Final Scientific Report

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4 Executive Summary:

The Denver Museum of Nature & Science (DMNS) designed and implemented an innovative ground source heat pump (GSHP) system for heating and cooling its new Education and Collection Facility (ECF) building addition. The project goal was to successfully design and install an open-loop GSHP system that utilized water circulating within an underground municipal recycled (non-potable) water system as the heat sink/source as a demonstration project. The expected results were to significantly reduce traditional GSHP installation costs while increasing system efficiency, reduce building energy consumption, require significantly less area and capital to install, and be economically implemented wherever access to a recycled water system is available.

The project added to the understanding of GSHP technology by implementing the first GSHP system in the United States utilizing a municipal recycled water system as a heat sink/source. The use of this fluid through a GSHP system has not been previously documented. This use application presents a new opportunity for local municipalities to develop and expand the use of underground municipal recycled (non-potable) water systems. The installation costs for this type of technology in the building structure would be a cost savings over traditional GSHP costs, provided the local municipal infrastructure was developed. Additionally, the GSHP system functions as a viable method of heat sink/source as the thermal characteristics of the fluid are generally consistent throughout the year and are efficiently exchanged through the GSHP system and its components. The use of the recycled water system reduces the area required for bore or loop fields; therefore, presenting an application for building structures that have little to no available land use or access.

At 126,000 ft^2, the ECF building has a diverse floorplan use with various critical climate requirements that are accommodated through the GSHP system. Diverse building environments are achievable through the use of GSHP systems that can simultaneously produce heating and cooling and are supported with diversified air handling units.

This GSHP application demonstrates the viability of underground municipal recycled (non-potable) water systems as technically achievable, environmentally supportive, and an efficient system.

5 Comparison of Project Goals and Actual Accomplishments:

The goal of the project was to design and install an innovative open-loop GSHP system as a demonstration project that would utilize water from a local municipal recycled water system owned and operated by Denver Water as the source of thermal cooling/heat to the heat pumps for a 126,000 ft^2 Education and Collection Facility (ECF). The proposed system advantages include reducing the traditional ground-loop GSHP system capital installation costs by at least 50%, eliminating the large footprint typically required for a borehole field, minimizing complex environmental and regulatory permitting required for traditional borehole or open-loop (pump and dump) systems, minimize energy consumed by traditional fluid circulation and improving relative efficiency of the system by minimizing the differential operating temperature range in the heat pumps.

The proposed innovative GSHP installation required assessing the technical and economic feasibility of this system. The system required the year-round supply of underground municipal recycled (non-potable) water systems that demonstrated the appropriate range of thermal properties and that were physically close to use. Use of the recycled water required the understanding and confidence of the water supply by both the municipality and the end user application. Depending on the style of use, the recycled water could potentially pass through various building system components. This situation required a firm operational understanding of the limits and use of the recycled water by the end user. Economic feasibility was analyzed to determine the viability of installation. Proximity, volume, and year-round availability of the recycled water were key components of the analysis and in this installation. Additionally, the lack of available land required for bore or loop fields made the recycled water more economically viable as a solution.

Detailed engineering understanding and design of the system was required for the implementation. Local municipality water use requirements were understood and in some cases, due to this unique application, were developed. The stringent requirement of separation of systems through the use of double walled flat plate heat exchangers was a key design development. With the heat exchanger application, thermal transfer between system loops was achievable. From the understanding of the recycled water use, the building heating, ventilation and air conditioning (HVAC) systems could be developed based on the end user requirements. For ECF, there were extensive requirements and systems implemented to support the end use design. The final energy modeling for the building estimated a savings of 62.2% of energy use and 50% energy cost over ASHRAE 90.1-2007.

Identification of the selected GSHP system was achieved based on the defined equipment requirements and their marketplace availability. The installation and integration of the equipment was completed during the construction of the ECF building. GSHP equipment was pre-ordered in the early stages of construction due to the limited installation window based on the building's structure and internal accessibility.

Commissioning of the GSHP system was completed with the overall building commissioning process at the end of the project. Due to the complex nature of the system and various loops, tuning and adjustments were required as systems became functional. The ECF building opened in February 2014 and was awarded LEED Platinum certification on June 30, 2014.

By early 2014, the ECF building was fully commissioned and operational. Data from the various building systems and electrical watt node meters installed in the building were captured by the building automation system. The U.S. Department of Energy retained CDH Energy and Oak Ridge National Laboratory to review and analyze the GSHP data for this project. In fall of 2014, daily data transfer to CDH Energy commenced

Through the extended measurement and verification (M&V) process for LEED, on-going analysis and reporting will occur through 2015 to document the energy savings and performance of the building systems. Outreach and educational programs were conducted in 2014 through DMNS Adult Programs offerings and through the design, development and installation of a visitor interactive feature at DMNS that guides the user through the heating and cooling process of system that they can experience first-hand.

National awareness for this recycled water application has been presented to various meetings and seminars including 2010 14th Annual Water Reuse and Desalination Research Conference, 2013 - various engineering chapters in the Denver area, 2014 WateReuse Workshop, Golden, CO, 2014 International WateReuse Association Meeting, Dallas, TX, and 2014 State of Colorado Recycled Water Managers (September).

6 Summary of Project Activities:

6.1 Funding Period:

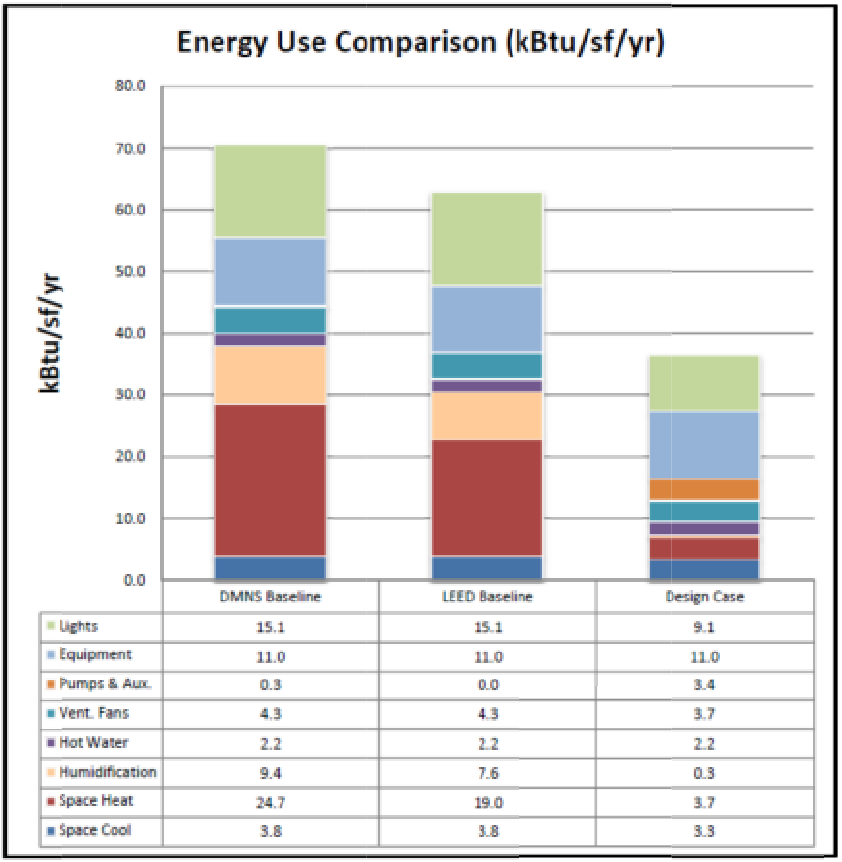
The GSHP funding period was originally December 29, 2009 through September 30, 2014. On July 29, 2014 (in Award Modification 0007), DOE approved a request to extend the funding period at no additional cost to December 28, 2014, due to schedule extensions required by building construction. The project cost was completed within the original grant budget.

6.2 Feasibility and Schematic Design (January 1, 2010 – February 28, 2011):

During feasibility for the new ECF building, one of the guiding requirements was to construct a building that was 50% more efficient than traditional buildings of its type according to ASHRAE 90.1-2007. In order to demonstrate that the performance of the design was in line with the energy and LEED goals for the project, two baseline models were completed:

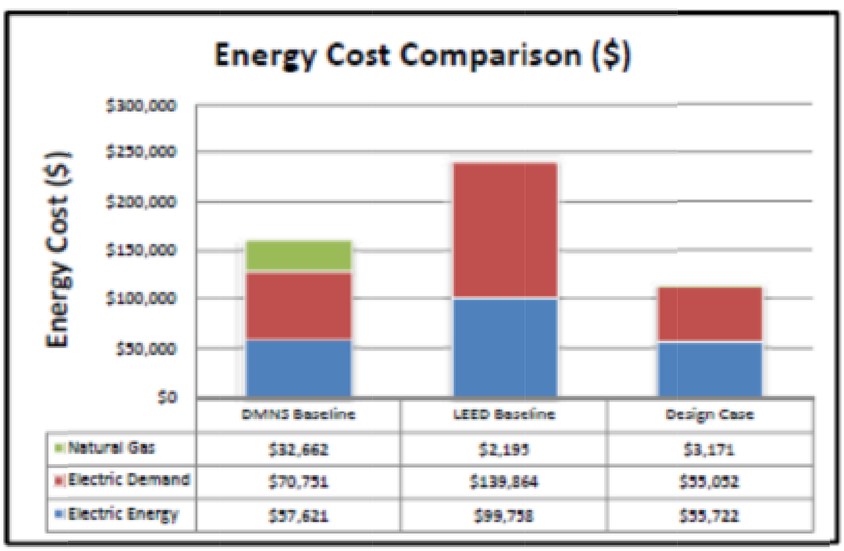
- **The DMNS Baseline** was a model minimally compliant with ASHRAE Standard 90.1-2007, but utilizing the Museum's existing gas-fired steam boilers as the source for heating and humidification. This baseline was used for demonstrating energy performance relative to the system the Museum would have chosen had they not gone with the water-to-water heat pumps and ultrasonic humidifiers.
- **The LEED Baseline** was a building minimally compliant with ASHRAE Standard 90.1-2007, and specifically following the modeling protocol referenced by LEED, which mandates that electric resistance heating and conventional electric humidification be used because of the principle sources of heating and humidification in the proposed design.

The Schematic Design energy results indicated that the project would save 48.3% energy use in comparison to the DMNS Baseline before accounting for the renewable energy measures in the design. Figures 1 and 2 show the Design Case performance compared to those of the DMNS and LEED Baselines. Figure 3 shows an energy use and energy cost breakdown by end-use for the Design Case.



	DMNS Baseline	LEED Baseline	Design Case
Lights	15.1	15.1	9.1
Equipment	11.0	11.0	11.0
Pumps & Aux.	0.3	0.0	3.4
Vent. Fans	4.3	4.3	3.7
Hot Water	2.2	2.2	2.2
Humidification	9.4	7.6	0.3
Space Heat	24.7	19.0	3.7
Space Cool	3.8	3.8	3.3

Figure 1: Annual energy use comparison (kBtu/sf/yr) for Design Case and Baseline Energy Models



	DMNS Baseline	LEED Baseline	Design Case
Natural Gas	$32,662	$2,195	$3,171
Electric Demand	$70,751	$139,864	$55,052
Electric Energy	$57,621	$99,758	$55,722

Figure 2: Annual energy cost comparison for Design Case and Two Baseline Energy Models

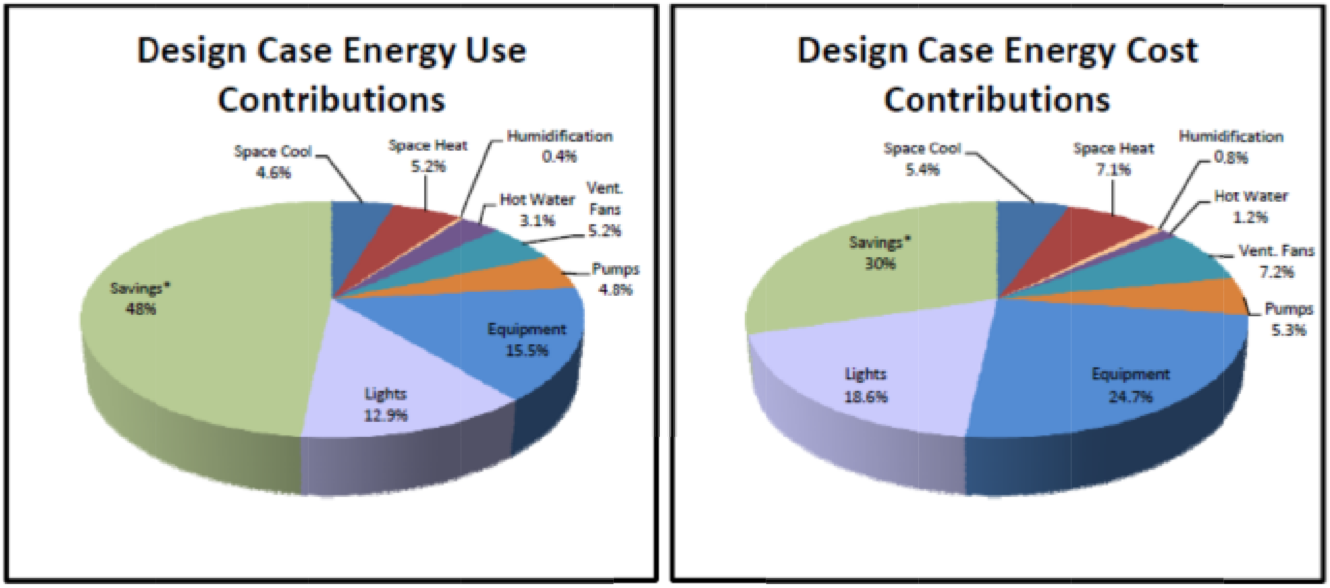


Figure 3: Design Case energy use and energy cost contributions from each end use

Modeling results showed that utilizing a ground-source heat pump system utilizing municipal recycled water would result in an energy cost savings of $47,088 per year compared to the DMNS Baseline. Additionally, simulated on-site energy consumption was reduced from 70.6 kBtu/ ft^2/yr to 35.9 kBtu/ ft^2/yr. Based on load modeling performed during schematic design, the preliminary building peak cooling load was predicted to be between 70 and 100 tons, and the preliminary building peak heating load was predicted to be between 780 and 1,140 MBH.

GSHP systems function through the simple principle of transferring heat from warmer sources to colder sources (Figure 4). Heat pump systems are located inside a building and connected to piping or tubing that is installed underground, below the frost line. As fluid flows through this piping system, it is able to extract heat from the ground and transfer it to the building through the use of the heat pump system in a heating season application. Similarly, during a cooling season application, heat is extracted from the building through the use of the heat pumps and is sunk back into the ground. The loops that are installed in the ground can be installed as closed loop or open loop applications. Closed loop applications are closed systems that have the same fluid circulating on a continual basis. Open loop applications are open systems that circulate fluid from a large water source.

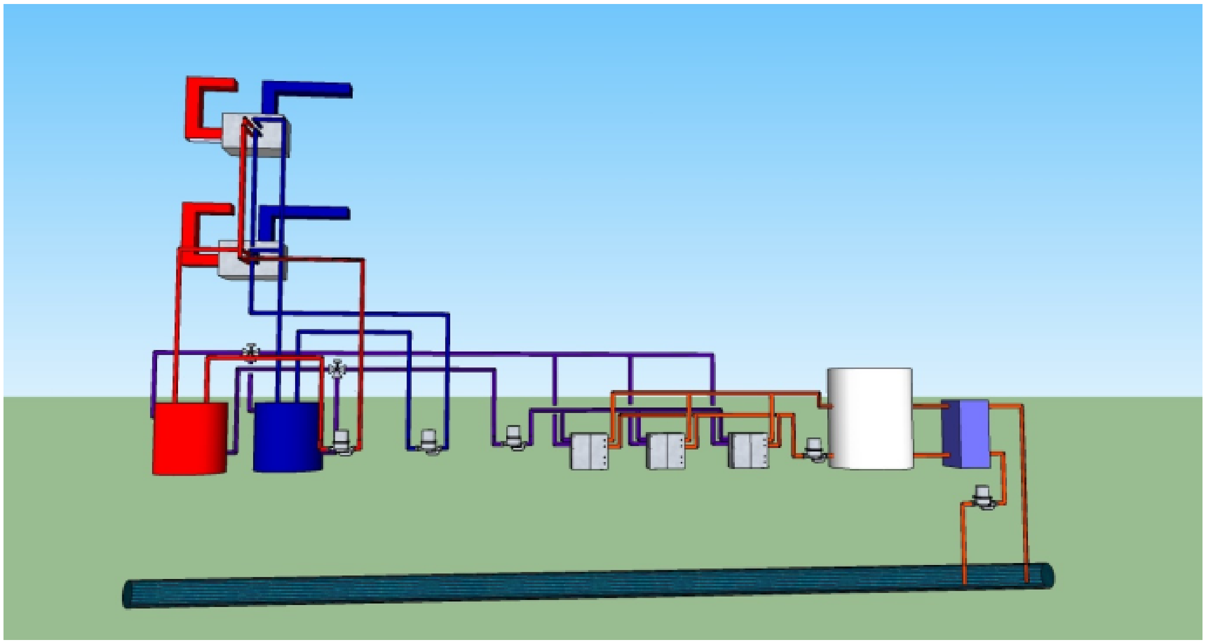


Figure 4: Typical Schematic GSHP Design

Located within the boundaries of City Park, the Denver Museum of Nature and Science could not install a typical closed system (Figure 5). This type of system would have required a large section of land to install bore wells or loop fields which was not available in the surrounding park environment. The open loop application was evaluated by utilizing the local municipal recycled water system owned and operated by Denver Water (DW) as the source of thermal cooling/heating to the heat pumps. Denver Water's current recycled water system is approximately 37 miles long, and provides non-potable water to parks, golf courses, and industrial and commercial operations in the City of Denver.

Figure 5: Aerial View of Denver Museum of Nature & Science (DMNS) within City Park, Denver, CO. (Google, 2014)

DW provides recycled water to the lake system on the south side of City Park for lake and irrigation uses. Additionally, a recycled water conduit is installed along the west side of City Park that continues along north of the Denver Zoo and bisects the City Park Golf Course. Prior to the ECF Project, recycled water from this conduit was utilized by City Park Golf Course and the Denver Zoo for support operations. During feasibility, there was an expressed interest by DW to expand recycled water operations through this conduit system such that a year-round supply with a minimal one-week annual outage was anticipated to be available. Evaluation of the recycled water system focused on four components:

1. Water characteristics including temperature, flow, volume, availability, and source location.
2. Ownership and maintenance rights needed to be established for the pipeline.
3. Water quality needed to be maintained through the entire process, per Colorado Regulation 84 for reclaimed water.
4. Financial modeling needed to be developed to support this type of water use.

Water Characteristics:

Historical recycle water temperatures indicated that while seasonal variation did occur, there was enough system stability to provide a consistent heat sink/source (Figure 6). The operational temperature ranges for the system were identified between 45-75°F.

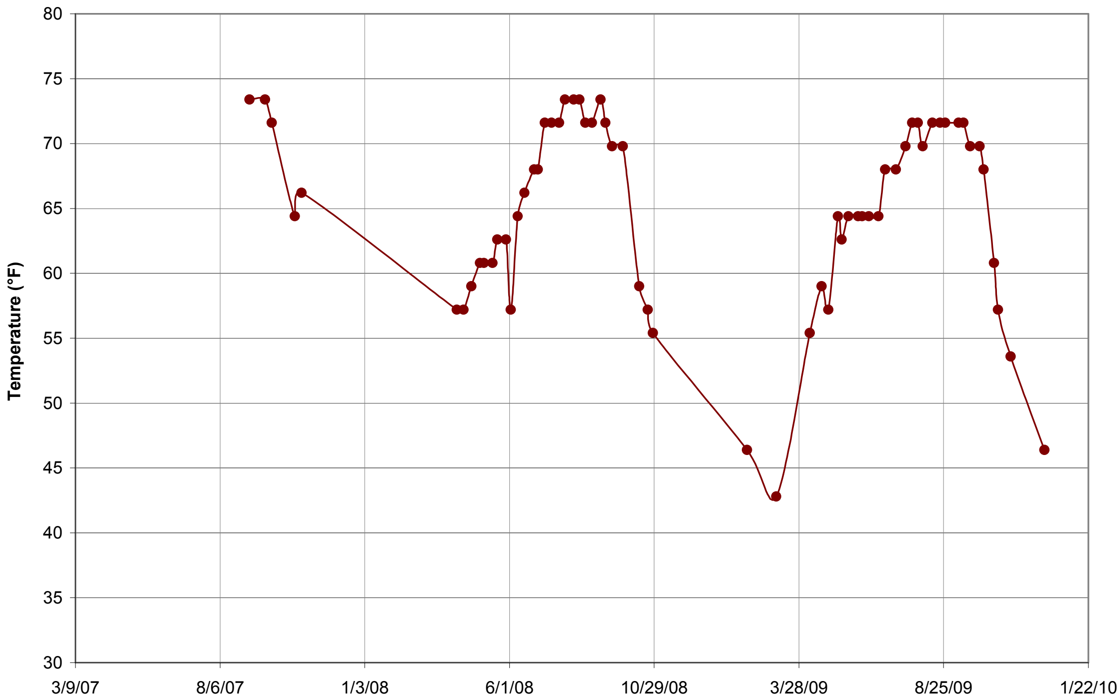


Figure 6: Recycle Water Temperature Profile (DW)

The initial design was to pull recycled water from the DW branch line, run it through the DMNS operations then return it to the existing City Park lake systems which accept and utilize recycled water. This design scenario would have required the construction of a dechlorination plant prior to entering the building systems for appropriate water quality for the pond system. During review, this design scenario became operationally challenging to execute due to a combination of factors including rules regarding Colorado Regulation 84 for reclaimed water usage, volume restrictions for the pond system, and expected usage volume by DMNS. As such, the next feasibility design scenario then strictly focused on a loop from the recycled water conduit to the ECF building and back. Water volume was evaluated and determined to be acceptable through the existing conduit system but not on any existing branch lines. Water pressure could be maintained through a pumping system installed on the recycled water side of the system at the ECF building.

Ownership:

With the loop design in consideration, pipeline ownership and maintenance requirements were addressed. Under the initial design with the dechlorination plant, the pipeline prior to the dechlorination plant that would have been installed and operated by DW and the remaining system would have been owned and operated by DMNS. The new loop configuration required a change in this ownership structure since DW does not typically install a service loop that they own and maintain. The loop would be owned and operated by DMNS as a private system from the meter location off of the main conduit for the entire system.

Water Quality:

In this unique situation, DMNS would be utilizing the recycled water in the conduit and returning it back into the DW system. Therefore, recycled water quality was required to be maintained along the entire stretch of the pipeline system. Multiple isolation valves and water quality inspection stations were required in the pipeline design. Integrating with the building systems required a double walled flat plate heat exchanger. This system would allow for the thermal transfer to occur while keeping the recycled water and building systems separate. Recycled water was not used in any other location or application in the ECF building.

Preliminary engineering analysis allowed the team to develop an initial system design. The operation of this system would use a series of circulation pumps to draw water out of recycled water pipe, pass it through a plate and frame heat exchanger, and then re-inject the water into the recycled pipe. On the opposite side of the plate and frame heat exchanger, a building loop would circulate condenser water to each heat pump located in the building. Storage buffer tanks would be added on the heating and chilled water loops to take advantage of higher flow periods versus low flow periods on a given time of day.

The plate and frame heat exchanger served two purposes. First, it separated the recycled water from the building water systems, which may exhibit different water compositions. This prevented any potential contamination on either side. If the water quality of the recycled water changed, this prevented potential negative impacts of the coaxial water-to-refrigerant coils inside the heat pump units that can have significant maintenance issues. Conversely, if anything were to happen to the building loop side of the system to have contaminants introduced, the risk of getting those contaminants into the recycled water was mitigated with the plate and frame heat exchanger.

The second purpose of the plate and frame heat exchanger was to enable optimized energy use for the building using the least amount of energy draw from the temperature difference of the building condenser water and the recycled water. In a theoretical sense, recycled water would be used only when needed. Therefore, during peak winter and peak summer conditions, the maximum amount of water would be drawn out of the recycled water piping, passing the water through the plate and frame heat exchanger where the building condenser loop would either absorb that heat (heating conditions) or reject the building heat (cooling conditions). However, during other seasonal periods when there would be either a balance of simultaneous heating and cooling zones or 50% of the zones off, no call for heat or cool, the recycled water circulating pump would be turned off. This would be controlled by temperature, with the nominal temperature of 55°F - 60°F for the recycled water, the recycled water pump would be turned off when the building loop temperature was 5°F below 60°F or 5°F above 70°F. Conversely, the recycled water pump would be turned on when the building condenser loop was outside that temperature range. This regime would balance not only the water use out of the recycled water pipe, but also the energy use of the recycled water circulating pump compared to the energy efficiency of the heat pump units for the Coefficient of Performance and Energy Efficiency Ratio at those same temperature ranges.

Financial:

Financial modeling was developed for this application of recycled water. Water is typically consumed by the end user; however in this application, the thermal characteristics of the water are used while the entire volume would be returned to the local municipality. This difference in operation required the establishment of a rate system that did not previously exist.

A schematic design narrative was developed based on the recycled water requirements and the building space use requirements. This narrative outlined the functional system requirements of the GSHP system, interior building loop systems and their functionality, and requirement to heat and cool simultaneously. Building system information outlined air handling units (AHUs), direct/indirect cooling and redundant backup systems for when the recycled system might not be available. Figure 7 shows a schematic layout of the plant operations.

Schematic design was approved through internal review processes and turned over to the design team.

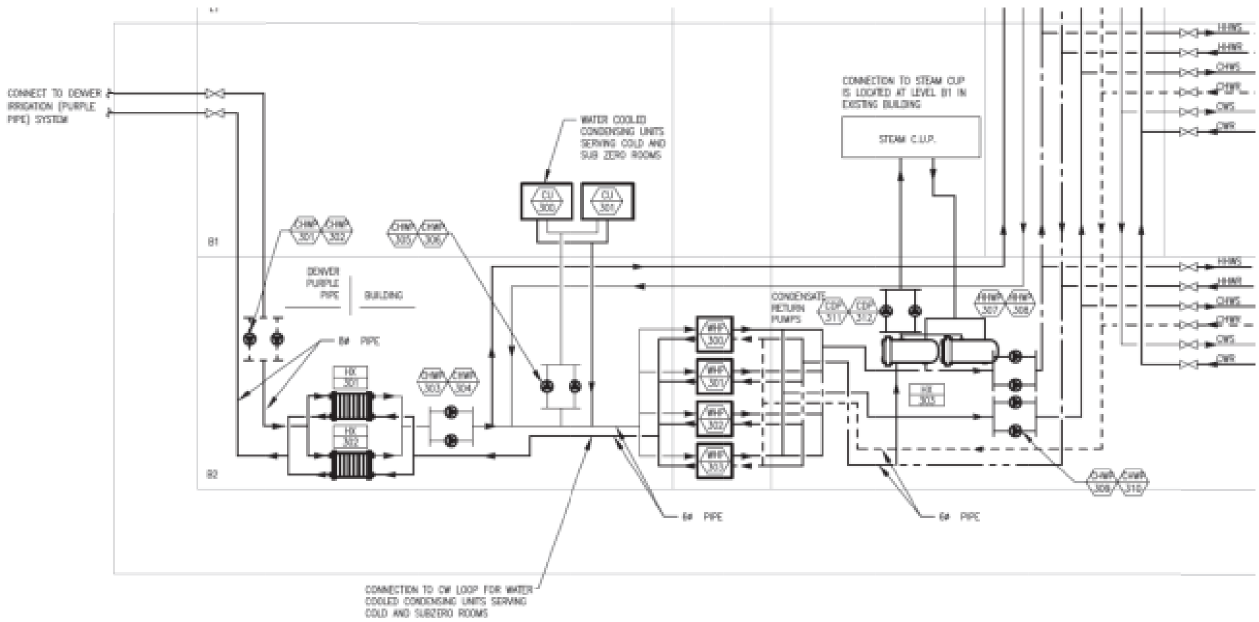


Figure 7: ECF Schematic Plant Operations

6.3 Engineering Design (July 17, 2010 – September 2011):

With the approved schematic design, engineering support for the project was integrated with the ECF design team to produce the final construction drawings and specifications for the project. Specific building requirements had been developed for the end use of each of the facility spaces such that the mechanical systems were further defined. The final requirements for the GSHP system in the building included:

1. LEED Platinum Certification.
2. 50% less energy consumption (compared to ASHRAE 90.1-2007).
3. General heating/cooling for 126,000 ft^2 building.
4. Special heating/cooling requirements for 70,000 ft^2 of collection storage space to 70°F +/-3°F.
5. Cooling for dehumidification to maintain RH 50% +/- 3% in collection storage spaces. Note that humidification requirements are not provided by the GSHP system.
6. Controls to allow simultaneous cooling and heating in various parts of the building, based on demand.
7. Controls to allow heat pump to be tasked seasonally for primary heating or cooling.
8. Controls and heat exchangers as required by Denver Water (DW) to protect the recycled water system.
9. Provide chilled water for special low temperature collection storage spaces.
10. Controls to allow alternative supply water in the event of disruption of the recycled water supply.

Based on the special HVAC and dehumidification requirements of the facility, the number of heat pumps (HP) increased from 4 to 7. Peak recycled water flow increased from 300 to 630 GPM and the double plate heat exchanger upgraded to handle increased flow and minimize the heat loss. Redundancy was added to the HP side of the system to accommodate 100% flow loss utilizing an existing boiler system and new cooling tower system.

The recycled water piping system is designed with an 8" PVC supply and return line. The connection is between the DW conduit located in City Park Golf Course to the ECF building and back. In total, the resulting pipeline is 3,300' in each direction. The supply line is required to be insulated with 2" of foam insulation to reduce thermal transfer between the lines. Isolation valves and a meter are required at the conduit connection. Remote water sampling stations are required on the lines between the conduit and building entry points. Isolation valves are required prior to entering the building.

For the building system, five air handling units (AHU), multiple unitary heat pumps and cabinet unit heaters support all five building levels. These systems are supported by five different loops in the ECF design (Figure 8). The recycled water is circulated by two redundant Variable Frequency Drive (VFD) pressure controlled pumps from the incoming supply, through a double walled flat plate heat exchanger and then returned back into the recycled water conduit. Based on preliminary design data, the incoming recycled water is expected to be 45°F to 75°F and the return water temperature is expected to be a 10°F differential. If the recycled water system will not support the load requirements or is unavailable for use, a new cooling tower or existing natural gas steam boiler will be utilized.

The source loop provides for heat transfer through the heat pump system and is circulated by two redundant 20 HP VFD pressure controlled pumps that flow water through the heat pump system. The source loop operating range is expected between 55°F and 80°F. The source loop has the ability to be heated through heat exchangers from alternate sources as previously mentioned.

The heating loop provides heating water to AHU preheat coils, Variable Air Volume (VAV) coils and other heating points of use. Water is circulated by two redundant 3 horse power (HP) VFD pressure controlled pumps. The operating range is expected between 105°F and 125°F. The heating loop redundancy is provided by circulation through a heat exchanger connected to the existing steam boiler system.

The cooling loop provides cooling water to AHU coils and precooling. Water is circulated by two redundant 15 HP VFD pressure controlled pumps. The operating range is expected between 55°F and 60°F with a maximum of 10°F return rise.

In later iterations of this phase of design, it was decided to couple the precooling loop directly to the source loop. Two redundant 5 HP VFD pressure controlled pumps would pump water from the source loop to a precooling loop that would circulate source water to precooling coils located in the five air handling units. This had several implications:

- Recycled water could be utilized for two purposes: 1) removing or adding heat from the heat pump plant, and 2) providing cooling directly to the air handling units (without a direct expansion refrigeration cycle as an intermediary).

- There would be two means for the building system to equalize simultaneous heating and cooling loads without any external energy source: 1) heat pumps operating simultaneously in heating and cooling and 2) heat pumps operating in heating and the precooling loop providing cooling.
- There would be less complexity in cooling tower piping/heat exchange for the cooling tower to provide the dual function of backing up recycled water for cooling and waterside economizing for precooling.
- To do this, the source loop would have to be operated at lower temperature than conventional condenser water loops, with a setpoint of 55°F in order to provide useful precooling temperatures. This would mean decreased utilization of recycled water during summer months with average recycled water temperatures expected to be higher than this setpoint, but would likely mean increased use of recycled water in other seasons for direct cooling, thus reducing heat pump and cooling tower operation.
- Additionally, the source loop would have to be controlled to a far tighter temperature range in order to be useful for precooling, with far smaller temperature swings (deadbands) than would be permitted in conventional ground/water loop heat pump systems, and requiring increased cycling of equipment for tighter temperature control.

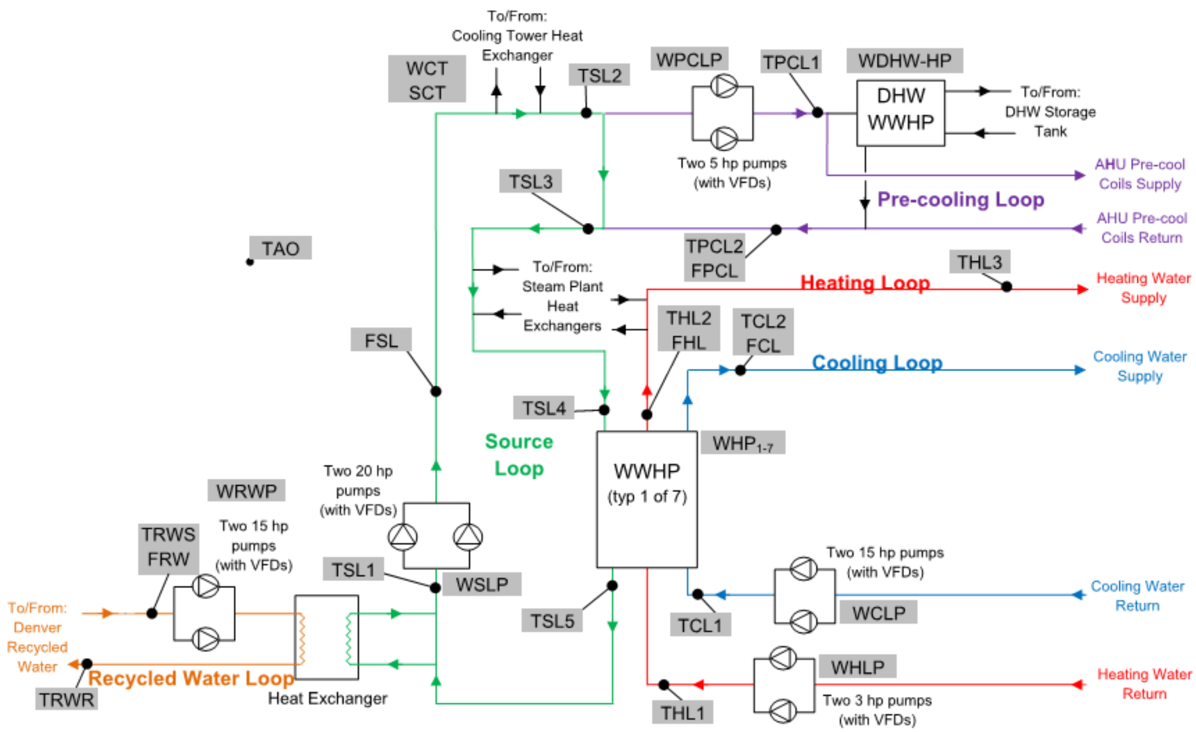


Figure 8: High Level Plant Operation Design (ORNL Monitoring Plan, 2013)

Controls sequencing is outlined in the design package with a complex sequence of operations. Monitoring of system parameters and performance is accomplished through the implementation of multiple sensor points throughout the system. Some of these sensor points are identified in Figure 6 (gray boxes). In addition, electrical sub-metering is required on all electrical panels and major equipment. The existing building automation system (BAS) records data from the various monitoring points as well as operate the mechanical systems. Some systems are directly controlled via the BAS while other systems operated through their own on-board programming systems and provide status reports to the BAS.

6.4 Construction (September 11, 2011 – January 16, 2014):

The two levels of underground storage in the ECF building required partial removal of existing exterior building walls and numerous utilities located in the construction area. Once this work was completed, site excavation began, lasting into 2012. By the end of 2012, foundation walls and underground floors were in place. In 2013, the remaining building structure, electrical, HVAC systems and interior finishes were completed. Final building inspections were completed at the end of 2014 with substantial completion achieved on January 16, 2014.

The GSHP equipment was selected and ordered early in the construction period to reduce overall lead time. Factors evaluated in GSHP selection included efficiency, performance, the ability to simultaneously provide heating and cooling, and footprint. Climacool UCH Series Model 30 was selected. Each 30 ton unit operates with R-410A refrigerant and when combined, provides 210 tons of capacity. The Climacool units have two compressor stages within each module that can operate in heating or cooling mode simultaneously.

Construction of the recycled water line started in January 2013. To minimize the construction impact, control cost, and improve on the efficiency of installation, the two lines were installed side by side in a 48" wide trench. The supply line was required to be insulated with 2" of foam insulation to reduce thermal transfer between the lines since they were in the same trench. Trench depth varied from 6 feet to 15 feet throughout the 3,300 foot pipe line installation. The pipeline installation was completed in April 2013.

Figure 9: Recycle Water Line Installation - west of DMNS

Figure 10: Recycled Piping - Supply and Return Lines

The heat pumps were installed in May 2013 prior to the completion of the floor space due to the size of the units. The units were not operational until the fall 2013 when the remaining systems were completed and brought on line.

Figure 11: Climacool heat pumps (7 units)

Figure 12: Heat pump Header Bypasses

Figure 13: Recycled Water Pumps

Figure 14: Recycled Water Heat Exchanger

Figure 15: Source Loop Pumps

The building automation programming was completed with each system startup. Extensive programming was required for the system operation. The ECF plant operation is reflected in Figure 16. The final building is pictured in Figure 17.

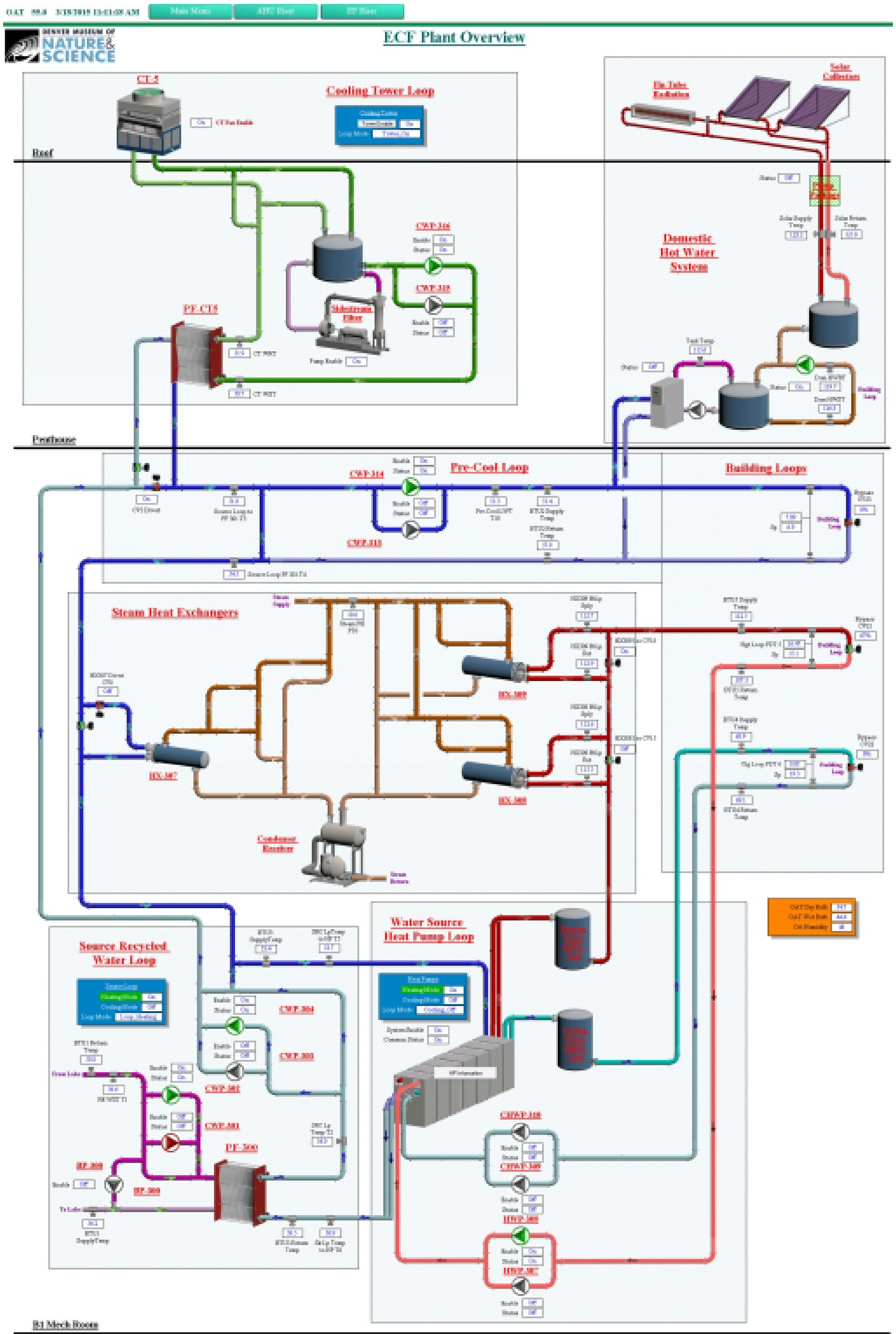


Figure 16: ECF Plant Overview

Figure 17: ECF Building

6.5 Commissioning (July 30, 2013 – May 16, 2014):

The GSHP commissioning was completed with the ECF building commissioning due to the interactions and interrelations of the systems. The commissioning agent worked on behalf of DMNS to ensure system functionality. The complexity of all of the building systems required substantial coordination between the design and construction teams to achieve the project requirements and basis of design. All equipment was subject to a pre-functionality check prior to start-up. This requirement was necessary prior to any formal commissioning process started on the system. An iterative process was required as each system component was brought online and interacted with other systems.

Tuning and timing of system components, specifically related to GSHP system pressure, flow, and temperature control, was a key finding during the commissioning process. One aspect of this was the utilization of a primary-only pumping configuration, where flows remain equal through both the heat pump plant and the building heating/cooling circulation loops. This is as opposed to a primary/secondary pumping configuration, where a primary loop flow is maintained through the heat pumps, and is coupled to a secondary loop, where a separate pump set is utilized to determine flow needs for the building loads. One of the challenges with the use of a variable flow primary-only pumping configuration in this system is that the heat pump array has explicit flow requirements throughout the system operating range (depending on the number of heat pumps in operation). This is opposed to a variable speed chiller, for example, which can be very flexible in chilled water flow above a minimum set point, such that the building loads can dictate chiller (primary) flow requirements. Significant time and effort was spent during commissioning to tune the GSHP operation to accommodate for different simultaneous flow needs (heat pumps versus building loops) and minimize flow and pressure fluctuations created by state changes in the system (such as heat pumps staging up/down to meet load).

6.6 Measurement and Verification (July 2, 2014 – present):

A measurement and verification (M&V) plan was developed for this project in conjunction with CDH Energy Corporation and Oak Ridge National Laboratory (ORNL). Some of the information in this final report is reflected in the M&V plan. As previously mentioned, key system monitoring points were identified during designs with sensors installed during construction. In total, 50 data points are being monitored and recorded for system performance. The data is collected each second and averaged or totaled over a 15 minute period based on the type of sensor installed.

From the data collection, the following formulas can be calculated to indicate system performance:

Equation 1: Net heat transfer to the municipal recycled water system through the recycled water loop:

Q_{RWL} = 500 X FRW X (TRWS-TRWR)/1000

Where:

Q_{RWL} = Heat Transfer through Recycled Water Loop (MBtu)

(Heat rejected MBtu <0, Heat extracted MBtu > 0)

FRW = Recycled Water Flow (GPM)

TRWS = Recycled Water Supply Temperature (°F)

TRWR = Recycled Water Return Temperature (°F)

Equation 2: Heat Supplied (heating operation) by $GSHP_{1-7}$ to Heating Loop:

Q_{HL} = 500 X (FHL) X (THL2-THL1)/1000

Where:

Q_{HL} = Heat supplied to Heating Loop by $GSHP_{1-7}$ (MBtu/h)

FHL = Heating loop flow rate (GPM)

THL1 = Temperature Heating Loop (Entering $GSHP_{1-7}$) (°F)

THL2 = Temperature Heating Loop (Leaving $GSHP_{1-7}$) (°F)

Equation 3: Heat Extracted (cooling operation) by $GSHP_{1-7}$ from Cooling Loop:

Q_{CL} = 500 X (FCL) X (TCL1-TCL2)/1000

Where:

Q_{CL} = Heat extraction from Cooling Loop by $GSHP_{1-7}$ (MBtu/h)

FCL = Cooling loop flow rate (GPM)

TCL1 = Temperature Cooling Loop (Entering $GSHP_{1-7}$) (°F)

TCL2 = Temperature Cooling Loop (Leaving $GSHP_{1-7}$) (°F)

Equation 4: Heat (heating mode) provided by $GSHP_{1-7}$ to Source Loop:

Q_{SLH} = 500 X (FSL) X (TSL5-TSL4)/1000

Where:

Q_{SLH} = Heat supplied to Source Loop by heat $GSHP_{1-7}$ (MBtu/h)

FSL = Source Loop flow rate (GPM)

TSL4 = Temperature Source Loop (Entering $GSHP_{1-7}$) (°F)

TSL5 = Temperature Source Loop (Leaving $GSHP_{1-7}$) (°F)

Equation 5: Heat (cooling mode) extracted by $GSHP_{1-7}$ from Source Loop:

Q_{SLC} = 500 X (FSL) X (TSL4-TSL5)/1000

Where:

Q_{SLC}	= Heat extracted from Source Loop by $GSHP_{1-7}$ (MBtu/h)
FSL	= Source Loop flow rate (GPM)
TSL4	= Temperature Source Loop (Entering $GSHP_{1-7}$) (°F)
TSL5	= Temperature Source Loop (Leaving $GSHP_{1-7}$) (°F)

Equation 6: Additional heat added by steam plant to Source Loop:

Q_{SP1} = 500 X (FSL) X (TSL4-TSL3)/1000

Where:

Q_{SP1}	= Heat added to Source Loop by steam plant (MBtu/h)
FSL	= Source Loop flow rate (GPM)
TSL3	= Temperature Source Loop (prior to steam plant) (°F)
TSL4	= Temperature Source Loop (after steam plant) (°F)

Equation 7: Additional heat added by steam plant to Heating Loop:

Q_{SP2} = 500 X (FHL) X (THL3-THL2)/1000

Where:

Q_{SP2}	= Heat added to Heating Loop by steam plant (MBtu/h)
FHL	= Heating Loop flow rate
THL2	= Temperature Heating Loop (Prior to steam plant) (°F)
THL3	= Temperature Heating Loop (After steam plant) (°F)

Equation 8: Heat extracted by domestic hot water (DHW) WWHP and coils from Pre-cool Loop:

Q_{DHW} = 500 X (FPCL) X (TPCL1-TPCL2)/1000

Where:

Q_{DHW} = Heat extracted by DHW WWHP and coils from Pre-cool loop (MBtu/h)

FPCL = Pre-Cool Loop flow rate (GPM)

TPCL1 = Temperature Pre-Cool Loop (prior to DHW WWHP) (°F)

TPCL2 = Temperature Pre-Cool Loop (after DHW WWHP) (°F)

Equation 9: Heat extracted from the Source Loop by Cooling Tower heat exchanger:

Q_{CT} = 500 X (FSL) X (TSL1-TSL2)/1000

Where:

Q_{CT} = Heat extracted from Source Loop by Cooling Tower (MBtu/h)

FSL = Source Loop flow rate (GPM)

TSL1 = Temperature Source Loop before Cooling Tower (°F)

TSL2 = Temperature Source Loop after Cooling Tower (°F)

Temperature data collected for different loops is presented in Table 1. Recycled water loop temperature ranges were improved from data collected during feasibility and design, with lower extremes in winter (warmer temperatures) and summer (cooler temperatures). Source and precooling loop temperatures are relatively stable and fluctuate with normal seasonal variations. During November 2014, recycled water was not available due to system maintenance. This outage lasted for almost the entire month. Additionally, the cooling tower was unavailable for redundant backup due to low outside air temperatures. The result is an increase in source loop temperatures during this month.

Month	Average Recycled Water Loop Temperature, T1	Average Source Loop Temperature, T2	Average Precooling Supply Temperature, T3
Jun-14	68.3	61.7	59.1
Jul-14	72.4	68.7	63.3
Aug-14	72.7	64.4	59.8
Sep-14	71.4	61.1	58.3
Oct-14	68.7	54.7	52.3
Nov-14**	67.4	59.1	58.3
Dec-14	53.6	54.0	52.9
Jan-15	51.6	53.2	52.6
Feb-15	50.1	52.6	52.2

Table 1: Loop Temperature Data
(* Negative values indicate energy removed, **During portions of November, recycled water was not available.)

Recycled water utilization for heating and cooling modes along with net energy is presented in Table 2. The energy added during heating and cooling corresponds directly to seasonal requirements. The usage of cooling during the heating season is an interesting change based on the design scenarios. Preliminary data indicates that heat rejection is occurring overnight as the ECF building is shedding excess heat loads. As a sole number, the net energy impact would appear negligible in the early months of 2015; however, the combination of heating and cooling loads is offsetting one another.

Month	Energy Added by Recycled Water Loop in Heating* (Mbtu)	Energy Added by Recycled Water Loop in Cooling* (Mbtu)	Net Energy Added by Recycled Water Loop* (Mbtu)
Jun-14	3.8	-31.5	-27.7
Jul-14	9.5	-111.2	-101.7
Aug-14	0.3	-13.7	-13.3
Sep-14	1.4	-8.5	-7.1
Oct-14	72.8	-0.5	72.2
Nov-14**	24.6	-8.8	15.7
Dec-14	45.8	-13.7	32.1
Jan-15	25.6	-20.5	5.1
Feb-15	30.2	-22.6	7.6

Table 2: Recycled Water Utilization
(* Negative values indicate energy removed, **During portions of November, recycled water was not available.)

Overall ECF building energy utilization is presented in Table 3.

Month	Energy Added by Recycled Water Loop in Heating* (Mbtu)	Energy Added by Recycled Water Loop in Cooling* (Mbtu)	Energy Added by Cooling Tower* (Mbtu)	Net Energy Added by Heat Pumps* (Mbtu)	Energy Added By Precool Loop* (Mbtu)	Energy Added By Steam HX-307* (Mbtu)	Net Load on Source Loop (Heat pumps + Precooling) (Mbtu)	Net Energy Added by Recycled Water Loop* (Mbtu)
Jun-14	3.8	-31.5	-245.6	-84.2	387.4	0.0	303.2	-27.7
Jul-14	9.5	-111.2	-499.3	349.8	244.1	0.0	594.0	-101.7
Aug-14	0.3	-13.7	-361.2	-9.2	407.5	0.0	398.4	-13.3
Sep-14	1.4	-8.5	-258.4	-74.3	367.6	0.0	293.3	-7.1
Oct-14	72.8	-0.5	-283.9	-178.0	258.8	0.0	80.7	72.2
Nov-14**	24.6	-8.8	-70.9	-163.2	192.5	39.5	29.3	15.7
Dec-14	45.8	-13.7	-98.8	-204.7	263.6	40.4	58.9	32.1
Jan-15	25.6	-20.5	-56.5	-189.8	252.9	20.3	63.1	5.1
Feb-15	30.2	-22.6	-38.8	-227.6	258.1	35.8	30.4	7.6

Table 3: ECF Energy Utilization
(* Negative values indicate energy removed, **During portions of November, recycled water was not available.)

Several preliminary observations have been made regarding initial operation:

- Cooling tower utilization is more prominent during the cooling season and is directly related to the combined use of the source and precooling loops. With direct coupling to the precooling loop, the source loop must operate at lower temperatures than conventional condenser loops in order to provide useful cooling to the air handling units. This reduces utilization of the recycled water in summer months; however, when outdoor wet bulb temperatures are higher (July), an increased utilization of the recycled water is seen. This is because the cooling tower is often not able to maintain the source loop temperature set point, and the source loop temperature rises above the recycled water loop temperature, such that recycled water can be used to provide some cooling.

- The precooling loop provides a large amount of cooling for the building, and consequently contributes significant a large amount of heat to the source loop, as the precooling loop cools the supply air in the air handling units. The heat load is then being shed between the use of GSHP and cooling tower operation. This is a predominant factor from June through September.
- In winter months, because the precooling loop can provide so much cooling, heat pump operation in cooling mode is minimized. Therefore, the heat pump plant is typically in net heating operation. The heat needed on the source loop for the heat pumps in heating on a monthly basis is comparable to the heat put into the source loop by the precooling loop. However, these loads are less coincident on a daily basis. At times, the recycled water system provides cooling during daytime operation when the building requires net cooling, while providing heating at night when building cooling needs are low, and the heat added by the precooling loop is less than is needed for the heat pumps providing hot water to the building.
- Total system operation from October 2014 on improves through seasonal changes and tuning improvements in the GSHP system. Trim control and set points are being evaluated for each of the systems to reduce equipment cycling and improve system energy and operational performance.

Through the use of this data and the extended M&V process for LEED certification, project performance reports have been developed for building operation in 2014. These reports will continue through 2015 and will be reviewed for potential system adjustments. Additionally in 2015, DMNS, CDH, and ORNL will review data to identify other efficiency improvements. Routine maintenance of the GSHP equipment has proceeded per Operations and Maintenance Manuals. The equipment has been added to the DMNS Operations Preventative Work System.

6.7 Outreach and Awareness for GSHP:

DMNS' commitment to science and education is central to our mission to be a catalyst that ignites our community's passion for nature and science. As such, this demonstration project on GSHP technology advances our mission. DMNS supports the sustainability efforts and GSHP project through our website at www.dmns.org. In the fall of 2014, DMNS and its representatives presented the project poster in a number of outreach programs including the 2014 WateReuse Workshop in Golden, CO, the 2014 International WateReuse Association Meeting in Dallas, TX and hosting 2014 State of Colorado Recycled Water Managers in September (Figure 18). In November 2014, DMNS held an Adult Programs event to discuss the sustainability aspects of the ECF Project, including the GSHP system. Representatives from DW and NORESCO along with DMNS staff were in attendance to present these concepts and features. Late in 2014, DMNS installed a permanent on-site exhibit dedicated to communicating the function and use of the GSHP system, highlighting the use of the recycled water for the heat sink/source. This hands-on exhibitory demonstrates the concepts of heat sink and heat source for the GSHP system (Figure 19).

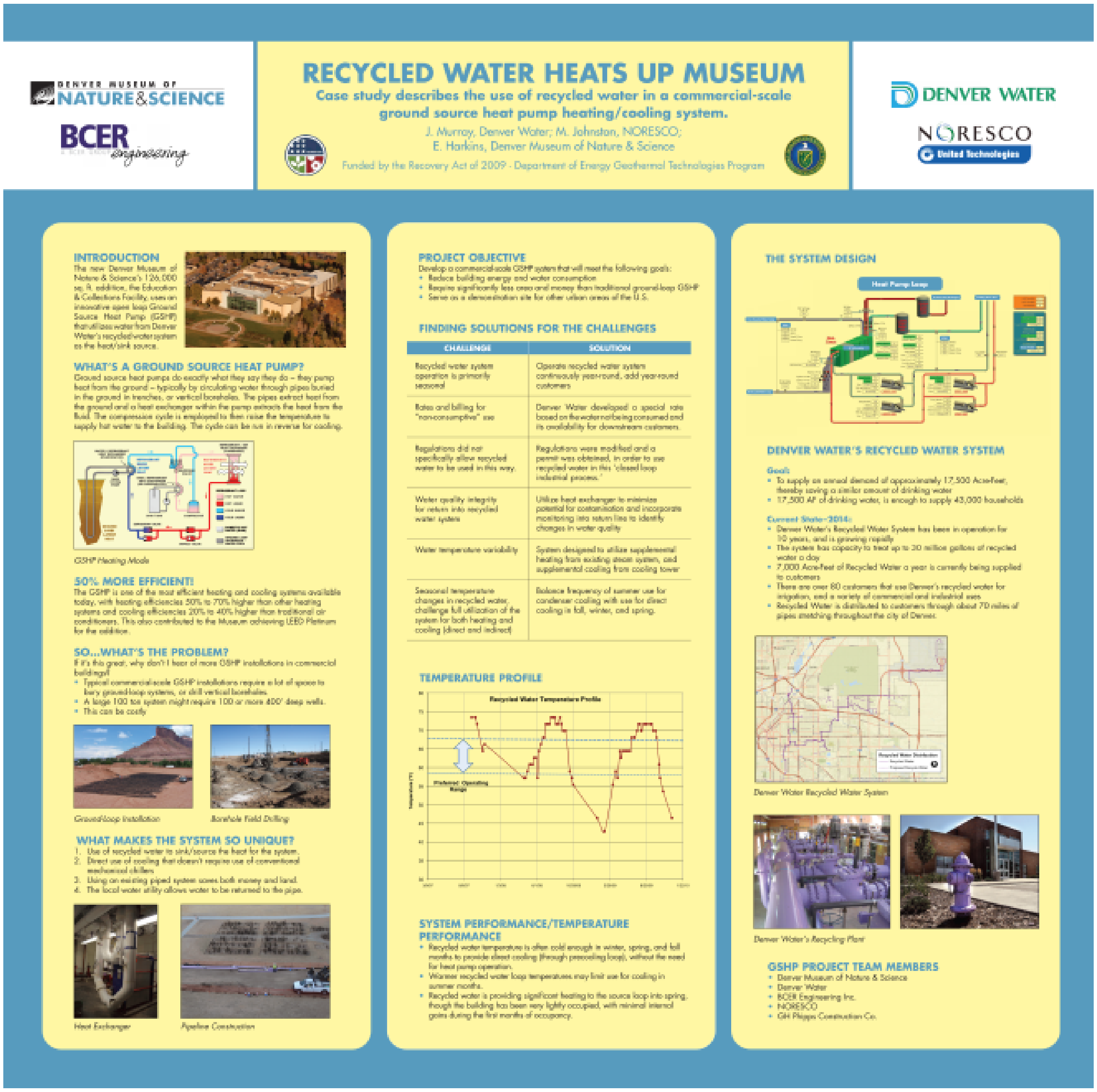


Figure 18: DMNS GSHP Poster

Figure 19: GSHP Exhibitry

DMNS continues its efforts to develop best operational practices and modeling tools for the GSHP system through our continued use and interaction with the system. The tools are currently under development in 2015.

7 Conclusions:

The goal of the DMNS GSHP project was to design and install an innovative open-loop GSHP system as a demonstration project that would utilize water from a local municipal recycled water system as the source of thermal cooling/heat to the heat pumps for a 126,000 ft^2 Education and Collection Facility (ECF). The proposed system advantages include reducing the traditional ground-loop GSHP system capital installation costs by at least 50%, eliminating the large footprint typically required for a borehole field, minimizing complex environmental and regulatory permitting required for traditional borehole or open-loop (pump and dump) systems, minimizing energy consumed by traditional fluid circulation and improving relative efficiency of the system by minimizing the differential operating temperature range in the heat pumps.

Through the completion of the ECF building, the GSHP system was completed and is utilizing local municipal recycled water. The equivalent of 420 bore wells was offset through the use of recycled water. The conduit infrastructure, water use criteria, operational conditions and financial modeling for recycled water were examined, developed, and utilized. In other areas of the US where recycled water systems are being developed due to limited water supplies and/or effluent water disposal is regulated, the potential to transfer this application is increased. Capital installation costs are tracking close to the expected 50% reduction in cost and operational efficiencies are under continued monitoring.

In 2015, DMNS, NORESCO, CDH and ORNL will continue data evaluation, monitoring and system performance evaluation to provide a baseline metric for recycled water usage.