ENERGY EFFICIENCY OF MORTON BUILDING

HEALTHY HOUSING RESEARCH INSTITUTE
ROCKVALE, COLORADO
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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). The shell of the building was finished in September, 2018. I then installed interior walls of knotty aspen to form two 'bedrooms' at one end of the building (tack rooms in a shop). I also built a 'kitchen' cabinet base section with a concrete countertop and a sink with hot and cold running water. Transfer of my office and lab from the adjacent house then occurred in early 2019. This document deals with the measured energy efficiency of the building.

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 analog meter occasionally, so I can calculate the total electrical energy used in the shop since the previous reading. 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 cost of heating the shop for that interval.

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.

Energy usage for the house and shop is given in Table 1 for 2018 and following. The house is 1500 ft^2, three bedroom, and two baths, on an uninsulated slab. It is partially bermed into the hill behind it. The back wall and the two side walls are concrete; the front wall is frame. Electric baseboard heaters supply the heat. Air conditioning is by evaporative cooler driven by two photovoltaic panels and a 24 VDC battery bank, hence does not affect the warm weather utility usage in Table 1. A tenant (my daughter's boy friend) moved into the house in early 2018. He did not mind a low thermostat setting of 65^{o}F or lower (a good thing) but liked to sleep with a window cracked open (a bad thing in cold weather!).

Another tenant moved to my site 10/11/19, leaving 1/15/20. She was 62 years old, thin, cold blooded, and quite ill with Parkinson's, Lyme, photosensitivity, and EHS. She lived in the house the first part of the period, then shifted to the shop.

Period	House	Shop	Total
12/11/17–1/10/18	768	-	768
1/10/18–2/9/18	943	-	943
2/9/18–3/12/18	909	-	909
3/12/18–4/11/18	596	-	596
4/11/18–5/11/18	389	-	389
5/11/18–6/12/18	221	-	221
6/12/18–7/12/18	301	-	301
7/12/18–8/13/18	324	-	324
8/13/18–9/12/18	308	-	308
9/12/18–10/10/18	328	-	328
10/10/18–11/9/18	816	-	816
11/9/18–12/11/18	1557	-	1557
2018	7460	-	7460
12/11/18–1/11/19	1576	233	1809
1/11/19–2/11/19	1453	1567	3020
2/11/19–3/12/19	1512	732	2244
3/12/19–4/11/19	999	400	1399
4/11/19–5/10/19	631	95	726
5/10/19–6/11/19	557	68	625
6/11/19–7/11/19	417	65	482
7/11/19–8/13/19	324	64	388
8/13/19–9/11/19	242	78	320
9/11/19–10/11/19	291	108	399
10/11/19–11/11/19	1103	340	1443
11/11/19–12/11/19	1167	908	2075
2019	10272	4658	14930
12/11/19–1/10/20	1509	1437	2946
1/10/20–2/11/20	1763	920	2683
2/11/20–3/12/20	1242	745	1987
3/12/20–4/10/20	729	615	1344
4/10/20–5/11/20	537	405	942
Year to date	5780	4122	9902

Table 1: Energy usage house and shop, kWh

The shop has six 1 kW baseboard heaters, three on a common thermostat on the wall and the other three on individual thermostats on the heaters themselves. The latter three are left completely off when no one else is staying here. The wall thermostat is set on 62^{o}F. I typically keep my cap, sweater, and jacket on during the heating season. Three heaters are quite adequate to maintain this low temperature setting.

I was curious about the maximum indoor temperature that could be reached with all six heaters. I turned everything off for a few days, allowing the interior temperature to drop to 37^{o}F. I then turned all heaters on. The thermostats would not allow 100% duty cycle, but allowed an input of 691 kWh over the period 1/14/19-1/21/19, an average of 4.11 kW. The indoor air temperature increased to 71^{o}F the second day of the test, but could not increase further. This would represent a monthly bill of over $540, just for shop heating. If a still warmer indoor temperature were desired, more heaters would need to be added, and monthly bills approaching $1000 would be expected.

I would characterize the building heat loss as extremely sensitive to the indoor temperature setting. The monthly bill for heating is on the order of $100/month at 62^{o}F, rising to the order of $500/month at 70 or 71^{o}F.

Is there anything that can be done to lower heating costs? Are the payback periods acceptable? These questions require a detailed analysis of heat flows in the building. If possible, we would like to determine which building components are the most lossy and discover a method to reduce those losses by some improvement with an acceptable payback period.

Instrumentation

Anticipating these questions, I installed some instrumentation during construction. 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 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

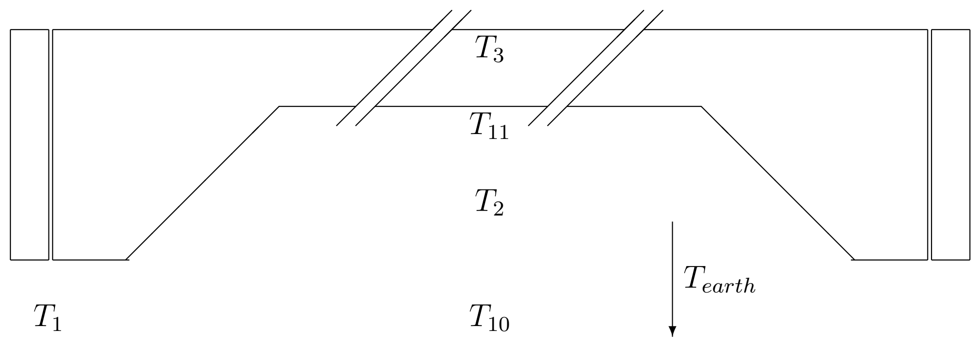

Figure 1: Monolithic foundation (Not to scale)

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 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. The average of these five thermocouples is 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. T_7 is set equal to T_{out}, the exterior temperature of the building, in calculations to follow.

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

- Ceiling
- Walls
- Windows
- Doors

- Slab
- Infiltration

The general form of 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.

Morton provided me an Envelope Compliance Certificate with R and U values that can be used for heat loss analysis. There was one column for "Proposed U-Factor" and another column for "Budget U-Factor". The budget U-factor values were equal to or larger than the proposed U-factors. I assume the proposed U-factors are the numbers provided by the various manufacturers and the budget U-factors represent an estimate of how good the installed component is likely to be. For example, the wall has R-19 fiberglass insulation. There are air spaces between the fiberglass and the metal panels that have R-values of 0.91 each. There are air films on the two sides of the assembly that add a total R-value of 0.85. Part of the wall consists of wood framing rather than insulation, with a different R-value. The process is like calculating the equivalent resistance of two parallel resistors. Morton calculated a total assembly R-Value of 21.311. The U-value is 1/21.311 = 0.047. They then list a budget U-value of 0.064, a value 36% higher. The also list a budget U-value for windows of 0.35 and a budget U-value for doors of 0.7.

We can now develop a combined heat flow for the walls, ceiling, windows, and doors, which we will call Q_{shell}.

$$Q_{shell} = [\frac{1325}{38} + (0.064)(1370) + (0.35)(83.4) + (0.7)(46.7)](T_{in} - T_{out}) \tag{2}$$

$$Q_{shell} = 184.43(T_{in} - T_{out}) \qquad \text{BTU/hr} \tag{3}$$

$$Q_{shell} = 0.05408(T_{in} - T_{out}) \qquad \text{kWh/hr} \tag{4}$$

where T_{in} and T_{out} are in degrees Fahrenheit.

We can now write an equation based on Conservation of Energy in the form of power in equals power out.

$$P_{in} = Q_{shell} + Q_{slab} + Q_{infil} - Q_{gain} \tag{5}$$

where P_{in} is the electrical power input (the difference between ending and beginning readings on the kilowatt hour meter divided by the elapsed number of hours), Q_{slab} is the power flowing out through the slab, Q_{infil} is the loss due to infiltration, and Q_{gain} is the power gained inside the building due to human occupancy (about 400 BTU/hr each) and to solar power entering the windows.

There is what is called a superinsulated or net zero house where Q_{gain} is able to supply essentially all the heating requirements of the house. This requires that the house be very tight, to not allow significant air leakage. But this means that the inside air gets stale, filled with the toxins outgassed by our building materials. It is therefore common for superinsulated houses to have a heat exchanger which recovers the heat from the heated inside air and adds it to the cold outside air as it is brought into the house. I want to avoid such a heat exchanger in any housing I build, because of the electromagnetic fields and the audible noise produced by the motors and fans, so my cabins may not be 'tight' according to superinsulated standards.

The heat loss through the slab is given by

$$Q_{slab} = \frac{A(T_{slab} - T_{earth})}{R} \qquad \text{BTU/hr} \tag{6}$$

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.

There are several difficulties in calculating Q_{slab} to any degree of accuracy. Much of the heat entering the slab will leave it horizontally through the perimeter rather than vertically into the earth. The R factor will vary substantially with the moisture content of the concrete base and the underlying soil. This moisture content will vary throughout the year due to precipitation. It appears to me that it is just not possible to determine an 'average' R value to use in this calculation. Instead, a sophisticated computer modeling program must be used, involving three-dimensional heat flow with appropriate boundary conditions. I have not looked to see if such a program is readily available. I have worked on enough similar problems in electrical engineering to know that learning to use such a program and entering the necessary boundary conditions would require more time than I am willing to spend. Instead we will look at my collected data to see if we can identify ballpark values for Q_{slab}.

Data Analysis

As mentioned, I collected hourly readings of 11 thermocouples for over a year. This is a *large* amount of data! Only the heating season is of real interest, of course. I identified 7 periods where I averaged the hourly data to get the results in Table 2.

Period	ΔT_{shell}	P_{in}	Q_{shell}	Net	ΔT_{slab}
2/25/19–3/3/19	19.77	0.743	1.069	-0.316	-
10/3/19–11/8/19	16.44	0.428	0.889	-0.461	5.01
11/10/19–12/11/19	17.27	0.989	0.934	0.056	10.72
12/20/10–1/15/20	28.09	2.021	1.519	0.502	16.37
1/16/20–2/17/20	25.01	1.027	1.352	-0.325	13.31
2/21/20–3/21/20	18.67	1.030	1.009	0.0203	12.93
3/23/20–4/20/20	15.35	0.814	0.830	-0.016	10.07

Table 2: Energy usage house and shop, kWh

The 7 day period spanning 2/25/19 to 3/3/19 should have minimal influence from the slab. 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 average inside air temperature was 54.8^{o}F so the steady heat loss through the slab would be minimal for this very small difference in temperature. The average outside air temperature was 35.05^{o}F. The temperature difference $\Delta T_{shell} = T_{in} - T_{out} = 19.77^o$F.

The energy input from the local utility was 124.8 kWh for the week or an average of 0.743 kW.

From Eq. 4, the heat loss through the shell is

$$Q_{shell} = 0.05408(19.77) = 1.069 \qquad \text{kW} \tag{7}$$

We now need to add a term for infiltration, which will vary widely depending on the quality of building construction. This can be estimated by doing a blower door test, which I did not do. From my Internet search, a well constructed building may have only 0.35 or 0.4 Air Changes per Hour (ACH). Typical buildings may have ACH values around 2.0. I found an equation on the Internet for Q_{infil}, which, for our numbers and assuming a well built building, yields

$$Q_{infil} = (0.018)(ACH)(Vol)(\Delta T) = (0.018)(0.35)(13250)(19.77) = 1650 \quad \text{BTU/hr} \tag{8}$$

or 0.484 kW. The total heat output (converted to electrical power units) $Q_{shell} + Q_{infil} =$ 1.553 kW, more than twice the input power of 0.743 kW. There will be some solar gain, which I estimate as no more than 0.19 kW, and my body heat, perhaps another 0.03 kW. We are 'off' by about a factor of two.

Possible Errors

It is embarrassing for me to have this big a discrepancy! I feel there is one, or perhaps several, errors/misinterpretations involved. I sense it could be a major effort to find and correct all the errors, and that it might not be possible to calculate all the terms to within ten or twenty percent. My guess is that such a major effort is not worth my time at this stage, so I will admit defeat and move on to other projects. But let me discuss some of the possible errors first.

I am confident of the amount of energy purchased from the utility. I did not do my own independent calibration of the watthour meter, but they are rugged instruments, rated at 0.1% accuracy.

I used budget R- and U-values in the calculation of Q_{shell} which might be overly conservative. In our lawsuit happy society, one hates to claim an inflated number for efficiency. As noted earlier, Morton suggests a U-value 36% greater than the calculated value. There is no exhaust fan in the shop so perhaps we did not get to the minimum 0.35 ACH.

I am far from expert in the use of LibreOffice Calc. It is definitely a possibility that I am systematically doing something wrong in computing average values.

Another possible source of error is the thermocouples, especially the ones in or under the slab. During a 24 hour period mid April, 2019, T_1 varied randomly from 52.2 to 52.5^{o}F. I consider this a reasonable error between readings. During the same period T_2 varied from 54.3 to 63.6, which I consider impossible. Something is wrong, possibly moisture around the thermocouple junction? T_3 varied from 57.9 to 58.7, T_{10} from 58.1 to 60.2, and T_{11} from 58.4 to 59.7. I consider this variability excessive. It appears that this installation of thermocouples is yielding poor data, with both noise and bias. I probably should have followed some waterproofing protocol on the buried junctions that I did not happen to read about on the Internet. This could easily invalidate all the results.

The slab and the earth below have considerable heat storage capability. That adds another (non trivial) number to our heat balance equation. 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) $= 1.2 \times 10^6$ 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) $= 450 \times 10^6$ 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.

A Reality Check on Heat Storage

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 temperatures were 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, and by 3.76^{o}F under the slab. I then calculated Q_{shell}, 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.

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^{o}F requires 4.7 kWh. The temperature drops listed above would give energies extracted from the slab of 21.3, and 17.7 kWh. The slab is not insulated so heat energy is also being extracted from the fill material below the slab. 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.

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.

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.

A cold floor is a disadvantage in the winter time but an advantage in the summer time. I leave the windows and doors closed in the summer and get by with just a fan (no swamp cooler). Adding insulation under the slab will make it essential to install some sort of air conditioning in the building.

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. I also like the idea of the twist tilt windows used in Europe. They appear to have better sealing through stronger mechanical construction. They also tilt into the room, thus not interfering with a metal screen across the entire window opening on the outside of the building.