Abbott Enerdrape System

University of Illinois at Urbana-Champaign

Spring 2024 ME 470 – Final Project Report

Ben Dixon	bmdixon2@illinois.edu	(847)-764-0305
Ben Goddard	bcg3@illinois.edu	(619)-394-0968
Daniel Kawiecki	drk3@illinois.edu	(708)-548-1261
Danny Koch	djkoch2@illinois.edu	(708)-699-9862
Aarish Ali Lakhani	aarishl2@illinois.edu	(847)-412-8378
Aman Mehta	amanm2@illinois.edu	(630)-402-5930
Nate Williamson	ncw4@illinois.edu	(224)-456-9079

Submission Date: May 3rd, 2024

Project Sponsor: Professor Nenad Miljkovic (nmiljkov@illinois.edu)

Submitted to: Professor Blake Johnson (bejohnso@illinois.edu)

TABLE OF CONTENTS

1. Executive Summary 3
2. Literature Review 6
3. Project Objectives and Deliverables 12
4. Product Design Specification (PDS) 13
5. Ideation and Concept Selection 14
6. Solution Procedure 18
7. Budget 25
8. Testing and Data Analysis 26
9. Conclusions and Recommendations 27
10. Appendix 29
11. References 34

Executive Summary

In collaboration with both Enerdrape and the Abbott Power Plant, this project aims to install and assess the performance of Enerdrape's geothermal panels within the steam tunnels of the Abbott Power Plant on the University of Illinois Urbana-Champaign (UIUC) campus. These panels are designed to capture waste heat from underground sources, contributing to energy efficiency and cost savings. The power plant's steam tunnels present an exciting opportunity for Enerdrape to install their technology in a new environment to characterize its performance. In a world with 20-50% of energy being lost to waste heat, Enerdrape's panels will act as a heat capture solution for Abbott Power Plant, the supplier of 75% of all energy on UIUC's campus.

The objectives of the project are to characterize the performance of Enerdrape's panels in the steam tunnels. This will allow us to quantify potential energy and cost savings. From this information, a feasibility study will be generated to assess the implementation of this technology across the steam tunnels on campus. It is important to make sure all of this is done while adhering to a strict budget of $50,000 for purchasing materials, accounting for labor and engineering costs, panel installation, and testing. This budget was successfully adhered to as the team spent just under $40,000 for the project's duration.

Initially, the team estimated the available waste heat within the steam tunnels from methods learned from literature review. Later in the semester, better results were found with a FLIR camera and CFD simulation. Characterization of the heat available in the steam tunnels is critical to making an informed decision on the feasibility of Enerdrape's geothermal panels.

A separate 1D thermal simulation in simscape was completed to inform the team in selecting a pump and chilling unit. Once the pump and chiller were selected, the team ordered all mechanical and electrical components including a programmable logic controller and data acquisition unit.

Installation began with ten panels being mounted to a wall in the steam tunnels. Next, all necessary hydraulic and electrical components were installed to complete the closed-loop system. Following the installation, the team was able to run two extended tests, collect data, and analyze the system's performance.

The results from these tests found that our system performed better than expected but considering the limited number of tests our team was able to conduct and analyze, our results do not provide significant evidence to thoroughly characterize Enerdrape's panels. The team was still able to extract useful temperature and heat loss data for the Abbott Power Plant, as well as some general performance characteristics of Enerdrape's panels in a power plant steam tunnel. The team has also provided documentation and recommendations for groups that may be continuing this project in future semesters.

1. Introduction

According to the US Department of Energy, it is estimated that between 20 and 50% of industrial energy input is lost as waste heat in the form of hot exhaust gases, cooling water, and heat loss from hot equipment surfaces and heated products [12]. Efforts to improve industrial energy efficiency usually focus on reducing the energy consumed by the equipment, however, another valuable approach is to capture and reuse the lost or *waste* heat which is intrinsic to every thermodynamic process. It is also reported that roughly 60% of unrecovered waste heat is low quality. Low quality means the temperature of the heat extracted is less than 232°C, making it challenging to recover economically because you would have to spend money to increase the temperature to a range that is useful in a practical application. However, this low-quality waste heat is ubiquitous and should not be overlooked in the drive towards solving the global climate change problem [12].

The mission of Enerdrape is to unlock the energy potential that lies in untapped environments, such as underground indoor environments, improving access to renewable thermal energy and providing sustainable contemporary heating and cooling solutions to cities and urban areas.

1.1 Enerdrape Background

The Enerdrape system transfers thermal energy between the installation environment and the heat pump using a single-phase fluid impelled by a circulation pump. The working fluid flows through the panels, which then absorbs heat via a combination of conductive and convective modes. As the panels are installed in thermal contact with walls, the primary mode of heat transfer is conduction. This allows efficient sourcing or sinking into the environmental thermal mass, depending on whether the heat pump system they are coupled to is in heating or cooling mode respectively. Although they lack convective enhancement, the panels can also absorb some waste heat from the environmental air.

Figures 1 and 2 depict Enerdrape's physical product and a schematic of ten panels connected in series, respectively. Overall, these panels can leverage a variety of environmental thermal sinks or sources of thermal energy, and are only limited in their application by heat pumping technology in general.

Figure 1. Enerdrape Geothermal Panel

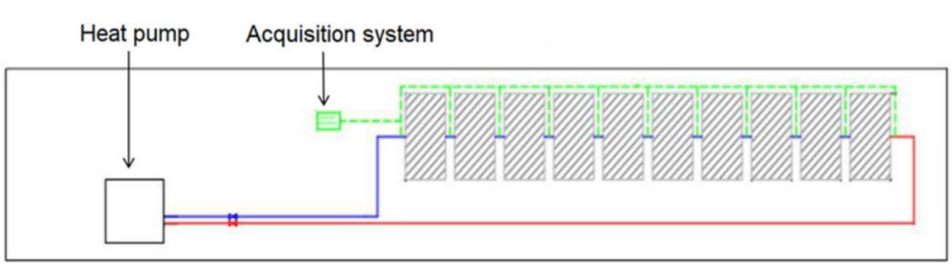


Figure 2. 10 Enerdrape panels connected in series

Enerdrape conducted a year-long pilot study of their technology in an underground parking garage in Lausanne, Switzerland. Three key results from this study were found [7]. First, up to 170 W/m² of thermal power could be harnessed by the panels (within the given environment) which is two to three times more energy than conventional geothermal exchanger that is drilled into the ground, leveraging the heat from the earth's core (e.g. 20 to 40 W/m² for energy walls). Second, the extracted thermal power reached a steady state in roughly 5 hours. Lastly, convective heat transfer from air accounts for 15% and conductive heat transfer from the walls accounts for 85% of the total heat transferred. Under the conditions of the pilot site, the installation allows an annual production of 350 kWh/m² for a heating period of 2300 hours (about 3 months).

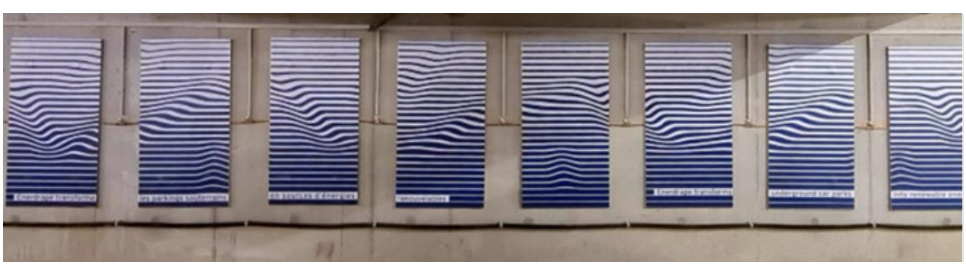


Figure 3. Enerdrape Panels at pilot demonstration site [7]

1.2 Problem Statement

Enerdrape previously generated an analysis of panel performance in several underground parking garages and are now interested characterizing the panels in a new setting: the steam tunnels at Abbott Power Plant (Figure 4). These tunnels are a promising environment due to the amount of heat-leak from the steam-carrying ducts which compose a vast network of tunnels that extend nearly 10.3 km across the UIUC campus. The problem is that this heat available for capture is currently lost to the environment either into the ground or through surface vents. Therefore, Abbott is interested in investing in technology with the potential to capture waste heat, save energy, and reduce cost and environmental impact. In the following literature review, the amount of waste heat being lost throughout campus is estimated.

Figure 4. Steam tunnels at Abbott Power Plant

2. Literature Review

2.1 Background on Primary Research

To develop a research-based approach as a solution to the Enerdrape installation in the Abbott Power Plant steam tunnels, a literature review was conducted. Heat loss calculations, thermal and velocity boundary layer assumptions, and applications of heat pumps in geothermal settings are analyzed. Specifically, heat loss calculations of steam pipes in underground tunnels are important for understanding the opportunity for waste heat recovery; boundary layer assumptions allow for more accurate thermal simulations; and analysis of heat pumps offers context for scalability of the project to supporting the heating of buildings.

2.2 Heat Loss Across Steam Pipes in Underground Tunnels

Using the measurements taken during the site visit to the steam tunnel (Figure 4), a rough estimate of heat loss from the steam pipes to the surroundings can be determined. The team observed two sections of the steam tunnel: one with ventilation, and one without. The section without ventilation saw an average ambient air temperature around the pipe of around 50 °C with little to no air flow, while the ventilated section saw a much lower air temperature of around 25 °C with moderate air flow down the tunnel. Both sections saw a pipe surface temperature of 63.1 °C. To estimate the heat losses, two cases can be considered: the non-ventilated section with only free convection, and the ventilated section with forced convection.

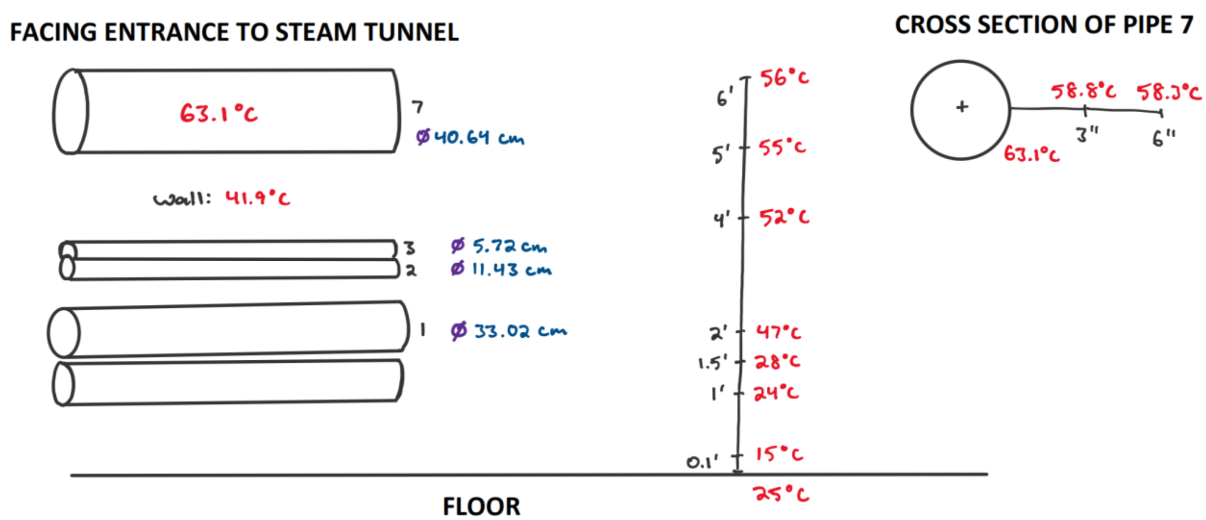


Figure 5. Site Visit Temperature Measurements and Dimensions

For the free convection case, the pipe is modelled as an infinitely long horizontal cylinder with a diameter of 0.457 m. Other assumptions include neglecting radiation and conduction effects and assuming steady state heat transfer. The Nusselt number, Nu_D, can be calculated using two methods, Morgan's equation (1) and Churchill and Chu's equation (2) where Ra_D is the Rayleigh number, Pr is the Prandtl number, h is the convective heat transfer coefficient, D is the cylinder diameter, and k_f is the conductive heat transfer coefficient.

$$Nu_D = C \times Ra_D \tag{1}$$

$$Nu_D = \left\{0.6 + \frac{0.387 {Ra_D}^{1/6}}{(1 + ({0.559}/{\mathrm{Pr}})^{9/16})^{8/27}}\right\}^2 \tag{2}$$

(3)

$$Nu_D = \frac{hD}{k_f}$$

The Rayleigh number is calculated using the equation below where Gr_D is the Grashof number. The Grashof number is calculated with g (acceleration due to gravity), ß (coefficient of expansion in the fluid), the temperature difference between the surface and environment, D (diameter), and v (kinematic viscosity of the fluid).

$$Ra_D = Gr_D \times Pr \qquad (4)$$

$$Gr_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2} \qquad (5)$$

Assuming that the air temperature is a uniform 50°C, the values of the variables in the above equation can be approximated as such:

$$\beta = 3.4 \times 10^{-3}\ {}^{1}/_{K}$$

$$\upsilon = 18.2 \times 10^{-6}\ {}^{m^2}/_{s}$$

$$\text{Pr} = 0.703$$

$$k_f = 28\ {}^{W}/_{m \times K}$$

The resulting calculation gives the following results. Note that the Morgan equation is used for the Nusselt number calculation. Both give similar results, but the Morgan calculation is used because this is a low-end estimate and Morgan gives the smaller of the two values.

$$Gr_D = 1.258 \times 10^8$$

$$Ra_D = 8.85 \times 10^7$$

$$Nu_D = 46.55$$

$$h = 2.77\ {}^{W}/_{m^2 \times K}$$

With the given temperatures and pipe dimensions, the heat loss per area as well as the heat loss per length of steam tunnel can be approximated as follows. Calculations are made with an assumption of five steam tubes per tunnel each with a diameter of 0.457 m.

$$q = 36.287\ {}^{W}/_{m^2}$$

$$q_t = 260.53\ {}^{W}/_{m}$$

Given that there are 10.3 km of walkable steam tunnels across campus, this means there is about 2681.6 kW of power lost throughout the steam tunnels, assuming there is uniform heat loss throughout the tunnels.

For forced convection in ventilated sections of the tunnel, a similar approximation can be made. Since the airflow is parallel to the direction of the tubes, the flow can be modelled as a flat plate. The Nusselt number is calculated using the following equation.

$$Nu_L = 0.0308 \cdot Re_L^{4/5} \cdot Pr^{1/3} \tag{6}$$

$$Re_L = \frac{\rho \cdot v \cdot L}{\mu} \tag{7}$$

The Reynold's number is calculated assuming an air speed of 3 m/s which gives the following results.

$$Re_L = 7.947 \times 10^5$$

$$Nu_L = 1440.52$$

$$h = 18.127 \ {}^{W}/_{m^2 \times K}$$

A check is done to determine if the flow results in mixed convection or if free convection effects are negligible. The check determines that free convection effects are negligible in this scenario.

Using the convection coefficient from above, the following heat losses per area and per meter of tunnel are calculated.

$$q = 690.64 \ {}^{W}/_{m^2}$$

$$q_t = 4.95 \ {}^{kW}/_{m}$$

This is likely an extremely high estimate for heat losses in the steam tunnels, as only certain small sections are ventilated, so it is unrealistic to apply this over the total length of steam tunnels. However, the team observed a 27.4 m section of ventilated tunnel during the site visit and using the estimate above this section, there is a loss of about 135.7 kW of energy.

For context, shown below in Figure 5 is the annual heating and cooling demands of the CIF (Campus Instructional Facility) at UIUC. The peak heating demands reach around 350 kW while the average heating demands in winter hovers around 150 kW. Using the free convection estimate from above, 7.6 buildings could be heated at peak load and 17.8 buildings could be heated at average load using the heat lost in the steam tunnels. Using the forced convection estimation, nearly one building at average load could be heated with the losses in the ventilated section observed.

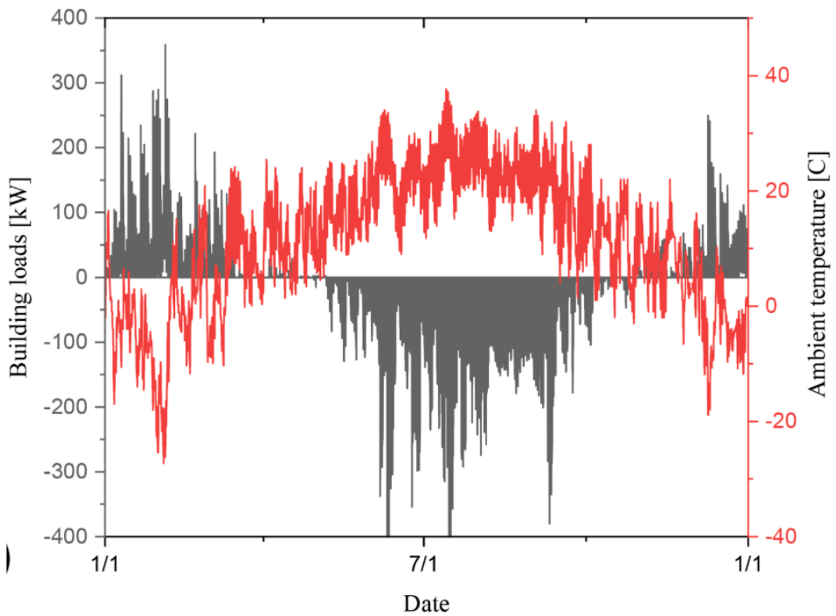


Figure 6. Heating and Cooling Demands of CIF [11]

The total cost to the university from this wasted heat can also be calculated. Using data from the National Renewable Energy Laboratory (NREL) [5], the cost of steam production using natural gas is approximated at $8.82/tonne. Using tabulated data on the energy available in steam as well as assuming an eight-month heating season and 80% efficiency in building heating systems, the total steam usage is calculated as 250,20 tonnes which leads to an estimated cost of $220,600 per year.

Coupling these results with figures from the Environmental Protection Agency (EPA) [2], the total carbon emissions caused by this wasted heat can be estimated. The EPA estimates carbon emissions from burning natural gas at 1.94 kg per cubic meter of natural gas burned. Using the NREL data for energy in natural gas of 38.37 MJ per cubic meter and a combustion efficiency of 81.7%, the total carbon emissions is calculated as 3135 tonnes of $CO2$ per year.

It should be noted that the original estimation of heat loss within the steam tunnels is performed using assuming only natural convection within the tunnels. However, there is evidently a lot of potential for energy harvesting from waste heat as well as cost saving and lowering emissions.

2.3 Velocity and Thermal Boundary Layer Simplifications

To develop an approach to the heat transfer mechanics of the geothermal panel system, simplifications and assumptions must be derived. In particular, the estimation of a constant thermal and velocity boundary layer is important to simulating heat transfer rate of the panels under idealized conditions. To do this, a study by Peltier et al. [4] was reviewed and implemented in application to the steam tunnels at Abbott Power Plant.

Within the paper, airflows in 500 m tunnels with various shapes were simulated using CFD, and the development of thermal and velocity boundary layers was analyzed. Notably, the governing equations employed within the models referenced Reynolds-averaged Navier Stokes equations, calculating an effective thermal conductivity of the tunnel, and creating an equation for equivalent hydraulic diameter due to the variation in tunnel shapes.

More specifically, to approach the heat transfer in solid and fluid regions of the tunnel, the energy conservation equation was employed. Mass and momentum conservation equations were also leveraged to account for air being a compressible fluid.

Following the simulation, correlations between thermal and velocity boundary layers and cross section shapes were derived, as shown below in Figure 6.

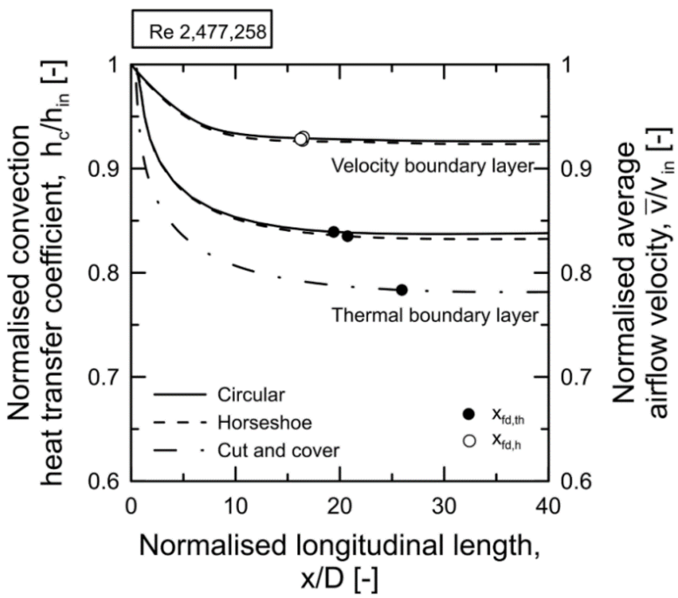


Figure 7. Development of Thermal and Velocity Boundary Layers for Different Cross-Sections [1]

For its applications to the steam tunnels at Abbott Power Plant, the following measurements are important to be noted.

Table 1. Abbott Measurements	
Tunnel Height (m)	2.44
Distance from Tunnel Entrance to Vault (m)	27.43
Tunnel Width (m)	1.83

In the paper, the equivalent hydraulic diameter was calculated using the following equation:

$$D = \frac{4A}{P} \tag{8}$$

The collected Abbott Measurements are then used to calculate the hydraulic diameter as follows:

$$A = 2.438\,m * 1.829\,m = 4.459\,m^2$$

$$P = 2 * 2.438\,m + 2 * 1.829\,m = 8.534\,m$$

$$D = 4 * \frac{4.459\,m^2}{8.534\,m} = 2.09\,m$$

It can then be extrapolated that installation should occur as close to 20.88 m (10*D*) from the vault to assume a constant thermal and velocity boundary layer in the steam tunnels. A constant thermal and velocity boundary layer are also assumed, such that the flow is not as turbulent, and the temperature surrounding the panels remains relatively constant.

However, it is also important to note the shortcomings of this literature implementation. This does not consider the change in airflow when the entrance is reached, where a door breaks whatever laminar flow might have developed. This also does not consider the possible turbulence caused by the pipes in the steam tunnels, which offer obstruction to the flow.

Another measurement that was considered in this study is surface roughness of the tunnels. While this may be helpful in the team's heat transfer calculations, it would be difficult to estimate what this value might be due to the presence of pipes within the steam tunnels. As a result, it was not used in these calculations.

2.4 Geothermal heat pump systems: status review

A study by Self et al. [9], reviews geothermal heat pumps in terms of costs, CO2 emissions, and other parameters such as coefficient of performance (COP). In the context of our project, coefficient of performance will be a key metric in characterizing the performance of the Enerdrape panel system. The term coefficient of performance is defined as the relationship between the power (kW) input to the system and the power (kW) generated by the system. According to this study, a typical COP for geothermal heat pumps is anywhere from 3-5 [9]. This metric can be used as a baseline for our project. If Enerdrape's panels can produce a COP of 3-5, the team will be able to confidently report back to Abbott that Enerdrape's system can be used as a competitive geothermal heat pumping system.

It should be noted that the project will not integrate a heat pump. This is because the scope of our project is to evaluate the performance of Enerdrape's technology in the environment of a steam tunnel, not to use the technology to heat a building. If the project is a success, a heat pump would to be integrated to fulfil the end goal which is to heat or cool a building.

3. Project Objectives and Deliverables

The goal of this project was to install Enerdrape's geothermal panels in the underground steam tunnels at Abbott Power Plant and characterize their performance. This involved many deliverables throughout the semester, with the first being a design proposal for installation for the panel array to PRVN (a design agency hired by Abbott Power Plant). After approval, the panels were successfully installed with the help of the contractor Davis-Houk. Once panel installation was complete, plumbing and hydraulic systems were installed by the team, and the closed-loop system was completed over a number of weeks. To finalize the system, the test cart was installed outside of the tunnel and connected to the system to supply it with a pump, chiller, water reservoir, filter, and auxiliary contacts with a thermal overload relay that were wired directly to the programmable logic controller. Some delays caused this to run a few weeks behind schedule, but the system was still finished in time to test. Upon completion, the initial goal was to conduct rigorous tests on the panels to collect data on temperature and pressure differential generated through the panels, flow rate, and power consumption. Using this data, the team intended to quantify the panel's performance based on their coefficient of performance (COP), energy, cost, and carbon emissions savings. This was to allow us to produce our main deliverable for Abbott, which is a feasibility report on Enerdrape's technology. This report will tell Abbott how much heat is lost to the environment, how much heat can be captured by Enerdrape's technology, and a timeline of when Abbott could see a return on investment should Abbott decide to install more panels in the steam tunnels.

As discussed in later sections of this report, time-limiting factors prevented us from achieving the number of tests we originally intended to achieve, and only one steady-state test provided sufficient data for all data sensors and the system. However, this was completed before the final week of April and allowed for the team to create a final presentation with findings for both the affiliates of the Abbott Power Plant and Enerdrape. Due to the lack of experimental results, a complete feasibility report could not be generated, but some useful conclusions could still be drawn from the testing data. The remainder of the report will demonstrate how the design solution was decided upon, and what took place following that decision to allow us to install a functioning system that provided results on the effectiveness of the panels in this environment.

4. Product Design Specification (PDS)

The team has used the PDS as an outline for the ideation process. Of the 29 primary elements identified in Figure 7, eight were selected as necessary for the project.

Figure 8. Primary Elements of the Product Design Specification

Three of the most important constraints for Enerdrape are performance, testing, and environment. Evaluating the heat losses, temperature gradients, work, and power are imperative to guiding proper coefficient of performance estimate models. Pressure drops with precision and repeatability are also necessary to account for, as the system components must be able to withhold up to 12.4 bar (180 psi) at any given time. Also, flow rate will be constantly monitored to ensure 9.1 LPM (2.4 GPM) is maintained for optimal panel performance. By collecting useful results from this project, the team may provide Abbott with useful data on waste heat capture for potential improvements to the current university steam tunnel system.

A few other important aspects of the product design specification include processes and standards, specifications, and legal aspects. An external design firm needs to approve the team's installation strategy and approach before allowing the project to move forward. There is a special process for installing the panels on the walls, connecting sensors, and using data acquisition systems. Meticulous attention to details during the planning and ideation processes are essential, and this will be possible with a thorough analysis of patents, literature, and product data.

Through conversations with the sponsor, the group also decided that maintenance and safety are much needed to allow contractors, the team, and plant workers to be able to move freely around and operate near the installed panels without obstruction. Proper installation and panel layout is the primary objective in fulfilling these constraints. Abbott is looking for an economically viable project, and without paying attention to these constraints the project can delay and cost more.

The group found it unnecessary to focus on elements of the product that are not involved directly with the installation and testing of the panels. For this reason, the remaining design boundary constraints are not being focused on due to irrelevance to the scope of our project.

5. Ideation and Concept Selection

Ideation for the geothermal panels is primarily focused on location and configuration of the installation. By changing panel layouts, selecting certain pump and chiller systems, and determining where in the tunnel to place the panels, system performance can be optimized.

Before going further, it should be known that all concepts include ten Enerdrape geothermal panels; five panels connected in series, connected in parallel with another five panels connected in series (5S2P). This configuration is a recommendation from Enerdrape's CTO, Professor Alessandro Rotta Loria. Our team will be able to easily change this configuration with push-to-connect fittings, should we need to. A data acquisition unit will collect measurements on temperature, mass flow rate, pressure, voltage, and amperage. This data is necessary to characterize the technology's performance. Lastly, the installation location of concepts 1-4 are on the flat walls of the steam tunnels within Abbott Power Plant shown in Figure 8. It may be difficult to see in the image, but there is sufficient room between the wall and pipes to install the panels. This location maximizes the amount of surface area shared between the panels and the conductive heat source (the wall).

Figure 9. Installation location of concepts 1-4

For the overall system, five primary concepts were considered. The first concept attempts to utilize an open loop system where there is no recirculation of fluid (Figure 9). This idea pulls water from the city water tap (located inside the Abbott Power Plant) into Enerdrape's geothermal panels through tubing and a pump. The water leaving the system will be emptied into a large reservoir. One flaw of this concept is that regular maintenance will be required to empty the reservoir at the end of the system. The next concept iterates on this idea by closing the loop and adding a chilling device.

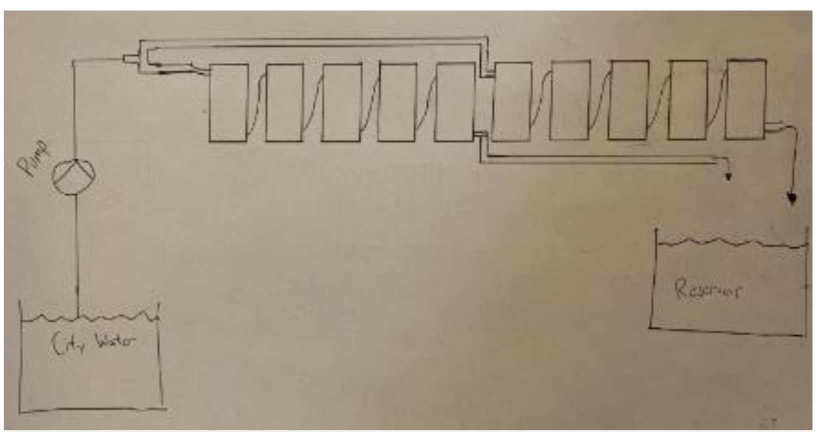


Figure 10. Schematic of Concept 1

In the second concept there is tubing connecting the outlet of the panels back to the city water tap making a closed loop system (Figure 10). This concept also implements a chiller to cool the water before entering the geothermal panels. Having control over the inlet water temperature will allow us to find the optimal inlet water temperature for maximum energy generation. The third concept uses this exact same system; however, the chiller is replaced with a car radiator and fan. The benefit of this concept is the reduced cost of buying a radiator rather than an expensive chiller.

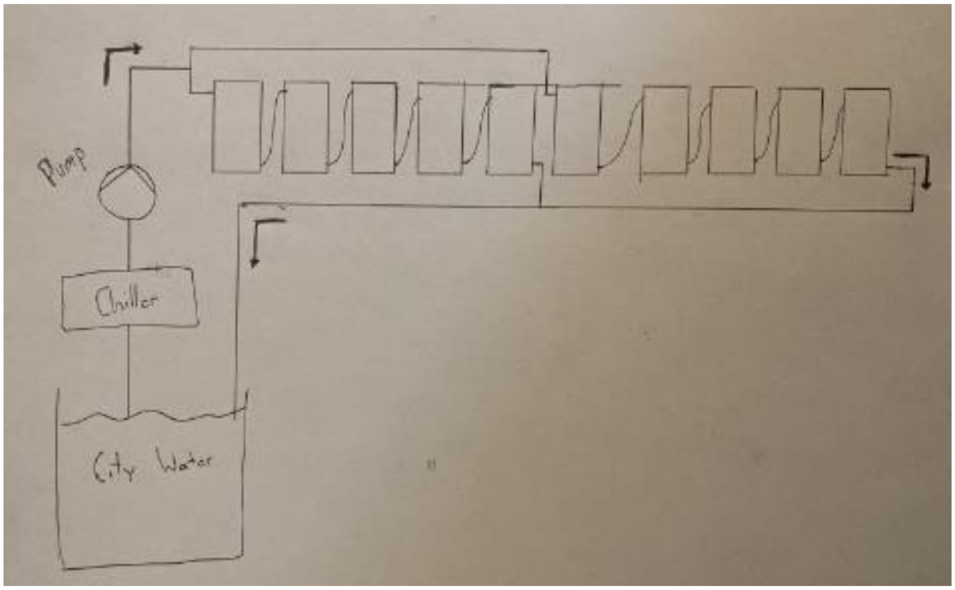


Figure 11. Schematic of Concepts 2 and 3

The fourth concept eliminates the need for a connection to the city water tap. This concept implements a portable water reservoir that the pump will draw water from and push through the panels (Figure 11). At the outlet panel, tubing will be routed back to the portable reservoir making it a closed loop system. There are two benefits associated with this concept. First, there is no risk of spilling large volumes of water in the steam tunnels if the case of a system failure such as a tube bursting or disconnecting. The amount of water that could be spilled is limited to the reservoir's size (roughly 30-45 liters). Second, there is no longer a need for the panels to be close to a large water source such as the city water tap. This is not as important for our installation because the tap happens to be close enough, however for different installation sites this may not be the case.

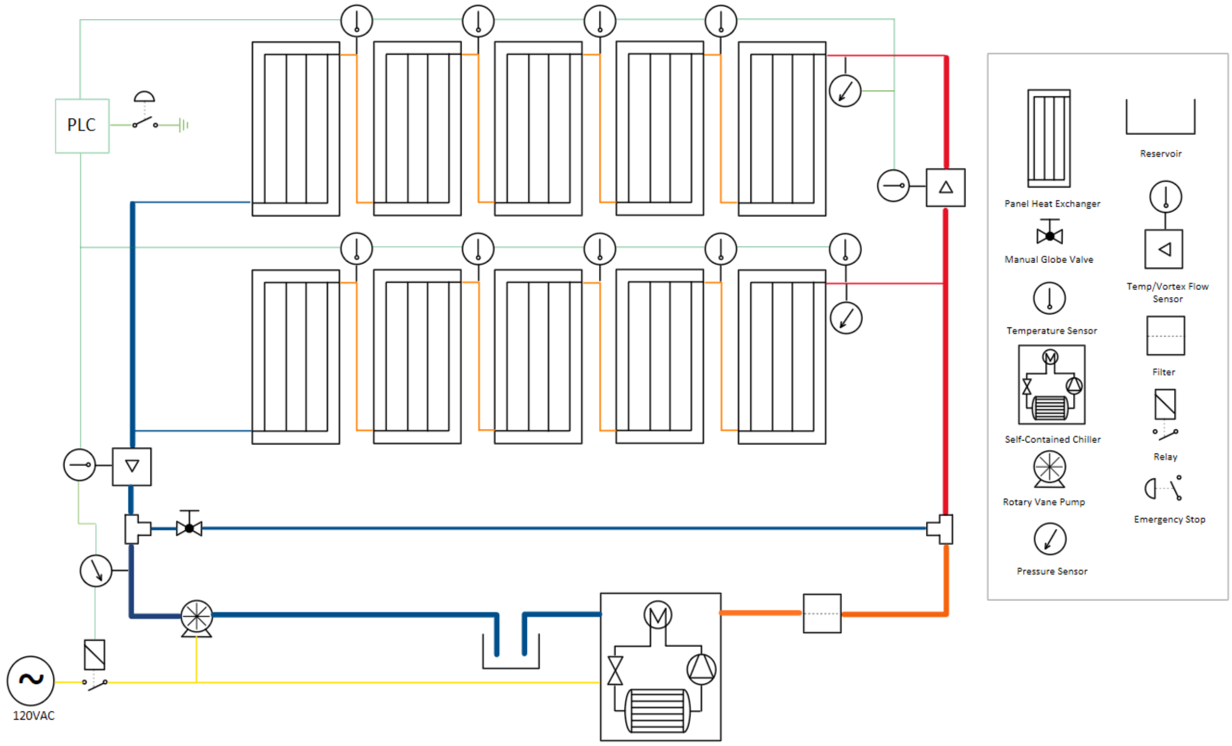


Figure 12. P&ID Schematic of Concept 4

The fifth concept implements all features within the fourth, however, the installation location is changed from the walls to directly on the steam ducts (Figure 12). The idea behind this concept is to maximize the temperature interfacing with the geothermal panels. Intuitively, this may seem like a good idea, but there are a few important drawbacks. Enerdrape's technology has been optimized so that the primary mode of heat transfer is conduction. In their pilot case study, it was found that their system is influenced by the ambient air temperature (convection) by roughly 15% [7]. This means that 85% of the system is influenced by conduction. Placing the rectangular panels directly on the circular steam ducts significantly reduces the amount of surface area shared between the panels and the heat source (steam ducts), and nearly removes conduction as a mode of heat transfer. In general, this concept forces the panels to rely on convection rather than conduction to generate heat which is not the technology Enerdrape has developed.

Figure 13. Installation location of concept five

Table 2 details five design elements each with an assigned weight. Efficiency and safety are the most important criteria while cost is the least important. Installation and maintenance are also important, just not as much as efficiency and safety. After ranking each concept according to the chosen criterion, it was found that concept 4 scored the highest. The defining feature of concept 4 is the portable water reservoir which minimizes the risk of water spilling into the steam tunnels and eliminates the need for installation to be near a water source. Along with a high safety score, efficiency with this concept is highest through elimination of the need for additional tubing and equipment that may create power losses. Less equipment also means less maintenance costs or man-hours needed to deal with potential issues. This is the design the team will be moving forward with.

Table 2. Numerical Decision Matrix for Five Approaches

Design Element	Weight Factor	Approach					Weighted Rating				
		1	2	3	4	5	1	2	3	4	5
Ease of Installation	3	3	5	4	2	1	9	15	12	6	3
Low Maintenance	3	1	3	2	5	4	3	9	6	15	12
Efficiency	5	1	3	2	5	4	5	15	10	25	20
Safety	4	1	3	2	5	4	4	12	8	20	16
Low Cost	1	5	3	4	2	1	5	3	4	2	1
Totals:	26						54	40	68	52	

6. Solution Procedure

To begin, acquiring temperature data and calculating the thermal conductivity of the wall and the steam ducts within the tunnels at Abbott Power Plant provided important information for performing hand calculations to predict the total heat extraction.

To experiment with different configuration parameters of the system more easily, a 1-D heat transfer model was simulated using Simscape. This enabled the team to decide on optimal pump flow rates, orientations and configurations of the panels, chiller properties, and various other important parameters. Figure 13 below shows the model used to recreate Enerdrape's test case. From this the team was ultimately able to estimate 2.08 kW of heat can be extracted at Abbott.

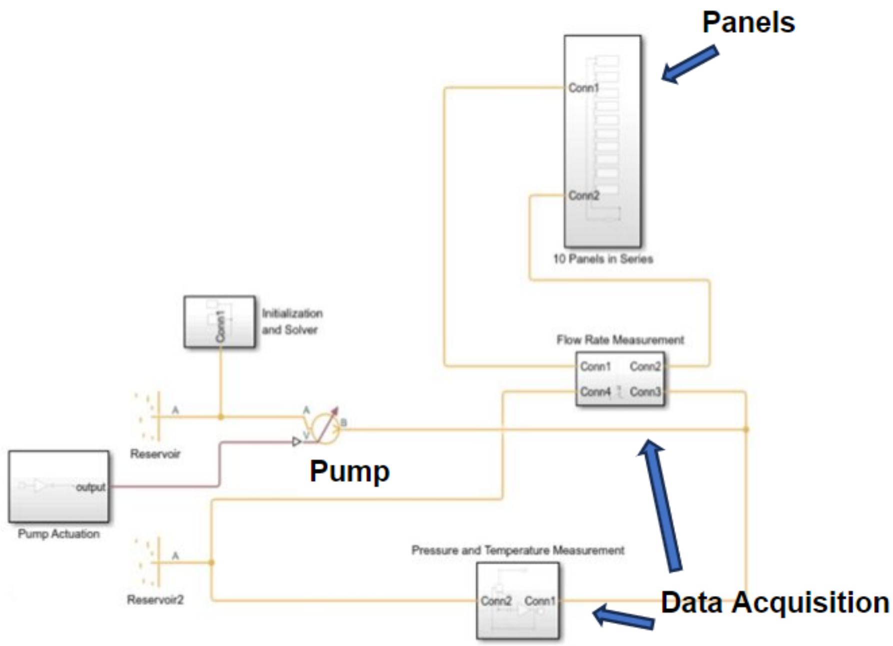


Figure 13. Model of Enerdrape Test Case

Using hand calculations and simulation to derive head ratings and pressure requirements due to pressure losses within the system, an appropriate pump and tubing were ordered. Specifically, the pump and the corresponding motor were ordered separately to reduce costs and assembled by the team. The chiller was selected by observing the heat extraction from the Simscape model and extrapolating the cooling power required by the chiller, with a 1.7 factor of safety to account for the reduced efficiency of the unit in elevated temperature environments.

In addition to the initial 1D thermal model that was developed from thermocouple measurements done at Abbott, the team generated a CFD analysis as well. The boundary conditions for this simulation were informed by a second round of measurements from an infrared thermal camera, which can be seen in the figure below.

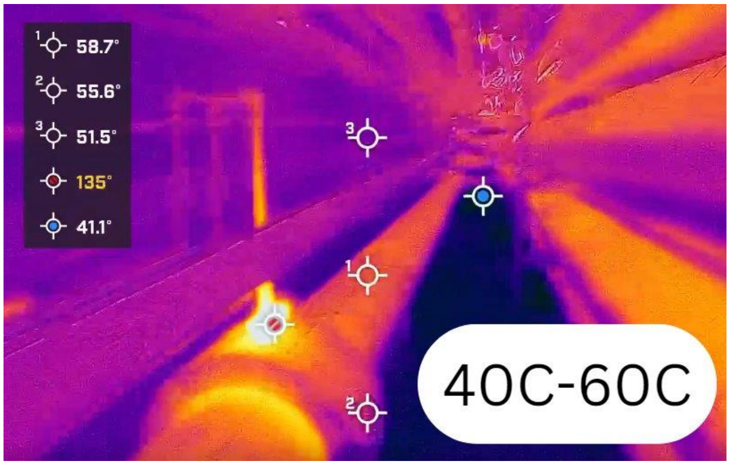


Figure 14. FLIR Camera Tunnel Image

As the tunnel was left undisturbed and normally ventilated before measurement, the readings taken were assumed to be representative of the steady state temperature gradients. Therefore, modeling the geometry as isothermal walls yielded the heat transfer rate to the walls of the tunnels, seen in the next figure.

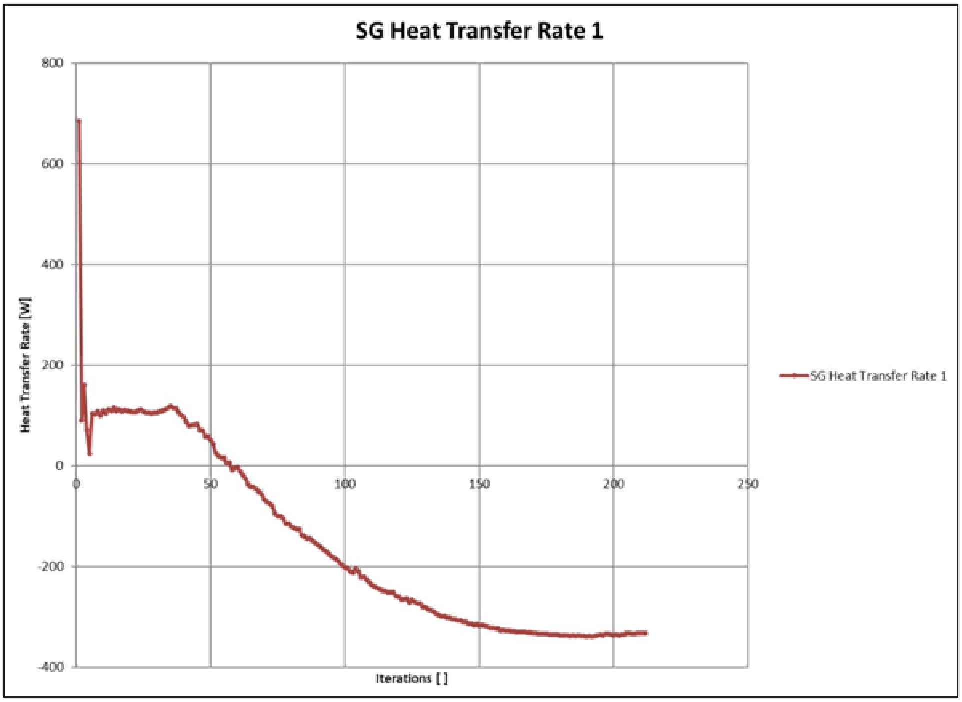


Figure 15. Isothermal Wall Geometry Heat Transfer Rate Model

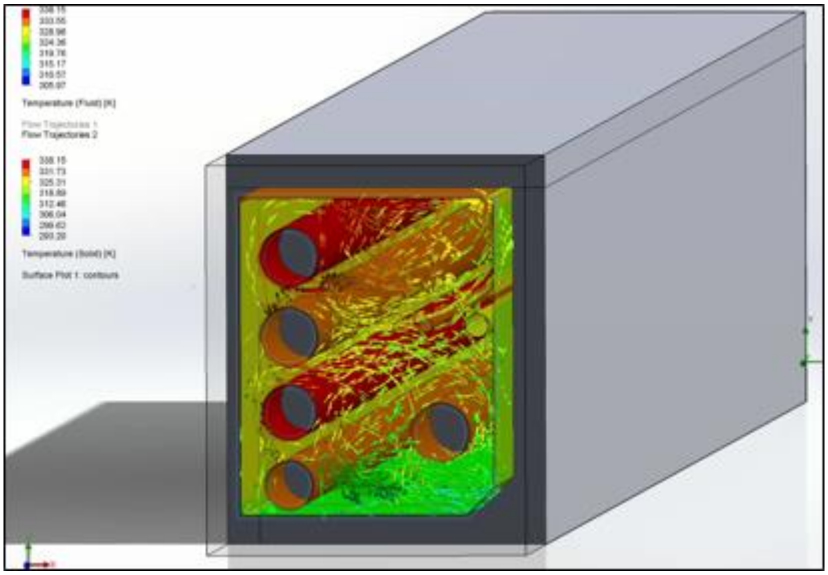


Figure 16. Computational Fluid Dynamics Analysis

The CFD analysis estimated that Abbott loses 12.5 W/m. Using the calculations seen in the appendix, the team concluded a cost hit of $40-45k in monetary losses for Abbott, throughout the 6.4 miles of steam tunnels, which represents enough energy to power 100 homes. The calculations for these losses can be seen in Appendix 10.1.

During the process of product sourcing, it was important to make sure that all the elements of the system were rated to the maximum temperature within the steam tunnel and maximum expected pressure, along with some factor of safety.

The Enerdrape panels were horizontally installed on the walls rather than vertically due to constraints from the piping. PRVN, a local engineering consulting agency, reviewed the panel orientation and design. Following the design review, Mike Larson from Abbott Power Plant carried out the contracting work to Davis-Houk to complete the installation of all ten panels (figure 17) on the tunnel walls.

Figure 17. Panel Array Installed in Steam Tunnel

To follow the closed-loop system, a pump attached to a cart will generate a controlled flow. Tubes will carry the water through the Enerdrape panels, and then return through a filter and into a chiller on the cart. The chiller will cool down the water temperature and allow for greater heat extraction due to the stronger thermal gradient.

A visual of the pump can be seen in the figure below:

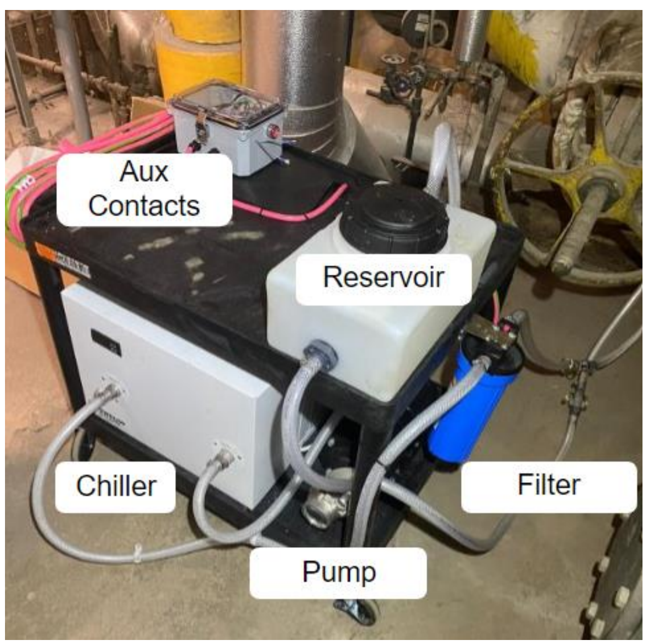


Figure 18. Cart for Component Housing Outside of Tunnel

We acquired a programmable logic controller (PLC), ethernet and memory data acquisition unit (DAQ), thermocouple and input/output (I/O) modules, and motor controllers to properly monitor and control the closed-loop system (see figure 19 below). To log data received from our thermocouples, flow meters, and pressure transducers, a PLC with attachable thermocouple modules and I/O modules will be used. Notably, the PLC has 24V relay outputs, which are then connected to two motor controllers or auxiliary contacts which control power to the chiller and the pump. The selected auxiliary contacts are meant for three-phase motors. Since three-phase motor controllers are sensitive to phase loss, the same line for our single-phase motor will be fed through each of the terminals corresponding to the three phases of the auxiliary contact. The motor controller for the pump also has a thermal overload relay, as the pump and its motor do not have one built in. For data acquisition and storage, the PLC will connect to the human machine interface (HMI) by ethernet cable, where all remaining data points will be stored by SD card.

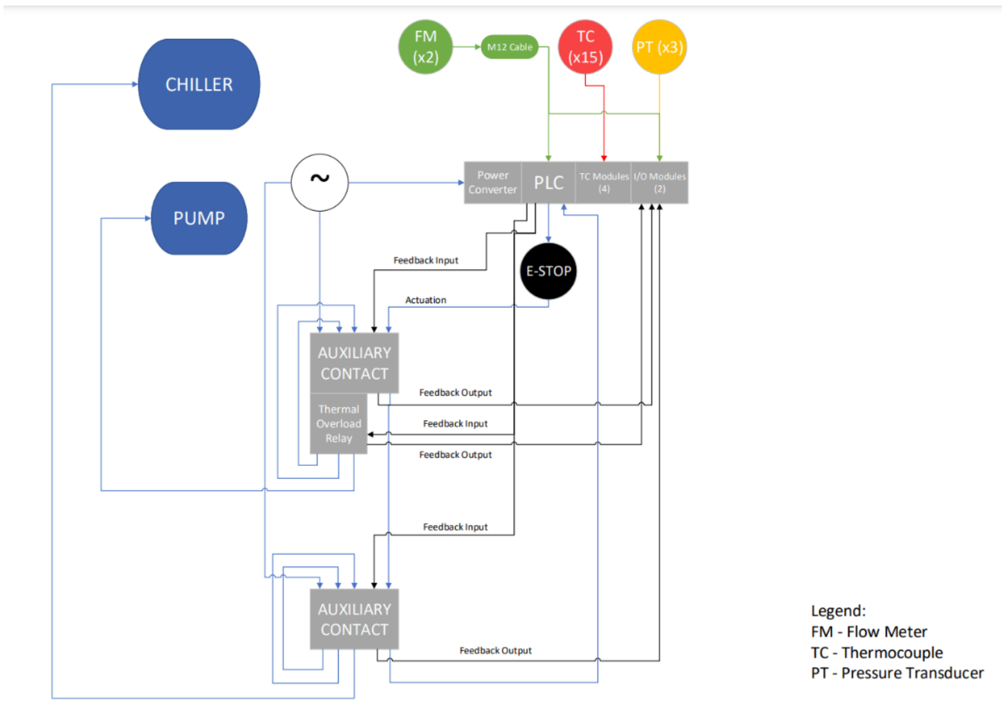


Figure 19. Electrical System Schematic

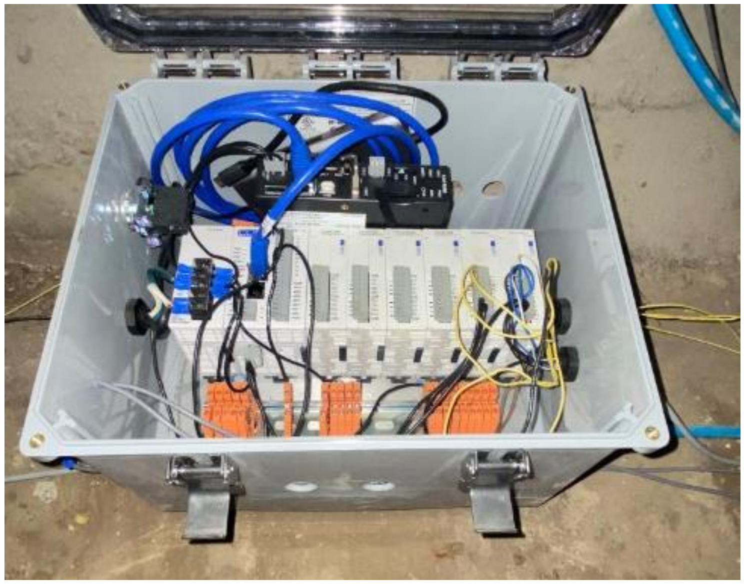


Figure 20. PLC and HMI Setup in Electrical Box

Regarding the controls logic, there are a few elements to our system. First, we have implemented an emergency stop button on the cart with the pump and chiller in case any unnoticed changes occur. Second, our PLC is programmed to shut off the system by use of the auxiliary contacts in two different situations; if pressure readings are out of range, and if flow readings are out of range. The reason that these two sensors dictate system operation is because if flow is too low, there is a leak in the system, and if pressure is too high, our system components may fail are they are rated to a certain pressure value, or there is excessive backpressure in our system. These logic components have been tested, both intentionally through setting adequate range values and through finding a leak in our system and having the PLC actively shut off flow. To follow the controls logic, a start-button on the PLC box will be pressed. There will be a 15 second delay, and then the system will turn on. It will run for another 30 seconds, allow time to manually adjust the flow valve, and attenuate to steady flow and pressure, after which conditions for pressure and flow range will be checked. If these values are out of range for another 25 seconds of operation, it is permitted to shut off and start up again once the values enter the range. After another 25 seconds, if the system shuts off, it is not able to start up again. This logic allows for manual adjustment of variables which must be controlled, along with grace for variability in flow and pressure readings, although we do not expect that the values should be out of range for no reason.

For data acquisition and storage, the data processed by the PLC will be transmitted to the C-more EA9-RHMI human machine interface (HMI). Through use of a standard RJ45 ethernet cable connection, the data from every sensor can be processed at one data point per second, and stored onto an SD card that is capable of logging 32GB of data. This potential storage is much more than what is needed for the timeline of this project, but provides for an easy form of data accessibility. With this, all system data can be logged once the HMI is turned on and can be continuously logged for hours and even days at a time while being left unattended. If some sort of system error trips the relay and causes system shutdown, this can be logged through C-more software's programming capabilities that allow for event alarms and exact time stamps available in .txt form. This can highlight the source of the issue and allow for efficient troubleshooting and maintenance of the system.

7. Budget

This project was allocated $50,000 in budget to spend on necessary installation materials, labor and engineering costs, and test equipment. The team spent $39493.30 leaving future groups $10506.70 left in the budget. Table 5 outlines the final budget and all components that make up the project's total expenses.

Table 3. Project Budget

Item	Price ($)	Quantity	Cost ($)
15 Enerdrape panels and mounting components	13801.00	1	13801.00
Davis Houk Installation Contractor Fee	10000.00	1	10000.00
PRVN Consulting Fee	5000.00	1	5000.00
316 Stainless Steel Water Chiller 1HP	1899.99	1	1899.99
Rotary Vane Pump Head and Induction Motor	768.71	1	768.71
Flow Meters	223.00	2	446.00
Pressure Transducers	107.56	3	322.68
Thermocouple Wire, Type T 16 Gauge	1.77/foot	250	442.50
Click PLC with 4 Temp. Modules and 2 I/O Modules	1393.00	1	1393.00
C-more HMI	521.00	1	521.00
Plastic Rolling Cart with Electrical Outlet	196.14	1	196.14
FLIR Smart Phone Adaptor	597.73	1	597.73
Tools (plier wrench set, heat gun, pinch clamp pliers, hose and tube clamp pliers, electrical stripper, wire ferrule crimper)	667.93	1	667.93
Semi-Flexible Tubing (½ Pipe Size, 100’ long)	50.87	4	203.48
Flexible Tubing (½ Pipe Size, 100’ long)	99.50	1	99.50

Miscellaneous Mechanical/Electrical Components	2827.47	1	2827.47
Lighting (2 Ground Lamps and 1 Headlamp)	306.13	1	306.13
Total			39493.30

8. Testing and Data Analysis

Upon completion of an overnight test, steady-state data was logged for the system at a desired flow rate of 2.1 gallons per minute. Despite the inability to log steady-state data for other flow rates, this data was still sufficient to draw conclusions on the coefficient of performance and heat extracted by the system.

After roughly 15 hours of our system running continuously in the steam tunnel, we were confident the system had reached steady-state. For our application, steady-state refers to the steady-state extraction of heat from our system. Due to an error in the HMI, no data was collected during the 15-hour test, however because the system had already reached steady-state, the team was able to quickly reset the HMI and collect data on our system for a 30-minute test.

This data was extracted into an excel file that allowed the team to easily calculate the average heat extraction, pumping power, and coefficient of performance (COP) of our system regarding the specified inlet operating conditions. These calculations are summarized in Table 6 and are detailed in Appendix 10.4.

Table 4. Steady-State Testing Results

Average Inlet Temp [°F]	70.37
Average Outlet Temp [°F]	77.51
Average Mass Flow Rate, ṁ [kg/s]	0.0752
Average Heat Extraction Q_{out} [kW]	2.245
Pumping Power, Q_{in} [kW]	0.058
Idealized Component COP	38.56

To calculate the coefficient of performance, the team took the ratio of the heat extracted by our system to the idealized pumping power required to overcome the measured pressure drop across our ten panels, which was averaged to be 63 psi for this test case. It's important to note this calculation neglects the electrical power drawn from the pump, PLC, and chiller to maintain generality our results, as their only purpose is to prescribe the flow conditions for our team's testing. In other words, the team thought the performance of the low-efficiency, budget pump and chiller should not hold any weight in our evaluation of Enerdrape's panels. In a robust Enerdrape installation, more efficient, quality components would be used.

The team could have calculated a more realistic denominator power in the COP ratio by assuming the current draw from the pump and chiller datasheets, but that would reflect how the entire system performed, rather than only the component of interest: Enerdrape's panels.

This idealized component COP is more useful to Enerdrape than our system's COP, as they can easily extrapolate our findings and determine how their panels will perform connected to their particular system in a specific environment.

The following graph, developed from our 1D thermal model, demonstrates the greater-than-expected performance of the panel array used for our experiments, as the generated COP value is considerably higher than what would is predicted for that flow rate.

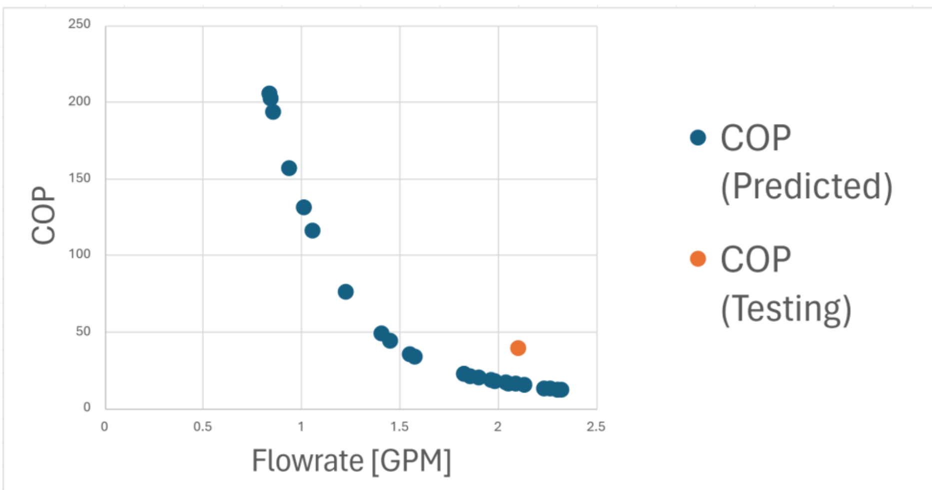


Figure 21. Flow Rate versus Coefficient of Performance for Assembled Panel Array

The model predicts that at a flow rate of 2.1 gallons per minute, the COP will be 15.7. Our actual results produced a COP of 38.56, which is 45% higher than expected. Hence, the panel array can extract much more heat than expected. However, this number alone does not give the team full confidence that the panels will provide a strong return on investment. The team simply doesn't have enough data across a variety of inlet temperatures and flow rates to confidently say the findings from this one test reflect the panels as a whole.

9. Conclusions and Recommendations

The team successfully assembled the test cart, organized and facilitated installation of the Enerdrape panel array and all parts of the hydraulic system, and completed all configuration of the control system and data acquisition system. This allowed for ample time to obtain significant data that could allow the team to draw conclusions on the effectiveness of the geothermal panels in a steam-tunnel environment.

Throughout the semester, all members of the group contributed in various ways to many different aspects of the project, with many subgroups being created but plenty of integration and collaboration ultimately allowing for success with the project. Initially, the group intended to test the system at many different flow rates and inlet temperatures to provide Enerdrape with multiple potential configuration settings for a system in this environment. Delays in order processing, mechanical issues with the chiller, and unexpected difficulty accessing the steam tunnels (due to safety protocol and the need for constant supervision) caused the project schedule to get backed up and prevented initial plans for data testing. Thankfully, the large number of resources within both the Mechanical Science and Engineering Department and the Abbott Power Plant allowed for assistance with processing orders and efficient mechanical repairs, as well as generous accommodation for the team when needed. Ultimately, the timely response by both the teammates and those helping with the project is what allowed for these problems to be solved in time for testing to still be complete. While the total number of tests wasn't what was originally planned, the group still obtained desired results from tests at one flow rate that allowed for calculation of the system's coefficient of performance. From the data the group obtained through experiments, however, there is no concrete evidence that demonstrates the installation of the geothermal panels being a worthy investment for either Enerdrape or the Abbott Power Plant.

Finally, we believe that future work can be done in testing the panels with various flow rates and inlet temperatures, along with tuning a simulation to predict the heat transfer of these panels in various areas such that experimentation is not needed to determine efficacy. This could be done through using an FLIR camera and automatically exporting the data to a simulation to determine heat transfer abilities, should the panels be installed in that location.

In particular, the test-cart chiller system should be modified in order to utilize system identification techniques, which rely on suites of tests with functional inputs. The chiller controller can be replaced by a function generator that can perform the necessary sinusoidal sweeps across multiple frequencies in order to extract system transfer function, as it is expected that it would be possible to model the installation as a quasi-LTI system at discrete temperature differentials. Through this technique, the modeling of the system and the extrapolation of its performance could be extended to a far greater variety of environments with much less computational power. One possible hurdle for this experiment is the low cooling capacity of the selected chiller. It was found that the chiller was unable to reduce the inlet temperature below 70 F even after 15 hours of operation. For this reason, in order to achieve sufficient input frequency range, the chiller should be replaced with a much higher capacity unit.

By implementing these future recommendations, a comparison of more results may demonstrate an advantageous solution for either Enerdrape or Abbott Power Plant in the efficacy and use of the panels.

10. Appendix

10.1 CFD Simulation Calculations

0.08-0.09 $/kWh → 60% is usable for electricity → 0.048-0.056 $/kWh

9.3 [J/s*m] * 31536000 [s/yr] = 293284800 [J/m*yr] * 1000 [m/km] = 2.932 e11 [J/km*yr]

2.932 e11 [J/km*yr] * 1/0.621 [km/mile] = 4.7227e11 [J/mile*yr]

0.048 [$/kWh] * 1/3000 [kWh/kJ] = 1.33e-5 [$/kJ] * 1/1000 [kJ/J] = 1.33e-8 [$/J]

1.33e-8 [$/J] * 4.7337e11 [J/mile*yr] = 6,297.043 [$/mile/yr]

Lower Bound: 6,297.043 [$/mile*yr] *6.4 miles = $40,301/yr

Upper Bound: 7,084.17 [$/mile*yr] * 6.4 miles = $45,338/yr

10.2 C-More Programming References

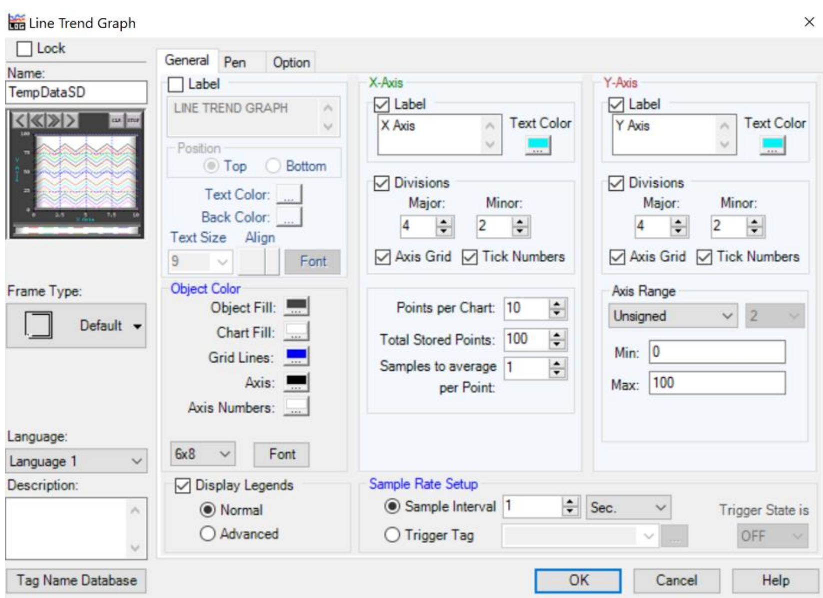
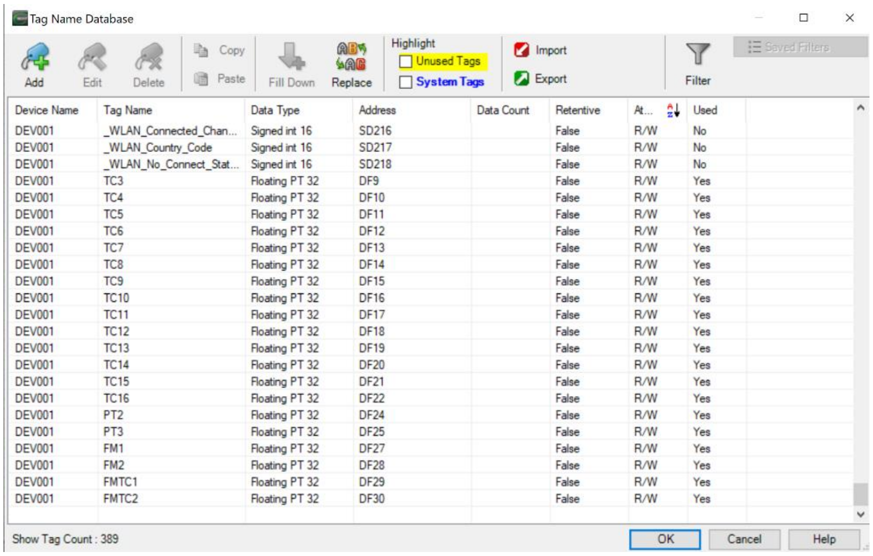


Figure 22. Configuration for Data Storage through C-more Program



Device Name	Tag Name	Data Type	Address	Data Count	Retentive	At...	Used
DEV001	_WLAN_Connected_Chan...	Signed int 16	SD216		False	R/W	No
DEV001	_WLAN_Country_Code	Signed int 16	SD217		False	R/W	No
DEV001	_WLAN_No_Connect_Stat...	Signed int 16	SD218		False	R/W	No
DEV001	TC3	Floating PT 32	DF9		False	R/W	Yes
DEV001	TC4	Floating PT 32	DF10		False	R/W	Yes
DEV001	TC5	Floating PT 32	DF11		False	R/W	Yes
DEV001	TC6	Floating PT 32	DF12		False	R/W	Yes
DEV001	TC7	Floating PT 32	DF13		False	R/W	Yes
DEV001	TC8	Floating PT 32	DF14		False	R/W	Yes
DEV001	TC9	Floating PT 32	DF15		False	R/W	Yes
DEV001	TC10	Floating PT 32	DF16		False	R/W	Yes
DEV001	TC11	Floating PT 32	DF17		False	R/W	Yes
DEV001	TC12	Floating PT 32	DF18		False	R/W	Yes
DEV001	TC13	Floating PT 32	DF19		False	R/W	Yes
DEV001	TC14	Floating PT 32	DF20		False	R/W	Yes
DEV001	TC15	Floating PT 32	DF21		False	R/W	Yes
DEV001	TC16	Floating PT 32	DF22		False	R/W	Yes
DEV001	PT2	Floating PT 32	DF24		False	R/W	Yes
DEV001	PT3	Floating PT 32	DF25		False	R/W	Yes
DEV001	FM1	Floating PT 32	DF27		False	R/W	Yes
DEV001	FM2	Floating PT 32	DF28		False	R/W	Yes
DEV001	FMTC1	Floating PT 32	DF29		False	R/W	Yes
DEV001	FMTC2	Floating PT 32	DF30		False	R/W	Yes

Figure 23. Examples of Data Tags in C-more Program, Utilizing DF Addresses

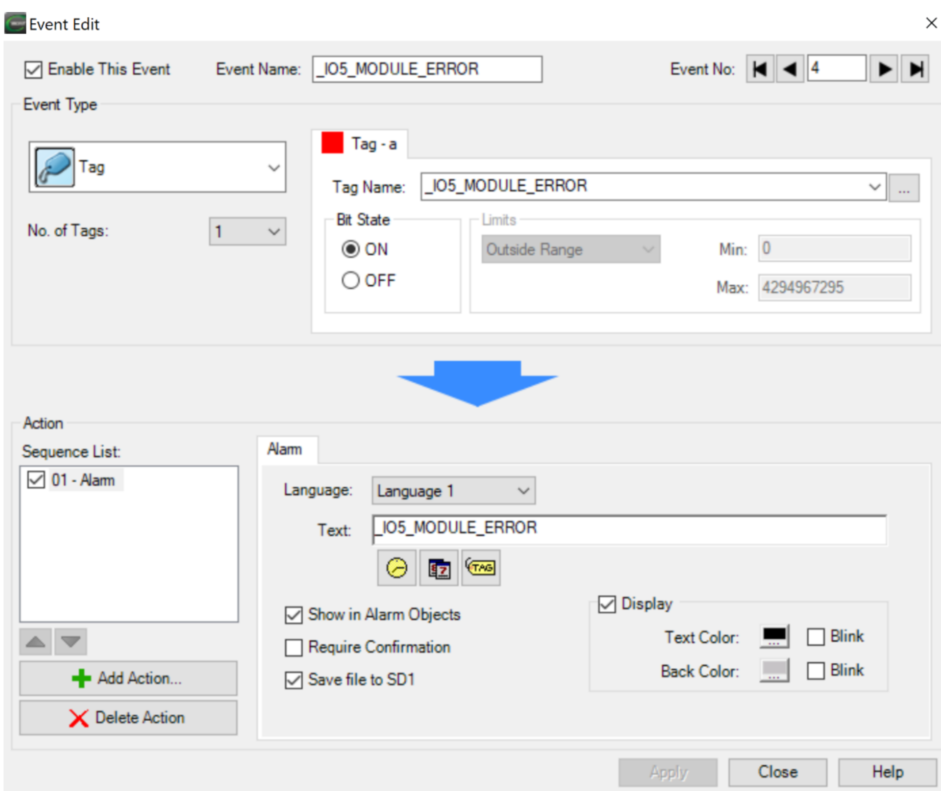


Figure 24. Examples of Event Alarm Tag in C-more Program

10.3 Click PLC Software References

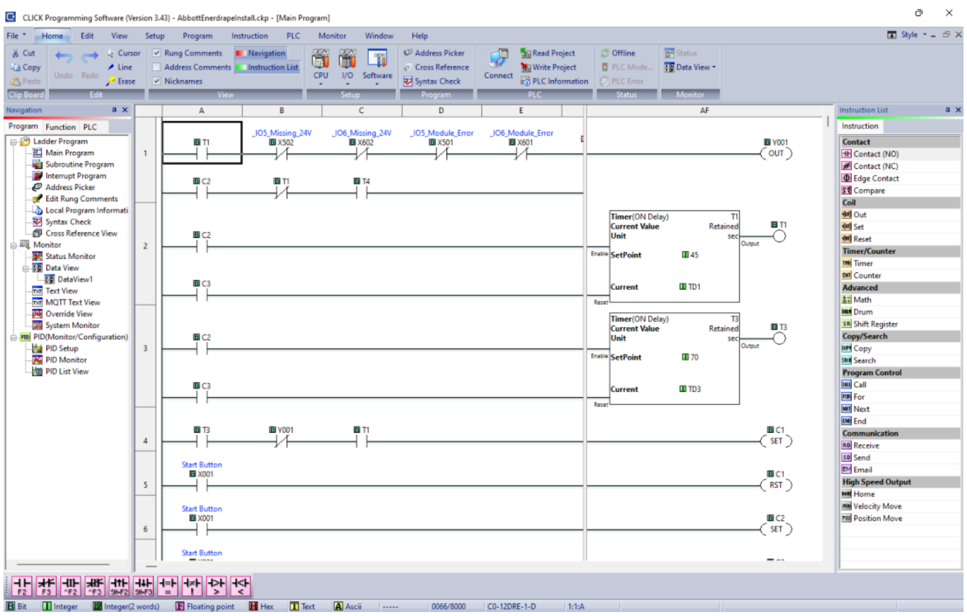


Figure 25. CLICK PLC Software Main Screen

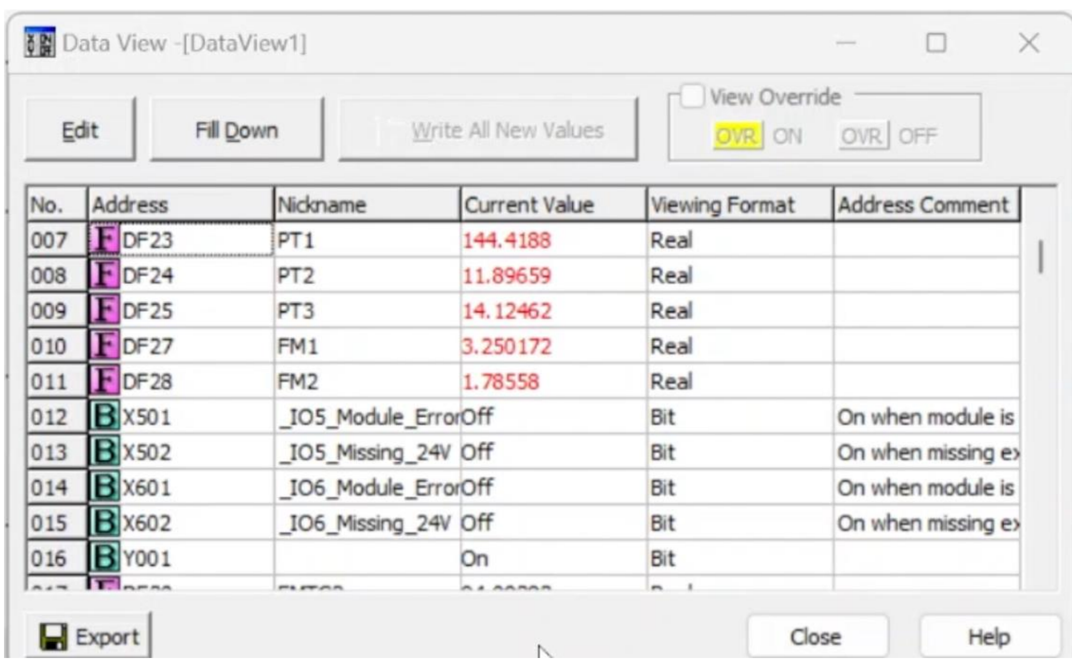


Figure 26. Data Monitor within CLICK PLC Software

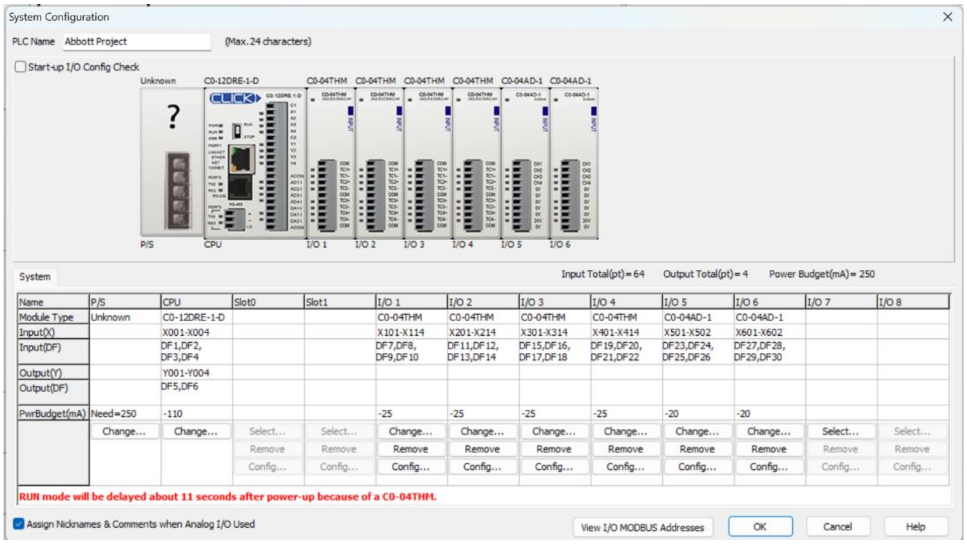


Figure 27. System Configuration for PLC Modules

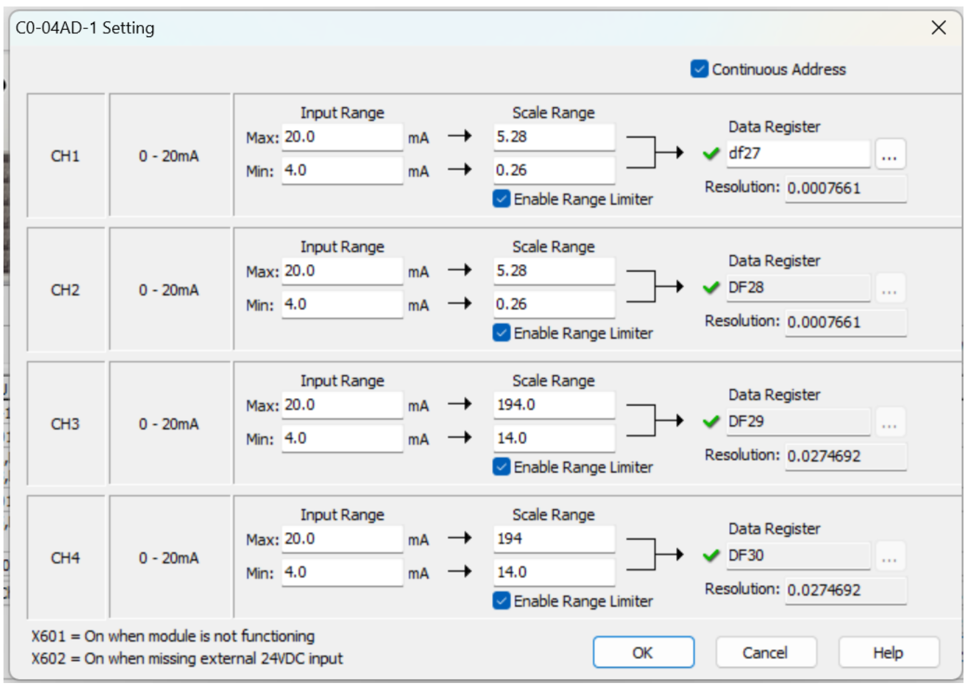


Figure 28. Configuration of Module Inputs (IO6 Flow and Temperature)

10.4 Test Result Calculations

$$Heat\ Extracted = \dot{m} c_p \Delta T$$

$$Pumping\ Power = \Delta p Q$$

$$COP = \frac{Heat\ Extracted}{Pumping\ Power}$$

11. References

[1] A. F. Mills and C F M Coimbra, *Heat transfer*. San Diego, Ca: Temporal Publishing, Llc, 2016.

[2] EPA, "Greenhouse Gases Equivalencies Calculator - Calculations and References | US EPA," *US EPA*, Jun. 23, 2022. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[3] M. De Carli, A. Galgaro, M. Pasqualetto, and A. Zarrella, "Energetic and economic aspects of a heating and cooling district in a mild climate based on closed loop ground source heat pump," *Applied Thermal Engineering*, vol. 71, no. 2, pp. 895–904, Oct. 2014, doi: https://doi.org/10.1016/j.applthermaleng.2014.01.064.

[4] M. Peltier, A. F. Rotta Loria, L. Lepage, E. Garin, and L. Laloui, "Numerical investigation of the convection heat transfer driven by airflows in underground tunnels," *Applied Thermal Engineering*, vol. 159, p. 113844, Aug. 2019, doi: https://doi.org/10.1016/j.applthermaleng.2019.113844.

[5] National Renewable Energy Laboratory, "Energy Tips," U.S. Department of Energy, Dec. 2000.

[6] O. US EPA, "EPA Issues Power Plant Emissions Data for 2021," *www.epa.gov*, Feb. 18, 2022. https://www.epa.gov/newsreleases/epa-issues-power-plant-emissions-data-2021

[7] "Performance of an Enerdrape System," Enerdrape, 2022.

[8] "Product Catalog," 2022. Accessed: Feb. 12, 2024. [Online]. Available: https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/equipment/unitary/water-source-heat-pumps/high-efficiency-h-v-wshp-1-1-2-to-6-tons/WSHP-PRC017T-EN_01072022.pdf

[9] S. J. Self, B. V. Reddy, and M. A. Rosen, "Geothermal heat pump systems: Status review and comparison with other heating options," *Applied Energy*, vol. 101, pp. 341–348, Jan. 2013, doi: https://doi.org/10.1016/j.apenergy.2012.01.048.

[10] T. L. Bergman, *Fundamentals Of Heat And Mass Transfer, Wileyplus Blackboard Card.* S.L.: John Wiley, 2019.

[11] Z. 8Zhao, Y.-F. Lin, A. Stumpf, and X. Wang, "Improving LEED-certified building loads on borehole heat exchangers by coupling subsurface variables," *Applied Thermal Engineering*, vol. 224, pp. 120119–120119, Apr. 2023, doi: https://doi.org/10.1016/j.applthermaleng.2023.120119.

[12] "Waste Heat Recovery: Technology and Opportunities in US Industry." US Department of Energy, US Department of Energy: https://www.energy.gov/eere/iedo/waste-heat-recovery-basics#:~:text=It%20is%20estimated%20that%20between,equipment%20surfaces%20and%20heated%20products.