Ground Source Geothermal District Heating and Cooling System

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Abstract

Ball State University converted its campus from a coal-fired steam boiler district heating system to a ground source heat pump geothermal district system that produces simultaneously hot water for heating and chilled water for cooling. This system will include the installation of 3,600 four hundred feet deep vertical closed loop boreholes making it the largest ground source geothermal district system in the country. The boreholes will act as heat exchangers and transfer heat by virtue of the earth's ability to maintain an average temperature of 55 degree Fahrenheit. With growing international concern for global warming and the need to reduce worldwide carbon dioxide loading of the atmosphere geothermal is poised to provide the means to help reduce carbon dioxide emissions. The shift from burning coal to utilizing ground source geothermal will increase electrical consumption but an overall decrease in energy use and reduction in carbon dioxide output will be achieved. This achievement is a result of coupling the ground source geothermal boreholes with large heat pump chiller technology. The system provides the thermodynamic means to move large amounts of energy with limited energy input.

Ball State University: http://cms.bsu.edu/About/Geothermal.aspx

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Executive Summary

BSU's ultimate objective was the creation of the nation largest Geothermal Heat Pump district energy system - the first ever 10,000 ton heat pump chiller system associated with closed loop borehole fields using geothermal-based heat pump chillers to heat and cool 47 major campus buildings. The research and subsequent implementation of the ground source heat pump geothermal district system demonstrated that a large-scale deployment of geothermal heat pump technology is feasible and provided greater understanding (and proof of concept) for the implementation of more large scale ground source heat pump geothermal installations across the U.S.

Dramatic energy efficiency improvement is another major benefit of the project. This project will eliminate the following emissions annually: 85,000 tons of carbon dioxide, 240 tons of nitrogen oxide, 200 tons of particulate matter, 80 tons of carbon monoxide, and 1,400 tons of sulfur dioxide. The net change will cut the university's overall carbon footprint nearly in half. With the geothermal installation, the combined COP will be 7.77 - a seven-fold increase in efficiency. In monetary terms, the university has begun to save $2 million annually in energy costs. The project has and will continue to provide several hundred contractors and suppliers' employment and an opportunity for an estimated 2,300 direct and indirect jobs. Nearly all components of the project are American made.

The Project had multiple funding sources, include State Bonds. Total project cost was $82.9M, and the DOE subset of the project was used to purchase the four needed 2,500 ton heat pumps and provide for installation costs.

The three tasks in the USDOE SOPO were completed as various stages of the project using $5M in USDOE funds and $5.7M in cost share provided by the university. The specific tasks are describe in more detail under appendix 17.

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Background

Founded in 1918, Ball State University is a state-assisted institution of higher education located in Muncie, Indiana, approximately 55 miles northeast of Indianapolis. The University is home to seven academic colleges offering almost 300 degrees at the baccalaureate, masters and doctoral level to approximately 20,000 students. Ball State's main campus occupies 731 acres of land and includes more than 47 major buildings enclosing approximately 6.5 million square feet of space for academic classrooms, administrative offices, sports facilities, and residence halls.

Campus structures are heated and cooled by a so-called district energy system. Such a system provides steam and chilled water to numerous buildings from central energy plants. Ball State's steam plant was powered by four coal-fired boilers and three natural gas fired boilers. The four coal-fired boilers were originally placed into service in the 1940s and 1950s. These four coal boilers due to condition, capacity limitations and EPA emission requirements were shut down as of March, 2014.

Project Description

Ball State University's geothermal conversion project replaces the university's existing coal-fired boilers and chilled water equipment with the nation's largest ground-source geothermal district energy system. This system simultaneously produces hot water and chilled water.

In 2005, the Indiana General Assembly authorized Ball State University to replace or upgrade its aging coal-fired boilers and provided the university with the initial $44.8 million to begin the project. After exploring a number of alternatives, the university decided to replace its existing heating and cooling system with a geothermal ground source heat pump system. The earth's ability to maintain a constant temperature makes it a renewable energy source.

The University's board of trustees approved the plan on February 6, 2009. On May 9, 2009, Senator Richard Lugar joined university officials in Muncie to break ground on the project.

Major Features

The geothermal energy system is composed of the following major elements:

- District Energy Stations:

Two "district energy stations" have been built at opposite ends of the campus. The stations include large capacity heat pump chillers (4 x 2500 ton capacity), which can produce 150 degree Fahrenheit water for heating purposes and 42 degree Fahrenheit water for cooling purposes. The heat pump chillers in these two buildings feed hot and cold water into the same distribution system that provided heating and cooling for all major buildings on campus.

- Boreholes:

Located in two separate fields totaling 25 acres, three thousand six hundred boreholes have been drilled to depths of 400 to 500 feet each. Inserted in each hole is a U-shaped piping that circulates water down to and up from the bottom of each borehole. After construction, borehole fields were restored to their previous use as parking lots and sports fields. A total of 1,800 boreholes have been completed on the north side of campus and serve the north district energy station. A total of 1,800 boreholes have been installed on the south side of campus and serve the south district energy station. The 3,600 borehole provide a heat transfer system that is composed of 1,100 miles of piping in contact with the ground.

It is important to note that the boreholes are not wells. No groundwater is used in any part of this "closed loop" geothermal system. Rather, water is introduced one time and re-circulates throughout the system on a continuous basis. This continuous flow of water supports a thermodynamic process whereby thermal energy is transferred into or out of the ground. Accordingly, the system does not draw from or pose an environmental threat to the underlying aquifer.

- Hot & Cold Water Distribution Network:

An extensive hot and cold water distribution loop has been constructed on campus to transport more than 20,000 gallons of water per minute between the geothermal fields, the district energy stations / heat pump chillers, and campus buildings. Nearly ten miles of new distribution loop has been installed.

- Building Interfaces:

Each building will require an interface connecting the building heating and cooling system with the distribution network. Those buildings that are currently heated with steam will be converted to hot water.

Benefits

The project is nearly completed, with final completion anticipated by mid-2017. The university has already retired its use of coal as a fuel source, eliminating the following emissions annually: 85,000 tons of carbon dioxide, 240 tons of nitrogen oxide, 200 tons of particulate matter, 80 tons of carbon monoxide, and 1,400 tons of sulfur dioxide. The net change will cut the university's overall carbon footprint nearly in half.

The project has and will continue to provide several hundred contractors and suppliers' employment and an opportunity for an estimated 2,300 direct and indirect jobs. Nearly all components of the project are American made.

Dramatic energy efficiency improvement is another major benefit of the project. The current stoker boiler system has a co-efficient of performance (COP) of .62. "COP" is the standard measure of heating/cooling efficiency - the higher the COP, the better. The current electric chiller system has a COP of 5.02. The weighted average of current systems is a 1.04 COP. With the geothermal installation, the combined COP will be 7.77 - a seven-fold increase in efficiency. In monetary terms, the university has begun to save $2 million annually in energy costs.

Additionally, the project has demonstrated that a large-scale deployment of geothermal heat pump technology is feasible. Through this demonstration, Ball State will stimulate broader application of this technology throughout the United States.

Ball State has already begun technology transfer activities that includes, among others, the Oak Ridge National Laboratory and the United States Department of Energy. Many of these entities have and are evaluating the technology for their own use. We have also been visited or contacted by many universities inquiring about the geothermal system. The list is extensive and includes over 40 universities to date, including for a few universities collaboration between their local municipalities.

Funding

Funding was authorized by the 2005 Indiana General Assembly in the amount of $44.8 million, and in 2013 the Indiana General Assembly provide authorization in the amount of $33.1 million, and in 2009 a $5 million grant from the U.S. Department of Energy from the American Recovery and Reinvestment Act (ARRA) provided additional funding thereby totaling $82.9 million for the project. Because of the efficiency of the system, the university has been able to reduce our annual utilities bills by more than $2 million.

Milestones

The project began with the north borehole field construction in May, 2009.
The north campus geothermal building was placed into service in January, 2012.
Ball State shut down its coal fired boilers in March, 2014.
The final quantities of boreholes were complete on October 17, 2014.
The south campus geothermal building was placed into service in January, 2015.

The University is currently in the process of designing and bidding the final portions of the work which includes the last phase of the installation of hot water distribution pipe in the south campus area and connecting several buildings along this distribution system. The project is expected to be completed by mid-summer 2017.

Overview Project Economics

In 2001, Ball State University ("the University") retained an independent consultant to conduct a condition analysis of its existing heat plant and district system. The heat plant produces steam that is used to heat buildings and to heat water for domestic use for the entire campus. The study concluded that the four coal-burning stoker boilers (ranging in age from 51 to 68 years), although well maintained, had outlived their rated lives by many years and warranted replacement within the next ten years (i.e. by 2011). The condition of the coal boilers, along with the increased environmental regulations regarding emissions, led to the University's decision to replace all four boilers.

In 2005, the Indiana General Assembly granted bonding authority to the University for the purpose of replacing the existing boilers. In January 2007, the University sold bonds in the amount of $44,900,000, with debt service to be provided by the State of Indiana on a fee replacement basis.

The University had planned to replace the existing boilers with the industry standard at that time, a coal-fired circulating fluidized bed (CFB) boiler. This option was chosen based in part on cost estimates provided by boiler manufacturers. This type of boiler, when compared to the stoker boilers, would provide modest improvements in efficiency and reductions in certain emissions such as nitrous oxide, sulfur oxide, and particulate matter. However, a CFB boiler would not reduce the emission of carbon dioxide.

During the early stages of procurement, it became apparent that the purchase of a CFB boiler was cost prohibitive. Due to the cost of raw materials, availability of suppliers, and market demand, the estimated cost of a CFB boiler and related improvements had increased to the point that the expenditure was not justified.

As a result of the increased cost of a CFB boiler, the University explored other options, analyzing up-front capital costs, future operating costs, environmental impact, and other criteria. Through discussions with the National Renewable Energy Laboratory (NREL), the Oak Ridge National Laboratory, and some of the top geothermal experts in the country, it was determined that a geothermal-based district energy system, despite high initial costs, would yield dramatic energy efficiency improvements, leading to future operational savings and an enormous reduction in carbon dioxide and other pollutants.

The following economic analysis is based on the conclusion that the existing system must be replaced. Therefore, the analysis compares the financial projections of installing a CFB boiler to the existing district system combined with the current electric centrifugal chiller operation versus converting the existing system to a geothermal-based district system.

Capital Costs

Initial cost estimates for a CFB boiler were provided in 2006 by one of the largest vendors in the United States. This estimate was the basis, in part, for the University's decision to pursue a CFB purchase. In late 2007, the University invited the known vendors to submit bids to provide the University with a CFB boiler. Each vendor declined to submit a bid. However, the University was contacted by one of the vendors regarding a proposal for a sole-source agreement. This was the same vendor that had prepared the earlier estimate. The resulting proposal was for a boiler package that represented a 60% increase over the earlier estimate. This increase was primarily due to increases in the price of steel and high demand for boilers in emerging economies (e.g. China and India).

Cost estimates for the geothermal-based system have been prepared by consultants retained by the University. These consultants specialize in the development of geothermal-based systems.

Regardless of the direction taken, the University would have also had to invest in other improvements to its district system. These improvements include, among other items, upgrades to the campus electrical distribution system that will ensure reliability throughout campus. Also, the existing stoker boilers would be decommissioned regardless of the option pursued.

The costs for each system, on a comparative basis, are shown below:

	CFB Boiler	**Geothermal System**	**Difference**
Base cost	$63,000,000	$83,400,000	$20,400,000
High voltage distribution improvements	3,900,000	3,900,000	-
Emergency generator	4,000,000	4,000,000	-
Decommissioning of existing boilers	2,000,000	2,000,000	-
Total Capital Investment	**$72,900,000**	**$93,300,000**	**$20,400,000**

The base cost of the geothermal system is comprised of the following:

Component	**Cost Estimate**
Borehole fields	$28,600,000
Energy centers	16,200,000
Building conversions	14,700,000
Hot water loop	12,600,000
Chilled water loop	4,400,000
Engineering & design fees	4,900,000
Site work	2,000,000
Total base cost	**$83,400,000**

Operating Costs

The primary costs to the University of operating a district heating and cooling system are Labor & Benefits, Utilities, and Maintenance. The labor costs to operate a CFB combined with an electric centrifugal chiller operation versus the proposed geothermal system that produces both hot water and chilled water are estimated to be essentially the same. The same number of workers would be required regardless of the system employed.

Utility costs vary greatly depending on the type of system installed. A CFB boiler, while 16% more efficient than the stoker boilers, still consumes a large amount of coal. A geothermal-based system, on the other hand, would not be dependent on the University purchasing coal, thereby resulting in approximately $3.0 million in annual savings. However, the electrical requirements of operating the geothermal system, due primarily to the pumping requirements, would increase electrical costs by approximately $1.0 million. The net savings in utility costs would be $2.0 million annually.

Coal boilers, whether they be stoker or CFB, are expensive to maintain due to wear and tear on feeder chains, sprockets, tubes, etc. It is estimate that conversion to a geothermal system which uses heat pump chiller technology would have annual operating costs similar to the existing electric centrifugal chillers. Therefore, the University would save the annual maintenance cost attributable to the CFB operation, estimated to be an additional $0.3 million per year.

The comparison of operating costs and the related savings between a CFB boiler and geothermal-based system are shown in the table below:

<u>Operating Costs</u>	CFB Boiler	Geothermal System	Savings
Labor & Benefits	$840,000	$840,000	$ -
Utilities, net	4,465,000	2,465,000	2,000,000
Maintenance	653,000	333,000	320,000
Total Capital Investment	**$5,958,000**	**$3,638,000**	**$2,320,000**

**Represents full year costs and savings upon completion of the entire system.*

Financial Analysis

Based on the independent study showing that replacement of the existing system must occur, any analysis of payback and other financial measures for the geothermal-based system should be based on not the stand-alone costs, but on the incremental cost compared to the alternative CFB boiler. In essence, these projects are mutually exclusive – only one need be done. This is a common problem in capital budgeting when managers must choose between two or more mutually exclusive projects. Looking at each individual project's payback period or internal rate of return does not provide definitive guidance as to which project offers the best return to the company or its investors. Fortunately, there is a simple and widely accepted approach that consistently shows the value of one project over another. This solution involves looking at various return metrics for an incremental project – where the cash flows of the incremental project are found by subtracting the year-to-year cash flows of the less expensive project from the more expensive project. Therefore, the measures below are calculated for the incremental cash flows associated between the CFB boiler and geothermal-based project.

Data
Initial Cash Flow = C_o = -$20,400,000
Annual Cash Flow = C_i = $2,320,000 for year 1 and inflated at 3% each year thereafter.

Payback Period
The simple payback for the University's geothermal-based system (versus a CFB boiler) would be 7.9 years.[1]

Internal Rate of Return (IRR)
The Internal Rate of Return, assuming a 50-year project, for the University's geothermal-based system (versus a CFB boiler) would be 14.3%.[2]

Return on Investment (ROI)
The expected Return on Investment, based on the incremental capital costs and savings, would be 11.4%.[3]

Recipient Cost Share – Source of Funding
As mentioned in the Overview of this appendix, the University sold bonds in 2007 for the replacement of the boiler plant. Of the initial $44,900,000 in bond proceeds, approximately $41,000,000 is available to commit to the conversion to a geothermal-based district system. These proceeds are invested in liquid securities. An additional $6,000,000 has been appropriated by the Indiana General Assembly from a future bond issuance. Debt service on both of these amounts is being provided entirely by the State of Indiana. None of these funds are provided by federal sources

[1] The number of years it would take to recapture the incremental capital costs of $20,400,000 using annual operating savings of $2,320,000 in year one and increasing at 3% annually.
[2] 14.3% is the interest rate that causes the Net Present Value of an initial cash outflow of $20,400,000 and then 50 annual cash inflows starting at $2,320,000 (and increasing at 3% annually) to equal zero.
[3] Annual savings of $2,320,000 from an investment of $20,400,000.

Cash Flow

Based on the information presented above, the projected cash flows for the first five years, including the construction period, are as follows:

Sources and Uses of Cash:	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Reduction in Operating Costs*	$ -	$ -	$ 1,160,000	$ 1,160,000	$ 2,320,000
Investment in PPE	(28,150,000)	(29,600,000)	(31,380,000)	(4,170,000)	-
Proceeds from DOE Cost Share	14,075,000	14,800,000	15,690,000	2,085,000	-
Proceeds from issuance of debt	-	6,000,000	-	-	-
Change in Cash	(14,075,000)	(8,800,000)	(14,530,000)	(925,000)	2,320,000
Cash at Beginning of Year	41,000,000	26,925,000	18,125,000	3,595,000	2,670,000
Cash at End of Year	$ 26,925,000	$ 18,125,000	$ 3,595,000	$ 2,670,000	$ 4,990,000

Appendix 1: Proof of Concept Heat Pump Chillers with Geothermal Storage

In 2008, our facilities management team began looking at replacing our existing coal-fired boilers with a more efficient conversion technology using Circulating Fluidized Bed Steam Boiler (CFB) and filtration devices to delimit production of the CO_2e gases and to increase the efficiency of the energy extraction from the source coal. Because of a coincidence of factors including a limited current construction market for installing this technology, and the commitment of the institution to the employment of best practices, the university turned to the National Renewable Energy Lab and Oak Ridge National Laboratories for consultation on whether in fact ground source geothermal could begin to meet the needs of a district-scale heating and cooling system; servicing some 47 buildings.

We identified consultants and designers; with their assistance we developed a series of design scenarios for scaling-up the geothermal technology to support a district heating and cooling system. To be sure of the capabilities of the design schemes, the university then undertook a proof-of-concept evaluation and a field test of technical application to determine the feasibility and cost effectiveness of the idea. With the success of the proof-of-concept and field testing, the confidence level took hold for moving forward with what we have discovered is the largest district-scale heating and cooling groundwater geothermal heat pump technology installation in the United States.

Appendix 2: Heating and Cooling Flow Diagram

The diagrams are provided to communicate the piping configuration which allows simultaneously the production and distribution of hot water and chilled water. At the center of the systems are heat pump chillers that use R-134A refrigerant. The condenser side of the system produces hot water for heating and the evaporator side of the system produces chilled water for cooling. The thermal energy removed on the evaporator side of the systems is moved via the refrigerant system to the condenser side. The ground or borehole field is connected in a manner to allow thermal energy to be deposited into the ground or removed from the ground.

Appendix 3: Heat Pump Chiller Control Diagram

YORK CYK Compound Centrifugal Liquid Units are factory-packaged including the evaporator, condenser, compressor, motor, lubrication system, control center, and interconnecting unit piping and wiring. Each compressor is a single-stage centrifugal type powered by an air-cooled electric motor. The flash economizer (intercooler) is a single-stage design. It consists of a vertical pressure vessel with internally mounted mesh eliminators and a liquid spray pipe, an externally mounted (field installed) level transmitter located with a liquid level pipe assembly, and an external control valve mounted in the liquid outlet to the evaporator. Refrigerant from the condenser, after expanding through the condenser sub cooler level control valve, enters through the internal spray pipe, where flash gas is removed and channeled through the mesh eliminator, out the top and into the high stage compressor section. The remaining liquid feeds out of the economizer through a liquid level control valve into the evaporator. Eight sight glasses are provided: two above and two below the mesh eliminators; two at the liquid spray pipe; and two in the liquid line leaving the economizer. Pre-rotation vanes (PRV) in each compressor modulate unit capacity from 100% to 15% of design for normal air conditioning applications. Operation is by an external, electric PRV actuator which automatically controls the vane position to maintain a constant leaving chilled liquid temperature (or leaving condenser temperature for a heat pump application). Rugged airfoil shaped cast manganese bronze vanes are precisely positioned by solid vane linkages connected to the electric actuator. Both compressors are normally operated to satisfy the evaporator load (or the condenser load in the case of a heat pump). Should the entering condensing water temperature drop below a preset temperature, a compressor will be taken off line. This allows the remaining compressor to continue operating more efficiently at low entering condensing water temperatures. Mesh eliminators or baffles are located above the tube bundle to prevent liquid refrigerant carryover into the compressor. The condenser is a shell and tube type, with discharge gas baffles to prevent direct high velocity impingement on the tubes. The baffles are also used to distribute the refrigerant gas flow properly for most efficient heat transfer. An integral sub-cooler is located at the bottom of the condenser shell providing highly effective liquid refrigerant sub-cooling to provide the highest cycle efficiency. Thermal type water flow switches are factory mounted in the chilled and condenser water nozzles, and are factory wired to the control panel. These solid state flow sensors have a small internal heating element. They use the cooling effect of the flowing fluid to sense when an adequate flow rate has been established. The CYK Compound unit incorporates a control strategy that allows a compressor to shut down automatically when two-compressor operation is no longer required. This allows the unit to take advantage of low-inlet condenser water temperatures to reduce energy consumption.

http://www.johnsoncontrols.com/~/media/jci/be/united-states/hvac-equipment/chillers/be_engguide_cyk_compound-centrifugal-liquid-units-style-g.pdf

Appendix 4: Heat Pump Chiller Sequence

The control and monitoring system in both the north and south district energy plants have been programmed to operate together through sensors and monitors as described in this specification section. The system also provides operating data that is produced daily in report format and sent the USDOE. This information is available for viewing and use by anyone.
http://energy.gov/eere/geothermal/articles/ball-state-completes-largest-us-ground-source-geothermal-system

Appendix 5: Typical DESS Loop Field Data Report

This is atypical excel format data collected from the lop field circuit.

Appendix 6: Typical DESS Heating Loop Data Report

This is typical excel format data collected from the heating loop circuit.

Appendix 7: Typical DESS Cooling Loop Data Report

This is typical excel format data collected from the cooling loop circuit.

Appendix 8: Formation Thermal Conductivity Test and Data Analysis

The first step in calculating the design of a borehole field is to conduct a "Formation Thermal Conductivity Analysis". An actual borehole is constructed and a controlled test results in determining the formation thermal conductivity of the geological formation. This information is used in the Thermal Dynamics GLD software that sues to determine ultimately the parameters of the designed borehole field to meet the thermal needs of the system.

http://www.groundloopdesign.com/

Appendix 9: Test Borehole Drill Log

The results of the drill log collected during the "Formation Thermal Conductivity Test", aids the drilling by providing geological formations down to the desired depth of the borehole. The driller can determine the type of drill bit to be used, and the depth to which overburden will be encountered. Overburden can be risking to stability of the borehole which may result in the use of a casing.

Appendix 10: Borehole Field Layouts

The boreholes are arranged in a 15 foot spacing resulting in a 225 square feet grid. We purposefully arranged the valve configuration to include thirty (30) boreholes per pod. The arrangement reduces the isolation of boreholes if and when a leak occurs in the future.

Appendix 11: Photos of Borehole and Drilling Process

These photos are presented to help communicate the drilling process:
Photo 1: this photo shows multiple drilling rigs lined in an organized manner, grout product nearby by along with the pvc tubing in reels ready to be installed.
Photo 2: this photo shows the operators and drilling rig arrangement and drilling in action.
Photo 3: this photo shows the multiple headers that enter the district energy station south that ultimately combined into a 30 inch diameter loop field supply line.
Photo 4: this photo shows a grout mixing rig with the tremie pipe that pumps the product to the bottom of the borehole up to the top of the borehole.
Photo 5: this photo shows the massive space require to maintain an organized site, store the HPDE pipe that will become the headers and the grout mixture or bentonite and sand products
Photo 6: this photo shows the connection of a double loop borehole to the header pipe. All piping is essentially HDPE fusion welded together, pressure tested before it leaves the factory, when it arrives on site, after it's installed in the borehole and after the header pipe is connected.
Photo 7: this phot shows a pvc valve that were installed on the supply and return sides of the headers which can isolate 30 boreholes or pods at a time. This configuration allows for isolating minimal amounts of boreholes should a leak occur.

Appendix 12: Report of Geophysical Survey (2D Resistivity Testing)

Ball State engaged Mundell and Associates to conduct a Two-Dimensional Electrical Resistivity Imaging (2-D ERI) of the north and south borehole fields. This information was provided within the construction documents used to seek bids for the drilling of the boreholes. The desired outcome was to assist drillers with subsurface geologically information that would aid in estimating the drilling process.
2-D ERI is used to provide highly detailed, cross-sectional views of the subsurface by Identifying the distribution of electrical resistivity variations in subsurface materials with depth. 2-D ERI is a *direct-contact* means of measuring vertical resistivity variations along a single line of data collection known as an apparent resistivity pseudo-section.
Electrical resistivity is one of the most widely varying of the physical properties of natural materials. Certain minerals, such as native metals and graphite, conduct electricity via the passage of electrons; however, electronic conduction is generally very rare in the subsurface. Most minerals and rocks are insulators, and electrical current preferentially travels through the water-filled pores in soils and rocks by the passage of the free ions in pore waters *(i.e.*, ionic conduction). It thus follows that the degree of saturation, interconnected porosity, and water chemistry (*i.e.*, total dissolved solids) are the major controlling variables of the resistivity of soils and rocks. In general, electrical resistivity directly varies with changes in these parameters. Fine-grained sediments, particularly clay-rich sediments such as glacial

till, are excellent conductors of electricity, often much better than fresh water found in the pores of sand and gravel.
Carbonate rocks (i.e., limestone and dolomite) are very electrically resistive when they are unfractured, but can have significantly lower resistivity values when fractured and/or weathered and solutioned.
The resistivity cross sections presented in this report are 2-dimensional representations of the general distribution of electrical resistivity in the 3-dimensional subsurface. There is no unique direct conversion from resistivity values to actual subsurface lithology. However, based on site knowledge, geometric shapes and relationships of various resistivity anomalies, and the observed ranges of resistivity values, reasonable geologic interpretations can often be made.

Appendix 13: Petrographic and hydrogeological Investigation

The collaboration on the Ball State University campus has been embraced by our geology faculty. The geothermal system has become a research opportunity for the faculty and at the same time the information that produce is valuable to us. Their information can tell us if the borehole fields are heating up or cooling down by data collected from monitoring wells. The monitoring wells are in fact wells drilled along the perimeter of the borehole field to the depth of the boreholes. Open piezometers of pvc conduits installed at various depths allows faculty, students and master students to measure water temperatures and elevations of the water table. This information can tell us what direction the underground aquafer is flowing, if the water is dispersing the thermal energy and if we need to modify the thermal flow to maintain balance. This paper was presented at conference in 2016 by several geology faculty members thereby sharing to the attendees information we have gathered.

Appendix 14: Embracing the Future: The Ball State University Geothermal Project

Early in the installation process a Ball State faculty member and several administrators collaborated on a paper that was ultimately included in a book titled “Climate Change Management” Universities and Climate Change, editor Walter Leal Filho, ISBN 1610-2002

Appendix 15: Typical Sustainable and Geothermal Presentation for advancing Student Knowledge

In addition to providing daily data output to the USDOE that can be shared with anyone, we at BSU continue to share the knowledge we have gained through presentations. This presentation is used to speak to university students, faculty, and staff and used when presenting at seminars. The presentation contains information related to other sustainable efforts undertaken at Ball State, the journey to Ground Source Geothermal, the benefits gained, and entities that have toured the campus top learn about the system. The university makes every attempt to share lessons learned and knowledge to any and all entities.

Appendix 16: Geothermal Campus Map

The map attempts to at a 30,000 foot view describe graphically the configuration of the district ground source geothermal system that we have installed. Two district energy stations were installed, one on the south and one on the north. These station were located next to university owned high voltage sub-stations were they receive 4,160 volt power. These locations also are nicely located next to open green spaces and parking lots where the boreholes were installed. These green spaces and parking lots will remain green spaces and parking lots as building cannot be built upon the boreholes given the depth of the header piping or 60 inches below the surface. Distribution piping, both hot and chilled water that is produced is then extended from these building throughout campus. The distribution piping is looped together to create a hydraulic loop the supports even pressure throughout campus.

Appendix 17: DOE "Statement of Project Objectives (SOPO)"

BSU's ultimate objective was to **create a District Energy System using geothermal-based heat pump chillers** to heat and cool 47 major campus buildings. This project involved the purchase and installation of four heat pump chillers connected to geothermal boreholes that sink heat during the summer or retrieves heat during the winter. The simultaneous production of chilled water and hot water is pumped throughout campus, connected to major buildings and provides cooling and heating water used in major air handling units.

The specific tasks to be performed from the SOPO included:
Task 1: Purchase Equipment for North and South District Energy Stations:
BSU purchased four, 2500 ton heat pump chillers for installation in the North and South District Energy Stations. Each unit also provides 38,000,000 BTUH of hot water capacity. The first two chillers were placed into service in the spring, 2012 in the North plant. The additional two chillers for a total of four were placed into service during the winter of 2014/15 in the South plant.

Task 2: Building Conversions:

The original SOPO task included the connections within 16 to 20 major buildings on the North side of campus but ultimately the project goal was to connect to all major buildings on campus. The SOPO task has been completed. This included the conversion of the mechanical systems in those buildings to utilize the hot and chilled water produced by the ground source heat pump chillers. This task included the interior retrofit of building systems, but not exterior installation of piping between buildings, or the district energy station.

Task 3: Data Collection:

Meters, instruments, and software associated with the collection of data to be submitted to the National Geothermal Data System was purchased and installed in both the north and south operating plants.

The Operational Data that is collected and is currently being supplied to the USDOE includes the following:

(1) Temperature of all fluids at each building interface.

(2) Volume of hot and chilled water required by each building on a 24/7 basis.

(3) HVAC electrical use at the energy station and each building.

(4) Volume of hot and chilled water produced at the energy station.

(5) Volume of water circulated through the borehole field.

(6) Entry and exit temperature of water circulated through borehole field.

(7) BTU energy information.

(8) Ground temperatures at several locations to a depth of 400 feet in and around borehole field.

Appendix 1: Proof of Concept Heat Pump Chillers with Geothermal Storage

Proof of Concept:

Heat Pump Chillers with Geothermal Storage

produced for

Ball State University

prepared by

MEP ASSOCIATES, LLC

and

Kirk T. Mescher, PE
of

CM ENGINEERING
Bright Solutions in Engineering

MEP Project No. B20.08.01

January 28, 2009

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INTRODUCTION

In today's economic climate of high and rising fuel costs, many managers of large 24-hour facilities do well to examine new and creative ways to trim energy bills. One smart option is to examine the potential of a source that is already available, repurposing heat that is ordinarily discarded by the HVAC system's condenser. By utilizing heat pump chillers with geothermal storage instead of ordinary chillers, the temperature of this formerly waste heat can be increased until it is suitable for a wide variety of heating applications, and utilized when it is needed.

This report provides a proof of concept for heat pump chillers with geothermal storage. It will allow Ball State University to have an introductory understanding of this type of system, as well as some preliminary operational costs developed by Kirk Mescher of CM Engineering, in order for University personnel to evaluate the compatibility of this technology with their campus.

THE CONCEPT

Heat Pump Chillers

A compound centrifugal chiller is a special kind of centrifugal chiller that utilizes a combination of two (i.e. compound) compressors, instead of just one, and a component called an intercooler. The additional compressor and the intercooler allow the compound centrifugal chiller to produce condenser water at a much higher temperature than was previously possible with a standard centrifugal chiller. No longer fit only for rejection out of the cooling tower, this hot water, which can reach up to 170˚F, is useful and can be utilized in a variety of heating applications that, until a few years ago, were the domain of boilers and heat pumps. Hence, this chiller is commonly called a heat pump chiller.

Although the advantages of this type of chiller are enormous, not every facility is a good fit, since not all facilities require simultaneous heating and cooling. Large facilities with 24-hour operation, such as hospitals, hotels, and universities, which have year-round demand for both heating and cooling, have tremendous potential to save energy. However, a careful examination of the loads throughout the year is prudent, in order to ensure that the heating and cooling produced by these chillers will be sufficiently utilized.

In addition, the second compressor can be turned off when the heating load is low. Although this will reduce the temperature of the condenser water leaving the chiller, it can be hot enough to meet the requirements of summer heating applications, such as reheat and domestic water, which typically do not require the high temperatures associated with winter heating. This will also allow the chillers to operate more efficiently, in the same way as a standard single compressor centrifugal chiller.

Geothermal Storage

Many facilities require simultaneous heating and cooling, but only utilize only a fraction of its peak heating during the summer. In this case, a heat pump chiller can still offer tremendous benefits with the addition of a renewable technology called geothermal storage. This allows a facility to store the heat it produces in the summer and use it in the winter. This is achieved by heating the earth several hundred feet below the ground what is called a loop field. This loop field is an area of land with several bores that are several hundred feet deep. Each bore houses u-shaped pipe that routes hot water and cold water down deep into the rock in the earth where it rejects or obtains load. This bedrock is an excellent thermal storage device. It can be charged with heating energy during the summer, hold this heat with minimal losses, and discharge it for utilization in the winter.

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THE APPLICATION

System Sizing

By examining the heating and cooling loads provided by university personnel (see Appendix A), a heat pump chiller plant with geothermal storage, including all distribution piping, was sized to meet the needs of the university's campus. Calculated by CM Engineering, the estimated annual electrical consumption for this system will be 50 million kWh and the annual operating cost will be $2.1 million.

System Layout

Three locations are proposed for the new heat pump chillers: a new energy center on the east side of the campus, and a new second energy center on the north side of the campus, and the third existing energy center on the south side of the campus. The new heat pump chillers can be connected directly to the existing chilled water piping system. A new hot water piping loop will need to be added to carry the hot water to the buildings. The source of the hot water, the three heat pump chiller plants, will be connected to this new hot water piping loop with branch pipes. Additional branch pipes will connect this loop to the destination of the hot water, the hot water side of the heat exchangers that currently use steam to provide hot water inside the buildings. For the buildings that do not have these heat exchangers, new air handling unit coils and terminal equipment will need to be installed, in order to accommodate the hot water. The current district heating and cooling system will remain in place and operational during the conversion.

A flow diagram of this system is shown in Appendix B. The system will provide 44˚F chilled water throughout the year, and 170˚F hot water in winter design conditions (with both compressors running). The hot water temperature will decrease proportionately with the outside air temperature, to a minimum of 110˚F in summer design conditions (with one compressor running). This hot water will be used for domestic hot water and summer heating applications, which do not require the hotter 170˚F water.

The hot water is circulated using variable frequency drive (VFD) pumps to the existing buildings until their immediate needs are met. If any heat is remaining, it is routed to a heat exchanger that deposits heat into the geothermal storage. This typically occurs during the summer. Conversely, during the winter, when an additional heat source is needed, heat is removed from the geothermal storage.

The specifics on the loop field are contained in Borehole Design Report in Appendix C. It is estimated that 3,750 bores will be needed. They will be 400 feet deep and 15 feet apart from each other. They will house two 1-inch u-bend pipes per bore. The grout thermal conductivity, which is a measure of how effectively the bedrock can hold heat, is estimated to be 0.84 Btu/hr·ft·˚F.

CONCLUSION

It is clear that heat pump chillers with geothermal storage offer tremendous potential for energy savings for Ball State University. It is our hope that this report will offer some helpful information, as we continue to perform further analysis on this type of system to meet the heating and cooling needs of the campus.

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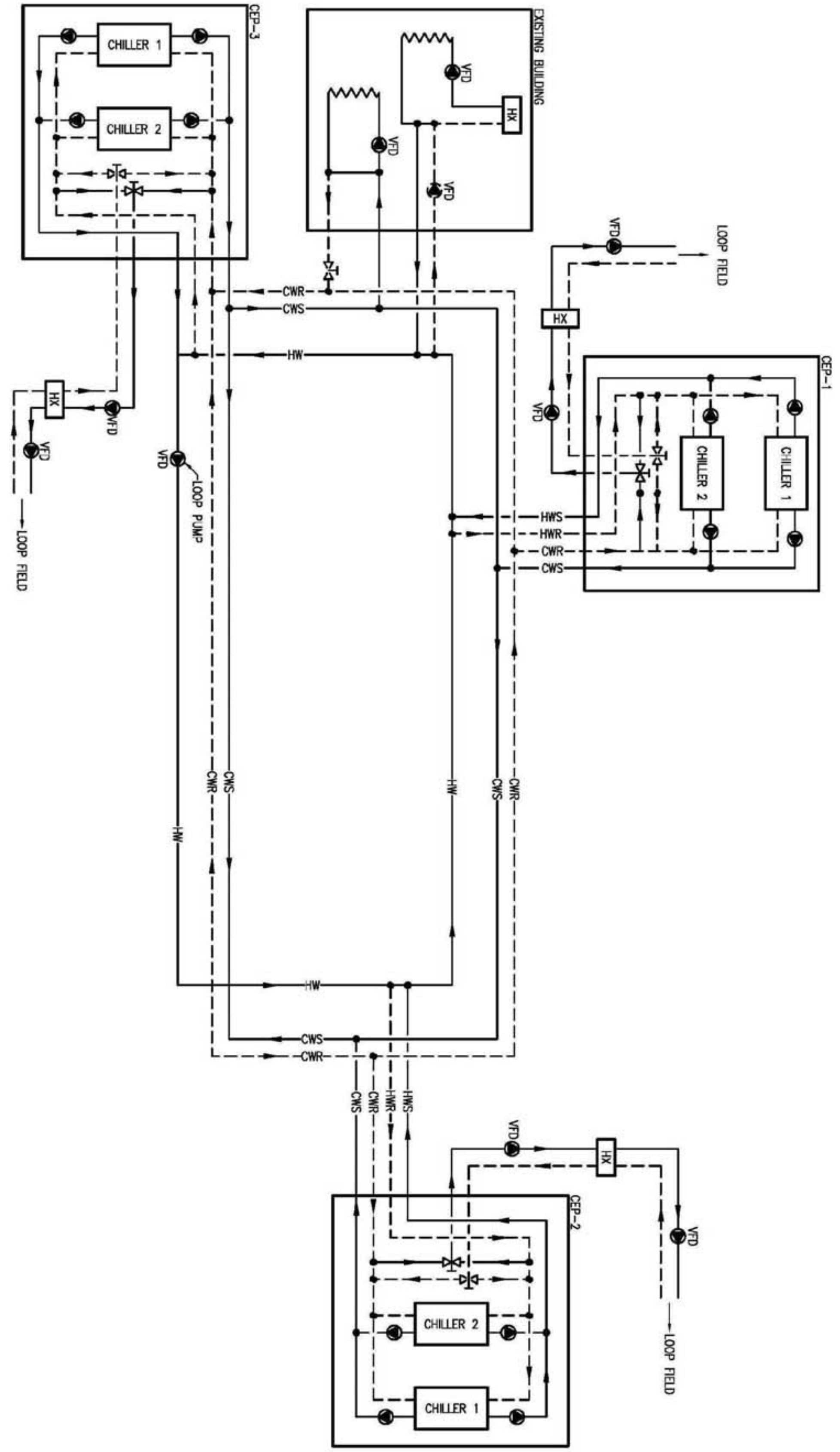
APPENDIX A: HEATING AND COOLING LOADS

Building Name	Address	Year Built	Area (ft^2)	Heating Load (MBtuh)	Hot Water (gpm)	Cooling Load (tons)	Chilled Water (gpm)
Carmichael Hall	1701 W. McKinley	1967	22,963	574	38	58	138
Johnson Hall (JA Botsford-Swinford; JB Schmidt-Wilson)	1601 N. McKinley	1967	262,432	6,561	437	141	338
LaFollette Halls (Village Expansion)	1515 N. McKinley	1964	531,792	13,295	886	211	507
Lewellen Pool	1400 N. McKinley	1967	56,415	1,410	94		0
Health/Phys Activities Building	1740 W. Neely	1989	110,710	2,768	185	186	445
Irving Gymnasium	1700 W. Neely	1962	135,039	3,376	225	186	445
Worthen Arena		1990	193,267	4,832	322	448	1,075
Architecture	1212 N. McKinley	1970	146,750	3,669	245	333	799
Subtotals				**36,484**	**2,432**	**1,562**	**3,748**
Robert P. Bell Building	1211 N. McKinley	1982	106,500	2,663	178	141	338
David Letterman Building	1201 N. McKinley Ave	2005	86,351	2,159	144	128	307
Edmund F. Ball Building	1109 N. McKinley	1986	84,594	2,115	141	256	614
Arts and Journalism Building	1101 McKinley	2000	207,141	5,179	345	218	522
Bracken Library	1100 N. McKinley	1972	321,800	8,045	536	640	1,536
University Theatre	920 N. McKinley	1960	83,667	2,092	139	179	430
Teachers College Building	901 N. McKinley	1966	125,650	3,141	209	288	691
Noyer Hall	1601 W. Neely	1962	238,320	5,958	397	448	1,075
Woodworth Halls	1600 W. Riverside	1956	164,626	4,116	274	202	484
Pruis Hall	1000 N. McKinley	1971	18,170	454	30	128	307
Bracken House	2200 W. Berwyn Rd.	1937	13,227	331	22	19	46
Whitinger Business Building	1200 N. McKinley	1978	93,763	2,344	156	160	384
Studebaker Halls East	1301 W. Neely	1965	97,406	2,435	162	51	123
Studebaker Halls West	1401 W. Neely	1964	242,080	6,052	403	294	707
Park Hall	1550 Riverside	2006	194,600	4,865	324	282	676
Music Building	1810 W. Riverside	1956	45,036	1,126	75	83	200
Music Instruction Building	1809 W. Riverside	2003	86,179	2,154	144	179	430
Emens Auditorium	1800 W. Riverside	1963	82,101	2,053	137	243	584
Arts and Communication Bldg.	1701 W. Riverside	1957	47,010	1,175	78	83	200
Health Center	1500 W. Neely	1962	19,527	488	33	32	77
DeHority Halls	1500 W. Riverside	1960	138,140	3,454	230	205	492
North Residence Hall	1400 W. Neely	2008	190,480	4,762	317	230	553
Subtotals				**67,159**	**4,477**	**4,490**	**10,775**
North Quad	1901 W. Riverside	1926	126,543	3,164	211	294	707
Applied Technology	2000 W. Riverside	1948	93,274	2,332	155	205	492
Fine Arts Building	2021 W. Riverside	1935	74,085	1,852	123	198	476
Cooper Physical Sciences	2111 W. Riverside	1965	130,090	3,252	217	461	1,106
Cooper Nursing	2111 W. Riverside	1965	47,580	1,190	79	122	292
Cooper Life Sciences	2111 W. Riverside	1968	113,843	2,846	190	442	1,060
Ball Gymnasium	Campus Drive	1939	83,197	2,080	139	115	276
West Quad	2301 W. Riverside	1936	57,593	1,440	96	109	261
Lucina Hall	2120 W. University	1927	60,014	1,500	100	128	307
Burris School	2201 W. University	1928	130,745	3,269	218	250	599
Elliott Dining	2100 W. Gilbert	1990	13,228	331	22	45	108
Wagoner Halls	301 N. Talley	1957	75,680	1,892	126	13	31
Elliott Hall	401 N. Talley	1937	51,627	1,291	86	32	77
Administration Building	2000 W. University	1912	54,136	1,353	90	96	230
Student Center	2001 W. University	1951	171,165	4,279	285	410	983
Burkhardt Building	601 N. McKinley	1924	61,439	1,536	102	70	169
Subtotals				**33,606**	**2,240**	**2,989**	**7,173**
Central Chiller	West Campus Drive	1965	7,909	198	13		
Field Sports Building	1720 W. Neely	1983	47,736	1,193	80		240
Greenhouses	Christy Woods	1965	4,381	110	7		
Heating Plant	2331 W. Riverside	1924	18,685	467	31		
South Service Bldg.	Campus Drive	1967	4,800	120	8		30
Expansion			300,000	7,500	500	640	1,500
Totals			**5,873,486**	**144,749**	**9,650**	**9,680**	**23,196**

APPENDIX B: FLOW DIAGRAM



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APPENDIX C: BOREHOLE DESIGN REPORT

Ground Loop Design

Borehole Design Project Report - 1/14/2009

Thermal Dynamics

Project Name:	**Ball State**		
Designer Name:	Jeff Urlaub		
Date:	12/9/2008	**Project Start Date:**	12/9/2008
Client Name:	**Ball State**		
Address Line 1:			
Address Line 2:			
City:		**Phone:**	
State:		**Fax:**	
Zip:		**Email:**	

Calculation Results

	COOLING	HEATING
Total Length (ft):	**132224.6**	**145224.0**
Borehole Number:	**375**	**375**
Borehole Length (ft):	**352.6**	**387.3**
Ground Temperature Change (°F):	**+1.2**	**+1.1**
Unit Inlet (°F):	**85.0**	**45.0**
Unit Outlet (°F):	**95.2**	**38.3**
Total Unit Capacity (kBtu/Hr):	**11119.7**	**12692.9**
Peak Load (kBtu/Hr):	**8418.7**	**12692.9**
Peak Demand (kW):	**674.3**	**617.7**
Heat Pump EER/COP:	**12.5**	**3.6**
System EER/COP:	**12.5**	**6.0**
System Flow Rate (gpm):	**2104.7**	**3173.2**

Input Parameters

Fluid		Soil	
Flow Rate:	3.0 gpm/ton	Ground Temperature:	56.0 °F
Fluid:	100% Water	Thermal Conductivity:	1.68 Btu/(h*ft*°F)
Specific Heat (Cp):	1.00 Btu/(°F*lbm)	Thermal Diffusivity:	1.12 ft^2/day
Density (rho):	62.4 lb/ft^3		

Piping

Pipe Type:	1 in. (25 mm)
Flow Type:	Turbulent - SDR11
Pipe Resistance:	0.071 h*ft*°F/Btu
U-Tube Configuration:	Double
Radial Pipe Placement:	Along Outer Wall
Borehole Diameter:	6.00 in
Grout Thermal Conductivity:	0.84 Btu/(h*ft*°F)
Borehole Thermal Resistance:	0.156 h*ft*°F/Btu

APPENDIX C: BOREHOLE DESIGN REPORT (cont.)

Input Parameters (Cont.)

Pattern		Modeling Time Period	
Vertical Grid Arrangement:	25 x 15		
Borehole Number:	375	Prediction Time:	10.0 years
Borehole Separation:	15.0 ft	Long Term Soil Temperatures:	
Boreholes per Parallel Circuit:	1	*Cooling:*	57.2 °F
Fixed Length Mode	Off	*Heating:*	57.1 °F
Grid File	None		
File:			

Heat Pumps			Optional Boiler/Cooling Tower		
Manufacturer:	Florida Heat Pump			Tower	Boiler
Series:	WP Series (Water to Water)		Load Balance	0 %	41 %
Design Heat Pump Inlet Load Temperatures:			Capacity (kBtu/Hr)	0.0	5204.1
	Cooling (WB)	*Heating (DB)*	Cooling Tower Flow Rate (gpm):	0.0	
Water to Air:	67 °F	70 °F	Cooling Range (°F):	10.6	
Water to Water:	55 °F	100 °F	Annual Operating Hours (hr/yr):	0	

Extra kW		Loads File
Pump Power:	0.0 kW	*09-01-09 Rev Ball State.zon*
Cooling Tower Pump:	0.0 kW	
Cooling Tower Fan:	0.0 kW	
Additional Power:	0.0 kW	

Loads

Design Day Loads

Time of Day	*Heat Gains (kBtu/Hr)*	*Heat Losses (kBtu/Hr)*
8 a.m. - Noon	5120.3	12692.9
Noon - 4 p.m.	6689.2	11806.2
4 p.m. - 8 p.m.	8418.7	10541.6
8 p.m. - 8 a.m.	6689.2	11806.2

Annual Eqivalent Full-Load Hours

COOLING 1500 *HEATING* 2762

Days Occupied per Week: 5.0

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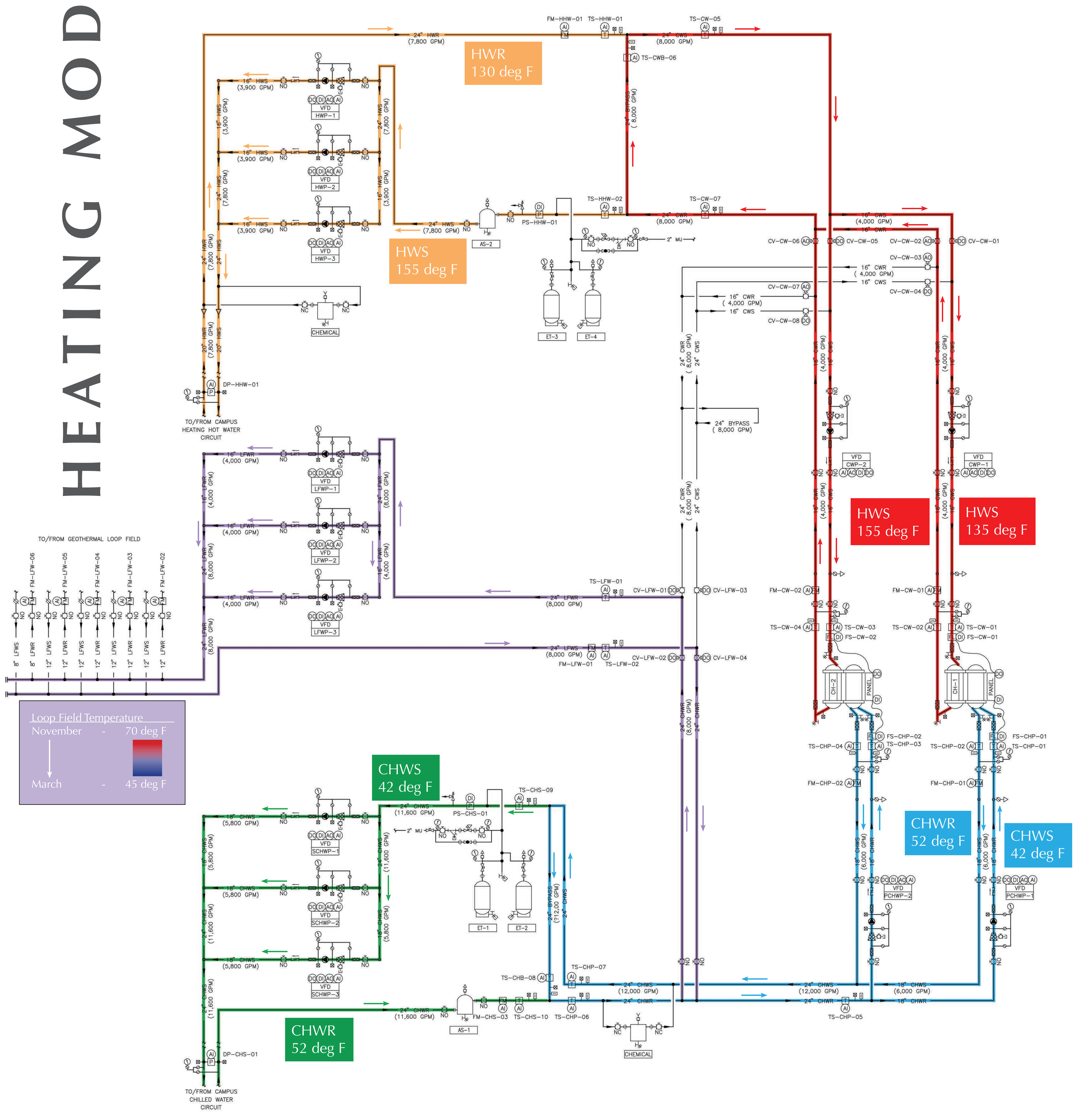
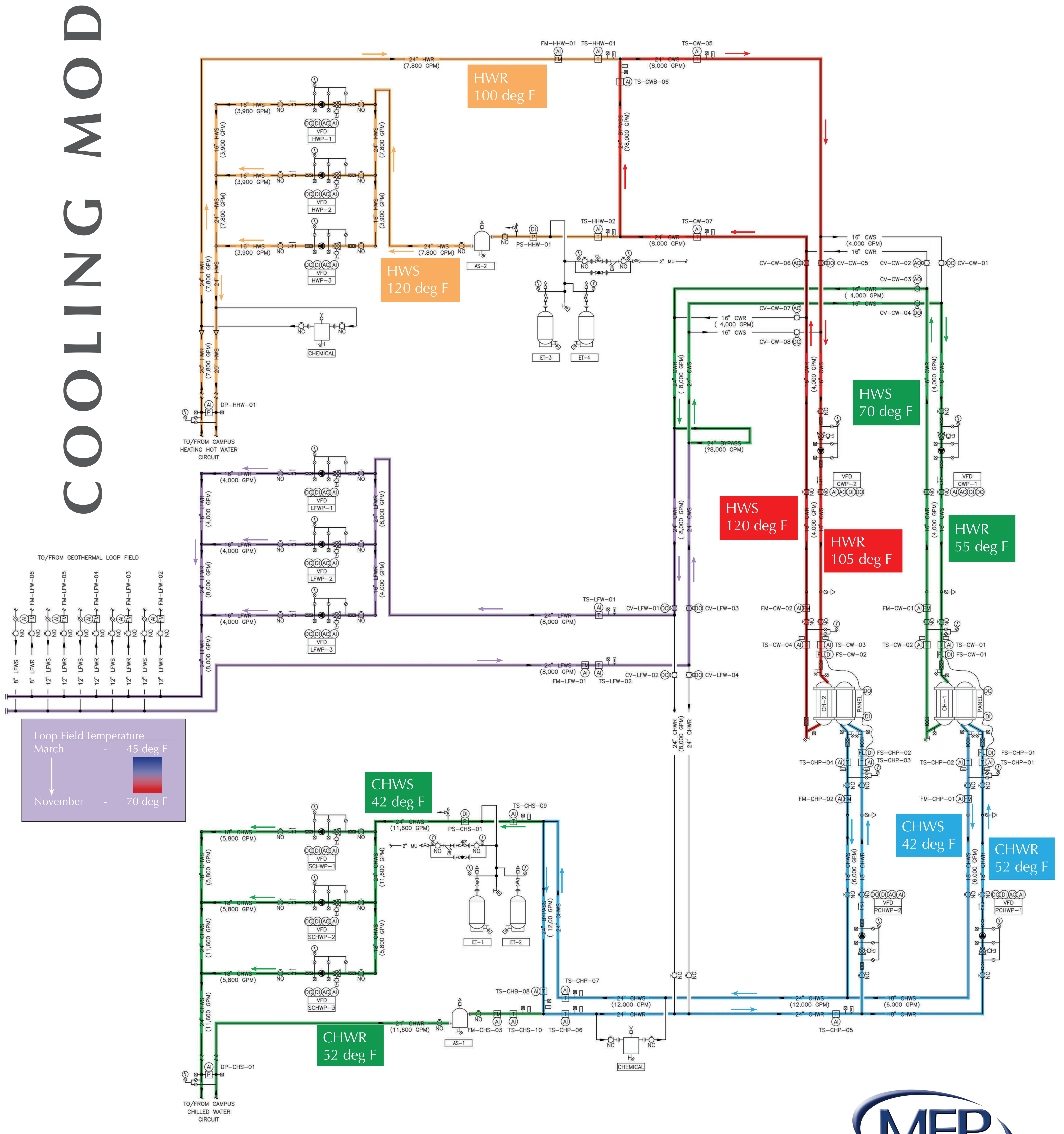
Appendix 2: Heating and Cooling Flow Diagram

HEATING MODE



COOLING MODE



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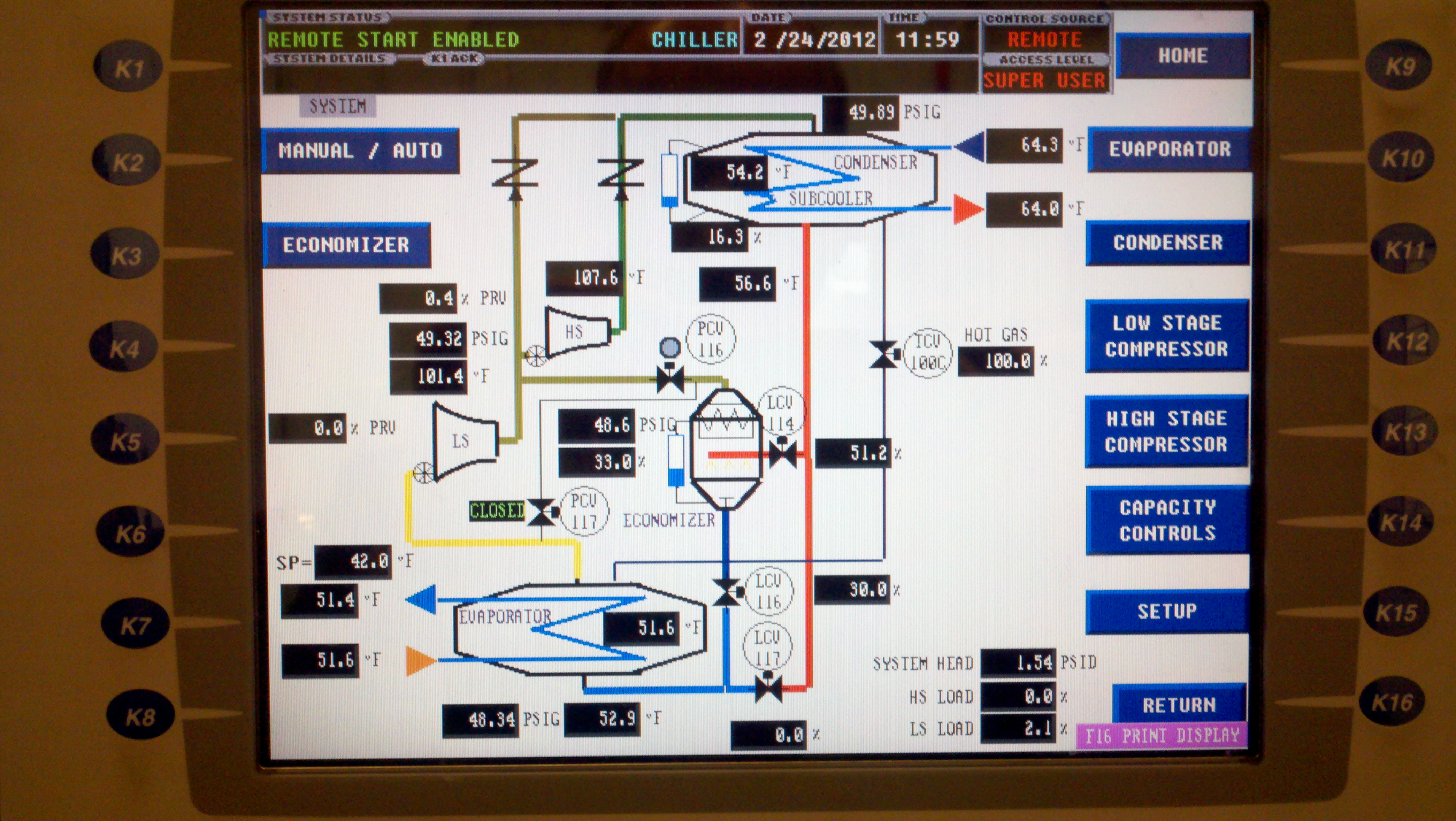
507.281.1632

Appendix 3: Heat Pump Chiller Control Diagram


SYSTEM STATUS
REMOTE START ENABLED
CHILLER
DATE
2 /24/2012
TIME
11:59
CONTROL SOURCE
REMOTE
ACCESS LEVEL
SUPER USER
SYSTEM DETAILS
K1 ACK
HOME
SYSTEM
MANUAL / AUTO
ECONOMIZER
EVAPORATOR
CONDENSER
LOW STAGE COMPRESSOR
HIGH STAGE COMPRESSOR
CAPACITY CONTROLS
SETUP
RETURN
F16 PRINT DISPLAY
K1
K2
K3
K4
K5
K6
K7
K8
K9
K10
K11
K12
K13
K14
K15
K16
49.89 PSIG
64.3 °F
64.0 °F
54.2 °F
CONDENSER
SUBCOOLER
16.3 %
107.6 °F
56.6 °F
0.4 % PRV
49.32 PSIG
101.4 °F
HS
PCV 116
TCV 100C
HOT GAS
100.0 %
0.0 % PRV
LS
48.6 PSIG
33.0 %
LCV 114
51.2 %
CLOSED
PCV 117
ECONOMIZER
SP= 42.0 °F
51.4 °F
51.6 °F
EVAPORATOR
51.6 °F
LCV 116
30.0 %
LCV 117
48.34 PSIG
52.9 °F
0.0 %
SYSTEM HEAD 1.54 PSID
HS LOAD 0.0 %
LS LOAD 2.1 %

Appendix 4: Heat Pump Chiller Sequence

SECTION 23 09 94

HEAT PUMP CHILLER SYSTEM CONTROL SEQUENCES

PART 1 - GENERAL

1.01 RELATED WORK

A. Section 23 09 13 - Instrumentation and Control Devices for HVAC.

B. Section 23 09 23 - Direct Digital Control System for HVAC.

C. Section 23 09 93 - Sequence of Operations for HVAC Controls.

1.02 SYSTEMS IN THIS SCOPE OF WORK INCLUDE, BUT ARE LIMITED TO:

A. System heating hot water loop circuit.

B. System chilled water loop circuit.

C. Geothermal loop field circuit.

D. Heat pump chiller circuit, first dedicated heating.

E. Heat pump chiller circuit, second dedicated cooling.

1.03 SPECIFICATION SECTION ORGANIZATION

A. Introduction.

B. Abbreviations.

C. Definitions.

D. Control system architecture.

E. System acceptance phase performance demonstration.

F. Operation modes.

G. Control algorithms.

1.04 ABBREVIATIONS

A. ºF - Degrees Fahrenheit.

B. %Open - Percent a control device is open.

C. BAS - Building Control Automation is the logic infrastructure that starts, enables, stops, disables, and controls equipment.

D. CS - Constant speed.

E. DDC - Direct Digital Control which is a control strategy consisting primary of electrical signals to monitor system status and issue status change.

F. ES - End suction pump which is a configuration that allows access to impeller by removing the front of impeller casing requiring pipe disruption.

G. H-O-A Switch - Hand-Off-Auto switch which is a device that allows an equipment piece to be manually turned on, turned off, or to be controlled remotely.

H. HP - Horsepower.

I. HSC - Horizontal split case pump which is a configuration that allows access to impeller by removing the top portion of the impeller casing without disrupting pipe.

J. LCP - Local control panel that features limited control capabilities normally capable of controlling a small number of equipment pieces.

K. MCP - Manufacturer's control panel typically provided as part of associated equipment from the manufacturer's factory.

L. Operator Work Station - Human interface device (computer terminal) where associated systems are monitored and controlled.

M. System - Connected load utilizing heating and/or cooling medium.

N. T&B - Test and Balance.

O. VFD - Variable frequency drive.

P. VS - Variable speed.

1.05 DEFINITIONS

A. Control algorithm shall be considered to mean equipment/system logic describing specific responses to monitored control points.

B. Geothermal loop field circuit shall be considered to mean equipment controlled to maintain either heat pump chiller (HPC) supply water temperature or HPC evaporator return water temperature depending on HPC(s) operating conditions. The system's circuit shall be considered to include piping between HPC(s) condenser water return connection / HPC(s) chilled water return connection and geothermal loop field pump inlets, piping between geothermal loop field pump outlets and HPC(s) condenser water supply connection / HPC(s) chilled water return connection, geothermal loop field pumps, isolation valves, and all associated piping specialties.

C. Heat pump chiller (CH-1) circuit, first dedicated heating shall be considered to mean equipment controlled to maintain its condenser water return setpoint temperature. Its primary function is to produce heating hot water utilized by campus terminal heating equipment or rejected to the geothermal loop field when necessary. Its secondary function is to produce evaporator chilled water utilized by campus terminal cooling equipment. The system's condenser water circuit shall be considered to include piping between the HPC condenser water return connection and the condenser water decoupler (bypass) inlet connection, piping between the condenser water decoupler (bypass) outlet connection and the HPC condenser water supply connection, condenser water pump, and all associated piping specialties. The system's chilled water side circuit shall be considered to include piping between the HPC evaporator water supply connection and the chilled water bypass inlet connection, piping between the chilled water decoupler (bypass) outlet connection and the HPC evaporator water return connection, chilled water pump, and all associated piping specialties.

D. Heat pump chiller (CH-2) circuit, second heating and cooling shall be considered to mean equipment controlled to maintain either its evaporator water supply setpoint temperature or condenser water return setpoint temperature depending on system load conditions. The system's chilled water circuit shall be considered to include piping between the HPC evaporator water supply connection and the chilled water decoupler (bypass) inlet connection, piping between chilled water decoupler (bypass) outlet connection and the HPC evaporator water return connection, chilled water pump, and all associated piping specialties. The system's condenser water circuit shall be considered to include piping between the HPC condenser water return connection and the condenser water decoupler (bypass) inlet connection, piping between the condenser water decoupler (bypass) outlet connection and the HPC condenser water supply connection, condenser water pump, and all associated piping specialties.

E. Heat pump chiller condenser loop circuit shall be considered to include HPC condenser, piping between the HPC condenser water supply connection and the condenser water decoupler (bypass) inlet connection, condenser water decoupler (bypass) piping, piping between the condenser water decoupler (bypass) outlet connection and the HPC condenser water return connection, condenser water pump, and all associated piping specialties.

F. Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) shall be considered to include HPC evaporator, piping between the HPC evaporator water supply connection and the chilled water decoupler (bypass) inlet connection, chilled water decoupler (bypass) piping, piping between the chilled water decoupler (bypass) outlet connection and the HPC evaporator water return connection, chilled water pump, and all associated piping specialties.

G. Lag equipment shall be considered to mean the equipment that has been active for the shortest cumulative time period of all inactive equipment.

H. Lead equipment shall be considered to mean the equipment that has been active for the longest cumulative time period of all active equipment.

I. Occupied operation mode shall be considered to mean either normally scheduled or unscheduled time periods when systems are activated.

J. Operation mode shall be considered to mean an event resulting in sequential activation/deactivation of control algorithms.

K. System chilled water loop circuit (chilled water secondary loop circuit) shall be considered to mean equipment controlled to distribute chilled water to campus terminal cooling equipment. The system's circuit shall be considered to include piping between the chilled water decoupler (bypass) inlet connection and campus terminal cooling equipment inlet connections, piping between campus terminal cooling equipment outlet connections and the chilled water decoupler (bypass) outlet connection, chilled water pumps, and all associated piping specialties.

L. System heating hot water loop circuit shall be considered to mean equipment controlled to distribute heating hot water to campus terminal heating equipment. The system's circuit shall be considered to include piping between the condenser water decoupler (bypass) inlet connection and campus terminal heating equipment inlet connections, piping between campus terminal heating equipment outlet connections and condenser water decoupler (bypass) outlet connection, heating hot water pumps, and all associated piping specialties.

M. Unoccupied operation mode shall be considered to mean either normally scheduled or unscheduled time periods when systems are deactivated.

N. Except as otherwise defined in greater detail, the terms “provide”, “furnish” and “install” as used in this specification section shall have the following meanings:
   1. “Provide” or “provided” shall mean “furnish and install”.
   2. “Furnish” or “furnished” does not include installation.
   3. “Install” or “installed” does not include furnishing.

1.06 SUBMITTALS

A. Submittals shall confirm control sequences specified herein.

B. Submittals shall include an electronic copy of actual control algorithm used to accomplish the design intent presented herein.

C. Submittals shall clearly identify enhancements to and deviations from the design intent presented herein.

1.07 WARRANTY

A. See Section 01 70 00 - Execution and Closeout Requirements, for additional warranty requirements.

B. Provide extended two year parts and labor warranty.

1.08 CONTROL SYSTEM ARCHITECTURE

A. The control system shall be automatic and function as specified herein.

B. The CONTRACTOR shall be responsible for providing all necessary control devices required for system operation to meet the design intent.

C. The CONTRACTOR shall be responsible for providing all necessary control components when the installed equipments control features are incapable of meeting the design intent.

D. This work shall exclude factory-installed manufacturer's control packages, but shall include all manufacturers' control panel interfaces, interlocks, equipment enabling/disabling components, and programming.

E. The CONTRACTOR shall be responsible for providing all Operator Work Station graphics for accurate system representation.

F. The Operator Work Station shall provide system wide control. It shall be capable of communicating with both hard wired components and equipment with open protocols. The system shall be capable of receiving static pressure, differential pressure, and temperature inputs and forwarding associated outputs to open protocol variable frequency drives.

G. Variable frequency drives (VFD's) shall feature an open protocol capable of communicating features included in the points list. Each VFD shall be capable of controlling associated equipment in response to external inputs.

H. At a minimum, the Operator Work Station shall display:
   1. Heat pump chiller (HPC) circuit:
      a. HPC's commanded and actual status.
      b. HPC's actual current draw and setpoint current draw limit.
      c. HPC evaporator loop circuit (chilled water primary loop circuit) evaporator return temperature, supply temperature, fluid flow status, and fluid flow rate in units of gallons per minute (gpm).
      d. HPC evaporator loop circuit (chilled water primary loop circuit) pump commanded and actual status, as well as, pump commanded and actual speed as applicable.
      e. HPC evaporator loop circuit (chilled water primary loop circuit) decoupler (bypass) temperature.
      f. HPC condenser loop circuit condenser return temperature, supply temperature, fluid flow status, and fluid flow rate in units of gallons per minute (gpm).
      g. HPC condenser loop circuit pump commanded and actual status, as well as, pump commanded and pump actual speed.
      h. HPC condenser loop circuit decoupler (bypass) temperature.
   2. System chilled water loop circuit (chilled water secondary loop circuit):
      a. System chilled water circuit (chilled water secondary loop circuit) supply temperature, return temperature, and fluid flow rate in units of gallons per minute (gpm).
      b. System chilled water loop circuit (chilled water secondary loop circuit) calculated actual instantaneous heat transfer in units of 12,000 BTUh (Tons) and totalized heat transfer in units of 12,000 BTUh-hours (Ton-hours).
      c. System chilled water loop circuit (chilled water secondary loop circuit) pump commanded and actual status, as well as, pump commanded and actual speed as applicable.

   d. System chilled water loop circuit (chilled water secondary loop circuit) differential pressure sensor setpoint differential pressure and actual differential pressure.
3. System heating hot water loop circuit:
   a. System heating hot water loop circuit return temperature, supply temperature, and fluid flow rate in units of gallons per minute (gpm).
   b. System heating hot water loop circuit calculated actual instantaneous heat transfer in units of 1,000 BTUh (MBh) and totalized heat transfer in units of 1,000 BTUh-hours (MBh-hours).
   c. System heating hot water loop circuit pump commanded and actual status, as well as, pump commanded and pump actual speed.
4. Geothermal loop field circuit:
   a. Geothermal loop field circuit main piping return temperature, supply temperature, and fluid flow rate in units of gallons per minute (gpm).
   b. Geothermal loop field circuit calculated actual instantaneous heat transfer in units of 1,000 BTUh (MBh) and totalized heat transfer in units of 1,000 BTUh-hours (MBh-hours) during both heat rejection and heat absorption from/to the heat pump chiller condenser loop circuit.
   c. Geothermal loop field circuit calculated actual instantaneous heat transfer in units of tons and totalized heat transfer in units of ton-hours during both heat rejection and heat absorption from/to the heat pump chiller evaporator loop circuit.
   d. Geothermal loop field circuit pump commanded and actual status, as well as, pump commanded and pump actual speed.
   e. Geothermal loop field circuit branch piping fluid flow rate in units of gallons per minute (gpm).
   f. Geothermal loop field circuit static pressure (fill pressure) status.

I. All alarm limits, dead-bands, offsets, sensor deviation alarm conditions, setpoints, time delays, and time periods shall be readily adjustable by facility operations personnel.

J. Heat pump chiller condenser loop circuit water temperature change design value for heat pump chiller condenser loop circuit artificial loading shall be readily adjustable by facility operations personnel.

K. Heat pump chiller evaporator loop circuit water temperature change design value for heat pump chiller evaporator loop circuit artificial loading shall be readily adjustable by facility operations personnel.

L. Setpoints shall be modified when approved by the Engineer of Record during system start-up and/or commissioning to accomplish the design intent and as directed by the Engineer of Record and / or Commissioning Authority.

1.09 SYSTEM ACCEPTANCE PHASE PERFORMANCE DEMONSTRATION

A. Each equipment and system operation mode specified herein shall be demonstrated to the Engineer of Record.

B. Demonstration shall occur:
1. Prior to substantial completion being granted.
2. After the Test and Balance Report has been completed by the Test and Balance Contractor, provided to the Engineer of Record, discrepancies have been corrected, and the Test and Balance Report has been approved by the Engineer of Record and / or Commissioning Authority.

C. Demonstration shall include:
   1. Participation by the Controls Contractor and Test and Balance Contractor to manipulate setpoints, over-ride actual measured values, etc. as directed by the Engineer of Record and / or Commissioning Authority to simulate each equipment and system operation mode specified herein.

D. Estimated time required for demonstration:
   1. Estimated time required to demonstrate all equipment and system operation modes specified herein for each system shall be:
      a. System heating hot water loop circuit: 4 hours.
      b. System chilled water loop circuit: 4 hours.
      c. Geothermal loop field circuit: 8 hours.
      d. Heat pump chiller circuits: 16 hours.
   2. Estimated time period is based on all participants being on-site, ready for testing, and in possession of all required instruments, tools, etc. required for testing.
   3. Additional time beyond this estimated time required to demonstrate compliance of each equipment and system operation mode specified herein shall not be considered a change to the contract.

E. Demonstration re-testing:
   1. System shall be re-tested as required to demonstrate satisfactory performance in accordance with the intent of the each equipment and system operation mode specified herein.
   2. The intent of each equipment and system operation mode shall be determined by the Engineer of Record.

1.10 OPERATION MODES AND CONTROL ALGORITHMS

A. Operation modes:
   1. Systems shall feature each of the following operation modes:
      a. Unoccupied.
      b. Manual start-up.
      c. Normal operation.
      d. Manual shut-down.

B. Control algorithms:
   1. System Heating hot water loop circuit shall feature each of the following control algorithms:
      a. Start-up.
      b. Normal operation.
      c. Alarm condition - equipment.
      d. Alarm condition - temperature.
      e. Energy usage monitoring.
      f. Automatic shut-down.
      g. Manual shut-down.
   2. System chilled water loop circuit (chilled water secondary loop circuit) shall feature each of the following control algorithms:
      a. Start-up.
      b. Normal operation.
      c. Alarm condition - equipment.
      d. Alarm condition - temperature.
      e. Energy usage monitoring.
      f. Automatic shut-down.
      g. Manual shut-down.
   3. Geothermal loop circuit shall feature each of the following control algorithms:
      a. Start-up.

b. Normal operation.
c. Alarm condition - equipment.
d. Alarm condition - temperature.
e. Energy usage monitoring.
f. Automatic shut-down.
g. Manual shut-down.

4. Heat pump chiller (CH-1) circuit, first dedicated heating shall feature each of the following control algorithms:
   a. Start-up.
   b. Normal operation.
   c. Condenser water temperature.
   d. Condenser artificial loading.
   e. Evaporator artificial loading.
   f. Condenser loop circuit pump.
   g. Evaporator loop circuit pump.
   h. Alarm condition - equipment.
   i. Alarm condition - temperature/flow.
   j. Automatic shut-down.
   k. Manual shut-down.
5. Heat pump chiller (CH-2) circuit, second heating and cooling shall feature each of the following control algorithms:
   a. Start-up.
   b. Normal operation.
   c. Condenser water temperature.
   d. Evaporator water temperature.
   e. Condenser artificial loading.
   f. Evaporator artificial loading.
   g. Condenser loop circuit pump.
   h. Evaporator loop circuit pump.
   i. Alarm condition - equipment.
   j. Alarm condition - temperature/flow.
   k. Automatic shut-down.
   l. Manual shut-down.

PART 2 - PRODUCTS

2.01 MATERIALS

A. Refer to sections stated under related work.

PART 3 - EXECUTION

3.01 CONTROL SEQUENCE - OPERATION MODES

A. Submittals shall confirm control sequences specified herein.

B. This section presents systems operation modes describing conditions resulting in the activation/deactivation of control algorithms and order of calling upon control algorithms.

C. Primary utility systems-wide operation modes:
   1. Unoccupied operation mode:
      a. General:
         1) BAS shall activate operation mode upon detection of all of the following conditions:
            (a) Manual unoccupied operation mode activation command having been issued from the Operator Work Station.

2) BAS shall deactivate operation mode upon detection of any of the following conditions:
   (a) Any other operation mode having been activated.

b. Setpoints points shall include:
   1) Inactive time period shall be 30 minutes.
c. Control points shall include:
   1) None.
d. Activation of operation mode:
   1) BAS shall disable system described under section “Manual shut-down operation mode“ with the exception of Operator interface.
   2) BAS shall allow change of equipment status and change of setpoint commands from Operator Work Station.
   3) BAS shall maintain unoccupied operation mode for inactive time period prior to allowing activation of any other operation mode.
e. Deactivation of operation mode:
   1) BAS shall pass control to superseding operation mode.

2. Manual start-up operation mode:
   a. General:
      1) BAS shall activate system operation mode(s) upon detection of manual activation command having been issued from the Operator Work Station.
   b. Activation of operation mode:
      1) BAS shall activate the system heating hot water loop circuit described under section "System heating hot water loop circuit start-up control algorithm".
      2) BAS shall activate the system chilled water loop circuit (chilled water secondary loop circuit) described under section "System chilled water loop circuit start-up control algorithm”.
      3) BAS shall activate heat pump chiller (CH-1) circuit, first dedicated heating described under section “Heat pump chiller (CH-1) circuit start-up control algorithm".
3. Normal operation mode:
   a. General:
      1) BAS shall activate operation mode upon completion of activation of manual start-up operation mode.
      2) BAS shall deactivate operation mode upon detection of any other operation mode being activated.
   b. Setpoints points shall include:
      1) Setpoints shall be identical to those described in "Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm" section.
   c. Control points shall include:
      1) Control points shall be identical to those described in “Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm” section.
      2) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the heating hot water return piping.
      3) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the heating hot water supply piping.
      4) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the heating hot water return piping.
      5) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the chilled water return piping.

6) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the chilled water supply piping.
7) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the chilled water return piping.

d. Activation of normal operation mode:
1) BAS shall continuously calculate system heating hot water loop circuit load via temperature sensors (TS-HHW-01) and (TS-HHW-02) and water flow meter (FM-HHW-01).
2) BAS shall continuously calculate system chilled water loop circuit (chilled water secondary loop circuit) load via temperature sensors (TS-CHS-10) and (TS-CHS-09) and water flow meter (FM-CHS-03).
3) BAS shall maintain active heat pump chiller (CH-1) circuit normal operation control algorithm.
4) BAS shall activate heat pump chiller (CH-2) circuit, second heating and cooling for supplemental cooling upon detection of all of the following conditions:
(a) System heating hot water loop circuit heating load being less than the system chilled water loop circuit (chilled water secondary loop circuit) cooling load for a five minute time period.
(b) System chilled water loop circuit (chilled water secondary loop circuit) cooling load being greater than the heat pump chiller (CH-1) circuit instantaneous cooling output capacity for a five minute time period.
5) Upon activation of the heat pump chiller (CH-2) circuit, second heating and cooling, for supplemental cooling the BAS shall:
(a) Confirm/modulate heat pump chiller (CH-1) condenser loop circuit water return control valve (CV-CW-02) to its 100 percent open position.
(b) Confirm/command the heat pump chiller (CH-1) condenser loop circuit water supply control valve (CV-CW-01) to its full open position.
(c) Confirm/modulate the condenser loop circuit water return control valve (CV-CW-03) to its 0 percent open position.
(d) Confirm/command the condenser loop circuit water supply control valve (CV-CW-04) to its full closed position.
(e) Activate “heat pump chiller (CH-2) circuit start-up control algorithm”.
(f) Control heat pump chiller (CH-2) to provide supplemental cooling in addition to that provided by heat pump chiller (CH-1) in accordance with heat pump chiller (CH-2) evaporator chilled water supply temperature control algorithm.
6) BAS shall deactivate heat pump chiller (CH-2) circuit, second heating and cooling for supplemental cooling and shall activate the geothermal loop field circuit automatic shut-down control algorithm upon detection of any of the following conditions:
(a) System heating hot water loop circuit heating load being equal to or greater than the system chilled water loop circuit (chilled water secondary loop circuit) cooling load for a five minute time period
(b) System chilled water loop circuit (chilled water secondary loop circuit) cooling load being equal to or less than the heat pump chiller (CH-1) circuit instantaneous cooling output capacity for a five minute time period.
7) BAS shall activate heat pump chiller (CH-2) circuit, second heating and cooling for supplemental heating upon detection of all of the following conditions:
(a) System heating hot water loop circuit heating load being greater than the system chilled water loop circuit (chilled water secondary loop circuit) cooling load for a five minute time period.

(b) System heating hot water loop circuit heating load being greater than the heat pump chiller (CH-1) circuit instantaneous heating output capacity for a five minute time period.

8) Upon activation of the heat pump chiller (CH-2) circuit, second heating and cooling, for supplemental heating the BAS shall:
   (a) Maintain heat pump chiller (CH-1) circuit normal operation control algorithm
   (b) Activate “heat pump chiller (CH-2) circuit start-up control algorithm”.
   (c) Control heat pump chiller (CH-2) to provide supplemental heating in addition to that provided by heat pump chiller (CH-1) in accordance with heat pump chiller (CH-2) condenser water return temperature control algorithm.
9) BAS shall deactivate heat pump chiller (CH-2) circuit, second heating and cooling for supplemental heating upon detection of any of the following conditions:
   (a) System heating hot water loop circuit heating load being equal to or less than the system chilled water loop circuit (chilled water secondary loop circuit) cooling load for a five minute time period
   (b) System heating hot water loop circuit heating load being equal to or less than the heat pump chiller (CH-1) circuit instantaneous heating output capacity for a five minute time period.

e. Deactivation of normal operation mode:
   1) BAS shall pass control to superseding operation mode.

4. Manual shut-down operation mode:
   a. General:
      1) BAS shall activate operation mode upon detection of a manual shut-down command issued from the Operator Work Station.
      2) BAS shall deactivate operation mode upon detection of a manual release command issued from the Operator Work Station and upon detection of any other operation mode being activated.
      3) Operation mode shall be considered distinct from unoccupied operation mode.
   b. Activation of manual shut-down operation mode:
      1) BAS shall deactivate Heat pump chiller (HPC) circuit, second dedicated cooling described under respective section “Heat pump manual shut-down control algorithm”.
      2) BAS shall deactivate Heat pump chiller (HPC) circuit, first dedicated heating described under respective section “Heat pump manual shut-down control algorithm”.
      3) BAS shall deactivate the system chilled water loop circuit (chilled water secondary loop circuit) described under section “System chilled water loop circuit manual shut-down control algorithm”.
      4) BAS shall deactivate the system heating hot water loop circuit described under section “System heating hot water loop circuit manual shut-down control algorithm”.
      5) BAS shall deactivate the geothermal loop field circuit described under section “Geothermal loop field circuit manual shut-down control algorithm”.
   c. Deactivation of manual shut-down operation mode:
      1) BAS shall pass control to superseding operation mode.

3.02 CONTROL SEQUENCE - CONTROL ALGORITHMS

A. This section describes general conditions, setpoints, control points, start-up, normal operation, alarm condition responses, and shut-down for each system.

B. System heating hot water loop circuit control algorithms describing general conditions, setpoints, control points, start-up, normal operation, alarm condition - equipment, alarm condition - temperature, energy usage monitoring, automatic shut-down, and manual shut-down are presented below.

1. Equipment associated with this system shall include pumps tagged (HWP-1, HWP-2, and HWP-3).
2. System heating hot water loop circuit start-up control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling operation mode.
        2) Control algorithm shall be deactivated by calling operation mode.
        3) VFD shall modulate pump speeds during pump active status.
    b. Setpoints points shall include:
        1) Pump VFD setpoint differential pressure shall be 15 psid and shall be fine tuned during system start-up.
        2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed.
    c. Control points shall include:
        1) BAS shall continuously monitor system heating hot water loop circuit pump VFD pressure via sensor (DP-HHW-01) located in the system heating hot water loop circuit.
        2) BAS shall continuously monitor pump motor speed via pump VFD interface.
        3) BAS shall continuously monitor pump motor status via pump VFD interface.
    d. Activation of start-up system response:
        1) BAS shall enable lag system heating hot water loop circuit pump VFD.
        2) VFD shall gradually increase pump motor speed to obtain setpoint.
        3) BAS shall immediately activate the following control algorithms up completion system start-up:
            (a) System heating hot water loop circuit normal operation control algorithm.
            (b) System heating hot water loop circuit alarm condition - equipment control algorithm.
            (c) System heating hot water loop circuit alarm condition - temperature control algorithm.
            (d) System heating hot water loop circuit energy usage monitoring.
3. System heating hot water loop circuit normal operation control algorithm:
    a. General:
        1) Control algorithm shall be activated immediately upon completion of "System heating hot water loop circuit system start-up control algorithm" section above.
        2) Control algorithm shall be deactivated by calling operation mode.
    b. Setpoints points shall include:
        1) Pump VFD setpoint differential pressure shall be 15 psid and shall be fine tuned during system start-up.
        2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed.
        3) Next available lag pump VFD activation setpoint shall be the inability to maintain setpoint differential pressure for a two minute time period.
        4) Lead pump VFD deactivation setpoint shall be water flow being equal to or less than 85 percent of the flow of all active pumps less the current flow of a single pump for a five minute time period.
    c. Control points shall include:
        1) BAS shall continuously monitor system heating hot water loop circuit pump VFD pressure via sensor (DP-HHW-01) located in the system heating hot water loop circuit.

2) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the heating hot water return piping.

d. Activation of normal operation system response:

1) VFD shall gradually increase system heating hot water loop circuit pump speed(s) toward maximum allowed motor speed upon detection of actual value being less than setpoint.
2) VFD shall gradually decrease system heating hot water loop circuit pump speed(s) toward minimum safe motor speed upon detection of actual value being less than setpoint.
3) BCS shall enable next available lag system heating hot water loop circuit pump VFD upon detection of setpoint conditions.
4) VFD's shall maintain equalized system heating hot water loop circuit pump speeds for equal load sharing.
5) BAS shall disable lead system heating hot water loop circuit pump upon detection of setpoint conditions.
6) BAS shall maintain active the following control algorithms:
   (a) System heating hot water loop circuit alarm condition - equipment control algorithm.
   (b) System heating hot water loop circuit alarm condition - temperature control algorithm.
   (c) System heating hot water loop circuit energy usage monitoring.

4. System heating hot water loop circuit alarm condition - equipment control algorithm:

a. General:

1) Alarm condition shall be activated upon any equipment pieces actual status being opposite of commanded status.
2) Alarm shall be capable of being reset at Operator Work Station.

b. Setpoints shall include:

1) Actual equipment status being opposite of commanded status for any time period.

c. Control points shall include:

1) BAS shall continuously monitor system heating hot water loop circuit pump status via interface with pump VFD interface.

d. Activation of failed system heating hot water loop circuit pump response:

1) BAS shall initiate an alarm condition at the Operator Work Station indicating which system heating hot water loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
2) BAS shall disable failed system heating hot water loop circuit pump.
3) BAS shall enable next available lag system heating hot water loop circuit pump.
4) BAS shall maintain normal pre-response status of heat pump chiller system, system chilled water loop circuit, and geothermal loop field circuit operation.
5) BAS shall disable the heat pump chiller system, system chilled water loop circuit, and geothermal loop field circuit upon detection of all system heating hot water loop circuit pumps having failed.

e. Cancellation of failed system heating hot water loop circuit equipment response:

1) BAS shall return to system pre-response operation.
2) BAS shall initiate an all clear status at Operator Work Station.

5. System heating hot water loop circuit alarm condition - temperature control algorithm:

a. General:

1) Alarm condition shall be activated upon detection of temperature being above or below alarm setpoint temperature as described below.
2) Alarm shall be capable of being reset at Operator Work Station.

3) BAS shall cancel temperature system alarm response upon detection of any of the following conditions:
    (a) Parameter formerly beyond allowable alarm limit becoming within allowable alarm limit.
    (b) Alarm notification being cancelled at Operator Work Station.

b. Setpoints shall include:
    1) System heating hot water loop circuit supply temperature being equal to or greater than one ºF above or below setpoint for a ten minute time period.

c. Control points shall include:
    1) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the system heating hot water loop circuit supply piping.

d. Cancellation of alarm condition - temperature system response:
    1) BAS shall return to system pre-response operation.
    2) BAS shall initiate an all clear status at Operator Work Station.

6. System heating hot water loop circuit energy usage control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling control algorithm.
        2) Control algorithm shall be deactivated by calling control algorithm.
        3) System heating hot water loop circuit shall feature energy monitoring for instantaneous energy usage in units of MBH and totalized energy usage in units of MBH.
    b. Setpoints shall include:
        1) None.
    c. Control points shall include:
        1) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the heating hot water return piping.
        2) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the heating hot water supply piping.
        3) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the heating hot water return piping.
    d. Activation of energy monitoring system response:
        1) System heating hot water loop circuit energy usage shall be calculated based on the following equation:
            (a) q = (500) (Flow) (Supply Temperature - Return Temperature) / (1,000).
    e. Deactivation of energy monitoring system response:
        1) Instantaneous and totalized energy usage calculations shall become inactive.

7. System heating hot water loop circuit automatic shut-down control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling operation mode.
        2) Control algorithm shall be deactivated by calling operation mode.
    b. Setpoints shall include:
        1) Not applicable.
    c. Control points shall include:
        1) Pump status.
    d. Activation of shut-down control algorithm:
        1) BAS shall disable pump VFD's.
        2) VFD shall gradually return pump speed(s) to minimum safe motor speed.
        3) VFD shall stop pump(s).
        4) VFD shall set pump motor speed reference(s) to minimum safe motor speed.

5) BAS shall return control to calling operation mode.

8. System heating hot water loop circuit manual shut-down control algorithm:
   a. General:
      1) Control algorithm shall be activated by command issued from the Operator Work Station.
      2) BAS shall deactivate operation mode upon detection of a manual release issued from the Operator Work Station.
   b. Setpoints points shall include:
      1) Not applicable.
   c. Control points shall include:
      1) BAS shall continuously monitor Operator Work Station interface.
   d. Activation of shut-down system response:
      1) BAS shall deactivate system heating hot water loop circuit described under section “System Heating hot water loop circuit automatic shut-down control algorithm.”

C. System chilled water loop circuit (chilled water secondary loop circuit) control algorithms describing general conditions, setpoints, control points, start-up, normal operation, alarm condition - equipment, alarm condition - temperature, energy usage monitoring, automatic shut-down, and manual shut-down are presented below.

1. System chilled water loop circuit associated equipment shall include pumps tagged (SCHWP-1, SCHWP-2, and SCHWP-3).
2. System chilled water loop circuit start-up control algorithm:
   a. General:
      1) Control algorithm shall be activated by calling operation mode.
      2) Control algorithm shall be deactivated by calling operation mode.
      3) VFD shall modulate pump speeds during pump active status.
   b. Setpoints points shall include:
      1) Pump VFD setpoint differential pressure shall be 15 psid and shall be fine tuned during system start-up.
      2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed as determined during system start-up.
   c. Control points shall include:
      1) BAS shall continuously monitor system chilled water loop circuit pump VFD pressure via sensor (DP-CHS-01) located in the system chilled water loop circuit.
      2) BAS shall continuously monitor pump motor speed via pump VFD interface.
      3) BAS shall continuously monitor pump motor status via pump VFD interface.
   d. Activation of system start-up system response:
      1) BAS shall enable lag system chilled water loop circuit pump VFD.
      2) VFD shall gradually increase pump motor speed to obtain setpoint.
      3) BAS shall immediately activate the following control algorithms up completion system start-up:
         (a) System chilled water loop circuit normal operation control algorithm.
         (b) System chilled water loop circuit alarm condition - equipment control algorithm.
         (c) System chilled water loop circuit alarm condition - temperature control algorithm.
         (d) System chilled water loop circuit energy usage monitoring.
3. System chilled water loop circuit normal operation control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “System chilled water loop circuit start-up control algorithm” section above.
      2) Control algorithm shall be deactivated by calling control algorithm.

b. Setpoints points shall include:
    1) Pump VFD setpoint differential pressure shall be 15 psid and shall be fine tuned during system start-up.
    2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed.
    3) Next available lag pump VFD activation setpoint shall be the inability to maintain setpoint differential pressure for a two minute time period.
    4) Lead pump VFD deactivation setpoint shall be water flow being equal to or less than 85 percent of the flow of all active pumps less the current flow of a single pump for a five minute time period.
c. Control points shall include:
    1) BAS shall continuously monitor system chilled water loop circuit pump VFD pressure via sensor (DP-CHS-01) located in the system chilled water loop circuit.
    2) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the chilled water return piping.
d. Activation of normal operation system response:
    1) VFD shall gradually increase system chilled water loop circuit pump speed(s) toward maximum allowed motor speed upon detection of actual value being less than setpoint.
    2) VFD shall gradually decrease system chilled water loop circuit pump speed(s) toward minimum safe motor speed upon detection of actual value being less than setpoint.
    3) BAS shall enable next available system chilled water loop circuit pump VFD upon detection of setpoint conditions.
    4) VFD's shall maintain equalized system chilled water loop circuit pump speeds for equal load sharing.
    5) BAS shall disable system chilled water loop circuit pump upon detection of setpoint conditions.
    6) BAS shall maintain active the following control algorithms:
        (a) System chilled water loop circuit alarm condition - equipment control algorithm.
        (b) System chilled water loop circuit alarm condition - temperature control algorithm.
        (c) System chilled water loop circuit energy usage monitoring.

4. System chilled water loop circuit alarm condition - equipment control algorithm:
    a. General:
        1) Alarm condition shall be activated upon any equipment pieces actual status being opposite of commanded status.
        2) Alarm shall be capable of being reset at Operator Work Station.
    b. Setpoints shall include:
        1) Actual equipment status being opposite of commanded status for any time period.
    c. Control points shall include:
        1) BAS shall continuously monitor system chilled water loop circuit pump status via interface with pump VFD interface.
    d. Activation of failed equipment piece system response:
        1) BAS shall initiate an alarm condition at the Operator Work Station indicating which system chilled water loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
        2) BAS shall disable failed system chilled water loop circuit pump.
        3) BAS shall enable next available lag system chilled water loop circuit pump.
        4) BAS shall maintain normal pre-response status of heat pump chiller system, system heating hot water loop circuit, and geothermal loop field circuit operation.

        5) BAS shall disable the heat pump chiller system, system heating hot water loop circuit, and geothermal loop field circuit upon detection of all system chilled water loop circuit pumps having failed.
    e. Cancellation of failed chilled water system loop pump system response:
        1) BAS shall return to system pre-response operation.
        2) BAS shall initiate an all clear status at Operator Work Station.
5. System chilled water loop circuit alarm condition - temperature control algorithm:
    a. General:
        1) Alarm condition shall be activated upon detection of temperature being above or below alarm setpoint temperature as described below.
        2) Alarm shall be capable of being reset at Operator Work Station.
        3) BAS shall cancel temperature system alarm response upon detection of any of the following conditions:
            (a) Parameter formerly beyond allowable alarm limit becoming within allowable alarm limit.
            (b) Alarm notification being cancelled at Operator Work Station.
    b. Setpoints shall include:
        1) System chilled water loop circuit supply temperature being equal to or greater than one ºF above or below setpoint for a ten minute time period.
    c. Control points shall include:
        1) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the system chilled water loop circuit supply piping.
    d. Cancellation of alarm condition - temperature system response:
        1) BAS shall return to system pre-response operation.
        2) BAS shall initiate an all clear status at Operator Work Station.
6. System chilled water loop circuit energy usage control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling control algorithm.
        2) Control algorithm shall be deactivated by calling control algorithm.
        3) System chilled water loop circuit shall feature energy monitoring for instantaneous energy usage in units of tons and totalized energy usage in units of ton-hours.
    b. Setpoints shall include:
        1) None.
    c. Control points shall include:
        1) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the chilled water return piping.
        2) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the chilled water supply piping.
        3) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the chilled water return piping.
    d. Activation of energy monitoring system response:
        1) System chilled water loop circuit energy usage shall be calculated based on the following equation:
            (a) q = (500) (Flow) (Return Temperature - Supply Temperature) / (12,000).
    e. Deactivation of energy monitoring system response:
        1) Instantaneous and totalized energy usage calculations shall become inactive.
7. System chilled water loop circuit automatic shut-down control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling operation mode.

2) Control algorithm shall be deactivated by calling operation mode.

b. Setpoints shall include:

1) Not applicable.

c. Control points shall include:

1) Pump status.

d. Activation of shut-down control algorithm:

1) BAS shall disable pump VFD's.
2) VFD shall gradually return pump speed(s) to minimum safe motor speed.
3) VFD shall stop pump(s).
4) VFD shall set pump motor speed reference(s) to minimum safe motor speed.
5) BAS shall return control to calling operation mode.

8. System chilled water loop circuit manual shut-down control algorithm:

a. General:

1) Control algorithm shall be activated by command issued from the Operator Work Station.
2) BAS shall deactivate operation mode upon detection of a manual release issued from the Operator Work Station.

b. Setpoints points shall include:

1) Not applicable.

c. Control points shall include:

1) BAS shall continuously monitor Operator Work Station interface.

d. Activation of shut-down system response:

1) BAS shall deactivate system chilled water loop circuit described under section "System chilled water loop circuit automatic shut-down control algorithm".

D. Geothermal loop field circuit control algorithms describing general conditions, setpoints, control points, start-up, normal operation, alarm condition - equipment, alarm condition - temperature, energy usage monitoring, automatic shut-down, and manual shut-down are presented below.

1. Equipment associated with this system shall include pumps tagged (LFWP-1, LFWP-2, and LFWP-3).
2. Geothermal loop field circuit start-up control algorithm:

a. General:

1) Control algorithm shall be activated by calling control algorithm.
2) Control algorithm shall be deactivated by calling control algorithm.
3) VFD shall modulate pump speeds during pump active status.

b. Setpoints points shall include:

1) Pump VFD speed control setpoint temperature change shall be forwarded to this control algorithm by calling control algorithm.
2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed.
3) Next available lag pump VFD activation setpoint shall be the inability to maintain setpoint temperature for a two minute time period.
4) Lead pump VFD deactivation setpoint shall be water flow being equal to or less than 85 percent of the flow of all active pumps less the current flow of a single pump for a five minute time period.

c. Control points shall include:

1) BAS shall continuously monitor geothermal loop field circuit return temperature via sensor (TS-LFW-01) located in the geothermal loop field circuit return water piping.
2) BAS shall continuously monitor geothermal loop field circuit supply temperature via sensor (TS-LFW-02) located in the geothermal loop field circuit supply water piping.
3) BAS shall continuously monitor geothermal loop field circuit water flow rate via water flow meter (FM-LFW-01) in the geothermal loop field circuit supply water

piping.

4) BAS shall continuously monitor pump motor speed via pump VFD interface.
5) BAS shall continuously monitor pump motor status via pump VFD interface.

d. Activation of start-up system response:
  1) BAS shall enable lag geothermal loop field circuit pump VFD.
  2) VFD shall gradually increase pump motor speed to obtain setpoint.
  3) BAS shall immediately activate the following control algorithms up completion system start-up:
    (a) Geothermal loop field circuit normal operation control algorithm.
    (b) Geothermal loop field circuit alarm condition - equipment control algorithm.
    (c) Geothermal loop field circuit alarm condition - temperature control algorithm.
    (d) Geothermal loop field circuit energy usage monitoring.

3. Geothermal loop field circuit normal operation control algorithm:
  a. General:
    1) Control algorithm shall be activated immediately upon completion of “Geothermal loop field circuit system start-up control algorithm” section above.
    2) Control algorithm shall be deactivated by calling control algorithm.
  b. Setpoints points shall include:
    1) System setpoints shall be identical to those described in “Geothermal loop field circuit system start-up control algorithm” section above.
  c. Control points shall include:
    1) System control points shall be identical to those described in “Geothermal loop field circuit system start-up control algorithm” section above.
  d. Activation of normal operation system response:
    1) VFD shall gradually increase geothermal loop field circuit pump speed(s) toward maximum allowed motor speed upon detection of actual value being less than setpoint.
    2) VFD shall gradually decrease geothermal loop field circuit pump speed(s) toward minimum safe motor speed upon detection of actual value being less than setpoint.
    3) BAS shall enable next available lag geothermal loop field circuit pump VFD upon detection of setpoint conditions.
    4) VFD's shall maintain equalized system heating hot water loop circuit pump speeds for equal load sharing.
    5) BAS shall disable geothermal loop field circuit pump upon detection of setpoint conditions.
    6) BAS shall maintain active the following control algorithms:
      (a) Geothermal loop field circuit alarm condition - equipment control algorithm.
      (b) Geothermal loop field circuit alarm condition - temperature control algorithm.
      (c) Geothermal loop field circuit energy usage monitoring.

4. Geothermal loop field circuit alarm condition - equipment control algorithm:
  a. General:
    1) Alarm condition shall be activated upon any equipment pieces actual status being opposite of commanded status.
    2) Alarm shall be capable of being reset at Operator Work Station.
  b. Setpoints shall include:
    1) Actual equipment status being opposite of commanded status for any time period.
  c. Control points shall include:
    1) BAS shall continuously monitor geothermal loop field circuit pump status via interface with pump VFD interface.
  d. Activation of failed geothermal loop field circuit pump response:
    1) BAS shall initiate an alarm condition at the Operator Work Station indicating which geothermal loop field circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.

2) BAS shall disable failed geothermal loop field circuit pump.
3) BAS shall enable next available lag geothermal loop field circuit pump.
4) BAS shall maintain normal pre-response status of heat pump chiller system, system chilled water loop circuit, and system heating hot water loop circuit operation.
5) BAS shall disable the heat pump chiller system, system chilled water loop circuit, and heating hot water loop circuit upon detection of all geothermal loop field circuit pumps having failed.

e. Cancellation of failed geothermal loop field circuit equipment response:
1) BAS shall return to system pre-response operation.
2) BAS shall initiate an all clear status at Operator Work Station.

5. Geothermal loop field circuit alarm condition - temperature control algorithm:
a. General:
1) Alarm condition shall be activated upon detection of temperature being above or below alarm setpoint temperature as described below.
2) Alarm shall be capable of being reset at Operator Work Station.
3) BAS shall cancel temperature system alarm response upon detection of any of the following conditions:
(a) Parameter formerly beyond allowable alarm limit becoming within allowable alarm limit.
(b) Alarm notification being cancelled at Operator Work Station.

b. Setpoints shall include:
1) Geothermal loop field circuit supply temperature being equal to or greater than one ºF above or below setpoint for a ten minute time period.

c. Control points shall include:
1) BAS shall continuously monitor geothermal loop field circuit supply water temperature via temperature sensor (TS-LF-02) located in the geothermal loop field circuit supply water piping.

d. Cancellation of alarm condition - temperature system response:
1) BAS shall return to system pre-response operation.
2) BAS shall initiate an all clear status at Operator Work Station.

6. Geothermal loop field circuit energy usage control algorithm:
a. General:
1) Control algorithm shall be activated by calling control algorithm.
2) Control algorithm shall be deactivated by calling control algorithm.
3) Geothermal loop field circuit during both heat rejection and heat absorption from/to the heat pump chiller condenser loop circuit for instantaneous energy usage in units of 1,000 BTUh (MBh) and totalized energy usage in units of 1,000 BTUh-hours (MBh-hours).
4) Geothermal loop field circuit shall feature energy monitoring during both heat rejection and heat absorption from/to the heat pump chiller evaporator loop circuit for instantaneous energy usage in units of tons and totalized energy usage in units of ton-hours.

b. Setpoints shall include:
1) None.

c. Control points shall include:
1) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the heating hot water return piping.
2) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the heating hot water supply piping.

3) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the heating hot water return piping.
4) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the chilled water return piping.
5) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the chilled water supply piping.
6) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the chilled water return piping.

d. Activation of energy monitoring system response:
1) System heating hot water loop circuit energy usage during both heat rejection and heat absorption from/to the heat pump chiller condenser loop circuit shall be calculated based on the following equation:
(a) q = (500) (Flow) (Supply Temperature - Return Temperature) / (1,000).
2) System chilled water loop circuit energy usage during both heat rejection and heat absorption from/to the heat pump chiller evaporator loop circuit shall be calculated based on the following equation:
(a) q = (500) (Flow) (Return Temperature - Supply Temperature) / (12,000).

e. Deactivation of energy monitoring system response:
1) Instantaneous and totalized energy usage calculations shall become inactive.

7. Geothermal loop field circuit automatic shut-down control algorithm:
a. General:
1) Control algorithm shall be activated by calling operation mode.
2) Control algorithm shall be deactivated by calling operation mode.
b. Setpoints shall include:
1) Not applicable.
c. Control points shall include:
1) Pump status.
d. Activation of shut-down control algorithm:
1) BAS shall disable pump VFD's.
2) VFD shall gradually return pump speed(s) to minimum safe motor speed.
3) VFD shall stop pump(s).
4) VFD shall set pump motor speed reference(s) to minimum safe motor speed.
5) BAS shall return control to calling operation mode.

8. Geothermal loop field circuit manual shut-down control algorithm:
a. General:
1) Control algorithm shall be activated by command issued from the Operator Work Station.
2) BAS shall deactivate operation mode upon detection of a manual release issued from the Operator Work Station.
b. Setpoints points shall include:
1) Not applicable.
c. Control points shall include:
1) BAS shall continuously monitor Operator Work Station interface.
d. Activation of shut-down system response:
1) BAS shall deactivate geothermal loop field circuit described under section “Geothermal loop field circuit automatic shut-down control algorithm.”

E. Heat pump chiller (CH-1) circuit, first dedicated heating control algorithms describing general conditions, setpoints, control points, start-up, normal operation, condenser return water temperature control, condenser artificial loading, evaporator artificial loading, condenser loop circuit pump, evaporator loop circuit pump, alarm condition - equipment, alarm condition - temperature/flow, automatic shut-down, and manual shut-down are presented below.

1. Heat pump chiller (CH-1) circuit, first dedicated heating shall be considered to include:
    a. Heat pump chiller, first dedicated heating tagged (CH-1).
    b. Primary chilled water pump tagged (PCWP-1).
    c. Condenser water pump tagged (CWP-1).
2. Heat pump chiller (CH-1) circuit start-up control algorithm:
    a. General:
        1) Control algorithm shall be activated by calling operation mode.
        2) Control algorithm shall be deactivated by calling operation mode.
    b. Setpoints points shall include:
        1) Heat pump chillers start-up setpoint current limit shall be 100 percent of maximum current.
        2) Heat pump chillers condenser water return setpoint temperature shall range proportionally between 120.0 ºF corresponding to outside air dry-bulb temperature equal to or greater than 50.0 ºF and 155.0 ºF corresponding to outside air dry-bulb temperature equal to or less than -0.5 ºF.
        3) Heat pump chillers evaporator chilled water supply setpoint temperature shall not be applicable.
        4) Heat pump chillers condenser water flow rate shall be 6,400 gpm.
        5) Heat pump chillers evaporator chilled water flow rate shall be 6,000 gpm.
    c. Control points shall include:
        1) BAS shall continuously monitor heat pump chillers condenser return water temperature via temperature sensor (TS-CW-01) located in its condenser water return piping.
        2) BAS shall continuously monitor heat pump chillers condenser water supply temperature via temperature sensor (TS-CW-02) located in its condenser water supply piping.
        3) BAS shall continuously monitor heat pump chillers condenser water flow rate via water flow meter (FM-CW-01) located in its condenser water supply piping.
        4) BAS shall continuously monitor heat pump chillers condenser proof of flow via flow sensor (FS-CW-01) located in its condenser water return piping.
        5) BASshall continuously monitor heat pump chiller condenser loop circuit decoupler (bypass) water temperature via temperature sensor (TS-CWB-06) located in the heat pump chiller condenser loop circuit decoupler (bypass) piping.
        6) BAS shall continuously monitor condenser water pump motor status via pump VFD interface.
        7) BAS shall continuously monitor heat pump chillers evaporator water flow rate via water flow meter (FM-CHP-01) located in its evaporator water supply piping.
        8) BAS shall continuously monitor heat pump chillers evaporator proof of flow via flow sensor (FS-CHP-01) located in its evaporator water return piping.
        9) BAS shall continuously monitor heat pump chiller evaporator loop circuit decoupler (bypass) water temperature via temperature sensor (TS-CWB-08) located in the heat pump chiller evaporator loop circuit decoupler (bypass) piping.
        10) BAS shall continuously monitor chilled water primary pump motor status via pump VFD interface.

d. Activation of start-up system response:
   1) BAS shall activate the heat pump chiller (HPC) circuit, first dedicated heating as follows:
      (a) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
      (b) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.
      (c) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.
      (d) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full closed position.
      (e) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) to its full closed position.
      (f) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-05) to its full closed position.
      (g) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its full open position.
      (h) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-08) to its full open position.
      (i) BAS shall confirm active geothermal loop field circuit normal operation control algorithm or activate geothermal loop field circuit start-up control algorithm as applicable.
      (j) Heat pump chiller condenser loop circuit pump (CWP-1) VFD shall gradually increase pump motor speed to obtain heat pump chiller condenser loop circuit setpoint water flow rate.
      (k) BAS shall confirm heat pump chiller condenser loop circuit water flow via flow sensor (FS-CW-01).
      (l) BAS shall enable chilled water primary pump (PCHWP-1) VFD.
      (m) Heat pump chiller evaporator loop circuit pump (PCHWP-1) VFD shall gradually increase pump motor speed to obtain heat pump chiller evaporator loop circuit setpoint water flow rate.
      (n) BAS shall confirm heat pump chiller evaporator loop circuit water flow via flow sensor (FS-CHP-01).
      (o) BAS shall enable heat pump chiller (CH-1).
      (p) Heat pump chiller (CH-1) MCP shall confirm condenser proof of condenser water flow.
      (q) Heat pump chiller (CH-1) MCP shall confirm evaporator proof of chilled water flow.
      (r) Heat pump chiller (CH-1) MCP shall initiate heat pump chiller start-up.
      (s) BAS shall immediately activate the following control algorithms up completion system start-up:
         (1) Heat pump chiller condenser loop circuit pump normal operation control algorithm.
         (2) Heat pump chiller evaporator loop circuit pump normal operation control algorithm.
         (3) Heat pump chiller system normal operation control algorithm.
         (4) Heat pump chiller system alarm condition - equipment control algorithm.
         (5) Heat pump chiller system alarm condition - temperature/flow control algorithm.

3. Heat pump chiller (CH-1) circuit normal operation control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm” section above.
      2) Control algorithm shall be deactivated by calling operation mode.
   b. Setpoints points shall include:
      1) System setpoints shall be identical to those described in “Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm” section above.
   c. Control points shall include:
      1) System control points shall be identical to those described in “Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm” section above.
   d. Activation of normal operation system response:
      1) BAS shall maintain active the following control algorithms:
         (a) Heat pump chiller condenser loop circuit pump normal operation control algorithm.
         (b) Heat pump chiller evaporator loop circuit pump normal operation control algorithm.
         (c) Heat pump chiller system alarm condition - equipment control algorithm.
         (d) Heat pump chiller system alarm condition - temperature/flow control algorithm.
      2) Heat pump chiller MCP shall modulate heat pump chiller output capacity to maintain condenser water leaving setpoint temperature via the heat pump chiller (CH-1) condenser water return temperature control algorithm.
4. Heat pump chiller (CH-1) condenser water return temperature control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm.”
      2) Control algorithm shall be deactivated by command from calling operation mode.
   b. Setpoints points shall include:
      1) BAS shall maintain setpoints described under section "Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm."
   c. Control points shall include:
      1) BAS shall maintain control points described under section "Heat pump chiller (CH-1) circuit, first dedicated heating start-up control algorithm."
   d. Activation of condenser water return temperature control system response:
      1) Heat pump chiller MCP shall maintain its condenser water return setpoint temperature.
5. Heat pump chiller (CH-1) condenser loop circuit artificial loading control algorithm :
   a. General:
      1) Control algorithm shall be activated upon detection all of the following conditions:
         (a) BAS calculated system heating hot water loop circuit load being less than BAS calculated system chilled water loop circuit load for a five minute time period.
         (b) Heat pump chiller condenser loop circuit water temperature change being less than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07) for a five minute time period.
      2) Control algorithm shall be deactivated upon detection all of the following conditions:
         (a) BAS calculated system heating hot water loop circuit load equal to or greater than BAS calculated system chilled water loop circuit load for a five minute time period.

(b) Heat pump chiller condenser loop circuit water temperature change being equal to or greater than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07) for a five minute time period.

b. Setpoints points shall include:
  1) System setpoints shall be identical to those described in "Heat pump chiller (HPC) circuit, first dedicated heating start-up control algorithm" section above.
  2) Heat pump chiller condenser loop circuit water temperature change design value shall be equal to 12.0 F.

c. Control points shall include:
  1) BAS shall continuously monitor heat pump chiller condenser loop circuit water return temperature via temperature sensor (TS-CW-01) located in its condenser water return piping.
  2) BAS shall continuously monitor heat pump chiller condenser loop circuit water supply temperature via temperature sensor (TS-CW-02) located in its condenser water supply piping.
  3) BAS shall continuously monitor heat pump chiller condenser loop circuit water return temperature via temperature sensor (TS-CW-07) located in its condenser water main return piping.
  4) BAS shall continuously monitor heat pump chiller condenser loop circuit water supply temperature via temperature sensor (TS-CW-05) located in its condenser water main supply piping.
  5) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the system heating hot water loop circuit return piping.
  6) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the system heating hot water loop circuit supply piping.
  7) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the system heating hot water loop circuit return piping.
  8) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the system chilled water loop circuit return piping.
  9) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the system chilled water loop circuit supply piping.
  10) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the system chilled water loop circuit return piping.

d. Activation of condenser artificial loading system response:
  1) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-02) to its 90 percent open position.
  2) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-01) to its full open position.
  3) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-03) to its 10 percent open position.
  4) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-04) to its full open position.
  5) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
  6) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.

7) BAS shall command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full open position.
8) BAS shall command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full open position.
9) BAS shall activate the geothermal loop field circuit start-up control algorithm.
10) Heat pump chiller condenser loop circuit water return and supply control valves shall be controlled as follows:
    (a) BAS shall continuously calculate heat pump chiller condenser loop circuit water temperature change via temperature sensors (TS-CW-05) and (TS-CW-07).
    (b) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-02) toward its closed position and shall simultaneously modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-03) to its open position upon detection of heat pump chiller condenser loop circuit water temperature change becoming less than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07).
    (c) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-02) toward its open position and shall simultaneously modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-03) to its closed position upon detection of heat pump chiller condenser loop circuit water temperature change approaching design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07).
11) Geothermal loop field circuit pump VFD(s) shall be controlled as follows:
    (a) BAS shall continuously calculate heat pump chiller condenser loop circuit water temperature change via temperature sensors (TS-CW-01) and (TS-CW-02).
    (b) BAS shall forward setpoint temperature change to geothermal loop field circuit pump VFD's.
    (c) Refer to geothermal loop circuit control algorithm for pump control algorithm.

e. Deactivation of condenser artificial loading system response:
   1) BAS shall deactivate geothermal loop circuit control algorithm.
   2) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-02) to its full open position.
   3) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-01) to its full open position.
   4) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-03) to its full closed position.
   5) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-04) to its full closed position.
   6) BAS shall maintain the geothermal loop field circuit chilled water control valve (CV-LFW-02) in its full closed position.
   7) BAS shall maintain the geothermal loop field circuit chilled water control valve (CV-LFW-04) in its full closed position.
   8) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.
   9) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full closed position.

6. Heat pump chiller (CH-1) evaporator loop circuit artificial loading control algorithm:
    a. General:
        1) Control algorithm shall be activated upon detection all of the following conditions:
            (a) BAS calculated system chilled water loop circuit load being less than BAS calculated system heating hot water loop circuit load for a five minute time period.
            (b) Heat pump chiller evaporator loop circuit water temperature change being less than design value as measured by temperature sensors (TS-CHP-06) and (TS-CHP-07) for a five minute time period.
        2) Control algorithm shall be deactivated upon detection all of the following conditions:
            (a) BAS calculated system chilled water loop circuit load equal to or greater than BAS calculated system heating hot water loop circuit load for a five minute time period.
            (b) Heat pump chiller evaporator loop circuit water temperature change being equal to or greater than design value as measured by temperature sensors (TS-CHP-06) and (TS-CHP-07) for a five minute time period.
    b. Setpoints points shall include:
        1) System setpoints shall be identical to those described in “Heat pump chiller (HPC) circuit, first dedicated heating start-up control algorithm” section above.
        2) Heat pump chiller evaporator loop circuit water temperature change design value shall be equal to 10.0 °F.
    c. Control points shall include:
        1) BAS shall continuously monitor heat pump chiller evaporator loop circuit water return temperature via temperature sensor (TS-CHP-06) located in its chilled water main return piping.
        2) BAS shall continuously monitor heat pump chiller evaporator loop circuit water supply temperature via temperature sensor (TS-CHP-07) located in its chilled water main supply piping.
        3) BAS shall continuously monitor heat pump chiller evaporator loop circuit water supply temperature via temperature sensor (TS-CHP-05) located in its chilled water main return piping.
        4) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the system chilled water loop circuit return piping.
        5) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the system chilled water loop circuit supply piping.
        6) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the system chilled water loop circuit return piping.
        7) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the system heating hot water loop circuit return piping.
        8) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the system heating hot water loop circuit supply piping.
        9) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the system heating hot water loop circuit return piping.
    d. Activation of evaporator artificial loading system response:
        1) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.

2) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full closed position.
3) BAS shall command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full open position.
4) BAS shall command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full open position.
5) BAS shall activate the geothermal loop field circuit start-up control algorithm.
6) Geothermal loop field circuit pump VFD's shall be controlled as follows:
   (a) BAS shall continuously calculate heat pump chiller evaporator loop circuit water temperature change via temperature sensors (TS-CHP-05) and (TS-CHP-07).
   (b) BAS shall forward setpoint temperature change to geothermal loop field circuit pump VFD's.
   (c) Refer to geothermal loop circuit control algorithm for pump control algorithm.

e. Deactivation of evaporator artificial loading system response:
   1) BAS shall deactivate geothermal loop field circuit control algorithm.
   2) BAS shall maintain the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.
   3) BAS shall maintain the geothermal loop field circuit condenser water control valve (CV-LFW-03) in its full closed position.
   4) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
   5) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.

7. Heat pump chiller (CH-1) condenser loop circuit pump control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (HPC) circuit, first dedicated heating start-up control algorithm.”
      2) Heat pump chiller condenser loop circuit pump shall operate at variable speed to maintain design intended constant evaporator flow throughout system dynamic operation and as heat pump chillers condenser tube pressure drop changes throughout the system's useful life.
   b. Setpoints points shall include:
      1) Heat pump chillers condenser water flow rate shall be 6,400 gpm.
      2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed as determined during system start-up.
   c. Control points shall include:
      1) BAS shall continuously monitor heat pump chiller condenser loop circuit water flow rate via water flow meter (FM-CW-01) located in its condenser water return piping.
      2) BAS shall continuously monitor pump motor speed via pump VFD interface.
      3) BAS shall continuously monitor pump motor status via pump VFD interface.
   d. Heat pump chiller condenser loop circuit pump normal operation control algorithm:
      1) VFD shall gradually increase heat pump chiller condenser loop circuit pump speed toward maximum allowed motor speed upon detection of actual value being less than setpoint.
      2) VFD shall gradually decrease heat pump chiller condenser loop circuit pump speed toward minimum safe motor speed upon detection of actual value being greater than setpoint.
      3) BAS shall maintain active the following control algorithms.

e. Heat pump chiller condenser loop circuit pump alarm condition control algorithm:
   1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller condenser loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
   2) BAS shall disable heat pump chiller (HPC) circuit, first dedicated heating as described under "Heat pump chiller (HPC) circuit, first dedicated heating automatic shut-down control algorithm".
f. Cancellation of failed heat pump chiller system evaporator loop circuit equipment response:
   1) BAS shall return to system pre-response operation.
   2) BAS shall initiate an all clear status at Operator Work Station.

8. Heat pump chiller (CH-1) evaporator loop circuit pump control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of "Heat pump chiller (HPC) circuit, first dedicated heating start-up control algorithm".
      2) Heat pump chiller evaporator loop circuit pump shall operate at variable speed to maintain design intended constant evaporator flow throughout system dynamic operation and as heat pump chillers evaporator tube pressure drop changes throughout the system's useful life.
   b. Setpoints points shall include:
      1) Heat pump chillers evaporator water flow rate shall be 6,000 gpm.
      2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed as determined during system start-up.
   c. Control points shall include:
      1) BAS shall continuously monitor heat pump chiller evaporator loop circuit water flow rate via water flow meter (FM-CHP-01) located in its chilled water supply piping.
      2) BAS shall continuously monitor pump motor speed via pump VFD interface.
      3) BAS shall continuously monitor pump motor status via pump VFD interface.
   d. Heat pump chiller evaporator loop circuit pump normal operation control algorithm:
      1) VFD shall gradually increase heat pump chiller evaporator loop circuit pump speed toward maximum allowed motor speed upon detection of actual value being less than setpoint.
      2) VFD shall gradually decrease heat pump chiller evaporator loop circuit pump speed toward minimum safe motor speed upon detection of actual value being greater than setpoint.
      3) BAS shall maintain active the following control algorithms:
         (a) Heat pump chiller evaporator loop circuit pump alarm condition control algorithm.
   e. Heat pump chiller evaporator loop circuit pump alarm condition control algorithm:
      1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller evaporator loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
      2) BAS shall disable heat pump chiller (HPC) circuit, first dedicated heating as described under "Heat pump chiller (HPC) circuit, first dedicated heating automatic shut-down control algorithm".
   f. Cancellation of failed heat pump chiller evaporator loop circuit equipment response:
      1) BAS shall return to system pre-response operation.
      2) BAS shall initiate an all clear status at Operator Work Station.
   g. Heat pump chiller evaporator loop circuit pump automatic shut-down control algorithm:
      1) BAS shall disable pump VFD.
      2) VFD shall gradually return pump speed to minimum safe motor speed.
      3) VFD shall stop pump.

4) VFD shall set pump motor speed reference to minimum safe motor speed.
5) BAS shall return control to calling operation mode.

9. Heat pump chiller (CH-1) alarm condition - equipment control algorithm:
   a. Activation of alarm condition system response:
      1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller (CH-1) circuit, first dedicated heating has failed upon detection of actual status being opposite of commanded status for any time period.
      2) BAS shall disable heat pump chiller (CH-1) circuit, first dedicated heating as described under "Heat pump chiller (CH-1) circuit, first dedicated heating automatic shut-down control algorithm".
   b. Cancellation of failed heat pump chiller (CH-1) circuit, first dedicated heating system response:
      1) BAS shall return to system pre-response operation.
      2) BAS shall initiate an all clear status at Operator Work Station.
10. Heat pump chiller (CH-1) alarm condition - temperature/flow control algorithm:
   a. General:
      1) Alarm condition shall be activated upon detection of any temperature or flow being beyond tolerance as described below.
      2) Alarm shall be capable of being reset at Operator Work Station.
      3) BAS shall cancel temperature/flow system alarm response upon detection of any of the following conditions:
         (a) Upon detection of parameter formerly beyond allowable alarm limit becoming within allowable alarm limit.
         (b) Alarm notification being cancelled at Operator Work Station.
   b. Setpoints - heat pump chiller condenser loop circuit shall include:
      1) Heat pump chillers condenser water return temperature being equal to or greater than one ºF above or below setpoint for a ten minute time period.
      2) Heat pump chillers condenser water supply temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      3) Heat pump chiller condenser loop circuit main condenser water return temperature being equal to or greater than one ºF above or below heat pump chillers condenser water return temperature for a ten minute time period.
      4) Heat pump chiller condenser loop circuit main condenser water supply temperature being equal to or greater than one ºF above or below heat pump chillers condenser water supply temperature for a ten minute time period.
      5) Heat pump chillers condenser water flow being equal to or greater than 15 percent above or below setpoint for a ten minute time period.
      6) Heat pump chiller condenser loop circuit decoupler (bypass) water temperature being equal to or greater than one ºF below the condenser water return temperature for a ten minute time period.
   c. Setpoints - heat pump chiller evaporator loop circuit (chilled water primary loop circuit) shall include:
      1) Heat pump chillers evaporator chilled water return temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      2) Heat pump chillers evaporator chilled water supply temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      3) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) main chilled water return temperature being equal to or greater than one ºF above or below heat pump chillers evaporator return water temperature for a ten minute time period.

4) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) main chilled water supply temperature being equal to or greater than one ºF above or below heat pump chillers evaporator supply water temperature for a ten minute time period.
5) Heat pump chillers evaporator chilled water flow being equal to or less than 15 percent above or below setpoint for a ten minute time period.
6) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) decoupler (bypass) water temperature being equal to or greater than one ºF above the chilled water supply temperature for a ten minute time period.

d. Control points - heat pump chiller condenser loop circuit shall include:
1) BAS shall continuously monitor heat pump chillers condenser water return temperature via temperature sensor (TS-CW-02) located in the condenser return piping.
2) BAS shall continuously monitor heat pump chillers condenser water supply temperature via temperature sensor (TS-CW-01) located in the condenser return piping.
3) BAS shall continuously monitor heat pump chiller condenser loop circuit main condenser water return temperature via temperature (TS-CW-07) sensor located in the heat pump chiller condenser loop circuit main return piping.
4) BAS shall continuously monitor heat pump chiller condenser loop circuit main condenser water supply temperature via temperature (TS-CW-05) sensor located in the heat pump chiller condenser loop circuit main supply piping.
5) BAS shall continuously monitor heat pump chillers condenser water flow rate via water flow meter (FM-CW-01) located in the condenser water return piping.
6) BAS shall continuously monitor heat pump chiller condenser loop circuit decoupler (bypass) condenser water return temperature via temperature sensor (TS-CWB-06) located in the decoupler (bypass) piping.

e. Control points - heat pump chiller evaporator loop circuit (chilled water primary loop circuit) shall include:
1) BAS shall continuously monitor heat pump chillers evaporator chilled water return temperature via temperature sensor (TS-CHP-01) located in the evaporator return piping.
2) BAS shall continuously monitor heat pump chillers evaporator chilled water supply temperature via temperature sensor (TS-CHP-02) located in the evaporator supply piping.
3) BAS shall continuously monitor chiller evaporator loop piping system (chilled water primary loop) main chilled water return temperature via temperature sensor (TS-CHP-06) located in the chiller evaporator loop piping system (chilled water primary loop) main return piping.
4) BAS shall continuously monitor chiller evaporator loop piping system (chilled water primary loop) main chilled water supply temperature via temperature sensor (TS-CHP-07) located in the chiller evaporator loop piping system (chilled water primary loop) main supply piping.
5) BAS shall continuously monitor heat pump chillers evaporator chilled water flow rate via water flow meter (FM-CHP-01) located in the evaporator return piping.
6) BAS shall continuously monitor heat pump chiller evaporator loop circuit decoupler (bypass) chilled water supply temperature via temperature sensor (TS-CHB-08) located in the decoupler (bypass) piping.

f. Activation of alarm condition - temperature/flow system response:
1) BAS shall initiate an alarm condition at the Operator Work Station indicating which temperature sensor or water flow meter is above or below alarm setpoint.

2) BAS shall maintain normal pre-response status of heat pump chiller system, system heating hot water loop circuit, system chilled water loop circuit, and geothermal loop field circuit operation.

g. Cancellation of alarm condition - temperature/flow system response:
   1) BAS shall return to system pre-response operation.
   2) BAS shall initiate an all clear status at Operator Work Station.

11. Heat pump chiller (CH-1) circuit automatic shut-down control algorithm:
   a. General:
      1) Control algorithm shall be activated by calling operation mode.
      2) Control algorithm shall be deactivated by calling operation mode.
   b. Setpoints points shall include:
      1) BAS shall activate system response upon detection of calling operation mode and upon detection of any of the following conditions:
         (a) Scheduled unoccupied time period having passed.
         (b) Manual shut-down command issued form Operator Work Station.
         (c) Alarm condition call for system shut-down.
      2) BAS shall deactivate system response upon detection of any of the following conditions:
         (a) Any other operation mode having been activated.
   c. Control points shall include:
      1) BAS shall continuously monitor time clock.
   d. Activation of shut-down system response:
      1) BAS shall deactivate heat pump chillers MCP.
      2) Heat pump chillers MCP shall initiate chiller shut-down.
      3) BAS shall take no action for time period required by heat pump chiller.
      4) BAS shall activate the heat pump chiller condenser loop circuit pump automatic shut-down control algorithm associated with the heat pump chiller (CH-1) circuit.
      5) BAS shall activate the heat pump chiller evaporator loop circuit pump automatic shut-down control algorithm associated with the heat pump chiller (CH-1) circuit.

12. Heat pump chiller (CH-1) circuit manual shut-down control algorithm:
   a. General:
      1) Control algorithm shall be activated by command issued from the Operator Work Station.
      2) BAS shall deactivate operation mode upon detection of a manual release issued from the Operator Work Station.
   b. Setpoints points shall include:
      1) Not applicable.
   c. Control points shall include:
      1) BAS shall continuously monitor Operator Work Station interface.
   d. Activation of shut-down system response:
      1) BAS shall deactivate heat pump chiller (CH-1) circuit described under section “Heat pump chiller (CH-1) circuit automatic shut-down control algorithm”.
      2) BAS shall deactivate heat pump chiller (CH-1) circuit regardless to any other conditions described under section “Heat pump chiller (CH-1) circuit automatic shut-down control algorithm”.

F. Heat pump chiller (CH-2) circuit, second heating and cooling control algorithms describing general conditions, setpoints, control points, start-up, normal operation, condenser return water temperature control, evaporator supply water temperature control, condenser artificial loading, evaporator artificial loading, condenser loop circuit pump, evaporator loop circuit pump, alarm condition - equipment, alarm condition - temperature/flow, automatic shut-down, and manual shut-down are presented below.

1. Heat pump chiller (CH-2) circuit, second heating and cooling shall be considered to include:
   a. Heat pump chiller, first dedicated heating tagged (CH-2).
   b. Primary chilled water pump tagged (PCWP-2).
   c. Condenser water pump tagged (CWP-2).
2. Heat pump chiller (CH-2) circuit start-up control algorithm:
   a. General:
      1) Control algorithm shall be activated by calling operation mode.
      2) Control algorithm shall be deactivated by calling operation mode.
   b. Setpoints points shall include:
      1) Heat pump chillers start-up setpoint current limit shall be 100 percent of maximum current.
      2) Heat pump chillers evaporator chilled water supply setpoint temperature shall not be applicable unless this heat pump chiller (CH-2) is supplementing evaporator chilled water circuit cooling from heat pump chiller (CH-1).
      3) Heat pump chillers evaporator chilled water supply setpoint temperature shall be 42.0 ºF.
      4) Heat pump chillers condenser water return setpoint temperature shall not be applicable unless this heat pump chiller (CH-2) is supplementing condenser water circuit heating from heat pump chiller (CH-1).
      5) Heat pump chillers condenser water return setpoint temperature shall range proportionally between 120.0 ºF corresponding to outside air dry-bulb temperature equal to or greater than 50.0 ºF and 155.0 ºF corresponding to outside air dry-bulb temperature equal to or less than -0.5 ºF when this heat pump chiller (CH-2) is supplementing condenser water circuit heat from heat pump chiller (CH-1).
      6) Heat pump chillers condenser water flow rate shall be 6,400 gpm.
      7) Heat pump chillers evaporator chilled water flow rate shall be 6,000 gpm.
   c. Control points shall include:
      1) BAS shall continuously monitor heat pump chillers evaporator return water temperature via temperature sensor (TS-CHP-03) located in its evaporator water return piping.
      2) BAS shall continuously monitor heat pump chillers evaporator water supply temperature via temperature sensor (TS-CHP-04) located in its evaporator water supply piping.
      3) BAS shall continuously monitor heat pump chillers evaporator water flow rate via water flow meter (FM-CHP-02) located in its evaporator water supply piping.
      4) BAS shall continuously monitor heat pump chillers evaporator proof of flow via flow sensor (FS-CHP-02) located in its evaporator water return piping.
      5) BAS shall continuously monitor heat pump chiller evaporator loop circuit decoupler (bypass) water temperature via temperature sensor (TS-CWB-08) located in the heat pump chiller evaporator loop circuit decoupler (bypass) piping.
      6) BAS shall continuously monitor chilled water primary pump motor status via pump VFD interface.
      7) BAS shall continuously monitor heat pump chillers condenser return water temperature via temperature sensor (TS-CW-04) located in its condenser water return piping.
      8) BAS shall continuously monitor heat pump chillers condenser water supply temperature via temperature sensor (TS-CW-03) located in its condenser water supply piping.
      9) BAS shall continuously monitor heat pump chillers condenser water flow rate via water flow meter (FM-CW-02) located in its condenser water supply piping.
      10) BAS shall continuously monitor heat pump chillers condenser proof of flow via flow sensor (FS-CW-02) located in its condenser water return piping.

11) BAS shall continuously monitor heat pump chiller condenser loop circuit decoupler (bypass) water temperature via temperature sensor (TS-CWB-06) located in the heat pump chiller condenser loop circuit decoupler (bypass) piping.
12) BAS shall continuously monitor condenser water pump motor status via pump VFD interface.

d. Activation of start-up system response:
1) BAS shall activate the heat pump chiller circuit as follows:
(a) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
(b) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.
(c) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full open position.
(d) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full open position.
(e) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) to its full closed position.
(f) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-05) to its full closed position.
(g) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its full open position.
(h) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-08) to its full open position.
(i) BAS shall confirm active geothermal loop field circuit normal operation control algorithm or activate geothermal loop field circuit start-up control algorithm as applicable.
(j) BAS shall enable condenser water pump (CWP-2) VFD.
(k) Heat pump chiller condenser loop circuit pump (CWP-2) VFD shall gradually increase pump motor speed to obtain heat pump chiller condenser loop circuit setpoint water flow rate.
(l) BAS shall confirm heat pump chiller condenser loop circuit water flow via flow sensor (FS-CW-02).
(m) BAS shall enable chilled water primary pump (PCHWP-2) VFD.
(n) Heat pump chiller evaporator loop circuit pump (PCHWP-2) VFD shall gradually increase pump motor speed to obtain heat pump chiller evaporator loop circuit setpoint water flow rate.
(o) BAS shall confirm heat pump chiller evaporator loop circuit water flow via flow sensor (FS-CHP-02).
(p) BAS shall enable heat pump chiller (CH-2).
(q) Heat pump chiller (CH-2) MCP shall confirm condenser proof of condenser water flow.
(r) Heat pump chiller (CH-2) MCP shall confirm evaporator proof of chilled water flow.
(s) Heat pump chiller (CH-2) MCP shall initiate heat pump chiller start-up.
(t) BAS shall immediately activate the following control algorithms up completion system start-up:
(1) Heat pump chiller condenser loop circuit pump normal operation control algorithm.
(2) Heat pump chiller evaporator loop circuit pump normal operation control algorithm.
(3) Heat pump chiller system normal operation control algorithm.
(4) Heat pump chiller system alarm condition - equipment control algorithm.

(5) Heat pump chiller system alarm condition - temperature/flow control algorithm.

3. Heat pump chiller (CH-2) circuit normal operation control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm” section above.
      2) Control algorithm shall be deactivated by calling operation mode.
   b. Setpoints points shall include:
      1) System setpoints shall be identical to those described in “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm” section above.
   c. Control points shall include:
      1) System control points shall be identical to those described in “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm” section above.
   d. Activation of normal operation system response:
      1) BAS shall maintain active the following control algorithms:
         (a) Heat pump chiller condenser loop circuit pump normal operation control algorithm.
         (b) Heat pump chiller evaporator loop circuit pump normal operation control algorithm.
         (c) Heat pump chiller system alarm condition - equipment control algorithm.
         (d) Heat pump chiller system alarm condition - temperature/flow control algorithm.
      2) Heat pump chiller MCP shall modulate heat pump chiller heating output capacity to maintain condenser water leaving setpoint temperature in accordance with heat pump chiller (CH-2) condenser water return temperature control algorithm when this heat pump chiller (CH-2) is supplementing condenser water circuit heat from heat pump chiller (CH-1).
      3) Heat pump chiller MCP shall modulate heat pump chiller cooling output capacity to maintain evaporator chilled water leaving setpoint temperature in accordance with heat pump chiller (CH-2) evaporator chilled water supply temperature control algorithm when this heat pump chiller (CH-2) is supplementing evaporator chilled water circuit cooling from heat pump chiller (CH-1).
4. Heat pump chiller (CH-2) condenser water return temperature control algorithm:
   a. General:
      1) Control algorithm shall be activated by command from calling operation mode.
      2) Control algorithm shall be deactivated by command from calling operation mode.
   b. Setpoints shall include:
      1) BAS shall maintain setpoints described under section “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.
   c. Control points shall include:
      1) BAS shall maintain control points described under section “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.
   d. Activation of condenser water return temperature control system response:
      1) Heat pump chiller MCP shall maintain its condenser water return setpoint temperature.
5. Heat pump chiller (CH-2) evaporator chilled water supply temperature control algorithm:
   a. General:
      1) Control algorithm shall be activated by command from calling operation mode.
      2) Control algorithm shall be deactivated by command from calling operation mode.

b. Setpoints shall include:
    1) BAS shall maintain setpoints described under section “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.
c. Control points shall include:
    1) BAS shall maintain control points described under section “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.
d. Activation of evaporator chilled water supply temperature control system response:
    1) Heat pump chiller MCP shall maintain its chilled water supply setpoint temperature.

6. Heat pump chiller (CH-2) condenser loop circuit artificial loading control algorithm:
    a. General:
        1) Control algorithm shall be activated upon detection all of the following conditions:
            (a) BAS calculated system heating hot water loop circuit load being less than BAS calculated system chilled water loop circuit load for a five minute time period.
            (b) Heat pump chiller condenser loop circuit water temperature change being less than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07) for a five minute time period.
        2) Control algorithm shall be deactivated upon detection all of the following conditions:
            (a) BAS calculated system heating hot water loop circuit load equal to or greater than BAS calculated system chilled water loop circuit load for a five minute time period.
            (b) Heat pump chiller condenser loop circuit water temperature change being equal to or greater than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07) for a five minute time period.
    b. Setpoints points shall include:
        1) System setpoints shall be identical to those described in “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm” section above.
        2) Heat pump chiller condenser loop circuit water temperature change design value shall be equal to 12.0 °F.
    c. Control points shall include:
        1) BAS shall continuously monitor heat pump chiller condenser loop circuit water return temperature via temperature sensor (TS-CW-03) located in its condenser water return piping.
        2) BAS shall continuously monitor heat pump chiller condenser loop circuit water supply temperature via temperature sensor (TS-CW-04) located in its condenser water supply piping.
        3) BAS shall continuously monitor heat pump chiller condenser loop circuit water return temperature via temperature sensor (TS-CW-07) located in its condenser water main return piping.
        4) BAS shall continuously monitor heat pump chiller condenser loop circuit water supply temperature via temperature sensor (TS-CW-05) located in its condenser water main supply piping.
        5) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the system heating hot water loop circuit return piping.
        6) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the system heating hot water loop circuit supply piping.

7) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the system heating hot water loop circuit return piping.
8) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the system chilled water loop circuit return piping.
9) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the system chilled water loop circuit supply piping.
10) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the system chilled water loop circuit return piping.

d. Activation of condenser artificial loading system response:
1) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) to its 10 percent open position.
2) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-05) to its full open position.
3) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its 90 percent open position.
4) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-08) to its full open position.
5) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
6) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.
7) BAS shall command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full open position.
8) BAS shall command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full open position.
9) BAS shall activate the geothermal loop field circuit start-up control algorithm.
10) Heat pump chiller condenser loop circuit water return and supply control valves shall be controlled as follows:
(a) BAS shall continuously calculate heat pump chiller condenser loop circuit water temperature change via temperature sensors (TS-CW-05) and (TS-CW-07).
(b) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) toward its closed position and shall simultaneously modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its open position upon detection of heat pump chiller condenser loop circuit water temperature change becoming less than design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07).
(c) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) toward its open position and shall simultaneously modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its closed position upon detection of heat pump chiller condenser loop circuit water temperature change approaching design value as measured by temperature sensors (TS-CW-05) and (TS-CW-07).
11) Geothermal loop field circuit pump VFD(s) shall be controlled as follows:
(a) BAS shall continuously calculate heat pump chiller condenser loop circuit water temperature change via temperature sensors (TS-CW-03) and (TS-CW-04).

(b) BAS shall forward setpoint temperature change to geothermal loop field circuit pump VFD's.
(c) Refer to geothermal loop circuit control algorithm for pump control algorithm.

e. Deactivation of condenser artificial loading system response:
1) BAS shall deactivate geothermal loop circuit control algorithm.
2) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) to its full closed position.
3) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-05) to its full closed position.
4) BAS shall modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its full open position.
5) BAS shall command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-08) to its full open position.
6) BAS shall maintain the geothermal loop field circuit chilled water control valve (CV-LFW-02) in its full closed position.
7) BAS shall maintain the geothermal loop field circuit chilled water control valve (CV-LFW-04) in its full closed position.
8) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full open position.
9) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full open position.

7. Heat pump chiller (CH-2) evaporator loop circuit artificial loading control algorithm:

a. General:
1) Control algorithm shall be activated upon detection all of the following conditions:
(a) BAS calculated system chilled water loop circuit load being less than BAS calculated system heating hot water loop circuit load for a five minute time period.
(b) Heat pump chiller evaporator loop circuit water temperature change being less than design value as measured by temperature sensors (TS-CHP-06) and (TS-CHP-07) for a five minute time period.
2) Control algorithm shall be deactivated upon detection all of the following conditions:
(a) BAS calculated system chilled water loop circuit load equal to or greater than BAS calculated system heating hot water loop circuit load for a five minute time period.
(b) Heat pump chiller evaporator loop circuit water temperature change being equal to or greater than design value as measured by temperature sensors (TS-CHP-06) and (TS-CHP-07) for a five minute time period.

b. Setpoints points shall include:
1) System setpoints shall be identical to those described in “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm” section above.
2) Heat pump chiller evaporator loop circuit water temperature change design value shall be equal to 10.0 °F.

c. Control points shall include:
1) BAS shall continuously monitor heat pump chiller evaporator loop circuit water return temperature via temperature sensor (TS-CHP-06) located in its chilled water main return piping.
2) BAS shall continuously monitor heat pump chiller evaporator loop circuit water supply temperature via temperature sensor (TS-CHP-07) located in its chilled water main supply piping.
3) BAS shall continuously monitor heat pump chiller evaporator loop circuit water supply temperature via temperature sensor (TS-CHP-05) located in its chilled

water main return piping.

4) BAS shall continuously monitor system chilled water loop circuit return water temperature via temperature sensor (TS-CHS-10) located in the system chilled water loop circuit return piping.
5) BAS shall continuously monitor system chilled water loop circuit supply water temperature via temperature sensor (TS-CHS-09) located in the system chilled water loop circuit supply piping.
6) BAS shall continuously monitor system chilled water loop circuit water flow rate via water flow meter (FM-CHS-03) located in the system chilled water loop circuit return piping.
7) BAS shall continuously monitor system heating hot water loop circuit return water temperature via temperature sensor (TS-HHW-01) located in the system heating hot water loop circuit return piping.
8) BAS shall continuously monitor system heating hot water loop circuit supply water temperature via temperature sensor (TS-HHW-02) located in the system heating hot water loop circuit supply piping.
9) BAS shall continuously monitor system heating hot water loop circuit water flow rate via water flow meter (FM-HHW-01) located in the system heating hot water loop circuit return piping.

d. Activation of evaporator artificial loading system response:
   1) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-06) to its full open position.
   2) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-05) to its full open position.
   3) BAS shall confirm/modulate the heat pump chiller condenser loop circuit water return control valve (CV-CW-07) to its full closed position.
   4) BAS shall confirm/command the heat pump chiller condenser loop circuit water supply control valve (CV-CW-08) to its full closed position.
   5) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.
   6) BAS shall confirm/command the geothermal loop field circuit condenser water control valve (CV-LFW-03) to its full closed position.
   7) BAS shall command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full open position.
   8) BAS shall command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full open position.
   9) BAS shall activate the geothermal loop field circuit start-up control algorithm.
   10) Geothermal loop field circuit pump VFD's shall be controlled as follows:
       (a) BAS shall continuously calculate heat pump chiller evaporator loop circuit water temperature change via temperature sensors (TS-CHP-05) and (TS-CHP-07).
       (b) BAS shall forward setpoint temperature change to geothermal loop field circuit pump VFD's.
       (c) Refer to geothermal loop circuit control algorithm for pump control algorithm.

e. Deactivation of evaporator artificial loading system response:
   1) BAS shall deactivate geothermal loop field circuit control algorithm.
   2) BAS shall maintain the geothermal loop field circuit condenser water control valve (CV-LFW-01) to its full closed position.
   3) BAS shall maintain the geothermal loop field circuit condenser water control valve (CV-LFW-03) in its full closed position.

4) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-02) to its full closed position.
5) BAS shall confirm/command the geothermal loop field circuit chilled water control valve (CV-LFW-04) to its full closed position.

8. Heat pump chiller (CH-2) condenser loop circuit pump control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.
      2) Heat pump chiller condenser loop circuit pump shall operate at variable speed to maintain design intended constant evaporator flow throughout system dynamic operation and as heat pump chillerss condenser tube pressure drop changes throughout the system's useful life.
   b. Setpoints points shall include:
      1) Heat pump chillerss condenser water flow rate shall be 6,400 gpm.
      2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed as determined during system start-up.
   c. Control points shall include:
      1) BAS shall continuously monitor heat pump chiller condenser loop circuit water flow rate via water flow meter (FM-CW-02) located in its condenser water return piping.
      2) BAS shall continuously monitor pump motor speed via pump VFD interface.
      3) BAS shall continuously monitor pump motor status via pump VFD interface.
   d. Heat pump chiller condenser loop circuit pump normal operation control algorithm:
      1) VFD shall gradually increase heat pump chiller condenser loop circuit pump speed toward maximum allowed motor speed upon detection of actual value being less than setpoint.
      2) VFD shall gradually decrease heat pump chiller condenser loop circuit pump speed toward minimum safe motor speed upon detection of actual value being greater than setpoint.
      3) BAS shall maintain active the following control algorithms:
         (a) Heat pump chiller condenser loop circuit pump alarm condition control algorithm.
   e. Heat pump chiller condenser loop circuit pump alarm condition control algorithm:
      1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller condenser loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
      2) BAS shall disable heat pump chiller (CH-2) circuit, second heating and cooling as described under “Heat pump chiller (CH-2) circuit, second heating and cooling automatic shut-down control algorithm”.
   f. Cancellation of failed heat pump chiller system evaporator loop circuit equipment response:
      1) BAS shall return to system pre-response operation.
      2) BAS shall initiate an all clear status at Operator Work Station.
   g. Heat pump chiller condenser loop circuit pump automatic shut-down control algorithm:
      1) BAS shall disable pump VFD.
      2) VFD shall gradually return pump speed to minimum safe motor speed.
      3) VFD shall stop pump.
      4) VFD shall set pump motor speed reference to minimum safe motor speed.
      5) BAS shall return control to calling operation mode.

9. Heat pump chiller (CH-2) circuit evaporator loop circuit pump control algorithm:
   a. General:
      1) Control algorithm shall be activated immediately upon completion of “Heat pump chiller (CH-2) circuit, second heating and cooling start-up control algorithm”.

2) Heat pump chiller evaporator loop circuit pump shall operate at variable speed to maintain design intended constant evaporator flow throughout system dynamic operation and as heat pump chillerss evaporator tube pressure drop changes throughout the system's useful life.

b. Setpoints points shall include:
   1) Heat pump chillerss evaporator water flow rate shall be 6,000 gpm.
   2) Minimum setpoint pump motor speed shall be 5 percent greater than minimum safe motor speed as determined during system start-up.

c. Control points shall include:
   1) BAS shall continuously monitor heat pump chiller evaporator loop circuit water flow rate via water flow meter (FM-CHP-02) located in its chilled water supply piping.
   2) BAS shall continuously monitor pump motor speed via pump VFD interface.
   3) BAS shall continuously monitor pump motor status via pump VFD interface.

d. Heat pump chiller evaporator loop circuit pump normal operation control algorithm:
   1) VFD shall gradually increase heat pump chiller evaporator loop circuit pump speed toward maximum allowed motor speed upon detection of actual value being less than setpoint.
   2) VFD shall gradually decrease heat pump chiller evaporator loop circuit pump speed toward minimum safe motor speed upon detection of actual value being greater than setpoint.
   3) BAS shall maintain active the following control algorithms:
      (a) Heat pump chiller evaporator loop circuit pump alarm condition control algorithm.

e. Heat pump chiller evaporator loop circuit pump alarm condition control algorithm:
   1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller evaporator loop circuit pump has failed upon detection of actual status being opposite of commanded status for any time period.
   2) BAS shall disable heat pump chiller (CH-2) circuit, second heating and cooling as described under “Heat pump chiller (CH-2) circuit, second heating and cooling automatic shut-down control algorithm”.

f. Cancellation of failed heat pump chiller evaporator loop circuit equipment response:
   1) BAS shall return to system pre-response operation.
   2) BAS shall initiate an all clear status at Operator Work Station.

g. Heat pump chiller evaporator loop circuit pump automatic shut-down control algorithm:
   1) BAS shall disable pump VFD.
   2) VFD shall gradually return pump speed to minimum safe motor speed.
   3) VFD shall stop pump.
   4) VFD shall set pump motor speed reference to minimum safe motor speed.
   5) BAS shall return control to calling operation mode.

10. Heat pump chiller (CH-2) alarm condition - equipment control algorithm:

a. Activation of alarm condition system response:
   1) BAS shall initiate an alarm condition at the Operator Work Station indicating heat pump chiller (HPC) circuit, first dedicated heating has failed upon detection of actual status being opposite of commanded status for any time period.
   2) BAS shall disable heat pump chiller (CH-2) circuit, first dedicated heating as described under "Heat pump chiller (CH-2) circuit automatic shut-down control algorithm.”

b. Cancellation of failed heat pump chiller (CH-2) circuit, second heating and cooling system response:
   1) BAS shall return to system pre-response operation.
   2) BAS shall initiate an all clear status at Operator Work Station.

11. Heat pump chiller (CH-2) alarm condition - temperature/flow control algorithm:
   a. General:
      1) Alarm condition shall be activated upon detection of any temperature or flow being beyond tolerance as described below.
      2) Alarm shall be capable of being reset at Operator Work Station.
      3) BAS shall cancel temperature/flow system alarm response upon detection of any of the following conditions:
         (a) Upon detection of parameter formerly beyond allowable alarm limit becoming within allowable alarm limit.
         (b) Alarm notification being cancelled at Operator Work Station.
   b. Setpoints - heat pump chiller condenser loop circuit shall include:
      1) Heat pump chillerss condenser water return temperature being equal to or greater than one ºF above or below setpoint for a ten minute time period.
      2) Heat pump chillers condenser water supply temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      3) Heat pump chiller condenser loop circuit main condenser water return temperature being equal to or greater than one ºF above or below heat pump chillers condenser water return temperature for a ten minute time period.
      4) Heat pump chiller condenser loop circuit main condenser water supply temperature being equal to or greater than one ºF above or below heat pump chillers condenser water supply temperature for a ten minute time period.
      5) Heat pump chillerss condenser water flow being equal to or greater than 15 percent above or below setpoint for a ten minute time period.
      6) Heat pump chiller condenser loop circuit decoupler (bypass) water temperature being equal to or greater than one ºF below the condenser water return temperature for a ten minute time period.
   c. Setpoints - heat pump chiller evaporator loop circuit (chilled water primary loop circuit) shall include:
      1) Heat pump chillerss evaporator chilled water return temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      2) heat pump chillerss evaporator chilled water supply temperature being equal to or greater than one ºF above or below alarm limit setpoint for a ten minute time period.
      3) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) main chilled water return temperature being equal to or greater than one ºF above or below heat pump chillerss evaporator return water temperature for a ten minute time period.
      4) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) main chilled water supply temperature being equal to or greater than one ºF above or below heat pump chillerss evaporator supply water temperature for a ten minute time period.
      5) Heat pump chillerss evaporator chilled water flow being equal to or less than 15 percent above or below setpoint for a ten minute time period.
      6) Heat pump chiller evaporator loop circuit (chilled water primary loop circuit) decoupler (bypass) water temperature being equal to or greater than one ºF above the chilled water supply temperature for a ten minute time period.
   d. Control points - heat pump chiller condenser loop circuit shall include:
      1) BAS shall continuously monitor heat pump chillerss condenser water return temperature via temperature sensor (TS-CW-04) located in the condenser return piping.

2) BAS shall continuously monitor heat pump chillerss condenser water supply temperature via temperature sensor (TS-CW-03) located in the condenser return piping.
3) BAS shall continuously monitor heat pump chiller condenser loop circuit main condenser water return temperature via temperature (TS-CW-07) sensor located in the heat pump chiller condenser loop circuit main return piping.
4) BAS shall continuously monitor heat pump chiller condenser loop circuit main condenser water supply temperature via temperature (TS-CW-05) sensor located in the heat pump chiller condenser loop circuit main supply piping.
5) BAS shall continuously monitor heat pump chillerss condenser water flow rate via water flow meter (FM-CW-01) located in the condenser water return piping.
6) BAS shall continuously monitor heat pump chiller condenser loop circuit decoupler (bypass) condenser water return temperature via temperature sensor (TS-CWB-06) located in the decoupler (bypass) piping.

e. Control points - heat pump chiller evaporator loop circuit (chilled water primary loop circuit) shall include:
1) BAS shall continuously monitor heat pump chillerss evaporator chilled water return temperature via temperature sensor (TS-CHP-03) located in the evaporator return piping.
2) BAS shall continuously monitor heat pump chillerss evaporator chilled water supply temperature via temperature sensor (TS-CHP-04) located in the evaporator supply piping.
3) BAS shall continuously monitor chiller evaporator loop piping system (chilled water primary loop) main chilled water return temperature via temperature sensor (TS-CHP-06) located in the chiller evaporator loop piping system (chilled water primary loop) main return piping.
4) BAS shall continuously monitor chiller evaporator loop piping system (chilled water primary loop) main chilled water supply temperature via temperature sensor (TS-CHP-07) located in the chiller evaporator loop piping system (chilled water primary loop) main supply piping.
5) BAS shall continuously monitor heat pump chillerss evaporator chilled water flow rate via water flow meter (FM-CHP-02) located in the evaporator return piping.
6) BAS shall continuously monitor heat pump chiller evaporator loop circuit decoupler (bypass) chilled water supply temperature via temperature sensor (TS-CHB-08) located in the decoupler (bypass) piping.

f. Activation of alarm condition - temperature/flow system response:
1) BAS shall initiate an alarm condition at the Operator Work Station indicating which temperature sensor or water flow meter is above or below alarm setpoint.
2) BAS shall maintain normal pre-response status of heat pump chiller system, system heating hot water loop circuit, system chilled water loop circuit, and geothermal loop field circuit operation.

g. Cancellation of alarm condition - temperature/flow system response:
1) BAS shall return to system pre-response operation.
2) BAS shall initiate an all clear status at Operator Work Station.

12. Heat pump chiller (CH-2) circuit automatic shut-down control algorithm:

a. General:
1) Control algorithm shall be activated by calling operation mode.
2) Control algorithm shall be deactivated by calling operation mode.

b. Setpoints points shall include:
1) BAS shall activate system response upon detection of calling operation mode and upon detection of any of the following conditions:
(a) Scheduled unoccupied time period having passed.
(b) Manual shut-down command issued form Operator Work Station.

(c) Alarm condition call for system shut-down.

2) BAS shall deactivate system response upon detection of any of the following conditions:

(a) Any other operation mode having been activated.

c. Control points shall include:

1) BAS shall continuously monitor time clock.

d. Activation of shut-down system response:

1) BAS shall deactivate heat pump chillerss MCP.
2) Heat pump chillerss MCP shall initiate chiller shut-down.
3) BAS shall take no action for time period required by heat pump chiller.
4) BAS shall activate the heat pump chiller condenser loop circuit pump automatic shut-down control algorithm associated with the heat pump chiller (CH-2) circuit.
5) BAS shall activate the heat pump chiller evaporator loop circuit pump automatic shut-down control algorithm associated with the heat pump chiller (CH-2) circuit.

13. Heat pump chiller (CH-2) circuit manual shut-down control algorithm:

a. General:

1) Control algorithm shall be activated by command issued from the Operator Work Station.
2) BAS shall deactivate operation mode upon detection of a manual release issued from the Operator Work Station.

b. Setpoints points shall include:

1) Not applicable.

c. Control points shall include:

1) BAS shall continuously monitor Operator Work Station interface.

d. Activation of shut-down system response:

1) BAS shall deactivate heat pump chiller (CH-2) circuit described under section “Heat pump chiller (CH-2) circuit automatic shut-down control algorithm”.
2) BAS shall deactivate heat pump chiller (CH-2) circuit regardless to any other conditions described under section “Heat pump chiller (CH-2) circuit automatic shut-down control algorithm”.

END OF SECTION

Appendix 5: Typical DESS Loop Field Data Report

DESS Ground Loop

Location: **Ball State University / Ball State Muncie** **Run Date: 8/1/2016 1:00:35 PM**

Time	TAO	TGWS	TGWR	FGW	SPDGWP4
7/24/2016 0:00	81.9	91.2	102.7	5,800.30	40
7/24/2016 0:30	82.1	91.1	102.9	5,800.30	40
7/24/2016 1:00	82.4	91.1	102.1	5,800.30	40
7/24/2016 1:30	81.9	91.1	102.4	5,821.40	40
7/24/2016 2:00	81.1	91.1	102.3	5,779.30	40
7/24/2016 2:30	80.4	91	102.7	5,800.30	40
7/24/2016 3:00	79.8	91	102.2	5,800.30	40
7/24/2016 3:30	79.4	90.9	102.1	5,779.30	40
7/24/2016 4:00	79.5	90.8	101.9	5,800.30	40
7/24/2016 4:30	77.7	90.8	101.5	5,800.30	40
7/24/2016 5:00	77.1	90.6	101.2	5,821.40	40
7/24/2016 5:30	76.4	90.5	100.7	5,821.40	40
7/24/2016 6:00	76.1	90.3	100.1	5,842.40	40
7/24/2016 6:30	75.6	90.1	99.3	5,800.30	40
7/24/2016 7:00	75.5	90	99.2	5,842.40	40
7/24/2016 7:30	80.8	89.9	98.6	5,821.40	40
7/24/2016 8:00	86.8	89.8	98.5	5,821.40	40
7/24/2016 8:30	90.3	89.7	98.7	5,779.30	40
7/24/2016 9:00	87.6	89.7	98.7	5,821.40	40
7/24/2016 9:30	90.8	89.7	99.2	5,821.40	40
7/24/2016 10:00	89.8	89.8	99.7	5,800.30	40
7/24/2016 10:30	92.7	89.9	100.5	5,800.30	40
7/24/2016 11:00	92.6	89.9	101	5,800.30	40
7/24/2016 11:30	91.8	90.1	101.9	5,800.30	40
7/24/2016 12:00	93.5	90.3	102.5	5,821.40	40
7/24/2016 12:30	93.9	90.6	102.9	5,800.30	40
7/24/2016 13:00	96.3	90.8	103.7	5,821.40	40
7/24/2016 13:30	96.9	91	104	5,800.30	40
7/24/2016 14:00	97.7	91.2	103.9	5,800.30	40
7/24/2016 14:30	97.8	91.4	104.4	5,800.30	40
7/24/2016 15:00	97.2	91.5	104.2	5,779.30	40
7/24/2016 15:30	99.9	91.6	104.7	5,842.40	40
7/24/2016 16:00	100	91.7	104.9	5,779.30	40
7/24/2016 16:30	99.9	91.8	103.9	5,842.40	40
7/24/2016 17:00	100.2	91.7	104.3	5,800.30	40
7/24/2016 17:30	100.9	91.8	104.6	5,800.30	40
7/24/2016 18:00	100.2	91.8	104.8	5,821.40	40
7/24/2016 18:30	103.8	91.9	104.9	5,821.40	40
7/24/2016 19:00	100.9	92	105	5,779.30	40

7/24/2016 19:30	99.7	92.1	105.2	5,800.30	40
7/24/2016 20:00	98.2	92.1	105.3	5,800.30	40
7/24/2016 20:30	96.6	92.2	105.3	5,800.30	40
7/24/2016 21:00	90.8	92.2	105.1	5,800.30	40
7/24/2016 21:30	88.8	92.2	105.1	5,779.30	40
7/24/2016 22:00	87.8	92.2	104.9	5,779.30	40
7/24/2016 22:30	86.7	92.2	104.7	5,779.30	40
7/24/2016 23:00	85.9	92.1	104.6	5,779.30	40
7/24/2016 23:30	84.9	92.1	104.2	5,758.30	40
7/25/2016 0:00	84.3	92	104	5,821.40	40
7/25/2016 0:30	83.6	91.9	103.5	5,821.40	40
7/25/2016 1:00	83.1	91.8	103.6	5,779.30	40
7/25/2016 1:30	82.6	91.8	103.4	5,800.30	40
7/25/2016 2:00	82.1	91.7	102.9	5,800.30	40
7/25/2016 2:30	80.3	91.6	102.1	5,800.30	40
7/25/2016 3:00	79.2	91.4	101.5	5,821.40	40
7/25/2016 3:30	78	91.2	100.7	5,821.40	40
7/25/2016 4:00	77.2	90.9	99.3	5,842.40	40
7/25/2016 4:30	76.6	90.5	99.6	5,779.30	40
7/25/2016 5:00	76.3	90.3	99.2	5,842.40	40
7/25/2016 5:30	76.1	90.1	98.2	5,821.40	40
7/25/2016 6:00	75.5	90	98.3	5,800.30	40
7/25/2016 6:30	75.1	89.8	98.4	5,821.40	40
7/25/2016 7:00	75.7	89.7	99.5	5,800.30	40
7/25/2016 7:30	76.3	89.7	99.8	5,800.30	40
7/25/2016 8:00	76.9	90.1	99.7	5,800.30	40
7/25/2016 8:30	79.8	90.1	100.4	5,821.40	40
7/25/2016 9:00	84	90.1	100.7	5,800.30	40
7/25/2016 9:30	88.5	90.1	100.7	5,800.30	40
7/25/2016 10:00	84.4	90	100.9	5,821.40	40
7/25/2016 10:30	84.2	90.1	100.6	5,800.30	40
7/25/2016 11:00	86.3	90.1	100.9	5,800.30	40
7/25/2016 11:30	86.9	90.2	101.1	5,800.30	40
7/25/2016 12:00	87.2	90.4	101.2	5,779.30	40
7/25/2016 12:30	87.6	90.5	101.4	5,800.30	40
7/25/2016 13:00	87.6	90.6	102.1	5,779.30	40
7/25/2016 13:30	89.6	90.7	102.7	5,779.30	40
7/25/2016 14:00	91.3	90.8	102.8	5,821.40	40
7/25/2016 14:30	91.3	91	103.3	5,800.30	40
7/25/2016 15:00	91.5	91.1	103.7	5,821.40	40
7/25/2016 15:30	92.7	91.3	104.3	5,800.30	40
7/25/2016 16:00	95.4	91.5	104.5	5,821.40	40

7/25/2016 16:30	93.5	91.7	104.7	5,800.30	40
7/25/2016 17:00	91.3	91.8	105.4	5,800.30	40
7/25/2016 17:30	93.6	92.1	106.4	5,779.30	40
7/25/2016 18:00	91.9	92.2	106.1	5,800.30	40
7/25/2016 18:30	94.9	92.4	106.8	5,779.30	40
7/25/2016 19:00	95.4	92.6	106.2	5,821.40	40
7/25/2016 19:30	96.9	92.7	106.6	5,779.30	40
7/25/2016 20:00	92.4	92.7	106.7	5,800.30	40
7/25/2016 20:30	88.4	92.7	105.5	5,800.30	40
7/25/2016 21:00	84.4	92.6	104.4	5,800.30	40
7/25/2016 21:30	82.9	92.6	103.8	5,821.40	40
7/25/2016 22:00	81.9	92.5	105.9	5,779.30	40
7/25/2016 22:30	80.9	92.4	104	5,821.40	40
7/25/2016 23:00	79.7	92.3	103.1	5,800.30	40
7/25/2016 23:30	79.2	92.1	102.4	5,779.30	40
7/26/2016 0:00	78.6	91.9	101.8	5,821.40	40
7/26/2016 0:30	77.8	91.6	101.9	5,800.30	40
7/26/2016 1:00	77.3	91.4	101.8	5,842.40	40
7/26/2016 1:30	76.3	91.1	100.5	5,800.30	40
7/26/2016 2:00	75.6	90.9	99.6	5,821.40	40
7/26/2016 2:30	74.2	90.7	99.2	5,842.40	40
7/26/2016 3:00	73.7	90.5	99.3	5,821.40	40
7/26/2016 3:30	72.9	90.3	98.4	5,821.40	40
7/26/2016 4:00	72.9	90.1	98.5	5,800.30	40
7/26/2016 4:30	72.4	89.9	98.1	5,779.30	40
7/26/2016 5:00	71.5	89.7	98.8	5,800.30	40
7/26/2016 5:30	70.6	89.6	98.2	5,821.40	40
7/26/2016 6:00	70.6	89.5	97.4	5,779.30	40
7/26/2016 6:30	71	89.4	98.2	5,779.30	40
7/26/2016 7:00	71.5	89.3	97.1	5,779.30	40
7/26/2016 7:30	76.1	89.2	97.6	5,800.30	40
7/26/2016 8:00	74.7	89.1	97.4	5,800.30	40
7/26/2016 8:30	74.5	89.1	100.1	5,758.30	40
7/26/2016 9:00	77.1	89.6	99.1	5,800.30	40
7/26/2016 9:30	82.1	89.7	99.6	5,779.30	40
7/26/2016 10:00	80.1	89.8	99.4	5,800.30	40
7/26/2016 10:30	81.9	89.9	100.4	5,779.30	40
7/26/2016 11:00	84.1	89.9	100.8	5,800.30	40
7/26/2016 11:30	85.8	90	100.7	5,800.30	40
7/26/2016 12:00	86.7	90.1	101	5,779.30	40
7/26/2016 12:30	88.3	90.2	101.3	5,800.30	40
7/26/2016 13:00	87.5	90.3	101	5,779.30	40

7/26/2016 13:30	85.9	90.4	100.8	5,800.30	40
7/26/2016 14:00	84.6	90.4	101.1	5,821.40	40
7/26/2016 14:30	86.2	90.4	101	5,800.30	40
7/26/2016 15:00	89.1	90.5	101.2	5,821.40	40
7/26/2016 15:30	89	90.5	98.6	5,800.30	40
7/26/2016 16:00	87.7	90.5	99.4	5,800.30	40
7/26/2016 16:30	89.5	90	99.6	5,800.30	40
7/26/2016 17:00	89.7	90	99.5	5,800.30	40
7/26/2016 17:30	89.4	90.1	99.5	5,821.40	40
7/26/2016 18:00	90.3	90.1	100.4	5,800.30	40
7/26/2016 18:30	96.7	90.1	101	5,800.30	40
7/26/2016 19:00	97.7	90.2	101	5,779.30	40
7/26/2016 19:30	97.7	90.2	100.9	5,779.30	40
7/26/2016 20:00	93.4	90.2	100.9	5,821.40	40
7/26/2016 20:30	91.1	90.2	100.5	5,800.30	40
7/26/2016 21:00	82.4	90.1	99.4	5,779.30	40
7/26/2016 21:30	79.2	90.1	99.1	5,821.40	40
7/26/2016 22:00	77.5	90	99.4	5,821.40	40
7/26/2016 22:30	77.1	90	99.2	5,821.40	40
7/26/2016 23:00	76	90	99.5	5,821.40	40
7/26/2016 23:30	75.1	89.9	99.4	5,800.30	40
7/27/2016 0:00	74.1	89.8	98.7	5,821.40	40
7/27/2016 0:30	73.5	89.6	98.6	5,779.30	40
7/27/2016 1:00	72.7	89.5	97.8	5,779.30	40
7/27/2016 1:30	71.9	89.4	98.3	5,758.30	40
7/27/2016 2:00	71.6	89.4	97.7	5,842.40	40
7/27/2016 2:30	71.2	89.3	97.8	5,800.30	40
7/27/2016 3:00	70.6	89.2	97.5	5,821.40	40
7/27/2016 3:30	70.1	89.1	97.4	5,800.30	40
7/27/2016 4:00	69.6	89	96.9	5,821.40	40
7/27/2016 4:30	69	88.9	97.2	5,863.40	40
7/27/2016 5:00	68.6	88.8	97	5,800.30	40
7/27/2016 5:30	68.3	88.7	97.1	5,779.30	40
7/27/2016 6:00	67.8	88.7	96.8	5,800.30	40
7/27/2016 6:30	67.8	88.7	96.6	5,821.40	40
7/27/2016 7:00	68.7	88.6	99.5	5,800.30	40
7/27/2016 7:30	69.9	88.8	99.1	5,800.30	40
7/27/2016 8:00	78.4	89.2	99.7	5,800.30	40
7/27/2016 8:30	81.3	89.3	99.2	5,800.30	40
7/27/2016 9:00	90	89.3	99.9	5,800.30	40
7/27/2016 9:30	89.8	89.5	99.9	5,821.40	40
7/27/2016 10:00	82.2	89.5	100	5,779.30	40

7/27/2016 10:30	83.2	89.6	100.4	5,779.30	40
7/27/2016 11:00	84.2	89.7	100.2	5,800.30	40
7/27/2016 11:30	84.5	89.8	100.1	5,779.30	40
7/27/2016 12:00	85.6	89.9	100.2	5,821.40	40
7/27/2016 12:30	86.8	90	100.5	5,779.30	40
7/27/2016 13:00	86.9	90	101	5,800.30	40
7/27/2016 13:30	87.2	90.1	100.8	5,800.30	40
7/27/2016 14:00	87.9	90.2	101.1	5,800.30	40
7/27/2016 14:30	88.9	90.3	101.1	5,779.30	40
7/27/2016 15:00	88.9	90.4	101.2	5,758.30	40
7/27/2016 15:30	90	90.5	101.2	5,779.30	40
7/27/2016 16:00	90.6	90.5	101.4	5,800.30	40
7/27/2016 16:30	91.4	90.6	101.5	5,779.30	40
7/27/2016 17:00	92.8	90.6	101.6	5,800.30	40
7/27/2016 17:30	93.9	90.6	101.3	5,800.30	40
7/27/2016 18:00	93.8	90.6	101.4	5,779.30	40
7/27/2016 18:30	96.1	90.6	101.6	5,779.30	40
7/27/2016 19:00	93.9	90.7	101.5	5,779.30	40
7/27/2016 19:30	90.5	90.8	101.3	5,800.30	40
7/27/2016 20:00	86.8	90.8	101.6	5,779.30	40
7/27/2016 20:30	93	90.8	101.5	5,779.30	40
7/27/2016 21:00	85.4	90.7	101.3	5,758.30	40
7/27/2016 21:30	82.1	90.7	100.9	5,800.30	40
7/27/2016 22:00	79.6	90.7	100.9	5,779.30	40
7/27/2016 22:30	78	90.6	100.3	5,779.30	40
7/27/2016 23:00	76.9	90.5	100.3	5,758.30	40
7/27/2016 23:30	75.9	90.5	100.7	5,779.30	40
7/28/2016 0:00	75	90.4	100.7	5,779.30	40
7/28/2016 0:30	75.9	90.3	100.3	5,779.30	40
7/28/2016 1:00	76.1	90.3	99.7	5,779.30	40
7/28/2016 1:30	76.1	90.3	100.3	5,779.30	40
7/28/2016 2:00	76	90.2	100.4	5,800.30	40
7/28/2016 2:30	76	90.2	100.5	5,779.30	40
7/28/2016 3:00	75.1	90.2	100.4	5,800.30	40
7/28/2016 3:30	74.4	90.2	100.6	5,800.30	40
7/28/2016 4:00	74.9	90.2	100.6	5,779.30	40
7/28/2016 4:30	73.6	90.2	100	5,779.30	40
7/28/2016 5:00	73.1	90.2	99.6	5,779.30	40
7/28/2016 5:30	72.7	90.2	99.7	5,800.30	40
7/28/2016 6:00	72.3	90.2	100	5,758.30	40
7/28/2016 6:30	72.4	90.2	100.7	5,821.40	40
7/28/2016 7:00	71.9	90.2	100	5,779.30	40

7/28/2016 7:30	74	90.2	99.9	5,779.30	40
7/28/2016 8:00	75.8	90.1	99.8	5,800.30	40
7/28/2016 8:30	76.7	90.5	99.3	6,556.90	45
7/28/2016 9:00	78.8	90.5	100	6,556.90	45
7/28/2016 9:30	82.7	90.5	99.8	6,556.90	45
7/28/2016 10:00	82.3	90.6	99.9	6,577.90	45
7/28/2016 10:30	82.7	90.6	100.7	6,535.90	45
7/28/2016 11:00	84.3	90.7	100.8	6,556.90	45
7/28/2016 11:30	85.9	90.8	100.7	6,409.80	45
7/28/2016 12:00	88.1	90.9	100.5	6,577.90	45
7/28/2016 12:30	89.5	91	101.3	6,556.90	45
7/28/2016 13:00	89.9	91.1	101.2	6,430.80	45
7/28/2016 13:30	91.5	91.2	101.4	6,556.90	45
7/28/2016 14:00	92	91.3	101.6	6,556.90	45
7/28/2016 14:30	92.2	91.4	101.5	6,535.90	45
7/28/2016 15:00	91.8	91.4	101.6	6,535.90	45
7/28/2016 15:30	91.9	91.5	99	6,577.90	45
7/28/2016 16:00	91.8	91.3	99.7	6,556.90	45
7/28/2016 16:30	94.1	91	99.9	6,598.90	45
7/28/2016 17:00	93.2	91	99.7	6,577.90	45
7/28/2016 17:30	93.1	91	99.9	6,577.90	45
7/28/2016 18:00	93.7	91	100.3	6,556.90	45
7/28/2016 18:30	97	91	101	6,577.90	45
7/28/2016 19:00	98.6	91.1	100.8	6,577.90	45
7/28/2016 19:30	97.4	91.1	101.1	6,556.90	45
7/28/2016 20:00	93.7	91.2	101.1	6,556.90	45
7/28/2016 20:30	88.4	91.2	100.9	6,577.90	45
7/28/2016 21:00	84.4	91.2	101.1	6,577.90	45
7/28/2016 21:30	82.6	91.1	100.4	6,556.90	45
7/28/2016 22:00	81	91	99.9	6,556.90	45
7/28/2016 22:30	79.6	90.9	99.2	6,620.00	45
7/28/2016 23:00	78.4	90.8	98.7	6,577.90	45
7/28/2016 23:30	79.1	90.7	98.5	6,577.90	45
7/29/2016 0:00	77.7	90.6	99	6,535.90	45
7/29/2016 0:30	76.6	90.4	98.4	6,556.90	45
7/29/2016 1:00	75.8	90.3	98.2	6,556.90	45
7/29/2016 1:30	75.7	90.2	98	6,535.90	45
7/29/2016 2:00	74.9	90.1	97.5	6,577.90	45
7/29/2016 2:30	73.8	90	97.3	6,556.90	45
7/29/2016 3:00	72.9	89.9	96.8	6,535.90	45
7/29/2016 3:30	72.3	89.7	97.3	6,556.90	45
7/29/2016 4:00	71.8	89.7	97	6,535.90	45

7/29/2016 4:30	71.6	89.6	96.7	6,556.90	45
7/29/2016 5:00	70.6	89.5	96.4	6,535.90	45
7/29/2016 5:30	69.9	89.4	96.8	6,535.90	45
7/29/2016 6:00	69.6	89.3	96.2	6,577.90	45
7/29/2016 6:30	69.1	89.3	96.7	6,556.90	45
7/29/2016 7:00	69.7	89.3	98	6,514.90	45
7/29/2016 7:30	75.1	89.8	98.2	6,556.90	45
7/29/2016 8:00	79.5	89.8	98.6	6,535.90	45
7/29/2016 8:30	81.7	89.9	99.3	6,535.90	45
7/29/2016 9:00	85.6	90.1	99.4	6,535.90	45
7/29/2016 9:30	86.4	90.2	99.2	6,514.90	45
7/29/2016 10:00	84.2	90.4	99.9	6,556.90	45
7/29/2016 10:30	85.2	90.5	100.7	6,535.90	45
7/29/2016 11:00	85.4	90.7	100.7	6,535.90	45
7/29/2016 11:30	88.5	90.9	101.3	6,556.90	45
7/29/2016 12:00	89.3	91	101.2	6,514.90	45
7/29/2016 12:30	90	91.2	102	6,556.90	45
7/29/2016 13:00	92.4	91.3	101.5	6,556.90	45
7/29/2016 13:30	92.3	91.5	102.2	6,556.90	45
7/29/2016 14:00	94.6	91.6	102.4	6,493.90	45
7/29/2016 14:30	89.4	91.7	102.5	6,556.90	45
7/29/2016 15:00	80.5	91.8	102.4	6,556.90	45
7/29/2016 15:30	78.6	91.9	100.7	6,535.90	45
7/29/2016 16:00	82.8	91.5	100.4	6,514.90	45
7/29/2016 16:30	84.6	91.2	100.5	6,577.90	45
7/29/2016 17:00	87.4	91.1	100.3	6,556.90	45
7/29/2016 17:30	89.1	91.1	100	6,556.90	45
7/29/2016 18:00	91.2	91.1	99.8	6,577.90	45
7/29/2016 18:30	86.7	91	100.3	6,577.90	45
7/29/2016 19:00	82.7	91.1	100.4	6,535.90	45
7/29/2016 19:30	79	91.1	100.6	6,577.90	45
7/29/2016 20:00	75.8	91	100.2	6,430.80	45
7/29/2016 20:30	72.8	90.9	99.5	6,535.90	45
7/29/2016 21:00	72.5	90.8	99.5	6,556.90	45
7/29/2016 21:30	72.9	90.7	99.3	6,577.90	45
7/29/2016 22:00	73	90.5	98.4	6,556.90	45
7/29/2016 22:30	72.7	90.4	98.4	6,535.90	45
7/29/2016 23:00	72.2	90.3	98.5	6,430.80	45
7/29/2016 23:30	71.9	90.1	98	6,556.90	45
7/30/2016 0:00	71.6	90	97.2	6,556.90	45
7/30/2016 0:30	71.1	89.9	97.6	6,514.90	45
7/30/2016 1:00	70.8	89.7	96.7	6,556.90	45

7/30/2016 1:30	70.4	89.6	96.6	6,535.90	45
7/30/2016 2:00	70.3	89.5	96.2	6,556.90	45
7/30/2016 2:30	69.9	89.4	95.8	6,535.90	45
7/30/2016 3:00	69.6	89.3	96.3	6,556.90	45
7/30/2016 3:30	69.2	89.2	95.8	6,514.90	45
7/30/2016 4:00	69.3	89.1	95.8	6,451.80	45
7/30/2016 4:30	69.6	89	96.1	6,556.90	45
7/30/2016 5:00	69.5	88.9	95.6	6,577.90	45
7/30/2016 5:30	68.9	88.9	95.7	6,577.90	45
7/30/2016 6:00	68.9	88.9	96	6,556.90	45
7/30/2016 6:30	68.7	89	98.4	6,556.90	45
7/30/2016 7:00	69.1	89.5	98.4	6,535.90	45
7/30/2016 7:30	69.6	89.6	98.5	6,556.90	45
7/30/2016 8:00	70.8	89.6	98.6	6,430.80	45
7/30/2016 8:30	72	89.7	97.8	6,556.90	45
7/30/2016 9:00	74.8	89.7	97.7	6,556.90	45
7/30/2016 9:30	77.1	89.8	98.3	6,535.90	45
7/30/2016 10:00	77.2	89.9	99.1	6,493.90	45
7/30/2016 10:30	78.1	90	99.4	6,556.90	45
7/30/2016 11:00	80.6	90.2	100	6,535.90	45
7/30/2016 11:30	80.9	90.3	100.2	6,577.90	45
7/30/2016 12:00	82.5	90.4	99.7	6,535.90	45
7/30/2016 12:30	84	90.6	100.3	6,535.90	45
7/30/2016 13:00	83.7	90.8	100.6	6,535.90	45
7/30/2016 13:30	83.6	90.8	98	6,556.90	45
7/30/2016 14:00	84.5	90.4	98.6	6,577.90	45
7/30/2016 14:30	84.5	90.4	99.2	6,556.90	45
7/30/2016 15:00	85.7	90.4	100	6,556.90	45
7/30/2016 15:30	87.6	90.5	100.2	6,556.90	45
7/30/2016 16:00	86.4	90.5	99.6	6,556.90	45
7/30/2016 16:30	89.1	90.5	99.2	6,556.90	45
7/30/2016 17:00	89.2	90.5	99.3	6,556.90	45
7/30/2016 17:30	89.4	90.5	98.6	6,556.90	45
7/30/2016 18:00	89.3	90.5	99.1	6,556.90	45
7/30/2016 18:30	94	90.5	99.7	6,556.90	45
7/30/2016 19:00	94	90.6	99.3	6,535.90	45
7/30/2016 19:30	94.3	90.6	99.9	6,535.90	45
7/30/2016 20:00	93.4	90.6	99.6	6,556.90	45
7/30/2016 20:30	88.8	90.5	99.2	6,556.90	45
7/30/2016 21:00	81.6	90.5	99.3	6,577.90	45
7/30/2016 21:30	79.8	90.5	98.6	6,577.90	45
7/30/2016 22:00	77.5	90.4	98	6,577.90	45

7/30/2016 22:30	77.6	90.3	98.1	6,556.90	45
7/30/2016 23:00	76.6	90.2	97.9	6,556.90	45
7/30/2016 23:30	74.7	90.1	97.3	6,430.80	45

SPDGWP5	SPDGWP6	SPDHWP4	SPDHWP5	SPDHWP6	SPDCHWP4	SPDCHWP5	SPDCHWP6
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55	0	55
40	0	60	60	0	56	0	56
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56	0	56
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	56.2	0	56.2
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	56	0	56
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	55	0	55
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	55.1	0	55.1
40	0	60	60	0	55.2	0	55.2
40	0	60	60	0	55.2	0	55.2
40	0	60	60	0	55.2	0	55.2
40	0	60	60	0	54.8	0	54.8

40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	54.8	0	54.8
40	0	60	60	0	55	0	55
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.1	0	55.1
40	0	60	60	0	56	0	56
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.1	0	55.1
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	56	0	56
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	56.2	0	56.2
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.2	0	56.2
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	56	0	56
40	0	60	60	0	56.2	0	56.2
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	54.9	0	54.9
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	56.2	0	56.2

40	0	60	60	0	55.2	0	55.2
40	0	60	60	0	55.4	0	55.4
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	55	0	55
40	0	60	60	0	55.5	0	55.5
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	55.2	0	55.2
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	55.3	0	55.3
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	56	0	56
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	55.8	0	55.8
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	56	0	56
40	0	60	60	0	55.6	0	55.6
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57.2	0	57.2
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	57	0	57
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.9	0	56.9

40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56	0	56
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.1	0	56.1
40	0	60	60	0	55.9	0	55.9
40	0	60	60	0	55.7	0	55.7
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	57	0	57
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	57	0	57
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.4	0	57.4
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	56.9	0	56.9
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57.4	0	57.4
40	0	60	60	0	57.9	0	57.9
40	0	60	60	0	57.6	0	57.6
40	0	60	60	0	57.9	0	57.9
40	0	60	60	0	57	0	57
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	56.9	0	56.9

40	0	60	60	0	57.2	0	57.2
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	56.8	0	56.8
40	0	60	60	0	57.2	0	57.2
40	0	60	60	0	56.9	0	56.9
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40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	56.3	0	56.3
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	56.4	0	56.4
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57.8	0	57.8
40	0	60	60	0	56.6	0	56.6
40	0	60	60	0	56.5	0	56.5
40	0	60	60	0	57	0	57
40	0	60	60	0	57.2	0	57.2
40	0	60	60	0	57.7	0	57.7
40	0	60	60	0	56.7	0	56.7
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	57.6	0	57.6
40	0	60	60	0	62.1	0	62.1
40	0	60	60	0	57.3	0	57.3
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	58.1	0	58.1
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	57.9	0	57.9
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	58.1	0	58.1
40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.5	0	57.5
40	0	60	60	0	57.6	0	57.6
40	0	60	60	0	56.7	0	56.7

40	0	60	60	0	57.1	0	57.1
40	0	60	60	0	57.7	0	57.7
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.1	0	57.1
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	56.2	0	56.2
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	56.8	0	56.8
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	57	0	57
45	0	60	60	0	57.1	0	57.1
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	56.1	0	56.1
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	55.9	0	55.9
45	0	60	60	0	56	0	56
45	0	60	60	0	57	0	57
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	55.8	0	55.8
45	0	60	60	0	55.4	0	55.4
45	0	60	60	0	55.4	0	55.4
45	0	60	60	0	56.6	0	56.6
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	56.6	0	56.6
45	0	60	60	0	55.9	0	55.9
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	56.2	0	56.2
45	0	60	60	0	57	0	57
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	57.4	0	57.4

45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	57.9	0	57.9
45	0	60	60	0	56.6	0	56.6
45	0	60	60	0	57.7	0	57.7
45	0	60	60	0	57.4	0	57.4
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.9	0	57.9
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	59	0	59
45	0	60	60	0	57	0	57
45	0	60	60	0	57.1	0	57.1
45	0	60	60	0	56.2	0	56.2
45	0	60	60	0	57.5	0	57.5
45	0	60	60	0	57	0	57
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.8	0	56.8
45	0	60	60	0	56.1	0	56.1
45	0	60	60	0	56.8	0	56.8
45	0	60	60	0	56.2	0	56.2
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	56	0	56
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	56.6	0	56.6
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	56.2	0	56.2
45	0	60	60	0	55.8	0	55.8
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	56.8	0	56.8
45	0	60	60	0	57.4	0	57.4
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	57	0	57
45	0	60	60	0	57.5	0	57.5
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.4	0	57.4

45	0	60	60	0	57.6	0	57.6
45	0	60	60	0	58.6	0	58.6
45	0	60	60	0	57.6	0	57.6
45	0	60	60	0	58.1	0	58.1
45	0	60	60	0	57.8	0	57.8
45	0	60	60	0	58.2	0	58.2
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	57.9	0	57.9
45	0	60	60	0	57.6	0	57.6
45	0	60	60	0	58.6	0	58.6
45	0	60	60	0	58.7	0	58.7
45	0	60	60	0	58	0	58
45	0	60	60	0	58.1	0	58.1
45	0	60	60	0	57.6	0	57.6
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.4	0	57.4
45	0	60	60	0	57.7	0	57.7
45	0	60	60	0	57.1	0	57.1
45	0	60	60	0	57	0	57
45	0	60	60	0	57.3	0	57.3
45	0	60	60	0	57.5	0	57.5
45	0	60	60	0	57.1	0	57.1
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	57.7	0	57.7
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	56.8	0	56.8
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	55.9	0	55.9
45	0	60	60	0	56.1	0	56.1
45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	57	0	57
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	55.9	0	55.9
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	55.9	0	55.9
45	0	60	60	0	56.4	0	56.4
45	0	60	60	0	56.6	0	56.6
45	0	60	60	0	56.1	0	56.1
45	0	60	60	0	56.3	0	56.3
45	0	60	60	0	56.9	0	56.9
45	0	60	60	0	57.2	0	57.2
45	0	60	60	0	56.6	0	56.6

45	0	60	60	0	56.5	0	56.5
45	0	60	60	0	56.7	0	56.7
45	0	60	60	0	57.2	0	57.2

Appendix 6: Typical DESS Heating Loop Data Report

DESS Heating Loop

Location: **Ball State University / Ball State Muncie** **Run Date: 8/1/2016 1:00:41 PM**

Time	THWR	THWS	FCHW	TAO
7/24/2016 0:00	101.9	107.4	0	81.9
7/24/2016 0:30	101.9	107.4	0	82.1
7/24/2016 1:00	102	107.4	0	82.4
7/24/2016 1:30	102	107.4	0	81.9
7/24/2016 2:00	102.1	107.3	0	81.1
7/24/2016 2:30	102.1	107.3	0	80.4
7/24/2016 3:00	102.2	107.4	0	79.8
7/24/2016 3:30	102.2	107.3	0	79.4
7/24/2016 4:00	102.2	107.3	0	79.5
7/24/2016 4:30	102.2	107.3	0	77.7
7/24/2016 5:00	102.1	107.3	0	77.1
7/24/2016 5:30	102.1	107.3	0	76.4
7/24/2016 6:00	102.1	107.3	0	76.1
7/24/2016 6:30	102.1	107.4	0	75.6
7/24/2016 7:00	102	107.3	0	75.5
7/24/2016 7:30	102	107.3	0	80.8
7/24/2016 8:00	102	107.3	0	86.8
7/24/2016 8:30	101.9	107.3	0	90.3
7/24/2016 9:00	101.9	107.3	0	87.6
7/24/2016 9:30	101.8	107.4	0	90.8
7/24/2016 10:00	101.8	107.4	0	89.8
7/24/2016 10:30	101.7	107.4	0	92.7
7/24/2016 11:00	101.6	107.4	0	92.6
7/24/2016 11:30	101.6	107.4	0	91.8
7/24/2016 12:00	101.5	107.3	0	93.5
7/24/2016 12:30	101.6	107.4	0	93.9
7/24/2016 13:00	101.6	107.4	0	96.3
7/24/2016 13:30	101.8	107.3	0	96.9
7/24/2016 14:00	101.8	107.4	0	97.7
7/24/2016 14:30	101.9	107.4	0	97.8
7/24/2016 15:00	102	107.4	0	97.2
7/24/2016 15:30	102.1	107.4	0	99.9
7/24/2016 16:00	102.1	107.4	0	100
7/24/2016 16:30	102.2	107.4	0	99.9
7/24/2016 17:00	102.4	107.5	0	100.2
7/24/2016 17:30	102.4	107.5	0	100.9
7/24/2016 18:00	102.6	107.5	0	100.2
7/24/2016 18:30	102.7	107.5	0	103.8
7/24/2016 19:00	102.8	107.6	0	100.9

7/24/2016 19:30	102.8	107.6	0	99.7
7/24/2016 20:00	102.9	107.6	0	98.2
7/24/2016 20:30	103	107.6	0	96.6
7/24/2016 21:00	103	107.7	0	90.8
7/24/2016 21:30	103.1	107.7	0	88.8
7/24/2016 22:00	103.1	107.7	0	87.8
7/24/2016 22:30	103.2	107.7	0	86.7
7/24/2016 23:00	103.2	107.8	0	85.9
7/24/2016 23:30	103.2	107.8	0	84.9
7/25/2016 0:00	103.2	107.8	0	84.3
7/25/2016 0:30	103.1	107.7	0	83.6
7/25/2016 1:00	103.1	107.7	0	83.1
7/25/2016 1:30	103.1	107.7	0	82.6
7/25/2016 2:00	103.1	107.7	0	82.1
7/25/2016 2:30	103.1	107.7	0	80.3
7/25/2016 3:00	103	107.6	0	79.2
7/25/2016 3:30	103	107.6	0	78
7/25/2016 4:00	103	107.5	0	77.2
7/25/2016 4:30	102.9	107.5	0	76.6
7/25/2016 5:00	102.8	107.5	0	76.3
7/25/2016 5:30	102.8	107.4	0	76.1
7/25/2016 6:00	102.7	107.4	0	75.5
7/25/2016 6:30	102.6	107.4	0	75.1
7/25/2016 7:00	102.6	107.4	0	75.7
7/25/2016 7:30	102.5	107.4	0	76.3
7/25/2016 8:00	102.4	107.4	0	76.9
7/25/2016 8:30	102.3	107.3	0	79.8
7/25/2016 9:00	102.2	107.4	0	84
7/25/2016 9:30	102.2	107.4	0	88.5
7/25/2016 10:00	102.1	107.4	0	84.4
7/25/2016 10:30	102	107.4	0	84.2
7/25/2016 11:00	101.9	107.4	0	86.3
7/25/2016 11:30	101.8	107.4	0	86.9
7/25/2016 12:00	101.7	107.3	0	87.2
7/25/2016 12:30	101.7	107.3	0	87.6
7/25/2016 13:00	101.6	107.3	0	87.6
7/25/2016 13:30	101.6	107.4	0	89.6
7/25/2016 14:00	101.6	107.3	0	91.3
7/25/2016 14:30	101.6	107.3	0	91.3
7/25/2016 15:00	101.6	107.3	0	91.5
7/25/2016 15:30	101.6	107.4	0	92.7
7/25/2016 16:00	101.6	107.4	0	95.4

7/25/2016 16:30	101.7	107.4	0	93.5
7/25/2016 17:00	101.7	107.4	0	91.3
7/25/2016 17:30	101.7	107.4	0	93.6
7/25/2016 18:00	101.7	107.5	0	91.9
7/25/2016 18:30	101.8	107.5	0	94.9
7/25/2016 19:00	101.8	107.5	0	95.4
7/25/2016 19:30	101.9	107.5	0	96.9
7/25/2016 20:00	101.9	107.6	0	92.4
7/25/2016 20:30	102	107.7	0	88.4
7/25/2016 21:00	102	107.7	0	84.4
7/25/2016 21:30	102	107.7	0	82.9
7/25/2016 22:00	102	107.7	0	81.9
7/25/2016 22:30	102	107.7	0	80.9
7/25/2016 23:00	102	107.7	0	79.7
7/25/2016 23:30	102	107.7	0	79.2
7/26/2016 0:00	102	107.7	0	78.6
7/26/2016 0:30	101.9	107.7	0	77.8
7/26/2016 1:00	101.9	107.6	0	77.3
7/26/2016 1:30	101.9	107.5	0	76.3
7/26/2016 2:00	101.9	107.5	0	75.6
7/26/2016 2:30	101.9	107.5	0	74.2
7/26/2016 3:00	102	107.4	0	73.7
7/26/2016 3:30	102	107.4	0	72.9
7/26/2016 4:00	102	107.3	0	72.9
7/26/2016 4:30	102	107.3	0	72.4
7/26/2016 5:00	102	107.3	0	71.5
7/26/2016 5:30	102	107.3	0	70.6
7/26/2016 6:00	102	107.3	0	70.6
7/26/2016 6:30	102	107.3	0	71
7/26/2016 7:00	101.9	107.2	0	71.5
7/26/2016 7:30	101.9	107.2	0	76.1
7/26/2016 8:00	101.8	107.2	0	74.7
7/26/2016 8:30	101.8	107.2	0	74.5
7/26/2016 9:00	101.7	107.2	0	77.1
7/26/2016 9:30	101.7	107.3	0	82.1
7/26/2016 10:00	101.6	107.3	0	80.1
7/26/2016 10:30	101.6	107.2	0	81.9
7/26/2016 11:00	101.5	107.2	0	84.1
7/26/2016 11:30	101.5	107.3	0	85.8
7/26/2016 12:00	101.4	107.3	0	86.7
7/26/2016 12:30	101.4	107.3	0	88.3
7/26/2016 13:00	101.3	107.2	0	87.5

7/26/2016 13:30	101.3	107.2	0	85.9
7/26/2016 14:00	101.3	107.2	0	84.6
7/26/2016 14:30	101.3	107.2	0	86.2
7/26/2016 15:00	101.3	107.3	0	89.1
7/26/2016 15:30	101.3	107.2	0	89
7/26/2016 16:00	101.3	107.2	0	87.7
7/26/2016 16:30	101.3	107.1	0	89.5
7/26/2016 17:00	101.3	107.2	0	89.7
7/26/2016 17:30	101.4	107.1	0	89.4
7/26/2016 18:00	101.4	107.1	0	90.3
7/26/2016 18:30	101.4	107.1	0	96.7
7/26/2016 19:00	101.4	107.1	0	97.7
7/26/2016 19:30	101.4	107.1	0	97.7
7/26/2016 20:00	101.4	107.1	0	93.4
7/26/2016 20:30	101.4	107.1	0	91.1
7/26/2016 21:00	101.4	107.1	0	82.4
7/26/2016 21:30	101.5	107.1	0	79.2
7/26/2016 22:00	101.5	107	0	77.5
7/26/2016 22:30	101.5	107	0	77.1
7/26/2016 23:00	101.5	107	0	76
7/26/2016 23:30	101.5	107	0	75.1
7/27/2016 0:00	101.6	107	0	74.1
7/27/2016 0:30	101.6	106.9	0	73.5
7/27/2016 1:00	101.6	106.8	0	72.7
7/27/2016 1:30	101.6	106.7	0	71.9
7/27/2016 2:00	101.7	106.8	0	71.6
7/27/2016 2:30	101.8	106.7	0	71.2
7/27/2016 3:00	101.8	106.7	0	70.6
7/27/2016 3:30	101.8	106.7	0	70.1
7/27/2016 4:00	101.8	106.7	0	69.6
7/27/2016 4:30	101.8	106.6	0	69
7/27/2016 5:00	101.7	106.7	0	68.6
7/27/2016 5:30	101.7	106.7	0	68.3
7/27/2016 6:00	101.6	106.7	0	67.8
7/27/2016 6:30	101.6	106.8	0	67.8
7/27/2016 7:00	101.5	106.7	0	68.7
7/27/2016 7:30	101.5	106.7	0	69.9
7/27/2016 8:00	101.4	106.8	0	78.4
7/27/2016 8:30	101.3	106.8	0	81.3
7/27/2016 9:00	101.3	106.8	0	90
7/27/2016 9:30	101.2	106.7	0	89.8
7/27/2016 10:00	101.2	106.8	0	82.2

7/27/2016 10:30	101.2	106.7	0	83.2
7/27/2016 11:00	101.1	106.8	0	84.2
7/27/2016 11:30	101.1	106.8	0	84.5
7/27/2016 12:00	101.2	106.7	0	85.6
7/27/2016 12:30	101.2	106.7	0	86.8
7/27/2016 13:00	101.2	106.7	0	86.9
7/27/2016 13:30	101.2	106.8	0	87.2
7/27/2016 14:00	101.3	106.7	0	87.9
7/27/2016 14:30	101.3	106.7	0	88.9
7/27/2016 15:00	101.3	106.9	0	88.9
7/27/2016 15:30	101.3	106.9	0	90
7/27/2016 16:00	101.3	107	0	90.6
7/27/2016 16:30	101.3	107.1	0	91.4
7/27/2016 17:00	101.3	107.3	0	92.8
7/27/2016 17:30	104.4	107.4	0	93.9
7/27/2016 18:00	105.9	107.5	0	93.8
7/27/2016 18:30	106.3	107.7	0	96.1
7/27/2016 19:00	106.5	107.7	0	93.9
7/27/2016 19:30	106.7	107.9	0	90.5
7/27/2016 20:00	106.9	107.9	0	86.8
7/27/2016 20:30	107	108.1	0	93
7/27/2016 21:00	107.1	108.1	0	85.4
7/27/2016 21:30	107.2	108.2	0	82.1
7/27/2016 22:00	107.2	108.2	0	79.6
7/27/2016 22:30	107.3	108.3	0	78
7/27/2016 23:00	107.4	108.4	0	76.9
7/27/2016 23:30	107.5	108.4	0	75.9
7/28/2016 0:00	107.5	108.5	0	75
7/28/2016 0:30	107.6	108.5	0	75.9
7/28/2016 1:00	107.6	108.6	0	76.1
7/28/2016 1:30	107.6	108.6	0	76.1
7/28/2016 2:00	107.7	108.6	0	76
7/28/2016 2:30	107.7	108.7	0	76
7/28/2016 3:00	107.7	108.6	0	75.1
7/28/2016 3:30	107.8	108.7	0	74.4
7/28/2016 4:00	107.9	108.7	0	74.9
7/28/2016 4:30	107.9	108.8	0	73.6
7/28/2016 5:00	108	108.8	0	73.1
7/28/2016 5:30	108	108.9	0	72.7
7/28/2016 6:00	108.1	108.9	0	72.3
7/28/2016 6:30	108.1	108.9	0	72.4
7/28/2016 7:00	108.1	109	0	71.9

7/28/2016 7:30	108.2	109	0	74
7/28/2016 8:00	108.2	109	0	75.8
7/28/2016 8:30	108.2	109.1	0	76.7
7/28/2016 9:00	108.3	109.1	0	78.8
7/28/2016 9:30	108.3	109.2	0	82.7
7/28/2016 10:00	108.3	109.1	0	82.3
7/28/2016 10:30	108.4	109.2	0	82.7
7/28/2016 11:00	108.5	109.2	0	84.3
7/28/2016 11:30	108.5	109.2	0	85.9
7/28/2016 12:00	108.5	109.3	0	88.1
7/28/2016 12:30	108.5	109.3	0	89.5
7/28/2016 13:00	108.5	109.3	0	89.9
7/28/2016 13:30	108.5	109.3	0	91.5
7/28/2016 14:00	108.6	109.3	0	92
7/28/2016 14:30	108.6	109.3	0	92.2
7/28/2016 15:00	108.6	109.4	0	91.8
7/28/2016 15:30	108.6	109.3	0	91.9
7/28/2016 16:00	108.6	109.4	0	91.8
7/28/2016 16:30	108.6	109.4	0	94.1
7/28/2016 17:00	108.6	109.4	0	93.2
7/28/2016 17:30	108.6	109.4	0	93.1
7/28/2016 18:00	108.7	109.4	0	93.7
7/28/2016 18:30	108.6	109.4	0	97
7/28/2016 19:00	108.7	109.4	0	98.6
7/28/2016 19:30	108.6	109.4	0	97.4
7/28/2016 20:00	108.7	109.5	0	93.7
7/28/2016 20:30	108.7	109.5	0	88.4
7/28/2016 21:00	108.7	109.5	0	84.4
7/28/2016 21:30	108.7	109.5	0	82.6
7/28/2016 22:00	108.7	109.5	0	81
7/28/2016 22:30	108.7	109.5	0	79.6
7/28/2016 23:00	108.7	109.5	0	78.4
7/28/2016 23:30	108.7	109.5	0	79.1
7/29/2016 0:00	108.7	109.5	0	77.7
7/29/2016 0:30	108.7	109.5	0	76.6
7/29/2016 1:00	108.7	109.4	0	75.8
7/29/2016 1:30	108.6	109.4	0	75.7
7/29/2016 2:00	108.6	109.4	0	74.9
7/29/2016 2:30	108.6	109.4	0	73.8
7/29/2016 3:00	108.6	109.4	0	72.9
7/29/2016 3:30	108.6	109.4	0	72.3
7/29/2016 4:00	108.6	109.4	0	71.8

7/29/2016 4:30	108.6	109.4	0	71.6
7/29/2016 5:00	108.7	109.4	0	70.6
7/29/2016 5:30	108.7	109.4	0	69.9
7/29/2016 6:00	108.7	109.4	0	69.6
7/29/2016 6:30	108.7	109.4	0	69.1
7/29/2016 7:00	108.7	109.5	0	69.7
7/29/2016 7:30	108.8	109.5	0	75.1
7/29/2016 8:00	108.8	109.5	0	79.5
7/29/2016 8:30	108.8	109.5	0	81.7
7/29/2016 9:00	108.8	109.5	0	85.6
7/29/2016 9:30	108.8	109.5	0	86.4
7/29/2016 10:00	108.8	109.5	0	84.2
7/29/2016 10:30	108.8	109.5	0	85.2
7/29/2016 11:00	108.9	109.6	0	85.4
7/29/2016 11:30	108.8	109.5	0	88.5
7/29/2016 12:00	108.8	109.6	0	89.3
7/29/2016 12:30	108.9	109.6	0	90
7/29/2016 13:00	108.9	109.6	0	92.4
7/29/2016 13:30	108.9	109.6	0	92.3
7/29/2016 14:00	108.9	109.6	0	94.6
7/29/2016 14:30	108.8	109.6	0	89.4
7/29/2016 15:00	108.9	109.5	0	80.5
7/29/2016 15:30	108.9	109.6	0	78.6
7/29/2016 16:00	108.9	109.6	0	82.8
7/29/2016 16:30	108.8	109.6	0	84.6
7/29/2016 17:00	108.8	109.6	0	87.4
7/29/2016 17:30	108.8	109.5	0	89.1
7/29/2016 18:00	108.8	109.6	0	91.2
7/29/2016 18:30	108.8	109.6	0	86.7
7/29/2016 19:00	108.8	109.6	0	82.7
7/29/2016 19:30	108.8	109.6	0	79
7/29/2016 20:00	108.9	109.6	0	75.8
7/29/2016 20:30	108.9	109.6	0	72.8
7/29/2016 21:00	108.8	109.6	0	72.5
7/29/2016 21:30	108.9	109.6	0	72.9
7/29/2016 22:00	108.9	109.6	0	73
7/29/2016 22:30	108.9	109.6	0	72.7
7/29/2016 23:00	108.9	109.6	0	72.2
7/29/2016 23:30	108.9	109.6	0	71.9
7/30/2016 0:00	108.9	109.6	0	71.6
7/30/2016 0:30	108.9	109.6	0	71.1
7/30/2016 1:00	108.8	109.6	0	70.8

7/30/2016 1:30	108.8	109.6	0	70.4
7/30/2016 2:00	108.8	109.6	0	70.3
7/30/2016 2:30	108.8	109.6	0	69.9
7/30/2016 3:00	108.8	109.6	0	69.6
7/30/2016 3:30	108.8	109.6	0	69.2
7/30/2016 4:00	108.8	109.6	0	69.3
7/30/2016 4:30	108.8	109.6	0	69.6
7/30/2016 5:00	108.8	109.6	0	69.5
7/30/2016 5:30	108.8	109.6	0	68.9
7/30/2016 6:00	108.8	109.6	0	68.9
7/30/2016 6:30	108.9	109.6	0	68.7
7/30/2016 7:00	108.9	109.6	0	69.1
7/30/2016 7:30	108.9	109.7	0	69.6
7/30/2016 8:00	109	109.7	0	70.8
7/30/2016 8:30	109	109.7	0	72
7/30/2016 9:00	109	109.7	0	74.8
7/30/2016 9:30	109	109.8	0	77.1
7/30/2016 10:00	109.1	109.8	0	77.2
7/30/2016 10:30	109.1	109.8	0	78.1
7/30/2016 11:00	109.1	109.8	0	80.6
7/30/2016 11:30	109.1	109.9	0	80.9
7/30/2016 12:00	109.1	109.9	0	82.5
7/30/2016 12:30	109.1	109.8	0	84
7/30/2016 13:00	109.1	109.9	0	83.7
7/30/2016 13:30	109.2	109.9	0	83.6
7/30/2016 14:00	109.1	109.9	0	84.5
7/30/2016 14:30	109.2	109.9	0	84.5
7/30/2016 15:00	109.2	109.9	0	85.7
7/30/2016 15:30	109.1	109.9	0	87.6
7/30/2016 16:00	109.2	109.9	0	86.4
7/30/2016 16:30	109.2	109.9	0	89.1
7/30/2016 17:00	109.2	109.9	0	89.2
7/30/2016 17:30	109.2	110	0	89.4
7/30/2016 18:00	109.2	109.9	0	89.3
7/30/2016 18:30	109.2	110	0	94
7/30/2016 19:00	109.2	110	0	94
7/30/2016 19:30	109.2	110	0	94.3
7/30/2016 20:00	109.2	110	0	93.4
7/30/2016 20:30	109.3	110	0	88.8
7/30/2016 21:00	109.3	110	0	81.6
7/30/2016 21:30	109.2	110	0	79.8
7/30/2016 22:00	109.2	110	0	77.5

7/30/2016 22:30	109.2	110	0	77.6
7/30/2016 23:00	109.2	110	0	76.6
7/30/2016 23:30	109.2	110	0	74.7

Appendix 7: Typical DESS Cooling Loop Data Report

DESS Cooling Loop

Location: **Ball State University / Ball State Muncie** **Run Date: 8/1/2016 1:00:31 PM**

Time	TCHWR	TCHWS	GPM	TAO
7/24/2016 0:00	55.3	45.5	9,510.00	81.9
7/24/2016 0:30	55.2	45.7	9,495.00	82.1
7/24/2016 1:00	55	45.5	9,525.00	82.4
7/24/2016 1:30	54.9	45.2	9,465.00	81.9
7/24/2016 2:00	54.9	46.1	9,495.00	81.1
7/24/2016 2:30	54.8	45.4	9,510.00	80.4
7/24/2016 3:00	54.6	45.1	9,525.00	79.8
7/24/2016 3:30	54.6	46.7	9,525.00	79.4
7/24/2016 4:00	54.4	45.1	9,540.00	79.5
7/24/2016 4:30	54.1	45.5	9,555.00	77.7
7/24/2016 5:00	54	44.9	9,450.00	77.1
7/24/2016 5:30	53.9	44.9	9,525.00	76.4
7/24/2016 6:00	53.8	45.2	9,540.00	76.1
7/24/2016 6:30	53.8	45	9,540.00	75.6
7/24/2016 7:00	53.7	45.6	9,510.00	75.5
7/24/2016 7:30	53.6	45.7	9,450.00	80.8
7/24/2016 8:00	53.7	45.9	9,525.00	86.8
7/24/2016 8:30	53.9	45.9	9,480.00	90.3
7/24/2016 9:00	53.9	45.6	9,510.00	87.6
7/24/2016 9:30	54.1	45.8	9,540.00	90.8
7/24/2016 10:00	54.2	45.5	9,525.00	89.8
7/24/2016 10:30	54.5	45.4	9,465.00	92.7
7/24/2016 11:00	55	45.8	9,465.00	92.6
7/24/2016 11:30	55.3	45.4	9,480.00	91.8
7/24/2016 12:00	55.6	46.6	9,480.00	93.5
7/24/2016 12:30	55.9	46.7	9,480.00	93.9
7/24/2016 13:00	56.1	45.5	9,480.00	96.3
7/24/2016 13:30	56.1	45.6	9,465.00	96.9
7/24/2016 14:00	56.1	45.9	9,510.00	97.7
7/24/2016 14:30	56.1	45.8	9,525.00	97.8
7/24/2016 15:00	56.2	45.7	9,540.00	97.2
7/24/2016 15:30	56.3	45.8	9,510.00	99.9
7/24/2016 16:00	56.4	45.8	9,510.00	100
7/24/2016 16:30	56.7	46.7	9,480.00	99.9
7/24/2016 17:00	57	46.7	9,465.00	100.2
7/24/2016 17:30	57.1	46.5	9,480.00	100.9
7/24/2016 18:00	57.2	46.6	9,495.00	100.2
7/24/2016 18:30	57.3	46.6	9,540.00	103.8
7/24/2016 19:00	57.3	46.8	9,450.00	100.9

7/24/2016 19:30	57.4	46.9	9,510.00	99.7
7/24/2016 20:00	57.4	46.7	9,510.00	98.2
7/24/2016 20:30	57.3	46.6	9,480.00	96.6
7/24/2016 21:00	57.2	47.2	9,525.00	90.8
7/24/2016 21:30	57.1	47	9,480.00	88.8
7/24/2016 22:00	57	46.5	9,480.00	87.8
7/24/2016 22:30	56.9	46.8	9,525.00	86.7
7/24/2016 23:00	56.8	46.5	9,465.00	85.9
7/24/2016 23:30	56.5	46.8	9,495.00	84.9
7/25/2016 0:00	56.4	46.8	9,510.00	84.3
7/25/2016 0:30	56.3	46.7	9,510.00	83.6
7/25/2016 1:00	56.2	46.3	9,495.00	83.1
7/25/2016 1:30	56.1	46.2	9,435.00	82.6
7/25/2016 2:00	55.9	47.1	9,555.00	82.1
7/25/2016 2:30	55.4	46.8	9,495.00	80.3
7/25/2016 3:00	55	46.6	9,495.00	79.2
7/25/2016 3:30	54.6	47	9,480.00	78
7/25/2016 4:00	54.5	46.3	9,510.00	77.2
7/25/2016 4:30	54.4	46.2	9,525.00	76.6
7/25/2016 5:00	54.2	46.3	9,465.00	76.3
7/25/2016 5:30	54.3	46.1	9,495.00	76.1
7/25/2016 6:00	54.3	46.4	9,510.00	75.5
7/25/2016 6:30	54.1	46.2	9,465.00	75.1
7/25/2016 7:00	54.1	44.8	9,540.00	75.7
7/25/2016 7:30	53.5	44.9	9,510.00	76.3
7/25/2016 8:00	53.2	44.7	9,540.00	76.9
7/25/2016 8:30	53.1	44.7	9,495.00	79.8
7/25/2016 9:00	53	43.9	9,435.00	84
7/25/2016 9:30	53.2	44.8	9,480.00	88.5
7/25/2016 10:00	53.3	43.8	9,555.00	84.4
7/25/2016 10:30	53.4	44.3	9,480.00	84.2
7/25/2016 11:00	53.7	44.3	9,495.00	86.3
7/25/2016 11:30	53.9	44.4	9,510.00	86.9
7/25/2016 12:00	53.9	45	9,480.00	87.2
7/25/2016 12:30	54.1	45	9,555.00	87.6
7/25/2016 13:00	54.2	45	9,540.00	87.6
7/25/2016 13:30	54.4	44.6	9,510.00	89.6
7/25/2016 14:00	54.6	44.6	9,525.00	91.3
7/25/2016 14:30	54.8	45	9,480.00	91.3
7/25/2016 15:00	55	44.5	9,495.00	91.5
7/25/2016 15:30	55.2	44.5	9,495.00	92.7
7/25/2016 16:00	55.3	45	9,540.00	95.4

7/25/2016 16:30	55.4	44.8	9,495.00	93.5
7/25/2016 17:00	55.3	45	9,510.00	91.3
7/25/2016 17:30	55.6	45.2	9,510.00	93.6
7/25/2016 18:00	55.7	45.1	9,510.00	91.9
7/25/2016 18:30	55.8	45.1	9,480.00	94.9
7/25/2016 19:00	55.6	45.1	9,495.00	95.4
7/25/2016 19:30	55.3	45.5	9,540.00	96.9
7/25/2016 20:00	55	44.6	9,465.00	92.4
7/25/2016 20:30	54.8	44.6	9,525.00	88.4
7/25/2016 21:00	54.6	45	9,450.00	84.4
7/25/2016 21:30	54.3	45.1	9,435.00	82.9
7/25/2016 22:00	54.1	44.3	9,495.00	81.9
7/25/2016 22:30	54	45	9,480.00	80.9
7/25/2016 23:00	54	44.9	9,540.00	79.7
7/25/2016 23:30	53.6	44.7	9,525.00	79.2
7/26/2016 0:00	53.3	44.8	9,465.00	78.6
7/26/2016 0:30	53.1	44.4	9,525.00	77.8
7/26/2016 1:00	52.9	43.9	9,510.00	77.3
7/26/2016 1:30	52.8	44.2	9,480.00	76.3
7/26/2016 2:00	52.6	45.4	9,480.00	75.6
7/26/2016 2:30	52.6	44.6	9,495.00	74.2
7/26/2016 3:00	52.4	44.3	9,540.00	73.7
7/26/2016 3:30	52.2	44.9	9,600.00	72.9
7/26/2016 4:00	52.1	44.6	9,525.00	72.9
7/26/2016 4:30	52.1	45	9,510.00	72.4
7/26/2016 5:00	52.1	44.1	9,480.00	71.5
7/26/2016 5:30	52	44.4	9,510.00	70.6
7/26/2016 6:00	52.1	44.6	9,435.00	70.6
7/26/2016 6:30	52.1	43.9	9,510.00	71
7/26/2016 7:00	52	44.6	9,510.00	71.5
7/26/2016 7:30	51.9	44.7	9,465.00	76.1
7/26/2016 8:00	51.9	44.5	9,510.00	74.7
7/26/2016 8:30	51.5	42.2	9,540.00	74.5
7/26/2016 9:00	51.2	43	9,480.00	77.1
7/26/2016 9:30	51.2	43.2	9,510.00	82.1
7/26/2016 10:00	51.3	43	9,480.00	80.1
7/26/2016 10:30	51.4	43	9,465.00	81.9
7/26/2016 11:00	51.6	42.7	9,525.00	84.1
7/26/2016 11:30	51.6	43.4	9,495.00	85.8
7/26/2016 12:00	51.8	42.7	9,510.00	86.7
7/26/2016 12:30	51.8	42.6	9,465.00	88.3
7/26/2016 13:00	51.9	43.3	9,585.00	87.5

7/26/2016 13:30	51.7	42.9	9,510.00	85.9
7/26/2016 14:00	51.9	43.1	9,495.00	84.6
7/26/2016 14:30	51.8	43.4	9,570.00	86.2
7/26/2016 15:00	52.1	42.7	9,540.00	89.1
7/26/2016 15:30	52	44.4	9,435.00	89
7/26/2016 16:00	52.4	44.6	9,540.00	87.7
7/26/2016 16:30	53	44.6	9,435.00	89.5
7/26/2016 17:00	53.1	45.1	9,510.00	89.7
7/26/2016 17:30	53.2	44.5	9,495.00	89.4
7/26/2016 18:00	53.3	44.4	9,495.00	90.3
7/26/2016 18:30	53.3	44.1	9,495.00	96.7
7/26/2016 19:00	53.3	45.3	9,510.00	97.7
7/26/2016 19:30	53.2	44	9,495.00	97.7
7/26/2016 20:00	53.1	44	9,495.00	93.4
7/26/2016 20:30	53	44.1	9,510.00	91.1
7/26/2016 21:00	53	44.8	9,540.00	82.4
7/26/2016 21:30	52.9	44.8	9,495.00	79.2
7/26/2016 22:00	53	44.7	9,510.00	77.5
7/26/2016 22:30	52.9	44.8	9,495.00	77.1
7/26/2016 23:00	52.8	45	9,510.00	76
7/26/2016 23:30	52.5	45	9,585.00	75.1
7/27/2016 0:00	52.5	44.5	9,510.00	74.1
7/27/2016 0:30	52.5	44.3	9,480.00	73.5
7/27/2016 1:00	52.4	44.8	9,540.00	72.7
7/27/2016 1:30	52.3	44.3	9,465.00	71.9
7/27/2016 2:00	52.2	44.4	9,480.00	71.6
7/27/2016 2:30	52.1	44.3	9,570.00	71.2
7/27/2016 3:00	52	45	9,480.00	70.6
7/27/2016 3:30	51.9	44.3	9,525.00	70.1
7/27/2016 4:00	51.9	44	9,510.00	69.6
7/27/2016 4:30	51.8	44.5	9,510.00	69
7/27/2016 5:00	51.8	44.4	9,555.00	68.6
7/27/2016 5:30	51.9	44.1	9,465.00	68.3
7/27/2016 6:00	51.9	44.2	9,465.00	67.8
7/27/2016 6:30	51.8	44.3	9,510.00	67.8
7/27/2016 7:00	51.7	43.7	9,510.00	68.7
7/27/2016 7:30	51.1	43.6	9,420.00	69.9
7/27/2016 8:00	51.1	42.6	9,495.00	78.4
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7/27/2016 9:00	51.1	42.7	9,555.00	90
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7/27/2016 10:30	51.5	42.6	9,570.00	83.2
7/27/2016 11:00	51.6	42.7	9,525.00	84.2
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7/27/2016 16:30	51.7	42.5	9,525.00	91.4
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7/27/2016 21:00	51.6	43	9,480.00	85.4
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7/28/2016 4:30	51.1	43.4	9,480.00	73.6
7/28/2016 5:00	51.1	43.1	9,510.00	73.1
7/28/2016 5:30	51.1	43.3	9,525.00	72.7
7/28/2016 6:00	51	42.8	9,480.00	72.3
7/28/2016 6:30	51.1	42.5	9,480.00	72.4
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7/29/2016 15:00	52.9	43	9,510.00	80.5
7/29/2016 15:30	52.5	44.1	9,495.00	78.6
7/29/2016 16:00	53.3	43.9	9,495.00	82.8
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7/30/2016 21:30	52.7	44.5	9,525.00	79.8
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7/30/2016 23:00	52.5	44.8	9,495.00	76.6
7/30/2016 23:30	52.2	44.5	9,540.00	74.7

Appendix 8: Formation Thermal Conductivity Test and Data Analysis

Geothermal
Resource
Technologies, Inc.

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P.O. Box 150
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WEB SITE:
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FORMATION THERMAL CONDUCTIVITY TEST AND DATA ANALYSIS

Analysis for: **LoopMaster International Inc.**
5700 W. Minnesota St., Building E-2
Indianapolis, IN 46241
Phone: (317) 246-5667
Fax: (317) 246-5668

Test location: **Ball State University**
Muncie, IN

Report Date: August 19, 2008

Test Performed by: **LoopMaster International Inc.**

Executive Summary

A formation thermal conductivity test was performed at the Ball State University site in Muncie, Indiana. The vertical bore was completed on July 21, 2008 by C&J Well Drilling. GRTI's test unit was attached to the vertical bore on the afternoon of July 29, 2008. Geothermal Resource Technologies, Inc. analyzed the collected data using the "line source" method.

This report provides a general overview of the test and procedures that were used to perform the thermal conductivity test along with a plot of the data in real time and in a form used to calculate the formation thermal conductivity. The following average formation thermal conductivity was found from the data analysis.

⇒ Formation Thermal Conductivity = 1.68 Btu/hr-ft-°F

Due to the necessity of a thermal diffusivity value in the design calculation process, an estimate of the average thermal diffusivity was made for the encountered formation.

⇒ Formation Thermal Diffusivity ≈ 1.12 ft^2/day

An estimate of the undisturbed formation temperature was determined from the initial temperature data at startup.

⇒ Undisturbed Formation Temperature ≈ 55-56°F

A copy of the original collected data is available either in a hard copy or an electronic format upon request.

Test Procedures

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) has published a set of recommended procedures for performing formation thermal conductivity tests for geothermal applications. GRTI is committed to adhering to ASHRAE recommendations. Some of these recommended procedures are listed below:

(1) Required Test Duration – A minimum test duration of 36 hours is recommended, with a preference toward 48 hours.

(2) Power Quality – The standard deviation of the power should be less than or equal to 1.5% of the average power, with maximum power variation of less than or equal to 10% of the average power. The heat flux rate should be 51 Btu/hr (15 W) to 85 Btu/hr (25 W) per foot of borehole depth to best simulate the expected peak loads on the u-bend.

(3) Undisturbed Formation Temperature Measurement – The undisturbed formation temperature should be determined by recording the minimum loop temperature as the water returns from the u-bend at test startup.

(4) Installation Procedures for Test Loops – The bore diameter is to be no larger than 6 inches, with 4.5 inches being the target diameter. To ensure against bridging and voids, the bore annulus is to be uniformly grouted from the bottom to the top using a tremie pipe.

(5) Time Between Loop Installation and Testing – A minimum delay of five days between loop installation and test startup is recommended if the formation is expected to have a low thermal conductivity or if low conductivity grouts (< 0.75 Btu/hr·ft·°F) are used. A minimum delay of three days is recommended for all other conditions.

GRTI's testing procedures deviate slightly from those above with regard to item (5). While item (5) bases the delay between installation and testing on the expected formation conductivity, GRTI bases its delay on the type of drilling used in the installation. When air drilling is required, a five-day delay is recommended to allow the bore to return to its undisturbed temperature. For mud rotary drilling, a minimum waiting period of two days is sufficient.

For a complete list of recommended procedures, refer to the ASHRAE 2007 HVAC Applications handbook, pages 32.12-32.13.

Data Analysis

Geothermal Resource Technologies, Inc. uses the "line source" method of data analysis. The line source equation used is not valid for early test times. Also, the line source method assumes an infinitely thin line source of heat in a continuous medium. If a u-bend grouted in a borehole is used to inject heat into the ground at a constant rate in order to determine the average formation thermal conductivity, the test must be run long enough to allow the finite dimensions of the u-bend pipes and the grout to become insignificant. Experience has shown that the amount of time required to allow early test time error and finite borehole dimension effects to become insignificant is approximately ten hours.

In order to analyze real data from a formation thermal conductivity test, the average temperature of the water entering and exiting the u-bend heat exchanger is plotted versus the natural log of time. Using the Method of Least Squares, the linear equation coefficients are then calculated that produce a line that fits the data. This procedure is normally repeated for various time intervals to ensure that variations in the power or other effects are not producing erroneous results.

Through the analysis process, the collected raw data is converted to spreadsheet format (Microsoft Excel®) for final analysis. A copy of this data can be obtained either in a hard copy or electronic copy format at any time. If desired, please contact Geothermal Resource Technologies, Inc. and provide a ship-to address or e-mail address at one of the following:

Phone: (828) 225-9166
Fax: (828) 281-4139
E-mail: grticam@aol.com

Formation Thermal Conductivity Test Report

Date .... July 29-31, 2008
Location .... Muncie, IN
Undisturbed Formation Temperature .... Approx. 55-56°F

Borehole Data – As Provided by LoopMaster International Inc.

Borehole Diameter .... 10 inches from 0-92 ft
5 5/8 inches from 92-300 ft

Note: 92 feet of casing was installed.

Drill Log ....

Top soil	0'-3'
Clay	3'-21'
Gravel	21'-24'
Clay	24'-38'
Gravel	38'-47'
Clay	47'-51'
Gravel	51'-55'
Clay	55'-61'
Gravel	61'-65'
Clay	65'-85'
Gravel	85'-90'
Clay	90'-92'
Limestone	92'-300'

Note: Bore produced approx. 10 gpm water at 100 ft; 20 gpm at 130 ft; 20 gpm at 200 ft; total yield of 50 gpm.

U-bend Size .... 1 inch HDPE
U-Bend Length .... 300 ft
Grout Type .... Baroid Benseal
Grout Solids .... NA
Grouted Portion .... Entire bore

Test Data

Test Duration .... 42.2 hrs.
Average Voltage .... 243.4 V
Average Power .... 6,218 W
Total Heat Input Rate .... 21,223 Btu/hr
Calculated Circulator Flow Rate .... 6.1 gpm

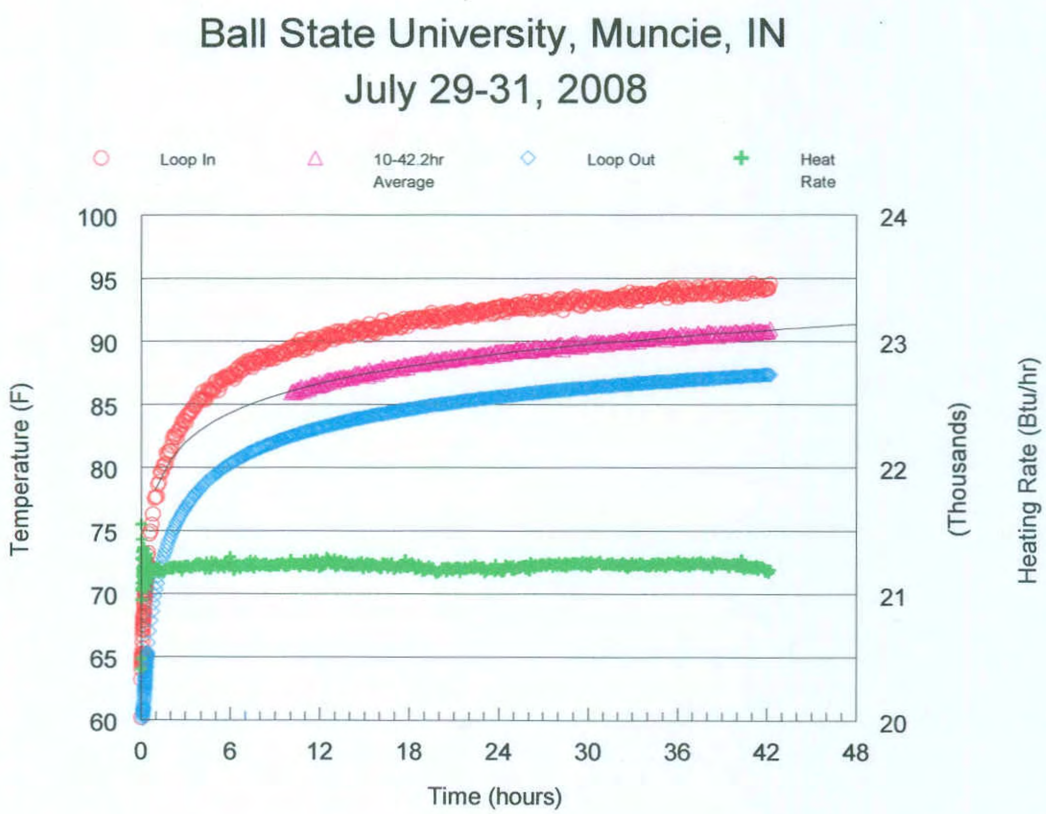


Figure 1: Temperature versus Time Data

Line Source Data Analysis

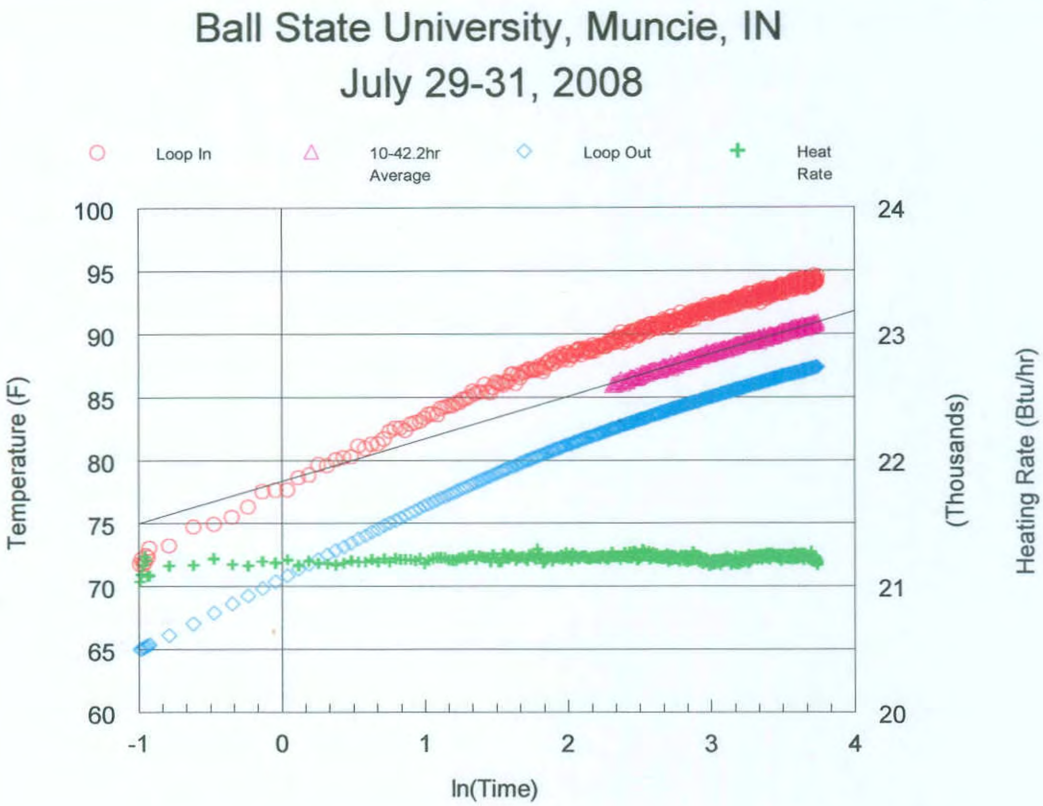


Figure 2: Temperature versus Natural Log of Time

Time Period	Slope: $\mathbf{a_1}$	Average Heat Input (Btu/hr-ft)	(W/ft)	Thermal Conductivity (Btu/hr-ft-°F)
10 – 42.2 hrs	3.36	70.7	20.7	1.68

The temperature versus time data was analyzed using the line source analysis for the time period shown above. An average linear curve fit was applied to the data between 10 and 42.2 hours. The slope of the curve (a_1) was found to be 3.36. The resulting thermal conductivity was found to be 1.68 Btu/hr-ft-°F.

Estimated Thermal Diffusivity

The reported drilling log for this test borehole indicated that the formation consisted of clay, gravel, and limestone. A heat capacity value for limestone was calculated from specific heat and density values listed by Kavanaugh and Rafferty (Ground-Source Heat Pumps - Design of Geothermal Systems for Commercial and Institutional Buildings, ASHRAE, 1997). A weighted average of heat capacity values based on the indicated formation was used to develop an average heat capacity for the formation. An estimated diffusivity value was then found using the calculated formation thermal conductivity and the estimated heat capacity. The thermal diffusivity for this formation was estimated to be 1.12 ft^2/day.

Est. Average Heat Capacity (Btu/ft^3 °F)	Thermal Conductivity (Btu/hr-ft-°F)	Est. Thermal Diffusivity (ft^2/day)
36.0	1.68	1.12

Frequently Asked Questions (FAQ's) Regarding FTC Testing

Q: Thermally-enhanced grout is specified for the final loop field design. The test bore was grouted with a low conductivity, 20% solids, bentonite grout. How do I adjust the thermal conductivity value to account for this?

A: While the conductivity of the grout is important for the loop field design, it is not important for determining formation thermal conductivity. We use the "line source" method to analyze data, which assumes an infinitely thin line rejecting heat at a constant rate into an infinite medium. The initial ten hours, which is influenced by the bore dimensions and grout conductivity, is ignored in the analysis. However, once the heat has penetrated into the formation, the temperature rise of the formation approaches steady-state. It is the slope of the temperature rise that is used in the analysis. Hence, no adjustment to the reported formation thermal conductivity is required.

Q: The software I use to design the loop field requires that I input a value for "soil conductivity". Is this the same as formation thermal conductivity?

A: Absolutely. Formation, soil, and ground are all used interchangeably to describe the conditions in which the u-bends will be installed. The use of the word "formation" simply implies that the installation conditions may be soil, rock, or some combination of the two.

Q: I've just received your report. I have a formation conductivity of 1.54 Btu/hr·ft·°F. How do I translate that into a loop length requirement, in terms of bore depth (in feet) per ton?

A: The formation thermal conductivity test provides values for three key parameters required for the ground loop design. These are the "Undisturbed Formation Temperature, Formation Thermal Conductivity, and Formation Thermal Diffusivity." These parameters, along with many others, are inputs to commercially available loop design software (e.g. GchpCalc, available at GeoKiss.com/software). The software uses all of the inputs to determine the required loop length in bore depth per ton.

Q: Is the "Undisturbed Formation Temperature" listed in the report the temperature that I enter into my loop design software where it calls for the "Deep-Earth Temperature"?

A: Generally, yes. The "Undisturbed Formation Temperature" is the constant temperature of the formation. We attempt to determine this value by measuring the temperature of the water entering the test unit at the beginning of the test. However, the value we measure and report may be inaccurate if the test is initiated too quickly after the installation of the test bore, or if the testing operator failed to activate the data acquisition unit prior to energizing the heating elements. If you suspect the temperature we are reporting to be too high or too low, we recommend that you investigate further through other sources.

Appendix 9: Test Borehole Drill Log

July 18, 2011

Jeff Urlaub
MEP Associates, LLC.
2720 Arbor Court
Eau Claire, WI 54701

Ball State Test Holes South Field

TEST BORE #1   1 INCH DOUBLE U-BEND

Formation Thermal Conductivity:	1.76 **Btu/hr-ft-f°**
Estimated Thermal Diffusivity:	**1.21 ft^2/day**
Tested Soil Temperature at 100':	**55.2 f°**
Average Heat Rate :	**30,642 Btu/hr**

Duration to drill to depth specified:	5½hrs.
Rock bit to 60'/PDC to bottom	
Did not need to case bore hole	
2 bags quick gel	

Borehole Diameter 5 5/8 inch

Drill Log	Overburden	0'-4'
	Clay	4'-12'
	Sand	12'-18'
	Clay	18'-23'
	Gravel	23'-38'
	Boulders	38'-43'
	Limestone	43'-54'
	Broken Limestone	54'-216'
	Shale	216'-253'
	Limestone with shale stringers	253'-420'
	Fracture	420'-424'
	Hard Limestone	424'-450'

U-bend size	1 inch
U-bend length	420'
NOTE: Geo Clips were installed on U-bends	
Grout Type	Wyo- Ben Therm- Ex
Grout Solids	100# sand/50# bentonite
Grouted Portion	entire bore length

Drilling Method	Mud Rotary

TEST BORE #2 1¼ INCH SINGLE u-BEND

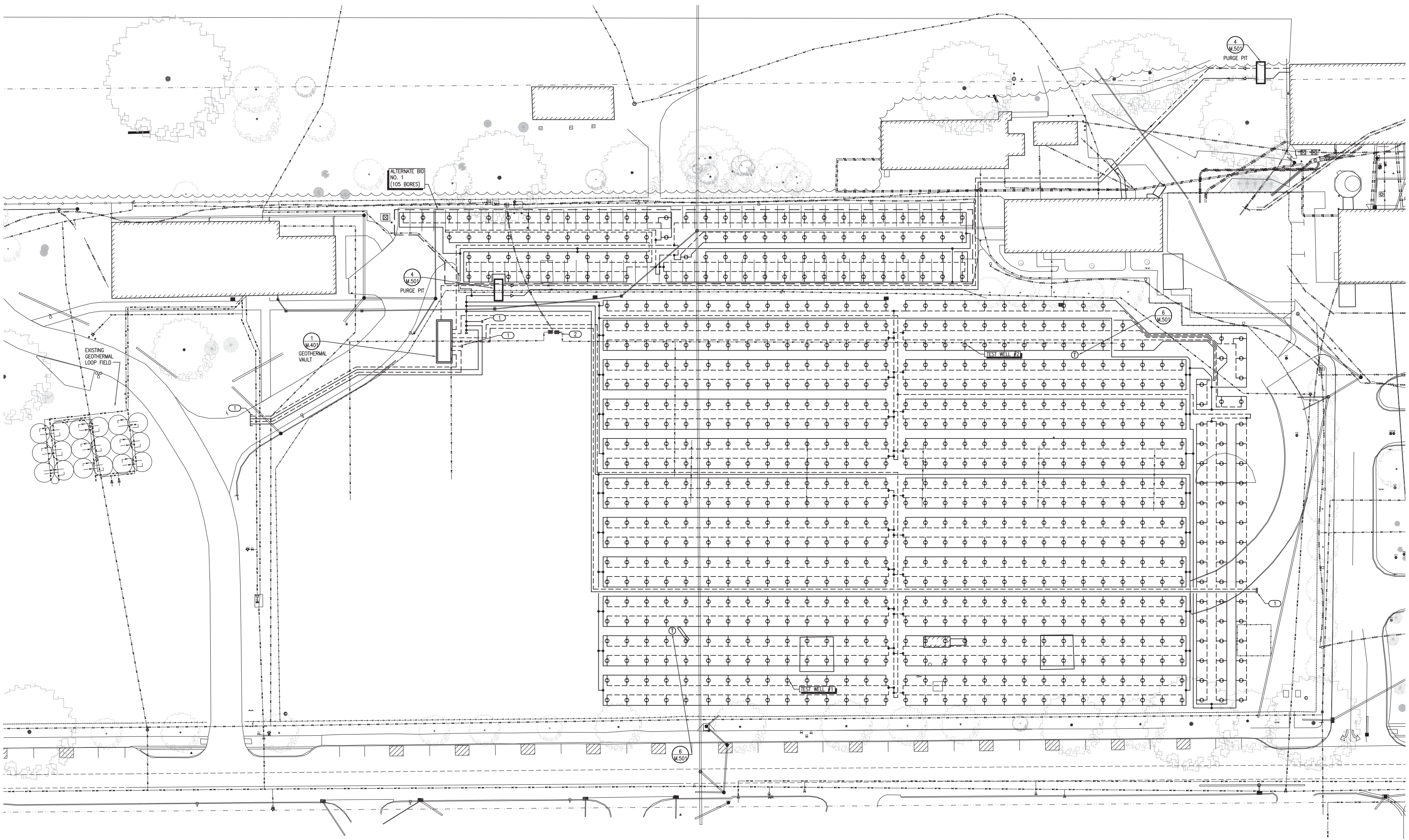
Formation Thermal Conductivity:	**1.51 Btu/hr-ft-°f**
Estimated Thermal Diffusivity:	**1.06 ft^2/ day**
Tested Soil Temperature at 100':	55.6 °f
Average heat rate:	**30,613 Btu/hr**

Duration to drill to depth specified:		5½hrs
	Rock bit to 60'/ PDC to bottom	
	Did not need to case bore hole	
	2 bags quick gel	
Borehole Diameter		6 inch
Drill Log	Overburden	0-4'
	Clay	4'-14'
	Sand	14'-18'
	Clay	18'-26'
	Gravel	26'-41'
	Boulders	42'-45'
	Limestone	45'-57'
	Broken Limestone	57'-218'
	Shale	218'-266'
	Limestone with Shale stringers	266'-432'
	Fracture	432'-437'
	Hard Limestone	437'-505'
U-bend Size		1¼ inch HDPE
U-bend Length		490'
NOTE: Geo Clips were installed on U-bend		
Grout Type		Wyo-Ben Therm-Ex
Grout Solids		200# sand/50# bentonite
Grouted Portion		entire bore
Drilling Method		Mud Rotary

Please feel free to call if you have any questions

Jim Huddleston
GITS, Inc.
jim@dedicatedgeo.com
763 486-6252

Appendix 10: Borehole Field Layouts



1 SOUTH WELL FIELD UTILIZATION - PHASE NO. 1 BORES (ALTERNATE NO. 1 - 105 BORES)

1" = 30'-0"

GENERAL NOTES

1. GLHE CONTRACTOR TO COORDINATE VERTICAL AND HORIZONTAL LOOP PIPING WITH NEW AND EXISTING SITE UTILITIES AND PIPING.
2. GEOTHERMAL TEST WELLS TO BE TIED INTO THE GEOTHERMAL PIPING CIRCUIT.
3. GLHE CONTRACTOR TO COORDINATE THE ELECTRICAL CIRCUIT TO THE VAULT WITH THE ELECTRICAL CONTRACTOR.

KEYED NOTES

(1) CAPPED FOR FUTURE CONNECTION.
(2) IRRIGATION WELL.

ENGINEER

MEP ASSOCIATES, LLC

CONSULTANT

SEALS

JEFF URLAUB REGISTERED No. 10703367 STATE OF INDIANA PROFESSIONAL ENGINEER

PROJECT

BALL STATE UNIVERSITY

GEOTHERMAL CONVERSION - SOUTH WELL FIELD

BALL STATE UNIVERSITY, MUNCIE, INDIANA

PROJECT

CAD: LAD
IN CHARGE: JAU
QA: JAU
ISSUE: CD
DATE: 08.01.2011

MARK	DATE	DESCRIPTION

BSU Project #: 2011-043.01 XU
MEP Project #: B20.10.01-13

ISSUE

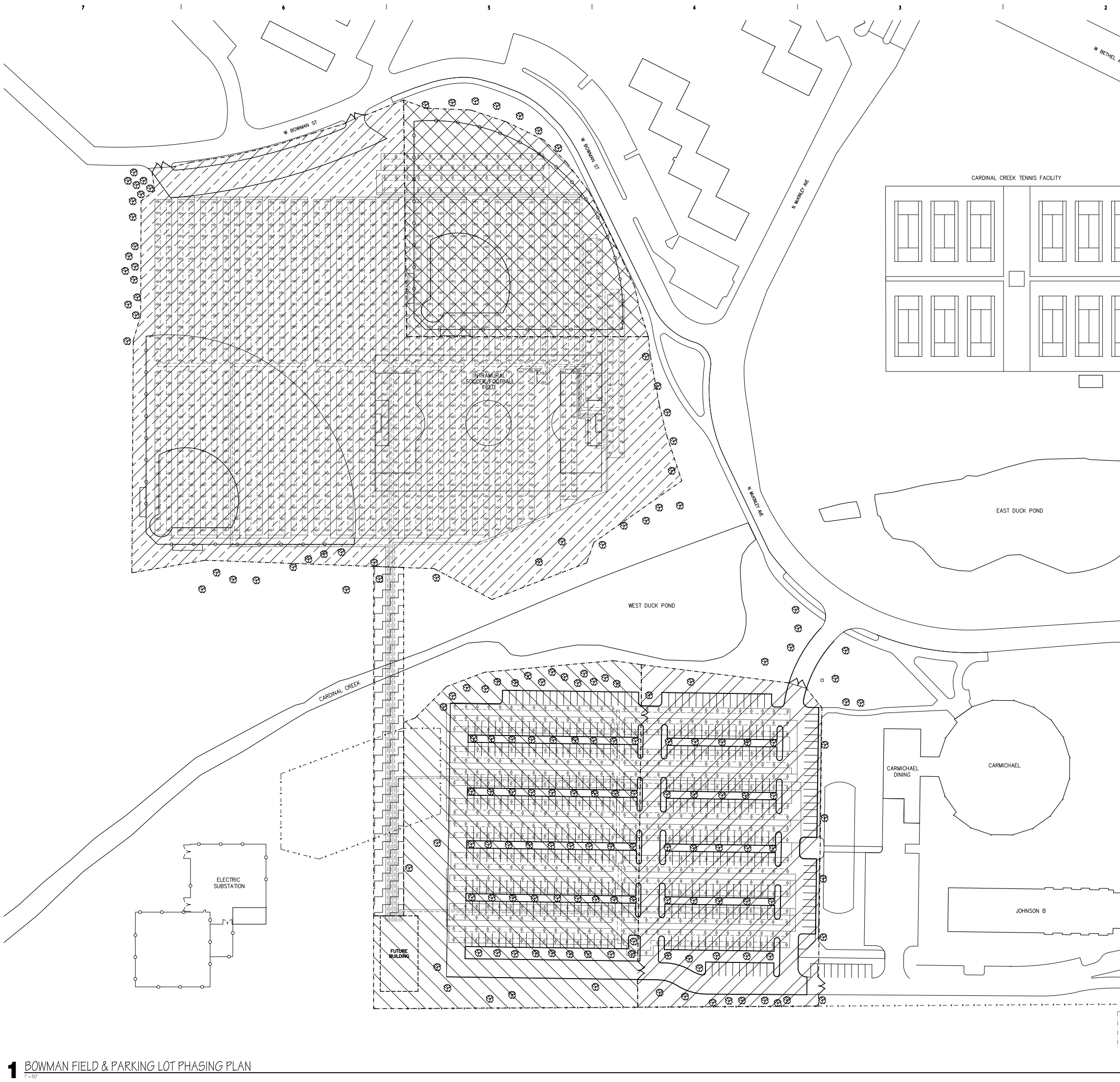
SOUTH WELL FIELD UTILIZATION-PHASE NO.1 BORES (ALTERNATE NO.1)

CONTENTS

M.102

SHEET NUMBER

Drawing name: t:\(B20) Ball State University\B20.10.01-13 South Geo Well Field\02-Design\Drawings\Working Documents\M.101-M.103.dwg Aug 01, 2011 - 9:42am



1 BOWMAN FIELD & PARKING LOT PHASING PLAN

NORTH

PHASING NOTES

1. ALL WORK UNDER THIS CONTRACT TO BE COMPLETED BY JULY 1, 2010.
2. ONE SOFTBALL FIELD SHALL BE AVAILABLE FOR USE AT ALL TIMES DURING THE COURSE OF THE PROJECT. THE CONTRACTOR SHALL ALLOW FOR SAFE ACCESS TO OPERATIONAL SOFTBALL FIELD.

LEGEND

PHASE A – BOWMAN FIELD
COMPLETE WORK IN THIS AREA AS TO ALLOW FOR COMPLETE RESTORATION OF SOFTBALL FIELD INCLUDING PLACEMENT OF SOD NO LATER THE NOVEMBER 1, 2009.

PHASE A – EAST PARKING LOT
COMPLETE ALL WORK IN THIS AREA INCLUDING ASPHALT PAVING AND OTHER SURFACE RESTORATION NO LATER THAN NOVEMBER 1, 2009.

PHASE B – BOWMAN FIELD
BEGIN WORK IN THIS AREA NO EARLIER THAN NOVEMBER 1, 2009 AND COMPLETE BY JULY 1, 2010. ALLOW FOR SAFE ACCESS TO AND FROM FIELD AND CONTINUED USE BY OWNER UNTIL NOVEMBER 1, 2009

PHASE B – WEST PARKING LOT
MAINTAIN ACCESS TO AND OPERATION OF THE WEST PARKING AREA DURING CONSTRUCTION OF PHASE A PARKING AREA. COMPLETE ALL WORK IN THIS AREA NO LATER THAN JULY 1, 2010.

PHASE B – DIRECTIONAL BORING
COMPLETE HORIZONTAL DIRECTIONAL BORING ALL RELATED CONNECTIONS AND RESTORATION NO LATER THAN JULY 1, 2010.

CONSTRUCTION LIMITS / PHASE BORDER

ARCHITECT/ENGINEER

MEP

CONSULTANT

SEALS

PROJECT

GEOTHERMAL CONVERSION, NORTH WELL FIELDS

Ball State University, Muncie, IN

NOT FOR CONSTRUCTION - FINAL REVIEW

PROJECT

CAD:	ARW
IN CHARGE:	KEK
QA:	JAU
ISSUE:	FINAL REVIEW
DATE:	03.30.2009

MARK	DATE	DESCRIPTION

Number: 820.09.01

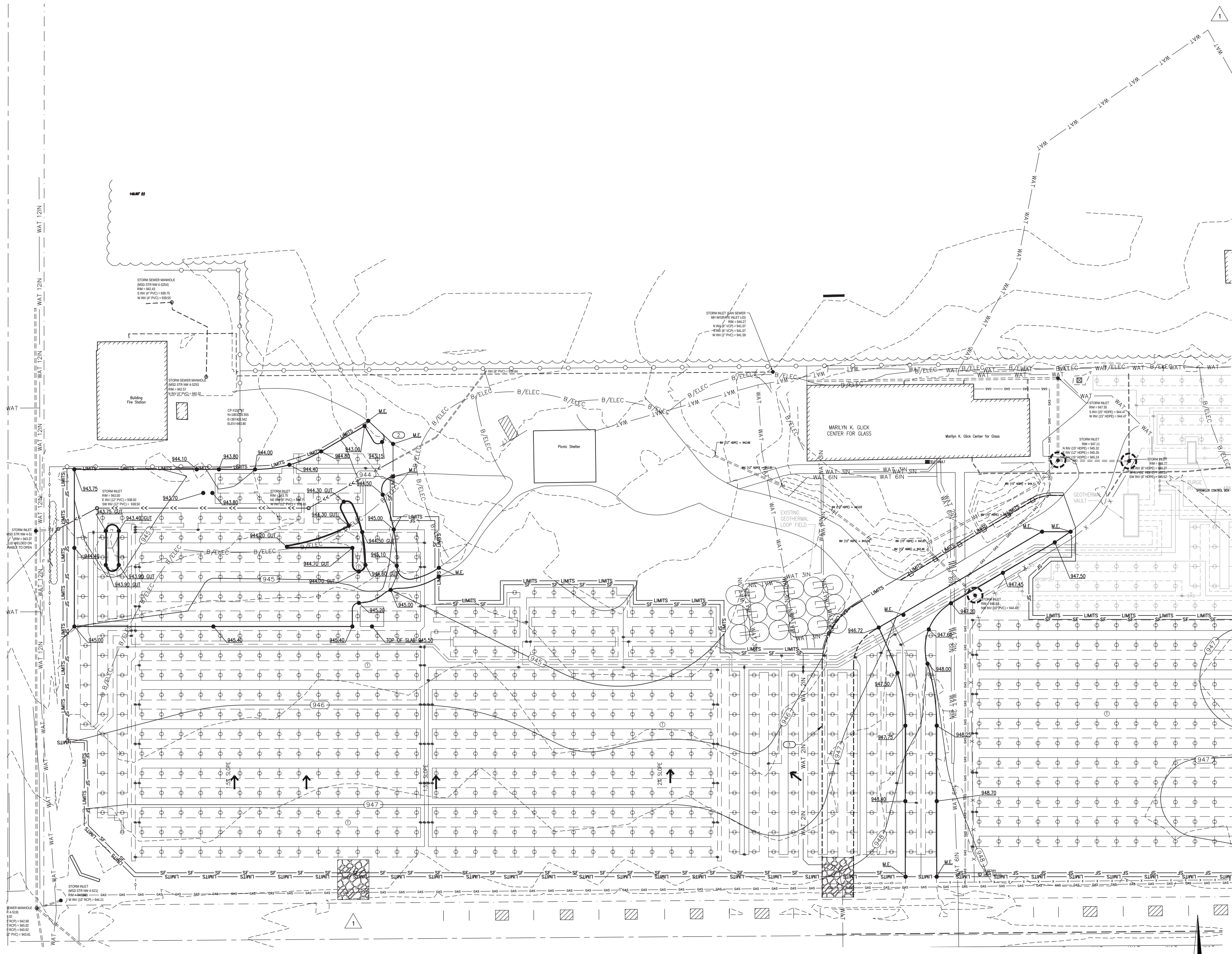
ISSUE

PHASING PLAN

CONTENTS

C.111

SHEET NUMBER



1 GRADING AND EROSION CONTROL PLAN
1" = 30'-0"

GENERAL NOTES

1. SEE SHEET C001 FOR GENERAL CONSTRUCTION NOTES, LEGENDS, AND OTHER IMPORTANT INFORMATION RELATED TO WORK SHOWN ON THIS PLAN.
2. SEE MECHANICAL PLANS FOR GEOTHERMAL WELLS AND PIPING INFORMATION.
3. GRADE ALL FIELD AREAS WITH SLOPE TO ENSURE PROPER DRAINAGE AND AVOID PONDING.

LEGEND

- 950 — EXISTING CONTOURS
- (950) — PROPOSED CONTOURS
- PROPOSED GEOTHERMAL VERTICAL WELL LOCATION
- PROPOSED GEOTHERMAL HDPE HEADER RETURN PIPE (5-FT MINIMUM BURY DEPTH).
- PROPOSED GEOTHERMAL HDPE HEADER SUPPLY PIPE (5-FT MINIMUM BURY DEPTH).
- >> — PROPOSED STORM SEWER
- SF — SILT FENCE. SEE DETAIL 1/C501
- HEAVY DUTY SILT FENCE. SEE DETAIL 2/C501
- INLET PROTECTION. SEE DETAIL 6/C502
- ROCK CONSTRUCTION ENTRANCE SEE DETAIL 3/C501
- 945.73 M.E. — FINISHED GRADE SPOT ELEVATIONS (M.E. = MATCH EXISTING)
- EXISTING SIGN
- EXISTING CONCRETE WHEEL STOP
- E, B/ELEC — EXISTING BURIED ELECTRIC CONDUIT, MANHOLE, LIGHT POLE, AND POWER POLE
- GM, GAS, GV — EXITING BURIED GAS LINE, METER, AND VALVE
- S — EXISTING SANITARY SEWER PIPE AND MANHOLE
- STM — EXISTING BURIED STEAM LINES
- D, MW — EXISTING STORM INLETS, MANHOLE, & MONITORING WELL
- EXISTING STORM SEWER PIPE
- B/TELE — EXISTING BURIED TELEPHONE LINE AND VAULT
- HYD, WAT, W, WV — EXISTING WATER LINE, HYDRANT, WELL, AND VALVE
- X — EXISTING FENCE

KEYED NOTES

1. TEMPORARY ACCESS ROAD
2. MAINTAIN ACCESS TO FIRE STATION FOR DURATION OF PROJECT.

ENGINEER

CONSULTANT

SEALS

PROJECT

GEOTHERMAL CONVERSION - SOUTH WELL FIELD PHASE #2

Ball State University, Muncie, Indiana

PROJECT

CAD: MTH
IN CHARGE: KEK
QA: BJJ
ISSUE: CD
DATE: 08.19.2013

MARK	DATE	DESCRIPTION
1	9/6/13	Addendum #1
2	9/30/13	Conformed Set

MEP PROJ #: B20.13.01-20
BSU PROJ #: 2011-043.01 XU

ISSUE

GRADING AND EROSION CONTROL PLAN

CONTENTS

C.401

SHEET NUMBER

Drawing name: K:\g-m\MEP-Assoc\14705003\civil\dwgs\C401 Grading Plan.dwg Oct 28, 2013 - 9:16am

Appendix 11: Photos of Borehole and Drilling Process


AUTO CRANE
The Well Guy

LOOP FIELD RETURN
LOOP FIELD SUPPLY
LOOP FIELD RETURN
LOOP FIELD SUPPLY
LOOP FIELD SUPPLY

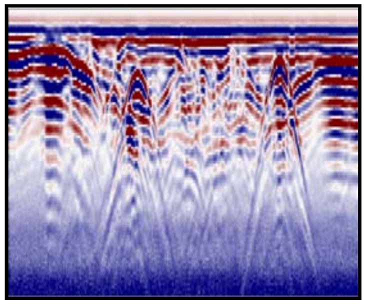

D2
10

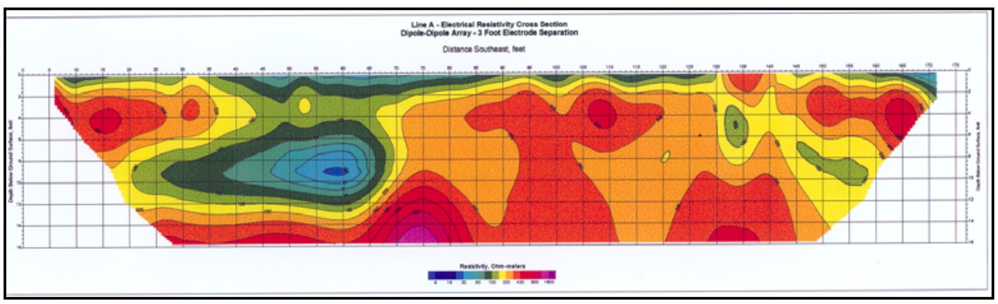
Appendix 12: Report of Geophysical Survey (2D Resistivity Testing)

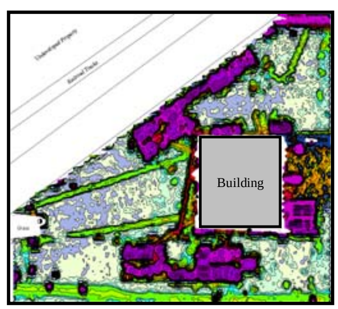
REPORT OF GEOPHYSICAL SURVEY

GEOPHYISCAL INVESTIGATION
BALL STATE MEP GEOTHERMAL PROJECT
MUNCIE, INDIANA

MUNDELL PROJECT NO.: M09005
MAY 5, 2009





MUNDELL & ASSOCIATES, INC.
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info@MundellAssociates.com

MUNDELL
& ASSOCIATES

110 South Downey Avenue
Indianapolis, Indiana 46219-6406
Telephone 317-630-9060
Facsimile 317-630-9065
www.MundellAssociates.com

May 5, 2009

Mssrs. Jerry Abernathy and Kraig Klund
MEP Associates, LLC
2720 Arbor Court
Eau Claire, WI 54701

Re: **Geophysical Survey**
Ball State University Geothermal Project
Energy Centers Conversion – Phase 1, North Loop Field #1
2000 West University Avenue
Muncie, Indiana 47306
MUNDELL Project No. M09005

Gentlemen:

In accordance with Proposal No. P09011 dated March 25, 2009, MUNDELL & ASSOCIATES, INC. (MUNDELL) is pleased to provide to MEP Associates, LLC (MEP) with this letter report documenting geophysical services at the above-referenced project site (the "Site"). The geophysical fieldwork was performed on April 7 and 8, 2009. The intent of this survey was to measure the variation in electrical resistivity of the subsurface materials in an effort to help evaluate the geologic and hydrogeologic conditions beneath the site, prior to the installation of 1,700 geothermal wells on the northwest side of campus. In addition, on April 7 and 8, 2009, MUNDELL mobilized to the Site to conduct downhole geophysical logging of two drill holes completed by others. Our documentation of this project is included in the following sections.

Introduction

The area of investigation for this project consists of a northern field containing two softball diamonds and a soccer field, and a southern parking lot, separated by Hiatt Ditch No. 2 (a.k.a. Cardinal Creek). This area is approximately 20 acres in size and is located south and west of the intersection of West Bowman Street and North McKinley Avenue (see **Figure 1**). It is our understanding that 1,700 geothermal wells will be installed at this site, each to a depth of 400 feet. Thus, the goal of this geophysical survey was to provide Ball State with non-intrusive data that provides insight into the geologic conditions beneath the site.

Technical Background

The site lies in the Tipton Till physiographic plain. In this part of the state, the thickness of the unconsolidated material (which consists predominantly of fine-grained glacial till with lesser amounts of interbedded coarse-grained sediments) ranges from approximately 20 to 140 feet. The underlying bedrock is composed of Silurian limestone and dolomite, which is prone to weathering and solutioning.

In general, a number of geophysical techniques can be applied to the mapping of subsurface features. However, certain methods, sensitive to a range of contrasting physical or electrical properties, can have attributes that make them more suitable than others depending on the site-specific conditions. Contrasting material properties that typically are found to be useful for mapping soil and bedrock include electrical conductivity or resistivity, acoustic velocity, density, and magnetic susceptibility. For this project, it was determined that two-dimensional electrical resistivity imaging (*i.e.*, 2-D ERI) would provide the best results. A brief description of this technique is presented in the section below.

Two-Dimensional Electrical Resistivity Imaging (2-D ERI)

2-D ERI is used to provide highly detailed, cross-sectional views of the subsurface by identifying the distribution of electrical resistivity variations in subsurface materials with depth. 2-D ERI is a *direct-contact* means of measuring vertical resistivity variations along a single line of data collection known as an apparent resistivity pseudo-section. The term “apparent resistivity” refers to the fact that the data are not actual measurements of the resistivity of subsurface materials, but measurements that are *apparent* at the earth’s surface.

For this project, resistivity data were collected with an *AGI SuperSting R8* earth resistivity meter using a dipole-dipole array of 60 electrodes along profile *Lines 2*, *4* and *6*, and a dipole-dipole array of 56 electrodes along profile *Lines 1, 3, 5 and 7*. The electrode spacing of each of the resistivity lines was dependent on the orientations of the lines and the amount of area available for data collection. Given this, *Line 1* has an electrode spacing of 3.5 meters (approximately 11.5 feet), *Line 2* has a spacing of 4 meters (approximately 13 feet), *Lines 4* and *7* have a spacing of 5 meters (approximately 16.5 feet), and *Lines 3*, *5*, and *6* have a spacing of 6 meters (approximately 20 feet). Resistivity profile *Lines 1* through *7* are presented as **Figures 2** through **8**. Once the data were collected, they were downloaded to a computer and subsequently inverse-modeled using the software *EarthImager 2D v1.8.1* to obtain an “actual”, true resistivity cross-section of the subsurface. This is obtained through the process of generating a model resistivity cross-section, calculating the apparent resistivity pseudo-section that would result from such a model, and comparing the calculated pseudo-section to the one collected in the field. The model is then altered through a number of iterations until the two pseudo-sections closely match each other. At this point, the model is considered to be a reasonable estimation of the true resistivity distribution of the actual subsurface materials.

Electrical resistivity is one of the most widely varying of the physical properties of natural materials. Certain minerals, such as native metals and graphite, conduct electricity via the passage of electrons; however, electronic conduction is generally very rare in the subsurface. Most minerals and rocks are insulators, and electrical current preferentially travels through the water-filled pores in soils and rocks by the passage of the free ions in pore waters *(i.e.*, ionic conduction). It thus follows that the degree of saturation, interconnected porosity, and water chemistry (*i.e*., total dissolved solids) are the major controlling variables of the resistivity of soils and rocks. In general, electrical resistivity directly varies with changes in these parameters. Fine-grained sediments, particularly clay-rich sediments such as glacial till, are excellent conductors of electricity, often much better than fresh water found in the pores of sand and gravel. Carbonate rocks (i.e., limestone and dolomite) are very electrically resistive when they are unfractured, but can have significantly lower resistivity values when fractured and/or weathered and solutioned.

The resistivity cross sections presented in this report are 2-dimensional representations of the general distribution of electrical resistivity in the 3-dimensional subsurface. There is no unique direct conversion from resistivity values to actual subsurface lithology. However, based on site knowledge, geometric shapes and relationships of various resistivitiy anomalies, and the observed ranges of resistivity values, reasonable geologic interpretations can often be made.

Scope and Results of Geophysical Survey Performed

As previously mentioned, seven (7) 2-D ERI lines were collected, and are presented as **Figures 2** through **8**. Based on our the survey results, it is apparent that the subsurface soil and bedrock conditions underlying the site are fairly complex, with rapidly changing conditions observed over distances of less than a hundred feet. However, while there is variability over all of the resistivity profiles, there are general patterns that are common among them. High resistivity values, *i.e.*, approximately 750 to 3000 ohm-meters, are generally interpreted to reflect the presence of dense, competent limestone rock (presented as a pink color). Moderately high values (300 to 750 ohm-meters) reflect areas where the bedrock is weathered, fractured or solutioned. Mid-range values (80 to 300 ohm-meters) are interpreted to be coarser-grained soils (sand and gravel) in the shallow subsurface and possible severely weathered/fractured rock in the lower subsurface or soil/water-filled voids. The lowest range of values, *i.e.*, less than 80 ohm-meters, is interpreted to be fine-grained soils with a high clay content (purple to green). A resistivity of 0 ohm-meters (dark purple) is indicative of buried metallic utilities and interference from buried electrical lines and the electrical substation in the southwestern corner of the Site.

In general, the majority of the profiles show a thin (10 to 20 feet) layer of silt and clay overlying a thicker (20 to 30 feet) body of sand and gravel, under which lies a clayey layer of variable thickness (30 to 70 feet). The estimated bedrock surface shown on these profiles is denoted by a black dashed line, and one can see that it is quite variable and undulating, ranging in depth from just over 20 feet on *Line 4* to 140 feet on *Line 3*. Some of this variability is likely due to solutioning of the calcareous limestone bedrock, and several solution prone features can be seen on the resistivity profiles, the most notable of which is located on *Line 4*, just west of a storm sewer inlet.

After the individual resistivity cross-sections had been generated, the interpreted bedrock surface from the individual profiles was digitized and uses to generate a top of bedrock topography map, which is presented as **Figure 9**. In addition to this map, several lateral (*i.e.*, constant elevation) resistivity slice maps were generated as well by combining the individual cross-sections into a three-dimensional data set and taking slices at various constant elevations. Resistivity slices taken at 920 feet, 900 feet, 840 feet, and 820 feet elevations are presented respectively as **Figures 10** through **13**. The 920 and 900 feet maps show the lateral extents of the shallower fine- and coarse-grained layers, while the 840 and 820 feet maps detail where the bedrock is competent and where it is more fractured and solutioned.

Further evidence of bedrock solutioning is found in the conductivity and caliper logs of the Bialecki and Ortman test well locations completed by MUNDELL on April 7 and 8, 2009 (see **Figures 14** and **15**). These logs show the presence of several fractured/solutioned zones, the most severe of which is located from approximately 360 feet to 400 feet below ground surface. This zone of severely weathered limestone and clay is very soft and was confirmed by the drilling logs.

Limitations

This study included a limited set of geophysical readings across limited portions of the Site. The results and interpretations of the geophysical survey performed are considered generally reliable and were conducted in a manner generally consistent with practitioners in the field of geophysical exploration and geophysical engineering. The methods used in this investigation are considered reliable; however, there may exist localized variations in the subsurface conditions that have not been completely defined at this time. The resistivity results are not unique to unconsolidated soil/limestone bedrock features and more than one geologic feature or model may give similar results.

The site features presented on the site base map are for informational purposes only and no representation is made as to the accuracy or completeness of this information. It is recommended that a practicing geosciences or geotechnical engineering professional be contacted prior to conducting verification drilling or excavating activities.

Closing

We appreciate the opportunity to provide geophysical services to you on this project. If you should have any questions regarding the enclosed information, please do not hesitate to contact us at (317) 630-9060.

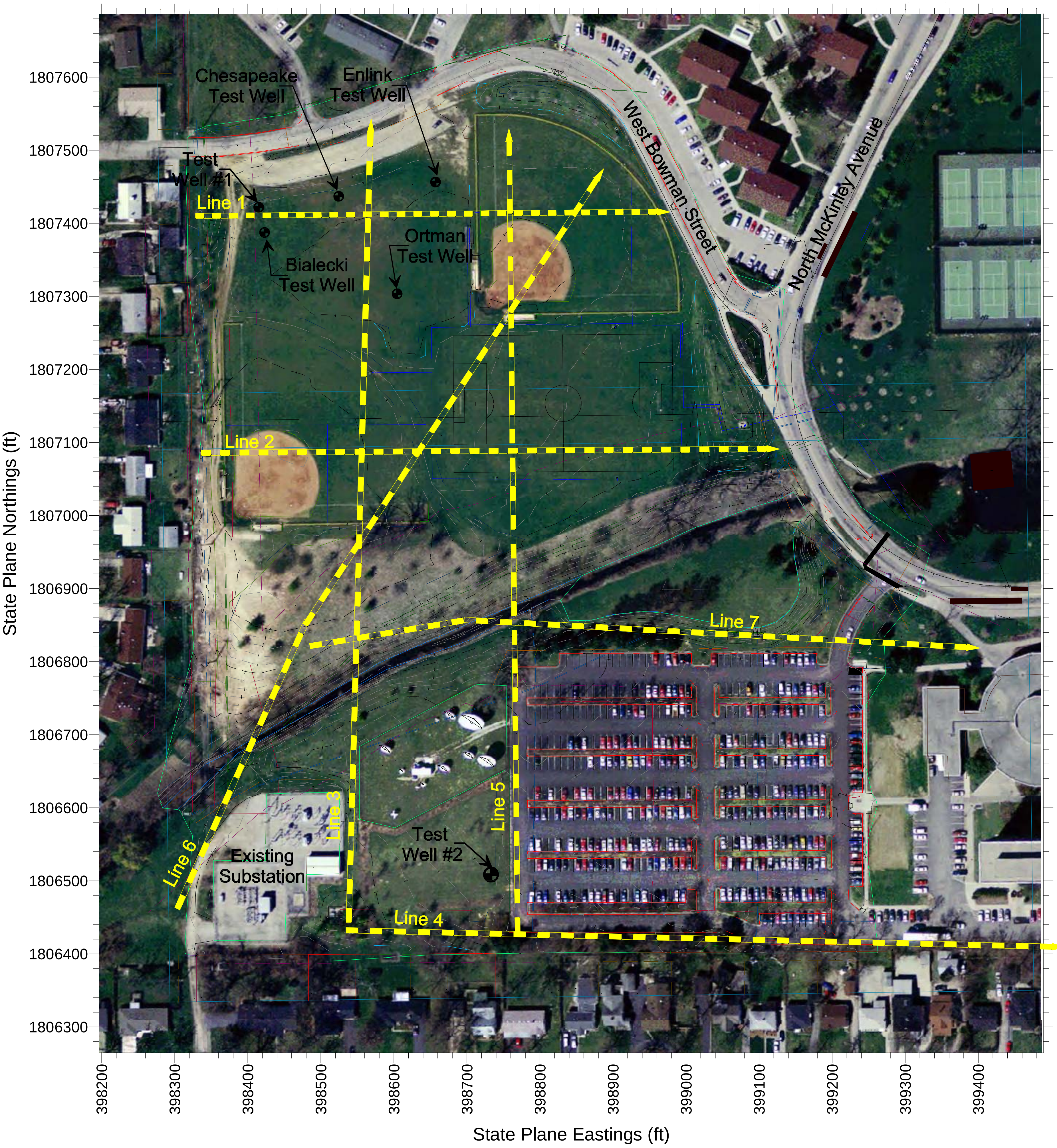
Sincerely,
MUNDELL & ASSOCIATES, INC.

Gabriel Hebert
Project Geophysicist

John A. Mundell, P.E., L.P.G.
President/Director of Geophysical Services

Attachments: Figure 1. Site Map
Figure 2. Resistivity Profile Line 1
Figure 3. Resistivity Profile Line 2

Figure 4. Resistivity Profile Line 3
Figure 5. Resistivity Profile Line 4
Figure 6. Resistivity Profile Line 5
Figure 7. Resistivity Profile Line 6
Figure 8. Resistivity Profile Line 7
Figure 9. Bedrock Topography Map
Figure 10. Resistivity Slice Map at 920 ft. Elevation
Figure 11. Resistivity Slice Map at 900 ft. Elevation
Figure 12. Resistivity Slice Map at 840 ft. Elevation
Figure 13. Resistivity Slice Map at 820 ft. Elevation
Figure 14. Bialecki Test Well Log
Figure 15. Ortman Test Well Log



Aerial Photo is provided for site reference only.
No claim is made as to the accuracy
or completeness of this information.

Indiana East State Plane Coordinates, Datum NAD83

LEGEND

N

Scale in Feet
0 50 100 150 200 250 300
Scale in Meters
0 10 20 30 40 50 60 70 80 90 100
1" = 150'

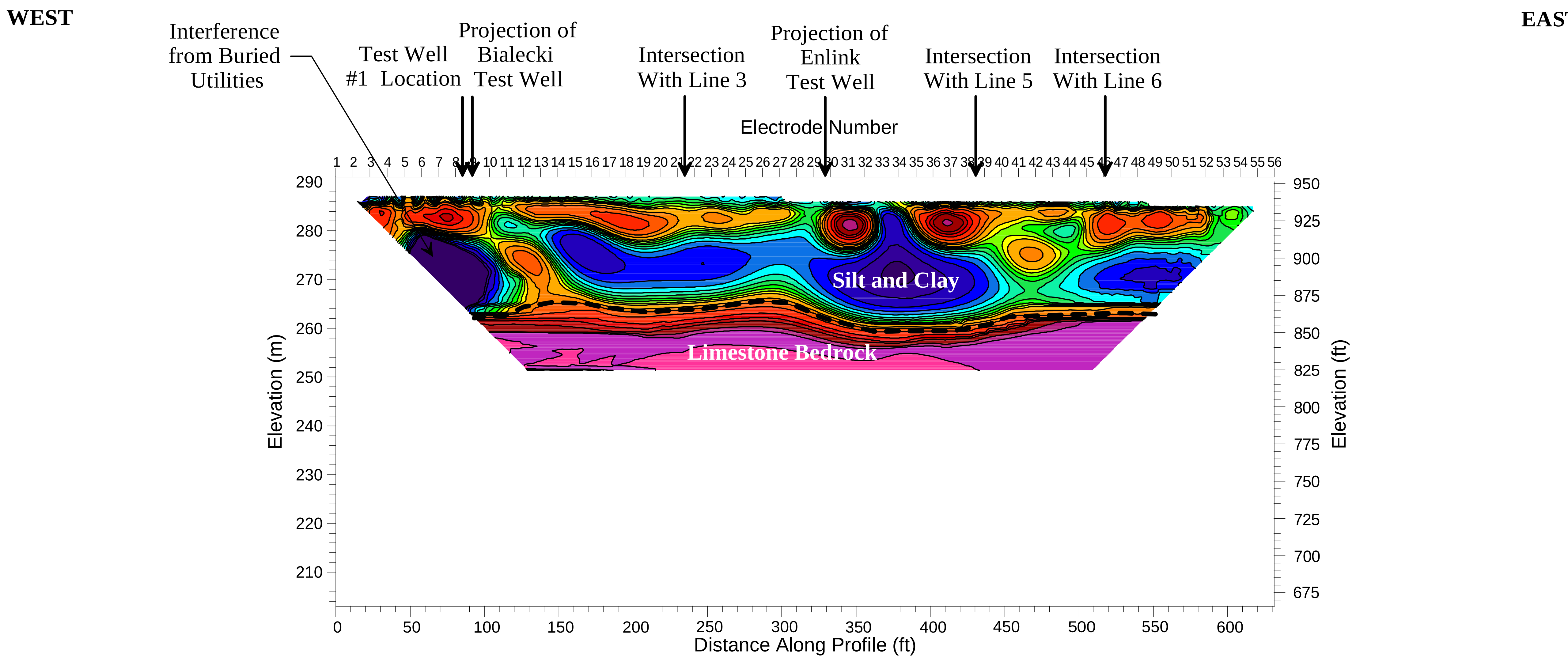
Water Line
Sanitary Sewer Line
Storm Sewer Line
Telecom Line
Electrical Line
Drainage Right-of-Entry
Resistivity Line Location

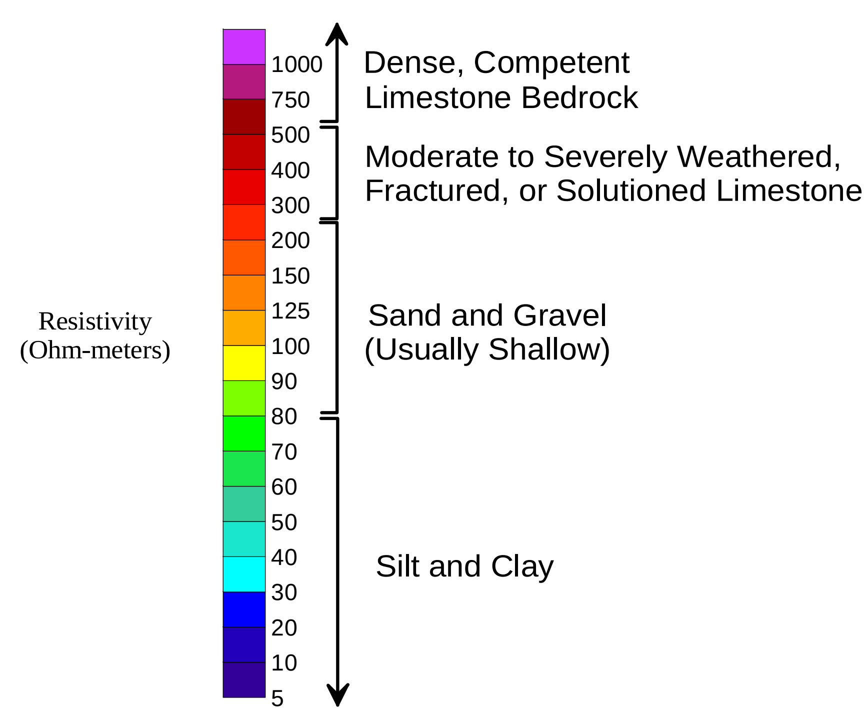
FIGURE 1

Site Map

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

MUNDELL & ASSOCIATES, INC.
Consulting Professionals for the Earth & Environment
110 South Downey Avenue
Indianapolis, Indiana 46219
317-630-9060, Fax: 317-630-9065





PROCESSING STATISTICS
Number of Iterations: 5
RMS Error: 10.60%
Total Number of Data: 665
Maximum Misfit: 40%

Line 1

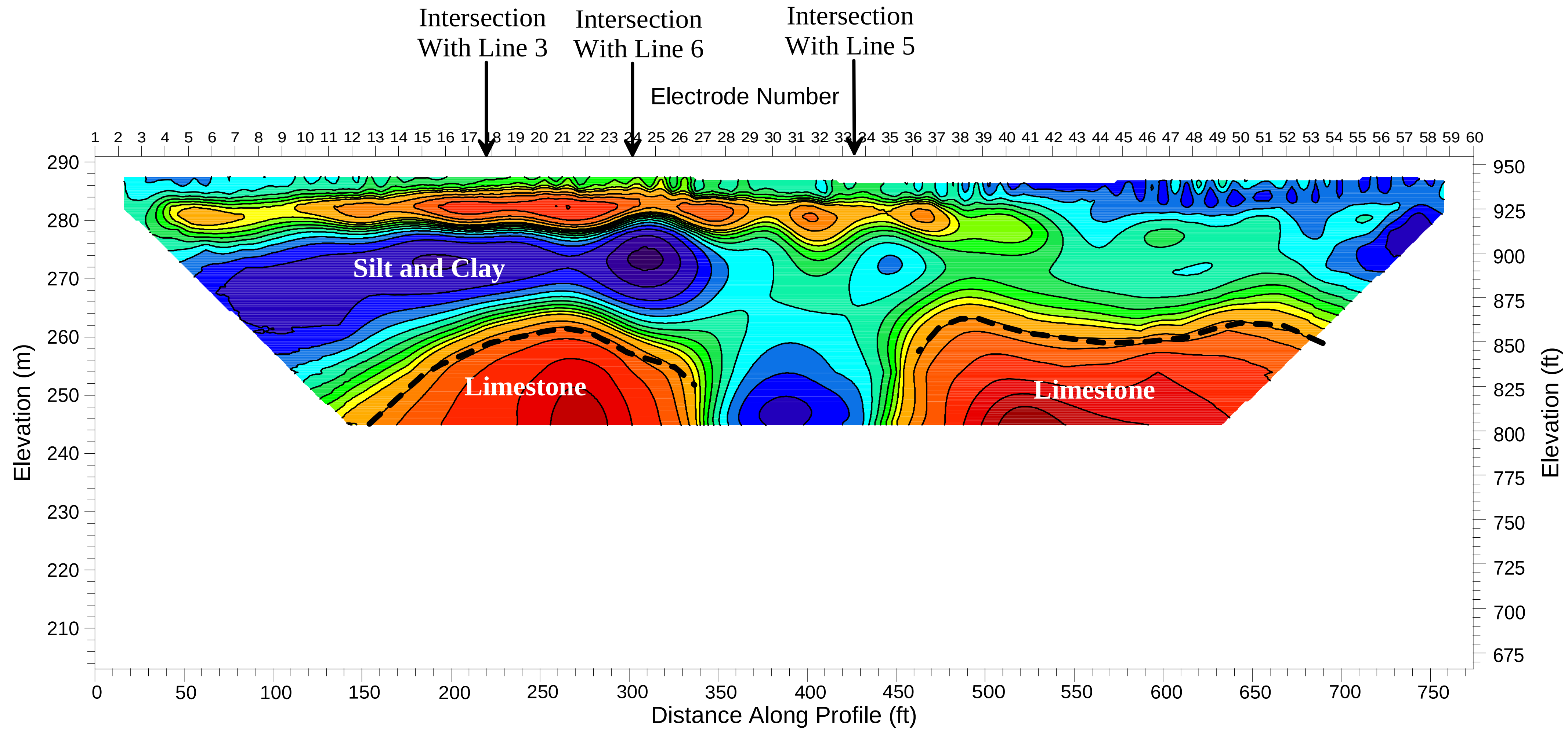
Geologic Exploration
Ball State University Geothermal MEP
Muncie, Indiana
MUNDELL Project No. M09005

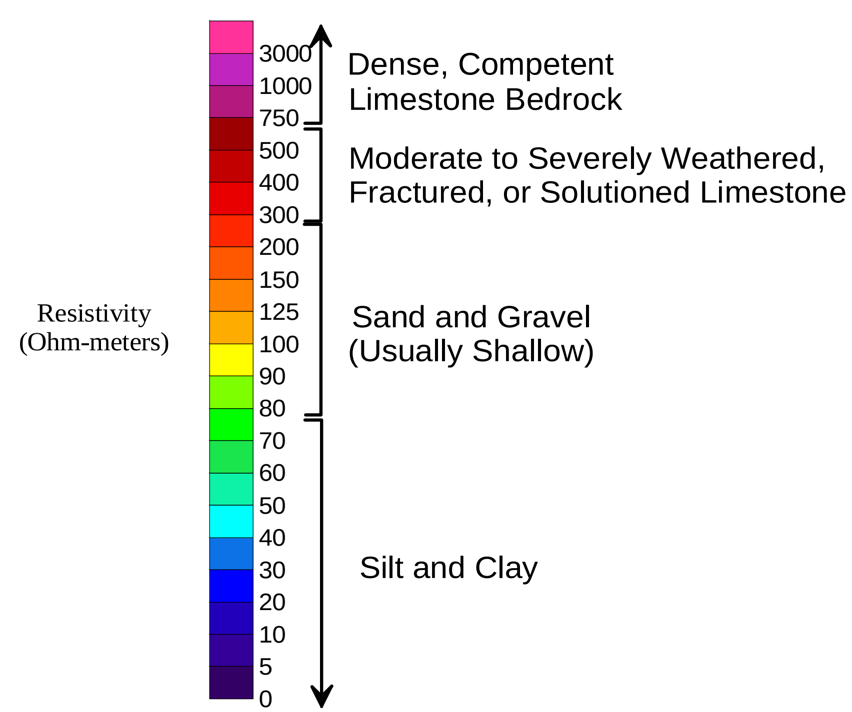
FIGURE 2

MUNDELL & ASSOCIATES, INC.
Consulting Professionals for the Earth & Environment
110 South Downey Avenue
Indianapolis, Indiana 46219
317-630-9060, Fax: 317-630-9065

WEST

EAST





PROCESSING STATISTICS
Number of Iterations: 5
RMS Error: 9.86%
Total Number of Data: 730
Maximum Misfit: 40%

Line 2

Geologic Exploration
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Muncie, Indiana
MUNDELL Project No. M09005

FIGURE 3

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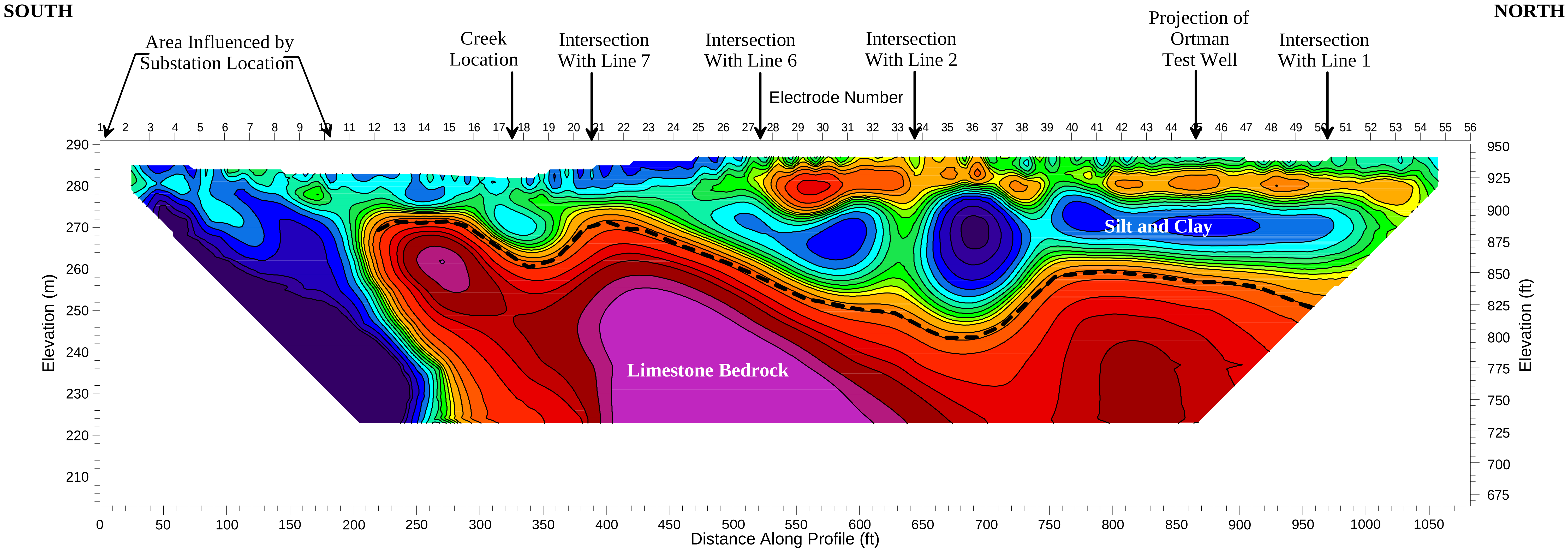

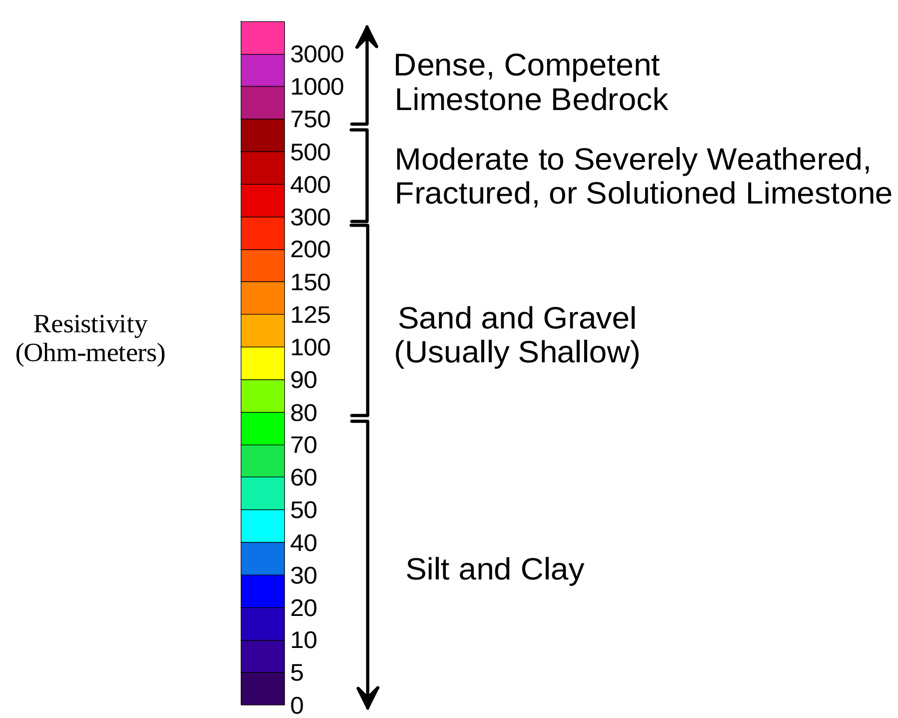

PROCESSING STATISTICS
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RMS Error: 7.85%
Total Number of Data: 677
Maximum Misfit: 27%

Line 3

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Muncie, Indiana
MUNDELL Project No. M09005

FIGURE 4

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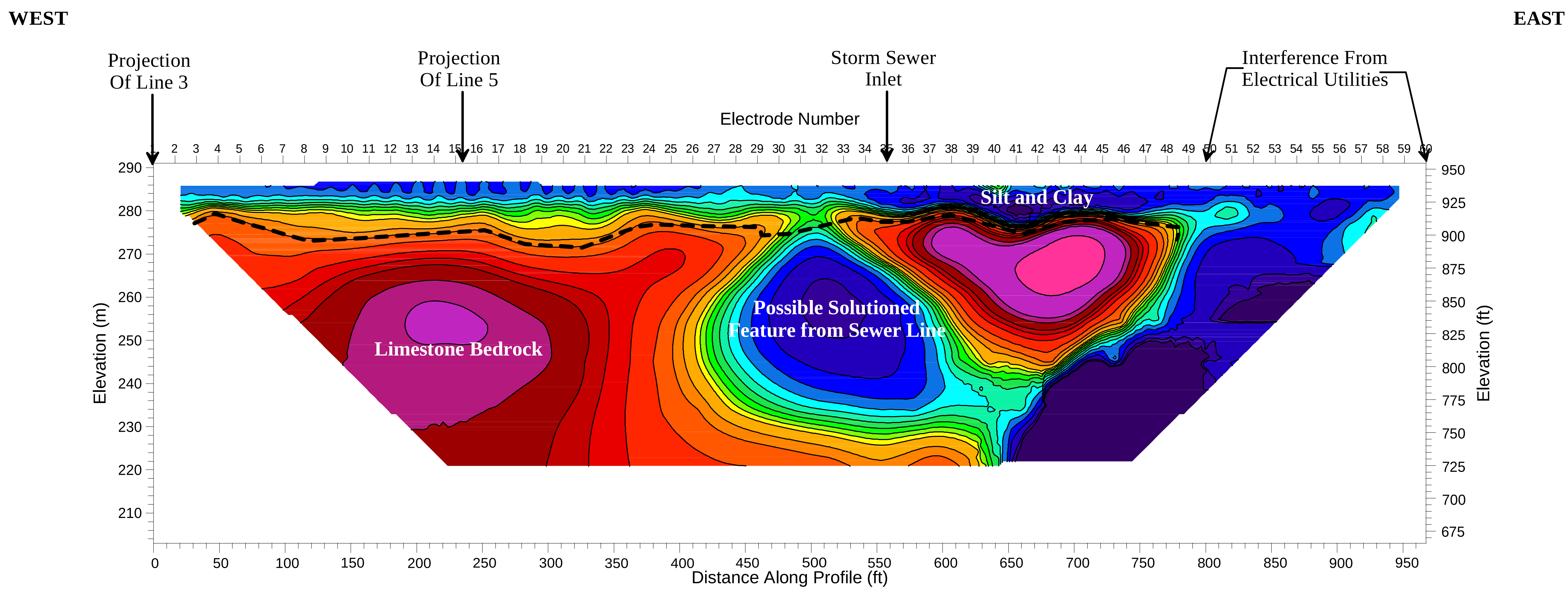

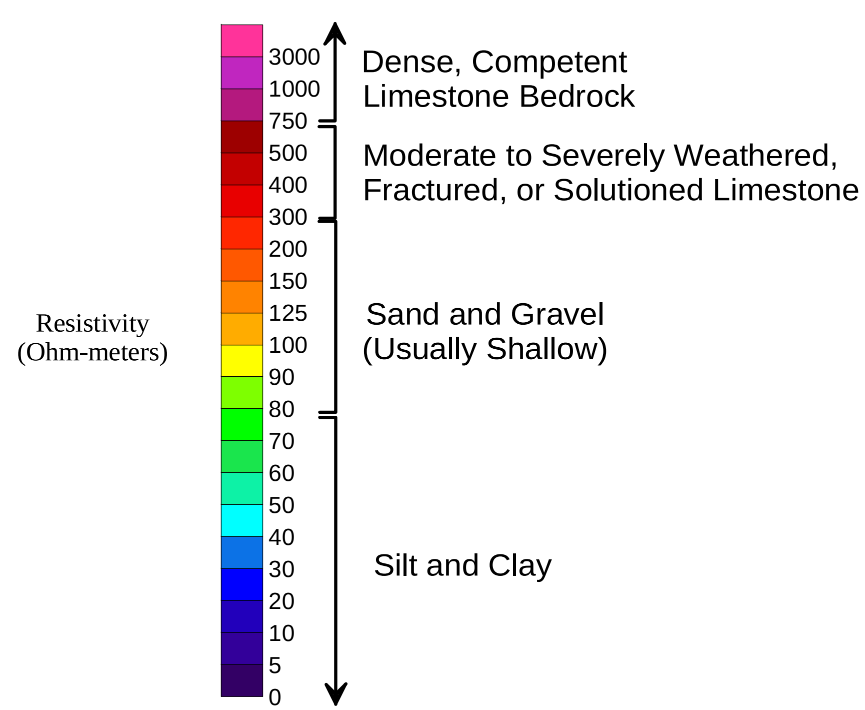

PROCESSING STATISTICS
Number of Iterations: 4
RMS Error: 11.22%
Total Number of Data: 741
Maximum Misfit: 40%

Line 4 Geologic Exploration Ball State University Geothermal MEP Muncie, Indiana MUNDELL Project No. M09005	FIGURE 5

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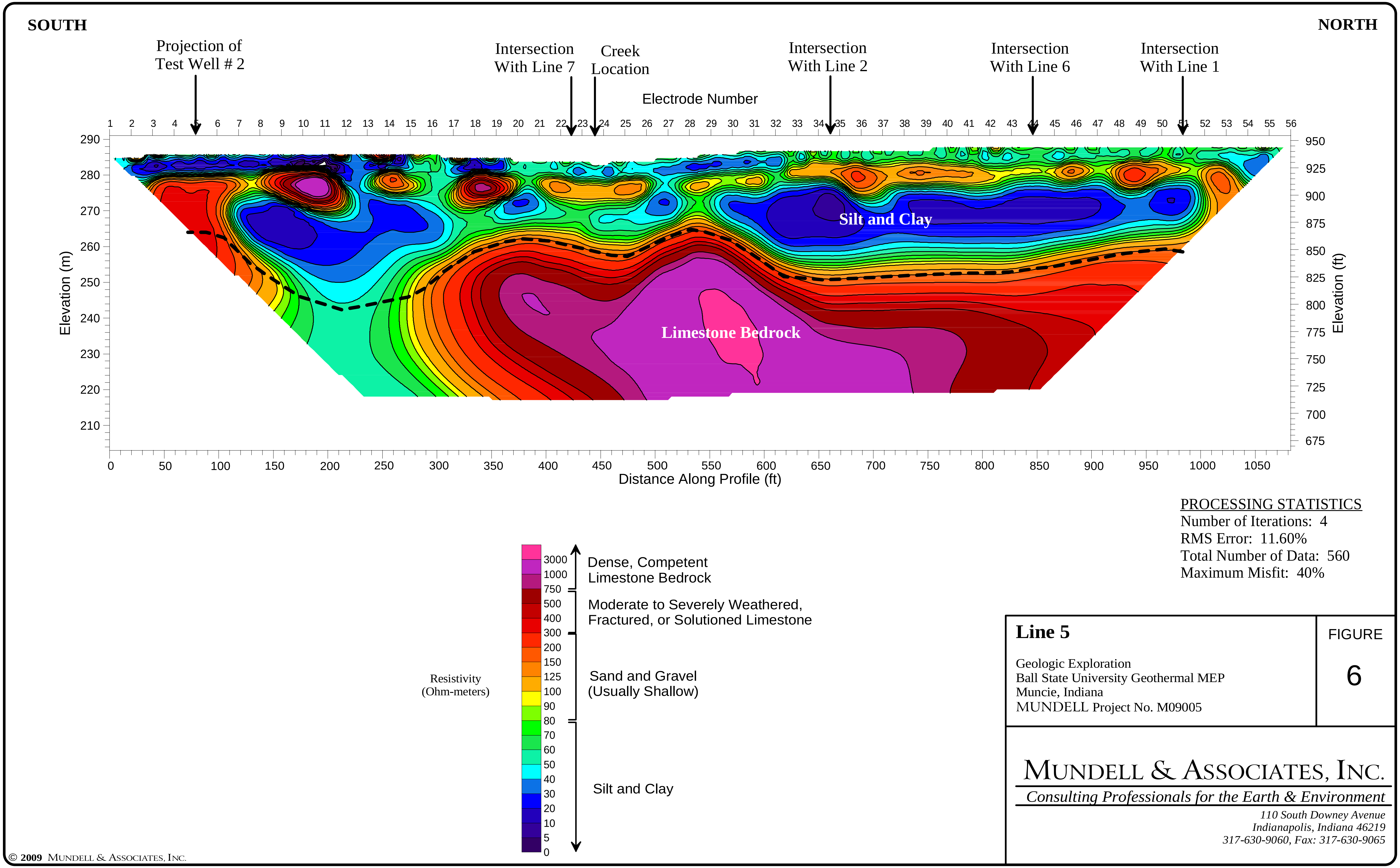
SOUTH
NORTH
Projection of Test Well # 2
Intersection With Line 7
Creek Location
Intersection With Line 2
Intersection With Line 6
Intersection With Line 1
Electrode Number
Elevation (m)
Elevation (ft)
Distance Along Profile (ft)
Silt and Clay
Limestone Bedrock
PROCESSING STATISTICS
Number of Iterations: 4
RMS Error: 11.60%
Total Number of Data: 560
Maximum Misfit: 40%
Resistivity (Ohm-meters)
3000
1000
750
500
400
300
200
150
125
100
90
80
70
60
50
40
30
20
10
5
0
Dense, Competent Limestone Bedrock
Moderate to Severely Weathered, Fractured, or Solutioned Limestone
Sand and Gravel (Usually Shallow)
Silt and Clay
Line 5
Geologic Exploration
Ball State University Geothermal MEP
Muncie, Indiana
MUNDELL Project No. M09005
FIGURE
6
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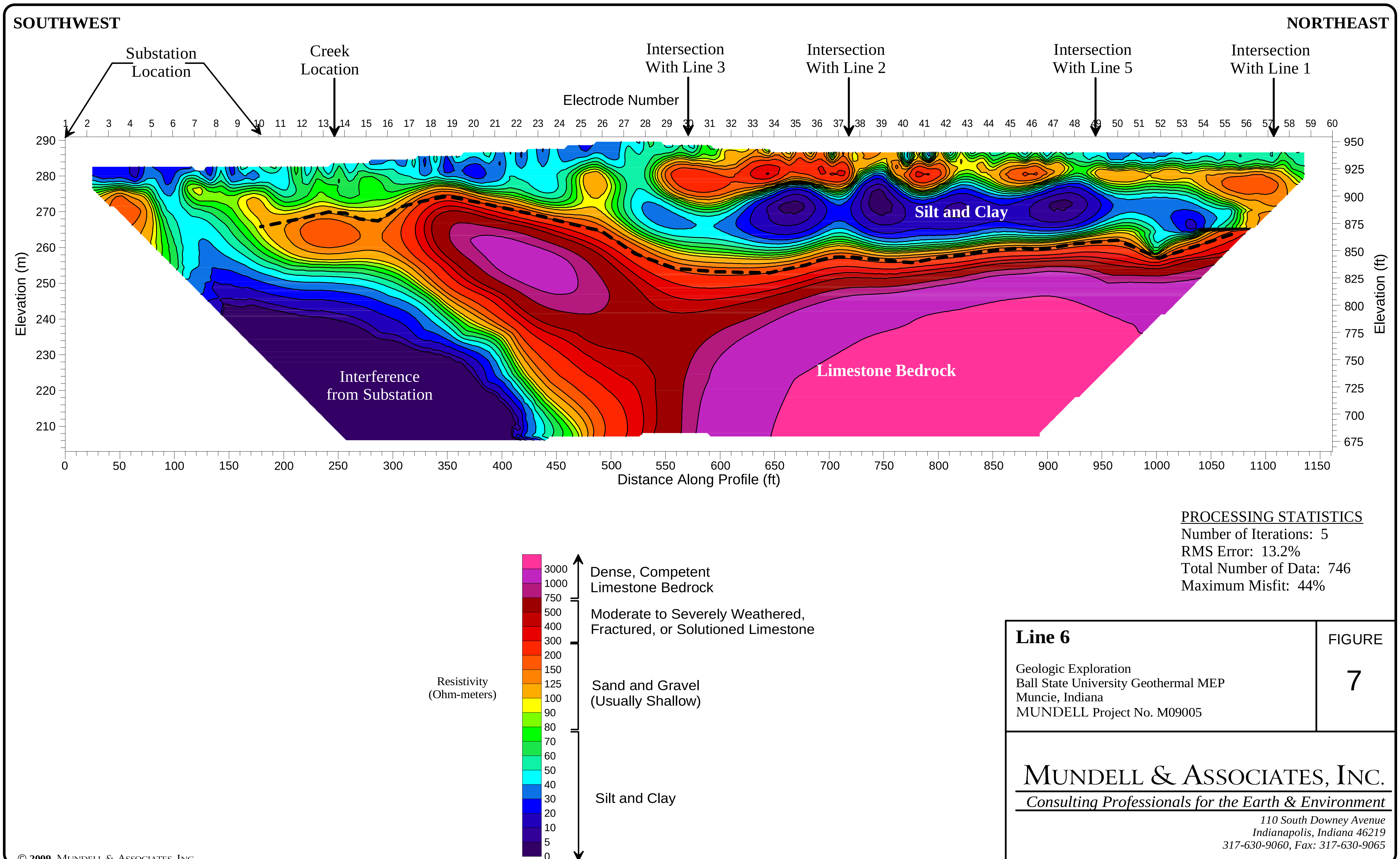

SOUTHWEST
NORTHEAST
Substation Location
Creek Location
Intersection With Line 3
Intersection With Line 2
Intersection With Line 5
Intersection With Line 1
Electrode Number
Elevation (m)
Elevation (ft)
Distance Along Profile (ft)
Silt and Clay
Interference from Substation
Limestone Bedrock
PROCESSING STATISTICS
Number of Iterations: 5
RMS Error: 13.2%
Total Number of Data: 746
Maximum Misfit: 44%
Resistivity (Ohm-meters)
3000
1000
750
500
400
300
200
150
125
100
90
80
70
60
50
40
30
20
10
5
0
Dense, Competent Limestone Bedrock
Moderate to Severely Weathered, Fractured, or Solutioned Limestone
Sand and Gravel (Usually Shallow)
Silt and Clay
Line 6
Geologic Exploration
Ball State University Geothermal MEP
Muncie, Indiana
MUNDELL Project No. M09005
FIGURE
7
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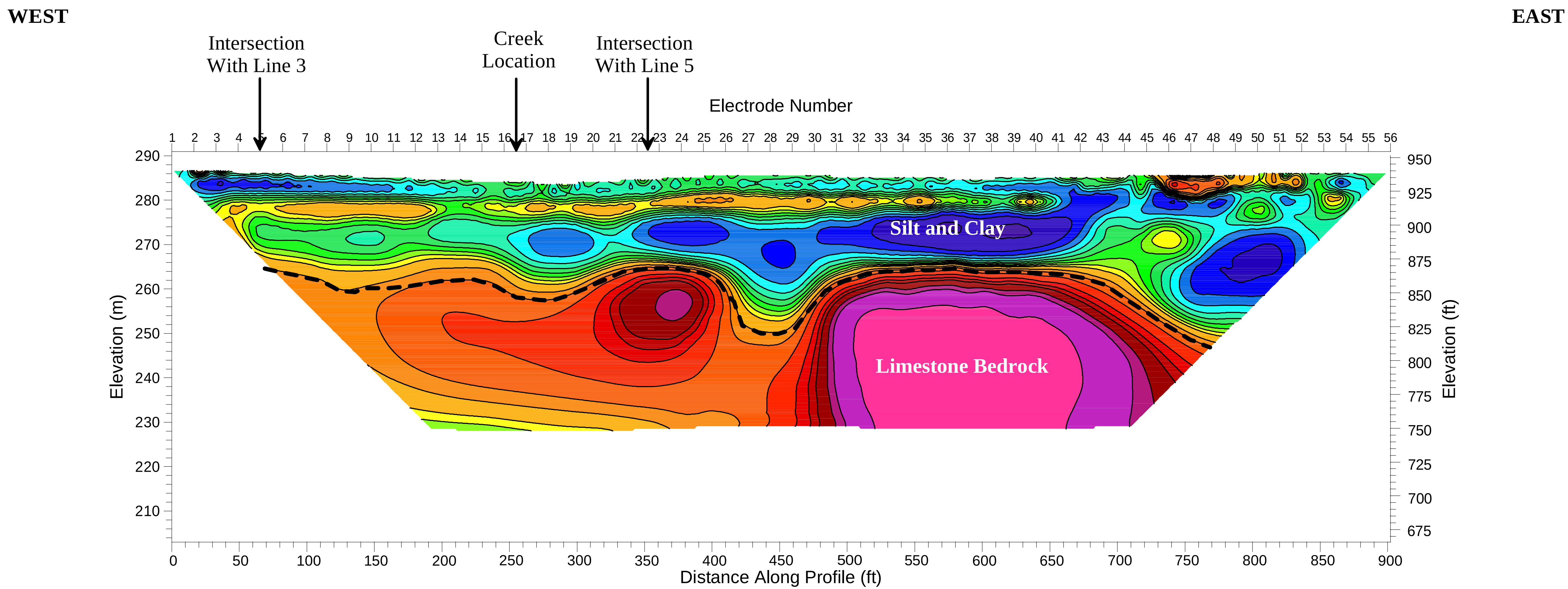

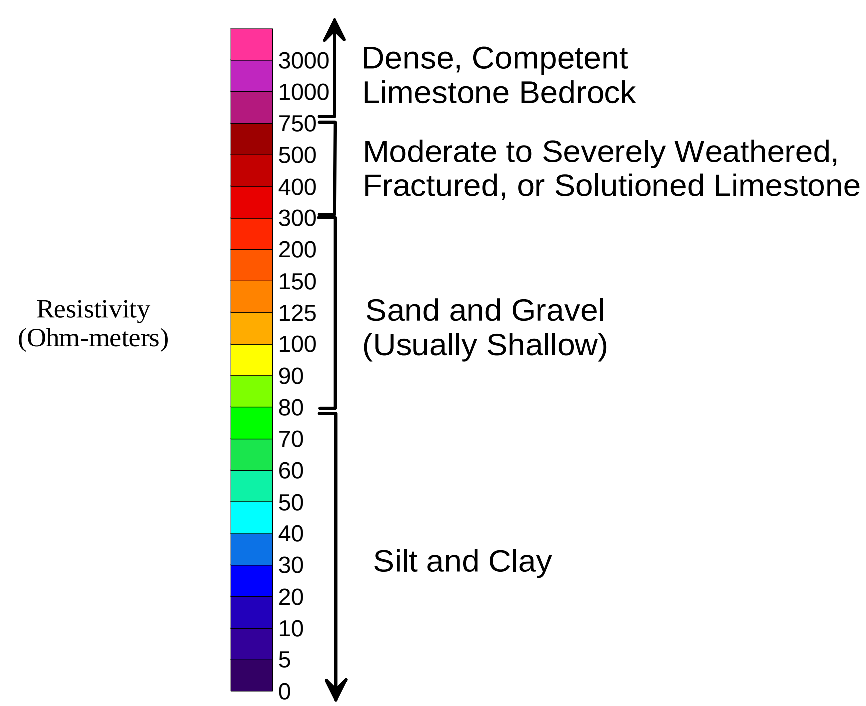

PROCESSING STATISTICS
Number of Iterations: 6
RMS Error: 5.23%
Total Number of Data: 648
Maximum Misfit: 18%

Line 7 Geologic Exploration Ball State University Geothermal MEP Muncie, Indiana MUNDELL Project No. M09005	FIGURE 8

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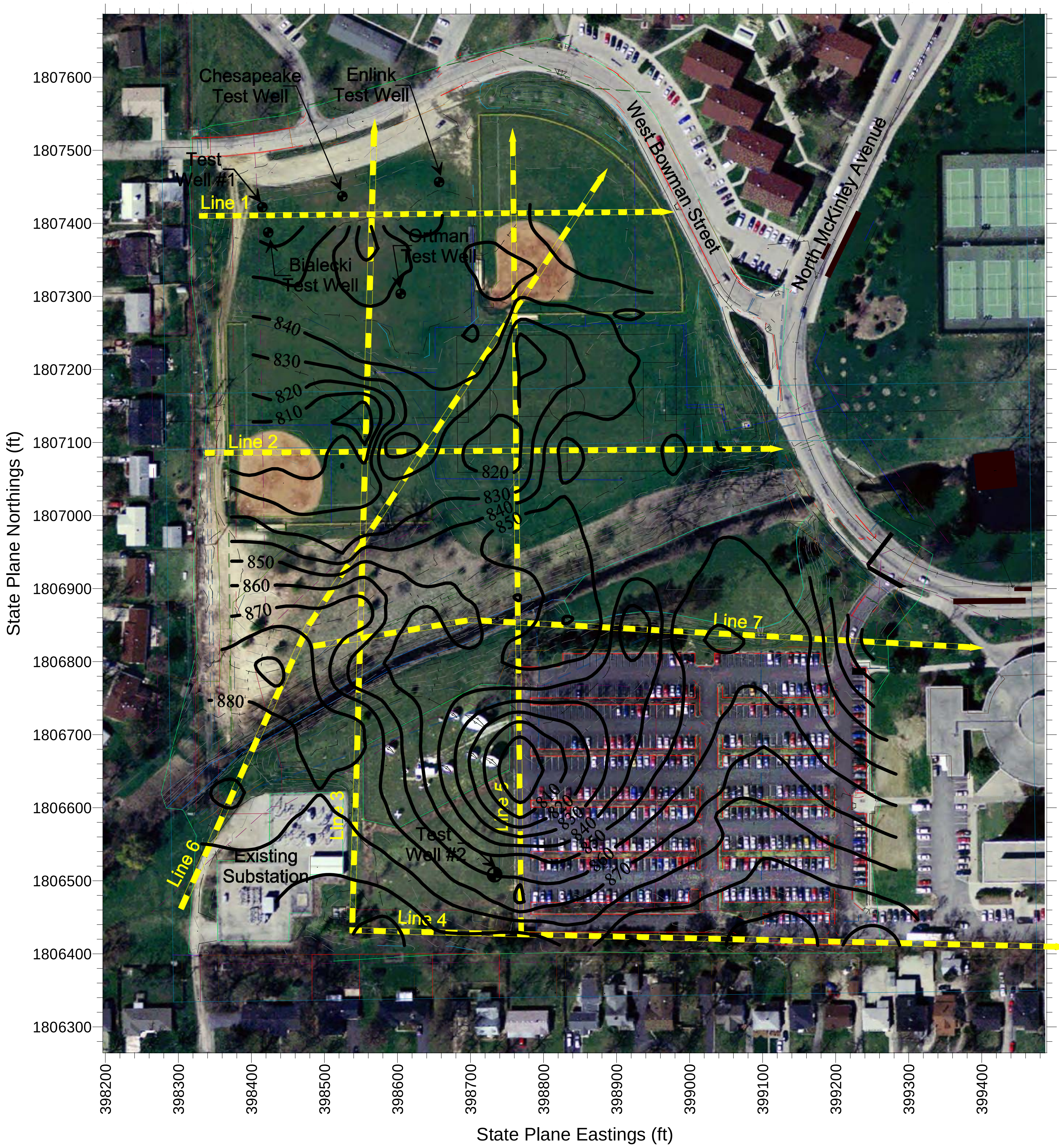

Aerial Photo is provided for site reference only.
No claim is made as to the accuracy
or completeness of this information.

Indiana East State Plane Coordinates, Datum NAD83

LEGEND

N

Scale in Feet

0 50 100 150 200 250 300

Scale in Meters

0 10 20 30 40 50 60 70 80 90 100

1" = 150'

Bedrock Elevation Contour Line

Resistivity Line Location

FIGURE 9

Bedrock Topography Map

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

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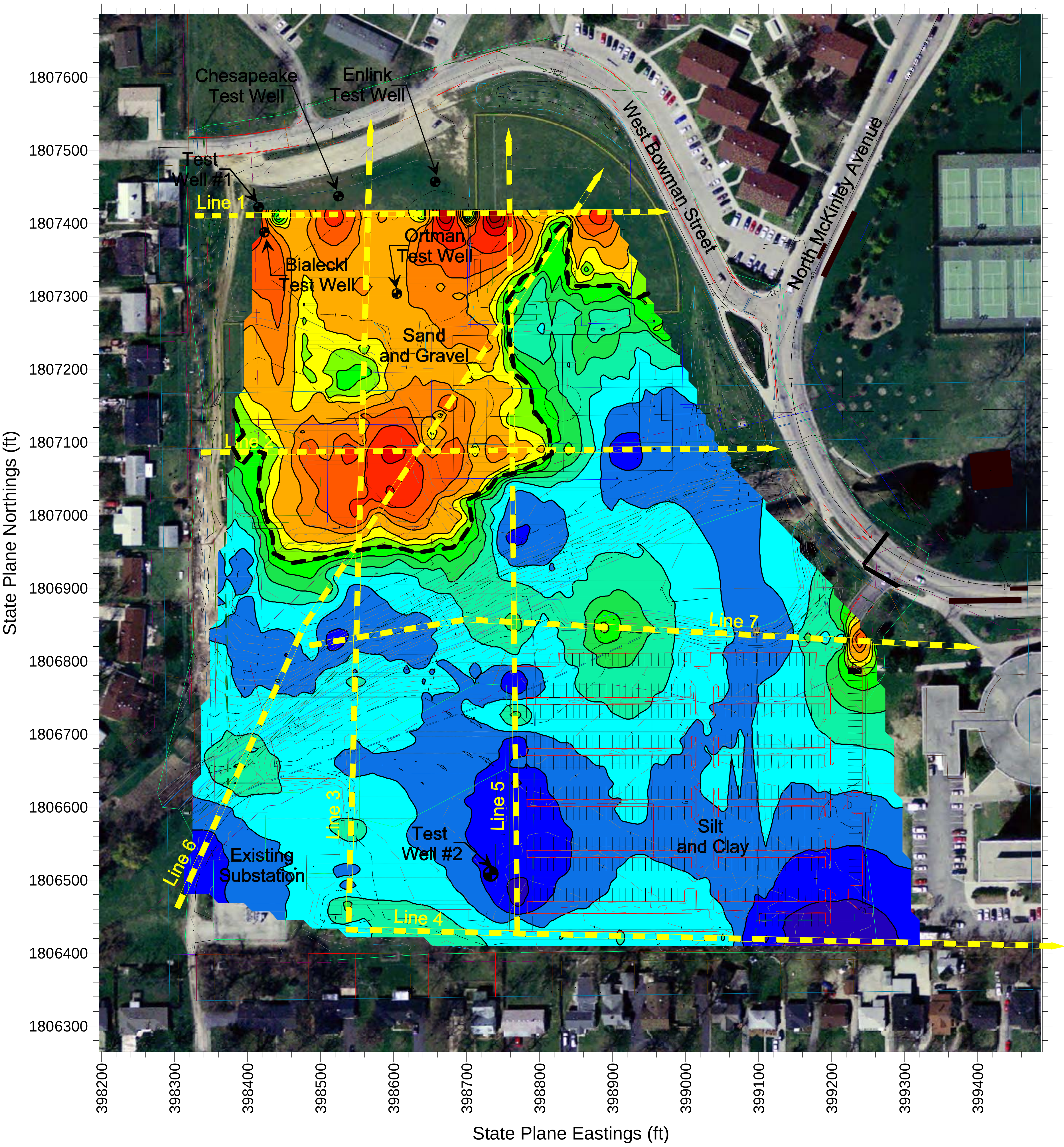

Aerial Photo is provided for site reference only.
No claim is made as to the accuracy
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Indiana East State Plane Coordinates, Datum NAD83

LEGEND

N

Scale in Feet

0 50 100 150 200 250 300

Scale in Meters

0 10 20 30 40 50 60 70 80 90 100

1" = 150'

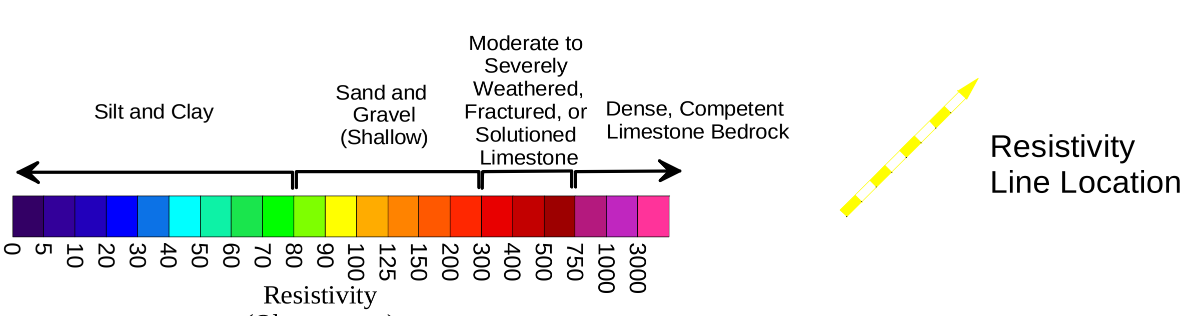

FIGURE 10

Resistivity Slice Map at 920 ft. Elevation

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

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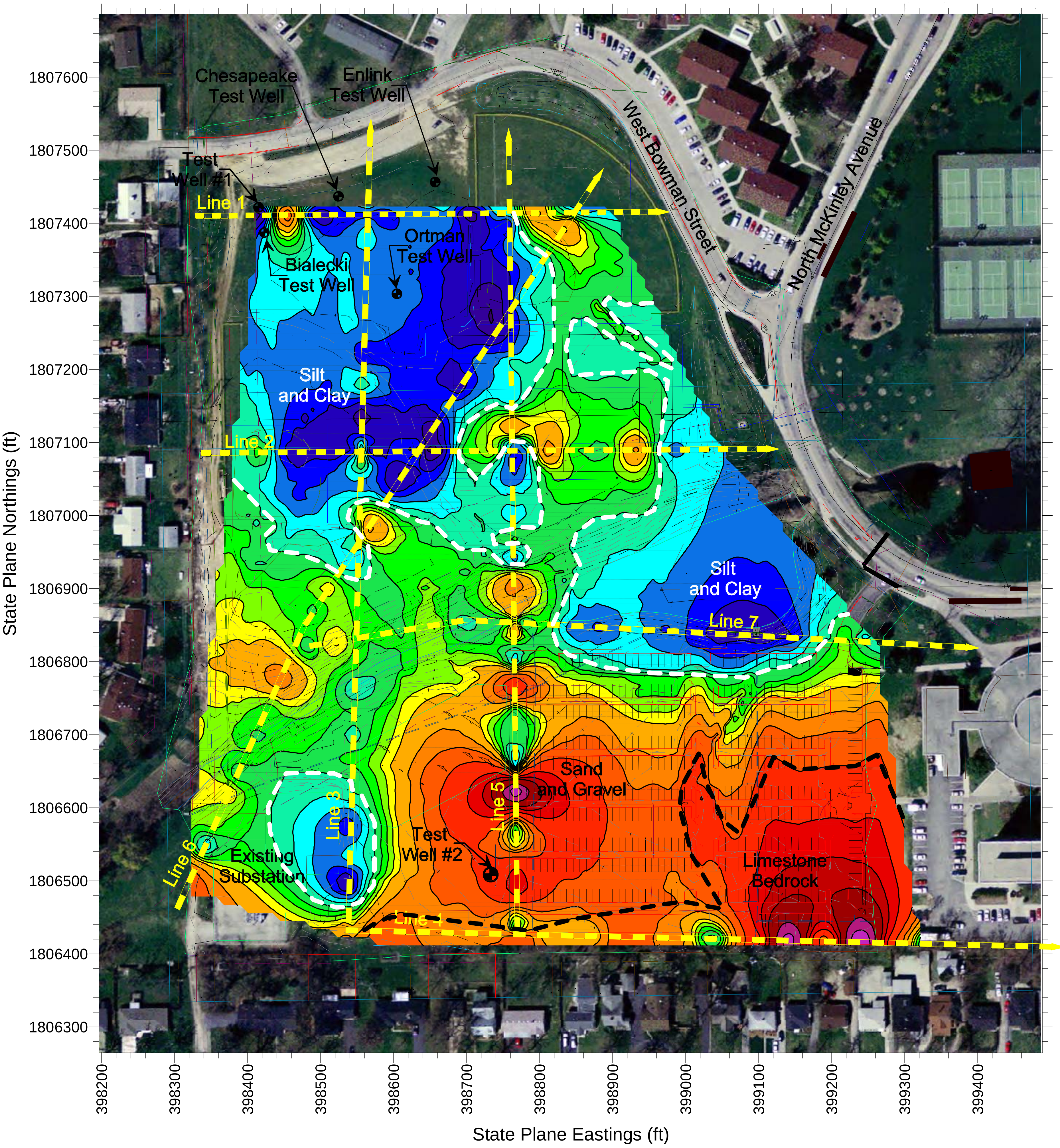

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Indiana East State Plane Coordinates, Datum NAD83

LEGEND

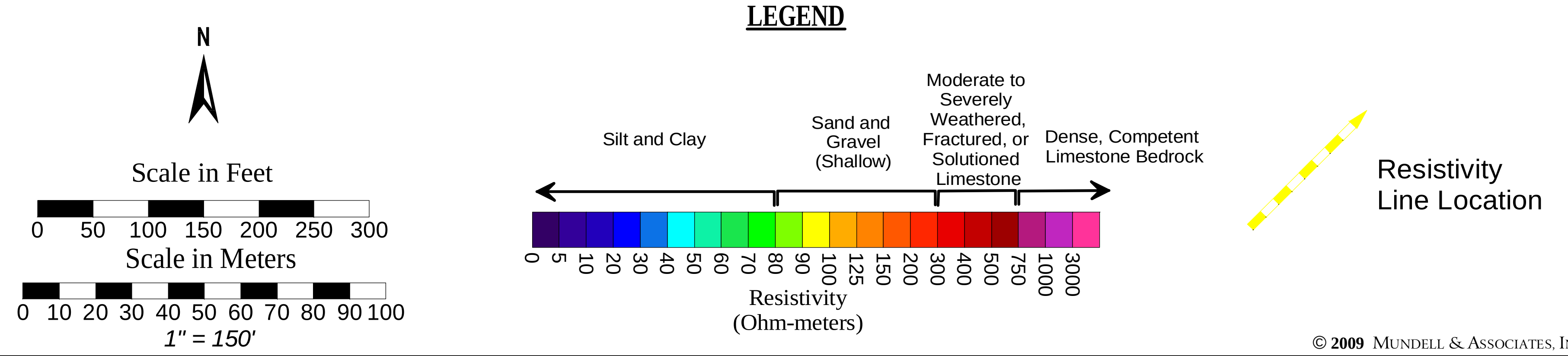

FIGURE 11

Resistivity Slice Map at 900 ft. Elevation

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

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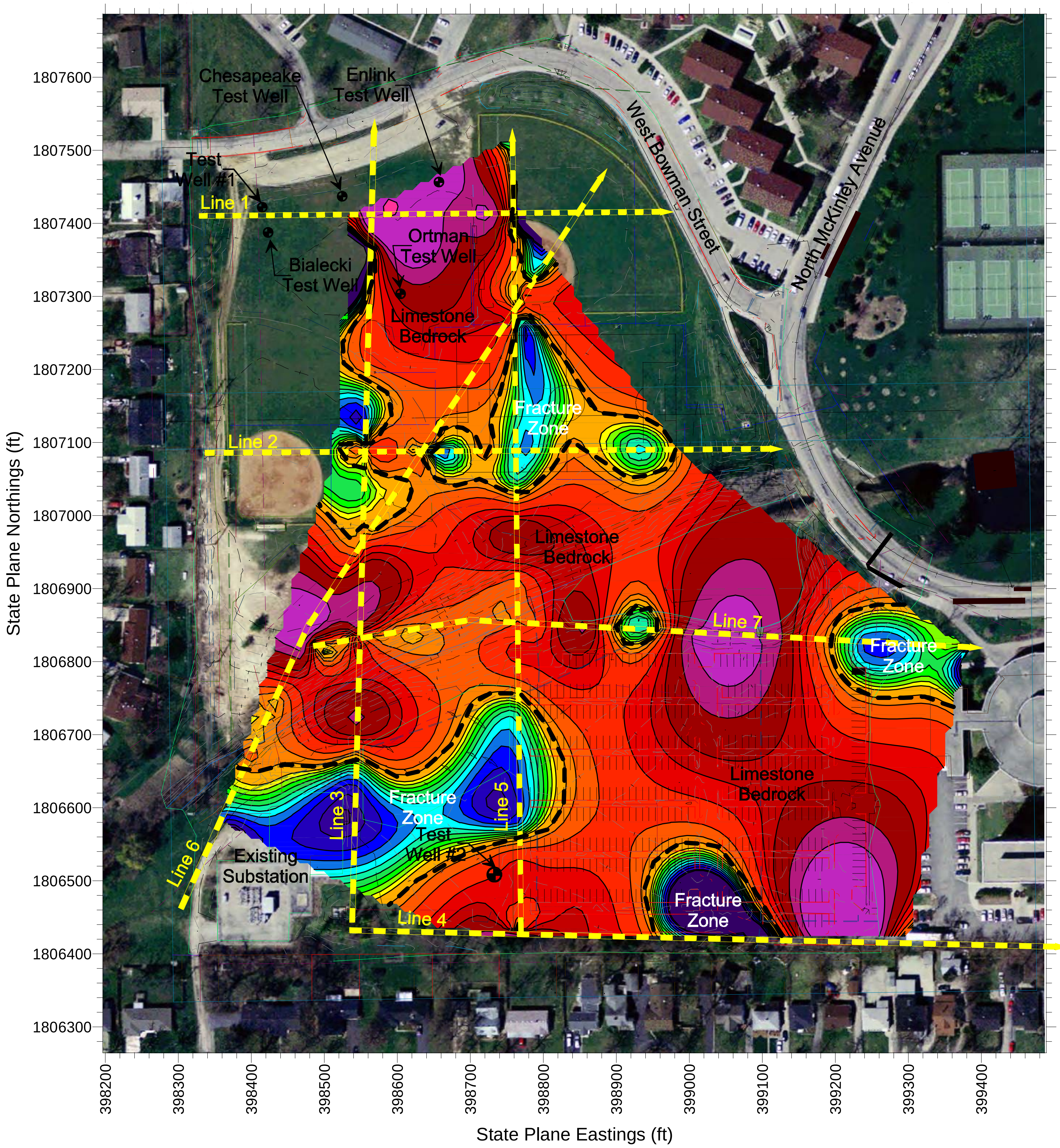

Aerial Photo is provided for site reference only. No claim is made as to the accuracy or completeness of this information.

Indiana East State Plane Coordinates, Datum NAD83

LEGEND

N

Scale in Feet: 0 50 100 150 200 250 300

Scale in Meters: 0 10 20 30 40 50 60 70 80 90 100

1" = 150'

Silt and Clay — Sand and Gravel (Shallow) — Moderate to Severely Weathered, Fractured, or Solutioned Limestone — Dense, Competent Limestone Bedrock

0 5 10 20 30 40 50 60 70 80 90 100 125 150 200 300 400 500 750 1000 3000

Resistivity (Ohm-meters)

Resistivity Line Location

FIGURE 12

Resistivity Slice Map at 840 ft. Elevation

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

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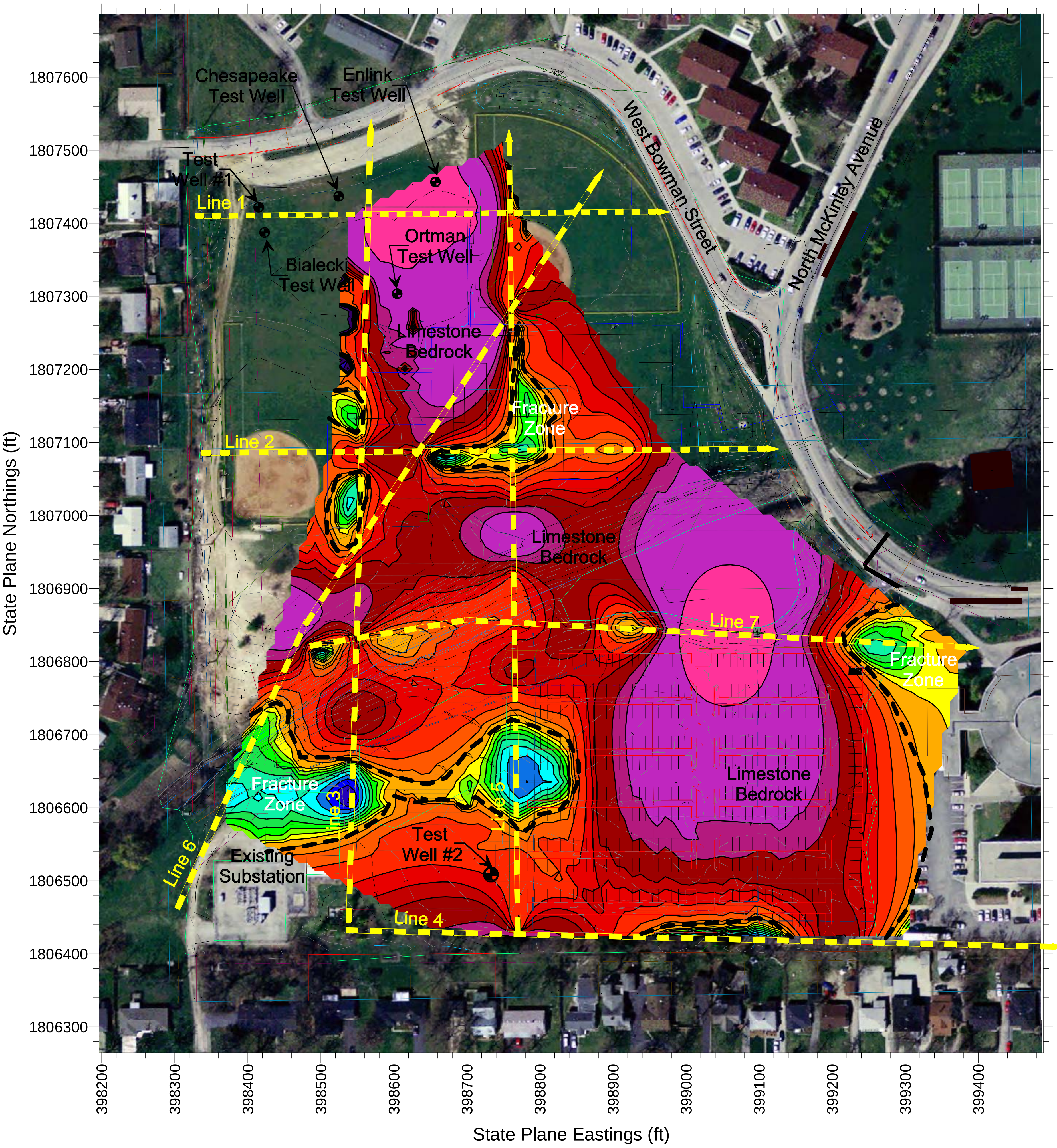
Indianapolis, Indiana 46219
317-630-9060, Fax: 317-630-9065



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or completeness of this information.

Indiana East State Plane Coordinates, Datum NAD83

LEGEND

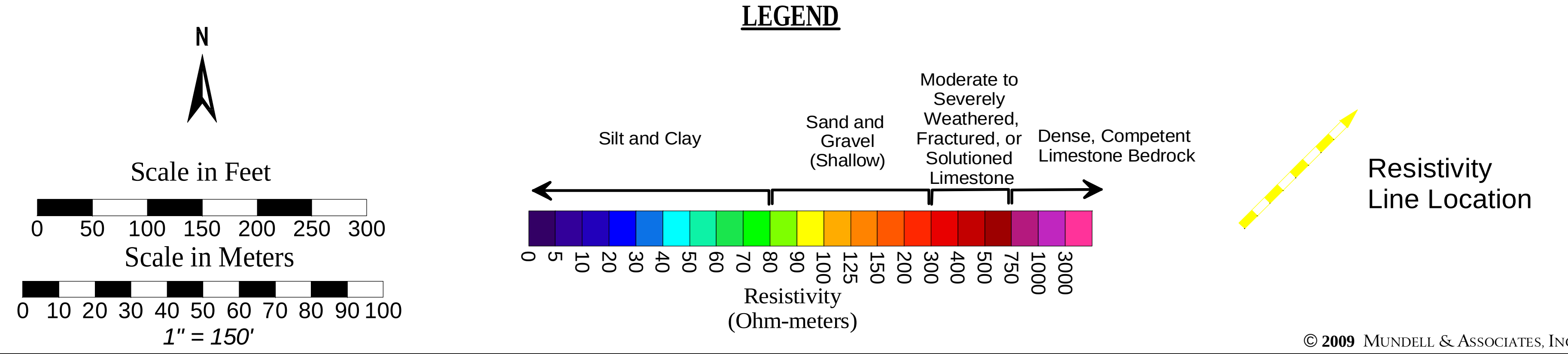

FIGURE 13

Resistivity Slice Map at 820 ft. Elevation

Geologic Exploration
Ball State Geothermal MEP
Muncie, IN
MUNDELL Project No. M09005

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Consulting Professionals for the Earth & Environment
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Indianapolis, Indiana 46219
317-630-9060, Fax: 317-630-9065

MUNDELL & ASSOCIATES, INC.

Consulting Professionals for the Earth and the Environment

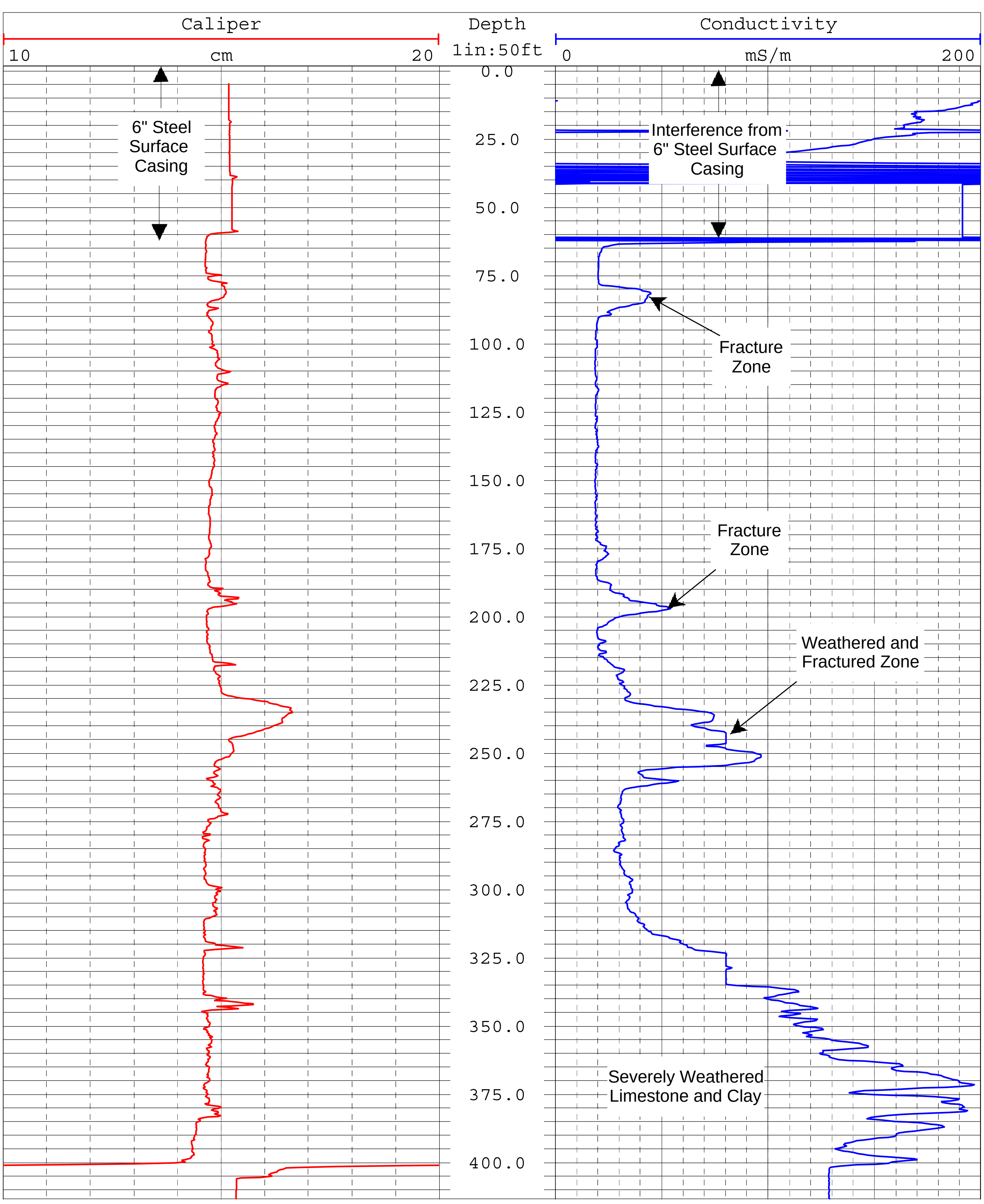
PROJECT NAME: Ball State Geothermal MEP
PROJECT NUMBER: M09005

CO Ball State University
WELL Bialecki Test Well
LOC Aprox. 30' SE of Test Well 1
CTY Muncie
STE Indiana
PROJECT NO. M09005

COMPANY	Ball State University
WELL ID	Bialecki Test Well
CITY	Muncie
STATE	Indiana
COUNTRY	U.S.A.
LOCATION	Approximately 30' SE of Test Well 1. 398423 ft. E, 1807387 ft. N, Indiana East State Plane Coordinates, NAD 83 Datum.
OTHER SERVICES	EM Conductivity and Caliper Logs
SEC	TWP	RGE

PERMANENT DATUM	ELEVATION N/A	K.B.	N/A
LOG MEAS. FROM	Ground Surface ABOVE PERM. DATUM	D.F.	N/A
DRILLING MEAS. FROM	Ground Surface	G.L.	N/A
DATE	04/28/09	TYPE FLUID IN HOLE	Drilling Mud
RUN No		SALINITY	N/A
TYPE LOG	EM Conductivity and Caliper	DENSITY	N/A
DEPTH-DRILLER	408' from GS	LEVEL	N/A
DEPTH-LOGGER	413.40' from GS	MAX. REC. TEMP.	N/A
BTM LOGGED INTERVAL	413.20 from GS	SEAL NUMBER	
TOP LOGGED INTERVAL	4.65' from GS		
OPERATING RIG TIME	N/A		
RECORDED BY	Gabriel Hebert		
WITNESSED BY	Tom Shelton		

RUN	BOREHOLE RECORD			CASING RECORD			
NO.	BIT	FROM	TO	SIZE	WGT.	FROM	TO



MUNDELL & ASSOCIATES, INC.

Consulting Professionals for the Earth and the Environment

PROJECT NAME: Ball State Geothermal MEP

PROJECT NUMBER: M09005

CO Ball State University
WELL Ortman Test Well
LOC Aprox. 225' SE of Test Well 1
CTY Muncie
STE Indiana
PROJECT NO. M09005

COMPANY Ball State University
WELL ID Ortman Test Well
CITY Muncie
STATE Indiana COUNTRY U.S.A.

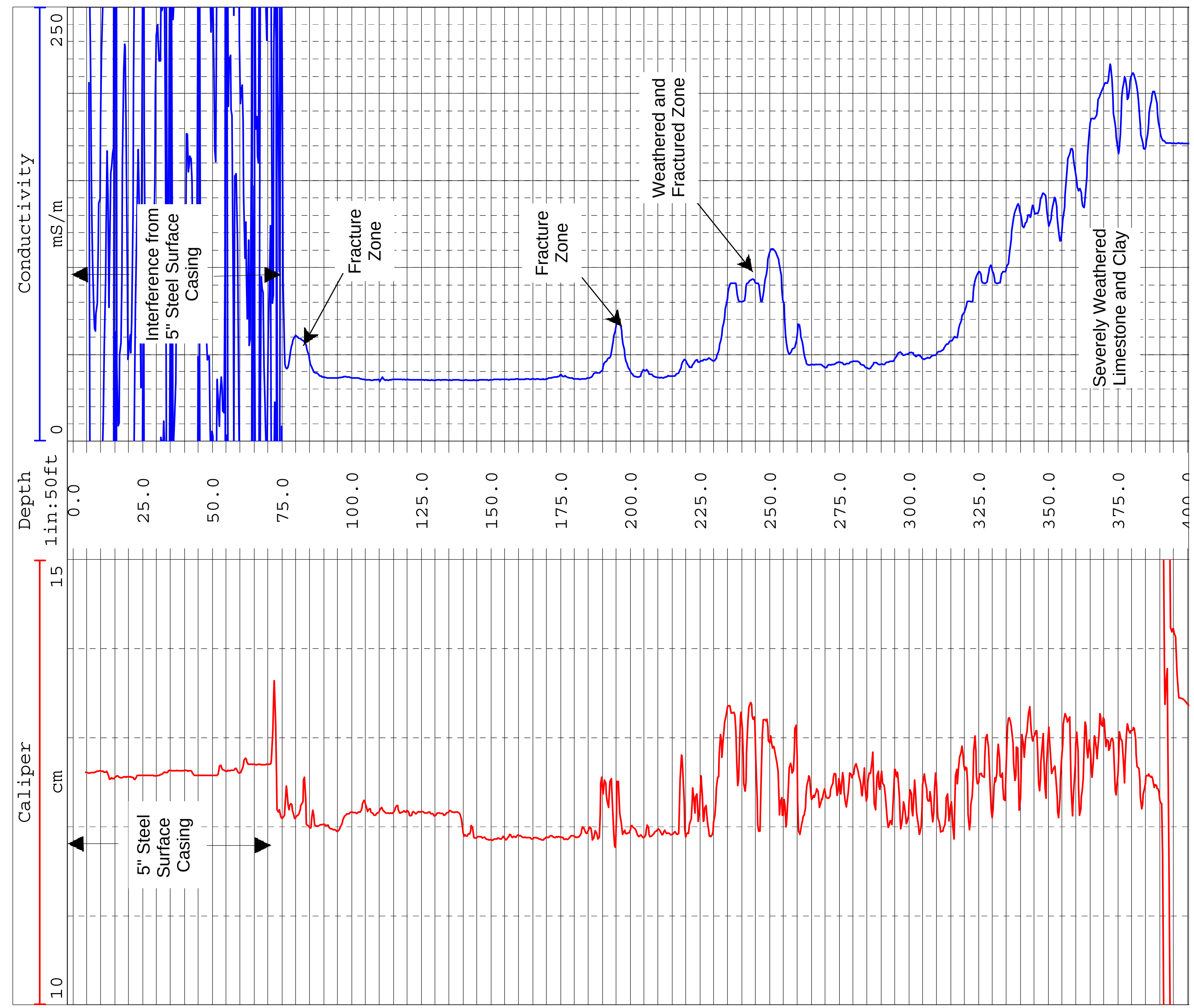
LOCATION
Approximately 225' SE of Test Well 1. 398605 ft. E, 1807304 ft. N, Indiana East State Plane Coordinates, NAD83 Datum.
SEC TWP RGE

OTHER SERVICES
EM Conductivity and Caliper Logs

PERMANENT DATUM	N/A	ELEVATION	N/A	K.B.	N/A
LOG MEAS. FROM	Ground Surface	ABOVE PERM. DATUM		D.F.	N/A
DRILLING MEAS. FROM	Ground Surface			G.L.	N/A

DATE	04/29/09	TYPE FLUID IN HOLE	Water
RUN No		SALINITY	N/A
TYPE LOG	EM Conductivity and Caliper	DENSITY	N/A
DEPTH-DRILLER	400' from GS	LEVEL	N/A
DEPTH-LOGGER	400.96' from GS	MAX. REC. TEMP.	N/A
BTM LOGGED INTERVAL	400.76' from GS	SEAL NUMBER	
TOP LOGGED INTERVAL	4.62' from GS		
OPERATING RIG TIME	N/A		
RECORDED BY	Gabriel Hebert		
WITNESSED BY			

RUN	BOREHOLE RECORD			CASING RECORD			
NO.	BIT	FROM	TO	SIZE	WGT.	FROM	TO



Appendix 13: Petrographic and hydrogeological Investigation

The Geological Society of America
Special Paper 519
2016

Petrographic and hydrogeologic investigations for a district-scale ground-coupled heat pump—Ball State University, Indiana

Andrew Siliski
Lee J. Florea
Carolyn B. Dowling
Klaus Neumann
Alan Samuelson
Marsha Dunn
Department of Geological Sciences, Ball State University, 2000 W. University Avenue, Muncie, Indiana 47306, USA

ABSTRACT

Thermal response tests are the industry standard for borehole heat exchanger design in ground-coupled heat pump systems. Two previously conducted thermal response tests in phase 2 of the district-scale ground-coupled heat pump system at Ball State University (BSU) measured a bulk "formation" thermal conductivity K_T between 2.6 and 3.0 W m^{-1} K^{-1}. Meanwhile, K_T from a core recovered near BSU averages 2.2 ± 0.006 and 3.5 ± 0.086 W m^{-1} K^{-1} for dry and water-saturated samples, respectively. The range in K_T data from saturated samples (1.8–7.2 W m^{-1} K^{-1}) leads to the conclusion that thermal response tests do not capture the vertical and horizontal heterogeneity of heat flux in layered sedimentary aquifers.

Characterization of the hydrogeologic environment can be one tool to tune district-scale ground-coupled heat pump systems to the specific on-site conditions that may influence the magnitude and mode of heat transfer. At BSU, temperature (T) changes in the groundwater environment at the active phase 1 field through October 2013 support this notion. After constant heat loading, a T increase of 14–18 °C was observed in the central monitoring well. The vertical structure in the T profile of this well may correlate to "thermofacies." For example, a T spike between 14 and 19.5 m in depth may correspond to a sand and gravel zone in the surficial glacial till, and a T dip at a depth of 70 m agrees with the position of the Brainard Shale—zones of higher permeability and lower measured K_T (2.0 W m^{-1} K^{-1}), respectively. Higher measured K_T zones, such as the low siliciclastic Silurian Salamonie Limestone and the Ordovician Whitewater Formation, may be target thermofacies for heat deposition and extraction. In contrast, sand and gravel zones within the glacial till may allow for significant thermal loading; however, groundwater advection may reduce the fraction of recoverable thermal load.

Siliski, A., Florea, L.J., Dowling, C.B., Neumann, K., Samuelson, A., and Dunn, M., 2016, Petrographic and hydrogeologic investigations for a district-scale ground-coupled heat pump—Ball State University, Indiana, *in* Dowling, C.B., Neumann, K., and Florea, L.J., eds., Geothermal Energy: An Important Resource: Geological Society of America Special Paper 519, doi:10.1130/2016.2519(04).

INTRODUCTION

Ground-coupled heat pump systems are an efficient, renewable energy source for heating and cooling (Curtis et al., 2005; Freedman et al., 2012; Sanner et al., 2003). They are becoming more widespread in the United States and Europe, including Germany, Switzerland, Sweden, Norway, and the UK. In the United States, ground-coupled heat pump systems have become more common at universities, for example, Hampton University (Hampton, Virginia), Lipscomb University (Nashville, Tennessee), and Minot State University (Minot, North Dakota; Geothermal Systems, n.d.). Large examples have been installed at Stockton College (Stockton, New Jersey; Taylor et al., 1998), West Chester University (West Chester, Pennsylvania; Helmke et al., 2013), and The Ohio State University (Columbus, Ohio; Bair and Torres, 2011). This paper concerns the ground-coupled heat pump system conversion at Ball State University (BSU), which is dramatically larger—by more than a factor of four—than the campus-wide ground-coupled heat pump system at Stockton College (Lowe et al., 2010). In this research, we consider geophysical, hydrogeologic, and petrophysical data collected during the BSU geothermal conversion to characterize the subsurface environment enclosing the borehole heat exchangers and compare these data against current temperature changes in monitoring wells installed in active portions of this district-scale ground-coupled heat pump system.

District-Scale Ground-Coupled Heat Pump Systems

As of 2005, over 600,000 ground-coupled heat pump systems had been installed in the United States (Curtis et al., 2005). For example, the Galt House in Louisville, Kentucky, now consumes only 53% of the energy of adjacent, similar-sized facilities following the installation of a ground-coupled heat pump (Lund et al., 2004).

Several configurations of ambient temperature systems are possible (Banks, 2008; Freedman et al., 2012), including both open- and closed-loop systems, and systems with horizontal and vertical borehole heat exchangers. Closed-loop ground-coupled heat pumps are the industry standard, with vertical borehole systems outnumbering horizontal systems (Armitage et al., 1980). Ground-coupled heat pumps rely on the ground as an energy reservoir. In the summer, heat is taken from air-conditioned facilities and “deposited” into the ground. In the winter, heat is withdrawn and used to keep the facility warm. This energy banking is predicted to result in a thermal cycling of the surrounding ground temperature—increasing during the summer and decreasing during the winter.

The scale of ground-coupled heat pumps has increased during the past decade with centralized energy-transfer stations and a distribution network of heated and chilled water. In many cases, ground-coupled heat pumps are not always built in regions where annual heating and cooling are balanced. As a result, maintaining thermal balance in the subsurface between periods of heating and cooling becomes a significant challenge. Without other means of equilibrating the thermal load, ground-coupled heat pumps constructed for cooling-dominated facilities will increase the ground temperature, while those facilities that are heating-dominated will decrease the ground temperature (Pertzborn et al., 2011). This annual difference in thermal load will accumulate over time and decrease the coefficient of performance (COP) of the heat exchangers, which may require additional sources of heating or chilling that may negate the positive impacts of these green energy initiatives.

For small-scale operations, the required temperature differential is almost always maintained. For example, long-term measurements of a residential ground-coupled heat pump in Elgg, Switzerland, have shown only a 1–2 °C shift of ground temperatures in over 15+ yr of operation, and most of that shift occurred during the first year (Rybach and Eugster, 2002). However, for district-scale ground-coupled heat pumps, less empirical information is available. In the Netherlands, the award-wining Schoenmakershoek residential development near Etten-Leur proposed 1400 residential units connected to ~2500 borehole heat exchangers in 2006 (Witte et al., 2006). Computer simulations for the Etten-Leur project suggested that significant cooling of groundwater could occur during long-term heating (Witte et al., 2006). The Stockton College ground-coupled heat pump system in New Jersey, activated in 1994 and one of the more published examples, is composed of 400 borehole heat exchangers that are each 130 m deep and arranged in a 4.6 m grid (Taylor et al., 1998). Monitoring data from the Stockton ground-coupled heat pump system suggest a significant heating of groundwater with a plume of “heated” groundwater with temperatures between 7 °C and 11 °C above baseline values within a year of activation (Epstein et al., 1996; Epstein, 1998; Epstein and Sowers, 2006).

Hydrogeologic Characterization of Ground-Coupled Heat Pumps

Physical characterization of the geology and hydrogeology underlying potential projects is rarely extensive, despite the concept of “thermofacies” in the literature (Sass and Götz, 2012) as applied to the characterization of permeability and thermal conductivity within geothermal reservoirs (Tester et al., 2005). As pointed out by Diao et al. (2004), nearly all design tools for ground-coupled heat pump systems are based on heat conduction only and ignore groundwater flow. Currently, the industry standard used to compute the number, depth, and style of borehole heat exchangers to be used in ground-coupled heat pumps is the borehole thermal response test. In these tests, input and output temperatures are monitored over time within fluid pumped through a borehole heat exchanger (Raymond et al., 2011). From the temperature data, average values of thermal conductivity are computed. In general, this method may be overly simplistic from the standpoint of system design and COP, and it neglects potential migration of thermal plumes, as observed in the Stockton ground-coupled heat pump, or variations in thermal conductivity in layered sedimentary aquifers. Measured values of thermal conductivity at ground energy sites in unconsolidated material include 2.8 W m^{-1} K^{-1} in gravel, sand, and clay in Germany (Sanner et al., 2003). Markle and Schincariol (2007) measured an average thermal conductivity of 2.4 W m^{-1} K^{-1} with a range from 2.1 to 2.7 W m^{-1} K^{-1} that was correlated to stratigraphic units (gravel, sand, and glacial till). These compare to thermal conductivity tests by Robertson (1988) of consolidated rocks that revealed values of 2.5–3.0 W m^{-1} K^{-1} for a saturated, low-porosity limestone and 1.3–1.8 W m^{-1} K^{-1} for a saturated, low-quartz, low-porosity shale.

Thermal response tests assume that heat is stored in or removed from a homogeneous and isotropic medium within a uniform cylinder around the borehole heat exchanger. However, the differences in thermal and hydraulic properties of layers of soil and bedrock may cause the stored heat to extend more into strata with greater permeability and thermal conductivity. Groundwater flow will skew this stored heat into a plume that may additionally disrupt the thermal balance by making stored heat unavailable during times of heat extraction.

Ball State University Ground-Coupled Heat Pump System

Construction of the district-scale ground-coupled heat pump system at BSU was done in two phases, with phase 1 completed in 2011 and phase 2 completed in 2015 (Fig. 1). Phase 1, located at the north end of the campus, consists of 1800 double-loop borehole heat exchangers (two exchangers in the same borehole) drilled through a cover of Quaternary glacial till to a depth of 122 m in Paleozoic bedrock and spaced 4.6 m on a rectangular grid. Phase 2 on the south end of campus comprises an additional 1800 single-loop borehole heat exchangers drilled to 153 m, also on a 4.6 m spacing. All borehole heat exchangers have a diameter of 15 cm and were completed with grout to the land surface. The general contractor in phase 2 maintained completion records for each borehole heat exchanger.

The BSU Facilities Department has provided exceptional access for system monitoring. Five nested monitoring wells were installed in phase 1 alongside eight open wells installed into the shallow glacial till aquifer (Dunn, 2013). In phase 2, the focus of this paper, 11 nested monitoring wells were installed, the eastern five are considered in this study. The BSU ground-coupled heat pump system includes two energy stations that simultaneously

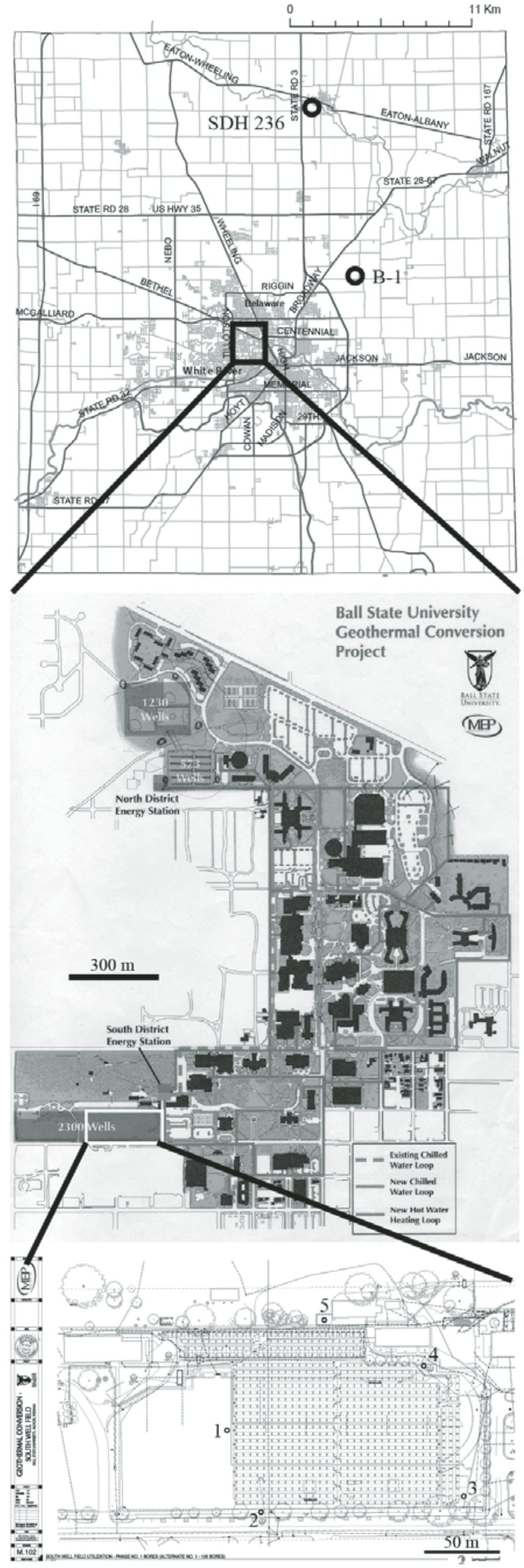


Figure 1. (Top) Delaware County, Indiana, with location of available core at the Indiana Geological Survey (SDH 236 and B-1). (Middle) Inset of the Ball State University (BSU) campus illustrating the location of borehole heat exchanger fields, district energy stations, and heat exchange loops constructed as part of the campus-wide geothermal conversion. (Bottom) Inset of the phase 2 borehole heat exchanger field on the BSU campus illustrating the location of borehole heat exchangers and the research monitoring wells 1–5.

produce the hot and chilled water necessary to heat and cool more than 45 major buildings that contain ~5.5 million ft^2 (~510,966 m^2) of air-conditioned space for the campus of more than 21,000 students. Long-term expectations are to reduce the carbon footprint of the campus by ~50% and realize ~$2 million in savings (Lowe et al., 2010). As of 2014, BSU has nearly achieved this goal, while only operating phase 1, by reducing CO_2 emissions by almost 50% or ~39,300 metric tons. Coal consumption has also dramatically reduced from more than 35,000 metric tons in 2008–2009 to ~1500 metric tons in 2013–2014 (http://ghgdata.epa.gov, accessed on 1 August 2014).

METHODS

This paper concerns the eastern half of phase 2 in the BSU ground-coupled heat pump system (Fig. 1) and includes data from five monitoring wells (wells 1–5) drilled during the fall of 2012. Data sets collected by BSU faculty and students over the past 3 yr include electrical resistivity tomography (ERT) (Mundell and Associates, 2009; Dransfield et al., 2012), drilling logs from the monitoring wells and the network of borehole heat exchangers (Catron et al., 2011; Siliski et al., 2013), temperature profiles from monitoring wells (Samuelson et al., 2011; Dunn et al., 2012; Dunn, 2013), cuttings and borehole geophysical data from wells 1–5 (Siliski et al., 2013), detailed petrophysical logs from two bedrock cores from Delaware County north and northeast of the BSU campus, and measurements of the hydraulic and thermal conductivity of select stratigraphic intervals collected from these bedrock cores. The data were compiled and archived within two M.S. theses at BSU by Dunn (2013) and Siliski (2014).

Electrical Resistivity Tomography

During December of 2011, ERT transects in the phase 2 field were collected in a cooperative agreement between Mundell and Associates, Inc., and BSU. Faculty and students examined the composition of the glacial till and the thickness. The surveys were conducted using an AGI Super String R8 with 56 electrodes configured in a dipole-dipole array. Seven transects were completed over a 2 d period. Transects 1–4 and 6 had an electrode spacing of 5 m. Transect 5 had a spacing of 6 m, and transect 7 had a spacing of 4.5 m. Transects 1 and 2 overlapped, as did transects 3 and 4. EarthImager 2D was used to compute inversions of the raw data.

Borehole Heat Exchanger Drill Logs

In total, 778 borehole heat exchangers were installed between January and August 2012 in the eastern half of phase 2 of the geothermal conversion. Messer, Inc., the general contractor for the drilling operations, provided completion logs for each borehole heat exchanger. Data for the depth to bedrock were extracted from each log. Contacts between rock types and formations were highly variable, inconsistently documented, and therefore considered inaccurate and not included in further analysis. Additionally, specific drill rigs noted bedrock contacts that were consistently higher or lower than neighboring rigs on parallel rows of borehole heat exchangers. Some of these data were also eliminated to reduce the potential bias upon a final bedrock surface map. Using the natural neighbor and polynomial contouring algorithms in Surfer, two surface plots were generated of the contact between the Quaternary glacial till and the underlying Paleozoic bedrock.

Monitoring Well Logs and Cuttings

Five nested monitoring wells were drilled associated with the phase 2 field. Wells 2–5 were drilled around the perimeter of the field, while well 1 is located in the middle of the field. We personally observed drilling operations conducted by Helvie and Sons, Inc., from Marion, Indiana, during September to November 2012. The contractors used a mud rotary top head drive Ingersol Rand TH-60 drilling rig. Cuttings of rock were collected from the returned drilling mud in composite increments of 10 ft (3 m) of drill stem. The lag time between cutting production at the drill bit and recovery from the returned drilling mud was not considered during sample collection.

Samples were cleaned in the laboratory, and the petrography was analyzed with a binocular microscope. The lithology was determined using 5% HCl to distinguish between carbonate and siliciclastic material and Alizarin Red to discriminate between limestone and dolomite. Texture, including grain size, sorting, and rounding (if practical), was characterized using the Dunham classification system for carbonate fabric (Dunham, 1962). Identifiable fossils, sedimentary structures, and secondary mineralization (e.g., pyrite) were also recorded. The collected information was archived in MPlot software from Mudlogging Systems, Inc.

Borehole Gamma, Resistivity, and Spontaneous Potential

Borehole gamma was collected from each of the five monitoring wells during the winter of 2013 in collaboration with Marni Karaffa of the Indiana Geological Survey and using a Matrix Logging System with a 2PGS-1000 Poly-Gamma Probe in R and SP mode. Resistivity and spontaneous potential data from well 3 were also acquired. These geophysical data were used to correlate formation data between wells, identify the contact between the glacial till and bedrock, and aid in interpretation of logged rock cuttings from the monitoring wells. Gamma data were most importantly used for correlating well cuttings to appropriate depths, but they were not available for well 5, which is consequently not considered in the remainder of this research. Data were collected every 0.05 m, but in the effort to eliminate background noise and prevent an overinterpretation of data, only data in intervals of 0.3048 m (1 ft) were considered.

Bedrock Cores

Two bedrock cores drilled in Delaware County were examined at the core repository archive of the Indiana Geological Survey in Bloomington, Indiana (Fig. 1). Cores SDH 236 collected in 1973 from the Muncie Stone Company, 16.2 km northeast of Ball State University (North American Datum [NAD] 83 Universal Transverse Mercator [UTM]: 16S 639102 E, 4466670 N), and B-1 collected in 1964 from the Irving Brothers Quarry, 8.7 km northeast of Ball State University (NAD 83 UTM: 16S 0641974E, 04455990N), were examined using a binocular microscope and a standard hand lens. Core logs were constructed for both cores at intervals of 1 ft (0.3048 m) using carbonate log sheets modified from those provided by Bebout and Loucks (1984) and utilized by Florea (2006). Methods to determine lithology and texture matched those applied to the cuttings. Additional information included relative quantification of pore type and size, relative induration, fossil type and abundance, sedimentary structures, and secondary alterations and mineralization.

Matrix Permeability and Porosity

Eight samples at key stratigraphic intervals (3.0 m, 12.0 m, 14.0 m, 22.0 m, 28.0 m, 32.0 m, 39.0 m, 53.0 m, 58.0 m, 62.0 m) distributed among the geologic formations and representative facies types were taken from the B-1 core to test for values of matrix permeability. The B-1 core was selected for testing because it included larger intact segments and had a better percent recovery. Core Labs in Houston, Texas, made the measurements using a steady-state micropermeameter. For each sample, 2.54-cm-diameter plugs were drilled from the sample perpendicular to the core direction. Thus, the measurements are representative of horizontal permeability, and no sense of anisotropy at the matrix scale could be determined. Values of bulk porosity were determined by measuring the volume of water needed to saturate the samples and comparing it to the sample volume. This water volume was determined by weight change test between unsaturated and vacuum-saturated samples. The sample volume was measured by the volume of water displaced in a graduated cylinder (estimated accuracy of ±5 mL).

Thermal Conductivity

Fourteen samples (3.0 m, 8.2 m, 10.4 m, 12.2 m, 14.3 m, 21.6 m, 23.8 m, 28.4 m, 35.4 m, 39.0 m, 48.8 m, 53.0 m, 57.9 m, 62.2 m) were selected from the B-1 core to test for values of dry and water-saturated thermal conductivity. Measurements were collected at the Indiana Geological Survey using a KD2 Sensor by Decagon Devices, Inc., with a RK-1 rock sensor package. Samples were generally selected based on formation type and facies relationships within the core; however, equipment restrictions guided the selection of specific samples. For each sample, a 6.8 mm hole was drilled through the vertical axis of the core and filled with thermal grease. Heating experiments with the thermal probe were replicated three times for each sample. The measurement time was 10 min for each run. A second set of triplicate measurements was collected on the same set of samples after vacuum saturation with water. Thermal conductivity (W m^{-1} K^{-1}), final temperature (°C), and error values were recorded along with the arithmetic mean and standard deviation for each set of measurements.

RESULTS

The data from this study reveal a complicated karstified bedrock surface beneath a glacial till aquifer. The thickness of this glacial aquifer ranges from 10 to 30 m. The underlying Paleozoic bedrock is composed of near-horizontal layers of dolostone, limestone, and shale dating from the Late Silurian and Ordovician Periods (Gray, 1972). These formations thicken slightly toward the southwest. Facies range from mudstone through grainstone and have matrix permeabilities ranging between 10^{-17} and 10^{-14} m^2. Matrix permeability and porosity are highest in the Silurian grainstones and vuggy limestones. Thermal conductivity dry samples ranged between 1.55 W m^{-1} K^{-1} and 3.32 W m^{-1} K^{-1}, with a linear relationship between dry and wet measurements of conductivity (Table 1).

Preglacial Bedrock Surface and Glacial Stratigraphy

The inversions of the ERT data in EarthImager 2D reveal a complex contact between the bedrock and an overburden of glacial till (Fig. 2). Resistivity values are typical of glacial till and carbonate rocks saturated with water and largely range between 100 and 1000 Ω·m. Lower values in these transects are consistent with soil or layers of silt or clay. The bedrock contact undulates and is generally at a greater depth toward the southeast. A nearly continuous layer of higher-resistivity material centered at ~10 m depth likely marks a sand and gravel zone within the glacial till.

TABLE 1. DRY AND WET THERMAL K AND *n*

D (m)	K-Dry ($Wm^{-1}K^{-1}$)	K-Wet ($Wm^{-1}K^{-1}$)	Formation	*n* (%)
3.0	2.83	4.11	Pleasant Mills	6.9
8.2	1.96	3.00	Pleasant Mills	6.5
10.4	1.55	2.42	Pleasant Mills	14.4
12.2	1.79	2.37	Waldron	4.7
14.3	1.45	1.79	Waldron	7.3
21.6	1.55	2.27	Salamonie	15.7
23.8	3.10	5.12	Salamonie	7.3
28.4	3.27	5.18	Salamonie	10.1
35.4	1.61	2.14	Cataract	2.8
39.0	1.70	2.21	Cataract	4.8
48.8	1.67	2.01	Brainard	3.2
53.0	3.32	7.24	Ft Atkinson	4.3
57.9	2.99	6.02	Whitewater	8.2
62.2	1.84	2.84	Whitewater	9.4

D—depth below top of core; K—thermal conductivity.

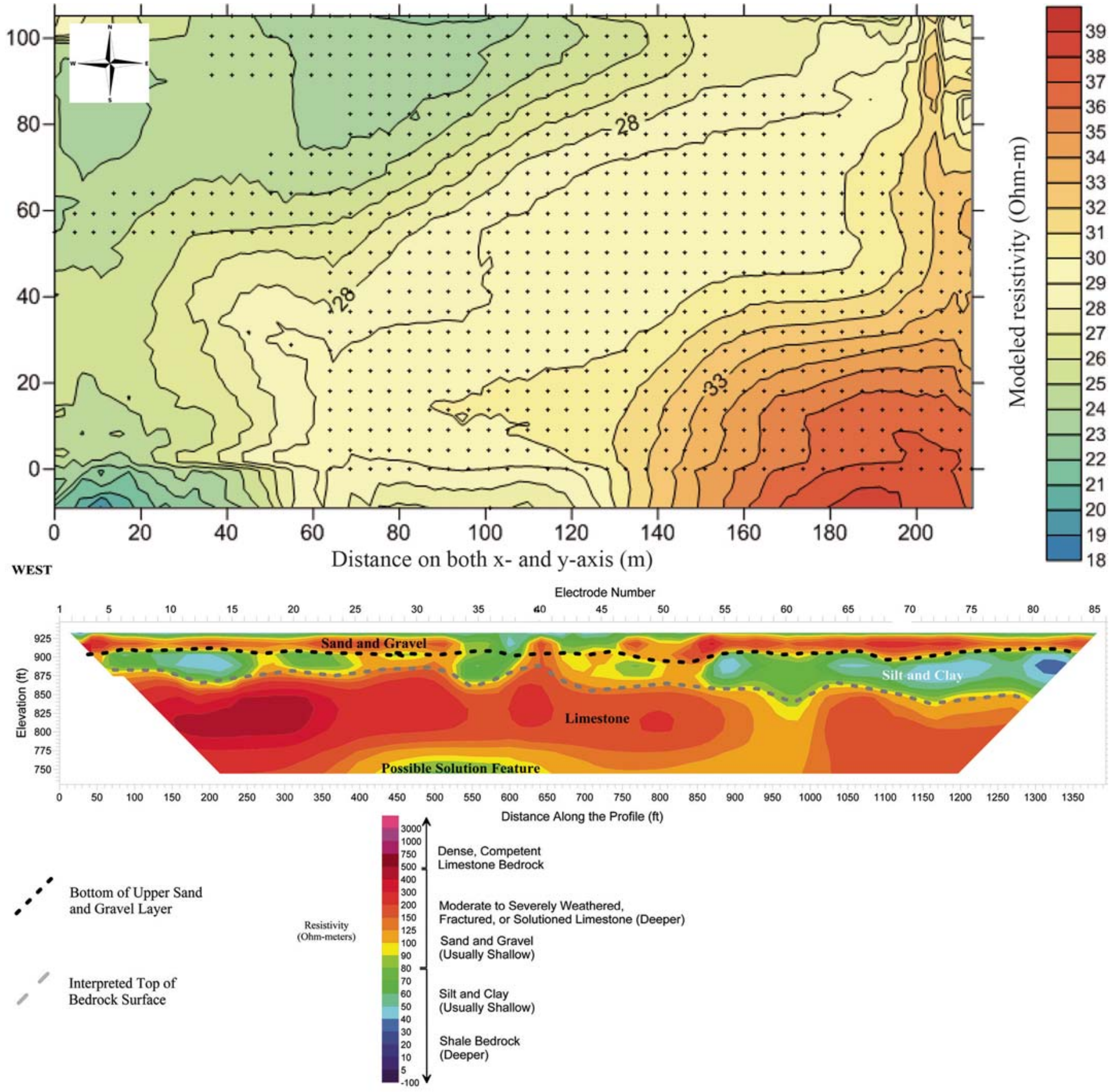


Figure 2. (Top) Depth to bedrock in the east half of phase 2 developed using a local polynomial contouring method in Surfer, and the depth to bedrock data from drill logs of the borehole heat exchangers (individual borehole heat exchangers noted as dots). Depths are listed as meters below the surface. (Bottom) East-west electrical resistivity tomography profile across the phase 2 borehole heat exchanger field (modified from Mundell and Associates, 2012).

The borehole heat exchanger drill logs identify the sand and gravel zone in the glacial till as a "chatter zone." These logs also record the complexity of the bedrock topography throughout the research area (Fig. 2). Natural neighbor and local polynomial contouring algorithms in Surfer give quite different results using the same data. The natural neighbor algorithm preserves the integrity of original data and results in an irregular contour plot suggesting a preglacial bedrock surface with depressions and rock pinnacles in the bedrock. However, inaccuracies in drill logs and actual bedrock topography are difficult to distinguish, as data are highly dependent on driller log accuracy. The local polynomial contouring method results in considerable smoothing of the data and shows a gentle trend toward deeper bedrock contacts toward the southeast (Fig. 2). Drill logs and gamma data from the monitoring wells support this thickening trend, with well 3 (the southeast well) having the greatest overburden of till.

Bedrock Stratigraphy and Structure

A combination of gamma data, cuttings from monitoring wells, and core logs was used to develop a stratigraphic column for the study area (Fig. 3). In all wells, Silurian-age limestone, dolostone, and shale of the Salina Group overlie the Ordovician-age limestone and shale of the Maquoketa Group. Rock unit nomenclature fits the stratigraphic organizations outlined by Gray (1972) and research in Henry County from Scarpone (1997). Peaks in the gamma data coincide with soil and clay in the overburden and organic-rich shale in the bedrock, such as within the Cataract Formation and Brainard Shale. The lowest gamma values occur at depths where the rock is composed of pure carbonate material, such as in portions of the Pleasant Mills and Salamonie Limestone. Strong deflections in the gamma data occur at the contact between the glacial till and the bedrock and at stratigraphic contacts within the bedrock.

Most formation boundaries have sharp contacts, both in core logs and in the gamma data (Fig. 3). For example, the contact between the glacial till and the Salina Group and the contact between the Salina and Maquoketa Groups represent significant disconformities in the sedimentary record. The topography of the preglacial bedrock surface is considerable from west to east, such that cuttings consistent with 6.5 m of dolostone from the Wabash Formation are only seen in well 1 in the west part of the borehole heat exchanger field. Cuttings from all other wells start in the Pleasant Mills unit.

Carbonate rocks of the Salina Group are visually similar in texture, grain size, facies, and fabric (Fig. 3). They alternate in centimeter to decimeter cycles between a packstone and a sucrosic grainstone with medium to coarse texture. Stringers of wackestone are also present in the more argillaceous portions of the Waldron, Salamonie, and Cataract Formations. The transition between the Salamonie and Cataract Formations is a gradational boundary composed of chert lenses, limestone, and shale stringers that are more easily identified in cores and not in the cuttings. These shale lenses do not show up as individual gamma spikes; instead, there is a relatively strong shift in gamma readings across this formational boundary (Fig. 3).

The mixed carbonate and siliciclastics of the Upper Ordovician Maquoketa Group have a wide range of texture, grain size, facies, and fabric (Fig. 3). For example, the upper Whitewater Formation is largely a well-indurated, fossil-rich, moldic limestone. Some molds include significant secondary mineralizations including pyrite. The lower Whitewater Formation, in contrast, becomes more argillaceous. The Ordovician Brainard Shale and Dillsboro Limestone both consist of centimeter-to-decimeter cycles of limestone and shale. These cycles are reflected in the rapidly changing gamma data. Cyclicity continues with a reduction of carbonate in the cuttings of the Kope Formation at the base of the sedimentary sequence in our wells.

Formation contacts reveal a slight dip toward the northeast. Well 2 and well 4 have the shallowest and deepest formation contacts, respectively. The north-to-south transect (wells 4 and 3; Fig. 4) and west-to-east transect (wells 1–3; Fig. 5) reveal average apparent dip angles toward the north and east of 0.76° and 0.34°, respectively. Formation-averaged true dip angle and dip direction were computed as 1.1° to the NNE at 25.4°.

Hydrostratigraphy

Values of matrix permeability are summarized in Figure 6, with a range from $<9.9 \times 10^{-17}$ m^2 in the lowermost Waldron Formation to 2.2×10^{-14} m^2 in the lowermost Cataract Formation. Matrix permeability generally decreases with increased siliciclastic content. Despite the small sample size ($n = 8$), there is some relationship between matrix permeability and facies. For example, the highest matrix permeability in the Salamonie Formation, 2.2×10^{-16} m^2, is from a poorly washed grainstone, and the lowest matrix permeability, $<9.9 \times 10^{-17}$ m^2, is from a wackestone. In the Whitewater Formation, the sample of poorly washed, but well-indurated, grainstone at 52.7 m has a matrix permeability of 7.9×10^{-16} m^2, compared to the mudstone-packstone facies at 57.9 m with a matrix permeability of 3.1×10^{-15} m^2.

Porosity changes with depth are also summarized in Figure 6. Similar to matrix permeability, values follow facies changes. For example, samples of grainstones that are sucrosic dolomites at 10.4 m in the Pleasant Mills Formation and 21.6 m in the Salamonie Formation show unusually high porosity values of 14.4% and 15.7%, respectively. In contrast, shale from the Waldron Formation, the Cataract Formation, and the Brainard Shale have porosities that range between 2.8% and 4.8%. Values in the vuggy limestones of the Whitewater Formation range between 8.2% and 9.4%.

Thermal Stratigraphy

Average dry thermal conductivity readings range from 1.5 W m^{-1} K^{-1} in the lower Waldron Formation to 3.3 W m^{-1} K^{-1} in the Fort Atkinson Limestone (Fig. 6), with standard deviations ranging between 0.006 and 0.086 W m^{-1} K^{-1}. There is no trend

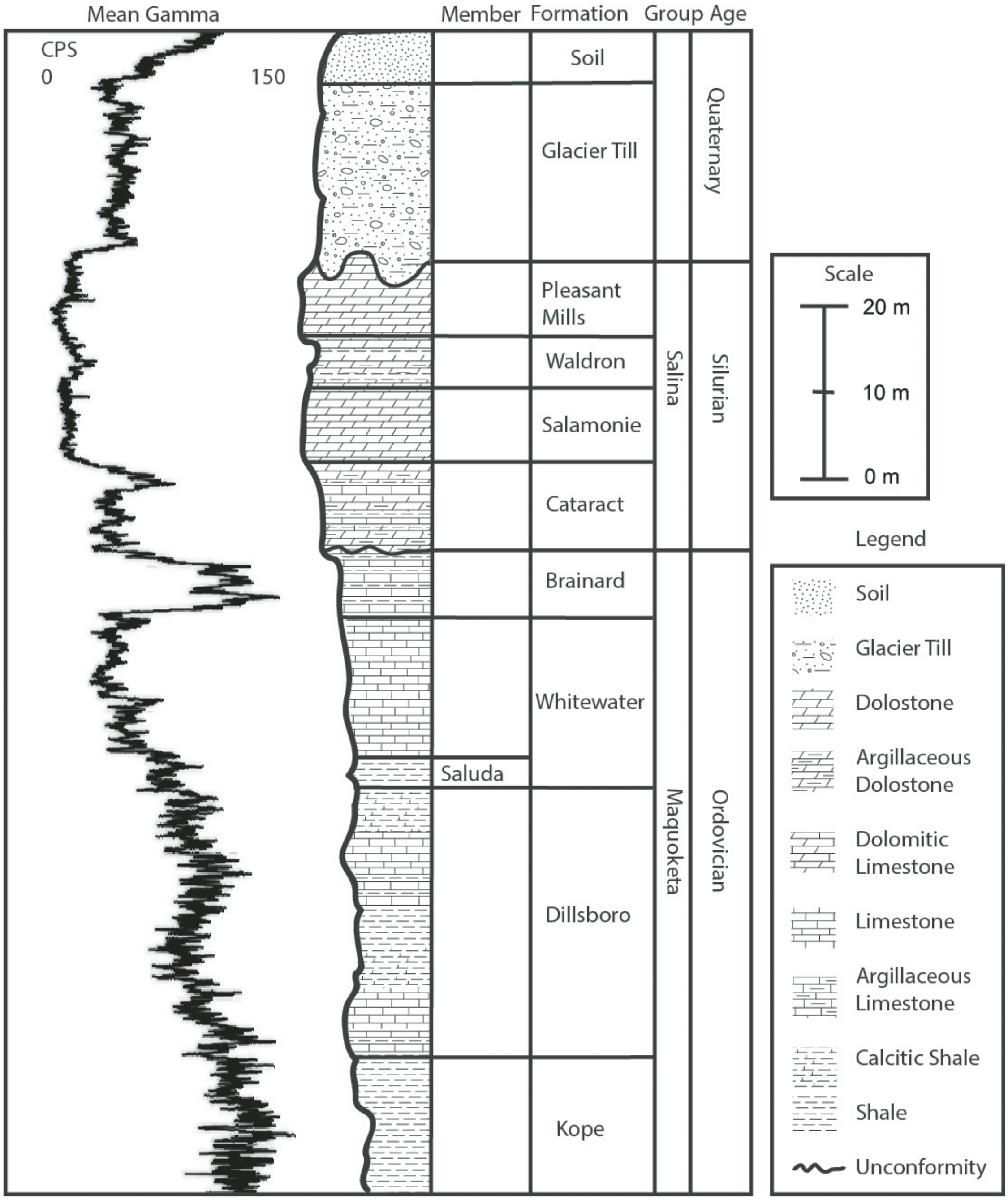


Figure 3. Stratigraphic column of strata underlying the Ball State University campus developed from cuttings and nearby core and including borehole gamma data. CPS—counts per second.

in values with depth, but there is some correlation with facies; carbonates are more conductive to heat, on average, than shale.

Water-saturated samples showed greater thermal conductivity than the equivalent dry samples (Fig. 6), attesting to the importance of a saturated zone for efficient heat transfer. The standard deviation of these water-saturated thermal conductivity measurements was also greater, most particularly in the upper Pleasant Mills and Fort Atkinson samples, where water convection may impact the stability of the measurement. Figure 7 illustrates the average value of saturated thermal conductivity versus the equivalent measurement in the dry sample. A relatively good linear relationship is seen between dry and wet ($r^2 = 0.91$), with water-saturated samples 2.3 times more conductive than the equivalent dry sample.

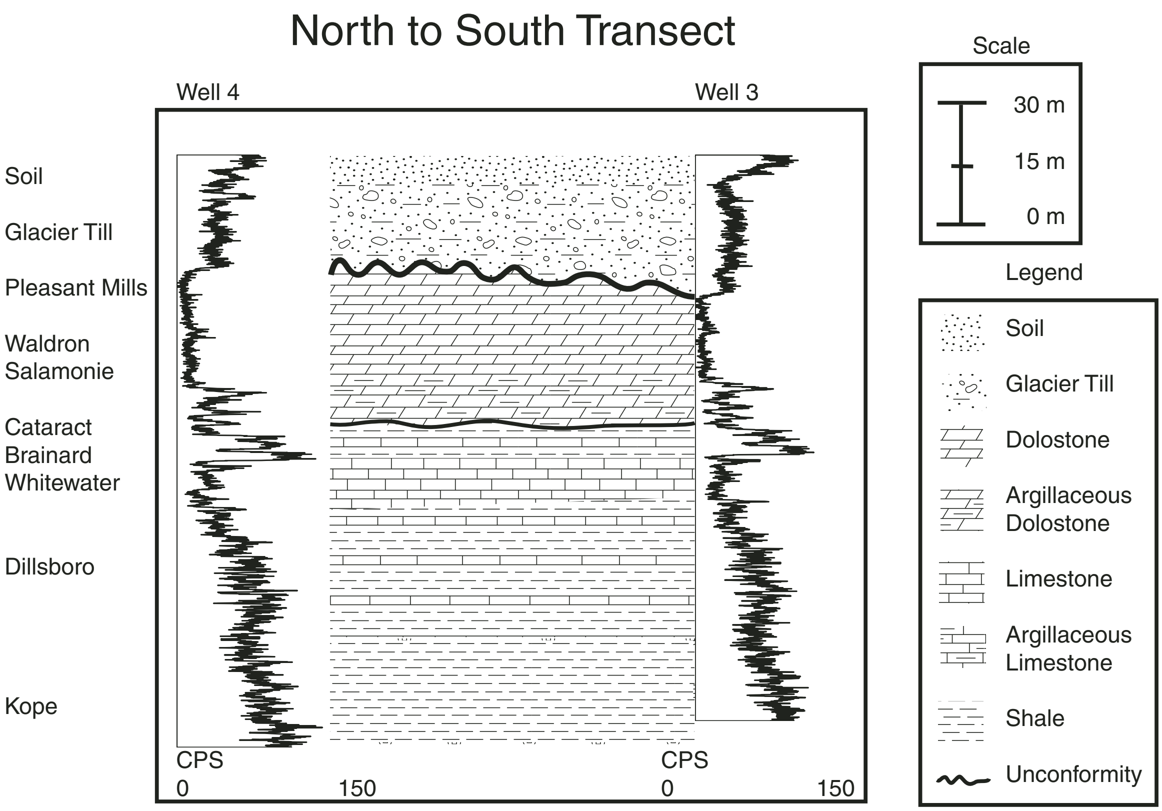


Figure 4. Stratigraphic cross section oriented north to south across the phase 2 borehole heat exchanger field on the Ball State University campus developed from cuttings and nearby core and including borehole gamma data. CPS—counts per second.

DISCUSSION

Research and design of ground-coupled heat pump systems are typically conducted using "black box" models, such as the thermal response test, that assume a homogeneous lithology without groundwater flow. This includes the ground-coupled heat pump system constructed at BSU. An unresolved question is whether or not thermal response tests give an accurate representation of system response to thermal loading in a layered sedimentary aquifer with groundwater flow, particularly in a large field of borehole heat exchangers, where interference or buoyant convection may play a significant role in the structure of the thermal plume.

Surficial and Glacial Geology

The near-surface geology of BSU and the greater east-central Indiana region is the product of repeated phases of Quaternary glaciation. Remnants of the most recent glacial phase comprise lateral and end-moraine features as well as thick glacial till. Based on the drilling and ERT data collected thus far (Fig. 2), the glacial till ranges between 15 and 46 m thick, and overlies a bedrock surface marked by an irregular epikarst. Drilling and ERT data also reveal that the glacial till is stratified, with at least one significant horizon of gravel and boulders wedged between finer-grained units and centered at ~10 m in depth (Fig. 2).

The thickness of the glacial stratigraphy changes over short distances within and around the study area. The natural-neighbor map of drilling depths to bedrock illustrates the potential irregularity of the bedrock surface from karst processes. In contrast, the local polynomial map of Figure 2 emphasizes overall trends in the bedrock surface. Both maps show thickening toward the southeast. Previous research (Samuelson, personal commun.) illustrates that this area is adjacent to the buried valley of the ancestral Anderson River.

The thickness of glacial till is the single most variable characteristic in the lithology of borehole heat exchangers in this study. This could have a profound impact on the bulk hydraulic and thermal conductivities in each borehole heat exchanger. For example, borehole heat exchangers drilled in the southeast corner of phase 2 (close to well 3) have ~37 m of glacial till (23% of the borehole depth). In contrast, wells 1 and 4 include 30 m of glacial till that comprises only 18% of the borehole heat exchanger depth. In the phase 1 area, the thickness of glacial till is even less (between 10 m and 20 m; Dunn, 2013). Even accounting for the shallower borehole heat exchangers of phase 1 (122 vs.

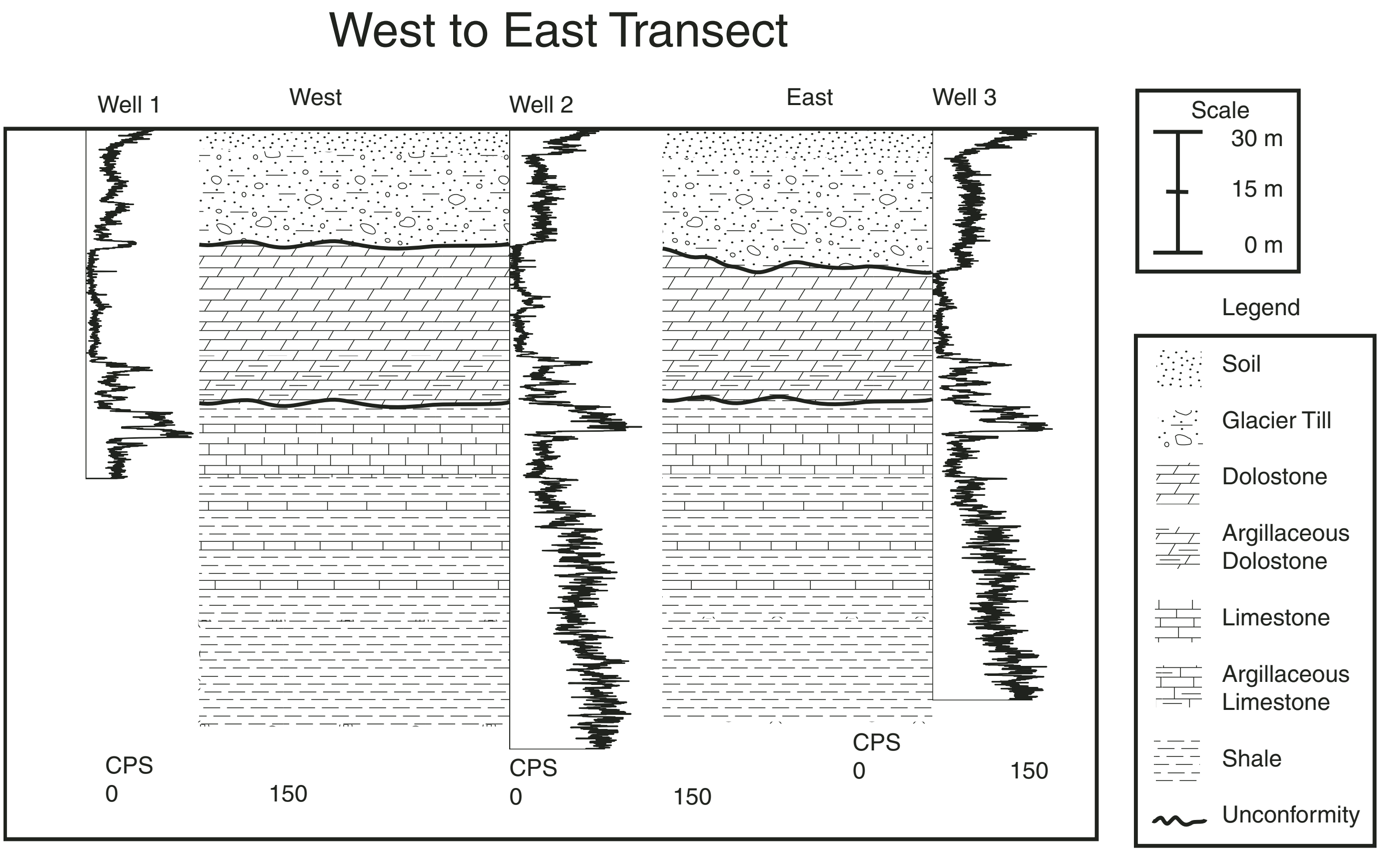


Figure 5. Stratigraphic cross section oriented west to east across the phase 2 borehole heat exchanger field on the Ball State University campus developed from cuttings and nearby core and including borehole gamma data. CPS—counts per second.

152 m), the glacial till is only 8%–16% of the total borehole heat exchanger. Although thermal conductivity measurements for glacial till have not been collected in this study, clay loam and glacial till have a conductivity that ranges between 2.14 W m^{-1} K^{-1} and 2.5 W m^{-1} K^{-1} (Shawn Naylor, 2014, personal commun.; Casás et al., 2013; Clauser and Huenges, 1995), values that are lower on average than for carbonate rocks (Robertson, 1988).

Thus, borehole heat exchangers with a large fraction of glacial till, such as those in the southeast part of the phase 2 field, may have reduced thermal capacities than those borehole heat exchangers with smaller fractions of glacial till. In contrast, borehole heat exchangers in the northwestern part of the phase 2 field may have greater thermal capacities due to reduced thickness of glacial till and the presence of the Mississinewa Shale Member of the Wabash Formation (Pinsak and Shaver, 1964; Owens, 1981) and potential presence of an overlying micritic dolostone facies (Droste and Shaver, 1983; Fig. 5 herein).

Ordovician–Silurian Stratigraphy

Beneath BSU, glacial deposits directly overlie near-horizontal layers of dolostone, limestone, and shale dating from the Late Ordovician and Silurian Periods that thicken slightly toward the southwest and dip slightly toward the northeast (Fig. 3). In all wells, Silurian-age limestone, dolostone, and shale of the Salina Group overlie the Ordovician-age limestone and shale of the Maquoketa Group. However, pinch outs, lateral facies changes, and changes in formation thicknesses do occur. More detailed characterization of the subsurface at BSU can further our understanding of stratigraphic capacity to store and transport thermal energy.

Furthermore, observed lithologies have differences from type sections (Shaver et al., 1961; Gray, 1972; Brown and Lineback, 1966). Since carbonate content is directly related to thermal conductivity (Robertson, 1988), formation composition has direct implications for the thermal capacity of the ground-coupled heat pump system. In one example, the Waldron Formation becomes more calcitic further southeast from the type section (NE¼ sec. 6, T. 11 N., R. 8 E at the abandoned Standard Materials Corp. quarry; Elrod, 1883; Pinsak and Shaver, 1964; Shaver et al., 1961). Pinsak and Shaver (1964) used the name Waldron for dominantly dolomitic facies in northern Indiana, and the core analysis near BSU shows shale laminae disseminated within a dense argillaceous dolostone. The Indiana Geological Survey reintroduced the Waldron as a member of the Pleasant Mills Formation in northern Indiana but was not able to account

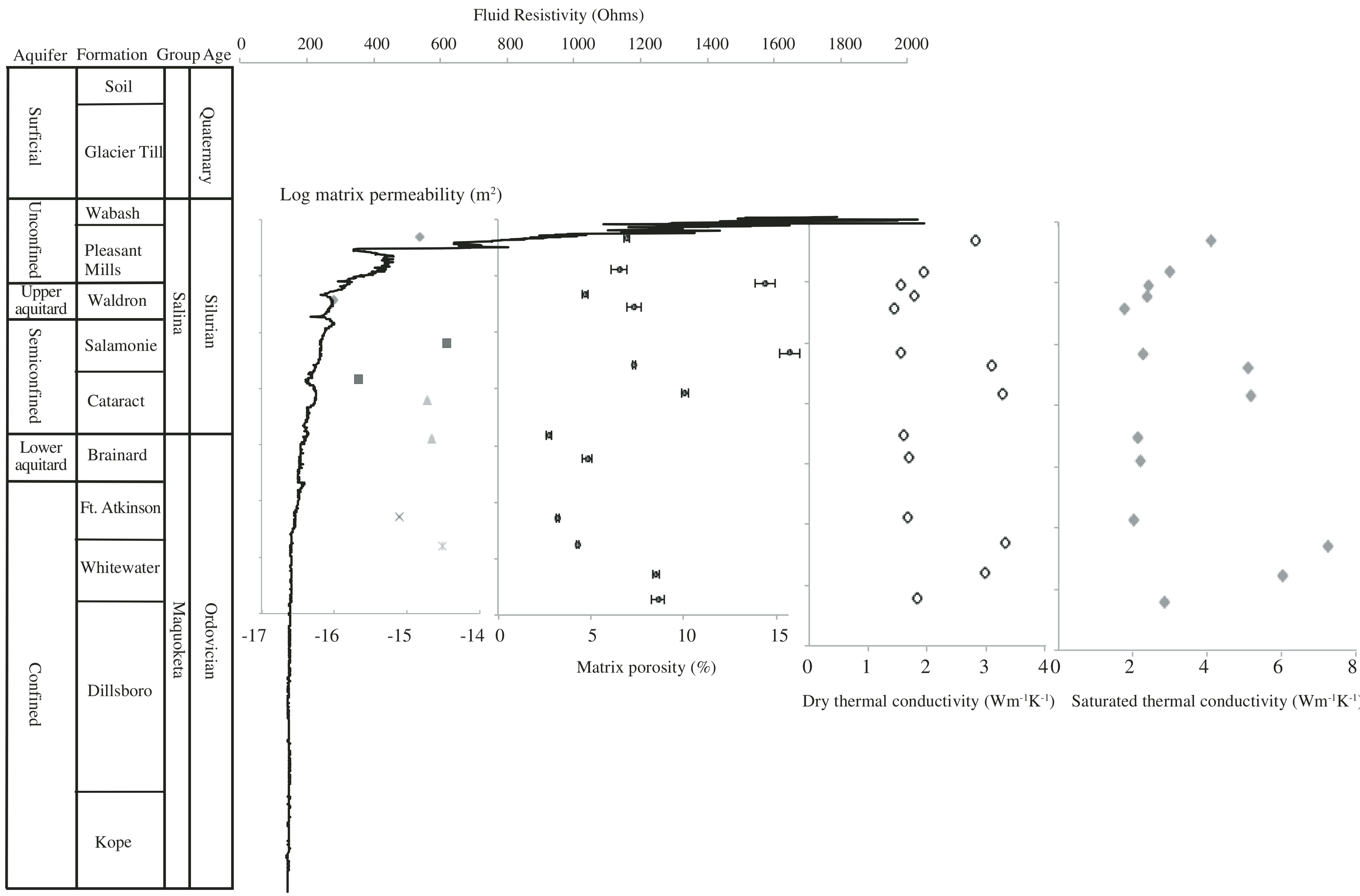


Figure 6. Petrophysical and hydrogeologic data including fluid resistivity from monitoring well 3 in the phase 2 borehole heat exchanger field and matrix permeability, matrix porosity, and thermal conductivity data measured on samples from core B-1. Aquifer divisions are identified based upon resistivity data.

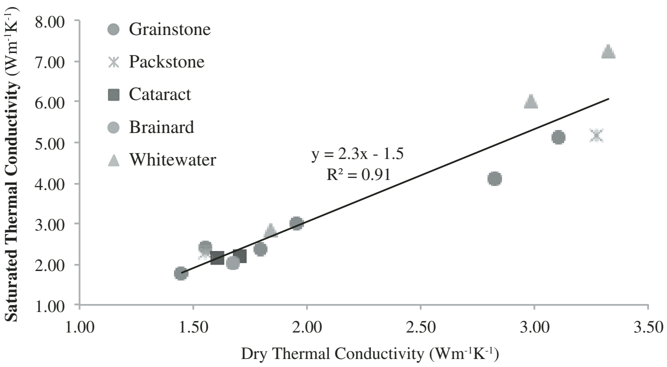


Figure 7. Dry vs. water-saturated values of thermal conductivity.

for thickly interbedded, gradational sequences of Waldron–Pleasant Mills units in some places (Shaver et al., 1986).

Cavernous porosity, identified by bit drops and loss of circulation during drilling operations, is common within the Silurian strata, particularly in the north field of phase 1. Unlike the extensive paleokarst encountered at the Ohio State ground-coupled heat pump (Bair and Torres, 2011), the "caves" under BSU may be related to the active circulation of shallow groundwater adjacent to the ancestral Anderson River prior to mantling by glacial till. So far in phase 2, BSU students collecting data alongside drilling rigs have only encountered a few signatures of these caves, but the ERT data and drilling logs display possible evidence of sinkholes on the preglacial surface (Fig. 2).

Variation in Thermal Conductivity

Measured values of thermal conductivity generally agree with Robertson (1988). Robertson's measurements from samples of pure crystals of calcite and dolomite yield slightly higher thermal conductivity values than the mixed lithologies of this study. Increased proportions of clay, silt, and sand cause an overall lowering of thermal conductivity, but the measurements in this study are within the range of reported values. The mixed lithology and facies in the BSU ground-coupled heat pump system greatly complicates the bulk thermal conductivity both vertically through each individual borehole heat exchanger and laterally through phase 2 (Fig. 6). Stringers of shale in the lower Salamonie Formation, the mixed lithology of the Cataract Formation, and the clay within the Whitewater and Dillsboro Formation are all examples of lithologies with lower thermal conductivities due to increased siliciclastics.

Thermal conductivity in saturated samples is 2.3 times higher than dry values (Fig. 7). This is due to the replacement of air with water and illustrates the great effect that water has on thermal conductivity. Values fall within two distinct groups: the group with lower thermal conductivity and significant amounts of clay, and the group with higher thermal conductivity composed of more pure carbonate. This effect is similar to that seen in Brigaud and Vasseur (1989) and Robertson (1988), where increasing clay content logarithmically decreases the thermal conductivity of sandstone.

Measured thermal conductivities in the Whitewater Formation in samples from depths of 57.4 and 62.7 m are much higher than maximum values from Robertson (1988). Porosity in these samples is low to moderate at 4.3% and 8.2%, respectively, and the matrix permeability is within the range of other samples. It is very likely that the elevated thermal conductivity values are due to water convection within large moldic pores encountered when drilling the pilot hole for the RK-1 thermal conductivity probe. Water not only has a higher conductivity than air, but thermal loading induces water convection in pores and thus significantly raises heat transfer and heat movement throughout a formation. It follows that these zones of moldic porosity could serve as target zones for heat transfer within borehole heat exchangers (Ellett and Naylor, this volume) and serve as an important heat sink/source for the entire ground-coupled heat pump system.

Hydrogeology

Cardinal Creek dominates the surface hydrology in the northern portion of BSU. It drains a storm-water retention pond and then flows between the borehole heat exchanger fields in phase 1 (Fig. 1). However, there are no permanent surface water features in phase 2, at BSU's southern edge; therefore surface water–groundwater interactions would be limited to infiltration from precipitation. Fluid resistivity data from the monitoring well in phase 2 illustrate the decreased influence of meteoric water with depth and subdivide the groundwater environment into six stratigraphic zones: a surficial glacial aquifer, an unconfined Silurian aquifer (Pleasant Mills Formation), a leaky Silurian aquitard (Waldron Formation), a semiconfined Silurian aquifer (Salamonie and Cataract Formations), an Upper Ordovician aquitard (Brainard Shale), and the confined Ordovician aquifer (Whitewater, Dillsboro, and Kope Formations; Fig. 6).

The direction of groundwater flow in the shallow glacial aquifer and the Silurian aquifer is generally toward the southwest in phase 1 (Samuelson, et al., 2011; Dunn, 2013). Water-level measurements in the phase 2 field also demonstrate this southward trend; measurements of water level from wells with screened intervals in the Silurian aquifer reveal a drop of 0.5 m from NW to SE, and screened intervals in the Ordovician aquifer show a drop of ~1.3 m from NE to SW. These data suggest different flow regimes in upper and lower aquifers. There are two caveats at this time. First, further development of the wells is necessary because of problems during construction. Second, ongoing drilling impeded the ability to monitor water levels in the middle of phase 2.

Results of slug tests in monitoring wells in the Silurian and the surficial glacial aquifer from phase 1 revealed permeability values between 1.7×10^{-13} m^2 and 2.7×10^{-13} m^2 (Dunn, 2013), and these are considerably greater than the matrix permeability measurements of this study, i.e., $<9.9 \times 10^{-17}$ m^2 in the lowermost Waldron Formation to 2.2×10^{-15} m^2 in the lowermost Cataract

Formation. This highlights the importance of bedding planes and fractures in groundwater movement (Pentecost and Samuelson, 1978). Similar data are not yet available for the Ordovician aquifer at either site.

Thermofacies

Ferguson (2007) considered the effects of horizontal heterogeneity in aquifer hydraulic conductivity on temperature distributions and energy recovery by injecting and pumping groundwater from virtual wells. This work utilized geostatistical simulations to generate virtual aquifers based on characteristics of the well-studied Borden sand aquifer in Ontario and the paleokarstic Carbonate Rock aquifer in Manitoba, Canada. The effect of heterogeneity in that study was to spread heat over greater distances in the aquifer.

At BSU, Dunn (2013) summarized the temperature changes in the groundwater at the active phase 1. As of October 2013, after constant thermal loading, a temperature increase of 14–18 °C has been observed in the center of the south borehole heat exchanger field in phase 1 (Fig. 8) with concurrent increases in three other monitoring wells. Three of the monitoring wells with increased temperatures overall also exhibit vertical structure in the temperature profiles that may correlate to lithologic units—a stratigraphic focusing of thermal flux that can be used to subdivide the subsurface into thermofacies (Sass and Götz, 2012). A temperature spike at a depth between 14 and 19.5 m may correspond to the sand and gravel zone of the surficial glacial aquifer (Fig. 2), and a temperature dip at a depth of 70 m agrees with the position of the Brainard Shale aquitard (Fig. 3), i.e., zones of higher permeability and lower thermal conductivity, respectively.

This vertical heterogeneity in temperature profiles is reminiscent of models of pump-and-treat remediation systems developed in MODFLOW and MT3D 96 by Vacher et al. (2006), where the variation in bulk permeability of the Ocala Limestone in Florida was utilized to demonstrate the heterogeneous penetration of a tracer during injection cycles of aquifer storage and recovery (ASR) wells in the upper Floridan aquifer (Vacher et al., 2006): These were characterized by high tracer mass transfer at first, followed by reduced efficiency as water flowing in from more-permeable layers became responsible for most mass transfer, and less-permeable regions became isolated. Rest periods would lead to "rebound," when temperature equilibrium was reestablished between low- and high-permeability zones. Analogous behavior of heat is expected in the geothermal system developed in a heterogeneous aquifer system.

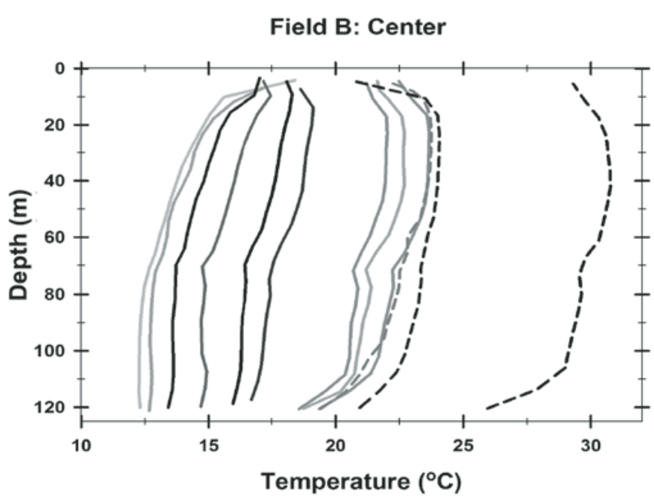


Figure 8. Time series of temperature profiles within phase 1 from October 2012 to October 2013, Ball State University geothermal conversion project (Dunn, 2013). Each month of the observation period resulted in temperature profiles warmer than the prior month.

SUMMARY: GEOLOGY MATTERS

In June of 2011, Geothermal Resource Technologies, Inc., conducted a pair of standard thermal response tests in phase 2 of the BSU ground-coupled heat pump system. The results of these two tests concluded a bulk "formation" thermal conductivity between 2.6 and 3.0 W m^{-1} K^{-1}. The average thermal conductivity from samples in this study, not weighted for formation thickness and not incorporating the shale-rich Dillsboro and Kope Formations, was 2.2 ± 0.006 and 3.5 ± 0.086 W m^{-1} K^{-1} for dry and water-saturated samples, respectively. However, the range in our thermal conductivity data from saturated samples (1.8–7.2 W m^{-1} K^{-1}) leads to the conclusion that the thermal response tests do not accurately capture in detail where the heat is stored and recovered or how the heat is transported, but rather reflect large-scale average behavior.

Our research at BSU, combined with preliminary temperature profiles in an active portion of the ground-coupled heat pump system, provides some new insight. First, zones of low siliciclastic content within the Silurian Salamonie Limestone and moldic porosity within the Ordovician Whitewater Formation may be target thermofacies for heat deposition and extraction. Sand and gravel zones within the glacial till may also allow for significant thermal loading; however, advection along groundwater flow paths in these high-permeability zones may reduce the fraction of recoverable thermal load. Portions of the unconfined Silurian aquifer may also be subject to significant thermal advection where paleokarst features increase aquifer permeability and influence groundwater flow. Characterization of the hydrogeologic environment can therefore be a vital tool for district-scale ground-coupled heat pumps by allowing system designers to tune the field of borehole heat exchangers to the specific on-site conditions that may influence the magnitude and mode of heat transfer.

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Appendix 14: Embracing the Future: The Ball State University Geothermal Project

Embracing the Future: The Ball State University Geothermal Project

by

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ABSTRACT

Ball State University will convert its campus from a coal-fired and natural gas-fired district heating system to a closed loop heat pump chiller district heating and cooling system serviced by more than 3,750 geothermal boreholes. It will be largest district geothermal system in the United States, and on May 29, 2009, The New York Times called Ball State "a pioneering university" for undertaking the initiative. The installation will include an integral program of research designed to inform the industry—especially the owners of 65,000 other district-heated buildings in the U.S.—how to significantly reduce the "first costs" and risks associated with intensive borehole drilling, piping, and looping. These issues are cited in a 2008 Department of Energy (DOE)-sponsored study as a major impediment to the more widespread adoption of geothermal systems. The planned research will incorporate 2D resistivity programming, geological surveys of the impact of high density boreholes on ground temperature, assessment of the role of soil and water pH, evaluation of the influence of variable system water flow, analysis of hydrological data, and verification of the claims made by new geoexchange pipe manufacturers for dramatically increased thermal transfer (40 to 50 percent) and the concomitant reduction in the number of required expensive boreholes (20 to 35 percent) to service a load.

BACKGROUND

In 2009, we find history repeating itself. The Ball brothers (founders of Ball Corporation, the renowned manufacturer of Ball canning jars) came to Muncie, Indiana, on the promise of reducing costs for their glass production business by pulling from the ground the "free" energy of the East Central Indiana natural gas deposits. Now, Ball State University, their founding namesake, will begin to save a net $2 million annually in avoided fuel costs (at today's prices) by pulling from the ground a different form of "free" energy—the geothermal energy stored (and storable)—in the earth's mantle.

In February of 2009, the Ball State University Board of Trustees approved recommendations from the Facility, Planning, and Management staff to replace the existing coal-fired boilers used for campus district heating with a ground-integrated heat pump technology. This geothermal district system will provide heating and cooling for the entire campus and will present opportunities for real-time, field-based research as the project comes online.

"Geothermal" as a terminology is itself not new but, in fact, is a rubric under which *many* differing technological applications find their home. In its purest form, the term "geothermal" applies to energy extraction for heating purposes using hot rock sources in various locales throughout the world in which steam extraction from the ground is used for space heating and water heating—or in select instances, for driving turbines that generate electricity. Geothermal as a broad term has been applied not only to such steam extraction but also to water extraction. In some instances, ground water is removed and used as an energy capacitor in a heat pump exchange providing either cooling or heating at a single-building residential or commercial scale. That water extraction, in turn, involves the challenge of disposing of the water once the heating or cooling energy has been exchanged, but most importantly introduces the potential for a depletion of the ground water supply. Often times with such single source extraction strategy, the ground water is pumped from the earth's mantle and after the energy exchange is rejected to a surface feature such as a stream or pond. By contrast, injection wells can be used to return the ground water to its original location. However, this open-loop technology is problematic in that the returning water can be a vector for contamination of the ground water aquifer.

To counter these complications, it is possible to use closed-loop re-circulating water technology; heat exchangers are sunk into the ground and by way of temperature differential, heat energy flows from hot to cold, only the heat energy is removed from, or injected into, the ground. A residual factor at times can be an improperly designed borehole field can result in an excessive buildup or reduction of ground temperature. The temperature of the ground will fluctuate throughout the year, but if the borehole field is properly designed, the average temperature will not change from the normal 55 degrees.

Some closed system installations make use of a horizontal looping of pipe at moderate depth in a sizable area of land; similarly a horizontal looping of pipe can be placed in a standing pond or flowing river, each of which act as a capacitor from which, and into which, thermal energy can be removed or embedded. These closed systems oftentimes include glycol mixtures to assure that the system will not freeze; this again can be problematic as they offer the potential for chemical contamination of the groundwater should a leak occur.

Certainly the open-loop and closed-loop systems are well-established in the market and yet there simply is no precedent for use of geothermal technologies in a large-scale district heating and cooling installation.

CONTEXT

With the growing international concern for global warming and the need to reduce and ultimately eliminate worldwide the carbon dioxide equivalent (CO_2e) loading of the atmosphere, there has been a developing interest in the geothermal technology as a means to avoid the combustion of a fossil fuel and so the avoidance of CO_2e production. Geothermal systems, of course, are powered by electricity which itself may come from a fossil-fuel-based generating facility.

But given these concerns for climate change and the role that universities can play in shepherding new visions for the future, a number of initiatives within the United States have taken hold including the creation of the American College and University Presidents Climate Commitment (ACUPCC) and the Sustainability Tracking Assessment and Rating System (STARS) both supported by the Association for the Advancement of Sustainability in Higher Education (AASHE). These reflect a growing desire on the part of universities to serve as exemplars of best practice and to educate their many constituents not only in the use of conservation practices but also new technologies that can reduce the institutional contribution to global warming. The national and international stage is being set to support and reward innovation.

Indiana itself has a long history of innovation, once vying to be the auto capital of the nation by hosting nearly 200 automobile manufacturers over the years. Now Indiana is applying that entrepreneurial spirit to the field of alternative energy. Recent headlines have publicized the growth of wind farms within Indiana, the migration of green companies to Indiana, and the origination of green technologies by Indiana entrepreneurs, including electric car initiatives, solar power advances, and more. And now Ball State University is adding to those headlines by building the largest district-scale heating and cooling groundwater geothermal heat pump technology installation in the country.

INTRODUCTION

Ball State University, which has a long-standing commitment to sustainability, is playing a key role in this alternative energy renaissance. The university has found itself uniquely positioned in this context: 1) our president was one of the twelve originating signatories to the American College and University Presidents Climate Commitment: 2) our university needed to replace its existing fossil-based coal-fired chain-bed boilers (which date to the 1940s); and 3) our university has been growing its engagement with principles and practices of sustainability as a triple-bottom line metric—an evaluation of social, economic, *and* environmental cost/benefit.

In 2008, our facilities management team began looking at replacing our existing coal-fired boilers with a more efficient conversion technology using Circulating Fluidized Bed Steam Boiler (CFB) and filtration devices to delimit production of the CO_2e gases and to increase the efficiency of the energy extraction from the source coal. Because of a coincidence of factors including a limited current construction market for installing this technology, and the commitment of the institution to the employment of best practices, the university turned to the National Renewable Energy Lab and Oak Ridge National Laboratories for consultation on whether in fact ground source geothermal could begin to meet the needs of a district-scale heating and cooling system; servicing some 47 buildings.

We identified consultants and designers; with their assistance we developed a series of design scenarios for scaling-up the geothermal technology to support a district heating and cooling system. To be sure of the capabilities of the design schemes, the university then undertook a proof-of-concept evaluation and a field test of technical application to determine the feasibility and cost effectiveness of the idea. With the success of the proof-of-concept and field testing, the confidence level took hold for moving forward with what we have discovered is the largest district-scale heating and cooling groundwater geothermal heat pump technology installation in the United States.

With the design and feasibility work completed, the university secured approval from state agencies to repurpose to the geothermal installation some $40 million that had been appropriated initially for the high-efficiency coal-fired district heating boiler replacement; with the approval of the board of trustees to commit to the longer-term build-out of this installation—using available funds to capitalize the first couple modules of installation and the use of savings from avoided fuel costs to underwrite subsequent stages of completion for the project. Since the adoption of the plan, the university continues to pursue federal funding to cover the marginal difference between the appropriation and the projected full cost of build-out.

DETAILED DISCUSSION

Initial consideration of geothermal; finding large scale geothermal designers/engineers

Because the university could not continue to pursue its CFB solution for financial reasons, it began to consider an alternative solution that would incorporate new geothermal heat pump technology. The university received assistance from the office of U.S. Senator Richard Lugar to arrange a teleconference with scientists and engineers from the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory. During that teleconference, the NREL and Oak Ridge personnel identified the top geothermal experts in the United States. Ball State proceeded to engage several of those experts in discussions about the challenges associated with a project whose size would make it the largest of its kind. Two of the experts are now under contract to design the geothermal system. Lugar, who spoke during the groundbreaking ceremony, called it "a bold endeavor" with significant consequences for the energy future of Indiana and the nation.

As the university focused on the geothermal option, it contacted a variety of designers. One of the initial realizations was that this project would be unprecedented in size. There are other universities that have installed geothermal systems to serve a handful of buildings. However, none is designed to heat and cool 5.5 million square feet of area in 47 major buildings spread across a 660-acre campus.

To be prepared, we gathered ahead of the initial meeting with the designers a tabulation of steam generating capabilities, boilers capacity, chilled water production capabilities, and chillers capacity. We also tabulated consumption history for both steam and chilled water. This information provided the basis for determining the load profiles for both heating and cooling. This also helped to determine whether the campus had a heating- or cooling-dominant need; with this information in hand and by documenting the specific equipment capacities within each of the 47 buildings, we enabled the designers to determine how many boreholes, and what capacity of heat pump chillers would be required.

We found that we had 14,000 tons of connected chilling load. This led to a ballpark calculation that we might need as many as 7,000 boreholes. As unitary geothermal systems were reputed to be the most efficient, our initial desire was to find a way to provide geoexchange capability within close proximity of each building. This proved to be impossible; the nearness of residential sectors of the city of Muncie and the concentration on campus of many of the buildings in “quads” yield insufficient available ground space for boreholes. And of course, using a lake or river as the geoexchange could not be considered because there is no major body of water on or adjacent to campus.

We could identify a reasonable amount of open ground adjacent to about one third of the campus buildings. In addition, the campus has several large open spaces used for parking lots, sports, and recreational activities. The eureka moment for this project was followed a set of discussions with engineers who thought it might be possible to use these remote open spaces as borehole fields that could provide the geoexchange necessary to service two or more “district energy stations” located in geographically separated areas of campus. The district energy stations would be connected by a large hot water pipe that would form a loop around campus. Each building would then be connected to the hot water loop.

Considerations

According to the experts at both the Oak Ridge National Laboratory and the National Renewable Energy Laboratory as well as those involved in our design, the use of heat pump chillers to produce chilled and hot water connected to a district heating and cooling distribution system has never been used on the scale (47 major buildings over 660 acres) that we propose. This is due to the only recent availability of the larger scale efficient heat pump chilling equipment with lower operating costs. In addition, the prospect that air quality requirements will be strengthened in the United States through a federally mandated carbon tax or cap and trade carbon accounting system added to our valuation of the benefits a geothermal system would provide. Given the fact that geothermal systems for individual buildings have been in place for many years and are considered a mature technology, our expectation is that while the first costs of such systems continue to be higher, the reduced operating costs should only improve.

Financial calculations

Final cost figures will not be known until the various parts of the project, including borehole drilling, installation of piping, heat pump chillers and pumps, and air handling changeovers for some buildings, etc., can be put to bid; nonetheless, it appears that the total price tag will be in the range of $70 million. The university currently has available $41.8 million from the proceeds of a bond issue, and the plan is to proceed in phases. The elements outlined above, using existing funding over the next several years, would result in the decommissioning of two boilers in the first phase. For the remaining components of the project, additional funds will be sought from sources involving federal alternative energy accounts, the federal stimulus package for green projects, private foundations, and operational savings. Since this project is now underway, it is the university's belief this project could be well positioned to apply for assistance in line with the expressed goals of the Congress as follows:

1. The project will greatly improve the heating and cooling energy efficiency on campus.
2. The initial borehole drilling and pipe installation, which represent about 40 percent of the overall project cost, is "shovel ready" and will put people to work very quickly.
3. In contrast to the CFB system, every component of the geothermal technology is made in America.

Advantages of the proposed project to the university include the following:

- replaces obsolete coal-fired boilers (three natural gas boilers will remain in place as backups);
- buffers against future fuel cost volatility;
- reduces long-term operating costs;
- reduces approximately 50 percent of the campus carbon footprint;
- eliminates other air pollutants;
- qualifies for Department of Energy funding;
- comprises American made components; and
- creates new jobs immediately in the engineering, construction, and manufacturing sectors.

THE ACADEMIC/FACILITY RESEARCH OPPORTUNITY

In scheming the system for our campus, it was necessary to consider the modulation of the construction for a number of reasons: 1) to fit the technology into the footprint of the campus; 2) to link the piping systems to the existing district heating and cooling network; 3) to scale and modulate the installation to match that of the cycles of budgeting and capital investment; and 4) to introduce field-based research on alternative detailed technical installations that could offer the promise of reducing first-cost of installation—the traditional barrier to a broader use of this technology.

One of the more interesting aspects of this enterprise is the need and opportunity to pull together faculty and engineering professionals of differing expertise. The research options include the evaluation of: 1) the use of differing types of piping for looping within the boreholes, the horizontal ground looping and the placement of distribution piping on the campus; 2) new material mixes in the piping to enhance heat exchange; 3) new geometries of pipe profile to enhance heat exchange; and 4) the rates of flow needed to balance energy exchange between the "sourcing" and "sinking" of energy using the capacitor effect of the geologic substrates of the campus; 5) the geologic substrate and its impact on the drilling of the boreholes; 6) the expected rate of extraction/injection of energy; 7) the influence of that on the spacing of the boreholes; 8) the patterning and looping of sets of boreholes in groups as "pods"; and 9) the interface of these energy exchange fields with the heat pumps that will drive the distribution of heating and cooling campus-wide.

One of the more appealing aspects of the heat pump chiller technology is its ability to generate both hot water at 170 degrees and chilled water at 45 degrees simultaneously. This technology can first transfer energy from the chilled water return loop to the hot water loop. When sufficient energy is not available, the heat pump chiller draws energy from the borehole loops. By looping buildings together in a district arrangement so as to exchange energy building to building as a first-order of energy flow management, this energy can be reused and not wasted. Once such exchanges are achieved, then the earth will be called upon as a source or sink for the energy difference.

From a first-blush economic point of view the $60-70 million price tag for this district system spread over a 5-10 year period of installation may seem to have a low-order return-on-investment. However it is important to acknowledge that the cost of installation of this system (as a net return-on-investment) must be measured as the marginal difference between the initial plan for capital expenditure (a more efficient CFB coal-fired plant) and the (highly efficient, modulated, and management-effective) ground source heat pump system. Given the likely savings of some $2 million per year (net) in avoided fuel costs—which accounts for the added cost for electricity from the Midwestern electrical grid—the projected yield is a significant return-on-investment in a simple straight line comparison. When leveraged to include the full range of impact, that ROI is even better.

One of the tributary impacts of this enterprise is the opportunity to stage the institution within the emerging carbon market enabling us to shift our focus to our electrical grid sourcing of energy and the potential for supporting the growth of a green economy—specifically green energy sources—feeding into the grid.

Within Indiana the last several years we have experienced a burgeoning development of wind farm installations for alternative energy supply into the grid; the potential long-term for the university is to source all of its electrical power from such green supply.

CONCLUSION

Although the future never can be fully known, Ball State University has positioned itself strategically to respond to the complexities of the times.

We are maximizing the use of a proven technology at a new scale of application that offers a sophisticated means for modulating energy management; we will be able to network buildings one-to-another to trim and finesse the balance of energy flows campus-wide before drawing on the earth as a source or sink of thermal resource.

The project will impact the local economy—offering immediate job opportunities and the chance for repurposed job training for well-drillers who can shift their expertise to that of borehole drilling, looping, and routing.

Over the longer term, through purchases of green power, the project will contribute regionally to the growth of the national green economy, supporting the regional green energy industries that will feed the electrical grid.

This coupled with the continuing opportunities for hands-on applied research offers an additional measure of return-on-investment, one that is not as readily monetized but certainly will accrue to the benefit of the university, the state, and the regional economy.

Most importantly, as a signatory to the American College and University Presidents Climate Commitment, Ball State University through its geothermal project will move substantially toward meeting the obligation of becoming a climate neutral campus.

Noted sources:

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Geoexchange.org, www.geoexchange.org/
Geothermal Heat Pump Consortium, Inc. (GHPC), www.ghpc.org
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http://intraweb.stockton.edu/eyos/energy_studies/content/docs/proceedings/TAYLO1.PDF

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Consulting-Specifying Engineer, Nov 2008

Geothermal Ground Source Heat Pumps A World Overview
J Lund, B Sanner, L Ryback, R Curtis, G Hellstrom
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Tapping the Potential Geothermal Energy
Bill Johnson
Facilities Manager Magazine, Nov/Dec 2008

Consultants:
Kevin Rafferty
Steve Kavanaugh

Proof of Concept:

Heat Pump Chillers with Geothermal Storage

Produced for

Ball State University

Prepared by

and

Kirk T. Mescher, PE
of

MEP Project No. B20.08. 01

January 28, 2009

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INTRODUCTION

In today's economic climate of high and rising fuel costs, many managers of large 24-hour facilities do well to examine new and creative ways to trim energy bills. One smart option is to examine the potential of a source that is already available, repurposing heat that is ordinarily discarded by the HVAC system's condenser.

By utilizing heat pump chillers with geothermal storage instead of ordinary chillers, the temperature of this formerly waste heat can be increased until it is suitable for a wide variety of heating applications, and utilized when it is needed.

This report provides a proof of concept for heat pump chillers with geothermal storage. It will allow Ball State University to have an introductory understanding of this type of system, as well as some preliminary operational costs developed by Kirk Mescher of CM Engineering, in order for university personnel to evaluate the compatibility of this technology with their campus.

THE CONCEPT

HeatPump Chillers

A compound centrifugal chiller is a special kind of centrifugal chiller that utilizes a combination of two (i.e. compound) compressors, instead of just one, and a component called an intercooler. The additional compressor and the intercooler allow the compound centrifugal chiller to produce condenser water at a much higher temperature than was previously possible with a standard centrifugal chiller. No longer fit only for rejection out of the cooling tower, this hot water, which can reach up to 170˚F, is useful and can be utilized in a variety of heating applications that, until a few years ago, were the domain of boilers and heat pumps. Hence, this chiller is commonly called a heat pump chiller.

Although the advantages of this type of chiller are enormous, not every facility is a good fit, since not all facilities require simultaneous heating and cooling. Large facilities with 24-hour operation, such as hospitals, hotels, and universities, which have year-round demand for both heating and cooling, have tremendous potential to save energy. However, a careful examination of the loads throughout the year is prudent, in order to ensure that the heating and cooling produced by these chillers will be sufficiently utilized.

In addition, the second compressor can be turned off when the heating load is low. Although this will reduce the temperature of the condenser water leaving the chiller, it can be hot enough to meet the requirements of summer heating applications, such as reheat and domestic water, which typically do not require the high temperatures associated with winter heating. This will also allow the chillers to operate more efficiently, in the same way as a standard single compressor centrifugal chiller.

Geothermal Storage

Many facilities require simultaneous heating and cooling, but only utilize only a fraction of its peak heating during the summer. In this case, a heat pump chiller can still offer tremendous benefits with the addition of a renewable technology called geothermal storage. This allows a facility to store the heat it produces in the summer and use it in the winter. This is achieved by heating the earth several hundred feet below the ground what is called a loop field. This loop field is an area of land with several bores that are several hundred feet deep. Each bore houses u-shaped pipe that routes hot water and cold water down deep into the rock in the earth where it rejects or obtains load. This bedrock is an excellent thermal storage device. It can be charged with heating energy during the summer, hold this heat with minimal losses, and discharge it for utilization in the winter.

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THE APPLICATION

System Sizing

By examining the heating and cooling loads provided by university personnel (see Appendix A), a heat pump chiller plant with geothermal storage, including all distribution piping, was sized to meet the needs of the university's campus. Calculated by CM Engineering, the estimated annual electrical consumption for this system will be 50 million kWh and the annual operating cost will be $2.1 million.

System Layout

Three locations are proposed for the new heat pump chillers: a new energy center on the east side of the campus, and a new second energy center on the north side of the campus, and the third existing energy center on the south side of the campus. The new heat pump chillers can be connected directly to the existing chilled water piping system. A new hot water piping loop will need to be added to carry the hot water to the buildings. The source of the hot water, the three heat pump chiller plants, will be connected to this new hot water piping loop with branch pipes. Additional branch pipes will connect this loop to the destination of the hot water, the hot water side of the heat exchangers that currently use steam to provide hot water inside the buildings. For the buildings that do not have these heat exchangers, new air handling unit coils and terminal equipment will need to be installed, in order to accommodate the hot water. The current district heating and cooling system will remain in place and operational during the conversion.

A flow diagram of this system is shown in Appendix B. The system will provide 44˚F chilled water throughout the year, and 170˚F hot water in winter design conditions (with both compressors running). The hot water temperature will decrease proportionately with the outside air temperature, to a minimum of 110˚F in summer design conditions (with one compressor running). This hot water will be used for domestic hot water and summer heating applications, which do not require the hotter 170˚F water.

The hot water is circulated using variable frequency drive (VFD) pumps to the existing buildings until their immediate needs are met. If any heat is remaining, it is routed to a heat exchanger that deposits heat into the geothermal storage. This typically occurs during the summer. Conversely, during the winter, when an additional heat source is needed, heat is removed from the geothermal storage.

The specifics on the loop field are contained in Borehole Design Report in Appendix C. It is estimated that 3,750 bores will be needed. They will be 400 feet deep and 15 feet apart from each other. They will house two 1-inch u-bend pipes per bore. The grout thermal conductivity, which is a measure of how effectively the bedrock can hold heat, is estimated to be 0.84 Btu/hr·ft·˚F.

CONCLUSION

It is clear that heat pump chillers with geothermal storage offer tremendous potential for energy savings for Ball State University. It is our hope that this report will offer some helpful information, as we continue to perform further analysis on this type of system to meet the heating and cooling needs of the campus.

APPENDIX A: HEATING AND COOLING LOADS

Building Name	Address	Year Built	Area (ft^2)	Heating Load (MBtuh)	Hot Water (gpm)	Cooling Load (tons)	Chilled Water (gpm)
Carmichael Hall	1701 W. McKinley	1967	22,963	574	38	58	138
Johnson Hall (JA Botsford-Swinford; JB Schmidt-Wilson)	1601 N. McKinley	1967	262,432	6,561	437	141	338
LaFollette Halls (Village Expansion)	1515 N. McKinley	1964	531,792	13,295	886	211	507
Lewellen Pool	1400 N. McKinley	1967	56,415	1,410	94		0
Health/Phys Activities Building	1740 W. Neely	1989	110,710	2,768	185	186	445
Irving Gymnasium	1700 W. Neely	1962	135,039	3,376	225	186	445
Worthen Arena		1990	193,267	4,832	322	448	1,075
Architecture	1212 N. McKinley	1970	146,750	3,669	245	333	799
Subtotals				**36,484**	**2,432**	**1,562**	**3,748**
David Letterman Building	1201 N. McKinley Ave	2005	86,351	2,159	144	128	307
Edmund F. Ball Building	1109 N. McKinley	1986	84,594	2,115	141	256	614
Arts and Journalism Building	1101 McKinley	2000	207,141	5,179	345	218	522
Bracken Library	1100 N. McKinley	1972	321,800	8,045	536	640	1,536
University Theatre	920 N. McKinley	1960	83,667	2,092	139	179	430
Teachers College Building	901 N. McKinley	1966	125,650	3,141	209	288	691
Noyer Hall	1601 W. Neely	1962	238,320	5,958	397	448	1,075
Woodworth Halls	1600 W. Riverside	1956	164,626	4,116	274	202	484
Pruis Hall	1000 N. McKinley	1971	18,170	454	30	128	307
Bracken House	2200 W. Berwyn Rd.	1937	13,227	331	22	19	46
Whitinger Business Building	1200 N. McKinley	1978	93,763	2,344	156	160	384
Studebaker Halls East	1301 W. Neely	1965	97,406	2,435	162	51	123
Studebaker Halls West	1401 W. Neely	1964	242,080	6,052	403	294	707
Park Hall	1550 Riverside	2006	194,600	4,865	324	282	676
Music Building	1810 W. Riverside	1956	45,036	1,126	75	83	200
Music Instruction Building	1809 W. Riverside	2003	86,179	2,154	144	179	430
Emens Auditorium	1800 W. Riverside	1963	82,101	2,053	137	243	584
Arts and Communication Bldg.	1701 W. Riverside	1957	47,010	1,175	78	83	200
Health Center	1500 W. Neely	1962	19,527	488	33	32	77
DeHority Halls	1500 W. Riverside	1960	138,140	3,454	230	205	492
North Residence Hall	1400 W. Neely	2008	190,480	4,762	317	230	553
Subtotals				**67,159**	**4,477**	**4,490**	**10,775**
Applied Technology	2000 W. Riverside	1948	93,274	2,332	155	205	492
Fine Arts Building	2021 W. Riverside	1935	74,085	1,852	123	198	476
Cooper Physical Sciences	2111 W. Riverside	1965	130,090	3,252	217	461	1,106
Cooper Nursing	2111 W. Riverside	1965	47,580	1,190	79	122	292
Cooper Life Sciences	2111 W. Riverside	1968	113,843	2,846	190	442	1,060
Ball Gymnasium	Campus Drive	1939	83,197	2,080	139	115	276
West Quad	2301 W. Riverside	1936	57,593	1,440	96	109	261
Lucina Hall	2120 W. University	1927	60,014	1,500	100	128	307
Burris School	2201 W. University	1928	130,745	3,269	218	250	599
Elliott Dining	2100 W. Gilbert	1990	13,228	331	22	45	108
Wagoner Halls	301 N. Talley	1957	75,680	1,892	126	13	31
Elliott Hall	401 N. Talley	1937	51,627	1,291	86	32	77
Administration Building	2000 W. University	1912	54,136	1,353	90	96	230
Student Center	2001 W. University	1951	171,165	4,279	285	410	983
Burkhardt Building	601 N. McKinley	1924	61,439	1,536	102	70	169
Subtotals				**33,606**	**2,240**	**2,989**	**7,173**
Central Chiller	West Campus Drive	1965	7,909	198	13		
Field Sports Building	1720 W. Neely	1983	47,736	1,193	80		240
Greenhouses	Christy Woods	1965	4,381	110	7		
Heating Plant	2331 W. Riverside	1924	18,685	467	31		
South Service Bldg.	Campus Drive	1967	4,800	120	8		30
Expansion			300,000	7,500	500	640	1,500

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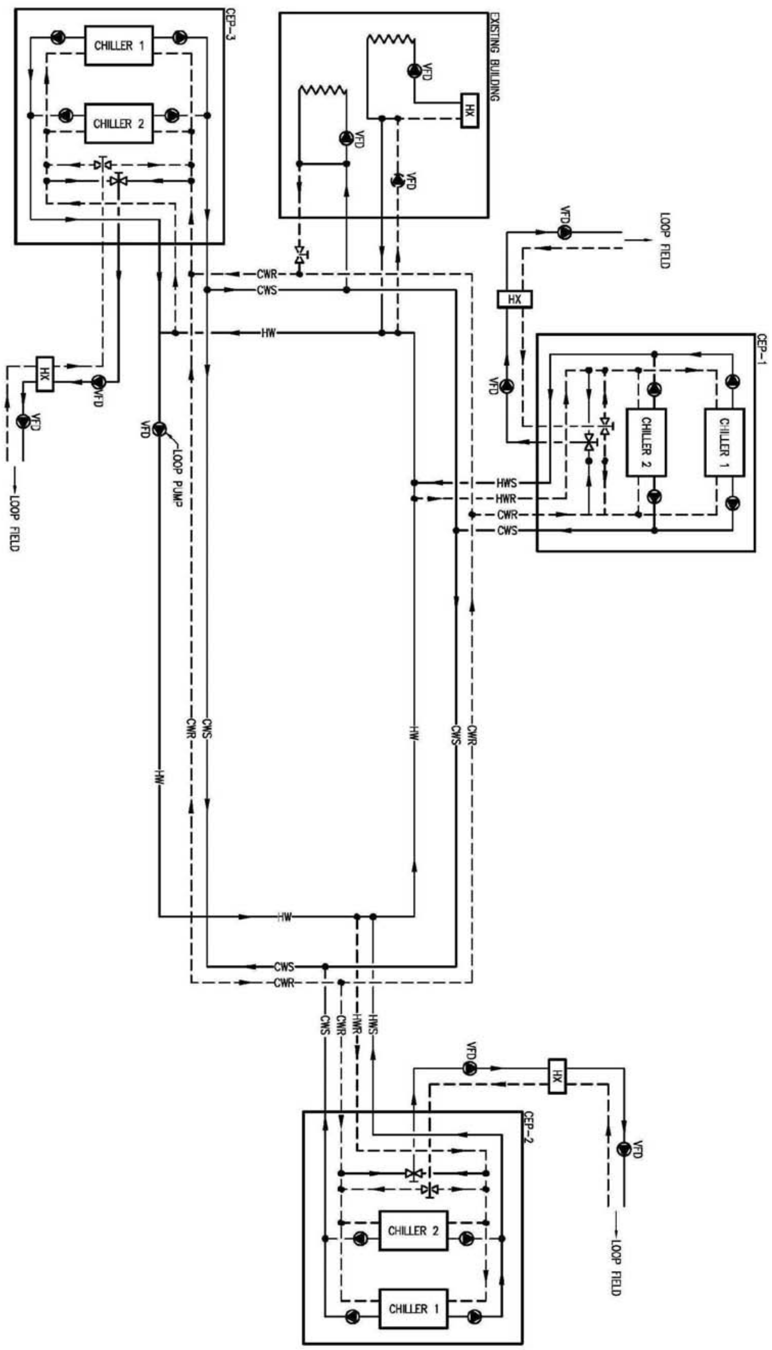
APPENDIX B: FLOW DIAGRAM



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APPENDIX C: BOREHOLE DESIGN REPORT

Ground Loop Design

Borehole Design Project Report - 1/14/2009

Project Name: Ball State
Designer Name: Jeff Urlaub
Date: 12/9/2008 **Project Start Date:** 12/9/2008
Client Name: Ball State
Address Line 1:
Address Line 2:
City: **Phone:**
State: **Fax:**
Zip: **Email:**

Calculation Results

	COOLING	HEATING
Total Length (ft):	132224.6	145224.0
Borehole Number:	375	375
Borehole Length (ft):	352.6	387.3
Ground Temperature Change (°F):	+1.2	+1.1
Unit Inlet (°F):	85.0	45.0
Unit Outlet (°F):	95.2	38.3
Total Unit Capacity (kBtu/Hr):	11119.7	12692.9
Peak Load (kBtu/Hr):	8418.7	12692.9
Peak Demand (kW):	674.3	617.7
Heat Pump EER/COP:	12.5	3.6
System EER/COP:	12.5	6.0
System Flow Rate (gpm):	2104.7	3173.2

Input Parameters

Fluid		Soil	
Flow Rate:	3.0 gpm/ton	Ground Temperature:	56.0 °F
Fluid:	100% Water	Thermal Conductivity:	1.68 Btu/(h*ft*°F)
Specific Heat (Cp):	1.00 Btu/(°F*lbm)	Thermal Diffusivity:	1.12 ft^2/day
Density (rho):	62.4 lb/ft^3		

Piping

Pipe Type:	1 in. (25 mm)
Flow Type:	Turbulent - SDR11
Pipe Resistance:	0.071 h*ft*°F/Btu
U-Tube Configuration:	Double
Radial Pipe Placement:	Along Outer Wall
Borehole Diameter:	6.00 in
Grout Thermal Conductivity:	0.84 Btu/(h*ft*°F)
Borehole Thermal Resistance:	0.156 h*ft*°F/Btu

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APPENDIX C: BOREHOLE DESIGN REPORT (cont.)

Input Parameters (Cont.)

Pattern		Modeling Time Period	
Vertical Grid Arrangement:	25 x 15		
Borehole Number:	375	Prediction Time:	10.0 years
Borehole Separation:	15.0 ft	Long Term Soil Temperatures:	
Boreholes per Parallel Circuit:	1	*Cooling:*	57.2 °F
Fixed Length Mode	Off	*Heating:*	57.1 °F
Grid File	None		
File:			

Heat Pumps			Optional Boiler/Cooling Tower		
Manufacturer:	Florida Heat Pump			Tower	Boiler
Series:	WP Series (Water to Water)		Load Balance	0 %	41 %
Design Heat Pump Inlet Load Temperatures:			Capacity (kBtu/Hr)	0.0	5204.1
	Cooling (WB)	*Heating (DB)*	Cooling Tower Flow Rate (gpm):	0.0	
Water to Air:	67 °F	70 °F	Cooling Range (°F):	10.6	
Water to Water:	55 °F	100 °F	Annual Operating Hours (hr/yr):	0	

Extra kW		Loads File
Pump Power:	0.0 kW	*09-01-09 Rev Ball State.zon*
Cooling Tower Pump:	0.0 kW	
Cooling Tower Fan:	0.0 kW	
Additional Power:	0.0 kW	

Loads

Design Day Loads

Time of Day	*Heat Gains (kBtu/Hr)*	*Heat Losses (kBtu/Hr)*
8 a.m. - Noon	5120.3	12692.9
Noon - 4 p.m.	6689.2	11806.2
4 p.m. - 8 p.m.	8418.7	10541.6
8 p.m. - 8 a.m.	6689.2	11806.2

Annual Eqivalent Full-Load Hours

COOLING 1500 *HEATING* 2762

Days Occupied per Week: 5.0

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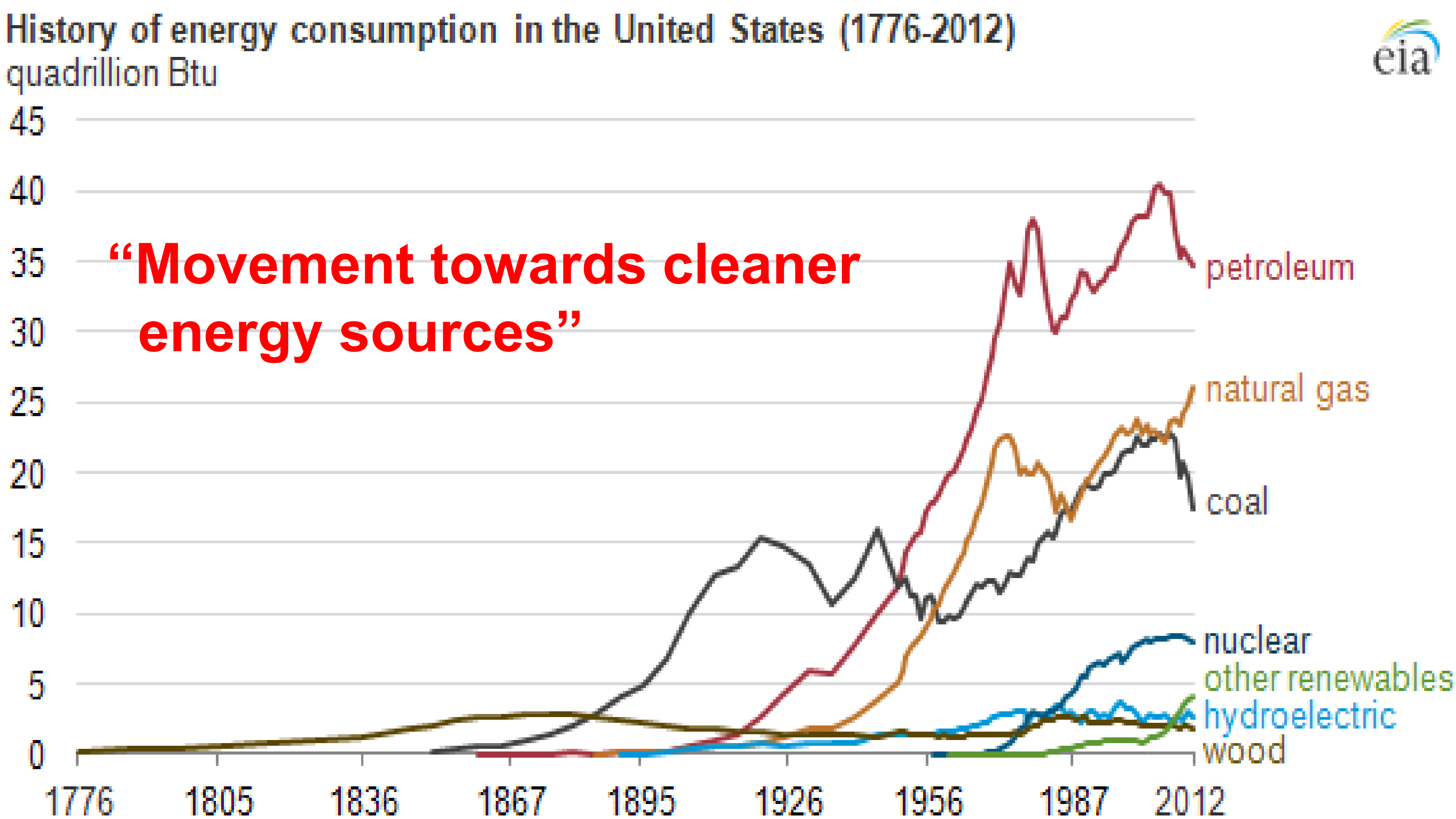
Appendix 15: Typical Sustainable and Geothermal Presentation for advancing Student Knowledge

Ball State University

"Sustainability and Ground Source Heat Pump Geothermal Conversion"

Residential Property Management
September 16, 2016
jlowe@BSU.edu
765.285.2805

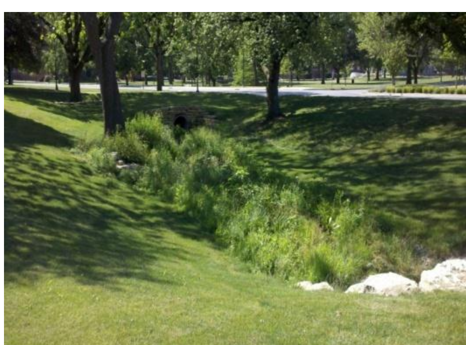
History of Energy Use



Ball State University Sustainability Initiatives

Landscaping/Storm Water Management

- Permeable concrete: Parking Lots
- Forestation: 8,000 trees
- Sediment basins: Ponds
- Green roof: Heat Reduction/Water Runoff
- Street sweeping: 700,000 pounds per Year
- Vortex/Storm Structures: Oil/Sediment Capture
- Vegetated Creek Banks: Erosion Control



Ball State University
Sustainability Initiatives

Transportation

- Hybrid electric vehicles
- Flex-fuel vehicles E85
- Shuttle bus operation
- B20 biodiesel fuel
- Pedestrian friendly campus
- Bike parking stalls
- Encourage use of webinars and conference calls
- Electric vehicle plug in stations

Ball State University Sustainability Initiatives

Demand side reduction

-T-8, T-5 and LEDS
-Natural Lighting
-Motion detectors/Occupancy sensors
-Heat recovery Units
-High efficient motors
-Direct digital controls
-Variable speed drives
-CO2 monitors for outside air intake
-Valence Units (convective heating/cooling)

Ball State University Sustainability Initiatives

Building Construction:

Leadership in Energy and Environmental Design (USGBC LEED) *

Silver certified: David Letterman, Park ,DeHority Hall, Jo Ann Gora Student Wellness, Thomas J. Kinghorn Hall

Gold certified: DESN, Studebaker East, Johnson A

* A metric to measure sustainability in design and construction

Steam and Chilled Water Plant Operations

Steam Plant:

4 Coal Fired Boilers

3 Natural Gas Fired Boilers

320,000 Lbs/Hr nameplate

240,000 Lbs/Hr current

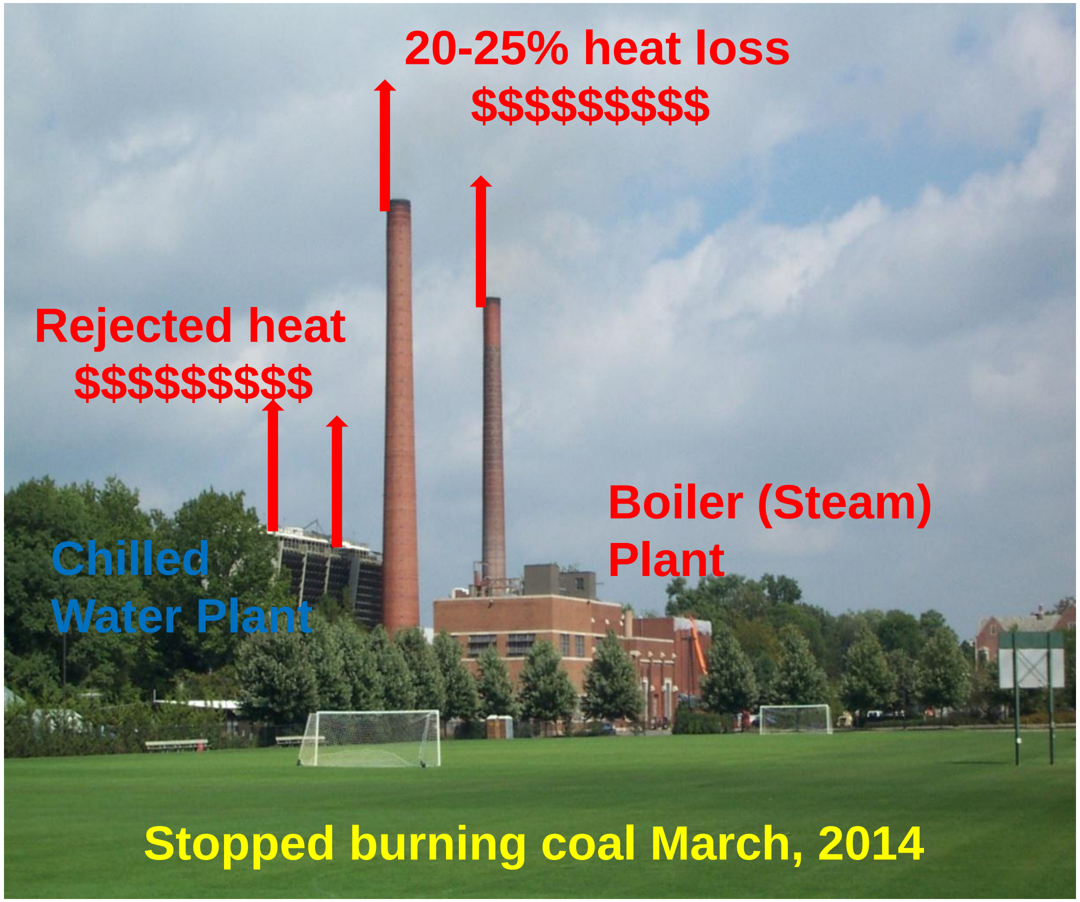
700,000,000 Lbs/Year

Chilled Water Plant:

5 Electrical Centrifugal Chillers

9,300 ton capacity

25,000,000 Ton Hours/Year



Pollutants/Waste Produced from Burning 36,000 tons of Coal

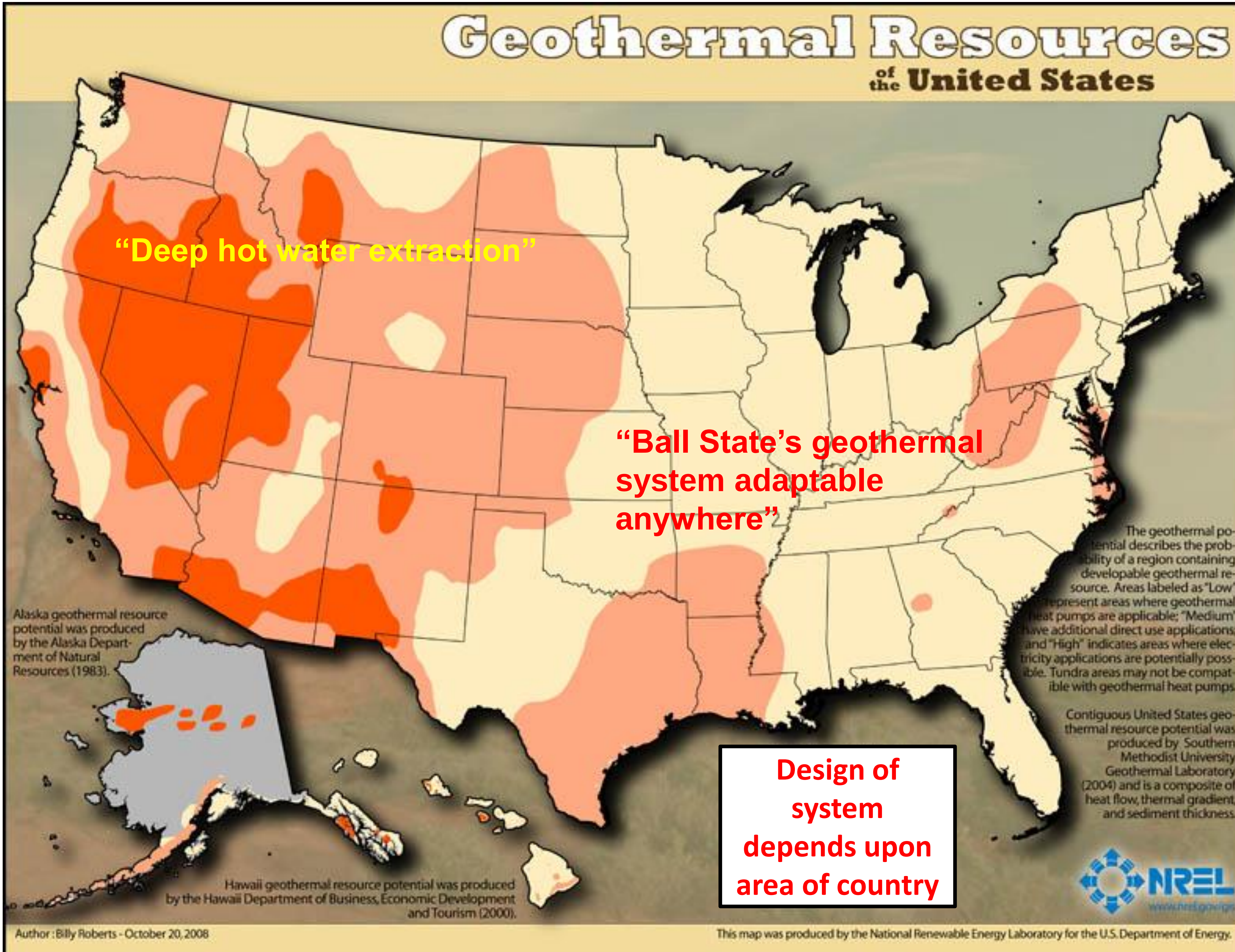
- Carbon Dioxide 85,000 tons (Global Warming)
- Sulfur Dioxide 1,400 tons (Acid Rain)
- Nitrogen Oxide 240 tons (Smog)
- Particulate Matter 200 tons (Breathing)
- Carbon Monoxide 80 tons (Headache)
- Multiple Hazardous Air Pollutants now regulated by EPA's Boiler MACT rules: Mercury
- 3,600 tons of coal ash

Alternatives evaluated

Fossil Fuel Boiler (CFB)	All Natural Gas Boiler	Ground Source Geothermal Heat Pump
High capital cost	Low capital cost	Highest capital cost
No CO2 reduction	CO2 half that of coal	Campus CO2 reduced 50%
High maintenance costs	Low maintenance cost	Low maintenance cost
Emission control equipment	No emission control	No emission control
Alternative fuel capable	High fuel costs	Electric power dependent

Note: BSU needed to make changes due to:

- **age/condition of equipment**
- **EPA regulations**
- **growth in campus**
- **reduction in equipment capacity**


Geothermal Resources
of the United States
“Deep hot water extraction”
“Ball State’s geothermal system adaptable anywhere”
Design of system depends upon area of country
Alaska geothermal resource potential was produced by the Alaska Department of Natural Resources (1983).
Hawaii geothermal resource potential was produced by the Hawaii Department of Business, Economic Development and Tourism (2000).
The geothermal potential describes the probability of a region containing developable geothermal resource. Areas labeled as “Low” represent areas where geothermal heat pumps are applicable; “Medium” have additional direct use applications; and “High” indicates areas where electricity applications are potentially possible. Tundra areas may not be compatible with geothermal heat pumps.
Contiguous United States geothermal resource potential was produced by Southern Methodist University Geothermal Laboratory (2004) and is a composite of heat flow, thermal gradient, and sediment thickness.
NREL
www.nrel.gov/gis
Author: Billy Roberts - October 20, 2008
This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

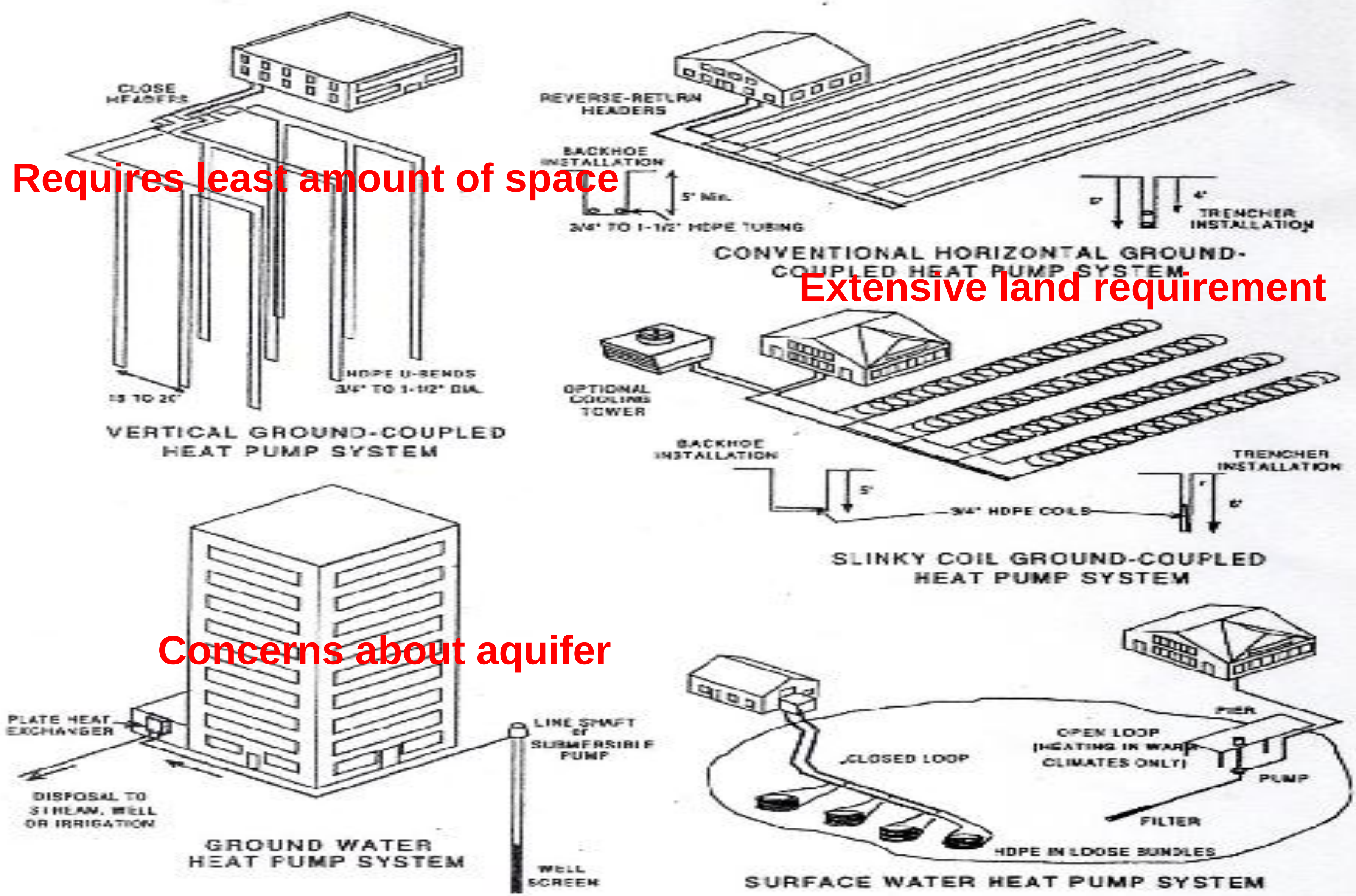
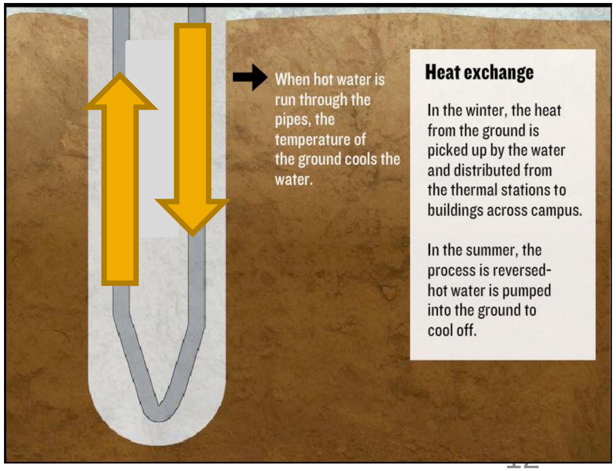


Figure 1.1 Ground-source (or geothermal) heat pump types.

Laws of Thermodynamics
"Engineers Holy Grail"

Zeroth law: **"Thermal equilibrium"**
if two thermodynamic systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.
First law: **"Conservation of energy"**
energy can neither be created nor destroyed. It can only change forms.
Second law: "Energy flows from higher to lower temperature objects"
heat can spontaneously flow from a higher temperature region to a lower temperature region, but not the other way
Third law: **"Minimum Kinetic Energy"**
As temperature approaches absolute zero, the molecula kinetic energy of a system approaches a minimum,
0 degrees K, -273.15 degree C or -459.67 degree F.



Law of Thermodynamics

- energy (heat) moves from a ***warmer*** area to the ***cooler*** area
- *Summer:* water entering the loop field is "*warmer*" than the ground--- heat moves from ***(warm) water*** to the ***(cool) ground***
- *Winter:* water entering the loop field is "*cooler*" than the ground---heat moves from ***(warm) ground*** and to the ***(cool) water***

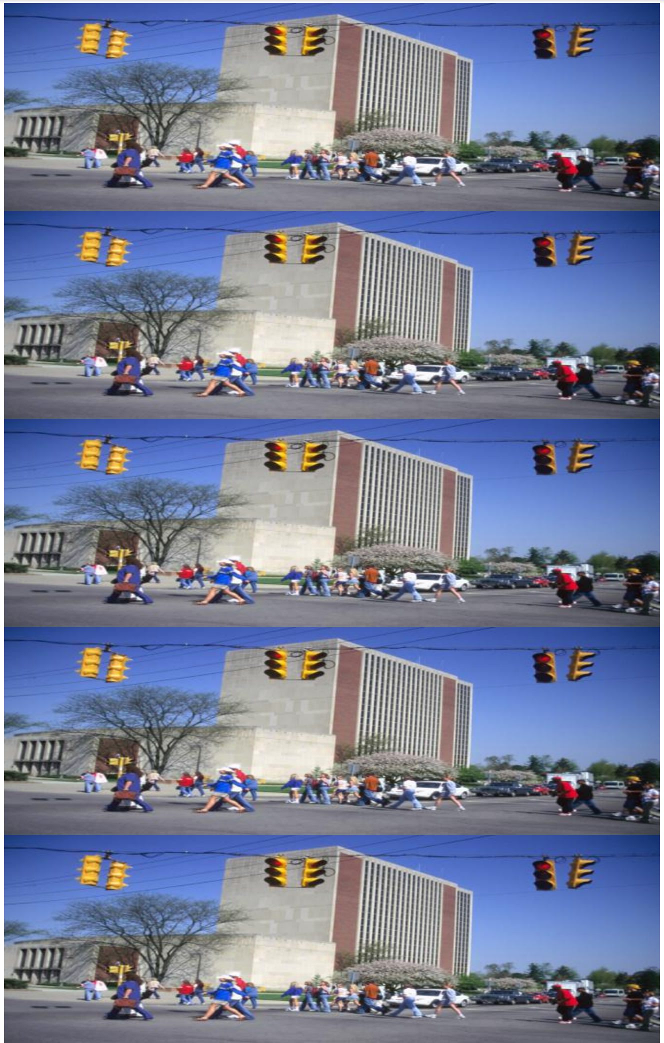
Borehole Construction

Drilling 400/500 Feet	Installing the Pipe
	

One borehole per day per rig

South Borehole Site

Borehole Depth
5 times taller than Teachers College



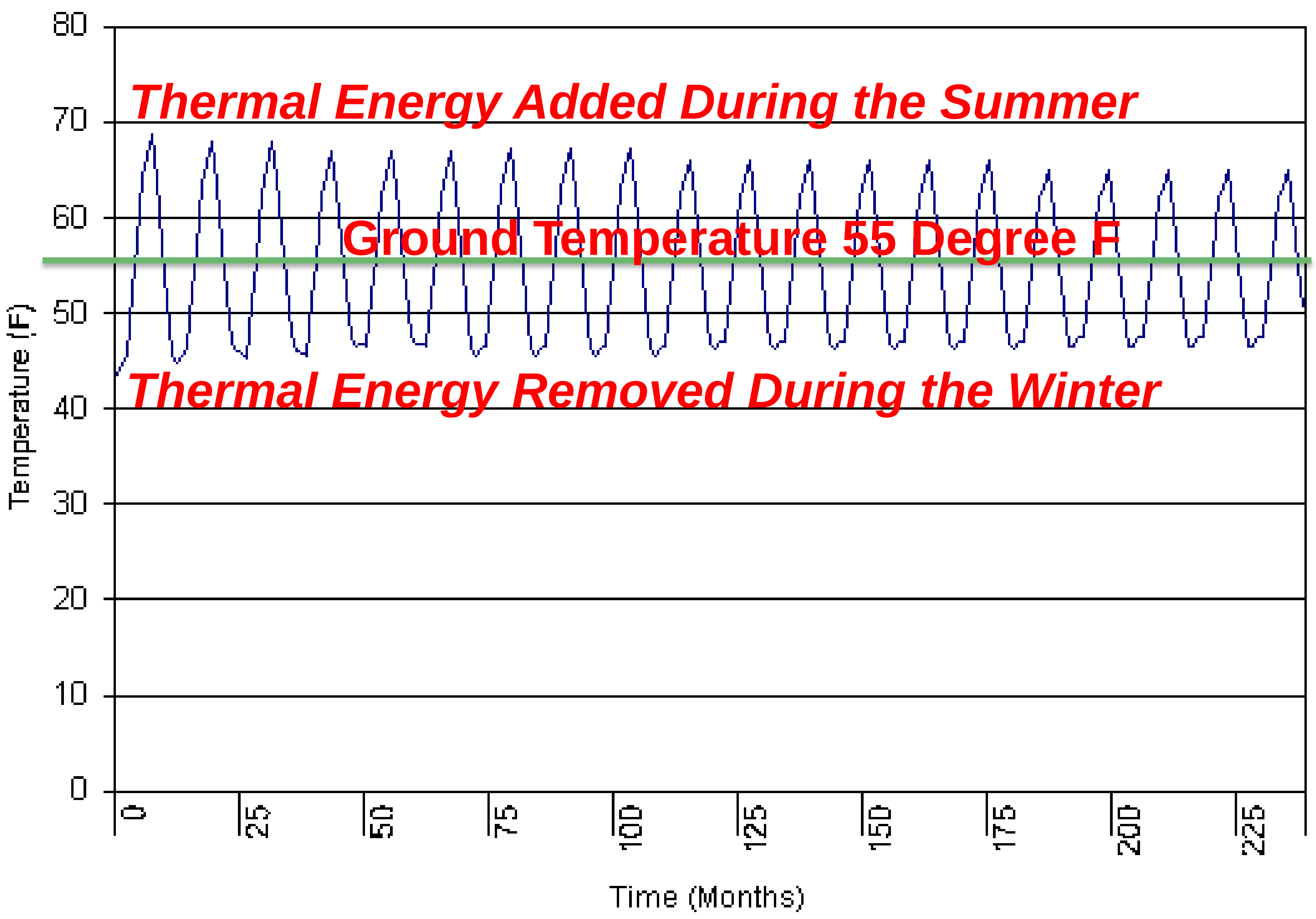
Borehole Design

- 15 feet apart
- 225 SF per borehole
- 400/500 feet deep
- Double and Single Loop
- 1-1/4 inch diameter pipe
- High Density Polyethylene

3,600 boreholes

(1,000 miles of pipe)

Ground Temperature Model

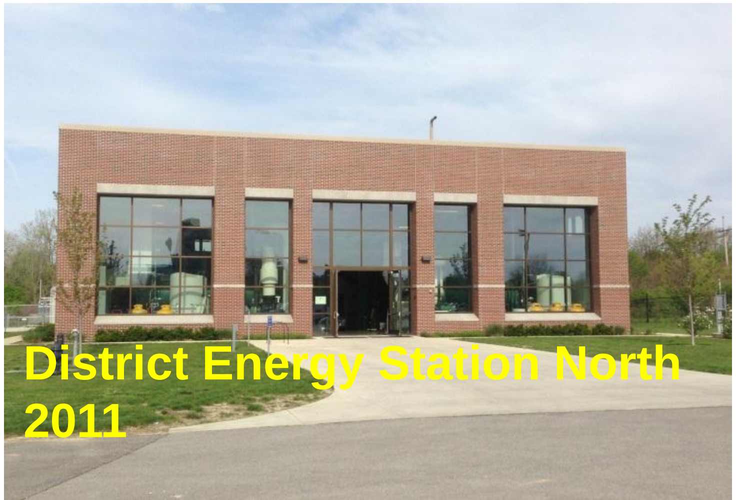


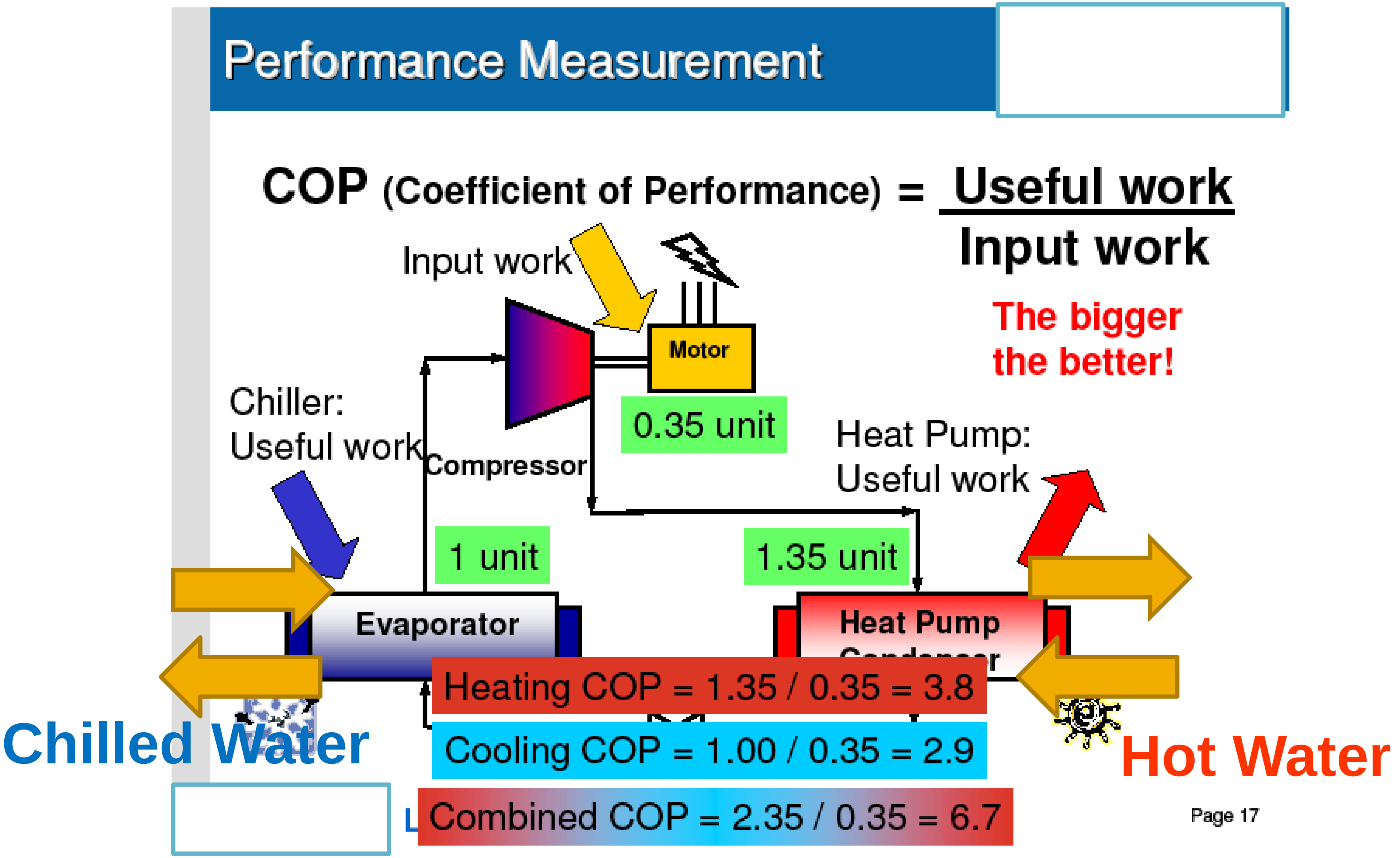
District Energy Station North

<u>(4) Heat Pump Chillers:</u>
R134A Refrigerant

Heating:
150 F Hot Water
38,000,000 BTU/Hour

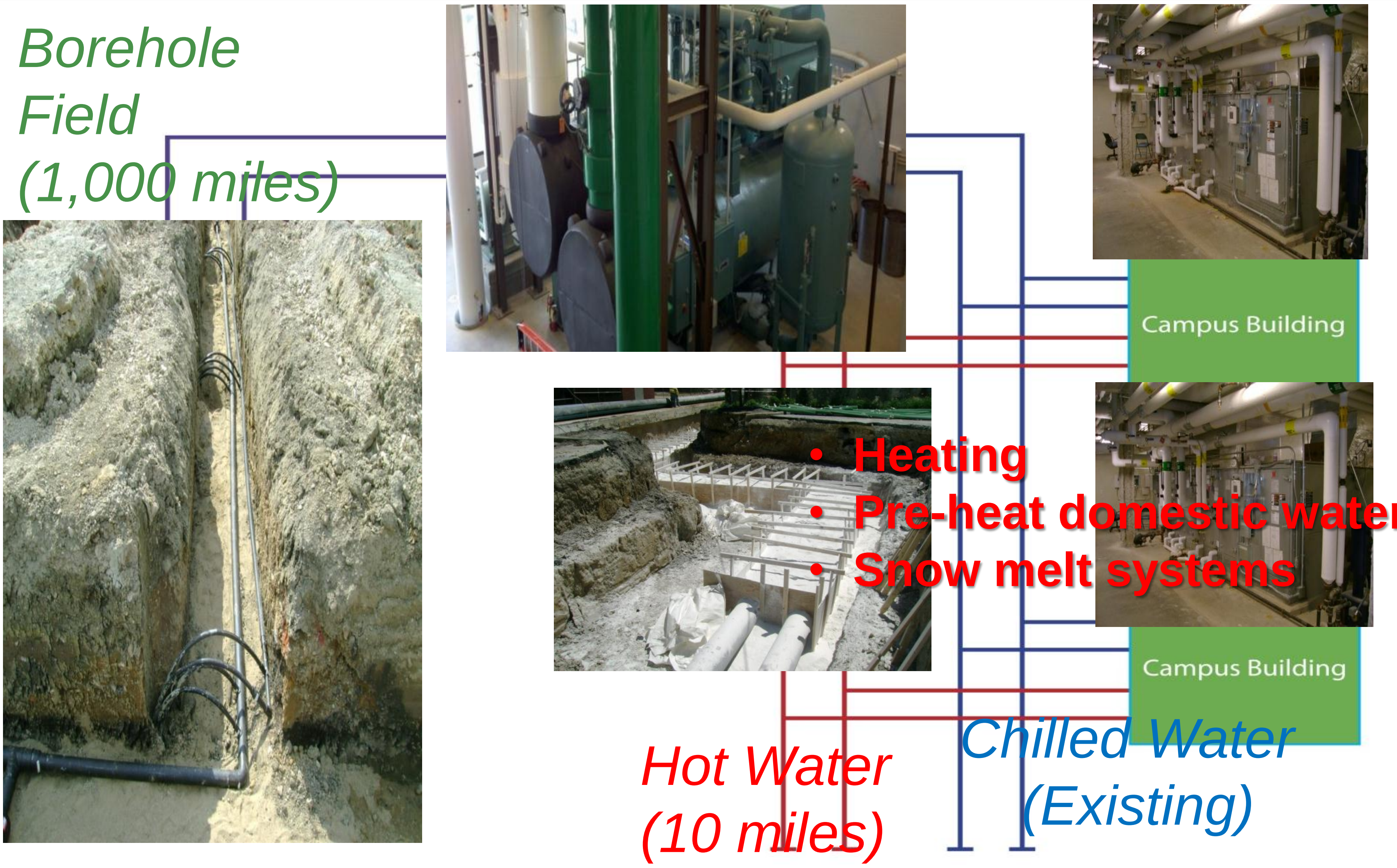
Cooling:
42 F Chilled Water
2,500 tons




Performance Measurement
COP (Coefficient of Performance) = Useful work / Input work
Input work
Motor
0.35 unit
Chiller:
Useful work
Compressor
Heat Pump:
Useful work
The bigger the better!
1 unit
1.35 unit
Evaporator
Heat Pump
Heating COP = 1.35 / 0.35 = 3.8
Cooling COP = 1.00 / 0.35 = 2.9
Combined COP = 2.35 / 0.35 = 6.7
Chilled Water
Hot Water
Page 17

Ball State's

Ground Source Heat Pump Geothermal System



District Energy Station South

Geothermal Conversion Costs
($ Millions)

• Boreholes	$27
• Distribution Pipe	$18
• Building HVAC Modifications	$8
• District Energy Buildings	$18.4
• Heat Pump Chillers	$7.5
• High Voltage Improvements	$4
Total Construction Cost	$82.9*

* US Department of Energy $5

* State of Indiana $77.9

Ball State's Geothermal System Benefits

Reduction in Emissions

• Carbon Dioxide	75,000 tons
• Sulfur Dioxide	1,400 tons
• Nitrogen Oxide	240 tons
• Particulate Matter	200 tons
• Carbon Monoxide	80 tons
• Coal ash	3,600 tons

Other Benefits

BTUs per year reduction:	500,000,000,000
BTUs/SF/Year reduction:	175,000 to 105,000 *(FY 15/16: 109,088)*
Water reduction:	45,000,000 gallons
Dollars Saved:	$2,200,000

Ball State University's Geothermal Project Visits and Inquiries

Colleges & Universities

- Dartmouth College
- Stanford University
- University of Notre Dame
- Ohio State University
- University of Iowa
- Northern Kentucky University
- Colorado College
- Slippery Rock University
- Hampton University
- Pratt Institute
- Oakland University
- Purdue University
- Miami University, Ohio
- Cornell University
- Toledo University
- Bowling Green State/Bowling Green
- Wright State/Dayton
- University of Michigan
- The Evergreen State College
- Northwestern University
- University of Illinois
- Ohio University
- Lake Land College
- Indiana University-Purdue University Indianapolis
- DePauw University
- University of Washington
- Montana State University-Bozeman
- Penn State University
- University of Kentucky
- Indiana State University
- Northampton Community College
- Colorado State University
- Berea College

Ball State University's Geothermal Project Visits and Inquiries

Other Organizations

- U.S. Department of Energy
- Indiana Department of Natural Resources
- Indiana Office of Energy Development
- Representatives of Isparta, Turkey
- National Wildlife Federation
- Union of Concerned Scientists
- Building Indiana Magazine
- WFYI Indiana Expeditions
- The Chronicle for Higher Education
- Delta Sky Magazine
- Second Nature
  (2010 Climate Leadership Award)
- Japan News Crew
- Geo Outlook Magazine
- Allison Transmission
- Waterwell Journal
- International District Energy Association
- Biz World
- The Christian Science Monitor
- National Public Radio
- Argonne National Laboratory
- National Ground Water Association
- Hoosier Environmental Council
  (2010 Technology Innovator
  of the Year Award)
- Waste Management
- General Service Administration
- Korea: Engineering Firm

Educational/Collaboration Opportunities

- Classroom: Natural Resources, Geology, Architecture, Construction Management
- Research: Geology Department
- Special Projects: Graduate Students
- Tours: Universities/k-12/Design Firms
- Conferences: **Geothermal Conference:**

  November 7, 2013

  April 10, 2014

  April 8, 2015

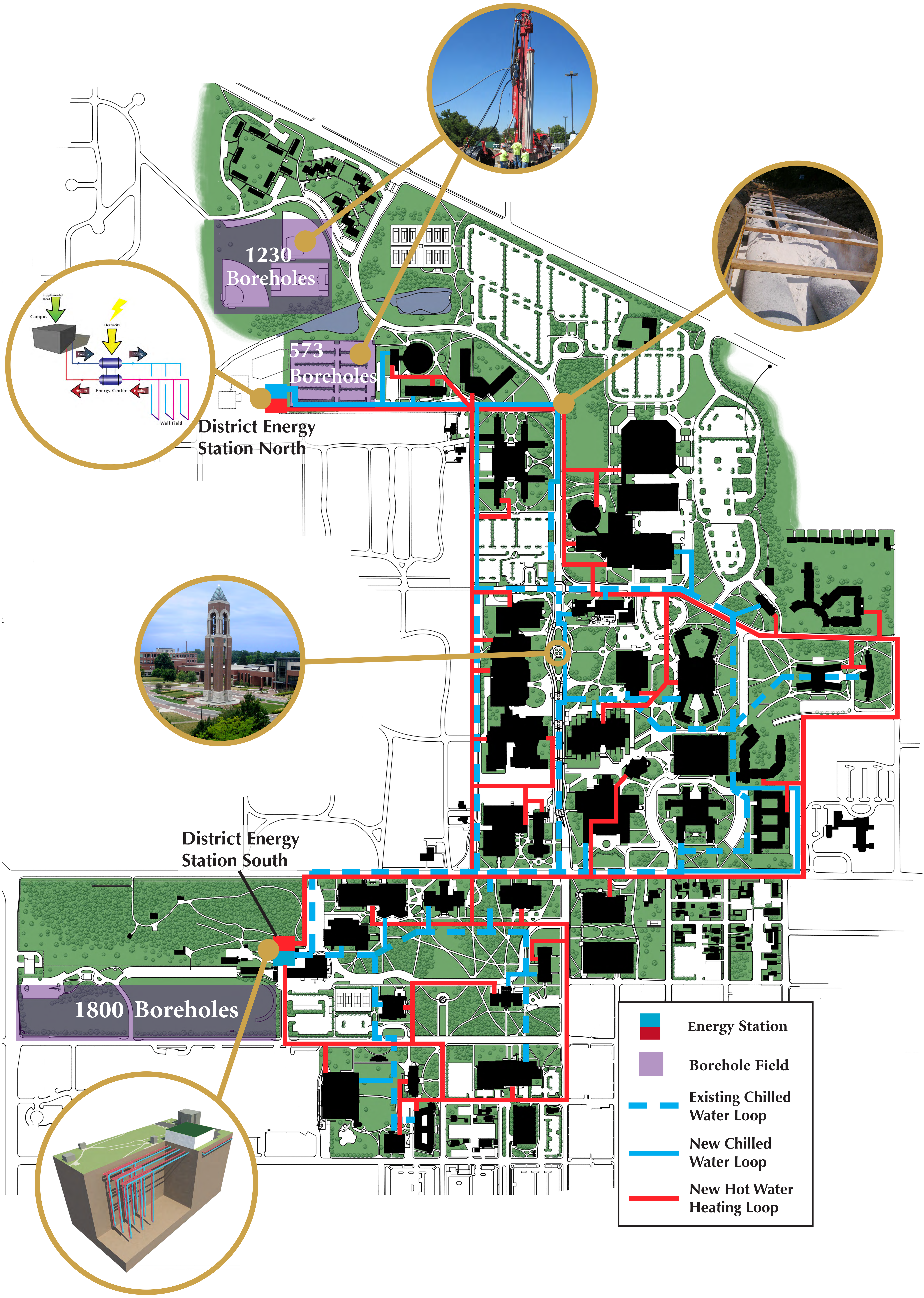
  NACUBO July, 2016

  www.bsu.edu

WWW.BSU.EDU/WEB/NEWS/GEOTHERMALVIDEO/

"Created by University Communications"

Appendix 16: Geothermal Campus Map


1230 Boreholes
573 Boreholes
District Energy Station North
District Energy Station South
1800 Boreholes
Energy Station
Borehole Field
Existing Chilled Water Loop
New Chilled Water Loop
New Hot Water Heating Loop

Appendix 17: DOE "Statement of Project Objectives (SOPO)"

STATEMENT OF PROJECT OBJECTIVES

Ball State University (BSU)

Recovery Act: Ball State University Geothermal Heat Pump District Heating and Cooling System (Phase I)

A. OVERVIEW

The Ball State University Geothermal Heat Pump (GHP) conversion program has many attributes that meet the specific goals of the American Reinvestment and Recovery Act. BSU determined that it needed to replace four aging (average 60 years old) stoker boilers with a GHP based district system.

The work performed under this Grant, and the balance of Phase I funded with other University funds will result in cutting BSU coal consumption by about 50% and will cut each of the following air pollutants by about 50%: (1) 85,000 tons of CO_2; (2) 240 tons of nitrogen oxide; (3)200 tons of particulate matter; (4) 80 tons of carbon monoxide; and (5) 1,400 tons of sulfur dioxide.

The University has engaged engineering/design firms to design the system. In the previously submitted Application, BSU provided specific design, efficiency, and cost information based on the entire project (Phase I and Phase II). However, the scope of this project (a portion of Phase I) is to complete only the components (two heat pump chillers, building connections, data collection, engineering and design fees) identified in the task descriptions below. Phase I will permit BSU to realize a net operating savings in excess of $1 million/year (we will buy 18,000 fewer tons of coal [$1.5 million savings] but will purchase approximately 12 MKwH of additional electricity at a cost of $500,000).

This project includes many innovative features. There is no other 10,000 ton heat pump chiller system associated with closed loop borehole fields in the country. The heat pump chillers of the size needed have only become commercially available in recent years. For the first time, this project will provide the data to demonstrate to the owners of district systems, that GHP in combination with vertical boreholes can provide efficient and dependable heating and cooling. It will also demonstrate to the water well drilling community how to expand business models and to effectively price and market services to potential geothermal system owners.

Phase I will develop a wealth of data for the National Geothermal Data System. It will be the only large scale district project to generate the data necessary to convince owners of large systems to consider GHP. BSU path-breaking work on this project will convince owners that they can replicate the huge operating savings through the transfer of what has been learned.

BSU will collect vital information for future owners by metering the following:
(1) Temperature of all fluids at each building interface.
(2) Volume of hot and chilled water required by each building on a 24/7 basis.
(3) HVAC electrical use at the energy station and each building.
(4) Volume of hot and chilled water produced at the energy station.
(5) Volume of water circulated through the borehole field.
(6) Entry and exit temperature of water circulated through borehole field.
(7) BTU energy information.
(8) Ground temperatures at several locations to a depth of 400 feet in and around borehole field.

Once Phase I is complete, with part of the funding provided under this grant, BSU will be able to provide precise "before and after" comparisons of the huge co-efficient of performance (COP) increase and overall energy savings associated with the conversion of the campus to GHP. All of this data will help potential owners understand how to estimate costs savings. It will also help reduce the "first costs" associated with GHP by developing a guide to best practices for large installations.

B. BACKGROUND

BSU has been in the planning stages of replacing its four coal fired stoker boilers (installed 1941, 1941, 1955 and 1958) since 2004. A formal independent analysis (Fosdick & Hilmer, 2001) concluded that the University should replace the stokers because they had outlived their rated lifetimes by many years and because the stokers would soon require additional pollution control devices. To proceed, BSU received bonding authority in 2005 from the Indiana General Assembly to replace the old equipment with the industry standard at that time. That technology included a coal fired circulating fluidized bed (CFB) boiler that offered the advantage of high efficiency and reduction of emissions. BSU ultimately obtained a sole source bid of $44 million for the CFB and a total project price of $63 million.

Not satisfied with the first option, BSU began to consider alternatives that would incorporate new geothermal heat pump technology. The University connected with scientists and engineers from the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory, and they were given contacts for some of the top geothermal experts in this country. Ultimately, BSU engaged the services of two of those experts.

The report issued in December 2008 by Oak Ridge entitled "Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers" (Oak Ridge, 2008) provided critical assistance to BSU in evaluating the relevance and applicability of such systems. Evaluation of this DOE supported report helped BSU decide to pursue a geothermal-based district energy system. The study evaluated the current market and addressed barriers to the application for geothermal technology on a large scale. While there are nearly 65,000 district heated buildings across the country (per statistics from DOE's Energy Information Administration in 2003), BSU will create the largest district system in the nation that is heated and cooled by closed loop ground source geothermal.

C. PROJECT OBJECTIVES

BSU's ultimate objective is the **creation of a District Energy System using geothermal-based heat pump chillers** to heat and cool 47 major campus buildings. Phase I will accomplish about 50% of the overall goal. This project will specifically purchase and install several of the components required to complete Phase I. The current system utilizes four stoker coal boilers and three natural gas boilers to produce steam to heat the 5.5 million square feet of space. A separate central chiller system, comprised of five electric centrifugal chillers, cools these buildings. This ambitious yet viable proposed initiative replaces the antiquated system with two district energy stations that contain high capacity heat pump chillers and use geothermal boreholes as heat sinks (summer) or heat sources (winter).

Dramatic energy efficiency improvement is another major objective of the project. The current stoker system has a Co-efficient of Performance (COP) of .62. The current electric chiller system has a COP of 5.02. The weighted average of the combined systems is a 1.04 COP. With the geothermal based installation, the combined COP will be 7.77 (calculations provided in PMP). The designed **647% improvement** is truly exceptional.

A final objective for the project is **immediate deployment and jobs creation**.

Ground was broken on May 9, 2009. Based upon the importance the ARRA places on 'shovel ready' projects, the University has pushed designers to complete the design for one segment of the project (the

North borehole field) and has awarded bids to put Americans to work immediately. Thus, site preparation began July 6, 2009. Although an estimated total of 2,300 jobs are set to be created through the completion of Phase I and Phase II, the requested ARRA portion of the project will create an estimated 278 jobs.

D. PROJECT SCOPE

The total scope of this project fits directly into the DOE's Geothermal Technologies Program for Ground Source Heat Pumps. It will impact the entire 660-acre BSU campus and will become the largest district ground water heating and cooling system in America. This will eliminate 85,000 tons of CO_2 and other pollutants each year after all four stoker boilers are decommissioned. The **campus will cease purchasing coal entirely** (average= 36,000 tons per year with the present system).

Only a portion of Phase I of the total project scope presented above will be funded through this DOE grant. Those portions that make up this project are discussed in the task descriptions below.

E. TASKS TO BE PERFORMED

Phase I:

Task 1: Purchase Equipment for North and South District Energy Stations:
BSU will purchase four, 2500 ton heat pump chillers for installation in the North and South District Energy Stations.

Task 2: Building Conversions:
The connections within 16 to 20 major buildings on the North side of campus will be installed, and the conversion of the mechanical systems in those buildings to utilize the hot and chilled water produced by the GHPs will be completed. This task includes the interior retrofit of building systems, but not exterior installation of piping between buildings, or the district energy station.

Task 3: Data Collection:
Meters, instruments, and software associated with the collection of data to be submitted to the National Geothermal Data System will be purchased and installed. Specific data points are described below:

Operational Data Collection:
BSU will collect and transmit to the National Geothermal Data System following:
(1) Temperature of all fluids at each building interface.
(2) Volume of hot and chilled water required by each building on a 24/7 basis.
(3) HVAC electrical use at the energy station and each building.
(4) Volume of hot and chilled water produced at the energy station.
(5) Volume of water circulated through the borehole field.
(6) Entry and exit temperature of water circulated through borehole field.
(7) BTU energy information.
(8) Ground temperatures at several locations to a depth of 400 feet in and around borehole field.

Task 4: Project Management and Reporting:
Reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein.