

Home Energy Conservation Exercise

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ABSTRACT

We have developed a home energy conservation exercise that illustrates the ways in which heat energy is lost from a home and ultimately, how it can be conserved. Students are asked to calculate the heat loss from a model home before and after applying energy conserving modifications. The difference in these calculations represents the amount of heat energy that could be conserved by making the modifications. To calculate total heat loss for each version of the home, students must account for convection, (heat transfer via air movement), and conduction, (heat transfer through solid materials). Students are provided with a list of building material costs and a budget of \$5,000 and are asked to retrofit the un-insulated home in such a way as to conserve the maximum amount of energy and heating cost per heating month. Introductory geology courses commonly include material on resources, energy, and the environment. Current news topics include discussion of the energy resources in the Arctic National Wildlife Refuge and the shortage of natural gas. This exercise takes a practical approach to energy conservation and applies it directly to conservation of a geological resource. When used in conjunction with classroom discussions concerning the detrimental effects of the use of fossil fuels and their limited supply, it is an effective way of demonstrating the concept of conservation as a source of energy and a means to preserve the environment. It is also a practical way to incorporate quantitative reasoning into the classroom.

Keywords: Environmental education exercise, home energy conservation, home heat loss calculations

INTRODUCTION

For a number of years, we have used a laboratory exercise, in its various stages of development, to illustrate the ways in which heat energy is lost from a home and, ultimately, how it can be conserved. We have used the home energy conservation exercise in an interdisciplinary course that is entitled Field Studies in Environmental Science. We use the exercise in conjunction with classroom discussions concerning the environmental problems associated with the use of fossil fuels (Hinrichs, 2002, p. 239-313), their diminishing supply (Minnear, 2000), and conservation as a cost effective, alternative source of energy. This exercise is

easily worked into a resource, energy, or conservation unit in an introductory geoscience or environmental geology course. Lectures congruent with this exercise include the origin of petroleum, its geology, production, reserves, chemistry, environmental concerns, use, and conservation. This laboratory goes beyond a simple exercise in gas mileage to challenge students to consider several factors that affect energy efficiency and provides an activity that may be useful in the students' future. Those of us who have built and/or upgraded homes using energy efficient technologies realize how important energy efficiency is for conservation of a geologic resource.

The premise of the exercise is very simple. We ask the students to calculate the amount of heat that is lost from a model house before and after energy conserving modifications have been made. By taking the difference between these calculated values, students are able to determine the amount of energy that can be conserved by insulating and sealing the home. The exercise is not only effective in demonstrating how to reduce energy consumption in a home, but also serves to acquaint students with the concept of heat transfer and the insulating characteristics of various building materials. Most importantly, the exercise clearly demonstrates the cost and environmental benefits of home energy conservation.

The utility of cooperative learning (Rogers, 2001) and the integration of quantitative reasoning into undergraduate science courses (Carlson, 2000, Guertin, 2000, Keller, 2000, MacDonald, 2000) have received a great deal of attention recently. This exercise encourages teams of students to examine a problem on a quantitative level in order to achieve an outcome that has practical significance. As such, it is an excellent tool for teaching quantitative skills.

HOME HEAT LOSS CALCULATIONS

Heat energy is transferred by the processes of (1) convection, the motion of a fluid or gas (air in this case); (2) conduction, molecular collisions of a hot object with a colder one; and (3) radiation, electromagnetic waves (Hinrichs, 2002, p. 125-149). Since radiation accounts for only a minor portion of the total heat loss experienced by a home, the present exercise focuses on convective and conductive heat loss.

Convective heat loss (q_v) equals the amount of heat carried out of the house through air exchange with the outdoors. This is dependent on the volume of the house,

The living space in the home is on a single floor with the dimensions 48' x 24' x 8'.

There are 12 single pane windows, each 15 square ft (curtains are generally kept open). Each has an R-value of approximately 0.9 ft²F/(btu/hr).

There are 2 wooden, exterior doors, each 20 square ft with an R-value of approximately 2.

Exterior walls are 3.5" thick and consist of 2x4 studs, 1/2" gypsum board, 3/4" plywood (Douglas Fir), and wood clapboard siding (See Table 3 for R-values).

For a rough estimation, it is not necessary to include heat loss through the 2x4s (that exist in the walls) in your calculation, or the increased R-value of walls and windows due to the stationary layer of air. These two factors approximately cancel each other out.

There is no insulation in the walls of the house or the attic.

The attic is not used, is well ventilated, and is approximately the same temperature as outdoors.

The ceiling, which includes acoustic tile, air space, and the wood sub-floor of the attic, has an R-value of approximately 3.

The basement is un-insulated and has the dimensions 48' x 24' x 7'. The temperature of the basement is maintained at approximately 50°F since it is completely below grade, has no windows, and is heated by the presence of the oil burner, hot water heater, and hot water pipes. Based on these characteristics, it is a good approximation to add 2000 btu/hr to the total heat loss that you calculate to compensate for heat loss through the basement of this model house (Parsons, 1997).

The house is heated with an oil-burning furnace that is located in the basement.

Table 1. Characteristics of the un-insulated house.

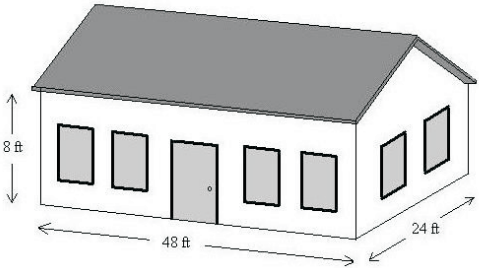


Figure 1. Diagram of the house showing the dimensions of the living area.

the number of air exchanges per hour (i.e., the number of times that the entire volume of air in the house is exchanged in one hour), the heat capacity of air, and the temperature inside and outside of the house (T_{inside} and T_{outside}).

$$q_v = [(house\ vol\ ft^3 \times (air\ exchanges/hr))] \times [C_{air} \times (T_{\text{inside}} - T_{\text{outside}}\ F)] \quad (1)$$

The heat capacity of air (C_{air}) is 0.018 btu/(ft³ F). The number of air exchanges per hour that an un-insulated home experiences is between 3 and 6 (Hinrichs, 2002, p. 135). With the addition of sufficient insulation, caulking, and weather stripping, this value is reduced to between 0.5 and 1.5 exchanges per hour.

An un-insulated home without storm windows or doors experiences approximately 4.5 air exchanges per hour. To reduce air infiltration, install caulking, weather stripping, and insulating inserts for electrical outlets. These modifications, along with some type of wall and attic insulation, will reduce air infiltration to approximately 1.0 air exchanges per hour.

To insulate the exterior walls of the home (without removing the existing siding) it will be necessary to use material that can be blown (or foamed) in through small holes. Possibilities include cellulose, fiberglass and polyurethane.

Cellulose can also be used to insulate the attic, although rolled fiberglass insulation (available in a variety of widths and R-values) can also be installed there.

Storm doors could be installed or, alternatively, the existing wooden doors could be replaced with insulated doors.

Storm windows could be added, or the existing single pane windows could be replaced with higher efficiency double pane units.

To further insulate the windows, heavy-duty shades or insulated cellular shades could be added. Note that shades are only effective insulators when they are kept closed. For a rough estimate, assume that the shades in a given room will remain closed 75% of the time. Hence, adjust the R-value that you use for shades by multiplying the reported value by 0.75.

Table 2. Potential Energy-Conserving Upgrades.

Conductive heat loss (q_d) depends on the inherent resistance to heat flow (R-value) of each material per unit area, the total area of the material (wall, floor, window, ceiling), and the difference in temperature between the inside and outside of the house. The resistance to heat flow is additive just like electrical resistance, but the conductance of heat, like electrical conductance, is proportional to the reciprocal of the total resistance.

$$q_d = (1/\text{sum of R-values})(\text{surface area ft}^2)(T_{\text{inside}} - T_{\text{outside}}\ ^\circ\text{F}) \quad (2)$$

where R-value is a measure of the thermal resistance of a given material in units of ft²F/(btu/hr). While heat loss due to convection can be calculated in one step using the first equation, heat loss due to conduction must be calculated for each component that separates the inside of a house from the outside (e.g., walls, ceiling, windows, etc.). These values are summed together to give the total heat loss due to conduction. Further complicating this calculation, a given component of the house might be composed of more than one type of material, and the R-values for each of these must be accounted for in the second equation. For example, a wall might be composed of wood siding, plywood, insulation, and gypsum board. To determine q_d for the wall, the R-values for each of these materials must be summed to give the total thermal resistance for the wall used in the second equation.

HOUSE DIMENSIONS AND CHARACTERISTICS

The model house that we use for our exercise is a simple ranch house. We provide students with a sketch of the house (see Figure 1), a cut-away view of the house showing potential sources of convective and conductive heat loss (Figure 2), and a list of characteristics of the un-insulated house (Table 1).

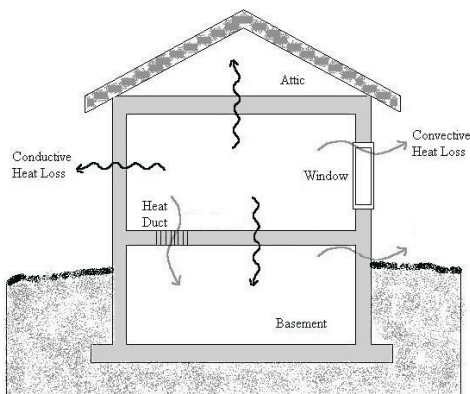


Figure 2. Cut-away diagram of the house showing potential sources of heat loss.

According to the American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE) Fundamentals Handbook (Parsons, 1997), a below-grade basement with a furnace and hot water heater will maintain an average temperature of 50° F. However, the temperature near the ceiling of the basement (the temperature varies from floor to ceiling) will be close to the temperature of the house. For that reason, it is not necessary to calculate heat loss through the floor of the house. The calculation to determine heat loss through the basement is fairly involved and takes into account the amount of insulation on the walls, the number of feet of wall space below grade (7 ft in this case), and a heat loss coefficient for each foot below grade (Parsons, 1997). Hence, we have chosen to simply provide our students with this number. Instructors may wish to have their students do this calculation themselves and provide them with the opportunity to add insulation to the basement walls as another option for improving the efficiency of their model home. Instructions for making this calculation are clearly delineated in the ASHRAE Fundamentals Handbook (Parsons, 1997).

It is also necessary to provide students with information concerning the climate of the region where the house is located. For example, we tell our students that the house is located in Saratoga Springs, NY which has approximately 270 heating days per year and the average temperature differential (between the inside and outside) is 25°F. This temperature differential is used in the convection calculation and in conduction calculations involving the doors, windows, walls, and ceiling (the temperature differential between the basement and outside of the house is 10°F, which is used in the approximation of heat loss through the basement, see above). Information regarding monthly average temperatures and the number of heating degree days per year (a heating degree day corresponds to each degree that a day's mean temperature falls below 65°F), for a particular region of the country, can be obtained from web resources such as <http://www.weather.com> and <http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/nrmhdd.html>. The number of heating days per year can be determined by dividing the number of heating degree days per year by the average temperature differential

(relative to 65°F) for days in which the mean temperature falls below 65°F.

LOGISTICS OF THE EXERCISE

Our students complete the exercise during the course of a three-hour laboratory period (most students finish the assignment within two hours). Alternatively, the exercise could be done as an out of class assignment or over the course of several shorter periods. We instruct students to carry out the task in groups of three. To make the assignment more interesting for them, we set up a scenario in which each team of students works for a separate contracting company that specializes in insulating homes for energy and cost conservation. Each company has been asked to provide a family with a bid for improving the insulation and reducing the air infiltration of their house. However, in lieu of a typical bid, the family wants each company to determine how much money they could save per heating month by making \$5,000 worth of modifications to their home. Student teams then compete to see which company can win the bid. To complete their bid, student teams must (1) calculate the present heat loss of the clients' home (considering both convection and conduction), (2) decide which modifications to make to the home while staying within the \$5,000 budget, (3) calculate heat loss for the modified home, and (4) determine the energy that would be saved by taking the difference between these two values.

In order to help them decide which modifications their company will recommend, we provide students with a list of information concerning the possible energy-conserving upgrades that can be made to a home (see Table 2). We also supply students with a list of building material costs (including installation) and R-values (see Table 3). We generated this list by visiting our local hardware store and consulting web resources such as <http://www.get-a-quote.net> and <http://www.ornl.gov>. Finally, we provide a Material Budget Form (see Figure 3) for students to complete with information regarding the modifications they choose and their costs.

For some students, the multiple step calculations in this exercise can be somewhat daunting. To help guide them and reduce their anxiety we provide them with a worksheet for completing the calculations (see Figure 4) and a step-by-step strategy (see Table 4). When they have completed the calculations, we ask students to answer a set of questions (see Table 5) prior to handing in the Materials Budget Form and Calculation Worksheet.

CONCLUSIONS

Most student teams calculate a monthly energy savings on the order of 20 million btu as a result of the modifications that they choose, reducing total heat loss by approximately two thirds. This corresponds to a cost savings of \$180 to \$200 per heating month (with oil heat). We have found that the competitive nature of the exercise (teams competing against one another to produce the greatest savings in energy and cost) inspires the students to examine the various components of the house carefully and run a number of test calculations prior to deciding on a final set of modifications. During this process, students develop a familiarity with the mathematical equations that are involved in the exercise and begin to recognize patterns and think on a quantitative level. In the end, they develop a very good

Material (Thickness in inches)	Cost (Including installation)	R-Values (ft ²) YF/(btu/hr)
Air Infiltration Reduction		
Caulking/weather stripping, etc.	\$200	N/A
Exterior Wall Insulation		
Fiberglass insulation (3.5")	\$0.60/sq ft	11.2
Cellulose insulation (3.5")	\$0.80/sq ft	12.3 (per 3.5" of cellulose)
Polyurethane insulation (3.5")	\$2.00/sq ft	21.7
Attic Insulation		
Cellulose insulation (increments of 3")	\$0.80/sq ft (per 3" thick application)	10.5 (per 3" of cellulose)
Fiberglass insulation (3.5")	\$0.60/sq ft	11
Fiberglass insulation (3.5")	\$0.67/sq ft	13
Fiberglass insulation (6.5")	\$0.73/sq ft	19
Fiberglass insulation (8.25")	\$0.88/sq ft	25
Fiberglass insulation (10.25")	\$0.91/sq ft	30
Fiberglass insulation (12")	\$0.99/sq ft	38
Exterior Door		
Add storm door	\$200	2
Replace existing door w/ insulated door	\$320	11
Windows		
Add storm windows	\$20 each	1
Replace w/ double pane	\$235 each	2.4
Replace w higher efficiency double pane	\$295 each	2.8
Add heavy duty shades	\$12 each	1
Add cellular insulating shades	\$40 each	3.8
Existing Materials		
Gypsum board (1/2")	N/A	0.45
Douglas Fir plywood (3/4")	N/A	0.93
Clapboard siding (5/8")	N/A	0.90
Single pane windows (1/4")	N/A	0.9
Wooden exterior doors	N/A	2

Table 3. Building material costs and R-Values.

1. Calculate heat loss by convection (q_v) using eq. 1 before and after modifications. You will only do this if your team decides to install caulking, weather stripping, and insulation (wall and attic) as part of the modifications.
2. Calculate heat loss by conduction (q_d) through each of the various components of the house (walls, windows, doors, and ceiling) using eq. 2 and sum all of these values to calculate the total heat loss through conduction. Do this for the present and modified home. *Note: To make these calculations, you will need to sum together the R-values of the various materials contained within each component of your house.*
3. Calculate total heat loss by adding heat loss due to convection and conduction together. Add 2000 btu/hr to this value to compensate for the loss of heat through the basement walls and floor. Do this for the present and modified home.
4. Convert these numbers in btu/hr to btu/30 day month; i.e. multiply by 30 days/month.
5. Take the difference in these values to determine the amount of heat loss that you could avoid per heating month if you modify the home.
6. Convert this number into the amount of money that you would save per heating month if you make the modifications. In doing this calculation, recognize that residential fuel oil has a heat content of about 150,000 btu/gallon (see www.eia.doe.gov). Considering that modern oil furnaces are 80% efficient and that the cost of heating oil is approximately \$1.15/gallon (this was the average price in New York for the winter of 2001/2002, see www.eia.doe.gov), heating a home by oil costs approximately 96¢ per therm (1 therm = 100,000 btu).

Table 4. Step-by-step strategy for completing the calculations.

1. Assuming that you make the modifications to your client's home, what amount of energy (in btu) and money will they save over the course of one year (assuming that there are 9 heating months out of the year)?
2. How much money would it cost them to heat their modified home with oil heat for one year? Note that the amount of heat lost from the home per month corresponds to the amount of heat energy that would have to be supplied to the home.
3. When your clients built their home, they had considered installing electric heat instead of oil heat. How much would it have cost them to heat their home with electric heat for one year? In doing this calculation, recognize that electric heat costs 10¢ per kilowatt hour (KWH), and that 1 KWH = 3412 btu. Note that the price of electric heat was estimated from a recent electric bill (Niagra Mohawk, 2002).
4. Your clients are also considering converting their home over to natural gas heat. How much money would it cost them to heat their home with natural gas for one year? Note: natural gas costs 40¢ per therm (as estimated from a recent gas bill from Niagra Mohawk, 2002)
5. If it costs \$5,000 to convert your clients' home from oil heat to natural gas, how long will it take to pay back the cost of conversion through energy savings?

Table 5. Questions to be answered at the end of the exercise.

Materials Budget Form			
Caulking/weather stripping	Materials	Number or sq ft where applicable	Cost
Windows			
Doors			
Walls			
Ceiling			
Total Cost			

Figure 3. Materials budget form used by the students to list recommended modifications and their cost.

quantitative sense of the thermal efficiencies of various building materials and excellent strategies for preventing home heat loss. Moreover, they are confronted with the staggering amounts of energy and money that are wasted in heating the un-insulated home.

It is important for students to recognize that there are financial and logistic limitations with respect to incorporating energy efficient technologies and materials into pre-existing homes. We point this out to our students and emphasize the fact that there are other effective design elements that can be utilized in new home construction such as super-insulation (see www2.srp.gov/homeenergymanager/advisor/superinsul.html) and solar heat gain (see www.eren.doe.gov).

We recognize that the repetitive nature of the calculations in this exercise lend themselves to the use of a spreadsheet. In fact, we offer our students the opportunity for extra credit if they wish to copy their worksheet and incorporate it into spreadsheet format. However, due to the time constraint of our laboratory period (teaching students the use of a spreadsheet would require a significant amount of time) and the esoteric nature of spreadsheet calculations, we have not made this a general requirement of the assignment. Instead, we believe that working through the calculations by hand gives students a better perspective of the types and sources of heat loss and their magnitudes. In addition,

by using a standard worksheet, we are better able to assist the students during the course of the exercise. Instructors adopting this exercise may wish to have their students do a few calculations by hand using the worksheet in Figure 4, and then transfer their work to a spreadsheet to complete the calculations.

In short, we have found the Home Energy Conservation Exercise to be a thought provoking and informative experience for our students, underscoring the cost (both in energy and money) of daily human activities and the power of conservation to preserve resources and protect the environment. Students enjoy competing with one another and are amazed by the magnitude of cost, energy, and resource savings that are realized by properly insulating and sealing a home. Moreover, by participating in this exercise, students begin to recognize the utility of a mathematical approach to solving problems of a scientific and/or practical nature.

ACKNOWLEDGMENT

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Home Energy Calculation Worksheet

Heat loss due to convection $q_v = (0.018 \text{ btu}/(\text{ft}^3 \text{ }^\circ\text{F}))(\text{volume } \{\text{ft}^3\})(T_{\text{inside}} - T_{\text{outside}} \{^\circ\text{F}\})(\text{air exchanges}/\text{hr})$

	Constant (btu/ft ³ F)	Volume (ft ³)	T (F)	Air Exchanges	q _v
Present Home					
Modified Home					

Heat Loss Due to Conduction, $q_d = (1/\text{sum of R-values})(\text{surface area } \{\text{ft}^2\})(T_{\text{inside}} - T_{\text{outside}} \{^\circ\text{F}\})$

	Component	Sum of R-values (ft ² F/(btu/hr))	1/Sum of R values	Areas (ft ²)	T (F)	q _d
Present Home	Windows					
	Doors					
	Walls					
	Ceiling					
Total q_d Present						
Modified Home	Windows					
	Doors					
	Walls					
	Ceiling					
Total q_d Modified						

Heat Loss Totals

	Q _v + q _d (btu/hr)	Basement walls/floor (btu/hr)	Total Heat Loss (btu/hr)	Total Heat Loss/Month (btu/month)
Present Home		2000		
Modified Home		2000		
Difference				
\$ Saved (oil heat)*				

* Conversions: Oil heat, 1 therm = 100,000 btu at a cost of \$0.96 per therm

Figure 4. Worksheet used by students to perform heat loss calculations.

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