REFLECTIONS ON THE INSULATED HOME: THE R-VALUE MYTH

Dan H. Donnellon[1]

INTRODUCTION

The R-value is defined as, "a measure of the resistance of an insulating or building material to heat flow, expressed as R-11, R-20, and so on; the higher the number, the greater the resistance to heat flow (Random House, 2016)." The first thermodynamic principle violated by the R-value is the singular use of the word heat flow. Heat flow, or transfer, occurs in three distinct ways; conduction, convection, and radiation. The R-value test will only measure a bulk insulations resistance to conductive heat transfer. This type of heat flow is almost undetectable in the built environment, regardless of climate or season - resulting in the R-value myth. In winter, the stack effect will cause convective flows through the home as warm air under pressure rises and escapes through the top, requiring an equal amount of cold replacement air to infiltrate at the bottom. On hot sunny days, the exterior of the home absorbs long wave ultra violet (UV) rays from the sun and reemits this radiant heat energy into the residence. The thermodynamics of an occupied structure under varying atmospheric conditions is not well understood, leading to major inefficiencies. The goal of this conceptual study is to reveal the shortcomings of current insulation practices at the residential level, conceptualize a series of related issues for future study and develop a preliminary methodological concept for resolutions to the problems identified. Conclusions indicate that further research needs to be dedicated to replacing the R-value rule with a realistic metric that considers the efficiency, health, and safety of the entire building.

KEYWORDS

R-value, heat flow, insulation, residential insulation practices, ventilation, stack effect, radiant heat transfer

1. A BRIEF HISTORY

The practice of blanketing the roofs and walls of a structure with some type of bulk material (IE straw, cotton, mud, saw dust, etc.) to retain warm or cool interior air goes back many years. In 1938 the Owens-Corning Fiberglas Corporation turned these primitive concepts

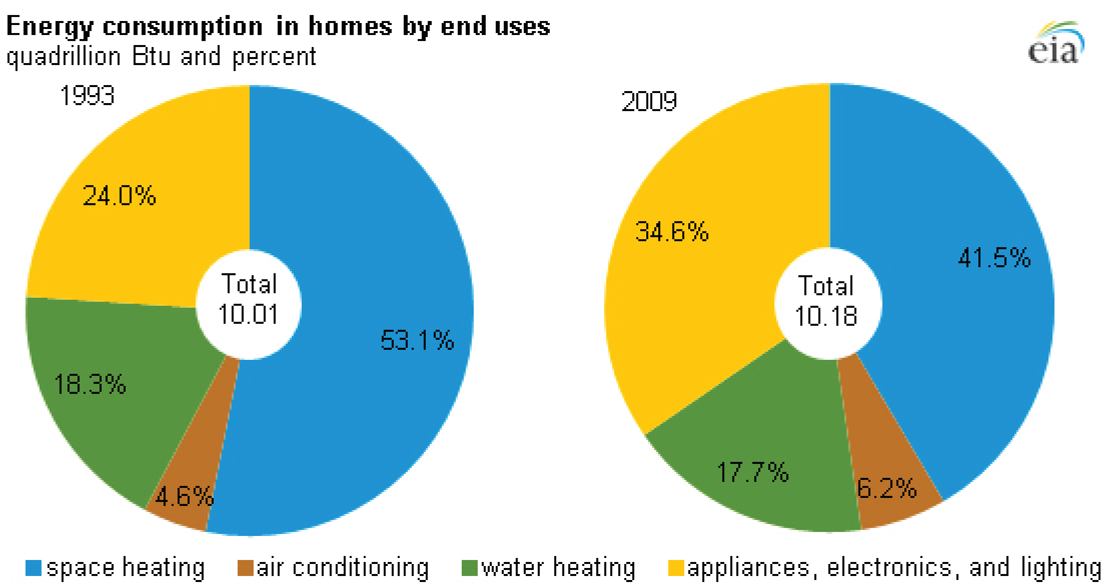
1. Owner Donnellon and Associates Inc., 3902 Custer Ave., Royal Oak, MI 48073, donnellon@aol.com.

into a product with the introduction of fiberglass insulation (Owens-Corning, 2016). Shredded newspaper or cellulose insulation followed in the early 1950's, but both products mostly sat on store shelves for the next two decades - until the fall of 1973. The beginning of the oil or energy crisis sparked a major consumer movement to improve residential energy efficiency. The cost to heat, cool, and electrify structures increased at unprecedented rates. The majority of homeowners responded by monitoring thermostats, turning off lights, and purchasing cellulose or fiberglass insulation for the first time. By 1979, after six years of energy crisis, the insulation market was large and unregulated. In an effort to protect consumers, the Federal Trade Commission (FTC) passed the R-value rule. A guideline written around many of the practices widely adopted by consumers during the previous six years, but never tested or understood. The R-value test strictly measures resistance to conductive heat flow, which is more of a benefit to cellulose and fiberglass manufacturers than it is to consumers. Although conductive heat flow has no effect on the energy efficiency of a structure, bulk insulation has been able to reduce residential energy use.

1.1 Residential Energy Use

In the United States, heating has always accounted for the majority of energy consumed by one and two family homes. In 2009, when looking at the entire residential sector, heating accounted for 42% of the total energy used by the average home (EIA, 2016).

FIGURE 1: Average U.S. residential energy consumption by end use. Reprinted from the EIA website.

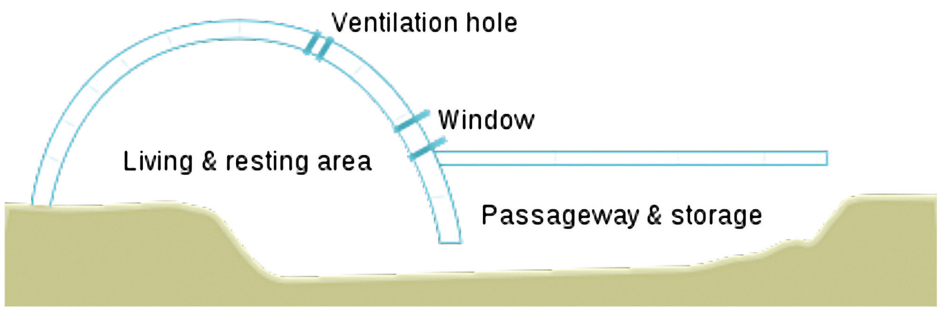


The main cause of excessive heating use is the uncontrolled ventilation of the building envelope due to the stack effect. If a residence lacks resistance to this natural, air pressure driven phenomenon, it will lose warm air at a constant rate on cold days. Prior to the energy crisis the typical home experienced high levels of uncontrolled ventilation. Although this resulted in dry and drafty conditions during the winter, there was no financial incentive to add insulation. The heating bills produced in the winter of 1973 quickly changed the typical U.S. homeowner's attitude towards insulation use. While adding cellulose and fiberglass has provided some monetary relief over the years, it is still not well known how insulation actually lowers heating use. In order to correctly identify the type of heat transfer mechanisms effecting the energy efficiency of an enclosed structure maintaining heat in the winter, we reference the igloo.

2. THE IGLOO

There are very few habitable structures that will conserve heat more efficiently than an igloo. When first occupied, body heat alone increases the air temperature through convection, melting the inner layer of snow to form a thin coating of ice. The ice is an air barrier, trapping warm buoyant air at the top of the igloo, resulting in a slightly positive interior air pressure. This gives the igloo maximum resistance from the stack effect pressure being applied by the cold, heavy arctic air. While stack effect resistance is critical to the energy efficiency of an igloo, it is also utilized to passively maintain optimal interior air quality. Small weep holes, strategically placed at the top, insure healthy and controlled ventilation. Although there is a large open entrance at the bottom of the structure, the only cold air allowed to enter is to replace the small amount of warm air seeping out of the weep holes (Figure 2):

FIGURE 2: Schematic of an igloo. Reprinted from "Igloo See Through Side View," Wikipedia, Wikipedia Foundation Inc.



The natural mechanisms at work inside of these ultra-efficient shelters are easy to understand, proven, and impossible to measure or explain with an R-value. An igloo is proof that conductive heat transfer does not occur through the air, ceiling, or walls of heated and occupied structures built in nature.

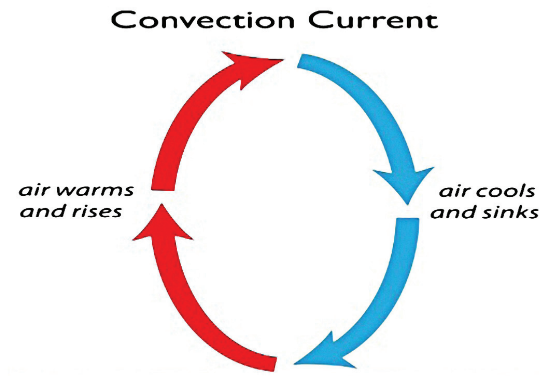
2.2 Thermodynamics of the Igloo

The igloo is the model of energy efficiency in the winter due to its ability to resist the convective force of the stack effect, while conserving the heat produced inside of the structure through convection and radiation:

Convection – Body heat, a candle, or some other small heat source will quickly warm the air inside of the igloo through convection. This warm air rises, but is then trapped by the air barrier of ice, causing it to cool, descend, and then repeat in a continuous convective cycle (Figure 3):

Resistance to the stack effect permits these natural and efficient convective flows within the igloo. Only the small amount of passive ventilation provided by the weep holes offers any interference. The ability to retain heat produced from convection, while resisting the convective force of the stack effect, allows human beings to survive in extreme cold.

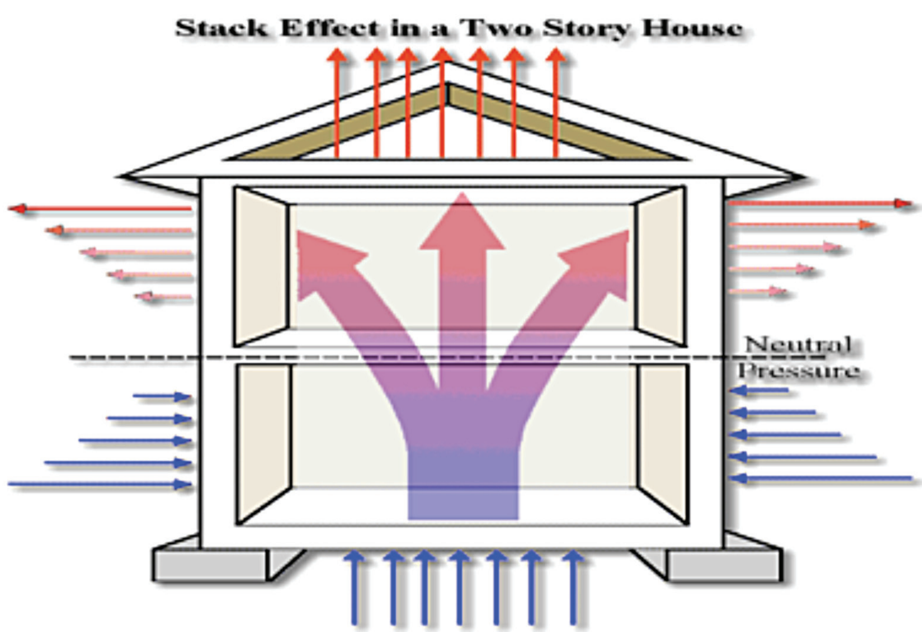
FIGURE 3: Natural convection, uninterrupted by the stack effect. Reprinted from "Convection Currents in the Earth's Mantle," CK 12 Foundation.



Radiation – The sun emits short wave ultra violet (UV) energy that is absorbed by dark surfaces and then reemitted in the form of long wave UV energy. Igloos are white, they do not absorb UV energy, they reflect most of it away. Radiant heat emitted by occupants or any other heat source inside of the igloo is also reflected back towards the original signal, adding to the efficiency of the structure.

Cellulose and fiberglass insulation are not designed to provide resistance to convective air loss or radiant heat gain. The level of resistance to conductive heat flow, or R-value of the insulation medium itself is the only metric provided. Resistance to air loss through convection or the effects of radiant heat transfer is barely considered.

FIGURE 4: The stack effect at work inside the residential building envelope. Stack Effect in a Two Story House is reprinted from Kinetic Energy Solutions, 2010



Air temperature differences between the building envelope and the exterior environment, combined with the height of the structure, determines the level of stack effect. The inability to stop air loss at the top of the typical home requires heating systems to continuously cycle throughout the winter months. Homeowners endure high utility bills, plus dry and drafty interior conditions. The typical home prior to 1973 had no resistance to the uncontrolled ventilation of the building envelope that results from the stack effect. Cellulose and fiberglass insulation have reduced residential energy use by inhibiting the stack effect, to varying degrees of success - allowing the typical home to retain more heated air. The problem is that these reductions have been far too limited and residential energy consumption remains high, particularly during the winter. As demonstrated by the igloo, a structure with high stack effect resistance provides maximum thermal efficiency and comfort. If a residential structure could duplicate the same level of stack effect resistance as an igloo throughout the winter months, natural and efficient convective heat flow inside of the home would look like figure 5.

FIGURE 5: Efficient convective heat flow Reprinted from "Technically Speaking: Principles of Heat Transfer," BPI Inc.

The other benefit of controlling the stack effect is the ability to reduce thermal transfer to the roof throughout winter, resulting in a cold roof.

3.1 Cold Roofs

An indicator of poor thermal resistance at the top of the building envelope in colder climates is snow melt. It is rare to see an occupied, peaked roof residential structure not produce icicles in the winter. A cold roof is nearly impossible to achieve with cellulose or fiberglass insulation; constant convective and radiant heat loss prevents it. The amount of snow melt on a roof accurately displays the homes level of energy efficiency and the type of heat being transmitted to the roof.

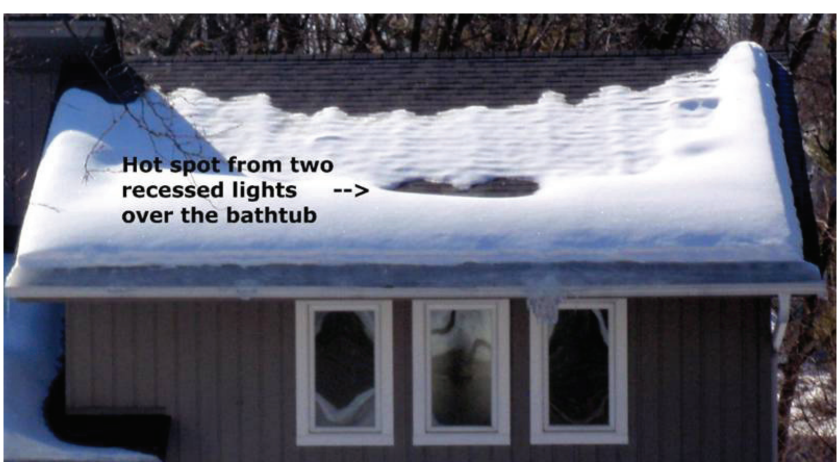


FIGURE 6: Convective and radiant heat loss. Reprinted from (C) HankeyandBrown.com.

The home in figure 6 demonstrates the loss of heated air through the roof deck, but mainly at the peak vents running along the ridge. Radiant heat transfer is also evident, particularly over the recessed bathroom lights. The snow melt draining off the roof refreezes at the eaves, causing ice dams, leading to other potential issues.

The apartment complex in figure 7 contrasts the effects of convective and radiant heat transfer in four separate units within the same building.

FIGURE 7: Townhouse roof snow melt patterns reveal heat loss. Reprinted from (C) HankeyandBrown.com.

Based on the snow melt, both 17 and 23 appear to be vacant. The other two units are occupied, but 19 either keeps the thermostat higher, has more occupants, more activity, or a combination of all the above. Heat transfer to the roof is frequently misinterpreted as being conductive in nature. This is impossible, no credible conductive heat source originates from inside of the home during the winter.

4. Radiant Heat Transfer

During the summer or in warm climates, radiant heat transfer is the primary reason for residential inefficiency and discomfort (figure 8). In addition to radiant heat transfer, the loss of cool interior air due to the stack effect in reverse also contributes to excess energy use. This occurs when either naturally cool or mechanically conditioned air settles at lower levels, escaping through open doors, windows, or any other gaps in the building envelope.

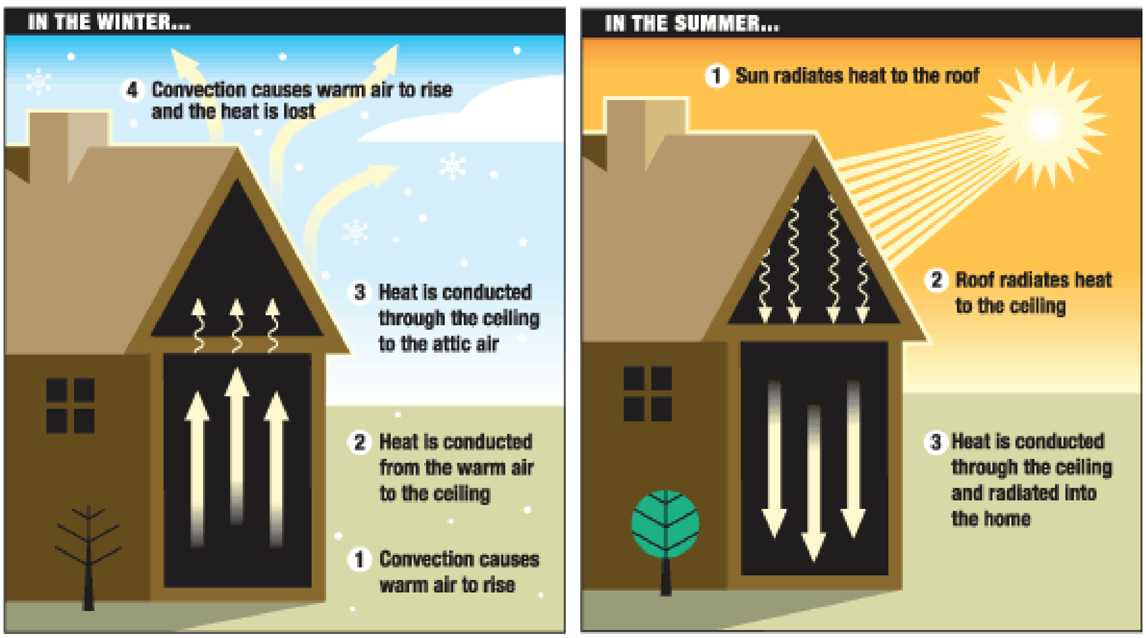
FIGURE 8: Radiant heat transfer in the home Reprinted from "Technically Speaking: Principles of Heat Transfer," BPI Inc.

Cellulose and fiberglass insulation provide no resistance to radiant heat transfer into the building envelope. In fact, while the R-based insulation practices in the winter can provide some value, bulk insulation in the summer can possibly increase energy use and discomfort. Radiant heat transfer is unobstructed and constant in an insulated home during the summer.

5. CONDUCTION MYTH

The R-value relies on; "faulty scientific information or research, especially when used to advance special interests (R.H., 2016)," also known as junk science, to promote the benefits of insulation. The R-value myth requires a false interpretation of conductive heat transfer in order to exist. Energy loss due to convection or radiation are incorrectly portrayed as being conductive in nature during the winter and summer months (figure 9):

FIGURE 9: Illustrating the conduction myth by season. Reprinted from "The Truth About R-value's," AI, INC.



An online image search titled, "conductive heat transfer in the home," provides many illustrations similar to figure 9 that demonstrate the level of misunderstanding. When looking at the winter home, air molecules are not capable of conducting heat from floor to ceiling, and then from ceiling to attic. When it comes to heat transfer in the summer home, there is also a bending of the rules. Part one and two are correct representations of radiant heat transfer into the structure. Part three should illustrate the flow of radiant energy from the roof being absorbed by the ceiling and reemitted into the home, not conducted. The R-value has created thermodynamic confusion in the home. Consumers have been falsely led to believe that a high resistance to conductive heat transfer, provided by a thick layer of bulk insulation, will provide comfort and efficiency – regardless of the weather.

The R-value based confusion regarding the thermodynamics of a structure also extends to the walls (figure 10).

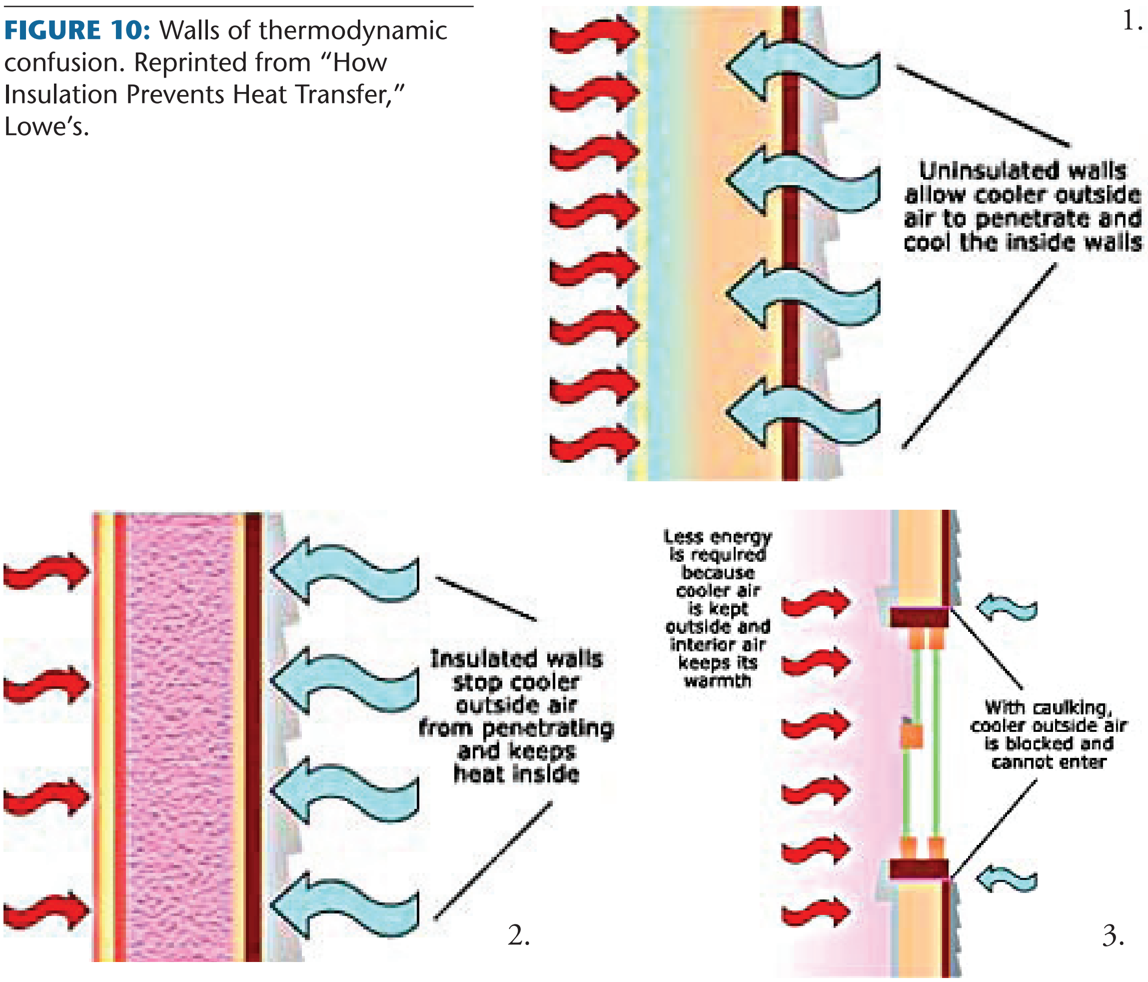


FIGURE 10: Walls of thermodynamic confusion. Reprinted from "How Insulation Prevents Heat Transfer," Lowe's.

1. Correct, but irrelevant. Cold does not radiate like heat. A cold wall by itself does not reduce interior air temperature, the icy walls of an igloo prove this fact.
2. Incorrect. Bulk insulation is not an air barrier, it will resist air infiltration, but never stop it. This type of insulated wall does little to improve the efficiency of the home. Air, under pressure, can always find a way inside.
3. Mostly correct. The main issue is cold air leaking in from the outside, but this is mainly caused by the air loss at the top of the structure. Air sealing will help, but the effect of this tactic is also limited. No home is hermetically sealed; it is impossible seal every gap in the building envelope.

These types of images are misleading to the general public and support the common misconception that a high R-value equates to energy efficiency. The Department of Energy actively promotes the R-value myth to U.S. consumers, as noted on their website:

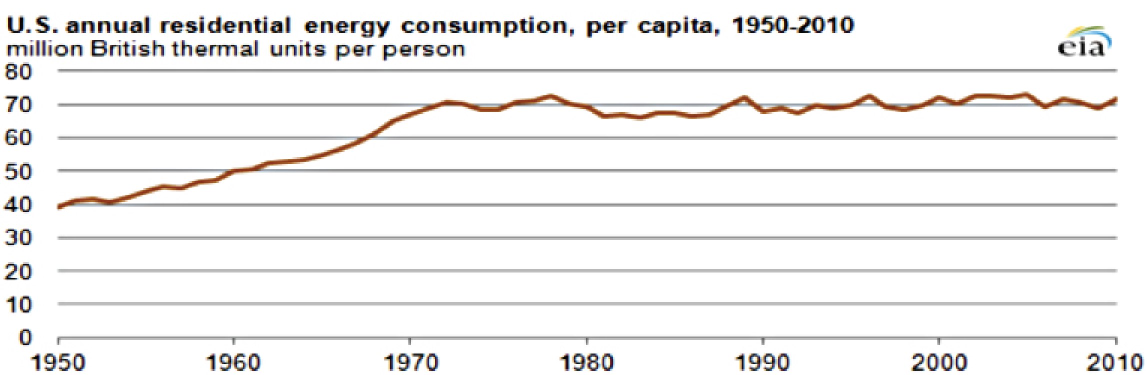
"*Conduction* is heat traveling through a solid material. On hot days, heat is conducted into your home through the roof, walls, and windows. Heat-reflecting roofs, insulation, and energy efficient windows will help to reduce that heat conduction (DOE, 2016)."

The first sentence is correct, the second is junk science, and the third is ineffective. Conductive transfer is heat traveling through a solid material, which air is not, the molecules are too far apart. Radiant energy from the sun is *absorbed* through the exterior of the home – conductive heat transfer is not present on any level. The radiant energy absorbed by roofs and walls is then retransmitted to the interior of the home throughout the day and well into the night. Bulk insulation alone provides no resistance from radiant heat transfer, if anything, it contributes to it. Heat-reflecting roofs is another ineffective recommendation to homeowners, but not because it will not work. A bright white roof will reflect a large portion of radiant energy away from the structure, like an igloo. The problem is aesthetics; homeowners do not want white roofs. UV resistant windows are also unnecessary to the efficiency of the home; a shade will work fine. Sun light is not the problem, a poor understanding of the thermodynamics of the home is the main obstacle to overcome.

6. THE INSULATED HOME

The natural phenomenon most responsible for excessive energy use at the residential level is clearly the stack effect. Prior to the energy crisis homes were hyperventilating, especially in the winter. The stack effect controlled the building envelope, constantly robbing the home of heat. This amount of energy consumption was no longer acceptable to homeowners after the oil crisis. The insulation market was born in the fall of 1973, and it quickly became a giant. A large portion of U.S. homeowners added insulation, slowing down the stack effect and conserving heat. This is reflected in residential energy use data collected by the U.S. Energy Information Administration (figure 11), which also notes on their website; "Per capita residential energy consumption in the United States remained generally flat since 1973 (EIA, 2016)."

FIGURE 11: Residential energy use since the wide spread adoption of insulation Reprinted from the U.S. Energy Information Administration.



In the span of a few years, a large percentage of homeowners in the United States added bulk insulation for the very first time. This directly led to the flattening of residential energy consumption for the first time in U.S. history. The reason residential energy use is not in decline is simply due to the fact that bulk insulation does not do enough to control the stack effect in the winter or resist radiant heat transfer in the summer. While it is acknowledged that bulk insulation has limited the stack effect enough to make small improvements energy efficiency, there has also been another, unrecognized benefit. In addition to energy efficiency, the evidence suggests that adding bulk insulation and limiting the stack effect has also increased the fire resistance of the home.

6.1 Residential Fires

Beginning a few years after the start of the energy crisis, the number of residential structure fires started to consistently decline for the first time in U.S. history. Prior to 1973 the United States led the industrialized world in structure fires, fatalities, injuries, and related property loss (National Commission on Fire Prevention and Control, May 4, 1973). Between the end of the World War II and the start of the energy crisis, the annual number of residential fires had always increased with the population. Before 1973 there was nothing to limit the uncontrolled ventilation of the home. This unimpeded air flow created optimal conditions for structure fires to ignite, grow, and spread quickly out of control. As a direct result of adding insulation, the annual number of residential fires in the United States have declined by over fifty percent (Karter, 2010). Residential energy use and structure fires both began to flatten simultaneously for the first in U.S. history starting in the early to mid-seventies. In 1977 the National Fire Protection Agency (NFPA) began tracking residential fire data on an annual basis. The U.S. fire problem has always been overwhelmingly a residential issue, as noted by the United States Fire Administration (USFA); "Although residential fires continue to represent the main component of the US fire problem, accounting for 75.5% of deaths from 2003-2007, they have declined by 50% since 1977 (USFA, 2011)."

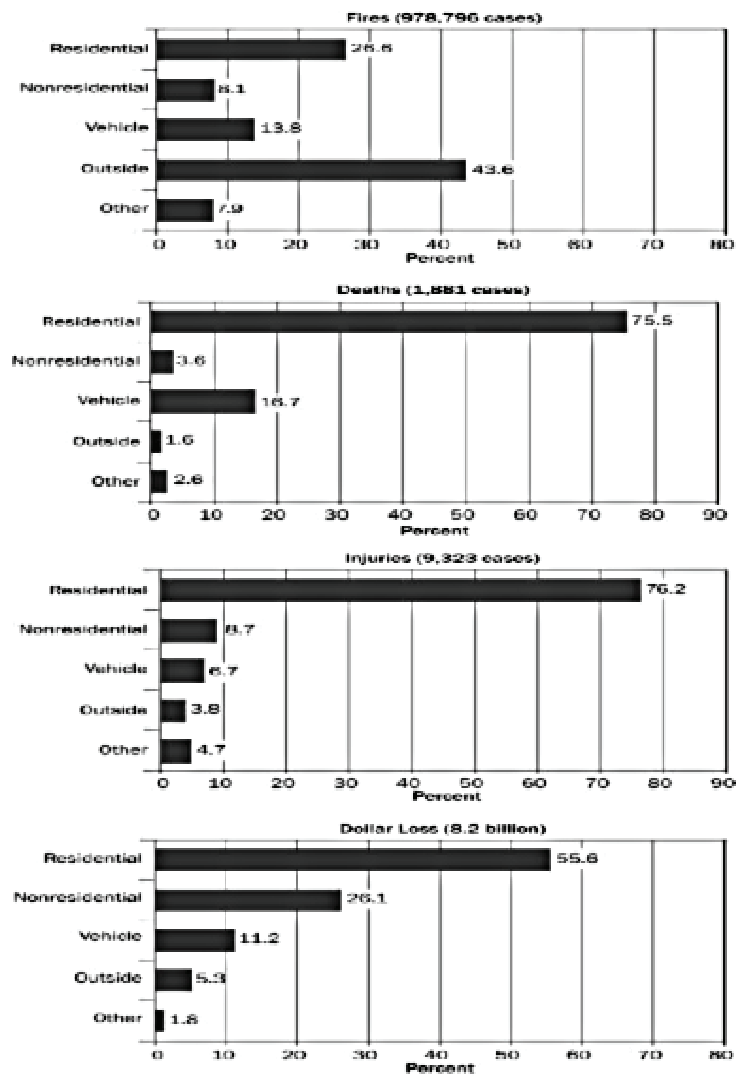


FIGURE 12: Residential fires in the United States. Topical Fire Research Series: One-and Two-Family Residential Building Fires (2007-2009), USFA.

Residential energy use and fire mortality rates have historically followed similar paths, both were positively influenced by insulation's ability to resist the uncontrolled ventilation of the home. A review of the natural mechanisms at work inside of an enclosed structure experiencing a fire provides the explanation for insulations ability to increase the fire resistance of the entire home.

6.2 STACK EFFECT INDUCED FIRES

When a firestorm occurs in nature, the natural convective forces at work in these large outdoor conflagrations are defined by the following accepted definition (figure 13):

"A firestorm is a conflagration which attains such intensity that it creates and sustains its own wind system. It is most commonly a natural phenomenon, created during some of the largest bushfires, forest fires, and wildfires. A firestorm is created as a result of the stack effect as the heat of the original fire draws in more and more of the surrounding air. This draft can be quickly increased if a low level jet stream exists over or near the fire. As the updraft mushrooms, strong gusty winds develop around the fire, directed inward which supply the fire with additional air. This would seem to prevent the firestorm from spreading on the wind, but the tremendous turbulence also created causes the strong surface inflow winds to change direction erratically (Wikipedia, 2015)."

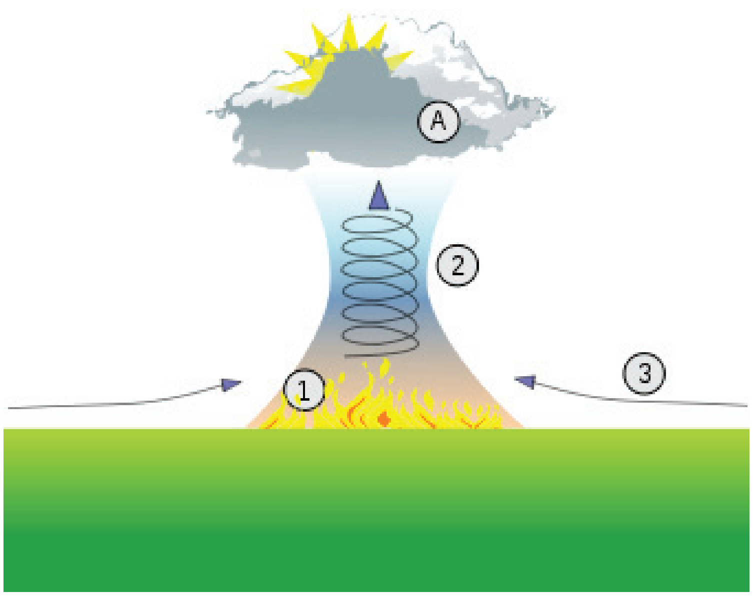
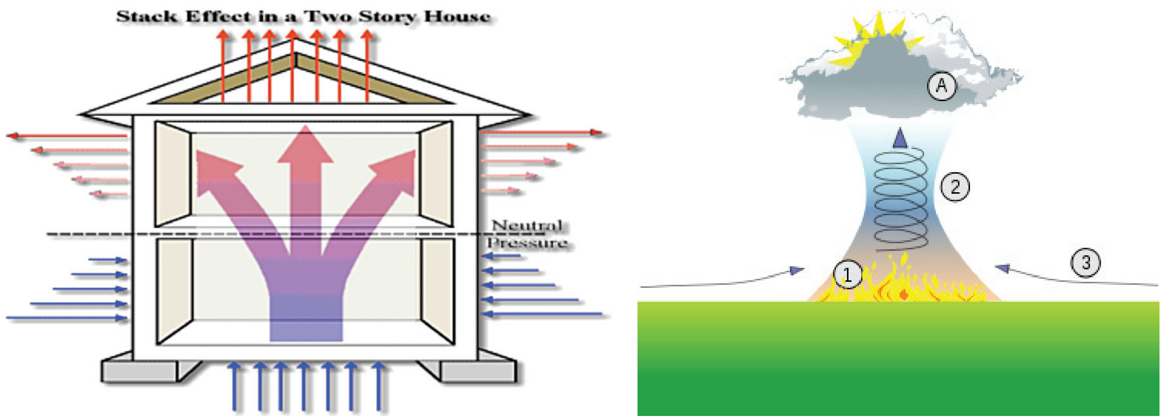


FIGURE 13: Firestorm stack effect system. Reprinted from "Firestorm", Wikipedia, Wikipedia Foundation Inc.

The fires that are able to ignite and grow in an enclosed structure operate on the same basic principles as large firestorms in nature, just on a smaller scale and in an enclosed environment (figure 14). The other difference; when a fire ignites within a structure, a second stack effect system (Fire) is created within an existing stack effect system (Building). These two open systems cannot coexist in the same space, only one will prevail. If prolonged exposure to uncontrolled ventilation results in the structure breaking down, allowing fire extension throughout, the building envelope loses. If the various components of the building envelope can resist the increase in pressure caused by the fire stack effect system, and no external openings are created, the likelihood of the structure surviving is increased.

FIGURE 14: Comparing the stack effect at work inside the Building Envelope and Firestorm Stack Effect in a Two Story House is reprinted from Kinetic Energy Solutions, 2010



The stack effect begins to impact the building envelope when an air pressure difference exists between the interior and exterior. Like a firestorm in nature, the structure fire grows by drawing in air at the bottom while exhausting smoke and heated gases out the top. Rising temperatures inside of a structure fire increases the stack effect pressure on the entire building envelope. If ventilation is not limited, it will lead to rapid fire growth and destruction. The addition of bulk insulation to the building envelope limits this uncontrolled ventilation, improving energy efficiency and fire resistance. Additional evidence in support of this theory is provided by the winter home.

6.3 Winter Fires

The stack effect is at its peak during the winter, when cold heavy outdoor air surrounds warm buoyant indoor air, increasing energy use and fire risk. Structure fires, fatalities, injuries and property loss always peak during the winter months, particularly at the residential level. This is reflected in USFA data;

"Thirty percent of all fires (543,600 averaged over 1996–98) occur during the winter months from November through February. These winter fires average 8,775 injuries, 1,910 deaths, and $3 billion in property loss each year. In residences, however, more fires occur in the winter (37%) than in the other two-thirds of the year. These residential fires are more damaging and deadly than that of all residential fires (USFA, 2001)."

During the heating season, particularly in colder climates, there is constant stack effect pressure on any building trying to maintain a preset temperature. A large air temperature difference between the interior and exterior environment increases the stack effect on the entire building envelope. On the coldest days and night, the number of air changes increase, resulting in dry drafty interiors, high utility bills, and increased fire risk. R-based insulation practices offer varying levels of resistance to convective air loss when heating a structure under these conditions.

Even today, 43 years after the start of the insulation movement, energy efficiency experts compare the loss of heated air through the roof of the typical American home as being comparable to leaving an upstairs window open all winter. That open upstairs window makes for a great chimney in a burning structure, which is why there is an increase in all fire related categories during the winter months. Existing insulation practices can never completely shut this window, but it can make the opening smaller, which will improve the efficiency and fire resistance of the entire structure.

7. CONCLUSION

In 1824 French military engineer Nicholas Leonard Sadi Carnot published a theoretical study titled, "Reflections on the Motive Power of Fire," providing the first scientific explanation for the inner workings of a steam engine. Steam engines had been in use for more than a century, but there was still a poor understanding of how they actually worked; leading to major inefficiencies in their operation. Carnot believed that efficiency could be increased if the operating temperature of the hot reservoir within the engine was also increased. His concepts began to be applied in the late nineteenth century, becoming the basis for advancements of internal combustion engine technology, while impacting many other fields of study. He became recognized as the "Father of Thermodynamics" for the principles outlined in his publication, that resulted in the second law of thermodynamics, which states:

"In all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less that of the initial state (Carnot, 1890)."

Much like the steam engine in 1824, there is confusion related to the structural thermodynamics of the building envelope. This has resulted in major inefficiencies and other negative consequences. While bulk insulation and the R-value rule did provide the critical first step towards reducing residential energy use, they failed to deliver solutions that adequately control thermal loss in the winter or thermal gain in the summer.

A final point to consider when discussing improved residential efficiency strategies, the health of the people living inside. Prior to the energy crisis the majority of homes were uninsulated and hyperventilating most of the time. Indoor air quality, mildew, and mold issues were for the most part non-existent. "Sick building" was an unknown term, uncontrolled ventilation prevented the majority of indoor air quality and moisture related issues that have become common today. Proper attention needs to be given to adequate ventilation and moisture control when planning to improve the energy efficiency of a home. A healthy home will breathe, an inefficient home will hyperventilate, while a sick one tends to suffocate. The R-value rule was critical to the evolution of the energy efficient structure, but the effectiveness of bulk insulation peaked by the time it was passed in 1979. Innovation has been stifled by the R-value. A balanced approach, along with a realistic metric is required to create truly efficient, healthy, and safe homes.

REFERENCES

Applegate Insulation, Inc. (2016). *The Truth About R-value's*. Retrieved from www.applegateinsulation.com270 × 301Search by image on September 20. 2016.

Building Performance Institute, Inc. (2016). *Technically Speaking: Principles of Heat Transfer*. Retrieved from www.bpihomeowner.org414 × 171Search by image on September 20, 2016.

Carnot, Sadi; Thurston, Henry (editor and translator) (1890). *Reflections on the Motive Power of Heat*. New York: J. Wiley & Sons.

CK-12 Foundation (2016). *Convection Currents in the Earth's Mantle*. Retrieved from www.pinterest.com736 × 885Search by image on September 26, 2016

Hankey & Brown Inspection Services (2016). *Ice Dams*. Retrieved from http://www.hankeyandbrown.com/icedams on September 20, 2016.

Karter Jr., Michael J (2010). *Fire Loss in the United States During 2009*. National Fire Protection Agency, Fire Analysis and Research Division, August 2010.

Kinetic Energy Solutions (2010). *Stack Effect*. Retrieved from http://www.kinetikenergysolutions.com/solutions/science/stack_effect_files/stackeffect.gif on May 11, 2010.

Lowe's (2016). How Insulation Prevents Heat Transfer. Reprinted from www.lowes.com230 × 178Search by image on September 20, 2016.

National Commission on Fire Prevention and Control (1973). *America Burning*. May 4, 1973, sec 1, pg. 1.

Owens-Corning (2016). *History*. Retrieved from http://media.owenscorning.com/history on August 5, 2016

Random House, Inc. (2016). *R-value*. Retrieved from http://www.dictionary.com/browse/r-value on October 4, 2016.

U.S. Energy Information Administration (2016). *FAQ: How much energy is consumed in residential and commercial buildings in the United States?* Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=86%t=1 on August 15, 2016.

U.S. Fire Administration (2001). *Topical Fire Research Series: Winter Residential Fires*, Vol. 1, issue13, February 2001 / revised December 2001, pg. 1.

U.S. Fire Administration (2011). *Topical Fire Research Series: One-and Two-Family Residential Building Fires (2007-2009)*. Vol. 12, issue 2, May 2011, pg. 8.