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APPENDIX

A. Executive Summary :

The final report for the T.C. Williams High School Replacement Project revisits the technical analyses pertinent to the development of a value engineering exercise that proposes an alternate to the original design and initial construction sequencing of the project. The analyses are tied together by the implementation of a Building Information Model that focuses on the interoperability between different software platforms required to perform all aspects of the exercise.

Extensive building material research has uncovered a partially prefabricated structural insulated concrete panel that will significantly improve the energy efficiency and erection time of the superstructure for the auditorium, gymnasium, mechanical/electrical wedge, and automotive strip of the T.C. Williams High School which was initially designed with CMU load bearing walls. A detailed description and construction sequence of the Solarcrete system exposes the potential for off-site controlled environment fabrication and just-in-time delivery to reduce field labor and material storage. The Solarcrete wall system will provide enough flexibility in the erection sequence of the aforementioned areas to allow the general contractor, Hensel Phelps Construction Company, to capitalize on a re-sequenced superstructure plan to alleviate site congestion and improve project safety.

A cost comparison exposes the Solarcrete system's higher initial cost while pointing out areas of potential cost savings due to the system's superior energy efficiency over the traditional CMU design. The analysis leads to redesign of the gymnasium acoustics to maintain the reverberation levels of the original design. An economical solution is presented through to procurement of FABRISORB™ high impact resistant acoustical wall panels. While the acoustics of the auditorium would generally be of greater concern due to the type of events held in the space, they were not considered since the initial design sought to improve the aesthetics of the space by completely covering the structural CMU walls with higher end finish materials. Therefore, the redesign of the structural system would have a minimal effect on the room acoustics in the auditorium.

Interoperability between the architectural and structural models is explored further through the design of a structural moment frame for the gymnasium. Research uncovered the standard practice of erecting a moment frame for the Solarcrete system when tall panels are employed that will be exposed to lateral loading.

The project aims to reveal the effectiveness of Building Information Modeling in value engineering, work sequencing, and site logistics while expressing the importance of BIM in our industry and the potential for implementing non traditional building materials to increase project value.

B. Project Background :

a. Overview :

The condition of the existing T.C. Williams High School building has been degrading over the last 50 years. The structure was originally designed to house grades 9th through 10th, but over the last five decades, the population of the district has grown and the freshman class had to be relocated to another facility. In addition the school district had been forced to hold classes in temporary classroom trailers.

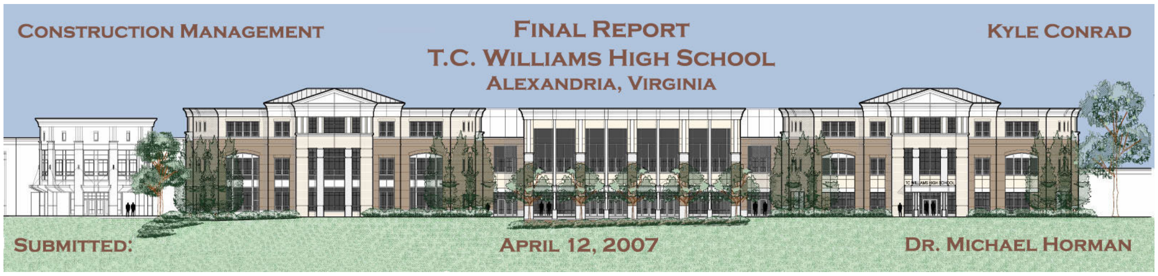
The new 469,507 ft² educational facility is designed to provide the school district with all of the amenities required to facilitate the education of its students. T.C. William's high school contains ample administration and standard classroom spaces as well as specialty classrooms (biology, marketing, chemistry, etc.), a planetarium, computer and science labs. A large commons area provides students with a pleasant dinning experience without having to leave the campus or exposing them to the traditional cafeteria style facility. The large auditorium has operable partitions that can be closed to create multiple lecture halls and for those students who have children of their own, they can now bring their babies to school with them. The "babies with babies" program provides daycare services to toddlers and infants which in turn creates a living lab to teach teenage parents, or expecting parents, appropriate parenting skills. An auxiliary gymnasium was added to provide additional multipurpose space for the main gymnasium. Protruding from the sides of the main 45'-8", three story, classroom towers are the music suites and auto service technology shops.

The owner, Alexandria City Public Schools, is the governing body of the Alexandria, Virginia school district. They are devoted to constructing a building that is both sustainable and reduces the consumption of raw materials, energy and impacts on the environment. An assigned owner representative, Dan Pierce, works with the general contractor, Hensel Phelps Construction Company [HP], to ensure that the client's expectations are exceeded.

b. Building Systems :

i. Demolition :

Phase A-1 was the demolition of the existing one story, career tech wing that was built on to the original school structure in the 1970's. The 22 ft. high structure required abatement for asbestos. Since the lead paint was contained, no abatement was required to remove the lead. After the new school facility is completed, phase B-1 will commence. In this phase, the existing three



story, 45 ft., T.C. Williams High School building will be demolished to make room for the construction of the parking garage. Asbestos abatement will be required during the demolition in phase B-1 as well.

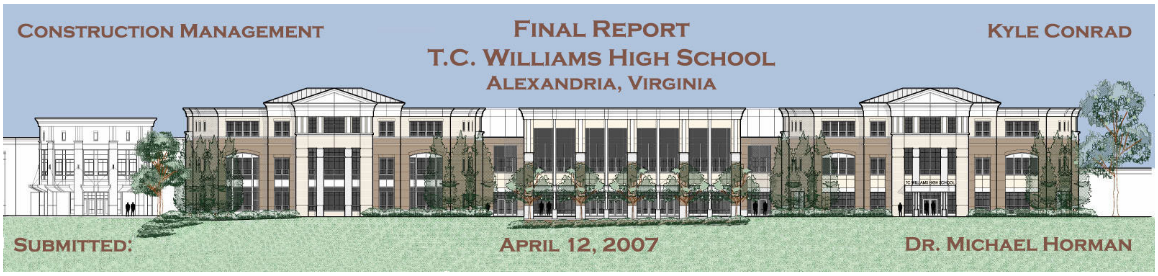
ii. Structural System (includes aspects of Structural Steel Frame, Cast-in-Place Concrete & Masonry) :

The foundation is designed for an allowable bearing capacity of 6000 psf. The soil has been classified as a type C soil. Due to poor soil conditions, areas of the foundation are supported with geopier rammed aggregate soil reinforcements. A machine, similar to a caisson drilling rig, bores holes into the soil and then packs crushed stone, in thin lifts, into the cavity to provide a solid base for the footing that rests on top of the geopier. A continuous footing system, 16 inches in depth, supports the extensive lengths of exterior and interior CMU walls. Spread footings distribute the loads from the steel columns. A series of grade beams and braces tie between the spread footings.

The classroom towers are three story, steel moment frame structures. The beams and girders are a wide range of ASTM A992 wide flange sizes and the columns range anywhere from ASTM A992 wide flange shapes (W) to ASTM A500 rectangle and round hollow structural shapes (HSS). The 4000 psi, cast-in-place, elevated concrete slabs are typically 4-1/2 inches thick over 1-1/2 inch – 18 gage composite galvanized floor deck that spans the beams. The concrete will be pumped to the areas where concrete is being poured. The k series open web steel joists bear on the beams which transfer the roof loads from the various specified metal roof decking to the columns. A 50 ton, mobile all-terrain crane was utilized by the steel erector. The mobile crane was primarily set in locations between the two classroom towers.

The East wing of T.C. Williams and the rooms at the South end of the classroom towers are single level, multi height spaces. Load bearing CMU walls, of varying thicknesses, run around the perimeter of the auditorium, gymnasiums, exterior of the East (technology) wing, and South wall of the school. Beam pockets in the CMU provide a bearing surface for the W-shape beams while the majority of the k series roof joists are tied into bond beams at the top of the CMU load bearing walls. The loads in these areas of the structure are transferred to the continuous footing.

Classification of Building Category / Use Group: II



Codes: 2000 VUSBC
2000 IBC (Effective 10/01/2003)
ACI 318-95 Building Code Requirements for Structural Concrete
ACI 301-96 Standard Specifications for Structural Concrete
AISC Specification for Structural Steel Buildings, Allowable Stress Design and Plastic Design – June 1, 1989
AISC Code of Standard Practice for Steel Buildings and Bridges – March 7, 2000

iii. Pre-cast Concrete :

An architectural pre-cast concrete ribbon runs around the majority of the building's perimeter and below various window units. The east and west sides of the facility contain architectural pre-cast concrete coping.

iv. Mechanical System :

Seventeen rooftop air handling units, ranging from 1,400 to 23,295 cfm, supply conditioned air to the majority of the spaces and employ the use of enthalpy wheels to recover total energy. Supply air entering the gymnasium, auto services, and building trades / construction technology spaces passes through reheat coils. Four additional indoor air handling units control the air in the auxiliary gymnasium, east and west commons areas and the remaining spaces in the East (technology) wing. The variable air volume (VAV) system utilizes 305 terminal units; most of them are equipped with reheating coils which are only activated when the minimum amount of supply air is being forced into a space. A four pipe system supplies and returns hot and chilled water to and from twelve fan coil units that locally returns and supplies conditioned air.

In addition, a water unit heater and an electric unit heater service the mechanical and equipment rooms respectively. A direct gas heating, make-up unit in the kitchen activates when the demand arises due to the large quantities of room air that are exhausted through the hoods.

The variable flow, hot and chilled water plant is driven by variable speed control pumps. Four natural gas-fired condensing boilers, with capacities of 1.68 million BTUH, heat water from 120^{o}F to 160^{o}F. Water is cooled to 38^{o}F by two, 600 ton water cooled, electric driven centrifugal chillers. Two 750 ton cooling towers condense the R-123 refrigerant so that it can be re-circulated through the chillers which will accept the heat from the systems chilled water lines.

The mechanical contractor brought in a 100 ton mobile, all-terrain crane for a duration of two days to set the mechanical equipment.

A five zone, wet pipe sprinkler system services T.C. Williams High School. Each zone covers 49,855 to 51,000 sq. ft. A 100 hp vertical in-line fire pump produces a flow rate of 1,000 GPM with a total head pressure of 120 psi. A mixture of sidewall and pendant sprinkler heads will service the spaces while concealed heads are required in all the stairwells.

Required Codes: NFPA 13
VUSBC
Local Authority: Virginia – American Water Company

v. Electrical System :

A 480 Y / 277, 3 phase, 4 wire primary feed services the building. Two main 4000 ampere, 3 phase switchboards distribute the required power to the electrical loads throughout the building. Separate switchboards for the chiller units are feed directly from the utility service. The life safety system is backed up by two 800kW, 480V, 3 phase 60 Hz, diesel fueled generators.

vi. Masonry :

The majority of the exterior wall system is face brick with CMU backing. The interior partition walls are primarily constructed of CMU as well. The masons utilize two scaffold systems which include a standard Mason King tube and coupling scaffold and a jacking platform system that mechanically raises and lowers to facilitate the laying of block and brick.

vii. Curtain Wall :

The court is enclosed in a pre-finished aluminum curtain wall system. Aluminum curtain wall units also span from the majority of second floor to first floor window openings of the classroom towers. The units are hoisted into place via a crane and secured on the floor levels to transfer the applied loads through the structural steel frame.

viii. Roofing System :

T.C. William's roof is primarily a Thermoplastic Polyolefin (TPO) Membrane system on a steel roof deck. The clerestories, which were constructed to allow natural light to enter the building through the roof, utilize pre-finished standing seam metal roofing systems except for one clerestory that has an EPDM membrane system. A pre-finished, sloping, standing seam, metal roofing system accents the two main entryways into the school facility while the garden roof assembly obtains additional LEED points.

ix. Support of Excavation :

Since the building was designed as a slab on grade structure and the site was relatively level, no significant excavation was performed that required additional support systems to be implemented. Permanent retaining walls were constructed at the south east corner of the site. Shot-Crete was sprayed onto the reinforcing rebar cage to minimize the amount of formwork required on site.

c. Project Delivery System :

The project was originally set up as a design-bid-build delivery method and was procured through a competitive hard bid. Hensel Phelps was the lowest bidder and was awarded the job. At 100% design completion, HP convinced the owner to transfer the risks associated with errors and omissions to HP by restructuring the project into design-build **(see figure 1 below).** Hensel Phelps holds the sole contract with the owner. After four months of GMP contract negotiations, a GMP was approved and HP was given the notice to proceed on the construction of phase A-2. The original architect, Moseley Architects, signed a new lump sum contract with Hensel Phelps under the new system. The design-build structure provides HP with an opportunity to actively pursue value engineering ideas. All potential value engineering [PVE] ideas are submitted to the owner and the architect for review. If the PVE is approved by both parties, the idea is executed. For their review time, HP agreed to pay the architect 8% of the cost savings from the executed PVE. The remaining cost savings are either kept by HP or passed down to the appropriate subcontractor.

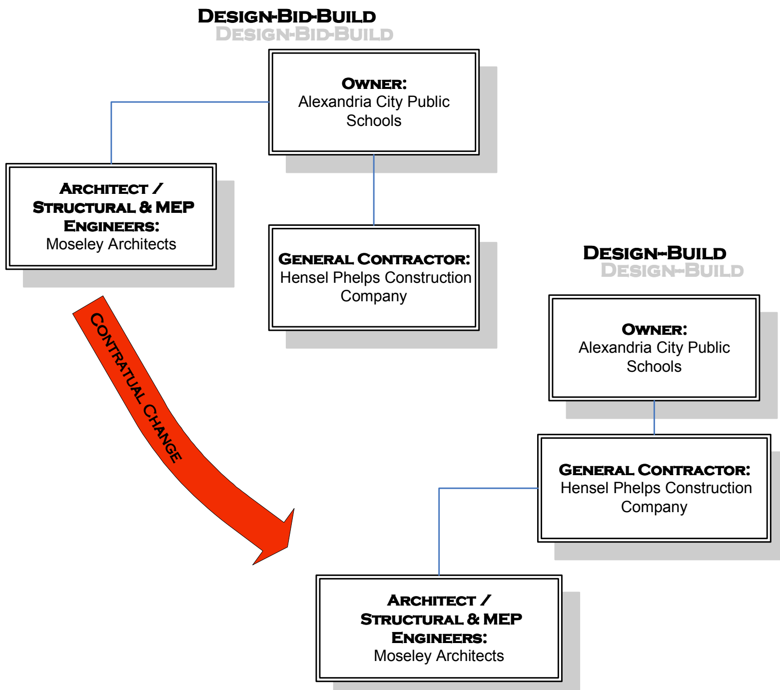
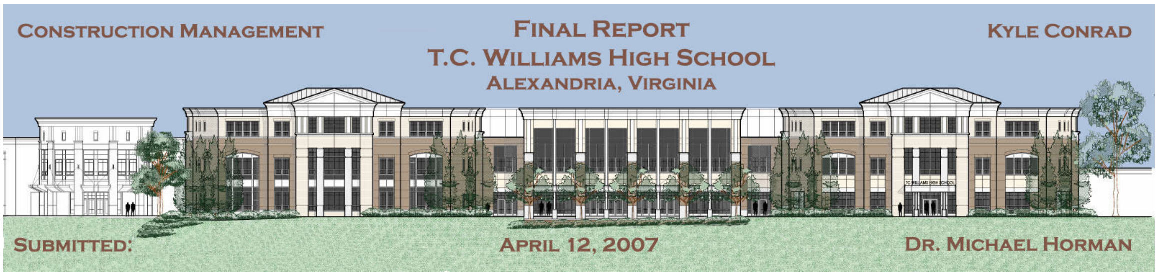


Figure 1 Restructuring of the project delivery system

While HP required each subcontractor to submit payment and performance bonds, the owner only required that HP provide a performance bond for the full amount of the project. All of the subcontractors hold lump sum contracts with Hensel Phelps except for the concrete contractor responsible for placing and finishing concrete. The concrete contract is unit price, based on the square foot of concrete. The rate varies depending on the thickness of the concrete. A thicker pour results in a lower rate. Refer to the project organizational chart **(see figure 2 below)** for a clear understanding of contractual arrangements.



d. Organizational Chart :

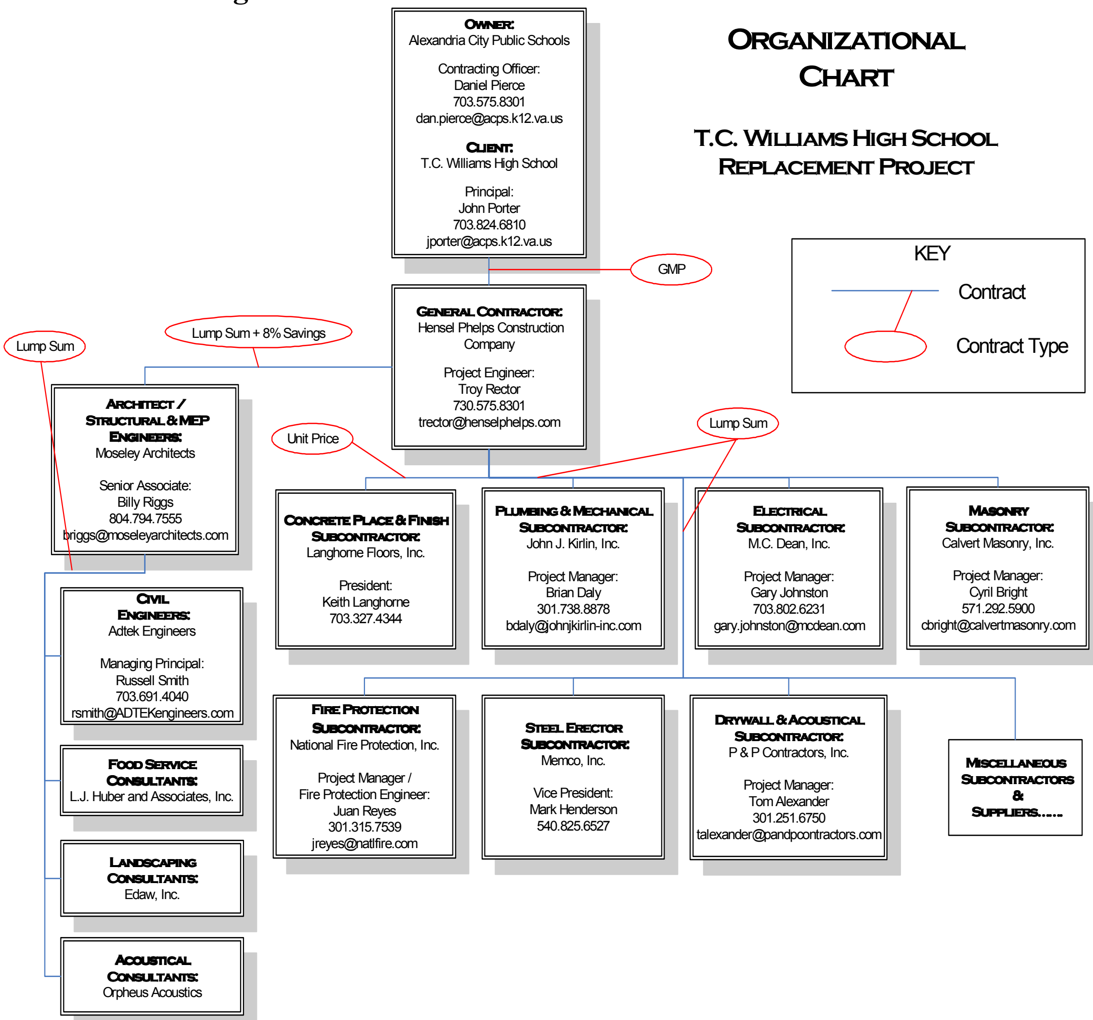


Figure 2 T.C. Williams High School Replacement Project Organizational Chart

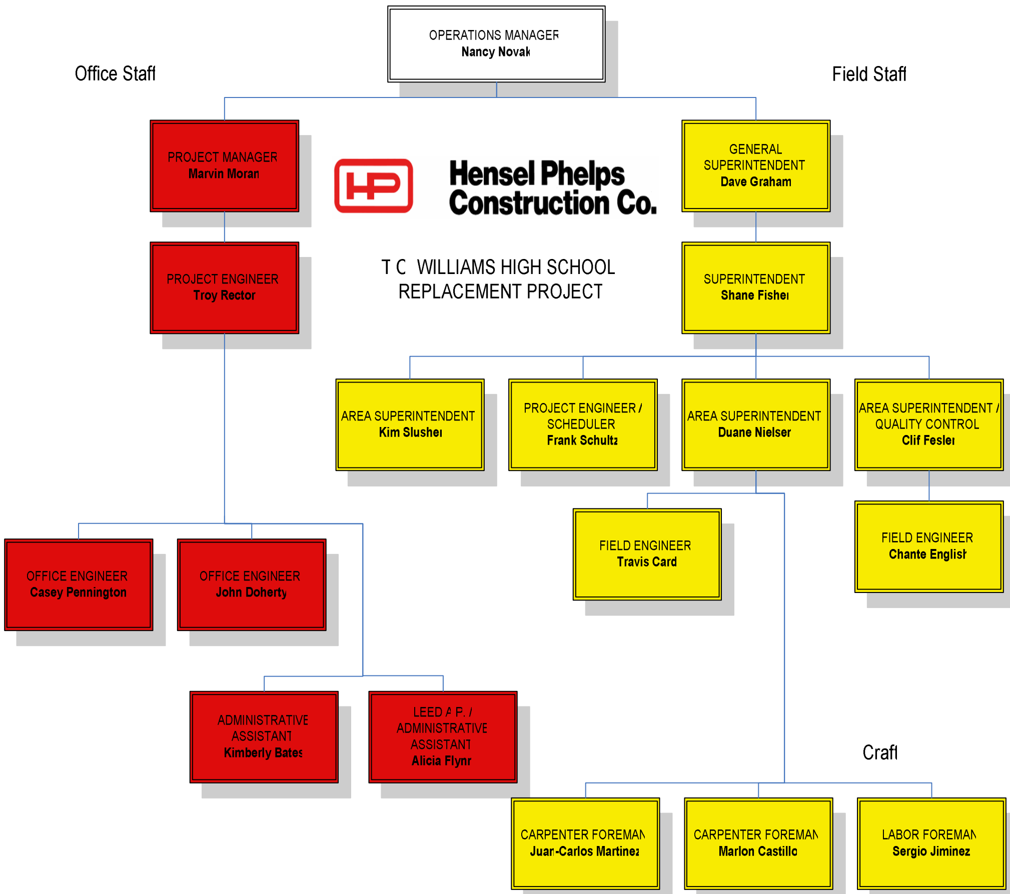


Figure 3 Hensel Phelps Construction Co. Project Staff Organizational Chart

e. Staffing Plan :

Hensel Phelps Construction Company **(see Figure 3 above)** provides a full time project management and field supervision staff on-site, complete with 17 carpenters and laborers to self-perform work.

General Contractor Self-performed Work:

- Door Frames, Doors, & Hardware
- Fire Extinguisher Cabinets
- Projection Screens
- Cast-in-place Concrete
  excluding site concrete (foundations, SOG, SOD, stairs)
- Site Erosion Control Maintenance
- Safety Maintenance (fall protection – handrails & hole covers)

The office staff is overseen by a project manager and project engineer. Since the T.C. Williams High School Replacement Project is seeking a LEED rating, Hensel Phelps sent an interested employee to train for her LEED certification. The general superintendent and superintendent are in charge of assuring that the work being performed in the field is in accordance with the design and on time. Hensel Phelps has a dedicated quality control department on-site to guarantee that the work in place meets their company's high standards as well as the expectations of their client.

C. Current Management :

a. Project Schedule Summary :

To permit the continued education of the student body on campus through the duration of the construction, the T.C. Williams High School Replacement Project was separated into four phases. The two A phases encompass the construction processes for the new school facility, while the B phases cover the construction of the two deck parking garage. Refer to **Appendix A** for a project summary schedule of phases A-1 and A-2.

i. Phase A-1 :

As depicted below, Phase A-1 **(see figure 4)** involved the demolition of the existing career tech wing, the removal of five temporary classroom buildings and the installation of two temporary classroom units in the center of the renowned Titan football field. Student parking was relocated to the eastern side of the lot and construction fence was installed around the perimeter of the A phase construction site boundary. Modifications to the bus loop and the storm sewer at King Street were required as well as the construction of a retaining wall along the East property line.

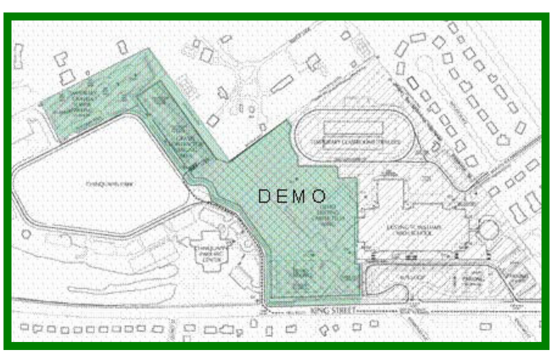


Figure 4 Phase A-1

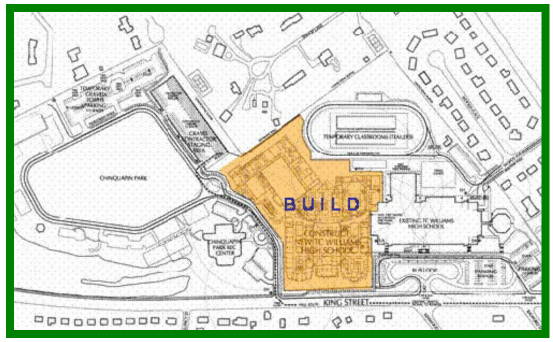


Figure 5 Phase A-2

ii. Phase A-2 :

Phase A-2 **(see figure 5)** concludes on 20 July 2007, as the construction of the new T.C. Williams High School reaches final completion.

iii. Phase B-1 :

Over the summer months of 2007, the district transitions from the existing school building to their new facility as the contractors repair the football field, after the removal of the temporary classroom units, and prepare for the demolition of the old school building. The contractor staging area is relocated to the North end of the construction site and another temporary parking area established in its place. After the temporary construction site fence is relocated, the demolition of the old school commences in Phase B-1 **(see Figure 6 below).**

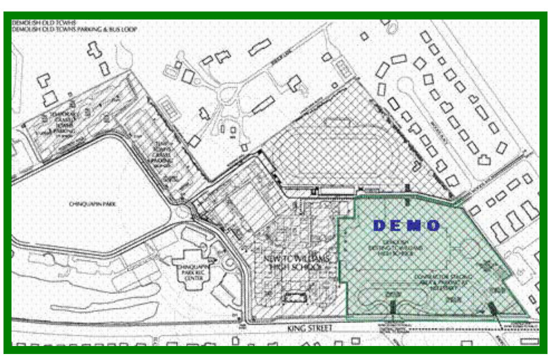


Figure 6 Phase B-1

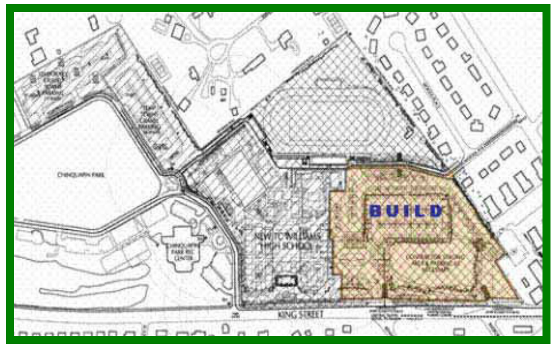


Figure 7 Phase B-2

iv. Phase B-2 :

The project concludes with Phase B-2 **(see Figure 7 above)**: The construction of the pre-cast concrete parking garage. As the project comes to a close, the bus and entry loops are completed and the practice fields are graded and restored. B phases will not be considered in the development of this thesis project, due to the size and complexity of the high school facility.

b. Detailed Project Schedule :

Hensel Phelps employed the use of Short Interval Production Scheduling [SIPS] to manage the construction of the classroom towers at T.C. Williams High School. In SIPS, the schedule activities are established through a detailed investigation of the construction processes and building layout. The building is zoned into manageable construction blocks through which the trades flow in a sequence and predetermined unit of time. Crews are balanced based on the duration required to complete individual activities within the designated blocks. SIPS is effective in highly repetitive structures. T.C. Williams was divided into seven areas, three of which were subdivided into blocks to facilitate SIPS **(see Table 1)**. Refer to **Appendix B** for a detailed project schedule.

T.C. WILLIAMS CONSTRUCTION AREAS		
AREA	DESCRIPTION	SIPS
1	NE Tower	✓
2	Center Court	
3	NW Tower	✓
4	Kitchen Wedge	✓
5	Gym Wing	
6	Mechanical / Electrical Wedge – Auto Strip	
7	Auditorium	

Table 1. Scheduling Areas for T.C. Williams High School

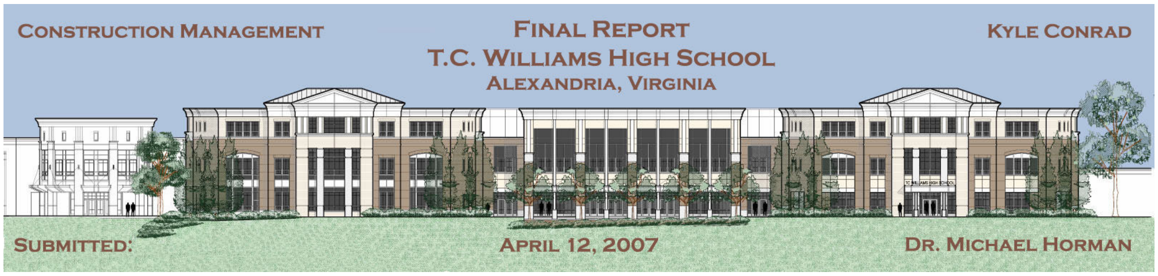
c. Site Layout Planning :

Refer to the site plan, in **Appendix E,** for the location of existing and new site utilities as well as the plan for public and construction traffic flow. With the student parking being so far from the existing school building, there is an increased level of pedestrian traffic around the site. Jersey barriers were set up in higher risk areas to direct the pedestrian flow and provide a safe lane for students to walk to the existing facility. These areas include a stretch along King Street at the North end of the construction site and on the one way portion of Chinquapin Drive near the contractor staging area where it is necessary for pedestrians to share a section of the road with vehicular traffic.

The construction workers are instructed to park at the east end of Chinquapin Drive. Students that drive to school are also granted parking privileges in the same location. Student and construction parking are separated into two designated areas. Construction foreman are permitted to park beside the office trailers on site.

Access to the site can be obtained through any of the five gates in the site fence. The two gates along King Street are primarily for steel and concrete deliveries while the majority of construction materials are delivered through the main staging area gate at the entrance to the Chinquapin Drive loop. Trucks either exit through the gate from which they entered or drive though the staging area and exit onto the one-way Chinquapin Drive loop. Limited access roads are provided for contractors to move materials around the East and South sides of the structure.

The work flow for the erection of the superstructure commences in the kitchen wedge (Area 4) and progresses through the auditorium (Area 7) and along the Northwest classroom tower. Concurrently, the masons are constructing the CMU load bearing walls in the gymnasium and



auto/mechanical/electrical wings (Areas 5 and 6 respectively). Afterwards, the steel joists are set in areas 5 and 6 and the erection of steel continues through the Northeast classroom tower (Area 1). Area 2 (the center court) contains the final sequences of the superstructure erection. The mobile crane was able to perform the majority of its structural steel picks from within the unobstructed center court area. As area 2 is constructed, the crane can back its way out from between the classroom towers as it positions the final steel members of the superstructure. Refer to the site layout plan **(Appendix F)** for clarification on the superstructure phase of work and traffic flow.

At the Northwest corner of the Northwest classroom tower, a concrete pump has been set up to ensure the ease of access for concrete trucks. Since the construction of Area 3 starts at the South side of the tower, the concrete is pumped along the structure and rises at the Southwest corner of the tower. Due to the long run of pipe, a relay pump may be required to force the concrete to the third floor for placement. The portable toilets and dumpsters have been strategically located on site to accommodate the construction personnel while maintaining their accessibility for waste removal trucks. Also, the man and materials hoist has been setup to provide a vertical form of transportation to an arterial corridor on second and third floors that runs East to West along the Area 1, 2, 3, 4, and 7 boundary lines out into the section of the gymnasium wing (Area 5) that occupies multiple stories.

D. Proposal :

a. Critical Issues Research:

Effectiveness of Building Information Modeling [BIM] in Value Engineering [VE], Work Sequencing, and Site Logistics:

Issue:

The development of Building Information Modeling is slow to gain acceptance into the building construction industry. Recently, the General Services Administration [GSA] has mandated that all the new construction projects designed by its Public Building Services, starting in the 2007 fiscal year, are required to utilize BIM in the design phase of the project. After attending the discussion sessions at the 2006 PACE Roundtable and first hand interviews with prominent companies in the industry, a broad spectrum of company knowledge of BIM has become evident. A few companies have advanced to the point where the majority of their projects capitalize on BIM tools from start to finish while others acted as though they were hearing about BIM for the first time.

Until the benefits of BIM are clearly understood and accepted by industry professionals, hesitation to implement the process will exist and construction projects will continue to incur unnecessary rework costs.

Methods of Analysis:

Harnessing the knowledge of the Penn State Architectural Engineering faculty members, recent graduates, current students, and industry professionals interested in the development of the virtual design of construction projects, a building information model will be developed, with BIM software, in order to perform and present the technical analyses, inevitably expressing the effectiveness of BIM in these construction processes.

Expectations:

By researching, developing, and presenting the potential benefits of BIM in processes of value engineering, work sequencing, and site logistics, the exposure of industry members to the effectiveness of BIM in the construction of a project will aid in alleviating some of the hesitation of implementing BIM into their own projects. While the acceptance of BIM into the construction industry will not come overnight, graduating college students that have had experience with BIM pose to be the greatest source of opportunity for construction industry companies to enter into the new era of construction.

b. Analysis # 1: Alternative Building Materials to CMU

Issue:

School facilities commonly use CMU as a building material due to its durable characteristics and low material cost. However, the installation of CMU is extremely labor and time intensive and is less than aesthetically pleasing. Research into alternative building materials will be performed to obtain suitable selections for value engineering, constructability, and schedule reduction analyses. Value engineering is often confused with cost cutting. In actuality, VE aims to provide the owner with the best product for the amount of money allocated.

Methods of Analysis:

Materials will be analyzed against cost, schedule impacts, heat transfer, sustainability, and quality. Material costs are dependent on initial costs as well as schedule delays due to the availability of the material and labor.

Transportation costs may increase the cost of the material if the manufacturer or supplier is removed from the area where the facility is being constructed. The erection speed of the material can have a significant impact on labor savings unless the subcontractors selected to perform the work are unfamiliar with the material, resulting in a substantial learning curve. Cost savings can be acquired through a reduction of heating costs with materials that have a higher resistance to heat transfer. Since the Alexandria City Public Schools are interested in constructing a building that has a low impact on the environment, the sustainability of the materials will be considered. Interest will be expressed in materials that would improve the quality of the students' learning environment while maintaining the durability obtained with CMU.

BIM will be utilized to demonstrate the ease of performing an alteration to the original contracted model as well as quantity takes-offs for the estimate comparison between materials. Schedule impacts will also be considered and displayed in the model.

Expectations:

After a detailed investigation into alternative building material, a prefabricated material will be discovered that will promote an elegant, acoustically satisfying gymnasium in which school will be proud to host guests to the school for sporting events and assemblies. The redesigned facility will be within the original contracted budget of the facility. The materials will require less labor and time to erect and provide a more aesthetically pleasing environment to enhance the education of the students while maintaining the durability inherent in CMU.

c. Analysis # 2: Gymnasium Acoustics

Issue:

High quantities of sound absorbing materials were added to reduce the level of noise in the CMU enclosed space.

Methods of Analysis:

In continuation of the analysis performed researching alternative building materials, an acoustical analysis of the gymnasium will be performed. A new acoustical design will be developed and a detailed analysis of the room absorption will be calculated to acquire the optimum reverberation time for a high school gymnasium.

Expectations:

By selecting a material with sound absorbing characteristics, value would be added to the space with the potential of saving money by reducing the need for additional sound panels. However, a material with poorer absorption coefficients may require additional sound absorbing materials to reduce the reverberation time to the initial design, adding cost to the project.

d. Analysis # 3: Work Sequencing and Site Logistics

Issue:

Due to the extensive concrete block work in the gymnasium, automotive strip, kitchen, and auditorium the CMU wall construction begins in the early phases and continues long into the project duration. The material storage and staging area is in the far Southeastern corner of the site and all of the work is progressing in a Southeast to Northwest direction **(described in detail in Section C. c.)**. The flow of work makes transportation of building materials toward the end of the project more congested.

Methods of Analysis:

Using the alternative building materials selected in analysis #1, the flow of work will be analyzed. BIM software will be used to develop and visualize the re-sequencing of schedule activities by detecting improper sequencing of work activities as the duration of the alternative building materials are integrated into the design of the facility.

Expectations:

With the quicker erection time of prefabricated materials, the work activities in the aforementioned areas will not be require to begin as early in the construction process. Successful re-sequencing of work activities will allow for easier access to the material storage and staging areas. Ultimately, the site congestion due to the transportation of building materials will be alleviated.

e. Weight Matrix:

During the course of the Spring 2007 semester, the technical analyses discussed above will be developed and incorporated with the Building Information Model. The predicted breakdown of my allocation of time and efforts has been provided in **Table 2** below.

Description	Research	Value Engineering	Constructability Review	Schedule Reduction	Total
Alternative Materials	10 %	10 %	5 %	10 %	35 %
Auditorium Acoustics	5 %	10 %	0 %	0 %	15 %
Sequencing & Site Logistics	0 %	5 %	10 %	5 %	20 %
BIM	5 %	10 %	5 %	10 %	30 %
Total	**20 %**	**35 %**	**20 %**	**25 %**	**100 %**

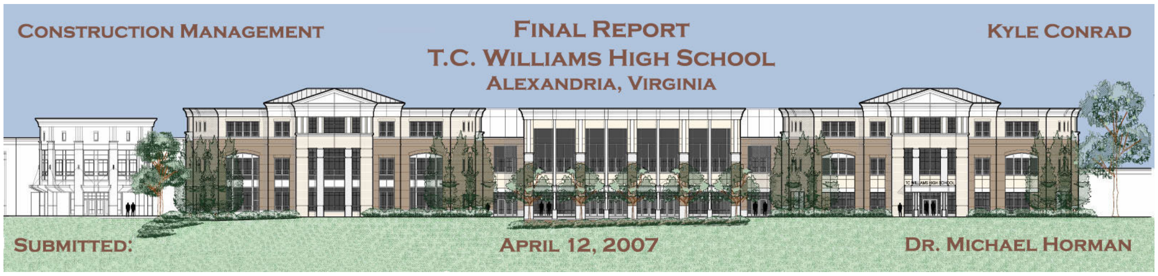
Table 2. Allocation of Time for the Spring 2007 Semester

E. Material Research :

The ultimate goal was to discover an alternative building material to CMU that would provide superior structural, thermal, and acoustical properties while maintaining the durability provided by CMU and reducing the erection time. After initial research, two products were selected for further analysis. The Aerated Concrete Corporation of America [ACCOA] manufactures an autoclave aerated concrete wall panel system that provides a superior thermal resistance and noise reduction coefficient to CMU but has a weaker compressive strength. Compared to CMU's thermal resistance of 1.11 (hr ft^2 ^{o}F)/BTU, the 7.14 (hr ft^2 ^{o}F)/BTU of the ACCOA panel shows potential. Furthermore, autoclave aerated concrete generates a noise reduction coefficient of 0.15 while the CMU lags with an NRC of 0.05. However the structural compressive strength is a concern. The T.C. William High School is designed to the 1500 psi compressive strength of CMU and the ACCOA only has a compressive strength of 580 psi and is comparable in thickness to the CMU. Significant structural redesigns would have to be considered.

The panels are available in maximum lengths of 20 feet, substantially longer the CMU. The other major concern was the panel's maximum width of 24 inches and thickness of 12 inches. While the company claims that the erection time is significantly less than CMU, the erection sequence is too similar to CMU to provide the flexibility in schedule that is of interest to the T.C. Williams High School Replacement Project.

Tri-State Solarcrete, LLC manufactures and installs a structural insulated concrete composite wall panel that will be the focus of the remainder of the report. The President of Tri-State Solarcrete, Don Oberlin, provided case studies, reports, and design manuals as well as additional incite that could only be acquired through experience with the product. The product is structurally superior to a CMU wall system and provides substantial potential for energy efficiency. The following section provides the details of the product.

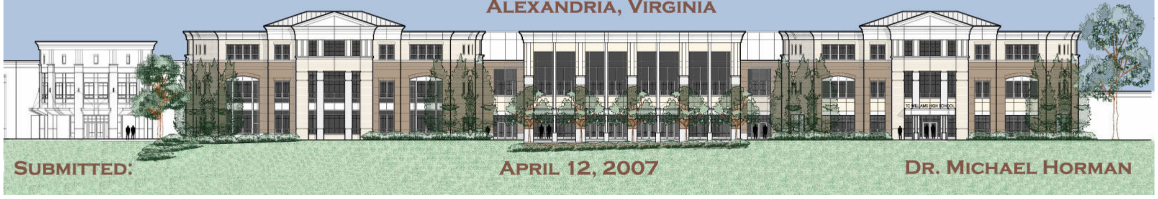


F. SOLARCRETE ™ :

a. Description :

Solarcrete is a structural insulated concrete composite wall panel that is constructed of 7 $^{1}/_{4}$” of expanded polystyrene (EPS) foam insulation surrounded by rebar and sandwiched between two 2 $^{3}/_{8}$” layers of shotcrete as shown in **Figure 8**. Shotcrete is a fiber reinforced concrete that is applied pneumatically to the exterior and interior surfaces of the insulated panels. The shotcrete bonds with the rebar to form a composite system. **Figure 9** depicts the wall panel ties of the Solarcrete System. The wall ties have been improved from their original steel version that transferred heat through the insulated wall. The new polymer alloy acts as a thermal barrier improving the energy efficiency of the wall. Plastic straps slide through the slots on the ties to band the wall panels together.

Figure 8 Solarcrete Wall Panel Sample



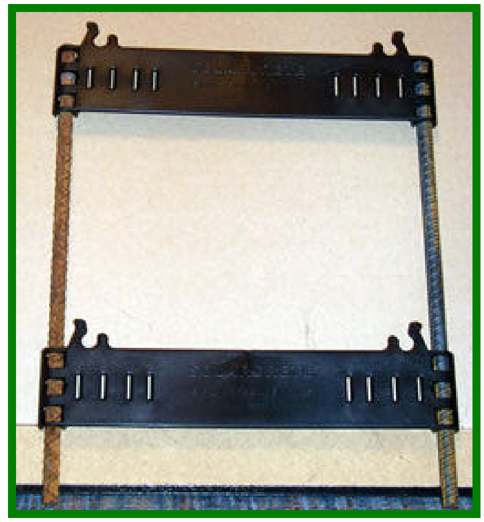


Figure 9 Solarcrete Wall Ties

Horizontal rebar snaps into the uniquely design hooks on the ties promoting improved concrete coverage. An R-value of 36 is obtained by the EPS foam insulation which provides an exceptional resistance to heat loss. The system saves on energy costs while reducing the impact on the environment by reducing the consumption of fossil fuels. Solarcrete also reduces the level of sound that is transferred through the walls. An evaluation of the wall system has revealed a Sound Transmission Class [STC] between 70 and 75. The naturally moisture resistant shotcrete effectively bonds with the EPS to form a moisture barrier. Moisture will not travel through the wall or accumulate on the interior surface of the wall. The system creates an environment that is not conducive to the growth of mold.

b. Construction Sequence :

i. Panel Fabrication :

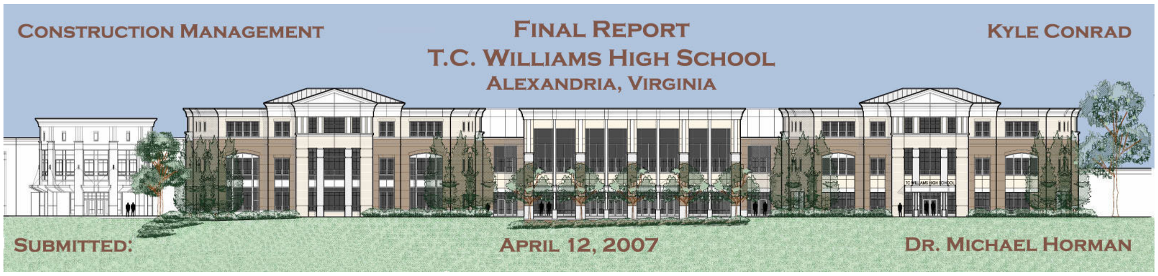
The insulated panels are fabricated in a controlled environment before being transported to site as in **Figure 10**. Off-site fabrication reduces site congestion and the controlled environment increases worker productivity. The composite shear wall ties are spaced 2'o.c. horizontally and vertically forming a 2' x 2' grid on both sides of the wall as the plastic strips band the panels together. The EPS foam insulation panels are reinforced with #3 grade 60 rebar. The vertical reinforcement bars run the entire height of the wall through the wall ties every 2' on both sides of the wall. Horizontal reinforcing rebar are clamped into the ties at 2' increments on alternating sides of the wall. Therefore, the horizontal reinforcement will appear to be at 4'o.c. when viewed from one side of the wall. Vertical control joints are installed on both sides of the wall at a maximum of 8'o.c. and at the corners of wall openings. The control joints are fastened to the horizontal reinforcement bars with wire ties.

Figure 10 Prefabrication of EPS Panels

ii. Transportation :

The panels are sequenced and loaded onto a trailer for transportation to the jobsite as **Figure 11** portrays. Just-in-time delivery practices can be implemented to reduce the need for on-site material storage areas and the inefficiency of double handling of materials.

Figure 11 Prefabricated Panels are Loaded for Delivery to Jobsite



iii. Steel Frame Erection :

Don Oberlin, the sales representative with Tri-State Solarcrete, assures me that the Solarcrete System is structurally superior to a CMU wall. High wall assemblies sometimes require a structural steel support frame to aid in the resistance of lateral loading as **Figure 12** demonstrates. Wind can cause significant loading on higher walls. Oberlin claims that the frame also makes the task of erecting the prefabricated panels simpler by providing a means to secure the panels while they are being permanently anchored.

Figure 12 Erection of Structural Steel Support Frame

iv. Panel Erection :

The lightweight prefabricated panels are generally laid flat on the ground in the proper sequence and tilted-up into their permanent location with a boom lift or crane. **Figure 13** and **Figure 14** show a boom lift tilting-up prefabricated EPS panels. The panels are anchored directly into the strip footing eliminating the need for additional foundation walls. **Figure 15** captures an EPS panel being lowered onto a strip footing. Before the footing is poured, 42” #3 dowels are bent at 8” into ‘L’ shapes and placed at 2’ o.c. to align with the wall ties of the prefabricated EPS panels. The 32” length of the dowel protrudes from the poured footing and is wire tied to the wall tie on the EPS panel at the second vertical tie.

Figure 13 Boom Lift Tilting-up an EPS Panel

Figure 14 Boom Lift Maneuvering an EPS Panel into Place

Figure 15 Anchoring Panels to Footers

v. Shotcrete Application :

Shotcrete technology allows for the installation of structural concrete without the labor intensive formwork process and enables curvilinear designs to be constructed at an economical cost. 4000 psi fiber reinforced concrete is sprayed with an air pressurized hose and screeded to a thickness of 2 $^{3}/_{8}$” on both sides of the reinforced EPS panels as **Figure 16** and **Figure 17** show. The application of the shotcrete gives the Solarcrete Wall Panels their structural integrity as it encases the rebar to generate a composite wall system.

Figure 16 Application of Shotcrete

Figure 17 Application of Shotcrete

vi. Finish Concrete Surface :

While the most common Solarcrete exterior wall finish is acrylic stucco which the finishers are applying in **Figure 18**, the owner is not limited to a stucco finish. Face brick has been secured to the Solarcrete wall system to give the building a traditional appearance. The interior shotcrete surface is typically finished with an elastomeric or an acrylic paint, but for durability issues, higher quality finish materials are recommended for the exterior surface.

Figure 18 Finishing of Shotcrete Surface

G. Acoustical Analysis of Current Gymnasium Construction :

The current gymnasium design consists of ground face CMU load bearing walls, athletic wood flooring, and an acoustical metal roof deck as the interior surfaces. Acoustic CMU is specified for approximately 3,750 sf of the bearing walls and wooden bleachers cover 2,626 sf of wall area on the North and South ends of the gymnasium. When extended, the bleachers cover 12,584 sf of the floor area as well. The East and West elevations of the current design can be found in drawing A-400 in **Appendix J**. Only the East and West elevations were drafted since the North and South elevations will not be effected by any of the redesign options. After discovering the materials specified by the architect, the manufacturers were contacted to obtain the correct sound absorption coefficients presented in **Table 3**. Generic material properties were acquired from *Architectural Acoustics,* by M. David Egan, for unspecified materials. Reverberation time calculations were performed to ensure that speech perception would be acceptable for audience members attending indoor sporting events or school assemblies. The open gymnasium was analyzed with the bleachers retracted, ¾ occupancy and full occupancy to compare the possible reverberation times. All calculations were performed for the full volume of the space since the divider curtains are constructed of mesh material that would allow sound to pass through freely and would only be used to divide the gymnasium during non-critical speech intelligibility events like physical education classes and would have minimal impacts on reverberation of the space. The M^{C} Squared System Design Group, Inc. recommends a target reverberation time of 1.5 to 1.8 seconds for a gymnasium that may be used for teaching purposes. The electronic report contains sound files linked below that demonstrate speech perception at 2 seconds and 5 seconds:

2 Seconds 5 Seconds

MATERIAL	SOUND ABSORPTION COEFFICIENTS						
	125Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
Soundblock®							
4" Type A Surface: Painted	0.12	0.85	0.36	0.36	0.42	0.45	0.50
10" Type RSC/RF Surface: Painted	0.18	0.64	1.02	0.72	0.80	0.58	0.80
Acousta-Wal®							
4" Type I Surface: Painted	0.18	0.82	0.40	0.35	0.43	0.36	0.50
10" Type IVRF Surface: Painted	0.21	0.78	0.97	0.80	0.68	0.73	0.80
Soft Sound™							
Impact Resistant 1" Fabric Acoustic Panel	0.31	0.55	0.89	1.07	1.05	1.15	0.90
Impact Resistant 2" Vinyl Acoustic Panel	0.28	0.69	1.07	1.11	1.06	1.08	1.00
Noise STOP Fabrisorb™							
High Impact Resistant 1-1/8" Fiberglass core / Fabric Facing	0.09	0.50	0.99	1.13	1.08	0.96	0.95
High Impact Resistant 2-1/8" Fiberglass core / Fabric Facing	0.45	0.91	1.09	1.14	1.02	0.98	1.05
High Impact Resistant 1-5/8" Fiberglas core / Vinyl Facing	0.23	0.64	1.16	1.16	1.14	1.02	1.05
Misc. Materials							
Concrete Block, Painted	0.10	0.05	0.06	0.07	0.09	0.08	0.05
Concrete, Rough	0.01	0.02	0.04	0.06	0.08	0.10	0.05
Concrete, Troweled	0.01	0.01	0.02	0.02	0.02	0.02	0.00
Acoustical Metal Roof Deck*	0.14	0.36	0.89	0.95	0.53	0.34	0.70
Wood parquet on Concrete	0.04	0.04	0.07	0.06	0.06	0.07	0.05
Steel Doors	0.05	0.10	0.10	0.10	0.07	0.02	0.10
Metal / Wood Seat - Unoccupied	0.15	0.19	0.22	0.39	0.38	0.30	0.30
Students, Informally Dressed Seated in Wood Chairs	0.30	0.41	0.49	0.84	0.87	0.84	0.65
Leather-Covered Upholstered Seats, Unoccupied	0.44	0.54	0.60	0.62	0.58	0.50	0.59
Glass, Ordinary Windows	0.35	0.25	0.18	0.12	0.07	0.04	0.15

* Acoustical Information obtained from Vulcraft Steel Roof and Floor Deck Catalog – 3NA, 3NIA Acoustical Deck (http://itecsteel.com/images/pdf/vulcraft_steel_deck.pdf)

Table 3 Sound Absorption Coefficients of the Gymnasium Materials

Table 4 depicts the results of the ¾ occupancy calculations of the current gymnasium design which proves to be the critical calculations for comparison in the redesign. The results reveal a reverberation time of 1.16 seconds at 500 Hz and 1.00 second at 1000 Hz which is far below the recommended target values. The reverberation calculations for the retracted bleachers and full occupancy analyses of the current gymnasium design appear in **Appendix H**.

Reverberation Time Calculator

$T_{60} = .05(V/a) = .05(V/\sum S\alpha)$

Reverberation Time Calculation for : CMU Walls	T.C. Williams High School Main Gymnasium Open Gym - 3/4 Occupancy King Street - Alexandria, VA					
			Absorption Coefficient		Sα	
Surface	**Material**	**Area (ft²)**	**500 Hz**	**1000 Hz**	**500 Hz**	**1000 Hz**
Floor	Athletic Wood Flooring	11,979.00	0.07	0.06	838.53	718.74
Floor	3/4 Students, On Bleachers	9,438.00	0.49	0.84	4624.62	7927.92
Floor	1/4 Wood Bleachers	3,146.00	0.22	0.39	692.12	1226.94
Ceiling	3" Deep Acoustical Roof Deck	24,563.00	0.89	0.95	21861.07	23334.85
North Wall	Ground Face CMU - Painted	1,365.33	0.06	0.07	81.9198	95.5731
North Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
North Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
North Wall	Metal Doors	42.00	0.10	0.10	4.2	4.2
South Wall	Ground Face CMU - Painted	1,323.33	0.06	0.07	79.3998	92.6331
South Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
South Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
South Wall	Metal Doors	84.00	0.10	0.10	8.4	8.4
West Wall	Ground Face CMU - Painted	4,315.78	0.06	0.07	258.9468	302.1046
West Wall	Acoustical CMU	1,872.66	1.02	0.72	1910.113	1348.315
West Wall	Metal Doors	168.00	0.10	0.10	16.8	16.8
West Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
West Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
East Wall	Ground Face CMU - Painted	4,105.78	0.06	0.07	246.3468	287.4046
East Wall	Acoustical CMU	1,872.66	1.02	0.72	1910.113	1348.315
East Wall	Metal Doors	378.00	0.10	0.10	37.8	37.8
East Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
East Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
					0	0
					0	0
					0	0
Room Length (ft):	203.00	ft	$a = \sum S\alpha$		35178.95	40957.28
Room Width (ft):	121.00	ft				
Room Height (ft):	33.33	ft	$T_{60} = .05(V/\sum S\alpha)$		**1.16**	**1.00**
Volume (ft³) :	**818,685**	ft³				
Target Reverberation Time: Gymnasium for Teaching*					1.5 to 1.8	1.5 to 1.8

* Target Reverberation Time obtained from the M² Squared System Design Group, Inc.

Table 4 Reverberation Time Calculations for ¾ Occupancy of the Current Gymnasium Design

H. Proposed Acoustical Redesign of Gymnasium :

Although the current design performs better than the recommended reverberation times, the redesigned gymnasium displayed in **Table 5** will seek to obtain a reverberation time equivalent to the current design in case unknown design factors were considered in the original design. Refer to **Appendix H** for all reverberation time calculations for the various gymnasium designs. The interior surface of the Solarcrete system is more sound reflective than the CMU walls and required the addition of sound absorbing materials to reduce the noise in the space and improve the speech perception of the space. Several manufacturers of acoustical wall panels were researched to select a product suitable to the gymnasium. High impact resistant panels were selected from two manufacturers to be applied to the redesign process of the gymnasium and compared in **Table 3**. The Acoustic Product Division of the American Micro Industries, Inc. out of Chambersburg, PA manufacturers a large line of SOFT SOUND™ acoustic wall panels. Their proximity to the D.C. area would reduce delivery costs and transportation time. The impact resistant model is recommended for areas of high probability of impact to ensure the panels are not damaged and unable to perform acoustically. The 1 in thick fabric panel was used as one of the design options for the gymnasium and appears in the gymnasium elevations drawing A-402 in **Appendix J**.

Acoustical Surfaces, Inc. based in Chaska, MN manufactures a similar line of acoustical wall panels marketed under the name FABRISORB™. These products were ultimately selected in the redesign of the T.C. Williams High School Main Gymnasium due to their superior performance and the eagerness of their salesman, Ted Weidman, to assist in the development of a quote and additional product information. The product specifications for these wall panels are included in **Appendix K** along with the official quote. An electronic version of the specifications is also available from their company website (http://www.acousticalsurfaces.com/fabric_panel/fpswallp.htm). Initially, the gymnasium was redesigned using the 1-5/8" vinyl covered impact resistant panels. After corresponding with Weidman, the 1-1/8" fabric panels proved to be more economical. The redesign resulted in the design presented in drawing A-401 of the gymnasium elevations, **Appendix J**. The addition of 4,320 sq ft of the 1-1/8" FABRISORB™ wall panels, required by the calculation shown in **Table 6**, will cost a total of $34,970.80 for the panels and installation accessories. A breakdown of the quote is available in **Table 7**. Since the material supplier is located in Minnesota, the delivery costs will be substantially higher than if the Pennsylvania based manufacturer was selected and could potentially have a negative impact on the lead time of the products.

Reverberation Time Calculator

$$T_{60} = .05(V/a) = .05(V/\sum S\alpha)$$

Reverberation Time Calculation for :	T.C. Williams High School Main Gymnasium Open Gym - 3/4 Occupancy					
Solarcrete System - w/o Acoustic Wall Panels	King Street - Alexandria, VA					
			Absorption Coefficient		Sα	
Surface	**Material**	**Area (ft²)**	**500 Hz**	**1000 Hz**	**500 Hz**	**1000 Hz**
Floor	Athletic Wood Flooring	11,979.00	0.07	0.06	838.53	718.74
Floor	3/4 Students, On Bleachers	9,438.00	0.49	0.84	4624.62	7927.92
Floor	1/4 Wood Bleachers	3,146.00	0.22	0.39	692.12	1226.94
Ceiling	3" Deep Acoustical Roof Deck	24,563.00	0.89	0.95	21861.07	23334.85
North Wall	Concrete, Troweled	1,365.33	0.02	0.02	27.3066	27.3066
North Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
North Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
North Wall	Metal Doors	42.00	0.10	0.10	4.2	4.2
South Wall	Concrete, Troweled	1,323.33	0.02	0.02	26.4666	26.4666
South Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
South Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
South Wall	Metal Doors	84.00	0.10	0.10	8.4	8.4
West Wall	Concrete, Troweled	6,188.44	0.02	0.02	123.7688	123.7688
West Wall	Metal Doors	168.00	0.10	0.10	16.8	16.8
West Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
West Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
East Wall	Concrete, Troweled	5,978.44	0.02	0.02	119.5688	119.5688
East Wall	Metal Doors	378.00	0.10	0.10	37.8	37.8
East Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
East Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
					0	0
					0	0
					0	0
					0	0
					0	0
Room Length (ft):	203.00	ft	$a = \sum S\alpha$		30989.22	37780.04
Room Width (ft):	121.00	ft				
Room Height (ft):	33.33	ft	$T_{60} = .05(V/\sum S\alpha)$		**1.32**	**1.08**
Volume (ft³) :	**818,685**	ft³				
Target Reverberation Time: Gymnasium for Teaching*					1.5 to 1.8	1.5 to 1.8

* Target Reverberation Time obtained from the M^c Squared System Design Group, Inc.

Table 5 Reverberation Time Calculations for ¾ Occupancy of the Solarcrete Gymnasium Redesign

Reverberation Time Calculator

$T_{60} = .05(V/a) = .05(V/\sum S\alpha)$

Reverberation Time Calculation for :		T.C. Williams High School Main Gymnasium Open Gym - 3/4 Occupancy				
Solarcrete System - w/ Fabrisorb™ Acoustic Wall Panels		King Street - Alexandria, VA				
			Absorption Coefficient		Sα	
Surface	Material	Area (ft²)	500 Hz	1000 Hz	500 Hz	1000 Hz
Floor	Athletic Wood Flooring	11,979.00	0.07	0.06	838.53	718.74
Floor	3/4 Students, On Bleachers	9,438.00	0.49	0.84	4624.62	7927.92
Floor	1/4 Wood Bleachers	3,146.00	0.22	0.39	692.12	1226.94
Ceiling	3" Deep Acoustical Roof Deck	24,563.00	0.89	0.95	21861.07	23334.85
North Wall	Concrete, Troweled	1,365.33	0.02	0.02	27.3066	27.3066
North Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
North Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
North Wall	Metal Doors	42.00	0.10	0.10	4.2	4.2
South Wall	Concrete, Troweled	1,323.33	0.02	0.02	26.4666	26.4666
South Wall	3/4 Students, On Bleachers	1,969.50	0.49	0.84	965.055	1654.38
South Wall	1/4 Wood Bleachers	656.50	0.22	0.39	144.43	256.035
South Wall	Metal Doors	84.00	0.10	0.10	8.4	8.4
West Wall	Concrete, Troweled	6,188.44	0.02	0.02	123.7688	123.7688
West Wall	Metal Doors	168.00	0.10	0.10	16.8	16.8
West Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
West Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
East Wall	Concrete, Troweled	5,978.44	0.02	0.02	119.5688	119.5688
East Wall	Metal Doors	378.00	0.10	0.10	37.8	37.8
East Wall	AT-4 Wall Padding	288.00	0.60	0.62	172.8	178.56
East Wall	Windows	122.22	0.18	0.12	21.9996	14.6664
					0	0
West Wall	1-1/8" Fabric Impact Resistant Acoustic Panels	2,160.00	0.99	1.13	2138.4	2440.8
East Wall	1-1/8" Fabric Impact Resistant Acoustic Panels	2,160.00	0.99	1.13	2138.4	2440.8
					0	0
					0	0
Room Length (ft):	203.00	ft	$a = \sum S\alpha$		35266.02	42661.64
Room Width (ft):	121.00	ft				
Room Height (ft):	33.33	ft	$T_{60} = .05(V/\sum S\alpha)$		1.16	0.96
Volume (ft³):	818,685	ft³	CMU Reverberation Time		1.16	1.00
Target Reverberation Time: Gymnasium for Teaching*					1.5 to 1.8	1.5 to 1.8

* Target Reverberation Time obtained from the M^c Squared System Design Group, Inc.

Table 6 Reverberation Time Calculations for ¾ Occupancy of the Gymnasium Redesign using 1-1/8" FABRISORB™ Acoustic Wall Panels

Acoustic Panel Quote				
Acoustical Surfaces, Inc.				
Item	Quantity	Units	Unit Price*	Cost
Fabrisorb 1-1/8" High Impact Fabric Wrapped Panels	4,320	sf	7.59	$32,788.80
Impaling Clips (10 per panel)	1,200	each	0.50	$600.00
PSA-29 Acoustical Panel Adhesive Tubes	144	each	9.25	$1,332.00
Packing/ Plywood Crating	2	each	125.00	$250.00
			Total:	$34,970.80

Note:
* Based on Quote Compiled by Ted Weidman on 5/11/2007 on 3,600sf of 4' x 9' panels

Table 7 1-1/8" FABRISORB™ High Impact Resistant Acoustic Wall Panel Quote

I. Heat Transfer :

In order to satisfy the school district's desire to construct an energy efficient building and continue the value engineering exercise, a heat transfer analysis was performed to compare the heating and cooling energy losses of the facility under the current CMU design and the proposed Solarcrete system. The designs were analyzed for the winter and summer months. Thermal gradients were sketched to express the contributions of each building element in the resistance to energy loss through the wall systems. The magnitude of the slope of the line through the cross section of the wall system corresponds to the material's degree of resistance to heat loss when compared to the other components of the wall system.

Equation Eq-1 was used to obtain the rate of heat flux through the wall assemblies.

$$Q'' = \frac{T_h - T_c}{1/h_h + R_1 + R_2 + R_i + 1/h_c} \qquad \text{(Eq-1)}$$

Exterior temperatures were obtained for the Alexandria, Virginia area from the 2004 edition of the *ASHRAE Fundamentals Handbook of Weather Data* and the interior temperatures were acquired from the Equipment Schedule M0.2 from the T.C. Williams High School construction drawing set. The material R-values were obtained from Dougal Drysdale's *Introduction to Fire Dynamics* and Faye McQuiston's *Heating, Ventilating, and Air Conditioning Analysis and Design* for the CMU wall assembly and the shotcrete components of the Solarcrete system. The data for the EPS panels in the Solarcrete wall system was taken from technical data sheets supplied by Tri-State Solarcrete, LLC. After performing the heat flux calculations for each system, the results proved that the Solarcrete wall system is over three times more efficient than the CMU wall system. The current CMU wall system allows 5.25 BTU/(hr ft^2 ^oF) of heat energy to transfer through the wall during the winter and 1.80 BTU/(hr ft^2 ^oF) during the summer. Meanwhile, the Solarcrete wall system only permits 1.60 BTU/(hr ft^2 ^oF) to transfer in the winter and 0.55 BTU/(hr ft^2 ^oF) in the summer.

Equation Eq-2 was used to determine the temperature difference on each side of a material within each wall assembly in both the winter and summer. When used sequentially from inside to outside, or vise versa, the exact temperature can be determined on each face of the wall components. **Table 8** and **Table 9** show the calculations run to determine the temperatures between the building materials of the CMU wall assembly shown in the thermal gradients in **Figure 19** and **Figure 20** for the winter and summer analyses respectively. Likewise **Table 10** and **Table 11** apply to the Solarcrete system walls in the thermal gradients in **Figure 20** and **Figure 21**.

$$T_x - T_y = Q''(R_x) \qquad \text{(Eq-2)}$$

Carrier's Hourly Analysis Program was utilized to run a full scale energy calculation to determine the additional amount of energy required to operate the supply fans and cooling system to compensate for the energy loss of the building through the main gymnasium walls. **Figure 23** displays the results of the analysis. An annual cost savings of $3,296 results in a total of $9,888 for all the three rooftop air handling units with the Solarcrete wall system over the previously designed CMU wall system. The costs are estimated off of $0.06 / kWhr energy utility costs.

HEAT TRANSFER DIAGRAM				
Wall Construction: Face Brick with CMU Backup				T_{IN} = 70.00 °F
Season: Winter				T_{OUT} = 15.00 °F
Calculations:				
$T_{IN} - T_1 = Q''(R_{INT. AIR FILM})$	70.00 °F	$- T_1$ =	5.25 (0.68)	T_1 = 66.43 °F
$T_1 - T_2 = Q''(R_{10'' CMU})$	66.43 °F	$- T_2$ =	5.25 (1.72)	T_2 = 57.40 °F
$T_2 - T_3 = Q''(R_{1/2'' Collar Joint})$	57.40 °F	$- T_3$ =	5.25 (0.10)	T_3 = 56.88 °F
$T_3 - T_4 = Q''(R_{8'' CMU})$	56.88 °F	$- T_4$ =	5.25 (1.11)	T_4 = 51.05 °F
$T_4 - T_5 = Q''(R_{1\text{-}1/2'' RIGID INSULATION})$	51.05 °F	$- T_5$ =	5.25 (5.00)	T_5 = 24.80 °F
$T_5 - T_6 = Q''(R_{3/4'' AIR SPACE})$	24.80 °F	$- T_6$ =	5.25 (1.26)	T_6 = 18.18 °F
$T_6 - T_7 = Q''(R_{4'' FACE BRICK})$	18.18 °F	$- T_7$ =	5.25 (0.43)	T_7 = 15.93 °F
$T_7 - T_{OUT} = Q''(R_{EXT. AIR FILM})$	15.93 °F	$- T_{OUT}$ =	5.25 (0.17)	T_{OUT} = 15.03 °F
			$\sum R$ = 10.47	

Table 8 Thermal Gradient Calculations for Gymnasium CMU Wall in the Winter

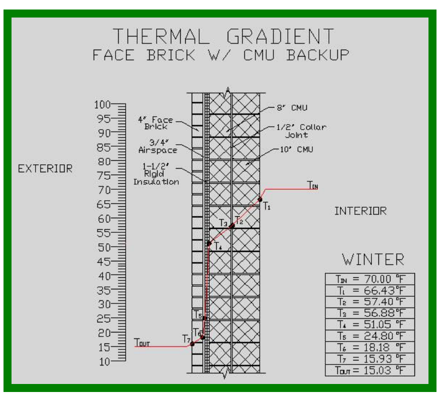


Figure 19 Thermal Gradient through CMU Gymnasium Wall in the Winter

HEAT TRANSFER DIAGRAM						
Wall Construction: Face Brick with CMU Backup						T_{IN} = 76.00 °F
Season: Summer						T_{OUT} = 95.00 °F
Calculations:						
$T_{OUT} - T_1 = Q''(R_{EXT.\ AIR\ FILM})$	95.00 °F	$- T_1$	=	1.80	(0.25)	T_1 = 94.55 °F
$T_1 - T_2 = Q''(R_{4''\ FACE\ BRICK})$	94.55 °F	$- T_2$	=	1.80	(0.43)	T_2 = 93.78 °F
$T_2 - T_3 = Q''(R_{3/4''\ AIR\ SPACE})$	93.78 °F	$- T_3$	=	1.80	(1.26)	T_3 = 91.51 °F
$T_3 - T_4 = Q''(R_{1\text{-}1/2''\ RIGID\ INSULATION})$	91.51 °F	$- T_4$	=	1.80	(5.00)	T_4 = 82.51 °F
$T_4 - T_5 = Q''(R_{8''\ CMU})$	82.51 °F	$- T_5$	=	1.80	(1.11)	T_5 = 80.51 °F
$T_5 - T_6 = Q''(R_{1/2''\ Collar\ Joint})$	80.51 °F	$- T_6$	=	1.80	(0.10)	T_6 = 80.33 °F
$T_6 - T_7 = Q''(R_{10''\ CMU})$	80.33 °F	$- T_7$	=	1.80	(1.72)	T_7 = 77.23 °F
$T_7 - T_{IN} = Q''(R_{INT.\ AIR\ FILM})$	77.23 °F	$- T_{IN}$	=	1.80	(0.68)	T_{IN} = 76.01 °F
				$\sum R$ = 10.55		

Table 9 Thermal Gradient Calculations for Gymnasium CMU Wall in the Summer

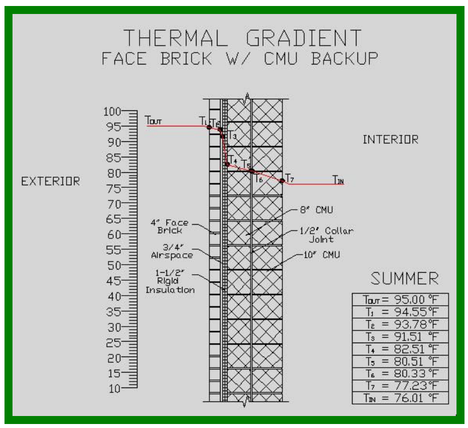


Figure 20 Thermal Gradient through CMU Gymnasium Wall in the Summer

HEAT TRANSFER DIAGRAM						
Wall Construction:	Solarcrete Wall System					T_{IN} = 70.00 °F
Season:	Winter					T_{OUT} = 15.00 °F
Calculations:						
$T_{IN} - T_1 = Q'' (R_{INT. AIR FILM})$	70.00 °F	$- T_1$	=	1.60	(0.68)	T_1 = 68.91 °F
$T_1 - T_2 = Q'' (R_{SHOTCRETE})$	68.91 °F	$- T_2$	=	1.60	(0.30)	T_2 = 68.43 °F
$T_2 - T_3 = Q'' (R_{EPS})$	68.43 °F	$- T_3$	=	1.60	(32.95)	T_3 = 15.71 °F
$T_3 - T_4 = Q'' (R_{SHOTCRETE})$	15.71 °F	$- T_4$	=	1.60	(0.30)	T_4 = 15.23 °F
$T_4 - T_{OUT} = Q'' (R_{EXT. AIR FILM})$	15.23 °F	$- T_{OUT}$	=	1.60	(0.17)	T_{OUT} = 14.96 °F
					∑ R = 34.40	

Table 10 Thermal Gradient Calculations for Gymnasium Solarcrete Wall in the Winter

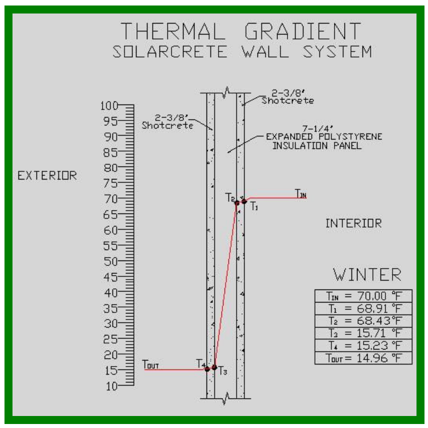


Figure 21 Thermal Gradient through Solarcrete Gymnasium Wall in the Winter

HEAT TRANSFER DIAGRAM						
Wall Construction:	Solarcrete Wall System					T_{IN} = 76.00 °F
Season:	Summer					T_{OUT} = 95.00 °F
Calculations:						
$T_{OUT} - T_1 = Q'' (R_{EXT. AIR FILM})$	95.00 °F	$- T_1$	=	0.55	(0.25)	T_1 = 94.86 °F
$T_1 - T_2 = Q'' (R_{SHOTCRETE})$	94.86 °F	$- T_2$	=	0.55	(0.30)	T_2 = 94.70 °F
$T_2 - T_3 = Q'' (R_{EPS})$	94.70 °F	$- T_3$	=	0.55	(32.95)	T_3 = 76.58 °F
$T_3 - T_4 = Q'' (R_{SHOTCRETE})$	76.58 °F	$- T_4$	=	0.55	(0.30)	T_4 = 76.41 °F
$T_4 - T_{IN} = Q'' (R_{INT. AIR FILM})$	76.41 °F	$- T_{IN}$	=	0.55	(0.68)	T_{IN} = 76.04 °F
					∑ R = 34.48	

Table 11 Thermal Gradient Calculations for Gymnasium Solarcrete Wall in the Summer

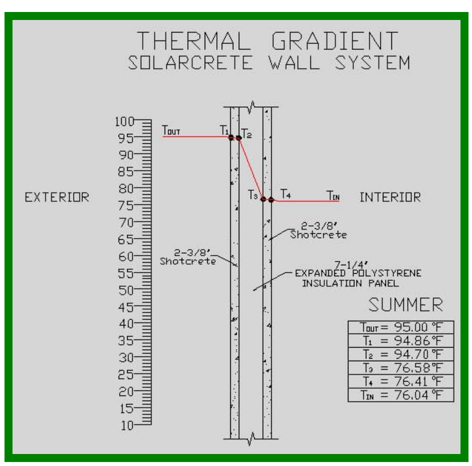


Figure 22 Thermal Gradient through Solarcrete Gymnasium Wall in the Summer

808Table 1. Annual Costs

Component	Existing School ($)	New School ($)
Air System Fans	6,832	3,522
Cooling	245	239
Heating	0	0
Pumps	0	0
Cooling Tower Fans	0	0
HVAC Sub-Total	**7,078**	**3,762**
Lights	3,575	3,575
Electric Equipment	1,655	1,655
Misc. Electric	0	0
Misc. Fuel Use	0	0
Non-HVAC Sub-Total	**5,230**	**5,230**
Grand Total	**12,308**	**8,992**

Table 2. Annual Cost per Unit Floor Area

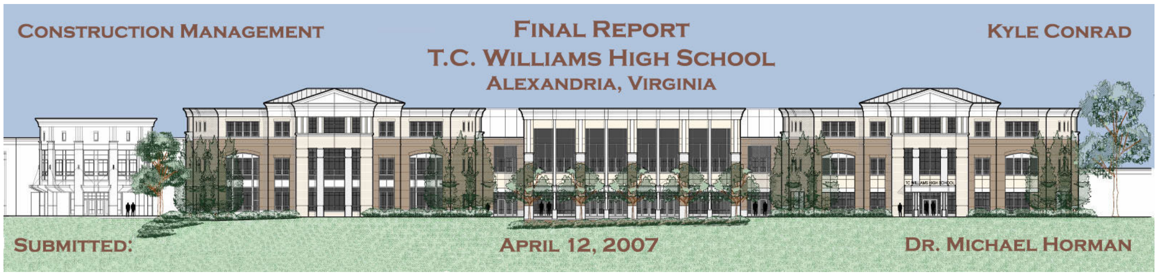
Component	Existing School ($/ft²)	New School ($/ft²)
Air System Fans	0.278	0.143
Cooling	0.010	0.010
Heating	0.000	0.000
Pumps	0.000	0.000
Cooling Tower Fans	0.000	0.000
HVAC Sub-Total	**0.288**	**0.153**
Lights	0.146	0.146
Electric Equipment	0.067	0.067
Misc. Electric	0.000	0.000
Misc. Fuel Use	0.000	0.000
Non-HVAC Sub-Total	**0.213**	**0.213**
Grand Total	**0.501**	**0.366**
Gross Floor Area (ft²)	24563.0	24563.0
Conditioned Floor Area (ft²)	24563.0	24563.0

Note: Values in this table are calculated using the Gross Floor Area.

Table 3. Component Cost as a Percentage of Total Cost

Component	Existing School (%)	New School (%)
Air System Fans	55.5	39.2
Cooling	2.0	2.7
Heating	0.0	0.0
Pumps	0.0	0.0
Cooling Tower Fans	0.0	0.0
HVAC Sub-Total	**57.5**	**41.8**
Lights	29.0	39.8
Electric Equipment	13.4	18.4
Misc. Electric	0.0	0.0
Misc. Fuel Use	0.0	0.0
Non-HVAC Sub-Total	**42.5**	**58.2**
Grand Total	**100.0**	**100.0**

Figure 23 Carrier's HAP Analysis of Gymnasium Designs



J. Building Information Modeling [BIM] :

Building Information Modeling is slowly gaining acceptance in the construction industry. When creating a Building Information Model, the developer must ask themselves what goal they wish to achieve by building the model. The most effective model may not require intricate levels of detail. By incorporating the useless detail, time and money will be wasted and the file sizes will increase causing the model to run slower unnecessarily. Ideally, a BIM will be initiated early in the project and incorporate all aspects of design, construction, and operation and maintenance of a facility. However, the issue of interoperability between the different software packages of the team members arises. The goal of the T.C. Williams High School Model will be to quickly perform quantity take-offs, manipulate the original design for value engineering purposes, design a structural moment frame, and visualize and re-sequence the construction schedules through 4D planning of areas 5, 6, & 7. Interoperability between the Autodesk Revit software, RAM Structural Systems, and NavisWorks will be researched to develop the BIM using the software applications.

a. Autodesk Revit Building 9.1 :

The structural grid displayed in **Figure 24** was developed using Autodesk Revit Building 9.1 based on the structural construction drawings provided by Hensel Phelps. All structural drawings were referenced to accurately model areas 5, 6, & 7 of the T.C. Williams High School Replacement Project. The initial model shown in **Figure 25** was modeled with generic walls to speed the modeling process. Areas 1-4 were created as a mass model since they are beyond the limits of the project analysis.

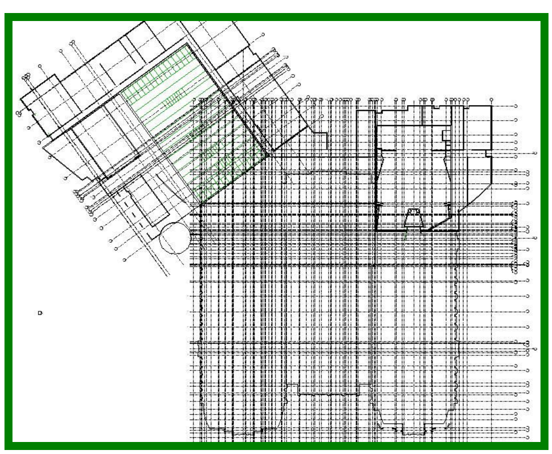
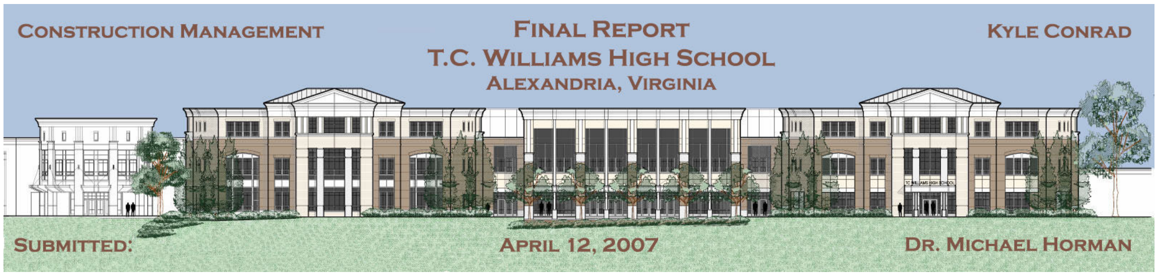


Figure 24 Autodesk Revit Building 9.1 - Structural Grid



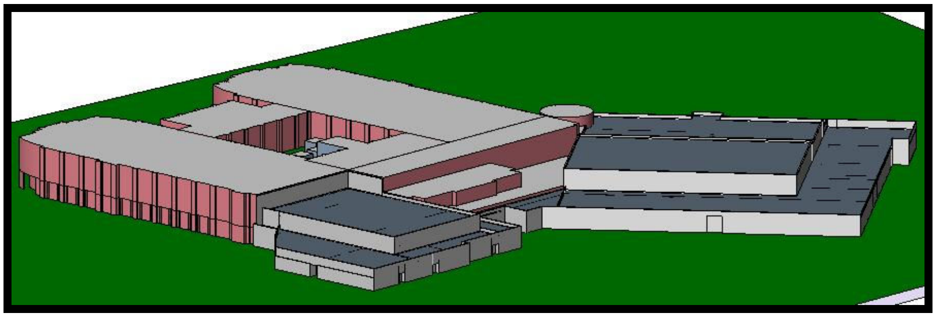


Figure 25 Autodesk Revit Building 9.1 - Generic Load Bearing Walls

After the entire model was complete, the wall types were changed from generic walls to the actual thickness of CMU designated by the structural engineers as **Figure 26** shows. The model was saved as a different file name to maintain the initial generic model. The wall types in the generic model were once again altered to convey the design of the Solarcrete Wall System shown in **Figure 27**. A wall schedule was created in both the CMU and Solarcrete models to generate a list of wall quantities to export to Microsoft Excel. Once the text files were opened in Excel, minor changes had to be made to the spreadsheet in order to create a functional spreadsheet to perform a summation of quantities and sort by wall types. When copying and pasting from the exported schedule, not all entries were automatically inserted into Excel as numbers. After manipulating the entries, quantity take-offs could be generated very easily. **Table 12** and **Table 13** provide summaries of the quantity take-offs of the wall areas of CMU and Solarcrete, respectively, for areas 5, 6, & 7 of the T.C. Williams High School facility.

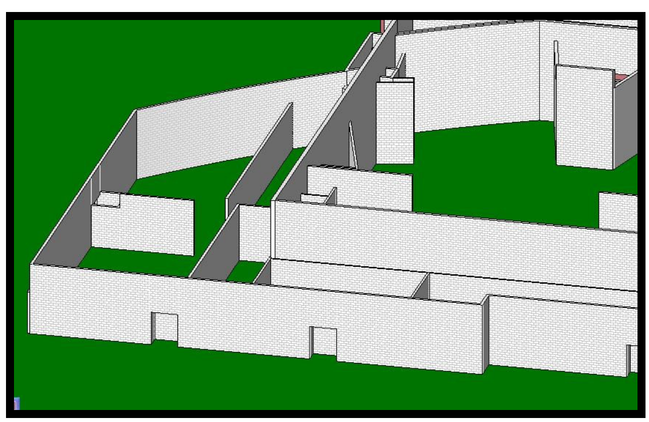


Figure 26 Autodesk Revit Building 9.1 - CMU Walls

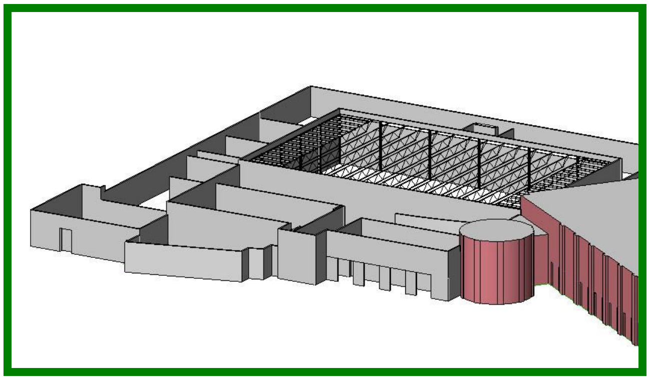


Figure 27 Autodesk Revit Building 9.1 - Solarcrete Wall System

T.C. Williams High School QTO - Current Construction		
Gymnasium		
	10" CMU	49,827 sf
	12" CMU	14,828 sf
	14" CMU	19,440 sf
	6" CMU	7,469 sf
	8" CMU	19,007 sf
	Sub-Total:	**110,571 sf**
Auditorium		
	10" CMU	19,046 sf
	12" CMU	8,281 sf
	14" CMU	13,981 sf
	6" CMU	8,661 sf
	8" CMU	10,857 sf
	Sub-Total:	**60,826 sf**
Mech/Elec Wedge - Auto Strip		
	10" CMU	16,587 sf
	6" CMU	1,625 sf
	8" CMU	5,217 sf
	Sub-Total:	**23,429 sf**
Misc.		**45 sf**
	Total:	**194,871 sf**

Table 12 Summary of Quantity Take-Off Developed from CMU Wall Schedule

T.C. Williams High School QTO - Solarcrete System		
Gymnasium		
12" Panel	66,167 sf	2,595 lf
Sub-Total:	**66,167 sf**	**2,595 lf**
Auditorium		
12" Panel	42,367 sf	1,900 lf
Sub-Total:	**42,367 sf**	**1,900 lf**
Mech/Elec Wedge - Auto Strip		
12" Panel	21,383 sf	1,220 lf
Sub-Total:	**21,383**	**1,220 lf**
Total:	**129,917 sf**	**5,715 lf**

Table 13 Summary of Quantity Take-Off Developed from Solarcrete Wall Schedule

After the structural steel moment frame is designed and modeled using Revit Structure 4 and RAM Structural Systems, the model is reloaded into either Revit Building 9.1 or Revit Structure 4 to develop structural framing and structural column schedules to export to Microsoft Excel for quantity take-offs of the structural steel involved in the construction of the moment frame to support the Solarcrete wall system in gymnasium. **Table 14** and **Table 15** provide summaries of the quantities and lengths of the structural steel members.

Structural Framing Schedule			
Count	**Family**	**Type**	**Length**
2	W-Wide Flange	W14X48	29' - 11"
3	W-Wide Flange	W24X68	36' - 0"
2	W-Wide Flange	W21X62	36' - 0"
1	W-Wide Flange	W24X68	36' - 5 15/16"
1	W-Wide Flange	W24X68	35' - 6 1/16"
2	W-Wide Flange	W12X50	29' - 11"
4	W-Wide Flange	W8X21	24' - 11"
6	W-Wide Flange	W8X18	24' - 0"
1	W-Wide Flange	W24X68	35' - 6 1/16"
14	DLH-Series Bar Joist	68DLH19	121' - 10"
30	W-Wide Flange	W12X26	23' - 11"

Table 14 Summary of Quantity Take-Off Developed from Structural Framing Schedule

Structural Column Schedule			
Count	**Family**	**Type**	**Length**
18	W-Wide Flange-Column	W14X145	32' - 8"
4	W-Wide Flange-Column	W10X49	32' - 8"

Table 15 Summary of Quantity Take-Off Developed from Structural Column Schedule

b. Autodesk Revit Structure 4 :

Autodesk Revit Structure 4 was used to design a generic moment frame to be analyzed and sized by RAM Structural Systems. The generic building model created in Revit Building 9.1 could be opened directly with Revit Structure 4. Additional grid lines were added to the gymnasium to make the RAM analysis easier. Grid lines were created at the location of each change in loading to allow loads to be snapped to grid intersections in the RAM software. Generic columns, beams and joists shown in **Figure 28** and **Figure 29** were designed in Revit Structure 4 due to the user friendly interface of the software. RAM International, the makers of RAM Structural System, had to be contacted to acquire a link for exporting a Revit Structure 4 model that would compatible with RAM Structural Systems. You must first register with RAM International, at http://www.ramint.com/support/revit.jsp, before they will email the link to your email address of choice. After the link is received via email, the link must be installed onto your computer. Once Autodesk Revit Structure 4 is reopened, the link will automatically appear under the Tools dropdown menu in the main toolbar. A RAM file will be saved in the same folder as the Revit file and can be directly open by RAM Structural Systems.

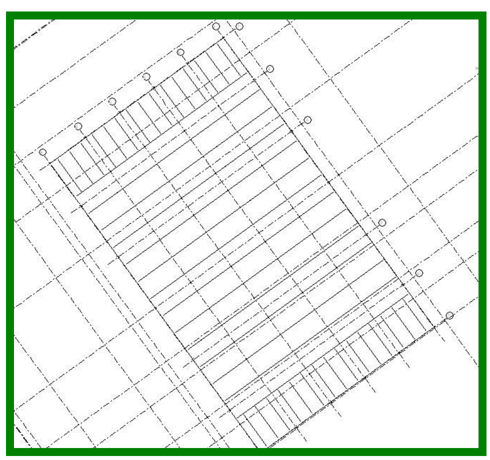


Figure 28 Generic Structural Moment Frame Created in Revit Structure 4

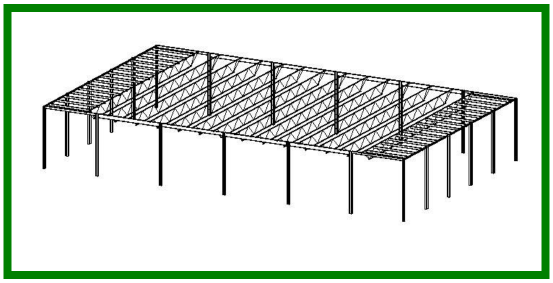


Figure 29 Revit Structure 4 - 3D model of Gymnasium Moment Frame

c. RAM Structural Systems :

RAM Structural Systems was used to apply the joist loadings specified in structural construction drawing S4-24 and the lateral wind loading. The wind loading was designed at a basic wind speed of 90 mph and exposure B. An importance factor of 1.15 was applied to the loading per the structural engineer's direction. The loads are created and applied in RAM Modeler which appears in **Figure 30**. The RAM Beams, RAM Columns, and RAM Structural Frame functions were used to analyze and size the structural members. After the frame was designed the model was saved and imported back into the Revit Structure 4 file.

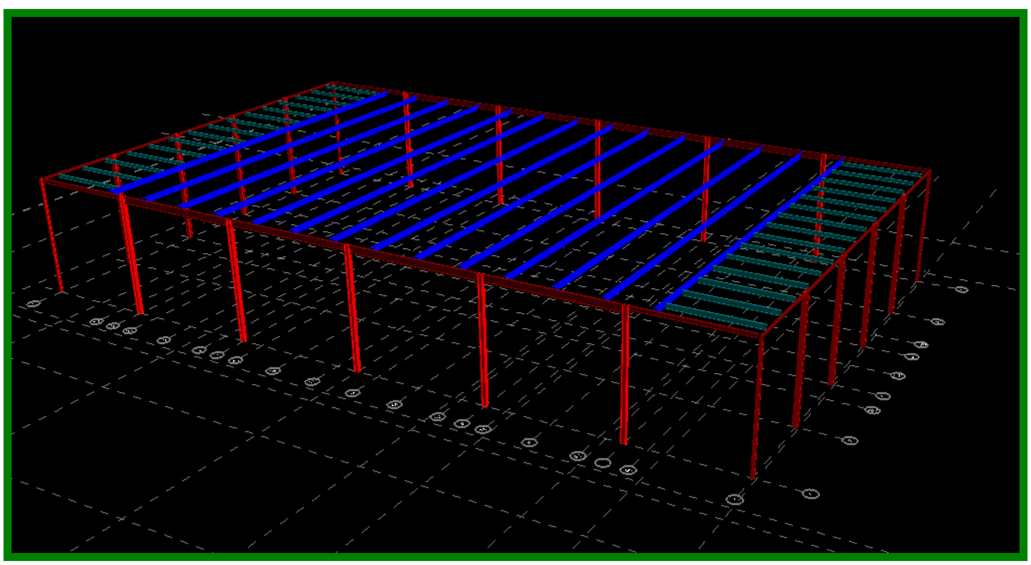


Figure 30 RAM Analysis of Structural Moment Frame

d. NavisWorks :

NavisWorks Timeliner assisted in the re-sequencing of the construction of the superstructure for the T.C. Williams High School Replacement Project. Autodesk Revit Building also contains a link to export a Revit model as a NavisWorks file under the tools dropdown menu in the main toolbar. A project schedule is linked to the NavisWorks file in the Timeliner mode from Microsoft Project or Primavera scheduling software. Microsoft Project was used for the schedule development. By attaching schedule tasks to building model components, a 4D model is generated and can be played to analyze and adjust the construction schedule. The visualization of the construction sequence allows the scheduler to notice errors in the sequence and avoid costly delays before the construction takes place in the field. A Windows Media file can be recorded to allow the 4D model to be viewed by any user with a Windows operating system.

K. Work Sequencing :

The current construction sequence of the superstructure requires that the work progress away from the material staging and storage areas as portrayed in the Superstructure Site Plan C-101 in **Appendix F**. Areas 5, 6, & 7 have an extremely large quantity of CMU load bearing walls. Since CMU construction is extremely labor and time intensive, the aforementioned areas must begin early in the structural sequencing to be completed when the steel framed towers top-out. The sequencing builds a barrier between the construction and the material staging and storage areas, creating the need for materials to be transported outside of the site fence onto a public access road due to site constraints on the East side of the site. Pedestrian traffic is also heavy along this roadway since the temporary student parking area and construction parking is located at the end of the roadway. An increased safety risk arises and additional resources will be required to flag vehicular and pedestrian traffic. Time will also be wasted transporting materials around the site and previously constructed portions of the structure.

The structural redesign schedule found in **Appendix D** reveals the schedule impacts due to the re-sequencing of the current CMU load bearing wall design and the proposed Solarcrete System. To re-sequence the current CMU design to accommodate the desired erection sequence proposed in the 4D models and the Re-Sequenced Superstructure Site Logistics Plan C-102 in **Appendix G**, the construction schedule would have to be extended by 252 work days. With the Solarcrete System, the schedule would be reduced by 17 work days. The rapid erection time of the Solarcrete system adds flexibility to the order of the construction of areas 5, 6, & 7 in the construction sequence and promotes a more efficient sequence in terms of site logistics.

L. Site Logistics Impact :

The re-sequenced construction schedule discussed in the previous section and presented in the Re-Sequenced Superstructure Site Logistics Plan C-102 in **Appendix G**, alleviates site congestion during the superstructure phase of construction. The work flow is permitted to progress toward the material staging and storage area in such a manner that extends the duration that the bulk of the construction materials can be transported to the designated areas of installation without interferences from concurrent construction.

M. Conclusions :

After reviewing the results from the Solarcrete value engineering exercise, the Solarcrete system would be a valuable solution to the proposed issues with CMU construction. **Table 16** provides a summary of the comparisons between the CMU and Solarcrete wall systems. While the initial cost of the Solarcrete wall system is approximately 15% greater than the CMU wall system, Solarcrete provides the owner with an equally durable wall system that provides exceptional energy efficiency. Further analysis could be performed to reduce the size of the air handling units and reduce the initial cost difference between the two wall systems. The Solarcrete system also provides for a safer and more efficient site by promoting an alternative sequence for the erection of the superstructure with a reduced schedule duration. The Solarcrete system outperforms the traditional CMU construction practices analyzed in terms of schedule impacts, construction labor hours, and energy efficiency.

T.C. Williams High School		
System Comparisons		
Description	**Solarcrete Construction**	**CMU Construction**
System Costs		
Solarcrete Panels	$2,057,679.00	$0.00
CMU	$0.00	$1,902,662.00
Additional Structural Steel	$132,547.00	$0.00
Fabrisorb Acoustic Wall Panels	$34,970.80	$0.00
Sub-Total:	**$2,225,196.80**	**$1,902,662.00**
Cost Difference:	**$322,534.80**	
Energy Savings		
Cost Savings on Supply Fan Load per Year	**$6,592.00**	$0.00
Heat Transfer Through Wall* - Winter	1.60 BTU/(hr ft^2)	5.25 BTU/(hr ft^2)
Heat Transfer Through Wall* - Summer	0.55 BTU/(hr ft^2)	1.80 BTU/(hr ft^2)
Schedule		
Schedule Impact**	158.5 days	695.0 days
Re-Sequenced Schedule Savings***	17 days	-252 days
Manhours		
Areas 5, 6 & 7 Labor Hours	8,979 mhrs	29,536 mhrs

Note:
* Analysis of Gymnasium Walls
** Based on Material Estimates
*** Current Structural System Schedule Duration = 395 days

Table 16 Summary of System Comparisons