ENERGY EFFICIENCY OF MORTON BUILDING

Preliminary Report

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A 30' by 48' test building was constructed in 2018 to examine the possibility of using this type of construction for housing for those with Electrical HyperSensitivity (EHS) and Multiple Chemical Sensitivity (MCS). It was permitted as a shop (no bathroom, no kitchen, bare concrete floors). This document deals with the measured energy efficiency of the building. This is a preliminary report. A final report will be issued sometime after a full year of data has been collected, hopefully in 2020.

The building is a metal skin structure built by Morton Building Company. This is a nation wide company that has been in business for over a century. This type of construction is widely used for shops, barns, garages, and commercial buildings, but in recent years is also used for houses. An inspection of the Morton website will reveal many attractive homes they have built. Their standard practice on insulated buildings is to use the same metal siding on the inside walls and ceiling as on the roof and exterior walls. This makes the building into what might be called a Faraday cage, a double metal wall structure built to keep electromagnetic signals out. The measurement of cell phone signals inside and outside the shop is the subject of another document found on the website www.emsri.org.

The standard Morton package has R-38 insulation in the ceiling, R-19 in the walls, and double glazed windows. The vapor barrier on the walls does not have penetrations for electrical outlets, which should result in the building being relatively tight regarding infiltration and exfiltration. The ceiling vapor barrier has penetrations for the light fixtures, which will cause some exfiltration heat loss. I did not ask for special treatment for this or any other leakage concern, so my measurements are for a 'standard' building.

Rockvale, Colorado is located in a relatively mild climate, sometimes referred to as the 'banana belt' of Colorado. The average number of Heating Degree Days is about 5000. We get several snows each winter, and often the ground will be bare again within

24 hours. I will be using the building as a shop/office/lab. If the weather is really bad I can stay at home. An uncomfortably low temperature in the shop is not a significant problem as long as the pipes do not freeze. Therefore I did not spend any 'extra' to get a high efficiency structure. But if this is to be a prototype for a house, built either nearby on an empty lot, or elsewhere in the country, we need to know the efficiency. This topic has been of considerable interest in the building trade for over a half century, so one can find much information on the Internet. Better information is available at a good University library in the form of technical papers not available for free on the Internet.

The question most of us want answered is: What will be the yearly operating cost for a given type of heating (and cooling)? This shop is all-electric, like the adjacent house. Electric power comes to a 300 A breaker box on the side of the house, then through a 100 A breaker into a conduit to the shop. I bought an old style analog electric meter on eBay ($28) and had the electricians install the meter between the main breaker box and the shop. I read the meter once a day, so I know the total electrical energy used during the previous day. I calculate the cost per kWh from the utility bill for the combination of house and shop ($0.1773/kWh for February, 2019). A simple multiplication gives me the daily cost of heating the shop.

Not all the electric power is consumed by the baseboard heaters. Some is used by lighting, some by a computer, etc. But except for the photons that escape through the windows, all the input power stays inside the building, and appears as heat. A house has more losses than a shop, of course, such as hot water from shower or washer going down the drain, and moist heated air from a clothes dryer being blown outside the house.

If we wanted to be really precise, we would include the heat gained from the sun shining through the windows and heating up the concrete slab. There are two windows on the southeast wall with a total glazing area of about 1.5 m^2, and likewise on the southwest wall. Solar radiation on a clear day is on the order of 1 kW/m^2. One can go through a significant amount of spherical trigonometry to find the equivalent area of glass perpendicular to the sun, which varies with time of day and day of year. Just to get a ballpark idea, we might assume 1.5 hours of full sun equivalent on the southeast wall and another 1.5 hours of full sun on the southwest wall. The solar heat received is then $(2)(1.5)(1.5)(1) = 4.5$ kWh/day. A mild winter day might only require 25 or 30 kWh for heating so solar gain is not really trivial. I do not have the proper instrumentation to measure solar gain, so will not treat it extensively in this paper.

I will assume all heat losses can be placed into the following six categories:

- Ceiling

- Walls
- Windows
- Doors
- Slab
- Infiltration

The heat loss for the first four items is given by

$$Q = \frac{A(T_{in} - T_{out})}{R} = UA(T_{in} - T_{out}) \qquad \text{BTU/hr (or W)} \tag{1}$$

where A is the area in ft^2 (or m^2), T_{in} and T_{out} are the inside and outside air temperature in ^{o}F (or ^{o}C), R is the 'resistance' of the building element to heat flow, with units (hr)(ft^2)(^{o}F)/(BTU) (or (^{o}C)(m^2)/W), and $U = 1/R$ is the heat transfer coefficient or the heat loss coefficient. This equation is valid only under steady state conditions, constant inside and outside temperatures, no wind, etc.

The inside dimensions of the building are about 28.5' wide by 46.5' long by 10' high. The ceiling area is A_c = 1325 ft^2 (= 125m^2). The total wall area is 1500 ft^2. There are two outside doors of size 41" by 82", giving a total area for doors A_d = 46.7 ft^2. There are 7 windows of size 52" by 33", giving a total area for windows of A_{wi} = 83.4 ft^2. Subtracting these two numbers from the gross wall area gives a net wall area of A_{wa} = 1370 ft^2. The building volume is (1325)(10) = 13,250 ft^3.

A Reality Check

I like to do a 'reality check' early in a long-term research project like this one, to see if I am collecting the right data in the right way. I picked a 7 day period spanning 2/25/19 to 3/3/19 where the influence of the slab was minimal. The slab temperature was 55.4^{o}F at both the beginning and the end of the period, suggesting no net energy flow into the earth. The yearly average outside temperature at this site is about 52^{o}F, as well as the temperature perhaps 10 meters down. The steady heat loss through the slab would be minimal for this very small difference in temperature. The average inside air temperature was 54.8^{o}F and the average outside air temperature was 35.05^{o}F. The energy input from the local utility was 124.8 kWh for the week. The ballpark figure for solar input was 31.5 kWh (if all days were sunny, which they were not). The calculated heat flow for ceiling and walls is

$$Q_c = \frac{1325(54.8 - 35.03)}{38} = 689 \qquad \text{BTU/hr} \tag{2}$$

$$Q_{wa} = \frac{(1370)(54.8 - 35.03)}{19} = 1426 \qquad \text{BTU/hr} \tag{3}$$

I do not recall Morton giving me the R-values for windows and doors, so I will just assume R-2.5 for both. This gives heat flow for windows and doors as

$$Q_{wi} = \frac{(83.4)(54.8 - 35.03)}{2.5} = 660 \qquad \text{BTU/hr} \tag{4}$$

$$Q_d = \frac{(46.7)(19.77)}{2.5} = 369 \qquad \text{BTU/hr} \tag{5}$$

There needs to be some infiltration to maintain air quality. I read some place that there needs to be at least 0.35 Air Changes per Hour (ACH) for this purpose. I found an equation on the Internet for Q_{ACH}, which, for our numbers, yields

$$Q_{ACH} = (0.018)(ACH)(Vol)(\Delta T) = (0.018)(0.35)(13250)(19.77) = 1650 \quad \text{BTU/hr} \tag{6}$$

The sum of these five quantities is 4794 BTU/hr (= 1.406 kW). Multiplying by 7 days and 24 hours/day gives a total outflow of energy of 236.2 kWh for the week, or 111.4 kWh more than I bought from the utility. The solar gain does not account for for more than a third of the difference. So why is there a discrepancy? I am confident of the amount of energy purchased from the utility, so if there was no net heat storage in the building and slab during the week, then my estimate of power lost must be too high. One possible error would be the ceiling insulation. It is loose material, blown in by a couple of kids. If they gave me an extra bag or if it has not fully settled yet, I could imagine an R-value as high as 50 or maybe a little more. The R-values of the doors and windows might be a little better than my estimate. There is no exhaust fan in the building so perhaps we did not get to the minimum 0.35 ACH. Or perhaps the slab gave up some of its stored energy that I just did not detect with my single sensor. At any rate, I consider these results somewhat encouraging. It looks possible to collect adequate data with my instrumentation.

I will take my calculations as a 'worse case' condition. They hopefully allow for an unusually cold month, or the kids running in and out frequently. A heat loss of 1.406 kW for a 30 day month would result in a bill for 1012 kWh. At an electricity cost of \$0.1773/kWh, the dollar amount would be about \$180. This only gets the inside temperature up to 55^{o}F which is at least 10^{o}F too low for most people. So now we need to estimate the energy required to raise the temperature to say 70^{o}F. For the five quantities above we just multiply by (70 - 35.03) instead of (54.8 - 35.03) and get a total of 8480 BTU/hr (= 2.49 kW). For a 30 day month this would require 1780 kWh or $317, just for the shell. Now we need to consider the slab.

I found an equation on the Internet in a University of Dayton report that stated

$$Q_{slab} = U(Area)(T_{in} - T_{soil}) = 0.0555(1325)(70 - 52) = 1324 \qquad \text{BTU/hr} \tag{7}$$

This would add another 280 kWh to my monthly bill. However, there is also heat storage under the slab. One has to raise the slab temperature from the deep soil temperature to the desired room temperature. Switching to the metric system, the heat capacity of soil is on the order of 0.8 J/(gm K) and the density is about 1.5 gm/cm^3. The heat capacity per m^3 is then (0.8 J/(gm K))(1.5 gm/cm^3)(10^6 cm^3/m^3) = 1.2×10^6 J/m^{3}K. The heat capacity of the top 3 m of soil under the Morton building is (1.2×10^6 J/m^{3}K)(125 m^2)(3 m) = 450×10^6 J/K = 125 kWh/K. That is, it takes 125 kWh to raise the soil temperature of the top 3 meters of soil under the slab by 1 K (= 1.8^{o}F). It would take 1000 kWh to raise the temperature by 8 K. So there will be a transient period while the slab and the soil underneath are heating up that the energy bill will be even higher than predicted by the steady state estimates. But after the transient, the monthly bill for the given climatic conditions should be about $1780 + 280 = 2060$ kWh (or $365).

I plan to use this summer to get the slab and soil under it into a new steady state condition where the slab is at least 65^{o}F for several months. Then in October I will turn on the electric heat to maintain the room temperature at a value of 68^{o}F or 70^{o}F. By January I should have a true measure of building efficiency.

Another reality check

The weekend of March 2, 2019 was forecast to have bad weather, cold and snow. I turned off all heat on 3/2/19 and did not return until 3/5/19. There were two 24 hour periods (ending at 9 am) where the only building heat was supplied by the stored heat in the concrete slab. The average inside temperature was 46.91 and 45.86^{o}F, respectively. The average outside temperatures were 8.08 and 13.82^{o}F. The slab temperature dropped by 4.53^{o}F in a saw cut, by 3.76^{o}F under the slab, and by 4.73^{o}F in the FluxTeq sensor lying on the slab. I then calculated Q_c, Q_{wa}, Q_{wi}, and Q_d using the same estimates as above, multiplied by 24 hours, added the two days, and got a sum of 270,000 BTU = 79.06 kWh for the heat lost through the ceiling, walls, windows, and doors for the two day period. The FluxTeq heat flux sensor lying on top the slab showed an average heat flux of -7.09 and -6.18 W/m^2 for the two days. Multiplying by the slab area of 125 m^2 and the number of hours gives us -21.27 and -18.54 kWh from the slab, or a total of -39.81 kWh. The difference between the two calculations is 39.25 kWh. Infiltration cannot be invoked since that would just make the discrepancy worse. It appears that I am over estimating the heat loss through the building envelop by a factor of two, or the FluxTeq sensor is reading low by a factor of two.

I then looked at the heat capacity of the slab. I assume a heat capacity of 1 kJ/kgK, a density of 2400 kg/m^3, and a slab thickness of 100 mm (4in). The total mass of the slab is then 30.5×10^3 kg. Changing the temperature of the slab by 1K requires 30.5×10^3 kJ = 8.47 kWh. Or changing the temperature by 1^oF requires 4.7 kWh. The three temperature drops listed above would give energies extracted from the slab of 21.3, 17.7, and 22.2 kWh. The slab is not insulated so heat energy is also being extracted from the fill material below the slab. The heat from another 4 inches = 0.1 m could easily get the total heat flux up to the -39.81 kWh measured by the FluxTeq sensor. And the heat from the next couple of feet of fill could easily get the total heat flow from the concrete up to the 79.06 kWh estimated for the heat flow through the building shell, if the FluxTeq sensor is reading low.

I have the feeling that I am not using the FluxTeq unit in its normal mode. I am inclined to just not use it in this investigation.

Instrumentation

Morton does not have a crew that pours concrete so I hired a local contractor to pour the foundation. It is called a monolithic pour since the foundation and slab are poured as a single unit. A not-to-scale sketch is shown in Figure 1. The slab is 4 inches thick. The outside edge of the foundation is about 2 feet in depth. The width of the building is 30 feet and the length is 48 feet. There are 2 inches of R-10 insulation against the perimeter of the foundation, all the way around the building. I also had the contractor place 6 mil vapor barrier over the fill before the concrete was poured. This helps to keep the humidity low by preventing moisture in the earth from wicking through the concrete into the interior of the building.There is no insulation under the slab. Neither Morton nor the contractor offered any significant advice about the desirability of insulation under the slab. I could not find an example on the Internet where someone had built a slab-on-grade building in similar climate and soil, and measured heat flow, so I decided to do it on this test building.

I bought a spool of Type T thermocouple wire and installed thermocouples at several locations in and under the concrete. T_1 is directly below the outside edge of the foundation, 30 inches down from the top of the slab. There are four thermocouples located in and under the slab near the center of the building. T_{10} is 27 inches below the top of the slab, while T_{11} is just under the vapor barrier next to the slab, both installed

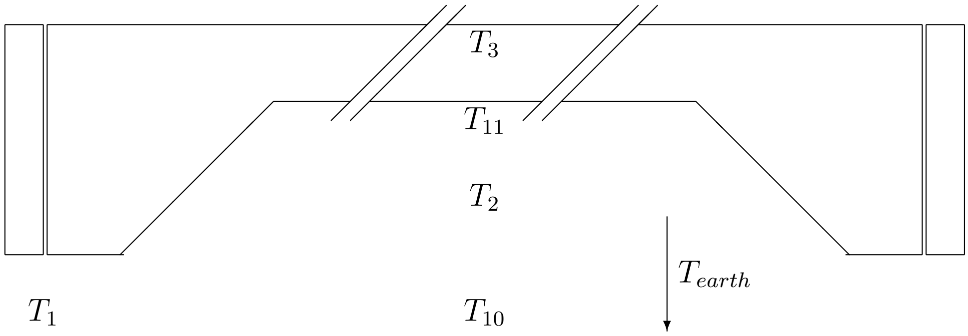

Figure 1: Monolithic foundation (Not to scale)

before the concrete was placed. During early testing I drilled a hole through the slab and installed T_2 about 18 inches below the top of the slab and T_3 in a saw cut.

I bought an Extech 12 channel thermocouple datalogger ($989) to record the temperature data on an SD card. This was programmed to record all temperatures once per hour. Every few days the SD card was removed and the data transferred to a computer for analysis. If the card was replaced during the one hour window between data collections, the Extech would just continue appending temperature data to the same file. A spreadsheet program was used to analyze the data. I tried Microsoft Excel first, but soon shifted to LibreOffice Calc, a Linux based application.

Thermocouples T_4, T_5, and T_8 are installed on wood nailers on the side of the building, low, high, and middle heights, close to the interior panels that would be installed later. T_6 is on the ceiling, near the center of the building. T_9 hangs below the metal enclosure holding the datalogger. There is very little stratification in temperature, so the average of these five thermocouples can be set equal to T_{in}, the interior temperature of the building. There is one thermocouple (T_7) outside the building, between the house and shop, about five feet above grade, protected by a plastic shroud.

At a sufficiently great depth, the temperature of the earth, T_{earth} will be constant year around. This is usually very close to the average air temperature, around 52^{o}F in Rockvale. If the air temperature is above this value, heat will flow into the earth. If below this value, heat flows out of the earth to heat the air. At depths of a few feet, the temperature will have a yearly cycle similar to the yearly air temperature, but with a lower amplitude and with a lag related to the time required for heat energy to propagate through the earth. T_1, located about two feet below grade will see both a yearly cycle and a daily cycle. For example, the 24 hour average of T_1 on 10/8/18 was 63.63^{o}F and on 2/20/19 was 46.49^{o}F. The average outside temperature on 2/20/19 was 26.29^{o}F following three weeks with an average temperature of 33.84^{o}F, so we would expect T_1 to be decreasing. The 24 hour average of T_1 on 2/21/19 was 45.75^{o}F, a decrease of 0.74^{o}F.

The building thermostat will almost certainly be set at 60^{o}F or higher, so with an uninsulated slab, there will always be heat flow straight down from T_{in} to T_{earth} during the heating season. There will also be heat flow horizontally through the slab. The top of the slab will typically be six inches or so above grade, so the temperature difference across the R-10 insulation around the foundation perimeter will be very close to $T_{in} - T_{out}$, substantially higher than the difference $T_{in} - T_{earth}$. That is the reason insulation around the perimeter is strongly recommended while insulation under the slab is treated as more optional.

Discussion of Different Heating Systems

There are many ways of heating a house. These include electrical resistance in baseboard heaters, a propane or natural gas furnace, a heat pump, solar thermal, and a wood stove. Resistance heaters are cheap to install but expensive to operate. The adjacent house uses resistance heaters. The climate in Rockvale is relatively mild, so a decision to use resistance heaters is not automatically a bad one. The conversion of electric power to heat is basically a 100% efficient process, which makes collecting data on efficiency simpler, so I chose this option.

There will be a noticeable 60 Hz magnetic field within two or three feet of each baseboard heater. Those with moderate sensitivity will need to avoid getting too close to the heaters. Those with severe sensitivity may need to turn off the heaters in the same room and let the thermal mass keep the temperature in an acceptable range.

Natural gas is not available in this subdivision. Propane is a fairly common fuel in town. A high-efficiency propane furnace can easily cost $5000 more than the electric baseboard heaters, installed, but the operating costs will be less. One can calculate a Simple Payback Period where the lower operating costs will offset the higher capital cost. If less than 8 or 10 years, buying a good propane furnace would be considered a wise investment. The decision to buy a furnace with a longer payback period is not as obvious.

Some people are highly sensitive to propane fumes. I know such a person living in northern Arizona who has to take extreme measures to vent his propane refrigerator and stove. In my situation, I want this facility to be healthy for as many people as possible, even if it costs more to operate.

Heat pumps are a good choice in most situations. They have a higher first cost than a propane furnace, but a lower operating cost. A heat pump with a Coefficient of Performance (COP) of 3 will have an output of the equivalent of 3 kWh of heat energy for the input of 1 kWh, so the operating cost would be one third that of electric baseboard heat for the same comfort level. They extract heat energy from either ambient air or from the earth. Historically, heat pumps get less efficient as the temperature of the source decreases. Some air source heat pumps will just turn off when the air temperature drops below freezing, and convert to what is basically resistance heating. In such a case the heat pump essentially fails just when needed the most. Because of this people in colder climates typically use ground source heat pumps to take advantage of warmer temperatures in the earth. Here in Rockvale, the expected temperature of well water is that of the average yearly temperature, or about 52^o F.

One can use several different methods of extracting this heat from the earth. In places with a high water table and no water restrictions, one can just pump water to the heat pump, extract the heat, and inject the water back into the water table, or even just dump it to the nearest stream. Other places one can dig a deep trench (6' or more) in a circular pattern of a hundred feet or more in diameter and put a water line in the trench. The line is filled with water, which is reused rather than dumped. The heat pump takes water from the line at earth temperature, cools the water by heat pump action, and puts the colder water into the other end of the line. As the water flows around the loop it absorbs heat from the earth, to be used again by the heat pump. The same idea can be used with a vertical loop rather than a horizontal one. A well is drilled, perhaps a hundred feet deep or more and the water in the closed system flows down and back up to supply the heat pump.

Colorado does not get a lot of precipitation at lower altitudes. Rockvale gets an average of about 12 inches per year. Wells may be as much as 600 feet in depth to reach water, and even then may produce only a few gallons per minute. It is not legal to drill a well on a lot less than 35 or 40 acres in size. Heat transfer from dry, sandy soil to a buried water line is not very effective, compared with heat transfer in wet soil. These facts make it difficult to impossible to use a ground source heat pump on my approximately 2 acre lots in Rockvale.

Wood stoves are legal and not uncommon in Rockvale. One can use either natural wood or wood pellets. Pellets can be used in a thermostat controlled stove, which makes it closer in character to the 'modern' fuels of electricity or propane. The room in which the stove is located will be toasty, but the other rooms in the house will be cool (unless fans are used). I assume that some sensitives will have a problem with the fumes. I once tried to heat a large attached room with an airtight wood stove, but gave up after a year or two because of the dust created when removing the ashes.

Solar thermal heating has the advantage for sensitives that it does not produce electromagnetic fields nor chemicals. Colorado is a good state for solar installations in that we have a good percentage of sunny days in the winter. One problem for some of us is the diurnal variation of temperature. The area with the south facing windows will be hot during the afternoon, and then cool off at least five to ten degrees F during the night. The rooms along the north side of the house may be uncomfortably cool if no fans are used. Another problem is the one or two times per year that we have clouds, snow, wind, and low temperatures for several days in a row. The house will cool off to uncomfortable levels. A secondary heating source is needed for these few days. A wood pellet stove would be an obvious choice for backup, or a few electric baseboard panels for on-grid locations.

Fans produce audible noise, which is a problem to some sensitives. Moving air may circulate allergens, and make allergies worse. It should be evident that every heating method has significant problems, at least to some people. All the problems have less total impact if less heat is necessary. We always need to work toward greater thermal efficiency in the places where we live.

The other data point that is needed is the temperature that I set on the thermostat. If I keep the shop at 62^oF the yearly heating cost may look quite acceptable, but if you keep your house at 72^oF you will get a rude surprise when the utility bill arrives. There are other variables of usage. How long a shower do you take? Do you sleep with a window open? How often do the kids or the pets run in and out?

There are also climatic variables. The cost of keeping the shop at 62^oF will be less in a mild winter than in a harsh winter. This is accounted for in weather data by something called Heating Degree Days (HDD). They assign a reference outdoor temperature at which most homes no longer require heating, usually 65^oF. If the average temperature for a day is 55^oF, that day is considered to have 10 HDD. If the average temperature is 45^oF, we have 20 HDD for that day. For Pueblo, the average HDD for the period 2003-2017 was 5040. The coldest winter saw 5751 HDD, while the mildest winter saw 4579 HDD. So we can expect a $\pm 10\%$ variation in cost just because of yearly temperature variation. The HDD calculation ignores wind speed so we might see another few percent difference from a calm winter to a windy one.

For research purposes, I need to know more than just the yearly energy cost. I need to know the energy consumption of different building components. If there is one spot the building is losing a large fraction of energy, I need to ask if there is some modification to the building that will fix the problem at an acceptable cost. Therefore we need to look at a detailed loss analysis of the building.

Another loss factor is infiltration, where leaks in the building envelope allow heated air to escape, to be replaced with cold outside air. This is a planned amount in modern buildings due to air quality concern. I once read somewhere that there needs to be at least 0.35 Air Changes per Hour (ACH) to maintain acceptable air quality. I would hope that this shop would not need this many ACH because there are almost no manmade chemicals inside. The shop has no exhaust fans so the actual ACH is due to the tightness of the building. Infiltration will be proportional to the wind speed, which I am not recording. To start to study infiltration, I would need to hire someone to do a blower door test, where someone places a large fan in a door and measures differential air pressure between inside and outside to find out how tight the building is. I am going to put this task off to a later time.

Early Conclusions

The building uses more energy for heating than I like. And the floor is cold, resulting in cold feet and less perceived comfort for a given air temperature. I will definitely insulate the slab in any future buildings I build. My concrete contractor tells me that he never insulates the slab except for the case where in-floor heating is used, and even then uses only R-10 insulation. It seems to me that this is a bad habit, dating back to the days of cheap energy. I will use at least R-10, and perhaps R-15 or R-20 pending some more economic analysis.

Attic insulation is not terribly expensive nor hard to install. Two kids showed up at noon, ran the hoses, blew in the specified depth of insulation, and were gone by 2 pm. Morton subcontracts this activity. They specify R-38, probably out of habit. It is not a problem to ask for deeper insulation, at a nominal price increase. I will definitely inquire about using R-60 or even higher in any future building.

Morton seems flexible about sourcing of windows and doors. I let them supply both on this building, but will look into higher efficiency components to buy myself for any future building. In particular, I will take a look at fiberglass windows rather than the vinyl windows in this building. One Internet site said this was a preferred efficiency upgrade in Canada.