times are much more sensitive to the changing occupant loads. There are no good options for controlling this change in room reverberation time. Any adjustments made to the space to compensate for the changes in relative humidity and occupant load will be rendered pointless. Variable occupant loads are a necessary part of normal auditorium operation. The application of the desiccant dehumidification units will hold the relative humidity load in a stable position and negate any ill affects that could be generated by variants in the space relative humidity load over time. Therefore, though there are some observed affects upon the space reverberation time from moisture and occupancy loads, these are either necessary loads, or they are being countered already, so further alterations to the interior finishes are unnecessary.

15. Renovation, Cost, and Environmental Impact

15.1: Construction and Life Cycle Costs

All of the benefits of the described renovations are meaningless if they are found to be cost prohibitive or to if they increase the environmental impact of the building. To verify the economic and environmental feasibility of the proposed changes, a series of analyses has been performed including a system life cycle cost analysis and an analysis of the building emissions.

The first calculation – the life cycle cost analysis - was a crucial checkpoint in determining whether or not to specify the proposed system changes. Completion of this analysis required a construction management expertise, as the construction costs were incorporated into the calculations for the life cycle cost analysis. The cost to renovate with the chosen system – including ductwork and piping demolition, equipment installation, possible mold remediation, and the construction of the new pipe and duct connections – was calculated using values from R.S. Means Mechanical, Interiors, and Construction cost databases. The cost of energy on-site was found from the EPA Energy Information Agency website. Average electricity and gas costs for Pennsylvania - $0.0827 / kWh, $13.57 / Therm, respectively – were used to provide a conservative estimate of the on-site energy costs.

The final results of the costs for the installed system were calculated to be $551,237.58. Additionally, an estimate was performed to determine cost of the repairs due to the moisture problems between building completion and today. This cost, including additional energy costs for the temporary scheduling solution, only totaled $58,597.31 for the three year period of building operation. (Construction cost calculations included in Appendix I.) The relatively small size of the moisture remediation costs in comparison with the proposed renovation costs served as a red flag that the renovation costs were not extremely cost effective. These costs are summarized in Table 15.1 below.

Life Cycle Cost and Construction Cost Results	
Calculation	**Results**
Installed System Costs	$551,237.58
Moisture Remediation Costs	$58,597.31
Payback Period	12 Years

Table 15.1: Cost and LCC Results

After the necessary prerequisite estimation calculations, the life cycle cost analysis was performed. The analysis procedure chosen was a simple payback calculation with depreciation, as described in the NIST 1995 Life Cycle Cost Handbook, with the depreciation numbers coming from the NIST 2005 Cost Supplement. Comprehensive calculations found that the payback with depreciation for the proposed renovation was 12 years. A copy of the payback calculations is included in Appendix J. Considering that the equipment life for the desiccant wheels is about 18 years, and the equipment life for the air handlers is about 25 years, this solution seems expensive for its proposed time of operation.

However, other factors affect the outcome of this analysis. Both the energy consumption and the equipment performance model were done using conservative estimates of energy use. The performance model was particularly conservative, because the equipment performance information was withheld as proprietary information due to the relative newness of the product. The technical information bulletin for the product – included in Appendix B – proposes slightly better performance. If this was considered as an actual proposal for renovation, the manufacturer sales engineer would provide a more complete breakdown of the system performance, sizing, and costs, and perhaps this application would become more financially sound. Other factors to consider include the reduction in emissions associated with the calculated energy savings.

15.2: Emissions Calculations

The emissions were calculated using information from Allegheny Energy, Union Gas natural gas utility, and from Smith – the boiler manufacturer. Allegheny Energy is the company that controls West Penn Power, the site electricity provider. Union Gas is a local natural gas company that has provided information about the composition of their natural gas supply. Smith had the specification and performance information on their boiler products that was necessary to complete the natural gas emissions calculations.

Emissions calculations were simplified by the information from Allegheny Energy. The utility had posted their electrical power station emissions on their website. This data was included in a series of graphs and charts included below.

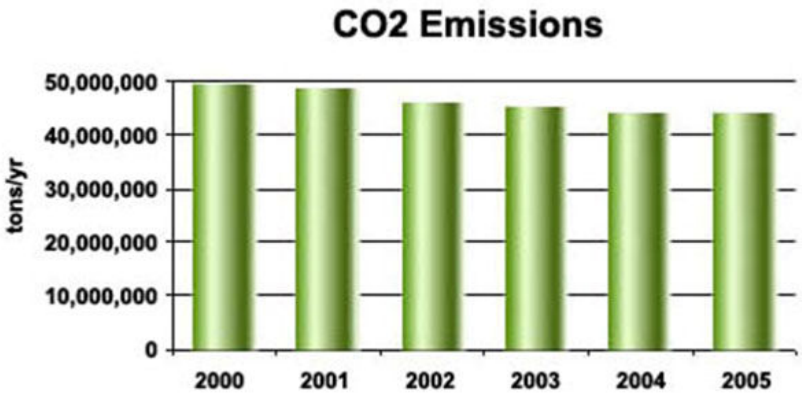


Figure 15.1: Electrical Carbon Dioxide Emissions

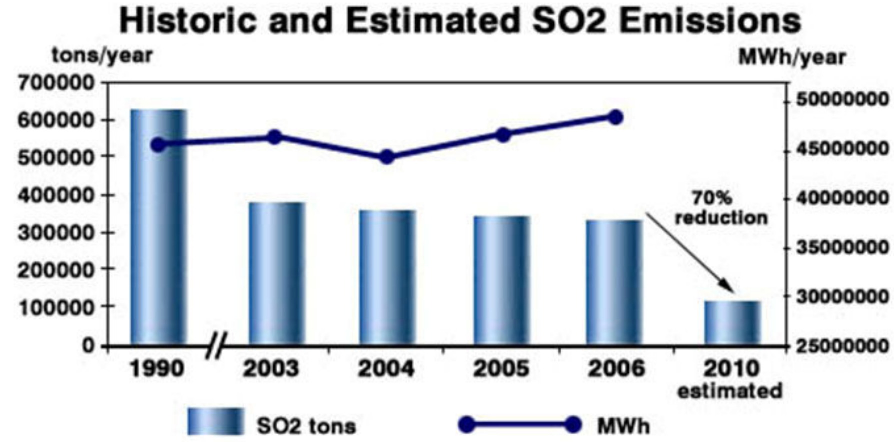


Figure 15.2: Electrical Sulfur Dioxide Emissions

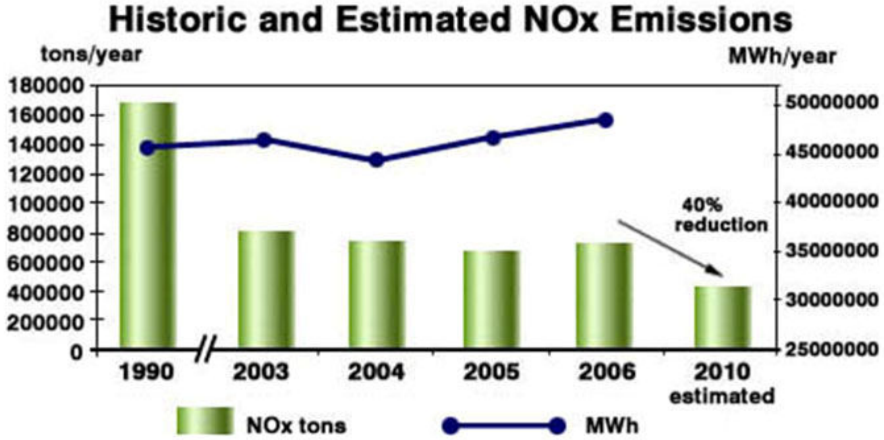


Figure 15.3: Electrical NOx Emissions

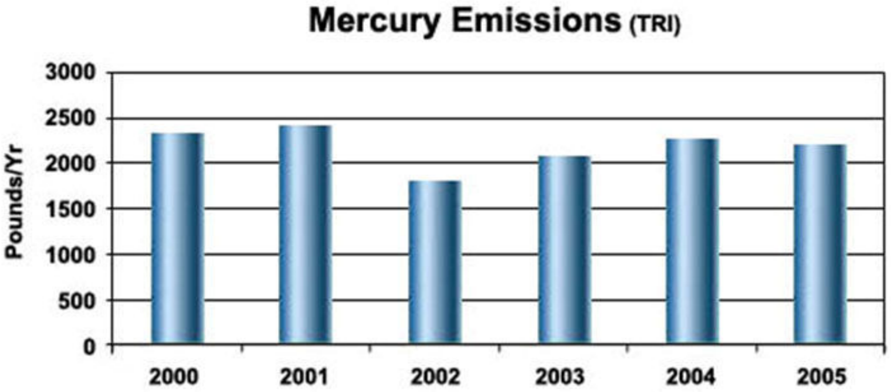
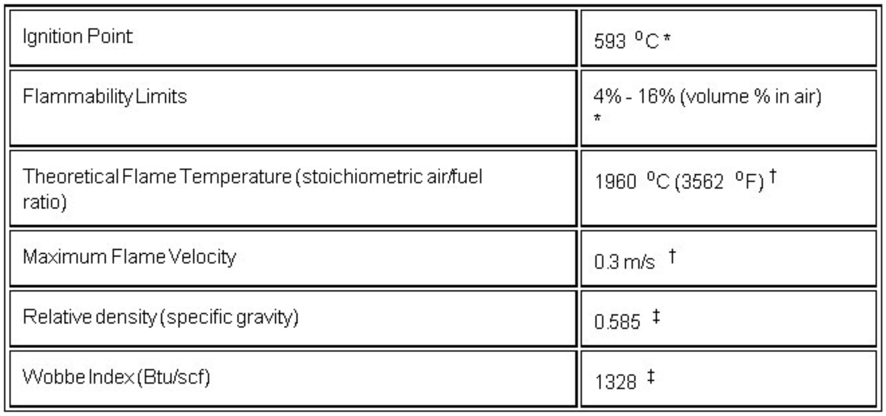


Figure 15.4: Electrical Mercury Emissions

The region natural gas composition was provided by Union Gas, and is included in the figures below.

Component	Typical Analysis (mole %)	Range (mole %)
Methane	94.9	87.0 - 96.0
Ethane	2.5	1.8 - 5.1
Propane	0.2	0.1 - 1.5
iso - Butane	0.03	0.01 - 0.3
normal - Butane	0.03	0.01 - 0.3
iso - Pentane	0.01	trace - 0.14
normal - Pentane	0.01	trace - 0.04
Hexanes plus	0.01	trace - 0.06
Nitrogen	1.6	1.3 - 5.6
Carbon Dioxide	0.7	0.1 - 1.0
Oxygen	0.02	0.01 - 0.1
Hydrogen	trace	trace - 0.02
Specific Gravity	0.585	0.57 - 0.62
Gross Heating Value (MJ/m^3), dry basis *	37.8	36.0 - 40.2

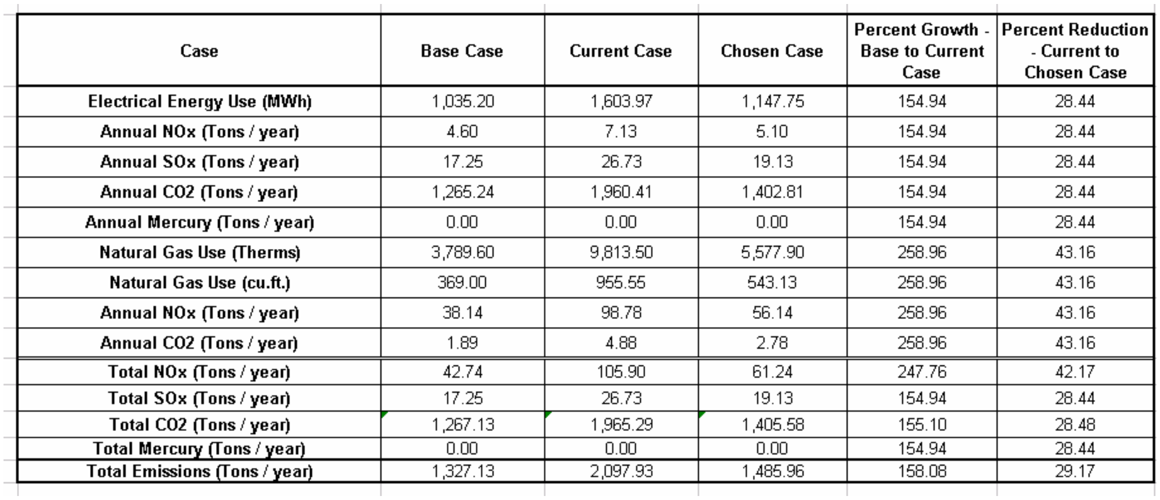
Figure 15.5: Natural Gas Composition Information



Ignition Point	593 °C *
Flammability Limits	4% - 16% (volume % in air) *
Theoretical Flame Temperature (stoichiometric air/fuel ratio)	1960 °C (3562 °F) †
Maximum Flame Velocity	0.3 m/s †
Relative density (specific gravity)	0.585 ‡
Wobbe Index (Btu/scf)	1328 ‡

Figure 15.6: Natural Gas Properties Information

The information included in Figures 15.1 – 15.6 was used in conjunction with the boiler performance information to calculate the annual building emissions. Boiler emissions calculations were included in Appendix K, along with the emissions calculations. The results of the emissions calculations are included in Table 15.2 below.



Case	Base Case	Current Case	Chosen Case	Percent Growth - Base to Current Case	Percent Reduction - Current to Chosen Case
Electrical Energy Use (MWh)	1,035.20	1,603.97	1,147.75	154.94	28.44
Annual NOx (Tons / year)	4.60	7.13	5.10	154.94	28.44
Annual SOx (Tons / year)	17.25	26.73	19.13	154.94	28.44
Annual CO2 (Tons / year)	1,265.24	1,960.41	1,402.81	154.94	28.44
Annual Mercury (Tons / year)	0.00	0.00	0.00	154.94	28.44
Natural Gas Use (Therms)	3,789.60	9,813.50	5,577.90	258.96	43.16
Natural Gas Use (cu.ft.)	369.00	955.55	543.13	258.96	43.16
Annual NOx (Tons / year)	38.14	98.78	56.14	258.96	43.16
Annual CO2 (Tons / year)	1.89	4.88	2.78	258.96	43.16
Total NOx (Tons / year)	42.74	105.90	61.24	247.76	42.17
Total SOx (Tons / year)	17.25	26.73	19.13	154.94	28.44
Total CO2 (Tons / year)	1,267.13	1,965.29	1,405.58	155.10	28.48
Total Mercury (Tons / year)	0.00	0.00	0.00	154.94	28.44
Total Emissions (Tons / year)	1,327.13	2,097.93	1,485.96	158.08	29.17

Table 15.2: Emissions Calculations Results

A total emissions reduction of about 30% will become more important as the country continues on its current trend in environmentally friendly building requirements. This factor must also be compared with the relative benefits of the payback period as well as the increased space moisture control.

16. LEED EB Evaluation

The LEED Green Building System provides several options for a building to receive LEED accreditation. These options include two that may apply to the current project: LEED for New Construction, and LEED for Existing Buildings. Because the scope of the proposed redesign project is relatively small an isolated, the LEED for Existing Building evaluation system has been selected as the most applicable rating system. This system is substantially different from the New Construction system, and requires constant vigilance form the building owners and operators to keep and submit the appropriate records, operating logs, and documentation. For evaluation purposes, an initial checklist for LEED EB certification has been completed. The LEED checklist is included is Appendix L.

An initial evaluation of the LEED applicability for this project has not been encouraging. While many of the operations practices for this building are unknown, the LEED checklist was completed with a good estimate or an unknown checkmark to provide a benchmark rating. The estimated LEED points generated from the current operation of the building resulted in 16 definite credits, 27 possible credits, and 28 absolutely unreachable credits.

A second review of the LEED checklist after completion of the design and recommendations has provided little benefit to the current credit state. Only a possible 10 credits are attached to building energy savings, which as been the primary focus of this redesign. As the minimum number of credits for a certified building is 32, these renovations will not become a major deciding factor in the certification of this building. Rather, with a LEED EB rating, the certification depends upon the records and operating practices of the building owner and operations manager. Therefore, while this renovation will garner about 3 additional LEED credits through the Energy Star building rating system and another 1 credit through emissions reduction reporting, the overall impact of the renovation upon a LEED certification bid is minimal. To gain a full Certification, the building owner should consider applying the following:

- green cleaning practices (5 additional credits)
- enhanced building metering and monitoring (5 additional credits)
- sustainable cleaning products (4 additional credits)
- documentation of productivity impacts (2 additional credits)

With the above practices, the owner should be able to easily attain at least a certified rating. To quote a very wise executive, “Go for the low hanging fruit. I believe in having an unfair advantage.” These above practices should be relatively simple, painless, and cost effective to implement after some initial research and time costs to develop a plan of action.

17. Final Notes

17.1: Project Summary

This project was conceived in response to a specific problem in an existing building. After the problem was identified, a series of inevitable steps were planned to assist in the solution of that problem. The source of the existing moisture problems had to be identified before any solutions could be identified. All proposed solutions had to be subjected to intensive study of their impact upon the building energy use before a final selection could be made. A selection of the final solution necessitated the study of the impacts of that selected system upon the existing building systems, structure, and other components. Finally, the impact of the renovation in cost and environmental terms finished the studies required to validate the solution. An analysis of the solution from a LEED certification standpoint investigated other possible benefits to the proposal.

17.2: Conclusions

While the problem set forth at the beginning of the project has been adequately solved, there has remained a relatively even balance between the system benefits and costs. The final decision to implement the findings is beyond the control of this report. There are a multitude of unseen benefits and soft cost savings associated with the proposed design. However, the payback for the required equipment is less than desirable for most commercial applications. As the owner in this project is a public university, a longer payback period may be overlooked in view of the long term energy savings associated with the use of the chosen equipment. In the end, this report has accomplished its objective. It has solved an existing problem within the building and has recommended a solution with its attendant cost and benefit tradeoffs. The final choice and implementation of the proposed system is dependant upon others, but this report provides excellent groundwork for future decisions to be made under similar circumstances.

18. Works Cited

18.1: Mechanical References

Ahmed, M.H., Fouad, M., Kattab, N.M. "Evaluation and Optimization of Solar Desiccant Wheel Performance." Renewable Energy Journal. Volume 30, Issue 3, March 2005. p. 305 – 325. http://www.sciencedirect.com.

ASHRAE Handbook: Fundamentals. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA. 2005.

Burnett, E., Straube, J. Building Science for Building Enclosures. Building Science Press. Westford, MA. 2005.

Cengel, Y., Cimbala, J. Fluid Mechanics: Fundamentals and Applications. McGraw Hill Higher Education. New York, NY. 2006.

"Chemical Composition of Natural Gas." Union Gas. April 2007. http://www.uniongas.com/aboutus/aboutng/composition.asp

"Environmental Performance" Allegheny Energy. April 4, 2007. http://www.alleghenyenergy.com/Environment/EnvironmentalPerformance.asp

"Green Building Rating System for Existing Buildings: Upgrades, Operations, and Maintenance." The U.S. Green Building Council. July 2005. http://www.usgbc.org/ShowFile.aspx?DocumentID=913

McQuiston, Parker, Spitler. Heating, Ventilation, and Air Conditioning: Analysis and Design. John Wiley & Sons, Inc. Hoboken, NJ. 2005.

Moffitt, Ronnie. "Taking the Heat out of Desiccants." HPAC Engineering. Issued March 2007. http://www.hpac.com/ArticleDraw.aspx?CID=45938&HBC=Issue&OAS=&NIL=False

"Mold Resources." The Environmental Protection Agency. March, 2007. http://www.epa.gov/mold/moldresources.html

Ozdeniz, M., Yilmazer, S. "The Effect of Moisture Content on Sound Absorption of Expanded Perlite Plates." Building and Environment Journal. Volume 40, Issue 3, March 2005. p. 311-318. http://www.sciencedirect.com.

Radermacher, Xuan. "Transient Simulation for Desiccant and Energy Wheels." Center for Environmental Energy Engineering, University of Maryland. College Park, MD. June 24, 2005.

Weber, Richard. "Masonry Wall Systems." Whole Building Design Guide. Jan., 2007. http://www.wbdg.org/design/env_wall_masonry.php

18.2: Electrical References

Hughes, David S. Electrical Systems in Buildings. Delmar Publishers Inc. Albany, NY. 1988.

NEC 2005: NFPA 70: National Electric Code. National Fire Protection Assocation. Salt Lake City, UT. 2005.

18.3: Structural References

Manual of Steel Construction: Load Resistance Factor Design. American Institute of Steel Construction, Inc. New York, NY. 2005.

Matthys, John. Editor. Masonry Designers' Guide. The Masonry Society. Boulder, CO. 2001.

18.4: Acoustical References

Egan, David M. Architectural Acoustics. McGraw-Hill Companies, Inc. New York, NY. 1988.

18.5: Construction References

Balboni, Barbara. Editor. Interior Cost Data. RSMeans. Construction Publishers & Consultants. Kingston, MA. 2006.

Mossman, Melville. Editor. Mechanical Cost Data. RSMeans. Construction Publishers & Consultants. Kingston, MA. 2006.

Waier, Phillip. Editor. Building Construction Cost Data. RSMeans. Construction Publishers & Consultants. Kingston, MA. 2005.

Appendices Index

Appendix A

WUFI Analysis Results

WUFI Results Compilation

Test Run	Characteristics	Max Moisture in Assembly - lb/sq.ft.	Percent difference from South facing	Notes
1	3" Brick face, 2" Air Space, 2" Expanded Polystyrene, 8" CMU	16.53		
2	3" Brick face, 2" Air Space, 2" Expanded Polystyrene, Polyethylene vapor barrier, 8" CMU	16.93		
3	3" Brick face, 2" Air Space, Polyethylene vapor barrier, 2" Expanded Polystyrene, 8" CMU	16.58		
4	4" brick concrete, polyethylene vapor barrier, 2" Extruded Polystyrene	5.39		Hygrothermal Conditions at interior surface.
5	4" brick concrete, 2" Extruded Polystyrene, polyethylene vapor barrier	5.24		
6	Option 1 + 2" of Acoustical (Fiberglass) Insulation)	16.89		* Relative Humidity between insulation panel and the wall reached past to 70% routinely, and even above 80 *Hygrothermal conditions bet. Wall and insulation @ design conditions.
7	Option 2 + 2" of Acoustical (Fiberglass) Insulation)	16.92		*this also had rh near 80% usually
8	Option 3 + 2" of Acoustical (Fiberglass) Insulation)	17.48		*hit up to 90% rh *hygrothermal conditions on interior… underside of acc panel is crawling.
9	Option 1 Oriented West	15.78	4.5	Vapor Retarder was more effective at stopping moisture progression
10	Option 2 Oriented West	15.86	6.3	
11	Option 3 Oriented West	16.43	0.9	
12	Option 6 Oriented West	16.45	2.6	RH inside acc reached almost to 90% 2.6, hygrthermal
13	Option 7 Oriented West	16.48	2.6	hyrothermal at brick / fbglass interface
14	Option 8 Oriented West	17.19	1.7	

15	Option 1 Oriented East	19.32	-16.9	
16	Option 2 Oriented East	19.68	-16.2	
17	Option 3 Oriented East	20.02	-20.7	Hygrothermal Conditions at interior surface.
18	Option 6 Oriented East	19.68	-16.5	
19	Option 7 Oriented East	19.71	-16.5	
20	Option 8 Oriented East	20.58	-17.7	
21	Option 1 Oriented North	18.91	-14.4	
22	Option 2 Oriented North	18.94	-11.9	
23	Option 3 Oriented North	19.51	-17.7	
24	Option 6 Oriented North	19.19	-13.6	
25	Option 7 Oriented North	19.21	-13.5	
26	Option 8 Oriented North	19.92	-14.0	
27	Option 4 without a vapor barrier	5.38		Hygrothermal Conditions at interior surface.

Appendix B

Series Desiccant System Information

TRANE®

engineers newsletter

volume 34–4 • providing insights for today's hvac system designer

advances in Desiccant-Based Dehumidification

Unlike "cold-coil" dehumidification, which removes moisture from the air by condensing it on a cold surface, desiccant dehumidification relies on adsorption or absorption. This *EN* reviews recent advances in the application of desiccant dehumidification in commercial and institutional buildings.

An introduction to desiccants

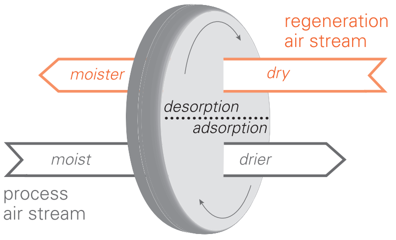
Desiccants are substances that attract water-vapor molecules from the air via an adsorptive or absorptive process.

Adsorption refers to a desiccant that does not change phase as it collects airborne moisture. Most adsorbents are solids; familiar examples include activated alumina, silica gel, and zeolites (molecular sieves). In *absorption*, collecting moisture changes the desiccant physically or chemically. Most absorbents, such as solutions of lithium chloride or triethylene glycol in water, are liquids.

There are literally hundreds of desiccants, each designed and manufactured for a specific task. They can be categorized by their ability to attract and hold water vapor at specific temperatures and relative humidities. The curve depicting this trait is a *desiccant isotherm*. Figure 1 shows typical isotherms for the Type I, Type II, and Type III desiccants that are often used for HVAC applications.

Adsorbents, or "solid" desiccants, are the focus of this article. Their most common application is the *desiccant wheel*, a cylindrical matrix of channels that are coated with or constructed from a solid desiccant. To maximize moisture collection, the wheel rotates slowly—only 10 to 30 rotations per *hour*—through two air streams (Figure 2).

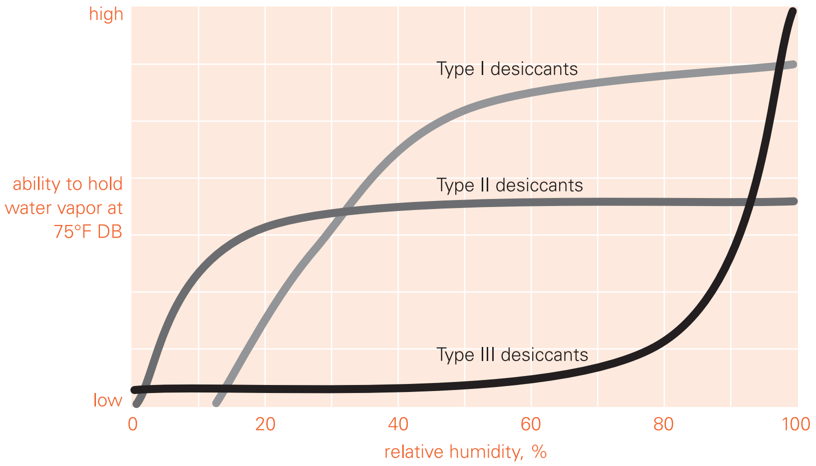
Figure 2. "Solid"-desiccant dehumidification wheel



"Process" air passes through one section of the wheel. Desiccant on that section adsorbs water vapor, making the air drier than when it entered. Wheel rotation then exposes the moisture-laden desiccant to a "regenerating" air stream that strips the captured moisture away from the desiccant (desorption).

Moisture transfer is enabled by the difference in vapor pressures at the desiccant surface versus the air passing over it. The desiccant collects

Figure 1. Typical desiccant isotherms



moisture when the surface vapor pressure is lower than that of the passing air, and releases it when the surface vapor pressure is higher. For practical purposes, since relative humidity (RH) is a function of vapor pressure, the direction of moisture transfer can be characterized by the difference between the relative humidities of the process and regeneration air streams.

The desiccant can retain little moisture when the regeneration-air RH is low, so water vapor will migrate from the desiccant to the regeneration air. When the RH of the process air is high, the desiccant can adsorb more moisture from that air stream. Maintaining an adequate difference between the relative humidities of the process and regeneration air streams is essential to dehumidify effectively using a desiccant wheel.

Note: Total-energy wheels, also known as "enthalpy wheels," perform differently than solid-desiccant dehumidification wheels; see inset (p. 5).

Traditional arrangements for parallel regeneration

Wheel upstream of cooling coil. Traditional parallel arrangements of desiccant dehumidification wheels use Type I or Type II desiccants and rotate between two discrete air streams (Figure 3). The regeneration air stream may be the building exhaust or a second outdoor air stream that's used solely to "regenerate" (reactivate) the desiccant. A heat source raises the dry-bulb temperature of the regeneration air, lowering its relative humidity. As a result, water vapor transfers from the higher-RH process air (OA) to the lower-RH regeneration air (RG').

However, the relative humidity of the air leaving the process side of the wheel (OA') can only get as low as the relative humidity of the air entering the regeneration side (RG'). The lower that the regeneration-air RH is, the lower the resulting process-air RH can be. Depending on the desired dryness, regeneration-air temperatures can range from 150°F to 300°F—hot enough that a gas-fired burner is typically used for this purpose.

In HVAC applications, desiccant wheels were historically used to dehumidify outdoor air brought indoors for ventilation. Figure 4 shows an example of wheel performance in this application, where a second, dedicated, outdoor air stream regenerates the desiccant.

A desiccant wheel removes moisture from the process air stream—but for every Btu of latent heat (moisture) removed, it adds more than one Btu of sensible heat. That is, air leaving the process side of the wheel (OA') is dry (at a low dew point) but hot (145°F DB in our example). Therefore, most applications include a cooling coil downstream of the wheel to recool the process air.

Due to the costs of regeneration and recooling, traditional desiccant wheels typically are used only when the required process-air dew point can't be achieved with standard mechanical equipment. (These costs become even more prohibitive as the price of natural gas rises.)

Figure 3. Desiccant dehumidification wheel *upstream* of cooling coil, parallel regeneration

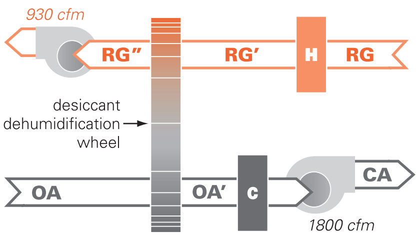
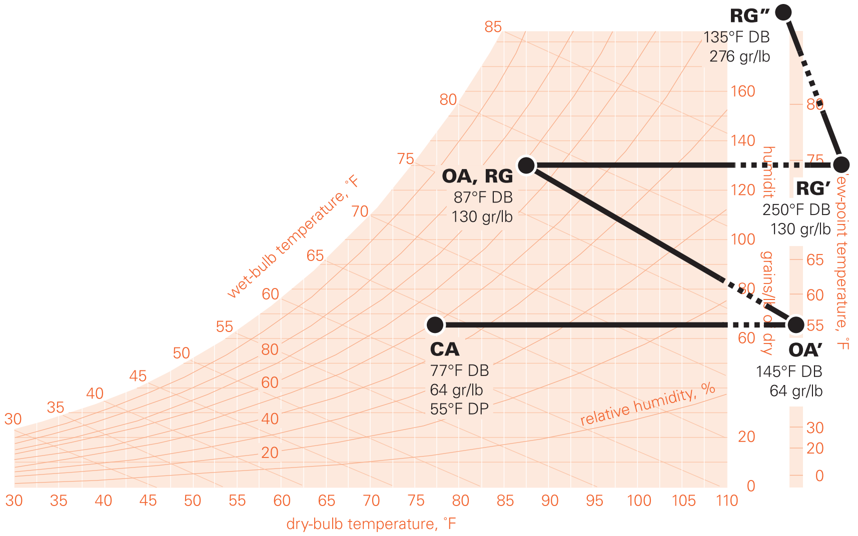


Figure 4. Performance example: Desiccant dehumidification wheel *upstream* of cooling coil, parallel regeneration (dedicated outdoor-air application)



Wheel downstream of cooling coil. One reason for the inefficiency of traditional desiccant systems is that the components are asked to perform at less-than-optimal conditions. A finned-tube cooling coil is most effective when wet, but the process air leaving the wheel requires only sensible cooling (so the coil is dry).

Desiccant performance suffers, too. Here's why:

- *Most desiccants adsorb more water vapor as the relative humidity of the process air rises.* While the RH of entering outdoor air varies widely during the cooling season, the RH of the air leaving an active cooling coil typically exceeds 90 percent. Therefore, the highest relative humidity in the system is directly downstream of an active cooling coil.
- *Most desiccants adsorb more water vapor as the dry-bulb temperature of the process air falls.* Again, the temperature of entering outdoor air varies significantly. But during the cooling season, the coldest temperature in the system is directly downstream of an active cooling coil.

Now, many systems are configured with the desiccant wheel *downstream* of the cooling coil (Figure 5), rather than upstream, to better apply the operating principles of cooling coils and desiccants. In this configuration, the process air (OA) first passes through a DX or chilled water cooling coil, where it's cooled and dehumidified. Then the cool, saturated air (CA) passes through the desiccant wheel, which adsorbs moisture from the high-RH air—lowering the dew point but raising the dry-bulb temperature. The resulting conditioned air (CA') is dry and warm—but not as hot as in the "wheel upstream" configuration (Figure 3) described earlier. Water vapor transfers from the desiccant to the regeneration air (RG') as the wheel rotates into the regeneration air stream.

Today, the "wheel downstream" configuration is most commonly used in dedicated outdoor-air applications, where the outdoor air is dehumidified to a low dew point and then delivered at a neutral dry-bulb temperature, either directly to the occupied spaces or to other local HVAC units. In the example shown in Figure 6, the "wheel downstream" configuration dehumidifies the process air to 55°F DP, while warming it to 77°F DB—roughly "neutral" compared to the space. The separate regeneration air stream is heated to 114°F DB to lower its RH and dry out the desiccant.

Compared with the "wheel upstream" arrangement, the "wheel downstream" configuration can dehumidify the process air to an equally low dew point and requires less recooling—perhaps none—because the leaving dry-bulb temperature isn't as hot. But it still requires a separate regeneration air stream, and that air typically must be heated to dry out the desiccant. The opportunity to regenerate the desiccant at a lower temperature means that heat from the condensing process of refrigeration equipment can be used for this purpose.

Figure 5. Desiccant dehumidification wheel *downstream* of cooling coil; parallel regeneration

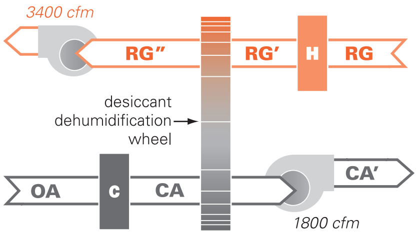
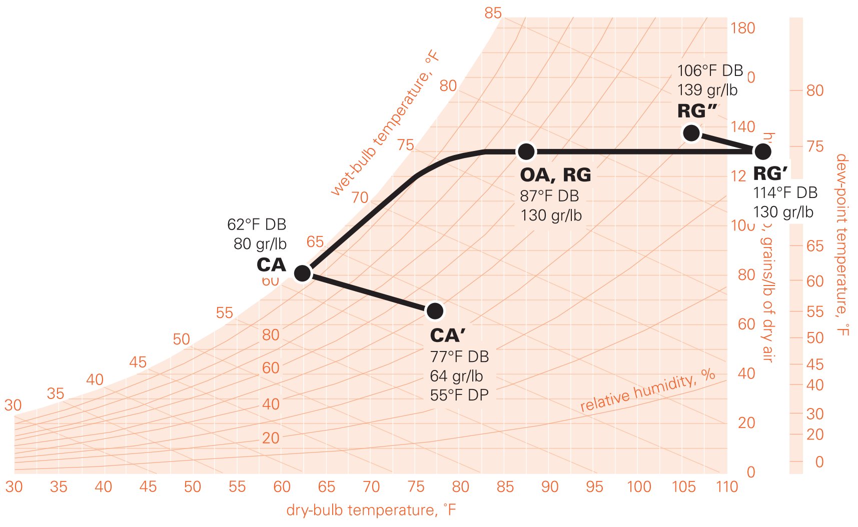


Figure 6. Performance example: Desiccant dehumidification wheel *downstream* of cooling coil, parallel regeneration (dedicated outdoor-air application)



A different approach: Series regeneration

The latest advance in desiccant-based dehumidification places the desiccant wheel *in series* with the cooling coil (Figure 7), with the regeneration side of the wheel upstream of the cooling coil and the process side downstream of the coil. Moisture transfer occurs within a single air stream: The series desiccant wheel adsorbs water vapor from the process air downstream of the cooling coil and then releases the collected moisture upstream of that coil, allowing the cooling coil to remove it through condensation. A separate, regeneration air stream isn't needed.

The series desiccant wheel uses a Type III desiccant selected specifically for this application. The desiccant's ability to adsorb water vapor is very high when the relative humidity of the air is high (Figure 1, p. 1); when the RH is below 80 percent, its moisture-holding ability drops significantly. Recall that air leaving an active cooling coil often exceeds 90 percent RH; at this condition, the series desiccant wheel can adsorb lots of water vapor from the air. When the wheel rotates upstream of the cooling coil, it's exposed to air with a lower relative humidity (typically 40 to 60 percent). At this condition, the desiccant can't retain the water vapor that it collected, so the moisture transfers from the wheel to the passing air stream.

Figure 7. Desiccant dehumidification wheel *downstream* of cooling coil, series regeneration

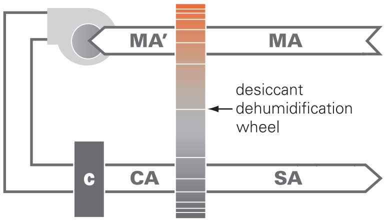
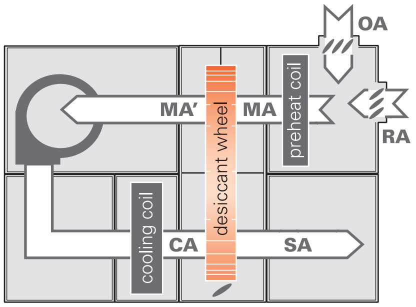


Figure 8. Desiccant dehumidification wheel (series regeneration) in a mixed air system



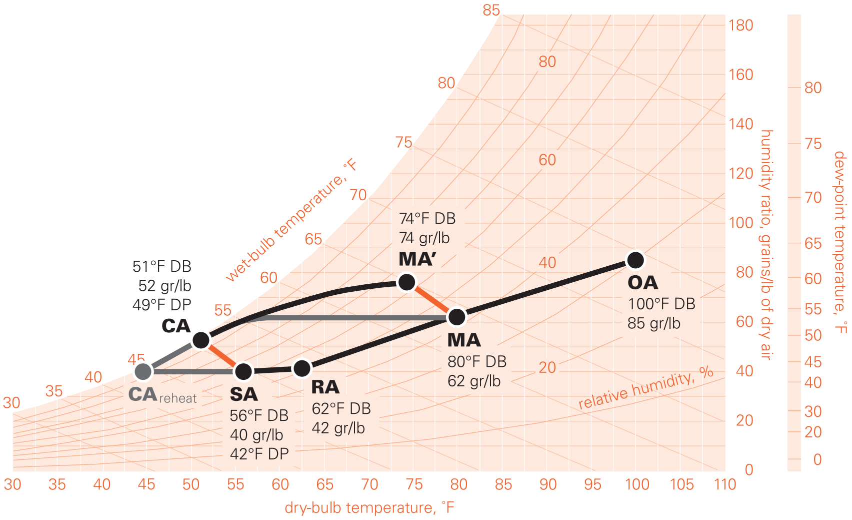
Adsorption isn't driven by hot regeneration air but by the Type III desiccant's ability to regenerate at low temperatures, often without supplemental heat. The design of the wheel and its rotation speed are engineered to maximize the transfer of water vapor while minimizing sensible-heat transfer. The increase in the dry-bulb temperature of the process air is associated only with the amount of heat produced by the adsorption process.

Series desiccant wheel in a mixed air application. Air leaving the process side of a series desiccant wheel is cooler than the space, not neutral or warmer. This makes the wheel suitable for use in the mixed air stream—and allows a single unit to both comfort-cool and dehumidify the space.

Figure 8 shows an example of a mixed-air air handler with a series desiccant wheel. The desiccant adsorbs water vapor from the air downstream of the cooling coil, enabling the system to deliver drier supply air (at a lower dew point) without lowering the coil temperature. The regeneration side of the wheel is located in the mixed air, upstream of the cooling coil. Because the RH of the air upstream of the coil is much lower than the RH of the air downstream, the adsorbed water vapor transfers upstream—and the cooling coil gets a second chance to remove the transferred water vapor via condensation.

Figure 9 shows the performance of this mixed air system in a surgery room. Air leaves the cooling coil (CA) at a high relative humidity. The series desiccant wheel adsorbs water vapor, drying the supply air (SA) to a dew point of 42°F (40 grains/lb). Sensible heat added by the adsorption process

Figure 9. Performance example: Desiccant dehumidification wheel *downstream* of cooling coil, series regeneration (mixed air application)

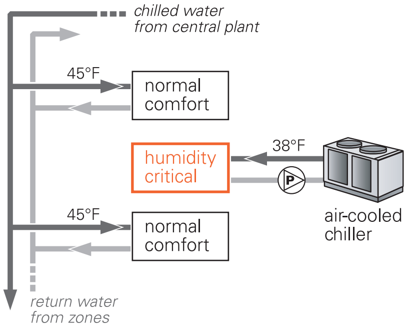


raises the supply-air temperature to 56°F DB.

Mixed air (MA) entering the regeneration side of the wheel is less humid, about 40% RH due to the low supply-air dew point in this example. At this RH, the wheel can no longer hold the water vapor it adsorbed downstream of the coil. Water vapor released from the wheel passes into the mixed air (MA') and then condenses on the cold coil surface.

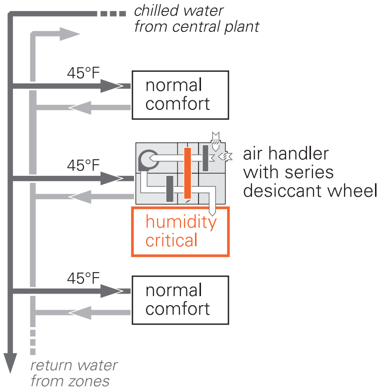
Basically, adding the series desiccant wheel changes the dehumidification performance of the traditional cooling coil, trading sensible capacity for more latent capacity. The latent (dehumidification) capacity of the cooling coil increases while the total cooling capacity (enthalpy change across the coil) remains the same.

Figure 10. Dedicated chiller for humidity-critical zones



To deliver the same supply-air (SA) condition using a traditional "cool+reheat" system, the cooling coil must cool the air to nearly 42°F DB to achieve 42°F DP (CA_{reheat}). Then the reheat coil must raise the dry-bulb temperature to 56°F (Figure 9). By contrast, the series desiccant wheel can deliver the same dew point using fewer tons, no reheat, and with a warmer leaving-coil temperature (51°F vs. 42°F DB). This warmer coil enables more efficient mechanical cooling (a higher suction temperature in DX equipment, warmer water or a lower flow rate in chilled water systems).

Figure 11. Air handler with series desiccant wheel for humidity-critical zones



A preheat coil can be added upstream of the regeneration side of the wheel (Figure 8) for applications that require even drier air. Activating the preheat coil raises the dry-bulb temperature slightly (5°F to 20°F) and *lowers* the relative humidity of the mixed air (MA). Lowering the relative humidity allows the desiccant to reject even more water vapor to the regeneration air, thus enabling it to adsorb more water vapor from the process air. In many cases, the modest amount of heat added by the preheat coil can be recovered from the condensing process of the refrigeration equipment.

Infrastructural side benefits.

Comparatively few spaces in a typical building (or campus of buildings) require supply air with a lower-than-normal dew point. For example, a hospital houses surgery rooms, certain laboratories, and pharmacy prep areas that may require supply air at 35°F to 50°F DP. But patient rooms, waiting rooms, office spaces, cafeterias, and service areas seldom need such dry supply air.

Let's revisit the surgery-room example (Figure 9). The existing central chiller plant supplies the cooling coil with 45°F water, which isn't cold enough to produce the 42°F supply air needed using a conventional "cool+reheat" system. A common solution is to install a dedicated, stand-alone chiller that delivers colder fluid than the central plant currently produces (Figure 10).

However, if each of the air handlers serving the humidity-critical spaces includes a series desiccant wheel, the required 42°F DP can be achieved with

Total-energy (enthalpy) wheels

The construction of a total-energy wheel (also known as an "enthalpy wheel") is similar to that of a solid-desiccant dehumidification wheel. Its channel surfaces are coated with or constructed from a solid desiccant (adsorbent), and the wheel rotates between the outdoor and exhaust air streams. But the performance of a total-energy wheel is dramatically different due to its rapid rotation—20 to 60 rotations per *minute* versus 10 to 30 rotations per *hour* for a desiccant dehumidification wheel.

Basically, the total-energy wheel acts as a simple heat and mass transfer device. When it's hot and humid outside, the wheel carries sensible heat and moisture (latent heat) from the outdoor air to the cooler, drier exhaust air. When it's cold and dry outside, the wheel carries sensible heat and moisture from the warmer, more humid exhaust air to the outdoor air.

Total-energy wheels can significantly reduce ventilation cooling and heating loads, especially at peak conditions, but they do *not* dehumidify the space. Think of it this way: If the wheel is 100 percent effective, the outdoor air leaving the supply side of the wheel can only get as dry as the exhaust air entering the other side. And the exhaust air comes from the space. Therefore, if the wheel is 100 percent effective, the outdoor air leaving the wheel can become as dry as—*but no drier than*—the space. If the supply air is no drier than the space, it can't *dehumidify* the space. The system still requires a cooling coil (or some other device) to make the supply-air dew point lower than the dew point in the space.

Total-energy wheels allow downsizing of cooling, dehumidifying, heating, and humidifying equipment, and reduce the energy associated with these processes. However, the additional pressure drop increases fan energy use, and most of the building exhaust air must be ducted back to pass through the exhaust-side of the wheel. (For more information, see Trane manual SYS-APM003-EN, available from www/trane.com/bookstore/.) •

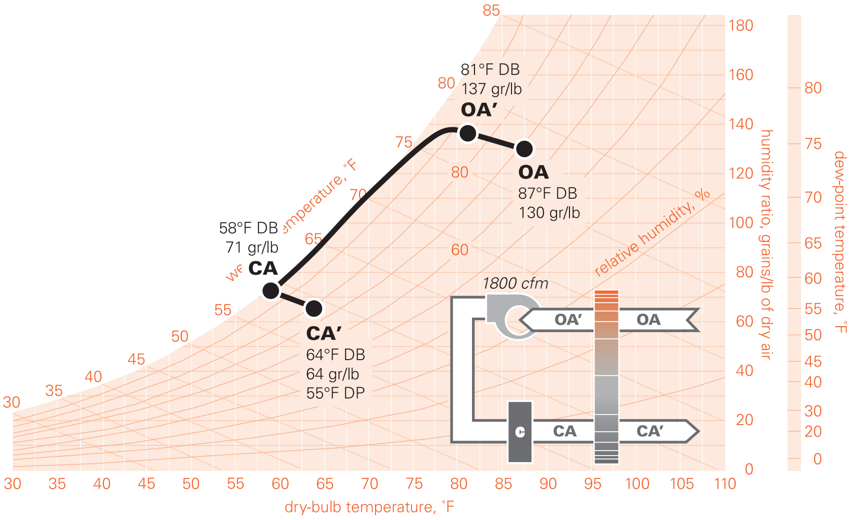
51°F DB air leaving the cooling coil. If sufficient capacity is available at the central plant, proper cooling coil selection could allow the existing 45°F water to produce 51°F air leaving the coil, thereby eliminating the need for a separate chiller (Figure 11, p. 5).

Series desiccant wheel in a dedicated outdoor-air application. The series desiccant wheel can be used in dedicated outdoor-air applications, too. Because the series desiccant wheel adds very little sensible heat to the process air, it raises the dry-bulb temperature (CA') only slightly.

Figure 12 shows such a system operating at the same conditions as the "wheel downstream with parallel regeneration" example in Figure 6 (p. 3). A comparison of psychrometric performance shows that the series regeneration arrangement delivers conditioned air that's not only as dry (55°F DP) as, but also much cooler (64°F DB versus 77°F DB) than, the conditioned air delivered by the "wheel downstream with parallel regeneration" arrangement. Note, too, that at this condition, supplemental regeneration heat is unnecessary for the series arrangement.

For most applications, whenever possible, *the dedicated outdoor-air unit should be designed to deliver the air cold—not warmed to neutral.* Delivering cold conditioned air takes advantage of the sensible cooling already performed by the cooling coil in the dedicated outdoor-air unit.

Figure 12. Performance example: Desiccant dehumidification wheel *downstream* of cooling coil, series regeneration (dedicated outdoor-air application)



This design strategy may require more cooling capacity at the dedicated outdoor-air unit, but the cooler supply air offsets some of the space cooling loads, allowing the local HVAC units to be smaller, quieter, and less expensive (Table 1). In most dedicated outdoor-air applications, the spaces won't be overcooled by delivering the outdoor air cold until the sensible load in the space drops significantly. Consider using communicating controls to determine when a space is at risk of overcooling, and limit use of reheat to those times.*

When the relative humidity of the entering outdoor air is high (on a mild rainy day, for example), it may be necessary to preheat the air entering the regeneration side of the series desiccant wheel in order to lower its relative humidity. Typically, the amount of heat is small and it may be required for only a few hours. Therefore, it may be practical to recover the needed heat from the condensing process of the refrigeration equipment. (A small, inexpensive electric heater is another option.)

Alternatively, a total-energy wheel can be added to the system (Figure 13). When high RH conditions occur, the total-energy wheel will transfer moisture from the entering outdoor air (OA) to the exhaust air (EA), thus

Table 1. Performance comparison: Parallel vs. series desiccant wheel[a]

	Parallel configuration (Figures 5, 6)	Series configuration (Figure 12)
Dedicated outdoor-air unit		
Supply-air dew point	55°F DP	55°F DP
Supply-air dry bulb	77°F DB	64°F DB
Cooling capacity	**8.6 tons**	**10.7 tons**
Leaving-coil temperature	62°F	58°F
Regeneration heat	**100 MBh**	**0 MBh**
Local HVAC terminals		
Cooling capacity	**15.0 tons**	**12.9 tons**
Supply airflow	**6,000 cfm**	**5,200 cfm**
Total system		
Total cooling capacity	23.6 tons	23.6 tons

No regeneration heat required. Added cooling capacity at the dedicated outdoor-air unit helps offset space cooling load, enabling smaller local HVAC terminals

[a] Dedicated outdoor-air application without energy recovery. Process side of desiccant wheel is *downstream* of cooling coil. Parallel configuration requires a separate source of regeneration heat; series configuration does not.

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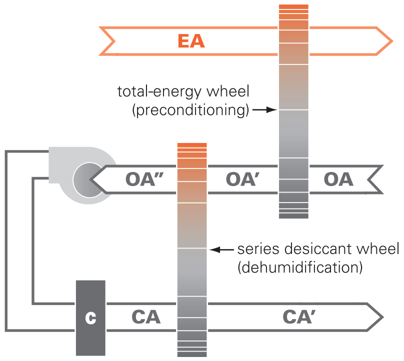
* See *Engineers Newsletter* volume 30-3, "Design Tips for Effective, Efficient Dedicated Ventilation Systems," available online at http://www.trane.com/commercial/library/vol30_3/enews_30_03.pdf.

Figure 13. Total-energy wheel preconditions outdoor air entering a dehumidifying series desiccant wheel



lowering the relative humidity of the air before it enters the regeneration side of the series desiccant wheel (OA′). In such cases, adding a total-energy wheel reduces (and often eliminates) the need to add regenerative heat. This gives the series desiccant wheel an advantage over the parallel regeneration arrangement.

Regardless of whether parallel or series regeneration is used, including a total-energy wheel will save both cooling and heating energy and offer the opportunity to downsize heating and cooling equipment. It may also be required by local energy codes or ASHRAE Standard 90.1.

When to consider using a desiccant

Mixed air systems. If the system provides both comfort cooling and dehumidification for the space, investigate the benefits of using a desiccant when the required supply-air dew point is below 50°F. Common applications are surgery rooms, laboratories, dry storage, archive rooms, museums, supermarkets, and many process applications.

- The series desiccant wheel can achieve a lower supply-air dew point without lowering the coil temperature. Unlike a system with a cooling coil alone, the supply-air dew point can be lower than the coil's surface temperature.
- The series desiccant wheel minimizes the addition of sensible heat, allowing it to supply cool air rather than warm—effectively meeting both the dehumidification (latent) and cooling (sensible) needs of the space.
- The series configuration requires only one air stream; a separate regeneration air stream is unnecessary.

Dedicated outdoor-air systems. For systems that dehumidify the outdoor air before delivering it directly to occupied spaces or to other local HVAC units, investigate the benefit of using a desiccant wheel:

- *when the conditioned outdoor air must be delivered at a neutral dry-bulb temperature.* But remember … Designing the dedicated outdoor-air unit to deliver the air cold, not neutral, takes advantage of the sensible cooling done by the cooling coil in the dedicated outdoor-air unit. This allows the local HVAC units to be smaller, quieter, and less expensive.
- *when the required dew point of the conditioned outdoor air cannot be achieved reliably with a traditional cooling coil alone.* However, the dew point that the dedicated outdoor-air unit must deliver often exceeds 48°F. (For guidance, see Trane manual SYS-APG001-EN.)

A series desiccant wheel dehumidifies the outdoor air to a low dew point, and then delivers it cool rather than neutral. Adding a total-energy wheel allows smaller-sized cooling, dehumidifying, heating, and humidifying equipment, and can reduce system energy use. It also reduces (or often eliminates) the need to add "regenerative" heat to the desiccant wheel when the relative humidity of the entering air is high. •

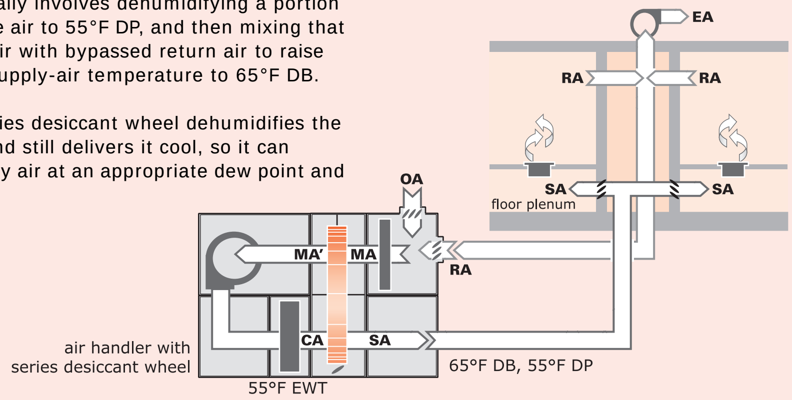
By John Murphy, applications engineer, and Brenda Bradley, information designer, both of Trane. You can find this and previous issues of the *Engineers Newsletter* at http://www.trane.com/commercial/library/newsletters.asp. To comment, e-mail us at comfort@trane.com.

The "series desiccant wheel" configuration described in this newsletter is marketed by Trane under the name CDQ™ (Cool, Dry, Quiet).

UAD and series desiccant wheels

Underfloor air distribution (UAD) systems usually distribute warmer air than traditional overhead systems—65°F versus 55°F, for example. When a UAD system is applied in a non-arid climate, the supply air first must be sufficiently dehumidified to avoid humidity problems in the space, and then warmed to a comfortable temperature. In practice, this typically involves dehumidifying a portion of the air to 55°F DP, and then mixing that dry air with bypassed return air to raise the supply-air temperature to 65°F DB.

A series desiccant wheel dehumidifies the air and still delivers it cool, so it can supply air at an appropriate dew point and dry bulb for a UAD application—and it does so with *a warmer leaving-coil temperature* (62°F vs. 55°F DB) than return-air bypass. In chilled water UAD systems, a warmer coil permits the use of warmer water (55°F, in this case) or an extremely low flow rate of cold water … perhaps even return water from other cooling coils in the system, allowing the same water to be used twice before returning to the chillers. •

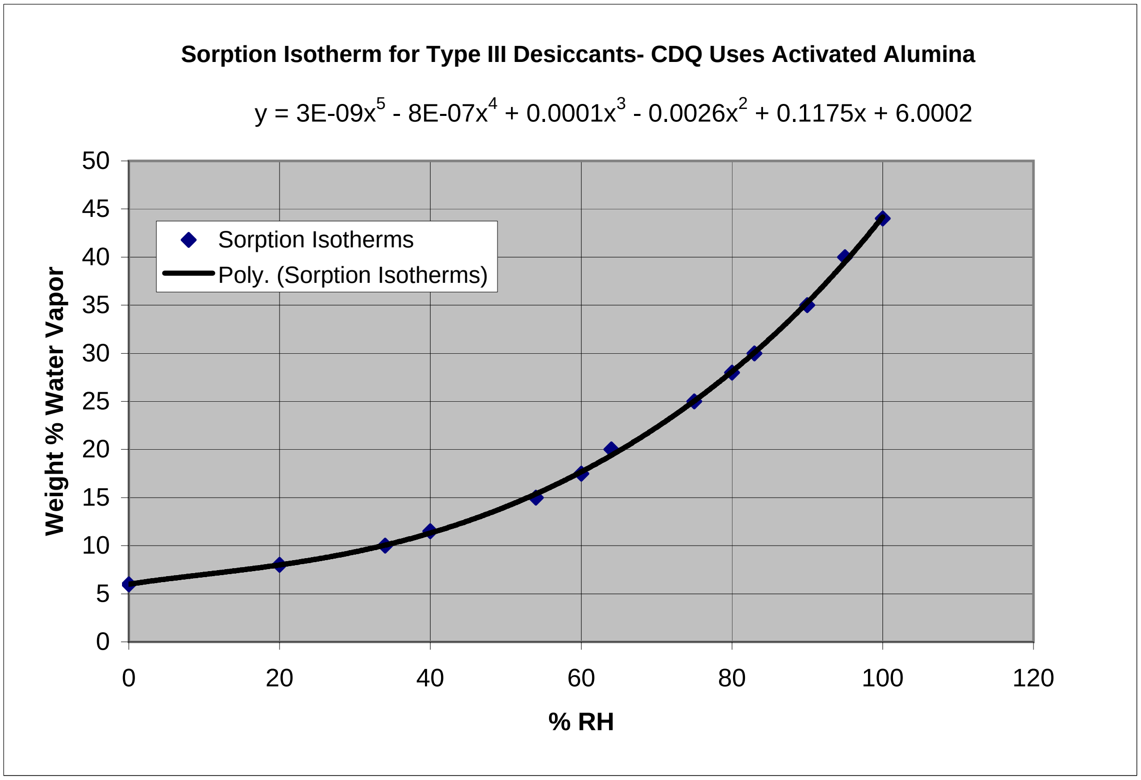


Appendix C

Product Modeling – EES and Excel

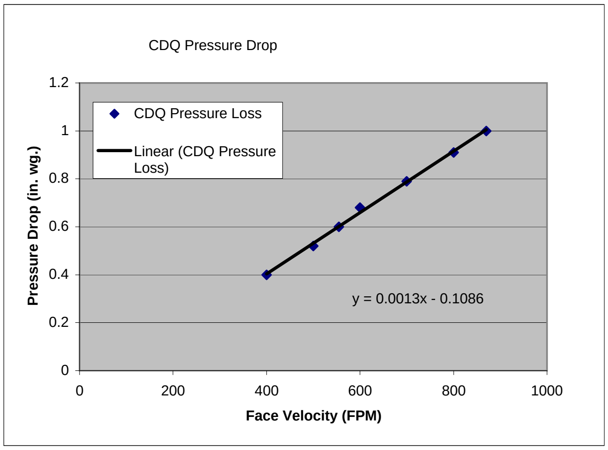
EES Program Results - Dehumidification Design Day Conditions

Original AHU Performance		Gr / Hour Removed	# AHU's	Total Gr/Hr Removed	CC Latent Heat (Btuh)	CC Sensible Heat (Btuh)	CC Total Heat (Btuh)	Sensible Heat Ratio
	Aux. Gym	1,831	1	1,831	126,329	137,454	263,783	0.52
	Arena	1,859	4	7,436	160,340	174,807	335,147	0.52
	Fitness	1,724	1	1,724	69,386	79,508	148,894	0.53
	Theater	1,849	2	3,698	116,911	123,921	240,832	0.51
Original Desiccant Performance								
	Aux. Gym	3,239	1	3,239	215,641	137,454	353,095	0.39
	Arena	3,553	4	14,212	299,543	174,807	474,350	0.37
	Fitness	2,738	1	2,738	105,435	79,508	184,943	0.43
	Theater	3,360	2	6,720	206,212	123,921	330,133	0.38
AHU without Preheat								
	Aux. Gym	1,833	1	1,833	126,440	137,312	263,752	0.52
	Arena	1,861	4	7,444	160,484	174,622	335,106	0.52
	Fitness	1,726	1	1,726	69,444	79,434	148,878	0.53
	Theater	1,850	2	3,700	117,016	123,785	240,801	0.51
Desiccant without Preheat								
	Aux. Gym	2,406	1	2,406	145,628	137,312	282,940	0.49
	Arena	2,570	4	10,280	190,808	174,622	365,430	0.48
	Fitness	2,121	1	2,121	76,945	79,434	156,379	0.51
	Theater	2,470	2	4,940	136,163	123,785	259,948	0.48
AHU, no Preheat, Recirculation Only								
	Aux. Gym	1,568	1	1,568	108,175	123,925	232,100	0.53
	Arena	1,560	4	6,240	134,579	155,761	290,340	0.54
	Fitness	1,539	1	1,539	61,950	73,825	135,775	0.54
	Theater	1,590	2	3,180	100,546	111,739	212,285	0.53
Desiccant, no Preheat, Recirculation Only								
	Aux. Gym	2,074	1	2,074	125,028	123,925	248,953	0.50
	Arena	2,176	4	8,704	160,826	155,761	316,587	0.49
	Fitness	1,901	1	1,901	68,765	73,825	142,590	0.52
	Theater	2,137	2	4,274	117,400	111,739	229,139	0.49



Density of Activated Alumina Desiccant: 48 lbm / cu.ft.

Cooling design conditions	**Percent**	**DB**	**MCWB**	**-**	**Occurs in:**
	0.4	89.8	72.5	-	July
Dehumidification design	**Percent**	**DP**	**HR gr/lbm**	**MCDB**	**Occurs in:**
	0.4	72.3	125.4	79.7	July



Sizing Calculations

Space	Aux. Gym	Fitness	Arena	Theater
Number of AHU's	1	1	4	2
Model # AHU's	12	8	17	12
CFM of AHU	6,000	3,500	7,500	5,500
Dimensions of the Module	39"h x 64"w	34"h x 48"w	44"h x 74"w	39"h x 64"w
Area of Module (ft)	17	11	23	17
Vace Velocity (FPM)	346	309	332	317
Pressure Drop for HEPA Filters (in.wg.)	0.89	0.89	0.89	0.89
Pressure Drop Over Wheel (in. wg.)	0.34	0.29	0.32	0.30
Previous Fan Pressure Drop (in. wg.)	4.40	3.90	4.30	3.70
w/out HEPA Fan Pressure Drop	4.74	4.19	4.62	4.00
New Fan Pressure Drop (in.wg.)	5.63	5.08	5.51	4.89
Additional Power Required (BHP)	0.56	0.35	0.50	0.66
Additional Power, HEPA Filters (BHP)	1.14	0.72	1.44	1.34
w/out HEPA Additional Power, (kW)	0.42	0.26	0.37	0.49
Additional Power in kW	0.85	0.54	1.07	1.00
Envelope Cooling Load (Trace)	50,639	81,319	21,187	60,055
People Cooling Load (Trace)	30,767	34,373	117,162	50,845
Latent Load (Gr/hr)	760,368	354,063	1,779,166	931,096
Latent load, no people (Gr/hr)	560,368	286,903	760,766	931,096

*Loads are from Trace and the

Latent Load Calculations

*Sized from Trane's fan performance charts

Actual Cooling Coil:				
Total MBH	227	110	319	226
Sensible MBH	173	98.2	219	162
Latent MBH	54	11.8	100	64
GPM	33	16	46	33
Load Removed (lbm wa/lbm a-hr)	1.859504132	0.696576151	2.754820937	2.404207363
Load Removed (lbm wa/lbm a-hr)	57,851	21,671	85,706	74,798
Load * # AHU's per space	57,851	21,671	342,822	149,595
Diff - full load to load removed	702,517	332,392	1,436,344	781,501
Diff - unocc. Load to load removed	502,517	265,232	417,944	781,501
Est. RH leaving CC	95	95	95	95
Point A - Mixed Air				
OA DB	79.9	79.9	79.9	79.9
OA WB	73.5	73.5	73.5	73.5
RA DB	70	70	70	70
RA WB	55	55	55	55
MA DB	77	78	76	77
MA WB	66	67	65	66
MA RH	55	57	53	55
OA / TA	0.33	0.24	0.38	0.33
lbm/hr, mix	444.44	259.26	555.56	407.41
lbm/hr water	4.89	2.70	6.56	4.48
Gr/hr water	34,222	18,874	45,889	31,370

Point B - Dehumidified Air				
% Weight of water, dw from SA	37.49	37.49	37.49	37.49
%Weight of Water, dw after	15.43	16.13	14.76	15.43
Area of Wheel in Module (sq.ft.)	0.93	0.52	1.24	0.93
Thickness of Wheel (ft.)	0.51	0.36	0.59	0.51
Volume of Desiccant (cu.ft.)	0.28	0.11	0.44	0.28
Density of Desiccant (lbm / cu.ft.)	48.00	48.00	48.00	48.00
Weight of Desiccant (lbm)	13.54	5.48	21.09	13.54
Water added (lbm/hr)	2.99	1.17	4.79	2.99
Moisture Added (Gr/hr)	20915.67	8187.28	134250.30	41831.35
DB	77.00	78.00	76.00	77.00
lbm / hr water	7.88	3.87	11.35	7.47
lbm water / lbm air	0.02	0.01	0.02	0.02

*Volume of desiccant = volume of wheel

* 0.6 - safety factor

```
"Heather Stapel"

"Trane CDQ Desiccant Wheels Analysis"


"Inputs in CFM, Deg.F., outputs in CFM, Percent, Btu/lbm, deg.F"

"Mixing Box Simulation"

PROCEDURE Mixing_Box_Conditions(OADB, OAWB, RADB, RAWB, V_dot_OA, V_dot_RA: MADBout, MAWBout, V_dot_MAout,
    m_dot_MAout, W_MAout)

V_OA = VOLUME(AIRH2O, T = OADB, B = OAWB, P = 14.7)

V_RA = VOLUME(AIRH2O, T = RADB, B = RAWB, P = 14.7)

m_dot_OA =  (V_dot_OA) / V_OA "lbm / min"

m_dot_RA =  (V_dot_RA) / V_RA

m_dot_MAout = m_dot_OA + m_dot_RA

MADBout = ((m_dot_RA * RADB) + (m_dot_OA * OADB)) / m_dot_MAout

MAWBout = ((m_dot_RA * RAWB) + (m_dot_OA * OAWB)) / m_dot_MAout

V_MA = VOLUME(AIRH2O, T = MADBout, B = MAWBout, P = 14.7)

V_dot_MAout = (V_MA * m_dot_MAout)

W_MAout = HUMRAT(AIRH2O, T = MADBout, B = MAWBout, P = 14.7)

END


"Preheat Coil Simulation"


PROCEDURE Preheat_Coil_Conditions(MADBin, MAWBin, m_dot_MAin, V_dot_MAin, T_water_enter, GPM_coil, W_MAin: PHDBout
    , PHWBout, W_PHout, T_water_out, BTUh_PHsensible)

Eff = 0.65

CP_MA = SPECHEAT(AIRH2O, T = MADBin, B = MAWBin, P = 14.7)

CP_water = SPECHEAT(WATER, T = T_water_enter, X =1)

V_dot_water = GPM_coil * (1 / 264.2) * 35.32 "CFM"

V_water = VOLUME(water, T = T_water_enter, X = 1)

m_dot_water = (V_dot_water) / V_water

C_water = m_dot_water * CP_water

C_air = CP_MA * m_dot_MAin
```

```
IF C_air > C_water THEN

    C_min = C_water "C_h"

    T_water_out = Eff * (MADBin - T_water_enter) + T_water_enter

    Q_max = C_min * (T_water_enter - MADBin)

    PHDBout = ((Eff * Q_max) / C_air) + MADBin

    ELSE

    C_min = C_air "C_c"

    PHDBout =  Eff * (T_water_enter - MADBin) + MADBin

    Q_max = C_min * (T_water_enter - MADBin)

    T_water_out = T_water_enter - ((Eff * Q_max) / C_water)

ENDIF

W_PHout = W_MAin

PHWBout = WETBULB(AIRH2O, T = PHDBout, P = 14.7, R = W_PHout)

BTUh_PHsensible = 1.08 * V_dot_MAin * (PHDBout - MADBin)

END



"Desiccant Performance - Adsorption Simulation"


"h_mod and w_mod are the height and width of the modules in question, in inches"

PROCEDURE Desiccant_Performance(DW_RPM, PHDBin, PHWBin, W_PHin, m_dot_MAin, w_mod, T_mod: DWDBout, DWWBout,
   W_DWout, R_DWout)

Weight_H2O = (W_PHin * m_dot_MAin)  "lbm water / min"

x = RELHUM(AIRH2O, T = PHDBin, B = PHWBin, P = 14.7)

y = 0.95

P_wt_ending = (3 * (10^(-9)) * (x^5)) - (8 * (10^(-7)) * (x^4)) +(0.0001 * (x^3)) - (0.0026 * (x^2)) + (0.1175 *x) +6.0002

P_wt_Starting = (3 * (10^(-9)) * (y^5)) - (8 * (10^(-7)) * (y^4)) +(0.0001 * (y^3)) - (0.0026 * (y^2)) + (0.1175 *y) +6.0002

A_dw = (PI * ((w_mod / 12) ^2) / (4 * 2))

Th_dw = T_mod / 12

Rho_des = 48 "lbm / cu.ft."
```

```
V_des = (A_dw * Th_dw) * 0.6 * DW_RPM

Weight_start = P_wt_starting * V_des * Rho_des

Weight_end = P_wt_ending * V_des * Rho_des

Weight_des_add = ABS(Weight_start - Weight_end)

Weight_H2O_After = Weight_H2O + Weight_des_add

W_DWout = (Weight_H2O_After / m_dot_MAin)

DWDBout = PHDBin

DWWBout = WETBULB(AIRH2O, T = PHDBin, W = W_DWout, P = 14.7)

R_DWout = RELHUM(AIRH2O, T = DWDBout, B = DWWBout, P = 14.7)

END


"Fan Performance Simulation"


PROCEDURE Fan_Performance(DWDBin, DWWBin, V_dot_MAin, HP_fan, Pressure_difference, W_DWin: FANDBout, FANWBout,
   W_FANout)

Eff_fan = (V_dot_MAin * Pressure_difference) / (6350 * HP_fan)

Power_wasted = (1 - Eff_fan) * HP_fan "In HP"

"Assume 75% of waster power goes into thermal gain."

Waste_Btuh = (Power_wasted / 0.001341) * 3.412

Delta_T = Waste_Btuh / (1.08 * V_dot_MAin)

FANDBout = DWDBin + Delta_T

FANWBout = WETBULB(AIRH2O, T = FANDBout, W = W_DWin, P = 14.7)

W_FANout = W_DWin

END


"Cooling Coil Performance Simulation"


PROCEDURE Cooling_coil_performance(W_FANin, FANDBin, FANWBin, m_dot_MAin, V_dot_MAin, T_cwater_enter, GPM_ccoil:
   CCDBout, CCWBout, T_cwater_out, W_CCout, BTUh_CCtotal, BTUh_CClatent, BTUh_CCsensible)

Eff_cc = 0.65

CP_FAN = SPECHEAT(AIRH2O, T = FANDBin, B = FANWBin, P = 14.7)
```

```
CP_water = SPECHEAT(WATER, T = T_cwater_enter, X =1)

V_dot_water = GPM_ccoil * (1 / 264.2) * 35.32 "CFM"

V_water = VOLUME(water, T = T_cwater_enter, X = 1)

m_dot_water = (V_dot_water) / V_water

C_water = m_dot_water * CP_water

C_air = CP_FAN * m_dot_MAin

IF C_air > C_water THEN

    C_min = C_water "C_c"

    CCDBout =  Eff_cc * (T_cwater_enter - FANDBin) + FANDBin

    Q_max = C_min * (T_cwater_enter - FANDBin)

    T_cwater_out = T_cwater_enter - ((Eff_cc * Q_max) / C_water)

    ELSE

    C_min = C_air "C_h"

    T_cwater_out = Eff_cc * (FANDBin - T_cwater_enter) + T_cwater_enter

    Q_max = C_min * (T_cwater_enter - FANDBin)

    CCDBout = ((Eff_cc * Q_max) / C_air) + FANDBin

ENDIF

W_CCout = HUMRAT(AIRH2O, T = CCDBout, B = CCDBout, P = 14.7)

CCWBout = CCDBout

GR_CCout = W_CCout * 7000

GR_FANin = W_FANin * 7000

BTUh_CCsensible = 1.08 * V_dot_MAin * (FANDBin - CCDBout)

BTUh_CClatent = 0.69 * V_dot_MAin * ABS(GR_CCout - GR_FANin)

BTUh_CCtotal = BTUh_CCsensible + BTUh_CClatent

END


"Desiccant Performance - Absorption Simulation"


PROCEDURE Desiccant_Absorption_Perf(DW_RPM, R_DWin, CCDBin, CCWBin, W_CCin, m_dot_MAin, w_mod, T_mod, MADBin:
```

```
    SADB, SAWB, W_SA, Percent_humrat_reduced)

DW_heat = 0.02 * MADBin

V_DA = VOLUME(AIRH2O, T = CCDBin, B = CCWBin, P = 14.7)

Weight_H2O = (W_CCin * m_dot_MAin)  "lbm water / min"

y = R_DWin

x = RELHUM(AIRH2O, T = CCDBin, B = CCWBin, P = 14.7)

P_wt_end = (3 * (10^(-9)) * (x^5)) - (8 * (10^(-7)) * (x^4)) +(0.0001 * (x^3)) - (0.0026 * (x^2)) + (0.1175 *x) +6.0002

P_wt_start = (3 * (10^(-9)) * (y^5)) - (8 * (10^(-7)) * (y^4)) +(0.0001 * (y^3)) - (0.0026 * (y^2)) + (0.1175 *y) +6.0002

A_dw = (PI * ((w_mod / 12) ^2) / (4 * 2))

Th_dw = T_mod / 12

Rho_des = 48 "lbm / cu.ft."

V_des = ((A_dw * Th_dw) *0.6) * DW_RPM

Weight_start = P_wt_start * V_des * Rho_des

Weight_end = P_wt_end * V_des * Rho_des

Weight_des_absorb = ABS(Weight_start - Weight_end)

Weight_H2O_After = Weight_H2O - Weight_des_absorb

W_SA =( Weight_H2O_After / m_dot_MAin)

SADB = CCDBin + DW_heat

SAWB = WETBULB(AIRH2O, T = SADB, W = W_SA, P = 14.7)

Percent_humrat_reduced = 1 - (W_SA / W_CCin)

END


"Moisture Removal"

PROCEDURE Grains_removed_per_hour(W_MAin, W_FANin, W_CCin, W_SAin: Delta_W, Gr_removed_per_hour, GR_MA, GR_SA
    , GR_FAN, GR_CC)

GR_MA = W_MAin * 7000

GR_FAN = W_FANin * 7000

GR_CC = W_ccin * 7000

GR_SA = W_SAin * 7000
```

```
Delta_W = W_FANin - W_SAin

Gr_removed_per_hour = (GR_FAN - GR_SA) * 60

END



"Call Section"

RADB = 70

RAWB = 65

CALL Mixing_Box_Conditions(OADB, OAWB, RADB, RAWB, V_dot_OA, V_dot_RA: MADBout, MAWBout, V_dot_MAout,
   m_dot_MAout, W_MAout)

MADBin = MADBout

MAWBin = MAWBout

V_dot_MAin = V_dot_MAout

m_dot_MAin = m_dot_MAout

W_MAin = W_MAout

CALL Preheat_Coil_Conditions(MADBin, MAWBin, m_dot_MAin, V_dot_MAin, T_water_enter, GPM_coil, W_MAin: PHDBout,
   PHWBout, W_PHout, T_water_out, BTUh_PHsensible)

PHDBin = PHDBout

PHWBin = PHWBout

W_PHin = W_PHout

DW_RPM = 1 / 13

CALL Desiccant_Performance(DW_RPM, PHDBin, PHWBin, W_PHin, m_dot_MAin, w_mod, T_mod: DWDBout, DWWBout,
   W_DWout, R_DWout)

DWDBin = DWDBout

DWWBin = DWWBout

W_DWin = W_DWout

R_DWin = R_DWout

CALL Fan_Performance(DWDBin, DWWBin, V_dot_MAin, HP_fan, Pressure_difference, W_DWin: FANDBout, FANWBout,
   W_FANout)

FANDBin = FANDBout

FANWBin = FANWBout
```

```
W_FANin = W_FANout

T_cwater_enter = 42

CALL Cooling_coil_performance(W_FANin, FANDBin, FANWBin, m_dot_MAin, V_dot_MAin, T_cwater_enter, GPM_ccoil: CCDBout,
    CCWBout, T_cwater_out, W_CCout, BTUh_CCtotal, BTUh_CClatent, BTUh_CCsensible)

CCDBin = CCDBout

CCWBin = CCWBout

W_CCin = W_CCout

CALL Desiccant_Absorption_Perf(DW_RPM, R_DWin, CCDBin, CCWBin, W_CCin, m_dot_MAin, w_mod, T_mod, MADBin: SADB,
    SAWB, W_SA, Percent_humrat_reduced)

W_SAin = W_SA

CALL Grains_removed_per_hour(W_MAin, W_FANin, W_CCin, W_SAin: Delta_W, Gr_removed_per_hour, GR_MA, GR_SA,
    GR_FAN, GR_CC)
```

Parametric Table: Table 1

	OADB	**OAWB**	**GPM_{ccoil}**	**GPM_{coil}**	**HP_{fan}**	**$Pressure_{difference}$**	**$\dot{V}_{OA}$**	**$\dot{V}_{RA}$**	**w_{mod}**
Run 1	79.7	72.3	33	23	8.1	4.74	2000	4000	64
Run 2	79.7	72.3	46	30	10.5	4.62	2815	4685	74
Run 3	79.7	72.3	16	12	5.35	4.19	840	2660	48
Run 4	79.7	72.3	33	22	5.66	4	1800	3700	64
Run 5	89.8	72.5	40	23	8.1	4.74	2000	4000	64
Run 6	89.8	72.5	53	30	10.5	4.62	2815	4685	74
Run 7	89.8	72.5	23	12	5.35	4.19	840	2660	48
Run 8	89.8	72.5	40	22	5.66	4	1800	3700	64
Run 9	65	50	33	23	8.1	4.74	2000	4000	64
Run 10	65	50	46	30	10.5	4.62	2815	4685	74
Run 11	65	50	16	12	5.35	4.19	840	2660	48
Run 12	65	50	33	22	5.66	4	1800	3700	64
Run 13	50	35	33	23	8.1	4.74	6000	0	64
Run 14	50	35	46	30	10.5	4.62	7500	0	74
Run 15	50	35	16	12	5.35	4.19	3500	0	48
Run 16	50	35	33	22	5.66	4	5500	0	64
Run 17	45	30	33	23	8.1	4.74	3000	3000	64
Run 18	45	30	46	30	10.5	4.62	3750	3750	74
Run 19	45	30	16	12	5.35	4.19	1750	1750	48
Run 20	45	30	33	22	5.66	4	2750	2750	64

Parametric Table: Table 1

	T_{mod}	**$T_{water,enter}$**	**CCWBout**	**CCDBout**	**DWDBout**	**DWWBout**	**FANDBout**	**FANWBout**
Run 1	6.065	200	*53.42*	*53.42*	*73.22*	*71.39*	*74.64*	*71.8*

Parametric Table: Table 1

	T_{mod}	$T_{water,enter}$	CCWBout	CCDBout	DWDBout	DWWBout	FANDBout	FANWBout
Run 2	7.065	200	*53.62*	*53.62*	*73.62*	*72.59*	*75.21*	*73.04*
Run 3	4.36	200	*53.33*	*53.33*	*72.32*	*69.57*	*74.36*	*70.18*
Run 4	6.065	200	*53.24*	*53.24*	*73.16*	*71.69*	*74.1*	*71.97*
Run 5	6.065	200	*54.56*	*54.56*	*76.47*	*71.46*	*77.89*	*71.87*
Run 6	7.065	200	*54.91*	*54.91*	*77.29*	*72.68*	*78.87*	*73.12*
Run 7	4.36	200	*54.14*	*54.14*	*74.64*	*69.61*	*76.69*	*70.22*
Run 8	6.065	200	*54.35*	*54.35*	*76.35*	*71.76*	*77.29*	*72.03*
Run 9	6.065	200	*51.72*	*51.72*	*68.34*	*64.56*	*69.77*	*65.03*
Run 10	7.065	200	*51.7*	*51.7*	*68.13*	*65.06*	*69.72*	*65.59*
Run 11	4.36	200	*52.1*	*52.1*	*68.81*	*64.51*	*70.86*	*65.19*
Run 12	6.065	200	*51.56*	*51.56*	*68.38*	*65.04*	*69.32*	*65.35*
Run 13	6.065	200	*45.31*	*45.31*	*50.04*	*42.06*	*51.46*	*42.78*
Run 14	7.065	200	*45.37*	*45.37*	*50.04*	*43.67*	*51.62*	*44.45*
Run 15	4.36	200	*45.53*	*45.53*	*50.03*	*39.99*	*52.08*	*41.06*
Run 16	6.065	200	*45.14*	*45.14*	*50.04*	*42.66*	*50.98*	*43.13*
Run 17	6.065	200	*47.79*	*47.79*	*57.12*	*52.76*	*58.55*	*53.36*
Run 18	7.065	200	*47.85*	*47.85*	*57.12*	*54.09*	*58.71*	*54.74*
Run 19	4.36	200	*48.01*	*48.01*	*57.12*	*51.04*	*59.17*	*51.93*
Run 20	6.065	200	*47.62*	*47.62*	*57.12*	*53.26*	*58.07*	*53.65*

Parametric Table: Table 1

	PHDBout	PHWBout	MADBout	MAWBout	W_{MAout}	$\dot{m}_{MAout}$	SADB	SAWB
Run 1	*73.22*	*45.58*	*73.18*	*67.4*	*0.01303*	*437.5*	*54.89*	*53.54*
Run 2	*73.62*	*45.79*	*73.59*	*67.7*	*0.01316*	*546.4*	*55.09*	*53.89*
Run 3	*72.32*	*45.12*	*72.29*	*66.72*	*0.01275*	*255.8*	*54.77*	*53.42*
Run 4	*73.16*	*45.55*	*73.12*	*67.35*	*0.01301*	*401.1*	*54.7*	*53.41*
Run 5	*76.47*	*47.14*	*76.43*	*67.44*	*0.01231*	*435.4*	*56.09*	*53.95*
Run 6	*77.29*	*47.54*	*77.25*	*67.75*	*0.01235*	*543.4*	*56.45*	*54.13*
Run 7	*74.64*	*46.25*	*74.61*	*66.75*	*0.01222*	*254.9*	*55.63*	*53.88*
Run 8	*76.35*	*47.09*	*76.31*	*67.39*	*0.0123*	*399.2*	*55.88*	*53.73*
Run 9	*68.34*	*42.99*	*68.31*	*59.93*	*0.009076*	*444.2*	*53.08*	*51.22*
Run 10	*68.13*	*42.87*	*68.1*	*59.29*	*0.00873*	*555.7*	*53.06*	*51.18*
Run 11	*68.81*	*43.25*	*68.78*	*61.34*	*0.009867*	*258.6*	*53.48*	*51.85*
Run 12	*68.38*	*43*	*68.34*	*60.02*	*0.009127*	*407.1*	*52.93*	*51.1*
Run 13	*50.04*	*32.7*	*50*	*35*	*0.0008954*	*466.4*	*46.31*	*42.52*
Run 14	*50.04*	*32.71*	*50*	*35*	*0.0008954*	*583.1*	*46.37*	*42.55*
Run 15	*50.03*	*32.7*	*50*	*35*	*0.0008954*	*272.1*	*46.53*	*43.21*
Run 16	*50.04*	*32.71*	*50*	*35*	*0.0008954*	*427.6*	*46.14*	*42.29*
Run 17	*57.12*	*36.85*	*57.08*	*46.92*	*0.004478*	*456.2*	*48.93*	*46.76*
Run 18	*57.12*	*36.85*	*57.08*	*46.92*	*0.004478*	*570.2*	*48.99*	*47.02*
Run 19	*57.12*	*36.85*	*57.08*	*46.92*	*0.004478*	*266.1*	*49.15*	*47.06*
Run 20	*57.12*	*36.85*	*57.08*	*46.92*	*0.004478*	*418.1*	*48.77*	*46.64*

Parametric Table: Table 1

	$T_{cwater,out}$	$T_{water,out}$	W_{CCout}	$\dot{V}_{MAout}$	W_{DWout}	W_{FANout}	W_{PHout}	W_{SA}
Run 1	*63.22*	*117.6*	*0.008672*	*5999*	*0.01611*	*0.01611*	*0.01303*	*0.008402*
Run 2	*63.59*	*117.8*	*0.008736*	*7499*	*0.01701*	*0.01701*	*0.01316*	*0.008546*
Run 3	*63.04*	*117*	*0.008641*	*3500*	*0.01488*	*0.01488*	*0.01275*	*0.00836*
Run 4	*62.87*	*117.5*	*0.008612*	*5499*	*0.01638*	*0.01638*	*0.01301*	*0.008375*
Run 5	*65.33*	*119.7*	*0.009046*	*5999*	*0.01541*	*0.01541*	*0.01231*	*0.008353*
Run 6	*65.97*	*120.2*	*0.009162*	*7499*	*0.01621*	*0.01621*	*0.01235*	*0.008371*

Parametric Table: Table 1

	$T_{cwater,out}$	$T_{water,out}$	W_{CCout}	$\dot{V}_{MAout}$	W_{DWout}	W_{FANout}	W_{PHout}	W_{SA}
Run 7	64.55	118.5	0.008906	3500	0.01437	0.01437	0.01222	0.008415
Run 8	64.94	119.6	0.008976	5499	0.01568	0.01568	0.0123	0.008281
Run 9	60.05	114.4	0.008138	5997	0.01213	0.01213	0.009076	0.007562
Run 10	60.02	114.3	0.008133	7496	0.01253	0.01253	0.00873	0.007545
Run 11	60.76	114.7	0.008255	3498	0.01198	0.01198	0.009867	0.007805
Run 12	59.76	114.4	0.00809	5497	0.01245	0.01245	0.009127	0.007534
Run 13	48.15	102.5	0.006383	6000	0.003825	0.003825	0.0008954	0.004869
Run 14	48.26	102.5	0.006397	7500	0.004545	0.004545	0.0008954	0.004872
Run 15	48.55	102.5	0.006437	3500	0.002926	0.002926	0.0008954	0.005135
Run 16	47.84	102.5	0.006342	5500	0.004091	0.004091	0.0008954	0.004808
Run 17	52.76	107.1	0.007018	5983	0.007462	0.007462	0.004478	0.006254
Run 18	52.86	107.1	0.007033	7479	0.008195	0.008195	0.004478	0.006365
Run 19	53.16	107.1	0.007076	3490	0.006546	0.006546	0.004478	0.006348
Run 20	52.44	107.1	0.006973	5485	0.007733	0.007733	0.004478	0.006231

Parametric Table: Table 1

	$Percent_{humrat,reduced}$	δ_W	$Gr_{removed,per,hour}$	GR_{SA}	GR_{FAN}	$BTUh_{PHsensible}$	$BTUh_{CCtotal}$
Run 1	0.03109	0.007712	3239	58.82	112.8	218.7	353095
Run 2	0.02176	0.008461	3553	59.82	119	284.6	474350
Run 3	0.03258	0.006519	2738	58.52	104.2	114.7	184944
Run 4	0.02751	0.008001	3360	58.62	114.6	209.3	330133
Run 5	0.07653	0.007054	2963	58.47	107.8	214.4	335458
Run 6	0.08631	0.007844	3294	58.6	113.5	278.3	449558
Run 7	0.05521	0.005952	2500	58.9	100.6	113.1	177515
Run 8	0.07745	0.007402	3109	57.96	109.8	205.3	314367
Run 9	0.0708	0.004564	1917	52.93	84.88	225.3	232404
Run 10	0.07221	0.004982	2092	52.82	87.69	294.2	304972
Run 11	0.05448	0.004179	1755	54.64	83.89	117.2	133882
Run 12	0.06876	0.00492	2066	52.74	87.18	215.4	221278
Run 13	0.2372	-0.001044	-438.5	34.08	26.78	248.2	113979
Run 14	0.2384	-0.0003264	-137.1	34.1	31.82	323.7	117753
Run 15	0.2022	-0.002209	-927.6	35.94	20.48	129.5	84110
Run 16	0.242	-0.0007161	-300.8	33.65	28.64	237.4	94463
Run 17	0.1089	0.001208	507.4	43.77	52.23	239.5	82346
Run 18	0.09508	0.001831	769	44.55	57.37	312.4	129746
Run 19	0.1029	0.0001979	83.12	44.44	45.82	125	51011
Run 20	0.1064	0.001502	630.8	43.62	54.13	229.1	82003

Parametric Table: Table 1

	$BTUh_{CCsensible}$	$BTUh_{CClatent}$
Run 1	137454	215641
Run 2	174807	299543
Run 3	79508	105435
Run 4	123921	206212
Run 5	151133	184326
Run 6	194103	255456
Run 7	85226	92289
Run 8	136228	178139
Run 9	116893	115512
Run 10	145863	159109
Run 11	70875	63007

Parametric Table: Table 1

	$BTUh_{CCsensible}$	$BTUh_{CClatent}$
Run 12	*105416*	*115862*
Run 13	*39846*	*74133*
Run 14	*50671*	*67082*
Run 15	*24769*	*59342*
Run 16	*34673*	*59790*
Run 17	*69519*	*12827*
Run 18	*87761*	*41985*
Run 19	*42077*	*8935*
Run 20	*61870*	*20133*

Appendix D

Trane Trace Results

Trane Trace Results

Current Conditions - Coils 100% On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,611,815.80	1,707,772.30	1,611,232.10	1,603,971.30
Gas Consumption (Therms)	9,653.70	10,015.10	9,686.80	9,813.50
Total Energy Consumption (kBtu / yr)	175,212.10	185,418.50	175,187.10	174,577.00

Desiccant Wheels with HEPA Filters - Coils 100% On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,710,756.60	1,821,906.10	1,714,693.40	1,688,960.90
Gas Consumption (Therms)	9,398.50	10,006.50	9,391.10	9,556.10
Total Energy Consumption (kBtu / yr)	185,075.00	197,096.80	185,470.40	183,009.10
kBtu / yr Saved	-9,862.90	-11,678.30	-10,283.30	-8,432.10
Percent Decrease from Base	-5.63	-6.30	-5.87	-4.83

Desiccant Wheels with Orginally Specified Filters - Coils 100% On

Alternative	Base Loads	Full Arena Load	Full Theater Load	Full Theater and Arena Load
Electric Consumption (kWh)	1,645,949.50	1,742,176.40	1,654,321.00	1,639,353.40
Gas Consumption (Therms)	9,622.50	10,230.00	9,655.00	9,785.20
Total Energy Consumption (kBtu / yr)	178,674.50	189,167.70	178,644.40	178,170.40
Total kBtu/yr Saved	-3,462.40	-3,749.20	-3,457.30	-3,593.40
Percent Decrease from Base	-1.98	-2.02	-1.97	-2.06
Percent Decrease from HEPA	3.46	4.02	3.68	2.64

Desiccant Wheels, Original Filters, Enthalpy based Economizer - Coils 100%On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,529,858.50	1,611,802.50	1,533,323.10	1,527,469.00
Gas Consumption (Therms)	9,029.10	9,324.60	9,018.20	9,142.90
Total Energy Consumption (kBtu / yr)	166,162.20	174,864.30	166,505.50	166,037.30
Total kBtu/yr Saved	9,049.90	10,554.20	8,681.60	8,539.70
Percent Decrease from Base	5.17	5.69	4.96	4.89
Percent Decrease from HEPA	10.22	11.28	10.23	9.27
Percent Decrease From Original F.	7.00	7.56	6.80	6.81

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - Coils 100%On				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,511,134.80	1,587,244.30	1,510,555.40	1,503,354.40
Gas Consumption (Therms)	8,968.50	9,202.40	8,999.90	9,131.70
Total Energy Consumption (kBtu / yr)	164,181.10	172,220.90	164,154.80	163,556.10
Total kBtu/yr Saved	11,031.00	13,197.60	11,032.30	11,020.90
Percent Decrease from Base	6.30	7.12	6.30	6.31
Percent Decrease from HEPA	11.29	12.62	11.49	10.63
Percent Decrease From Original F.	8.11	8.96	8.11	8.20
Percent Decrease From Previous	1.19	1.51	1.41	1.49

Base Case - 100% on at Night, 50% on Sundays				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,378,903.40	1,417,596.00	1,400,342.40	1,380,005.90
Gas Consumption (Therms)	3,785.30	3,483.50	3,766.40	3,811.10
Total Energy Consumption (kBtu / yr)	145,184.60	148,829.00	147,360.00	145,324.60

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - 100% On at Night, 50% On - Sundays				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,154,734.80	1,147,650.90	1,190,394.60	1,154,755.50
Gas Consumption (Therms)	5,412.60	5,577.90	5,262.40	5,448.60
Total Energy Consumption (kBtu / yr)	123,942.60	123,391.10	127,436.00	123,982.60
kBtu / yr Saved	21,242.00	25,437.90	19,924.00	21,342.00
Percent Decrease from Base	14.63	17.09	13.52	14.69

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - 60% On at Night, Follow Loads with Around 30% Increase				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,308,571.40	1,301,008.30	1,359,849.30	1,308,446.90
Gas Consumption (Therms)	7,384.30	7,548.90	7,400.70	7,419.30
Total Energy Consumption (kBtu / yr)	141,771.00	141,169.80	147,039.10	141,795.10
Total kBtu/yr Saved	3,413.60	7,659.20	320.90	3,529.50
Percent Decrease from Base	2.35	5.15	0.22	2.43
Percent Decrease from Previous	-14.38	-14.41	-15.38	-14.37

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - 60% On at Night, Follow Loads with Around 30% Increase - Add power for DW Motor				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,308,721.50	1,360,000.50	1,308,596.50	1,301,157.50
Gas Consumption (Therms)	7,384.30	7,400.70	7,419.30	7,548.90
Total Energy Consumption (kBtu / yr)	141,786.40	147,054.60	141,810.40	141,185.10
Total kBtu/yr Saved	3,398.20	1,774.40	5,549.60	4,139.50
Percent Decrease from Base	2.34	1.19	3.77	2.85
Percent Decrease from 2	-14.40	-19.18	-11.28	-13.87
Percent Decrease 3	-0.01	-4.17	3.56	0.43

Better Efficiency Desiccant Wheels, Original Filters, Enthalpy based Economizer - 100% On at Night, 50% On - Sundays - Add Power for DW Motor				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,154,831.40	1,190,490.90	1,154,851.80	1,147,746.80
Gas Consumption (Therms)	5,412.60	5,262.40	5,448.60	5,577.90
Total Energy Consumption (kBtu / yr)	123,952.50	127,445.90	123,992.40	123,401.00
Total kBtu/yr Saved	21,232.10	21,383.10	23,367.60	21,923.60
Percent Decrease from Base	14.62	14.37	15.86	15.09
Percent Decrease from 2	-0.01	-3.29	2.70	0.47
Percent Decrease From 3.	12.57	9.72	15.67	12.97
Percent Decrease From Previous	12.58	13.33	12.56	12.60

Base Case				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,032,727.60	1,052,184.30	1,026,228.80	1,035,213.00
Gas Consumption (Therms)	3,829.10	3,789.10	3,491.20	3,789.60
Total Energy Consumption (kBtu / yr)	109,782.10	111,732.40	109,234.70	109,995.10

Desiccant Wheels with HEPA Filters				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	977,323.40	1,001,223.90	980,504.60	972,325.20
Gas Consumption (Therms)	5,125.50	4,906.10	5,084.90	5,185.40
Total Energy Consumption (kBtu / yr)	105,473.40	107,689.90	105,756.40	105,024.60
kBtu / yr Saved	4,308.70	4,042.50	3,478.30	4,970.50
Percent Decrease from Base	3.92	3.62	3.18	4.52

Desiccant Wheels with Orginally Specified Filters				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	973,549.60	987,211.50	972,412.20	964,780.80
Gas Consumption (Therms)	5,196.40	5,104.70	5,199.80	5,300.00
Total Energy Consumption (kBtu / yr)	105,161.60	106,464.10	105,048.70	104,372.80
Total kBtu/yr Saved	4,620.50	5,268.30	4,186.00	5,622.30
Percent Decrease from Base	4.21	4.72	3.83	5.11
Percent Decrease from HEPA	0.30	1.14	0.67	0.62

Desiccant Wheels, Original Filters, Enthalpy based Economizer				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	950,029.10	972,571.10	953,092.50	946,015.10
Gas Consumption (Therms)	5,197.30	4,972.20	5,155.30	5,252.30
Total Energy Consumption (kBtu / yr)	102,754.00	104,825.40	103,023.50	102,401.00
Total kBtu/yr Saved	7,028.10	6,907.00	6,211.20	7,594.10
Percent Decrease from Base	6.40	6.18	5.69	6.90
Percent Decrease from HEPA	2.58	2.66	2.58	2.50
Percent Decrease From Original F.	2.29	1.54	1.93	1.89

Base Case - Normal Loads				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	1,032,727.60	1,074,684.40	1,053,184.10	1,035,213.00
Gas Consumption (Therms)	3,829.10	3,446.70	3,780.80	3,789.60
Total Energy Consumption (kBtu / yr)	109,782.10	113,676.00	111,826.10	109,995.10

Desiccant Wheels with HEPA Filters, Better Effectiveness				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	975,062.40	1,004,617.40	974,119.30	965,495.40
Gas Consumption (Therms)	5,112.60	5,026.40	5,127.80	5,236.60
Total Energy Consumption (kBtu / yr)	105,238.90	108,164.00	105,147.80	104,379.10
kBtu / yr Saved	4,543.20	5,512.00	6,678.30	5,616.00
Percent Decrease from Base	4.14	4.85	5.97	5.11

Desiccant Wheels with Orginally Specified Filters, Better Effectiveness				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	970,705.10	991,955.10	973,742.60	961,265.30
Gas Consumption (Therms)	5,196.50	4,972.10	5,154.50	5,313.30
Total Energy Consumption (kBtu / yr)	104,870.40	106,810.20	105,137.30	104,026.70
Total kBtu/yr Saved	4,911.70	6,865.80	6,688.80	5,968.40
Percent Decrease from Base	4.47	6.04	5.98	5.43
Percent Decrease from HEPA	0.35	1.25	0.01	0.34

Desiccant Wheels, Original Filters, Enthalpy based Economizer, Better Effectiveness				
Alternative	**Base Loads**	**Full Arena Load**	**Full Theater Load**	**Full Theater and Arena Load**
Electric Consumption (kWh)	947,184.40	968,434.40	950,218.60	938,169.60
Gas Consumption (Therms)	5,197.20	4,972.10	5,155.30	5,312.30
Total Energy Consumption (kBtu / yr)	102,462.70	104,401.70	102,729.20	101,660.70
Total kBtu/yr Saved	7,319.40	9,274.30	9,096.90	8,334.40
Percent Decrease from Base	6.67	8.16	8.13	7.58
Percent Decrease from HEPA	2.64	3.48	2.30	2.60
Percent Decrease From Original F.	2.30	2.25	2.29	2.27

Appendix E

Physical Layout

Air Handling Unit 1: Auxiliary Gymnasium			
Unit Size:	12		
Module	**Width**	**Length**	**Height**
Mixing Box and Filters	64	34	39
Filters	In M. Box		
Dampers	64	15.5	39
Heating Coil	64	19	39
Access Door	64	11	39
Desiccant Wheel	64	6.065	39
Fan	64	39	39
Turning Vanes	64	39	39
Cooling Coil	64	15.5	39
Discharge Plenum	64	39	34

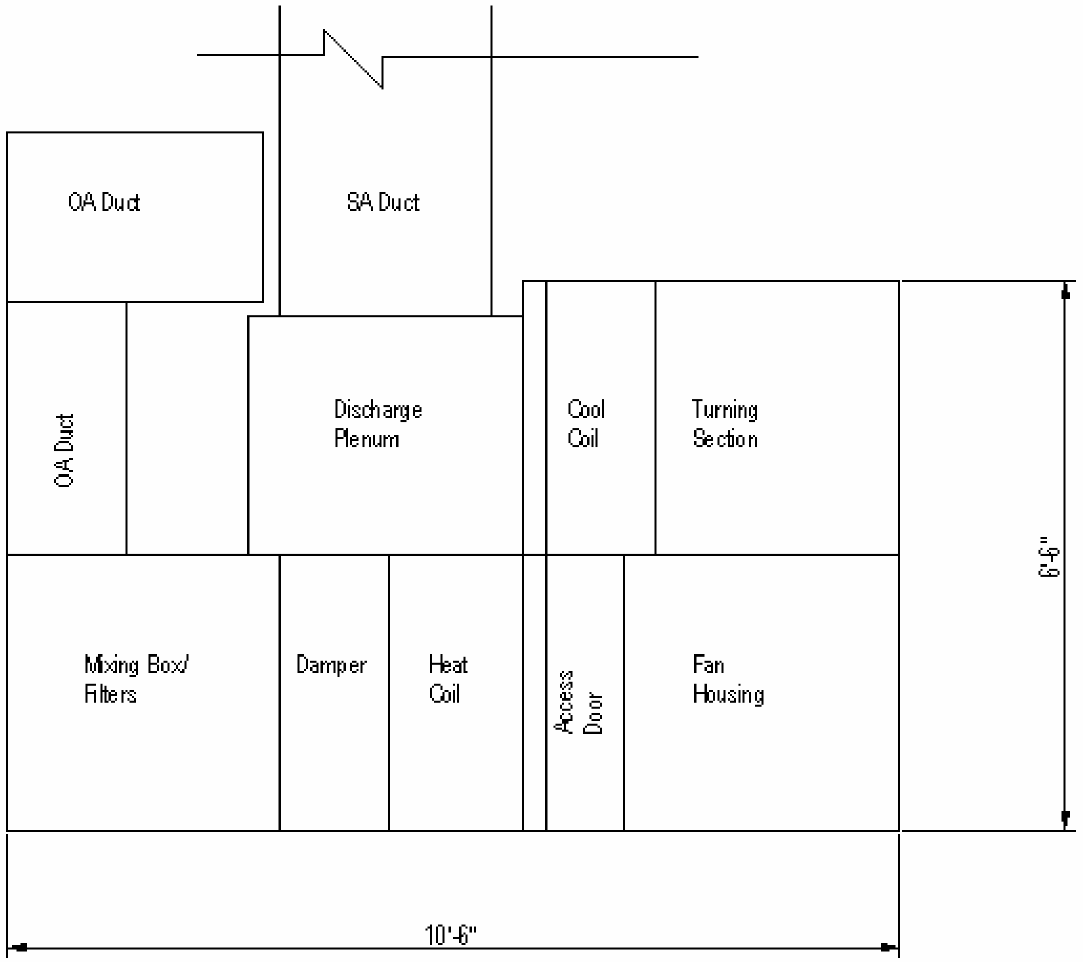
Air Handling Unit 2 - 5: Main Arena			
Unit Size:	17		
Module	**Width**	**Length**	**Height**
Mxing Box	74	34	44
Filters	In M.Box		
Dampers	74	15.5	44
Heating Coil	74	15.5	44
Access Door	74	15.5	44
Desiccant Wheel	74	7.065	44
Fan	74	44	44
Turning Vanes	74	44	44
Cooling Coil	74	15.5	44
Discharge Plenum	74	34	44

Air Handling Unit 6: Fitness Center			
Unit Size:	8		
Module	**Width**	**Length**	**Height**
Mixing Box and Filters	48	34	34
Filters	In M. Box		
Dampers	48	15.5	34
Heating Coil	48	15.5	34
Access Door	48	34	34
Desiccant Wheel	48	6.065	34
Fan	48	44	34
Turning Vanes	48	40.5	34
Cooling Coil	48	15.5	34
Discharge Plenum	48	34	34

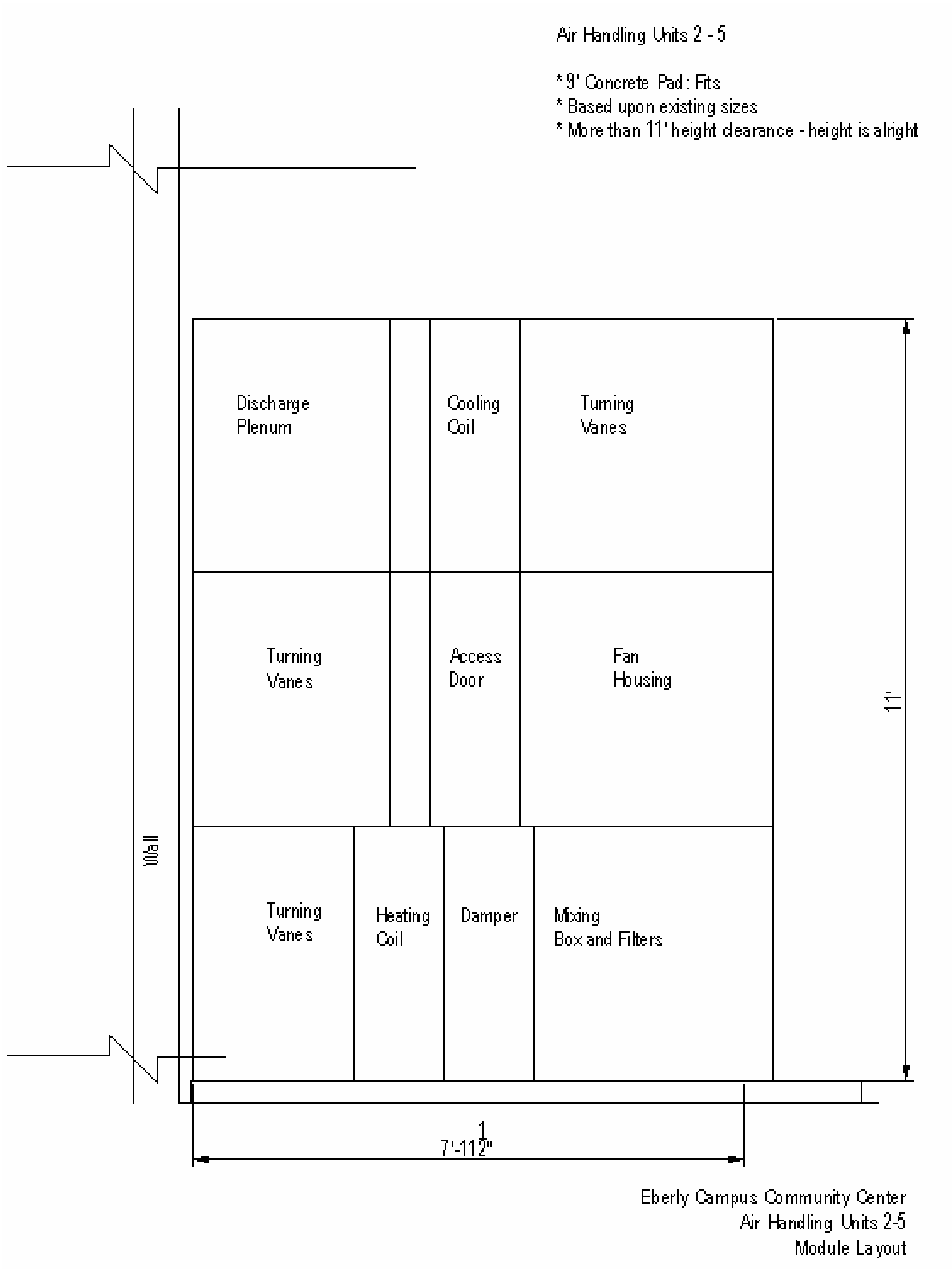
Air Handling Unit 9 - 10: Theater			
Unit Size:	12		
Module	**Width**	**Length**	**Height**
Mixing Box and Filters	64	34	39
Filters	In M. Box		
Dampers	64	15.5	39
Heating Coil	64	15.5	39
Access Door	64	34	39
Desiccant Wheel	64	6.065	39
Fan	64	39	39
Turning Vanes	64	39	39
Cooling Coil	64	15.5	39
Discharge Plenum	64	34	39

Air Handling Unit 1

* 11' Concrete Pad fits
* Sized using existing Conditions
* Vertical Height has not changed



Eberly Campus Community Center
Air Handling Unit 1
Module Layout



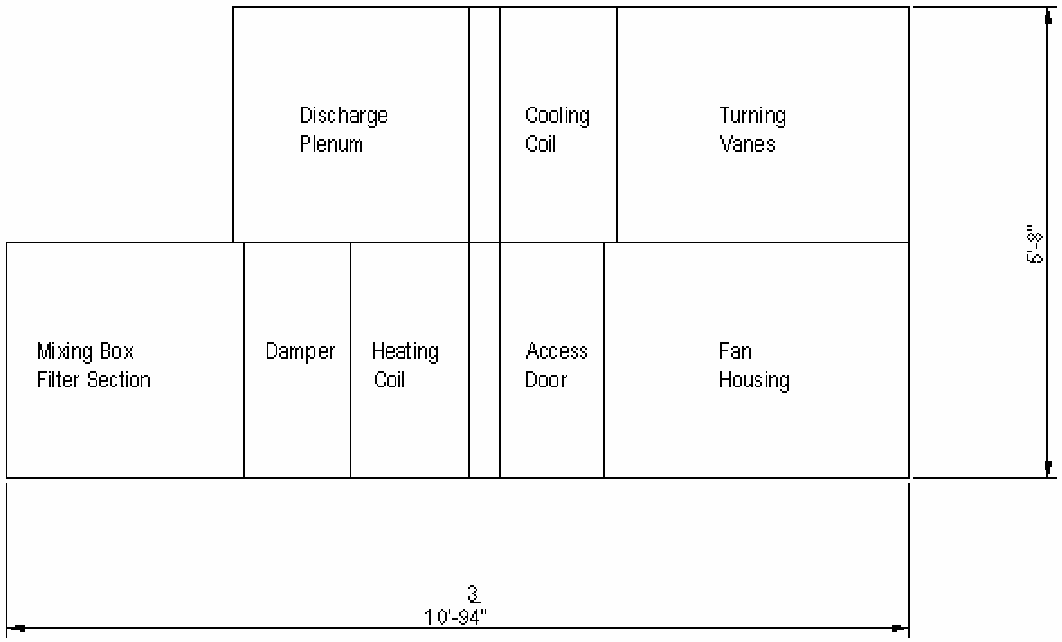
Air Handling Units 2 - 5

* 9' Concrete Pad: Fits
* Based upon existing sizes
* More than 11' height clearance - height is alright

Eberly Campus Community Center
Air Handling Units 2-5
Module Layout

Air Handling Unit 6

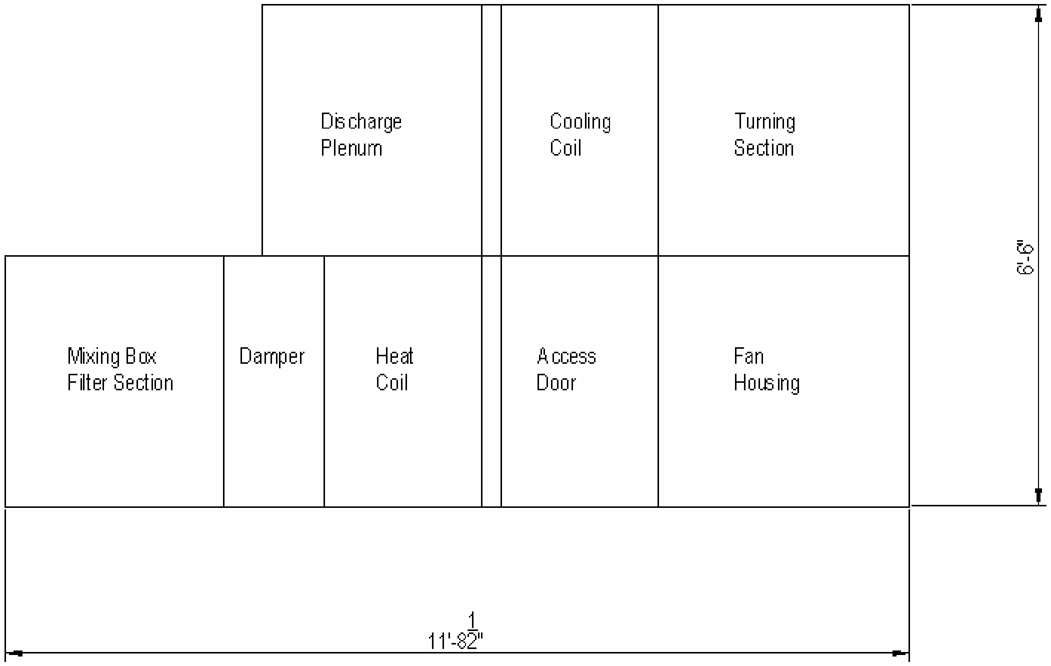
* 11' Concrete Pad Limiting Factor
* Vertically fits
* Second Tier cuts it close with OA ductwork, but fits



Eberly Campus Community Center
Air Handling Unit 6
Module Layout

Air Handling Unit 9 - 10

* 14' Concrete Pad: fits
* Sized according to existing equipment



Eberly Campus Community Center
Air Handling Units 9-10
Module Layout

Appendix F

Electrical System Checks

PANEL 4MEC -ORIGINAL			480/277 VOLT, 3 PHASE, 4 WIRE								225 AMP MLO
Location / Item	VA	Wire	BKR	Pole	CKT	CKT	Pole	BKR	Wire	VA	Location / Item
FC-2,UV-1,102C	1400	12	20	1	1	2	3	20			SPARE
AHU-9	2016	12	20	3	3	4					
	2016	12			5	6					
	2016	12			7	8	3	20		566	MUA-2
AHU-10	2016	12	20	3	9	10				566	
	2016	12			11	12				566	
	2016	12			13	14	3	20		2016	EF-2
AHU-8	5566	8	40	3	15	16				2016	
	5566	8			17	18				2016	
	5566	8			19	20	3	60		10000	XFMR T-5
SPARE			20	1	21	22				10000	
SPARE			20	1	23	24				10000	
SPARE			20	1	25	26	1	20	12	831	EF-1 ON ROOF
SPARE			20	1	27	28	1	20	12	831	EF-1 ON ROOF
SPARE					29	30	1	20	12	831	EF-1 ON ROOF
SPACE					31	32					SPACE
SPACE					33	34					SPACE
SPACE					35	36					SPACE
SPACE					37	38					SPACE
SPACE					39	40					SPACE
SPACE					41	42					SPACE

VA: 28794

TOTAL VA: 69033

VA: 40239

TOTAL AMPS: 144

PANEL 4MEC - UPDATED				480/277 VOLT, 3 PHASE, 4 WIRE							225 AMP MLO
Location / Item	VA	Wire	BKR	Pole	CKT	CKT	Pole	BKR	Wire	VA	Location / Item
FC-2,UV-1,102C	1400	12	20	1	1	2	3	20			SPARE
AHU-9	2518	12	20	3	3	4					
	2518	12			5	6					
	2518	12			7	8	3	20		566	MUA-2
AHU-10	2518	12	20	3	9	10				566	
	2518	12			11	12				566	
	2518	12			13	14	3	20		2016	EF-2
AHU-8	5566	8	40	3	15	16				2016	
	5566	8			17	18				2016	
	5566	8			19	20	3	60		10000	XFMR T-5
SPARE			20	1	21	22				10000	
SPARE			20	1	23	24				10000	
SPARE			20	1	25	26	1	20	12	831	EF-1 ON ROOF
SPARE			20	1	27	28	1	20	12	831	EF-1 ON ROOF
SPARE					29	30	1	20	12	831	EF-1 ON ROOF
SPACE					31	32					SPACE
SPACE					33	34					SPACE
SPACE					35	36					SPACE
SPACE					37	38					SPACE
SPACE					39	40					SPACE
SPACE					41	42					SPACE

VA: 31806

TOTAL VA: 72045

VA: 40239

TOTAL AMPS: 150

INCOMING FEEDER: 4 4/0 - 4 GROUND IN 2-1/2" C

AMPACITY = 260 * 0.8 = 208 A: 150 * 1.25 = 188 A: OK

Factor of 0.8 for 4 - 6 Conductors in Raceway

Conclusion: This panelboard can handle the extra load with space to spare

BRANCH CIRCUITS:

AHU-9, AHU-10: 2518 VA = 5.3 A Circuit
#12 Wire Holds 30 A: 5.3 * 1.25 = 6.6 A: OK

PANEL 4MEA-ORIGIN 480/277 VOLT, 3 PHASE, 4 WIRE 600 AMP MLO

Location / Item	VA	Wire	BKR	Pole	CKT	CKT	Pole	BKR	Wire	VA	Location / Item
AHU-1	2933	12	20	3	1	2	1	20	12	270	FC-2 Q104J14A
	2933	12			3	4	1	20	12	1190	FC-1 106-112
	2933	12			5	6	3	20	12	433	EF-15
P-2	3733	10	30	3	7	8			12	433	
	3733	10			9	10			12	433	
	3733	10			11	12	3	30	10	3733	AHU-2
P-1	3733	10	20	3	13	14			10	3733	
	3733	10			15	16			10	3733	
	3733	10			17	18	3	30	10	3733	AHU-4
AHU-3	800	12	30	3	19	20			10	3733	
	800	12			21	22			10	3733	
	800	12			23	24	3	20	12	2016	AHU-5
AHU-5	1266	12	30	3	25	26			12	2016	
	1266	12			27	28			12	2016	
	1266	12			29	30	3	225	.4/0	23788	PANEL 4MEC
AHU-7A	7950	6	20	3	31	32				23788	
	7950	6			33	34				23788	
	7950	6			35	36	3	40	8	5817	P-3
SPACE				3	37	38			8	5817	
					39	40			8	5817	
					41	42	3	30	10	3878	P-2
XFMR T-4	7950		70	3	43	44			10	3878	
	7950				45	46			10	3878	
	7950				47	48	1	20			SPARE
BP-1	831		20	3	49	50	3	20	12	942	CAU-1
	831				51	52			12	942	
	831				53	54			12	942	
SPARE		12	20	1	55	56	3	225	.4/0	22947	PANEL 4MEC
SPARE		12	20	1	57	58			.4/0	22947	
SPARE			20	1	59	60			.4/0	22947	
BP-2	831	12	20	3	61	62	3	40			SPARE
	831	12			63	64					
	831	12			65	66					
SPARE		12	30	3	67	68	3				SPACE
		12			69	70					
		12			71	72					

VA: 90081

TOTAL VA: 293402

VA: 203321

TOTAL AMPS: 611

PANEL 4MEA - UPDAT				480/277 VOLT, 3 PHASE, 4 WIRE							600 AMP MLO
Location / Item	VA	Wire	BKR	Pole	CKT	CKT	Pole	BKR	Wire	VA	Location / Item
AHU-1	3360	12	20	3	1	2	1	20	12	270	FC-2 Q104J14A
	3360	12			3	4	1	20	12	1190	FC-1 106-112
	3360	12			5	6	3	20	12	433	EF-15
P-2	3733	10	30	3	7	8			12	433	
	3733	10			9	10			12	433	
	3733	10			11	12	3	30	10	4115	AHU-2
P-1	3733	10	20	3	13	14			10	4115	
	3733	10			15	16			10	4115	
	3733	10			17	18	3	30	10	4115	AHU-4
AHU-3	1182	12	30	3	19	20			10	4115	
	1182	12			21	22			10	4115	
	1182	12			23	24	3	20	12	2286	AHU-6
AHU-5	1648	12	30	3	25	26			12	2286	
	1648	12			27	28			12	2086	
	1648	12			29	30	3	225	.4/0	24015	PANEL 4MEC
AHU-7A	7950	6	20	3	31	32				24015	
	7950	6			33	34				24015	
	7950	6			35	36	3	40	8	5817	P-3
SPACE				3	37	38			8	5817	
					39	40			8	5817	
					41	42	3	30	10	3878	P-2
XFMR T-4	7950		70	3	43	44			10	3878	
	7950				45	46			10	3878	
	7950				47	48	1	20			SPARE
BP-1	831		20	3	49	50	3	20	12	942	CAU-1
	831				51	52			12	942	
	831				53	54			12	942	
SPARE		12	20	1	55	56	3	225	.4/0		PANEL 4MEC
SPARE		12	20	1	57	58			.4/0		
SPARE			20	1	59	60			.4/0		
BP-2	831	12	20	3	61	62	3	40			SPARE
	831	12			63	64					
	831	12			65	66					
SPARE		12	30	3	67	68	3				SPACE
		12			69	70					
		12			71	72					

VA: 93654

TOTAL VA: 231717

VA: 138063

TOTAL AMPS: 483

FEEDER WIRE: 2 SETS (4)350KCM & 1 GROUND IN 3" C

Max conductors for 3" C, 350 KCM = 4: OK

All wires: 90 deg. C, Heat Resistant Type THHN

AMPACITY = 350 * 2 * 0.8 = 560 A: 483 * 1.25 = 604 A.

Factor of 0.8 for 4 - 6 Conductors in Raceway

Conclusion: The system wiring will be fine, just do not connect any more loads if possible

BRANCH CIRCUITS:

AHU-1: 3360 VA = 7 A Circuit
#12 Wire Holds 30 A: 7 * 1.25 = 8.75 A: OK

AHU-2, AHU-4: 4115 VA = 8.6 A Circuit
#10 Wire Holds 40 A: 8.6 * 1.25 = 10.75 A: OK

AHU-3: 1182 VA = 2.5 A Circuit
#12 Wire Holds 30 A: 2.5 * 1.25 = 3.13 A: OK

AHU-5: 1648 VA = 3.4 A Circuit
#12 Wire Holds 30 A: 3.4 * 1.25 = 4.25 A: OK

AHU-6: 1648 VA = 4.8 A Circuit
#12 Wire Holds 30 A: 4.8 * 1.25 = 6 A: OK

Grounding Electrode Check

2 Electrodes, located within feet of one another.

- Tripod type Rod and Pipe electrode
- Metal Underground Water Pipe

Both coming off of the MDP
- Tripod connected to the ground bus
- Water Main connected to the panelboard enclosure

Complys with following NEC Recommendations:

150.104 Bonding of Piping Systems and Exposed Structural Steel
  (D)(1) - Shall be bonded at system's grounding electrode
    Exception 1: Separate Bonding Jumper not req. where
    metal water piping system is used as grounding electrode.

250.52 Grounding electrodes
  (A) Permitted electrodes (1) Metal Underground Water Pipe

250.53 Grounding Electrode System Installation
  (D) Metal Underground Water Pipe
    (2) Supplemental Electrode Required
    connected to any part of the system

Appendix G

Structural System Checks

Air Handling Unit 1: Auxiliary Gymnasium					
Unit Size:	12				
Module	**Width**	**Length**	**Height**	**Weight**	**Original Weight**
Mixing Box and Filters	64	34	39	334	334
Filters	In M. Box			223	223
Dampers	64	15.5	39	213	213
Heating Coil	64	19	39	405	405
Access Door	64	11	39	240	240
Desiccant Wheel	64	6.065	39	1051	
Desiccant Wheel Motor				12	
Inlet Guide Vanes				46	46
Starter				65	65
VFD				180	180
Fan	64	39	39	632	632
Turning Vanes	64	39	39	333	
Cooling Coil	64	15.5	39	405	405
Discharge Plenum	64	39	34	279	279
	Total Length:	124.565	**Totals:**	4418	3022
			Change:	23.66	lb / sq. ft.

Area of Concrete Pad:	59	sq. ft.	
Weight of Concrete Pad (6") - 150 pcf:	4,425	lb	
Weight of Floor System:	75.00	lb / sq.ft.	*6" Concrete SOG with 6x6 W2.9xW2.9 WWF
Weight of Selected Metal Rail:	498	lb	
Initial Weight per Unit Area:	233	lb / sq.ft.	
Estimated Live Load:	150.00	lb / sq.ft.	*From structural specifications
New Live + Dead Load:	383	lb / sq.ft.	
Floor System Span:	- SOG -		
Floor System Allowable Load:			

Air Handling Unit 2 - 5: Main Arena

Unit Size:	17				
Module	**Width**	**Length**	**Height**	**Weight**	**Original Weight**
Mxing Box and Filters	74	34	44	405	405
Filters	In M.Box			284	284
Dampers	74	15.5	44	244	244
Turning Vanes	74	15.5	44	147	147
Heating Coil	74	15.5	44	505	505
Access Door	74	15.5	44	147	147
Desiccant Wheel	74	7.065	44	1311	
Desiccant Wheel Motor				12	
Inlet Guide Vanes				57	57
Starter				65	65
VFD				180	180
Fan	74	44	44	868	868
Turning Vanes	74	44	44	420	
Cooling Coil	74	15.5	44	505	505
Discharge Plenum	74	34	44	327	327
	Total Length:	147.065	**Totals:**	5477	3734
			Change:	27.67	lb / sq. ft.

Area of Concrete Pad:	63.00	sq. ft.	
Weight of Concrete Pad (6") - 150 pcf:	4,725.00	lb	
Weight of Floor System:	52.97	lb / sq.ft.	*3" R.W. Concrete, 2" - 20 gauge
Weight of Selected Metal Rail:	586.14	lb	composite metal decking
Initial Weight per Unit Area:	224.21	lb / sq.ft.	with 6x6 W2.1xW2.1 WWF
Estimated Live Load:	150.00	lb / sq.ft.	*From structural specifications
New Live + Dead Load:	374.21	lb / sq.ft.	
Floor System Span:	5.00	ft.	
Floor System Allowable Load:	400.00	lb / sq.ft.	*Floor Deck System is OK

Air Handling Unit 6: Fitness Center

Unit Size:	8				
Module	**Width**	**Length**	**Height**	**Weight**	**Original Weight**
Mixing Box and Filters	48	34	34	253	253
Filters	In M. Box			323	323
Dampers	48	15.5	34	213	213
Heating Coil	48	15.5	34	281	281
Access Door	48	34	34	190	190
Desiccant Wheel	48	6.065	34	617	
Desiccant Wheel Motor				12	
Inlet Guide Vanes				38	38
Starter				65	65
VFD				180	180
Fan	48	44	34	518	518
Turning Vanes	48	40.5	34	239	
Cooling Coil	48	15.5	34	281	281
Discharge Plenum	48	34	34	223	223
	Total Length:	149.065	**Totals:**	3433	2565
			Change:	15.84	lb / sq. ft.

Area of Concrete Pad:	54.80	sq. ft.	
Weight of Concrete Pad (6") - 150 pcf:	2,739.97	lb	
Weight of Floor System:	52.14	lb / sq.ft.	*3" R.W. Concrete, 1-1/2" - 20 gauge
Weight of Selected Metal Rail:	582	lb	composite metal decking
Initial Weight per Unit Area:	175.40	lb / sq.ft.	with 6x6 W2.1xW2.1 WWF
Estimated Live Load:	150.00	lb / sq.ft.	*From structural specifications
New Live + Dead Load:	325	lb / sq.ft.	
Floor System Span:	4.50	ft.	
Floor System Allowable Load:	400.00	lb / sq.ft.	*Floor Deck system is OK

Air Handling Unit 9 - 10: Theater

Unit Size:	12				
Module	**Width**	**Length**	**Height**	**Weight**	**Original Weight**
Mixing Box and Filters	64	34	39	334	334
Filters	In M. Box			223	223
Dampers	64	15.5	39	213	213
Heating Coil	64	15.5	39	405	405
Access Door	64	34	39	240	240
Desiccant Wheel	64	6.065	39	1051	
Desiccant Wheel Motor				12	
Inlet Guide Vanes				46	46
Starter				65	65
VFD				180	180
Fan	64	39	39	632	842
Turning Vanes	64	39	39	307	
Cooling Coil	64	15.5	39	405	405
Discharge Plenum	64	34	39	279	279
	Total Length:	144.065	**Totals:**	4392	3232
			Change:	19.76	lb / sq. ft.

Area of Concrete Pad:	58.70	sq. ft.	
Weight of Concrete Pad (6") - 150 pcf:	4,402.50	lb	
Weight of Floor System:	52.14	lb / sq.ft.	*3" R.W. Concrete, 1-1/2" - 20 gauge
Weight of Selected Metal Rail:	570	lb	composite metal decking
Initial Weight per Unit Area:	211.67	lb / sq.ft.	with 6x6 W2.1xW2.1 WWF
Estimated Live Load:	150.00	lb / sq.ft.	*From structural specifications
New Live + Dead Load:	362	lb / sq.ft.	
Floor System Span:	4.50	ft.	
Floor System Allowable Load:	400.00	lb / sq.ft.	*Floor Deck system is OK

Air Handling Unit 7A: Racquetball Ct.		
Unit Size: 6		
Module	**Length**	**Weight**
Mixing Box and Filters	28.75	203
Filters		175
Dampers	15.5	127
Heating Coil	15.5	238
Access Door	15.5	95
Fan	44	418
Cooling Coil	15.5	238
Discharge Plenum	34	190
	Total:	1684
Total Length:	168.75	

Area of Concrete Pad:	36.00	sq. ft.	
Weight of Concrete Pad (6") - 150 pcf:	2,700.00	lb	
Weight of Floor System:	52.14	lb / sq.ft.	*3" R.W. Concrete, 1-1/2" - 20 gauge
Weight of Selected Metal Rail:	653	lb	composite metal decking
Initial Weight per Unit Area:	145.29	lb / sq.ft.	with 6x6 W2.1xW2.1 WWF
Distributed Additional Weight per Unit Area:	46.78	lb / sq.ft.	
Estimated Live Load:	150.00	lb / sq.ft.	*From structural specifications
New Live + Dead Load:	342.07	lb / sq.ft.	
Floor System Span:	4.50	ft.	
Floor System Allowable Load:	400.00	lb / sq.ft.	*Floor Deck system is OK

Heather Stapel

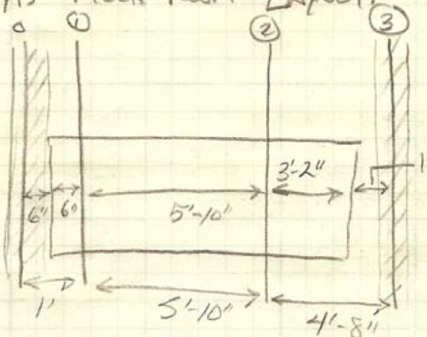
LRFD Structural Beam Calculations

mech room Live load: 150 PSF

SOUTH SIDE OF THE MAIN ARENA

TYP. MECH ROOM LAYOUT

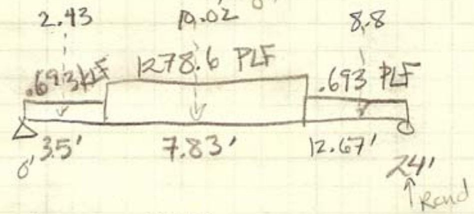
EQUIPMENT DEAD: 374.21 PSF



Beam 0: only Floor Slab D + L

ALL BEAMS W12×35

Beam 1

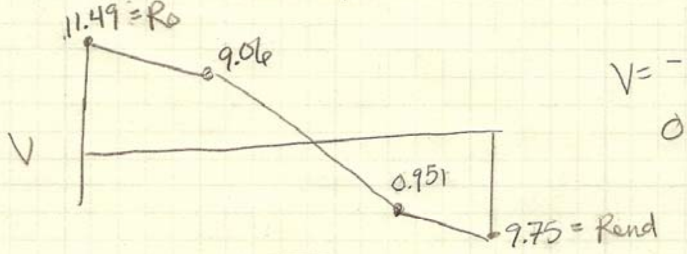


$$R_{end} = \frac{\left(2.43\left(\frac{3.5}{2}\right) + 10.02\left(3.5+\left(7.83/2\right)\right) + 8.8\left(3.5+7.83+\frac{12.7}{2}\right)\right)}{24}$$

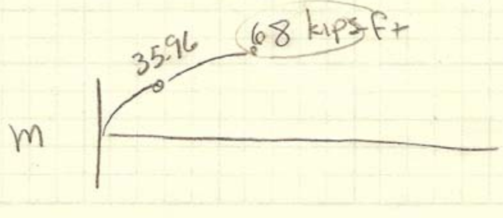
$R_{end} = 9.75$ kips

$V = -1.28L + 13.54$

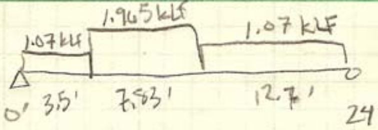
$0 \text{ @ } 10.58'$



Mu = 68 kip-ft

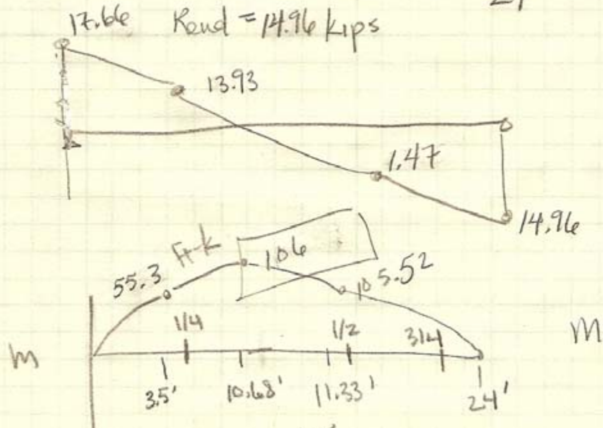


②



$$R_{end} = \frac{3.73\left(\frac{3.5}{2}\right) + 15.4\left(3.5 + \frac{7.83}{2}\right) + 13.49\left(3.5 + 7.833 + 12.667/2\right)}{24}$$

Rend = 14.96 kips



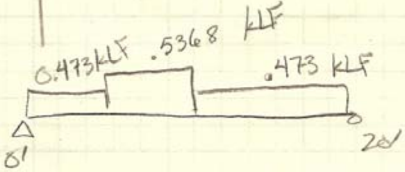
Ra = 17.66 kips

$$V = -\frac{15.4L}{7.833} + 20.81$$

0 @ 10.682'

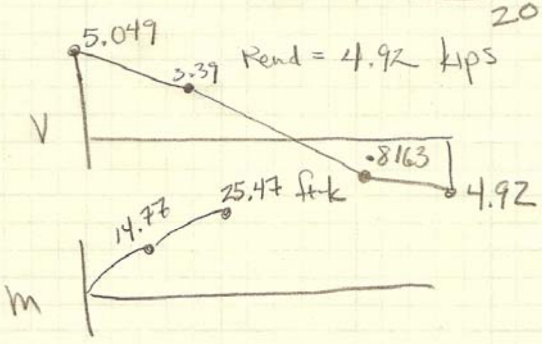
Mu = 106

③



$$R_{end} = \frac{1.66\left(3.5/2\right) + 4.205\left(3.5 + \frac{7.83}{2}\right) + 4.1\left(3.5 + 7.83 + 8.667/2\right)}{20}$$

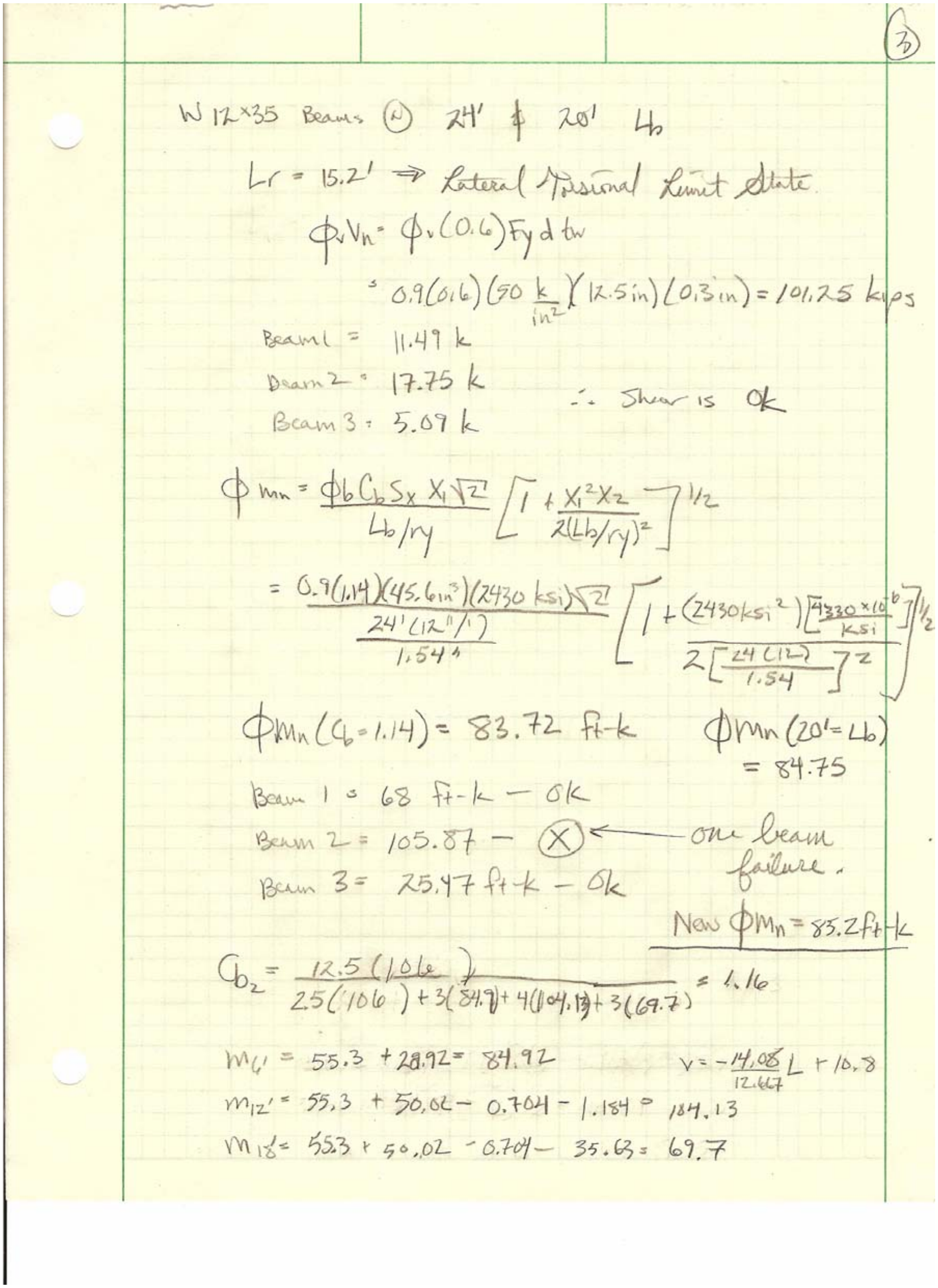
Rend = 4.92 kips



$V = -0.537L + 5.2695$

0 @ 9.813

Mu = 25.47 ft-k



③

W 12×35 Beams ⓐ 24' ∮ 20' Lb

$L_r = 15.2' \Rightarrow$ Lateral Torsional Limit State

$\phi_v V_n = \phi_v (0.6) F_y\, d\, t_w$

$= 0.9(0.6)\left(50\ \frac{k}{in^2}\right)(12.5\,in)(0.3\,in) = 101.25$ kips

Beam 1 = 11.49 k

Beam 2 = 17.75 k

Beam 3 = 5.09 k

∴ Shear is Ok

$$\phi M_n = \frac{\phi_b C_b S_x X_1 \sqrt{2}}{L_b/r_y}\left[1 + \frac{X_1^2 X_2}{2(L_b/r_y)^2}\right]^{1/2}$$

$$= \frac{0.9(1.14)(45.6\,in^3)(2430\ ksi)\sqrt{2}}{\dfrac{24'(12''/')}{1.54''}}\left[1 + \frac{(2430\,ksi^2)\left[\dfrac{4330\times10^{-6}}{ksi}\right]}{2\left[\dfrac{24(12)}{1.54}\right]^2}\right]^{1/2}$$

$\phi M_n (C_b = 1.14) = 83.72$ ft-k

$\phi M_n (20' = L_b)$
$= 84.75$

Beam 1 = 68 ft-k — Ok

Beam 2 = 105.87 — ⓧ ← one beam failure.

Beam 3 = 25.47 ft-k — Ok

New $\phi M_n = 83.2$ ft-k

$$C_{b_2} = \frac{12.5(106)}{2.5(106) + 3(84.9) + 4(104.13) + 3(69.7)} = 1.16$$

$M_{6'} = 55.3 + 28.92 = 84.92$

$V = -\frac{14.08}{12.667}L + 10.8$

$M_{12'} = 55.3 + 50.02 - 0.704 - 1.184 = 104.13$

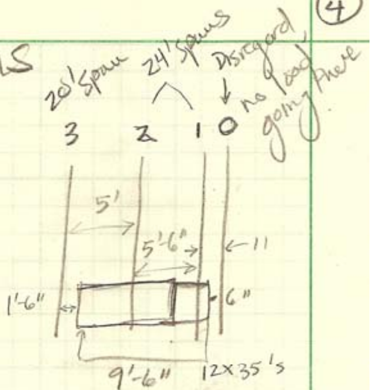
$M_{18'} = 55.3 + 50.02 - 0.704 - 35.63 = 69.7$

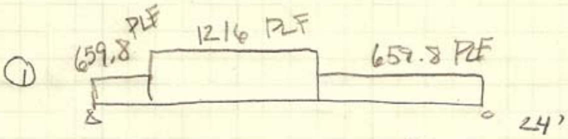
④

NORTH ARENA MECH ROOMS

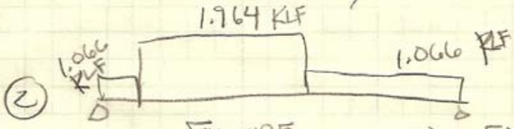
Floor weight + Live = 203 psf.

Equip (incl. Live) = 374.21 psf

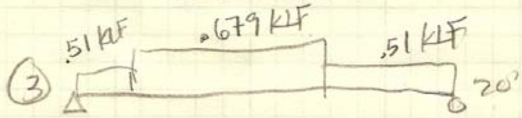


①


PRev. worked, ok

②


FAILURE ⟶ SAME CONDITIONS AS ORIGINAL SOUTH BEAM

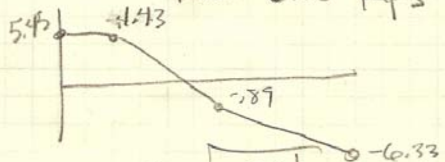
③


CHECK, UNSURE : $\phi_b M_n = 106$ k-ft

$$R_{end} = \frac{1.62\left(\frac{3.5}{2}\right) + 5.32\left(3.5 + \frac{7.833}{2}\right) + 5.44\left(3.5 + 7.833 + \frac{10.667}{2}\right)}{20}$$

$R_{end} = 6.33$ kips

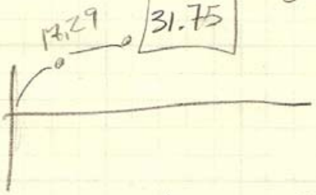
$R_0 = 5.45$ kip



$5.32 / 7.83 = 0.679$

$V = -0.679L + 6.81$

0 @ 10'



$M_u = 17.75$ ∴ ok

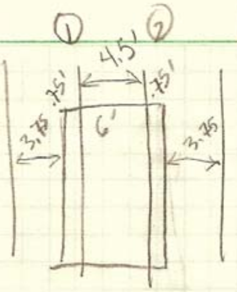
< 83 kip-ft

⑤

THEATER/AUDITORIUM
BEAM CHECK

SLAB: 202 PSF

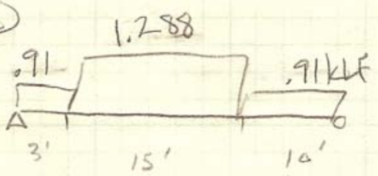
AHU: 362 PSF



W16x31's

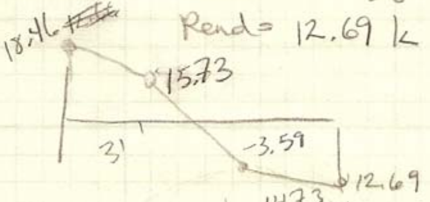
28' Span

① = ②



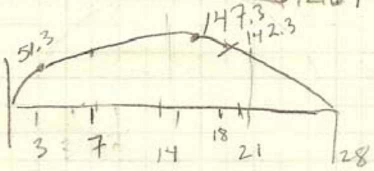
$$R_{end} = \frac{2.73(3/2) + 19.32(3+7.5) + 9.1(3+15+5)}{28}$$

Rend = 12.69 k   Ro =



$V = -1.288L + 19.6$

0 @ 15.2



$M_u = 147.3$ kip ft

∴ Ok

$$C_b = \frac{12.5(147.3)}{2.5(147.3) + 3(70) + 4(145) + 3(138)} = C_b = 1.171$$

$L_b = 28$ $L_p = 4.13$ $L_r = 11$

$\phi V_n = \phi V (0.6) F_y\, d\, t_w$

$= 0.9(0.6)(50)(15.9")(0.275") = 118$ kips

∴ Ok

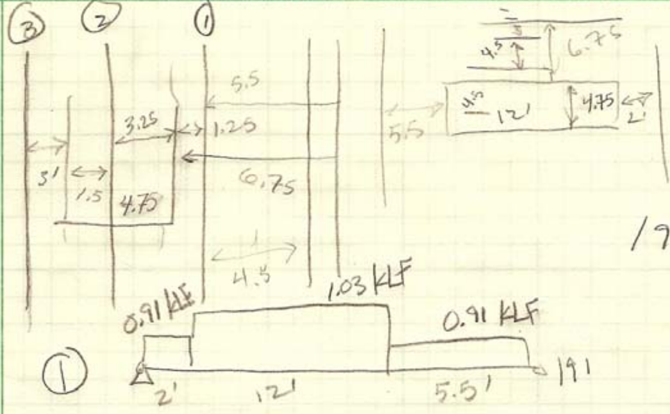
$$\phi M_n = \frac{\phi C_b S_x X_1 \sqrt{2}}{L_b/r_y}\left[1 + \frac{X_1^2 X_2}{2(L_b/r_y)^2}\right]$$

$r_y = 1.17$
$X_1 = 1740$
$X_2 = 19900 \times 10^{-6}$
$S_x = 47.2$

$\phi M_n = 496$ ft k

FITNESS CENTER: BEAM CHECK

⑥



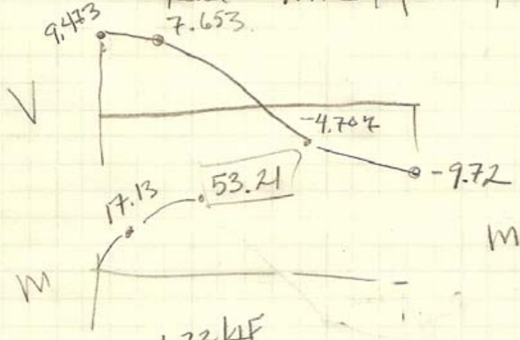
Attic → 325 lb/ft^2

Floor → 202 lbm/ft^2

19' Spans of W12x26

$$R_{end} = \frac{1.82(1) + 12.36(2+6) + 5.01(2+12+2.75)}{19}$$

R_{end} = 9.72 kips R_o = 9.473 kips

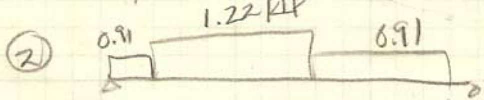


V = −1.03x + 9.713

0 @ 9.43 ft

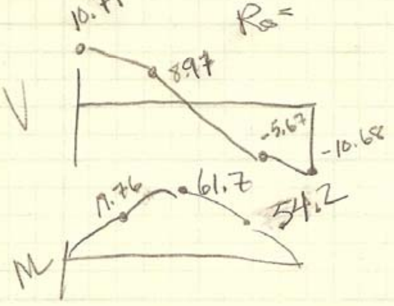
M_u = 53.2 kip-ft

ok



$$R_{end} = \frac{1.82 + 14.64(2+6) + 5.01(16.75)}{19} = 10.68\ k$$

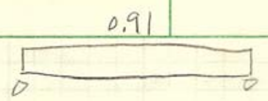
R_o =



V = −1.22x + 11.41

0 @ 9.35

M_u = 61.7 k-ft   ok

③ 

19'

FITNESS CENTER
CONTINUED

$M_u = \frac{w\ell^2}{8} = 41$ k-ft ok

$L_b = 19'$ W12×26 LAT-TORS BUCKLING?

$L_p = 5.33'$ $L_r = 13.8'$

$\lambda = b_f/2t_f = 8.54$ $\lambda_r = .38\sqrt{E/F_y} = 9.15$

$h/t_w = 47.2$ $\lambda_p = 3.76\sqrt{E/F_y} = 90.6$

compact beam

$\phi_v V_n = 0.9(0.6)F_y d t_w = 0.9(.6)(50)(12.2'')(0.23'')$

$\underline{\phi_v V_n = 75.8 \text{ kips}}$

SHEAR LOADS = OK

$$C_b = \frac{12.5(61.7)}{2.5(61.7) + 3(25) + 4(58) + 3(52)} = 1.3$$

$$C_{b,\text{1st failure}} = \frac{12.5(104.6)}{2.5(104.6) + 3(60) + 4(104.3) + 3(50)} = 1.42$$

$$\phi M_n = \frac{\phi_b C_b S_x X_1 \sqrt{2}}{L_b/r_y}\left[1 + \frac{X_1^2 X_2}{2(L_b/r_y)^2}\right]^{1/2}$$

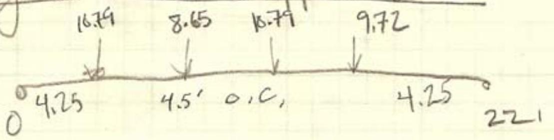
$\phi_b = 0.9$ $C_b = 1.3$ $S_x = 33.4''$

$X_1 = 1820$ $X_2 = 13900 \times 10^{-6}$

$L_b = 19'$ $r_y = 1.51''$

$\phi M_n = 78.7$ ft-k [w/ $C_b = 1.3$ → check for o/r loadings]

Bearing on Fitness Support Girdes

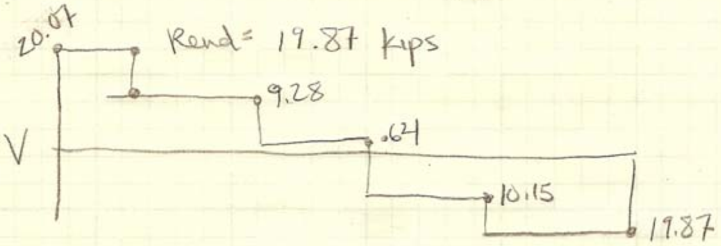


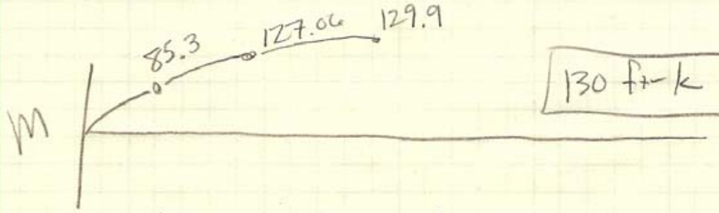
W16×31

Point Loads @ 4.5' spacing
max bearing from Fitness center beam
: 10.79 kips.

$$R_{end} = \frac{4.25(10.79) + 8.75(8.65) + 13.25(10.79) + 17.75(9.72)}{22}$$

Rend= 19.87 kips





$\boxed{130 \text{ ft-k max}}$

$L_b = 22'$ $L_r = 11'$ [Lat-Tors.]

$\phi V_n = \phi(0.6)F_y d t_w = 0.9(0.6)(50)(15.9)(0.275)$

$\phi V_n = 118$ kips ∴ OK

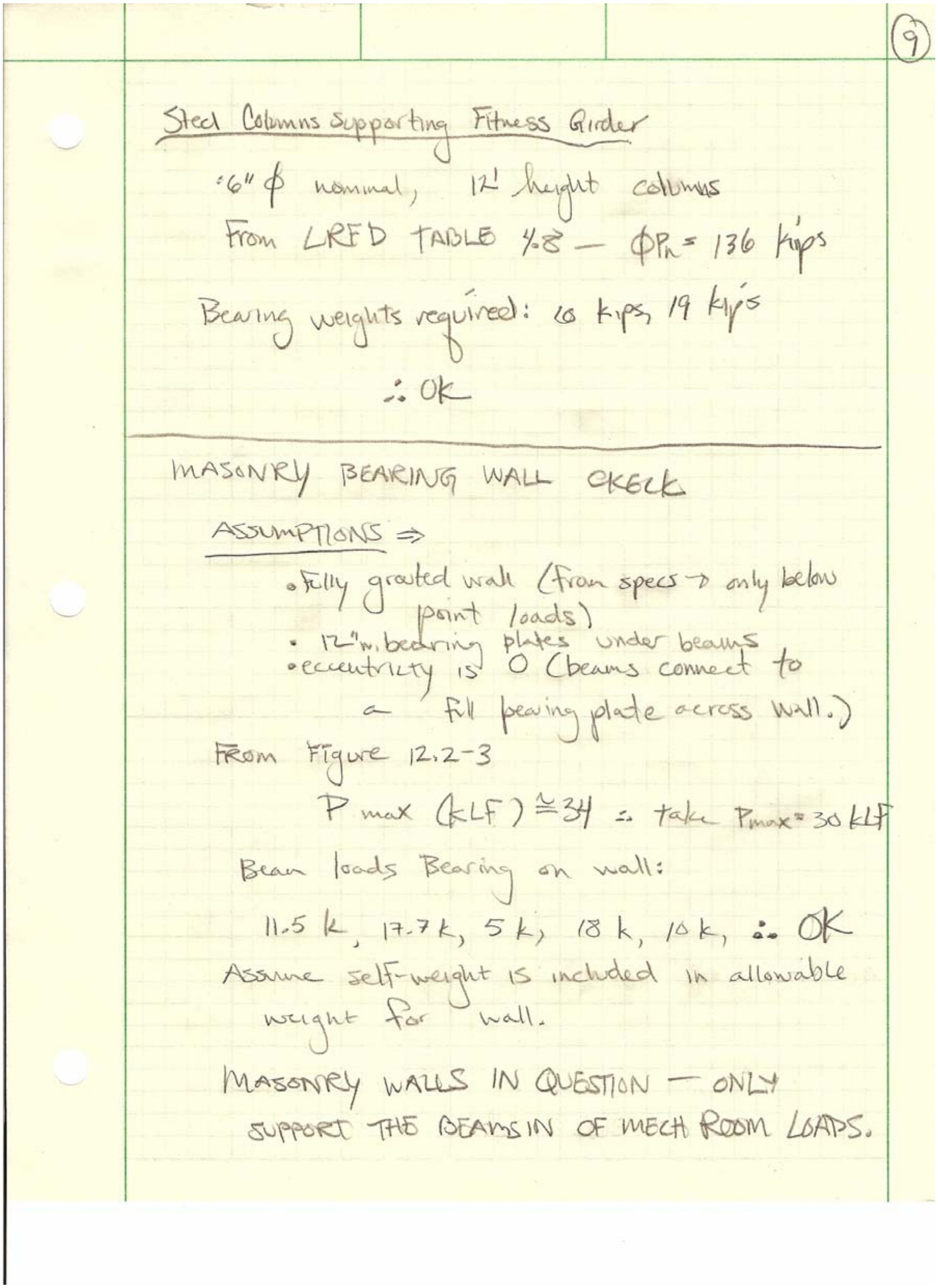
$C_b = 1.14$

$$\phi M_n = \frac{\phi C_b S_x X_1 \sqrt{2}}{L_b/r_y}\left[1 + \frac{X_1^2 X_2}{2[L_b/r_y]^2}\right]^{1/2}$$

$\phi = 0.9$
$S_x = 47.2 \text{ in}^3$
$r_y = 1.17$ in
$X_1 = 1740$ ksi
$X_2 = 0.0199$ /ksi^2

$\phi M_n = 663.5$ k-in $= 55.3$ ft-K

stiffener @ 11' → $L_b = L_R$ $\phi M_{rx} = 142$ ft-K ∴ OK



9

Steel Columns Supporting Fitness Girder

"6" ϕ nominal, 12' height columns

From LRFD TABLE 4.8 — $\phi P_n = 136$ kips

Bearing weights required: 16 kips, 19 kips

∴ OK

MASONRY BEARING WALL CHECK

ASSUMPTIONS ⇒

- fully grouted wall (from specs → only below point loads)
- 12"w. bearing plates under beams
- eccentricity is 0 (beams connect to a full bearing plate across wall.)

FROM Figure 12.2-3

P max (KLF) ≅ 34 ∴ take $P_{max} = 30$ KLF

Beam loads Bearing on wall:

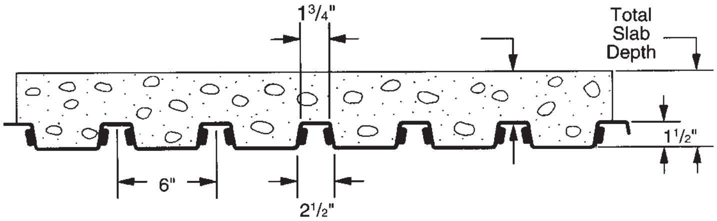
11.5 k, 17.7 k, 5 k, 18 k, 10 k, ∴ OK

Assume self-weight is included in allowable weight for wall.

MASONRY WALLS IN QUESTION — ONLY SUPPORT THE BEAMS IN OF MECH ROOM LOADS.

1.5 VLR

Maximum Sheet Length 42'-0
Extra Charge for Lengths Under 6'-0



STEEL SECTION PROPERTIES

Fy= 40 KSI

Deck Type	Design Thick.	Weight PSF	Ip in^4/Ft	In in^4/Ft	Sp in^3/Ft	Sn in^3/Ft
1.5VLR22	0.0295	1.78	0.182	0.150	0.186	0.178
1.5VLR21	0.0329	1.97	0.205	0.174	0.215	0.209
1.5VLR20	0.0358	2.14	0.222	0.195	0.240	0.231
1.5VLR19	0.0418	2.49	0.260	0.239	0.288	0.274
1.5VLR18	0.0474	2.82	0.295	0.282	0.327	0.315
1.5VLR17	0.0538	3.19	0.335	0.331	0.371	0.361
1.5VLR16	0.0598	3.54	0.373	0.373	0.411	0.404

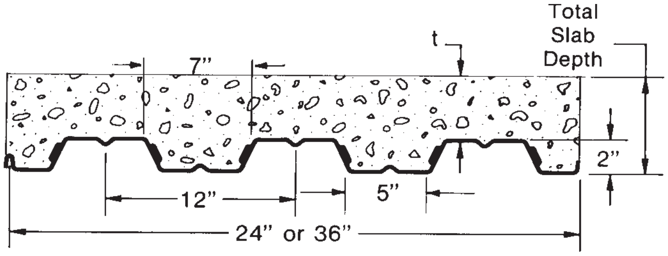
(N=9) NORMAL WEIGHT CONCRETE (145 PCF)

Total Slab Depth	Deck Type	SDI Max. Unshored Clear Span			Superimposed Live Load, PSF Clear Span (ft.-in.)														
		1 Span	2 Span	3 Span	5'-0	5'-6	6'-0	6'-6	7'-0	7'-6	8'-0	8'-6	9'-0	9'-6	10'-0	10'-6	11'-0	11'-6	12'-0
	1.5VLR22	5'-1	6'-9	6'-10	314	255	227	203	183	166	151	138	127	117	108	100	87	76	67
3 1/2"	1.5VLR21	5'-7	7'-6	7'-7	331	294	240	215	194	176	160	147	135	124	115	104	91	80	70
	1.5VLR20	6'-0	8'-0	8'-2	345	306	275	225	203	184	168	154	141	130	120	108	94	82	73
(t=2")	1.5VLR19	6'-9	8'-8	9'-0	372	330	296	268	220	200	182	167	154	142	132	116	101	88	78
	1.5VLR18	7'-3	9'-3	9'-7	395	351	315	285	260	214	195	179	165	152	141	123	107	94	82
38 PSF	1.5VLR17	7'-10	9'-11	10'-3	397	353	316	286	261	239	196	180	166	153	142	131	114	99	87
	1.5VLR16	8'-4	10'-5	10'-10	397	353	316	286	261	239	221	180	165	153	142	132	119	105	92
	1.5VLR22	4'-10	6'-6	6'-7	339	298	264	236	213	193	176	161	148	136	125	116	108	100	92
4"	1.5VLR21	5'-4	7'-2	7'-3	385	315	279	250	225	204	186	171	157	144	134	124	115	107	99
	1.5VLR20	5'-8	7'-7	7'-9	400	356	292	261	236	214	195	179	164	151	140	130	121	112	105
(t=2 1/2")	1.5VLR19	6'-5	8'-3	8'-7	400	383	344	283	255	232	212	194	179	165	153	142	132	123	115
	1.5VLR18	6'-11	8'-10	9'-2	400	400	365	330	272	248	226	207	191	177	164	152	142	132	122
44 PSF	1.5VLR17	7'-5	9'-5	9'-9	400	400	366	331	302	248	227	208	192	177	164	153	142	133	124
	1.5VLR16	7'-11	9'-11	10'-3	400	400	365	330	301	276	226	207	191	176	163	152	142	132	124
	1.5VLR22	4'-8	6'-2	6'-3	389	342	303	271	245	222	202	185	170	156	144	133	124	115	107
4 1/2"	1.5VLR21	5'-1	6'-10	6'-11	400	361	321	287	259	235	214	196	180	166	153	142	132	123	114
	1.5VLR20	5'-5	7'-3	7'-5	400	377	335	300	270	245	224	205	188	174	161	149	139	129	120
(t=3")	1.5VLR19	6'-1	7'-11	8'-2	400	400	393	324	293	266	243	223	205	189	175	163	151	141	132
	1.5VLR18	6'-7	8'-5	8'-9	400	400	400	378	312	284	259	238	219	202	188	174	162	152	142
50 PSF	1.5VLR17	7'-1	9'-0	9'-4	400	400	400	378	345	284	259	238	219	203	188	175	163	152	142
	1.5VLR16	7'-6	9'-6	9'-10	400	400	400	377	344	315	258	237	218	202	187	174	162	151	141
	1.5VLR22	4'-5	6'-0	6'-1	400	387	344	308	277	251	229	209	192	177	164	151	140	130	121
5"	1.5VLR21	4'-10	6'-7	6'-8	400	400	363	325	293	266	243	222	204	188	174	161	150	139	130
	1.5VLR20	5'-3	7'-0	7'-1	400	400	379	339	306	278	253	232	214	197	182	169	157	146	136
(t=3 1/2")	1.5VLR19	5'-10	7'-7	7'-10	400	400	400	367	331	301	275	252	232	214	199	184	172	160	149
	1.5VLR18	6'-3	8'-1	8'-5	400	400	400	391	353	321	293	269	248	229	212	198	184	172	161
56 PSF	1.5VLR17	6'-9	8'-8	8'-11	400	400	400	400	353	321	293	269	248	229	213	198	184	172	161
	1.5VLR16	7'-2	9'-2	9'-5	400	400	400	400	388	320	292	268	247	228	212	197	183	171	160
	1.5VLR22	4'-3	5'-9	5'-10	400	400	385	344	310	281	256	235	216	199	183	170	157	146	136
5 1/2"	1.5VLR21	4'-8	6'-4	6'-5	400	400	400	364	328	298	272	249	229	211	195	181	168	156	145
	1.5VLR20	5'-0	6'-9	6'-10	400	400	400	380	343	311	284	260	239	221	204	190	176	164	153
(t=4")	1.5VLR19	5'-7	7'-4	7'-7	400	400	400	400	371	337	308	282	260	240	222	207	192	179	168
	1.5VLR18	6'-0	7'-10	8'-1	400	400	400	400	395	359	328	301	278	257	238	221	206	193	180
62 PSF	1.5VLR17	6'-6	8'-4	8'-7	400	400	400	400	395	359	328	301	278	257	238	221	206	193	180
	1.5VLR16	6'-11	8'-10	9'-1	400	400	400	400	393	357	327	300	276	255	237	220	205	192	179
	1.5VLR22	4'-2	5'-7	5'-8	400	400	400	382	344	312	284	260	239	220	204	188	175	162	151
6"	1.5VLR21	4'-6	6'-1	6'-2	400	400	400	400	364	330	301	276	254	234	216	201	186	173	161
	1.5VLR20	4'-10	6'-6	6'-8	400	400	400	400	380	345	315	289	265	245	227	210	196	182	170
(t=4 1/2")	1.5VLR19	5'-5	7'-1	7'-3	400	400	400	400	400	374	341	313	288	266	247	229	213	199	186
	1.5VLR18	5'-10	7'-6	7'-10	400	400	400	400	400	398	364	334	308	285	264	245	229	214	200
68 PSF	1.5VLR17	6'-3	8'-1	8'-4	400	400	400	400	400	398	364	334	308	285	264	246	229	214	200
	1.5VLR16	6'-8	8'-6	8'-9	400	400	400	400	400	396	362	332	306	283	262	244	228	213	199

Notes:
1. Minimum exterior bearing length required is 1.5 inches. Minimum interior bearing length required is 3.0 inches. If these minimum lengths are not provided, web crippling must be checked.
2. Always contact Vulcraft when using loads in excess of 200 psf. Such loads often result from concentrated, dynamic, or long term load cases for which reductions due to bond breakage, concrete creep, etc. should be evaluated.
3. All fire rated assemblies are subject to an upper live load limit of 250 psf.
4. Inquire about material availability of 17, 19 & 21 gage.

2 VLI

Maximum Sheet Length 42'-0
Extra Charge for Lengths Under 6'-0
ICBO Approved (No. 3415)



STEEL SECTION PROPERTIES Fy= 40 KSI

Deck Type	Design Thick.	Weight PSF	Ip in^4/ft	In in^4/ft	Sp in^3/ft	Sn in^3/ft
2VLI22	0.0295	1.62	0.332	0.329	0.274	0.277
2VLI21	0.0329	1.81	0.378	0.375	0.317	0.321
2VLI20	0.0358	1.97	0.418	0.415	0.355	0.360
2VLI19	0.0418	2.30	0.493	0.492	0.435	0.443
2VLI18	0.0474	2.61	0.557	0.557	0.512	0.518
2VLI17	0.0538	2.96	0.633	0.633	0.589	0.589
2VLI16	0.0598	3.29	0.704	0.704	0.653	0.653

(N=9) NORMAL WEIGHT CONCRETE (145 PCF)

Total Slab Depth	Deck Type	SDI Max. Unshored Clear Span			Superimposed Live Load, PSF Clear Span (ft.-in.)														
		1 Span	2 Span	3 Span	5'-6	6'-0	6'-6	7'-0	7'-6	8'-0	8'-6	9'-0	9'-6	10'-0	10'-6	11'-0	11'-6	12'-0	12'-6
	2VLI22	6'-6	8'-9	8'-10	274	239	211	164	145	129	115	104	94	85	78	71	65	59	54
4"	2VLI21	7'-2	9'-5	9'-8	294	255	224	200	155	138	123	111	100	91	83	76	69	64	58
	2VLI20	7'-8	9'-11	10'-3	310	269	236	210	188	146	130	117	106	96	87	80	73	67	62
(t=2")	2VLI19	8'-8	11'-0	11'-4	344	298	261	231	207	186	169	130	117	106	97	88	81	74	68
	2VLI18	9'-6	11'-10	12'-3	373	324	285	253	228	206	188	172	159	122	112	103	95	87	81
39 PSF	2VLI17	10'-4	12'-7	13'-0	400	351	308	273	245	221	201	184	170	157	120	111	102	94	87
	2VLI16	10'-11	13'-2	13'-5	400	376	330	292	261	235	214	195	180	166	154	118	109	100	93
	2VLI22	6'-2	8'-4	8'-5	319	278	217	190	168	150	134	121	109	99	90	83	76	69	63
4 1/2"	2VLI21	6'-9	8'-11	9'-3	341	297	261	204	180	160	144	129	117	106	97	88	81	74	68
	2VLI20	7'-3	9'-5	9'-9	361	313	275	244	190	169	152	136	123	112	102	93	85	78	72
(t=2 1/2")	2VLI19	8'-2	10'-5	10'-10	400	346	303	268	240	216	168	151	136	124	113	103	94	86	79
	2VLI18	9'-0	11'-3	11'-8	400	376	331	295	264	239	218	200	156	142	130	119	110	102	94
45 PSF	2VLI17	9'-9	12'-0	12'-5	400	400	358	318	284	257	234	214	197	153	140	129	118	109	101
	2VLI16	10'-4	12'-7	13'-0	400	400	383	339	303	274	248	227	209	193	150	137	126	117	108
	2VLI22	5'-11	7'-9	8'-0	364	285	247	217	192	171	153	138	125	113	103	94	86	79	72
5"	2VLI21	6'-5	8'-6	8'-10	389	338	266	233	206	183	164	147	133	121	110	101	92	84	78
	2VLI20	6'-11	9'-0	9'-4	400	356	313	246	217	193	173	156	141	128	116	106	97	89	82
(t=3")	2VLI19	7'-9	10'-0	10'-4	400	394	345	306	273	214	192	172	156	141	128	117	107	99	91
	2VLI18	8'-7	10'-9	11'-2	400	400	377	336	301	273	249	195	178	162	148	136	126	116	107
51 PSF	2VLI17	9'-3	11'-6	11'-10	400	400	400	362	324	293	266	244	192	175	160	147	135	125	116
	2VLI16	9'-10	12'-1	12'-5	400	400	400	386	346	312	283	259	238	187	171	157	144	133	123
	2VLI22	5'-8	7'-2	7'-4	400	320	278	244	216	192	172	155	140	127	116	106	97	89	81
5 1/2"	2VLI21	6'-2	8'-2	8'-5	400	379	298	261	231	205	184	166	150	136	124	113	104	95	87
	2VLI20	6'-7	8'-8	8'-11	400	400	351	276	244	217	194	175	158	143	131	119	109	100	92
(t=3 1/2")	2VLI19	7'-5	9'-7	9'-11	400	400	388	343	271	241	215	193	175	159	144	132	121	111	102
	2VLI18	8'-2	10'-4	10'-8	400	400	400	377	338	306	243	219	199	182	167	153	141	130	121
57 PSF	2VLI17	8'-10	11'-0	11'-5	400	400	400	400	364	329	299	237	215	196	180	165	152	140	130
	2VLI16	9'-4	11'-7	12'-0	400	400	400	400	388	350	318	290	230	210	192	176	162	150	138
	2VLI22	5'-5	6'-8	6'-10	400	355	308	270	239	213	191	172	156	141	129	118	108	99	90
6"	2VLI21	5'-11	7'-11	8'-1	400	381	331	290	256	228	204	184	166	151	137	126	115	105	97
	2VLI20	6'-4	8'-4	8'-7	400	400	350	306	271	241	215	194	175	159	145	132	121	111	102
(t=4")	2VLI19	7'-2	9'-3	9'-7	400	400	400	381	301	267	239	215	194	176	160	146	134	123	113
	2VLI18	7'-10	10'-0	10'-4	400	400	400	400	375	299	269	243	221	202	185	170	157	145	134
63 PSF	2VLI17	8'-6	10'-7	11'-0	400	400	400	400	400	364	331	263	239	218	199	183	169	156	144
	2VLI16	9'-0	11'-2	11'-6	400	400	400	400	400	388	352	322	255	233	213	195	180	166	154
	2VLI22	5'-1	6'-2	6'-4	400	390	339	297	263	234	210	189	171	155	141	129	118	108	99
6 1/2"	2VLI21	5'-9	7'-6	7'-6	400	400	363	318	281	250	224	202	183	166	151	138	126	116	106
	2VLI20	6'-1	8'-1	8'-4	400	400	385	337	297	264	237	213	193	175	159	145	133	122	112
(t=4 1/2")	2VLI19	6'-10	8'-11	9'-3	400	400	400	375	330	293	262	236	213	193	176	161	147	135	124
	2VLI18	7'-7	9'-8	9'-11	400	400	400	400	400	329	296	268	243	222	203	187	172	159	147
69 PSF	2VLI17	8'-2	10'-3	10'-7	400	400	400	400	400	400	320	289	262	239	219	201	185	171	158
	2VLI16	8'-8	10'-9	11'-2	400	400	400	400	400	400	387	309	280	256	234	215	198	183	169

Notes:
1. Minimum exterior bearing length required is 2.0 inches. Minimum interior bearing length required is 4.0 inches. If these minimum lengths are not provided, web crippling must be checked.
2. Always contact Vulcraft when using loads in excess of 200 psf. Such loads often result from concentrated, dynamic, or long term load cases for which reductions due to bond breakage, concrete creep, etc. should be evaluated.
3. All fire rated assemblies are subject to an upper live load limit of 250 psf.
4. Inquire about material availability of 17, 19 & 21 gage.

Single-Piece Shipment Limitations

The specifications provided in Table 4 indicate the maximum values for a single-piece shipment. If either the maximum weight or maximum length is exceeded, the M-Series unit will ship in multiple pieces.

Note: These limits are based on a four-point lift.

Table 4. Shipping length and weight limitations for single piece shipments

Unit Size	Maximum Unit Weight (lb.)	Baserail Unit Maximum Unit Length (in)	Non-Baserail Unit Maximum Unit Length (in)
3–30	<2,500	98	96
35	<3,900	98	96
40	<4,300	98	96
50–57	<5,100	98	96
66-120	<4300-6000	102	n/a

Base Rail Weight Calculations

To determine the weight of the base rail for each shipping split, use the following equation and the weight factors provided in Table 5:

Weight = (A × length) + B

Note: When an M-Series unit ships in multiple pieces, a base rail may be provided for each piece (if ordered). In these instances, the base rail weight must be calculated for each piece. M-Series unit sizes 66 to 120 have integral base rails; module weights for these module sizes include the base rail.

Table 5. Base rail weight calculation factors

	Weight Factors per Unit Size													
Variable	3	6	8	10	12	14	17	21	25	30	35	40	50	57
A	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
B	23	29	30	36	37	39	42	43	43	49	51	57	62	62

Inlet Guide Vane Weights

Fan weights include inlet guide vane weights; therefore, when inlet guide vanes are not included on a fan module, subtract the weights in the table below from the fan module weight to determine the actual module weight.

Table 6. Inlet guide vane weights

	Weights (lb.) per Unit Size																
Fan Type	3	6	8	10	12	14	17	21	25	30	35	40	50	57	66	80	100	120
FC fan	n/a	38	38	43	46	55	57	65	70	70	105	128	155	155	155	n/a	n/a	n/a
AF fan	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	36	43	54	n/a	64	93	111	n/a
Plenum fan	n/a	n/a	n/a	n/a	n/a	n/a	n/a	25	29	29	40	64	74	74	100	122	118	118

Motor Weights

Fan weights provided in this manual include the heaviest ODP (open drip-proof) motor. Approximate weights below are based on A.O. Smith brand motors.

Table 7. Approximate motor weights

		Horsepower																				
Motor Type	Voltage	1/6	1/4	1/3	1/2	1	1-1/2	2	3	5	7-1/2	10	15	20	25	30	40	50	60	75	100	125
Energy efficient ODP (EEOP)	115s	12	14	16	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	230s	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	200/3	-	-	-	-	34	43	43	80	78	106	119	170	210	240	284	631	404	772	838	1091	-
	230/460/3	-	-	-	-	36	42	42	64	76	110	132	164	210	240	278	631	360	-	-	-	-
	575/3	-	-	-	-	37	48	50	70	78	106	119	170	212	240	284	631	440	-	-	-	-
Energy efficient TEFC (EETC)	200/3	-	-	-	-	60	60	65	81	89	142	154	250	290	358	-	639	705	794	860	1224	
	230/460/3	-	-	-	-	60	60	65	84	90	140	138	252	283	356	436	661	705	794	860	1224	1562
	575/3	-	-	-	-	60	60	65	81	89	142	154	250	287	358	436	661	705	-	-	-	-
NEMA Premium ODP (HEOP)	200/3	-	-	-	-	-	-	-	83	94	141	126	220	250	310	300	639	720	-	-	-	-
	230/460/3	-	-	-	-	-	-	-	87	94	118	126	217	250	309	300	676	616	-	-	-	-
	575/3	-	-	-	-	-	-	-	87	94	141	124	220	250	310	306	676	720	794	860	1224	-
NEMA Premium TEFC (HETC)	200/3	-	-	-	-	-	-	-	92	99	158	200	259	290	358	-	-	-	-	-	-	-
	230/460/3	-	-	-	-	-	-	-	92	99	158	175	275	308	418	424	750	740	-	-	-	-
	575/3	-	-	-	-	68	56	66	92	99	158	200	290	290	358	436	750	686	799	904	-	-

Approximate motor weights in pounds. Motor manufacturers vary and this data may change without notification.

Starter/VFD Weights

Fan weights do not include starter/VFD weights. The table below gives approximate starter/VFD weights.

Table 8. Approximate starter and VFD weights

	Weights (lb.) per Horsepower															
Horsepower	1	1.5	2	3	5	7.5	10	15	20	25	30	40	50	60	75	100	125
Starter[a]	65	65	65	65	65	65	65	65	65	97	97	97	97	97	97	97	97
VFD[1]	75	75	75	75	75	180	180	180	180	260	260	260	260	260	260	260	n/a

[a] These weights represent the largest available starter/VFD.

Appendix H

Acoustic Performance Study

Acoustical Breadth: Moisture's Effects Upon Reverberation Time

Space Under Consideration:	Theater	
Volume of Space:	108400	ft^3
Use Group of Space:	Multipurpose Auditorium	

Frequency	125 Hz	500 Hz	4002 Hz
Preferred Reverberation Time	2.3	1.8	1.4

Surface:		**Input Data**			**50% RH, Empty**			**60% RH, Empty**			**70% RH, Empty**		
Floor													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**
Carpet Tile on Concrete	2460	0.02	0.14	0.65	49.20	344.40	1,599.00	49.20	344.40	1,599.00	49.20	344.40	1,599.00
Upholstered Seating	2160	0.19	0.56	0.59	410.40	1,209.60	1,274.40	410.40	1,209.60	1,274.40	410.40	1,209.60	1,274.40
Carpet Tile - with Audience	1920	0.02	0.14	0.65									
Audience	2700	0.39	0.8	0.87									
Wood (stairs and stage front)	800	0.15	0.1	0.07	120.00	80.00	56.00	120.00	80.00	56.00	120.00	80.00	56.00
Ceiling													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**									
Gypsum Board Bulkhead / Ceiling ~50% RH	3968	0.15	0.06	0.13	595.20	238.08	515.84						
~ 60% RH	3968	0.16	0.1	0.18				634.88	396.80	714.24			
~ 70% RH	3968	0.17	0.12	0.2							674.56	476.16	793.60
Acoustic Ceiling Tile	1452	0.76	0.83	0.94	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88
North Wall - Main Entrances													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**									
Interior Wood Doors	126	0.15	0.1	0.07	18.90	12.60	8.82	18.90	12.60	8.82	18.90	12.60	8.82
Wood Base	38	0.15	0.1	0.07	5.70	3.80	2.66	5.70	3.80	2.66	5.70	3.80	2.66
Fab. Wrapped Acoustical Panels - 50% RH	458	0.15	0.06	0.13	68.70	27.48	59.54						
~ 60% RH	458	0.16	0.1	0.18				73.28	45.80	82.44			
~ 70% RH	458	0.17	0.12	0.2							77.86	54.96	91.60
Wood Panels	68	0.28	0.17	0.11	19.04	11.56	7.48	19.04	11.56	7.48	19.04	11.56	7.48
Window (Triple Pane)	26	0.35	0.18	0.04	9.10	4.68	1.04	9.10	4.68	1.04	9.10	4.68	1.04
Painted CMU	576	0.1	0.06	0.08	57.60	34.56	46.08	57.60	34.56	46.08	57.60	34.56	46.08
West Wall - Interior Side Door													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**									
Interior Wood Door	24.5	0.15	0.1	0.07	3.68	2.45	1.72	3.68	2.45	1.72	3.68	2.45	1.72
Wood Base	23.5	0.15	0.1	0.07	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65
Fab. Wrapped Acoustical Panels - 50% RH	324.8	0.15	0.06	0.13	48.72	19.49	42.22						
~ 60% RH	324.8	0.16	0.1	0.18				51.97	32.48	58.46			
~ 70% RH	324.8	0.17	0.12	0.2							55.22	38.98	64.96
Wood Panels	168.6	0.28	0.17	0.11	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55
Wood Proscenium Soffitt	36	0.19	0.09	0.05	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80
Painted CMU	756.4	0.1	0.06	0.08	75.64	45.38	60.51	75.64	45.38	60.51	75.64	45.38	60.51
East Wall - Exterior Side Door													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**									
Exterior Aluminum Door	24.5	0.05	0.1	0.02	1.23	2.45	0.49	1.23	2.45	0.49	1.23	2.45	0.49
Interior Wood Doors	42	0.15	0.1	0.07	6.30	4.20	2.94	6.30	4.20	2.94	6.30	4.20	2.94
Wood Base	23.5	0.15	0.1	0.07	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65
Fab. Wrapped Acoustical Panels - 50% RH	324.8	0.15	0.06	0.13	48.72	19.49	42.22						
~ 60% RH	324.8	0.16	0.1	0.18				51.97	32.48	58.46			
~ 70% RH	324.8	0.17	0.12	0.2							55.22	38.98	64.96
Wood Panels	168.6	0.28	0.17	0.11	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55
Wood Proscenium Soffitt	36	0.19	0.09	0.05	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80
Painted CMU	714.4	0.1	0.06	0.08	71.44	42.86	57.15	71.44	42.86	57.15	71.44	42.86	57.15
South Wall - Proscenium Arch to Stage													
Finish	**Area (ft^2)**	**α 125**	**α 500**	**α 4000**									
Wood Base	17	0.15	0.1	0.07	2.55	1.70	1.19	2.55	1.70	1.19	2.55	1.70	1.19
Fab. Wrapped Acoustical Panels - 50% RH	136	0.15	0.06	0.13	20.40	8.16	17.68						
~ 60% RH	136	0.16	0.1	0.18				21.76	13.60	24.48			
~ 70% RH	136	0.17	0.12	0.2							23.12	16.32	27.20
Wood Proscenium Soffitt	248.5	0.19	0.09	0.05	47.22	22.37	12.43	47.22	22.37	12.43	47.22	22.37	12.43
Painted CMU	252	0.1	0.06	0.08	25.20	15.12	20.16	25.20	15.12	20.16	25.20	15.12	20.16
Empty Stage	420	0.3	0.45	0.28	126.00	189.00	117.60	126.00	189.00	117.60	126.00	189.00	117.60
Stage Curtains	84	0.4	0.68	0.76	33.60	57.12	63.84	33.60	57.12	63.84	33.60	57.12	63.84
Curtains over the Stage Front	171.9	0.4	0.68	0.76	68.76	116.89	130.64	68.76	116.89	130.64	68.76	116.89	130.64
Wood Facing on the Stairs	22.5	0.15	0.1	0.07	3.38	2.25	1.58	3.38	2.25	1.58	3.38	2.25	1.58
Gyp. Board over CMU	175	0.12	0.07	0.04	21.00	12.25	7.00	21.00	12.25	7.00	21.00	12.25	7.00
Gyp. Board Soffitt	192	0.55	0.08	0.11	105.60	15.36	21.12	105.60	15.36	21.12	105.60	15.36	21.12
	Volume (ft^3)	**α 125**	**α 500**	**α 4000**									
Air, 50% RH	108.4	0	0.5	10.2	0.00	54.20	1,105.68						
Air, 60% RH	108.4	0	0.2	9.5				0.00	21.68	1,029.80			
Air, 70% RH	108.4	0	0.05	8							0.00	5.42	867.20
				Total Sabines:	3,281.93	3,871.17	6,685.89	3,334.04	4,047.11	6,870.59	3,386.16	4,135.08	6,812.23
A Surfaces Total	16,518.50			Reverberation Time:	1.65	1.40	0.81	1.63	1.34	0.79	1.60	1.31	0.80
A Panels Total	1,243.60												
Percent Area, Panels to Total	0.08			Acceptable?	N	N	N	N	N	N	N	N	N
					50% RH, Empty			**60% RH, Empty**			**70% RH, Empty**		

50% RH, Half Full			60% RH, Half Full			70% RH, Half Full			50% RH, Full			60% RH, Full			70% RH, Full		
α 125	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**	**α 125**	**α 500**	**α 4000**
24.60	172.20	799.50	24.60	172.20	799.50	24.60	172.20	799.50									
205.20	604.80	637.20	205.20	604.80	637.20	205.20	604.80	637.20									
19.20	134.40	624.00	19.20	134.40	624.00	19.20	134.40	624.00	38.40	268.80	1,248.00	38.40	268.80	1,248.00	38.40	268.80	1,248.00
526.50	1,080.00	1,174.50	526.50	1,080.00	1,174.50	526.50	1,080.00	1,174.50	1,053.00	2,160.00	2,349.00	1,053.00	2,160.00	2,349.00	1,053.00	2,160.00	2,349.00
120.00	80.00	56.00	120.00	80.00	56.00	120.00	80.00	56.00	120.00	80.00	56.00	120.00	80.00	56.00	120.00	80.00	56.00
595.20	238.08	515.84							595.20	238.08	515.84						
			634.88	396.80	714.24							634.88	396.80	714.24			
						674.56	476.16	793.60							674.56	476.16	793.60
1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88	1,103.52	1,205.16	1,364.88
18.90	12.60	8.82	18.90	12.60	8.82	18.90	12.60	8.82	18.90	12.60	8.82	18.90	12.60	8.82	18.90	12.60	8.82
5.70	3.80	2.66	5.70	3.80	2.66	5.70	3.80	2.66	5.70	3.80	2.66	5.70	3.80	2.66	5.70	3.80	2.66
68.70	27.48	59.54							68.70	27.48	59.54						
			73.28	45.80	82.44							73.28	45.80	82.44			
						77.86	54.96	91.60							77.86	54.96	91.60
19.04	11.56	7.48	19.04	11.56	7.48	19.04	11.56	7.48	19.04	11.56	7.48	19.04	11.56	7.48	19.04	11.56	7.48
9.10	4.68	1.04	9.10	4.68	1.04	9.10	4.68	1.04	9.10	4.68	1.04	9.10	4.68	1.04	9.10	4.68	1.04
57.60	34.56	46.08	57.60	34.56	46.08	57.60	34.56	46.08	57.60	34.56	46.08	57.60	34.56	46.08	57.60	34.56	46.08
3.68	2.45	1.72	3.68	2.45	1.72	3.68	2.45	1.72	3.68	2.45	1.72	3.68	2.45	1.72	3.68	2.45	1.72
3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65
48.72	19.49	42.22							48.72	19.49	42.22						
			51.97	32.48	58.46							51.97	32.48	58.46			
						55.22	38.98	64.96							55.22	38.98	64.96
47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55
6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80
75.64	45.38	60.51	75.64	45.38	60.51	75.64	45.38	60.51	75.64	45.38	60.51	75.64	45.38	60.51	75.64	45.38	60.51
1.23	2.45	0.49	1.23	2.45	0.49	1.23	2.45	0.49	1.23	2.45	0.49	1.23	2.45	0.49	1.23	2.45	0.49
6.30	4.20	2.94	6.30	4.20	2.94	6.30	4.20	2.94	6.30	4.20	2.94	6.30	4.20	2.94	6.30	4.20	2.94
3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65	3.53	2.35	1.65
48.72	19.49	42.22							48.72	19.49	42.22						
			51.97	32.48	58.46							51.97	32.48	58.46			
						55.22	38.98	64.96							55.22	38.98	64.96
47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55	47.21	28.66	18.55
6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80	6.84	3.24	1.80
71.44	42.86	57.15	71.44	42.86	57.15	71.44	42.86	57.15	71.44	42.86	57.15	71.44	42.86	57.15	71.44	42.86	57.15
2.55	1.70	1.19	2.55	1.70	1.19	2.55	1.70	1.19	2.55	1.70	1.19	2.55	1.70	1.19	2.55	1.70	1.19
20.40	8.16	17.68							20.40	8.16	17.68						
			21.76	13.60	24.48							21.76	13.60	24.48			
						23.12	16.32	27.20							23.12	16.32	27.20
47.22	22.37	12.43	47.22	22.37	12.43	47.22	22.37	12.43	47.22	22.37	12.43	47.22	22.37	12.43	47.22	22.37	12.43
25.20	15.12	20.16	25.20	15.12	20.16	25.20	15.12	20.16	25.20	15.12	20.16	25.20	15.12	20.16	25.20	15.12	20.16
126.00	189.00	117.60	126.00	189.00	117.60	126.00	189.00	117.60	126.00	189.00	117.60	126.00	189.00	117.60	126.00	189.00	117.60
33.60	57.12	63.84	33.60	57.12	63.84	33.60	57.12	63.84	33.60	57.12	63.84	33.60	57.12	63.84	33.60	57.12	63.84
68.76	116.89	130.64	68.76	116.89	130.64	68.76	116.89	130.64	68.76	116.89	130.64	68.76	116.89	130.64	68.76	116.89	130.64
3.38	2.25	1.58	3.38	2.25	1.58	3.38	2.25	1.58	3.38	2.25	1.58	3.38	2.25	1.58	3.38	2.25	1.58
21.00	12.25	7.00	21.00	12.25	7.00	21.00	12.25	7.00	21.00	12.25	7.00	21.00	12.25	7.00	21.00	12.25	7.00
105.60	15.36	21.12	105.60	15.36	21.12	105.60	15.36	21.12	105.60	15.36	21.12	105.60	15.36	21.12	105.60	15.36	21.12
0.00	54.20	1,105.68							0.00	54.20	1,105.68						
			0.00	21.68	1,029.80							0.00	21.68	1,029.80			
						0.00	5.42	867.20							0.00	5.42	867.20
3,597.83	4,308.57	7,047.69	3,649.94	4,484.51	7,232.39	3,702.06	4,572.48	7,174.03	3,913.73	4,745.97	7,409.49	3,965.84	4,921.91	7,594.19	4,017.96	5,009.88	7,535.83
1.51	1.26	0.77	1.48	1.21	0.75	1.46	1.19	0.76	1.38	1.14	0.73	1.37	1.10	0.71	1.35	1.08	0.72
N	Y	N	N	Y	N	N	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
50% RH, Half Full			**60% RH, Half Full**			**70% RH, Half Full**			**50% RH, Full**			**60% RH, Full**			**70% RH, Full**		

Appendix I

Construction Estimates

Selective Demolition and Renovation - Replacement of 10 Air Handling Units

Air Handling Unit Costs: from Trane Trace

5000 CFM and Under	$5-6/cfm	Added Cost for Desiccant Wheel:	$5-6/cfm	Total Cost:	$10-12/cfm
Over 5000 CFM:	$3.5-4/cfm	Added Cost for Desiccant Wheel:	$3-4/cfm	Total Cost:	$7-8/cfm

Demolition Costs

Equipment	Crew	Daily Output	Labor Hours	Amount	Unit	Material	Labor	Equip	Total	O&P Multiplyer	Total, plus O&P	Notes
AHU-1	Q-6	1.3	18.462	1	Ea.		$740.00		$740.00	1.132	$837.68	
AHU-2	Q-6	1.2	20	1	Ea.		$805.00		$805.00	1.137	$915.29	
AHU-3	Q-6	1.2	20	1	Ea.		$805.00		$805.00	1.137	$915.29	
AHU-4	Q-6	1.2	20	1	Ea.		$805.00		$805.00	1.137	$915.29	
AHU-5	Q-6	1.2	20	1	Ea.		$805.00		$805.00	1.137	$915.29	
AHU-6	Q-5	0.95	16.842	1	Ea.		$655.00		$655.00	1.144	$749.32	
AHU-9	Q-6	1.3	18.462	1	Ea.		$740.00		$740.00	1.132	$837.68	
AHU-10	Q-6	1.3	18.462	1	Ea.		$740.00		$740.00	1.132	$837.68	
Spiral, prefab	Q-9	400	0.4	8	LF		$1.52		$12.16	1.54	$18.73	AHU 1 Duct
Spiral, prefab ductwork	Q-9	400	0.4	48	LF		$1.52		$72.96	1.54	$112.36	AHU 2-5 Duct Connections
Spiral, prefab ductwork	Q-9	400	0.4	10	LF		$1.52		$15.20	1.54	$23.41	AHU 6 Duct Connections
Spiral, prefab ductwork	Q-8	400	0.4	1	LF		$0.52		$0.52	1.54	$0.80	AHU 9-10 Duct Connections
1-1/2" Metal Pipe and Under	1 Plum	200	0.4	160	LF		$1.63		$260.80	1.51	$393.81	Connection Demo to prepare for new
2" - 3.5" Metal Pipe	2 Plum	150	0.53	20	LF		$2.18		$43.60	1.5	$65.40	Demo to prepare for new
											$7,538.00	**Subtotal: Demolition**

New Installation Costs

Equipment	Crew	Daily Output	Labor Hours	Amount	Unit	Material	Labor	Equip	Total	O&P Multiplyer	Total, plus O&P	Notes
AHU-1	Q-6	1.3	18.462	1	Ea.	$48,000.00	$740.00		$48,740.00	1.132	$55,173.68	
AHU-2	Q-6	1.2	20	1	Ea.	$60,000.00	$805.00		$60,805.00	1.137	$69,135.29	
AHU-3	Q-6	1.2	20	1	Ea.	$60,000.00	$805.00		$60,805.00	1.137	$69,135.29	
AHU-4	Q-6	1.2	20	1	Ea.	$60,000.00	$805.00		$60,805.00	1.137	$69,135.29	

AHU-5	Q-6	1.2	20	1	Ea.	$60,000.00	$805.00		$60,805.00	1.137	$69,135.29	
AHU-6	Q-5	0.95	16.842	1	Ea.	$42,000.00	$655.00		$42,655.00	1.144	$48,797.32	
AHU-9	Q-6	1.3	18.462	1	Ea.	$44,000.00	$740.00		$44,740.00	1.132	$50,645.68	
AHU-10	Q-6	1.3	18.462	1	Ea.	$44,000.00	$740.00		$44,740.00	1.132	$50,645.68	
											$481,803.50	**Subtotal: AHU's**

Accessories

Equipment	Crew	Daily Output	Labor Hours	Amount	Unit	Material	Labor	Equip	Total	O&P Multiplyer	Total, plus O&P	Notes
1.5" Type L Copper	1 Plum	52	0.154	62	LF	$5.40	$6.30		$396.00	1.573	$622.91	
2" Type L Copper	1 Plum	42	0.19	130	LF	$8.40	$7.80		$1,022.40	1.296	$1,325.03	
2.5" Type L Copper	Q-1	62	0.258	64	LF	$12.75	$9.50		$620.75	1.281	$795.18	
52x18				203	lb							
30" round				682	lb							
24x36				1042	lb							
54x22.75				111	lb							
16x76				708	lb							
18x25				83	lb							
22 round				1742	lb							
20x24				974	lb							
Ductwork, AL, over 5000 lb	Q-10	145	0.166	5545	lb	$1.50	$6.20		$34,380.50	1.455	$50,023.63	
Balancing									$445.32	1	$445.32	Multizone AC and Heating Unit
Balancing									$8.06	1	$8.06	High Ceiling, ducts etc.
Balancing									$91.09	1	$91.09	Main and duct reheat coils
Balancing									$88.63	1	$88.63	Fan coil unit (CHW)
Stiffener Plates				2	Cwt.	$43.00			$43.00	1.105	$47.52	
DDC Controls				8	Ea.	$1,018.59			$8,148.72	1	$8,148.72	H'stat
OSHA Testing			Day	1	Ea.		$300.00		$300.00	1	$300.00	H'stat
											$61,896.08	**Subtotal: Accessories**
											$551,237.58	**Total: AHU Renovation**

Mold and Moisture Problems: Associated Costs

Resurfacing of the Gym Floor

Services	Crew	Daily Output	Labor Hours	Amount	Unit	Material	Labor	Equip	Total	O&P Multiplyer	Total, plus O&P	Notes
Refinish wood floor	1 Clab	400	0.2	10073	SF	$0.71	$0.55		$12,691.98	1.294	$16,423.42	
											$16,423.42	**Subtotal: Gym Floor**

Mold Remediation

Services	Crew	Daily Output	Labor Hours	Amount	Unit	Material	Labor	Equip	Total	O&P Multiplyer	Total, plus O&P	Notes
OSHA Testing			Day						$300.00	1	$300.00	Minimum, Technician
Pre-cleaning	A-10	12000	0.005	12722	SF	$0.01	$0.21		$2,798.84	1.294	$3,621.70	HEPA Vacuum and wet wipe
Collect and bag bulk material	A-9	400	0.16	6	Ea.	$1.15	$6.25		$44.40	1.51	$67.04	3 CF bags
Cart bags 50' to dumpster	2 Asbe	400	0.04	6	Ea.		$1.56		$9.36	1.583	$14.82	Not including haul, min.
Disposal Charges				1	C.Y.		$75.00		$75.00	1	$75.00	Not including haul, min.
Set up neg. air machine	1 Asbe	4.3	1.86	1	Ea.		$72.50		$72.50	1	$72.50	1-2kCFM/25MCF Volume
New Auditorium Seating, upholstered				2	Ea.	$1,250.00			$2,500.00	1.1	$2,750.00	Area seatin, 3 seat straight unit
											$6,901.06	**Subtotal: Mold**

Direct and Indirect Energy Costs

Utility	Average Annual Consumption	Cost of Energy	Years	New Annual Consumption	Cost of Energy	Units	Energy Difference	Cost of Energy - Additional	Total	Notes
Electricity	1,035,213.00	$6,521.84	3	1,603,971.30	$10,105.02	kWh	568,758.30	$3,583.18	$10,749.53	Demand charge excluded
Natural Gas	3789.6	$5,142.49	3	9,813.50	$13,316.92	Therms	6,023.90	$8,174.43	$24,523.30	
									$35,272.83	**Subtotal: Energy Costs**
									$58,597.31	**Total Costs**

Appendix J

Life Cycle Cost Analysis Calculation

Life Cycle Cost Analysis

Cost of Electricity:	0.0827	$/kWh
Cost of LNG:	13.57	$/Therm
O&M Costs:	7000	$/year
Life of DW:	18	years
Life of Units:	25	years
Energy Inflation:	2	%

*From EIA Website

	Base Case	Best Case	Current Case
Electric Use (KWh)	1035213.00	1147746.80	1603971.30
LNG Use (Therms)	3789.60	5577.90	9813.50

***Note: All Costs are in Thousands of Dollars**

Service Year	Initial Cost, LNG	Energy Price Index, LNG	Initial Cost, Electric	Energy Price Index, Electric	Base Case Energy Costs	Best Case Energy Difference	Current Case Energy Difference	Best Case Difference From Current Case	O&M Costs
0	$1.36	1.00	0.0827	1.00	$1,405.10	$0.00	-$55.21	$0.00	$0.00
1	$1.36	0.96	0.0827	0.96	$1,348.89	$0.00	-$53.00	$0.00	$0.00
2	$1.36	0.93	0.0827	0.92	$1,306.74	$0.00	-$50.88	$0.00	$0.00
3	$1.36	0.90	0.0827	0.92	$1,264.59	-$10.75	-$50.63	$39.88	$0.00
4	$1.36	0.89	0.0827	0.95	$1,250.56	-$11.00	-$51.96	$40.96	$2.00
5	$1.36	0.89	0.0827	0.99	$1,250.57	-$11.37	-$53.84	$42.47	$2.00
6	$1.36	0.90	0.0827	1.03	$1,264.63	-$11.77	-$55.80	$44.03	$2.00
7	$1.36	0.92	0.0827	1.09	$1,292.74	-$12.38	-$58.79	$46.41	$2.00
8	$1.36	0.95	0.0827	1.13	$1,334.90	-$12.82	-$60.92	$48.09	$2.00
9	$1.36	0.98	0.0827	1.18	$1,377.06	-$13.36	-$63.51	$50.15	$2.00
10	$1.36	1.02	0.0827	1.22	$1,433.26	-$13.83	-$65.72	$51.89	$2.00
11	$1.36	1.04	0.0827	1.24	$1,461.36	-$14.06	-$66.83	$52.76	$2.00
12	$1.36	1.07	0.0827	1.27	$1,503.52	-$14.42	-$68.48	$54.07	$2.00
13	$1.36	1.11	0.0827	1.31	$1,559.72	-$14.89	-$70.69	$55.81	$2.00
14	$1.36	1.16	0.0827	1.35	$1,629.97	-$15.38	-$72.98	$57.60	$2.00
15	$1.36	1.19	0.0827	1.39	$1,672.13	-$15.82	-$75.11	$59.28	$2.00
16	$1.36	1.23	0.0827	1.42	$1,728.33	-$16.20	-$76.85	$60.65	$2.00
17	$1.36	1.27	0.0827	1.45	$1,784.53	-$16.58	-$78.58	$62.01	$2.00
18	$1.36	1.30	0.0827	1.48	$1,826.68	-$16.93	-$80.24	$63.31	$2.00
19	$1.36	1.34	0.0827	1.51	$1,882.88	-$17.30	-$81.98	$64.67	$2.00
20	$1.36	1.38	0.0827	1.55	$1,939.09	-$17.77	-$84.19	$66.41	$2.00
21	$1.36	1.41	0.0827	1.58	$1,981.24	-$18.13	-$85.84	$67.72	$2.00
22	$1.36	1.45	0.0827	1.62	$2,037.44	-$18.60	-$88.05	$69.46	$2.00
23	$1.36	1.48	0.0827	1.66	$2,079.60	-$19.04	-$90.18	$71.14	$2.00
24	$1.36	1.52	0.0827	1.69	$2,135.80	-$19.42	-$91.92	$72.50	$2.00
25	$1.36	1.56	0.0827	1.73	$2,192.01	-$19.89	-$94.12	$74.24	$2.00

Life Cycle Cost Analysis Continued

Definitions:

Base Case: Building operating with the equipment and schedules as originally designed, at the current occupancy rates

Current Case: Building operating with design equipment running at 100% on all the time to counteract unusual humidity accumulation

Current Case: Building equipment redesign - series desiccant wheels, enthalpy based economizer, with nightly purges and otherwise normal schedule

	Best Bet Cummulative Savings - Compared to Current Case					Best Bet Net Savings - Compared with Current Case	
Year	Cost, d=0%	Cost, d=3%	Base Case Initial Cost	Best Case Initial Investment	Current Case Initial Cost	Best Net Savings, d=0%	Best Net Savings, d=3%
0	$0.00	$0.00	$2,000.00	$0.00	$2,000.00	$0.00	$0.00
1	$0.00	$0.00	$2,000.00	$0.00	$2,000.00	$0.00	$0.00
2	$0.00	$0.00	$258,597.31	$0.00	$258,597.31	$0.00	$0.00
3	$39.88	$38.69	$258,597.31	$551.24	$258,597.31	-$511.35	-$512.55
4	$78.84	$76.42	$258,597.31	$551.24	$258,597.31	-$472.39	-$474.82
5	$119.31	$115.61	$258,597.31	$551.24	$258,597.31	-$431.93	-$435.63
6	$161.35	$156.33	$258,597.31	$551.24	$258,597.31	-$389.89	-$394.91
7	$205.76	$199.35	$258,597.31	$551.24	$258,597.31	-$345.48	-$351.89
8	$251.85	$244.00	$258,597.31	$551.24	$258,597.31	-$299.38	-$307.24
9	$300.01	$290.65	$258,597.31	$551.24	$258,597.31	-$251.23	-$260.59
10	$349.90	$338.98	$258,597.31	$551.24	$258,597.31	-$201.34	-$212.25
11	$400.66	$388.16	$258,597.31	$551.24	$258,597.31	-$150.57	-$163.07
12	$452.73	$438.61	$258,597.31	$551.24	$258,597.31	-$98.51	-$112.63
13	$506.54	$490.74	$258,597.31	$551.24	$258,597.31	-$44.70	-$60.50
14	$562.14	$544.61	$258,597.31	$551.24	$258,597.31	$10.90	-$6.62
15	$619.42	$600.12	$258,597.31	$551.24	$258,597.31	$68.19	$48.88
16	$678.07	$656.95	$258,597.31	$551.24	$258,597.31	$126.83	$105.71
17	$738.08	$715.09	$258,597.31	$551.24	$258,597.31	$186.84	$163.86
18	$799.39	$774.51	$258,597.31	$551.24	$258,597.31	$248.15	$223.27
19	$862.06	$835.24	$258,597.31	$551.24	$258,597.31	$310.82	$284.00
20	$926.48	$897.66	$258,597.31	$551.24	$258,597.31	$375.24	$346.42
21	$992.19	$961.35	$258,597.31	$551.24	$258,597.31	$440.96	$410.11
22	$1,059.65	$1,026.72	$258,597.31	$551.24	$258,597.31	$508.41	$475.48
23	$1,128.79	$1,093.72	$258,597.31	$551.24	$258,597.31	$577.55	$542.49
24	$1,199.29	$1,162.05	$258,597.31	$551.24	$258,597.31	$648.05	$610.81
25	$1,271.53	$1,232.06	$258,597.31	$551.24	$258,597.31	$720.29	$680.82

Results: 11 Year Simple Payback with Depreciation
Energy Savings: Initially about $40,000 / year, increases with inflation
Outside Influences: Using less energy to cover the moisture remediation solution

Pennsylvania Electricity Profile 2005 Edition

DOE/EIA-0348
Date of Data: 2005
Data Release Date: March 2007

Table 1. 2005 Summary Statistics (Pennsylvania)

Item	**Value**	**U.S.Rank**
NERC Region(s)		**ECAR/ERCOT/MAAC**
Primary Energy Source		**Coal**
Net Summer Capability (megawatts)	**44,897**	**4**
Electric Utilities	4,956	34
Independent Power Producers & Combined Heat and Power	39,941	2
Net Generation (megawatthours)	**218,091,125**	**3**
Electric Utilities	33,243,828	31
Independent Power Producers & Combined Heat and Power	184,847,298	2
Emissions (thousand metric tons)		
Sulfur Dioxide	1,019	2
Nitrogen Oxide	186	5
Carbon Dioxide	126,713	4
Sulfur Dioxide (lbs/MWh)	10.3	6
Nitrogen Oxide (lbs/MWh)	1.9	33
Carbon Dioxide (lbs/MWh)	1,281	33
Total Retail Sales (megawatthours)	**148,272,940**	**6**
Full Service Provider Sales (megawatthours)	137,220,957	4
Deregulated Sales (megawatthours)	11,051,983	10
Direct Use (megawatthours)	**3,268,349**	**12**
Average Retail Price (cents/kWh)	**8.27**	**16**

More Tables on Pennsylvania's Electricity Profile:	**Formats**	
Table 1. 2005 Summary Statistics	xls	
Table 2. Ten Largest Plants by Generating Capability, 2005	xls	
Table 3. Top Five Providers of Retail Electricity, 2005	xls	
Table 4. Electric Power Industry Capability by Primary Energy Source, 1990 Through 2005	xls	printer friendly version pdf
Table 5. Electric Power Industry Generation by Primary Energy Source, 1990 Through 2005	xls	
Table 6. Electric Power Delivered Fuel Prices for Coal, Petroleum, Natural Gas, 1990 Through 2005	xls	
Table 7. Electric Power Industry Emissions Estimates, 1990 Through 2005	xls	
Table 8. Retail Sales, Revenue, and Average Retail Price by Sector, 1990 Through 2005	xls	
Table 9. Retail Electricity Sales Statistics, 2005	xls	

see also:
Electric Power Monthly
Electric Power Annual
annual electricity statistics back to 1949
projected electricity capacity to 2030
international electricity statistics

Natural Gas Prices

(Dollars per Thousand Cubic Feet, except where noted)

Area: Pennsylvania **Period:** Monthly

Show Data By: ● **Data Series** ○ **Area**	Aug-06	Sep-06	Oct-06	Nov-06	Dec-06	Jan-07	View History
City Gate Price	10.14	9.32	8.16	9.90	9.57	9.12	1989-2007
Residential Price	20.96	19.56	15.76	14.48	13.90	13.70	1989-2007
Commercial Price	13.57	13.37	12.40	13.01	13.10	12.55	1989-2007
Percentage of Total Commercial Deliveries	100.0	100.0	100.0	100.0	100.0	100.0	1989-2007
Industrial Price	10.55	9.91	9.47	11.18	12.12	12.90	2001-2007
Percentage of Total Industrial Deliveries	4.4	6.6	6.7	4.9	5.8	4.6	2001-2007
Electric Power Price (New Definition)	8.54	5.45	5.92	7.99	NA		2002-2006

Last Updated 03/29/2007
- = No Data Reported; **NA** = Not Available; **W** = Withheld to avoid disclosure of individual company data.

Notes: Gas volumes delivered for use as vehicle fuel are included in the State annual totals through 2005 but not in the State monthly components. Through 2001, electric power price data are for regulated electric utilities only; beginning in 2002, data also include nonregulated members of the electric power sector. See Definitions, Sources, and Notes link above for more information on this table.

Appendix K

Emissions Calculations

Emissions Calculations Worksheet

Background Utility Information	
Electrical Utility - West Penn Power, part of Allegheny Energy	
Electricity Produced (MWh / yr)	36,000,000.00
Electrical NOx Emissions (Tons / yr)	160,000.00
Electrical SOx Emissions (Tons / yr)	600,000.00
Electrical CO2 Emissions (Tons / yr)	44,000,000.00
Electrical Mercury Emissions (Pounds / yr)	2,250.00
Electrical NOx Emissions (Pounds / MWh)	8.89
Electrical SOx Emissions (Pounds / MWh)	33.33
Electrical CO2 Emissions (Pounds / MWh)	2444.44
Electrical Mercury Emissions (Pounds / MWh)	0.00
LNG Utility - Columbia Gas of PA	
LNG NOx Emissions (Pounds / cu.ft.)	206.74
LNG SOx Emissions (Pounds / cu.ft.)	Negligible
LNG CO2 Emissions (Pounds / cu.ft.)	98.90
LNG Mercury Emissions (Pounds / cu.ft.)	Negligible

Case	Base Case	Current Case	Chosen Case	Percent Growth - Base to Current Case	Percent Reduction - Current to Chosen Case
Electrical Energy Use (MWh)	1,035.20	1,603.97	1,147.75	154.94	28.44
Annual NOx (Tons / year)	4.60	7.13	5.10	154.94	28.44
Annual SOx (Tons / year)	17.25	26.73	19.13	154.94	28.44
Annual CO2 (Tons / year)	1,265.24	1,960.41	1,402.81	154.94	28.44
Annual Mercury (Tons / year)	0.00	0.00	0.00	154.94	28.44
Natural Gas Use (Therms)	3,789.60	9,813.50	5,577.90	258.96	43.16
Natural Gas Use (cu.ft.)	369.00	955.55	543.13	258.96	43.16
Annual NOx (Tons / year)	38.14	98.78	56.14	258.96	43.16
Annual CO2 (Tons / year)	1.89	4.88	2.78	258.96	43.16
Total NOx (Tons / year)	42.74	105.90	61.24	247.76	42.17
Total SOx (Tons / year)	17.25	26.73	19.13	154.94	28.44
Total CO2 (Tons / year)	1,267.13	1,965.29	1,405.58	155.10	28.48
Total Mercury (Tons / year)	0.00	0.00	0.00	154.94	28.44
Total Emissions (Tons / year)	1,327.13	2,097.93	1,485.96	158.08	29.17

Boiler Emissions Calculations:

Known:

From Smith (Boiler Manufacturer):
T_stack = 475 °F

From Union Gas Natural Gas information:
Composition of LNG, % Volume:

- 94.9% CH_4
- 2.5% C_2H_6
- 1.6% N_2

Sulfur is evident at a rate = 5.5 mg / m^3

$(5.5 \text{ mg} / \text{m}^3) * (\text{m}^3 / 35.32 \text{ ft}^3) * (\text{kg} / 1*10^6 \text{ mg}) * (2.205 \text{ lbm} / \text{kg}) =$

$= 3.434*10^7 \text{ lbm}_S / \text{ft}^3$

Flammability Limit of LNG lies between 4% - 16% by Volume

$S.G._{LNG} = 0.585$

From AE 598A Notes:
F/A Ratio, LNG, Stoichiometric = 0.0585

From Fluid Mechanics Fundamentals and Applications:
$\rho_{H2O} = 62.36 \text{ lbm} / \text{ft}^3$ at Std. Conditions – 60 °F, 1 atm

Assumptions:
F/A Ratio of burner = fuel lean = 0.05

Calculations:

0.05 Parts Fuel to 0.95 Parts Air = 1:19 Fuel:Air

Combustion Equation:

$$[0.949\ CH_4 + 0.025\ C_2H_6 + 0.016\ N_2] + 19\ [0.21\ O_2 + 0.79\ N_2] =>$$

$$X\ CO_2 + y\ H_2O + z\ NO_2 + xx\ N_2 + yy\ O_2$$

Simplify:

$$[0.949CH_4 + 0.025C_2H_6 + 0.016N_2] + 3.99O_2 + 15.01N_2 =>$$

$$1\ CO_2 + 2\ H_2O + 2\ NO_2 + 28\ N_2 + 0\ O_2$$

$S.G._{LNG} = 0.585 = \rho_{LNG} / \rho_{H2O}$

ρ_{LNG} = 0.585 * 62.36 lbm / ft^3 = 36.48 lbm / ft^3

Sulfur in LNG:

(3.434*10^7 lbm$_S$ / ft^3) / (36.48 lbm / ft^3) = 9.41*10^9 % Volume
Therefore – Sulfur, and SO_x, are negligible.

From the combustion equation:

1 mol LNG : 1 mol CO_2 : 2 mol NO_2

Molar Mass of LNG:
[0.949 + (2*0.025)]*12 + [(4*0.949) + (6*0.025)]*1 + [0.016*2]*14 = 16.24 lbm / mol

Molar Mass of CO_2:
12 + (2*16) = 44 lbm / mol

Molar Mass of NO_2:
2*[14 + (2*16)] = 92 lbm / mol

Volume of 1 mol LNG:
1 mol LNG * (16.24 lbm / mol) * (ft^3 / 36.48 lbm) = 0.445 ft^3 LNG

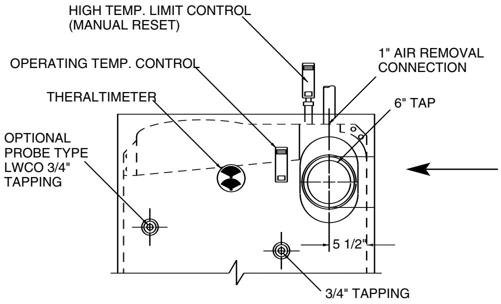
Mass of Emissions:
For every 0.445 ft^3 LNG, 44 lbm CO_2 and 92 lbm NO_2 are produced

-or-

For every 1 ft^3 LNG, 98.9 lbm CO_2 and 206.74 lbm NO_2 are produced

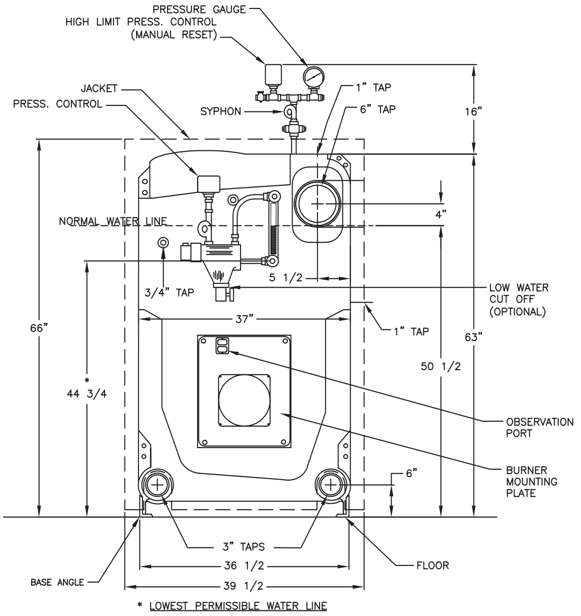
LIGHT OIL, GAS, OR GAS/LIGHT OIL

I=B=R Ratings – Gross Output 900 to 4,629 MBH



FRONT VIEW

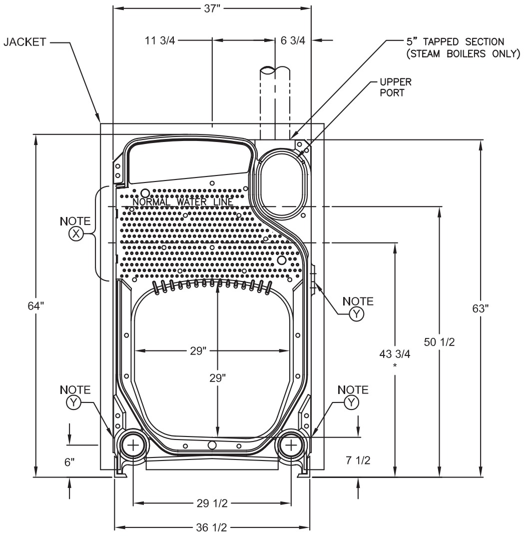
(Water Boiler)



FRONT VIEW

(Steam Boiler)

MEA #273-89-E



INTERMEDIATE SECTION

Note X – Flue cleanout opening. Allow 36" clear work space for using flue brush.

Note Y – 1-1/2" Inspection tappings when ordered.

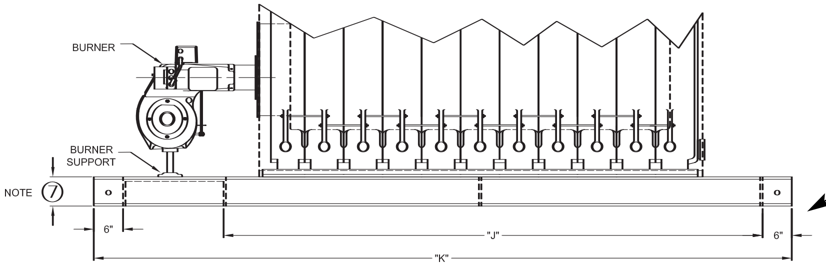
I=B=R Ratings, a

Designed and Tested According to the A.S.M.E. Boiler and Pressure Vessel Code

Boiler Number (Note 1)	Boiler Horse-power	I=B=R Gross Output (MBH)	Net I=B=R Ratings (Note 2)					Heating Surface (Sq. Ft.)	Furnace Volume (Cu. Ft.)	Water Contents (Gals.)		Water Working Weight (Lbs.)	Overall Length —		
			Steam		Water	I=B=R Burner Capacity							(Note 8)		
			Sq. Ft.	MBH	MBH	Oil GPH (Note 3)	Gas MBH (Note 4)			Steam	Water		Carlin	Beckett	Power Flame
†28A-Δ-4	27	900	2813	675	783	8.0	1154	81.2	12.04	103.8	123.4	4,215	62¼	64	71⅝
†28A-Δ-5	35	1166	3646	875	1014	10.4	1491	105.3	16.14	125.8	150.3	5,038	70¼	72	83⅛
†28A-Δ-6	43	1433	4538	1089	1246	12.6	1827	129.4	20.24	147.8	177.2	5,861	80⅛	80¼	91⅛
†28A-Δ-7	51	1699	5458	1310	1477	15.0	2163	153.5	24.34	169.8	204.1	6,684	88⅛	88⅝	99⅛
†28A-Δ-8	59	1965	6358	1526	1709	17.4	2499	177.6	28.44	191.8	231.0	7,507	96⅛	96¾	107⅛
†28A-Δ-9	67	2232	7221	1733	1941	19.6	2836	201.7	32.54	213.8	257.9	8,331	108⅞	104¾	115⅛
†28A-Δ-10	75	2498	8079	1939	2172	22.0	3172	225.8	36.64	235.8	284.8	9,169	116⅞	116⅜	128
†28A-Δ-11	83	2764	8942	2146	2403	24.5	3508	249.9	40.74	257.8	311.7	9,992	125⅛	124⅜	137⅛
†28A-Δ-12	91	3031	9804	2353	2636	26.5	3844	274.0	44.84	279.8	338.6	10,815	133⅛	132½	145⅛
†28A-Δ-13	98	3297	10667	2560	2867	29.0	4180	289.1	48.94	301.8	365.5	11,649	141⅛	—	153⅛
†28A-Δ-14	106	3563	11525	2766	3098	31.5	4517	322.2	53.04	323.8	392.4	12,467	149⅛	—	161⅛
†28A-Δ-15	114	3830	12392	2974	3330	33.5	4853	346.3	57.14	345.8	419.3	13,511	—	—	169⅛
†28A-Δ-16	122	4096	13250	3180	3562	36.0	5189	370.4	61.24	367.8	446.2	14,375	—	—	177⅛
†28A-Δ-17	130	4362	14113	3387	3793	38.5	5525	394.5	65.34	389.8	473.1	15,239	—	—	191⅛
†28A-Δ-18	138	4629	14975	3594	4025	40.5	5862	418.6	69.44	411.8	500.0	16,103	—	—	199⅛

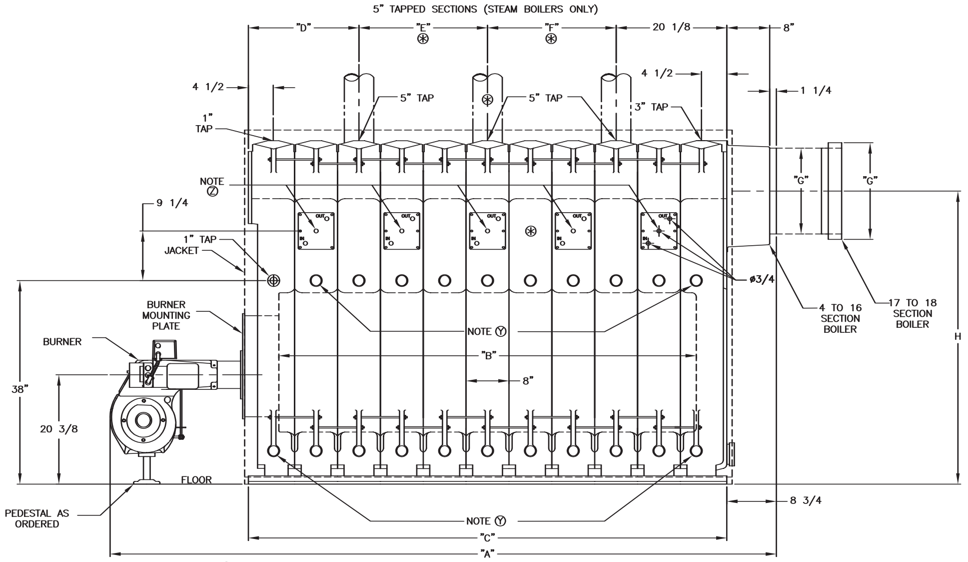
(Note 1) Important Ordering information
(†) Add Prefix for type of fuel to be burned. "LO" for light oil, "G" for Gas or "GO" for gas/oil.
(Δ) Insert "S" for steam, "W" for water.
Example: LO-28A-S-6 is the model no. for a six section steam boiler firing light oil.
(Note 2) Net I=B=R Water Ratings are based on an allowance of 1.15. Net I=B=R Ratings for steam boilers are based on piping and pick-up factor as follows: 4 and 5 section = 1.333, 6 section = 1.305, 8 section and larger = 1.288.

(Note 3) Light oil having a heat content of 140,000 BTU/Gal.
(Note 4) Gas having a heat content of 1,000 BTU/Cu. Ft., 0.60 specific gravity
(Note 5) Burner operation: Low-fire start, high-fire run, two position air.
(Note 6) Burner operation: On-off, (4 sect.); Low-fire start, high-fire run, two position air (5-14 sect.).
* When 5th heater is required—relocate steam uptake and dimensions "E" = 32 in. and "F" = 16 in.



OPTIONAL ASSEMBLED SECTION AND PACKAGED BASE

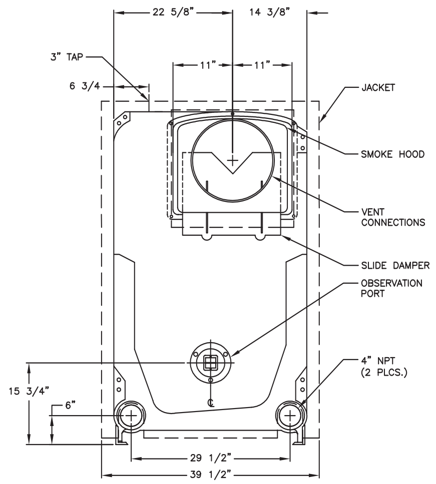
Caution: Add 6" to all vertical measurements on 4-14 section boilers and 8" on 15-18 sections



⊛When 5th heater is required-relocate steam uptake and dimensions "E" = 32 in. and "F" = 16 in.

SIDE VIEW

Note Z – Tankless heater sections when ordered.
Allow 36" clear space for heater withdrawal.



REAR VIEW

nd Dimensions (inches)

e , Section IV for maximum allowable working pressure, steam 15 psig, water 80 psig.

– “A”		Opt. Packaged Base Dimensions				Furnace Length “B”	Boiler Length “C”	Steam Uptake Locations (Note 9)			Draft Loss Ins. W.C.	Firebox Press Ins. W.C.††	Dia. Vent Conn. “G”	(Note 7) Height Vent Conn. “H”	Boiler Number (Note 1)
		Carlin & Beckett		Power Flame, Webster and Gordon Piatt											
Webster	Gordon Piatt	“J”	“K”	“J”	“K”			“D”	“E”	“F”					
66⅜	70⅝	54¼	83¼	54¼	91¼	23⅓	33	12½	—	—	.24	.34	10	57⅝	†28A-Δ-4
74⅜	81⅛	62¼	91¼	62¼	104¼	31⅓	41	20½	—	—	.25	.35	10	57⅝	†28A-Δ-5
82⅜	89⅛	70⅜	99⅛	70⅜	112⅜	39⅓	49	12½	16	—	.26	.36	10	56⅝	†28A-Δ-6
90⅜	97⅛	78⅜	107⅛	78⅜	120⅜	47⅓	57	12½	24	—	.27	.37	12	56⅝	†28A-Δ-7
98⅜	105⅛	86½	115¼	86½	128½	55⅓	65	12½	32	—	.28	.38	12	55⅝	†28A-Δ-8
110⅜	113⅛	96½	123¼	94½	136½	63⅓	73	12½	40	—	.29	.39	14	55⅝	†28A-Δ-9
118⅜	121⅛	102⅝	135¼	102⅝	144⅝	71⅓	81	20½	40	—	.30	.40	14	55⅝	†28A-Δ-10
126⅜	129⅛	110⅝	143¼	110⅝	157⅝	79⅓	89	20½	24	24	.31	.41	14	55⅝	†28A-Δ-11
134⅜	137⅛	118¾	151¾	118¾	165¾	87⅓	97	20½	24	32	.33	.43	14	54⅝	†28A-Δ-12
142⅜	145⅛	126¾	159¾	126¾	173¾	95⅓	105	20½	32	32	.34	.44	14	54⅝	†28A-Δ-13
150⅜	154⅞	134⅞	167⅞	134⅞	181⅞	103⅓	113	20½	32	40	.35	.45	16	54⅝	†28A-Δ-14
158⅜	162⅞	—	—	142⅞	189⅞	111⅓	121	20½	40	40	.36	.46	16	54⅝	†28A-Δ-15
166⅜	170⅞	—	—	150⅜	198	119⅓	129	20½	48	40	.37	.47	16	54⅝	†28A-Δ-16
183⅞	178⅞	—	—	159	206	127⅓	137	20½	48	48	.38	.48	18	54⅝	†28A-Δ-17
191⅞	186⅞	—	—	167⅛	214¾	135⅓	145	20½	56	48	.39	.49	18	54⅝	†28A-Δ-18

(Note 7) When unit is assembled or packaged, add 6" to heights for 4-14 sect., 8" to heights for 15-18 sect.

(Note 8) Add 2-3/4" to sect. 14 thru 18 for smoke hood adaptor.

†† Based on 0.10 ins. W.C. pressure at boiler outlet. If vent sizing results in a back pressure greater than 0.10 ins. W.C., consult Smith.

The Smith representative should be consulted before selecting boilers for installation having unusual piping and pick-up requirements, such as intermittent system operation, extensive piping systems, etc. The boiler ratings have been determined under previous governing forced draft units.
NOTE: Dimensions are approximate. Should not be used to “rough-in” equipment.

28A SERIES FEATURES

Series 28A Boilers Include:

- Rugged cast iron construction
- Integral flue gas collector
- Cast-in heat extraction pins for increased performance
- Wet-base design for top performance
- Graphite port connectors provide the installation ease of a gasket and the long life of a push nipple
- Short, individual section draw rods to simplify assembly, reduce stress
- Front and rear observation ports
- Aluminized steel breeching damper can be easily adjusted and locked in position
- Easy access side cleaning
- Obround shaped upper port for improved internal circulation and dry steam
- Wide variety of tankless heater options

OPTIONAL EQUIPMENT

- Combination low water cutoff and feeder
- Tankless heaters
- Tankless heater sections, with cover plate
- Assembled sections
- Inspection tappings, 1-1/2", 3 per section
- Factory start-up
- Return yoke: grooved or threaded – (steam/water)
- Barometric damper
  10 inch for 4 – 6 sections
  12 inch for 7 and 8 sections
  14 inch for 9 – 13 sections
  16 inch for 14 – 16 sections
  18 inch for 17 – 18 sections
- Packaged

Burner Specifications

Boiler Number	Burners - Light Oil								Burners - Gas				Burners - Gas/Oil			
	Carlin (Note 5)		Beckett (Note 5)		Power Flame (Note 6)		Webster (Note 6)		Power Flame (Note 6)		Webster (Note 6)		Power Flame (Note 6)		Webster (Note 6)	
	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.	Model No.	H.P.
†28A-Δ-4	702CRD	½	CF1400	½	C1-0	½	JB10-03	⅓	J30A-12	⅓	JB1G-03	⅓	C1-G0-12	½	JB1C-03	⅓
†28A-Δ-5	702CRD	½	CF1400	½	C1-0	½	JB10-03	⅓	J50A-15	⅓	JB1G-03	⅓	C1-G0-12	½	JB1C-03	⅓
†28A-Δ-6	801CRD	¾	CF2300	¾	C2-0A	¾	JB10-07	⅓	J50A-15	⅓	JB1G-05	⅓	C2-G0-15	¾	JB1C-03	⅓
†28A-Δ-7	801CRD	¾	CF2300	¾	C2-0A	¾	JB10-07	¾	J50A-15	⅓	JB1G-05	½	C2-G0-15	¾	JB1C-07	¾
†28A-Δ-8	801CRD	¾	CF2300	¾	C2-0B	1	JB10-07	¾	C2-G-20A	¾	JB1G-05	½	C2-G0-20A	1	JB1C-07	¾
†28A-Δ-9	1050FFD	1	CF2300	¾	C2-0B1	1½	JB20-10	1	C2-G-20B1	1	JB2G-10	1	C2-G0-20B1	1½	JB2C-10	1
†28A-Δ-10	1050FFD	1	CF2500	2	C2-0B1	1½	JB20-10	1	C2-G-20B1	1	JB2G-10	1	C2-G0-20B1	1½	JB2C-10	1
†28A-Δ-11	1150FFD	1½	CF2500	2	C3-0	2	JB20-10	1	C3-G-20	1½	JB2G-10	1	C3-G0-20	2	JB2C-10	1
†28A-Δ-12	1150FFD	1½	CF3500A	2	C3-0	2	JB20-20	2	C3-G-25	1½	JB2G-15	1½	C3-G0-25	2	JB2C-20	2
†28A-Δ-13	1150FFD	1½	CF3500A	2	C3-0	2	JB20-20	2	C3-G-25	1½	JB2G-15	1½	C3-G0-25	2	JB2C-20	2
†28A-Δ-14	—	—	—	—	C3-0	2	JB20-20	2	C3-G-25	1½	JB2G-15	1½	C3-G0-25	2	JB2C-20	2
†28A-Δ-15	—	—	—	—	C3-0B	3	JB20-30	3	C3-G-25B	3	JB2G-30	3	C3-G0-25B	3	JB2C-30	3
†28A-Δ-16	—	—	—	—	C3-0B	3	JB20-30	3	C3-G-25B	3	JB2G-30	3	C3-G0-25B	3	JB2C-30	3
†28A-Δ-17	—	—	—	—	C4-0A	5	JB30-30	3	C4-G-25	3	JB3G-30	3	C4-G0-25	5	JB3C-30	3
†28A-Δ-18	—	—	—	—	C4-0A	5	JB30-30	3	C4-G-25	3	JB3G-30	3	C4-G0-25	5	JB3C-30	3

Note: Low-High-Low or Modulation Firing consult Smith.

Appendix L

LEED EB Checklist

LEED for Existing Buildings v2.0
Registered Building Checklist

Project Name: Eberly Campus Community Center
Project Address: **Penn State Fayette Campus**

Yes	?	No			
3	6	5		**Sustainable Sites**	**14** Points
Y	ok		Prereq 1	**Erosion & Sedimentation Control**	Required
Y	ok		Prereq 2	**Age of Building**	Required
	1		Credit 1.1	**Plan for Green Site & Building Exterior Management -** 4 specific actions	1
		1	Credit 1.2	**Plan for Green Site & Building Exterior Management -** 8 specific actions	1
		1	Credit 2	**High Development Density Building & Area**	1
1			Credit 3.1	**Alternative Transportation -** Public Transportation Access	1
		1	Credit 3.2	**Alternative Transportation -** Bicycle Storage & Changing Rooms	1
		1	Credit 3.3	**Alternative Transportation** - Alternative Fuel Vehicle	1
		1	Credit 3.4	**Alternative Transportation -** Car Pooling & Telecommuting	1
1			Credit 4.1	**Reduced Site Disturbance -** Protect or Restore Open Space (50% of site area)	1
1			Credit 4.2	**Reduced Site Disturbance -** Protect or Restore Open Space (75% of site area)	1
	1		Credit 5.1	**Stormwater Management -** 25% Rate and Quantity Reduction	1
	1		Credit 5.2	**Stormwater Management -** 50% Rate and Quantity Reduction	1
	1		Credit 6.1	**Heat Island Reduction -** Non-Roof	1
	1		Credit 6.2	**Heat Island Reduction -** Roof	1
	1		Credit 7	**Light Pollution Reduction**	1

Yes	?	No			
2	1	2		**Water Efficiency**	**5** Points
Y			Prereq 1	**Min** ****do the calculations!!	Required
Y	chec		Prereq 2	**Discharge Water Compliance**	Required
	1		Credit 1.1	**Water Efficient Landscaping -** Reduce Potable Water Use by 50%	1
		1	Credit 1.2	**Water Efficient Landscaping** - Reduce Potable Water Use by 95%	1
		1	Credit 2	**Innovative Wastewater Technologies**	1
1			Credit 3.1	**Water Use Reduction -** 10% Reduction	1
1			Credit 3.2	**Water Use Reduction -** 20% Reduction	1

Yes	?	No			
1	6	6		**Energy & Atmosphere**	**23** Points
Y			Prereq 1	**Existing Building Commissioning**	Required
Y	check		Prereq 2	**Minimum Energy Performanc** - Energy Star 60	Required
Y		ok	Prereq 3	**Ozone Protection**	Required
			Credit 1	**Optimize Energy Performance**	1 to 10
				☐ Energy Star Rating - 63	1
				☐ Energy Star Rating - 67	2
				☐ Energy Star Rating - 71	3
				☐ Energy Star Rating - 75	4
				☐ Energy Star Rating - 79	5
				☐ Energy Star Rating - 83	6
				☐ Energy Star Rating - 87	7
				☐ Energy Star Rating - 91	8
				☐ Energy Star Rating - 95	9
				☐ Energy Star Rating - 99	10
		1	Credit 2.1	**Renewable Energy -** On-site 3% / Off-site 15%	1
		1	Credit 2.2	**Renewable Energy** - On-site 6% / Off-site 30%	1
		1	Credit 2.3	**Renewable Energy** - On-site 9% / Off-site 45%	1
		1	Credit 2.4	**Renewable Energy** - On-site 12% / Off-site 60%	1
	1		Credit 3.1	**Building Operation & Maintenance -** Staff Education	1
	1		Credit 3.2	**Building Operation & Maintenance -** Building Systems Maintenance	1
	1		Credit 3.3	**Building Operation & Maintenance -** Building Systems Monitoring	1
1			Credit 4	**Additional Ozone Protection**	1

	1		Credit 5.1	**Performance Measurement -** Enhanced Metering (4 specific actions)	1
	1		Credit 5.2	**Performance Measurement -** Enhanced Metering (8 specific actions)	1
		1	Credit 5.3	**Performance Measurement -** Enhanced Metering (12 specific actions)	1
	1		Credit 5.4	**Performance Measurement**- Emission Reduction Reporting	1
		1	Credit 6	**Documenting Sustainable Building Cost Impacts**	1

Yes	?	No			
	4	12		**Materials & Resources**	**16** Points
Y			Prereq 1.1	**Source Reduction & Waste Managemen** - Waste Stream Audit	Required
Y			Prereq 1.2	**Source Reduction & Waste Management** Storage & Collection	Required
Y			Prereq 2	**Toxic Material Source Reduction** Reduced Mercury in Light Bulbs	Required
		1	Credit 1.1	**Construction, Demolition & Renovation Waste Management** -Divert 50%	1
		1	Credit 1.2	**Construction, Demolition & Renovation Waste Management** -Divert 75%	1
		1	Credit 2.1	**Optimize Use of Alternative Materials** - 10% of Total Purchases	1
		1	Credit 2.2	**Optimize Use of Alternative Materials** - 20% of Total Purchases	1
		1	Credit 2.3	**Optimize Use of Alternative Materials** - 30% of Total Purchases	1
		1	Credit 2.4	**Optimize Use of Alternative Materials** - 40% of Total Purchases	1
		1	Credit 2.5	**Optimize Use of Alternative Materials** - 50% of Total Purchases	1
		1	Credit 3.1	**Optimize Use of IAQ Compliant Products** - 45% of Annual Purchases	1
		1	Credit 3.2	**Optimize Use of IAQ Compliant Products** - 90% of Annual Purchases	1
	1		Credit 4.1	**Sustainable Cleaning Products & Materials** - 30% of Annual Purchases	1
	1		Credit 4.2	**Sustainable Cleaning Products & Materials** - 60% of Annual Purchases	1
	1		Credit 4.3	**Sustainable Cleaning Products & Materials** - 90% of Annual Purchases	1
	1		Credit 5.1	**Occupant Recycling** - Recycle 30% of the Total Waste Stream	1
		1	Credit 5.2	**Occupant Recycling** - Recycle 40% of the Total Waste Stream	1
		1	Credit 5.3	**Occupant Recycling** - Recycle 50% of the Total Waste Stream	1
		1	Credit 6	**Additional Toxic Material Source Reduction** - Reduced Mercury in Light Bulbs	1

Yes	?	No			
9	10	3		**Indoor Environmental Quality**	**22** Points
Y			Prereq 1	**Outside Air Introduction & Exhaust Systems**	Required
Y			Prereq 2	**Environmental Tobacco Smoke (ETS Control**	Required
Y			Prereq 3	**Asbestos Removal or Encapsulation**	Required
Y	check		Prereq 4	**PCB Removal**	Required
1			Credit 1	**Outside Air Delivery Monitoring**	1
		1	Credit 2	**Increased Ventilation**	1
1			Credit 3	**Construction IAQ Management Plan**	1
	1		Credit 4.1	**Documenting Productivity Impacts** - Absenteeism & Healthcare Cost Impacts	1
	1		Credit 4.2	**Documenting Productivity Impacts** - Other Productivity Impacts	1
		1	Credit 5.1	**Indoor Chemical & Pollutant Source Control** - Reduce Particulates in Air System	1
		1	Credit 5.2	**Indoor Chemical & Pollutant Source Control** - Isolation of High Volume Copy/Print/Fa	1
1			Credit 6.1	**Controllability of Systems** - Lighting	1
1			Credit 6.2	**Controllability of Systems** - Temperature & Ventilation	1
1			Credit 7.1	**Thermal Comfort** - Compliance	1
1			Credit 7.2	**Thermal Comfort** - Permanent Monitoring System	1
1			Credit 8.1	**Daylight & Views** - Daylight for 50% of Spaces	1
	1		Credit 8.2	**Daylight & Views** - Daylight for 75% of Spaces	1
1			Credit 8.3	**Daylight & Views** - Views for 45% of Spaces	1
	1		Credit 8.4	**Daylight & Views** - Views for 90% of Spaces	1
	1		Credit 9	**Contemporary IAQ Practice**	1
1			Credit 10.1	**Green Cleaning** - Entryway Systems	1
	1		Credit 10.2	**Green Cleaning** - Isolation of Janitorial Closets	1
	1		Credit 10.3	**Green Cleaning** - Low Environmental Impact Cleaning Policy	1
	1		Credit 10.4	**Green Cleaning** - Low Environmental Impact Pest Management Policy	1
	1		Credit 10.5	**Green Cleaning** - Low Environmental Impact Pest Management Policy	1
	1		Credit 10.6	**Green Cleaning** - Low Environmental Impact Cleaning Equipment Policy	1

Yes	?	No			
1				**Innovation & Design Process**	**5** Points
			Credit 1.1	**Innovation in Upgrades, Operation & Maintenance**	1
			Credit 1.2	**Innovation in Upgrades, Operation & Maintenance**	1
			Credit 1.3	**Innovation in Upgrades, Operation & Maintenance**	1
			Credit 1.4	**Innovation in Upgrades, Operation & Maintenance**	1
1			Credit 2	**LEED™ Accredited Professional**	1

Yes	?	No		
16	27	28	**Project Totals (pre-certification estimates)**	85 Points

Certified: 32-39 points, **Silver:** 40-7 points, **Gold:** 48-63 points, **Platinum:** 64-85