Introduction

In this project we were all transformed into scientist and engineers. Our job was to optimize an existing experiment in order to make an accurate approach toward designing a successful passive solar water heating system. After doing in-depth research we have found valuable resources that helped us understand more about this project as well as what we might be able to do to improve the existing water heating system. We are working with passive solar water heating systems which use no electricity, and rely on gravity and convection to operate the system. The design of the collector, geometrical positioning, and insulation are some of the most important factors when using solar water heating. We came to agreement that improving the insulation around the water tank would greatly improve the system’s efficiency. We decided to use Styrene foam board which is the best for insulating liquid storage tanks. We compared different types of insulation based on its R-Value, cost, and reliability. R-Value is a measure of a substance insulating value or resistance to heat flow.

Hypothesis

Based on the information we have gathered during our research, we predict that with each layer of insulation added to the water tank the rate of heat lost will decrease overtime. It will also be more cost efficient using only three (3) layers of insulation based on the amount of heat that is lost with more or less insulation. We will use the Scientific Method in order to test our theories.

1. Observe the situation or problem.
2. Formulate a Hypothesis that is testable and consistent to the observed situation.
3. Test the Hypothesis
4. Gather Data from tests and analyze if the data disproves the Hypothesis.
5. Modify the Hypothesis and repeat 3 and 4 until a Hypothesis without discrepancies is reached.
The process to test our hypothesis includes the volume of water in the tank, depths of the probes within the water, cost of energy and materials, layers of insulation, and temperature loss over time. To start the experiment we used no insulation in order to find our controlled variable. During each passing week we added 1 layer of insulation with a thickness of ¾ and R-value of 4. The cost of the insulation was $6.98 per 2 cubic foot sheet. We used our best three days each week in order to plot the data accordingly.

The Results:

**Week 1: No Insulation :: OCT 16th – OCT 18th 2007**

During this week we had a bad start because the power cord wasn’t attached to the computer therefore the computer shut off during the collection process. Usually we record the best three (3) days of the week but for this week we only have enough accurate data for two (2) days. Without insulation we have found our controlled variable or temperature without applying insulation. After analyzing the data recorded we applied our formula, which was temperature over time and total cost equal to cost of energy plus cost of insulation. We calculated the average temperature loss of each which was T/t = .907 Degree’s Celsius per Hour. The total cost also plays an important factor in this process, but since we didn’t use any insulation this week we only account for the cost of energy. The total cost is $5.79.

This information tells us the average cost and the amount of heat that is lost without insulation during this weeks’ collection. We will compare this data as we progress in order to make acquisitions with our hypothesis. Now we have our controlled variable.

**Temperature over Time**

<table>
<thead>
<tr>
<th>▲T</th>
<th>▲t</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.41</td>
<td>17.25</td>
</tr>
<tr>
<td>18.92</td>
<td>17.25</td>
</tr>
<tr>
<td>1.815</td>
<td>2</td>
</tr>
</tbody>
</table>

We did not add any insulation during this week, because we needed to find the controlled variable in order to determine the heat loss without a dependent variable. We measured the amount of water inside the tank; it was 13 liters. We decided to place the probe at different depths because of convection and to test different temperature changes at multiple levels. The placement of the probes were thirteen (13) inches and eight (8) inches below the water table and one was placed inside of the solar collector.
**Cost of Energy** (Ce)

613.25 BTU / 1,000,000 = 0.000613 x $20.49 = $0.0126 x 365 Days = $4.58  
Total Cost = $11.58

936.54 BTU / 1,000,000 = 0.000936 x $20.49 = $0.0191 x 365 Days = $7.00  
Average Cost = $5.79

**Cost of Insulation** (Ci):

No cost.

**Total Cost**

\[ Ct = Ce + Ci \]

\[ $5.79 + 0 = $5.79 \]

**Week 2: (1) Layer of insulation :: OCT 18\(^{th}\) – OCT 23\(^{rd}\) 2007**

We began to add layers of insulation during this week. The styrene foam board cost us $3.49 per cubic square foot. The material was exactly ¾ of an inch thick. The insulation was placed on all sides of the water tank including the top and the bottom. We used .36 cubic feet out of 2 cubic feet of insulation which is 18% of the cost per sheet. The total cost of the insulation used was $1.26.

The data we collected was slightly different from last week, but we are getting closer to our prediction. The data shows that by using a layer of insulation the average amount of heat loss went down .081 degrees Celsius per hour, which is good. Since we added one (1) layer of insulation we want to account for the dollar cost for energy. Based on the data we received we calculated that this weeks average cost of energy was $5.84. We are also including the cost of insulation so the cost of the insulation and energy comes to a total cost of $7.10.

This weeks trail tells us that by adding insulation the amount of heat loss decreases and the cost of insulation increases. Ultimately the cost of energy should decrease as we put additional layers of insulation on because we are using less energy to contain the heat.

**Temperature over Time**

\[ \Delta T = 14.23 = .779 \]
\[ \Delta T = 16.82 = .909 \]
\[ \Delta T = 16.43 = .791 \]
Average = 2.479 = .826

\[ \Delta t = 18.5 \]
\[ \Delta t = 18.5 \]
\[ \Delta t = 20.75 \]
\[ 3 \]

**Cost of Energy** (Ce):

704 BTU / 1,000,000 = 0.000704 x $20.49 = $0.0144 x 365 Days = $5.26  
Total Cost: $17.53

830.5 BTU / 1,000,000 = 0.000830 x $20.49 = $0.0170 x 365 Days = $6.21  
Average Cost: $5.84

814 BTU / 1,000,000 = 0.000814 x $20.49 = $0.0166 x 365 Days = $6.06
**Cost of Insulation (Ci):**
Used: .36 cubic feet of 2 cubic feet 
.18% of $6.98 = $1.26

**Total Cost:**
\[ Ct = Ce + Ci \]
$5.84 + 1.26 = $7.10

**Week 3: (2) Layers of insulation :: OCT 23rd – OCT 30th 2007**

We attached another layer of the styrene foam board this week making it two layers. We used exactly .42 cubic feet of insulation at cost of $1.46. Since we used an additional sheet of insulation the cost of energy should have decreased. The new cost of energy for this week was $4.68. We have to understand that both cost of energy and insulation are important factors.

This week’s data was also very positive we are beginning to see a consistent pattern which agrees with our hypothesis. Having two (2) layers of insulation has reduced the amount of heat loss from the previous week by exactly .125 degrees Celsius per hour. We have used two (2) layers of insulation and because the cost of insulation obviously increased. The cost of energy this week came to a total of $4.68. The total cost of this weeks test came to $6.14 considering the amount of energy and insulation used.

We this data we have found that our total cost is beginning to decrease and drop below the complete cost without having insulation. We the decrease in heat loss and decrease in total cost we feel comfortable that adding another sheet of insulation we continue to improve our final results.

**Time over temperature:**

<table>
<thead>
<tr>
<th>△T</th>
<th>△t</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.64</td>
<td>18.25</td>
</tr>
<tr>
<td>13.77</td>
<td>18</td>
</tr>
<tr>
<td>14.59</td>
<td>18</td>
</tr>
</tbody>
</table>

Average = 2.103 = .701

**Cost of Energy (Ce):**

<table>
<thead>
<tr>
<th>Energy (BTU)</th>
<th>Multiplier</th>
<th>Cost (Million BTU)</th>
<th>Days</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>475.75</td>
<td>0.000475</td>
<td>$0.0097</td>
<td>365</td>
<td>$3.54</td>
</tr>
<tr>
<td>684.75</td>
<td>0.000684</td>
<td>$0.0140</td>
<td>365</td>
<td>$5.11</td>
</tr>
<tr>
<td>723.25</td>
<td>0.000723</td>
<td>$0.0148</td>
<td>365</td>
<td>$5.40</td>
</tr>
</tbody>
</table>

Total cost: $14.05
Average: $4.68

**Cost of Insulation (Ci):**
Used: .42 cubic feet of 2 cubic feet 
.21% of $6.98 = $1.56
Today is the day we test a major part of our hypothesis. We believed that using three (3) layers was our answer. The third layer of insulation was .52 cubic feet and cost of $1.88. The amount of energy we used equaled a cost of $4.93 for this week.

Again the data represents a positive outcome exactly what we wanted to see. During this week we experienced drastic changes in the climate, it began to get colder outside and the sun wasn’t out as much. Even though we were hoping for better results having three (3) layers of insulation still decreased the amount of heat lose from the previous week by .025 degrees Celsius per hour. However the cost of energy slightly increased from the previous week because of the changes in weather. The total cost including the energy and insulation is now $6.81. Although this is an increase of cost from last week, our data still represents that having three (3) layers of insulation are greater then having none.

We still believe that having three (3) layers of insulation is the answer but to make adjustments to our hypothesis we will continue and see that having four layers (4) will greatly improve both total, and heat loss.

Time over temperature:

\[ \Delta T = 12.9 = 0.678 \]
\[ \Delta T = 13.36 = 0.651 \]
\[ \Delta T = 13.86 = 0.701 \]
\[ \text{Average} = \frac{2.03}{3} = 0.676 \]

Cost of Energy (Ce):
638 BTU / 1,000,000 = 0.000638 x $20.49 = $0.0130 x 365 Days = $4.74
660 BTU / 1,000,000 = 0.000660 x $20.49 = $0.0135 x 365 Days = $4.93
684.7 BTU / 1,000,000 = 0.000684 x $20.49 = $0.0140 x 365 Days = $5.11

Total cost: $14.78
Average: $4.93

Cost of Insulation (Ci):
Used : .54 cubic feet of 2 cubic feet
0.27% of $6.98 = $1.88
This week we have used four (4) layers of insulation which was .66 cubic feet and cost $2.30. With a consistent weather conditions our results came out just as we predicted. The amount of heat loss decreased greatly during this week’s collection, from a total of .201 degree Celsius per hour for the previous week. With four layers of insulation we have found that we have only spent $2.87 on energy and a total $5.17 including cost of insulation.

This information is great because we are starting to notice that with three to four layers of insulation the amount of heat loss and total cost is starting to come in our favor. Instead of jumping to conclude already we must see if this data is consistent. We want to come to an optimal point in which the total cost is agreeable with the amount of heat loss. So we will conclude that with more additional layers the amount of heat loss will decrease but we want to find out when it comes to a point where it begins to get more expensive then its worth.

### Time over temperature:

<table>
<thead>
<tr>
<th>△T</th>
<th>△t</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.44</td>
<td>9.5</td>
<td>.467</td>
</tr>
<tr>
<td>10.9</td>
<td>21</td>
<td>.519</td>
</tr>
<tr>
<td>8.05</td>
<td>18.25</td>
<td>.441</td>
</tr>
<tr>
<td>1.427</td>
<td>3</td>
<td>.475</td>
</tr>
</tbody>
</table>

### Cost of Energy (Ce)::

- 220 BTU / 1,000,000 = 0.000220 x $20.49 = $0.0045 x 365 Days = $1.64
- 539 BTU / 1,000,000 = 0.000539 x $20.49 = $0.0110 x 365 Days = $4.02
- 396 BTU / 1,000,000 = 0.000396 x $20.49 = $0.0081 x 365 Days = $2.96
- **Total cost: $8.62**
- **Average: $2.87**

### Cost of Insulation (Ci)::

- Used : .66 cubic feet of 2 cubic feet
- .33% of $6.98 = **$2.30**

### Total Cost:

- Ct = Ce + Ci
  - $2.87 + $2.30 = **$5.17**
Week 5: (5) Layers of insulations : NOV 13\textsuperscript{th} – NOV 20\textsuperscript{th} 2007

This week was our final collection and would tell us the rest of the story we needed to know. We now have five (5) layers of insulation around the tank. With this layer we used .80 cubic feet of insulation. As we already predicted the cost of insulation went up, sticking with its consistent pattern. The cost of insulation for this week was $2.79.

We already know from previous tests that by using multiple layers of insulation the amount of heat loss should decrease, but we want to see if it’s worth it. During the week the weather again is beginning get worse with colder temperatures and less solar light. With five (5) layers the amount of heat loss actually increased .062 degrees Celsius per hour, which isn’t much. The cost of energy did increase however to $3.55 and a total of $6.34 including the costs of insulation.

This information concludes our tests. We come to an agreement that using more then four layers of insulation isn’t worth the amount of money it takes to decrease heat loss.

\textbf{Time over temperature:}

\begin{align*}
\Delta T &= 9.75 = .541 \\
\Delta t &= 18 \\
\Delta T &= 10.74 = .588 \\
\Delta t &= 18.25 \\
\Delta T &= 8.44 = .482 \\
\Delta t &= 17.50 \\
\text{Average} &= \frac{1.611}{3} = .537
\end{align*}

\textbf{Cost of Energy (Ce):}
482.6 BTU / 1,000,000 = 0.000482 x $20.49 = $0.0099 x 365 Days = $3.61 \quad \text{Total cost: } $10.65

531.5 BTU / 1,000,000 = 0.000531 x $20.49 = $0.0108 x 365 Days = $3.94 \quad \text{Average: } $3.55

417.7 BTU / 1,000,000 = 0.000417 x $20.49 = $0.0085 x 365 Days = $3.10

\textbf{Cost of Insulation (Ci):}
Used : .80 cubic feet of 2 cubic feet \quad .40\% \text{ of } $6.98 = $2.79

\textbf{Total Cost:}
Ct = Ce + Ci \quad $3.55 + $2.79 = $6.34
Visual Data:

**Temperature over time:**

\[
\frac{\text{Change in Temperature}}{\text{Change in Time}} = \text{Rate of Heat Loss (Degrees Celsius per Hour)}
\]

This graph represents the rate of heat loss based on the change of temperature and the change of time. The graph shows the heat loss each week for each layer added. Each layer, with the exception of layer five, showed a significant change in the rate of heat loss. Week 5, layer four, is the optimal amount of insulation needed to reduce the rate of heat loss.

**Cost of Energy:**

\[ \text{Ce} = \text{BTU} \times 1,000,000 = N \times 20.49 = Na \times 365 \text{ Days} = \text{COST} \]

This graph represents the cost of energy over the coarse of six (6) weeks starting with zero (0) layers of insulation and ending with five (5) layers of insulation. This graphs shows that cost of energy drops with additional layers of insulation but then increases as you add more layers after layer four.

**Cost of Insulation:**

\[ \text{Ci} = \frac{\text{C} \times \text{ft used/actual amount}}{\text{x(%) x Cost}} \]

This graph represents the total cost of the insulation in which we used per layer. It visually displays that as we add insulations the cost will increase. With this graph and the Cost of energy we can now calculate total cost. See below for total cost \( Tc = Ce + Ci \).
Discussion:

The purpose of the experiment was to find the optimal amount of insulation that can be used on the passive solar powered water heater. During our research we found that there were many different types of insulation that could be used to insulate a water tank, but only one insulation type was optimally efficient for our purpose. We chose styrene foam board most of all because it was safest to use concerning our safety and the safety of those around us. Most insulations are extremely hazardous to the health of an individual. Some of the insulations that we researched (other than polyurethane foam) that were applicable to insulating the water tank were vermiculite and mineral/rock wool insulation. Vermiculite looked as if it may have been feasible at first but the research warned that if it was disturbed there was a danger of asbestos being released into the air. With vermiculite ruled out, I started to look towards rock wool insulation. But there have been extensive tests performed on the factory workers that manufacture the insulation because it has been suspected that it causes breathing problems among other health hazards. If protective breathing masks are not worn or if someone breathes in the particles of rock wool insulation, the long term effects could be emphysema. The styrene foam board had a high r-value; a measure of the resistance of an insulating or building material to heat flow. The higher the number, the greater the resistance to heat flow. The styrene foam board was cheap and very effective with respect to the r-value of the board. The styrene foam board had an r-value of 4 for it’s thickness of ¾ of an inch. It also is extremely effective for use on a water tank because it uses the motion of air through the process of convection to insulate the water tank. Also, if there were to be a leak in our system, it is easily removed so that we would be able to find the source of the leak. The insulation was resistant to the radiation of heat as well as the conduction of heat through the foam board.

Our hypothesis was that three layers of insulation would be the most effective when it came to cost vs. heat loss. The hypothesis was wrong by one layer. The data supported that four layers of insulation was much more effective than three layers of insulation. The data did not support that any more layers of insulation was more effective than four. In fact, we found that five layers of insulation actually increased the heat loss out of the water tank. This was probably a system error because there is no reason why five layers of insulation should be worse than four layers. With three layers of insulation, it cost $6.81 to operate the system and there was heat loss of .676 degrees C per hour. This is compared to a total cost of $5.17 to operate the system with a heat loss of .475 degrees C per hour with four layer
of insulation. It was cheaper to operate the system for the week, and the heat loss was lower by .201 degrees C per hour. The cost to operate the system was cheaper because while the cost of insulation increases slightly with each layer that is added to the water tank, it was about $2 cheaper since we saved more energy through the use of the extra layer of insulation.

Our work advances the state of the art of solar water heating with respect to local water heating because our research shows the most efficient way to save energy through the insulation of the water tank. If more energy is saved with less insulation then the passive solar water heater can be optimized to be more efficient and more cost effective. If a person can spend less money on the materials to operate a passive solar powered hot water heater, then perhaps they will be able to save more money by installing one in their home, while at the same time not sacrificing the luxury of hot water when they need it and when they want to use it. If a the water tank is able to retain its heat longer, then a person should be able to have hot water when they want it, which in return will be a higher quality of life because not many people like cold showers. In addition, if a person can afford a hot water heater such as the one we built, they would be able to consume less fossil fuels, and rely more on renewable energy. The best aspect of the system is that the heat from the sun that powers the water heater is free. With our research and our data, passive solar water heaters may look more promising than they did before because it shows that they are realistic options, consume less energy, and cause less pollution through the use of less fossil fuel than a conventional hot water heater that is most popular in homes at the moment. One interesting aspect of the experiment was that the cost of energy followed a jagged pattern, increasing and decreasing. But overall, the cost of energy gradually followed a decreasing pattern. So the cost of energy would go down with each layer of insulation that is placed on the hot water heater. Even though the cost of insulation rises, the cost of energy offsets that cost and makes the system more efficient to use.

The only problem that we faced while covering the water tank with insulation was that we found that we had to increase the size of each side of the insulation by a total of one and a half inches to completely cover the water tank with another layer of insulation. This was easily remedied after we found out how much more insulation we would need, and it also sped up the construction process each time we had to add a layer. Another problem that we faced was that when we came back to the lab some weeks, our computer had either stopped collecting data, or a power outage had caused us to lose all of our data. My recommendation to this problem for future tests would be to check on the status of the data collection every day or two and save the results in the process. This will maximize data collection. This is important because the more data that there is to back up your findings, the better. We would have had more data, and hence more of a conclusion is we did this. If someone were to continue this experiment I would urge them to only use styrene foam board because it is safe to use in a lab environment, it is cost effective, and it is easy to use.

Some of the consequences that I found through my research of passive hot water heaters is that convection is slow compared to the use of pumps in active hot water heaters. Thus, the heating of the water tank would be slow as well. I will use the example of a hot tub since that was the objective of this experiment. If we were to heat a hot tub using a passive hot water heater, the uses would be a little limited because since someone would be using the sun to power their hot water heater, they would only be able to use it in the daytime. At night the hot tub would get too cold for practical uses. Also, since heat rises, and hot tubs are not enclosed while in use, insulation would be lost primarily through the water’s surface. The idea of using a passive hot water heater for a hot tub is sound, but the water would move a little slowly for most people to want to use it for their hot tubs. If a pump were placed on the system, then I propose that it would work more efficiently. But this would also defeat the purpose of researching a passive solar hot water heater, and the experiment would be completely different.
Conclusions and Recommendations

Our hypothesis states that with each layer of insulation added to the tank we would see a reduction in heat loss. We also recognize that with the addition of insulation there would be added cost. It was the job of our team to optimize the variables of cost and heat conservation. Our insulated tank collected a total of 10354 Btu. That is an average of 1725 Btu per week of our experiment. With each week of our study we ran into issues with our water tank such as differentials in outdoor weather patterns. This affected the overall temperature within the solar water heating system because our solar panel was unable to collect sufficient solar energy. Even with limited solar energy the results of our testing met our expectations of heat conservation.

An example of this information is seen in week 3 layer 2 (Oct 23 to Oct 30 2007). We observed a positive shift (although gradual) in the amount of Btu's collected. Our data informed us that we saw an increase of 540 btu, which tells us that even with deplorable conditions we were able to reduce energy loss and observe a 23% energy increase from the prior week's data. This tells us that we would save a total of $27.66 dollars per 365 days. What this also tells us is that the minimal savings is the reason why there are not large quantities of alternative energy products. Without an increase in fossil fuel energy we will not see an increase in the use of passive solar water heating.

The consensus within the group for recommendations for future work would be to test the solar water heating system and insulation during seasons where solar energy will be optimal. A suggestion would be to experiment with the project during warmer months of the spring and summer. This should reduce the chance of weather related data interference.

Bibliography


This source contained the most helpful of all resources I found while researching. It gave me guidance on the important facts to help support my hypothesis. The website reviewed large amounts of information about insulation, and which variables would be most useful for this project. Since this is a government related website and the organization responsible for the data was support by other scientist I believe this source is reliable.


The state energy conservation office has provided a detail explanation on solar water heating systems on this site. The source not only gave me valuable facts but also provided more links to other resources that elaborated on certain topics. It also provided useful graphs and drawings of each component to making a successful system. The “Solar Water Heaters” document is a very reliable source because the majority of the data was obtained from a government agency.
This source contained helpful information about all types of solar water heating systems and various variables that may apply. The bulk of the data that I obtained from this source explained how solar collectors work, and what components made up the best collector for this project. However the website lacked in information that could help my group understand the process of making a device would work. Overall this source was very useful for explaining the basics.


This book was very useful because it shows different materials that are good at retaining heat throughout the day. It shows actual houses that use passive solar systems and how they use solar power to run every aspect of the home including allowing maximum sunlight in, what materials are best to use, and the systems that heat and cool the house. I found the materials that they used were the most useful piece of information.


This was a very useful resource because it showed me different types of passive solar powered hot water heaters that people are able to use one their homes. It showed how they worked and how they were constructed. The book also told how to heat and cool a house just by using the sun’s energy in connection with the way the house was built.


This book was useful in explaining what the difference was between passive and active solar powered hot water heaters. It was also useful in showing me the different types of ways that energy flows in and out of a system. It told me about convection, conduction, and radiation. It also briefly went over how thermodynamics played into each one.