FINAL PROJECT REPORT

Performance Analysis of Solar Walls in Minnesota
Agreement # B16337

Submitted by:
Minnesota State University, Mankato

Submitted to:
The Office of Energy Security
Minnesota Department of Commerce

Submitted on: June 14, 2011
Amended on: September 27, 2011

Acknowledgements

Completion of this project would not have been possible without the assistance of various public and private entities.

Breck School
3rd Precinct Police Station
AVEDA Corporation
Interdistrict Downtown School (FAIR School Downtown)
St. Anthony – New Brighton School District
Hibbing Courthouse
Cunningham Group
Michaud Cooley Erickson
Automated Logic
McKinstry Co.
Architectural Resource Inc.
Conserval Engineering Inc.
City of Minneapolis
Office of Facilities Management – Minnesota State University, Mankato
RETScreen International

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FINAL REPORT SUMMARY

Performance Analysis of Solar Walls in Minnesota

A study of unglazed transpired solar collectors (referred to as solar walls for this report), has been undertaken. Several installations in the Twin Cities, MN region have been identified, researched, and studied. A combination of weather stations, data logging systems, and building energy management systems were used to collect experimental data on four buildings. Performance calculations were then performed for these buildings and compared with various performance/modeling tools.

Solar walls save energy by pre-heating incoming building air using solar radiation. Buildings that do not require an outside air intake would not benefit substantially from this technology. Solar walls operate by replacing glazing with a perforated absorber plate. The boundary layer effects that develop allow a large portion of the absorbed solar radiation to be transferred to the incoming air. This air is pre-heated thus saving energy that would otherwise be expended in the building. Using too high a volume flowrate of air lowers efficiency as the air is not in contact with the absorber long enough. Alternatively, too low a flowrate results in insufficient pressure to eliminate wind and suction effects; thus lowering efficiency. There is also an energy savings from “recaptured” and “reduced” wall loss. Heat loss from the warm interior of the building passes through the building wall and into the solar collector, instead of being lost to the environment. The solar wall also effectively increases the thermal resistance (insulation) of the building. These effects are relatively small (~ 1% of total savings) and become smaller for buildings that are already heavily insulated. However, this phenomenon does allow the solar wall to continue functioning after sunset by making use of rejected thermal energy that was stored in the building wall during the day.

A few simple design/installation suggestions can be made. Solar walls should be placed on south facing walls. Shading during the winter of any type should be avoided whenever possible as this will lower overall efficiency. While more solar wall area means more energy collected this must be balanced with the air flow needs to obtain the approach velocities for best performance (4 cfm/ft^2). Installation of a bypass damper is recommended. This eliminates the need to pull air through the solar wall in summer and allows the solar wall to naturally vent excess heat. As with any HVAC system, to use it most efficiently the operator needs to be familiar with control/operation system in use (including temperature set points, operation schedule, and damper systems present). If the owner wishes to measure energy savings with the solar wall a means of measuring or determining outside air temperature, air temperature leaving the collector, and air flowrate through the collector is required.

The analysis of actual installations showed the solar walls to be simply constructed and essentially maintenance free. Average collector efficiencies were found to be between 30 and 55% with some of the highest values during the colder months. These values are slightly below the various manufacturer and research laboratory performance claims but are consistent given differences in design and operation in real settings. Temperature rise through the collectors of 40° F or more were not uncommon, in agreement with performance claims. Values of total energy savings per area were found to range from 73 to 238 kBtu/ft^2 per year. The low value (73 kBtu/ ft^2) is below manufacturer claims due to a lower than recommended approach velocity (which results in a collector efficiency less than what manufacturer predictions assume). The more hours a day air is required, the higher the savings value will be.

There have been competing claims that the solar wall helped or hurt building performance during the summer (cooling season). Interviews with site personnel and measurement of interior and exterior wall temperatures (using infrared thermometers) could not verify either claim. Current theoretical and modeling studies of this are also inconclusive. The experimental procedure used for this project was not designed to collect all of the data that eventually was determined to be required for a more in-depth study. Options for future studies include:

- Conducting a pre- and post-retrofit study of cooling requirements for a solar wall installation.
- Conducting measurements with additional temperature sensors within the solar wall to determine which is larger; the radiative heat transfer to the building wall or the convective heat loss from the collector absorber plate (thus determining whether the building is heated or cooled).

Several performance prediction tools were studied. In general the DOE energy worksheet for transpired collectors will overestimate savings by assuming the ideal solar wall efficiency of 68%. RETScreen version 3 was found to predict savings and efficiency more accurately than the DOE worksheet, within the bounds of uncertainties due to local weather. However, version 3 is not very flexible in terms of duplicating actual use conditions (such as night time setback temperatures) and will not produce month by month values. Version 3 is also not readily available. RETScreen version 4 has the potential to closely predict savings if the default solar irradiance and wind speeds can be adjusted to more closely match the site under study. Version 5 entered Beta testing in 2011 with an expected public release in 2012. With any tool or model there are several factors to keep in mind:

- The efficiency should take into account approach velocity, wind speed, and shading (if possible).
- The operating hours used should be chosen carefully to reflect the actual use of the solar wall.
- When specifying multiple set point temperatures is not possible, comparing predictions with several different values will allow a range of possible savings to be determined, and a measure of the sensitivity to this factor to be determined.
- Normal variations in weather (by location and year) will affect the accuracy of results. For example, RETScreen reports differences of over 30% just for local variation from regional weather.

Recommendations for future studies would be:

- Measure additional data addressing the cooling season issues by installing supplementary sensors on an existing solar wall (for a building that is occupied in the summer) or by constructing a mock up solar wall specifically for study.
- Repeat the performance studies with RETScreen version 5 when it is released to determine how it compares to versions 3 and 4.

- Construct a performance model which can take into account the various control system sequences and operating schedules that are possible in real buildings. Use this to conduct a parametric analysis to determine the optimum manner to operate a solar wall.
- Continue to gather any performance data to broaden the data base of energy savings (this will improve the statistical significance of the results). However, most buildings do not have a temperature sensor installed to measure the air temperature exiting their solar walls. This would be required.

FINAL REPORT NARRATIVE

Performance Analysis of Solar Walls in Minnesota

Task 1: Identify existing solar walls and manufacturers.

1.1 Locate regional wall installations through contacts with the Department of Commerce (DOC), American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), architects, and energy industry.

Six examples of solar wall installations were identified in the Twin Cities region.

- Breck School, (123 Ottawa Avenue North, Minneapolis MN)
- 3rd Precinct Police Station, (3000 Minnehaha Avenue South, Minneapolis, MN)
- AVEDA Corporation, (4000 Pheasant Ridge Drive, Blaine, MN)
- Interdistrict Downtown School, now known as the FAIR School Downtown, (10 South 10th Street, Minneapolis, MN)
- St. Anthony Village High School, (3303 33rd Avenue NE, St. Anthony, MN)
- Hibbing Courthouse Annex, (1814 East 14th Avenue, Hibbing, MN)

Detailed information on each of these installations is provided in Appendix 1.1. More detailed information is provided on the first four sites since they were used for data collection.

1.2 Arrange with building owners/managers to perform data collection and collect mfg performance claims.

Initially arrangements were made with the Breck School, the 3rd Precinct Police Station, and the AVEDA Corporation to collect experimental data. As described in Task 2.2 several challenges arose. The Interdistrict Downtown School was originally selected as an experimental site, however; challenges in identifying and measuring all of the required data for that system forced it to be set aside for a time. Eventually it was determined that the required sensors were already installed in the system but were not operational. Even when activated options for logging only allowed limited data to be collected. Due to system characteristics, changing personnel and construction projects no data was collected from St. Anthony. Likewise, due to security concerns it was not possible to gather data from the Hibbing Courthouse.

Discussion of performance claims can be found in later Tasks.

1.3 Gather data and performance claims from solar wall manufacturers.

Three major manufacturers of unglazed transpired solar collectors were identified:

- Conserval Engineering Inc. (SolarWall©)
- ATAS International Inc. (InSpire™)

- Matrix Energy (MatrixAir™)

The majority of patents concerning unglazed transpired solar collectors have been held by Conserval. Conserval has zealously defended these patents. Batiparos s.a.r.l. declared bankruptcy after Conserval brought suit against them in 2010. It appears there are currently five primary patents related to the SolarWall technology. These are all utility patents with 20 year lifespans. As such all but the last two patents have expired. The 5,692,491 patent deals with a perforated (porous) absorber surface and is of the most relevance. The last patent concerns a combination of solar thermal absorber with photovoltaics.

- 4,774,932 Method and apparatus for preheating ventilation air for a building
- 4,899,728 Method and apparatus for preheating ventilation air for a building
- 4,934,338 Method and apparatus for preheating ventilation air for a building
- 5,692,491 Unglazed transpired solar collectors having a low thermal-conductance absorber
- 5,935,343 Combined solar collector and photovoltaic cells

ATAS is licensed to manufacture and sell the Conserval technology within the United States. Matrix Energy produces a very similar product but with a minor design difference that apparently avoids patent infringement (i.e. they pull heated air into the building from the bottom of their collector). However, Conserval and MatrixAir (which is also a Canadian company) have worked on projects together.

Conserval performance claims are that solar walls can raise the air temperature by 30-70° F, can deliver 1.5-3.5 therms/ft^2 (150,000-350,000 Btu/ ft^2) per year, reduce CO_2 emissions by 0.2 ton/m^2 (0.02 ton/ft^2), and reduce annual heating costs by \$3 - \$10 per ft^2. MatrixAir claims temperature rise of 30-50° F. The Federal Technology Alert from 1998 predicts temperature rise up to 40° F, up to 240,000 Btu/ft^2 annually, and solar radiation capture efficiencies of 60-75%. Studies from the National Renewable Energy Laboratory (NREL) predict overall efficiencies of 50% or higher, but only with careful design and operation.

There are also several performance tools for solar walls:

- RETScreen (Excel based feasibility tool)
- U.S. Department of Energy worksheets (sizing and savings calculations)
- ATAS Performance Monitoring (real-time and historical performance data)

Comparisons for several buildings using RETScreen and the DOE worksheets are presented in the results for Task 3.

1.4 Research existing literature (including Energy Star and LEED listings) for data on other installations in similar, northern climates.

Of the buildings studied only Hibbing (which we were unable to collect data at) is LEED certified. However, a listing of LEED certified installations is provided by Conserval on their corporate website (http://solarwall.com/en/products/solarwall-air-heating/architects-and-engineers.php). LEED is a point based system where points can be earned for different sustainable building practices, including but not limited to energy efficiency. Conserval claims that customers have received up to 6 points due to solar wall installations and this number could be as high as 10 under new guidelines (LEED recently updated their guidelines to Version 3 which includes more points for Optimizing Energy Performance and Renewable Energy use). In addition, some LEED credits can be acquired for using recycled components. MatrixAir provides certification that all products contain a minimum of 30% recycled content.

While there are examples of buildings that have received Energy Star status through the Canadian government using solar walls, examples within the continental United States are harder to come by. However, within the U.S. LEED certification has been much more sought after by building owners, architects, and design firms. Therefore, the lack of Energy Star solar wall examples is probably not indicative of anything to do with the technology.

Task 2: Collect experimental data on selected installations.

2.1 Setup experimental data logging systems to gather data.

Experimental data was collected from four sites. Energy added by the solar walls was determined using the temperature difference across the wall and the amount of air flowing through the wall. Since each building system was installed and operated differently each building required a unique experimental approach. In general, data for each site was collected with a combination of a data logging weather station and information from the building's energy management system (EMS). Information on the general sensor equipment used can be found in Appendix 2.1.1. Information on specific sensor installations and use of energy management systems can be found in Appendix 2.1.2.

2.2 Perform data collection through one heating season and one cooling season.

Data from the weather stations and EMS systems have been collected for:

- Breck: April 2009, October 2009 through April 2010
- 3rd Precinct: Jan. through Feb. 2010, April 2010, Nov. 2010 through Jan. 2011
- AVEDA: October 2009 through April 2010
- IDDS: November 2010 through January 2011

Since the project team was not given full access to any of the site's energy management systems data collection was dependent on the assistance of site personnel and the abilities of each system. This prohibited collection from starting, or continuing, at the same rate for all sites. Assistance from the sites was wholly voluntary and was greatly appreciated. However, this did result in some loss of collected data when business interests took priority or when communications problems arose between the MSU team, site managers, and technicians. As should be expected with any experimental study instrumentation faults also arose resulting in intermittent loss of data. These included items such as failed batteries, ice covering the systems, insufficient sun to power the transmitter solar cells, and component failures.

When the loss of data was on the order of a month, it was excluded from the results entirely. The total energy savings for the resulting months with recorded data was then calculated (denoted by Actual in the associated tables). For short periods of data loss on the order of a day, the missing data was found by monthly extrapolation, as explained in Appendix 4 (denoted by Extrapolated in the associated tables). Data for Breck was complete, with no missing days. Data for AVEDA and 3rd Precinct contain months with missing days ranging from 0 to 10 (as shown in Appendix 4, Tables 5 and 6). The extrapolation method parallels typical procedures used in industry and it is not believed this unduly biases the results. In addition, the majority of these missing days occurred in November, rather than the primary heating months of December through February; lessening their potential impact.

None of the sites studied use the solar wall during the cooling season, as would be expected. During the summer AVEDA and 3rd Precinct make use of bypass dampers allowing air to be pulled in without going through the solar wall. In general, Breck does not run their air handlers (which are designed for heating) at all during the summer months. Without air moving through the solar walls there was no data to be collected and no calculations that could be performed for the cooling seasons.

2.3 Collect energy use data.

Data concerning energy use for the various buildings included things such as temperature set points, energy sources, system efficiencies, providers of energy, and pricing information. Combined with the data from Task 2.2 this allowed the calculation of heating degree days and the determination of various performance measures. The resulting calculations and values are presented in the results for Task 4.

As mentioned under Task 2.2 calculations during the cooling season were not possible and therefore, cooling degree days were not calculated.

For sites to monitor their own savings much of the required information is already available to them. A means of determining or monitoring volume air flow ($\dot{V}$) through the solar wall is needed. For simple systems this can be estimated through previous air balancing studies (for constant volume fans) or from energy management system indications of fan frequency (for variable frequency systems). If the fan is pulling air from multiple paths (i.e. not just through the wall) additional information specific to the installation will need to be determined or measured to compute the air flowrate (as in the case of the Interdistrict Downtown School). A measurement of the outside air temperature (T_{OA}) is required, however, this is available in most energy management systems already. A value of the outside air humidity, if desired, can be approximated. Critical to the energy savings determination is a measurement of the air temperature leaving the solar collector (T_{SWOA}). This sensor is not always installed as part of the energy management system. The resulting energy savings can then be found with the following equation (where ρ is the average air density and c_p is the average air specific heat).

$$\dot{Q}_{save} = \dot{V} \cdot \rho \cdot c_p (T_{SWOA} - T_{OA})$$

The temperature change across the collector and the resulting energy savings should be sufficient for a site to assess the solar wall's performance. However, if a determination of collector efficiency is desired it would also require a solar irradiation sensor or weather station to determine solar energy input to the wall (although this data could be approximated with regional data from the National Weather Service of the National Renewable Energy Laboratory).

2.4 Measure temperature distribution on the absorber plate and the exterior wall of the building to determine temperature distributions across the collector.

A grid of temperature sensors was installed at the Breck School to measure the temperature distribution on the absorber plate and exterior wall of the building (i.e. inside the solar wall). The installation of these sensors is described in Appendix 2.1.1.

Data was logged with this system for various periods of time (depending on battery life). In addition, during some summer weeks the Breck School activated their solar wall fan so that we could get data with full air flow through the wall. Data was recorded for:

- Dec-09 12/22-12/31
- Jan-10 1/1, 1/8-1/17
- Feb-10 2/12-2/22
- May-10 5/13-5/26
- Jun-10 6/23-6/30
- Jul-10 7/1-7/6

Examples of the resulting temperature profiles are shown in Appendix 2.4. The results were utilized in the completion of Task 3 to verify the proper boundary conditions of the numerical model. Beyond this, the data indicates that there are complex fluid, heat transfer, and thermodynamic processes occurring. This data could lead to a better understanding of the technology but the scope of this research is beyond this project.

<u>Task 3: Create a numerical model to predict the energy impact of the solar wall.</u>

3.1 Create a numerical model for the solar wall that could be used by architects and engineers to predict its energy impact on a building.

A simple one-dimensional model has been constructed within an Excel spreadsheet making use of macros and VBA programming. The program solves for the various temperatures across the solar wall construction, the energy savings, and the overall collector efficiency. The model requires the following input:

- the collector (solar wall) area (ft^2)
- solar radiation data on a vertical surface for a given location ($Btu/ft^2.h$). This data is available by the National Renewable energy Lab (the solar radiation data manual for flat-plate collectors, Redbook)
- inside conditioned air space temperature (°R)
- outdoor air temperature (°R)
- R-value of the building wall adjacent to the solar collector ($hr.ft^2.°F/Btu$)
- intake volumetric air flow rate (ft^3/h)
- absorptivity of the collector (if not known, a value of 0.9 may be assumed)
- emissivity of the collector (if not known, a value of 0.9 may be assumed)
- emissivity of the building wall adjacent to solar collector (if not known, a value of 0.9 may be assumed)

A detailed description of the mathematics behind this and instructions on how to use the spreadsheet are provided in Appendix 3.1.

3.2 Verify the model with experimental data from buildings.

Several prediction tools that can model solar walls were researched. For this study the ones that appeared to be most relevant were the Department of Energy worksheets for transpired collectors and the RETScreen Excel based worksheet. These tools, along with a new Excel spreadsheet model (developed by Moaveni), were used to find energy savings for AVEDA, Breck, and 3rd Precinct. The results were compared to the experimentally determined values.

In Table 1a the second column (DOE) represents the normal DOE spreadsheet which calculates savings for an entire heating season. In order to calculate savings for 3rd Precinct (which did not have a full heating season of experimental data) the spreadsheet was used with operating hours adjusted for one month at a time and then summed (the third column). A value was calculated similarly for Breck to verify this method. The fourth column represents the older version of RETScreen (version 3) which only allows full heating seasons to be computed. The fifth column represents RETScreen (version 4) which allowed month by month computation for 3rd Precinct.

The sixth column represents the new Excel model developed by Moaveni. The seventh column represents the experimentally determined energy savings without extrapolation for missing days. The final column represents the experimentally determined energy savings with missing days extrapolated using monthly averages.

In Table 1b savings predictions calculated with RETScreen (version 4) are shown. The second through fourth columns use solar irradiance values determined from the NASA Climatology Resource for Sustainable Buildings based on the specific geographic locations. Wind values are from the same NASA source but are varied above and below the predicted (100%) values to determine the influence of wind speed on the result. The fifth column shows the RETScreen predictions with default values for irradiance and wind (as also seen in Table 1a).

Table 2 compares the solar efficiencies calculated in several of the models with the experimentally determined values. The fifth column represents values computed with the ideal theoretical equation given in the RETScreen theory manual (and related technical publications). It should be noted that there are several ways that solar efficiency can be calculated and reported.

Table 3 shows the difference of the predicted energy savings with the extrapolated experimental values.

The following conclusions can be made about these prediction tools:

- The DOE spreadsheet is conceptually simple and allows building operators to make a rough calculation of the maximum solar gain possible over a heating season by making reasonable estimates about the operating conditions of the solar wall.
- The DOE spreadsheet assumes an ideal efficiency based on a 4 cfm/ft^2 approach velocity. Therefore, in most cases it will over estimate the potential energy savings (as noted in the Breck and 3rd Precinct results).
- The DOE spreadsheet is limited in that it does not allow for variations in operating hours, temperature set points, or local weather.
- RETScreen version 3 correctly matched the measured solar wall efficiency but only allows one temperature set point to be used. If a building makes use of something like a setback thermostat (such as Breck does at night) RETScreen version 3 may overestimate the potential savings.
- While RETScreen version 4 includes some useful features (such as month by month calculation) it does require careful attention to the solar irradiance and wind speed values that are used.
- The DOE worksheet and RETScreen version 3 over estimate the efficiency of the 3rd Precinct wall. This can be explained by the fact that this wall likely experiences partial shading on some days. Shading is something that should be avoided if possible since it lowers the potential savings.

- The Moaveni spreadsheet for simplicity neglects the savings potential from energy stored in the thermal mass of the building wall. This causes an underprediction of savings for buildings which run their systems during the night when this energy can be recaptured (such as AVEDA).
- The solar wall efficiency is dependent on local wind speeds. Typical wind speeds in the Twin Cities region are on the high end of most solar wall efficiency charts, resulting in lower than ideal efficiencies when used in the prediction tools (i.e. over prediction of savings).

Table 1a: Comparison of savings predictions with different tools (in MBtu)

SITE	DOE	DOE by months	RETScreen Version 3	RETScreen Version 4	Moaveni Spreadsheet	Actual	Actual Extrapolated
Aveda	208.42		257.90	164.20	84.1	261.37	302.2
Breck	123.97	118.52	91.30	35.30	132.5	60.20	60.2
3rd Precinct	123.37[1]	80.68	98.60[1]	50.70[2]	19.0	40.00	44.2
St Anthony	106.46			76.40	54.4		

[1] These values are for a complete heating season and do not match the experimental data range.

[2] This value is calculated on a month by month basis and not the entire heating season.

Table 1b: Comparison of savings predictions with RETScreen 4 with irradiation and wind inputs from NASA (in MBtu)

SITE	20% wind	100% wind	180% wind	RETScreen defaults
Aveda	178.2	159.3	103	164.2
Breck	65.4	63.6	40.8	35.30
3rd Precinct[2]	49.7	33.3	23.5	50.70

[3] These values were determined based on the actual geographic location from data located at: http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/timeseries.cgi?email=daily@larc.nasa.gov

Table 2: Comparison of solar efficiencies used in the different methods of Table1.

SITE	DOE	RETScreen Version 3	RETScreen Version 4	Predicted by Equation	Actual
Aveda	68.26%	64.0%	27.3%	68.00%	54.9%
Breck	68.26%	34.0%	8.8%	32.00%	30.5%
3rd Precinct	68.26%	54.0%	15.1%	58.00%	30.7%
St Anthony	68.26%		21.2%	68.26%	

Table 3: Difference of predicted energy savings with actual (extrapolated) results.

SITE	DOE	DOE by months	RETScreen Version 3	RETScreen Version 4	Moaveni Spreadsheet
Aveda	-31.0%		-14.7%	-45.7%	-72.2%
Breck	105.9%	96.9%	51.7%	-41.4%	120.1%
3rd Precinct	179.1%	82.5%	123.1%	14.7%	-57.0%

None of the tools studied can be expected to give consistently accurate results. RETScreen version 4 has the potential to be the most accurate of the modeling tools compared. This is dependent on having accurate values for solar irradiance and wind speed; likely different than the provided default values. While obtaining appropriate solar irradiance values for specific previous years is fairly straightforward, obtaining accurate wind values for input is problematic. When used to calculate future savings, lacking an in-depth site study, the analyst will likely have to rely on 20 year average values for input.

With any tool or model there are several factors to keep in mind:

- The efficiency should take into account approach velocity, wind speed, and shading (if possible).
- The operating hours used should be chosen carefully to reflect the actual use of the solar wall.
- When specifying multiple set point temperatures is not possible, comparing predictions with several different values will allow a range of possible savings to be determined, and a measure of the sensitivity to this factor to be determined.
- Normal variations in weather (by location and year) will affect the accuracy of results. For example, RETScreen reports differences of over 30% just for local variation from regional weather.

3.3 Use the numerical model to predict performance of the wall and its energy impact on the fourth building. Modify the model if necessary.

The previous section describes the results from using the new numerical model (Moaveni column). All of the tools have the potential for refined results, however; careful attention would need to be made to the input values. Several of these values would depend on the actual use profile of the solar wall and may not be accurately known prior to installation.

In general, Moaveni's model underestimates the overall energy savings due to the following two reasons.

1. To determine the convective heat loss from the absorber plate (the solar wall), the model assumes an average wind speed of 14 mph for all months of operation. This assumption was made to create a model that was simple to use.
2. The model calculates only the heat transfer to the air during the daylight hours and neglects the thermal energy stored in the adjacent building wall, which is eventually released into the conditioned space and the air in the plenum.

In future studies, these assumptions could be studied in more detail and relaxed. For additional explanations, please see Appendix 3.1 and copies of the papers that were accepted for presentations at the ASME sponsored Fifth International Conference on Energy Sustainability.

Task 4: Evaluate solar wall's performance and GHG impact.

4.1 Calculate building specific degree day data based on traditional 65° F base temperature.

Complete results are presented in Appendix 4, section I. The results are summarized here in Table 4.

Table 4: Comparison of site-specific and National Weather Service heating degree days

Month	Breck	3rd Precinct	Aveda	Average	National Weather Service
Oct 09	689		705	697	667
Nov 09	687	647	708	681	663
Dec 09	1475	1438	1492	1469	1470
Jan 10	1604	1559	1617	1593	1605

Feb 10	1267	1209	1273	1250	1260
Mar 10	770	729	774	757	735
Apr 10	338	292	353	328	293

4.2 Examine the validity of the 65° F base temperature for degree day calculations.

Heating degree days (HDD) are calculated relative to a specified base temperature. Traditionally a value of 65° F has been used. However, several factors can influence what the actual balance point (i.e. base temperature) of the building is. Heavily insulated buildings (such as might be found in Minnesota), ones with a large internal heat generation due to equipment, high wind conditions, even occupant's perception of comfort could affect the appropriate base temperature.

For the calculations shown above a value of 65° F was used in order to maintain consistency with industry practice. However, as discussed in Appendix 4 section IV, the Breck and 3rd Precinct sites appear to have base temperatures that are below this value (54° F for Breck and 61° F for 3rd Precinct in 2009-2010 and 58° F in 2010-2011).

A base temperature for Aveda was not calculated. A HDD normalization presupposes a constant or at least consistent set point temperature. We did not monitor the set point temperature of the conditioned space at Aveda; the temperature of the ventilation air after passing through the pre-heat unit, however, showed considerable variation and the average preheat temperature was significantly greater (by approximately 10^{o} F) for the warmer months than for the colder months. Insufficient data to determine auxiliary heating and the building R value was obtained for IDDS to predict the correct base temperature, partially due to time constraints, difficulty in identifying who has the required data, and the unique construction of this site. For this site NRG Energy Center data for HDDs were used (which assume a 65° F base point).

4.3 Normalize energy use by HDD, and CDD as needed.

As described in Appendix 4 section III, normalization of energy use with HDD was computed for Breck and 3rd Precinct. The resulting value for Breck was 586 MBtu/HDD. For 3rd Precinct the data indicated that the normalization value shifted between the two heating seasons. A value of 64 MBtu/HDD was found for 2009-2010 and 30 MBtu/HDD for 2010-2011 (estimated from partial heating season data). Note that the 3rd Precinct building is heavily insulated and thus has a much lower heating requirement per HDD. Making use of an external source of HDD values for IDDS, a normalization of 271 MBtu/HDD was found. The lack of a steady set point for AVEDA prevented computing values for this site.

4.4 Compute solar wall efficiency using measured solar irradiance and temperature values.

As described in Appendix 4 Section V, the solar efficiency for Breck, 3rd Precinct, and AVEDA were calculated for individual months and then averaged. The ranges and average values of these sites compare as:

• Breck	8 % to 54%	30.5% (7 month average)
• AVEDA	37% to 76%	54.9% (6 month average)
• 3rd Precinct	3% to 42%	30.7% (6 month average)

The Breck average was for the 7-month period from Oct 09 through Apr 10, a period which included 96% of the HDD of the 2009-2010 heating season. The Aveda average was for the 6-month period from Oct 09 through Mon 10, a period which included 91% of the HDD of the 2009-2010 heating season. The 3rd Precinct average was for 3 months in each of two successive heating seasons.

As noted in the Appendix, a better indication of performance is the monthly solar efficiency taken from a cold month (December, January, and February) when the solar walls are used nearly continuously. When compared on this basis the average values for these three months are:

• Breck	50%
• AVEDA	55%
• 3rd Precinct	41%

4.5 Determine correlation between energy saved and GHG reduction.

The amount of green house gas (GHG) reduction is dependent on the fuel source that is being, and replaced by the solar wall preheating. For this study, CO_2 reduction has been focused on. Results for the main buildings studies are found in Appendix 4 sections II.A, II.B, and II.C. Calculated on the basis of the heating season the total reduction and fractional reduction (relative to the total amount produced in heat needs) are:

• Breck	14 tons	9.2%
• AVEDA	15 tons	-
• 3rd Precinct	3 tons	15.7%

The fractional reduction for AVEDA has not been computed. AVEDA provides partial heating by using recaptured waste heat from other parts of the manufacturing building with a heat pump system. It is difficult to actually determine how many greenhouse gases would be produced if the solar wall was not present since the waste heat would be generated regardless.

4.6 Compare results to other buildings with available data.

Table 10 of Appendix A.4 gives a comparison to two well known solar wall case studies. In general, the values that were measured for energy savings, energy savings per collector area, and efficiency were below those of the comparison studies. These differences can be attributed to inefficiencies in the original design/installation (i.e. an approach velocity out of the suggested range resulting in a lower efficiency) or a difference in operation schedule (i.e. the more time the wall is on the more that is saved).

Table 5 compares a number of possible savings factors for the three main sites studied. These values are based on the extrapolated experimental data. While energy savings per area, HDD, or hour are commonly presented by different studies and manufacturers it is clear that there is no one value for these that is consistent for all sites. Values per area and HDD can be biased by the number of operating hours the wall is used (e.g. the AVEDA site has values that are higher because they used their wall more). Values per hours of operation are also biased by operation schedules but in a reverse fashion. If a wall is only used part of a day it stores energy which results in a jump for the per hour value when it is turned on. Combining area and time into a normalization also did not yield a consistent value between sites.

A general rule of thumb used by manufacturers for energy savings is 160 BTU/hr ft^2. This is apparently a best case value determined through ideal lab condition testing. It is over twice as large as the values determined through our study. The 160 BTU/hr ft^2 value should be viewed as a “best case” savings which is unlikely to be achieved.

Table 5: Comparison of possible savings factors.

Site	kBTU/ft^2	kBTU/HDD	kBTU/hr	BTU/HDD ft^2	BTU/hr ft^2	BTU/hr HDD ft^2
Aveda	238.0	48.6	82.6	38.3	65.0	0.0105
Breck	73.0	8.8	24.8	10.7	30.1	0.0044
3rd Precinct	57.8[3]	5.9	46.7	7.8	61.1	0.0082

[4] This value was computed based on a partial heating season and is therefore abnormally low.

There have been competing claims that the solar wall helped or hurt building performance during the summer. Interviews with site personnel and measurement of interior and exterior wall temperatures (using infrared thermometers) could not verify either claim. A review of current theoretical and modeling research in this area also shows conflicting results and is inconclusive. The results are very sensitive to uncertainties in the convective heat transfer coefficients used and minor differences between sites (i.e. small changes alter the outcome of the study). One argument is that the solar wall captures less solar radiation in the summer due to the higher solar angles. Combined with forced or natural convection the resulting thermal load is “shed” before being absorbed into the building; thus lowering the building’s cooling requirements. The competing argument is that the higher temperature of the solar wall results in a radiative heat gain to the building that outweighs the thermal energy lost by convection; thus raising the building's cooling requirements. Additional analytical and numerical studies may provide further insight into this problem. However, given the uncertainties in input properties it is likely these will continue to be inconclusive.

Further experimental studies to determine the velocity and temperature conditions inside the solar wall could help alleviate some of this uncertainty. However, it is very difficult to obtain these experimental readings on existing buildings since they will likely require damage or modification to the solar wall. This project was able to obtain some interior temperature readings from the Breck solar wall, but surface temperatures of the normal (uncovered building wall) were not obtained. In addition, the fact that the Breck building was not in use or cooled during the summer alters the experimental conditions, limiting any conclusions that can be drawn. Designing an experimental study which can install instrumentation at the time of construction may be the best option for a more conclusive answer. If done the following data would need to be measured at multiple points across the wall (due to the two-dimensional temperature profile that results across the wall):

- Temperature of the inside surface of the solar wall perforated panel.
- Temperature of the outside surface of the building wall behind the solar wall.
- Temperature of the outside surface of the building wall without the solar wall.
- Temperature and flowrate of the air exiting the solar wall.
- Outside air temperatures, wind speeds, and inside building temperatures.

One alternative to address this issue in the future would be to conduct a pre- and post-retrofit study on a solar wall installation. By recording cooling requirements before and after installation it might be possible to determine an impact for that particular building (given the cooling seasons are consistent in other regards). Additional factors such as building temperature set points, operating schedule, and weather would also need to be carefully monitored to other outside influences.

Task 5: Leverage results and dissemination.

5.1 Disseminate results to others in Minnesota.

1. Dr. Tebbe was interviewed as part of an article in the Twin Cities Daily Planet for October 12, 2008. The article was titled "Passive solar: Actively heating local government buildings". It is available online at: http://www.tcdailyplanet.net/article/2008/10/11/passive-solar-actively-heating-local-government-buildings.html
2. A presentation was made at the 2010 American Society for Engineering Education (ASEE) North Midwest Section conference in Mankato, MN. The title was "Impact of

Student Involvement in a Solar Wall Study for the State of Minnesota". The accompanying paper is available online at: http://cset.mnsu.edu/mece/asee/conf_papers_10.pdf

3. A 90-minute workshop was offered at the 2011 Energy Design Conference and Expo in Duluth, MN on February 22nd, 2011. The title was "Unglazed Transpired Solar Collectors – Basics and Feasibility". A copy of the presentation is available online at: http://www.duluthenergydesign.com/agendas/2011_agenda/day1.php
4. On April 27th, 2011 Dr. Tebbe and Dr. Schwartzkopf made a presentation on the solar wall study at the Minnesota State University American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Student Chapter meeting in Mankato, MN.
5. On June 10th, 2011 Dr. Schwartzkopf will give a talk on the solar wall project to the Region 9 Renewable Energy Task Force at the Intergovernmental Center in Mankato, MN.
6. A brief press release concerning the project is being released through Minnesota State University, Mankato. An informational fact sheet has been included with this report.

* Activities in this area will continue after conclusion of the project as part of the investigator's normal work activities

** The requirement of two workshops to building and facilities managers, architects, and designers is satisfied by items 3 and 5, as well as item 1 under section 5.2

*** The requirement of two presentations it local chapters of ASHRAE is satisfied by items 4 and item 1 under section 5.2. The national ASHRAE meeting was heavily attended by MN members with a number present in the audience.

5.2 Disseminate results to broader region and nationally.

1. A presentation was made on February 2, 2011 in Las Vegas, NV at the 2011 ASHRAE Winter Conference. It was titled "Study of Unglazed Transpired Solar Collector Installations in the Twin Cities Minnesota Climate". The accompanying technical paper is published in the peer reviewed 2011 ASHRAE Transactions, Volume 117.
2. A paper entitled "A Numerical Model for Thermal Performance of an Unglazed Transpired Solar Collector" has been submitted and accepted for publication in the Proceedings of the Fifth International Conference on Energy Sustainability ES2011. An accompanying presentation will be made at the conference in Washington, DC August 7-11, 2011.
3. A paper entitled "The Magnitude of the Thermal Energy Stored in a Building Wall Adjacent to an Unglazed Transpired Soar Collector" has been submitted and accepted for publication in the Proceedings of the Fifth International Conference on Energy Sustainability ES2011. An accompanying presentation will be made at the conference in Washington, DC August 7-11, 2011.

*** activities in this area will continue after conclusion of the project as part of the investigator's normal work activities

5.3 Make results available through Grantee website.

A website has been created to disseminate the results of this study. It can be located at http://mavweb.mnsu.edu/tebbep/solarwall

5.4 Final report includes description of activities and results of Tasks 1-5, including experimental data, data analysis and the numerical energy impact model. Final format and content must be approved by the DOC.

The final report has been submitted with hard copies of all published papers. An accompanying CD contains digital copies and data files from the study.

APPENDIX 1.1
Descriptions of Solar Wall Installations Identified

<u>Breck School</u>

Breck School is an Episcopal school that teaches grades K – 12. It was founded in 1886 and was named after pioneer missionary Reverend James Lloyd Breck. Over the years, Breck School went through many changes and moved locations several times. In 1981, Breck moved to its current location. This location and building was the former middle and high school for the city of Golden Valley. Refurbishment of the facility, which included the building of a new chapel, was started shortly after the move.

In 2002, a new activity center was opened that included a solar wall on the southeast side of the building. The purpose of the wall was to preheat the air entering the building thereby reducing the amount of energy required to obtain a comfortable temperature.

Figure 1.1.1: Solar wall installation on Breck School gymnasium wall.

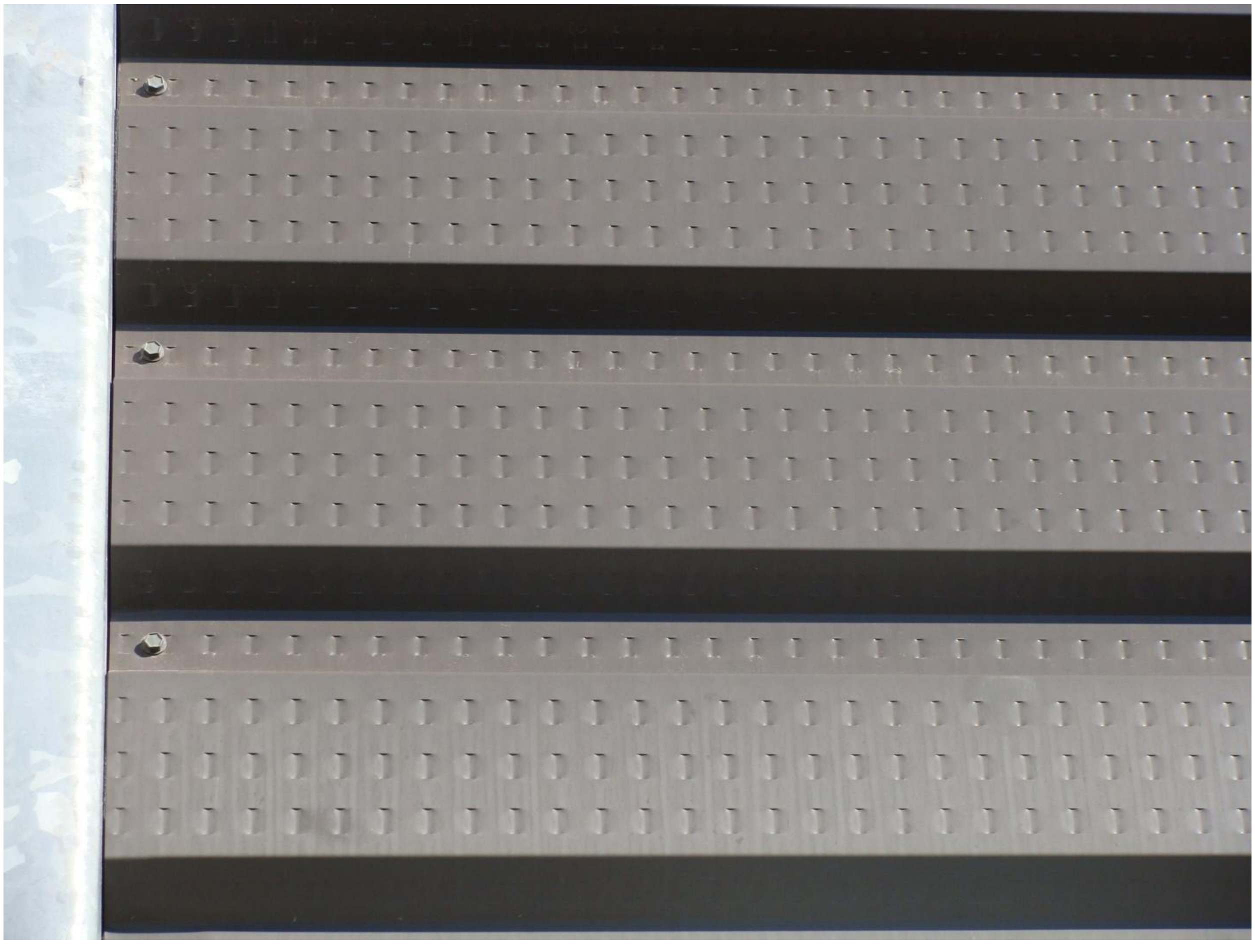

Figure 1.1.2: Close-up of Breck School solar wall perforation patterns.

The Breck solar wall is dark brown in color and split into 8 individual sections. Each section is horizontally mounted and installed in its own steel tube frame. The length and height of each section is 26 ft by 16.5 ft. This adds up to a total wall area of 3400 ft^2. Four fans are connected to the solar wall system and provide a maximum 16,000 ft^3 of preheated air used for ventilation in the gym.

The solar wall for Breck School is located on the south facing wall of the field house and serves four separate air handling units. All fresh air for the field house is provided by the solar wall. The channels of the wall panels run horizontally and have a slotted, not a hole, design. Each wall is connected to its own fan unit on the inside of the gymnasium. The air from each SolarWall is extracted at four points and combined in a manifold before entering the fan unit. Air from the solar wall is mixed with return air before being filtered and heated by one or both natural gas fired heat stages, depending on the room temperature. The air is then distributed to the field house through a ceiling mounted duct and diffusers. The system is only operated during the heating season.

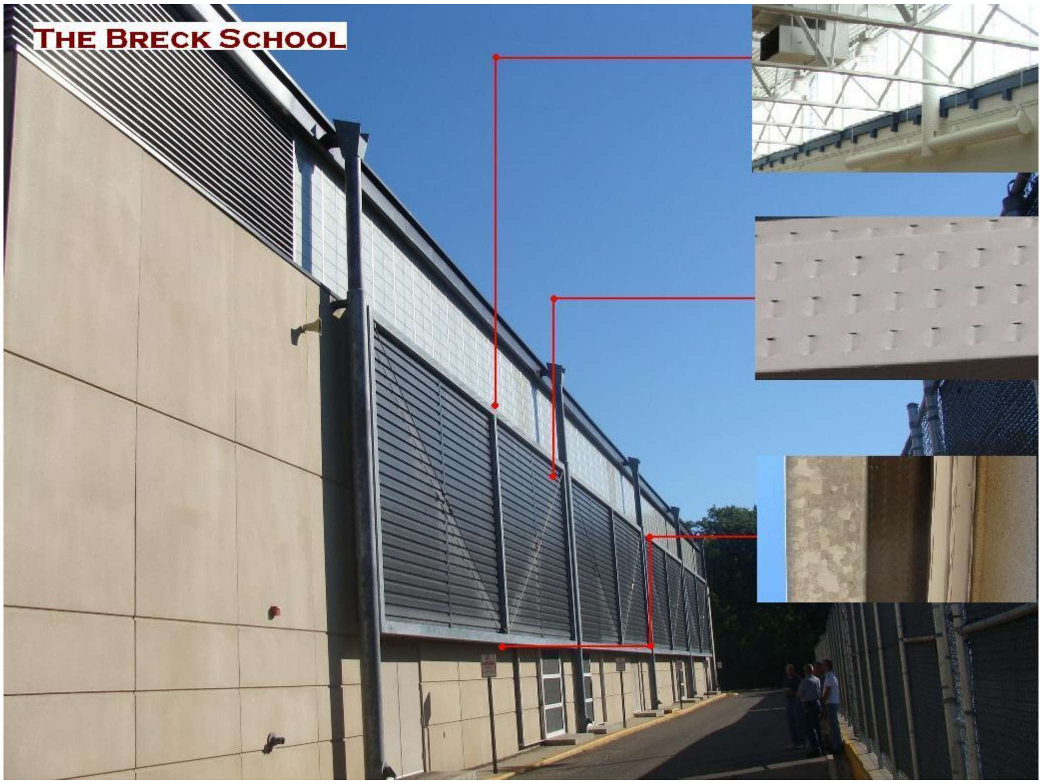

Figure 1.1.3: Breakdown view of the Breck School wall.

The fan unit on the east end is operated at a higher temperature during the winter for gymnasts who are not as active as the basketball players using the remaining space. There is no fresh air bypass for the fan units to use, which can lead to cooling issues and overheating of the space. The management system in place currently measures the temperature of the air leaving the fan unit, the air at the end of the duct, and the room temperature. The fans operate at a constant speed so a constant flow rate could be assumed.

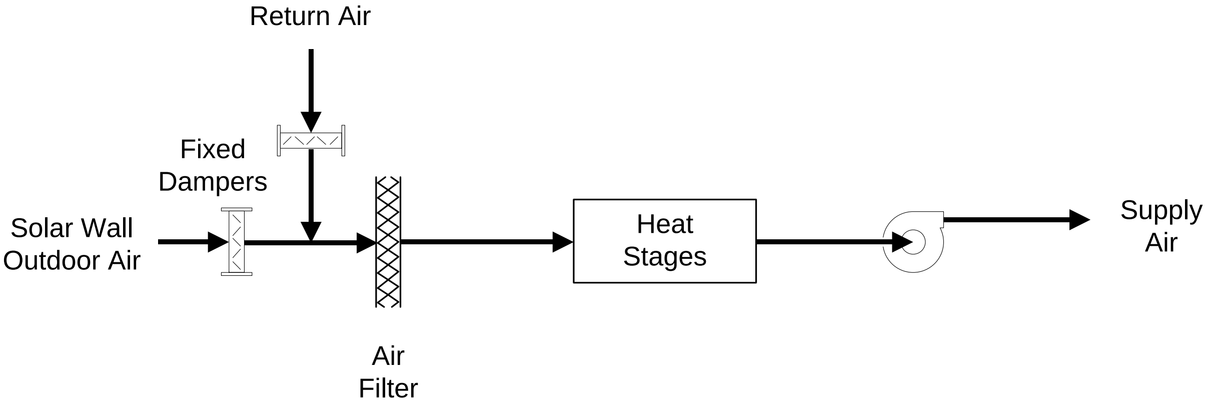

Figure 1.1.3: HVAC system diagram for the Breck School solar wall installation.

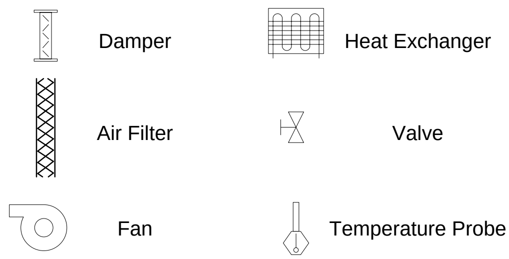

Figure 1.1.4: Component icons used in system diagram pictures.

3rd Precinct Police Station

The 3rd Precinct Police station serves one of five police precincts in Minneapolis, MN. Geographically, it is the largest in the city. 3rd Precinct is headquarters for patrol officers, investigators, community crime prevention programs, and community response teams. The precinct also has two safety centers.

From 2003 to 2005, the original building (built in the early 1980's) was renovated and expanded with a new addition. During this time, new mechanical and electrical systems were installed in the building. Included in the installation was a solar wall on the building's south side. The solar wall was then used to preheat the incoming ventilation air to help reduce energy costs.

The solar wall at 3rd Police Precinct is constructed with a steel frame made from 18 gauge galvanized steel. The frame is attached to the building using fasteners provided by the installation contractor and a butyl tape to help seal the wall to the building. The outer flashing and inner frame are the first pieces to be installed. Next the canopy frame is installed on the top portion of the wall. Then drip edges and solar panels are installed. Finally, the canopy is enclosed and the top trim flashing is attached. Components are fastened using #14 by 1" self-tapping galvanized screws for the internal frame connections and 3/16 diameter by 1/4" stainless steel rivets for solar wall panels and external flashing.

Figure 1.1.5: Solar wall installation at 3rd Precinct Police station.

3rd Precinct has their solar wall located on the south-facing wall. All building ventilation air is drawn through the outdoor air intake louvers or through the solar wall. The building management system determines whether to open the damper for the solar wall or the damper for the outdoor air depending on whether it is heating or cooling, respectively. After drawing in outside air from either source it is mixed with return air and filtered. Finally, the air is conditioned to the required supply dry-bulb temperature and relative humidity before being distributed throughout the building.

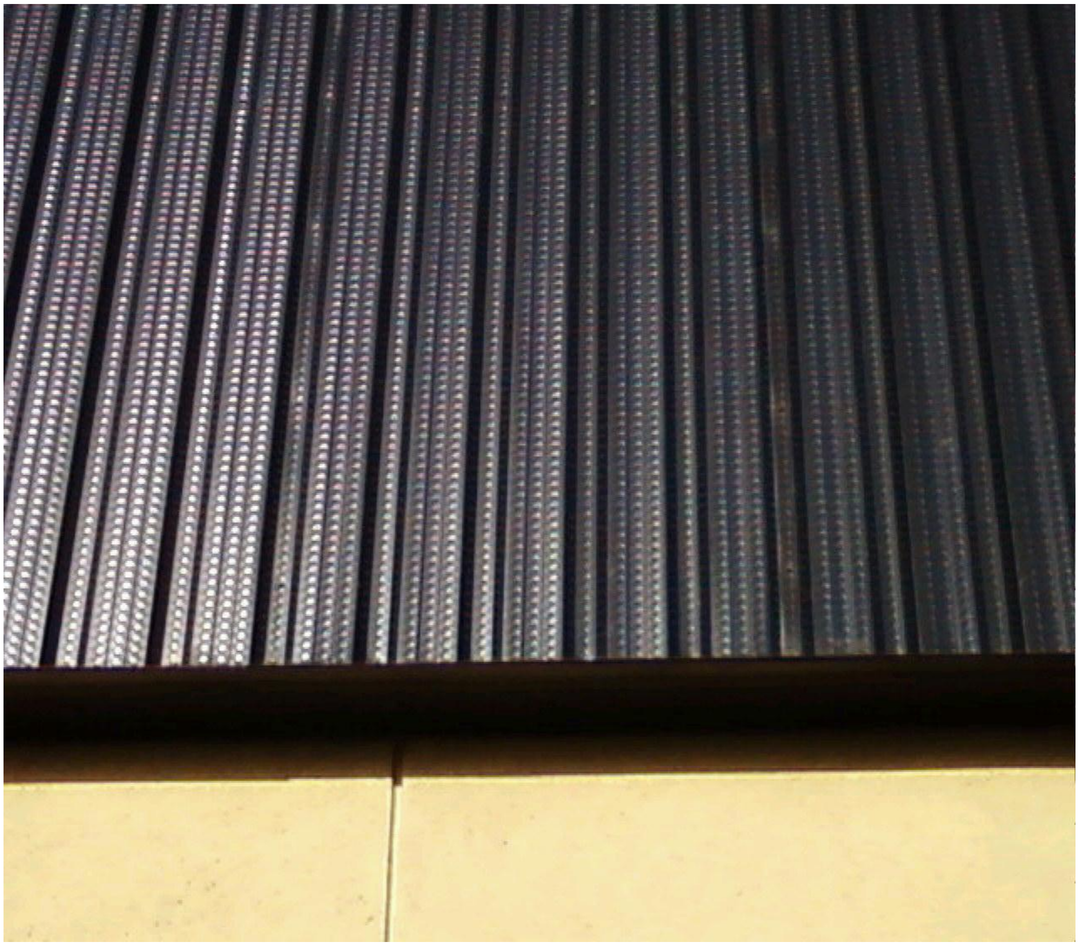

Figure 1.1.6: Close-up of 3rd Precinct solar wall perforation patterns.

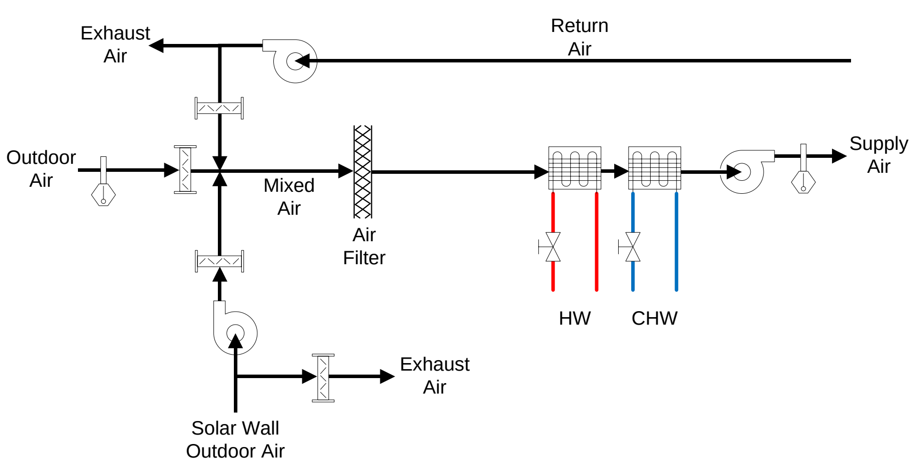

Figure 1.1.7: HVAC system diagram for the 3rd Precinct solar wall installation.

AVEDA Corporation

Aveda, founded in 1978, is a botanically based beauty product manufacturer with the goal of supplying high performance products to professionals that work in the beauty industry. These products are plant-based and include such things as hair care products, skin care products, and makeup. Aveda's products can be found in Aveda stores or in almost 7,000 salons and spas in 24 countries. Their headquarters is located in Blaine, Minnesota.

In 1992, the company requested an energy audit by their local utility company and inquired into methods to improve energy conservation in their building. A suggestion was to install a solar wall to preheat incoming ventilation air. Now the manufacturing facility in Blaine has a 1400 square foot solar wall on its upper south wall to help reduce energy costs.

Aveda's solar wall is located on the south-facing wall of their manufacturing facility. Since the system uses 100% ventilation air, there is no mixing with return air as with Breck and 3rd Precinct. The ventilation air is drawn from either the solar wall or from outdoor air intake louvers as appropriate. The air is then filtered and conditioned before being supplied to the manufacturing floor.

The solar wall installation at Aveda is located on a tier of the roof above the manufacturing facility. The air from the solar wall is ducted to a single fan unit directly behind it on the inside. The channels of the solar wall run vertically and have a hole design. The solar wall has an offset section following the architecture of the wall on which it is mounted. From the inside, it appears that there are two air outlets, one for each section of the solar wall. Air from the collector is extracted from the center of the east section, and pulled from the side at the offset from the other. The fan unit also has a fresh air bypass located on top of the tier when air from the solar wall is too high. Aveda has construction plans from Conserval in possession, but any copies need to be authorized by Aveda. The management system in place measures temperatures from the solar wall and from the bypass. The fan used is also rated for a constant speed, so flow rates could be estimated.

Figure 1.1.8: Solar wall installation at AVEDA Corporation Headquarters.

Figure 1.1.9: Close-up of AVEDA solar wall perforation patterns.

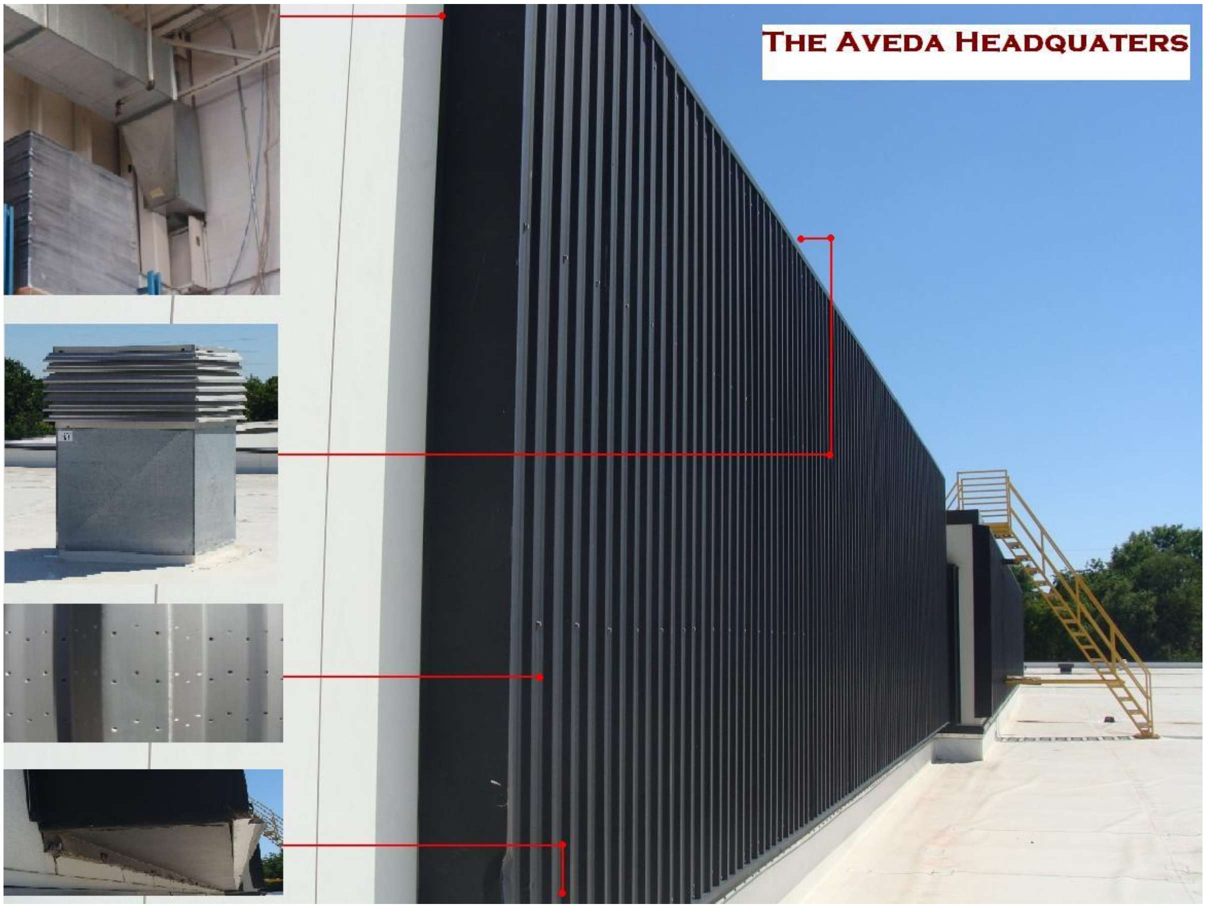

Figure 1.1.10: Breakdown of AVEDA solar wall components.

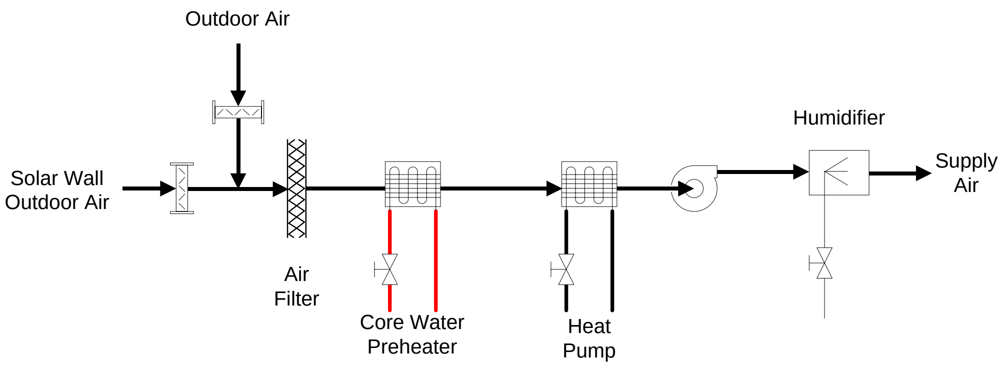

Figure 1.1.10: HVAC system diagram for the 3rd Precinct solar wall installation.

IDDS (InterDistrict Downtown School)

In 1989, Minneapolis public schools and eight neighboring school districts formed the West Metro Education Program (WMEP). In 1998, the WMEP opened its first school known as the InterDistrict Downtown School (IDDS). Shortly after, the WMEP expanded to include two more school districts. The WMEP also has a school located in Crystal, MN. IDDS is now known as the FAIR School Downtown. IDDS is a 500 student, K – 12 school located in downtown Minneapolis, MN. The school emphasizes multicultural learning, experiential learning, and technology as learning resources. The school also reaches out to the downtown community to provide students with learning partners in the arts, government, business, and other public and private sectors.

When the school was built, a solar wall was installed along with additional energy saving devices. The solar wall sits on the south side of the school's mechanical penthouse and is used to preheat incoming ventilation air, which reduces heating costs in the winter. The solar wall also acts as an educational tool for the school's Solar Education Program.

The IDDS solar wall is made from black painted aluminum panels and has an area approximately 2115 ft^2. The building itself consists of five floors with a parking ramp located underneath the building. The solar wall installation is located on the top tier of the building, mounted on the south facing wall of the mechanical penthouse (5^{th} floor). All of the fresh air for the building enters either through outdoor air intake louvers or through the solar wall air intake plenum so several air vents break up the solar wall along its length. This intake plenum runs most of the length of the mechanical penthouse above the outdoor air intake plenums. A normally-closed damper is between the solar wall plenum and the outdoor air intake plenum for energy recovery unit 2 (ERU-2). Once open, this damper allow for mixing between the solar wall outdoor air (SWOA), and the OA intake plenum.

The mixed air then flows with assist from variable frequency drives (VFD) through the ERU-2 where it is warmed by the return air. The air then enters the outdoor air intake plenum for air handling units 3 and 4. These two air handling units supply air to the 3^{rd} and 4^{th} floors of the building.

Figure 1.1.11: Solar wall installation at Interdistrict Downtown School.

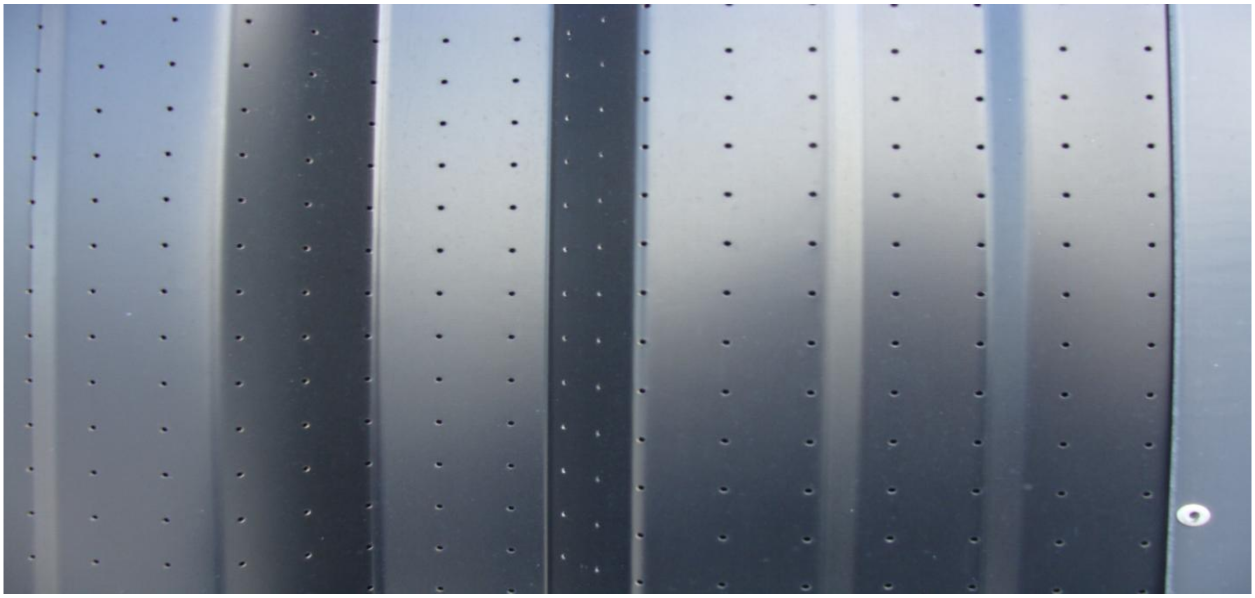

Figure 1.1.12: Close-up of IDDS solar wall perforation patterns.

Figure 1.1.13: Close-up of IDDS bypass air entry.

Figure 1.1.13: Breakdown of IDDS solar wall components.

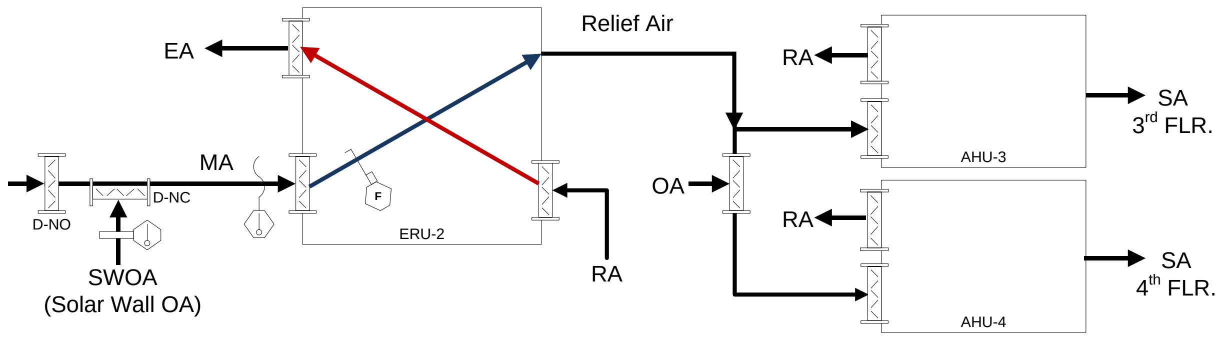

Figure 1.1.14: HVAC system diagram for the IDDS solar wall installation.

St. Anthony Village High School

The St. Anthony Village High School is located in St. Anthony, MN and shares facilities with the St. Anthony Village Middle School. The School Board of St. Anthony entered into contract with McKinstry Co. to improve the energy efficiency of the Middle/High School buildings in 2007. One of the modifications was the addition of a solar wall as a pre-heating system. It was installed on the south side of the penthouse mechanical room where it delivers air to two air handling units. The wall has approximately 739 ft^2 of collector for a total air volume of 2830 ft^3/min.

The St. Anthony buildings are not equipped with air conditioning and the majority of heating comes from a radiant system. Fresh air needs for ventilation are determined based on a CO_2 sensor. The system is also equipped with a bypass damper system. When the outside air falls below approximately 50° F fresh air for the building is pulled in through the solar wall. The current system has temperature sensors installed to measure the temperature change across the wall, however; there is not a direct way to measure the air flowrate.

At the time initial discussions were held with St. Anthony their wall was still under an energy efficiency contract which prohibited us from installing sensors. Later that year the air handling units were also scheduled for replacement. While efforts were continued to acquire some experimental data from this site, changes in personnel and difficulty in determining the air flowrates limited the applicability of this site. While initial design and construction information was received, no experimental data was obtained.

Figure 1.1.15: Solar wall installation at St. Anthony Village High School (Source: Bernie Eikmeier, MnKinstry Co.).

Hibbing Courthouse Annex

Originally built in the 1950's, the courthouse Annex was formerly the Hibbing Mesaba Clinic. In 2006 it was remodeled and reopened as a government services center. It currently provides space for Veterans Services and Health & Human Services. The building currently uses a two level solar wall installation that totals 1,232 ft^2. The Hibbing Courthouse Annex is LEED certified due to its sustainability features.

The Annex is steam heated. Contacts with Property Management there (Tony Mancusso) state that on sunny days of 25° F they do not require any steam from the city due to preheating from the solar wall.

Some discussions were held with contacts at the Hibbing Annex. The building automation system does log some data that would be required, such as temperature differences. However, analysis on performance has not been done and no records of performance have been kept. Some basic construction information was obtained but a more in-depth study was not possible due to security concerns at the site.

Figure 1.1.16: Solar wall installation at Hibbing Courthouse front view (Source: Conserval case study.).

Figure 1.1.17: Solar wall installation at Hibbing Courthouse 2nd elevation (Source: Conserval case study.).

Figure 1.1.18: Hibbing solar wall ducting on roof (Source: Conserval case study.).

APPENDIX 2.1.1
Sensors Used to Monitor Solar Wall Performance

Several different sensors were used to monitor data such as temperatures, wind speed, and humidity. Below are a list of sensors that were used, their specifications, and a description of how they work.

Weather Station Sensors

1. Temperature/Relative Humidity Sensor (Used with solar radiation shield)

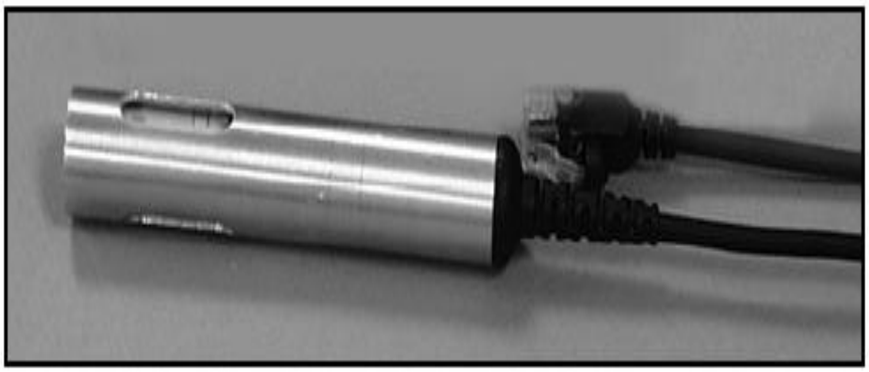

Figure 1: Temperature/Relative Humidity Sensor

The temperature/relative humidity sensor, used on the weather stations, is used to monitor the ambient air temperature and relative humidity and each of the locations (Breck, Aveda, 3rd Precinct, IDDS). This sensor was used in conjunction with a solar radiation shield; which was needed to eliminate any error that would occur from solar radiation since each weather station was out in the open. The temperature range of the sensor is -40^{o}C to 70^{o}C (-40^{o}F to 167^{o}F) and has an accuracy of ±.7^{o}C at 25^{o}C (±1.3^{o}F at 77^{o}F). The relative humidity range of the sensor is 0 to 100% between 0^{o} and 50^{o}C (32^{o}F and 122^{o}F) with an accuracy of ±3% (±4% in condensing environments). Other specifications for this sensor are shown in Table 1[1].

2. Solar Radiation Shield

Figure 2: Solar Radiation Shield

The solar radiation shield is used to protect various sensors from the sun's radiation which can alter the sensors readings causing an error in data taken. These shields are used on the weather stations to protect the temperature/relative humidity sensors. The height, width, and depth of the shield (not including the mounting bracket) are 152mm (6.0 in), 210mm(6.5 in), and 187mm(7.4 in) respectively [2].

Table 1: Specifications for Temperature/Relative Humidity Sensor

Specifications	**Temperature**	**RH**
Measurement Range	-40°C to 75°C (-40°F to 167°F)	0 to 100% RH between 0° and 50°C (32°F and 122°F)
Accuracy	± 0.7°C at 25°C (1.3°F at 77°F), see Figure 1 for detail	± 3%; ± 4% in condensing environments
Resolution	0.4°C at 25°C (0.7°F at 77°F), see Figure 1 for detail	0.5% RH at 25°C (77°F)
Drift	< 0.1°C (0.2°F) per year (typical)	± 1% RH per year (typical); an additional reversible drift up to +3% can occur when the average relative humidity is above 70%
Calibration	N/A	Factory recalibration available
Response Time	8 minutes, typical to 90% in 2 m/s (4.5 mph) airflow	5 minutes, typical to 90% in 2 m/s (4.5 mph) airflow
Operating Temperature Range	-40°C to +75°C (-40°F to +167°F)	
Environmental Rating	Weatherproof: 0 to 100% RH Intermittent Condensing Environments up to 30°C, and non-condensing above 30°C. The Temp/RH Smart Sensor should be mounted so that water does not impact or collect in the RH sensor.	
Housing	Stainless steel	
Dimensions	1.6 cm x 8.6 cm (5/8 in x 3.5 in)	
Weight	2 meter: 60 g (2 oz), 6 meter: 140 g (5 oz), 17 meter: 370 g (13 oz)	
Bits per Sample	8	
Number of Data Channels *****	2	
Measurement Averaging Option	No	
Cable Lengths Available	2 meter – S-THA-M002 (6.5 ft), 6 meter – S-THA-M006 (19.7 ft), 17 meter – S-THA-M017 (55.7 ft)	
Length of Smart Sensor Network	2 meter – S-THA-M002 (6.5 ft), 6 meter – S-THA-M006 (19.7 ft), 17 meter – S-THA-M017 (55.7 ft)	
Part Numbers	S-THA-M002 (2 meter cable), S-THA-M006 (6 meter cable), S-THA-M017 (17 meter cable)	
Specification	This product meets CE specification EN61326 criterion C for ESD, criterion C for Radiated Immunity, criterion B for Fast Transient, criterion A for Conducted Immunity, and criterion A for Power Frequency Magnetic Fields. To minimize measurement errors due to ambient RF, use the shortest possible probe cable length and keep the probe cable as far as possible from other cables.	

3. Solar Radiation Sensor

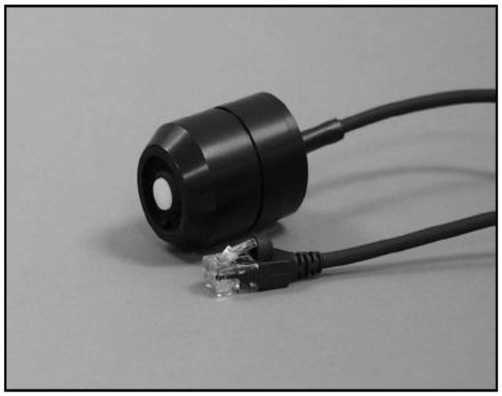

Figure 3: Solar Radiation Shield

The solar radiation sensor is a radiation sensor that is used on the weather stations. Its purpose is to monitor the average intensity of solar radiation at each location (Breck, Aveda, 3rd Precinct, IDDS). The measurement range for the solar radiation sensor is from 0 to 1280 W/m^2 and the sensors spectral range is from 300 to 1100 nm. Additional specifications for this sensor are given in Table 2 [3].

Table 2: Specifications for Solar Radiation Sensor

Measurement parameters	average over logging interval, user-defined sampling interval from 1 second
Measurement range	0 to 1280 W/m^2
Operating Temperature Range	-40° to 75°C (-40° to 167°F)
Accuracy	±10 W/m2 or ±5%, whichever is greater in sunlight. Additional temperature induced error ±0.38 W/m^2 /°C from 25°C (0.21 W/m^2/°F from 77°F)
Resolution	1.25 W/m^2
Drift	<±2% per year
Spectral Range	300 to 1100 nm
Cosine Response Error	±5%, 0° to 70°; ±10%, 70° to 80° from vertical
Azimuth Error	±2% error at 45° from vertical, 360° rotation
Calibration	Factory recalibration available
Housing	anodized aluminum housing with acrylic diffuser and o-ring seal
Dimensions	4.1 cm high x 3.2 cm diameter (1 5/8 in. x 1 1/4 in.)
Approximate Weight	120 g (4 oz)
Cable Length	3 m (9.8 ft)

4. Light Sensor Mounting Bracket

Figure 4: Light Sensor Mounting Bracket

The light sensor mounting bracket is used to support the solar radiation sensor and to secure it to the weather station. It also helps to isolate the sensor from the other components. This bracket has a 16.5 inch reach, 11 inch height, and a 1.38 inch width [4].

5. Wind Speed and Direction Sensor

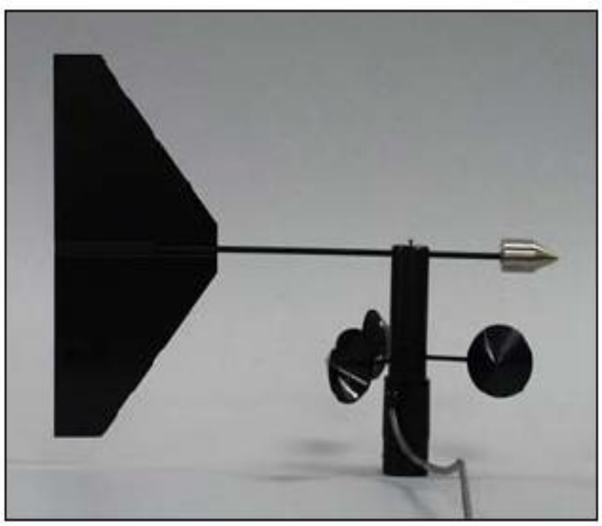

Figure 5: Wind Speed and Direction Sensor

The wind speed and direction sensor is used on the weather stations to monitor the average wind speeds, the highest three second wind gust, and the average wind direction during a set interval at each location (Breck, Aveda, 3^{rd} Precinct, IDDS). It has a wind speed measurement range of 0 to 44 m/s (0 to 99 mph) and a wind direction measurement range of 0 to 358 degrees (with a 2 degree dead range). Other specifications for this sensor are given in Table 3.

Table 3: Specifications for the Wind Speed and Direction Sensor [5]

Specifications	**Wind Speed/Gust**	**Wind Direction**
Measurement Range	0 to 44 m/s (0 to 99 mph)	0 to 358 degrees, 2 degree dead band
Accuracy	± 0.5 m/s (± 1.1 mph) ± 3% 17 to 30 m/s (38 to 67 mph) ± 4% 30 to 44 m/s (67 to 99 mph)	± 5 degrees
Resolution	0.19 m/s (0.42 mph)	1.4 degrees
Starting Threshold	0.5 m/s (1.1 mph)	0.5 m/s (1.1 mph)
Damping Ratio	NA	0.4
Distance Constant	Approximately 3 m (9.8 ft)	0.8 m (2.6 ft)
Maximum Wind Speed Survival	54 m/sec (120 mph)	
Measurement Definition	Cup revolutions are accumulated every three seconds for the duration of the logging interval. Wind speed is the average speed for the entire logging interval. Gust speed is the highest three-second wind recorded during the logging interval.	Vector components of wind direction are accumulated every three seconds for duration of logging interval. Average direction is calculated from the sum of the vector components every logging interval.
Operating Temperature Range	-40°C to +75°C (-40°F to +167°F)	
Environmental Rating	Weatherproof	
Service Life	2 to 5 years typical depending upon environmental conditions	
Housing	Anodized aluminum housing, injection-molded plastic cups, stainless steel fasteners, Acetal base, and black anodized aluminum mounting rod.	
Bearing Type	Stainless steel shielded ball bearing	Bushing
Turning Radius	108 mm (4.25 in.)	Approximately 305 mm (12.5 in.)
Dimensions	317 mm (12.5 in.) H x 419 mm (16.5 in.) W, 12.7 mm (0.5 in.) diameter mounting pole	
Weight	Approximately 700 g (1.5 lbs)	
Bits per Sample	8 for each channel, 24 total	
Number of Data Channels	3	
Measurement Averaging Option	Automatic averaging (see Measurement Definition)	
Cable Length Available	3.0 m (9.8 ft)	
Length of Smart Sensor Network Cable	3.0 m (9.8 ft)	
Part Number	S-WCA-M003	
Specification	This product meets CE specification EN61326 criterion C for ESD, criterion C for Radiated Immunity, criterion B for Fast Transient, criterion A for Conducted Immunity, and criterion A for Power Frequency Magnetic Fields. To minimize measurement errors due to ambient RF, use the shortest possible probe cable length and keep the probe cable as far as possible from other cables.	

6. Half Cross Arm Mounting Bracket

Figure 6: Half Cross Arm Mounting Bracket

The half cross arm mounting bracket is used to support the wind speed and direction sensor and to mount it to the weather station. It also helps to keep this sensor away from other components that could affect the wind speed and direction measurement. The arm is 49 cm (19 in) in length [7].

7. Weather Station Data Logger

Figure 7: HOBO Weather Station

The weather station data logger is the brain of the weather stations. Its purpose is to collect and store all the data from the sensors. The data logger also controls the rate at which data is collected from the sensors. It has the ability to collect data at intervals of 1 second to 18 hours, and this interval is specified by the user. 512 K of data storage is available on this logger and will collect data from a maximum of 15 data channels. Additional specifications on the weather station data logger is given in Table 4 [8].

Table 4: Specifications for HOBO Weather Station data logger.

Operating Range	-20° to 50°C (-4° to 122°F) with alkaline batteries, -40° to 70°C (-40° to 158°F) with lithium batteries
Sensor Inputs	10, expandable to 15 with optional adapters
Data Channels	Maximum of 15 (some sensors use more than one data channel; see sensor manual for details)
Communication	3.5 mm serial port or weatherproof external connector
Dimensions	23 cm H x 10 cm D x 18 cm W (9 x 4 x 7 inches)
Weight	0.9 kg (2 lbs)
Memory	512K nonvolatile flash data storage
Memory Modes	Stop when full, wrap around when full
Operational Indicators	Seven status lights provide logging and sensor network status
Logging Interval	1 second to 18 hours, user-specified interval
Battery Life	1 year typical use (up to 10 sensors with 10 minutes or longer logging interval)
Battery Type	Four standard AA alkaline batteries included (for operating conditions -20° to 50°C [-4° to 122°F]); optional AA lithium batteries available for operating conditions of -40° to 70°C (-40° to 158°F)
Time Accuracy	0 to 2 seconds for the first data point and ±5 seconds per week at 25°C (77°F)
Data Type	Supports measurement averaging based on availability of supporting data from sensor
Logger Start Modes	Immediate, push-button, or delayed start options
Data Communication	Current reading while logging, offload while logging, or offload when stopped
Environmental Rating	Weatherproof
Mounting Mast	(3.8 cm [1.5 inches] maximum diameter) or wall mount
Enclosure Access	Hinged door secured by four screws
Sensor Network Cable Length	100 m (328 ft) maximum

8. Wireless Data Transceiver

Figure 8: Wireless Data Transceiver

The wireless data transceiver works with the data logger on the weather stations. Its purpose is to automatically transmit the data to a secure internet server and also to alert someone (by email or text message) if any user defined alarm conditions arise. Information that is sent from the data transceiver can then be accessed by any computer with an internet connection where it can be viewed or downloaded. Specifications for the transceiver are given in Table 5 [9].

9. Weather Station Tripod and Base

Figure 9: Weather Station Tripod

The weather station tripod is the base of the weather station. It is what all the sensors, the data logger, and the wireless transceiver are mounted to. It stands 3 meters (9.84 ft) tall and can be placed on any slope less than 13 degrees. Other specifications for the weather station tripod can be found in Table 6 [10]. Traditionally these tripods are staked to the ground. Since this was not possible on the buildings a based had to be designed. The base of the tripod, shown in Figure 10, is a triangle with 54 inch sides and constructed from 2' x 6' treated lumber. It was weighed down with sand bags.

Table 5: Specifications for wireless data transceiver.

Temperature Range	-40 to 80 C (-40 to 176 F)
Power	1 Watt solar panel and rechargeable battery pack designed to last up to 15 years.
Solar charging	Temperature compensated charging voltage optimizes battery life and performance. Typically requires an average of one to two hours of direct sunlight per day. Will typically operate for one month in clouded conditions.
Weight	1.4 kg (3 lbs)
Dimensions	12.7 X 7.6 X 17.8 cm (5 X 3 X 7 inches)
Environmental Rating	NEMA 6 weatherproof. Indoor and outdoor versions available.
Communication	Two serial ports for configuration and interfacing with external serial device
Operational modes	Standby and low power
LED's	Four LED's indicate Power, In Range, Transceiver On, and Low Battery.
Server update	User configurable from every 5 minutes to once a month
Remote alarms	User configurable low battery alarm and high/low sensor value alarms. Maximum latency: logging interval plus two minutes during typical network conditions.
Remote control	SolarStream and the attached weather station can be controlled over the Web. Functions include checking battery state and changing the server update rate or data logging interval.
Data formats	Tab-delimited text, HOBOware, and BoxCar Pro
Mounting	Sun-facing wall or pole, angled upward. Tilt angle based on latitude. Separate bracket (sold separately) recommended for mounting on poles from 1.5 to 2 inches in diameter.
Frequency	920 MHz
Wireless Networks	USA Mobility, SkyTel, and Space Data
Coverage	Works in areas including over 90 percent of the US population, and significant areas of Canada, Mexico,Puerto Rico, and the Virgin Islands. Detailed coverage maps exist at www.usamobility.com.
Federal specifications	FCC certified for use in the U.S. and authorized for use in Canada

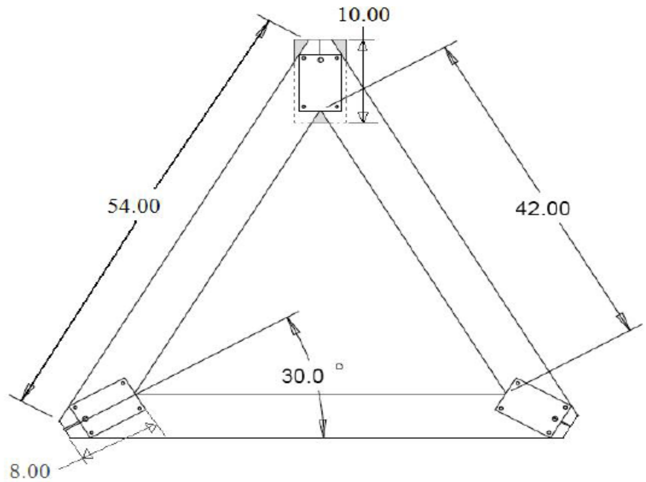

Figure 10: Tripod base design (all dimensions are in inches)

Table 6: Specifications for weather station tripod.

Cross arm height range:	2.74 to 3.20 m (9 to 10.5 ft.)
Leg height (to top of legs):	1.32 m (4.3 ft.)
Mast diameter:	4.1 cm (1.63 in.)
Tripod footprint:	91 cm (3 ft.)
Weight:	28 lbs.

10. Sensor Installation at 3rd Precinct

At 3rd Precinct there were no temperature sensors installed on the solar wall. Therefore, two temperature sensors were installed in the air duct coming off the solar wall and integrated with the weather station data logging. The two sensors were installed in the same duct to allow redundancy in the temperature readings. The temperature sensors were installed by drilling holes into the air duct coming from the solar wall. They were then mounted to the air duct using a metal plate, sheet metal screws, silicon sealant, and a pipe compression fitting (Figures 11 and 12).

Figure 11: Close-up of first installed temperature sensor and mounting at 3rd Precinct.

Figure 12: Close-up of both installed temperature sensors at 3rd Precinct (one on top and one on side).

The wiring for the sensors was then run along the top of the solar wall (Figure 13) to the weather station. Here they were connected to the weather station data logger were the air duct temperatures were monitored and recorded. These sensors were then integrated into the completed weather station that was assembled on the roof near the solar wall (Figure 14).

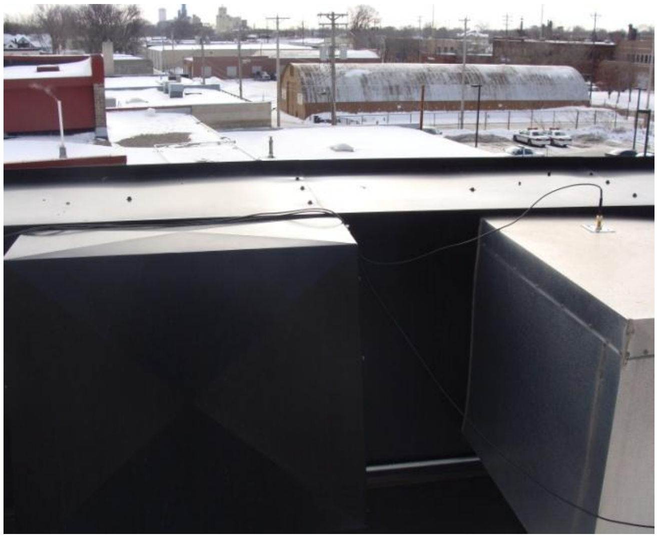

Figure 13: Routing of sensor wires over ductwork.

Figure 14: Completed 3rd Precinct weather station.

11. Sensor Installation at the Breck School

Just as for 3rd Precinct, the Breck School energy management system did not have temperature sensors installed on the solar wall. The first sensors to be installed were two 8-bit temperature sensors that were installed in an air duct leading from one section of the solar wall on the southeast side of the gym (Figure 15). Note, this is near the top of the gymnasium ceiling and was accomplished with a scissor lift. Attachment was done by drilling two holes in the air duct, inserting the temperature sensors into the duct, and fastening them to the duct using a metal plate, self taping sheet metal screws, silicon sealant, and a pipe compression fitting. Again, two sensors were used for redundancy.

Figure 15: Air duct temperature sensors installed at the Breck School.

Next the wires were strung along the east wall of the gym (Figure 16) to the northeast corner where there was an open vent in the wall allowing outside access. The wires were fed through the vent and then they were strung back up the wall to the roof. From here the wires were fed along the top of the east wall to the weather station (Figure 17); which was located on the south east corner of the roof. Here they were connected to the weather station were the air duct temperatures were monitored and recorded.

The weather station was the assembled (Figure 18) on the roof of the gym. This is where the sensors for monitoring weather conditions were mounted. These sensors included the wind speed and direction sensor (top right), solar radiation sensor (top middle), wireless data transceiver (just below the solar radiation sensor), temperature/relative humidity sensor with solar radiation shield (white object), and the weather station data logger (lowest object, just before the tripod).

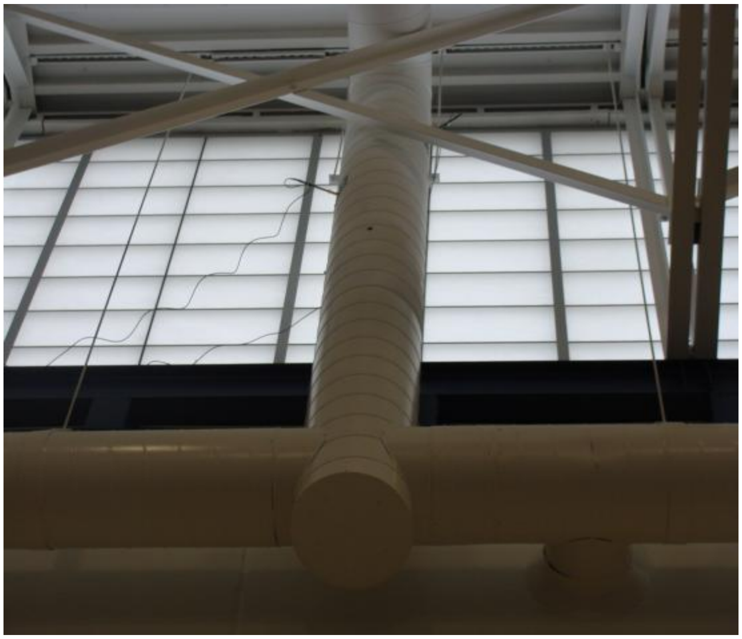

Figure 16: Temperature sensor wiring from air duct temperature sensors.

Figure 17: Temperature sensor wiring leading to the weather station.

Figure 18: Assembled weather station for the Breck School.

12. Wall profile temperature measurement used at the Breck School.

The Breck School installation also had the challenge of measuring the two-dimensional temperature profile across one solar wall section. Eighteen thermocouples were installed on one section of the solar wall. Nine of the thermocouples monitored the temperature of the external surface of the solar wall and the other nine thermocouples monitored the internal temperature of the solar wall next to the building (i.e. the outside surface of the building wall). The data was then collected by a data logger (separate from the weather station) and stored. This data had to then be manually downloaded periodically. Information on the thermocouples, wiring, and the data logger are listed in the following figures. A challenge and limitation of this data logger was the fact that it had to be battery powered. Most batteries are not rated for the extreme low outside temperatures the data logger experienced. While several different types were tried (including more expensive lithium ion batteries) they would generally fail after 1-2 weeks of operation. A special trip would then have to be planned to the Breck School to replace them.

Surface temperatures are more difficult to measure accurately than air temperatures. Experiments with several different types of temperature probes and mountings were conducted in the laboratories at Minnesota State University. Eventually it was determined that an air film temperature just short of the actual surface would suffice for the measurements. This simplified the experimental task and eliminated the need for custom temperature probes. An additional consideration was finding a mounting technique that caused the minimal amount of damage to the Breck wall and which allowed the sensors to be easily removed following the study. Since the solar wall panels are bolted to the frame a thermocouple with a bolt-on washer design was the best option for the outside surface temperature (Figure 19).

Figure 18: Bolt on washer thermocouples from Omega Inc..

The surface thermocouples had the following features:

- Rugged design
- Comes in sizes that fit #6, #8, #10, and 1/4" screw sizes
- Made from 20 AWG Glass-On-Glass or PFA Insulated Special Limits of Error Wire
- Stocked in 12, 24, 36, 48 and 60" Lengths with Stripped End Leads
- Rated up to 480°C (900°F) for Glass-On-Glass Insulation
- Rated up to 260°C (500°F) for PFA Insulation

The thermocouples that were installed at Breck were 12" long and had male connector ends installed on them instead of stripped wire ends. These thermocouples have a copper positive lead and a constantan copper-nickel negative lead. This gives them a temperature range of -270^{o}C to 400^{o}C (-454^{o}F to 752^{o}F) [12].

The internal thermocouples were easier to select. These were inserted through the outer layer of the solar wall and were mounted in place using a compression fitting. They had the following features:

- Male Connector Permanently Molded to Probe Sheath
- Standard Size Thermocouple Connectors, Color-Coded with Calibration Code
- Choice of 304SS, 321SS or Inconel Sheath
- High Strength Bendable Design
- Withstands Vibration, High Temperature, and High Pressure
- Connector Body Rated to 220°C (425°F)

The internal thermal couples that were used at Breck were 18 inches long, 3/16 inches in diameter, had an exposed thermocouple end, and had a sheath made with 304 stainless steel. These thermocouples have a copper positive lead and a constantan copper-nickel negative lead. This gives them a temperature range of -270^{o}C to 400^{o}C (-454^{o}F to 752^{o}F) [13].

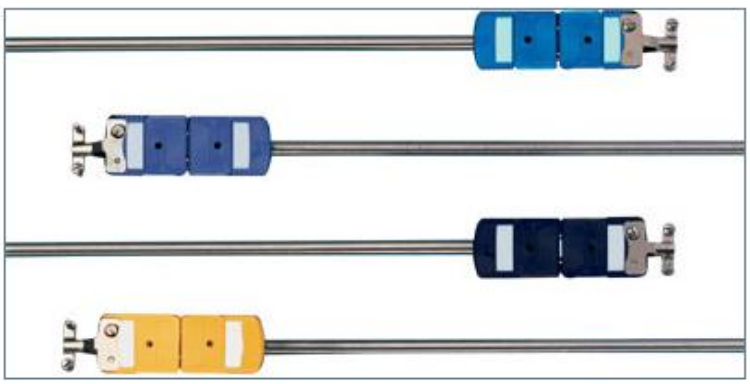

Figure 18: Thermocouple temperature probes from Omega Inc..

The thermocouple extension wire used at Breck consisted of one copper lead and one constantan copper-nickel lead (i.e. standard thermocouple wire). This made it compatible with the thermocouples used. The wire was then fitted female connector ends for easy connection to the thermocouples. These connectors also have one copper lead and one constantan copper-nickel lead.

The thermocouple wire has the following features [14]:

- High quality type “T” thermocouple grade wire
- Various insulation, wire gage, and length choices

The wire connectors have the following features [15]:

- Captive cover screws
- Quick connect contact washers
- Hollow pin construction
- Accepts standard or solid wire up to size 14 AWG
- OSTW series rated to 220^oC (500^oF)
- Available with quick wiring caps

Figure 19:IntelliLogger data logger used for the wall profile measurements at the Breck School.

The IntelliLogger data logger system for the Breck solar wall is a versatile stand alone system that can monitor and record data from a wide range of applications. A few of its capabilities are that it can sample analog and digital inputs, process and store this information in its memory, and can report or signal an alarm if any problems arise. This system is easily programmed by the user to handle simple or very complex tasks. Some of the areas that this IntelliLogger data logger system have been used in are product field tests, energy audits, measurement and verification applications, and lab use [16].

For the Breck solar wall, the Intellilogger data logger system was installed outside. One feature that was important for this situation was that the system came integrated with a lockable, waterproof, protective enclosure. This protected the system from the weather and also from being tampered with. The box used was a IL-300 model that was 12”wide, 18” high, and 7” deep. Other features include [16]:

- Hardshell ABS construction with integral structural reinforcing ribs
- Dual door closing latches with lock
- Silicone gasketed door
- Sealing gland fittings for bottom wiring ingress/egress
- Wall mount hanger
- IL-20 with up to 3 additional ILIM-7 modules (with slide-out mounting)
- IL-80 with up to 2 additional ILIM-7 modules (with slide-out mounting)
- IL-80 (in hinged mounting bracket with SRB-1 batteries beneath)
- Heavy duty surface mounting hanger plate. Projects above and below enclosure
- Door mounted D-cell (6) battery pack
- Door-mounted PSM-2 (link to existing www) Sensor Excitation power supply. The PSM-2 can provide programmable voltage excitation for sensor loops or excitation.
- Cellular modem for packet-switched communication via the cellular network and gland fitting equipped antenna
- Non-licensed Spread Spectrum radio for communication back to a base station radio on a LAN or at a PC location
- 802.11b/g WiFi bridge for wireless connectivity to a wireless access point on a LAN
- One or two SRB-1 12AH rechargeable sealed lead acid batteries for autonomous power, sensor excitation, radio or other telecom power, etc.
- Charge controller for SRB-1 charging from photovoltaic array or other source
- Other custom options

The IntelliLogger data logger system instrument model at Breck is an IL-80. It is a programmable model that includes HyperWare-II software. Features of this model are shown in Table 7 [16]. This model also came equipped with a BBus expansion port. This allowed for extra interface modules to be added to the system which would then increase the number of channels that data logger can read. The data logger used a Breck came with 2 extra ILIM-7 interface modules daisy-chained to the original IntelliLogger system. Features of the interface modules are shown in Table 8 [16].

Table 7: Specifications of the IntelliLogger IL-80 instrument module.

Feature	Channel Qty	Function	Comments
Analog Input (programmable range)	2	**Vdc Input ranges:** -10 to 20mVdc -35 to +60mVdc -45 to +80mVdc -60 to +100mVdc -120 to +200mVdc -300 to +500mVdc -600mV to +1.0Vdc -1.2 to +2.0Vdc **Thermocouple:** J, K, E, T, R, S and N types **mAdc Input ranges:** -100 to ++200uAdc -350 to +600 uAdc -450 to +800uAdc -600uA to +1mAdc -1.2 to +2mAdc -3 to +5mAdc -6 to +10mAdc -12 to +20mAdc	Channels can be field configured for Vdc input, Thermocouple input or mAdc input. These channels utilize a 10 bit ADC providing approximately 1 part in 1000 resolution over the full scale. NOTE: For higher resolution needs, the IL-80 and/or the ILIM-7 analog input expansion module can provide up to 20 bits (!) of resolution which equates to 1PPM. When channels are configured for thermocouple applications, the CJC temperature is automatically sensed and used in compensation.
Analog Input (fixed range)	1	Vdc Range: 0 to 3.2Vdc mAdc range: 0 to 32mA	Field configurable for a single range of mAdc or Vdc input. 10 bit resolution.
Internal Temperature Sensor	1	Used for CJC for System Base thermocouple measurements	Sensor can also be used for monitoring or logging of IntelliLogger temperature per user's Program Net
Digital Input	4	**Frequency:** 10Hz to 20Khz down to 100mVpp sine input. Range expands with increased amplitude input. **Count:** 3Vpp to 24Vpp up to 25KHz input **Event:** 0/3Vdc minimum, 0/24Vdc max driven input	Programmable as Event, High- speed counter or Frequency input per channel. Channels are provided with debounce and pull-up under program conrtrol allowing for non-powered (contact closure or opto) inputs for Event and Count functions.
Analog Output	2	0 to 10Vdc (8 bit)	Under IntelliLogger program control. 10Vdc output requires unit supply voltage to be >10.5Vdc.
+5Vdc Fixed Output	1	0/5Vdc output; current and short circuit protected at 25mA	Control via IntelliLogger program
Status LED	2	Green LED output	Control via IntelliLogger program
Relay Output	2	Form C (NO, NC and Com)	Control via IntelliLogger program
TTL Output	2	0/5Vdc current limited outputs	Control via IntelliLogger program
Ethernet Port	1	10base-T	Modbus TCP Server option is available for this port. Cellular network modem uses this port.
RS-232 (PC)	1	DB-9F for PC	Modbus RTU Slave option is

		Communication	available for this port.
RS-232 Comm	1	DB-9M for external comm device support (modems, radios, etc)	
USB	1	For PC Communication	
LCD Display	1	4 line x 20Character	Status messages as well as custom messages under program control
Isolated Analog Input (programmable range)	8	**Vdc Input ranges:** +/-19mVdc +/-39mVdc +/-78mVdc +/-150mVdc +/-300mVdc +/-600mVdc +/-1.2Vdc +/-2.2Vdc +/-7.5Vdc (on 4 chans only) +/-15Vdc (on 4 chans only) +/-30Vdc (on 4 chans only) **Thermocouple:** J, K, E, T, R, S and N types with both Full and Limited ranges available. **mAdc Input ranges:** +/-190uAdc +/-390uAdc +/-780uAdc +/-1.5mAdc +/-3.0mAdc +/-6.0mAdc +/-12mAdc +/-22mAdc	Channels can be field configured independently for bipolar Vdc input, Thermocouple input or mAdc input. These channels utilize a high resolution ADC providing up to 20 bits of signal resolution (i.e. one PPM). The default is 16 bits (one part in ~64,000) and the setting is user programmable. Channels are all isolated from each other as well as from the system base. When channels are configured for thermocouple applications, the CJC temperature is automatically sensed and used in compensation. Four of the eight channels when configured as Vdc inputs can be programmed to accept 3 additional higher voltage ranges up to 30Vdc. Contact Logic Beach for information about higher Vdc input ranges.
5Vdc Output	1	25mA current limited and regulated 5Vdc output for sensor excitation	Pulsed on under software control. Can be used for sensor excitation.

Table 8: Specifications of the IntelliLogger ILIM-7 interface modules.

Feature	Channel Qty	Function	Comments
Isolated Analog Input (programmable range)	8	**Vdc Input ranges:** +/-19mVdc +/-39mVdc +/-78mVdc +/-150mVdc +/-300mVdc +/-600mVdc +/-1.2Vdc +/-2.2Vdc +/-7.5Vdc (on 4 chans only) +/-15Vdc (on 4 chans only) +/-30Vdc (on 4 chans only) **Thermocouple:** J, K, E, T, R, S and N types with both Full and Limited ranges available. **mAdc Input ranges:** +/-190uAdc +/-390uAdc +/-780uAdc +/-1.5mAdc +/-3.0mAdc +/-6.0mAdc +/-12mAdc +/-22mAdc	Channels can be field configured independently for bipolar Vdc input, Thermocouple input or mAdc input. These channels utilize a high resolution ADC providing up to 20 bits of signal resolution (i.e. one PPM). The default is 16 bits (one part in ~64,000) and the setting is user programmable. Channels are all isolated from each other as well as from the system base. When channels are configured for thermocouple applications, the CJC temperature is automatically sensed and used in compensation. Four of the eight channels when configured as Vdc inputs can be programmed to accept 3 additional higher voltage ranges up to 30Vdc. Contact Logic Beach for information about higher Vdc input ranges.
5Vdc Output	1	25mA current limited and regulated 5Vdc output for sensor excitation	Pulsed on under software control. Can be used for sensor excitation.

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APPENDIX 2.1.2
Energy Management System (EMS) Descriptions

1. Breck School

Breck school's EMS controls four independent air handlers, with two independent heating sections each, to provide heating to the gymnasium. Each air handler receives feedback from a temperature probe located in its section of the space. When the EMS detects one of the temperature probes reading below the desired space temperature, it will engage the appropriate heating section until the space is sufficiently heated. During the cooling season (May through September), the air handlers are not operated. During the heating season, space temperatures are maintained at 65°F from 8am to 6pm Monday through Friday. At night and on weekends the temperature is reduced to 55°F.

Data was collected from the EMS at Breck for the northeastern air handler. The EMS logged temperatures every eight minutes, heat stage one every twenty minutes, heat stage two every thirty minutes, and supply fan every sixty minutes. The variables recorded were:

- East Heat Stage 2 On-Off
- East Supply Air Temp
- East Fan On-Off
- O.A. Temp
- East Current Set Point
- East Heat Stage 1 On-Off
- East Space Temp
- East Set Point

2. 3rd Precinct Police Station

The EMS in 3rd Precinct monitors the mixed air temperature to determine whether to draw fresh air from the solar wall or from an outdoor air damper. If the mixed air is too hot and must be cooled before distribution then the solar wall is bypassed. On the other hand, if the mixed air must be heated before distribution then the outdoor air damper is closed and the solar wall provides ventilation air. The system has the capability of regulating the outdoor air/return air ratio providing extra ventilation on mild days to reduce the need for air conditioning. The building is kept at a constant year-round temperature of 70°F.

3rd Precinct's EMS provided data for the following variables: mixed air temperature, supply air temperature, supply fan speed, solar wall fan on/off, solar wall isolation damper open/closed, solar wall relief damper open/closed, and outdoor air damper/return air (OA/RA) damper position. The logging interval for the temperatures, supply fan, and OA/RA damper was five minutes. For the solar wall dampers and solar wall fan, a data point was recorded each time their values were altered, i.e., each time the isolation damper was actuated and the fan turned on or off a data point was logged showing the time and date.

- Solar Supply Fan Status
- Solar ISO Damper Status
- Solar REL Damper Status
- Solar Supply Fan Status
- Discharge Air Temperature
- Mixed Air Temperature
- Return Air Temperature
- Return Fan Status Hz
- Supply Fan Status Hz
- OA/RA Dampers

An example of the 3rd Precinct EMS control screen can be seen in Figure 1.

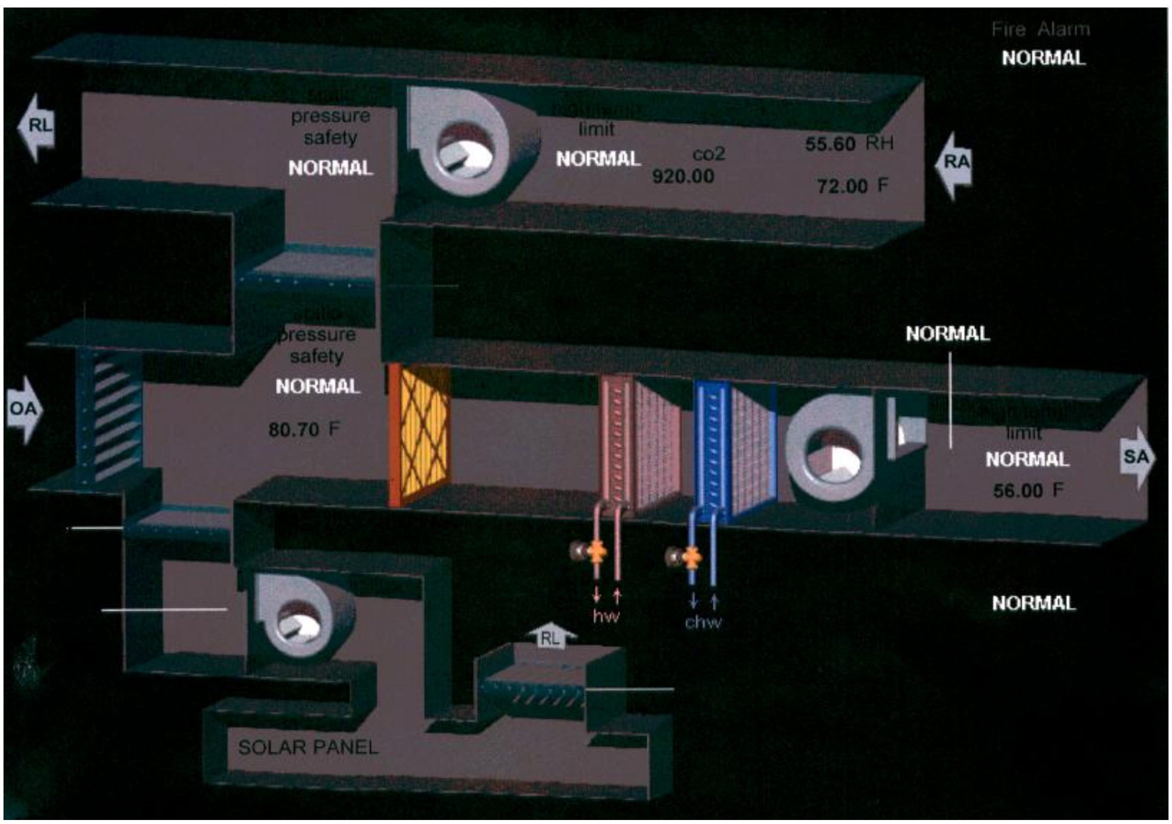


Figure 1: Screen capture of the 3rd Precinct EMS control screen.

3. AVEDA

The AVEDA EMS already included temperature sensor inputs from the solar wall. This meant that only weather station information needed to be collected with our system. Data collected through the EMS included:

- Supply Fan On-Off
- Damper Statuses
- Solar Wall Outlet Temperature
- Room Temperature

An example of the AVEDA EMS interface can be seen in Figure 2.

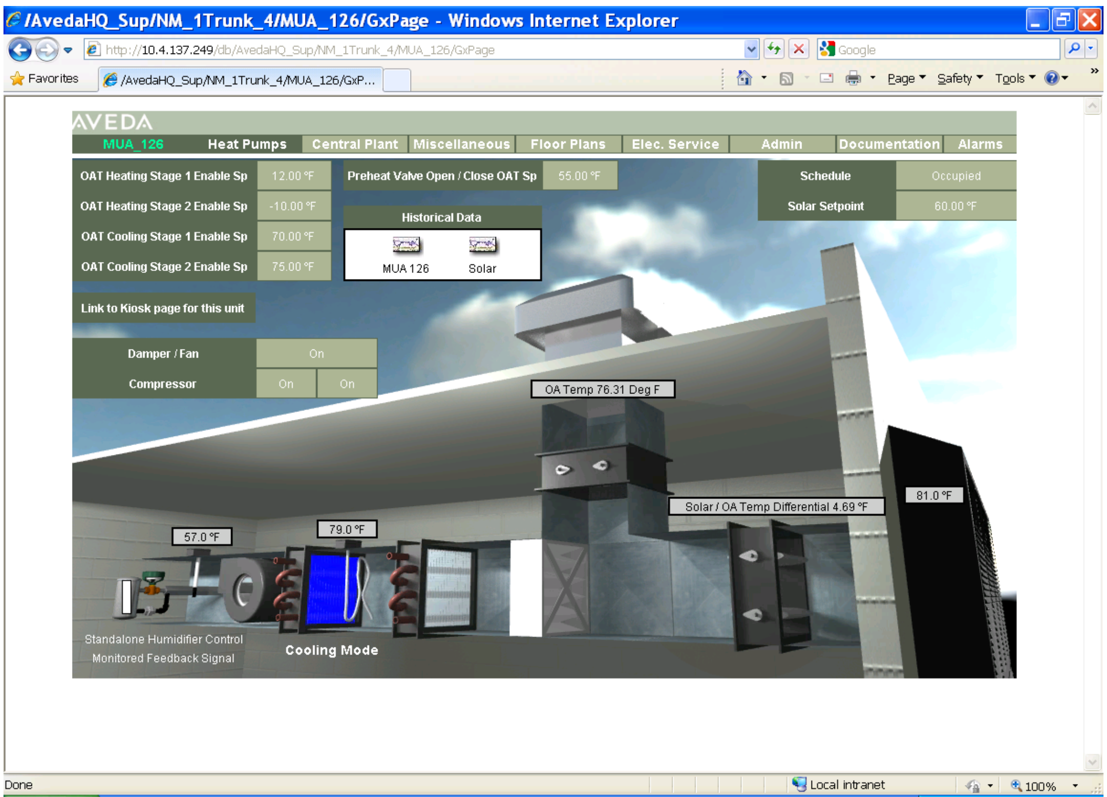


Figure 2: Screen capture of the AVEDA EMS control screen.

4. Interdistrict Downtown School (IDDS)

The system is monitored through the WebCTRL® system by Automated Logic. This DDC system controls the dampers and variable frequency drives (VFD) speeds from feedback from temperature and air flow sensors. Initially the system was not setup to read temperatures from the various air ducts. However, once it was determined that these sensors existed it was possible for Automated Logic to activate them within the system. Unfortunately this only allowed one day (24 hours) of data to be analyzed. The system was never successfully setup to do long term data logging. Therefore, the data that was collected was gathered by students who logged into the system once a day to download the previous 24 hours worth of data. Figure 3 shows an example of this system's user interface.

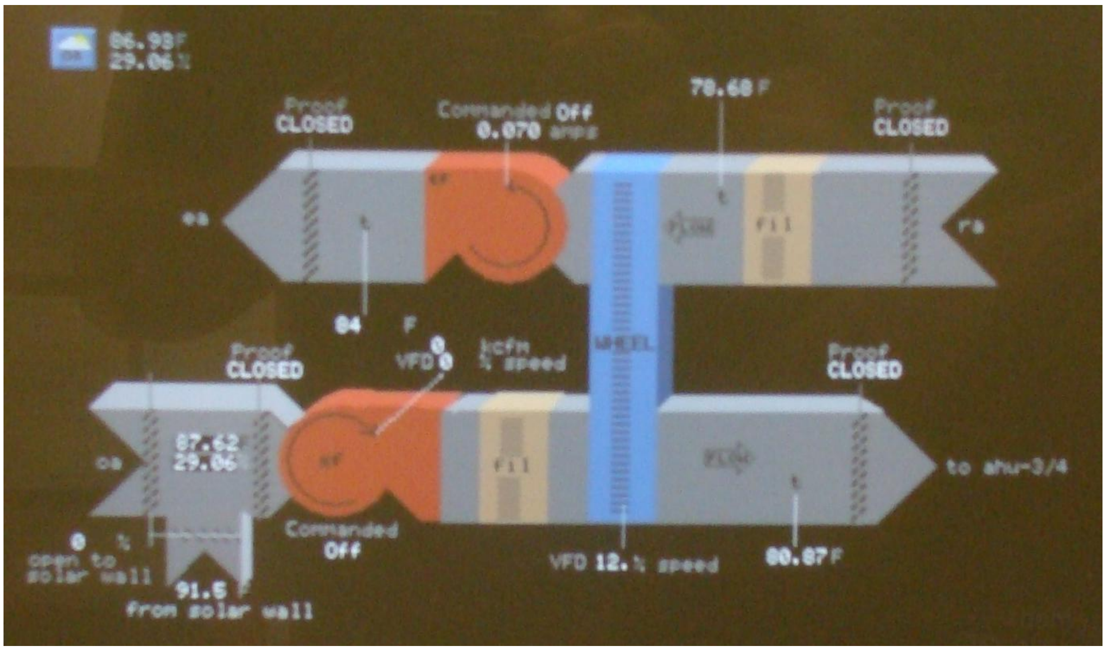


Figure 3: Screen capture of the IDDS EMS control screen.

APPENDIX 2.4
Measured Temperature Distributions Across the Breck Solar Wall

The following data was taken on February 12, 2010 at 1:50 pm. Figure 1 shows a contour plot of the temperature distribution across the outside surface of the perforated absorber plate. Figure 2 shows the temperature distribution of the air film along the back wall of the solar wall (i.e. the outside surface of the building wall). These results are from a 3 x 3 grid of temperature sensors.

For both profiles the temperature distribution was approximately symmetric across a vertical centerline. The outside surface temperature varied by 7 °F horizontally and by 12 °F vertically. The inside surface temperature varied negligibly horizontally (~1 °F) but showed an almost 20 °F difference vertically.

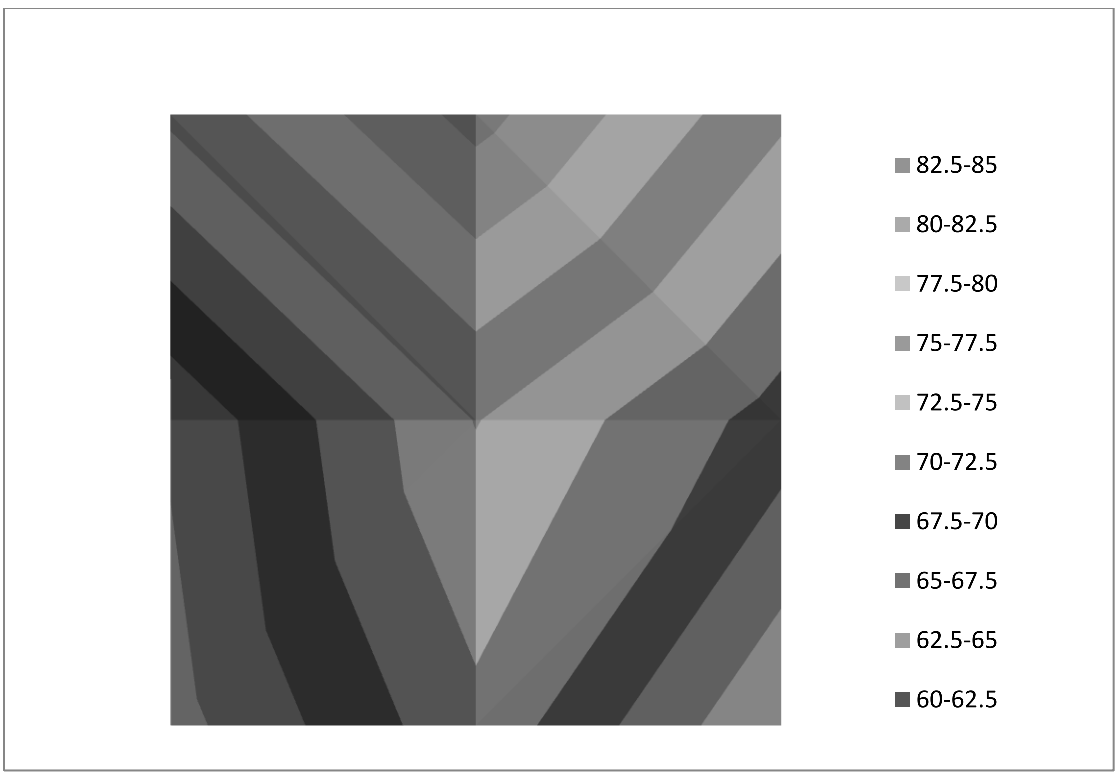


Figure 1: Temperatures on the outer surface of the absorber plate (°F).

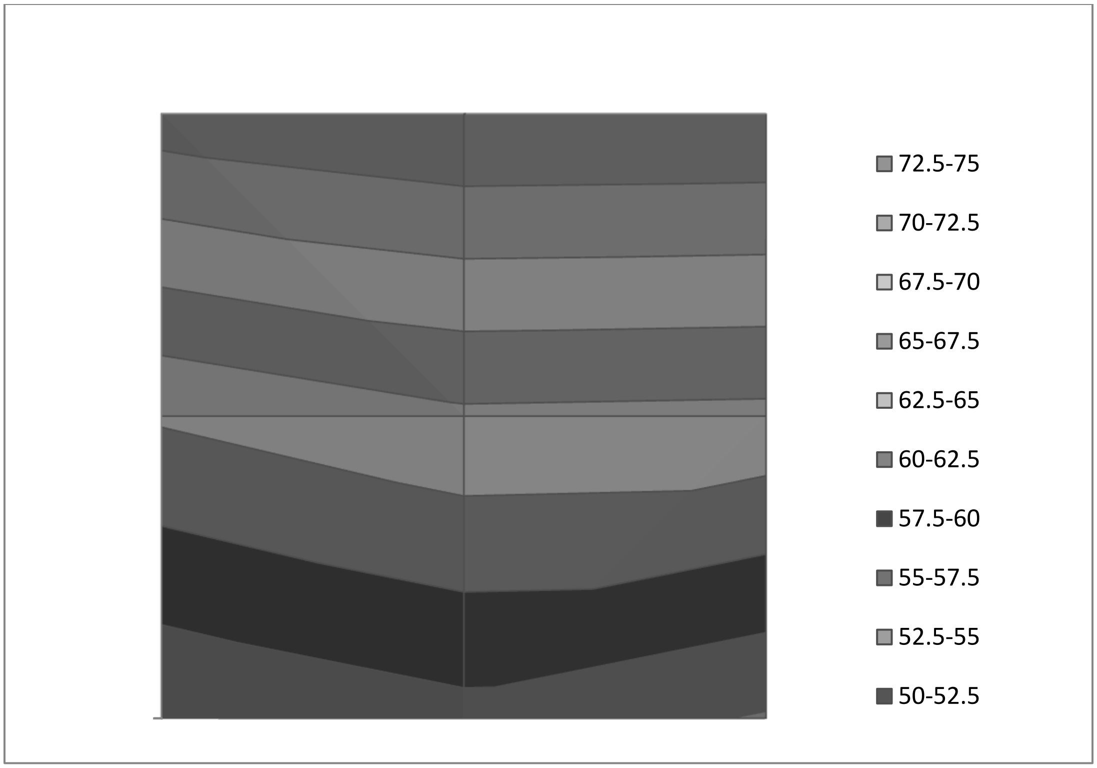


Figure 2: Temperatures of the air film over the building outer wall inside the collector (°F).

APPENDIX 3.1

A Thermal Model for the Collector

A schematic drawing of an unglazed solar collector and its adjoining building wall is shown in Figure 1.
To aid in presenting the various modes of heat transfer involved in the thermal analysis of the solar collectors and the adjoining wall for the Breck's field house, Figure 2 is also provided. Shown in Figure 2, are the modes of heat transfer considered in the energy balance for the wall and the collectors. Node 1 represents the temperature of the conditioned space. Nodes 2, 3, and 5 are the surface temperatures of the building wall and the absorber plate. The average air temperature inside the plenum is represented by node 4, and node 6 represents the outside air temperature. The plenum exit air temperature is denoted by node 7. The modes of heat transfer between various nodes should be self evident: convection between nodes 1 and 2, conduction between nodes 2 and 3; radiation exchange between nodes 3 and 5; convection between nodes 3 and 4; convection between nodes 5 and 4; convection between nodes 5 and 6; radiation exchange between the absorber plate and its surroundings, and the solar gain by the absorber plate.

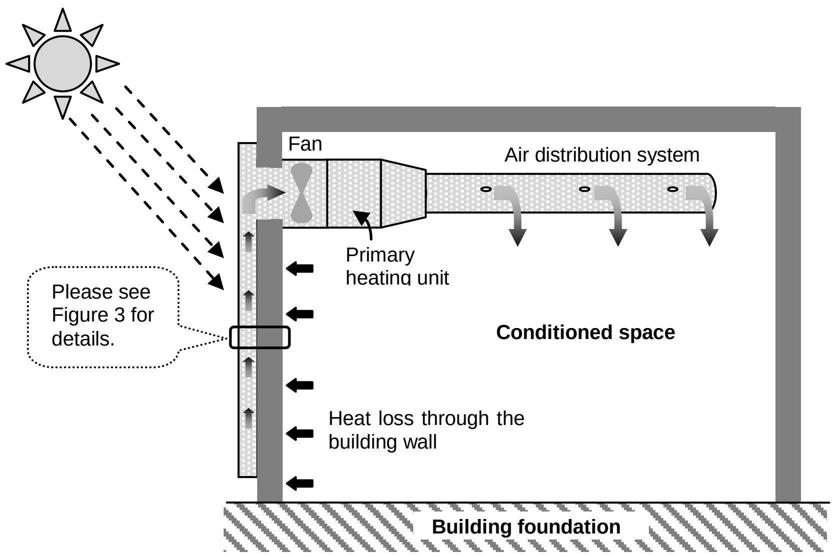


FIGURE 1 A SCHEMATIC OF AN UNGLAZED SOLAR COLLECTOR ALONGSIDE A BUILDING.

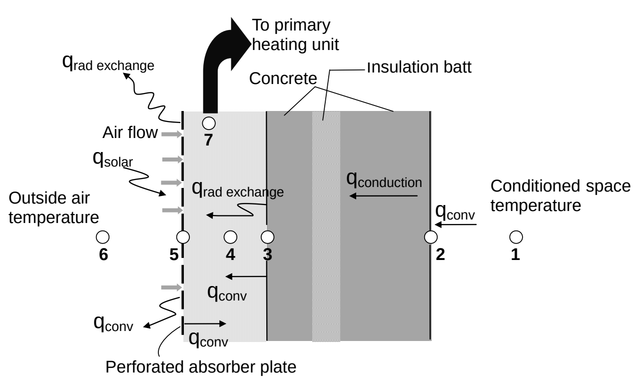


FIGURE 2 THE MODES OF HEAT TRANSFER CONSIDERED IN THE ENERGY BALANCE FOR THE WALL AND THE SOLAR COLLECTORS.

In the analysis that follows and for the sake of simplicity we have assumed constant properties (independent of temperature) and one-dimensional heat flow. The thermophysical properties were obtained from [1]. Under quasi-steady state conditions, applying an energy balance to the air inside the plenum (our control volume) we have: the time rate of energy inflow into the control volume ($\dot{E_{in}}$) should equal the rate of energy outflow($\dot{E_{out}}$).

$$\dot{E_{in}} = \dot{E_{out}} \tag{1}$$

The $\dot{E_{in}}$ term has two components:

(1) The collector panels absorb thermal radiation (αIA), part of which is transferred to air inside the plenum. α is the absorbtivity of the collector plate, I is the solar radiation on a vertical surface, and A is the total area of the collectors.

(2) The heat loss from conditioned space through building wall, which is recaptured by the plenum is given by $[\left(\frac{T_1 - T_3}{R_{conv,i} + R_{wall}}\right) A]$. The resistance to heat flow due to convection within the conditioned space (inside air film resistance) and the conduction through the building wall are represented by $R_{conv,i}, R_{wall}$.

The $\dot{E_{out}}$ term has four components:

(1) The convective heat loss from the collector panels to surrounding ambient air, which is given by $[\left(\frac{T_5 - T_6}{R_{conv,o}}\right) A]$. The air film resistance for the ambient air is represented by $R_{conv,c}$.

(2) The radiation exchange between the collector panels and the surrounding $[\varepsilon_5 \sigma A(T_5^4 - T_6^4)]$. ε_5 is the emissivity of the collector panels, σ is the Stefan Boltzman constant, and A is the total area of the collector panels.

(3) The radiation exchange between the building exterior surface and the collector panels are given by $[\frac{A\sigma(T_3^4 - T_5^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1}]$. ε_3 is the emissivity of the exterior surface of the building wall.

(4) The energy transported out of the plenum by air is given by $\rho c\dot{V}(T_7 - T_6)$, where $\rho, c, \dot{V}$ represent the density, specific heat, and volume flow rate of air, respectively.

Substituting all these terms into Equation (1), we get:

$$\alpha IA + \left[\frac{T_1 - T_3}{R_{conv,i} + R_w}\right] A = \left[\left[\frac{T_5 - T_6}{R_{conv,o}}\right] A + \varepsilon_5 \sigma A(T_5^4 - T_6^4) + \frac{A\sigma(T_3^4 - T_5^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1} + \rho c\dot{V}(T_7 - T_6)\right] \tag{2}$$

Next, we apply the energy balance to surface 3. The heat loss from the inside of the building (the conditioned space) to the plenum air is given by:

$$q_{through\ building\ wall} = \frac{T_1 - T_3}{R_{conv,i} + R_{wall}} = \frac{T_1 - T_4}{R_{conv,i} + R_{wall} + R_{conv,c}} \tag{3}$$

Where T_4 is the average air temperature inside the plenum. That is: $T_4 = \frac{T_6+T_7}{2}$. Now solving for T_3, we get:

$$T_3 = \frac{(R_{conv,c})T_1 + (R_{conv,i} + R_{wall})T_4}{R_{conv,i} + R_{wall} + R_{conv,c}} \tag{4}$$

We also need to apply the energy balance to the absorber plate, surface 5. This application results in:

$$\alpha I A = \left[\left[\frac{T_5 - T_6}{R_{conv,o}}\right]A + \varepsilon_5 \sigma A(T_5^4 - T_6^4) + \frac{A\sigma(T_3^4 - T_5^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_5} - 1} + \left[\frac{T_5 - T_4}{R_{conv,c}}\right]A\right] \tag{5}$$

We have three equations [Equation (2), (4)), (5)] with three unknowns T_7, T_3, and T_5. To solve for the unknown temperatures, the numerical scheme shown in Figure 3 was followed. First, an initial guess for T_7 is made. Next, we solve for T_3 from Equation (4). We then solve for T_5 from Equation (5), and use the values of T_3 and T_5 to solve for the new value of T_7 from Equation (2). Next, the new and old values of T_7 are compared and if their difference is not within an acceptable predefined value (*e*), we repeat the process using the new T_7 value. We stop the iterative process when the difference between the current and previous T_7 values is less than or equal to e.

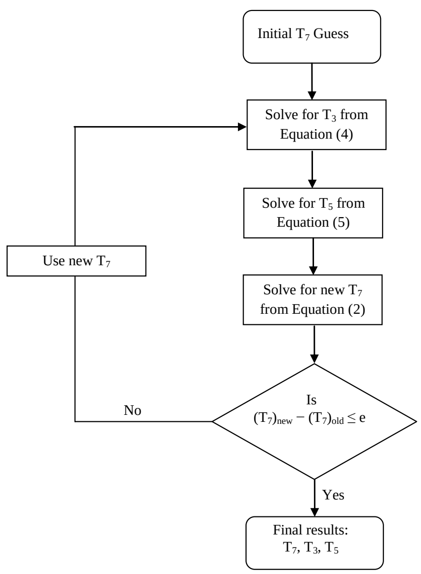


FIGURE 4 THE FLOWCHART FOR THE ITERATIVE SCHEME USED TO OBTAIN T_7, T_3, and T_5.

A SAMPLE CALCULATION FOR MARCH 2009

In the analysis that follows, the following resistance values were used from ASHRAE Fundamental Handbook [2]: the inside film resistance, $R_{con,i}$ = 0.68 hr·ft^2·°F/Btu (0.38 m^2. °C/W), the outside film resistance ($R_{con,o}$ = 0.17 hr·ft^2·°F/Btu (0.097 m^2. °C/W), and for the thermal resistance due to the convective currents in the plenum ($R_{con,c}$ = 0.25 hr·ft^2·°F/Btu the inside film resistance, $R_{con,i}$ = 0.68 hr·ft^2·°F/Btu (0.38 m^2. °C/W), the outside film resistance ($R_{con,o}$ = 0.17 hr·ft^2·°F/Btu (0.097 m^2. °C/W), and for the thermal resistance due to the convective currents in the plenum ($R_{con,c}$ = 0.25 hr·ft^2·°F/Btu (0.14 m^2·°C/W).

For the field house on the Breck campus in Minneapolis, Minnesota the following data was collected: conditioned space temperature T_1, ambient air temperature T_6, wind speed, wind direction, the plenum exit air temperature T_7. The average air temperature inside the plenum T_4 was estimated as the mean of the ambient temperature T_6 and plenum exit air temperature T_7.

The 30 year daily average radiation for the month of March on a vertical surface in Minneapolis, Minnesota was obtained from reference [3]: $4.1\,\frac{\text{kWh}}{\text{m}^2.\text{day}} = 1300\,\frac{\text{Btu}}{\text{ft}^2.\text{day}}$. Moreover, for the month of March, and latitude of 45 degrees north, average length of day (with solar radiation) is 11.8 hours [4]. As the result, the average hourly solar radiation on a vertical surface for Minneapolis, Minnesota during March is $I = \left(1300\,\frac{\text{Btu}}{\text{ft}^2.\text{day}}\right)\left(\frac{\text{day}}{11.8\ \text{h}}\right) = 110\,\frac{\text{Btu}}{\text{ft}^2.\text{h}}$

Additional data used in the numerical model include:

$\rho c = 0.0184\,\frac{\text{Btu}}{\text{ft}^3.\,°\text{R}}$

A = 3432 ft^2

T_1 = 525 °R

T_7 = 500 °R (initial guess)

T_6 = 490 °R (average outdoor air temperature for March)

$\grave{V} = 348000\ \frac{\text{ft}^3}{\text{h}}$

α = 0.9

$\varepsilon_3 = \varepsilon_5$ = 0.9

With the initial guess of T_7 = 500 °R, and e = 0.1°R
the results converged after 13 iterations to T_7 = 503 °R.

The energy savings per hour, day, and month are then calculated in the following manner:

$$Q_{saving} = \rho c\grave{V}(T_7 - T_6) \qquad (6)$$

$$[Q_{saving}]_{hourly} = \left(0.0184\,\frac{\text{Btu}}{\text{ft}^3.\,°\text{R}}\right)\left(348000\,\frac{\text{ft}^3}{\text{h}}\right)(503-490)°R = 83240\ \frac{\text{Btu}}{\text{h}}$$

$$[Q_{saving}]_{daily} = \left(83240\ \frac{\text{Btu}}{\text{h}}\right)\left(11.8\,\frac{\text{h}}{\text{day}}\right) = 982230\,\frac{\text{Btu}}{\text{day}}$$

$$[Q_{saving}]_{monthly} = \left(982230\,\frac{\text{Btu}}{\text{day}}\right)\left(31\,\frac{\text{days}}{\text{month}}\right) = 30{,}450{,}000\,\frac{\text{Btu}}{\text{month}}$$

And the average efficiency for the month of March was determined from:

$$Efficiency = \frac{Q_{saving}}{I} \qquad (7)$$

$$Efficiency = \frac{83240\,\frac{\text{Btu}}{\text{h}}}{\left(110\,\frac{\text{Btu}}{\text{h.ft}^2}\right)(3432\text{ft}^2)} = 22\%$$

The Q_{saving} was also determined from onsite measured data. The Q_{saving} for the month of March was 26760000. The percent error between the model and the measured energy savings is:

$$\%\,difference = \frac{|30450000 - 26760000|}{26760000} = 13.8\%$$

The predicted Q_{saving} is slightly higher than the measured Q_{saving}, because, we used the average ambient temperature for the entire month of March, instead of using the average ambient temperature only for the hours with solar radiation. However, if the model is to be user friendly, it has to make use of easily available climatic data.

NOMENCLATURE

A	absorber (collector) area, ft^2
c	average specific heat of air, J/kg.K
I	solar radiation on a vertical surface, $kW.h/m^2.day$
e	convergence error, K
R	thermal resistance, K/W
$R_{con,c}$	film resistance inside the plenum, K/W
$R_{con,i}$	film resistance due to inside air, K/W
$R_{con,o}$	film resistance due to outside air, K/W
R_w	wall thermal resistance, K/W
T_1	conditioned space air temperature, K
T_2	inside wall temperature, K
T_3	outside wall temperature, K
T_4	average air temperature inside plenum, K
T_5	average absorber plate temperature, K
T_6	outside air temperature, K
T_7	exit plenum air temperature, K
$\grave{V}$	volumetric flow rate of air, m^3/h

Greek

α	absorbtivity of collector plate
ε_3	emissivity of building wall
ε_5	emissivity of the absorber plate
ρ	average air density, kg/m^3
σ	Stefan-Boltzman constant, $W/m^{2\cdot}K^4$

REFERENCES

1. Incropera, F.P., and DeWitt, D.P., *Fundamentals of Heat and Mass Transfer, 2nd Ed.*, John Wiley & Sons, 1985.
2. ASHRARE Handbook, *Fundamental Volume*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 1985.
3. The Solar Radiation Data Manual for Flat-Plate and Collectors, Redbook, National Renewable Energy Lab
4. The Astronomical Applications Department, U.S. Naval Observatory, Washington, DC, http://www.usno.navy.mil/USNO/astronomical-applications/data-services

A USER GUIDE

Disclaimer: This numerical simulation of a Solar Wall™ (collector) was funded by a grant from the Minnesota Department of Energy Security. The Minnesota State University, Mankato and the Minnesota Department of Energy Security make no guarantees, warranties, or assurances of any kind, express or implied, with respect to such information, including any information on linked sites and including, but not limited to, accuracy of the information or its completeness, usefulness, adequacy, continued availability, or ownership.

Audience: These sheets are intended for use by Facility Engineers and Architects who have backgrounds in Heat Transfer and HVAC.

Procedure:

1. In the Security Warning section, Enable Macro.

2. The user needs to input the following data in the appropriate cells: The collector area in ft2, the temperature of the indoor conditioned space in °F, thermal resistance (R-value) of the building wall adjacent to the collector in hr.ft2.°F/Btu, air volumetric flow rate in ft3/h. The absorbtivity and the emissivity of the collector and the emissivity of the building wall if known.

3. After you have input the required data, in the Excel Tool Bar, click on Developer, next click on Macro and then in the Macro window click Run.

APPENDIX 3.2
Energy Savings Prediction Tools

This Appendix serves as a reference as to how values for the DOE worksheet and Retscreen spreadsheet were chosen and used. Examples of the DOE worksheet

I. DOE Worksheet Calculations

Thermal Energy Savings Equations

$$Q_{solar} = \frac{A_{coll} q_{solar} (\frac{t_{days}}{7})}{10^3} = \_\_\_\_ \frac{MBtu}{year}$$

$$Q_{wall} = \frac{A_{coll} U_{wall} t_{hours} (\frac{t_{days}}{7})}{10^6} = \_\_\_\_ \frac{MBtu}{year}$$

$$Q_{saved} = \frac{Q_{solar} + Q_{wall}}{E_{htg}} = \_\_\_\_ \frac{MBtu}{year}$$

A_{coll}= collector Area
t_{hours}=time that there is airflow through the collector in hrs/day
t_{days}=time that there is airflow through the collector in days/week
q_{solar}=useful energy from the collector in kBtu/ft2/year
U_{wall}=heat loss coefficient for the building
HDD=annual heating degree days
Q_{solar}=solar energy collected
Q_{wall}=wall heat recaptured
Q_{saved}=thermal energy savings

For Breck, Aveda, and 3rd precinct:
A_{coll} the area of the collector was known
t_{hours} was determined by summing the number of hours that the fan was on during the heating season and dividing that by the number of days in the heating season. This gave an average for the number of operating hours per day.
T_{days} was determined by observation from the data. If the fan turned on in a day, regardless of how long, it was added into the average.
q_{solar} was determined differently for each site. For Aveda q_{solar} was read directly from the DOE calculation packet.

Breck and 3rd Precinct were both calculated using a spreadsheet from NREL of 30 year averages for solar radiation. These values were given as an average qsolar per day. To get an average qsolar per month, the number of operating days in that month was multiplied by qsolar/day. For the DOE calculation qsolar is given as the "useful energy" meaning that they have added a correction factor built into qsolar. To determine this correction factor the total qsolar for a heating season from our data is summed and then qsolar is divided by the value from the DOE figure. An efficiency of 68% was obtained for the given data. This "efficiency" was then multiplied by qsolar per month to obtain the actual qsolar per month.

In short: For breck and 3rd precinct month by month

$$q_{solar} = (q_{solar-day}) \times (Days\ per\ month) \times ("efficiency")$$

$\mathbf{U_{wall}}$ is a property of the wall that was known

HDD is the number of heating degree days per year. This data was obtained from spreadsheets that were created for each site. For Aveda HDD was the sum of the HDD per month for the entire heating season. When the calculations were done on a monthly basis, as is the case in Breck and 3rd Precinct, the values for HDD per month were used for the respective month.

1. Aveda was calculated based on the above information
2. Breck was calculated on both a monthly basis and a yearly basis. In the case of calculating Qsaved on a monthly basis, it follows that the sum of all these months will give a value for Qsaved per year.
3. 3rd precinct was done on a monthly basis only. In this case the same method used in calculating Breck was followed.

II. Retscreen

The inputs for Retscreen are very similar to that for the DOE calculation. That being said the following list is the inputs needed for Retscreen:

$\mathbf{A_{coll}}$= collector Area

$\mathbf{t_{hours}}$ **per week day**=time that there is airflow through the collector in hrs/day during the work week

$\mathbf{t_{hours}}$ **per weekend day**=time that there is airflow through the collector in hrs/day during the weekend

$\mathbf{t_{days}}$ **per week**=time that there is airflow through the collector in days/week for a work week.

$\mathbf{t_{days}}$ **per weekend**=time that there is airflow through the collector in days/week for the weekend

$\mathbf{U_{wall}}$=heat loss coefficient for the building

Design air flow rate= flow rate of air through the collector in cfm

Indoor Temp= Temperature of the inside air

Air Temp Max= Temperature of the air inside the solar collector

Slope of the solar wall

Percentage of the month that is to be used. Needed if doing a month by month calculation.

Type of solar wall being used. The manufacturer and color of the wall, if known, can be specified.

Cost of electricity

Collector Sizing

Collector sizing depends on the magnitude of the building ventilation and the wall area available for mounting the transpired solar collector.

V_{bldg}	=	building outdoor airflow rate	______	cfm
A_{avai}	=	available wall area for collector	______	ft^2
v_{min}	=	minimum collector flow rate (typically about 8 cfm/ft^2)	______	cfm/ft^2
v_{max}	=	maximum collector flow rate (typically about 8 cfm/ft^2)	______	cfm/ft^2
A_{min}	=	minimum collector area (ft^2)		
A_{max}	=	maximum collector area (ft^2)		
A_{coll}	=	design collector area (ft^2)		
V_{coll}	=	total flow rate through the collector (cfm)		
v_{coll}	=	flow rate per unit collector area (cfm/ft^2)		

A_{min} = ______ V_{bldg} ÷ ______ V_{max} = ______ ft^2

A_{max} = ______ V_{bldg} ÷ ______ V_{min} = ______ ft^2

1) if $A_{avail} > A_{max}$, then

$A_{coll} = A_{max}$	=	______	ft^2
$V_{coll} = V_{bldg}$	=	______	cfm
$v_{coll} = v_{min}$	=	______	cfm/ft^2

2) if $A_{min} < A_{avail} < A_{max}$, then

$A_{coll} = A_{avail}$	=	______	ft^2
$V_{coll} = V_{bldg}$	=	______	cfm
$v_{coll} = V_{bldg} \div A_{avail}$	=	______	cfm/ft^2

3) if $A_{avail} < A_{min}$, then

$A_{coll} = A_{avail}$	=	______	ft^2
$V_{coll} = A_{avail} \times v_{max}$	=	______	cfm
$v_{coll} = v_{max}$	=	______	cfm/ft^2

Figure 1: DOE Solar Wall Collector Sizing Sheet.

Annual Energy Savings

A_{coll}	=	collector area	______	ft^2
t_{hours}	=	time that there is airflow through the collector (length of collector operating day)	______	hours/day
t_{days}	=	time that there is airflow through the collector (length of collector operating week)	______	days/week
t_{weeks}	=	time that there is airflow through the collector (length of collector operating season)	______	weeks/year
q_{solar}	=	useful energy from the collector (from Map 1)	______	$kBtu/ft^2$-year
q_{fan}	=	fan energy for airflow through the collector (typically about 1 W/ft^2)	______	W/ft^2
U_{wall}	=	heat loss coefficient for the building wall	______	Btu/°F-ft^2-hour
HDD	=	annual heating degree-days (from Map 2)	______	°F-days/year
E_{htg}	=	efficiency of the conventional heating system	______	fraction
Q_{solar}	=	solar energy collected (MBtu/year)		
Q_{wall}	=	wall heat recapture (MBtu/year) (only significant for very poorly insulated walls)		
Q_{saved}	=	thermal energy savings (MBtu/year)		
Q_{fan}	=	fan energy use (kWh/year)		

Thermal Energy Savings:

$$Q_{solar} = \underset{A_{coll}}{\_\_\_\_} \times \underset{q_{solar}}{\_\_\_\_} \times (\underset{t_{days}}{\_\_\_\_} \div 7) \div 10^3 = \_\_\_\_\_\_ \text{ MBtu/year}$$

$$Q_{wall} = \underset{A_{coll}}{\_\_\_\_} \times \underset{U_{wall}}{\_\_\_\_} \times \underset{t_{hours}}{\_\_\_\_} \times (\underset{t_{days}}{\_\_\_\_} \div 7) \times \underset{HDD}{\_\_\_\_} \div 10^6 = \_\_\_\_\_\_ \text{ MBtu/year}$$

$$Q_{saved} = (\underset{Q_{solar}}{\_\_\_\_} + \underset{Q_{wall}}{\_\_\_\_}) \div \underset{E_{htg}}{\_\_\_\_} = \_\_\_\_\_\_ \text{ MBtu/year}$$

Electrical Energy Parasitics:

$$Q_{fan} = \underset{A_{coll}}{\_\_\_\_} \times \underset{q_{fan}}{\_\_\_\_} \times \underset{t_{hours}}{\_\_\_\_} \times \underset{t_{days}}{\_\_\_\_} \times \underset{t_{weeks}}{\_\_\_\_} \div 10^3 = \_\_\_\_\_\_ \text{ kWh/year}$$

Figure 2: DOE Annual Energy Savings Sheet.

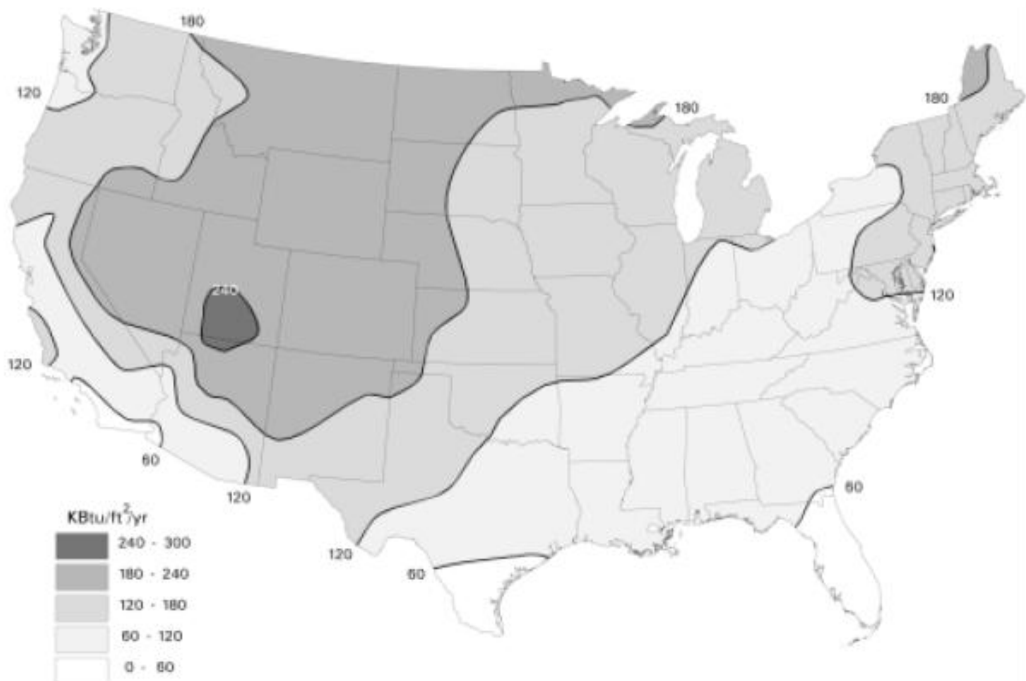


Figure 3: Useful energy delivered by collector to be used with DOE worksheet.

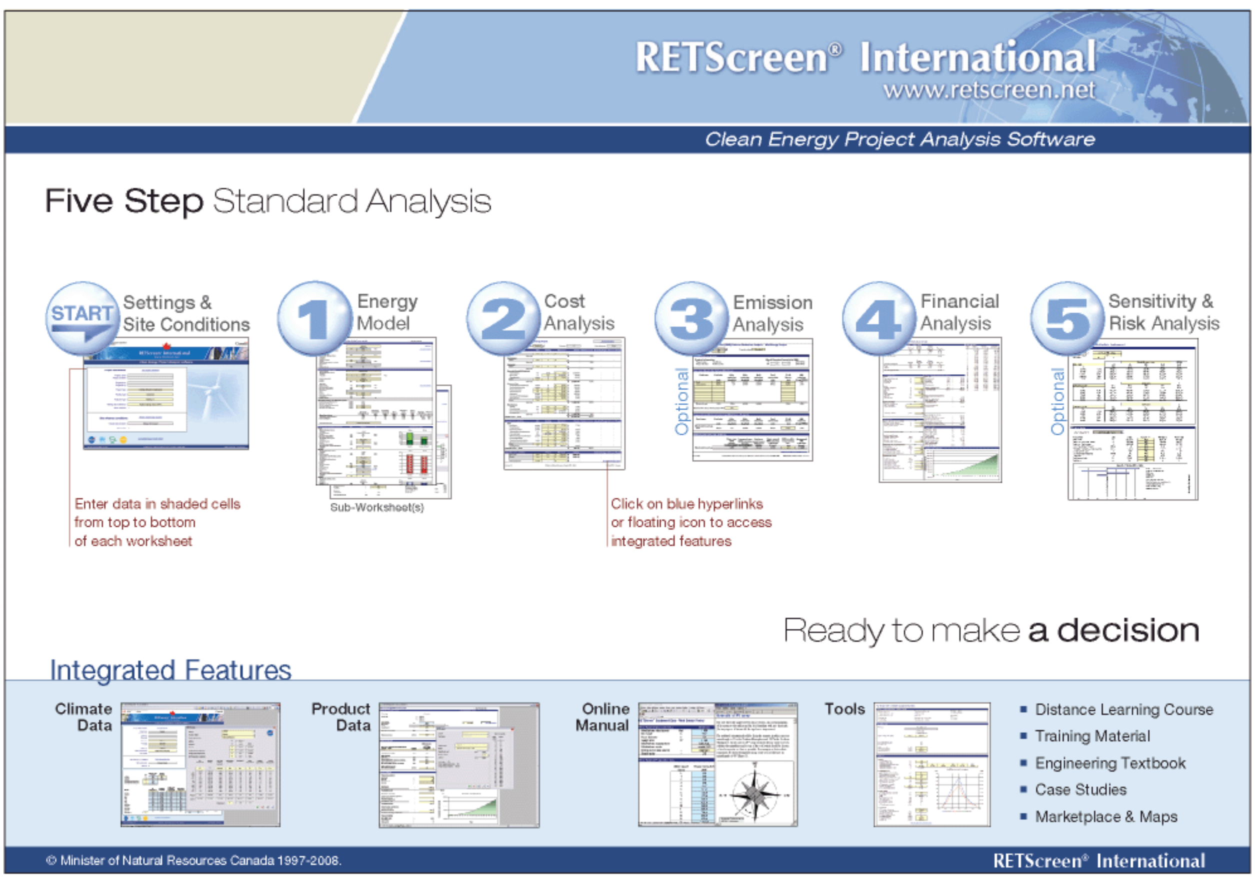


Figure 4: Example of inputs for the RETScreen spreadsheet (Source: www.RetScreen.net)

APPENDIX 4

Task 4. Evaluate solar walls' performance and GHG impact. Evaluate the performance of existing solar walls in terms of energy use and GHG emissions.

I. Building-specific degree day data and solar radiation data

The energy saved by a solar wall in a heating season depends on both the characteristics of the solar wall itself (including its area and efficiency) and the amount of solar radiation incident on the wall during the heating season. Likewise, the energy required to heat a building during a heating season depends on both the characteristics of the building (including the size of the building, the properties of the building envelope, and its ventilation requirements) and the length and severity of the winter, as determined by the number of heating degree days (HDD) in the heating season.

Heating degree days per month (based on a 65^{o}F base temperature) were calculated for each site from the outside temperature data obtained from our weather stations. The results are shown in Table 1 below for the months from Oct. 09 through Apr. 10, along with monthly heating degree days for the Minneapolis-St. Paul metropolitan area for an entire year (NOAA/National Weather Service 2011). The NWS data shows 6996 heating degree days total in the 2009-2010 heating season; of these, 6693 (96% of the total) occurred during the seven months from Oct. 09 through Apr. 10. Monthly heating degree days are consistent from site to site, although there are some slight variations. Monthly heating degree days are lowest for all months at 3rd Precinct and highest at Aveda, although the difference between 3rd Precinct and Aveda values is at most 10% with the exception of Apr. 10, for which it is 18%. Likewise, the averages over all three sites of monthly heating degree days are consistent with the National Weather Service (NWS) heating degree days, with some slight differences for each month, the average of the three sites is within 5% of the NWS value, again except for Apr. 10 for which the difference is 11%; for Dec. 09, Jan. 10, and Feb. 10 the average is within 1% of the NWS value.

Table 1. Comparison of site-specific and National Weather Service heating degree days

Month	Breck	3rd Precinct	Aveda	Average	National Weather Service
Jul 09					8
Aug 09					18
Sep 09					55
Oct 09	689		705	697	667
Nov 09	687	647	708	681	663
Dec 09	1475	1438	1492	1469	1470
Jan 10	1604	1559	1617	1593	1605
Feb 10	1267	1209	1273	1250	1260
Mar 10	770	729	774	757	735
Apr 10	338	292	353	328	293
May 10					210
Jun 10					12
Total					6996

The incident solar irradiance on a horizontal surface was also measured at each site by our weather stations. The irradiance values were summed, and the sum divided by the area of the solar wall, to get the monthly solar radiation on a horizontal surface for each site; the results are shown in Table 2. The solar radiation in a given month is very nearly the same at each site, with some slight differences. The monthly solar radiation at Aveda is consistently 10% greater than at Breck, most likely because of a difference in calibration or orientation of the sensors, and the monthly solar radiation at 3rd Precinct is consistently a few percent greater than at Breck, most likely for the same reasons.

Table 2. Comparison of monthly solar radiation on a horizontal surface at the three sites

	Solar radiation on a horizontal surface (kBtu/ft^2·month)			
Month	Breck	Aveda	3rd Precinct	Average
Oct 09	16.6	18.2		17.4
Nov 09	15.4	17.0	15.8	16.1
Dec 09	11.1	12.3	11.6	11.7
Jan 10	15.6	17.4	15.7	16.2
Feb 10	24.2	27.0	24.9	25.4
Mar 10	34.4	37.9	35.8	36.0
Apr 10	45.0	48.8	46.0	46.6

In Table 3 the average monthly solar radiation at the three sites is compared with 30-year averages from the National Renewable Energy Laboratory (NREL 2011). With each average, NREL provides the standard deviation, a measure of the amount by which one would expect a monthly value in a single year to differ from the 30-year average. Also included in the table is NREL's 30-year average monthly solar radiation on a south-facing surface (such as the surface of a solar wall). We see from the table that the daily average monthly solar radiation on a horizontal surface at our sites is within one standard deviation of the NREL average for four of seven months, and within two standard deviations for two additional months. It is only for Oct 09 that the average at our sites differs significantly from the NREL average. Hence the daily average monthly solar radiation for the 2009-2010 heating season fell within historic norms. Since the solar radiation for the 2009-2010 heating season was typical, we can use the NREL averages on a south-facing vertical surface to calculate the efficiencies of the solar walls at our sites.

Table 3. Comparison of average solar radiation to NREL 30 year averages

	Average solar radiation at our sites horizontal surface		NREL average horizontal surface	NREL average south-facing vertical surface	
Month	$kBtu/ft^2 \cdot month$	$Btu/ft^2 \cdot day$	$Btu/ft^2 \cdot day$	$Btu/ft^2 \cdot day$	$MBtu/ft^2 \cdot month$
Oct 09	17.4	561	880 ± 73	1110	34.4
Nov 09	16.1	537	540 ± 47	860	25.8
Dec 09	11.7	377	430 ± 35	820	25.4
Jan 10	16.2	523	560 ± 36	1060	32.9
Feb 10	25.4	907	860 ± 53	1230	34.4
Mar 10	36.0	1160	1190 ± 90	1180	36.6
Apr 10	46.6	1550	1490 ± 116	1040	31.2

II. Energy saved, conventional energy used, cost savings, and GHG emissions reductions

A. Breck

The monthly values of the energy saved by the solar wall (Q_{save}) and of the energy provided by conventional heat sources (Q_{aux}) at the Breck field house were calculated from Oct. 09 through Apr. 10 and tabulated in Table 4 below. The conventional heat sources at Breck were ceiling-mounted two-stage natural gas-fired heaters. Also shown in the table is the fraction of energy saved ($= Q_{save} /(Q_{aux} + Q_{save})$); the cost of the natural gas and the cost savings from the use of the solar wall; and the CO_2 emissions and the reduction in CO_2 emissions from the use of the solar wall. The natural gas use was calculated from the gas-fired heaters' rated efficiency of 80%, then the cost of the natural gas was calculated using a price of $0.796/therm, the Minnesota price of natural gas sold to commercial consumers in 2009 (EIA 2011a). CO_2 emissions were calculated using the CO_2 emission factor of 115.99 lb CO_2/MBtu for natural gas (MPCA 2009).

A summary of the main results for Breck is shown after the table. The energy savings are 243 MBtu from Oct. 09 through Apr. 10, a period which includes 96% of the HDD of the 2009-2010 heating season.

Table 4. Breck: Energy savings, cost savings, and reductions in CO_2 emissions

Month	Q_{aux} (MBtu)	Q_{save} (MBtu)	Fraction of energy saved	Cost of natural gas	Cost of natural gas saved	CO_2 emissions (tons)	Reduction in CO_2 emissions (tons)
Oct-09	187	15.0	7.4%	$1862	$150	10.9	0.87
Nov-09	189	19.9	9.5%	$1881	$198	11.0	1.15
Dec-09	666	51.9	7.2%	$6629	$516	38.6	3.01
Jan-10	716	67.2	8.6%	$7121	$668	41.5	3.89
Feb-10	401	51.4	11.4%	$3994	$511	23.3	2.98
Mar-10	171	26.8	13.5%	$1705	$266	9.9	1.55
Apr-10	48	8.7	15.3%	$481	$87	2.8	0.51
Total	2379	240.8	9.2% (average)	$23,673	$2396	138.0	14.0

Breck 2009-2010

Summary of energy savings, cost savings, and CO_2 emissions reductions

Energy savings

Conventional energy used to heat the field house (Q_{aux})	2379 MBtu
Energy saved due to solar wall (Q_{save})	241 MBtu
Energy required had solar wall not been used ($Q_{aux} + Q_{save}$)	2620 MBtu
Fraction of energy saved ($Q_{save} / (Q_{aux} + Q_{save})$)	9.2%

Natural gas cost savings

Cost of natural gas	$23,673
Reduction in cost due to solar wall	$2,396
Cost had solar wall not been used	$26,070
Fractional savings in cost	9.2%

Reductions in CO_2 emissions

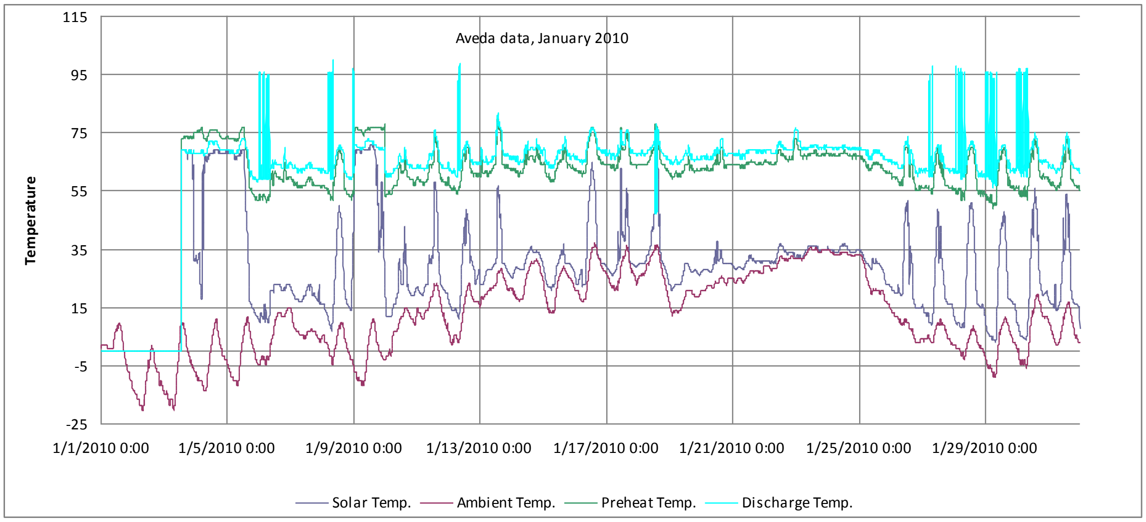
CO_2 emissions	138 tons
Reduction in emissions due to solar wall	14 tons
Emissions had solar wall not been used	152 tons
Fractional reduction in emissions	9.2%

B. Aveda

The system at Aveda is more complicated than that at Breck in that there are two sources of conventional heat. After being drawn through the solar wall or being drawn from outside the ventilation air first passes through a pre-heat stage then through a heat pump before being discharged into the building. In the preheat stage, a heat exchanger adds heat from inside the Aveda facility to the ventilation air. Fig. 1 below shows Aveda temperature data for a typical month; shown are the outside (ambient) temperature, the temperature at the output of the solar wall (the solar temperature), the temperature after the preheat unit (the preheat temperature), and the temperature after the heat pump, just before the ventilation air is discharged into the building (the discharge temperature). We see that most of the heat added comes from the heat exchanger rather than the heat pump. Also, the heat pump occasionally acts in an erratic manner and cycles rapidly between approximately 65^{o}F and 95^{o}F. (Between 1/5/2010 and 1/9/2010 this happens twice; from 1/25/2010 to the end of the month, it happens four more times.) *We therefore disregard the heat pump and calculate only the heat added in the pre-heat stage*.

A further complication with the Aveda data is that there are occasionally time periods over which the solar temperature is not logged (the first two days of January, for example, as seen in Fig. 1). There are also periods of up to a day in length or occasionally longer in which the system is shut off; when this happens, the solar temperature rises rapidly to room temperature (the discharge temperature) and plateaus there until the system turns back on, at which time the solar temperature falls rapidly and begins tracking the ambient temperature again. This happens for a period starting

Fig 1. Aveda: Temperature data, January 2010



1/4/2010 and ending 1/5/2010 and again on 1/9/2010. *For time periods like this the data are not valid and are disregarded.*

The monthly values of the heat added in the pre-heat stage (Q_{aux}) and the energy saved by the solar wall (Q_{save}) for Aveda are tabulated in Table 5 below. In columns two and three are the values of Q_{aux} and Q_{save} using the valid data only; the fraction of energy saved ($= Q_{save}/(Q_{aux} + Q_{save})$) by month is shown in column four. The number of days with valid data in a month is shown in column five. Q_{aux} and Q_{save} for the entire month are extrapolated by dividing the values of Q_{aux} and Q_{save} in columns two and three by the number of days with valid data in the month to get average daily values, then multiplying by the number of days in the month; the extrapolated values of Q_{aux} and Q_{save} are in the sixth and seventh columns, respectively. The total extrapolated energy saved by the solar wall (Q_{save}) from Oct. 09 through Mar. 10 was 302 MBtu; the total extrapolated energy required to heat the building ($= Q_{aux} + Q_{save}$) for the same period was 1555 MBtu.

We considered two options to calculate the cost savings and the GHG emissions reductions. For the first option, we assume that had the solar wall not been used, the pre-heat unit would have supplied extra energy Q_{save}. In this case, no additional fuel or electricity would be required, so there would be no cost reduction or reduction in greenhouse gas emissions. For the second option, we assume that the heat pump would have provided the additional energy, had the solar wall not been used. Then the heat pump would have required extra electricity for it to produce the extra 302 MBtu ($= Q_{save}$) over the heating season. The coefficient of performance (COP) of the Aveda heat pump is 3.8, so the electricity required is 23.3 MWh. The electricity provider for Aveda is Xcel; the CO_2 emission rate for electricity from Xcel is 1317.17 lb CO_2 / MWh (MPCA 2009) and the average retail price of electricity to commercial customers in Minnesota in Oct 09 was $0.0767 / kWh (EIA 2011b), so the estimated cost savings to Aveda would have been $1786, and the reduction in CO_2 emissions would have been 15.3 tons over the heating season. The results for Aveda are summarized after Table 5.

Table 5. Aveda: Energy savings

Month	Q_{aux} (MBtu) valid data only	Q_{save} (MBtu) valid data only	Fraction of energy saved	Days with valid data	Q_{aux} (MBtu) extrapolated to entire month	Q_{save} (MBtu) extrapolated to entire month
Oct-09	146	16.5	10.2%	22	200	22.8
Nov-09	128	21.4	14.3%	20	195	32.6
Dec-09	201	57.9	22.3%	26	241	69.2
Jan-10	195	56.8	22.6%	25	240	69.9
Feb-10	200	74.3	27.1%	28	200	74.3
Mar-10	177	33.4	15.9%	31	177	33.4
Total	1047	260	19.9% (average)	152	1253	302.2

Aveda 2009-2010

Summary of energy savings, cost savings, and CO_2 emissions reductions

Assumption:

The conventional heat (Q_{aux}) is supplied solely by the pre-heat unit. (The heat supplied by the heat pump is much smaller and is ignored.)

Option 1: If the solar wall were not used, Q_{save} would be contributed by the *pre-heat unit*.

Summary: (Based on extrapolated values of Q_{aux} and Q_{save} for months with some invalid data)

Energy from pre-heat unit (Q_{aux})	1253 MBtu
Energy saved due to solar wall (Q_{save})	302 MBtu
Total energy required ($Q_{aux} + Q_{save}$)	1555 MBtu
Fraction of energy saved ($Q_{save}/(Q_{aux} + Q_{save})$)	19.9%
Reduction in cost of electricity due to solar wall (Option 2)	0
Reduction in CO_2 emissions due to solar wall (Option 2)	0

Option 2: If the solar wall were not used, Q_{save} would be contributed by the *heat pump*.

Summary: (Based on extrapolated values of Q_{aux} and Q_{save} for months with some invalid data)

Energy from pre-heat unit (Q_{aux})	1253 MBtu
Energy saved due to solar wall (Q_{save})	302 MBtu
Total energy required ($Q_{aux} + Q_{save}$)	1555 MBtu
Fraction of energy saved ($Q_{save} / (Q_{aux} + Q_{save})$)	19.9%
Reduction in cost of electricity due to solar wall (Option 2)	$1800
Reduction in CO_2 emissions due to solar wall (Option 2)	15 tons

Comparison with Aveda claim:

In informational literature, Aveda states, "The preheated ventilation air has reduced energy consumption at Aveda by approximately 4000 therms each year." Our study finds a reduction in energy consumption of 3020 therms from October 09 through March 10, a period which includes 91% of the HDD of the 2009-2010 heating season.

C. 3rd Precinct

Values of energy saved (Q_{save}) and conventional energy used (Q_{aux}) for 3rd Precinct for three months in the 2009-2010 heating season – Jan. 10, Feb. 10, and Apr. 10 – and for three months in the 2010-2011 heating season – Nov. 10, Dec. 10, and Jan. 11 – and tabulated in Table 6 below. Complete data were obtained for all six months except for the first two days of Apr. 10, the first eight days of Nov. 10, and the last 11 days of Jan. 11. For the three months for which complete data were not obtained, values of Q_{aux} and Q_{save} for the entire month were extrapolated from the data, in the same way as was done for the Aveda data.

The conventional heat at 3rd Precinct is supplied by three identical boilers; the efficiency of heat transfer from the boilers to the ventilation air is approximately 80%. The cost of the natural gas used was calculated using a price of $0.756/therm, the Minnesota price of natural gas sold to commercial consumers in 2010 (EIA 2011a). CO_2 emissions were calculated using the CO_2 emission factor of 115.99 lb CO_2 / MBtu for natural gas (MPCA 2009).

A summary of the main results for 3rd Precinct is shown after the table. The total energy savings are 39 MBtu for the 6-month period of the study. In calculating the total energy savings, values of energy savings extrapolated to the entire month are used for the three months for which there is only partial data.

Table 6. 3rd Precinct: Energy savings

Month	Q_{aux} (MBtu)	Q_{save} (MBtu)	Fraction of energy saved	Days with data	Q_{aux} (MBtu) extrapolated to entire month	Q_{save} (MBtu) extrapolated to entire month
Jan-10	75.1	9.7	11.5%	31	75.1	9.7
Feb-10	66.1	11.1	14.4%	28	66.1	11.1
Apr-10	6.6	0.69	9.4%	28	7.1	0.74
Nov-10	11.9	2.6	18.0%	22	16.3	3.6
Dec-10	28.9	8.3	22.4%	31	28.9	8.3
Jan-11	23.4	6.9	22.8%	20	36.2	10.7
Total	212.1	39.4	15.7% (average)	160	229.7	44.2

3rd Precinct: 6 months, 2009-2011

Summary of energy savings, cost savings, and CO_2 emissions reductions

Energy savings (Extrapolated)

Conventional energy used to heat the building (Q_{aux})	230 MBtu
Energy saved due to solar wall (Q_{save})	44 MBtu
Energy required had solar wall not been used ($Q_{aux} + Q_{save}$)	274 MBtu
Fraction of energy saved ($Q_{save} / (Q_{aux} + Q_{save})$)	15.7%

Natural gas cost savings (Estimated)

Cost of natural gas	$2,171
Reduction in cost due to solar wall	$418
Cost had solar wall not been used	$2,589
Fractional savings in cost	15.7%

Reductions in CO_2 emissions (Estimated)

CO_2 emissions	17 tons
Reduction in emissions due to solar wall	3 tons
Emissions had solar wall not been used	20 tons
Fractional reduction in emissions	15.7%

III. Heating degree day normalization of energy use

The energy required by a building ($Q_{aux} + Q_{save}$) to make up for ventilation losses and heat transfer losses through the building envelope is greater for a colder month having more heating degree days (HDD) than for a warmer month with fewer HDD. One can get the HDD normalization of a building (the ratio of energy required to HDD) by graphing $Q_{aux} + Q_{save}$ versus HDD for each month for which data are taken. The graphs of $Q_{aux} + Q_{save}$ versus HDD for the Breck field house and the 3rd Precinct building are shown below; the values of HDD plotted are site-specific HDD.

The graph for the Breck field house is a straight line, which shows that $Q_{aux} + Q_{save}$ for a month is a linear function of the number of HDD in the month. The normalization is the slope of the line: 586 kBtu / HDD for the field house. The *y*-intercept of the line represents the internal gains of the field house: 197 kBtu / month.

The graph for the 3rd Precinct building consists of two straight lines, one for the 2009-2010 heating season and the other for the 2010-2011 heating season. The graph shows that the heating needs of the building changed from one year to the next: in 2009-2010, the requirement was 64 kBtu / HDD; in 2010-2011, it was 30 kBtu / HDD, less than half its value the previous year, most likely because of a reduction in ventilation requirements. Internal gains changed but not by much from one year to the next: from 8.51 MBtu / month in 2009-2010 to 6.81 MBtu / month in 2010-2011.

An attempt to find the HDD normalization of energy use for Aveda was unsuccessful. A HDD normalization presupposes a constant or at least consistent set point temperature. We did not monitor the set point temperature of the conditioned space at Aveda; the temperature of the ventilation air after passing through the pre-heat unit, however, showed considerable variation, and the average preheat temperature was significantly greater (by approximately $10^{o}F$) for the warmer months (Oct. 09, Nov. 09, and Mar. 10) than for the colder months (Dec. 09, Jan. 10, and Feb. 10).

Fig 2. Breck 2009-2010 HDD normalization of energy use

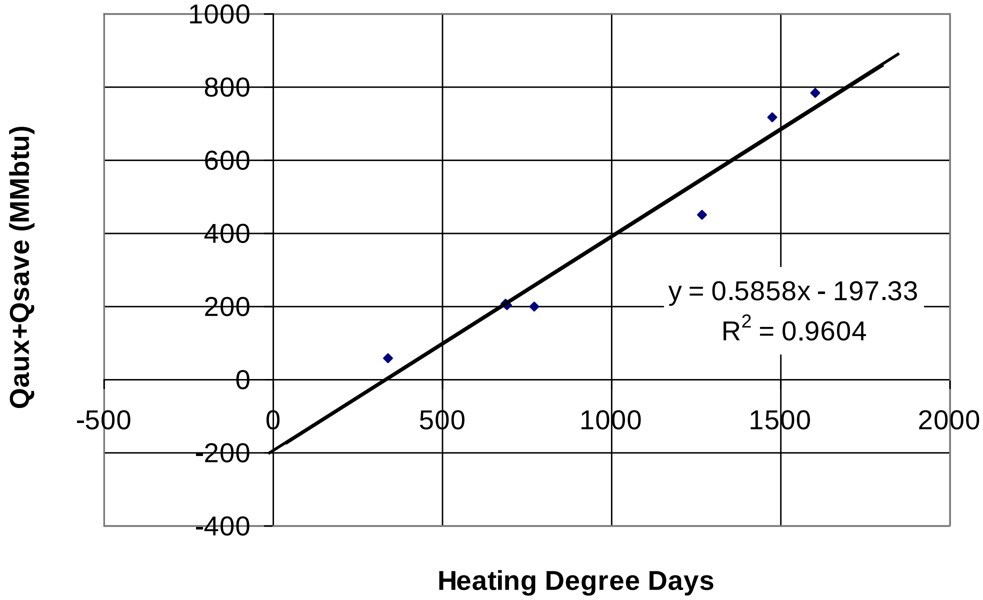
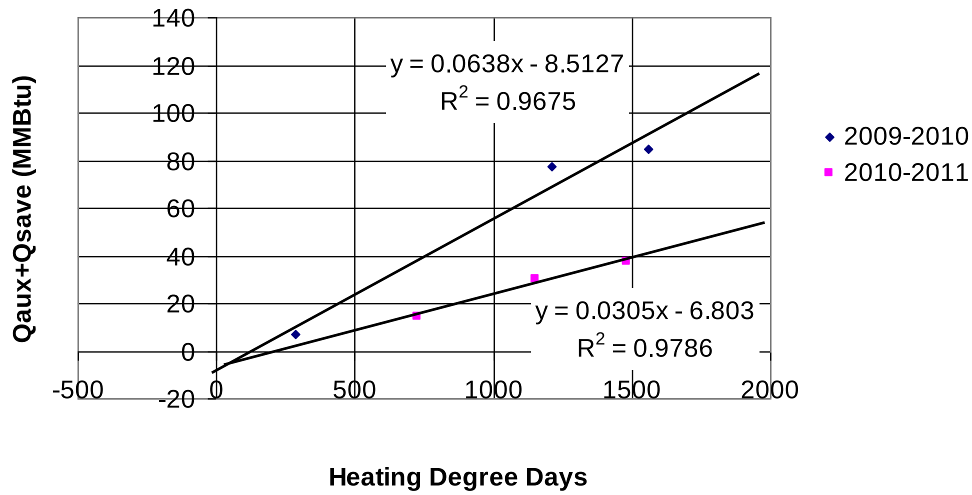


Fig 3. 3rd Precinct 2009-2011 HDD normalization of energy use



IV. Validity of 65°F base temperature for degree days

A base temperature of 65°F for heating degree days (HDD) means that at an outside air temperature of 65°F the energy supplied to a building by conventional heat sources and solar wall if present ($Q_{aux} + Q_{save}$) will be zero. The set point temperature inside the building will be higher, commonly 68°F; the extra heat necessary to maintain the 68°F set point temperature when the outside temperature is 65°F comes from internal gains. Also at a base temperature of 65°F and outside temperature of 65°F, HDD = 0. Since at a base temperature of 65°F and outside temperature of 65°F, both $Q_{aux} + Q_{save}$ and HDD are zero, a graph of $Q_{aux} + Q_{save}$ versus HDD will pass through the origin.

This is clearly not the case in either Fig. 2 or Fig. 3. It is evident from the figures that the base temperature for the Breck fieldhouse and for the 3rd Precinct building is *lower* than 65°F: By definition, the base temperature is the temperature at which $Q_{aux} + Q_{save}$ is zero, yet for all three plots HDD is greater than zero (so the average outside temperature is less than 65°F) when $Q_{aux} + Q_{save}$ is zero. From the values of the *x*-intercepts of the plots, we can find the base temperatures. For the Breck fieldhouse the base temperature was 54°F in 2009-2010; for the 3rd Precinct building, the base temperature was 61°F in 2009-2010 and 58°F in 2010-2011.

V. Solar efficiencies

There are two major contributions to the energy saved (Q_{save}), the active solar gain (Q_{solar}) and the recaptured wall loss (Q_{wall}); $Q_{save} = Q_{solar} + Q_{wall}$. The active solar gain Q_{solar} is the heat added to the ventilation air from the heat of the sun. The recaptured wall loss Q_{wall} is the heat that has been conducted through the building wall from the hotter interior to the cooler exterior, then recaptured by the solar wall and added to the ventilation air. For a building with well-insulated walls, Q_{wall} is relatively small. Q_{wall} is typically 10% of Q_{save} -- less for well-insulated buildings, more for poorly-insulated buildings.

The solar efficiency is defined to be the active solar gain Q_{solar} divided by the incident solar radiation on the solar wall, per square foot of the solar wall. For Aveda, the solar wall system operated 24 hours a day, and Q_{solar} could be found directly from the increase in Q_{save} during daylight hours. For Breck and 3rd Precinct the solar fan was on only during daylight hours; for these two installations the recaptured wall loss Q_{wall} was estimated by month using Department of Energy (DOE) worksheets (DOE 1998, 11), then Q_{solar} was found from the equation $Q_{solar} = Q_{save} - Q_{wall}$. These monthly values of Q_{solar} were then compared to the monthly NREL 30-year average values of vertical solar radiation to find the solar efficiencies by month. The results are shown in Tables 7, 8, and 9 below.

Each table is somewhat different in format from the others to reflect both differences in the method of finding Q_{solar} and differences in data collection at the three installations. At Breck, complete data were collected for all months of the study. At Aveda, complete data were collected for all months, but some of the data were invalid; when a month had invalid data, values of Q_{save} and Q_{solar} for the valid data were extrapolated to the entire month. At 3rd Precinct, data were not collected for the first eight days of Nov. 10 or the last 11 days of Jan. 11; to get Q_{solar}/A in Btu/ft^2-day for these months, we divided by the number of days for which data were taken (not by the number of days in the month).

Table 7. Breck solar efficiency

Month	Qsave (MBtu)	Qwall (MBtu)	Qsolar (MBtu)	Qsolar/A (Btu/ft^2-day)	Vertical solar radiation (Btu/ft^2-day)	Efficiency
Oct-09	15.0	1.0	14.0	137	1110	12.3%
Nov-09	19.9	1.0	18.8	190	860	22.1%
Dec-09	51.9	7.0	44.9	439	820	53.5%
Jan-10	67.2	8.5	58.7	574	1060	54.1%
Feb-10	51.4	4.1	47.3	512	1230	41.6%
Mar-10	26.8	0.9	25.9	253	1180	21.5%
Apr-10	8.7	0.2	8.6	86	1040	8.3%
Total	240.8	22.6	218.2			30.5% (average)

Table 8. Aveda solar efficiency

Month	Qsave (MBtu) extrapolated to entire month	Qsolar (MBtu) extrapolated to entire month	Qsolar/A (Btu/ft^2-day)	Vertical solar radiation (Btu/ft^2-day)	Efficiency
Oct-09	22.8	16.1	409	1110	36.9%
Nov-09	32.6	16.4	431	860	50.1%
Dec-09	69.2	14.9	377	820	46.0%
Jan-10	69.9	19.4	492	1060	46.5%
Feb-10	74.3	32.3	908	1230	73.8%
Mar-10	33.4	35.4	898	1180	76.1%
Total	302.2	134.4			54.9% (average)

Table 9. 3rd Precinct solar efficiency

Month	Days with data	Qsave (MBtu)	Qwall (MBtu)	Qsolar (MBtu)	Qsolar/A (Btu/ft^2-day)	Vertical solar radiation (Btu/ft^2-day)	Efficiency
Jan-10	31	9.72	0.17	9.56	403	1060	38.0%
Feb-10	28	11.14	0.13	11.01	514	1230	41.8%
Apr-10	28	0.69	--	0.69	32	1040	3.1%
Nov-10	22	2.62	0.05	2.57	153	860	17.7%
Dec-10	31	8.35	0.18	8.17	344	820	42.0%
Jan-11	20	6.90	0.17	6.74	440	1060	41.5%
Total	160	39.4	0.7	38.7			30.7% (average)

The values of solar efficiencies in Tables 7, 8, and 9 above are *monthly* solar efficiencies: the active solar gain in a month divided by the incident vertical solar radiation in a month, per square foot of collector area. We have to calculate solar efficiencies this way because we have only monthly values of incident vertical solar radiation (the NREL 30-year averages), and for Breck and 3rd Precinct only monthly estimates of Q_{wall}. But monthly solar efficiencies grossly underestimate the performance of the solar walls in warmer months when the solar wall only has to operate for a fraction of the total daylight hours to maintain the set point temperature in the conditioned space. For Breck, the solar wall operates only for roughly three-fourths of the possible daylight hours during Oct. 09, Nov. 09, and Mar. 10, and only for one-fourth of the possible daylight hours in Apr. 10. Likewise, for 3rd Precinct the solar wall operates for only a little more than half the possible daylight hours in Nov. 10 and for only a tenth (three days) of the possible daylight hours in Apr. 10. On the other hand, the Aveda solar wall operated 24 hours a day for the entire time for which we have data, from Oct. 09 through Mar. 10.

A much better measure of the performance of the Breck and 3rd Precinct solar walls are the monthly solar efficiencies during the coldest months of the year – December, January, and February – when they are on nearly all the time during daylight hours. When we average the monthly solar efficiencies for Breck and 3rd Precinct just for these winter months, we find solar efficiencies of 50% for Breck and 41% for 3rd Precinct, compared to 55% for Aveda.

The Aveda solar wall approaches the theoretical maximum solar efficiency of 70-80%, in particular in Feb. 10 and Mar. 10. The other two installations have reasonably consistent values of solar efficiency for the cold winter months but they are nowhere near the theoretical maximum. A possible reason for this at Breck is the relatively low rate of flow of air through the Breck solar wall, which makes possible the disruption of flow by the wind. The approach velocity, defined as the total flow rate (in cfm) divided by the total collector area (in ft^2), must be greater than a threshold value of 4 ft/min to prevent loss of efficiency because of wind effects (Kutscher 1993, 186); for Breck, the approach velocity is 1.76 ft/min, considerably below this threshold. The reason for the relatively low value of solar efficiency at 3rd Precinct is not known, although one possible reason is the shadowing of the solar wall by another building just across a parking lot to the south. Shadowing could be especially troublesome in winter months, when the sun is low in the southern sky.

VI. Comparison with other studies

We compare in Table 10 below the results at our three installations with the results of two other studies, of the solar wall installations at the Ford of Canada automobile assembly plant in Oakville, Ontario (Enermodal 1994), and at the General Motors Battery Plant in Oshawa, Ontario (Brunger 1999, 20-29). The quantities Q_{save}, Q_{save}/A, vertical solar radiation, and Q_{solar}/A in the table are totaled over the entire period of study and tabulated; the length of the period of each study is included with total Q_{save}. The quantity Q_{save} is the sum of Q_{solar}, the active solar gain, and Q_{wall}, the recaptured wall loss. The Breck, Aveda and GM Oshawa studies cover roughly one heating season; the 3rd Precinct and Ford of Canada studies include months from two successive heating seasons. The total vertical solar radiation for our studies is found by summing the NREL 30-year averages (ref) over the appropriate months.

The total energy saved, Q_{save}, depends on the size of the solar wall: for the mid-size solar walls at Breck, Aveda and GM Oshawa (areas between 1000 and 10,000 ft^2), Q_{save} is hundreds of MBtu per heating season; less, for a smaller wall (3rd Precinct), and more, for a larger wall (Ford of Canada).

The overall solar efficiency is the total Q_{solar}/A divided by the total vertical solar radiation. But the overall solar efficiency underestimates the performance of the Breck and 3rd Precinct solar walls, as has been pointed out in Section IV, because the Breck and 3rd Precinct solar fans shut off for periods during daytime hours in the warmer months when the conditioned space is at the set point temperature; the solar fans at the other three installations in the comparison all ran 24 hours a day during the entire period of study. A better measure of the performance of the solar walls at Breck and 3rd Precinct is the efficiency for just the cold winter months of December, January, and February. These efficiencies have been calculated and included in the table.

Only the installation at GM Oshawa approaches the maximum theoretical solar efficiency of 70-80%. Possible reasons for the relatively low efficiencies of the Breck and 3rd Precinct solar walls have been discussed in the previous section.

Table 10. Comparison with other studies

	Breck	Aveda	3rd Precinct	Ford of Canada	GM Oshawa
Area (ft^2)	3300	1270	765	20,200	3930
Total Q_{save} (MBtu)	241 (7 months)	302 (6 months)	44.2 (6 months)	2620 (9 months)	760 (8 months)
Total Q_{save}/A ($kBtu/ft^2$)	73.0	238	57.8	130	193
Total Vertical Solar Radiation ($kBtu/ft^2$)	221	190	183	199	204
Total Q_{solar}/A ($kBtu/ft^2$)	66.1	106	56.7	95	145
Solar Efficiency	30% (49% during winter months)	55%	31% (41% during winter months)	51%	71%

VII. Calculation of energy use per heating degree day (HDD) for IDDS

Results for the Interdistrict Downtown School (IDDS) are shown in Table 11 below. HDD were included on monthly heating bills for IDDS from NRG Energy Center Minneapolis LLC for the periods 10/26/2010 – 11/23/2010 (Nov. 10) and 11/23/2010 – 12/28/2010 (Dec. 10). The conventional heat supplied to IDDS is steam heat; Q_{aux} was determined by assuming that one pound of steam yields 1000 Btu of heat, and that 100% of the heat from the steam goes into heating the building. Data was obtained from the IDDS solar wall for 21 days in Nov 10 and 21 days in Dec. 10. Q_{save} was calculated for the period in each month with data, then extrapolated to get a value for the entire month.

The energy use normalization by HDD for IDDS was obtained by taking the difference in $Q_{aux} + Q_{save}$ between Dec. 10 and Nov. 10, and dividing by the difference in HDD between Dec. 10 and Nov. 10; an energy use normalization of 271 MBtu / HDD was found.

Table 11. IDDS: Energy savings

Month	Q_{aux} (MBtu)	Q_{save} (MBtu)	Days with data	Q_{save} (MBtu) extrapolated to entire month	$Q_{aux} + Q_{save}$ (MBtu) extrapolated to entire month	HDD (^{o}F)
Nov-10	211	17	21	24	235	703
Dec-10	463	23	21	34	497	1669

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