9.0 Mechanical System Redesigns:

The approach taken in the mechanical system redesigns of South Jefferson High School is that of the green design initiative. A motivator for green design is lowering the total cost of ownership through resource management and energy efficiency. Sustainable green design is useful in a school project because of tight budgets, close observation within the community, and typically long time periods between renovation or new construction of a school. A secondary benefit associated with green design is the increased productivity from a building that is comfortable and provides healthful conditions. Comfortable students are less distracted, able to focus better on their tasks/activities, and occupants will appreciate the physiological and physical benefits good green design provides.

The first alternative design researched was a VAV system with chilled water plant. The intent of this redesign was to show the improvements of having a central chilled water plant compared to many DX condensing units as the main cooling source for the building's roof top units. This system design alternative required the least amount of redesign because of its similarity to the existing system. Still, adding a chilled water plant required alterations and additions to the current building design.

The second alternative researched was a ground source heat pumps system. This system is a very energy efficient but costly to construct. Implementing a ground source heat pump system for South Jefferson High School required extensive redesign and analysis. The only similarities to the existing mechanical system were the use of a 2-pipe hydronic distribution system and any single space air handling units remained in tact. All other equipment was revamped.

Energy recovery was incorporated into both systems. In the VAV with chilled water plant alternative enthalpy wheels were added into the existing roof top units. This added initial cost and did not lower the size of existing heating and cooling equipment enough to declare the wheels a viable addition to the system. The ground source heat pump system uses dedicated outdoor air units for any units serving multiple spaces. These dedicated outdoor units require energy recovery and utilize enthalpy wheels.

Humidity control was the final step in improving the existing system. Indoor air quality is a major concern in schools. The approach to relieve these concerns was the addition of enthalpy wheels and humidity control into air handling units serving multiple spaces.

Many of the values used in the analysis of the mechanical system redesign were generated using the Trane Trace 700 software package.

9.1 VAV System with Chilled Water Plant:

A chilled water plant contains chillers that generate chilled water to serve cooling coils in equipment. The chilled water is distributed to the cooling coils through schedule 40 steel chilled water piping. A main benefit of using a chilled water plant is the plant's ability to take advantage of load diversity throughout the building. The load can be matched more efficiently with a central cooling system compared to multiple scattered compressors of a direct expansion system. The energy benefits amount to a savings of 0.26 KW/ton compared to distributed systems. Appendix B shows separate schematics for the chilled water plant and how it ties into the airside equipment.

-Air-Cooled versus Water-Cooled:

There are two primary methods of rejecting heat from a chiller, air-cooled and water-cooled. Air-cooled packaged chillers have enjoyed market appeal because of the simplicity of installation. The units are completely factory piped and wired so that the user has only to connect the chilled water piping and power wiring to have a performing chiller system. Higher operating costs and sound levels accompany an air-cooled selection; however, they are still typically more efficient than a direct expansion type system. In addition, most school maintenance staffs are familiar with this type of equipment and can maintain it without requiring outside maintenance contracts.

Conversely, water-cooled chillers are those that employ a cooling tower or fluid cooler heat exchange medium. They are usually the most expensive first cost chiller equipment due to the separation of the chiller and the cooling tower, which is usually located on the roof. Water-cooling is more energy efficient than air –cooling. However, most school maintenance staffs do not have the in-house expertise to deal with the chemical requirements associated with make up water or inhibitors required when the cooling towers are laid up for the winter. Usually water-cooled chillers require a school district to employ some type of outside chiller maintenance contract. Table 5 shows a simple comparison of a quality air-cooled chiller and water cooled chiller providing levels for particular issues.

	Quality Air-Cooled	Water-Cooled
Sound	(-) Loudest (1)	Medium
First Cost	(+) Lowest (2)	(-) Highest
Operating Cost	(-) Medium(3)	Lowest
Size	(-) Largest	Split
Longevity	(-) 15-20 years	(+) 20-25 years
Environmentally Friendly	134A	134A, 123
Electrical Service Size	(-) Highest	Medium

Table 5 – Quality Air-Cooled vs. Water-cooled Chillers

-Chiller Selection:

In order to select chillers for South Jefferson High School, calculated cooling capacities for the existing packaged direct expansion roof top units were developed in the Trane TRACE 700 software (Table 6). This data shows that the total peak load cooling tonnage is 591 tons for a design day. This load is handled completely by the roof top units' condensing units. Installing a central chilled water plant replaces the DX condensing units with air-cooled chillers.

		Peak Plant Loads		Block Plant Loads		
Plant	System	Main Coil ton	Peak Total ton	Time Of Peak mo/hr	Main Coil ton	Block Total ton
Cooling plant - 001		585.9	590.4	7/12	573.2	577.7
	AHU-8	6.4	10.9	7/12	6.4	10.9
	AHU-2	82.4	82.4	7/12	81.5	81.5
	AHU-3	30.2	30.2	7/12	30.2	30.2
	AHU-4	68.1	68.1	7/12	68.1	68.1
	AHU-5	40.7	40.7	7/12	40.7	40.7
	AHU-6	20.5	20.5	7/12	20.5	20.5
	AHU-7	49.3	49.3	7/12	47.5	47.5
	AHU-1	72.7	72.7	7/12	72.7	72.7
	AHU-9	37.1	37.1	7/12	36.6	36.6
	AHU-10	42.2	42.2	7/12	42.2	42.2
	AHU-11	10.0	10.0	7/12	4.5	4.5
	AHU-12	32.6	32.6	7/12	32.6	32.6
	AHU-13	46.1	46.1	7/12	44.4	44.4
	AHU-14	47.6	47.6	7/12	45.4	45.4
Building totals		585.9	590.4		573.2	577.7

Building peak load is 590.4 tons.
Building maximum block load of 577.7 tons occurs in July at hour 12 based on system simulation.

Table 6 – Design Cooling Load

When comparing the number and size for the air-cooled chillers, there were several possibilities to choose between. The first option, which is not very viable with air-cooled chillers, is to use just one chiller to meet the building's full peak load. Since air cooled chillers are typically available only between 150 to 500 tons and the building peak load was 591 tons this was not a viable option.

The second option would be to have two chillers in parallel which each meets half the calculated peak loads or approximately 300 tons each. A third option would be to have two chillers sized at a 60/40 split of the peak load. However, this option was not as lucrative as the regular 50/50 load split when compared to the chiller load profiles developed in Trane TRACE 700. The capacity of the 40% chiller (at 240 tons) would only meet the cooling demands during the winter months. The 60% chiller (at 360 tons) would have to operate for almost the entire year. In comparison, one of the 50% chillers (at 300 tons) could meet the cooling loads of the building for approximately four months out of the year.

Additional options for the chiller plant arrangement include using three chillers, each at one-third of the peak load (at 200 tons each). This was not a feasible solution and only represented a higher first cost with no real benefits in operating efficiency.

After comparing all these possibilities, it was determined that the two air-cooled chillers should operate in parallel and split the load in half at 300 tons each. This way, if one chiller would break down, the second chiller could meet up to half the load of the building. A school is not a critical facility like a hospital or data center, but some redundancy is important and logical.

The next design consideration was the type of chiller to select. Table 7 shows the Department of Energy's recommended chiller types according to tonnage. The type of chiller selected for South Jefferson is a screw chiller which operates well under the specified 300 tons. Under standard operating conditions the chiller achieves an EER of 12.4.

Chiller Size Recommendation	
<= 100 tons	1st choice: Reciprocating 2nd choice: Scroll 3rd choice: Screw
100 – 300 tons	1st choice: Screw 2nd choice: Scroll 3rd choice: Centrifugal
> 300 tons	1st choice: Centrifugal 2nd choice: Screw

Table 7 – Recommended Electric Chiller Types

-Variable Speed Control:

Another design consideration deals with the speed control of the compressors on the air-cooled chillers. It is recommended to use Variable Frequency Drives (VFD) on the chillers to increase the overall energy efficiency. This slightly increases the energy usage at peak loading with the rated kW/ton of the chillers. But in perspective, the chiller plant will only be operating at peak load conditions for a very small percentage (5% or less) of the time during the year. About 95% of the time is spent at part load conditions, which operate more efficiently with the use of VFD controllers on both chillers.

9.2 Ground Source Heat Pump:

Ground source heat pump (GSPH) systems take advantage of the earth's relatively constant temperatures just below its surface (53° in Charles Town, WV). The system uses a refrigeration cycle to extract and transfer heat to and from the ground. This system circulates a fluid (usually an antifreeze solution) through a subsurface loop (well field) of pipe to a heat pump. The subsurface loop typically consists of polyethylene pipe, which is placed horizontally in a trench or vertically in a bore hole. This thin-walled pipe is a heat exchanger, transferring heat to and from the earth. Fluids inside the pipe circulate to the heat exchanger of an indoor heat pump where they exchange heat with the refrigerant. The refrigerant loop typically consists of copper pipes that contain a refrigerant. The ground source heat pump system typically utilizes the earth as a source of heat in the winter and as a source of cooling in the summer.

System Variations:

Hybrid or independent, two-pipe and one pipe ground source heat pump systems were all considered in the redesign of South Jefferson High School.

-Two-Pipe versus One-Pipe:

In comparison of two-pipe versus one-pipe hydronic distribution systems, operating cost and first costs associated with each will differ. The overall cost of piping is better in the one-pipe system, but it also requires more pumps due to its distributed secondary pumping scheme. Since conserving energy is the main approach, a two-pipe system was selected.

-Hybrid versus Independent:

A hybrid GSHP system uses the aid of an additional heat exchanger other than the ground to reject heat, while the independent GSHP system uses only the ground. Both the hybrid and independent GSHP systems require a well field to be sized. The well field was modeled in the GHLEPro software package. The results, as seen in Appendix F, showed that all heat rejection could be done by the ground without the aid of any supplemental heat exchangers. In total, 240 boreholes at 20 foot intervals were required with each bore hole being 8 inches in diameter and drilled to a depth of 475 feet. The entire 480 x 200 foot well field can be constructed under the football and soccer practice fields at South Jefferson, and space still remains to construct a pump house containing two 25 horsepower pumps and all associated data collection equipment. This outcome makes an independent 2-pipe ground source heat pump system feasible for the redesign of South Jefferson.

9.3 Air-to-Air Heat Recovery:

Energy recovery was incorporated into both alternative systems. Both alternatives recover energy in the building's air distribution system, through the use of air-to-air heat recovery. Enthalpy or total energy wheels are used to transfer heat and moisture between a leaving exhaust air stream and entering outdoor air stream. In the VAV with chilled water plant alternative enthalpy wheels were added to the existing roof top units. This added first cost and did not significantly lower the size of existing heating and cooling equipment enough to declare the wheels a necessary addition to the system.

The ground source heat pump system uses dedicated outdoor air units for any units serving multiple spaces. The dedicated outdoor air units require energy recovery and utilize enthalpy wheels.

9.4 Humidity Control:

The density of the school's population results in large amounts of outdoor air that must move through the building to assure proper ventilation. If the air is not properly conditioned, small amounts of moisture in the outdoor air can lead to too much indoor moisture and moisture-related problems during the varying seasons.

One of the drawbacks to using ground source heat pumps in lieu of the other systems is that humidity control is not as good with heat pumps. In order to aid with this problem, dedicated outdoor air units have been used in place of the existing roof top units serving multiple spaces (Appendix B).

In each redesign, humidity controls are incorporated with the use of enthalpy wheels in the air handling equipment. The goal in using humidity controls is to maintain humidity levels below 60%, ideally between 30% and 50%. Simulations of both systems show that most spaces fell within the ideal humidity range. A few exceptions did exist in spaces with increased activity levels, such as the weight room and dance studio.

9.5 Cost Analysis:

Initial Cost:

The addition of a chilled water plant did not drastically increase first cost compared to the existing mechanical system. The difference between the existing system and VAV with chilled water plant is a just over $310,000. A detailed unit cost estimate of the VAV with chilled water system can be seen in Appendix D.

The ground source heat pumps system cost estimate was derived from the existing mechanical system cost estimate. Adjustments to the cost estimate were taken into account by having dedicated outdoor air units replacing the roof top units serving multiple spaces, fan powered boxes were replaced by less expensive heat pumps, and boilers were eliminated. These changes resulted in a reduction in cost, but this system requires a geothermal well field which can be very expensive. The cost for the well field and pump house accounts for an additional $1,807,847 to the project's cost. The cost estimation for the geothermal well field can be seen in Appendix D. These differences amount to a $1,012,044 increase in first cost between the existing and ground source heat pump system (Appendix D).

Maintenance Cost:

Maintenance costs were calculated using the ASHRAE HVAC Applications Handbook, 2003 mechanical maintenance cost estimation. Calculated results can be seen in Appendix D.

The VAV system with chilled water plant's maintenance cost is the highest of the alternative designs. Even though maintenance would be more centralized, and the number of compressors is reduced significantly with a plant. The increased cost of a 4-pipe system compared to a 2-pipe system significantly outweighs any other factor in the calculation. This also causes the maintenance cost for VAV system with chilled water plant to be more than the DX system. Not as surprising, is the result of the ground source heat pump system saving over $20,000 dollars annually over the DX system.

Life Cycle Cost:

The VAV system with chilled water plant does not yield returns in either life cycle payback or simple payback within 20 years. The ground source heat pump system starts to generating returns in 18.7 years within the 20 year life expectancy of a school (Table 8). The well field is the main element effecting first cost of the ground source heat pump system. If a hybrid GSHP system were designed it may have generated returns sooner. Reducing the well field size could influence cost more than adding a fluid cooler and boiler to the system. A hybrid system was not designed because it is not as energy efficient as an independent system.

Alternative	Installed Cost	1st Year Utility Cost	20th Year Utility Cost	1st Year Maint. Cost	20th Year Maint. Cost	Life Cycle Cost
VAV with DX	$4,222,200	$215,145	$455,386	$55,003	$96,448	$7,226,134
VAV with Chiller	$4,532,793	$202,850	$427,374	$80,826	$141,729	$7,657,171
Ground Source HP	$5,234,266	$142,594	$300,424	$33,593	$58,906	$7,187,856

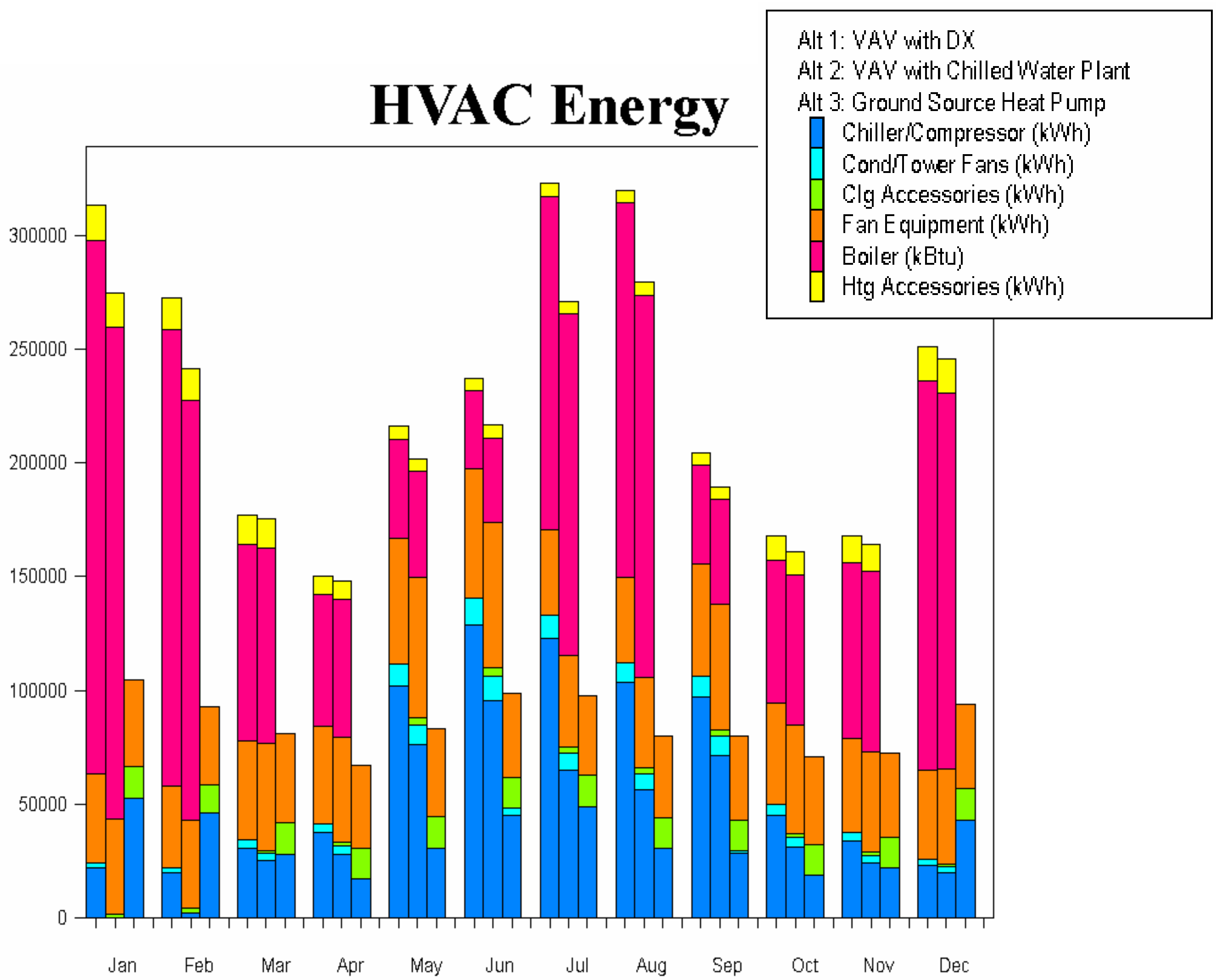
Altern. to Altern.	1st Cost Difference	Simple Payback	Net Present Value	Life Cycle Payback	Internal Rate of Return
Chiller to DX	$310,593	No pay back	-$431,038	No pay back	No pay back
GSHP to DX	$1,012,066	10.7 years	$38,278	18.7 years	10.5%
GSHP to Chiller	$701,473	6.5 years	$469,316	9 years	17.7%

Table 8 – Economic Comparison

9.6 Energy Analysis:

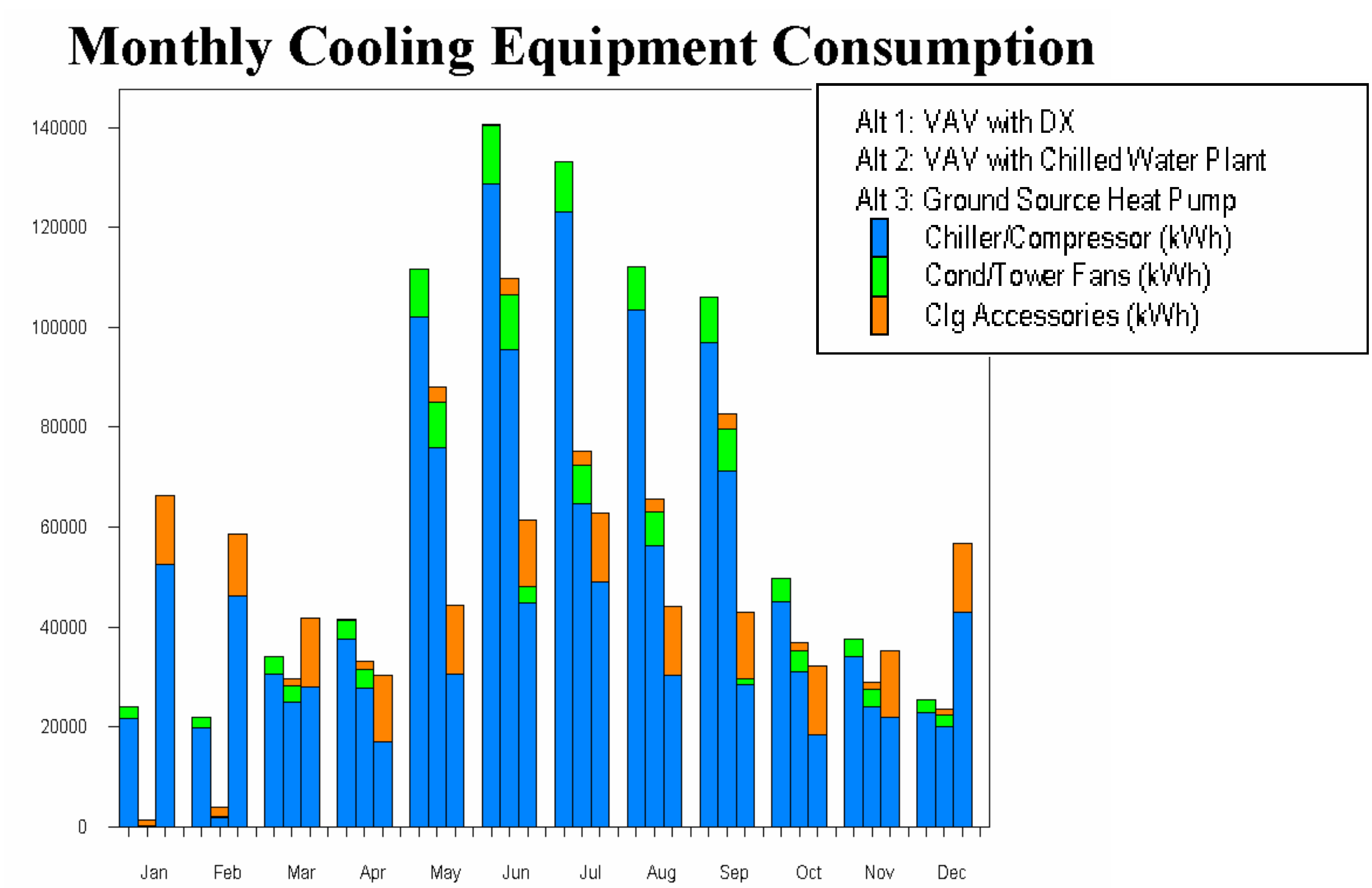
The VAV with chilled water plant alternative saves only a marginal amount of energy over the existing DX system. Most of the energy savings did show in space cooling and heat rejection, but the pump energy doubled (Appendix C) resulting in only 6% reduction in total building energy consumption. This reduction amounts to a $13,295 savings per year. The energy savings the air-cooled chiller has over the existing system is a direct result of the reduced KW/ton of the chiller and the energy recovered from the roof top units enthalpy wheels. Monthly HVAC energy consumption can be seen in Figure 2 to see system energy usages. One of the main reasons that the chilled water plant does not save more energy over the existing system is because the cooling equipment in both cases is air-cooled. If the chillers were to be water-cooled the energy savings would be much more noticeable, because of a higher COP. The counter to the water-cooled chiller is that the initial costs and maintenance costs for the system would be much higher.

Figure 2 – Monthly HVAC Energy Consumption



The ground source heat pump system produced much better results, saving nearly 25% of the total building energy consumption. This reduces the operating cost $73,551 per year. Considering that the school is located in West Virginia, this outcome is comparable to results found in other case studies for ground source heat pump systems in northern schools. The only area where the ground source heat pump system consumes more energy than the existing system is in pump energy. The pump energy is higher because of the added 25 hp pumps needed to pump water through the geothermal well field. The ground source heat pump's 22.8 EER for cooling and 4.6 COP for heating help account for most of the energy consumption savings. Heating consumption is reduced 51% and cooling consumption is reduced 69%. The cooling reduction can be seen on a monthly basis in Figure 3.

Figure 3 – Monthly Cooling Equipment Energy Consumption



9.7 Emissions:

Both redesign alternatives reduce total building energy consumption over the existing building mechanical system. Therefore, the alternatives also reduce the amount of pollutants emitted into the air. Electricity is used for power at South Jefferson creating no on-site emissions. Still, generating the electricity at a power plant and transferring it to the site is only 33% efficient and the plant produces its own emissions. South Jefferson High School uses a national power plant to generate its electricity; the mix of national power plant according to fuel types is shown in Table 9. Calculated pounds of harmful emissions can also be seen in the table. Assuming the plant that serves South Jefferson is a coal plant, the VAV with CHP reduces emissions be 7% and the ground source heat pump system reduces emissions by 30%.

lbm $Pollutant_j$/ kWh U.S.					
Fuel	% Mix U.S.	Particulates/kWh	SO_2/kWh	NO_x/kWh	CO_2/kWh
Coal	55.7	6.13E-04	7.12E-03	4.13E-03	1.20E+00
Oil	2.8	3.03E-05	4.24E-04	7.78E-05	5.81E-02
Nat. Gas	9.3	0.00E+00	1.26E-06	2.36E-04	1.25E-01
Nuclear	22.8	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro/Wind	9.4	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Totals	100.0	6.43E-04	7.54E-03	4.44E-03	1.38E+00

Variable Air Volume with Direct Expansion Roof Top Units					
Fuel	kWh	Particulates	SO_2	Nox	CO_2
Coal	3,448,083	2.11E+03	2.45E+04	1.42E+04	4.13E+06
Oil	3,448,084	1.04E+02	1.46E+03	2.68E+02	2.00E+05
Nat. Gas	3,448,083	0.00E+00	4.33E+00	8.14E+02	4.30E+05
Nuclear	3,448,083	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro/Wind	3,448,083	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Variable Air Volume with Chiller Water Plant					
Fuel	kWh	Particulates	SO_2	Nox	CO_2
Coal	3,219,302	1.97E+03	2.29E+04	1.33E+04	3.86E+06
Oil	3,219,302	9.74E+01	1.36E+03	2.51E+02	1.87E+05
Nat. Gas	3,219,302	0.00E+00	4.04E+00	7.60E+02	4.01E+05
Nuclear	3,219,302	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro/Wind	3,219,302	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Ground Source Heat Pump					
Fuel	kWh	Particulates	SO_2	Nox	CO_2
Coal	2,409,015	1.48E+03	1.71E+04	9.94E+03	2.88E+06
Oil	2,409,015	7.29E+01	1.02E+03	1.87E+02	1.40E+05
Nat. Gas	2,409,015	0.00E+00	3.02E+00	5.68E+02	3.00E+05
Nuclear	2,409,015	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro/Wind	2,409,015	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 9 – Emissions Comparison

9.8 Conclusions and Recommendations:

The main goal in the redesign of South Jefferson High School's mechanical systems is green design. The focus in green design is lowering the total cost of ownership through resource management and energy efficiency and secondly increasing healthful benefits.

The first alternative (VAV with chilled water plant) does not meet these demands and is not a recommended design for South Jefferson. The system does not pay back in a 20 year life cycle and only has a marginal improvement in energy efficiency and indoor air quality.

The second alternative redesign (ground source heat pump system) is a recommended system redesign. The alternative yields returns in 18.7 years, while significantly reducing energy consumption and costs, cutting back on source emissions, and improving indoor air quality by alleviating humidity concerns.