

DESIGN OF A SOLAR - GEOTHERMAL HEATING AND COOLING RETROFIT FOR A PHYSICS LABORATORY

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ABSTRACT

The US Geological Survey Physics Laboratory is currently heated by electric boiler and cooled by an air cooled condenser supplying chilled water to a central air handling unit. The building's forced air system provides heating and cooling for laboratory and office spaces. An additional air handler provides electric resistance heat for separate storage and maintenance zones. Domestic water is heated by electric resistance heater. The dominant energy use is for winter space heating with minor summer cooling loads.

A combination solar and geothermal heating and cooling system has been designed to replace the existing systems. The solar heating system will provide heat to 5 water source heat pumps and directly to the outside air intake. The solar heating system improves efficiency of the geothermal heat pump by raising the inlet water temperature above that available from the ground loop and by preheating outside air more efficiently than the heat pump.

1. THE EXISTING PHYSICS BUILDING

The Physics Building is a combination laboratory, maintenance and storage facility located on the grounds of the US Geological Survey Headquarters in Reston, VA. The building use has evolved since its construction in 1970 and is currently used to conduct geophysical experiments, maintain field test equipment, and store geological samples. The building has a footprint of 100,000 square feet with approximately one third of the building used for lab and office spaces and two thirds for maintenance and storage.

The building is constructed in three sections with different roof heights. Each roof is a flat roof supported by bar joists above structural steel columns and beams. The roof covering is a built up roof over 2 inches of insulation.

The all electric building, uses an electric resistance boiler to feed a heating coil in a central multi-zone air handling unit. A separate air handler provides heat to one of the storage spaces using electric resistance heat. Chilled water is provided to the multizone unit from a packaged air cooled chiller located outside the mechanical room. Domestic hot water is provided by an electric resistance, tank type water heater in the mechanical room.

Office and lab air returns to the air handler unit via ceiling plenums and is mixed with outside air before returning to the air handler. Fume hoods exhaust above the roof line. Other building exhaust from lavatories and maintenance areas require a constant supply of make up air.

2. GEOTHERMAL AND SOLAR FEASIBILITY STUDIES

A study was conducted to determine the feasibility of replacing the electric resistance and packaged cooling system with a geothermal heat pump.

The heating dominated nature of the building was evident from the electric energy usage chart shown in Figure 1. The analysis of the utility bills and rate structure determined that both energy and electric demand could be reduced by the use of the geothermal heat pump retrofit.

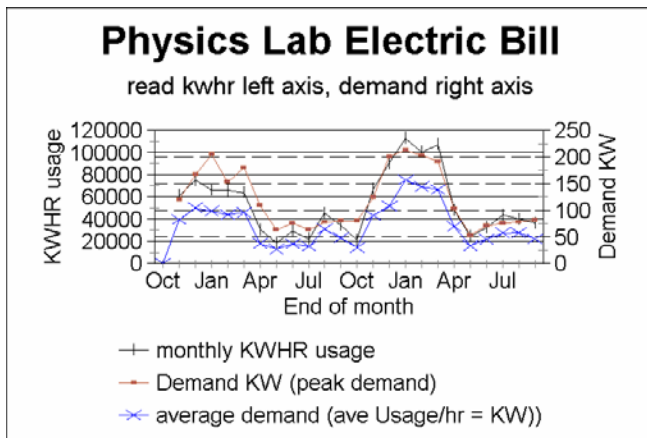


Fig. 1 Physics Lab electricity use

Annual costs of electricity were on the order of \$33,000. The average charge per KWHR was \$0.0546 and demand was \$5.52 per KW. However, the marginal electric energy costs were very low at \$0.00276/KWHR in winter and \$0.01135/KWHR in summer, but the marginal demand costs were very high at about \$17 per KW saved per month for peak shifting and \$25 per KW per month for reducing both demand and energy consumption.

The electric load on the building in May represents essentially a zero heating and cooling load. Minor increases in July and August represent the air conditioning load and significant increases from October to April represent the heating load. The electricity consumption for winter heating represents nearly 75% of the total annual electric use and causes the highest demand. Reducing heating demand was the obvious target for efficiency improvement.

3. GEOHERMAL HEATING AND COOLING ANALYSIS

A feasibility study was conducted to assess the benefits of installing a geothermal heating and cooling system. The initial feasibility study focussed only on the replacement of the heating and cooling system with two geothermal heat pumps. The analysis assumed two 40 ton water to water heat pumps supplying the coils in the multi-zone air handler. A ground loop was comprised of 7,500 feet of pipe installed in 300 foot vertical boreholes.

Modeling indicated a reduction in peak demand of 76 % of the existing building electric demand from 245 KW to 59 KW in January and 72% reduction in energy use from 518 KWHR to 146 KWHR per year.

In many geothermal heat pump applications, the heating and cooling loads are better balanced or quite often the building's HVAC loads are 'cooling dominated'. In these

cases, the heat rejected to the ground in the summer becomes a heat source in the winter. This summer heating of the ground prevents the ground water temperature from dropping excessively in the late winter when heat extracted from the ground for building heating.

In the Physics Building, occupancy is limited and the summer air conditioning load is minimal. Very little heat rejection to the ground from the summer air conditioning loads was planned. The imbalance between summer heat rejection and winter heat extraction from the ground indicated that the return water temperatures from the ground would drop to between 45 and 55 degrees in late winter.

This temperature range is within the design envelope of the heat pumps. However, the lower temperatures reduce the performance of the heat pump compared to a higher temperatures in the 70-75 degree range. For example, the heat pump considered in the feasibility study had a Coefficient of Performance (COP) of 3.2 at 45 degrees F ground water and 120 F leaving water temp to the coils, extracting 243,000 BTU/hr from the ground. This is a 24% lower COP than the same heat pump operating at 70 degrees F ground water with a COP of 4.2 and extracting 366,000 BTU/hr.

Given a constant thermal conductivity between the ground and the ground loop, the heat pump operating with a lower ground temperature will require a larger ground loop to deliver the same flow of heat per hour. It will also require a larger heat pump to achieve the same heating capacity as a would be possible with a warmer return water temperature.

4. SOLAR ENERGY ANALYSIS

In late 1970s and early 1980s, there was some development by the US Dept. of Energy and others in the field of solar assisted heat pumps. Evidence from a variety of experiments showed that combining solar energy systems with heat pumps could considerably improve energy use compared to stand alone heat pumps or solar collectors. See References 1 and 2.

At the time, air source heat pumps were not well developed and geothermal heat pumps were even less well developed. Davis discusses heat pump COPs of 1.8 to 2 compared to today's models operating at COPs of 4 to 5. Budget cuts and other issues severely reduced any follow on research in this area. However, the fundamental opportunity of improving the heat pump and collector performance was well known at the time, and is still relevant today. Using this "old" solar technique and some new solar technology provided an opportunity to improve upon the "geothermal only" system for the USGS Physics Building.

Following the feasibility study for the geothermal retrofit, a separate study was undertaken to evaluate the opportunity to add solar heating to the heat pump. The heating system considered was the solar thermal tile air heating system (Fig 2) with a water thermal storage tank. The thermal storage tank would be connected at a three way valve to the geothermal return water piping from the ground loop. The three way valve would blend the warm solar heated water with the cooler return water to deliver warm water at a maximum of 70 F to the heat pump. Whenever the 70 water was delivered, the heat pump would operate at peak COP of 4.2.



Fig. 2 Diamond Slate solar thermal tiles

In addition to the gains in heat pump performance, the solar heating system is known to collect solar heat at much higher efficiency than heat pumps. The COP of typical solar thermal system is between 15 and 30 compared to the COP of heat pumps between 2.5 and 5. Therefore, any heat gathered by the high COP solar system boosts the COP of the combined system.

A third opportunity to improve performance with the solar heating system was to use the warm air gathered by the solar tile systems as a source of outside air for the building. Every cubic foot of solar heated air supplied to the building air intakes is a cubic foot of cold outside air that is displaced. Any additional BTU value from the warmer solar air represents a direct reduction in the heating load required to be met by the heat pump.

The secondary effect of supplying both the solar heated water and the solar heated air to the heat pumps is to further reduce the heat extraction from the ground by the heat pumps. This helps maintain higher ground temperatures and

therefore higher COP of the heat pumps even when solar heating is not available.

An initial review indicated that the building and adjacent carport had adequate space to support about 5,000 square feet of solar thermal tiles. However, it was not known whether the building roof had sufficient structural strength to support the solar tiles in self ballasting pans placed directly on the roof. Local interferences from tree shading, and the presence of fume hoods on one part of the roof suggested that the 5000 square foot solar tile system might need to be scaled back. In addition, the feasibility study had assumed conductivity of the geothermal ground loop based on typical conductivity established for other geothermal systems in the region. Both of these assumptions indicated sufficient uncertainty to merit a more thorough design of the systems.

As a result, the US Geological Survey commissioned a full detailed design of the solar geothermal system including a structural analysis of the roof and a conductivity test of the geothermal field. The USGS also requested the solar design include a complete re-roofing of the Physics Building, below the solar tile supports, since the existing roof was nearing the end of its useful life.

5. DETAILED DESIGN OF THE SOLAR GEOTHERMAL RETROFIT

The shading of the different roof elements was evaluated using a low cost sextant and compass to shoot sight lines to the tree tops. It was determined that the highest and southernmost of the three roofs experienced little shade during the winter solstice and could be covered with solar tiles arranged on sloped frames facing southwest, square to the building walls. The solar fields on the two lower roofs required setbacks from the portion with the higher roof due to shading by the building. In addition, the fume hoods eliminated a portion of the middle roof from consideration.

The structural engineers determined that the existing bar joists would not be sufficient to hold any additional weight and meet the revised snow load criteria that had been required since the building was originally constructed. Therefore, a new structural design would be required to support the tiles on, or above the roof.

It was decided that extending the solar tile fields above the roof provided the best solution. The approach was to install stub columns from the existing building columns to a height of about 16 inches above the roof. Light gauge steel trusses would be installed on these stub columns to span between columns and support the solar tile decking material. All systems would be square to the building wall. The

suspended trusses would allow a new spray applied foam roof to be installed over the existing built up roof. The new roof would add an R value of 13 to the existing insulating value of the roof and seal all penetration of the structure.

The plan reduced the available solar tiles on the building roof to 1900 square feet. There would be 3 systems of 800, 500 and 400 square feet. An additional 1300 square feet would be installed on the adjacent parking canopy. See Fig. 3

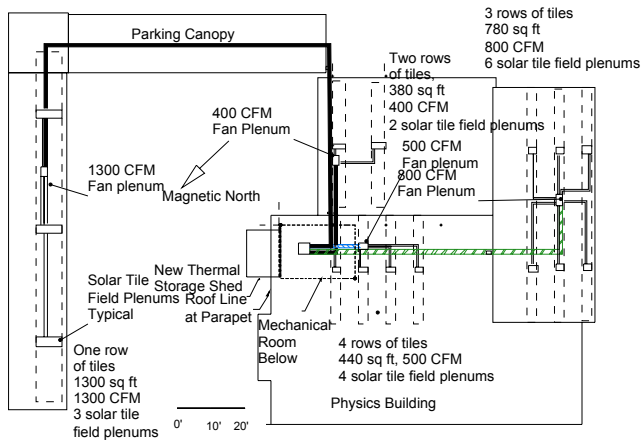


Fig. 3 Roof top solar tile plan

Each system would have a separate solar fan to collect solar heated air from multiple solar tile fields. The solar heated air is delivered via insulated ducts installed in the supporting truss work, to a roof plenum above the mechanical room. Within the mechanical room, each system supplies solar heated air to an air-to-water heat exchanger coil. Each coil receives water from thermal storage tanks using small circulating pumps.

The thermal storage tanks are ASME certified pressure tanks with a total of 3900 gallons capacity. The pressure tanks were required to accommodate the geothermal system pressures. This was determined to be more efficient, less complicated, and more reliable than installing low cost atmospheric tanks with either booster pumps or heat exchangers to isolate the solar loop from the higher pressure geothermal systems.

There are two interconnected tanks of 2300 and 1600 gallon capacity. The larger tank is designated as the low temperature tank and receives return water from the ground loop and feeds the air-to-water coils. The small tank receives hot water for the coils and feeds the heat pump through the three way valve. See Fig. 4. The two tanks allow some physical stratification, and fit the available

space in a new thermal storage shed adjacent to the mechanical room. See Fig. 3

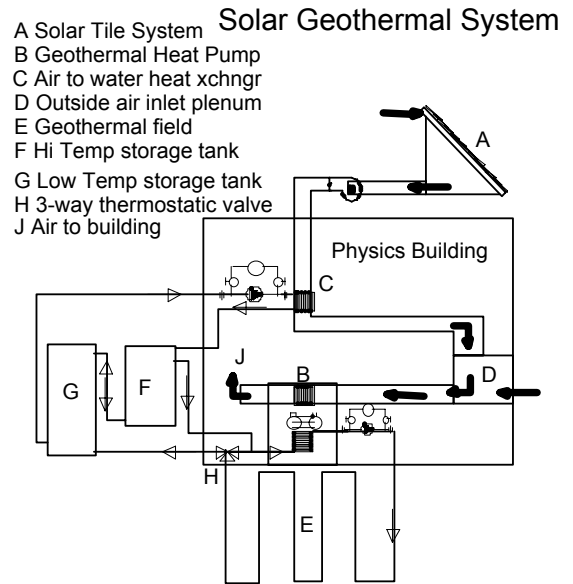


Fig. 4 Solar geothermal system schematic

The thermal storage system is assumed to begin each day at the same temperature as the returning ground water temperature (51 F in February). This assumes that all the solar heated water in the thermal storage tanks has been delivered to the heat pumps via water flow through the three-way valve and replaced with return water from the ground loop. The coils are designed to raise the water temperature 35 F and drop the temperature of the solar heated air by 65 degrees to about 55 to 60 F in the March timeframe. When outside air temperatures go above 65F, thermostats shut off the fans and pumps.

Three of the solar tile systems exhaust this cool air to the atmosphere. However, the largest system operating at 1300 cubic feet per minute (CFM) of air flow exhausts the cool air to the outside air intake plenum for the heat pumps. This is just slightly more than the maximum required flow rate for the heat pumps. Any excess air is simply exhausted to the atmosphere at the front of the intake plenum.

This secondary use of the solar heated air provides a slight temperature boost for the heat pumps compared to the temperatures they would see from ambient outside air. In this way nearly all the BTUs gathered by the 1300 CFM solar system are transferred to the heat pumps via water or air heating.

Because the solar tile system is an air heating system, there is no water exposed to ambient temperatures and no freeze hazard, outside the building envelope. While it is not likely, freezing of the water in the coils is possible from cold night

air settling through the coils. Backdraft dampers minimize the air flow from cold air settling to the lower coil locations. However, positive freeze protection is accomplished by continuously running the small circulating pumps which are connected to the thermal storage tanks. Since the tanks never get below ground return water temperature, there is adequate heated water to keep the coils from freezing. Freeze protection must be provided to the coils even if located in conditioned spaces. Dampers and low air temperature fan cut off switches can be used as well as constant circulation of the tank water through the coils.

The detailed geothermal system design incorporates 5 smaller water to air heat pumps to eliminate the large air handler units. Each heat pump supplies a different zone within the building. Two pumps supply water to the heat pumps from the ground loop and/or thermal storage tanks.

6. IMPROVED EFFICIENCY OF THE COMBINED SOLAR GEOTHERMAL SYSTEM

The combined solar air-geothermal heating system improves the efficiency of each component compared to that of individual systems. The principle benefits are higher heat pump efficiency, higher solar collector efficiency, greater solar operating hours, 100% use of solar heated air, and domestic water heating. There are also future opportunities to reduce ground loop and heat pump size and manage the thermal resource to reduce peak demand charges.

One efficiency improvement of the solar geothermal system is that the solar heated air can be delivered to the coils or the outside air inlet at below building indoor air temperatures and still be useful. This allows the solar tiles to operate at lower temperatures than would normally be delivered if the solar heat were used directly for space heating at 90+ degrees F. The lower collector operating temperature ensures more days of operation when compared to other water based collectors which would be shut down for freeze protection concerns. The lower solar air temperatures also significantly improve collector efficiency compared to delivering air directly to the building at higher temperatures.

In the case of the air to the water coils, the expected lowest temperature of the water from the tank bottom (ground return) is 51 degrees F. Allowing a 5 degree temperature differential between coil entering water temp and leaving air temperature means that air delivered at 56+ degrees would still transfer some heat to the coils. Since the solar tile system can easily deliver air at 60 degrees above ambient, this means the collectors could work at outside air temperatures near 0 F. Water based collectors, typically shut down when outside air temperatures go below about 38 F.

In the Reston, VA area, there are about 1900 hours per year where temperatures drop below 38 F. Average high temperatures in January are only 42 degrees, four degrees above the shut down temperature for water heating collectors. During many days the water heating collectors would deliver very little heating but the air heating collectors can continue to deliver heat to the coils or preheat the outside air for the heat pumps.

Operating the collectors at a low temperature differential with the outside air improves collector efficiency. Using the previous example of a 0 degree F day, the 1300 CFM air heating collector could deliver 60 degree F air to the coils and preheat the outside air to about 55 degrees F, delivering 100% of the collected energy to the building. If the collector had to supply air at comfort heating temperatures of 90 F above ambient, efficiency would be expected to drop to about 13 – 16 %. However, because the collectors operate at a lower temperature, the collector efficiency would be in the range of 20-25%, increasing the output of the collector by 56%.

A final efficiency in the system is the use of the geothermal heat pumps to deliver domestic hot water heating. A small desuperheater from one of the heat pumps is piped to the drain valve connection of the domestic hot water tank. By constantly circulating hot water across the desuperheater, the water tank remains hot from heat pump waste heat. If the heat pump capacity is not sufficient for any reason, the existing electric heaters in the tank deliver additional heating. Because the heat pumps are drawing heat from the solar heated water, the solar heating system is also contributing to the domestic water heating.

Finally, there is a potential opportunity in future expansions of the system to reduce any growth in the ground loop and heat pump size by accounting for the solar contribution. Initial indications are that a ground loop reduction of 30% might be feasible for the existing system, given an annual solar contribution of about 34% of the heating load. However, peak heating loads, the likely duration of periods without solar heating, and management of the thermal storage system must all be considered before reducing the heat pump and ground loop size.

Management of the thermal storage system offers an opportunity to reduce demand costs for both heating and cooling loads. For the heating case, solar heated water collected during the day could be used to reduce heat pump loads during the peak night time heating periods simply by withholding solar heated water until the peak period approached. A variety of control mechanisms can be employed that release the storage based on time clocks, outside air temperatures, or heat pump electric loads. With

each marginal KW of heat pump demand costing \$17 per month, the economics of installing controls seems quite favorable.

Similarly, the thermal storage tanks could be used for summer chilled water storage with only minimal control and piping changes. This would allow the thermal storage tanks to store chilled (ground temperature) water during off peak hours. During peak hours, the heat pumps will operate continuously and draw chilled water from both the tank and the ground to meet the heat rejection needs of the heat pumps. Without the thermal storage, ground water return temperatures would rise higher during peak hours as the ground loop slowly rejected the heat to the earth. With the thermal storage, the ground loop temperatures could be kept slightly lower. The lower temperatures seen by the heat pump during the peak hours would improve the efficiency the heat pump in a manner similar to that caused by higher temperatures during the heating cycle.

A second approach to managing the thermal storage system is to use a separate air to water heat pump or evaporative cooler to charge the tank with water at lower than the ground water temperatures. Dry bulb temperatures and humidity in the Washington area prevent this approach from being realized without some cooling contribution from the conditioned building exhaust air. However a desiccant evaporative cooling cycle, using waste heat from the collectors, could provide dehumidification for the air intakes and low temperature air that could be used to create the chilled water in the tanks. See Reference 3. By operating these systems during non peak hours, the cost of reducing the thermal storage temperature can be lower than the cost of meeting the peak demand with water from the ground loop and geothermal heat pump. The lower chilled water storage temperatures result in a much higher cooling efficiency of the geothermal heat pump. By targeting peak hours with high demand charges, the system can reduce energy costs compared to operating just the geothermal system with ground loop heat exchanger.

7. CONCLUSIONS

The retrofit of a solar geothermal heating system for the USGS Physics Building appears practical and cost effective.

The combined system offers substantial improvement in the efficiency of both the heat pump and the solar collector.

There are opportunities to further improve the cost effectiveness by improving controls of the thermal storage system to reduce peak demand.

There appear to be opportunities to reduce the size of the heat pump and ground loop based on the solar contribution and improved efficiency of the solar and geothermal components.

8. ACKNOWLEDGEMENT

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9. REFERENCES

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