

Building Heat Loss and Passive Solar Gain

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Abstract:

As energy conservation becomes increasingly important in our society, we explored the relationship between the selection of insulating materials and heat loss through a building. Our research has both environmental and financial ramifications. Taking into consideration the advantages of our available insulation options, we designed a super-insulated home that is both energy efficient and cost effective. Our design uses fiberglass insulation, rigid foam sheathing, plywood, vinyl siding, and gypsum board to insulate our home. Our calculations suggest that this chosen design best balanced the installation costs and the costs saved through energy from insulation. However there are other materials, locations, and systems that we could study in the future to possibly find a better solution.

Introduction:

In the past ten years, the world's fuel consumption has skyrocketed. Higher than ever before, natural gas consumption increased by 2.5% in 2006 and continues to grow. The United States alone accounted for 22% of total natural gas usage in 2006. In the past year, all major forms of energy usage except for nuclear energy rose. [1] In response, the cost of owning a home has risen more than ever, and maintaining heating and cooling has

become increasingly difficult. The average cost per million Btu of natural gas has nearly tripled in ten years. [1] Fuel consumption also increases the pollution in our global community and there is a constant search for clean, renewable fuels. This difficulty has led to a greater need for homeowners to build homes that are more fuel-efficient and encourage conservation.

In attempts to create "greener" homes and to resist rising fuel costs, more and more people are turning to alternative energy source options such as photovoltaics, or solar panels, passive solar water heating, skylights and windows, and sealed ventilation. [2] A key approach is to build homes with increased insulation to prevent heat exchange and unnecessary fuel consumption. Every year, insulation in U.S. buildings saves consumers over 12 quadrillion Btu—42% of the energy that would have been necessary without insulation. [3] By building ceilings, walls, floors, windows, and doors with layers of various insulating materials, heat loss can be prevented in cold climates and cool temperatures can be maintained in hotter environments.

Greater quantities of building materials result in better insulation, and therefore less fuel consumption when maintaining the home. Insulation materials exist in a wide range of varieties and prices, but it is up to the homeowner to decide on the balance between price and quality. In addition, the cost of building

materials and maintenance should not exceed the cost of fuel saved through insulation. Our research focused on this balance, and the qualities and science behind various insulation techniques. As we each hope to become homeowners in the future, this area of study was especially relevant. By going deeper into the subject and gaining more knowledge in reducing fuel consumption, we will be creating a brighter outlook for others, the environment, and ourselves.

Background Information:

Many measures have been taken by the government, research groups, and industries to promote insulation as a way to save energy. The building industry provides many options for home insulation. Insulating materials currently used for walls and ceilings include cellulose, mineral fiber, fiberglass, foam, and various fiber materials. These materials come in the form of pellets, liquid foams, solid sheets, and blankets in varying thicknesses. [4] Heat is also lost through windows, doors, and floors. For windows, glazing and multiple panes with air spaces provide better insulation. Doors can be improved with additional storm doors, greater thickness, or layers of insulating materials such as Styrofoam. Heat loss through floors is dependent on whether the home possesses a slab floor or a basement.

New insulation materials are being developed as need increases and technology progresses. In the past, asbestos was a common insulator, but is not commonly used in new homes due to its health hazards. A popular insulator today is cellulose fiber, derived from recycled materials such as newspapers. Current research shows options for new

materials in mushroom fibers [5] and nanotechnology.

The effectiveness of insulation is measured by its thermal resistance, referred to as its R-value. A greater R-value indicates a greater thermal resistance, and better insulation. R-value varies with thickness and material. In theoretical work, extensive tables may be referenced to obtain R-values of different materials in various thicknesses and situations. For practical uses, R-values are also indicated on the packaging of insulation bought in stores. The performance of insulation is also dependent on the location of the home. This factor is calculated by HDD, or heating degree days, of different locations. HDD values show the relationship between the temperature during each day and the energy required for heating. [6] The National Climatic Data Center, part of the U.S. Department of Commerce, is an archive of weather data, including the heating degree days for each month in different states. [7] With this data, the effect of insulation can be determined.

Another method of checking insulation and sealing in an existing home is the blower door test. A blower door is a powerful fan mounted into an exterior doorway. All exterior doors and windows are closed, and the fan pulls air out of the house. By monitoring the air pressure inside and outside of the house, the air tightness of the sealing can be confirmed and air leaks can be detected. [8]

Studies continue to be conducted in order to more fully understand effectiveness of different energy saving techniques. For example, in a 1998 report by Baruch Givoni of the Department of Architecture at UCLA, "Effectiveness of mass and night ventilation in lowering the

indoor daytime temperatures,” buildings of different masses in South California were observed for effectiveness of different ventilation and shading conditions. It was concluded that buildings of low-mass levels in South California were not greatly affected by nighttime ventilation. High-mass buildings were, however, greatly affected by daytime ventilation and were effectively cooled during high outside temperatures. [9] With a knowledge of practical heat loss calculations combined with current research, we were able to successfully design an efficient, cost-effective home.

Design Constraints:

Our goal was to design a cost efficient home; in other words, to balance the cost of insulating materials with the cost for heating. To find the minimum cost for building and heating the home, we calculated the cost using many different materials and fuels. The combination that yielded the lowest annual cost for heating and installation would be the best design for this home in terms of heating.

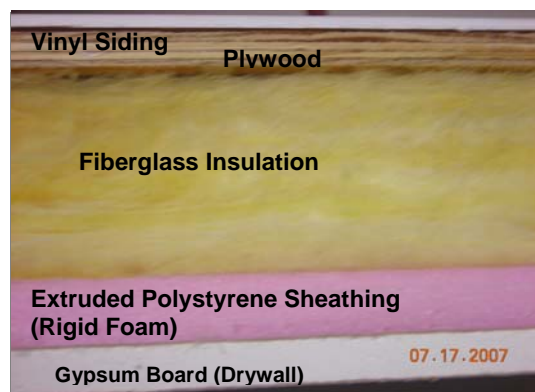
Fig. 1 Single-story home design



We were asked to design a single-story house on an unheated concrete slab, located in Trenton, NJ, with a perimeter of 190 ft and floor area of 1900 ft². The slab floor was edged with 2 ft of rigid foam insulation. The walls were a standard 8 ft high and contained a 5/8” gypsum board over a 4-mil polyethylene sheet as a vapor

barrier. The ceiling was composed of 24” loose fill mineral fiber insulation, 5/8” gypsum board sheathing, and a vapor barrier similar to the one used in the walls. We were required to have 255 ft² of triple-glazed windows with 1/4” air spaces and wood frames. There were two 2” foam-filled steel doors that were each 3’x6’8”. The infiltration rate was minimized by caulking and sealing and was estimated to be 1/4 air change per hour after a blower door test. Additional air exchange for freshness was 1/4 air change per hour through an air-to-air heat exchanger that promised to recover 70% of the exhausted heat. These conditions factor into how much heat the house would lose in an average year, but could not be tweaked by us to lower the cost.

Fig. 2 Sample insulated wall



The following are variables that were considered in calculating the optimal design: siding, sheathing, and insulation materials for the wall. For siding, our major choices were vinyl, stucco, and 5/8” lapped plywood. For sheathing, we tried plywood, oriented strand board, blackboard, and expanded, extruded polystyrene. We considered, for insulation, sprayed foam, blown in cellulose; loose fill mineral fiber, and fiberglass batts. Often, the price of insulation rises with the thermal resistance, or R-value, so to determine which materials were the most cost efficient, we divided the cost by the R-value and area. The material with the

lowest cost per R-value per unit area was theoretically the optimal material for building. However, there were other considerations. For example, certain locations require a certain R-value based on their climate. There is no purpose on spending money on insulation with a high R-value if most of the year is spent in hot weather. Conversely, in cold climates, higher R-values are necessary to keep the house warm. Furthermore, some materials are more environmentally friendly or require less hassle and money to maintain.

Initial Calculations:

To determine the total cost for heating the home, we began by calculating the R-value of the walls, ceiling, windows, and doors. The R-value is a measure of a material's resistance to heat flow and is the inverse of the thermal conductance, or U-value. The total R-value for each part of the building is a sum of its components, including the inside and outside surfaces. The R-values of the walls in many homes must account for the presence of wood framing. Heat is lost more easily through wood than through insulation, so the R-value must be calculated separately for the wall over insulation and over framing. A weighted average was then taken at a ratio of 85 to 15, insulation to framing. However, in the case of this house, the effect of framing was ignored in both the ceiling and walls because there was no continuous line of wood through the insulation due to the way the walls were constructed. The R-values for the walls, ceiling, windows, and doors could be used for future calculations.

Next, the heat loss factor, or HLF, of the house was determined. The total HLF for the house is the sum of the HLFs for each individual component: ceiling,

walls, windows, doors, slab floor, and air exchange. The HLF for the ceiling, walls, windows and door was calculated by

$$HLF_i = A/R$$

where A is the area of the component and the R is the sum of the R values of the component materials that we just calculated. For the windows, the R value was calculated by finding the inverse of the thermal conductance, U. The HLF for the slab is

$$HLF = F * P$$

where F is the conductance and P is the perimeter. The HLF for air exchange, uncontrolled infiltration or ventilation, is given by

$$HLF = 0.018 * V * (\text{air changes/hour}) * (1 - \epsilon)$$

where V is the volume of the house and ϵ is the heat recovery efficiency. The HLF for the entire house, HLF_{total} is then

$$\sum HLF_{\text{component}} + HLF_{\text{slab}} + \sum HLF_{\text{air change}}$$

This heat loss factor is needed to calculate the heat loss for the entire house in an average year.

We then calculated the average amount of heat lost by the home in a year. To do this we need to know the number of heating degree days per year for this location, Trenton, NJ. The heating degree days, or HDD, are the number of degrees per day that the mean of the maximum and minimum recorded temperatures is below a certain base temperature. The HDD for each month at base 65 was initially referenced. However, for this problem, we wished to calculate the HDD for if we wished to operate the house at an average

indoor air temperature of 65°F and for 75 °F. For a normal house, the base temperatures we would use to calculate the HDD would then be 55 and 65, respectively. However, this home was considered to be super-insulated, so the base values we needed were actually 40 and 50, because less heat was needed to maintain the desired temperature of the home. Then, the HDD for the proper bases were calculated using the formula:

$$HDD = HDD_{65} - 30 * (65 - base) * (1 - factor)$$

$$factor = (1.05 - 0.01 * (65 - base) - \frac{HDD_{65}}{60 * (65 - base)})^{1.9}$$

if HDD_{65} was less than $50 * (65 - base)$, otherwise:

$$HDD = HDD_{65} - 30 * (65 - base)$$

The total HDD for the entire house is the sum of the HDD for individual months. The heat loss for the house is finally calculated as

$$\text{Heat Loss} = 24 * HLF * HDD$$

in Btu. This value is easily converted to MBtu by dividing by 1,000,000. Now that the total amount of heat needed was found, the cost to purchase that much heat per year was determined.

By multiplying the cost per MBtu by the total MBtu needed to heat the home, the total cost for heating the home can be calculated for each type of fuel. The choice that yields the lowest yearly cost is the most economic. However, when determining what type of fuel to use, it is also important to consider environmental and safety concerns. Nonetheless, in our quest to determine the most cost efficient

home, we simply chose the one with the lowest price.

Finally, the cost for heating is dependent on the type of fuel chosen to heat the home. The choices are natural gas, heating oil, LP gas, coal, electricity, and wood. Each of these fuels has its advantages and disadvantages. The cost per unit of fuel is calculated by

$$\$ / MBtu = \frac{10^6 (\$/unit)}{(unit\ heat\ value)(efficiency\ of\ conversion)}$$

We calculated the total yearly cost for heating our home by following these steps for various combinations of materials. By choosing a different type of insulation, siding, and sheathing each time, we were able to find the combination that would yield the lowest cost of heating per year.

Detailed Design:

After experimenting with different materials for insulation, interior and exterior sheathing, and siding, we successfully selected the combination that would yield the optimum value. We also needed to determine the final cost for the materials comprising the house. For the ceilings of our house we used mineral fiber insulation with a thickness of 24". The heat loss factor for our ceiling including all other components of the ceiling was 12.08 Btu-ft/F°. For the walls of our house we used fiberglass insulation with a thickness of 11.25". Other components of the wall included 5/8" gypsum board, 1/4" vinyl siding, 15/32" plywood siding, and 1.5" extruded polystyrene sheathing. The following

information in Fig. 3 shows the R-values for each of the materials of our wall:

Fig. 3 R-Values of Wall Materials

Material	Thickness	R-Value
Fiberglass Insulation	24"	41.79
Extruded Polystyrene (rigid foam) sheathing	1.5"	4
Vinyl siding	1/4"	1
Plywood (underneath siding)	15/32"	0.59
Gypsum Board	5/8"	0.56

The heat loss factor for our wall was 25.11 Btu-ft/F°. In order to find the total Heat Loss Factor for the house we found the Heat Loss Factor of the parts of the house as follows: ceiling, walls, windows, doors, floors, and heat lost through air changes of the house. We then added them to obtain the total Heat Loss Factor of the house. The total Heat Loss Factor of the house was found to be 306.17 Btu-ft/F°.

However this number did not tell us the house's heat loss in useful units of Btu. In order to determine the heat loss of the house, we had to first determine the Heating Degree-Days of the location of the house. The heating degree-days are the number of degrees per day that the daily average temperature, the mean of the maximum and minimum recorded temperatures, is below a base temperature, usually 65°F. Using a base temperature of 65° for a location near Trenton, New Jersey we found in a table, we were able to determine the heat loss of the house. Fig. 4 shows the Heating Degree Days for a location near Trenton, New Jersey translated to different base temperatures:

Fig. 4 Heating Degree Days for Trenton, NJ

	HDD 65	HDD 40	HDD 50
January	989	257.06	539
February	885	173.66	435
March	753	78.17	303
April	309	0	6.86
May	121	0	0
June	12	0	0
July	0	0	0
August	0	0	0
September	57	0	0
October	264	0	0
November	576	0	160.81
December	924	204.08	474
	4890	712.97	1918.66

Using the following formula we determined our total heat loss for our designed house in Btu:

$$\text{Total Heat Loss} = 24 \cdot \text{HLF} \cdot \text{HDD}$$

Using a base temperature of 40°F the heat loss for our house was determined to be 5.24 MBtu/ year. We now had to determine which fuel source would be the best to use for our design. Our choices of fuel sources were natural gas, heating oil, LP gas, coal, electricity, and wood. Given the heat value, efficiency and unit cost of each fuel, wood was determined to be the optimum fuel source for our design as Fig. 5 describes:

Fig. 5 Fuel Information

Fuel	Heat Value	Efficiency	Unit Cost	Cost per Mbtu	Total Yearly Cost
Natural Gas (per therm)	1.00E+05	0.9	\$1.65	\$18.33	\$96.05
Heating Oil (per gallon)	1.38E+05	0.75	\$2.25	\$21.74	\$113.89
LP Gas (per gallon)	9.20E+04	0.88	\$2.35	\$29.03	\$152.07
Coal (per ton)	2.50E+07	0.68	\$220.00	\$12.94	\$67.80
Electricity (per kWh)	3.41E+03	1	\$0.16	\$46.89	\$245.67
Wood (per cord)	2.20E+07	0.65	\$175.00	\$12.24	\$64.11

We then calculated how much our house would cost annually as well as the installation cost of our materials. Our materials' costs can be found on Fig. 6:

Fig. 6 Cost of Materials

Material	Cost of material	Area being covered	Total cost of material
Fiberglass	\$1.65 per square foot	1225	\$2,021.25
Extruded Polystyrene	\$1.40 per square foot	1225	\$1,715
Plywood	\$1.30	1225	\$1,592.50
Vinyl	\$2.75 per square foot	1225	\$3,368.75
TOTAL COST			\$8,697.50

We then added the annual cost of heating and the cost of our materials and calculated that the annual heating and the cost of walls was \$ 8,761.61.

Future Work:

Heat loss in buildings is a major concern for all homeowners and prospective homeowners. There are many possible building materials, all with different thermal resistances and costs, and exponentially more possible combinations. Advances in technology have yielded yet more materials with higher resistances. Furthermore, thermal resistance and cost are both directly proportional to the thickness of the material, opening up a whole new dimension of possibilities. There are many more possible combinations of building and insulation materials at different thicknesses that could be analyzed to determine which yields that highest insulation at the lowest price. In our study, we only changed the materials used for siding, sheathing, and insulation in the walls. Theoretically we could explore the all the possible materials that can be used. In practice, we must also

consider availability of materials. We could also explore the use of these countless materials in the ceiling and floor as well.

Additionally, there are more conditions to choosing building materials than just their cost and thermal resistance. First of all, how the house looks often sways the decision of what type of siding to use more than its thermal resistance. A homeowner may choose to use stucco because it looks prettier than plain vinyl siding, even if it does cost more. Moreover, certain materials are more environmentally friendly than others. For example, cellulose is usually made of shredded, recycled newspaper, but is just as good, if not better, than traditional insulating materials [10]. Another concern when choosing building and insulating materials is how much it costs to maintain them. Some materials are more prone to mold or fissures than others and will cost more to repair or replace. In these cases it may make more economic sense to buy a material that costs more to install, but is cheaper in the long run. Finally, there are health and safety issues associated with some of these materials. A famous historical example is that of asbestos.

Fig. 7 Asbestos [11]



Asbestos was a fairly common insulating material found in buildings until it shown that exposure causes asbestosis and/or lung cancer. [11] However, many of the insulating materials that are still popular

today may pose health risks. Fiberglass, which we used to build our models, is a skin irritant, may cause lung disease if inhaled, and possibly even cancer. [12] Although in normal circumstances, the insulating material will not be exposed to those living in the home, safety and health concerns should still be considered when choosing which building and insulating materials to use. We studied which materials would be the best economically, but there are other considerations that should be included in future studies.

Finally, it would be rewarding to study heat loss in homes in a more realistic situation. Various conditions such as compression of insulation will lower the R-value and thus lower its usefulness. Calculations done to simulate common problems found when installing these materials and that occur as the house settles over time should yield interesting results as to how heat loss in a home changes over time. Furthermore, the R-values labeled on the building and insulation materials are measured in a laboratory. In real practice, these values are not always accurate. [14] It would be beneficial to measure the R-values of real homes rather than simply calculate theoretical values. In addition, while the effect of the roof is not accounted for in calculations because attics are usually well ventilated, in real situations, this may not always be the case. By supplementing the study with experimental data, future work will be able to provide a more realistic view of homes and heat loss.

The goal of future work in this area would be to provide both more generalized and more specific information concerning heat loss in homes and optimal building materials. Our study could be expanded in a number of ways. First, more materials, in

different combinations, can be tried in the walls, ceilings, and floors. Furthermore, other considerations, such as aesthetics, maintenance, environmental concerns, and health could be factored into the decisions as to which materials are the best. Additionally, different locations should be analyzed because the results of this study are very specific to the Trenton area. More types of homes with different structures can be used to gain a more comprehensive view of heat loss in different buildings. Lastly, real measurements could be made to supplement our theoretical results. The possibilities for further work in this area are boundless, and the results are sure to be rewarding to all who own homes.

Challenges in Generalizing Our Model:

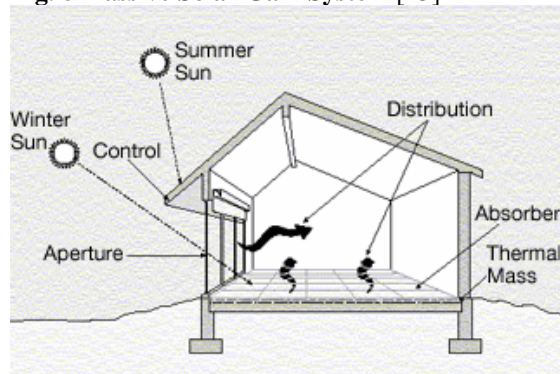
This study could also be expanded by calculating the values for the home in different locations. Naturally, homes in different climates will lose heat in different ways and therefore could potentially have different optimum materials.

While Trenton, the location of our home, annually has 4980 HDD at a base temperature of 65°F, Detroit, Michigan has 6232 HDD and Miami, Florida has 214 HDD. Clearly, these varied heating requirements mean that the optimal homes for these locations will likely be different. There is no need to spend a fortune on a super-insulated home in Miami where the average winter temperature is 71.1. In conducting a further study encompassing other climates and suitable building materials, valuable information can be obtained for future homeowners.

Furthermore, any change in structure would likely change our results.

The amount of heat lost through an object is directly proportional to its area, and therefore changing the dimensions of the home, adding floors, or even adding or subtracting windows and doors will affect the heat lost per year and potentially necessitate different building and insulation materials. To some degree, even changing the types of windows and doors, or perhaps adding storm windows and doors, will change how much heat is lost. A basement, rather than the slab floor we calculated with, will also complicate calculations because heat is lost differently for each foot deeper underground. More dramatically, the effect of frames in most homes is about 15%, but in the case of our Trenton house, the wood did not pass all the way through and therefore did not need to be accounted for. Since much of the heat lost through walls is lost through the framing, the effect of framing on finding the most economic material should be investigated.

Fig. 8 Passive Solar Gain System [13]



Additionally, the use of various passive solar systems such as the one in Fig. 8 will alter the calculations and therefore also which materials would be the best to use. These systems, including direct gain, solar greenhouses, water heating, Trombe walls, roof ponds, and overhangs, would, hopefully, allow the sun to freely heat the home without too much extra cost for installing the system. Expanding our study to include many

other house dimensions, layouts, and heating systems would make this foray into the realm of very specific to that one story home with a set perimeter and area. Any change in dimension or the addition of various building materials and heat loss far more complete.

Conclusion:

Utilizing the background knowledge of heat loss in buildings, we were able to minimize the cost of heating while choosing insulating materials with a high R-value. Our results were specific to a single location, in Trenton, NJ, and a specific floor area and so should not be generalized for all homes. However results for any alternate house can be obtained using the same methods used in this study. Our design for the wall for Trenton was limited by our choices for materials, however more cost and energy efficient materials may be found. This may be applied to different areas in the future to design the most cost and energy efficient buildings possible.

Through our prior research we learned the percentages of the total heat loss that each component of a house contributes. With this it can be determined which component of a house needs to be insulated better, resulting in less heat loss. Both structural and material engineering play a large role in designing such a cost efficient home. Material engineers can recommend materials that will allow a structural engineer to construct and heat efficient and structurally sound house.

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Citations:

[1] *BP Statistical Review of World Energy June 2007.*

<http://www.bp.com/statisticalreview>.

[2] US Department of Energy. A Consumer's Guide to Energy Efficiency and Renewable Energy.

<http://www.eere.energy.gov/consumer/>

[3] "*Green and Competitive: The Energy, Environmental, and Economic Benefits of Fiber Glass and Mineral Wool Insulation Products*". Energy Conservation Management, Inc., et al. June 1996.

[4] Types of Insulation. EERE Consumer's Guide, September 2005. http://www.eere.energy.gov/consumer/your_home/insulation_airsealing/index.cfm/mytopic=11510

[5] Young inventors insulate with mushrooms. CBC News, June 2007. <http://www.cbc.ca/technology/story/2007/06/25/tech-mushrooms.html>

[6] Williams, Jack. Heating and cooling degree days. USA Today Weather, July 2007.

<http://www.usatoday.com/weather/resources/askjack/waskdays.htm>

[7] U.S. Climate Normals. National Climatic Data Center, June 2005. http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&prodtype=HCS5&subnum=

[8] Blower Door Tests. EERE Consumer's Guide, September 2005. http://www.eere.energy.gov/consumer/your_home/energy_audits/index.cfm/mytopic=11190

[9] Givoni, Baruch. Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Department of Architecture, School of Arts and Architecture, UCLA, Los Angeles, CA, USA. 1998.

[10] "The Colorado Study." Cellulose Insulation Manufacturer's Assn.

http://www.cellulose.org/pdf/cellulose_benefits/colorado-study.pdf

[11] "Asbestos." Canada Mortgaging and House Corporation. http://www.cmhc-schl.gc.ca/en/co/maho/yohoyohe/inaiqu/inaiqu_001.cfm

[12] Kilcoyne, Scott. "Our Work Environment, 'Is it Really SAFE?'" <http://www.pct.edu/wtc/pdf/WT C%20Tech%20Update%20work%20environment.pdf>

[13] Fig. 8. Passive Solar Gain system. www.eere.energy.gov/de/passive_solar_design.html

[14] Cellulose Insulation Manufacturer's Association. "Beyond R-Value" http://www.cellulose.org/pdf/cellulose_benefits/cons-report-1.pdf